Accelerators – Achievements and future projections*

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Charged particle accelerators are being used not only for basic research but also for various applications. Accelerator activity started in India almost four decades back and we have now the capability and expertise to design, build and operate many types of accelerators which are required. International collaboration has been pursued in programmes involving large accelerators. In the present article, a brief description of the Indian Accelerator Programme, its achievements and future projections, is given.

CHARGED-particle accelerators are being increasingly used, both directly and indirectly, for research in many frontier areas of science. They are also indispensable for varied applications ranging from materials science to medicine and, more recently, even for radioactive-waste transmutation.

As India has achieved, over the years, the distinction of being able to design, build and operate many types of accelerators which are required, it is timely to take stock of the Indian Accelerator Programme. Just as the design and construction of a reactor involves competence in several areas and integration of several subsystems, so does the design and construction of an advanced accelerator, and the units of the Department of Atomic Energy (DAE) are uniquely equipped to undertake this task. Further, with increasing interest in indigenous accelerators, both for research and for applications, and possibilities of increased participation in international projects, both in construction and for research, it is useful to review our achievements and attempt to define future possibilities in this area. It is inevitable that this paper emphasizes the work done in the DAE – considering the affiliation of the authors – but we have tried to include, to the best of our knowledge, the contributions to this field from the university system.

Historical development up to the eighties

The work related to various types of accelerators began in India in the forties and the fifties, though in a modest way. In the sixties India had a reasonably large size accelerator in the form of the 5.5 MV Van de Graaff accelerator at the Bhabha Atomic Research Centre (BARC), purchased from High Voltage Engineering Corporation, USA. The accelerator-building activity took a quantum jump with the indigenous development and commissioning of an 88 in. variable energy cyclotron at Calcutta (VECC) in the seventies (see Box 1). Around the same time a 2 MV tandem Van de Graaff accelerator was made operational fully through indigenous efforts at Trombay. In the eighties, to catch up with the ongoing research in the important area of heavy ions, we embarked on a medium-energy heavy-ion facility in Bombay (see Box 2). Though the 14 MV pelletron, the first of its kind in India, was imported from National Electrostatics Corporation (NEC), USA, several subsystems such as the 25 m high, 5.5 m wide accelerator tank to contain the SF_6 gas at high pressures, the four storage tanks for SF_6 gas, the beam lines and the experimental facilities were all fabricated and set up indigenously. This joint BARC–TIFR facility located at the Tata Institute of Fundamental Research (TIFR) campus has now been operating for more than five years and in this period with the use of this facility considerable research work has been carried out in the field of heavy-ion nuclear reactions and in interdisciplinary areas.

Growth in the nineties

In the year 1990, the second pelletron, a 16 MV NEC machine was made operational in Delhi at the Nuclear Science Centre (NSC) of the University Grants Commission (see Box 3). To augment the scope of accelerators for areas other than nuclear physics, a 3 MV NEC pelletron was commissioned in the Institute of Physics, Bhubaneswar, in 1991. Work has already started in converting the 5.5 MV Van de Graaff accelerator at BARC into a folded 7 MV tandem accelerator. The Centre for Advanced Technology (CAT) at Indore (see Box 4) was started a few years back for development of technologies associated with accelerators, lasers and related systems. The first Indian synchrotron radiation source, based on a 450 MeV electron storage ring, Indus-1 (see Figure B4), is already at an advanced stage of construction at CAT. This facility when completed will consist of a 20 MV microtron, followed by a 700 MeV synchrotron and the storage ring. This storage ring will

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provide soft X-ray and vacuum ultraviolet radiation over a wide spectrum. In the next phase, a 2 GeV storage ring Indus-2 (see Figure B4) to deliver harder X-rays through dipole magnets and wigglers will be built.

Other developments related to the accelerators described above include the work started for the building of superconducting LINAC boosters to enhance the heavy-ion energies from the present pelletrons. At VECC, a versatile electron cyclotron resonance (ECR) ion source has been built and will soon be used as an injector to the present cyclotron to deliver high-energy heavy-ions for experiments from this facility. Plans are also under way to build a superconducting cyclotron at Calcutta. At BARC, work is going on in completing an REQ accelerator which, in principle, can also serve as an injector for a bigger accelerator. There are also plans to build low-energy electron accelerators primarily for medical and industrial applications both in CAT and in BARC. CAT is also building a 20 MeV proton Linac which will consist of a 750 keV RFQ operating at 202 MHz and a drift tube Linac also operating at 202 MHz.

