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Editorial

Ancient Greeks and Indians had the conception of atoms. They thought and debated in great lengths about the fundamental constituents of matter. They were limited in what they can do, besides talking, due to the paucity of Particle Accelarators. In the last few decades, this has been rectified. We have many particle accelerators. Particle accelerators are what Feynman described as smashing swiss watches to find out how it works and what's inside. Particle Accelerators smash atoms against each other in the hope of revealing the inner structure and constituents.

Although accelerators were developed for particle physics, many thousands of them are put to practical uses in other branches of scientific research as well as in industry and medicine. The majority of these are small linear accelerators used in factories to polymerise plastics, treat waste and sterilise food, and in hospitals for therapy. In the field of medicine we also find cyclotrons at work producing isotopes to supply the hospitals of the world with modified biological chemicals whose location can be traced in the body by the particles they emit. Some, by their biochemical nature, can even select certain sites in the body for diagnosis or treatment.

There are more than ten thousand particle accelerators in the world from the linear accelerators used for cancer therapy in modern hospitals to the giant 'atom-smashers' at international particle physics laboratories used to unlock the secrets of creation. Many scientists and engineers spend their lives designing, constructing, and operating these machines - yet few universities include the subject of particle accelerators in their curricula. The few courses that do exist and the summer schools run by the big accelerator laboratories lack a simple introduction which covers the essentials of the subject for the many who need to learn how these machines work.

This bulletin fills that gap and takes the reader through each of the aspects of a modern accelerator giving enough information to unlock the door to the subject but does not overload the understanding with mathematics. Anyone with a general interest in modern technology based on a fascinating variety of physics and engineering will find much of interest in these writings by experts in this field.

I am grateful to Dr.S. Kailas, for having willingly approved to do this capacious work as Guest Editor and to all the expert authors for providing articles for the benefit of the members of IANCAS.

G.A. Rama Rao

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An Overview of Accelerator Programmes in India

One of the important aims of modern science has been to acquire a deeper understanding about the fundamental constituents of matter and the forces governing the natural phenomena. Most of our understanding of the structure of the atomic nucleus has come through the study of nuclear reactions caused by the energetic charged particles such as protons, deuterons, alpha particles and heavy ions. However, in order to penetrate the nucleus the kinetic energy of these particles should be larger than the height of the Coulomb barrier caused by the repulsive force between the positively charged nucleus and the impinging charged particle. Particles of higher and higher energies are also needed to investigate the microscopic structure of matter on shorter and shorter wave-length scales. Hence, several types of particle accelerators have been developed and over the years, progress in nuclear and particle physics research has been intimately linked to the advances in accelerators in providing particle beams of different types and increasing energies. These accelerators developed for basic research in the various areas of atomic, nuclear and particle physics are also finding applications in various fields such as analytical science, medicine, industry etc.

Starting with the electrostatic low energy accelerators of the early years, there have been continuous developments in the acceleration methods and technologies which have led to increase in the available particle energy by more than six orders of magnitude in the last sixty years. Our present understanding of the structure of atomic nuclei is largely derived from the research work utilizing the accelerators of different types such as tandem Van de Graaff accelerators, variable energy cyclotrons, synchrotrons and linear accelerators. These machines have served to provide a variety of projectile species with increasingly large energies over the years. For particle physics research, synchrotron accelerators with the colliding beams have also been built to provide the highest collision energy needed for these studies. Today accelerators are capable of providing particles with such small de Broglie wave-length that one is able to probe the very fine details of the structure of nucleon itself to a length scale of 10^{-18} cm or less. Accelerators such as the SPS accelerators at CERN and RHIC at BNL have also provided relativistic heavy ion beams to study nucleus-nucleus collisions at relativistic energies to study the theoretical prediction of phase transition from the hadron matter to the quark-gluon plasma at the very high energy densities reached in these collisions. Presently, a Large Hadron Collider (LHC) machine is under construction at CERN, Geneva for studies at even higher collision energies.

Protons and Heavy Ion Accelerators in India

A million-Volt Cockcroft-Walton accelerator (Cascade Generator) was installed at TIFR, Mumbai in 1953 which provided beams of protons and deuterons of energies upto 1 MeV and beam currents of upto 200 micro-amperes. At SINP, Kolkata a cyclotron modeled after the 38 inch cyclotron at Berkeley (USA) was built and put into operation in April, 1960 with an internal beam of proton. The accelerator based research work took a significant leap in the sixties with the setting up of the 5.5 MV Van de Graaff accelerator at the Bhabha Atomic Research Centre (BARC). By the beginning of eighties, this machine was exploited to its fullest

potential for nuclear physics research and applications. In the nineties, this machine was dismantled and in its place in the same building utilizing the available infrastructure, a 6MV Folded Tandem Ion Accelerator (FOTIA) has been installed, which is being put to use for low energy heavy-ion based research covering interdisciplinary fields. In the seventies, a 2 MV Van de Graaff Accelerator was also put in operation at the Indian Institute of Technology, Kanpur which could provide low energy proton, deuteron and alpha particles and also fast neutrons could be produced by secondary reactions. In the early ninetees, a 2.5 MV Tandem Vande Graaff Accelerator was set up at the Institute of Physics, Bhubaneswar for interdisciplinary low energy heavy ion beam based research.

Subsequently, the 224 cm size cyclotron, first of its kind in India, indigenously developed and set up at the Variable Energy Cyclotron Centre(VECC), Bidhannagar at Kolkata became operational in the late seventies and over the years, this cyclotron has been utilized for a variety of experimental studies. In the recent years, an Electron Cyclotron Resonance (ECR) Ion source for producing heavy ions with high charge state, like O^{5+}, N^{5+}, Ar^{6+} etc. has been set up to inject and accelerate heavy ions in the cyclotron. An Isotope Separator On Line (ISOL) facility has also been set up at VECC for the study of short-lived radioisotopes far away from the β-stability line and to provide in the first phase a Radioactive Ion Beam (RIB) facility of low energy ion beams.

A superconducting cyclotron with bending limit K of 520 is presently under construction at VECC. With this machine, light mass heavy-ion beams with energy about 80 MeV/A and medium mass heavy-ion beams with energy about 20 MeV/A will become available. The experiments with such intermediate energy heavy-ion beams will aim also at the understanding of complex phenomena such as compression of nuclear matter, hydrodynamical flow, multifragmentation, possible liquid-gas phase transitions in nuclei and creation of hot and dense nuclear matter.

In the eighties, a considerable interest had grown globally in the studies of nucleus-nucleus collisions at medium energies. A Medium Energy Heavy Ion Accelerator (MEHIA) was set up in the eighties under a collaborative project of the Bhabha Atomic Research Centre (BARC) and the Tata Institute of Fundamental Research (TIFR) at the campus of TIFR in Mumbai. Scientists from BARC and TIFR have worked together to set up this facility to pursue research in nuclear physics and allied disciplines. The facility is based on a 14 million volt tandem Van de Graaff (Pelletron) accelerator capable of providing beams of accelerated nuclear particles such as protons, alpha particles and different species of heavy ions. With its commissioning in 1989, this became the first accelerator facility of its kind in India to enable scientists to undertake nuclear physics research with medium energy heavy ions. It also enabled new applications in other related fields such as nuclear chemistry, atomic physics and solid state physics. In order to further increase the energy of heavy ions, a superconducting LINAC booster is being added to the pelletron accelerator. The LINAC is based on quarter -wave resonators of OFHC copper coated on its inside surface with thin films of lead to serve as the superconducting material.

A 15 MV pelletron Accelerator facility was set up and commissioned at the Inter University Accelerator Center (IUAC), Delhi in Dec.1990. The IAUC was set up by University Grants Commission to enable university researchers to pursue accelerator based research in various fields such as nuclear physics, atomic physics, material science, bio-science and inter-disciplinary fields. In order to further increase the energy of heavy ions, IUAC is constructing a superconducting LINAC booster based on quarter wave resonators with Nb as superconducting material.

Electron Accelerators for Synchrotron Radiation Sources at RR-CAT, Indore

India's first synchrotron source, a 450 MeV electron storage ring, INDUS-1 became operational at the Raja Ramanna Centre for Advanced Technology (RR-CAT), Indore in 1999. INDUS-1 is designed to provide VUV radiation in the range of 30 – 2000A^o. It is a small ring with a circumference of 18.96 m, and the critical wavelength of the radiation emitted from its four 1.5 T bending magnets is 61 A^o. A 3T wiggler is planned in this ring to provide radiation of critical wave length 31 A^o Source Indus-1.A 2.5 GeV electron ring, INDUS-2, to provide synchrotron radiations in the X-ray region is at present under commissioning.The injector systems, for

both the rings consists of 20 MeV microtron and a synchrotron which can deliver upto 700 MeV electrons, suitable for injection also into INDUS-2. All the accelerator components of INDUS-1 and INDUS-2 have been indigeneously designed, fabricated, characterized and commissioned in house.

INDUS-1, a national facility, is being utilized for research by scientists from national laboratories and academic institutions. INDUS-1 has five beam lines for electron spectroscopy, soft X-ray reflectivity, angle resolved photo-electron spectroscopy, high resolution spectroscopy and for general purpose experiments. The beam lines proposed at INDUS-2 include those for studies of small Angle scattering, trace element analysis, high pressure-x-ray diffraction, high resolution x-ray diffraction, single crystal and power diffraction and proton crystallography.

High Energy Accelerators for Nuclear Energy Applications

In recent years, there is considerable global interest in the development of high power proton accelerators of high energy (~1 GeV) and large current (~10 mA) to generate fission power in a sub-critical core (effective multiplication factor k < 1) by terminating fission chains initiated by spallation neutrons generated by the interaction of high energy protons with a high Z target. Since k <1, such an Accelerator Driven sub-critical reactor system (ADS) opens up opportunities for new reactor concepts by allowing possibilities of reactor cores of any composition of fissile fuels, even consisting of mainly plutonium or Minor Actinides (MA), not permitted in critical reactors due to their small delayed neutron fraction. This makes ADS attractive for incineration of troublesome MA and Fission Product (FP) waste. Safe disposal of nuclear waste is certainly an urgent and important issue to be tackled for further growth of nuclear power, particularly in countries already having a large nuclear power programme; Hence in recent years, there has been considerable upsurge of interest in ADS.

For India which has abundant reserves of thorium, ADS is relevant because one can also exploit its potential to design hybrid reactor systems that can produce nuclear power with the use of thorium as the main fuel.ADS requires a high current (10 mA) proton accelerator of about 1 GeV protons. Thus, harnessing nuclear energy with ADS has to meet new technological challenges involved in the development of a high power GeV proton accelerator, beam window and spallation target. In view of lots of hopes and expectations from ADS, there is presently intense R&D in progress globally. In India also, at present, efforts are underway to develop key accelerator technologies for a high power proton accelerator. As a first step, a low-energy section of a high current proton linear accelerator has been planned at BARC which will consist of an ECR ion source, radio-frequency quadrupole (RFQ) and drift-tube linac (DTL) tanks-all of normal conducting type. This accelerator is designed to deliver several mA of proton beam of about 20 MeV. At RR-CAT, Indore setting up of a major facility of spallation neutron source based on proton synchrotron is under consideration, which will be useful also for ADS related research.

In conclusion, accelerators are needed for basic research in atomic ,nuclear and particle physics ,condensed matter physics and material science ,biology and medicine and several other areas of science and technology. These are also finding applications in various fields such as analytical science ,archeology ,industry and nuclear energy. This short article has focused mainly to give an overview of the accelerator development programmes in India.

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Guest Editorial

Dr. S. Kailas

Charged particle accelerators along with nuclear reactors and lasers are the major tools employed in science and technology programmes. Accelerators primarily developed for basic research in nuclear and particle physics are increasingly being used in a variety of applications in diverse fields. It has a role to play not only in physics research but also in chemical, biological and engineering sciences. The prosperity of a nation is often measured in terms of its per capita energy/electricity consumption. Extensive use of accelerators in science and technology programmes can be another yardstick for a developed country. Accelerators contribute to national development and hence to national security. Accelerator is indeed a fine example of high technology which is driven by science.

In this monograph, we have two articles devoted to linear and cyclic accelerators, related to the two broad categories of accelerator types. Both ion and electron accelerators are dealt with in this summary. To bring out the importance of accelerator in basic sciences, we have chosen its role in astro, nuclear and particle physics, chemical science, material science and radiation biology in the form of articles in these fields. As accelerators have extensive applications, we have also covered their impact in healthcare, agriculture, industry and ultra sensitive mass spectrometry programmes. The programmes at the national synchrotron radiation source – INDUS 1 and 2 based on electron accelerator are covered in an article. The upcoming high energy and high current proton accelerator based Accelerator Driven Sub – Critical System and the related technology in the country is also discussed in a separate contribution. Portable and table top accelerators for a variety of applications are also covered in another article. Over all the effort has been to make the young researchers aware of a wide variety of accelerator concepts and types , their applications and the opportunities for accelerator based research and applications in the country.

I am indeed very grateful to my colleagues who readily agreed to write the articles covering the various subjects in this monograph. It has been an enjoyable experience doing the job as a guest editor, on behalf of IANCAS. All my colleagues that contributed articles in this bulletin join me in complimenting IANCAS for taking the initiative to bring out this monograph on "Accelerators for frontiers in science and technology" which we hope will be well received by the young researchers and the seasoned professionals. I personally thank Dr. Rama Rao, FCD for giving me this opportunity to be associated with this monograph.

Principles of DC and RF Linear Accelerators

Dr. Pitamber Singh *did his M.Sc. from Aligarh Muslim University in 1975 and joined Nuclear Physics Division, BARC in 1976 after one year of Nuclear Orientation programme. He received his Ph.D. degree in Physics from Mumbai University in 1983. In addition to designing and building the first 2 MV Tandem Accelerator, he has made an outstanding contribution in setting up the 6 MV Folded Tandem Ion Accelerator (FOTIA) facility at BARC. He was conferred DAE's Technical Excellence Award for the year 2000 for his excellent contributions towards indigenous development of the accelerator technology in the country. He has more than 200 scientific publications to his credit and is a life member of "The National Academy of Sciences, India". Dr Singh is working on the development of High Intensity Proton Accelerators for ADS programme. Presently, he is Head, FOTIA Section of the Nuclear Physics Division, BARC.*

Shri S.V.L.S. Rao *did his Masters in Physics from University of Hyderabad in 2000 and joined Nuclear Physics Division in 2001 after one year of Orientation programme at BARC. Shri Rao is presently involved in development of High Current Accelerators.*

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Introduction

Broadly speaking linear accelerators are the ones in which particles move on a linear path, which are accelerated by DC or RF fields. The accelerators using DC fields for acceleration of charged particles are Cockroft-Walton [1], Van de Graaff [2] and Tandem accelerators [3]. In DC accelerators the field is electrostatic and hence the kinetic energy gained by charged particles is restricted to the potential energy corresponding to the maximum voltage difference between the terminals. However, in RF accelerators the high energies are achieved by repeated acceleration through steps in energy, which are much smaller than the final energy achieved. Although RF linear accelerators for multi-GeV energies have been built, the highest terminal voltage for which a DC accelerator has been designed so far is 30 MV at Strassburg, France. In the following sections some of the DC and RF linear accelerators are discussed.

DC Accelerators

Cockroft-Walton Accelerator

Cockroft and Walton, in 1932, developed an electrostatic accelerator based upon the voltage multiplier principle. The basic principle of operation is to charge a large number of condensers connected in parallel and to discharge them in series when the

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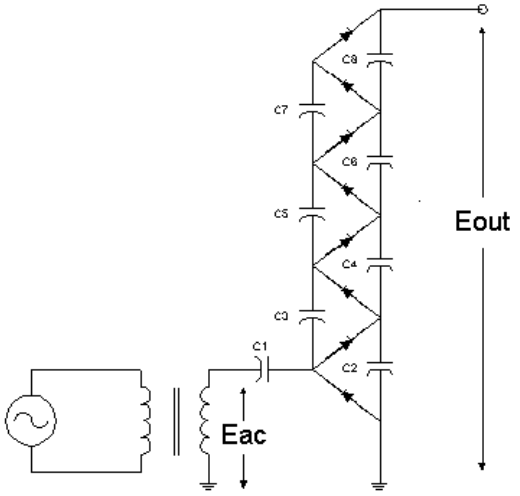

Fig. 1 Schematic of Cockroft-Walton accelerator.

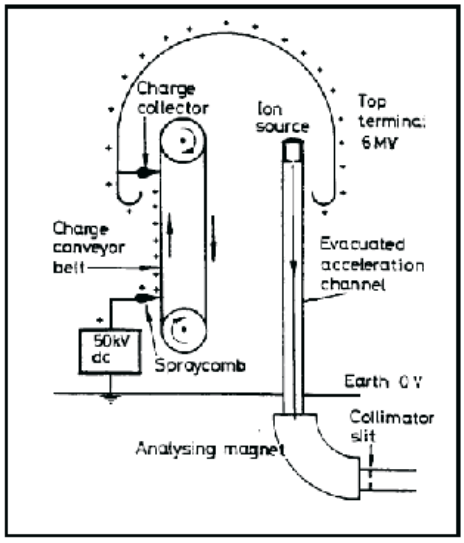

Fig. 2 Schematic of a Van de Graaff Accelerator.

voltage across them is equal to the sum of the voltages on the individual condensers. The schematic diagram of Cockroft-Walton accelerator is shown in Fig. 1.

This machine has the advantage of simplicity of design and construction. The Cockroft-Walton accelerator cannot sustain high voltage gradients because of low electrical breakdown voltage in air. Though the maximum energies, which can be obtained, are low compared with those from other accelerators, it provides fairly large ion currents at constant voltage. It is very useful for experimental work at moderate particle energies.

Van de Graaff Accelerator

The design of this accelerator is based on the principle that if a charged conductor is brought into the internal contact with a hollow second conductor, all of its charge transfers to the hollow conductor no matter how high the potential of the later may be. The schematic diagram of the Van de Graaff accelerator is shown in Fig. 2. It consists of a high voltage terminal supported by an insulating column structure. The entire structure is placed in a pressure vessel filled with insulating gas- normally a mixture of N_2 (80%) and CO_2 (20%). The charge is supplied to the terminal by means of a fast moving insulating belt. Positive charge, spread on the belt at the grounded end, is carried up into the terminal by the belt and is removed by a collector system within the terminal. The high voltage terminal together with pressure vessel forms a capacitor of capacity C. The terminal is raised to a voltage V given by V=Q/C, where charge Q is supplied to it. The maximum voltage to which the terminal voltage can be raised depends on the value of C. The use of gas at high pressure increases the dielectric constant of the medium, which in turn increases the maximum voltage on the terminal.

In the Van de Graaff accelerator the ion source is located in the high voltage terminal and therefore the type of ion sources that can be mounted are restricted due to problems of power and space. Normally, the Van de Graaff accelerators have been used to accelerate protons and alpha particles upto energies of 10-20 MeV.

Tandem Accelerator

In the tandem accelerator the ion source is outside the high voltage terminal and is at ground potential, where unlimited power can be available to produce any kind of ions. In principle even Uranium ions can also be accelerated. In a tandem accelerator (Fig. 3), two accelerating tubes are cascaded together with a common high voltage terminal. Negative ion beam with kinetic energy E_i is injected

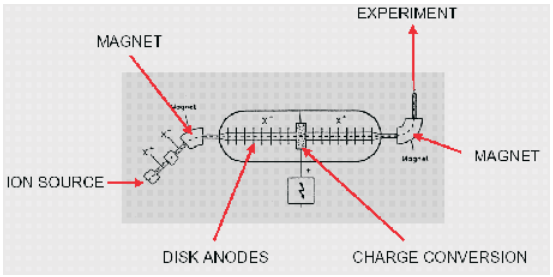

Fig. 3 Schematic diagram of a Tandem accelerator.

at the grounded end of the low energy accelerating tube. The high voltage V achieved at the terminal is used for accelerating singly charged negative ions to energy 'eV' and then to further accelerate the positive ions produced in a foil/gas stripper, located inside the high voltage terminal, to energies qeV, where q is the charge state of the positive ions. The final energy E_f of the beam is therefore $(1+q)eV+E_i$. The stability of the terminal voltage and hence the energy resolution depends on the rate at which the charge is transferred to the terminal. Due to dust and lint produced on the insulating belt, the transfer of charge to the terminal is not uniform leading to instability in the terminal voltage. In recent years, tandem accelerators use metallic pellet chains (Fig. 4) instead of insulating belt for charging the high voltage terminal. This results in uniform transfer of charge to high voltage terminal, which leads to better voltage stability. The tandem accelerators with pellet chain charging system are called Pelletrons [4,5].

RF Linear Accelerators

RF linear accelerators, also called Linacs, range from ones where the particles are accelerated by a succession of distinct gaps to those where a traveling wave produces a smooth, continuous force. Many different electrode structures have been devised and tested, but all have the common feature that their field pattern includes a travelling-wave component whose phase velocity is same as that of the accelerated particles. Since the particle velocity increases as the particle travels through the accelerator, the phase velocity of the accelerating wave must also increase with distance along the accelerating structure. At extreme relativistic energies, when the particle velocity approaches very closely the velocity of light, it becomes possible to equate the phase velocity to the velocity of light, so the design of high-energy electron linear accelerators can be somewhat simpler than that of non-relativistic accelerators used for protons and heavier particles.

Early Designs of RF Linear Accelerators

The first linear accelerator was formally proposed by G. Ising (1924) of Stockholm [6]. It used time-dependent fields and the particles were accelerated by pulsed voltages (generated by a spark discharge) applied across adjacent metallic drift

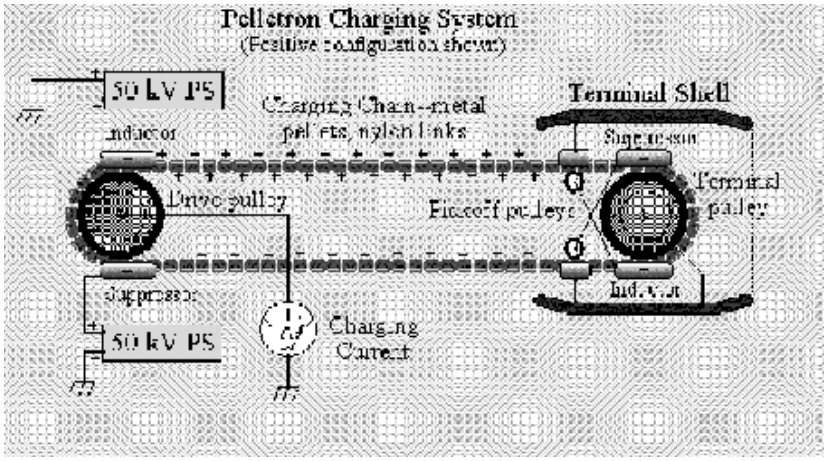

Fig. 4 Pellet Charging System.

tubes, which were arranged in a sequence in a straight vacuum tube. The concept proposed by Ising was not tested at that time and the first successful RF linear accelerator was conceived and demonstrated experimentally by R. Wideroe in 1927 [7]. His accelerating structure was similar in appearance to that of Ising, but his drift tubes were connected alternately to a source of high frequency (1MHz) wave and to ground. The length of the drift tubes and the frequency were chosen such that the ions arriving at the gaps between drift tubes and the fields were in synchronism. When the field was in the opposite (decelerating) direction the particles were shielded by the drift tubes. It was shown that, with an RF voltage of 25 kV, sodium or potassium ions could gain upto 50 keV energy. In 1931, Sloan and Lawrence built a Wideroe type linac with 30 drift tubes and applying 42 kV at a frequency of 10 MHz, mercury ions were accelerated to 1.26 MeV at a beam current of 1μA. By 1934, the output energy had been raised to 2.85 MeV [8], using 36 drift tubes.

The original Wideroe linac concept was not suitable for acceleration of proton and electron beams to high energies. Hence, L. Alvarez [9] proposed a more efficient high frequency proton accelerating structure based on linear array of drift tubes enclosed in a high Q cylindrical cavity which accelerated protons from 4 MeV to 32 MeV. At about the same time at Stanford, a disk-loaded or iris-loaded waveguide [10] consisting of an array of pillbox resonators was proposed for relativistic electrons. This development eventually led to the 3 km long linac at Stanford Linear Accelerator Center (SLAC), where electrons were accelerated to 50 GeV. From these two projects were born the first modern proton and electron linac.

General Properties of Accelerating Structures

For a given RF structure the safe limit to the value of peak surface electric field depends on the operating frequency f_0 and is given by Kilpatrick [11]:

$$f_0 = 1.64\, E^2 \exp\left(-\frac{8.5}{E}\right)$$

where f_0 is in MHz and E is the value of the surface electric field in MV/m.

A good accelerating structure should exhibit a large accelerating field with limited RF power and good stability of the RF field. For a given accelerating field, the EM field distribution should be such that the peak surface field is less than the limit provided by the Kilpatrick criterion. Also the structure should be insensitive to the perturbations, both intrinsic (beam loading, transient phenomenon) and extrinsic (mechanical). Some of the fundamental cavity parameters are listed below.

(a) Transit-time factor (T)

The energy gain of a particle in a time varying field is always less than the energy gained in a constant dc field equal to that seen by a particle in the centre of the gap. This is known as transit-time effect. The transit-time factor is the ratio of the energy gained in the time varying field to that in a dc field of voltage $V_0\cos\phi$, where ϕ is the synchronous phase. Therefore, the energy gained in an RF gap is given by

$$\Delta W = qV_0 T\cos\phi$$

where T is the transit-time factor defined by

$$T = \frac{\int_{-L/2}^{L/2} E(0,z)\cos\left(\frac{2\pi z}{\beta\lambda}\right)dz}{\int_{-L/2}^{L/2} E(0,z)dz}$$, L being the cell length.

(b) Effective shunt-impedance (Z_{eff})

The effective shunt-impedance of the structure indicates the efficiency of acceleration for a given dissipated RF power per unit length.

$$Z_{eff} = \frac{(E_0 T)^2}{-dP/dz}\ \text{M}\Omega/\text{m}$$

(c) Quality factor (Q)

The Quality factor is defined as the ratio of the energy stored in the cavity to the energy lost due to RF dissipation in the cavity per radian of the RF cycle.

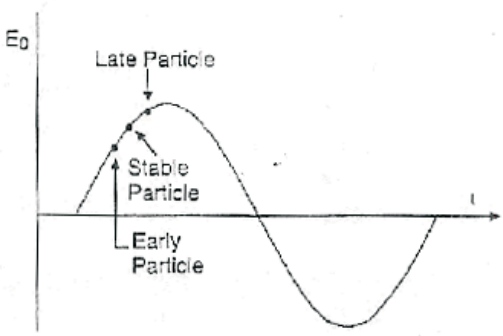

Fig. 5 Phase stability of linac.

$$Q = -\frac{\omega U}{\left(\frac{dP_z}{dz}\right)}$$

where U is the energy stored in the cavity.

(d) Duty factor (η)

The duty factor indicates the fraction of time during which the accelerator is in active mode. It is given as the product of the pulse length and repetition rate.

(e) Group velocity (v_g)

Group velocity is defined as the velocity at which the RF energy flows through the accelerator.

$$v_g = \frac{P}{W}$$

where P = power flowing in the structure and
W = energy stored per unit length.

Phase Stability

(a) Longitudinal Particle Dynamics

For efficient acceleration of all particles, the first requirement is to have a wave with an electric field component in the direction of the beam, and with a wave velocity equal to the intended speed of all the particles. Particles on the appropriate half of the wave will be accelerated, and if the peak electric field exceed a certain threshold depending on the rate of increase of wave velocity, there will be two phases as shown in Fig. 5, at which a particle can stay, moving along with the wave and gaining velocity at the same rate as the wave.

In the neighbourhood of $-\phi_s$ there is "phase stability", since the early particle will gain energy more slowly, become slower than the wave, and drift back towards $-\phi_s$; while the late particle receives some extra acceleration and will tend to catch up. As a result, particles close to $-\phi_s$ will oscillate about the synchronous phase $-\phi_s$, gaining energy on the average at the correct rate. On the other hand, ϕ_s is an unstable point; particles a little away from it will be driven still further away.

In practice, proton and heavy ion-linacs operate in the regime of phase oscillations. Therefore, a section of proton linac will only accelerate over the designed range of energies, and its RF level must be above threshold; while a section of v = c electron linac will accelerate any sufficiently relativistic particle at any RF level. The phase stability necessitates the pre-bunching of the beam for efficient acceleration [12].

(b) Transverse particle dynamics

The phase stability, which is especially important for ion-linacs, results in transverse RF electric fields that defocus the beam. Longitudinal acceleration and bunching of the beam will take place in the 1st quadrant of the RF wave and transverse focusing will take place in the 2nd quadrant. Since, simultaneous acceleration and transverse focusing of particles is not possible, external transverse focusing elements have to be used. This is normally done by using magnetic quadrupole lenses mounted inside the drift tubes of linacs.

Accelerating Structures

(i) Travelling-wave structure

Traveling-wave structures are mainly used for the acceleration of relativistic electrons. These linacs consist of a sequence of identical tanks, each consisting of an array of accelerating cells separated by the irises. The electromagnetic wave is launched at the input cell of each tank; the wave propagates along the beam direction, and beam bunches are injected along the axis for acceleration by the wave. The electromagnetic energy is absorbed by the conductor walls and by the beam, and the field amplitude attenuates along each tank. At the end of

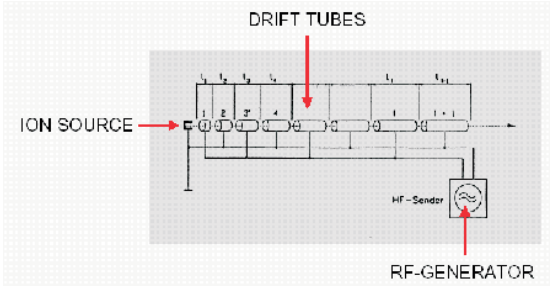

Fig. 6 Wideroe or Sloan-Lawrence structure.

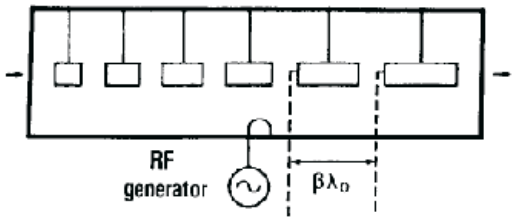

Fig. 7 Alvarez Drift tube linac.

each tank the remaining energy is delivered to an external resistive load.

(ii) Standing-wave structure

Standing wave structures make use of a waveguide, which is axially resonant so that there are waves travelling in two opposite directions from one gap to the next in the same time as the particle moves that distance. Thus, both the forward and the backward waves are synchronous with the beam, arriving at the gaps at the right time for acceleration. The fields in the standing-wave structure build up in time and therefore some time must be allowed for the fields to build up in the resonant structure to essentially equilibrium values before the particles are injected. These structures are mainly used for the acceleration of ions and non-relativistic electrons. Some of the standing wave structures used for the acceleration of ions are discussed below.

(A) Wideroe Linac

The Wideroe linac is used for acceleration of heavy ions with velocity below 0.03c, for which a relatively low frequency structure, usually < 100 MHz is needed to keep the gap spacing practical and to maintain a large aperture without reducing acceleration efficiency. The beam moves within an array of hollow cylindrical electrodes to which an RF voltage is applied. Acceleration takes place in the gaps between the electrodes. The characteristic property of the Wideroe linac is that the voltages applied to successive electrodes alternate in signs as shown in Fig. 6.

The electric field reverses in successive gaps, giving the Wideroe linac the appearance of a π-mode standing-wave structure. The linac is designed so that the synchronous particle with velocity $\beta_s c$ travels from the centre of one gap to the centre of the next gap in half an RF period. Hence, the cell length is $L=\beta_s\lambda/2$. An example of this structure is the 27-MHz Wideroe at the UNILAC linac [13] at GSI, Germany.

(B) Alvarez Linac

In Alvarez structure, the fields in all cells have the same phase so that the multicell structure can be said to operate in a 0 or 2π-mode. The resulting accelerating structure is known as Drift Tube Linac (DTL), which operates in TM_{010} mode. The length of the drift tubes is designed so that the synchronous particle with velocity $\beta_s c$ traverses each of them in one full RF period. Consequently, the cell length is $L=\beta_s\lambda$. The Alvarez structure is shown in Fig. 7, and is very efficient for $0.05<\beta<0.3$.

(c) Coupled-cavity Linac

The Coupled-Cavity Linac (CCL) consists of a linear array of resonant cavities coupled together to form a multicavity accelerating structure. It is used for acceleration of higher velocity beams of electrons and protons in the typical energy range $0.4<\beta<1.0$. The individual cavities are called cells, and each cell usually operates in a TM_{010} like standing wave mode. A CCL cell is only half as long as DTL cell at the same velocity; however unlike DTL cells, CCL cells have end walls on which additional power is dissipated. For low velocities the wall power loss is the disadvantage for the CCL, which favours the more open DTL structure, whereas at higher velocities the transit-time factor effect favours the CCL. The schematic of the CCL is shown in Fig. 8.

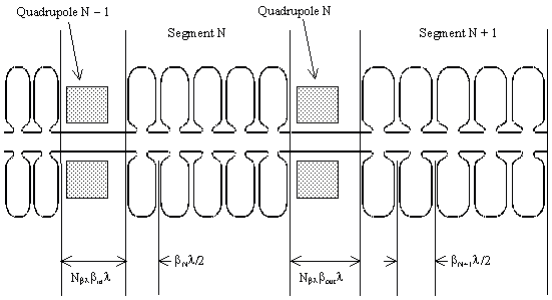

Fig.8 Schematic of CCL.

(d) IH-DTL Structure

Room temperature IH-DTL (interdigital H-mode or $H_{11(0)}$) structures are used at different places now for the acceleration of heavy ions with A/q ratios up to 65 and velocities between 0.016c and 0.1c. These structures have a high shunt impedance due to smaller drift tubes and allow the acceleration of very intense beam at high accelerating gradients. The high current injector at GSI [14] consists of the first IH-DTL (Fig. 9) structure for heavy ions.

(e) CH-DTL Structure:

The CH-DTL (Cross H mode or H_{21}) can operate at higher frequencies (175-800 MHz) compared to IH-DTL structures and can accelerate ions to higher energies. The mechanical rigidity of the CH-DTL [15] cavity is far better than IH-DTL cavity, however they are yet to be tested. These structures are more efficient for beam energies upto 150 MeV per nucleon. The schematic of the CH prototype DTL is shown in Fig. 10.

(f) Radio frequency quadrupole (rfq):

Earlier conventional buncher cavities were used to bunch the beam, before injection into RF linacs. The bunching efficiency of these buncher cavities was less than 50%, resulting in poor transmission. The Radio Frequency Quadrupole (RFQ) accelerator was proposed by Kapchinsky and Tepliakov [16], which bunches the beam adiabatically, resulting in a bunching efficiency and transmission more than 90%. It is the only RF structure, which can accept the incoming DC beam

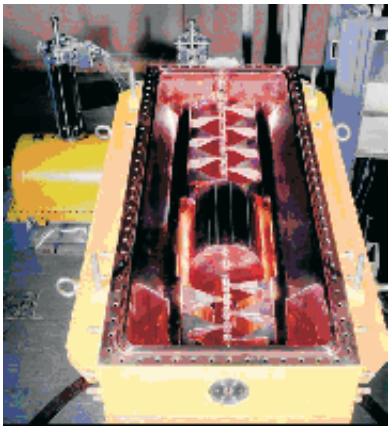

Fig. 9 Prototype of IH-DTL cavity.

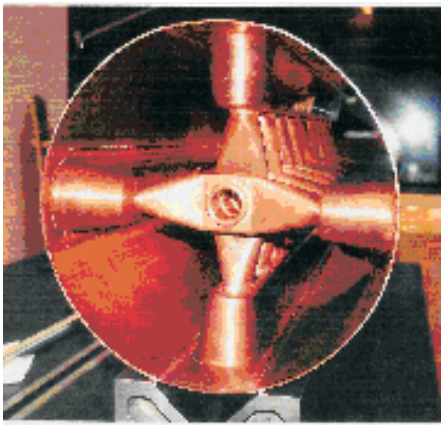

Fig. 10 Prototype of CH-DTL cavity at IAP, Frankfurt.

and simultaneously focus, bunch and accelerate the beam to high energy. The vanes of the RFQ are modulated along the longitudinal direction in order to provide longitudinal field for acceleration. These structures are well suited for acceleration of beam in the velocity regime of about 0.01c-0.06c. Because of these attractive features, RFQ's are presently being used world wide as a low energy injector for high intensity linacs. There are two types of RFQ structures: a) four rod structure, which is used at lower frequency for heavy ions and (b) four vane structure, which is used at higher frequency for lighter ions. The schematic of four-vane and four-rod structures are shown in Fig. 11.

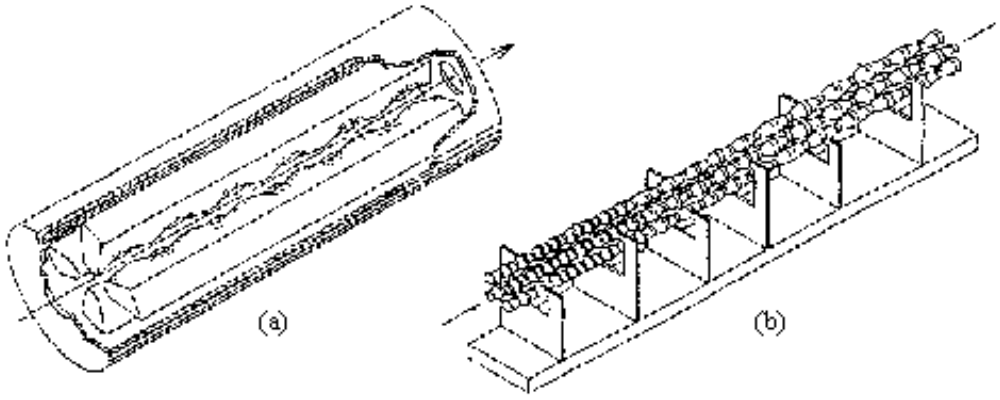

Fig. 11 (a) four-vane (b) four-rod RFQ structures.

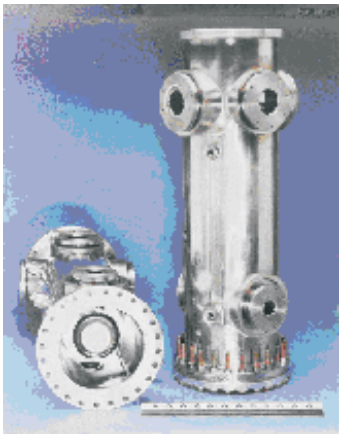

Fig. 12 Quarter wave resonator.

Fig. 13 Split loop resonator

(g) Superconducting rf linacs

One of the disadvantages of conventional copper-cavity linacs is the large RF power required because of ohmic power dissipation in the cavity walls. As a result, the costs of RF equipment and ac power for accelerator operations are high, so the normal conducting structure becomes inefficient. In order to overcome this problem the superconducting linacs have been considered, where the RF power dissipation is very less compared to copper cavity, so these structures become more efficient for acceleration. The shunt impedance for these cavities is very high, so the high electric field gradients can be obtained for a given power. As a result the length of the accelerator reduces. The Q factor for these cavities are very high (~10^8), so these structures are very sensitive to the frequency perturbations.