Box 1. Variable Energy Cyclotron Centre, Calcutta

The cyclotron at Calcutta became operational in the late seventies and has been delivering beams of alpha particles for not only nuclear physics investigations but also for other areas of science. Recently, both protons and deuterons of different energies have become available to the user community. Beams of high resolution (about 70 keV) are available for research. In the near future it is expected to reach a value of 10–15 keV. When the ECR ion source is coupled to the present machine, a large variety of medium- to high-energy heavy-ions will be available from VECC. A recently completed experiment utilizing 15–20 MeV/A alpha particles interacting with aluminium has given interesting answers to the production mechanism of fragments heavier than the projectile. From systematic studies of break-up of ^6Li using alpha particles from VECC, important results of relevance to astrophysics have been obtained (Figure B1). Another area of research is the study of properties of nuclei far from the line of beta stability, an emerging area of great potential. For this purpose, an isotope separator on-line (ISOL) facility has been developed.

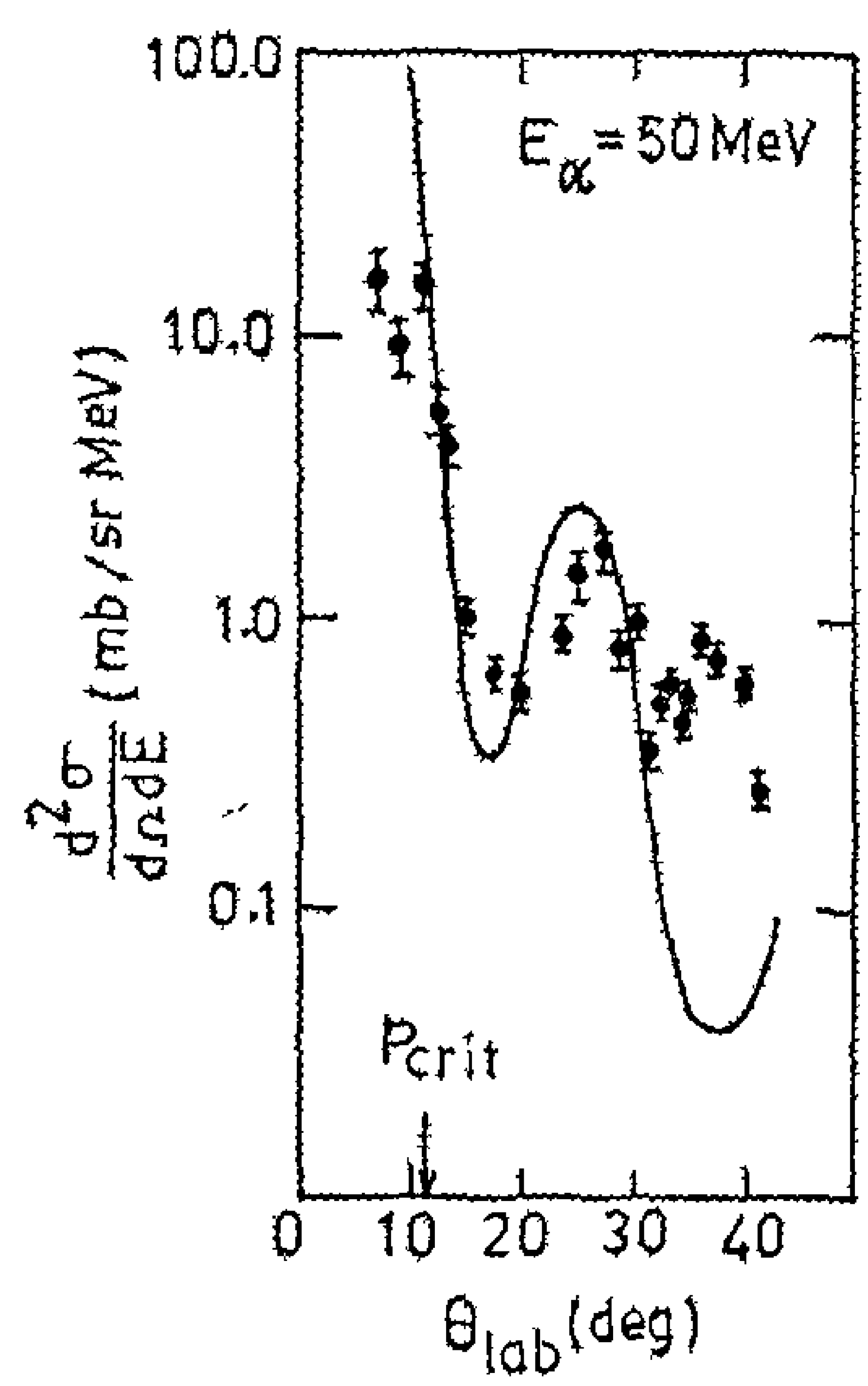

Figure B1. Alpha particle-induced, $^6Li \rightarrow \alpha + d$, target breakup reaction at VECC, Calcutta. The finding of a critical momentum transfer – $p_{crit} = 117$ MeV/C – which signifies the dominance of the Coulomb breakup, is important in the context of nuclear astrophysics.

Box 2. Pelletron in Bombay

The commissioning of the medium-energy heavy-ion accelerator facility, 14 MV pelletron, in Bombay six years ago has enabled the nuclear physicists in this country for the first time to explore the nucleus in many previously inaccessible regions of excitation, spins and configurations. In order to carry out research in several possible frontier areas, a number of facilities have been set up which include: (a) A general-purpose 1 m diameter scattering chamber of capacity 500 l, (b) Large-area position-sensitive ionization chamber, (c) Array of NaI, BGO, Phoswich and HpGe detectors, (d) Fast electronics and PC/transputer-based data acquisition systems.

Amongst the many interesting results which have come out of this facility, the notable ones are establishing the fission time scales through the use of 'neutron clock' and the experimental verification of the preequilibrium fission mechanism by the BARC group from a series of fission fragment angular distribution measurements (Figure B2). From recent investigations related to quasimolecular resonances in light compound nuclei, it has been possible to establish superdeformed structures in shapes of nuclei with major to minor axis ratio between 2 and 3.