(h) Superconducting linac booster

In most of the tandem accelerators (Pelletron) facilities, the accelerated heavy ions are further accelerated using superconducting linac boosters. Different types of structures like quarter-wave resonators (Fig.12) [17,18], split loop resonators (Fig. 13) [19] etc. have been used for this purpose. The resonating structures are formed either of bulk niobium or coated internally with lead/niobium. It has been seen at Legnaro, Italy the higher accelerating gradients are achieved in the resonators built using bulk Niobium.

(iii) Linear collider

In fixed target experiments, all the energy of the accelerated particles is not available for exploring the high-energy frontiers. Achievement of

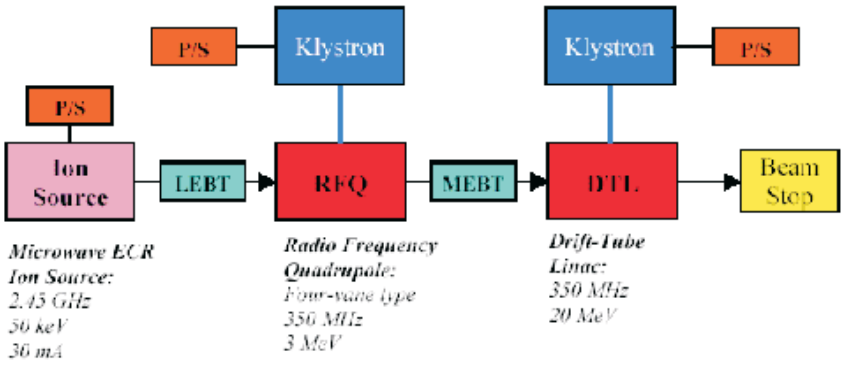

Fig. 14 Schematic of 20 MeV High Intensity Proton Accelerator being built at BARC, Mumbai.

highest centre of mass energies is possible if experiments are performed in a frame in which the centre of mass of the colliding particles is at rest. This is possible in a collider setup. A 100 GeV linear e^- - e^+ collider, also called the Stanford Linear Collider (SLC) was built at SLAC in 1989. A 1 TeV e^- - e^+ linear collider (JLC) has been proposed at KEK, Japan and design studies are in progress. The active linac length per beam of this collider is 11.5 km. A Next Linear Collider (NLC) [20] of energy 1 TeV and active linac length per beam of 7 km has also been proposed at SLAC.

Advantages of Linear Accelerators

The main advantage of a linear accelerator over circular accelerator is its capability for producing high-energy, high-intensity charged particle beams of small diameter and small energy spread. Since, the beam traverses the structure in a single path, repetitive error condition causing destructive beam resonances are avoided. Also, there is no power loss from synchrotron radiation, which is a limitation, particularly for high-energy electron beam in circular accelerators. Besides, injection and extraction are simpler than in circular accelerators, since the natural orbit of the linac is open at each end; special techniques for efficient beam injection and extraction are not needed. The linac can operate at any duty factor, which results in acceleration of beams with high average current. Linacs have therefore become the obvious choice for Accelerator Driven Systems (ADS) [21], which are being developed for a) energy generation, b) transmutation of nuclear waste and c) breeding of the fissile material. The practical realization of ADS requires development of a high energy (~1GeV) and high current (>10 mA) proton accelerator [22]. One of the most challenging parts of such a CW proton accelerator is development of the low-energy injector, typically up to 20 MeV, because the space charge effects are maximal at these energies. With this in mind, BARC has initiated the development of a Low Energy (20 MeV) High Intensity Proton Accelerator (LEHIPA) as shown in Fig. 14, as front-end injector of the 1 GeV accelerator for the ADS programme [23,24]. The major components of LEHIPA are a 50 keV ECR ion source, a 3 MeV RFQ and a 20 MeV DTL. The physics design of LEHIPA has been completed and fabrication of its prototype is in progress.

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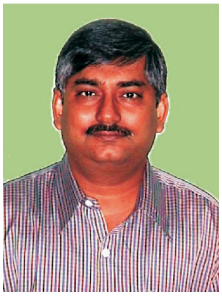
Cyclic Particle Accelerators

Dr R.K. Bhandari *is a leading accelerator scientist and technologist of the country. Born in 1948, he is a Ph.D in Science with specialization in the field of accelerator physics. He was a prominent member of the team that constructed the largest accelerator of India i.e. the Variable Energy Cyclotron (VEC). He was instrumental in developing an advanced Electron Cyclotron Resonance (ECR) heavy ion source for the VEC. He is the key scientist behind construction of the superconducting cyclotron at the Variable Energy Cyclotron Centre (VECC). He is also leading the team that is setting up a medical cyclotron for radio-pharmaceutical production in Kolkata. Dr. Bhandari is Associate Director of VECC and Director of the Superconducting as well as Medical Cyclotron Projects at VECC.*

Dr V. S. Pandit*, M.Sc. (Physics) from Magadh University Bodh Gaya (Bihar) in 1980, joined joined accelerator physics group at VECC, Kolkata in 1981 through 24th batch of BARC Training School. Since then he has been working on design and development in the cyclotron field. He received his Ph.D degree from University of Calcutta in accelerator physics. Dr Pandit has made important contributions in the development of variety of ion beams at VECC for experiments. He is a leading accelerator physicist at VECC contributed both theoretically and experimentally in the beam dynamics calculations of central region of cyclotrons, design of bunchers, inflectors, space charge simulations, measurement of beam phase space etc. At present he is working on the beam dynamics of space charge dominated beams and development of high current cyclotrons.*



Introduction

The basic aim of building the particle accelerators is to generate streams of nuclear particles with high kinetic energy. These energetic particles are then used for basic science experiments to investigate structure of matter or commercially for material processing, food preservation etc. They are also used for cancer therapy and production of radioisotopes for medical diagnostic applications. Accelerators impart energy to the charged particles utilizing the electromagnetic fields. Their motion is governed by the Lorentz force equation given by:

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} \qquad (1)$$

where, q is the charge of the particle of mass m moving with velocity. Here and are the electric and magnetic fields, respectively. The rate of change of kinetic energy is given by:

$$\frac{dT}{dt} = \frac{d}{dt}\left(\vec{F} \cdot d\vec{S}\right) = q\vec{E} \cdot \vec{v} + q\left(\vec{v} \times \vec{B}\right) \cdot \vec{v} \qquad (2)$$

It is clear from the equation (2) that there is no change in the kinetic energy of the particle in a constant magnetic field and in an electric field that is perpendicular to the direction of the velocity of the particle. Thus, an electric field along the direction of motion of particles is essential for them to gain energy and this fact is common to all accelerators. This electric field can be produced by dc voltage or by time varying voltage or by time varying magnetic field. Various methods to generate electric field and different ways of utilizing it to accelerate particles led to the developments of various kinds of accelerators.

The term circular accelerator refers to any machine in which particle beams describe a closed orbit. In all the circular accelerators, a vertical

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magnetic field is used to bend particles trajectories and one or more radio frequency (rf) gaps are used to accelerate the particles that pass through the same acceleration gap several times. Thus, a high kinetic energy can be achieved with relatively low rf voltage. The main characteristic of circular accelerators is synchronization (resonance) between the frequency of accelerating fields and the frequency of particle revolution. There are two broad categories of resonant circular accelerators: cyclotrons and synchrotrons.

A cyclotron has constant magnetic field and constant rf frequency. Cyclotrons can be used to accelerate ions only. However, microtron, also known as electron cyclotron, is a special case of cyclotron used to accelerate electrons. Relativistic effects limit maximum beam energy from a conventional cyclotron. Azimuthally Varying Field (AVF) cyclotron is a major improvement over the uniform field cyclotron for acceleration of relativistic ions. A separated sector cyclotron is a special case of AVF cyclotron. Superconducting cyclotrons are also AVF cyclotrons where the magnetic force is supplied by using superconducting coils instead of copper coils consuming little power and produce high magnetic field. A synchrocyclotron is a special case of uniform field cyclotron where rf frequency is modulated to maintain the particle synchronization into the relativistic regime to accelerate particles to very high energy.

In synchrotrons both the magnitude of the magnetic field and the rf frequency are varied to maintain a synchronous particle at a constant orbit radius. Here the bending and focusing fields are only over a small ring-shaped volume. This minimizes the cost of the magnets, thus allowing construction of large-diameter machines. Synchrotrons are used to accelerate both ions and electrons. Depending upon how the focusing forces are achieved to confine the particles around the orbit, a synchrotron can be a weak focusing synchrotron or a strong focusing synchrotron. In the modern synchrotrons, known as separated function synchrotrons, bending magnetic field is obtained by bending magnets and quadrupole magnets placed between the bending magnets provide the transverse focusing field. A storage ring is also a synchrotron where magnetic fields are constant in time. Here energetic particles are 'stored' at constant energy for very long periods of time. A collider is dual synchrotron or dual storage ring where particles moving in opposite directions are made to collide head-on at a number of positions on the circumference of the machine for high energy physics experiments.

In this article we will discuss the basic principles of cyclotrons and synchrotrons and briefly give an idea of the relevant technologies. We shall also describe the latest developments in the field on the Indian scene. For more details readers are advised to see the references.

Cyclotron

E.O. Lawrence originated the concept of the cyclotron accelerator in 1929. It is based on a combination of rf acceleration and bending of charged particles in a magnetic field. This way the same electrode is used over and over again to give acceleration to the particles. Lawrence built the first cyclotron in 1931 and it produced proton beam of 1 MeV energy.

The basic operating principle of a cyclotron is shown in Fig. 1. Particles are accelerated in spiral paths inside two semicircular, flat metallic electrodes called dees (D's). The dees are connected to an rf generator and are placed in a nearly uniform magnetic field. Charged particles are produced by an ion source located at the centre of the cyclotron between the dees and extracted by a puller electrode at the same potential as the dee. The magnetic field causes the particles to move in a plane called median plane in approximately circular orbits inside the dee and across the gap between them. At each gap, particles are accelerated and, therefore, they follow a spiral path as they gain energy. This is because the radius of orbit, being a function of the particle velocity, increases with time. At the edge of the magnet, full energy particle beam is pulled out (extracted) as an external beam by an electrostatic deflector. The dees, deflector, ion source etc are enclosed in a flat vacuum chamber where a low pressure of the order of $\sim 10^{-6}$ torr is maintained. High vacuum is essential to generate high voltages on dee and deflector as well as to avoid the beam loss by scattering during acceleration.

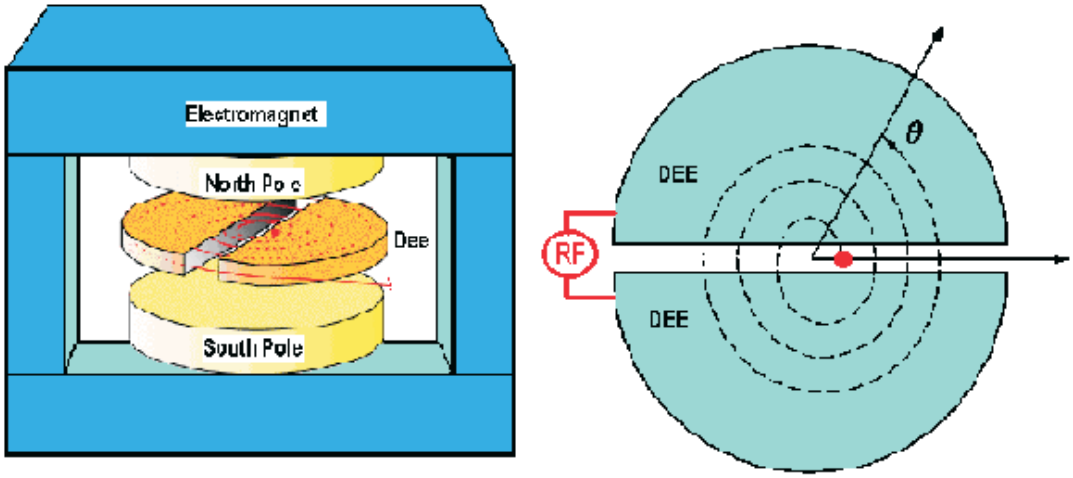

Fig. 1 Schematic layout of a cyclotron, showing the two dees (hollow semi-circular electrodes for acceleration), driven by an rf power source. The charged particles move on a spiral orbit from their point of creation in an ion source located in the centre.

If r be the radius of the circular path of a particle of mass m and charge q moving with velocity v in a magnetic field B, then at every instant the force due to magnetic field supplies the centripetal force required for a circular path. The basic equations are:

$$\frac{mv^2}{r} = qvB, \quad p = mv = qBr, \quad \omega = \frac{qB}{m} \qquad (3)$$

The orbital frequency ω depends only on B and is independent of the energy of the particle as long as m is constant. For a given B, orbit radius r is proportional to momentum p of the particle. If the voltage on one dee is $V = V_D \cos(\omega_{rf} t)$and on the other dee it is 180° out of phase $\omega_{rf} = \omega$ and if, then a particle that starts out at right time (at the peak of rf) will experience an increase in the kinetic energy $\Delta T = 2qV_D$ each time it crosses the gap. The particle does not experience the electric field except while crossing the gaps

Resonance condition

For repeated acceleration, we need resonance between the particle revolution frequency and the accelerating rf frequency i.e.

$$\omega_{rf} = \omega \quad \text{or} \quad \omega_{rf} = h\omega \qquad (4)$$

Here, h=1,2,3,…. is known as harmonic number. Cyclotrons are operated in harmonic mode h>1 mostly for heavy ion acceleration where the revolution frequency is, generally, low. Resonance condition must be fulfilled throughout the acceleration process. Any discrepancy between particle revolution frequency ω and rf frequency ω_{rf} results in a phase shift ϕ between the beam and the driving rf given by:

$$d(\sin\phi) = 2\pi hn \frac{\omega_{rf} - \omega}{\omega} \qquad (5)$$

where, n is the number of turns. In this case particles will receive an increase in the kinetic energy $\Delta T = 2qV_D \cos(\phi)$ each time it crosses the gap. The limit of acceleration occurs when ϕ reaches the value $\pm 90^0$. Particles are decelerated and lost if the phase is beyond $+90^0$ or -90^0.

Final kinetic energy of the particle

As long as the particles do not reach relativistic energies the maximum achievable kinetic energy depends on the type of the particle, the magnetic field B, and the maximum orbit radius R (extraction radius) possible in the cyclotron and is given by:

$$T = \frac{1}{2} mv^2 = \frac{q^2B^2R^2}{2m} = \frac{e^2B^2R}{2m_p} \cdot \frac{Q^2}{A} = K \cdot \frac{Q^2}{A} \quad (6)$$

where, e is electronic charge, m_p is the mass of proton, A and Q are the mass and charge numbers of the ion, respectively. K is, generally, called the K-value or K-bending of a cyclotron. It is measure of the maximum rigidity that a particle can achieve in the cyclotron. The final kinetic energy can also be, roughly, expressed in terms of dee voltage V_D as:

T = number of turns × energy gain /turn
= n × 2qV$_D$

Orbit Stability

In a truly uniform magnetic field particle orbits have no stability in the axial direction. A particle moving with even a small component of velocity in the axial direction will soon strike the inside of a dee and be lost. Moreover, in a nominal beam current (μA), there are trillions of particles that repel each other due to coulomb repulsion. It is, therefore, necessary to provide some additional field components so that particles, which have an upward or downward velocity component must feel a stabilizing force back towards the median plane.

Classical Cyclotrons

In the earlier cyclotrons (before 1955) designers used to provide axial (vertical) focusing to the beam by decreasing the average magnetic field with radius. It is easy to see from Fig. 2 how a field decreasing with radius is associated with a convex field pattern that provides restoring force towards the median plane whereas a field increasing with radius does the opposite.

In this kind of magnetic field, particles away from the designed orbit or equilibrium orbit execute simple harmonic motion about the equilibrium orbit in axial and radial directions and remain confined. These oscillations are known as betatron oscillations. Focusing forces in axial and radial directions in a cyclotron are characterized by two dimensionless parameters, ν_z and ν_r, known as betatron tunes, respectively. They represent the number of oscillations per revolution and are given by:

$$\nu_z = \frac{\omega_z}{\omega} = \sqrt{n} \qquad \nu_r = \frac{\omega_r}{\omega} = \sqrt{1-n} \quad (7)$$

where, $n = -\frac{r}{B}\frac{dB}{dr}$, is called the field index. Stability in both the directions corresponds to real values of ν_z and ν_r and thus field index must satisfy the inequality $0 \leq n \leq 1$. This corresponds to a magnetic field decreasing with radius.

Limitations of Classical Cyclotrons

The resonance condition requires that ωrf = ω = qB/m should be constant throughout the acceleration. This is in conflict with the axial focusing requirement (B should decrease as radius r increases), as discussed above. The situation is in fact worse than this because of the relativistic variation of mass with velocity. As the energy of the particle increases, so do the mass and the radius of the orbit r. As a consequence, ω does not remain constant as higher radii. If particle revolution frequency is different from rf frequency there is a shift of phase and particle will not reach the accelerating gaps at the proper time. As a consequence of phase shift a limit will be reached where there will be no acceleration. The maximum kinetic energy of ions in a classical cyclotron is limited to ~2% of the rest mass energy of the particle.

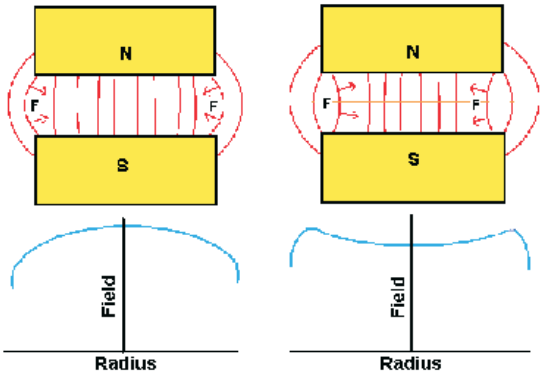

Fig. 2 The magnetic field in the magnet gap, showing the focusing and defocusing forces due to the decreasing and increasing field with radius.

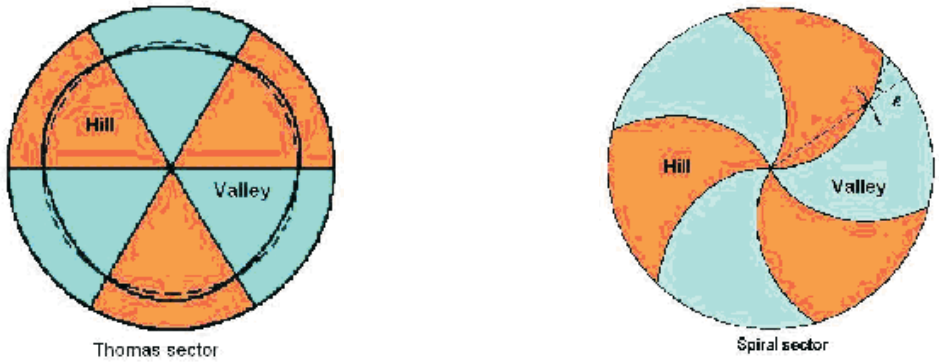

Fig. 3 Geometry of the magnet pole faces of a straight sector and spiral sector AVF cyclotrons. Solid line shows the scalloped particle orbit oscillating around a perfect circle (dashed line).

It is clear from the resonance condition that either the rf frequency or the magnetic field or both must be modified to compensate for the increasing mass in order to have beam particles arrive at the gap in phase. The former is done in a synchrocylotron. These machines are not built now-a-days due to complexity and limitation on beam intensity.

Azimuthally Varying Field (AVF) Cyclotron

The conventional cyclotron cannot accelerate ions to very high energy due to the loss of synchronization caused by the relativistic increase in mass of the ion. The synchronization between ω and ω_{rf} can be preserved only if the average magnetic field increases with radius. This leads to the axial defocusing. In order to provide vertical stability an extra source of axial force is required. One way is to introduce azimuthal variation in the magnet field (first proposed by L.H. Thomas in 1938). Thus came the AVF cyclotron on the scene.

In an AVF cyclotron the orbital frequency is maintained constant i.e. $\omega = \omega_{rf}$ by increasing the average magnetic field according to:

$$\langle B(r)\rangle = \gamma B_0 = \left(1+\frac{T}{E_0}\right)B_0 = \frac{B_0}{\sqrt{1-(r/r_0)^2}} \qquad (8)$$

where, γ is the well known relativistic factor ($m=\gamma m_0$), is the magnetic field at the center of the cyclotron and $r_0 = c/\omega$. The magnetic field with this feature is called isochronous field. Such a field profile gives an axial defocusing given by:

$$\Delta\nu_z^2 = -\frac{r}{\langle B\rangle}\frac{d\langle B\rangle}{dr} = -\beta^2\gamma^2 = -(\gamma^2-1) \qquad (9)$$

In order to achieve the axial stability, magnet pole faces are contoured to provide an azimuthal variation in the field strength. In practice this can be achieved by dividing the poles into N symmetrical straight sectors (see Fig. 3) each consisting of a hill with small gap and high field B_H and a valley with large gap and low field B_V. The different radii of curvature in hill and valley lead to a scalloped closed orbit oscillating around a perfect circle. This implies a radial velocity component v_r, strongest at the hill valley boundary where the hill-fringing field provides B_θ component. The combined effect is an axial focusing force at every hill valley boundary. This is called Thomas focusing and its contribution to the axial focusing is:

$$\Delta\nu_{zT\,homas}^2 = F^2 = \frac{\left(B_H-\langle B\rangle\right)\left(\langle B\rangle - B_v\right)}{\langle B\rangle^2} \qquad (10)$$

An additional axial focusing force can also be obtained from the field pattern produced by spiral shaped sectors. In this case at every hill-valley boundary the fringing field has a radial component B_r with a gradient that points in at one edge and out at the other. While passing through these radial fields, a particle with azimuthal velocity v_θ , experiences a focusing force at one edge and defocusing force at the other. The net effect is focusing due to the alternating gradient principle (discussed in

synchrotron). The contribution of spiral effect to the axial focusing is:

$$\Delta\nu^2_{zspiral} = 2F^2 \tan^2 \varepsilon \qquad (11)$$

where, ε is known as the spiral angle, which at any point is defined as the angle between the radius vector and tangent to the spiral at that point. Adding all the contributions we have

$$\nu_z^2 = -(\gamma^2 - 1) + F^2 (1 + 2\tan^2 \varepsilon) \qquad (12)$$

From equation (12) it is clear that axial focusing will be achieved as long as the magnitude of the second term will be greater than that of the first term. When the second term becomes equal to the first term we have a limiting value of the kinetic energy above which there will be no axial stability. This energy is known as the focusing limit of the cyclotron. It reaches quickly for the particles with small rest mass energy E_0 and that is why we cannot accelerate electrons in a cyclotron. The radial betatron tune is not affected (in the first order) by the sectors and the spirals and is given by:

$$\nu_z^2 = 1 + \frac{r}{\langle B \rangle}\frac{d\langle B \rangle}{dr} + \ldots\ldots = \gamma^2 + \ldots. \qquad (13)$$

In an AVF cyclotron, isochronous average magnetic field $\langle B(r) \rangle$ increases with radius as:

$$\langle B(r) \rangle = \langle B_0 \rangle \cdot \gamma(r)$$

Where, $\langle B_0 \rangle$ is the average magnetic field at the centre. The required shape of the magnetic field can be obtained by following different methods:

1. By using circular trim coils placed at the pole faces. This facility permits the acceleration of different types of ions to different final kinetic energy. Trim coils require careful tuning.
2. By increasing the azimuthal width of the hill at the expense of azimuthal width of the valley as radius r increases. This technique severely limits the flexibility in acceleration.
3. By decreasing the gap between the poles with radius r. This method is not suitable when high beam intensity is required.

The focusing properties of cyclotrons are determined by betatron tunes ν_z and ν_r which depend on hill field B_H, valley field B_V, average field $\langle B \rangle$, number of sectors N and the spiral angle ε. Magnetic fields must be carefully designed to avoid harmful resonances during the acceleration process. Cyclotrons with N=2 sectors will be unstable from the centre and, therefore, they do not exist. In the medium energy range, say up to 100 MeV protons, either N=3 or N=4 sectors cyclotron is most appropriate. However, for high-energy protons more number of sectors is needed.

In earlier cyclotrons there were only two gap crossings per turn, which corresponds to two dees with each having an angle 180^0. But many AVF cyclotrons have now been constructed with four, six or even eight gap crossings per turn. Dee's are no more in the shape of "D". They have now wide variety of structures (even spiral) with much lower angles. The energy gained by ions per turn is given by;

$$\Delta E = 2NqV_D \sin\left(\frac{hD}{2}\right)\cos\phi \qquad (14)$$

where, N is the number of dees, q is the charge of ion, V_D is the dee voltage, D is the dee angle, h is harmonic number and ϕ is the phase of the rf voltage when ion is in the middle of the gap. Clearly, more number of dees produces more energy gain per turn.

The Variable Energy Cyclotron (VEC) at Kolkata is a three spiral sector compact AVF cyclotron with K=130 MeV. It can accelerate protons from 6-60 MeV, deuterons 12-65 MeV and heavy ions 130 Q^2/A MeV. It has only one dee (vacuum chamber or the rf liner acts as another dee) for acceleration and an electrostatic deflector for beam extraction. A single dee facilitates installation and operation of the injection and extraction elements. The VEC provides light ions using internal Penning Ion Gauge (PIG) ion source and heavy ions using external Electron Cyclotron Resonance (ECR) ion source with injection line (discussed in a following section).

Separated Sector Cyclotron (SSC)

As mentioned earlier, SSC is also an AVF isochronous cyclotron where magnet sectors are separated by empty (zero field) valleys. The rf accelerating structures are situated in the valleys

between the magnets. This feature helps to make the magnet gaps quite small and thus improves the vertical focusing properties. In this type of cyclotron, the large space available in the valleys provides access to house powerful accelerating structures. It also enables to use high injection energy. The injection is usually from another accelerator. The radial separation between the orbits is sufficiently large which leads to almost loss less extraction. These unique features enable SSC to accelerate high beam current. Ring Cyclotron at PSI, Switzerland is an eight separated sector (spiral) ring cyclotron. It delivers 590 MeV protons. It has four rf cavities and uses 72 MeV separated sector cyclotron (N=4) as an injector. At present it is the cyclotron delivering highest output beam power (2mA, 590 MeV). It is used for the production of pions and spallation neutrons.

Superconducing Cyclotrons

Superconducting cyclotrons are compact AVF cyclotrons where the magnetic force is supplied by superconducting coils, which consume little power. Superconducting coils (made of Nb-Ti and cooled with liquid helium) are placed around the magnet pole in a cryostat. Magnetic field of ~5-6 Tesla is produced for bending the particles. Since the maximum energy is proportional to the square of the magnetic field (see equation (6)), the size of the magnet and, hence, the weight of the iron is significantly reduced (by a factor of ~20), compared to the same energy room-temperature cyclotron. The superconducting cyclotron K-500 at MSU, USA is a compact AVF cyclotron having three-spiral sectors with three-spiral dees (six accelerating gaps). It is capable of accelerating variety of light as well as heavy ions. An external ECR ion source produces the ions to be accelerated. A similar cyclotron is in an advanced stage of construction at VECC, Kolkata.

Cyclotron Ion Sources

In most ion sources, positive ions are produced by bombarding the neutral atoms or molecules by energetic electrons. For high production of a given charge state, the electron energy should be about three times the ionization potential that means 10-40 eV for singly charged ion, several hundreds eV for multiple charged states and few keV to tens of keV for highly charged ions. The time necessary for an

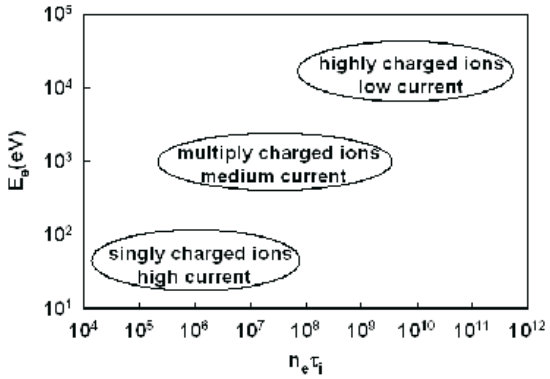

Fig. 4 Showing the operating region of various types of ion sources.

atom to reach a certain charge state depends on the cross section and the electron density. In competition with the ionization are the loss processes such as diffusion of ions out of the ionization volume and the charge exchange processes with neutral atoms. For high charge states high electron energy, low pressure and long containment time is needed. A quantity $n_e\tau_i$, known as the figure of merit, where n_e is the electron density and τ_i is the ion containment time, plotted versus electron energy E_e in Fig. 4, shows the operating regions of the different types of ion sources.

Most of the early cyclotrons were equipped with internal ion sources. These sources were small in size and thus it was possible to confine them in the limited space available in the cyclotron central region. These sources were capable to provide only light ions. The most popular ion source used, internally, in the AVF cyclotrons is Penning Ion Gauge (PIG) source.

The acceleration of heavy ions or polarized ions requires ion sources of larger dimensions that could not be confined in the central region of the cyclotron. This calls for external injection systems injecting ions either radially or axially. It is also needed when a cyclotron works as a booster accelerator for another cyclotron or a linear accelerator. Radial injection is used mostly in separated sector cyclotrons where there is plenty of space available to house large inflector and/or stripper. Most compact cyclotrons utilize versatile

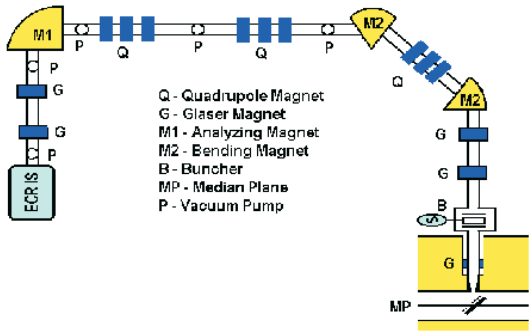

Fig. 5 A typical external injection system used to axially inject heavy ion beam into a cyclotron using an external ion source.

external ion source together with an external injection system injecting the ions axially. A typical layout of an external injection system (e.g. for VEC) is shown in Fig. 5.

The beam from ECR ion source is extracted using a high voltage electrode (usually 10–20 keV). The extracted heavy ion beam from the source is transported to an analyzing magnet where the required charge state of the ion is selected. The analyzed beam is then transported to the buncher, which converts the dc beam from ECR ion source into bunched beam for proper rf matching. This bunched beam is guided to the inflector in the central region, which bends the beam by 90^0 into the median plane and places the beam on the orbit for acceleration.

Beam Extraction from the Cyclotron

After acceleration to maximum energy, particles must somehow be pulled out of their orbits to form an external beam for utilization by experimentalists. The device used for this purpose is known as deflector. It consists of a channel formed by two electrodes across which an electrostatic field directed outwards (for positive ions) is maintained. As the particle advances in the channel, magnetic field gets progressively weaker and thus the channel width increases. The basic equation that holds at each point in the channel for central trajectory is:

$$qvB - qE = \frac{mv^2}{\rho} \qquad (15)$$

where, E is the electric field in the channel and ρ is the radius of curvature of the channel at the point of consideration. In addition to an electrostatic deflector, magnetic shielding i.e. a magnetic channel is also used to reduce the fringe field. A properly designed magnetic channel helps in the extraction process and also provides radial focusing to the beam. The combination of electrostatic deflector and magnetic channel gives high extraction efficiency particularly at high beam energy.

In many cyclotrons, designed to accelerate only protons, negative hydrogen ions (H^-) are accelerated. At a chosen radius in the acceleration chamber a thin foil (usually carbon) is inserted into the circulating beam. As a result, virtually all the H^- ions are converted into protons by stripping. The radius of curvature of the orbit is, therefore, reversed and all the protons bend out of the cyclotron magnet. By changing the radial position of the stripper foil one can also easily change the extraction energy. The extraction efficiency is ~99% or more. Unfortunately, it is not possible to simply increase the magnetic field in the cyclotron to achieve any desired extraction energy due to electromagnetic stripping forces, which tend to remove the outer electron bound only by .775eV and leaves a neutral hydrogen atom. For energies in the range of 20 MeV to 50 MeV, the compact H^- cyclotron is a far more economical choice for high intensity beam than a proton cyclotron. In order to go up in energy for H^- cyclotron, the size (i.e. extraction radius) of the magnet can be increased keeping the magnetic field low to avoid the electromagnetic stripping. The disadvantage is that the magnet becomes very bulky. The designers, therefore, try to find an optimum solution.

The compact AVF cyclotrons are widely utilized for medical applications e.g. cancer therapy, isotope production etc. Modern isotope production facilities employ compact H^- ion cyclotrons in the energy rang 10-30 MeV with extracted beam current ~500 μA. For cancer therapy, cyclotrons in the energy range 70-250 MeV with low beam current are utilized.

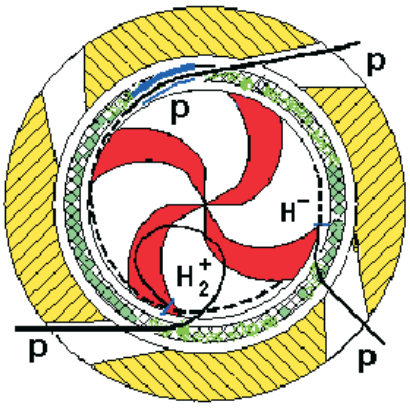

Fig. 6 Beam extraction processes used in cyclotrons: electrostatic deflector for proton (or positive ions), stripping for negative hydrogen and molecular hydrogen.

In order to obtain high intensity proton beams, another way is to accelerate molecular hydrogen H_2^+ beam. The extraction of the beam can be accomplished by a stripper foil, which produces two protons by breaking the molecule. The binding energy of hydrogen molecule is 16.3 eV and it allows utilization of a high magnetic field. Ion sources that produce highly intense beams of H_2^+ should be available.

Beams from AVF Cyclotron

The beam from a cyclotron consists of short pulses arriving at the frequency of the rf oscillator. The time duration and energy width of each pulse are largely dependent on the phase width accepted from the ion source into the acceleration process. The quality of the beam is generally defined by its two transverse emittances (relating position and divergence) and one longitudinal emittance (relating energy resolution and time structure).

Transverse Emittance

It is a measure of the correlation between the position and divergence of the particles in the beam. It is defined as the area of the phase space containing all the representative points of particles in its interior. For (x, x′) phase space:

$$\varepsilon_x = \iint dxdx' \qquad (16)$$

and, similar expression is applicable for (y, y′) phase space. Here, the derivative of x is with respect to z, the beam direction. When an ellipse bounds the domain we have,

$$\varepsilon_x = \pi ab \qquad (17)$$

where, a and b are the semi axises of the ellipse. If the beam has no sharp envelope then either 90% or rms emittance is used. Emittance is generally expressed in units of mm-mrad. For the particles whose total energy is constant, the phase space area of representative points will remain constant during passage through magnetic field or electric field as well as through the field free regions. This is due to the Liouville's theorem. Typical values of horizontal and vertical emittance of the extracted cyclotron beam are ~20 to 80 mm-mrad and vary from cyclotron to cyclotron. The brightness of the central part is intense and thus the emittance can be reduced using a collimator. The emittance of the beam emerging from an accelerator is usually limited by the space available for axial and radial oscillations during acceleration and sometimes by extraction system rather than the characteristics at the injection.

Energy Resolution

In an AVF cyclotron under normal operating conditions the beam has energy spread $\Delta E/E \sim 0.5\%$ (FWHM). The major contributing factor to this energy spread comes from the multi-turn extraction nature as a result of overlapping of orbits at the extraction radii. The energy resolution can be improved by using slits at the central region or an external analyzing magnet and slits in the beam line.

Time Structure

In a cyclotron, out of the full rf cycle (360^0), acceleration takes place only for a small phase width (~ 40^0 - 60^0). Thus, AVF cyclotrons normally produce a continuous train of nano-second (~5-15 ns) pulses separated in time equal to the period of the rf (~50-200 ns) depending on the rf frequency. The pulse width (FWHM) is generally called as the time structure and is influenced by the accuracy of the isochronous magnetic field and the stability of the dee voltage. For slow experiments, cyclotron appears to yield a continuous beam (100% macro duty cycle) whereas to fast experiment it appears to

yield a sharply pulsed beam (1-3% micro duty cycle).

Synchrotron

The problem of energy limitation of cyclotrons imposed by the relativistic mass increase was immediately solved by invention of synchrotons. Today, synchrotron is the only accelerator, which can accelerate protons to TeV energy range. It is based on the principle of phase stable synchronous acceleration first proposed by Veksler and McMillan in 1945. Such accelerators can be used to accelerate protons and electrons as well as heavier positive ions.

In a synchrotron, the radius of the orbit is kept constant by synchronous adjustment of angular frequency $\omega_{rf}(t)$ of the rf and the magnetic field B(t). Most synchrotrons are built using sector bending magnets separated by field free straight sections. Thus the particles trajectories are bent into orbits are composed of arcs and straights. The guiding magnetic field is only required in the path (no magnetic-pole pieces with diameter of the orbit are needed any more like in the betatron and the cyclotron) and is provided by a number of individual dipole magnets positioned around the circumference of the ring. Charged particles travel in evacuated pipes (pressure ~ 10^{-10} torr) placed along the orbit. Acceleration is achieved by providing one or more rf cavities located in the straight sections between the magnets. Particles get an energy increment every time they cross the accelerating gap. Particles are first pre-accelerated in a linear or any suitable accelerator and injected into the synchrotron ring using fast switchable kicker magnets. Once a short pulse is injected at low field, the magnetic field rises in proportion to the momentum of particles as they are accelerated to ensure that the radius of orbit remains constant. Particles make hundreds of thousands of turns before reaching full energy and are then extracted out of the machine. At this point (after extraction of a pulse) magnets return to the initial excitation value. Typical cycling frequency of the magnets lies in the range of 5 to 50 Hz. Figure 7 shows the schematic of a typical modern synchrotron.

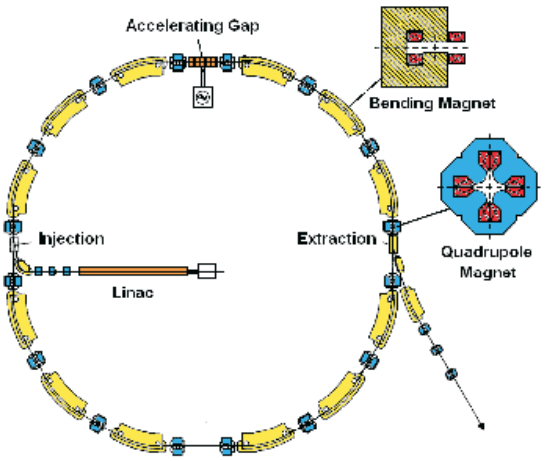

Fig. 7 Schematic of a typical, separated function synchrotron showing the arrangement of bending magnets, quadrupole magnets, rf cavity, injection system, extraction system etc.

Resonance condition: For proper and repeated acceleration of particles in a synchrotron following conditions need to be fulfilled, simultaneously:

(a) The angular frequency of the accelerating rf field must be an integer multiple of the angular frequency of the particle i.e.

$$\omega_{rf}(t) = h\omega(t) = \frac{hv(t)}{C} = \frac{hc\beta(t)}{C} \qquad (18)$$

where, C is the circumference of the ring consisting of curved and straight parts. Since $\omega(t)$ increases with the velocity v(t) of the particle, the rf frequency ω_{rf} should also be increased synchronously. Once the particles become fully relativistic i.e. v = c, rf frequency ω_{rf} can be kept constant. For the electrons, since they become relativistic rather quickly (within few MeV), ω_{rf} can be kept constant, but for protons it has to be increased synchronously with the particle frequency in the increasing magnetic field. As mentioned earlier, h in equation (18) is called harmonic number.

(b) In the bending magnet, momentum of particle and the magnetic field are related as:

$$p(t)=\gamma(t)m_0 v(t)=\frac{m_0 c\beta(t)}{\sqrt{1-\beta^2(t)}}=qB(t)R \qquad (19)$$

where, R is the radius of the particles in the bending magnet. R being a constant in the synchrotron, the magnetic field B(t) must increase from a minimum value of B_i at the time injection ($p_i = qB_iR$) to the maximum value of B_e at the time of extraction ($p_e = qB_eR$) given by the final energy of the particles. It is necessary to know how the revolution frequency $\omega(t)$ will vary as the magnetic field B(t) changes. We can know this by solving equation (19) for $\beta(t)$ and using it in equation (18). The result is:

$$\omega(t) = \frac{c}{C}\frac{B(t)}{\sqrt{A+B^2(t)}} \qquad (20)$$

where, the constant $A = m_0c/qR$, depends only on the ion type and radius R.

Phase Stability

Phase stability is general to all rf accelerators except the fixed-frequency, isochronous cyclotron. The effect is that a bunch of particles, with an energy spread, can be kept bunched throughout the acceleration cycle by simply injecting them at the appropriate phase of the rf voltage.

The energy gain per turn ΔE, in the synchrotron, is proportional to the rate of change of magnetic field and it is also equal to $qV_0 \cos(\phi)$, the energy gained by particles in the rf cavity. The amplitude V_0 of the accelerating voltage and phase ϕ of the particle must be in step with the rising magnetic field. This condition can be satisfied for only one phase called the synchronous phase ϕ_s of the particle. Particles in the bunch whose phase differ slightly from the synchronous phase gain less or more energy than the synchronous particle and perform stable oscillations about the synchronous phase according to the principle of phase stability. These oscillations in energy and phase are called synchrotron oscillation. For all the particles, the time average of their energy gain matches the rising magnetic field.

To provide phase stability, the synchronous phase ϕ_s must be chosen to be within the proper quarter cycle of the rf voltage. At energies

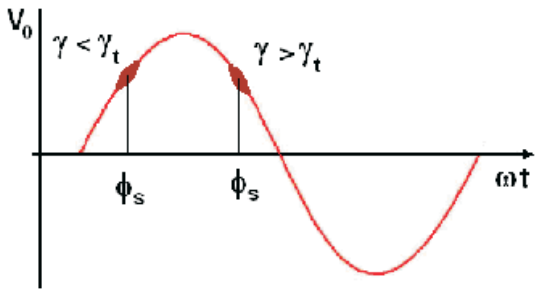

Fig. 8 Position of the synchronous phase required for phase stability to protect the bunch structure of the beam when the particles are crossing the accelerating gap.

comparable to or less than E_0, particles are non-relativistic, their velocity depends on energy and an increase in the momentum of the particle causes decrease in the revolution time. In this regime, particles with higher energies than those of synchronous particle in a beam bunch take a shorter time to complete the circuit of the accelerator and return to the acceleration cavity. Therefore, phase stability exists if the synchronous particle crosses the accelerating gap when the voltage is rising ($0 < \phi_s < \pi/2$). At relativistic energies, particle velocity is almost independent of energy. The particle orbit circumference is the main determinant of the revolution time and an increase in momentum of the particle causes increase in the revolution time. In this regime, particles with higher energies than those of synchronous particle in the bunch have larger orbit radii and therefore, take more time to return to the acceleration gap. For stability of bunch synchronous phase must be in the region of falling voltage ($\pi/2 < \phi_s < \pi$). The energy that divides the two regimes is called the "transition energy" γ_t, where $\gamma = E/E_0$, is well known relativistic factor. At the transition energy, there is no change in the particle revolution time with change in momentum. In a conventional proton synchrotron, transition is encountered midway through the acceleration cycle. In this case it is essential to shift the phase of the rf field before the bunched structure of the beam is lost. A better choice is to inject the beam in the synchrotron above transition energy. This effect is unimportant in electron synchrotrons because electrons are always injected above the transition

Fig. 9 Shape of the magnetic field with large positive and negative gradients. Focusing is obtained in both the horizontal and vertical planes by arranging them alternately separated by a suitable distance.

energy. An isochronous cyclotron always operates at the transition energy. Figure 8 shows the position of synchronous phase required for phase stability when the particle is crossing the accelerating gap for the two above-mentioned cases.

Orbit Stability

Constant Gradient (Weak focusing) Synchrotron

In the early synchrotrons, the orbit stability was obtained by shaping the magnet poles to provide constant gradient decreasing towards the outside i.e. away from the orbit centre. Since the field gradient $n = -\frac{r}{B}\cdot\frac{dB}{dr}$ must satisfy the inequality $0< n <1$ to provide stability in both the transverse and radial planes, such focusing is inherently weak. Horizontal and vertical tunes are less than one and, consequently, amplitudes of the betatron oscillations are large. This necessitates the use of large aperture for the vacuum chamber and costly magnets with large gap dimensions to contain the beam. These types of synchrotrons become very expensive if the energy exceeds more than a few GeV. Such machines are now obsolete.

Alternative Gradient (Strong Focusing) Synchrotron (AGS)

In the year 1952, Courant, Livingston and Snyder proposed the concept of strong focusing, also known as alternating-gradient (AG) focusing. According to this principle, an alternating series of focusing and defocusing lenses leads to an overall focusing if the distances between the lenses are not too large. This new principle revolutionized the synchrotron design. It allowed smaller magnets to be used and higher energies to be envisaged with better beam quality and higher intensity. It is directly analogous to a well-known result in geometrical optics. The combined focal length F of a pair of lenses of focal lengths f_1 and f_2 separated by a distance d is given by:

$$\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}-\frac{d}{f_1 f_2} \qquad (21)$$

For example, let us consider that lenses have equal and opposite focal lengths i.e. $f_1 = -f_2 = f$. In this case overall focal length, $F = f^2/d$ is always positive (focusing). In fact, F remains positive over quite a large range of values when f_1 and f_2 have unequal values but are still of opposite sign. The physical explanation of this is that a ray is always further from the axis in a focusing lens than in a defocusing lens, so that the convergence angle always exceeds the divergence angle. This is always true no matter which lens comes first. Though the net focusing is a second order effect, the lens gradients can be made very large to get strong focusing.

This idea was applied in the synchrotron by using the combination of strongly focusing and defocusing magnets. If this is done by providing a radially varying field in the bending magnets, the machine is called combined function synchrotron. However, if this is achieved by using uniform field dipoles and separate quadrupoe magnets, the machine is called separated function synchrotron.

We know that a radially increasing magnetic field focuses horizontally and defocuses vertically. In this case the field index $n>1$. On the other hand, a radially decreasing field with field index $n<0$, defocuses horizontally and focuses vertically (Fig. 9). In combined function machines these two types of bending magnets are arranged in such a way

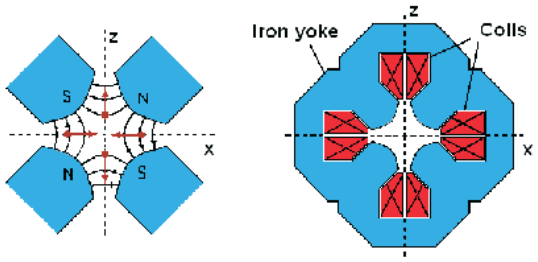

Fig. 10 Cross section of a quadrupole magnet. Arrows indicate how particles are focused in one plane and defocused in the other plane. The particles move perpendicular to the plane of the paper with the central particle at the center of the magnet.

that a magnet with large positive gradient is followed by a magnet with large negative gradient. In the AGS, the absolute value of field index n is in the range of 10 to 100 compared to n ~ 0.5 in the weak focusing synchrotrons.

All modern synchrotrons are separate function machines. They use separate, uniform field dipole magnets for bending the particles and quadrupole magnets for strong focusing in so called FODO (focusing-free space-defocusing-free space) configuration. A quadrupole magnet as shown in Fig. 10 has four poles N-S-N-S with hyperbolic contour on faces. It provides focusing in one plane and defocusing in the other plane. It is to be noted here that a FODO configuration of quadrupoles for horizontal plane automatically becomes a DOFO configuration for vertical plane. Sextupole magnets are also included in the ring to increase the tolerance of the focusing system to beam energy spread (chromaticity correction). The arrangement of bending and quadrupole magnets around the synchrotron ring is known as a focusing lattice and it is designed carefully to maintain a stationary beam envelope. A great advantage of separated function synchrotrons is that focusing forces are adjustable independent of the bending field.

Figure 10 shows how particles experience focusing and defocusing forces in a magnetic quadrupole field. The arrows indicate the Lorentz force experienced by a positively (negatively) charged particle moving into (out of) the plane of the drawing. Particles in the (x, y) plane are focused, whereas in the (z, y) plane there is defocusing. A pair of such quadrupole magnets in series, rotated by 90 degrees, has a net focusing effect in both the planes due to the alternating gradient principle.

Energy Limit

The high-energy limit for proton synchrotrons is set by the strength of the bending magnets and the area available for the machine. The relation between energy E and radius of curvature R of particle in the magnet of the ring is given by:

$$BR = \frac{1}{qc}\sqrt{\left(E^2 - E_0^2\right)} \qquad (22)$$

where, B is the peak value of the magnetic field in the dipole magnet. In case of relativistic protons,

$$B[\text{tesla}] \,.\, R[\text{m}] = 3.3E[\text{GeV}]$$

The effective radius R_{eff} of ring can be obtained by adding straight and curved paths together,

$$2\pi R_{eff} = 2\pi R + L$$

For a given bending magnet strength, higher energies can be achieved only by making the radius of the ring larger. The use of superconductivity in proton machines has made the possibilities of achieving very high energies within affordable size. Most ion synchrotrons accelerate protons because of highest q/A, which helps to reach highest energy per nucleon in a given magnetic field. For heavy ions acceleration in a synchrotron a thin foil is used after the pre-accelerator to enhance the charge state by stripping. Ions with only high charge states are selected for injection.

In the case of electron synchrotrons, the maximum energy is limited by the losses due to emission of synchrotron radiation. Synchrotron radiation is an electromagnetic radiation emitted by the charged particles circulating in a synchrotron when they are accelerated (deflected) by the magnetic field in the dipole magnets. The energy loss per turn is directly proportional to the fourth power of the particle energy and inversely proportional to the orbit radius and is given by:

$$U_0 = \frac{e^2}{3\varepsilon_0}\frac{\beta^3\gamma^4}{R} \text{ or } U_0(\text{MeV}) = 0.0885\frac{E^4[\text{GeV}]}{R[\text{m}]} \quad (23)$$

In the electron synchrotron higher energy is possible only by a larger ring radius and higher power input to the accelerating cavities. However, this scaling is very weak and expensive. Linear accelerators are better choice to reach higher electron energy. However, electron synchrotrons have become a unique source of intense radiation over a wide spectral range (infrared to several keV energy). These are known as synchrotron radiation sources and are actively employed in applied physics research, particularly, in atomic and solid state physics.

Synchrotron radiation has a negligible effect in ion accelerators. Compared to electrons, the power loss is reduced by a factor of $(m_e/m_i)^4$.

Storage Rings and Colliders

Storage Ring

Storage rings are used for the colliding beam experiments and production of synchrotron radiation. A storage ring is essentially a separated function synchrotron, except that it is designed just to keep the particles circulating at a constant energy for long time. The magnetic fields are constant in time. However, the particles must still pass at least once through the accelerating cavity each time they circle the ring. It is required for longitudinal beam manipulation in case of protons and ions and compensation of the energy loss due to synchrotron radiation in the case of electrons. A storage ring holds particles for several hours, whereas the process of acceleration of particles up to their design energy takes only seconds. A stringent requirement for a storage ring is the vacuum; it must be much better vacuum (~ 10^{-10} torr) than that in a normal synchrotron.

Storage Ring Collider

This is a special type of synchrotron storage ring or dual storage ring used for high-energy physics experiments, where particles moving in opposite directions are brought to collide (interact) at a number of positions in the ring. In physics experiments, the useful energy for production of new particles is the energy that is available in the centre-of-mass system. The use of colliding beams significantly increases the energy available in the centre of mass system. When an accelerator beam is used on a fixed target, only a fraction of the energy E of the particle appears in the centre-of-mass system ($E_{cm} \approx \sqrt{(2EE_0)}$ whereas for two equal particles in a head-on collision, all the energy of the particles is available (E_{cm}=2E). For example, it would need a fixed target accelerator of over 1 TeV to match the centre-of-mass energy available in the 2 x 26 GeV proton colliding rings. The storage-ring collider now dominates the high-energy physics field. Single-ring colliders, use particles and antiparticles circulating in the opposite directions where as for collision of similar particles double rings are required. Colliders have been operated (or are planned) for counter-rotating beams of protons (pp collider), electrons and positrons (e^-e^+), and protons and antiprotons ($p\bar{p}$). Some noticeable examples are: (a) LEP II (at CERN): e^+e^- collider with 2 × 100 GeV energy; (b) Tevatron at FNAL: single ring $p\bar{p}$ collider with 2 × 0.9 TeV energy; (c) Large Hadron Collider (LHC) project at CERN: a double ring for pp collisions with 2 × 7TeV energy.

In India, we have two synchrotron radiations sources INDUS-1 and INDUS-2 at the Raja Ramanna Centre for Advanced Technology, Indore. The INDUS-1 is a 450 MeV storage ring for production of the radiation in the ultraviolet region with a critical wavelength ~ 61 angstrom. Its injection accelerators consist of a 20 MeV microtron and a booster synchrotron. The INDUS-2 is a 2.5 GeV synchrotron storage ring for production of synchrotron radiation in hard x-ray region with critical wavelength ~1.98 angstrom. The injection system for INDUS-2 is same as that for the INDUS-1. In the case of INDUS-1, the booster synchrotron boosts the electron energy up to 450 MeV before injection while for INDUS-2 the same booster operates at 700MeV energy. INDUS-2 subsequently raises the beam to 2.5 GeV and stores it for production of synchrotron radiation.

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Accelerators in Astro, Nuclear and Particle Physics

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Introduction

Advancement in knowledge about the fundamental forces of nature has taken place over the years by using accelerators producing collisions among subatomic particles. Advancement in accelerator technology has grown at an exponential rate, to keep pace with the requirements, but still falls short of the ever increasing demands of the experimentalist and theoretician.

After Rutherford's discovery of the atomic nucleus in 1919, scientists turned their attention to building machines that could probe matter at short distances. The Cockroft-Walton accelerator (1932) demonstrated nuclear reactions using protons. The same year, the first cyclotron was designed by Ernest O. Lawrence and M. Stanley Livingston at the University of California, Berkeley. This was a forerunner to the Bevatron accelerator that discovered the antiproton in 1955. Now we have accelerators that can be as much as 27 Km in circumference. The first observation of the top quark came in 1994 using the Tevatron accelerator at Fermilab and the Higgs boson (particle crucial to the Standard Model of particle physics) is awaiting discovery.

Particle accelerators are an essential tool in the study of particle and nuclear physics and have contributed substantially in understanding the basic processes and cross sections in the stellar models of astrophysics. The results obtained from particle accelerators are at the cutting edge of today's science. In this brief article we highlight some of the important areas where accelerator based experiments are helping us to gain deeper knowledge.

Accelerators in Nuclear Physics and Astrophysics

In order to produce and study nuclear reactions, an accelerator is the best tool. Other ways of inducing nuclear reactions are: radioactive sources, reactor neutrons and cosmic rays (nature's accelerator). With accelerators we produce charged particle beams of controlled intensity and well defined direction, which can be further collimated as required.

The study of nuclear reactions using accelerators in recent years has contributed significantly to our understanding of the reaction mechanism. As a function of the impact parameter and the beam energy we can classify reactions as direct, pre-compound and compound. Direct reactions take place at high beam energies and/or large impact parameters. They are peripheral reactions involving the exchange (transfer) of a few nucleons amongst the target and projectile. In the particle-hole picture, the interaction causes the excitation of particle-hole pairs. In a direct reaction we have only 1 such pair. Internal collisions in the composite system can result in creation of further particle-hole pairs. This process of particle-hole creation is an equilibration process. If the system proceeds to complete equilibration it loses memory of how it was formed and we have Bohr's compound nucleus. If particles are emitted before equilibration

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is complete, then these are called pre-equilibrium or pre-compound emitted particles. Particles emitted after equilibration have a spectrum and relative emission probability that is well described by the Statistical Model of nuclear reactions.

Nuclear reactions lead to the formation (as compound nuclei, or products of deep inelastic scattering and multi-fragmentation) of nuclei, which are relatively short lived with high excitation energies (E*), high angular momenta (J) and neutron-proton ratios (N/Z) away from those found in naturally occurring nuclei. Therefore the production of these nuclei with accelerators provides a rich laboratory for the spectroscopic study of nuclear structure. Models of nuclear structure have emphasised the role of the key parameters, E*, J, N/Z and deformation in influencing the way the nucleons interact amongst each other to produce bound states.

Nuclear masses, the onset of nuclear deformation and isomers can be studied in nuclear reactions and these results are connected with the nuclear reactions taking place in the stars which is responsible for producing light in the universe as well as in nucleo-synthesis - the process by which elements are produced in the stars. One of the unanswered questions in nuclear astrophysics is about the origin of the heavy elements beyond iron.

Current topics of research in nuclear reactions include compound and pre-equilibrium effects and statistical fluctuations in nuclear reactions, high energy heavy-ion reactions with projectile fragmentation, nuclear multi fragmentation, deeply inelastic heavy-ion collisions, phase transitions in nuclear and hadronic systems, nuclear structure and symmetry principles, supersymmetry in many-body systems, semi-classical techniques applied to heavy ion reactions, collective effects in nuclear reactions and models, the role of rotational degrees of freedom in heavy-ion collisions at low and moderate energies, pion interactions within nuclei, meson production and interactions of mesons.

Heavy-ion reactions at intermediate energy (between 20A and 200A MeV) are useful for studying reaction dynamics. Light-hadron-nucleus collisions in the range of 1 to 15 GeV can probe the nuclear equation of state (EOS), the liquid-gas phase transition of nuclear matter and the interplay between the statistical and dynamical break-up of nuclei under extreme conditions of density, temperature, shape and isospin (neutron-proton asymmetry).

The thermodynamic properties of nuclear matter e.g. the critical temperature, T_{crit} and the nuclear compressibility, K, are of fundamental importance. Knowing the bulk properties of nuclear matter is important to understand the characteristics of objects such as neutron stars or the nucleosynthesis of heavy elements in supernovae explosions. In the crusts of neutron stars, exotic nuclei with extreme N/Z ratios are speculated to exist. It is important to know how the thermodynamic quantities T_{crit} and K depend on the N/Z ratio. One means of probing T_{crit} and K is by measuring the limiting temperature of finite nuclei. New accelerators providing beams of radioactive nuclei are being used for examining the dependence of the nuclear equation-of-state on N/Z.

The decay properties of hot nuclear matter prior to reaching equilibrium are of fundamental importance in understanding the nuclear equation-of-state (EOS), which is central to understanding the existence of neutron stars or supernovae explosions. Nuclear matter under extreme conditions of temperature, density, and isospin can be prepared by colliding two heavy-ions ($3 \leq Z \leq 92$) at intermediate energies ($20 \leq E/A \leq 200$). The collision process also allows one to examine the interplay between statistics and dynamics in a finite, strongly-interacting, two-component quantal system.

Two relatively newer areas of research, which are gaining importance, are highlighted in this article.

Radioactive Ion Beam (RIB) Physics

Beams from accelerators are normally of stable species. In recent times, accelerator facilities have been developed which produce beams of particles of unstable, i.e. radioactive ion-beams. These beams are of much lower intensities than can those of stable ions. Nevertheless, with these beams it has become possible to probe reaction mechanism and nuclear structure in new regions of N/Z very far from stability. Towards the proton and neutron drip lines,

new phenomena are beginning to show up. The study of the nuclear equation of state referred to above can be explored with respect to the isospin degree of freedom. One of the first phenomena to be observed and studied with RIB was the structure of halo nuclei. It was noticed that it is possible to create nuclei with excess neutrons or protons hovering far away from the main core. The radial density distribution shows a central region followed by a dip and increase again. These structures are called proton or neutron halo.

Production of Super Heavy Elements (SHE)

Is there a heaviest element in the periodic table? Theory predicts that there should be another "island" of stability after the actinide elements. The observation and location in the (N,Z) landscape of the next spherical doubly magic gap (stability is related to magic numbers) is essential experimentally if one wants to establish and validate theoretical models. During the last decades, the search for super heavy nuclei went on mainly at the Berkeley, GSI and Dubna laboratories. The discovery of the six heaviest elements of the periodic table of the elements up to element 112 has been one of important milestones of nuclear physics research and the quest for SHE continues.

Accelerators in Particle Physics and Astrophysics

Particle physics has made great advances in the unification of the fundamental forces of nature. There are many interesting topics of current research such as measuring high-energy quark-gluon scattering to learn where the proton gets its spin, learning the scale of forces that can distinguish between a left- or right-handed universe. The Relativistic Heavy Ion Collider (RHIC) at Brookhavn,USA is built to search for the quark-gluon plasma, a new state of matter predicted by quantum chromodynamics. RHIC also provides accelerated polarized protons upto 250 GeV. Two oppositely circulating beams of protons intersect in a detector STAR, which has been setup. The spin structure of the protons can be studied looking at the collisions of the two protons where the quarks and gluons in the protons interact violently. Such violent collisions can create high-energy photons and jets of particles such as pions. The STAR detector is designed to detect electrons, photons and jets of particles over a large solid angle.

Relativistic heavy ion physics is pertinent to nuclear physics, particle physics and astrophysics. The primary goal of this field of research is to re-create in the laboratory a novel state of matter, the quark-gluon plasma (QGP), which is predicted by the standard model of particle physics (Quantum Chromodynamics) to have existed ten millionths of a second after the Big Bang (origin of the Universe) and may exist in the cores of very dense stars. The quest to obtain a fundamental understanding of the microscopic structure of hadronic interactions, at the level of quarks and gluons, at high energy densities is well underway.

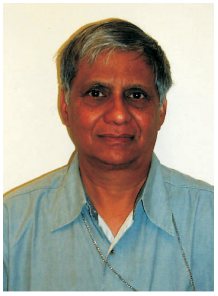
Since its discovery in 1977 the bottom quark played a prominent role in the Standard Model of elementary particles due to its heaviness and long lifetime. These unique features allowed scientists to develop special approaches to study its properties both in theory and experimental techniques.

The top quark is by far the heaviest of all known fundamental particles. Its discovery in 1995 at Fermilab's Tevatron collider was the culmination of a search that had taken almost two decades, and involved hundreds of physicists. Since then the top quark remains the subject of active investigations at the Tevatron, as the unusually high mass of this particle is believed to hold clues for surprises, and possibly new discoveries.

Conclusion

Scientific research has provided an increasingly comprehensive insight into the structure of matter and of the development of the universe. At the same time, the new insights generated many technical developments and applications. The bigger part of the insights attained we owe to experiments at accelerator facilities.

Beamlines on Indian Synchrotron Radiation Source Indus-1 and Indus-2



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Introduction

In India, at the Raja Ramanna Centre for Advanced Technology (RRCAT, Indore), a 450 MeV electron synchrotron radiation source Indus-1 has been working and Indus-2, a 2.5 GeV electron source is under commissioning. Indus-1 gives synchrotron radiation from soft X-rays, vacuum ultra violet (VUV) rays to infrared. To use this radiation from Indus-1 for different experiments, six beamlines and experimental stations are installed. Of these six beamlines, four are now operational and the rest are under commissioning.

Indus-2 gives a good photon flux in hard X-rays, soft X-rays and VUV region. Many beamlines are under design and fabrication. We give a brief description of these sources and how to use them.

Synchrotron Radiation

Synchrotron Radiation (SR) has emerged as a tool for basic and applied research in physics, chemistry, biology, medicine etc., because of its unique characteristics, namely broad spectrum (from far-infra red to X-rays), small beam size and small divergence and hence high brightness, short pulse duration and high degree of polarization.

It is well known that whenever a charged particle is accelerated it emits electromagnetic radiation. The acceleration can be due to change of speed or a change in the direction of motion of the charged particles. To generate SR a charged particle, with speed very near to speed of light, is forced to move in a curved path under the action of a magnetic field. The particle experiences centripetal acceleration and hence emits radiation as shown in

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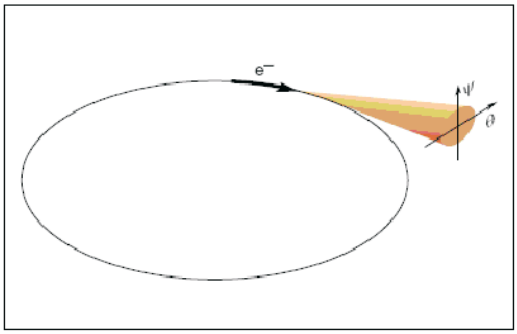

Fig. 1 SR occurs when a charge moving at relativistic speed follows a curved path.

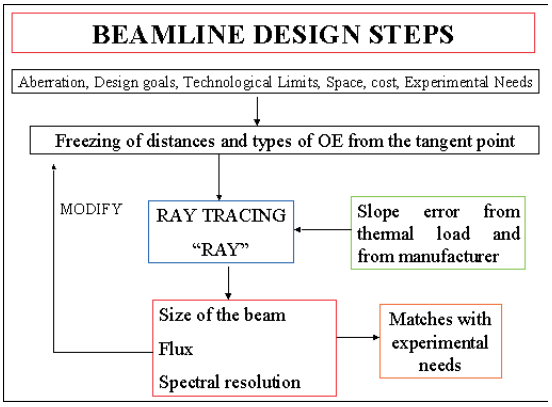

Fig. 2 Procedure for beamline design.

Fig. 1. The wavelength and intensity of the emitted radiation depend upon the strength of the magnetic field, and the mass, charge and energy of the charged particle. The loss of energy in the form of SR is very severe for lighter particles. For this reason, electrons or positrons are mostly used to generate SR.

If E is the electron energy and R is the radius of curvature, then the bending radius ρ in practical units is given by:

$$\rho(\mathrm{m}) = \frac{3.3E(\mathrm{GeV})}{B(\mathrm{T})}$$

Where B is the bending magnetic field and E is the energy of the electrons.

The properties, which are associated with SR, can be obtained by visualizing the relativistic electron as an oscillating dipole subjected to Lorentz transformation and then applying the laws of classical electrodynamics to the motion of electrons. These properties are (a) broad spectrum (from infrared to optical to vacuum ultraviolet, soft X-rays and X-rays), (b) high intensity and high brilliance, (c) high degree of collimation, (d) high degree of polarization and (e) pulsed time structure.

The critical wavelength, λ_c the wavelength above and below which the total radiated power is divided equally, also depends upon E and B through

$$\lambda_c(\mathrm{nm}) = \frac{1.864}{E^2(\mathrm{GeV})B(\mathrm{T})}$$

Beamline

To make use of this radiation for any specific application, be it in the field of physics, chemistry biology, medicine, materials science etc. it has to be brought up to the target or sample under investigation in the experimental chamber in a prescribed form. This prescription of the beam at the target depends upon the type of application and experiment. To obtain radiation in such prescribed form at the target is not so simple. It involves intricate instrumentation in between the experimental chamber and the tangent point (from where SR emanates). This instrumentation is generally known as the beamline. The beam line is usually developed and maintained by a team of scientists and engineers having expertise in diverse fields. For designing a beamline, a set of complex iterative procedures needs to be followed depending on a particular application and a particular type of source (Fig. 2)

The beamline instrumentation basically involves computer simulation, optics, precision mechanical engineering in ultrahigh vacuum (UHV), electronics and computer controls. The task of this team is to give the user a beam of his choice. The user will be interested in the following characteristics of the beam (1) energy or wavelength, (2) energy resolution, (3) flux or intensity, (4) beam spot size, and (5) polarization. The design and construction of a beam line depends upon wavelength range, resolution and the power of radiation. Beamlines can be tapped either from the

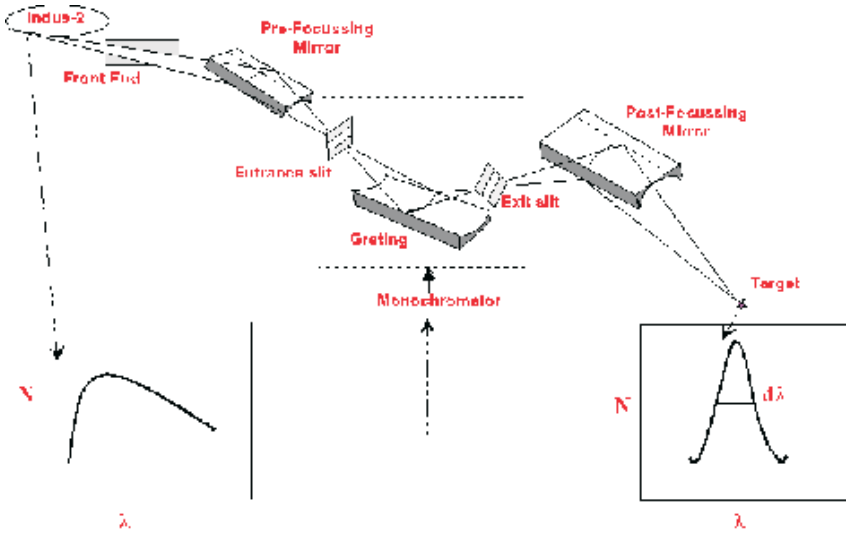

Fig. 3 Schematic of a typical VUV beamline.

bending magnet of the accelerator or from the insertion devices. Insertion devices called wigglers or undulators are periodic magnetic structure inserted in the straight section of the charged particles in motion. Using these insertion devices the radiation spectrum can be modified. Beam line design and construction depend upon from where the beam line is taken. Again the design and development of beamline depends upon the type of storage ring or the energy spectrum it gives. For example a beamline for experiments in hard x-ray is different from that of a beamline for vacuum ultraviolet range.

The schematic of a beam-line or a beam transport channel is shown in Fig. 3. The goal in general, of a beamline is to maximize flux (N), maximize $\lambda/\Delta\lambda$, and the image quality should be good. Optical elements, which are used, are mirrors, windows, filters, gratings, slits etc. The typical spectrum of radiation is given on the left side. It denotes the photon flux against wavelength. After monochromatisation, the typical spectrum one gets is represented on the right. The front end shown in the figure consists of a fast acting valve, a shutter (water-cooled in case of high power sources) and an ultrahigh vacuum valve. In between the front and the first optical mirror, an acoustic delay line is placed. Any catastrophe in vacuum will close the fast acting valve before the shock wave reaches the storage ring, which is under ultrahigh vacuum. A water-cooled shutter is necessary to take the entire beam power load. This way the ultrahigh vacuum in the ring is not disturbed by any catastrophe in the vacuum system of the beamline.

The beam transport channel for any beamline consists of a pre-mirror to focus incident radiation, a monochromator, and a post-mirror to focus monochromatic beam onto the target. The choice of optical elements and their configuration vary from beamline to beamline depending upon the need of an experiment, e.g. spectral resolution, spot size, intensity. To achieve the desired specifications of a beamline a monochromator plays an important role.

The radiation emitting from a synchrotron radiation (SRS) is divergent in nature. The vertical divergence σ_v is very small, 2-5 mrad (1mrad=0.05^0) and its wavelength dependence is given as

$$\sigma_v\,(\text{mrad}) = \frac{570}{\gamma}\left[\frac{\lambda}{\lambda_c}\right]^{0.43}$$

Where $\gamma = E/m_oc2 = 1957\ E(GeV)$ and λ_c is the critical wavelength (61 Å for Indus-1 and 4 Å for Indus-2).

The horizontal divergence is decided by the vacuum port size of the beam and typically this

divergence required for different experiments ranges from 1 mrad to 30 mrad. For special applications it may be as high as 60-80 mrad (e.g. IR beamline). The first task is now to bring this diverging radiation on to a focus. The focusing has to be done both in the meridian plane as well as in the sagittal plane. Several variants to do this job exist. However, due to the very small reflectivity in the wavelength range of interest (soft x-ray and vacuum ultraviolet rays) and due to high aberrations at these wavelengths aspherical mirrors at grazing incidence are employed. The physical dimensions of the mirror depend upon its distance from the tangent point. For SRS where the power of radiation is high, the mirror or the first optical component has to be placed further from the tangent point and has to be cooled. Another optical component, which is the heart of the beam line, is a monochromator. For vacuum ultraviolet beam lines, this range of wavelength may be divided into two ranges (i) 25-200 nm and (ii) 2-100 nm. For the first range, normal incidence monochromators are used. A typical example of this is a Seya Nomioka Monochromator. Materials which are normally coated on the gratings of this monochromator are gold, aluminium etc. These monochromators are important if one wants to study atomic or molecular physics. For example, the first ionization limits with converging Rydberg series fall into this wavelength range.

For shorter wavelength, i.e. between 2-100 nm the reflectivity at normal incidence is very low and hence one has to go to grazing incidence geometry. In the grazing incidence optics, the geometrical aberrations increase significantly for spherical optics. To reduce this, aspheric optics is generally employed in grazing incidence geometry. For wavelengths in the hard x-ray region, i.e. 0.1-1 nm, crystals such as silicon are used as monochromators. Our subsequent discussion will be based on VUV type of monochromator as a representative. The monochromator consists of an entrance slit, an exit slit and gratings. Gratings are used to disperse wavelengths into different directions. The angle between incoming and outgoing rays is so adjusted that radiation of one wavelength passes through the exit slit. This, and for that matter every monochromator, has an inherent instrumental resolution, i.e. the full width at half maximum of the wavelength (or energy) profile. This instrumental resolution depends upon various parameters like source size, slit width etc. The radiation dispersed by his monochromator also contains higher harmonics. The choice of the monochromator therefore depends upon energy range, flux, resolutions and higher harmonic contents. For this, different types of monochromators can be used depending upon the experimental requirement. Once the radiation is dispersed, the monochromatic radiation of interest is allowed to pass through the exit slit.

This monochromatic radiation is again divergent in nature. This radiation is brought to a focus or made into a parallel beam depending upon the requirement, using appropriate mirror called a post mirror. Again the radiation will have to fall on this mirror at a grazing incidence and aspheric mirrors are used for this purpose.

The above discussion was for vacuum ultraviolet (VUV) and soft x-ray beam line. The typical length of the beamline, i.e. the length from the tangent point to the experimental station is dictated by the choice of optics. The choice of optics, as discussed earlier, depends upon the type of beam tailoring required at the target. The typical beamline length is 10-15 meters which is determined beforehand by computer simulation. Ray tracing calculations are performed using the laws of geometrical optics, to arrive at a choice of optical components.

The throughput of the beamline is defined as the number of photons available at the target in contrast to the incident photons. The throughput also depends upon the choice of reflective coating on these components. Gold, platinum, nickel etc. are some typical examples of this coating. The throughput or transmission for a good, well-aligned beam line may not be higher than a few percent.

The alignment of optical elements namely mirrors, monochromators, slits etc. is very critical. For example, a tilt of a few tenths of microradians of the premirror in the direction of the incident beam will change the focus drastically. Similarly, for the wavelength scan the monochromator has to be moved by an angle of the order of a few milliradians. All these movements are to be performed in ultra high vacuum. Kinematic mounts are used for such

movements. The grating is moved inside UHV using sine-bar movement.

Electronics is required for UHV systems. Sputter ion pump power supplies, vacuum measurement equipments, stepper motor controllers etc. are a few typical examples. The movement of grating is monitored through a stepper motor controller via a personal computer.

For a hard x-ray machine like Indus-2 the design of the beamline becomes different. The monochromators, which are employed here, are crystal monochromators. Unlike ion etched gratings on VUV machines like Indus-1, the heat load which the crystals of monochromators and other optical components will face is rather high and hence cooling of the optical components is essential. This heat load is still higher if the radiation is tapped from insertion devices like wigglers than bending magnets. In hard x-ray region the SR source, beamline and experimental station can be isolated using beryllium windows. Though the vacuum requirement in beamlines for Indus-2 type of machine is not as stringent as that of Indus-1 type machine, it is necessary to keep these components in high vacuum. Bremsstrahulng is another parameter which should be minimized at the target end, a stringent requirement for high energy machines.

Applications of SR

Synchrotron radiation sources have many applications both in basic sciences as well as in industries. The fields of research in which SR plays a dominant role can be categorized into (a) condensed matter physics, (b) surface science, (c) atomic and molecular physics and chemistry, (d) life sciences, and (e) industrial applications.

Condensed matter studies encompass physics and chemistry of solids and materials science. These involve chemical compositional studies, structural studies and electronics structure studies. For chemical composition or elemental analysis, techniques like photoelectron spectroscopy to measure electronic core level binding energies, X-ray absorption spectroscopy and X-ray fluorescence spectroscopy are employed. New generation of high brilliance sources together with their time structure and analysis techniques would provide new and unique possibilities of studies involving dynamics such as diffusion and inter diffusion in interfaces.

The study of crystal architecture is always exciting and techniques like neutron diffraction and conventional X-ray diffraction are available. However, the unique properties associated with SR have not only strengthened this area but also opened new areas, which were hitherto not possible. For example, high brightness helps in getting data sets which are much more extensive than those obtained with a laboratory X-ray or vacuum ultra violet source. Due to high degree of collimation, difference Fourier techniques are now feasible to isolate effects of atoms in non-stoichiometric materials. Study of crystals under ultra high pressure and high magnetic fields using diamond anvils has opened up a new area with high brilliance sources. In the area of nano science and technology, synchrotron radiation has become an important tool.

For electronic structure of solids, angle-resolved photoelectron spectroscopy, EXAFS, XANES etc. are some techniques which are used using SR. Magnetic X-ray absorption and scattering were so far only considered theoretically, as the cross-section for such scattering is very small. Now due to the availability of high brightness sources, magnetic scattering studies are possible. Magnetic circular dichroism is a technique, which uses circularly polarized light of opposite helicity from SR to find the spin and orbital magnetic moments in a material. Another technique which was not possible earlier is X-ray Raman effect due to its weak nature.

The study of surfaces is gaining interest because properties of the surfaces are determined by one or two monolayers of the atoms. Here also SR is playing an important role. The study of heterogeneous catalysis, atomic structure of surfaces, surface electronic structure are some of the areas where techniques like X-ray diffraction, small angle scattering, EXAFS, etc are employed.

In life sciences, study of biological systems to understand the intricate relationship between the structure of the system and its biological activity is a fascinating subject. Imaging of biological molecules, protein crystallography, structural

TABLE 1. Parameters of Indus-1 and Indus-2

	Indus-1 (operational)	Indus-2 (Under Commissioning)
Electron energy	450 MeV	2.5 GeV
Beam current	100 mA (achieved=160 mA)	300 mA
Beam lifetime	1.8h (achieved 1 h)	18 h
Dipole bending field	1.5T	1.5 T
Critical Wavelength (energy)	61.38 Å (202eV)	1.98 Å(6.2 keV)
Circumference	18.96 m	172.4 m
Beam emmitance (V)	21 $X10^{-9}$ m.rad	$5.81x10^{-9}$m.rad
Bunch length	113 mm	22.3 mm
Revolution frequency	15.82 MHz	1.748 MHz
Harmonic number	2	291
Straight sections for Insertion devices	1	5

studies of active site of enzymes, study of fibre and self-assembly, membrane system, etc. are a few examples. These experiments have now gained momentum and study of this will lead to modern drug design.