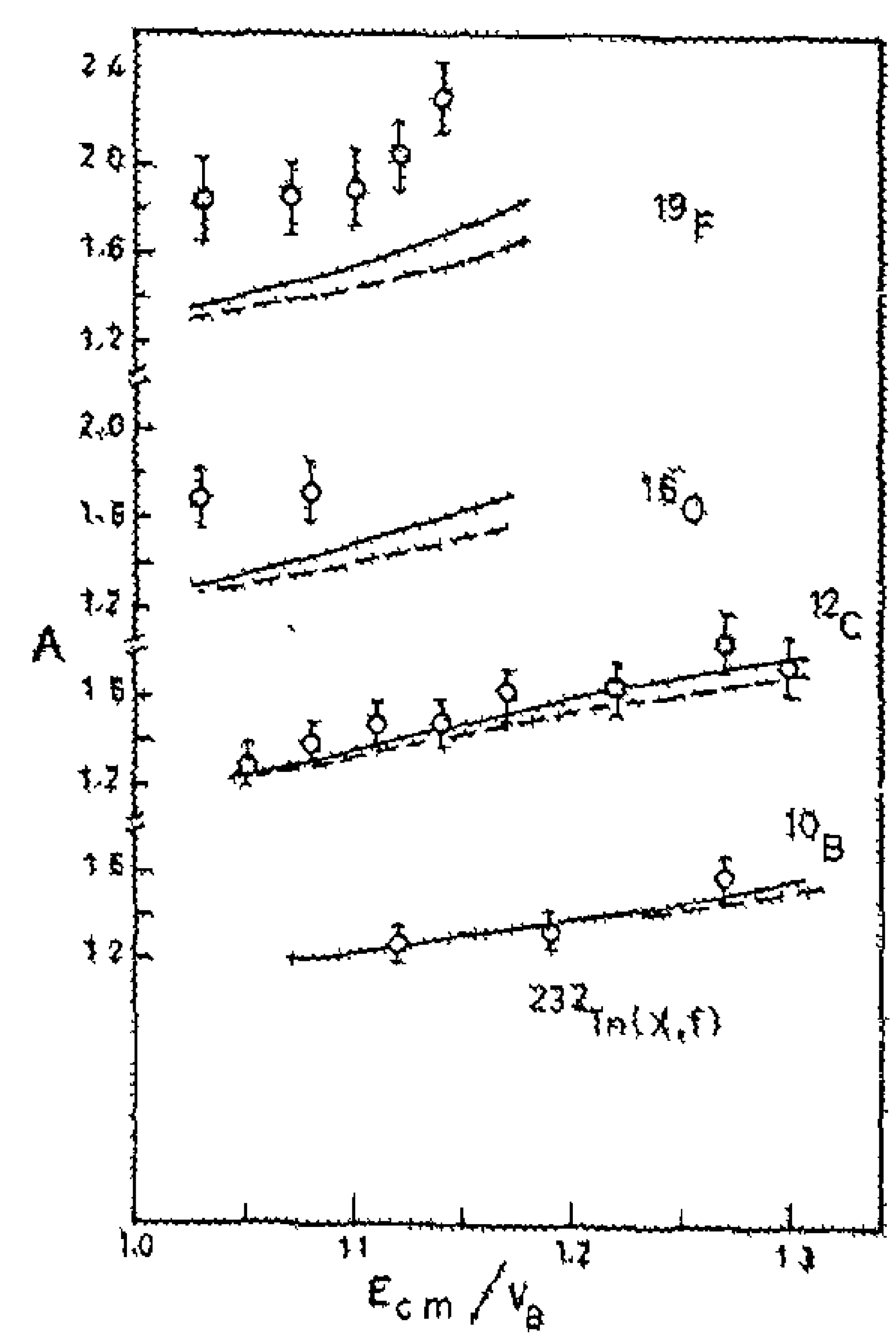

Figure B2. Fission-fragment anisotropies for ^{10}B, ^{12}C, ^{16}O and $^{19}F + ^{232}Th$ systems measured using the Bombay pelletron. While the systems ^{10}B and $^{12}C + ^{232}Th$ exhibit 'normal' anisotropies, the ^{16}O and $^{19}F + ^{232}Th$ systems exhibit 'anomalous' anisotropies. This observation is consistent with the expectations of pre-equilibrium fission model proposed by the Trombay group earlier.

Box 3. Pelletron in Delhi

A heavy-ion facility with a 16 MV terminal has been operational at NSC, Delhi, for the last few years. The NSC user family has members from more than 30 universities, 3 IITs, IISc, besides national labs like NPL, BARC, VECC, IOP, SINP and TIFR. Some of the major experimental facilities which are available in this centre are: (1) The heavy-ion recoil analyser (HIRA) for detection of slow-moving heavy recoils, with a mass resolution of better than 1/200. (2) Gamma detector array consisting of a set of HpGe detectors with anti-Compton shields for high-spin spectroscopy. Additional array of BGO detectors is provided for total energy measurement and it also serves as a multiplicity filter. (3) 1.5 m diameter scattering chamber. Using these facilities a number of experiments have been performed related to subbarrier fusion phenomena and high-spin spectroscopy (Figure B3).

To augment the energies available from these facilities, both at Bombay and Delhi, LINAC boosters based on superconducting technologies are being built. While the one at Bombay will be based on Pb, the one at NSC will be Nb-based. The NSC is collaborating with Argonne National Lab, USA, on this LINAC project.