One major industrial application of synchrotron radiation is in deep x-ray lithography and extreme ultra violet (EUV) lithography. EUV lithography is used writing structures with high resolution (sub micron). Deep x-ray lithography is used for making Micro Electro Mechanical Systems.

The list of applications of SR given above indicates only some major applications and the list is not exhaustive.

Characteristics of Indus-1 and Indus-2

Table 1 gives the parameters of Indus-1 and Indus-2. Indus-1 became operational in 1999. The stored electron beam current of ~200 mA has been achieved though the lifetime at this current is rather small. The designed value of ~100 mA and one hour lifetime is achieved at this current as against 1.8h. This lifetime will increase after continuous operation of the beam due to 'beam cleaning of the vacuum chambers', thereby reducing the outgassing rate due to photon-induced desorption of walls of the vacuum chambers. Details of the Indus-1 source can be found elsewhere /1/. Indus-2 is a 2.5 GeV electron storage ring from where a good photon flux will be available in the sub Angstrom region. Indus-2 storage ring has been assembled and the trials for beam circulation are in progress. Details of Indus-1 and Indus-2, its present status, various beamlines and the research using these SR sources can be seen at www.cat.ernet.in.

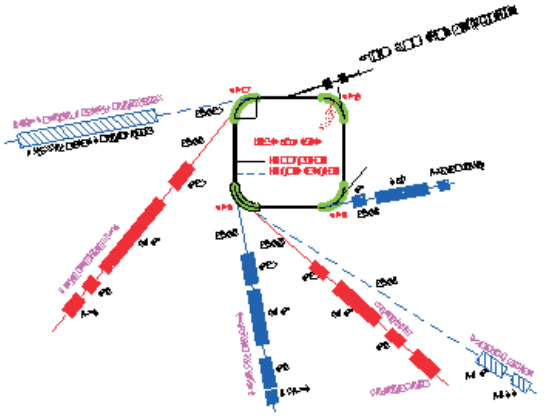

Fig. 4 Schematic representation of experimental hall Indus-1 along with location of various beamlines.

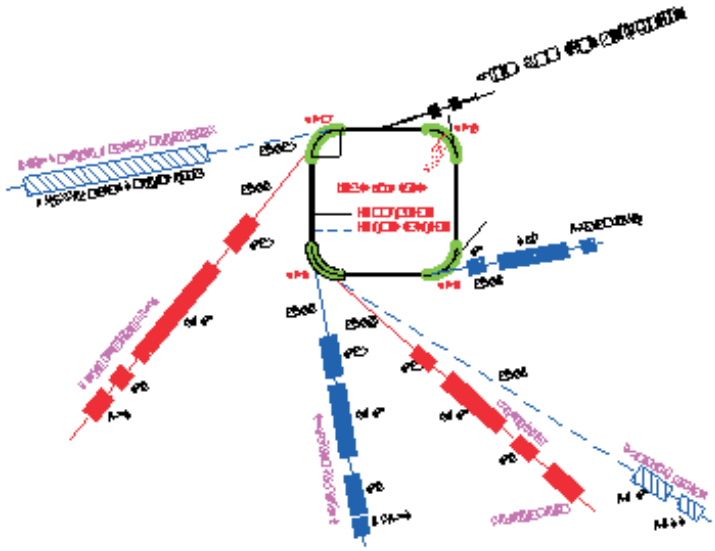

Fig. 4 Schematic representation of experimental hall Indus-1 along with location of various beamlines.

TABLE 2. Characteristics of these beamlines on Indus-1 SR facility

Beamline	λ – range	Monochromator	Organisation	Status
1. Reflectivity	40 – 1000 Å	TGM	RRCAT, Indore	Operational Nov. 2000
2. Angle integrated PES	60 – 1600 Å	TGM	CSR_DAE, Indore	Operational Nov.2000
3. Angle resolved PES	40 – 1000 Å	TGM	BARC, Mumbai	Commissioned in Dec, 2002
4. Photophysics	500 - 2500 Å	Seya-Namoika	BARC, Mumbai	Commissioned in March, 2003
5. High resolution VUV	400 - 2500 Å	Off-plane Eagle	BARC, Mumbai	Construction
6. Photo absorption (PASS)	20 - 120 Å	SX700	BARC, Mumbai	Construction

Beam lines on Indus-1 and Indus-2

Indus-1 has four bending magnets of field 1.5 Tesla and radius of 1 meter. Each bending magnet vacuum chamber has two ports at $10^0$and 50^0. Beamlines can be drawn from only three bending magnets as the fourth magnet is close to the injection septum magnet. From these three bending magnets, it is possible to tap six beamlines. Figure 4 gives the schematic representation of the experimental hall showing various locations of beamlines. At present four beamlines are operation. Two more beamlines are in the advanced stage of commissioning and will be operational soon. The characteristics of these beamlines are given in Table 2.

The reflectivity beamline is designed taking 10 mrad as horizontal and 5 mrad as vertical divergence from bending magnet DP2 of Indus-1. The pre-mirror is a toroidal mirror to focus the SR beam on to the entrance slit of the monochromator with a

vertical deflection. The beam is incident at 4.5^0 to the mirror surface. This mirror is gold coated and has a demagnification ratio of 2:1. The monochromator used in this beamline is a toroidal grating monochromator (TGM) type. The entrance slit of the monochromator can be changed in horizontal direction from 0.4 mm to 3 mm in four discrete steps, whereas the vertical slit is adjustable from 0.0 to 1.8 mm continuously. The deflection angle at the grating is 162^0. The three interchangeable gratings (200,600 and 1800 lines/mm) cover the wavelength from 4 to 100 nm. The average spectral resolution for this wavelength range is ≈500. The post mirror is also a toroidal type to refocus the monochromatic beam on to the target, which is kept at a distance of 1.8 meters from the center of the mirror. The demagnification ratio is 1:1. The typical spot size is 1 mm (h) x 1 mm (v). The experimental station on this beamline is a multipurpose reflectometer. It operates in the vacuum of 5×10^{-8} mbar and has a two-axis goniometer with independent and coupled rotation of sample and detector with an angular resolution of 2.5 mdeg. In between the beamline and the reflectometer a differential pumping station is installed as the beamline is under vacuum of 10^{-9} mbar. It is possible to set the reflectometer in either s or p polarization geometry. The detectors that are used are either Si or GaAsP photodiodes.

Angle Integrated PES beamlines is built by the Consortium for Scientific Research , Indore. This is again a TGM based beamline on bending magnet DP1, with toroidal mirrors as pre and post focusing optics. The acceptance of the beamline is 10 mrad (h) x 4 mrad (v). The entrance arm length of the monochromator is 1500 mm and the exit arm length is 2634 mm. The wavelength that can be covered by three interchangeable gratings is 6to 160 nm. The experimental station is an indigenously built angle integrated photoelectron spectrometer. It comprises of an ultra high vacuum chamber in which a 100 mm radius hemispherical analyzer and a channeltron detector are housed. The chamber is equipped with sample manipulator with x-y-z motors, sample heating (900^0 C) and sample cooling (liquid nitrogen temperature) facilities. The sample preparation chamber has a diamond file to scrub the sample surface and a quick load lock system with a magnetically coupled transfer rod. The measured resolution of the energy analyzer is 800 meV.

TABLE 3. Beamlines on Indus-2 under construction/ planning

Sl. No.	Beamline	E-range
1.	Powder Diffraction	5-25 keV
2.	XRF microprobe	2-20 keV
3.	Energy Dispersive XRD	10-70 keV
4.	Protein Crystallography	6-25 keV
5.	EXAFS	5-20 keV
6.	Grazing Incidence Mag. Scattering	5-15 keV
7.	Photo Electron Spectroscopy	0.8-15 keV
8.	Small Angle x-ray Scattering (SAXS)	8.0, 16.0 keV
9.	Infra red beamline	2-100 μm
10.	MCD on Undulator	0.1-1.5 keV
11.	White Beam Lithography	1.5-20 keV
12.	Imaging	15-35 keV
13.	Multipurpose EDXRD	5-40 keV
14.	MCD/PES on Bend	0.030-4 keV

An angle resolved photoelectron spectroscopy beamline is built by Bhabha Atomic Research Centre (BARC), Mumbai on bending magnet DP2. It is based on a toroidal grating monochromator. The UHV chamber of the spectrometer contains both angle resolved and angle integrated electron analysers. The chamber also has a low energy electron diffraction and an Auger probe to determine the orientation of single crystals, a sample manipulator and an argon-ion sputter etch gun for in situ sample cleaning. Expected resolution of the analyzer is between 50 to 100 meV.

Photophysics beamline is also built by BARC on the bending of magnet DP3. The wavelength that can be covered by using a 1 metre Seya-Namioka monochromator with a spherical grating (2400 1/mm, gold coated) is 50 to 250 nm. The beamline acceptance is 41 (h) x 5.6(v). The experimental station consists of a 250 mm diameter UHV cell for absorption and emission spectroscopy experiments

in gas phase and an UHV chamber and a sample holder for solid samples.

In addition, two more beamlines are under fabrication stage. These are high resolution spectroscopy beamline with a 6.65 metre spectrometer in the off axis eagle mount having gold coated concave grating, and a photo absorption spectroscopy beamline on a plane grating monochromator to study the absorption edges in the energy range 100-70 eV. These beamlines will take a while before they are set up on Indus-1.

Indus-2 has 22 bending beamline ports and 5 straight sections. In all 27 beamlines can be installed. For Indus-2 beamlines, the work on the design and fabrication on some of the beamlines has started. Existing plan of the various beamlines under construction is given in Table 3. Assembly of high-resolution x-ray diffraction and EXAFS has already started, and are expected be available to users by the end of 2007.

Applications of Energetic Ion Beams in Materials Science

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Introduction

Energetic ion beams produced by particle accelerators are being routinely used for both material modifications and quantitative analysis. The central theme of both these applications is the well understood basic physics that governs the interaction of energetic ion beams with solids. Modern materials science requires materials with exquisite properties and heavy ion implantation has the potential to create such new materials. Ion implanters were fabricated for the purpose of shallow-impurity doping into semiconductors and the implantation technique found its niche applications in semiconductor-IC processes because of its non-thermal nature. Good controllability of doping levels as well as the spatial distribution of impurity with manipulation of ion energy, current density and implantation period are the advantages of implantation over conventional thermal processes. Another attractive aspect is the non-equilibrium nature of the implantation process. For instance, 1ev corresponds to 10^4 degrees K and 1Mev is 10^{10}K. Even though the energy stored is rapidly relaxed within the solid, highly non-equilibrium states which are never obtained in thermal equilibrium conditions are created leading to materials with novel physical properties [1]. Non-equilibrium materials science has unlimited possibilities for the future. Energetic heavy ion beams which can cause physical and chemical effects (doping and alloying) are technologically very important and attractive. The interaction of impurities, ion-beam induced defects and the control of these processes in the nano scale are emerging as new challenges for the material scientist.

Rutherford back scattering (RBS) is one of the most important and commonly applied techniques to determine the nature, concentration and depth profile of heavier impurity elements in materials [2]. RBS involves the energy analysis of ions elastically scattered from a material. The process is schematically depicted in Fig. 1. The energy spectrum of the back scattered ions represents a convolution of target mass and the depth of the scatterer. Deconvolution provides the depth profile of the impurity in the solid. The number of back scattered ions is proportional to the square of the atomic number of the target element and this information is used to extract relative impurity concentration. The energy dependence of the back scattered ions on the mass of the target element provides the tool to identify the scatterers in the target. RBS is particularly useful to identify heavy dopants or impurities is a light target material. It is

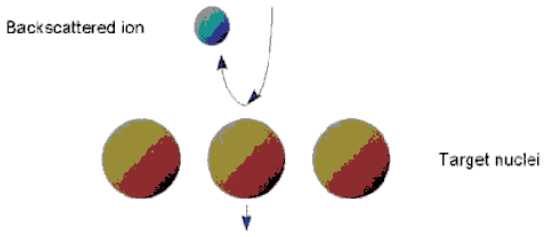

Fig. 1 Schematic representation of Rutherford Back Scattering.

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Fig. 2 An artist view of Channeling in Single Crystal.

often used to establish graded compositions and film thicknesses in multilayer structures. The choice of a particular beam or its energy is often determined by the analytical problem under investigation. The mass and the depth resolutions have to be optimized for a given condition by suitable choice of experimental geometries.

MeV ion beams directed onto oriented single crystal targets can channel down crystal axes and planes over rocking angles of ~1^0. The channeling effect arises because rows or planes of atoms can steer energetic ions by means of a correlated series of gentle small angle collisions when the ions are incident at an angle less than a critical angle [3]. An artist's view of the process is shown in Fig. 2.

Backscattering and other small impact parameter processes such as inner shell ionization and PIXE get significantly suppressed under channeling conditions. As a result, the yield for these processes reduce substantially as the orientation of the single crystal target is changed with respect to the incident beam such that the crystal axis aligns with the beam. The main applications of channeling in material science are in (i) lattice location of impurity atoms in a single crystalline host. (ii) Composition and thickness determination of amorphous surface layers and (iii) characterization of lattice disorders. The channeled component of the beam, in a way, acts as a probe to detect atoms, either host or impurity, that have been displaced from substitutional lattice sites by distances exceeding about 0.1 to 0.2 A^0. By studying the yields and angular distributions of channeled ions, the amount of disorder, the number of non substitutional impurity atoms and their depth distribution can be determined and this has proved to be a very powerful tool to study and characterise materials.

Ion Implantation

In ion implantation, energetic ions from an ion accelerator are made to impinge on the surface of the material which is required to be doped. The depth to which the dopants are implanted primarily depends

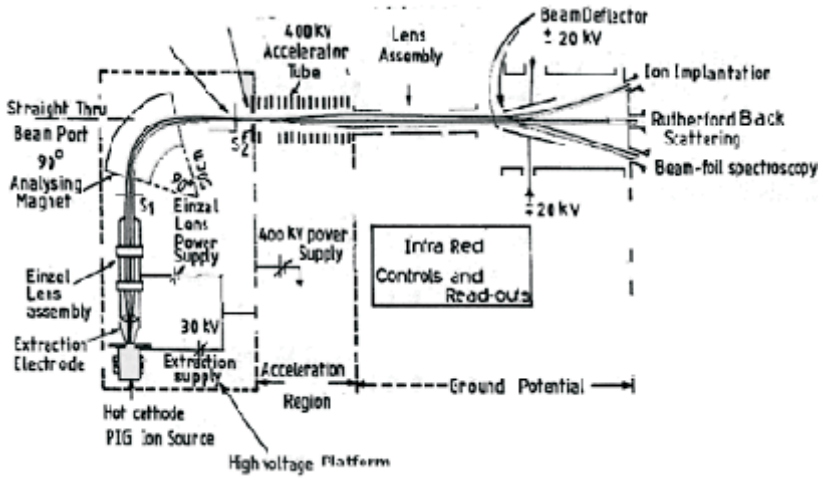

Fig. 3 Schematic Diagram of a Variable Energy (50-400 keV) Ion Beam Facility.

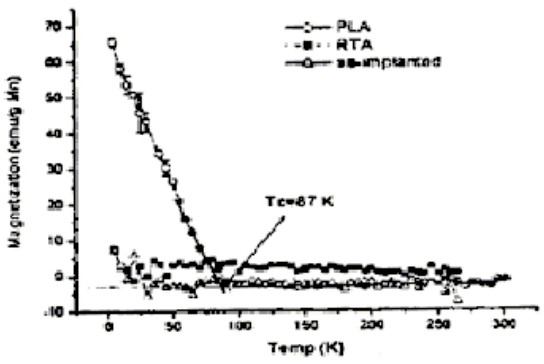

Fig. 4 M vs T plots of PLA, RTA and un-annealed samples.

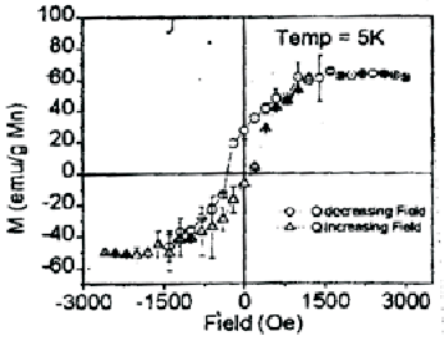

Fig. 5 M vs H curves for GaAs: 3% Mn PLA sample at 5K.

on the energy of the ion beam. The range of energies commonly used in ion implantation varies from a few KeV to a few MeV depending on the particular application. A schematic diagram of a typical variable energy (50-400 Kev) ion beam facility used for ion implantation is given in Fig. 3.

The required ions for implantation are produced in the ion source, mass analysed in a bending magnet, accelerated through a high voltage field to acquire the required energy and then focused and directed into the implantation chamber. The vacuum in the implanter, particularly in the implantation chamber has to be of the order of or better than 10^{-6} torr. The number of ions implanted into the target are measured using a high sensitivity current integrator.

As the energetic ions come to rest in the target, they collide with the target atoms displacing many of them from their lattice sites creating lattice damage. The dopant ions finally come to rest in unpredictable locations in the target which result in many of the dopant ions not being in correct substitutional sites and therefore are electrically inactive. To restore the crystal quality with incorporation of the implanted ions at desired lattice sites, post implantation annealing is often required. Several techniques such as thermal, flash lamp, laser etc. are used for annealing. Examples of rapid thermal annealed and pulsed laser annealed Mn doped GaAs samples displaying ferromagnetic transition is shown in Fig. 4 [4]. It can be seen that magnetization in PLA samples rises sharply at low temperatures with a curie temperature estimated to be ~ 87^0 K. Fig.5 shows a distinct ferromagnetic loop of the sample at 5K. No ferromagnetic transition was observed in the RTA sample emphasizing the role of the annealing method in sample preparation.

The introduction of dopants in semiconductors is the most common application of implantation and semiconductor processors use it for doping in Si integrated circuits. In some cases such as rare earth implants in Si, post implantation annealing often makes the implanted ions precipitate. In such cases implantation can be carried out at elevated temperatures so that in-situ annealing of the defects is achieved. An example of substitutional incorporation of Eu in Si substrate by implantation at 623^0 K is shown in Fig. 6 [5]. It can be seen from this result that at 623^0 K of the substrate, most of the lattice damages are annealed and that a significant fraction of the implanted Eu ions become substitutional.

Apart from direct ion-implantation, for high dose applications, ion beam induced mixing of thin evaporated films on solid substrates has been employed as a successful doping process. The basic principle involved is illustrated in Fig. 7. A thin film of the desired dopant is evaporated on the substrate and is irradiated with heavy ion beam such as A_r^+ or Xe^+ with an energy such that its projected range is slightly larger than the thickness of the evaporated layer.

The irradiation produces intermixing of atoms between the thin film and the substrate producing doping. The concentration of dopants and the

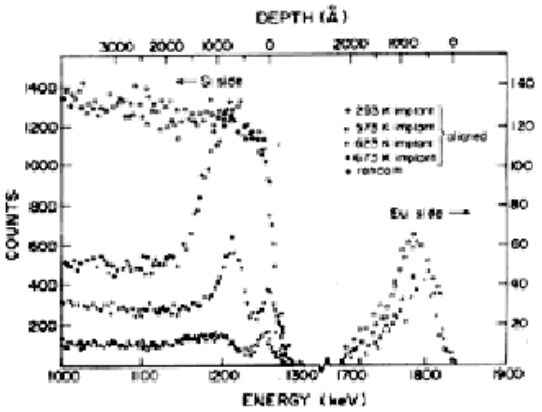

Fig. 6 The 2 MeV α-particle channeling spectra along (100) direction of ^{151}Eu implanted Si (dose 10^{15} ions/cm^2) at different temperatures. For clarity the Eu profile in the aligned and random cases is shown only for the 623 K implantation.

thickness of the intermixed region can be controlled by the energy and dose of the primary beam. An example of Sn on Si intermixed with Ar^+ beam is shown in Fig. 8 [6]. The concentration dependence and the variation in thickness of the intermixed layer with energy and dose of Ar^+ beam are clearly visible from this result.

Other implantation procedures such as plasma immersed implantation and cluster ion implantation are also used for specific applications such as for surface finishing, nitriding, corrosion control, adhesive coating etc. The dynamical behaviour at the surface region of a solid as a result of the cluster ion impact is of current interest both for fundamental studies as well as applications [7]. AFM images of surfaces exposed to cluster beams have shown formation of nanoscale craters and hillocks on the surface. Kinetic energy transfer from the stopping cluster to the substrate lattice causing shallow-layer melting at the collision spot followed by liquid melt out and quenching is the proposed mechanism for their formation. It is expected that better understanding of cluster-surface interaction will help develop cluster ion beam processing as a powerful technology for the production of materials with novel functional and structural properties.

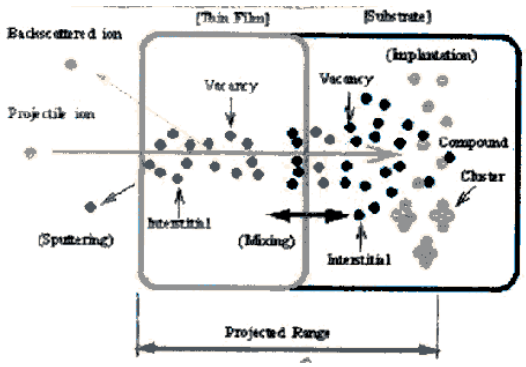

Fig. 7 Schematic presentation of Ion Beam Mixing.

Rutherford Backscattering Spectroscopy (RBS)

When a projectile of mass M_1 gets elastically scattered by a target atom of mass M_2, as shown in Fig. 9 energy is transferred from the moving to the stationary particle. The projectile energy E_1 after the elastic collision is related to the initial projectile energy E_0 through the relation $E_1 = KEo$ where K is a kinematic factor depending only on M_1, M_2 and the scattering angle. The value of M_2 can thus be determined by measuring E_1 provided E_0 and M_1 are known. By using α particle of known energy as projectiles, it is possible to determine M_2 by measuring E_1. This is the basic principle governing RBS.

In a target which contains more than one type of atoms that differ in mass such that the change in the energy of the scattered particles is measurable, the masses of the different types of atoms present in the target can be determined. In thin film samples, the width of the energy spectrum of the elastically scattered α-particles gives a measure of the thickness of the film. Since Rutherford scattering cross-section for a given projectile is proportional to Z_2^2 where Z_2 is the atomic member of the target, heavy atoms are much more efficient scatters than the light ones. This implies that RBS is very sensitive to detect extremely small concentrations of heavier elements in light targets. Fig. 10 illustrates the power of RBS in determining the composition of multicomponent thin film targets [9]. Here the composition of a thin film bubble material target as

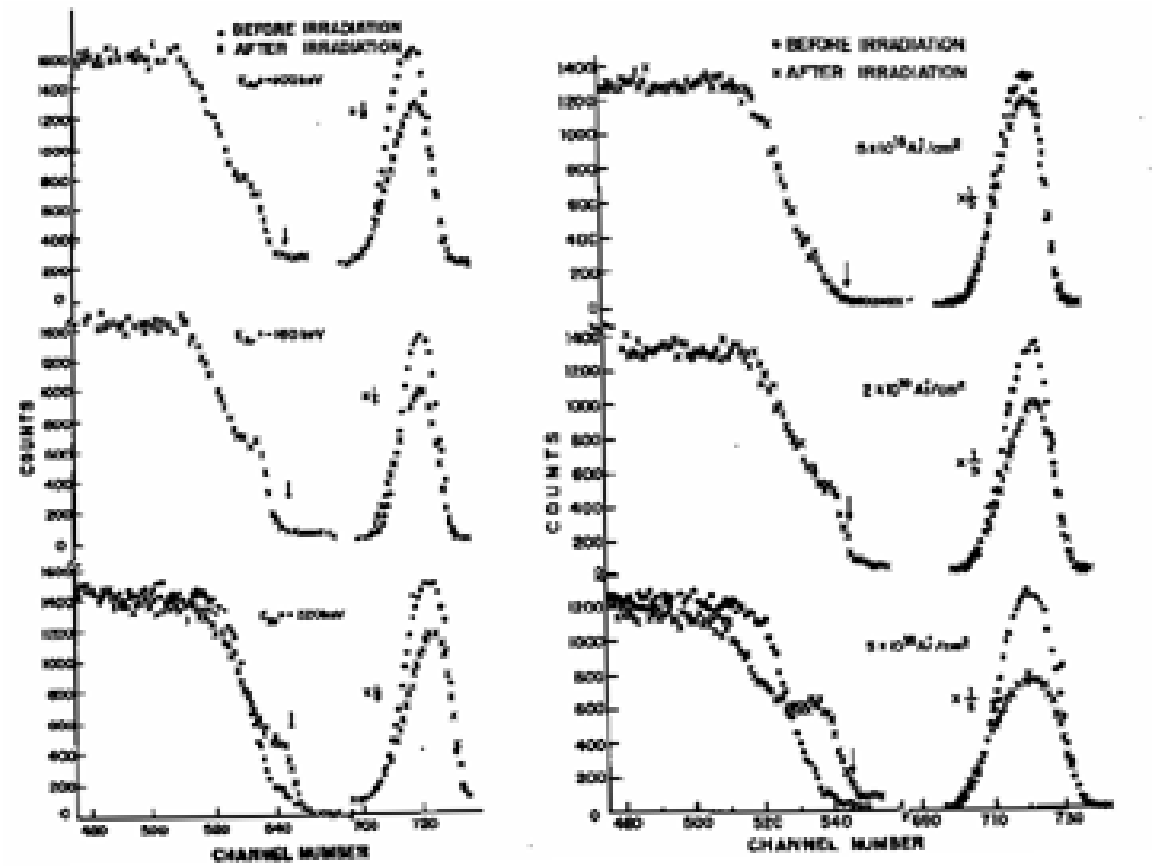

Fig. 8 *RBS spectra (Eα=3MeV) of 450 Å Sn on Si, irradiated with Ar^+ ions at different energies and doses. The arrows show the position of pure Si edge in the RBS spectra. The interface mixing after Ar^+ irradiation is clearly visible.*

determined by RBS is compared with the known nominal composition and it can be seen that the agreement is very good.

The energy E_1 of the detected particle can be related to the depth x at which the scattering event occures in a monoisotopic elemental ample. By knowing the energy loss of the projectile in the target, it is possible to compute the depth 'x' from the measured E and KE_0. The scattering events are illustrated in Fig. 9. It is also possible to convert the measured energy loss of the scattered particle to a depth scale. Using the depth scale, RBS is employed to analyse thin films and layered structures. In this case, the backscattering signals display features of both the front surface and the interfaces.

Backscattering spectroscopy has many applications in different disciplines. It is a very powerful tool to study impurities at the surface and in the bulk on elemental targets. Compositional analysis using RBS is a well established technique. Diffusion profiles of heavy impurities in light targets can be measured with high resolution. Multilayered films and interfaces can be analysed quantitatively using RBS. The concentration profiles of ion implanted impurities in substrates can be determined by this spectroscopic technique and detailed study of impurity migration upon annealing can be easily investigated.

Ion implantation of metal elements in glass substrates can lead to the formation of nanometer

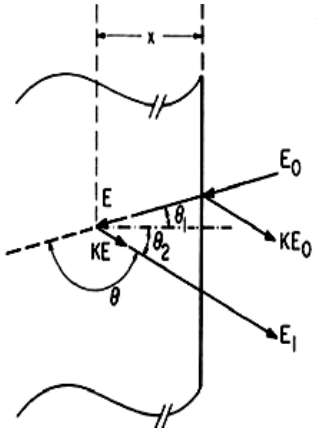

Fig. 9 Schematic diagram of backscattering event in a mono isotopic target.

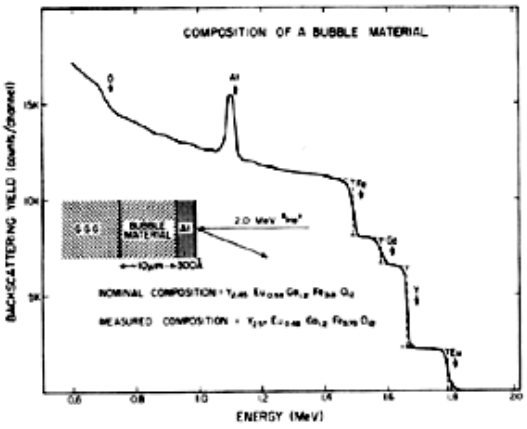

Fig. 10 Backscattering spectrum of 2.0 MeV ^4He ions on a thick target consisting of a magnetic bubble material with a thin surface of Al. The bubble material was known to have the garnet composition X_8O_{12} with the nominal composition = $Y_{2.45}Eu_{0.55}Ga_{1.2}Fe_{3.8}O_{12}$ and measured composition = $Y_{2.57}Eu_{0.48}Ga_{1.2}Fe_{3.75}O_{12}$. [From Nicolet and Chu (1975).]

radius colloidal particles in a thin surface layer. These metal nanocluster composite glasses exhibit an enhanced intensity dependant refractive index which makes it a possible candidate for an-all optical switching device. In these materials the knowledge of the cluster size distribution as well as the spacial correlation function is important in order to relate the morphological characteristics to the physical

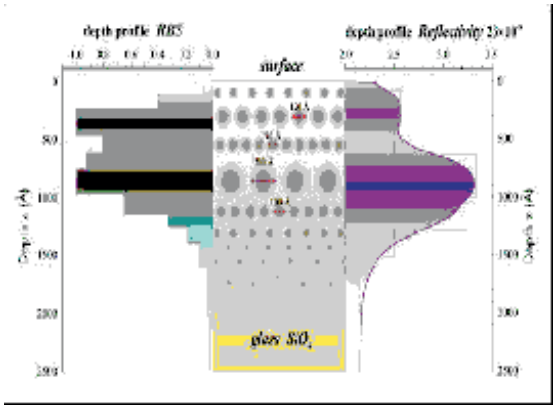

Fig. 11 Comparison of Ni profiles from RBS and Reflectivity.

properties. RBS spectroscopy is best suited for these studies and a lot of results correlating profile distributions measured by RBS with other physical observations can be seen in the recent literature [10]. Fig. 11 shows the in-depth nickel distribution as measured by RBS and the corresponding reflectivity profile. The correlation between the two is remarkable. Grazing incidence x-ray diffraction on these samples gives evidence for fcc nickel clusters.

Ion Channeling

Ion channeling occurs in single crystalline targets when rows or planes of atoms can steer energetic ions by means of correlated small angle scatterings. In the language of RBS, channeling effects produce large reduction in the yield of back scattered particles as the orientation of the single crystal target is changed in relation to the incident beam. Fig. 12 shows a model of lattice atoms depicting the atomic configurations in a diamond type lattice viewed along (a) random, (b) planar and (c) axial directions. The figure is very suggestive that pronounced effects would occur when crystal orientation gets aligned with the beam direction. The channeled ions do not approach the lattice atoms in the axial rows and the planes closely enough to undergo large angle scatterings. The channeling technique offers a remarkably powerful analytical tool to study lattice location of impurity ions, disorders in lattice, strained superlattices, amorphous layers on a single crystal target, etc.

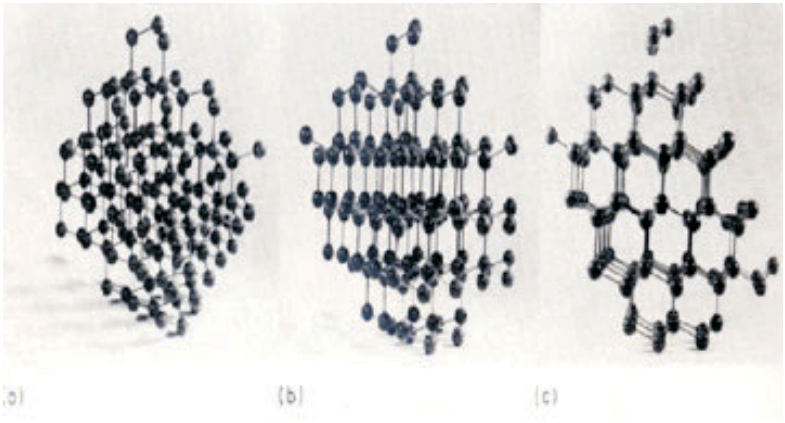

Fig. 12 Model of lattice atoms showing the atomic configuration in the diamond type lattice along a) random, b) planar and c) axial directions.

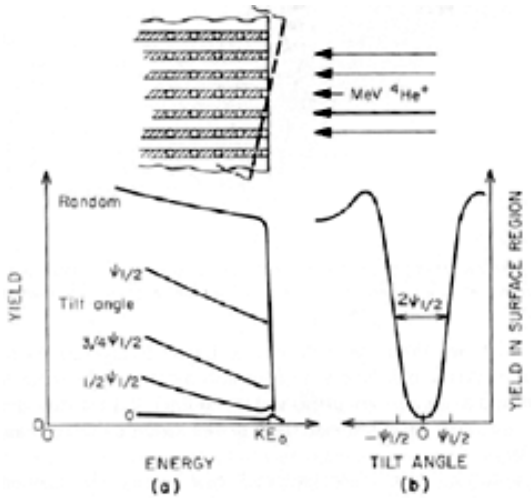

Fig. 13 Random spectrum and aligned spectra at different tilt angles (a) and the angular yield profile (b) measured from the scattering yield in the surface region of the crystalas a function of tilt angle.

Experimentally the system requirement is similar to that of the RBS except that (i) the target has to be mounted on a goniometer allowing crystal alignment and (ii) the beam has to be parallel and well collimated (about 0.5 mm x 0.5 mm size). Usually α-particle beams of around 2 MeV are used for channeling measurements. The back scattered spectra in a random orientation is similar to the normal RBS spetra from amorphous samples and as the crystal gets aligned with respect to the beam by the manipulations of the goniometer, the yield of the back scattered events reduce drastically. This is schematically shown in Fig. 13 where the tilt angle is defined as the angle made by a crystal axis with respect to the beam. The characteristic angle ψ for channeling is given by $\psi = [2Z_1 Z_2 e^2/Ed]^{1/2}$ where E is the incident energy in MeV, d the atomic spacing in angotroms along the axial direction and Z_1 and Z_2 the atomic members of the projectile and targets atoms respectively. For MeV α particles, the typical half angles $\psi_{1/2}$ are in the range 0.3 to 1^0. It can be seen from fig. 14 that as the tilt angle approaches the value zero, the back scattered yield χ becomes a minimum and this value of χ_{min} is a measure of the crystalline quality. The $\psi_{1/2}$ and χ_{min} are the two experimentally determined parameters which help get information on substitutionality and crystal imperfections.

The analysis of the backscattered spectra to obtain information of the lattice site location of impurities on substitutional lattice sites is rather simple. It is done by comparing the ratio of the aligned minimum yield to the random yield for the impurity signal to that of the host signal and if the ratios match the impurities are substitutional. It can be seen in Fig. 6 that E_u signal for the sample implanted as 623^0K shows reduction on alignment compared to the random one while the sample implanted at 293^0K does not; implying that the sample implanted with E_u at 623^0K incorporates

about 30% of the E_u ions substitutionally in the Si host.

When an amorphous or highly disordered layer is grown or produced on top of a single crystal target, the scattering yields in the aligned orientation from both the surface layers and the underlaying signle crystal will be different. A study of this difference can give information of the depth and nature of the disordered surface layers. It can be seen from fig. 6 that implantation of E_u ions into Si at 293K has produced an amorphous surface layer of thickness about 1100 A^0, well beyond the projected range of 600 A^0 for the 150KeV Eu ions. The amorphasization reduces as the implantation temperature is increased and at 623^0K implant the surface damage produced by implantation is negligible. These studies have also shown the interesting dynamics of Eu impurities in Si as a consequence of annealing the samples at elevated temperatures.

Irradiation by MeV ion beams

The transfer of energy to the target atom in a high energy heavy ion collision occurs through electronic energy loss (S_e) and nuclear energy loss (S_n). At MeV energies the electronic energy loss (S_e) is the dominant factor and determines the consequent material modification. In spite of a long history of studies, S_e is not adequately described over all ranges of ions, energies and targets. Depending on the energy loss in the target material, its response to the incident ion will change. The resulting equilibrium state of the irradiated target will thus depend on the initial response coupled with subsequent dynamics of the solid target. This is often complex and target specific. For example, glassy materials show non-saturating anisotropic plastic deformation during swift heavy ion (SHI) irradiation as explained by the viscoelastic model [8]. While glasses exhibit a continuous transition to their liquid phase, amorphous silicon is expected to show a melting transition with a volume contraction to dense metallic silicon liquid [9]. However under MeV ion irradiation it has been shown that amorphous silicon not only flows plastically in the same way as glass, it also shows swelling [10]. Study of the surface modifications in single crystal targets as a result of SHI is very important and recent studies have shown that nano scale hills and craters are created at the surface and the dimensions of these features are dependent on the fluence [11]. In Polymeric films, SHI irradiation produces lattice deformations which can result in latent tracks that can be suitably etched to provide micro and nano pores [12]. Such track etched membranes are used as molecular filters, sensing devices etc. SHI irradiation is also used to produce columnar defects in high T_c superconductors to generate pinning centres. A number of other applications such as preparation of buried layers, alloy spraying, modification of optical properties of thin oxide films, etc are also of intense current interest.

Conclusion

Energetic ion beams are being used to study a number of phenomena in condensed matter science. They are employed both as agents of change and tools of analysis. We have discussed here a few examples from different areas of materials science. However the applicability of heavy ion beams extends far beyond. A number of ion beam facilities are available at different laboratories in our country and optimal utilization of them can provide exciting opportunities for research in materials science.

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Accelerators in Radiation Chemical Research

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Chemistry has come a long way from the stage of mixing reagents in a reaction vessel under certain conditions, identifying the products, establishing overall mechanism from macroscopic investigations and optimization of the parameters so as to get maximum yield. But chemist of today is not satisfied with this. He wants to know more. What are the various elementary reactions involved in a reaction, and what is the detailed dynamics of each elementary reaction?

In order to monitor the chemical act, which lasts only for a picosecond or so, we need faster techniques, with extremely short time resolution. The development of lasers and accelerators have greatly helped in this endeavour. One can prepare the reactants in well-defined quantum or energy states, and monitor the journey of the reactants from the energy valley to the exit valley by taking snapshot from the time zero- i.e. the time chemical act starts. Work was initiated in BARC to investigate reactions at faster time scale in the early eighties, and has brought a sea change in the quality of research now carried out in BARC. This is now a matured programme and bearing fruits of quality chemical research.

After nearly two decades of operation, BARC can boast of an ultra-modern facility of LINAC-based pulse radiolysis study. Both fundamental and applied work has been carried out.