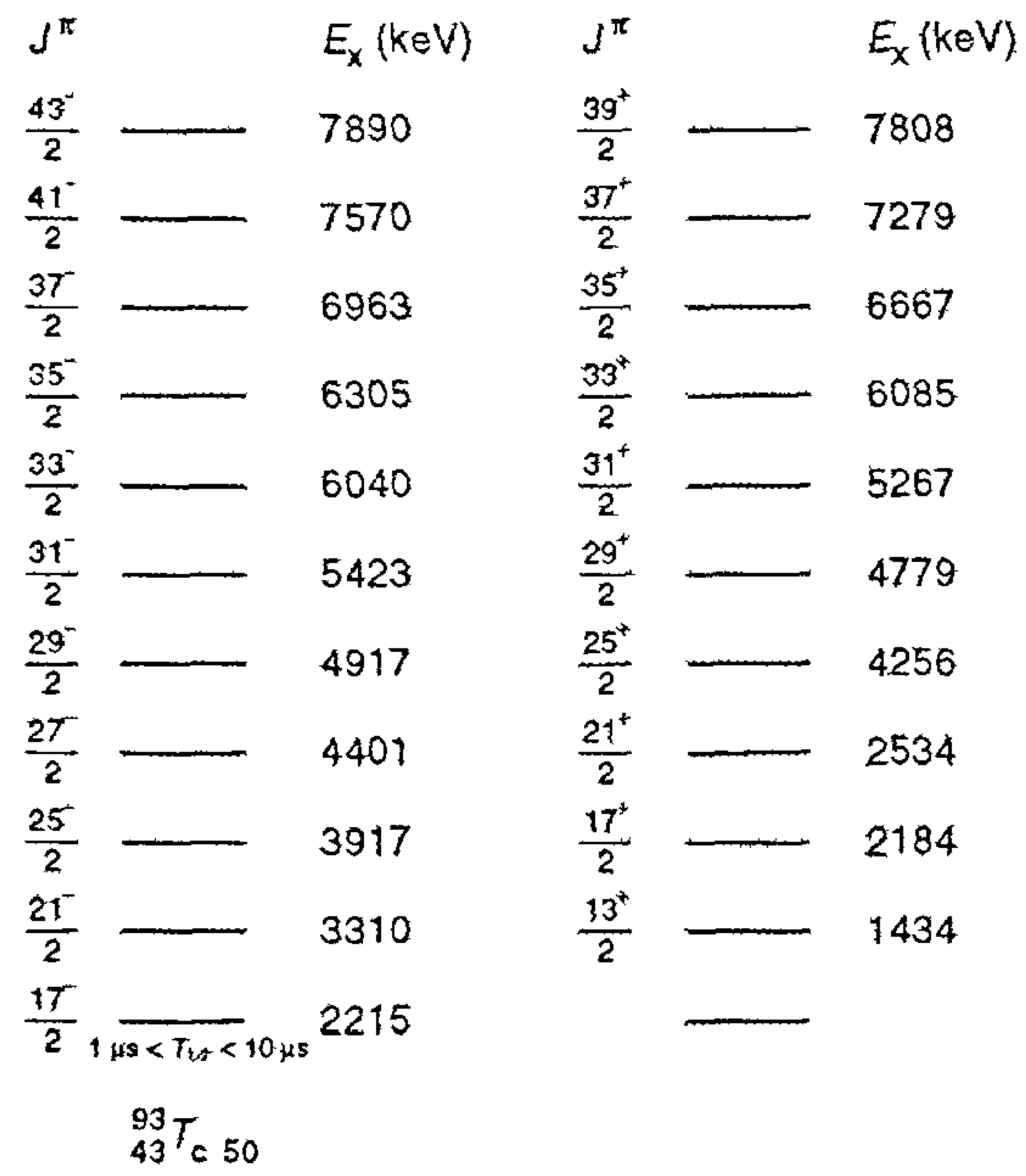

Figure B3. High spin states in ^{93}Tc. Level scheme for ^{93}Tc showing excitation energies and spins (parities), populated through ^{66}Zn (^{31}P, 2p2n) ^{93}Tc reaction at the Delhi pelletron accelerator facility.

A Centre for Compositional Characterization of Materials (CCCM) is being set up by BARC at Hyderabad and some of the analytical techniques used there will employ a 3 MV tandem accelerator. All these go to show that we have in this country several strong groups in the accelerator field and also the necessary infrastructure to design and build indigenously new generations of accelerators and related experimental facilities.

The various accelerator facilities in the country are collectively presented in what can be called the accelerator map of India (Figure 1).

International collaboration

It is very clear that no single country in the world can now afford to build and operate major accelerator facilities and related detector set-ups. International collaborations have become necessary. Our country has been collaborating with major international accelerator facilities in Europe and USA. Our contributions are both in the area of accelerator building and in the development of large-size detectors. The CAT is collaborating with CERN, Europe, both in LEP (large electron–positron collider) and PS (proton synchrotron)/SPS (super proton synchrotron) accelerator upgrades. Titanium sublimation pump bodies have been exported to CERN. It has also supplied other vacuum components and corrector magnets in substantial numbers. A group from BARC and VECC has developed the control software for accelerating Pb ions at SPS facility.

The high-energy physics group from TIFR has been actively collaborating with CERN for a number of years. For the L3 experiment, the TIFR group has supplied 1100 brass proportional chambers, SS housings, precision machined Cu–Te pieces and also a few thousand PCBs. The TIFR group has also contributed to the software and physics aspects of this joint programme, in particular the precision tests of the standard model of particle physics and a search for one of its cornerstones: the Higgs particle. Three major achievements of this experiment are: (1) the number of neutrino species has been established to be three; (2) precision measurement of the electroweak mixing angle; and (3) estimate of the top quark mass.

With the recent availability of relativistic heavy ions from CERN at SPS, the group from VECC has been collaborating with CERN on experiments related to the experimental search for the quark gluon plasma (QGP). The VECC group has built a photon multiplicity detector consisting of 55,000 pads of small plastic scintillators (20 mm × 20 mm) for efficiently detecting the photons as signals of QGP. The optical fibres are inserted diagonally in each pad to pick up the light signal. One successful run has already been completed with a sulphur beam of 200 GeV/nucleon energy using the CERN SPS. Recent analysis of the photon data has perhaps given the first hint of the QGP, entirely from the photon spectrum. Besides VECC, several scientists and students from Institute of Physics, Bhubaneswar, and Indian universities – Chandigarh, Jammu and Jaipur – are also collaborating in this international venture.

Recently, BARC has also entered into collaboration with USA on using the Brookhaven National Lab (BNL) relativistic heavy-ion collider facility (RHIC) in the Photon Electron New Ion Experiment (PHENIX) to

Box 4. Centre for Advanced Technology, Indore

A major centre for advanced technologies (CAT) – accelerator and laser related – has been set up at Indore by the DAE. Work on the first major accelerator facility consisting of a microtron, synchrotron and storage ring for production of high-energy electrons and associated synchrotron radiation is progressing very well at Indore. Major indigenous effort has gone into building this facility from design to fabrication (Figure B4). Sputter ion pumps of speeds 30, 70, 140 and 270 l/s have been developed at CAT for the accelerator and subsystems to achieve vacuum of the order of 10^{-10} mbar. All-metal Pirani and Penning gauges have also been developed to measure pressures from atmosphere to 10^{-9} mbar. Two vacuum furnaces for bulk degassing of SS components for accelerators have been developed at CAT. The furnace has a hot zone volume of 400 l which can attain a temperature of 700°C at 10^{-5} mbar

The electron beam from 20 MeV microtron injector has been recently extracted. The synchrotron is fully assembled and all components well-aligned All subsystems have been tested and this machine is expected to be operational in 1995. The transfer lines between the various machines have been assembled.

The electron beam from the synchrotron is being planned to be stored in Indus-1 in 1995. This will be a 450 MeV storage ring whose critical wavelength (defined as the median wavelength which divides the emitted synchrotron radiation energy into two equal parts) will be 61 Å. Useful flux can be obtained for wavelengths as short as 20 Å. The beam lines for the various experiments to be performed with Indus-1 are: (1) Photophysics (300–3000 Å), (2) Reflectivity measurements (40–1000 Å), (3) High-resolution spectroscopy, (4) Photoelectron spectroscopy, (5) L-edge spectroscopy, (6) EXAFS (100–1000 Å).

Indus-2 will have a critical wavelength of 4 Å from the bending magnets and a much lower wavelength of about 1 Å from the superconducting wiggler magnets. The major experimental programmes being planned for Indus-2 are: trace element analysis, lithography, small-angle scattering, diffraction, absorption-based spectroscopy, photoelectron spectroscopy and X-ray topography. The Indus-2 ring is expected to be commissioned in 1998.