Radiation Chemistry

Soon after the discovery of radium at the end of the eighteenth century, the effect of the radiation emanating from the radioactive isotope on chemical substances became evident. Ramsay's observation that H_2 and O_2 are generated upon the irradiation of water is often quoted as the beginning of the field of radiation chemistry. In the nearly a century that followed the field has matured to engulf a broad range of materials from simple molecules to complex composites. Today, the effects of radiation are utilized in numerous technologies, from food preservation to initiation of polymerization, from power generation to arms production and from radiotherapy to sterilization. Yet, studies are still conducted on the fundamental aspects of the effects

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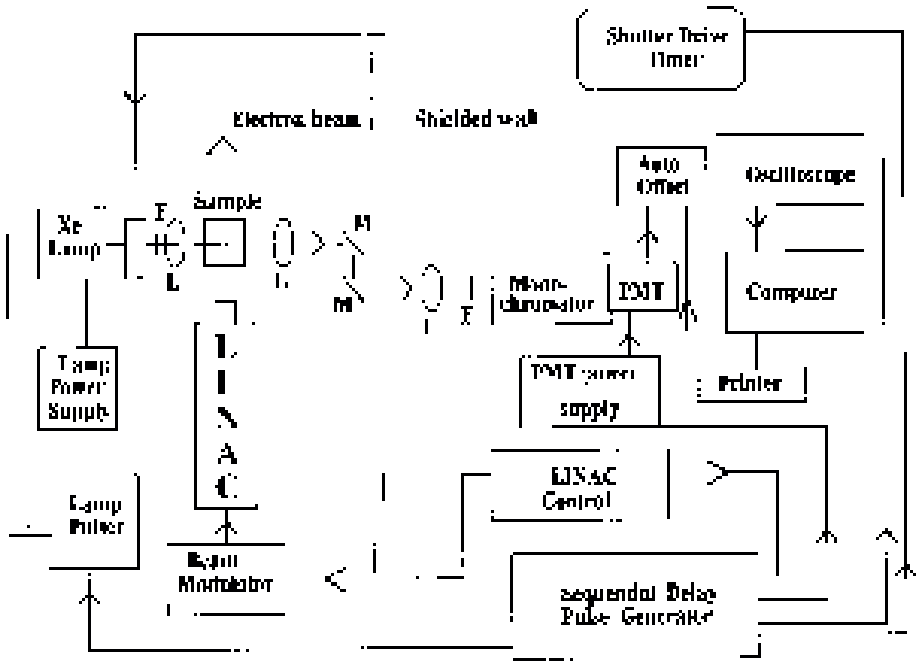

Fig. 1 Black diagram of the pulse radiolysis facility at Chemistry Group, BARC.

of radiation in diverse exotic media from supercritical fluids to wet soils.

In the initial phase, techniques available were extensively used for the estimation of low concentrations of stable radiolysis products.

There was active interest in studies on the radiation stability and free radical reactions. We were actively pursuing the free radical reactions of biologically important molecules and drugs. The redox properties of these compounds were evaluated not only in aqueous media, but also in micellar media, which mimic the lipid membranes.

Pulse Radiolysis Studies

Whereas much of the underlying mechanisms for the effects of radiation on materials were outlined using steady-state radiation sources, the advent of pulse radiolysis on the heels of flash photolysis opened a window into direct observation of the intermediates. One of the early discoveries utilizing pulse radiolysis was the spectrophotometric detection of the hydrated electron by Boag and Hart. Since then thousands of rate constants, absorption spectra, one-electron redox potentials and radical yields have been collected using the pulse radiolysis technique. The Radiation Chemistry Data Center at the University of Notre Dame accumulates this information and posts it (at www.rcdc.nd.edu/) for the scientific community to use. They cover the reactions of the primary radicals of water and many organic radicals and inorganic intermediates.

To collect this volume of data, linear accelerators with nanosecond time resolution were, and still are now, routinely used around the world. A programme was initiated to establish a Pulse Radiolysis Facility using nanosecond electron pulses from a linear accelerator. Only the linear electron accelerator was imported, and the rest of the set-up, including the kinetic spectrophotometer, with detection system, on-line data acquisition and analysis, was assembled in-house (Fig. 1). Till June 2005, this was the only machine available in India for pulse radiolysis experiments, and has been successfully used by a number of researchers from all over India and many from abroad. BRNS has

funded University of Pune to set up a similar facility with similar design and improved detection system. The centre is named as National Centre for Free Radical Research (NCFRR), of which this author is the Chairman, Users & Implementation Committee.

Organic molecules are capable of reacting with a large number of primary species like e^-_{aq}, H-atom and $OH^\bullet$, generated from pulse radiolysis of the solvent water. While e^-_{aq} and $H^\bullet$ are reductants, acting by one-electron reduction process, $OH^\bullet$ may either add to the ring or some suitable substituent position and give rise to one-electron oxidation to some form of transient. The reduction can occur as follows (Q denotes an organic molecule, e.g. a quinone):

$$H_2O \text{ -^^^^^}\rightarrow \quad e^-_{aq}, H, OH^\bullet, H_2, H_2O_2 \quad (+ \text{ other products}) \qquad (1)$$

$$Q + e^-_{aq} \rightarrow Q^{\bullet -} \qquad (2)$$

$$Q + H^\bullet \rightarrow QH^\bullet \leftrightarrow Q^{\bullet -} + H^+ \qquad (3)$$

In aqueous solutions containing sodium formate, the reaction may be:

$$HCOO^- + OH^\bullet (H) \rightarrow CO_2^{\bullet -} + H_2O\ (H_2) \qquad (4)$$

$$Q + CO_2^{\bullet -} \rightarrow Q^{\bullet -} + CO_2 \qquad (5)$$

As reaction (2) also takes place, yield of $Q^{\bullet -}$ ncreases in this case.

In aqueous alcoholic solutions containing either methanol and isopropanol, following reactions take place.

$$CH_3OH + OH^\bullet(H) \rightarrow {}^\bullet CH_2OH + H_2O(H_2) \qquad (6)$$

$$(CH_3)_2CHOH + OH^\bullet (H) \rightarrow (CH_3)_2C^\bullet OH + H_2O(H_2) \qquad (7)$$

$$Q + {}^\bullet CH_2OH \xrightarrow[H_2O]{} Q^{\bullet -} + H_2CO + H^+ \qquad (8)$$

$$Q + (CH_3)_2C^\bullet OH \rightarrow Q^{\bullet -} + (CH_3)_2CO + H^+ \qquad (9)$$

Higher alcohols may also be used. However, more branched radicals, e.g. $CH_2(CH_3)_2COH$ (formed by reactions of $OH^\bullet$/ H with tert-butanol) are normally unreactive.

In most cases, an aqueous solution of the substrate has been used for radiation chemical studies. However, the reaction sequence depends entirely on the added scavengers/ chemicals like sodium formate, methanol, isopropanol, tertiary butanol or others. This author's group has extensively used a relatively novel solvent system comprising of a mixture of isopropanol (5 mol dm^{-3}) and acetone (1 mol dm^{-3}) in water (32.5 mol dm^{-3}). The advantage of this system, over and above solubilizing insoluble (in water) molecules, lies in the chemistry involved.

In our aqueous-organic mixed solvent system, reactions (2),(3),(4) and (5) are supplemented with reactions (7), (9), (10) and (11).

$$e^-_{aq} + (CH_3)_2CO \rightarrow (CH_3)_2CO^- \qquad (10)$$

$$(CH_3)_2CO^- + H_2O \rightarrow (CH_3)_2C^\bullet OH + OH^- \qquad (11)$$

The solute quinone (Q) is reduced to its semiquinone by any combination of the above reactions.

Optical Absorption Characteristics

Study of physical chemistry of organic molecules relies heavily on knowledge of optical absorption characteristics of the radicals, namely, absorption maxima and extinction coefficients. As dose can be calculated fairly accurately, the yield of radicals can be easily estimated. From the observed absorbance at a given dose, extinction coefficient of the radical can be calculated.

The observed absorbance (ΔA) after an electron pulse is given to the solution containing quinone and a suitable additive, will constitute a difference absorption spectrum given by:

$$\Delta A = (\varepsilon_{semiquinone} - \varepsilon_{quinone}).\ \Delta C_{quinone}\ .l \qquad (12)$$

where, l = optical path length, $\Delta C_{quinone}$ is the amount of quinone converted into the semiquinone and ε terms are the respective molar extinction coefficients.

As $\varepsilon_{quinone}$ is known at all wavelengths, and $\Delta C_{quinone}$ can be easily calculated at a given dose (as G-value is known under different experimental conditions),

$\varepsilon_{semiquinone}$ can be calculated at any given wavelength by using equation (13).

$$\varepsilon_{semiquinone} = \varepsilon_{quinone} + \frac{\Delta A_{obs} \times (G\varepsilon)_{dosimeter}}{A_{dosimeter} \times G_{semiquinone}} \qquad (13)$$

A plot of $\varepsilon_{semiquinone}$ vs λ will constitute a corrected absorption spectrum of the radical.

Acid-base Dissociation Constants

Radical anions can undergo protonation steps to form neutral radicals or in very strong acidic solution, cation radicals. On the other hand radical anions containing ionisable H can undergo deprotonation to form dianions, trianions or even polyanions. A plot of A vs pH can yield the values of pK_1, pK_2, pK_3, etc.

In case of benzo-semiquinone the pK value is 4.1. However, in case of substituted quinones, especially OH-substituted quinones, the anion gets extra stabilised due to intramolecular H-bonding. As a result, pK(1) values are lower.

Charge on the Semiquinone

One important aspect of chemistry of free radicals is determination of charge on the molecule. Conventional ionic salt effect studies in absence of any buffer often gives indication of the net charge at near neutral pH. However, we have shown that ionic salt effect studies, together with pulsed conductance studies and electron spin resonance spectroscopy can identify the ionic charge on the molecule without any doubt. Once charge on a species at a given pH is known, charge at other pH values can be ascertained by knowing the pK values of the transient.

To test this hypothesis, we have demonstrated the efficacy of the techniques by comparing the yield of the semiquinone derived from naphthazarin with the normalised ESR signal. Not only an extremely good correlation was obtained, but the chemical structure of the semiquinone, with the odd electron delocalised over the entire structure, could also be established.

Rate Constants for Formation

Quinones are electron attracting type of molecules and can be reduced by a large variety of reducing radicals. Typically, rate constants for formation of radical anions due to reactions with e^-_{aq} (or, e_{solv}) are virtually diffusion-controlled and fall around (1-5) x 10^{10} dm^3 mol^{-1} s^{-1}. These rate constants are normally directly calculated from a ΔA vs t plot at ~720 nm, representing decay of e^-_{aq}, and correcting for the matrix. Alternatively, competition kinetics with another solute may also be used. In the presence of substituents, the electron affinity of the molecule changes. However, it has been difficult to have a direct correlation between e^-_{aq} rate constants and substitution effects.

Disproportionation Reactions

In de-oxygenated aqueous solutions, semiquinone normally undergoes a bimolecular disproportionation reaction, forming the parent quinone and two-electron reduced hydroquinone.

2 semiquinone $\rightarrow$ quinone + hydroquinone (14)

Typical rate constants fall in the range of 10^8-10^9 $dm^3mol^{-1}s^{-1}$. However, in cases where substituents are present, an equilibrium of the type of reaction (15) has been observed over a range of intermediate pH values.

2 semiquinone $\leftrightarrow$ quinone + hydroquinone (15)

Especially in the case of hydroxy-substituted naphthoquinones and anthraquinones, such equilibrium was seen to lie heavily to the left, showing exceptional stability of the semiquinones. In case of naphthazarin, for example, we could preserve a de-oxygenated solution containing high concentration of the naphthazarin semiquinone for months!

It was conclusively established that such exceptional stability was due to the nearness of the E^1 (one-electron reduction potential), E^2 (second one-electron reduction potential) and E^m (two-electron reduction potential) values of the quinone and their characteristic change as a function of pH as a consequence of the pK values of the

species (quinones, semiquinones and hydroquinones) involved.

One-electron Reduction Potentials

The reduction potentials for semiquinones are those for formation from the parent quinones, i.e. the one-electron reduction potential of the parent quinone, E ($Q/Q^{\bullet -}$), and for reduction to hydroquinone, i.e. the second one-electron reduction potential, E($Q^{\bullet -}/Q^{2-}$) for addition of the second electron to the quinone. These reduction potentials depend on pH as Q, $Q^{\bullet -}$ and Q^{2-} can all be protonated.

Pulse radiolysis has been established as possibly the "cleanest" method for determining these potentials. After the anionic form of a semiquinone has been formed at low concentration by the action of an appropriate electron-donating reducing agent, it is possible to establish an equilibrium of the type

$$Q^{\bullet -} + R \leftrightarrow Q + R^{\bullet -} \qquad (16)$$

with a reference redox couple $R/R^{\bullet -}$, under ideal chemical conditions, before $Q^{\bullet -}$ can disappear by disproportional or other chemical reactions. Measurement of equilibrium optical absorbance can then give the equilibrium constant K for reaction (16). If the reduction potential E($R/R^{\bullet -}$) is known, the value of E($Q/Q^{\bullet -}$) at 25°C vs NHE can easily be derived as

$$E(Q/Q^{\bullet -}) = E(R/R^{\bullet -}) - 59.16 \log K \qquad (17)$$

where all E values are in mV.

The reduction potential E($Q^{\bullet -}/Q^{2-}$) is obtained from:

$$E(Q^{\bullet -}/Q^{2-}) = 2E\,(Q/Q^{\bullet -}) - E(Q/Q^{\bullet -}) \qquad (18)$$

where E(Q/Q^{2-}) is the known two-electron potential of the quinone.

It is imperative to have an accurate value for the reference from the literature. Care has to be taken about solvent also, as Mukherjee et al have demonstrated. For example, the E^1 (MV^{2+}/MV^{+}) is -450 mV in aqueous system while it is -330 mV in isopropanol-acetone-aqueous (mixed) solvent. Over last two decades a large number of E^1 values have been determined accurately by this simple method.

When only a single ionisation of the semiquinone is considered, E($Q/Q^{\bullet -}$) is related to pH as:

$$E(Q/Q^{\bullet -}) = E(Q/Q^{\bullet -})_7 + 59.16 \log (K+[H^+]/K+10^{-7}) \qquad (19)$$

where K is the ionisation constant. Thus in the pH-independent region (pH > pK), the redox process is the simple addition of an electron, whereas in the acidic region, it also involves addition of a proton (i.e. $Q + H^+ + e^-_{aq} \rightarrow QH^{\bullet}$).

Reactivity with Oxygen

When an electron pulse is given to a solution which contains known quantity of oxygen, initially both semiquinone and O_2^- (superoxide radical) may be produced depending on the relative concentrations and rate constants. However, in all cases studied so far, the following reaction

$$\text{quinone} + O_2^- \leftrightarrow \text{semiquinone} + O_2 \qquad (20)$$

occurs, with equilibrium, if any, established within a few hundred microseconds. The exact course of reaction depends entirely on the relative one-electron reduction potential of O_2/O_2^- system (E^1 = -155 mV at 25°C vs NHE, when oxygen concentration is expressed in mol dm^{-3} unit) and $Q/Q^{\bullet -}$ system.

The rate constant for the important reaction

$$O_2^{\bullet -} + \text{Adriamycin} \leftrightarrow O_2 + \text{adriamycin semiquinone} \qquad (21)$$

could be determined pulse radiolytically as 3.5×10^8 $dm^3\ mol^{-1}s^{-1}$. If one assumes $E^1(O_2/O_2^{\bullet -})$=-155 mV and E^1 (adriamycin/adriamycin semiquinone) = -341 mV, one can calculate the equilibrium constant as 7.04×10^{-4} at pH 7. In the acidic pH, upto pH ~5, the K value does not change much. At pH <5, $HO_2^{\bullet}$ forms from $O_2^{\bullet -}$. At pH>7, the equilibrium is even more to the left. This consideration clearly shows that superoxide radicals are formed by reaction of the semiquinone with O_2, a finding of great biomedical significance.

Presence of oxygen in the vicinity of enzymatically produced anthracycline semiquinone

leads to predominant formation of $O_2^{\bullet-}$, sometime leading to concomitant OH formation, causing cardiotoxicity and cytotoxicity. The equilibrium reaction (21) may be used in calculating $E^1(Q/Q^{\bullet-})$ system by either measuring equilibrium concentrations or by measuring rate constants. Results are in agreement with the Marcus theory of electron transfer reactions.

Triplet Excited States

Phototendering and fading of anthraquinonoid dyes are believed to involve the triplet excited states. Apart from known photochemical excitation techniques, irradiation of quinone solutions in nonpolar solvents give rise to triplet states of quinones via the geminate recombination of initially formed ion pairs. Most popular solvents for such studies involve acetonitrile and cyclohexane, having no abstractable hydrogen atoms. In polar solvents like alcohols, initially formed triplets will react with the solvents by hydrogen atom abstraction to form semiquinone radicals.

In many cases where direct photo-generation of the triplet states of quinones is not very facile, pulse radiolysis offers a viable route, e.g. ubiquinone. T-T absorption spectra, extinction coefficient, triplet quantum yields and kinetic parameters have been successfully measured for a number of quinones.

Sulphur and Halo-Compounds

Although $^{\cdot}OH$ radical is the most powerful oxidizing radical, no evidence on one-electron oxidation of halogenated organic compounds existed in the literature. Radiation chemists in the Chemistry Group were always worried about the absence of direct proof for the formation of radical cation of these compounds. Low temperature matrix isolation studies suggested the formation of radical cations of halogenated organic compounds. The questions coming to their minds were: (1) Is the oxidation potential of halogenated organic compounds more than that of $^{\cdot}OH$ radical? (2) Are the radical cations too short-lived to be detected by our experimental facilities? and (3) Are the experimental conditions not suitable for their formation, and subsequent detection? Due to high electron affinity of halogens, $^{\cdot}OH$ radical, instead of undergoing one-electron oxidation, was either adding or abstracting H atom. In order to facilitate one-electron oxidation, the electron withdrawing power of $^{\cdot}OH$ radicals has to be increased. This was done by carrying out the experiments in acidic solutions, and the formation of radical cations was thus demonstrated. Pulse radiolysis studies of acidic aqueous solutions of halogenated organic compounds were carried out to evaluate the kinetic, spectroscopic and redox properties of radical cations of a large number halogenated organic compounds. It was also shown that higher amount of H^+ is required for halogenated organic compounds having higher electron affinity. It has been demonstrated that a linear relationship exists between electron withdrawing power of the halogen and concentration of H^+ required to form solute radical cation. These experimental conclusions are supported with theoretical calculations. In addition to one-electron oxidation of halogenated organic compounds, one-electron reduction studies on substituted fluorobenzenes have shown that the site of attack of e_{aq}^- and fluorine elimination depends on the nature of the substitution. The steady-state product analysis and identification of transient species have helped to identify the site of attack of radiolytic species of water. In this way, not only complete radiation chemistry could be understood, but also the progress of radiation chemical reaction could actually be seen.

Hydroxyl radical is known to undergo one-electron oxidation of dialkyl sulfides (R_2S) to form sulfur-centered dimer radical cation, $(R_2S)_2^{\cdot+}$, via a complex sequence of reactions, involving α–thio radicals, OH-adduct and monomer radical cations. The experimental evidence was not available in the literature. A number of organic sulfur compounds, with varying electron withdrawing power, and varying chain length between sulfur and the functional group, were synthesized. Pulse radiolysis studies of these sulfur compounds have clearly shown the existence of different intermediate steps involved in the formation of dimer radical cations. It has been demonstrated that the nature of reaction of OH radical with organic sulfur compounds depends on the nature of the groups present, pH of the solution and the distance between sulfur and the substituted

group. The experimental data have been complemented with theoretical calculations.

Antioxidant Research

A significant amount of work has been carried out in the front-line research area of antioxidants, both natural and synthetic, phenolic and non-phenolic ones. The physico-chemical properties and the chemical kinetic factors contributing to the free radical reactivity of several phenolic natural antioxidants have been evaluated, employing fast reaction techniques, like nanosecond pulse radiolysis and stopped-flow techniques. Pulse radiolysis has been found to be extremely important in elucidating the free radical reactions, as it provides an exclusive tool to directly monitor the reactions with hydroxyl, superoxide, peroxyl radicals, which are produced in the biological systems by enzymatic pathways and Fenton reactions. Such studies have also been extended to medicinal plant extracts and herbal formulations. New methodologies, employing pulse radiolysis, coupled with other radiobiological techniques, are being developed to evaluate such herbal compounds as probable radioprotectors.

A collaborative research programme has been initiated with a pharmaceutical company to test, and develop herbal extracts as antioxidants. A number of extracts have been tested for their antioxidant activity. These extracts were analysed for their composition, and free radical scavenging action of each of the components was studied. New methods were developed to determine the free radical scavenging activity and correlated with standard antioxidants. Based on these studies, a few herbal extracts are selected for in vivo studies.

Among the large number of compounds/antioxidants studied to understand the modus operandi of their actions are folic acid, carotenoids, gingeroids, curcuminoids, bakuchiol, melatonin, pyridoxal, sesamol, ferulic acid, vanillin, etc. Only recently, in our laboratory, it has been shown for the first time that folic acid is a very good antioxidant in both aqueous and membrane systems, and the molecule has now been coined as antioxidant vitamin. With the help of phenolic and non-phenolic compounds, it has been possible to put an end to a long-standing controversy of whether an alkyl side chain or a methylene β-diketone moiety plays a significant role in antioxidant property of such compounds where these are present along with a phenolic group. These research works are being well appreciated by the international community involved in antioxidant research.

Radiation Chemistry of Drugs and their Model Compounds

From physical chemistry point of view, the mechanism of action of several drugs, especially related to cancer, AIDS, diabetes, neuro-defects, inflammation, etc., was investigated using pulse radiolysis. It has been demonstrated through biochemical and medicinal experiments that free radicals of these drugs might be fully or partly responsible for drug action and/or toxic effects, like cytotoxicity, cardiotoxicity, etc. Starting from the anthracycline anticancer agents adriamycin, daunomucine, AZT (anti AIDS drug) etc., a large number of drugs have been subjected to pulse radiolysis, wherein the reactions of the substrates with primary and secondary radicals, both oxidizing and reducing, have been investigated. Valuable data on free radicals and their characteristics have been obtained, which, in turn, has led to establish mechanism of action of the drugs. At least thirty such drugs have been studied.

In order to simplify the study of reactions of some drugs with complex chemical structures, a series of model simpler compounds (from the viewpoint of chemical structures) have been studied. Most important in this series have been model substituted quinones (model anthracyclines). BARC has been one of the best research Schools for radiation chemical and photochemical studies on quinones.

The one-electron reduction potential values of a large number of such drugs and their model compounds, and also many other antioxidants and other organic chemicals have been estimated using the pulse radiolysis technique with suitable reference compounds. Where-ever possible, cyclic voltammetry has also been used as an additional technique. These values have found place in the atlas for such potentials, published by University of Notre Dame Data Centre and individual authors of publications.

Metal Nanoparticles Studies

Radiolysis was found to be a useful tool in the synthesis of nanoparticles. Henglein and coworkers and Belloni and coworkers prepared many metallic (and pre-metallic) particles of a large variety of compositions over the last two decades. Both groups were able to show size dependence of the redox potential of the metallic ion/metallic atom (or cluster) couples from single atoms to relatively large clusters. Commonly the synthesis involves radiolytic reduction of metal ions in aqueous solutions but radiolytic production of silver particles was recently achieved in supercritical fluids as well. The particles produced by radiolytic reduction of the ions can be designed to assume a variety of morphologies, from core-shell structures to alloys. The size and size distribution of the particles can be judiciously controlled and methodologies for narrowing size distribution of seed metallic particles were developed. This high quality of particles in turn allowed Hodak et al. to determine the cooling processes in the ultrafast time regime following fs laser excitation. Furthermore, exploiting dissociative electron transfer processes (e.g., release of halide ions from alkyl halides or sulfide from thiols upon reaction with e_{aq}) one can initiate growth of semiconductor materials (e.g., of AgX or CdS respectively) using radiolytic techniques. Thus, the instantaneous initiation of growth processes afforded by radiolytic techniques offers opportunities to study the growth processes of semiconductor materials essentially from the stage of the single molecule to the bulk size materials. In analogy with the redox potential of metallic clusters, the stability constant of the molecule obtained from the two component ions depends on the size of the cluster. A single CdS molecule is highly soluble and its dissociation is essentially complete in water even though the solubility product of this material is only $3.6x10^{-29}$ M^2.

The fundamental nature of the studies described above find applications in many other technologies. To cite a few examples, the growth of silver seeds upon reduction of silver ions led Belloni and coworkers to develop a model for silver development in photographic processes. Ultimately this insight into silver photography led the same group to develop methodologies to significantly enhance the sensitivity of the process using "current-doubling" in formate doped silver halides matrixes. As already mentioned, the pioneering studies of Henglein and coworkers on multi-electron redox catalysis is now implemented in many energy conversion schemes.

Work on nanoparticle research using radiation was started in BARC a few years back. It has been demonstrated that radiation can be successfully used to prepare nanoparticles in aqueous solution, microemulsion, as self supporting powder and dispersed on the surface of Al_2O_3 and SiO_2. In microemulsion, the size of the water droplets was used as microreactors to control the size of the particles. The size-dependent catalytic and magnetic properties of these materials have also been evaluated, and used in a number of reactions. It has been shown that the catalytic activity of the sols prepared by radiolysis is better than that of the standard supported metal particles. Also, it was shown that metal sols prepared by radiolysis can be used to coat metal nanoparticles on the surface of SiO_2. These coated particles showed better results in terms of catalytic activity and stability. Effect of intense laser beams on the morphology of several metal nanoparticles has also been demonstrated. A large number of metal nanoparticles (Ag, Au, Tl, Hg, Ni, Co, Fe, Cd, etc.) have been prepared in different shapes and sizes. Several organic molecules of interest have been coated on nano-metals (e.g., Ag) and their characteristics have been studied by Surface-Enhanced Raman Scattering (SERS) as well as Surface-Enhanced Resonance Raman Scattering (SERRS) techniques. Magnetic characteristics of several nanometals (Ni,Co,Fe etc.) have been studied.

Dilute Chemical Decontamination Studies

Radiation chemical characteristics of many new dilute chemical decontamination system has been studied by gamma and pulse radiolysis. Their stability, free radicals generated from them and their characteristics, etc., have been studied. This study has helped in comparison of different chemical systems available.

Current Developments

Most of the techniques used in the analysis of intermediates are utilized today in pulse radiolysis as well. These include spectrophotometric, emission, near-IR, conductivity, resonance-enhanced Raman, and ESR techniques. Early attempts to observe surface-enhanced Raman scattering (SERS) from adsorbed radicals were inconclusive but they led to the realization that the sensitivity of SERS may rival that of absorption spectrophotometry. Indeed recent experiments using confocal microscopy have shown SERS from single dye molecules adsorbed on single colloidal silver and gold particles. Whereas no experiment has yet demonstrated such capabilities on irradiated samples, we fully expect implementation of single molecule spectroscopies in radiation chemistry, especially on large biomolecules, in the foreseeable future. Combined with microbeams that were developed in the last decade and single-cell microdosimetry they will contribute significantly to radiation biology. On the practical side, such an approach may help resolve the low-dose threshold issue that has been debated for many years in the radiobiology community. However, such capabilities will reach beyond the obvious applications to the nano-size regime. Because of the very short penetration depth of high-LET radiation, the availability of microscopic detection techniques should allow time-domain studies with heavy-ion irradiation.

Faster, picosecond linac machines were built first in Toronto and then at Argonne National Laboratory. Picosecond accelerators for pulse radiolysis have been in use for nearly three decades at Argonne, at the Osaka University Radiation Laboratory, and the University of Tokyo Nuclear Engineering Research Laboratory in Japan. These machines operate with electron pulses of several tens of ps and led to the observation of scavenging of the precursor to the hydrated electron. Using sub-ps laser techniques this species, in fact a variety of precursors, were later discovered upon photo-ionization. These early events are presently a matter of discussion in the literature and faster time resolution will be required in order to directly observe and identify the radiolytic precursors to the hydrated electron.

To exploit the capabilities of fast lasers, a new picosecond Laser-Electron Accelerator Facility (LEAF) has been recently developed at Brookhaven National Laboratory, USA and several other laboratories like ELYSE in Orsay, France and three laboratories (Osaka, Tokyo) in Japan. In LEAF facility, laser light impinging on a photocathode inside a resonant cavity gun merely 30 cm in length produces the electron pulse. The emitted electrons are accelerated to energies of 9.2 MeV within that gun by a 15 MW pulse of RF power from a 2.9 GHz klystron. The laser pulse is synchronized with the RF power to produce the electron pulse near the peak field gradient (about 1 MeV/cm). Thus the pulse length and intensity are a function of the laser pulse properties, and electron pulse lengths as short as 5 ps are attainable. Similar machines are presently under construction at several other laboratories around the world. In addition to the obvious advantages of the shorter electron pulses that such machines provide, the close synchronization between the laser and electron pulses is a major advantage. To observe the chemical events that occur at the fast time domain, a pulsed probe laser is required and therefore, timing of the probe with the electron pulse is of major importance. Since the same laser can be used to generate the white probe light, jitter between the two pulses can be minimized. Other designs of even faster linac facilities, based on laser technologies are currently under consideration at other laboratories.

Accelerators for heavy ions abound but low currents and limitations imposed by short penetration depth hamper their use in radiation chemical pulse radiolysis applications. Nonetheless, a high LET pulse radiolysis facility, based at the Heavy Ion Medical Accelerator in Chiba, Japan, has been recently used to determine yields of radicals in the radiolysis of water. Beams of 24 MeV He^{2+} and 6 MeV H^{+} with pulses of 5 or 10 μs were used and because of the short penetration (~ 400 μm in water) a tightly focused narrow laser beam was required for the spectrophotometric detection. The common observation of reduced primary radicals yields upon increasing the LET was observed with these μs time-resolution machines as well. The advent of synchrotron radiation, now in its third generation with a fourth on the horizon, led to an explosion of information primarily, however, from various X-ray diffraction, scattering, absorption and emission

spectroscopies. Even though many of them can provide very short ps-regime pulses of ionizing radiation, time domain experiments on synchrotrons today are limited to structural determinations. It is quite conceivable that future machines will provide high enough dose rates to allow detection of chemical intermediates initiated by the passage of the radiation. Laser flash photolysis, in conjunction with pulse radiolysis to generate radicals can be used to probe the photochemistry and photophysics of radicals. This may lead to rather unusual photochemistry and unexpected photophysics in the radical doublet manifold. Perhaps not surprisingly, the quartet manifold in simple radicals has never been convincingly reported. Most probably, the presence of the quartet state will be observed only with ultra-fast sub-picosecond laser techniques.

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Accelerators in Biosciences

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Introduction

Following the discovery of polonium and radium by Marie Curie and her husband, Pierre Curie, and colleague, it was soon realized that exposure of living tissues to radiations emitted by these particle produced deleterious effects on human body. Although basic mechanisms of biological damage by low Linear Energy Transfer (LET) radiation like x rays and γ rays remain similar [1-3] but biological effectiveness of high LET radiations such as alpha particles, neutrons, and highly energetic heavy charged particles is substantially greater ascribed to high rate of deposition of energy in the medium [4,5]. These differences in low and high LET radiations are generally characterized in terms of their quality factor. Studies on the mechanism of damage by high-energy charged particles have remained an active area of

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investigation and have acquired greater importance over the years due to human health concerns in space flight missions. Current developments in accelerator technology have made it possible to produce proton, helium, carbon, nitrogen, carbon, iron and many other charged particle nuclei of considerably high energies, which have opened new vistas in heavy ion radiobiology.

Many laboratories in the world are actively engaged in understanding the charged particle effect at cellular and molecular levels and study area spans from mechanism of radiation action to radiation protection in space. Extensive studies have also led to diagnostic therapy applications with charged hadrons. Based on the electromagnetic principle, which is used to accelerate the charge particle, accelerators are classified into different categories. Particle accelerators which have initially been developed as tools for basic research in physical, chemical and material have given rise to a wealth of new knowledge on the mechanism of damage processes. Progress in research results have been exploited for developing a variety of applications in industry such as radiation processing, sterilization, food preservation, pollution control, material defect detection and inspection etc. Within the scope of this article, we would like to focus on some of these applications of accelerators in biomedical area especially in medical diagnostics and cancer therapy. We present brief outline of recent advances in several areas of the radiobiology of these densely ionizing radiations commonly known as heavy ions. Substantial advances have been made in understanding the DNA damage and repair, chromosome aberrations, mutagenesis, neoplastic transformation in vitro, genomic instability, normal tissue radiobiology and carcinogenesis in vivo. The major focused of research has been on technical innovations, including novel applications of pulsed-field gel electrophoresis, fluorescence in situ hybridization (FISH), linkage analysis, and studies of gene expression and protein expression. It is important to realize the use of new cellular and animal systems, including those with defined DNA repair deficiencies, as well as epithelial cell model systems to assess neoplastic transformation both in vitro and in vivo. Continued studies are warranted to understand the genotoxic effects of heavy ions as well as their distinct effects on tissue homeostasis. The applications of these radiations in cancer therapy have been discussed. The use of both heavy-ion and proton therapy is on the upswing in several major centers around the world in view of their unique energy deposition characteristics that enhance the therapeutic effect and help reduce damage to normal tissue.

Accelerator in Biomedical Research

Radiobiological Research Perspectives

Investigations on the inactivation of cells resulting in lethal or aberrant effects by charged particles are actively growing research field. Charged particles at extremely high LET are capable of completely eliminating cell-type and cell-line differences in their repair capacity. It is, however, unclear whether the cellular repair systems are inactivated, or merely heavy ion induced lesions are less repairable. Studies are required correlating the particle induced inactivation dose of radioresistant cells with the intact DNA. Analysis of results obtained by pulse field gel electrophoresis and other techniques would address some of the fundamental questions. Moreover, experiments are also needed to assess the fidelity of repair mechanisms in the particle-irradiated cells. Research has revealed that particle irradiation of cells between LET of 40–100 keV/μm reduces cellular viability [6], but evidence exists for induced activation of specific genes in mammalian cells, and induction of certain repair processes in bacteria. New data are accumulating on the mechanism of inactivation of vital processes in several systems including seeds, and cells of the nematode C. elegans. Experimental and theoretical research is focusing on exploring particle-induced inactivation of endpoints assessing cellular functionality and not just their lethality. It is important to evaluate molecular damage and genetic effects arising in damaged but non-inactivated cell survivors. The discrete nature of selective types of particle damage as a function of radiation quality indicates the value of accelerated ions as probes of normal and aberrant biological processes. But, information obtained from molecular analyses of damage and repair needs to be integrated into the context of cellular and tissue functions of the organism.

The biological effectiveness of particle is ascribed to its radiation quality. But precise mechanisms of cellular and molecular damage are presently understood on the basis of certain assumptions, and much remains to be understood for critical early molecular damage. The identification of critical cellular targets continues to be an active area of research and availability of powerful microbeam through development of accelerator technology has generated new excitements and hopes to underpin the radiation targets leading to mutation and causing cellular/tissue pathology. Analyses of microscopic features of the stochastic structures of radiation tracks have led to hypotheses of clustered damage in DNA and associated molecules. Clustered damage of greater complexity or severity is suggested to be less repairable and therefore, to dominate the biological consequences. Biological damage by high-energy charged particles is characterized in terms of effectiveness of damage by a particular accelerated charged particle and damage is quantified by comparison with low LET radiation dose producing the same damage termed as relative biological effectiveness (RBE). It commonly observed that biological damage increases with the LET of radiation within certain range. Studies have shown that the RBE peaks at a LET which is particle dependent (for proton, RBE is maximum at approx. 30 KeV/μm) indicating that LET factor was the major determinant of the microscopic energy deposition and consequent biological tissue damage.

Biological and Clinical Applications

The biomedical research by using accelerator technology is an expanding field and considerable research is focused on the mechanism of the biological effects caused by heavy-ion irradiation [7]. Conventional methods of random heavy-ion irradiation posed the problem of ambiguity in identification of the irradiation effects precisely due to coexistence of both radiation hit and unhit cells. This problem can now be tackled precisely by the advent of heavy ion microbeam irradiation system. It has become possible to irradiate a single living cell by heavy ion onto a particular site in the cell at an accuracy of the ìm order. For instance, it is possible to compare the irradiation effects when only cell nucleus is irradiated with those when only cytoplasm is irradiated. Furthermore, it is possible to delineate the distinctive functions of various cell components by observing the effects on the cell caused by the damages of nucleus and other cellular components separately.

It is becoming possible to visualize the spatial distribution and dynamics of various ion elements in a single cell at a spatial resolution of 1 μm, by irradiation with a proton beam into the cell from outside and detection of generated secondary X rays. Interestingly, recent developments have enabled to visualize the intracellular distributions of trace elements in cancer cell and the intra-nuclear distribution of anticancer drugs. These advances hold great promise in unraveling the mysteries of cell function in real time. Innovative research is growing in the study of dynamics of trace elements in cells. Potential of research is enormous to study functional aspects of cancer, intracellular dynamics of the trace elements in response to radiation, anticancer agent, and other drugs.

Cancer is known to be the second major cause of death in modern world. It is estimated that about one third of the population on earth would develop some form of cancer during their lifetime. Fortunately, it is now possible to cure successfully (survival of more than 5 years) ~ 45% of these cancers. The success rate is greater if the treatment can be done locally before the occurrence of metastasis. It is important to note that about 50% of these cancers are treated by ionizing radiation in radiotherapy clinic.

Treatment using Electron and Photons

Presently, the vast majority of cancer therapy facilities the world over are based on electron accelerators. These machines are capable of producing beams of monoenergetic electrons with a depth range of 2– 10 cm as the machine energy varies between 4 and 25 MeV. They can also produce photon beams obtained by bremstrahlung phenomenon observed in a heavy target. Despite its impressive successes, this technique has met with several drawbacks in practice. Electrons deliver a relatively uniform dose over certain defined ranges and therefore, while well suited for superficial and semi-deep tumors, they suffer from insufficient

range for deep seated tumors and undesirable sideways spreading.

On the other hand, photons are characterized by an exponential energy dose distribution and have ability to reach deep seated tumors but, to minimise damage to the overlaying healthy tissues, it necessitates the use of sophisticated irradiation technique with multiple converging beams delivered by an isocentric gantry capable of rotating around the patient. Photon therapy can also be achieved through radioactive pharmaceuticals, which can be targeted to a specific location in the body. Such radio-therapeutics have long been produced in nuclear reactors. There is a growing tendency now to use dedicated compact cyclotrons for therapy and health care applications [8].

Treatment with Neutron Particle

Neutrons are quite effective for the treatment of some radio-resistant tumors because of their high specific energy deposition, but, like photons, they suffer from the problem of exponential energy deposition decrease. Of course, another recent advancement of neutron radiation based therapy is neutron boron capture therapy (NBCT), which utilizes property of boron compounds to accumulate in certain tumors [9]. When irradiated with neutrons, boron atoms capture them and subsequently produce high energy but short-range alpha and lithium particles, which kill the tumor more effectively and spare the damage to surrounding normal tissues.

Cancer Therapy with Proton Particle

Irradiation of tissues with protons gives more precise energy deposition that has proved to be more advantageous in clinic. Utilization of protons beam in treatment of tumors, which display resistance to treatment with photons or electrons, is a generally recommended mode of treatment of cancer. The main advantage consists in the highly localized energy deposition, which perhaps allows delivering a lethal dose to every tumor cell. Proton beam method is therefore well adapted for the treatment of deep-seated tumors, such as those located close to the spinal chord, in the abdomen or in the brain.

Pencil-like proton beams are also used for radiosurgery to treat small brain or eye lesions. The main drawback of proton therapy is that this technique calls for particles in a 70 to 250 MeV energy range, an energy at which the beam transport is already highly complicated. Nevertheless, it is estimated that more than 15,000 patients around the world have been cured in by this particle technology. It is hoped that more and more such treatment facilities will be created to treat cancer more effectively.

Use of Light Atoms Ions in Cancer Therapy

Beams of light ions, such as, those of carbon, oxygen or neon travel in straight lines and deposit an even larger fraction of their energy than protons at the end of their travel. This allows a superior and better-defined in-depth dose deposition in tumor than with protons. The high local ionization is believed to be the reason why ions are effective against radio-resistant tumors [10,11]. Ion therapy has been pioneered in USA, Japan and some European countries.

Accelerator based Medical Diagnostics

Positron Emission Tomography (PET)

Positron emission tomography (PET) is a technique that combines computed tomography (CT) and nuclear scanning. During a PET scan, a radioactive substance called a tracer is combined with a chemical, such as glucose. This mixture is generally injected into a vein, often in the arm, but sometimes drug is delivered through inhalation. The tracer emits tiny positively charged particles called positrons that produce signals. The choice of chemical molecule and radioactive tracer for the test varies depending on the area of the body being investigated.

The PET scan consists in the patient being injected with a radioactive substance and placed on a flat table that moves in increments through a "donut" shaped housing. This housing contains the circular γ ray detector array, which has a series of scintillation crystals that are connected to a photomultiplier tube (PMT). The crystals convert the γ rays emitted from the patient to photons of light, and the photomultiplier tubes convert and amplify the photons to generate electrical signals. The software is utilized to generate images, which then processes these electrical signals. The table is then moved, and

the process is repeated, resulting in a series of thin slice images of the body over the region of interest such as brain, breast, liver etc. Eventually, these thin slice images are assembled into a three dimensional picture of the patient's body.

Single Photon Emission Tomography (SPECT)

SPECT is a technique similar to PET. But the radioactive substances used in SPECT (Xenon-133, Technetium-99, Iodine-123) have longer decay times than those used in PET, and emit single instead of double γ rays. SPECT can provide information about blood flow and the distribution of radioactive substances in the body. Its images have less sensitivity and are less detailed than PET images, but the SPECT technique has advantage of being less expensive than PET.

In the SPEC methodology, similar to a PET scan, a radionuclide is injected intravenously into the body. Tissues absorb the radionuclide as they circulated into the blood. As a camera rotates around the patient, it picks ups photons, the radionuclide particles. This information is transferred to a computer that converts the data onto a film. One of the significant advance has been that since the images are vertical and/or horizontal cross-sections of the body part and they can be rendered into 3-D picture format.

Accelerator Mass Spectroscopy

Accelerator mass spectrometry (AMS) has become the preferred method for radiocarbon dating because it was so much quicker than the traditional method of scintillation counting, which counts the number of ^{14}C atoms that decay over time [12]. The half-life of ^{14}C is short enough (5,730 years) that counting decayed atoms is feasible, but it is time-consuming and requires a relatively large sample. Other radioactive isotopes have half-lives as long as 16 million years and thus have such slow decay rates that huge samples and impossibly long counting times are required. The high sensitivity of AMS meant that these rare isotopes could be measured for the first time.

The remarkable sensitivity of AMS opens the way to a host of other new diagnostic tests : assays for early detection of various disorders, tests that determine the efficacy of therapeutic regimens, studies of how the body handles various nutrients and vitamins, and assessment of the effects of environmental substances and toxins. When combined with such imaging technologies as magnetic resonance imaging, accelerator mass spectrometry will be able to assess changes in tissues, hormone levels, and metabolites in real time.

AMS is also changing the study of the effects of vitamins and minerals in our daily diet. It is known that they are needed for healthy living, but their effects are virtually unknown. Moreover, illnesses may result from their absence in our diet. AMS is finally allowing researchers to trace such nutrients in the human body.

With the use of ^{41}Ca and AMS, the kinetics of calcium in the human skeleton can, for the first time, be studied directly, enabling studies of fundamental bone processes and providing indicators of an individual's bone health.

In recent times many more techniques such as use of microtrons, dual energy X-ray beam accelerator have also come up which have shown potential to offer better results with lesser risk. The field is rapidly growing and intensive research and development are being focused for more and more sophisticated techniques to provided efficient and effective therapeutic outcome in hospital settings.

Accelerator for Radioisotope Applications

Production of New Radioisotope

The continuing importance and status of development of radionuclide generator systems for nuclear medicine are well recognized. Radioisotope costs and availability are two important factors, and both nuclear reactors and accelerator facilities are required for production of the parent radioisotopes. Radionuclide generator research is currently focused on the development of generators which provide radioisotopes for positron emission tomography (PET) applications and daughter radioisotopes for various therapeutic applications, which decay, primarily by particle emission. Generator research continues to be influenced by developments and requirements of complementary technologies, such as the increasing availability of PET. In addition, the availability of a wide spectrum of tumor-specific antibodies, fragments, and peptides for

radio-immunodiagnosis and radioimmunotherapy has stimulated the need for generator-derived radioisotopes. The advantages of treatment of arthritis of the synovial joints with radioactive particles (radiation synovectomy) is expected to be of increasing importance as the elderly population increases, and many of these agents are prepared using generator-derived radioisotopes such as yttrium-90 and rhenium-188. Therapeutic use of the in vivo generator is a new approach, where the less radio-toxic parent radioisotope is used to prepare tissue-speciic therapeutic agents. Following in vivo site localization, decay of the parent provides the daughter for therapy at the target site. The principal foundation of most diagnostic agents will continue to require technetium-99m from the molybdenum-99/technetium-99m (Moly) generator. With the limited availability of nuclear reactors and facilities necessary for production and processing of fission ^{99m}Tc and the significant issues and problems associated with radioactive waste processing, however, the possibility of utilizing lower specific activity ^{99}Mo produced from neutron activation of enriched ^{98}Mo may become practical in the future [13].

Accelerators in Food Preservation

The idea for using high-energy ionising radiation to preserve food has been around for over 50 years. The economic importance of this application becomes overriding factor when one considers that in many countries some 20 % of the food production is lost because of improper storage and lack of appropriate preservation measures. Radiation can avoid the sprouting of products like potatoes or onions. Radiation is able to destroy insects, parasites and pathogens and to prolong the storage duration of poultry, fish or fresh fruits while preserving their nutritional value. As for sterilization, food preservation by radiation would avoid the use of chemical disinfectants, which are not only toxic but sometimes even pose carcinogenic risk.

Pollution Control

High-energy radiation produced by accelerators can contribute in various ways to reduce environmental pollution and the associated health hazards.

- The treatment of waste water and sewage sludge is a major problem in all countries. Radiation can destroy toxic bacteria and permit the recycling of water, which becomes increasingly scarce in many places, and the safe use as fertilizer of sewage sludge and excreta from farm animals which still have a high nutrient content.

- Electron beams can ionize the soot particles contained in the gaseous effluents from power stations, chemical- or waste-incineration plants. Electrostatic precipitators can then remove them.. The same process has been shown to be capable of trapping SO_2 and NOx through conversion into complex salts of ammonium, if a small amount of ammonia is added beforehand.

- The generation of energy by fusion or accelerator driven fission reactors as discussed later could avoid the production of greenhouse gases. With a proper nuclear fuel cycle (use of thorium and associated transmutation of long-life waste) this could become a safer and more acceptable future energy source.

Conclusions and Future Perspectives

Application of accelerators in biosciences has proved to be usually beneficial more so in areas like cancer therapy, imaging etc. The use of electron linear accelerators for radiation therapy, 10-20 MeV proton cyclotrons for radio nuclide production and elemental analysis, 50-60 MeV proton accelerator for neutron therapy or for treatment of eye melanomas, to the use of large proton accelerators used for cancer therapy has exemplified the use of new age technology for the benefit to mankind. The rapid progress in science and technology of accelerators is opening newer and newer possible applications in diagnosis and therapy. A wealth of new knowledge is accumulating to help understanding of underlying basic damage processes in living tissues by accelerators. Extensive future research is highly warranted for developing technologies with potential to contribute to progress and welfare of mankind.

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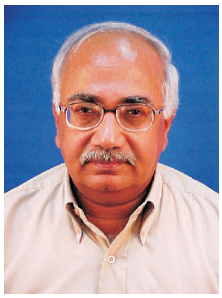
Role of Accelerators in the Industry



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Introduction

Traditionally, accelerators have been employed for pursuing research in basic sciences. But over the last couple of decades their uses have proliferated into the applied fields as well. Industry is one of those areas which has been extremely benefited. Although both ions & electron beams are being used for this purpose, but major role is being played by electrons and the radiations generated through them. This article is a brief account of the impact made by the accelerators in the industry and the efforts initiated by India for building the required base in this technology. Since 1930 accelerators are being extensively employed for doing research in basic sciences. The thirst for acquiring more and more knowledge is still continuing. That is why so many high energy accelerators like TEVATRON, LEP, LHC, HERA etc. have appeared on the scene. Quite a few more are in the offing too. Simultaneously, it is also being observed that accelerators have started contributing a lot to the applied fields as well. They have revolutionized almost all the areas including processing of materials, treatment of pathogenic germs, cleaning of water, curing of cancers, cargo inspection, non destructive testing, imaging, telecommunication, semiconductor doping etc. So much so that high energy, high power electron beams are now being conceived as potential drivers for the sub critical reactor systems. In this paper, the roles of accelerators and the attempts being made by India for building a strong base in this technology, are highlighted.

Accelerators Vis a Vis Industry

Applications involving Electron Beams

Radiation Processing of Materials

Charges particle beams with varying energy and power have been extensively employed for this purpose. Major credit for this goes to electron beams [1,2]. Electrons up to an energy of 0.5 MeV and a power of 10 kW are being used for curing of coatings, adhesives and paints. Heat shrink materials use electron beams in the range of 0.5 MeV to 2 MeV. To improve upon the lubrication property,

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Teflon is treated with 2 MeV, 10 kW beams. Diamonds with exotic colours are produced by using 5-7 MeV electrons having powers up to 10 kW. Green strength of the rubber gets enhanced by exposing it to 2 MeV, 30 kW beams. Beams up to 10 MeV and 10 kW are routinely used for crosslinking of cable, food preservation, medical sterilization etc.

As is evident, for all these processes, the energy has to be kept within 10 MeV. Otherwise the nuclear processes start dominating and render the processed materials, radioactive. In a situation where the penetration depths are not met even by 10 MeV beam, either double sided irradiations or X rays, generated from the electrons, are used.

Both, DC & RF accelerators have been put into service for the radiation processing applications. Depending upon the requirement of beam powers, up to an energy of 3 MeV, DC accelerators are employed. But from 3 to 10 MeV, RF accelerators like Linacs, Rhodotrons & Microtrons are preferred. Recently, Rhodotron, a new type of machine has also emerged on the scene. The concept of this machine was given in the literature [7]. It is an RF but cyclic accelerator and has been developed & marketed by IBA Belgium. A view of an assembled Rhodotron & its inner configuration is shown in Fig.1. Rhodotrons with energies from 3-10 MeV and power up to a level of 200 kW, are commercially available.

Fig. 1 A view of a Rhodotron.

An Indigenous Approach

Department of Atomic Energy (DAE) adopted a two way approach in this direction. One was to buy a few machines for developing the radiation processes and the other, to build a few indigenously, in parallel. Keeping this methodology in mind, an ILU 6 machine having electron energy as 2 MeV and power of 20 kW was purchased from Russia. This accelerator has extensively been used for process development and training of personnel. Quite a few of these personnel belonged to the private enterprise as well. ILU 6 is now located at BRIT Vashi, Navi Mumbai and is in regular use, for developing processes as well as commercial utilisation.

For building an indigenous base, the task of developing a 500 keV/10 kW DC, 3 MeV/30 kW DC and a 10 MeV/10 kW, RF linac was undertaken by APPD/BARC. The first one is located at BRIT Vashi, Navi Mumbai & is in use for surface modification & cross linking applications [3]. A view of this machine is shown in Fig. 2. The other two machines are being housed at Electron Beam Centre (EBC) Kharghar, Navi Mumbai [4,5,6]. In Fig. 3 is depicted the 10 MeV/10 kW RF linac. This linac has been installed and is presently going through a phase of debugging. Similar, indigenous efforts in this field are also being carried out at CAT (Centre for Advanced Technology) Indore, with the help of Russia.

Simultaneously, two of the private enterprises namely M/S Nicco of Kolkata & M/S Radiant of Hyderabad, have entered into radiation processing field commercially. Each one of them has purchased a 3 MeV DC machine from USA, having powers as 150 kW and 50 kW respectively. Before entering

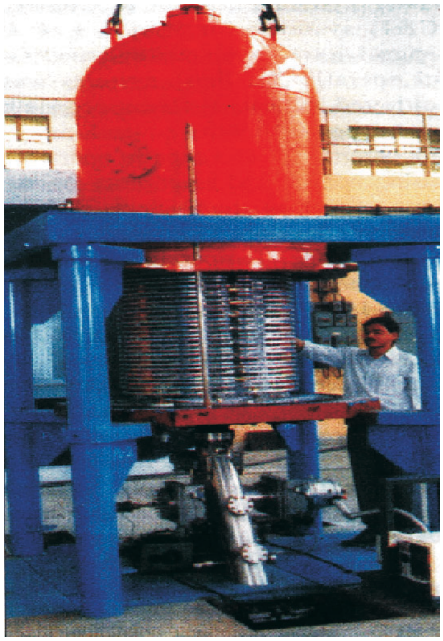
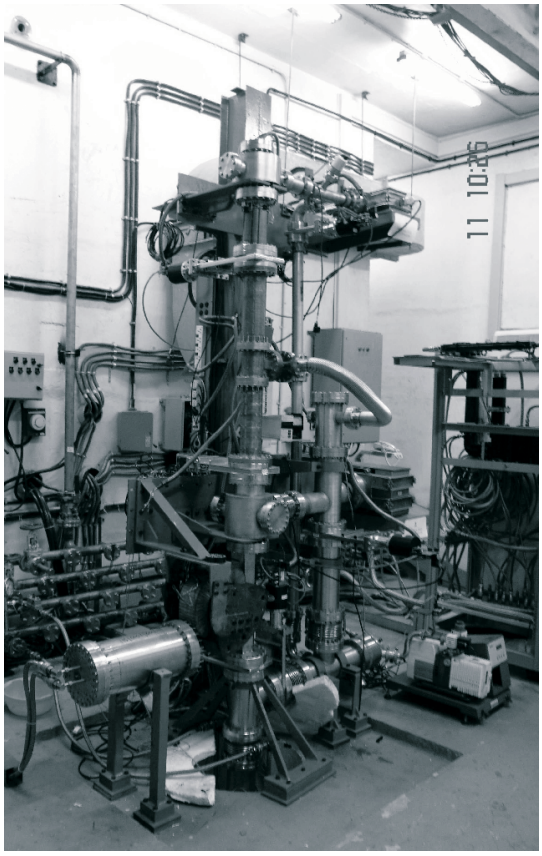


Fig. 2 500 keV DC Accelerator.

into this commercial venture the personnel from these companies went through a training at BARC for proper understanding of the electron beam machines and the related process development techniques.

Environment Cleanliness & Anti Pollution Measures

Electron Beam (EB) treatment of flue gases and polluted water from industry, provide a clean environment. Energetic electron beams produce large concentration of highly reactive free radicals in aqueous solutions. These radicals change the hazardous organic pollutants to non hazardous fragments. Extremely high flow rates of flue gases can be treated by the electron beams. Detailed studies of all types of wastes including chemical & biological ones, emanating from various industries, have been carried out. Data shows that for a 100 MW power plant, almost 2 MW of EB power at an energy of 1 MeV will be required. This in turn will ask for 20 EB machines, each delivering a power of 100 kW. To tackle the pollution problem, a large number of EB accelerators can be deployed around the plant.



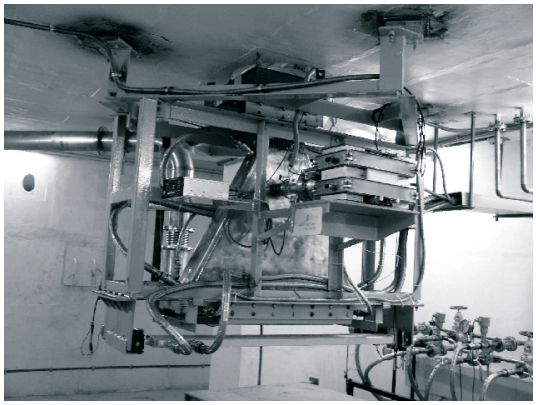


Fig. 3 A View of 10 MeV RF electron Linac, installed at EBC Kharghar

X Rays Radiography for Cargo Inspection & Security Systems

The X rays radiography is another area where electron beams are playing a vital role. When X rays

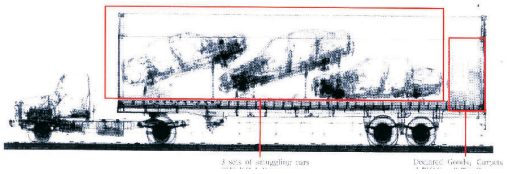


Fig. 4 Cargo Inspection by X rays.

fall upon a material, they get either scattered, absorbed or transmitted. These scattered or transmitted X rays can be used for constructing the radiographic images. Thus the objects which are otherwise hidden to the naked eye, can be seen with the help of X rays. An example of this is shown in Fig. 4. This utility has immense potential in the industry and can play a vital role in strengthening the security of a nation, too. Many countries are now employing the X rays cargo scanning systems for checking the inflow of illegal arms, drugs, narcotics, ammunitions, explosives etc. By installing these devices flow of such goods can be stopped.

The cargo scanning system consists of two major parts. One of which pertains to the generation of X rays and the other, to its detection. The X ray source is usually built around an RF electron linac. The energy of the linac lies between 2 MeV to 10 MeV. The typical dose rate required is around 30 Gray/min at a distance of one meter. Many countries including USA, China, Korea etc. have commercialized these machines.

India has also initiated steps in this direction. DAE has decided to go in for an indigenous development in parallel to a direct procurement of a few machines. For this purpose, APPD/BARC/DAE Mumbai and ECIL/DAE Hyderabad, have entered into a collaboration for developing & setting up a prototype unit, the accelerator of which will be more or less a duplicate of the 10 MeV industrial RF electron linac but with a power of 2 kW [7]. A test facility for this source is planned and is being set up at ECIL, Hyderabad. This system is expected to be operational by 2006.

Flash X rays Radiography (FXR) for Nuclear Power Industry

X-ray radiographs are routinely used for detecting the cracks and defects in materials. But if

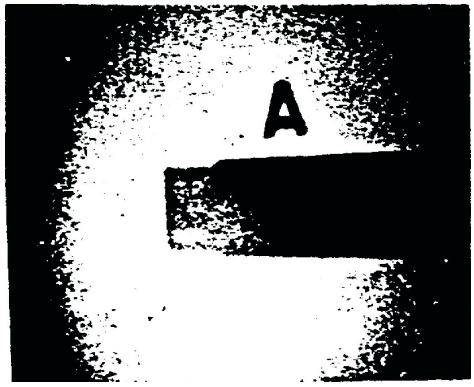


Fig. 5 FXR of a 2 Curie Ir^{192} Radio Isotope.

the object to be radiographed is itself a source of high radiations or X rays, it becomes extremely difficult to derive the inference. For example take the case of Nuclear Power Industry. The fuel bundles used in nuclear power plant are highly radioactive. They emit γ rays. The conventional radiograph in this case will be a smeared one due to the γ background. In such cases, Flash X rays Radiography (FXR) is a unique solution. In this process highly intense X rays in the form of a flash are employed to produce the radiographs. Due to such intense X rays, the effect of background radiations becomes more or less negligible. Figure 5 is a FXR of a 2 Curie Ir^{192} Radio Isotope. Thus FXR can be made to play an extremely important role in the industry, specially the Nuclear Power ones. The flash X rays can be produced by striking the high power pulsed electron beams on a Tungsten target. All one requires is a high power pulsed electron accelerator at the site of a nuclear power plant. These accelerators should be able to deliver electron beams to the tune of a few tens of a GW having energies in the range of a few MeV. Quite a few such pulsed power electron accelerators like AURORA, ANGARA, HERMS etc. are being developed worldwide.

About two decades back, APPD/BARC also took up initiative of starting a high power pulsed electron accelerator programme. By now, it has perfected this technology. Quite a few systems like KALI 200, KALI 1000 etc., have been built. A more powerful system is KALI 5000 [8] and is depicted in Fig. 6. It delivers electron beams with a power of 40 GW at an energy of 650 keV & a pulse width of 100 ns. It is a single shot system built around a MARX

Fig. 6 A View of KALI 5000 for Flash X rays Radiography.

bank. Electron beams are produced through an REB diode.

High Power Microwaves (HPM) & Hardening of Devices

The pulsating electron beams are an excellent source of electromagnetic radiations including microwaves. Like any electromagnetic radiations, microwaves too are a carrier of electric & magnetic fields. These fields when come in contact with any semiconductor based device, they affect its functioning adversely. Depending upon the amplitude of the field, its frequency & the sensitivity of the device, HPM can render the device totally ineffective. Hence, computers, electrical installations, communication network, control & instrumentation systems etc. will stop functioning when subjected to HPM. This can bring the whole infrastructure of a country to a complete halt. It is an extremely dangerous scenario. The only way to come out of this situation is to invent novel materials, adopt new shielding techniques and harden them against HPM effects.

To accomplish this one needs a detailed & systematic study of the effect of HPM on all types of systems getting effected by it. For this HPM sources having power in the range of a few tens of GW and frequencies from 1-10 GHz, are required. These types of machines are being built worldwide. An experimental programme for initiating such a study is also planned at BARC by using the HPM sources built by APPD. These sources can deliver power to the tune of 2 GW in the frequency range of 2-4 GHz.

Applications Involving Ion Beams

Semiconductor Industry

Semiconductor industry is among the first ones which has used ion beams extensively. In this case low energy, high current heavy ion beams of Boron, Phosphorous etc. are implanted in Silicon, Arsenic and Gallium. This doping changes their physical & electrical properties, drastically. Not only that, the devices produced from these materials are also found to be highly rugged and reliable. Ion implantation has transformed the vacuum tube based electronics industry into a solid state one. These days Focused Ion Beams (FIB) are also being used for tailoring the ICs and Memories. Ion cluster deposition, Ion milling, buried conductors, deep amorphous layers and ROM programmes are some of the other areas where ion beams have made a big mark. Now MeV beams are also being employed for this purpose. Bombardment of a few MeV proton beams on Silicon, produces GTO thyristors with highly improved characteristics.

Microporous Membranes for Filter Industry

Heavy ion beams have found wide applications in microporous membrane filter industry. Membranes with holes diameter between 0.05 μm to 1 μm can be produced having porosities from a few percent to 30%. Xenon beams with energies as 10 MeV / Nucleon and intensity as 10^{12} pps, suffice the purpose. Argon & Krypton beams are also used for producing these membranes. A heavy ion accelerator like GANIL (France) is being routinely used for conducting R & D in this field [9].

Neutron Generators, Non Destructive Testing & Activation Analysis

Ion Beams are an excellent source of neutrons also. These neutrons have multiple applications in industries including radiography and activation analysis. Thermal to fast neutrons can be used for all such applications. The neutrons are produced through various nuclear reactions using protons or deuterons beams. Deuterium, Tritium, Lithium and Beryllium etc. are normally employed as targets.

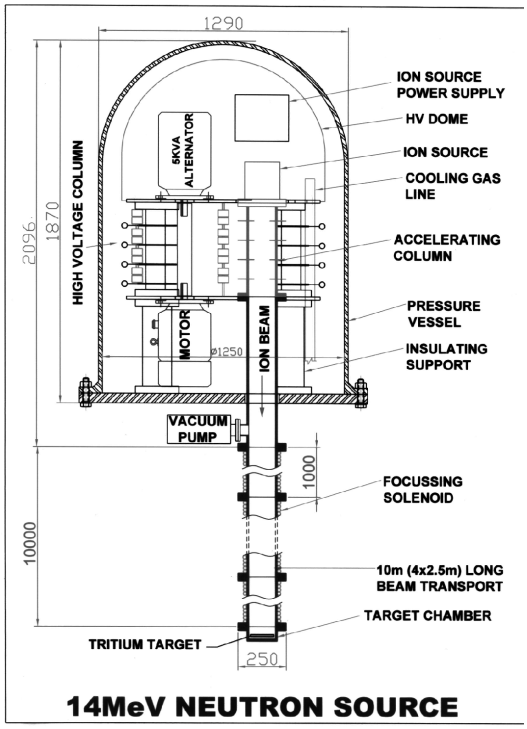


Fig. 7 A (d,t) based 14 MeV neutron Generator.

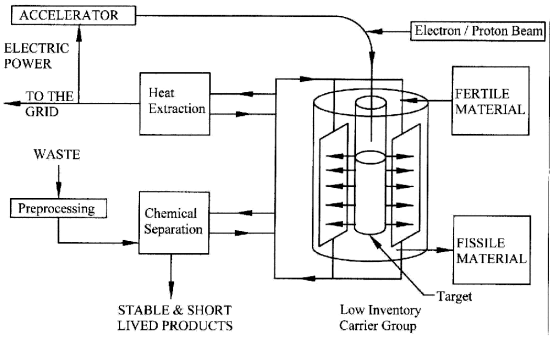


Fig. 8 A schematic of an Accelerator Driven subcritical System.

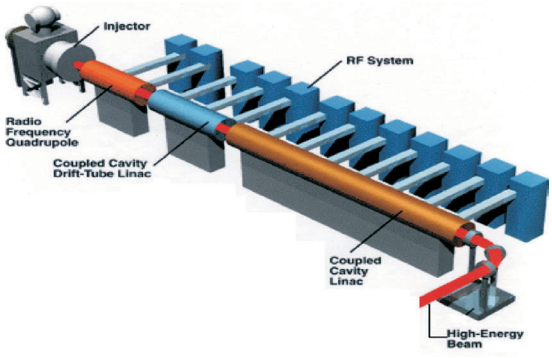


Fig. 9 Configuration of a proton RF Linac for ADS.

Depending upon the target, proton or deuteron beams with energies of a few hundred keV to about 50 MeV, are being used. Cockroft Waltons, RF linacs and Cyclotrons are generally the accelerators, employed for this purpose. 14 MeV neutron generators using (d,t) reactions have been found to be the simplest & cost effective. Deuteron energy of about 300 keV – 400 keV are considered as sufficient for this type of generator. At Purnima labs. BARC, a 14 MeV low flux neutron generator is operational. One more generator is also being conceived by APPD/BARC and is shown in Fig. 7. This will deliver neutrons to the tune of 10^{12} n/sec.

Nuclear Power Industry

Nuclear Power has now become an established industry. But this industry cannot be on a firm footing until & unless satisfactory solutions to the problems of shortage of fissile material and stockpiling of long lived nuclear wastes, are addressed. Accelerator Driven subcritical Systems (ADS) are being conceived as possible solutions to these problems. In this case, proton/deuteron beams having energy in the range of 1-2 GeV & power of a few tens of a MW, are allowed to strike the Pb or Bi target, externally. The intense flux of neutrons thus produced through spallation mechanism can be used either for fissioning the fissile material for producing power, or converting the fertile material into a fissile one or transmutating the long lived nuclear wastes into short lived ones. This flux can also be used to perform all the three functions, simultaneously [10,11]. Neutrons flux to the tune of 10^{16} or higher, is needed. A schematic of the ADS is shown in Fig. 8. The high energy, high power proton RF linacs with a configuration shown in Fig. 9, are being conceived as the possible accelerators for this purpose. Already, about 30 countries have initiated R & D activity in this direction.

But all the ion RF linacs being planned for this purpose suffer from a few serious defects. They are

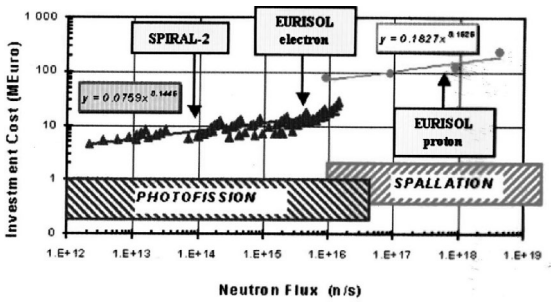


Fig. 10 Cost Comparison of Spallation and Photo neutron process.

not only huge in size (a km or so) but also demand very heavy investments. This investment can be as high as a few billion US $ or even more. Because of these drawbacks, neutron generation through electron-photo-fission process is also being investigated, in parallel. A comparison of cost for generation of neutrons by both, spallation as well as photo fission process, is depicted in figure 10. The studies reveal that if the required neutron flux is less than 10^{16}, photofission process is more cost effective. RF electron linacs having energy of about 70 MeV and power of about 5 MW are considered as adequate. In fact Russia has taken serious steps in this direction and has gone ahead to build a SCANUR facility, based on the photo fission process.

Conclusions

As is evident from the above discussion, accelerators have percolated into all types of industries. The field is expanding at a fast pace with more and more avenues opening up daily. Moreover, this process is not confined to just one type of accelerator or one type of particle. Rather, it is spread to all types of accelerators delivering all type of beams including the secondary ones. Hence, in the coming decade, one can look forward to a more and more involvement of accelerators in the industry.

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Accelerators in Healthcare

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Introduction

Discoveries of radiation and radioisotopes more than a century ago were immediately and inevitably followed by their applications in many fields. Medicine has been among the early and highly benefited areas of such applications. Particle accelerators, originally developed for basic research in nuclear and particle physics, have matured into versatile tools for applications in many other branches. Charged particle accelerator, as a source of several kinds of radiations, plays an important role in the healthcare sector.

The invention of cyclotron in 1932 by Ernest O Lawrence and M. Stanley Livingston, wherein charged particles could be accelerated to high energies, was the first device used for production of artificial radionuclides in appreciable quantities. This device opened the gate for application of radionuclides in medicine. Soon, in 1935 radiotracer studies were performed by Georg de Hevesey in animals while in 1936 John H. Lawrence, the brother of Ernest, made the first clinical therapeutic application of an artificial radionuclide when he used phosphorus-32 to treat leukemia. Advent of nuclear reactors later in 1942, paved way for production of large quantities of a wide variety of radionuclides. Although both particle accelerators as well as nuclear reactors are used for production of radionuclides, each of these have a niche in the applications area owing to the different natures of the products that arise from them. Charged particle accelerators, most often proton accelerators, invariably produce neutron deficient isotopes while neutron absorption in reactors often yield neutron rich isotopes. The neutron deficient isotopes with amenable decay characteristics have made a strong impact in nuclear medicine. With the increased understanding of effects of radiation on living systems, radiations of various kinds have been tested for their utility in treatment of diseases, particularly cancers. In the regime of accelerators, the availability of electron, proton, ion beams and through ion implantation the provision of intense secondary neutron beams have been increasingly employed for various applications ranging from the therapy of advanced tumours to production of medical isotopes for diagnostic purposes. An attempt to give an overview of the various applications of accelerators in medicine is made here.

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Accelerator Produced Radionuclides in Nuclear Medicine

Neutron deficient radionuclides that are produced by bombardment of targets with charged particles such as protons, often decay by electron capture or positron emission. Among these, the nuclides with reasonable half life (few hours to few days), gamma emission of suitable energy (100-200 keV) or positron emission (resulting in two photons of 511 keV each in opposite directions) and having feasibility of regular production in adequate quantities (GBq-TBq; few hundreds of mCi to few Ci levels) have been employed in diagnostic nuclear medicine. In diagnostic nuclear medicine, a radiolabeled bio-molecule is introduced into the body (in-vivo) and its distribution within the body is monitored to obtain information of diagnostic importance. The shape & size of various organs, presence of nodules/ tumours/abscesses, rate of blood flow through an organ (such as heart, kidneys, lungs, brain), presence of cancerous growth (particularly metastasis) are some types of information sought in this speciality. The radiolabeled bio-molecule or radiopharmaceutical, would concentrate in the target organ owing to its biological properties. After adequate time post injection, the patient is "imaged" using a suitable system that will precisely detect and quantitate the radiations emanating out of the patient's body. The image will clearly delineate the defects if any and help the treating doctor in diagnosis. Since the radionuclide serves as a tracer in diagnostic radiopharmaceuticals, it is desired that the radiation dose to the patient is minimal and the image quality is adequately good. Hence nuclides with short half life, devoid of particulate emissions and emitting photons of low energy are preferred.

Many neutron deficient nuclides that decay by Electron Capture emit gamma photons of single energy which are advantageous for imaging. Single Photon Emission Computed Tomography (SPECT) technique is capable of yielding high quality images using a Gamma Camera to obtain 3 dimentional (tomographic) images reconstructed from the slices ('tomes'). This is due to the possibility of precise calculations with the advanced computations when photons of single energy are attenuated in tissues. ^{67}Ga, ^{111}In, ^{123}I, ^{201}Tl are some of the SPECT

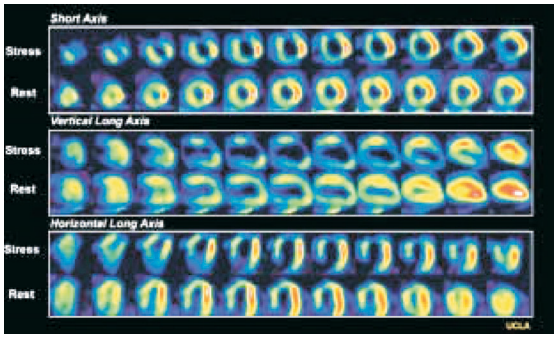


Fig. 1 SPECT images from a heart scan.

radionuclides produced in accelerators and used regularly.

A set of typical SPECT images from a heart scan (Fig. 1) during exercise ("stress") and "rest" from a patient with coronary artery disease, shows where the heart muscle lacks adequate blood flow. The radiopharmaceutical, thallium-201, mimics potassium and accumulates more in regions of normal blood flow.

Positrons when emitted from a nuclide, would annihilate in the matter after losing its energy to result in emission of two photons of 511 keV each at 180°. Precise measurement of these photons by co-incidence detection using detectors placed diametrically opposite, can give high quality images, capable of delineating very small defects (< few mm) which is not possible with most other imaging modalities. Positron Emission Tomography or PET scanning has hence acquired a unique and important place in diagnostic medicine. The actual utility of a radionuclide, will however depend on the feasibility of production of that nuclide, which in turn depends on the reaction, need for enriched targets, energy of the accelerated particle to be used, separation of the nuclide in pure form and its chemical reactivity to radiolabel molecules. Thus, among several radionuclides produced in a cyclotron, few reach the stage of actual use in nuclear medicine. In both SPECT and PET, the scans look like multiple slices through the body. In SPECT, a gantry rotates one or more detectors around the body to acquire many image projections. PET scanners usually surround the body with a stationary ring of detectors.

Among the cyclotron produced radioisotopes, ^{18}F merits special mention because of its widespread use and popularity. Among the PET radionuclides ^{18}F has relatively longer half life of nearly 110 min and has been the most explored. ^{18}F-fluoro deoxy glucose (^{18}F-FDG) is an analog of glucose and is taken up by the multiplying cells like glucose. However, once inside the cell, due to the difference in structure, ^{18}F-FDG does not get metabolized like glucose and hence is trapped. This property has enabled ^{18}F-FDG to be used in a variety of situations. For example, when ^{18}F-FDG is injected in patients with cancerous lesions, it is avidly taken up by the fast multiplying cancer cells and a PET scan clearly lights up the affected areas. In case of patients suspected of myocardial infarction, ^{18}F-FDG PET scan can give information on the extent of damage to the heart muscles and whether the affected areas are dead or reversibly damaged. In nervous system disorders such as epilepsy, the exact location and extent of brain damage could be delineated. Maximum utility of ^{18}F-FDG PET is in oncology to diagnose the occurrence of metastatic cancer lesions and for follow-up of cancer patients after treatment.

Although production of ^{18}F and the utility of ^{18}F-FDG has been established since more than three decades, the use of ^{18}F-FDG has been growing in leaps and bounds since the past 15 years owing to the advent of machines capable of giving good images. The electronics and computer industries have enabled the availability of high quality PET machines leading to this phenomenal growth that earned the name of "Molecule of the Millennium" to ^{18}F-FDG, at the turn of last century.

Fig. 2 are ^{18}F-FDG PET scans of a normal person (left) and a patient with cancer lesion (right).

The brain scan as shown reduced glucose metabolism in a pattern characteristic of Huntington's disease, much before the patient exhibited symptoms of this disease.

Currently, there are several ^{18}F based radiopharmaceuticals such as ^{18}F-Fluoro-L-Tyrosine (FLT), ^{18}F-FLuoride etc. used regularly for various diagnostic purposes.

The other PET radionuclides are much less used due to the logistic problems arising owing to

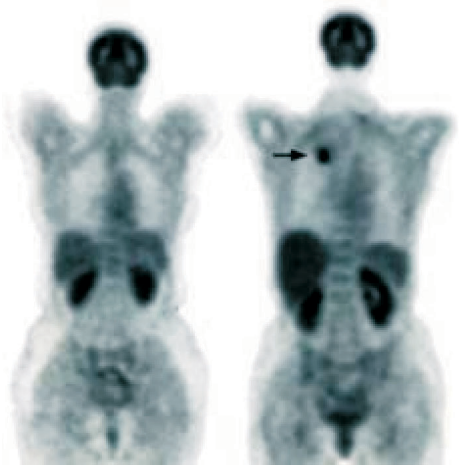
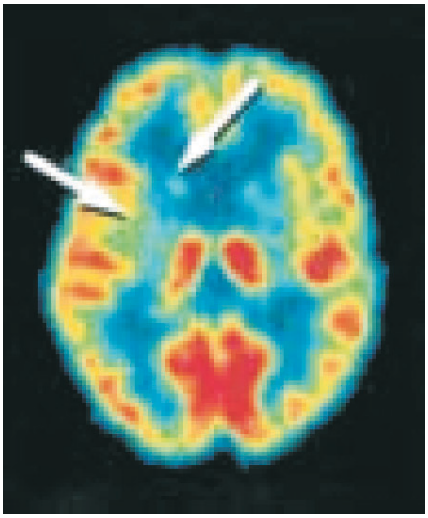


Fig. 2



their short half lives. But, the SPECT nuclides such as ^{123}I, ^{111}In and ^{67}Ga are sought after. In particular, ^{123}I is considered an excellent nuclide for SPECT studies, since it can replace the well established ^{131}I that emits high energy gamma rays and beta particles, and give better diagnostic images with much lower dose to the patient. ^{123}I-radiopharmaceuticals such as ^{123}I-iomazenil (for brain imaging), are being regularly used world-wide.

Apart from diagnostic applications, a few radionuclides produced in accelerators find application in therapy owing to the emission of suitable X-rays or Auger electrons. While X-rays are

The following table lists the commonly used accelerator produced radionuclides in medicine

Radio-nuclide	Decay mode	$T_{1/2}$	Production route/s	Typical uses
DIAGNOSTIC APPLICATIONS				
				SPECT
^{67}Ga	EC	78 h	^{68}Zn(p,n) ^{65}Cu(α,2n)	^{67}Ga-citrate used in imaging tumours, infections/inflammations
^{123}I	EC	13.3 h	^{123}Te(p,n) ^{124}Te(p,2n) ^{124}Xe(p,pn)^{123}Xe(EC) ^{127}I(p,5n) ^{123}Xe (EC)	Several products are being used; thyroid imaging and for studies on brain function
^{201}Tl	EC	73 h	^{203}Tl(p,p2n)	As Tl+ for blood perfusion in heart
^{111}In		67 h	^{112}Cd(p,2n) ^{109}Ag(α,2n)	Several products- labeled antibodies, blood cells etc. being used
				PET
^{18}F	β +	109.7 m	^{18}O(p,n) ^{20}Ne(d,α)	^{18}FDG- most widely used in oncology; many other compounds too are established
^{11}C	β +	20.3 m	^{14}N(p, α) ^{11}B(p,n)	Studies on drugs; particularly brain function
^{13}N	β +	9.96 m	^{18}O(p, α)	Lung studies with ^{13}N-ammonia
^{15}O	β +	2.04 m	^{14}N(d,n) ^{13}C(p,n) ^{15}N(p,n)	^{15}O-water for studies in blood
THERAPEUTIC APPLICATIONS				
^{103}Pd	EC	17.0 d	^{103}Rh(p,n)	Prostate cancer brachytherapy
^{211}At	α	7.2 h	^{209}Bi(α,2n)	cancer therapy radiopharmaceutical
^{64}Cu	β+,β– EC	12.7 h	^{64}Ni(p,n) ^{65}Cu(p,pn)	Radioimmunotherapy & PET
^{67}Cu	β–	2.6 d	^{68}Zn(p,2p)	Radioimmunotherapy
^{124}I	EC, β+	4.2 d	^{124}Te(p,n)	Radioimmunotherapy & PET
^{57}Co	EC	271.8 d	^{57}Fe(p,n)	Radiometric assays

used in treating localized lesions such as those in prostate cancer, Auger electrons are therapeutic when placed in proximity of the DNA in the nucleus of the cancer cell. ^{103}Pd is an isotope widely used for brachytherapy treatment of prostate cancers and in fact, there are medical cyclotrons producing just this one isotope to cater to the demands.