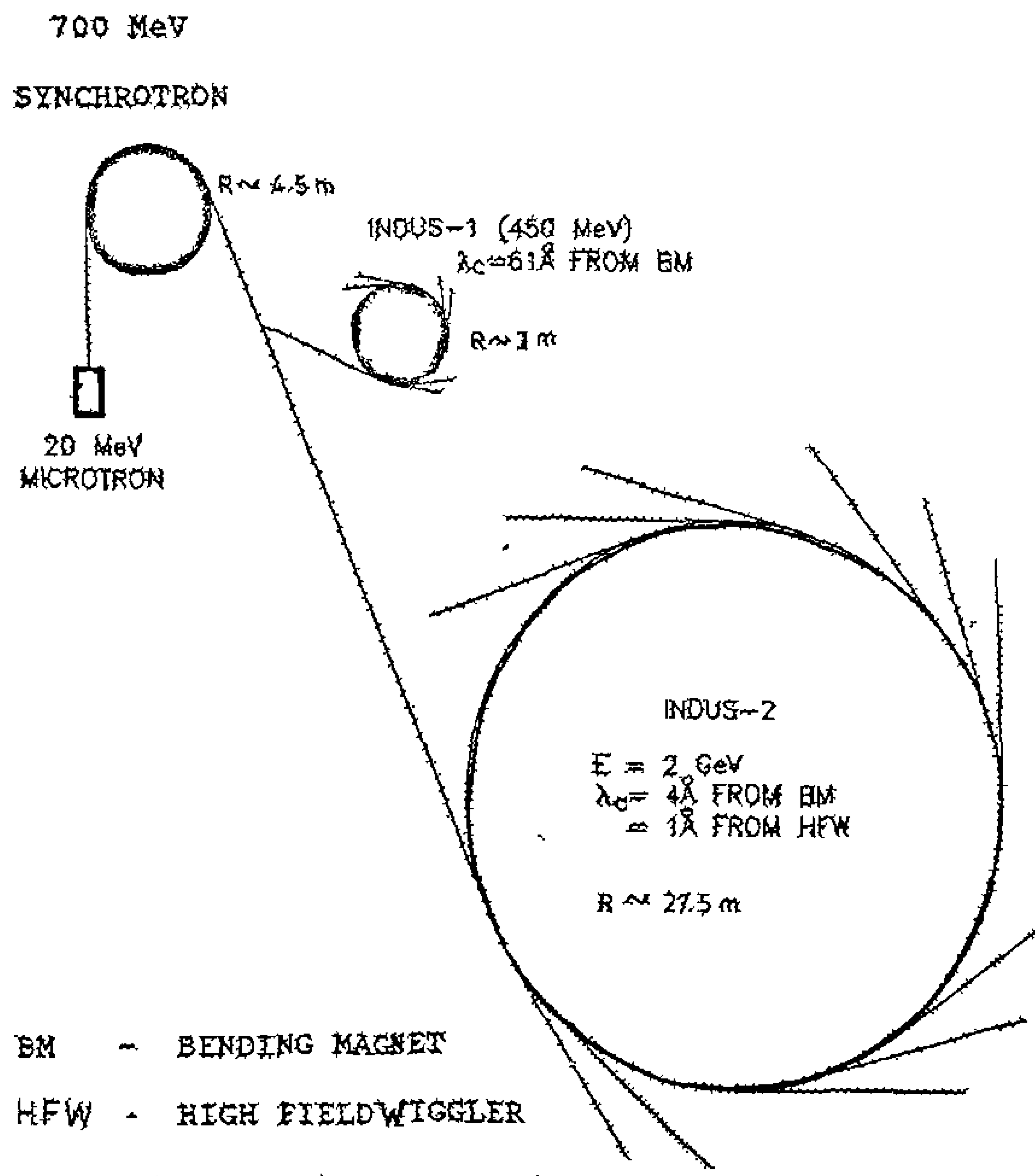

Figure B4. A schematic drawing of the synchrotron radiation source facility coming up at CAT, Indore.

search for the QGP. The BARC group will be involved in the design and the fabrication of the muon arm of PHENIX and also in the computer simulation related to this experiment.

The Indian scientists from TIFR and from Delhi and Chandigarh universities are also collaborating at the Fermi Lab, USA, on several frontier experiments and they are part of the teams which discovered recently the 'top quark'. In the future, India will also be collaborating in the currently planned highest-energy accelerator programme – the large hadron collider (LHC) – to be built in CERN.

Finally, the implication of all these laboratory experiments, in the context of the fundamental question of the origin of the universe a microsecond after the proposed 'big bang', when the universe must have consisted of quarks, gluons, leptons and photons, is in the postulation of the route to the synthesis of micro-cosmos and macrocosmos.

For several years, BARC has been collaborating with the Rutherford Appleton Laboratory in UK, which has a spallation neutron facility. The BARC group has built and installed a specialized neutron spectrometer in this centre – the so-called ΔT-window spectrometer – which uses the difference in temperature of two Be blocks to provide an ultrahigh energy resolution window for neutron inelastic scattering experiments.

Accelerator applications in industry and medicine

The charged-particle accelerators, primarily built for basic research in science, are being increasingly used for a variety of applications. Dedicated accelerators are also being built and operated for medical and industrial applications. The alpha particles from VECC have been used for characterization of (compound) semiconductors for oxygen. The helium-induced defects in refractory materials like Nb, Ta, W and V and in compound semiconductors like GaAs, GaP and InSb have been characterized. Information regarding migration of vacancies and the formation of vacancy clusters and helium bubbles has also been obtained from these studies. Some of these studies have direct implications for the mechanical and the metallurgical properties of refractory metals in a reactor environment. The helium jet recoil facility has been set up as a prelude to on-line isotope separation. Further, the alpha beams have been used for tribological investigations. Low-energy heavy-ion beams from Bhubaneswar have been used for materials science studies. Recently, using the proton backscattering tech-