Several other accelerator produced radionuclides have been used in medicine for diagnosis or therapy or in research, which have not been listed here owing to the limited proven utility.

Accelerator Beams in Therapy

Radiotherapy is one of the most common methods of treatment of cancers. External beam therapy or teletherapy employs radiation to kill the cancer cells by focusing the radiation on the affected area. Conventionally, gamma rays from Co-60 or Ir-192 have been used in teletherapy. But, linear accelerators that employ energetic electron beams to produce energetic X-rays is being increasingly used for this purpose.

Linear accelerators or LINACs are common features in radiotherapy departments world over. Depending on the energy of the X-rays, they can be used to destroy cancer cells on the surface of the body (lower energy) or deeper into tissues and organs (higher energy). Compared with other types of radiation, X-rays can deliver radiation to a relatively large area. The efficacy of external beam radiotherapy in the treatment of malignant disease depends on maximising the dose received by the intended tumour volume while minimising the dose received by healthy and possibly critical surrounding normal tissue. In the recent past, 3D conformal radiotherapy and, Intensity Modulated Radio Therapy using photon beams from clinical linear accelerators have greatly enabled to attain this goal.

Apart from the photons, other particle beams such as neutrons, electrons, , heavy ions (such as helium and carbon) and pi-mesons (also called pions, which are small, negatively charged particles produced by an accelerator and a system of magnets) are also employed in therapy. , synchrotrons and cyclotrons, are used to produce and accelerate the particles required for this type of radiation therapy. The interest in light ion therapy has been growing owing to the unique depth dose characteristics of protons and other ions, and the minimal effects on the surrounding healthy cells compared with those in conventional electron beam and X-ray radiation therapy. In brief, the reason for better therapeutic efficacy is attributed to the fact that light ions produce a well-defined high dose region (Bragg peak) within a tumour and have the potential to spare most of the surrounding normal tissue from unnecessary irradiation. They demonstrate a higher linear energy transfer than photon beams with consequent higher relative biological effectiveness and reduced dependence on tumour hypoxia. It is believed that ion therapy offers the potential to significantly improve the outcome in selected tumour sites that are difficult to treat by surgery and/or conventional photon based techniques.

Application of neutron beams for therapy started almost soon after discovery of neutrons by Sir James Chadwick in 1932. Just six years later, clinical trials were begun to treat cancer with neutrons produced by E.O. Lawrence's cyclotron in Berkeley, California. These trials were terminated during World War II. Clinical research began again in 1965 and soon it was found that for certain tumors, local control could be achieved using neutron irradiation. Encouraged by these results, further work was carried out in the early 1970s. One significant finding which came out of the multi-institutional trials was that only neutron beams produced by protons with energies greater than about 60 MeV (neutron dose rates typically about 0.50-0.60 Gy/min) could produce tumor control with side effects no worse than low LET radiation. Thus far a large number of patients have been treated with neutron beams and the observations based on these varied studies are: (1) in general, the results with neutrons have been at least as good as those of the photons in terms of local control, although the incidence of significant side effects have been higher; (2) survival advantages with neutrons are comparable to those with protons (3) neutrons are efficacious for certain specific tumor types such as nonepidermoid, radioresistant tumors (sarcoma of bone and soft tissue and melanoma) with consistantly high local control rate, while in the central nervous system, both normal tissues and tumors appear to be exceptionally sensitive to neutron irradiation leading to poor therapeutic effect.

Boron Neutron Capture Therapy (BNCT) is yet another use of neutrons for therapy wherein the neutrons are focused onto the cancerous lesion after allowing accumulation of boron in the lesion. Here, the reaction of boron with neutrons to produce alpha particles which kill cells in the near vicinity (range of few cells) owing to their high LET, is utilized for therapeutic effect. However, this modality has not grown much due to the difficulties in preferably concentrating boron in the cancerous lesions.

Proton beam therapy is now an established mode of therapy, wherein a proton beam is directed solely at a tumor lying deep within the body in order to destroy the tumor. The ability to treat a variety of difficult-to-treat diseases has drawn attention to proton beam therapy worldwide. Currently, proton beam therapy is used in cancers that are difficult to treat by surgery, such as chondrosarcoma (a kind of brain tumour), ocular melanoma, retinoblastoma, some cancers of the head and neck, cancers of the

prostate, brain, and lung. Recently there has been increased interest in building dedicated proton accelerators of a few hundred MeV for treatment of deep lying tumors. Protons deposit most of their energy near the end of their path, minimizing the radiation dose to surface tissue and vital organs close to the target zone. Particle beams that can penetrate only a short distance into tissue are often used to treat cancers located on the surface of or just below the skin.

Among other light ions, treatment using carbon ions is attracting attention based on the results obtained from the initial clinical studies carried out at centres in Germany and Japan, currently equipped to perform such treatments. As irradiation with such ions induces positron emitters within the body and the German investigators have developed an innovative use of PET scanners for real time imaging of therapy dose distributions.

Accelerator Produced Laser Beams

Further on, accelerators could provide laser beam scalpels for precision surgery. Lasers are already used in surgery to remove damaged tissue with high precision, but often the surrounding healthy tissue gets damaged due to the hard nature of these lasers. Accelerator driven free electron lasers (FELs), capable of fraction-of-a-millimetre precision, could provide a solution with practically no damage to surrounding tissue.

Sterilization of Medical Device Using Electron Beams

Electron beams were used for sterilization of medical devices as early as 1956 by Johnson & Johnson. However, due to the poor reliability of the early machines, this field did not grow. With the progress in development of accelerators, particularly for medical applications (radiology, radiation oncology), and with the advances in computation technology, the situation has changed and there now exists a growing interest in electron-beam-based sterilization systems. Although both gamma ray irradiation as well as ethyleneoxide gas sterilization are effective and readily available technologies, E-beam has a big advantage of having the shortest processing time (of just a few seconds exposure resulting in 5-7 min total processing time), among the currently recognized sterilization methods. The ability of E-beam systems to change over quickly from one requirement to another is another major advantage. For example, an E-beam system can make the transition from a product requiring a 25-kGy dose to a different product requiring an 18-kGy dose in the same 5- to 7-minute time frame. E-beam sterilization of medical devices involves the use of high-energy electrons—typically with energies ranging from 3 million to 10 million electron volts (MeV) generated by accelerators that operate in both a pulse and a continuous-beam mode. As the beam is scanned through the product, the electrons interact with the device materials and create secondary energetic species such as electrons, ion pairs, and free radicals. It is these secondary energetic species that are responsible for disrupting the DNA chains of any microorganisms, inactivating them and thus rendering the product sterile.

Conclusion

Accelerators have played a significant role in scientific research right from the beginning. Their utility in multiple areas render them unique and in the health sector too they have made significant impact. It would not be an overstatement to say that accelerators have made a niche in nuclear medicine and medical cyclotrons are an important branch of cyclotron industry.

Acknowledgements

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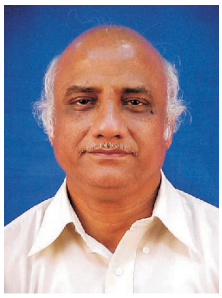
Applications of Accelerators in Food and Agriculture



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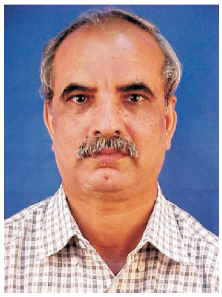

Introduction

Green revolution has made a dramatic change in India. There was a time when food grains had to be imported in our country. Now, India is world's second largest producer of food. The cruel paradox is that in the land of plenty, there is still scarcity and thousands starve even today. In addition to difficulties of distribution and economic incapabilities of certain segments of the population, post-harvest losses in food and agricultural commodities are very high (10-36%). Therefore, increased agricultural productivity needs to be complemented by post harvest processing particularly to reduce wastage.

Radiation processing is an important emerging technology that can help the nation by strengthening

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food security, improving food safety and boosting exports of agricultural commodities. It can cut down food losses caused by storage insects, microorganisms and physiological changes. Radiation processing of foods can help reduce the risk of food-borne illnesses by killing pathogens and parasites in food, thus improving food safety. Finally, it can boost international trade by overcoming quarantine barriers and by improving the quality (1).

Radiation preservation of food is a treatment of food with ionizing energy such as electron beam, X-rays or gamma rays under controlled conditions. International and national regulatory authorities allow only three types of sources for food irradiation viz., gamma rays from a radioisotope or cesium-137, electrons (10 MeV) and X-rays (7.5 MeV) from machine sources i.e. accelerators (2).

Gamma Sources

Cobalt-60 emits ionizing radiation in the form of gamma rays (1.17 and 1.33 MeV). This isotope is stored in stainless steel capsules (like pencils of cobalt), in underground water tanks. Cobalt-60 has several advantages, as up to 95% of its emitted energy is available for use and its gamma rays penetrate deeply. However, its 5.3-year half-life is disadvantageous as this source requires frequent replenishment and the treatment of the food is relatively slow. Cesium-137 (0.667 MeV) is other gamma source that is also used for food irradiation. Cesium-137 emits less penetrating gamma radiation but a longer half-life, making it more suitable under certain circumstances.

Electron Beam Facilities

Electron beam facilities employ an electron beam linear accelerator. The accelerators are DC (Direct Current) type microwave and radio frequency linear accelerator (LINAC) type. In both these types the electrons are concentrated and accelerated to 99% of the speed of light and energies up to 10 MeV in an evacuated tube. The efficiency of electron accelerators is about 20% higher than that of gamma sources as electron beam can be directed at the product. Energy and current determine the output capacity of the accelerator. Penetration of electron beam is very low and thus it cannot be used for bulk packages. This difficulty can be overcome by converting electron beam into X-rays.

X-Ray Facilities

X-ray facilities use an electron beam accelerator to target electrons on a metal plate. Although some energy is absorbed, the rest is converted to X-rays. Like gamma rays, X-rays are penetrating, and can be used on food boxes 15 inches thick or more. This allows food to be processed in a shipping package.

Characteristics of accelerators that make them more appropriate for food processing

Both isotopic and machine sources have their own strengths and weaknesses. While gamma sources have been used for many years, electron beam because of its certain characteristics is now gaining acceptance for food processing. These characteristics are:

- Non-nuclear nature
- High throughput
- Penetration
- Utility for irradiation at low temperatures
- SPS application and International trade

Non-nuclear nature

Electron beam technology does not involve use of radioisotopes and accelerator generated radiation is available as needed and can be switched ON or OFF as per the requirement. Because e-beams are generated electrically, they do not require replenishment of the source, as does cobalt-60. The total world supply of cobalt-60 is inadequate to satisfy the demanded high throughputs and hence there is need of machine sources. The current world supply of Co-60 isotope is of the order of a few hundred MCi and it is mostly used for sterilization of medical products and radiation therapy. Dedicated expensive nuclear reactors will be required to be built and commissioned if the global demand of Co-60 is to be met and its (Co-60) price is expected to rise many times. Further, machine sources on the other hand, provide constant output without decay normally associated with isotope sources and there is no radioactive waste. Electron beam systems are also flexible in terms of size. Energy of the beam and size

of the radiation field can be adjusted to suit the size of the packages. Therefore, one can get the desired max/min dose ratio in the irradiated product. A portable truck mounted accelerator facility can thus be taken from village to village for irradiation of agricultural products. Such a portable type of accelerator will be a boon for India. The developments in the technology of electron accelerators during last two decades has made it possible to manufacture high power reliable accelerators at a reasonable cost.

High Throughput

The sketch of a typical electron accelerator is shown in Fig.1. It consists of six main components. These are the accelerator, scanning horn, product conveyor, radiation shield, ventilation system and control system. An electron accelerator of 15 kW-10 MeV is capable of providing a throughput of 27 kGy – Ton/hr, when used in electron beam mode and 2.7 kGy – Ton /hr when used with 5 MeV photon beam mode. As compared to this a ^{60}Co source of 225 kCi will be needed to achieve a throughput of 2.7 kGy – Ton/hr (3). The international and national regulatory authorities also permit use of photon beam generated from a bremsstrahlung target, bombarded by 5 MeV electrons for the same purpose. At 5 MeV the X-ray conversion efficiency of the target is very poor, resulting in poor utilization factor of incident electron power. More recent work has indicated that this limit of energy is unnecessarily conservative and, recently an experts committee of the International Atomic Energy Agency has made a recommendation to allow photon energies up to 7.5 MeV to be used for food processing purpose. For maximizing photon yield and minimizing neutron production three x-ray converters, tantalum, tungsten and gold have been found especially suitable for use with 7.5 MeV. Modern high power accelerators are now commercially available which provides very high throughput as compared to isotopes. These can process an entire 20,000 kg truckload in 60-90 minutes, including off-load and reload time.

Penetration Depths

Electrons have a predictable penetration depth which depends on two parameters, electron energy and product density. The penetration is proportional

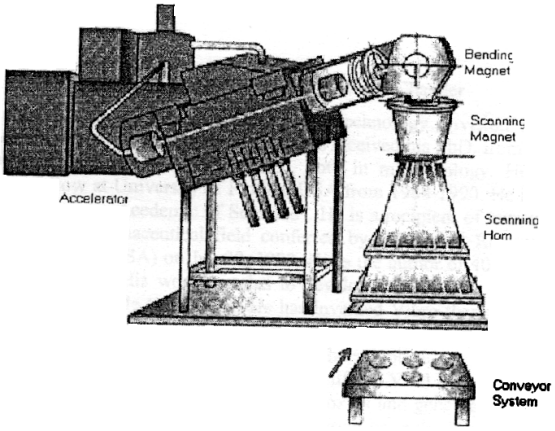

Fig. 1 Sketch of a typical electron accelerator.

to the energy and inversely proportional to the density. The basic formula that describes penetration is:

$$\text{Penetration (cm)} = (0.524E - 0.1337)/d$$

where, E = beam energy in MeV and d = density in grams/cc.

This equation applies to energies greater than 1 MeV. Electron beam is used directly for small packages of food that need high dose but it cannot be used directly for large size food packages due to its low penetrability. X-rays can be used for the food products in large packing size but requiring low doses. The irradiation can be given in two ways. Single side and double side irradiation.

Single Side Irradiation

When product thickness is small, single side electron irradiation is selected. When product is irradiated from a single side, the total volume irradiated does not get uniform dose throughout the thickness. The thickness should be such that the dose does not drop below 60% of the maximum value. The typical values of useful penetration for 1 MeV, 5 MeV, 10 MeV electron beam is 1.0 cm, 2.25 cm, and 3.6 cm respectively. The disadvantage of the technique is that a major fraction of the incident power escapes out without use hence its efficiency is very low.

Double Sided Irradiation

To increase the efficiency irradiation is done from both sides of the product. The useful thickness for double-sided irradiation is more than twice that for single sided irradiation.

Electrons have mass and an electric charge and therefore, are absorbed fairly quickly as they penetrate dense materials. For food products with densities similar to water (1 g/cm^3), 2-sided treatment with e-beam will penetrate through approximately 3.5 inches (9 cm). However, in reality, packages with depths much greater than 3.5 inches can be decontaminated or disinfested with e-beam because most commercially packaged foods have a lower overall density than water. For instance, e-beam can effectively process a stack of 8 quarter-pound hamburger patties packaged in a master case of 6 inch depth. Unlike electrons, x-ray photons have no mass or electric charge. Therefore, x-ray photons penetrate products to a greater depth than electrons. In terms of linear distance, x-ray photons emitted at the maximum allowed energy of 5 MeV will penetrate through approximately 13 times thicker material than electrons emitted at the maximum allowed 10 MeV given the same material density.

Irradiation at Low Temperatures

Meat, meat products and seafood are exported in frozen conditions (-16 to 18^oC) and rules are very stringent for maintaining these low temperatures. Temperature abuse (rise) by 2^oC may result in the rejection of the consignment for export. So, it is mandatory to maintain these temperatures during radiation processing. Dose rate from gamma ray sources being low may pose technological problems in processing frozen products at doses of 4 to 7 kGy without temperature abuse. Electron beam and x-rays are most suitable for radiation processing of frozen foods because the dose rate is very high (10^4 and 10^9 Gy/sec). This enables the product to be treated within a short time without significant change in the temperature of foods (<1^oF).

An additional advantage with electron beams is that their application provides better oxidative stability to foods with high fat content than exposure to gamma rays. Many radicals are produced when foods are irradiated. Oxygen can add to some of those radicals, giving rise to peroxy radicals. In such reactions the small quantity of oxygen present in water or in a food can be consumed quickly when that water or food is irradiated. Because diffusion of oxygen from the atmosphere is rather slow, in electron irradiation any dose higher than about 0.6kGy creates an anoxic (or anaerobic) condition in the irradiated sample. Gamma sources on the other hand, deliver a radiation dose at a much lower dose rate than electron accelerators. Therefore, oxygen has time to diffuse into the material unless the sample is irradiated in vacuum or under nitrogen or other protective gas. Because of the difference in dose rate, the electron irradiation of high fat foods can result in reduced oxidative changes than those observed with gamma irradiation at the same dose. This apparent dose rate effect is thus actually an oxygen effect. Most of the studies on food irradiation have been done with gamma rays, and the data obtained with gamma rays extrapolated to electron irradiation may not hold true in evaluating the efficacy of electron irradiation and the safety of electron-irradiated products. This is evident from the studies of Todoriki and Hayashi (4) who investigated the effects of gamma rays and those of electron beams on lipids, because lipid peroxidation is responsible for both the deterioration of foods and the inactivation of living cells caused by irradiation. Phosphatidylcholine was irradiated in the state of a film or liposome with gamma rays or electron beams, and the amount of peroxide generated was determined to compare the effects of the two types of radiation. The amounts of peroxide formed in both the film and liposome with gamma rays were significantly larger than those with electron beams, when the samples were irradiated at the same dose.

SPS Application and International Trade

Government of India has approved irradiation as a Sanitary and Phytosanitary (SPS) measure. The Agreements on Sanitary and Phytosanitary (SPS) Practices and Technical Barriers to Trade (TBT) under the World Trade Organization (WTO) has resulted in the acceptance of irradiation as an SPS measure in international trade. Thus, irradiation can be applied to overcome quarantine barriers, and to hygienize products for international trade in agro-horticultural foods among the WTO member

states. Thus there is a good scope for accelerators for such applications.

An accelerator facility to be economically viable needs very high quantities of food and agricultural commodities to be processed throughout the year. In India the produce is scattered over vast areas and it costs a lot in transporting the materials for processing. Thus it will be advantageous for the accelerator to be located at the port city. It can cater to the needs of all such foods and commodities that need irradiation before export. Thus all these materials can be received from all over India at the facility and exported from the port itself. Some examples of export of food and agriculture commodities are:

Hygenization of Spices

Spices are high value commodities and an important source of valuable foreign exchange for the country. Indian exports of spices per year earn on an average foreign exchange worth about Rs.2000 crores. Spices being low in the moisture content are inherently stable to spoilage; however, storage under humid conditions can result in spoilage by molds and infestation. Presence of pathogens poses risk to human health, especially when spices are added to food after cooking. Radiation processing offers a very effective and safe alternative to steam sterilization or ethylene oxide treatment for disinfestations and microbial decontamination of spices. Being a cold process it does not affect the delicate aroma and flavor compounds in spices.

Pet foods

Pet foods are another emerging export market and good source of foreign exchange for the country. These products have low moisture content, and are, therefore, inherently stable to spoilage. However, inadequate drying can result in fungal spoilage. Presence of pathogens, mainly Salmonella has resulted in rejection of many consignments of pet foods. Therefore, many importing countries now insist that pet food should be processed by radiation for hygienization.

Emerging Applications

Radiation Processing of Natural Polymers (e.g. Chitosan)

Radiation processed polysaccharides have been shown to possess important biological activities such as anti-microbial activities, growth promotion of plants, suppression of heavy metal stress in plants, presence of phytoalexins, etc. Radiation technology can be beneficially utilized to process natural polymers that are available in abundance. Chitin in one such bio-polymer found in the exoskeleton of shrimps, crab, shell fish and micro-organism. This abundance, combined with the specific chemistry of chitin and its deacylated derivative, chitosan, has resulted in an array of applications in the fields such as medicine, agriculture, biotechnology and wastewater treatment. The most important aspect is that it is recovered from "waste" material from fisheries industry. In recent studies including those from BARC, it has been shown that chitin can be extracted under much milder conditions from irradiated shrimp waste as compared to the unirradiated material.

Chitosan has many applications in food processing and preservation owing to its diverse properties. However, low solubility at neutral pH, high viscosity and high molecular weight limits its use. Chitooligosaccharides obtained by chemical treatments and enzymatic means have been reported to possess better properties than native chitosan (5). Radiation treatment has been used to produce chitoligosaccharides. Radiation processed chitosan had increased antioxidant activity as assessed by various chemical assays. Its potential in retarding lipid peroxidation has been assessed in irradiated lamb meat stored at chilled temperatures (6), shelf stable mutton sheekh kababs and bacon (7). Chitosan has strong antimicrobial properties and radiation treatment at low doses does not affect antimicrobial properties of chitosan (7).

Like the antibacterial activity of chitosan, its antifungal activity has also been an area of interest in recent years. Ha et al. have recently reported that irradiated chitosan possesses higher anti-fungal activity as compared to unirradiated chitosan (8). The anti- fungal activities of both unirradiated and

irradiated chitosan have been compared by Hien et al. (9). Studies have been conducted in Japan and Vietnam on the efficacy of irradiated chitosan as a fruit preservative for mangoes and banana. Banana with chitosan coating irradiated at 25 kGy could keep good quality. After 20 days, bananas acquired the natural ripening, uniform yellow color, and good flavor and desired firmness. Similarly, for the mango, chitosan irradiated to a dose of 250 kGy was found to be effective to prevent spoilage of mangoes for up to 10 days. These results show that irradiated chitosan coating is effective for preservation of fresh fruits. It could extend the shelf life by limiting the growth of fungi without affecting the ripening characteristics of the fruit.

Growth Promotion of Plants and Phytoalexins in Plants

It has also been reported that oligosaccharides including degraded alginate and oligochitosan obtained by irradiation play a role in cell signaling in plants for induction of phytoalexin. Therefore, treating plants with degraded alginate not only stimulates growth but also increases the disease resistance of the plant. Radiation depolymerized alginates, chitosan and carragennans have been found to promote the growth of rice and peanut (10). In India, the growth promoting effect of radiation degraded products of alginate and chitosan on seedling growth of wheat (Triticum aestivum) and chickpea (Cicer arietinum) was studied by Chaudhari (11). Between the two polysaccharides, radiation degraded products of chitosan have relatively better biological activity.

Sludge Hygienization

In a few countries, including the United States and South Africa, pilot-scale studies using electron-beam accelerators have also been carried out for treatment of wastewater. Sludge has the potential as an excellent soil conditioner because the humus material in the sludge provides a good matrix for root growth, while the nutrient elements are released in approximately the right combination for optimal plant growth. Soil microbes would assist in further stabilization of any biodegradable organics remaining. Nutrient release with sludge is slower than with chemical fertilizer, allowing the nutrients to become available, as the crop needs it. Land spreading of sludge will thus become more popular as energy and nutrients become scarce.

Thus, recycling of the sewage sludge to agricultural land can be an important outlet provided it is carried out in a manner that protects human and animal health as well as environment at large. The sludge, after conventional treatment process, still contains a heavy pathogenic microbial load and therefore needs to be hygienized before application in the agricultural processes. Since land application of sewage sludge on a larger scale is relatively recent, it may not have been considered in the design of sewage treatment plants. The utilization of sewage sludge on a large scale and in a safe manner will necessitate development of accelerator technology which would treat the sludge in a reliable, efficient and cost effective manner.

Mechanism of Food Preservation by EB

Packaged food is exposed to ionizing radiation in specially designed and stringently shielded facilities. Electron Beam inactivates microbes and reproductively sterilizes insects by damaging nucleic acids. This damage occurs directly as a result of electron and photon contact with DNA and RNA, as well as indirectly through the action of charged ions further reacting with the nucleic acid.

DNA is the most Critical Target of Ionising Radiation

The DNA is affected more than other molecules by electron beam / X-rays treatment because it is the largest molecule in the cell (12). For the same reason, organisms with larger genomes are more susceptible than those with smaller genomes, and therefore, pathogenic organisms are more susceptible than many spoilage organisms. The probability (x) that a molecule with molecular weight M will change upon irradiation is given by

$$x = 10^{-7} \times G \times M \times D.,$$

Where G = number of changes per 100 eV of absorbed energy, D = the dose in kGy

The value for G is usually not above 4 when aqueous systems are irradiated.

If water (M=18) is irradiated with a dose of 10 kGy, then

$x = 10^{-7} \times 4x\ 18 \times 10 = 7.2\ X10^{-5}$

This means that only 7.2 out of every 100,000 molecules of water would change.

If DNA with a molecular weight of 10^9 daltons is irradiated, we get x=4000. This means that each DNA molecule has been changed 4,000 times or at 4,000 locations. Most of these changes may not be lethal, but double strand breaks usually are. The G value for double strand breaks is about 0.07. This DNA would have received double strand breaks ($x = 10^{-7} \times 0.07 \times 10^9 \times 10 = 70$).

In addition to DNA being more prone to radiation damage, its intactness is important for the survival of cells as it carries the genetic information. Only one copy of a DNA molecule is present in the cell thus making cell survival difficult in case of DNA damage. Damage to the DNA disables the organism's ability to grow or multiply. The radiation dose to which a food is exposed is based on extensive research to ensure the destruction of pests and pathogens while preserving the wholesomeness of foods at the same time.

Commercial Radiation Processing by Electron Beam

More than 15,000 electron accelerators are in industrial use for varied applications (3) but only few are dedicated to food irradiation. The areas required for commercial facilities for food irradiation ranges from 300 to 4,000 ft^2 (30 - 370 m^2) depending on the processing capacity, volume throughput rates, package size and a few other parameters. A high power accelerator with low cost performance ratio and operational simplicity has been designed using digital computers and software.

Accelerators with beam power of few hundred kW are operational worldwide and have further potential for advancement in the accelerator power. Few of the accelerators currently operational in the field include a dual mode 10 MeV/200 kW electron beam irradiation facility at Nuclear Fuel Industries, Japan (3). West Japan Irradiation Service Co. Ltd. also has installed a new facility "Kansai Electron Beam Irradiation Centre" with dual mode of processing using a 5 MeV Dynamitron accelerator (13). Two electron accelerators with throughput of 50 kGy-Ton/hr and 100 kGy-Ton/hr are in operation in Odessa, Russia since 1980 for disinfestations of food grains (14). An irradiation facility using e-beam technology in Sioux City, Iowa has been treating frozen beef since May 2000. Some 200 metric tonnes of ground beef per day have been irradiated in Iowa, USA. US Department of Agriculture has allowed irradiation of meat to eliminate food borne pathogens, particularly Escherchia coli O157:H7. An X-ray facility on the big island of Hawaii treats high quality papaya and other tropical fruit for insect disinfestation prior to shipment to the mainland. An X-ray facility is under construction in Russellville, Arkansas adjacent to Zero Mountains cold storage facility, which caters for more than 30 clients including some of the largest international exporters of poultry and beef. This facility will be used to pasteurize poultry and meat products.

Conclusion

The application of EB treatment may have clear advantages over gamma radiation in the area of microbial decontamination of frozen foods such as meat, meat products, sea foods and disinfestation. The efficiency of the EB seems to be higher than that of the gamma radiation in inactivation of microorganisms while the chemical changes induced are minimum. In addition, since radionucleotides are not a part of the process, it may help to allay traditional public concerns/fears surrounding nuclear hazards to worker safety and environment. Indigenous technology for designing, fabrication and commissioning of electron beam facilities for food irradiation, though being developed, should be done at the accelerated pace. Else, we keep on playing a second fiddle to developed countries in this branch of science which has great potential for strengthening food security, improving food safety and promoting international trade by phytosanitation.

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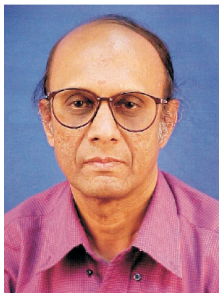
Accelerator Based Ultra Sensitive Mass Spectrometry



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Introduction

Accelerator Mass Spectrometry (AMS) has become a powerful technique for analysis of stable and long lived radioactive nuclei which are present in extremely small abundance and available in very small amount (mg-ng) respectively. This field of activity started nearly three decades back, is intensely pursued in more than 50 accelerator facilities in the world. The AMS is widely used in different branches : Dating in archaeology, dating of ground water, exposure dating and erosion of surface rocks, half lives and cross section measurements of interest to nuclear physics; releases from nuclear industry, trace elements in semiconductor materials and biological samples, search for exotic particles. The AMS technique has been mainly applied to cosmogenic nuclei like ^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl, ^{129}I. The importance and excitement of this field of research is judged by the fact that international meetings on AMS are regularly held once in 3 years for the past 25 years. The tenth AMS conference was held in 2005. The proceedings of this conference series are regularly published [1]. There are also excellent reviews on AMS available in the literature [2-8].

Salient features of AMS

The conventional mass spectrometry, based on positive ion source, though extremely powerful has some limitations e.g. in separating ^{14}C (half life = 5730 yrs) from the interfering molecules ($^{12}CH_2$, ^{13}CH) and isobar (^{14}N) all having nearly the same mass. Further, the radioactive decay counting method which is the most popular method for quantification of the cosmogenic nucleus ^{14}C is limited and will take an extremely long time for counting if the sample is available only in small amounts. Just to gauge the power of AMS and the limitations of conventional radioactive decay counting, let us take the example of the conventional radioactive decay counting of ^{14}C in a contemporary carbon sample. e.g. 70 microgram of carbon sample will have about 35×10^{17} atoms of ^{12}C and 42×10^{5} atoms of ^{14}C, assuming the usual ratio of $^{14}C / ^{12}C$ to be 1.2×10^{-12}. To obtain 10,000 counts (to achieve 1% statistical uncertainty) by decay of ^{14}C, the counting time can be estimated to be about 20 years. However, using the AMS technique, having 70 microgram of carbon sample in ion source, it is possible to extract easily carbon ions of intensity 1.6 microampere (1 microampere has around 6×10^{12} carbon atoms). This will have about 10^{13}, atoms of ^{12}C and hence will also have 1.2×10^{1} atoms of ^{14}C. Operating the ion source at this intensity for nearly 15 minutes, we can measure around 10,000 atoms of ^{14}C in a suitable detection device. The tremendous power of AMS can be judged by this example. In this technique , we do not wait for the atoms to decay to estimate the yield the atoms of interest. In fact we count the atoms as they exist in the sample. This way the significant enhancement in sensitivity at a fraction of the time taken for conventional decay counting is achieved. As it will be shown below,

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even the interference form the molecules and isobar is completely eliminated in the AMS of ^{14}C

The charged particle accelerator traditionally used for nuclear physics programmes has been put to use to measure rare isotopes at very low abundance ratios with good precision and in a small time interval. A schematic of the AMS set up is given in the figure (Fig.1). The salient features are : 1) Use of Tandem accelerator : Negative ions from the ion source are accelerated first. Then they are made to pass through a stripper foil. In this process the negative ions are converted to positive ions of different charge states. These positive ions are further accelerated to achieve a final energy of E= (q+1)V where V= Voltage(HV) at the terminal of accelerator, q = atomic charge of the positive ion. 2) Use of negative ions : While it is possible to produce negative ions of ^{14}C ($^{14}C^-$) it is not so in the case of ^{14}N as $^{14}N^-$ does not exist. Similarly, while $^{129}I^-$ is possible, the interfering isobar ^{129}Xe does not form. This feature is advantageous to get rid of interfereing isobars in particular from the subsequent acceleration. 3) Mass selection of ion species through injector magnet: Here mass of interest will be selected and other masses will be filtered out. However, interfering isobars/ molecules will accompany the ions of interest after this stage. 4) Acceleration and charge stripping (elimination of interfering molecules)-negative ion becomes multiply charged positive ions in passing through the carbon foil (or gas stripper) located at the HV terminal. Highly energetic negative ions passing through the foil become positively charged. Molecules with charged states above 3^+ do not exist long enough to be further accelerated. After passing through the stripper foil in the terminal, the ions of interest are free from interfering molecules. 5) Momentum analysis of accelerated particles - (p/q or mE/q^2 with q= atomic charge of the ion, v is the velocity of the ion, m is the mass and E is the energy of the accelerated ion). The ion of interest passes through the anyalysing magnet where a particular E is selected along with the corresponding q. This stage is usually followed by a switching magnet to achieve a better p/q selection. 6) Velocity filter(v) or electrostatic analyzer(E/q) is employed after this stage to get rid of the intense but degraded and unwanted fragments of molecules which come out of the analyzing magnet along with the isotope of

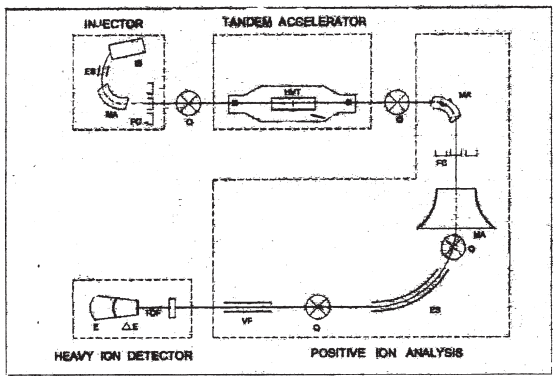

Fig. 1 Schematic of the lay out for AMS measurement (IS = ion source, ES = electrostatic analyzer, MA=magnetic analyzer, Q=quadrupole lens, HVT = high voltage terminal, FC = Faraday cup, VF = velocity filter, TOF = time of flight).

interest. This step is essential to enhance the signal (isotope of interest) to noise (interfering unwanted isotopes/fragments) ratio. 7) Detection set up – Time of flight technique to identify the mass (knowing energy), Detector Telescope consisting of a thin ΔE (small part of energy is lost) followed by a thick E (most of energy is deposited here). This enables identification and quantification of isotope or ion of interest.

Starting from the ion source to the final detection, the interfering species are continuously reduced to obtain the best and unique identification of the specific isotope of interest.

In AMS for ^{36}Cl, the procedure followed is given below : suppose the desired ^{36}Cl ion is with charge state q=5+ and accelerated with V=10 MV at the terminal, then the energy of the ion is [E ((q+1) V] is 60 MeV. First, the more abundant isotopes, ^{35}Cl and ^{37}Cl are mass selected and accelerated with the terminal voltages of 10x36/35 MV and 10x36/37 MV respectively. (To match ME/q^2 of ^{36}Cl). The magnetic rigidity values of analyzing magnet , switching magnet and other focusing (magnetic) elements are kept the same for all the three isotopes. Essentially only the terminal voltage is scaled for mass difference amongst the isotopes as discussed above. As ^{35}Cl and ^{37}Cl are more intense, they are

chopped in intensity by known amount before acceleration. The currents are measured in a Faraday Cup. The current ratio of ^{35}Cl and ^{37}Cl should be as per normal abundance ($^{35}Cl/^{37}Cl$ = 3.13). Having optimised the machine for $^{35,37}Cl$, the injector magnet at the ion source is adjusted to select ^{36}Cl. The same is accelerated, with a terminal voltage of 10 MV as mentioned earlier. As the intensity for these ions will be very small($10^{-10} – 10^{-14}$ of $^{35,37}Cl$ intensity), ^{36}Cl ions after passing through the analysing and switching magnets are directly counted in a detector. Here a segmented anode gas detector[9] is usually employed, to separate ^{36}Cl from the interfering isobar ^{36}S (which might originate from impurities in the ion source holder). Typically the entire procedure of acceleration and detection of the stable Cl isotopes ($^{35,37}Cl$) and the unstable ^{36}Cl, in sequential manner can be completed in 30 minutes to one hour.

Applications of AMS

As mentioned earlier, the AMS technique is widely used in many branches of science and technology. The long lived nuclei (with their half lives) which are mainly used in this programme are : ^{14}C (5730 years), ^{10}Be (1.51 x10^6 years) , ^{26}Al (7.17 x 10^5 years), ^{36}Cl (3.01 x 10^5 years), ^{41}Ca (1.02 x 10^5 years), ^{129}I (1.57 x 10^7 years). Stable isotopes are also used for AMS. The ultra sensitivity of AMS is exploited in measurement down to sub – ppb levels of platinum group elements directly in mineral grains. Estimation of trace level impurities in semi-conductors is another application. The measurement of low nuclear cross sections (low levels of reaction products in the large matrix of the target atoms) and half lives of long lived nuclei is also accomplished using the AMS. One of the interesting cases is the one related to half-life determination of ^{32}Si, which is placed between 130 and 170 years and as such is still uncertain. Hydrology is one of the important areas where AMS technique is very powerful. ^{36}Cl has found application in determining the ages of ground water and in measuring the recharge rates. This information is crucial in choosing the potential sites for nuclear or chemical waste storage.

Radiochemical dating is a powerful and popular usage of the ultra sensitive mass spectrometry. The small sample capability of AMS is fully exploited in the area of archaeology based on ^{14}C. It is possible to date samples as old as 50, 000 years with very good precision using this technique. Applications of AMS based radio carbon dating to archaeological finds are: authentication of ancient art like antique furniture, paintings, art pieces, cave and rock art. Radionuclides are used in the earth sciences both as chronometers and as tracers. The mixing of the ocean is an important influence on global climate and the relative age differences amongst surface and deep-water masses are especially important in understanding the rates of this mixing. This can be studied using the AMS technique and the long lived ^{10}Be isotope.

As the AMS technique is very sensitive using which even smaller number of atoms in a large substrate can be detected, its use has been steadily growing in biological and environmental tracing programmes. Radiotoxicity and biochemistry of Al can be studied by injection of ng level of long lived ^{26}Al in humans and measuring the same isotope in blood unambiguously at low concentrations. In a similar manner, the bone loss can be monitored using ^{41}Ca as a tracer. ^{26}Al and ^{41}Ca are especially useful for tracing elemental metabolism. Tracing ^{14}C labeled compounds through natural systems is the most widely used application of biomedical AMS. Because AMS significantly reduces the chemical and the radiological dose (typically 10 nCi or less) given to subjects, human studies can be conducted for validation of animal models and for clinical applications. More tests of drugs using human subjects and the doses that AMS can measure will expand the base of information on metabolism, efficacy and toxicity. With ^{41}Ca and AMS, the kinetics of Ca in the human skeleton can for the first time be studied directly, providing an indication of individual's bone health.

Conclusion

A brief account of AMS technique has been provided. The wide-ranging applications of AMS to many areas of science and technology are discussed in detail in Ref. 1-8. Only a brief account of this is given in this article. In India, the AMS for ^{14}C, is available at Institute of Physics, Bhubaneswar, The Inter University Accelerator Centre (formerly Nuclear Science Center), New Delhi has demonstrated feasibility studies for ^{10}Be. At the

Mumbai Pelletron, efforts are underway for ^{36}Cl acceleration and detection. A preliminary study has yielded encouraging results.

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Accelerator Driven Systems (ADS) for Nuclear Power Programme

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Introduction

The large-scale application of nuclear power in electricity generation leaves behind some unresolved issues in the nuclear fuel-cycle. The main amongst them include:

(i) Sustainability of nuclear fuel resources in long-term power programmes.

(ii) Safe and secure disposal of spent fuel from power reactors to close the fuel cycle that is acceptable to population in general.

(iii) Enhancement of reactor safety to deterministic rather than probabilistic levels.

Available nuclear fuel in the nature consists of only one fissile species- a meager concentration of just 0.7% of U-235 in the natural uranium. To utilize more abundant other fertile isotopes like U-238 and Th-232, these need to be first transmuted through nuclear reactions to breed Pu-239 and U-233 respectively. With such breeding possibility, the global nuclear fuel resources would last for several centuries at present or even enhanced rates of energy consumption.

Entire nuclear fuel cycle in nuclear power programme generates large amounts of radiotoxic spent fuel, which require technological solutions to safely dispose either by deep underground burial or transmutation into acceptable forms that do not pose long-term radiological hazards to mankind. Such options have yet to mature into affordable technologies.

Basic configuration of Accelerator-Driven System (ADS), which has potential for resolving all these issues, consists of coupled operation of proton/deuteron accelerator, a heavy element target and the sub-critical reactor (Fig. 1). Neutrons emitted from the spallation cascades, created by interaction of high-energy protons in heavy element

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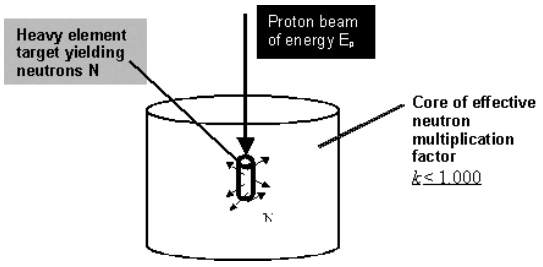

Fig. 1 Schematic of ADS configuration.

target, drive the fission chains in the sub-critical core. These fission chains are essentially self-terminating reactions as against the chain reactions that would continue indefinitely (at least in theory) once triggered in conventional reactors. This is the basic difference between ADS and conventional reactors.

The spallation cascades are basically endothermic nuclear reactions where one pays for the energetic cost of accelerated primary particles. The spallation target is essentially a mass of heavy element(s) which, when struck with high-energy light ions from a charged particle accelerator, emits several neutrons (Fig.2). Among the candidate primary particles-deuteron and proton, the yield is about 10% more with the former. However, the inevitable loss of particles during acceleration process contaminates acceleration system significantly more by neutron-induced activation in case of deuterons. So, the use of proton is more beneficial from radiological safety considerations.

Although there are several candidate target heavy elements- tungsten, tantalum, mercury, lead, thorium, uranium etc.; for technological problems encountered in extracting very high volumetric heat deposition in the target, the best material appears to be molten lead or an eutectic of lead-bismuth (LBE). Lead has melting point of 327^0C and LBE ~125^0C. Flowing molten metals function as target and also carry away the deposited heat from proton beam.

A factor k in reactor physics indicates neutronic multiplicity and it is equal to the ratio of number of neutrons in two successive generations of fission chains. For safe and sustained operations of a conventional reactor, it should be maintained exactly at value 1. ADS reactor can, however, continue to generate heat from fissions that are triggered by neutrons from spallation reaction when its k is < 1.

The accelerator input power needed for a given output thermal fission power of the ADS core is proportional to $\Delta k/k$ (see next section 2). A part of the electrical power generated in the ADS reactor plant is utilized in sustaining operation of the accelerator. This required power feedback is dependent on the degree of sub-criticality ($\Delta k = 1-k$) of the reactor. In a typical ADS designs, the accelerator may consume about 10% of gross electrical output from the plant.

ADS as Energy Amplifier

Let there be N neutrons from target (Fig. 1) which enter sub-critical core and initiate self-terminating fission chains, such that first

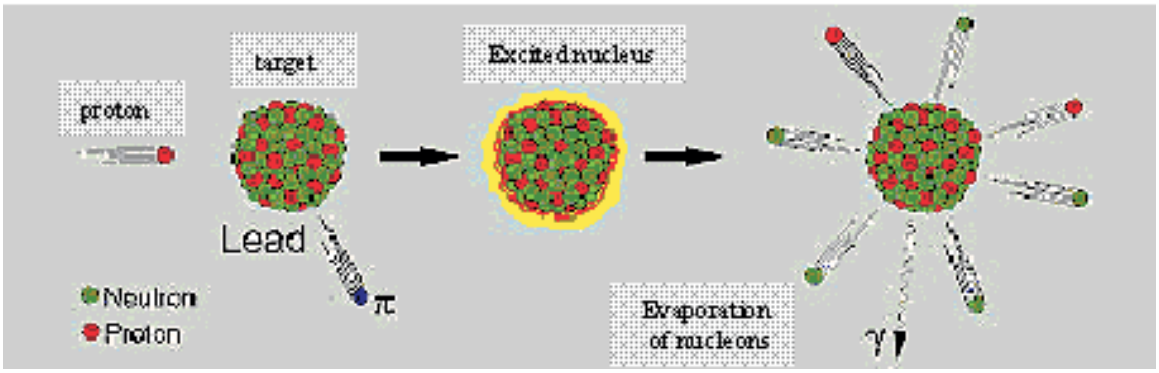

Fig. 2 Schematic of spallation nuclear reaction.

generation of resultant neutrons in core will be $k*N$, second generation will have k^2*N and r^{th} one k^r*N. and so on.

Sum of total neutrons due to spallation plus fissions in the self-terminating chains will be,

$$N_t = N.\ (1 + k + k^2 + k^3 \ldots\ldots \infty) \text{ from where,}$$

$$N_t = \frac{N}{(1-k)} \text{ (for } k<1) \qquad (1)$$

It can be shown with some analysis of neutronics in sub-critical core of ADS by assuming- ν as the number of fission neutrons per fission reaction, E_f as the energy released in core from each fission, ν_s as the number of spallation neutrons per incident proton on target, and E_p as average primary particle energy; that, the ratio of total fission energy from the self-terminating fission chains to the input proton beam energy, P_f/P_{beam} called Gain (G) of the ADS functioning as an energy amplifier; can be expressed as

$$\text{Thus, } G = \frac{E_f}{E_p} \cdot \frac{\nu_s}{\nu} \cdot \frac{k}{(1-k)} = G_0 \cdot \frac{k}{(1-k)} \text{ and,}$$

P_{beam} for desired $P_f = P_f$. $\Delta k/k$ as above. For a 1000 $MW_{thermal}$ (~ 300 $MW_{electrical}$ gross) ADS reactor performance, values may be assumed for E_f and E_p as 180 & 1000 MeV; and ν_s and ν are 22 neutrons/proton and 2.5 neutrons/fission respectively. Therefore, typically with k= 0.97, power input to accelerator with 40% efficiency (=percent ratio of beam power to net input electrical power) will be about 49 $MW_{electrical}$.

It would be readily realized that higher values of k are good for energy production from the ADS reactor, somewhat lower k would be good in dedicated breeder (explained in next section 3) which is self-sufficient in energy requirement for driving its accelerator; whereas reactor with very low k is not sustainable as ADS from economic considerations, since its accelerator would consume very large fraction of plant's gross power.

ADS as Effective Breeder

Proven reserves of Uranium- the only natural resource with fissile species (^{235}U), in India are rather limited, but those of fertile thorium are much more abundant. Conversion of fertile Th into fissile ^{233}U in conventional critical reactor would initially need neutrons from fission of ^{235}U, which is obtained from mined uranium. While this is true for the first start up supply of ^{233}U-fuled reactor, the sustainability thereafter by its own regeneration of fissile material could be possible. However, the estimated growth of installed nuclear power capacity in this way, according to presently available knowledge, is estimated to be inordinately slow.

The application of ADS helps in the above scenario of thorium utilization in both the stages of initial start up as well as during capacity growth. It offers the neutrons from non-fission process-spallation of other abundant materials like lead, bismuth, tungsten, tantalum and even thorium itself. Moreover, the ADS reactor using thorium-^{233}U fuel, can be made to enhance internal and/or external breeding, achieve higher fuel burn up and have many other attractive features of neutron economy in the core, as shown below.

The ratio of probability of neutrons undergoing radiative captures to that resulting in fission in a fissile species in a reactor, is given by $\alpha = \sigma_c/\sigma_f$; where σ_c and σ_f are microscopic capture and fission cross-sections in the fissile species.

Using the notations as previously it can be shown for a sub-critical ADS core surplus neutrons per fission, that are essential for breeding in core would be,

$$N_{surplus} \text{ per fission} = \{\nu/k - (1 + \alpha)\} = \frac{\nu}{k} - (1 + \alpha)$$

During fuel breeding in core, for each fission event considered above, $1+\alpha$ neutrons destroy same number of fissile species (by fission and capture) per fission. So, at breeding ratio of 1, at least one must replenish the number of $1+\alpha$ fissile species just consumed in by absorption of equal number of neutrons. Therefore, ($N_{surplus}$ per fission) - $(1+\alpha)$ should be greater than other parasitic losses ν_c per fission. So that, condition for effective fuel breeding ratio greater than 1 in core requires that:

$$\nu/k - 2(1 + \alpha) - \nu_c \geq 0$$

Compared to a critical reactor where k is equal to unity, ADS would provide not just ν but ν/k

TABLE 1. Comparison of surplus neutrons per fission in the two fissile isotopes

Fissile isotope	Neutron spectrum	Neutrons per fission	α = capture/ fission ratio	Surplus Neutrons for k = 1; ν_c= 0.25	Neutron balance for k = 0.95; ν_c= 0.25	Percentage improvement with k=0.95	Remark on breeding potential
Pu-239	Thermal	2.871	0.36	-0.10	0.05	150%	Poor breeding with & without ADS.
Pu-239	Fast	2.98	0.14	0.45	0.61	35%	Can breed without ADS
U-233	Thermal	2.492	0.09	0.06	0.19	216%	Poor k=1 breeding; ADS helps
U-233	Fast	2.492	0.093	0.06	0.19	216%	Poor k=1 breeding; ADS helps

neutron per fission, which represents a significant gain for fuel breeding and consequent shortening of fuel doubling time.

For the two main breeding schemes of ^{239}Pu and ^{233}U, each under fast or thermal neutron spectrum reactor cores, the effect of external (spallation) neutrons can be understood well from table-1. In case of ^{239}Pu breeding in thermal reactor, the surplus neutron in critical system is negative value 0.10 per fission with typical figure of $\nu_c \sim 0.25$, self-breeding will not be possible. However, ^{239}Pu can be bred profusely in fast neutron spectrum of critical reactor and use of ADS with k=0.95 would be superfluous.

In case of ^{233}U breeding, allowing for $\nu_c \sim 0.25$ may make breeding just possible in either of the fast or thermal neutron spectra of critical reactors. But, self-breeding schemes with ADS and k of about 0.95 would make appreciable improvements under both the spectra. For these reasons, significant shortening of fuel doubling periods have been estimated for Th-^{233}U fuel cycle with ADS sub-critical reactor.

ADS as Nuclear Waste Incinerator

Nuclear power programmes so far have been utilizing uranium as nuclear fuel in light water reactors on a large scale. Un-reprocessed spent fuel discharged from these reactors has been accumulating globally to a very large tonnage. For reasons of keeping this radiotoxic nuclear waste away from the biosphere and not allowing use of plutonium content (~ 0.5-1% weight content) in civilian reactors for the fear of nuclear weapons

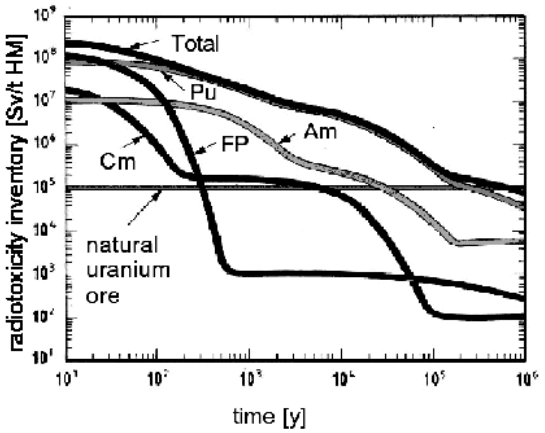

Fig. 3 Radiotoxicity reduction of spent fuel from LWRs by natural decay in geological repository.

proliferation this issue has become a global problem for safe and secure storage.

This spent fuel, when reprocessed, has four main groups of its contents- (i) Uranium, which can be recovered and disposed of or recycled, (ii) Plutonium (Pu) is also recoverable and may be consumed by fission in reactors- with thermal and fast neutron spectrum; (iii) minor actinides (Np, Am and Cm), and (iv) fission products (FP)- both with short and a few of them, with long half lives. Figure 3 shows the effects of natural decay process on (ingestion) radiotoxicity of above-mentioned content of spent fuel. In order to reach radiotoxicity level of natural uranium ore, from where its all started, most fission products would decay in less than 1000 years.

Plutonium can be eliminated by complete fission in thermal and fast reactors. If the minor actinides can also be eliminated by fission, the problem of nuclear waste elimination would then, in principle at least, become resolvable by eliminating most of the radiotoxically offending long-lived contents of spent fuel from uranium-fed reactors.

A pre-requisite for such reductions in overall nuclear waste radiotoxicity shown in this figure is a nearly complete fission of the minor actinides, for which multi-recycling in reactors is necessary.

There are two possibilities for eliminating of plutonium and minor actinides like this by their multiple recycling in conventional critical reactors and/or dedicated ADS. This in conventional reactors becomes difficult, if not impossible, due to the neutronic characteristics of minor actinides in the reactor environment; e.g.:

(i) Minor actinides (MA) mixture from LWR spent fuel are neutronic poisons (parasitic neutron absorers) in thermal spectrum reactors and can be fissioned completely only in the neutron spectrum of fast reactors

(ii) Fuels containing only plutonium and minor actinides without a fertile species (^{238}U or ^{232}Th) have very low delayed neutron fractions (Table 2) and Doppler coefficients in fast neutron spectrum. Higher delayed neutron fractions in fuel provide benevolent and error-forgiving margins in critical reactor operations in case of sudden rise of fission rates in the core and thus, add to its inherent safety.

The above are non-trivial issues, and there is general agreement among the nuclear programme planners that application of sub-critical reactors is the safest and most design-error forgiving way to incinerate LWR spent fuel waste of Pu & MA. This is the basic reason why countries with sizable nuclear power generation (e.g. France, Germany & Europe, USA, Russia and Japan etc.) and having massive spent fuel inventories, are in the forefront of developing ADS technologies.

Development of sub-systems for ADS

The difficult technological aspects of realizing ADS today are the availability of 1-GeV proton beam accelerator and its corresponding spallation target. The requirement of 1-GeV proton energy is dictated by the energetic efficiency for optimum number of spallation neutrons per unit proton beam power. As shown in Fig. 4, it (upper curve) saturates in the proton energy range of 1-1.2 GeV. In technological perspective, 1-GeV proton accelerator to drive a sub-critical reactor would require at least an order higher performance in beam intensity than the best existing proton accelerators in the world.

TABLE 2. Ratio of yield of delayed neutrons to the total fission neutron per fission of Pu and MA isotopes in fast reactor. These values of Y_d/Y_{total} for Np, Am and Cm are abut half for conventional fast reactor and one sixth of that in LWR.

Isotope	Y_d/Y_{total}
^{238}U	0.0151
^{232}Th	0.0209
^{235}U	0.00673
^{239}Pu	0.00187
^{241}Pu	0.00462
^{242}Pu	0.00573
^{237}Np	0.00334
^{241}Am	0.00114
^{243}Am	0.00198
^{242}Cm	0.00033

The other equally difficult technological aspects include -absorbing the intense power of proton beam in spallation target with efficient heat dissipation and maintaining an isolation barrier between ultra-high vacuum of accelerator channel and the coolant vapour environment. This barrier, called beam window, will undergo neutron and charged particle (proton) beam irradiation up to estimated ~100 displacements per atom (DPA) per year along with deleterious effects of corrosion and erosion in molten liquid metal (lead or LBE). This neutronics irradiation renders beam window material as brittle and unsafe for operation within a short time.

ADS in Indian Context

Above features and technical aspects of ADS were subject of study by an ADS coordination

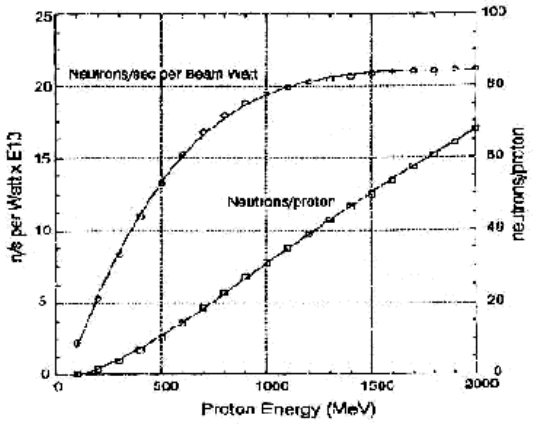

Fig. 4 Energetic cost, i.e. neutrons per sec per watt of beam, of spallation neutrons for various energy of proton beam striking lead target (upper curve) .It reaches a plateau around 1-1.2 GeV. However, neutrons produced per proton keep on increasing with proton energy (lower curve).

committee in BARC during 1999-2001 period. Results of these studies highlighted the beneficial aspects of ADS with respect to thorium utilization schemes under the three-stage nuclear power programme that ultimately relies on efficient utilization of indigenous thorium fuel reserves. Development of ADS sub-systems to meet requirement of breeder reactor configuration appears highly desirable, although in long-term perspective, the one to transmute nuclear waste would be equally relevant. For these reasons, Department of Atomic Energy (DAE) has evolved a roadmap on development of relevant ADS technologies with definitions of certain priority areas in proton accelerator and molten lead-bismuth eutectic systems.

The activities planned in BARC on development of ADS sub-systems have been initiated as X five-year (2002-07) plan projects. The deliverables envisaged on completion of this phase of developments, are as following:

- Construction and commissioning of a high current proton linac up to 10-MeV energy and consisting of Ion source, RFQ and DTL acceleration sections.
- Studies in high-energy particle reactions and transport code, and benchmarking of calculational tools for target design.
- Thermal hydraulics studies and code development for lead and lead-bismuth eutectic (LBE) liquid system in a LBE process system loop with diagnostics for code validation, material tests and experience of process system.

Summary

Neutronic superiority and inherent safety in sub-critical reactor operation are the major attractive features of ADS. These can be utilized in the transmutation of long-lived actinides and fission products from the spent fuel as well as in establishing self-sustained fuel cycle to utilize thorium reserves for nuclear power generation. Most advanced countries favour developing individual ADS sub-systems to integrate them into a nuclear waste incinerator for the elimination of transuranic elements and long-lived fission products in the spent fuel from uranium-fueled reactors that has accumulated over past half-a century.

However, developing a realistic ADS presents many technological challenges in all its three sub-systems. Therefore, development of these multi-disciplinary sub-systems of accelerator driven sub-critical reactor has been taken up as a national programme in India. Realizing various technological challenges that need to be adequately addressed to, a stage-wise approach has been adopted and R&D on a few identified aspects have been initiated by the DAE.

Portable Accelerators

Dr. R.P. Anand *has joined BARC in 1967 after passing out from the physics stream of 10th batch of Training School. He has been mainly working in the field of neutron induced reactions like capture, n.2n and fission. At present he is heading the Neutron Generator Section of High Pressure Physics Division. He has been involved in the up gradation of a 14 MeV, T(d,n) neutron generator which produces 14-MeV neutrons with a yield of ~10^9 to10^{10}n/s using T(d,n) reaction using a 400 keV accelerator at Purnima Labs, BARC. This generator is planned to be used as an external neutron source to drive a Nat-U + Light water Purnima Sub-critical Assembly for the experimental study of the physics and neutronic characteristics of sub-critical systems. He has also been involved in the theoretical studies using 3-dimentional Monte Carlo methods using latest MCNP codes employing various cross section data libraries for studying the neutronics of critical, sub-critical reactor systems and fusion reactor blankets. The Monte Carlo method was used to simulate the neutron flux, neutron spectra, neutron multiplication and dynamic behavior using pulsed neutron source and reaction rates for various threshold detectors for the case of the Purnima sub-critical assembly.*

Introduction

The use of compact accelerators has grown dramatically in the last few years for a variety of applications in security and industrial fields. Most of the important applications require the Production of fast neutrons with the help of compact accelerators. The important applications include detection of small quantities of fissile materials, detection of clandestine explosive materials and drugs. They are also found very useful in mobile neutron radiography, applied material science and in many other fields. There are several types of compact devises which can be used for the production of neutrons depending on the neutron yield required for a particular application. The important types of compact accelerator based neutron sources are given below.

Gas Discharge Based Devices

There is considerable demand in the scientific community for a neutron source with an output greater than 10^6 n/s that can be switched on and off, emits fusion neutrons, portable and not very expensive at the same time. Though D-D and D-T neutron tube sources with solid targets (both vacuum and gas filled) are available commercially, they are expensive, both in capital cost and operating cost and have limited short life. The inertial electrostatic confinement (IEC) devices made in the nineties have potentially provided an alternative portable neutron source for various applications. Farnsworth, an inventor who developed the technology behind early television, carried out much of the early work in this field. In this method, the fusion core is contained by an electric field unlike in the traditional magnetic confinement fusion.

In inertial electrostatic confinement fusion, the deuterium gas is ionized and an electric field is used to accelerate individual ions to the energy at which they would fuse. This is more efficient than heating an entire volume of gas and is best achieved in a spherical device. The build-up of positive ions near the Centre would attract negative electrons. Farnsworth reasoned that the radial focussing of electron currents would produce a space charge potential well in the hollow anode cavity. This well was confining and concentrating ions, which were produced from residual gas. Robert Hirsch developed a theory to explain the inertial

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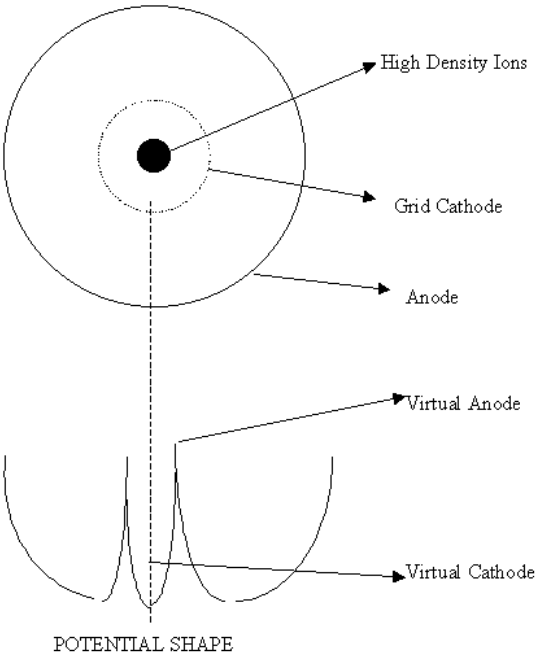

Fig. 1 Principle of inertial electrostatic confinement fusion-formation of virtual anode and cathode.

electrostatic confinement of ionized gases in spherical geometry. His solution of the Poisson equation for bipolar currents indicated spatially periodic solutions, which represent alternate formations of virtual anodes and cathodes. At the Centre of the spherical cavity, there exists a high-density energy region, which can be of interest for controlled fusion reactions. Farnsworth's machine used ion-guns to fire beams of nuclei inside a spherical cavity. Later Hirsch replaced this arrangement with a simpler spherical grid system made of wire 1 mm thick in which the ions were generated by glow discharge. More than two decades later, Miley and others developed this technique further and put IEC on more solid foundation, both experimentally and theoretically. The principle of IEC involves the confinement of fusion plasma inside one or more potential wells that are created at the Centre of a hollow spherical cathode as shown in Fig. 1. A self-sustaining plasma discharge generates deuterium ions throughout the spherical volume. The semi-transparent cathode will attract ions, generating a spherical ion "beam" which flows

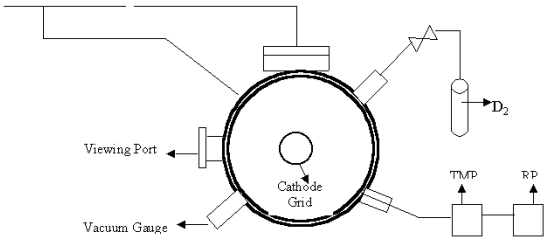

Fig. 2 Schematic view of a spherical IEC device.

radialy into the cathode. The grid wires generating secondary electrons will intercept some ions. These electrons will scatter out into the cathode and will be trapped and attracted to the accumulated space charge (virtual anode) at the Centre. They can thus create a virtual cathode - which is fully transparent and would not cause ion-losses. Ions trapped inside this well would oscillate back and forth until they fuse (producing neutrons) or get scattered out of the well. The location of virtual anode and virtual cathode inside the grid space is also shown in Fig.1.

Spherical Experimental Devices

The experimental set up of an IEC device by Masami Ohnishi et al is shown in Fig. 2. A stainless steel sphere of inner diameter 350-mm is the vacuum chamber. It has many ports for high voltage feed, vacuum gauge, vacuum pump, gas feed, observation window etc. Vacuum pump system consists of a 160 l/s turbo-molecular pump with a back up rotary pump. The Deuterium gas is fed from a gas cylinder through a mass flow controller. The hollow cathode supported by the high voltage feedthrough is of 57-mm diameter and is made of 1-mm dia. tantalum wire with a geometrical transparency of 91 %. The high voltage feed-through has its insulation specially shaped to suppress any possible breakdown between the conductor rod and insulator surface through very fine pinholes created due to the energetic ion bombardment and also to reduce the field distortion inside the chamber. The system is evacuated to a vacuum of 4×10^{-5} Pa initially. Then the deuterium gas is filled up to the required pressure using the gas mass flow controller. With this device a steady state neutron yield of 1.46×10^6 n/s was obtained with V = 32 kV and I_{dis} = 30 ma, gas pressure being in the range 1- 2 Pa. The maximum yield reported is 10^7 n/s. It was observed that the neutron output varied as

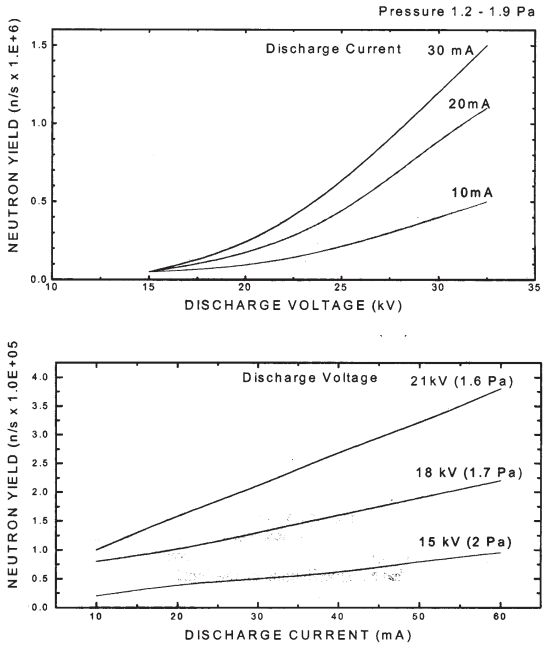

Fig. 3&4Dependance of Neutron Yield on Discharge Voltage

$V^{3/2}$. The design of the spherical grid plays an important role in the fusion output. Though initially it was thought that a tightly wound grid with smaller gaps between wires was needed, it was found that a design like the latitudes and longitudes on a globe with larger holes performed better. The neutron output from existing low current (<50 ma) IEC devices scales linearly with current during steady state operation. The neutron output scaling with voltage closely follows the fusion cross-section as a function of energy. The remaining factors determined to affect the neutron production rate are the grid transparency, grid radius and IEC chamber radius. The neutron output can be written as : $N\ (n/s) = 3.2 \times 10^6\, i\sigma\tau^2\, [\mathrm{sech}\, c_1(\tau - c_2)]\, r_{chamber}/r_{grid}$ Where i = Current, σ = Fusion cross-section, τ = Grid transparency and c_1 & c_2 are constants. The optimum grid transparency was found to be 0.86. The ion-density is found to be inversely proportional to the square of the grid radius. This results in the fusion rate in the plasma being inversely proportional to the grid radius.

Star Mode Operation

Experimental studies have shown that the fusion neutron production is increased when the IEC is operated in a regime known as the star mode. This mode is characterized by beams of light (due to intense ionization) emanating from the center of the chamber and passing through the holes of the grid. The advantage of the star mode is that the ion bombardment of the grid is significantly reduced. Based on the experimental studies, the optimum grid radius for maximum fusion rate was found to be 1 cm. However this is difficult to realize in practice. The grid should be designed to be as spherical as possible with sufficient number of holes for microchannels, giving a transparency of about 0.86 which means that thicker wires will form a larger grid than thinner wires. The grid wire surface should also have enough surface area to dissipate the heat generated. In general, $r_{grid}/r_{chamber}$ shall be between 0.1 and 0.2. This ensures that it is large enough to dissipate the heat.

Pulsed Operation

Studies of neutron yield scaling above 25-mA input current have been prevented by a combination of current limitations of the available high voltage power supplies and by cathode grid overheating. Because of these limitations, a simple pulsed experiment was designed to test the neutron yield v/s current at high pulse currents. These experiments showed I^2 scaling during pulsed operation. Based on these results, it appears that IEC could be operated with 3 A, 100 kV repetitive pulses with 10 % duty factor to produce neutron yields of 10^{10} n/s. The formation of a double potential well, which traps the ions, was confirmed in these experiments.

C-Device

This device also operates on the principle of IECF, differing from the spherical device only in its shape. It is a cylindrical glass vessel 61 cms long and 10 cms dia. and has two dish like spherical SS anode reflectors at the two ends as shown in Fig. 5. The cathode is an SS tube 9 cms dia. and 10 cms long and is fed negatively biased HV power by a feed-through at the midpoint of a chamber wall. Anode reflectors are electrically grounded. C-device is initially pumped to 1.33×10^{-5} Pa using a turbovacuum pump.

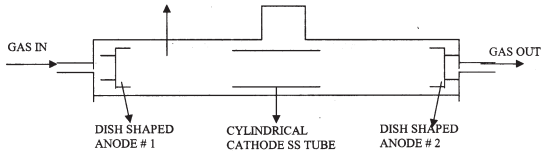

Fig. 5 Schematic diagram of a C-device.

The chamber is then filled with deuterium gas to 1.33 X 10^{-2} Pa. The high negative voltage is then applied to the cathode tube. The HV causes gas breakdown separating electrons from neutral atoms, which are accelerated by the HV bias in opposite directions. Electrons are accelerated towards the anode, producing additional electron pairs. Ions are accelerated towards the cathode, reaching maximum speed at cathode tube entrance and maintain this speed as they travel through the tube. After exiting the cathode tube, the ions are decelerated and eventually come to a stop before reaching the anode dishes. Immediately following the full stop, they are accelerated back again towards the cathode tube. Thus they oscillate back and forth along the electrostatic field lines many times until they fuse. During oscillation, once the ions reach sufficiently high speed, they collide and fuse with background atoms or with other oscillating ions, producing neutrons. Most neutrons are produced inside the cathode volume due to exponential increase in fusion cross section for high-speed ions. Dish anodes reflect ions to the cathode structure. They provide good confinement of oscillating ions by guiding them to the tube. Cathode electrode is cylindrical in shape and 100% transparent to the oscillating ions, allowing high ion re-circulation. Based on the experiments mentioned above, sealed C-devices have been made giving a neutron source strength of 10^6 n/s (60kV, 20 ma) which can operate for a few thousand hours of operation before it needs refilling of gas. The IEC device has also been operated in the pulse mode, giving a neutron output as high as 10^{10} n/s.

Commercially Available Accelerator based Mobile Neutron Sources

The accelerator based GENIE family of mobile neutron sources developed by SODERN in France, covers neutron tubes having a yield of 10^6 to $5x10^{11}$n/s in 4π steradians. All these sources make use of sealed tubes filled with deuterium and/or tritium. They have a lifetime of several hundred hours and are transportable. They can be operated either in a continuous or in a pulsed mode (pulses of duration 10 μs with a frequency of 20 kHz).

In an ultra high vacuum tube, deuterium ions are produced and accelerated up to 100-200 keV, in order to hit a target containing deuterium/tritium atoms thus producing 2.5 or 14.1-MeV neutrons through D (d, n) or T (d, n) reactions respectively

Ion Source

The penning type ion source is used which enables low-pressure operation with a high rate of ionization due to the presence of a permanent magnetic field in the tube. Applying high voltage of –125/-250 kV to the target accelerates the beam of extracted ions.

GENIE Type Sealed Neutron Tubes

This type of neutron generating tube has been developed for industrial requirements in activation analysis, irradiation and image processing. It is a mobile computer controlled sealed tube having a typical emission of 10^8 n/s to 10^{11} n/s in a continuous or pulsed mode and has high emission stability. They have a long lifetime of few hundred to one thousand hours and have high emission stability. The full system includes the following equipment:

(i). MEN 46 neutron emission module
(ii). VHV Generator and power supply
(iii). Low voltage power supply cabinet
(iv). Coolers
(v). Control rack
(vi). Connecting cables

Neutron Emission Module (MEN 46): It includes a neutron tube TN 46 and a power supply for the ion source protected by a sealed metallic housing. High voltage of –225 kV is applied to the tritium target to obtain a single gap acceleration of the ion beam. The activity resulting from the tritium contained in the ion source reservoir and the target is approximately 75 Curies (2.8 x 10^{12} Bq). An electronic gas pressure control device in the tube and a self replenishing of the target with impinging deuterium and tritium ions enable a stable neutron

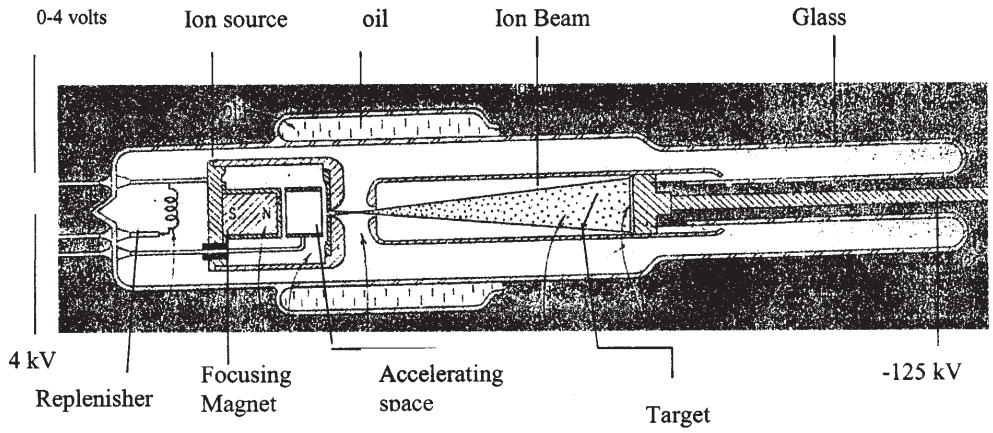

Fig. 6 A Typical Sealed Neutron Tube.

emission throughout the life of the tube which is a few hundred hours. The ion source and target are cooled by closed loop circulating oil and water respectively. The electrical insulation is provided by oil impregnation and potting.

The MEN 46 tube has a diameter of 25 cm and a length of 91 cm and it weighs 75 kg and the total weight of the full system including all power supplies, oil and water coolers and control rack is about 400 kg. Fig.3 shows the inside configuration of a typical sealed neutron tube.

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NUCLEUS

There's No Rebottling the Nuclear Genie

Sixty years after Hiroshima and Nagasaki, the specter of atomic power hovers over us.

Nukes haunt our past, they loom large in our present, and they are destined to loom even larger in our future—fueling our industries, as well as our fears.

Two different Nobel Prizes just announced bespeak this nuclear omnipresence. Last week the Nobel Peace Prize went to Mohamed ElBaradei, director general of the International Atomic Energy Agency. ElBaradei, of course, became famous three years ago when he disputed the Bush administration's claims about Iraqi weapons of mass destruction. No doubt anti-Americanism helped inspire the Nobel Committee to bestow the prize on him. But the committee also stipulated that the prize was going to the IAEA as an institution. And that's an endorsement for the agency's official mandate: "to promote safe, secure and peaceful nuclear technologies."

And on Monday the Nobel Prize in economics went to Thomas Schelling and Robert Aumann, both of whom advanced "game theory"—a math-based approach to clarifying the choices that individuals and countries face—and applied it to a variety of situations, most notably the use or nonuse of nuclear weapons.

Many people yearn, to be sure, for the abolition of the atomic bomb, but harder heads agree that the best we can hope for is a logical system of nuclear controls.

As for nuclear weapons, the logic is increasingly pretzelizing—and proliferating. The U.S. seems destined to fail in its effort to peacefully persuade North Korea and Iran from moving ahead with their robust nuclear programs. Other countries, too, are thought to be developing covert programs. From their point of view, why shouldn't they? The only reason Pakistan, for example, gets any respect around the world is because of its huge atomic arsenal.

But in addition to military power, four other factors are combining to push the planet in a more nuclear direction as an alternative to continued dependence on fossil fuels. First and most obvious is the concern over record-high oil prices, which infuriates rich countries and further impoverishes poor countries. Second, nations worry about their strategic vulnerability, because so much oil flows through the war-wracked Persian Gulf. Third, many countries fear pumping additional money into, say, Saudi Arabia, so that the sheiks can pump additional money into Islamic radicalism. And fourth, there's the widespread sentiment that global warming is linked to increased carbon dioxide emissions.

That's why nuclear power is on the verge of a big comeback. China is planning for 60 new nuclear plants. Last month in New York City Secretary of State Condoleezza Rice called for accelerating the use of nuclear power. In one of the few instances in which an American official has had anything nice to say about France, she noted the French get 80 percent of their electricity from nukes—the figure for the U.S. is a paltry 20 percent.

Moreover, just Tuesday, Prime Minister Tony Blair urged his fellow Britons to keep "an open mind" about nuclear power. Blair has become increasingly skeptical about the political feasibility of limits on CO_2 emissions, as mandated by the Kyoto Treaty, which expires in 2012. So nukes offer him a "third way" between unworkable caps and unlimited CO_2 output.

Still, the close connection between nuclear power and nuclear weapons is a linkage that's yet to be broken. For now, nuclear energy is the genie whose magic can be used either to create or to destroy. Just as Arab fables are full of the paradoxical consequences of being granted one's wish—for example, the wisher gets eternal life but not eternal youth - so nukes seem destined to be both promising and problematic.

The genie is out of the bottle. So even as some of the world's finest minds are being rewarded for their efforts to harness it for good, other fine but fearsome minds are eager to unleash it for pure lethal evil.

(Source: Newsday October 13, 2005)