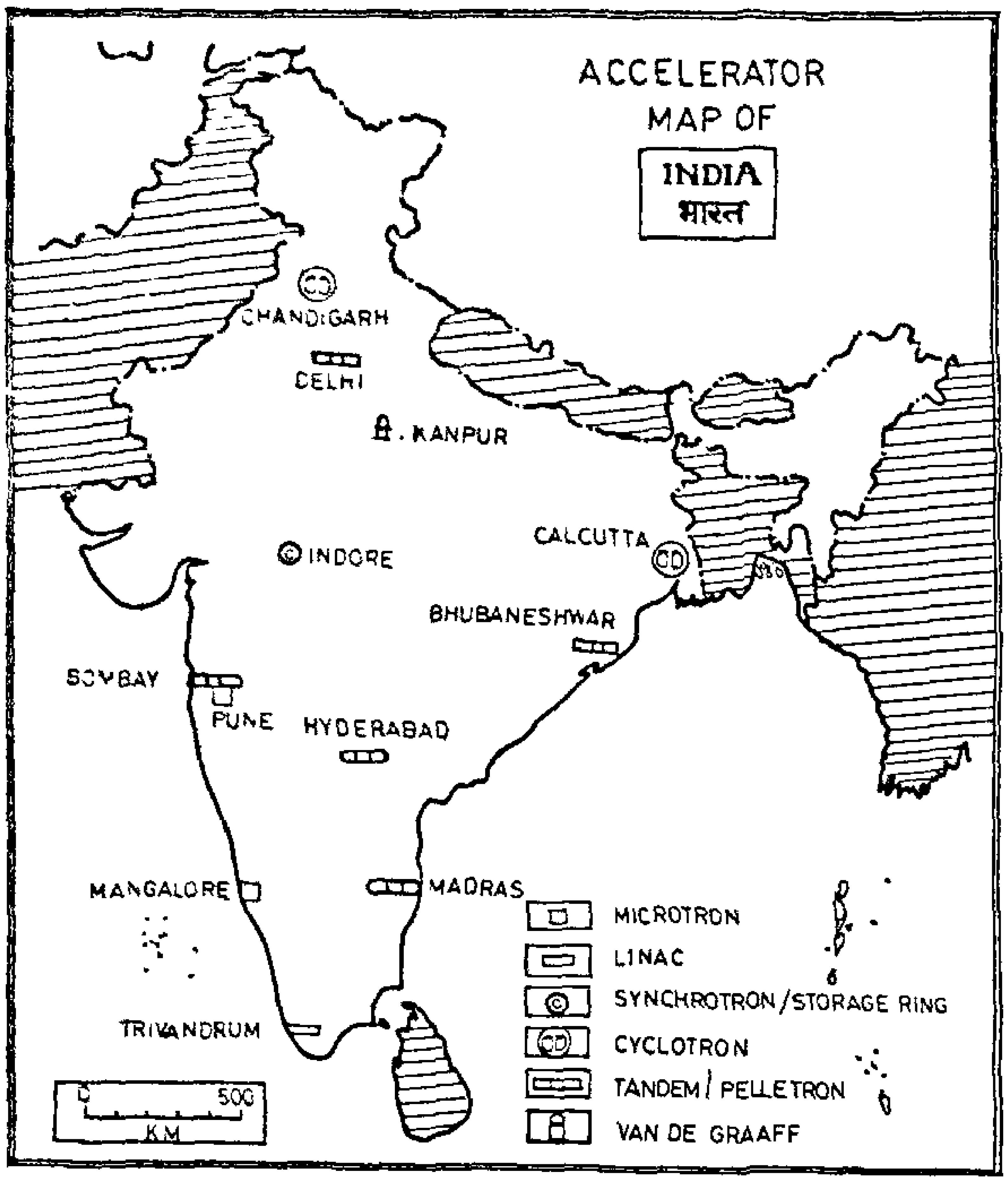

Figure 1. Accelerator map of India.

nique, the stoichiometry of thin VN films has been determined. Earlier, using the proton beam from Trombay Van de Graaff accelerator, the carbon build-up on the surface of a thorium target was estimated using the nuclear resonance technique. At the NSC, Delhi, a dedicated beam line has been developed for materials science studies, including high-energy heavy-ion irradiation to strengthen thin Cr films, characterization of superconducting films and bulk samples, and other ion-induced defects specifically involving high-energy heavy ions.

The use of particle accelerators in the study of problems in medicine and biology has been long recognized as a specific and powerful tool. The accelerators are being employed for both diagnosis and therapy. Certain specific radioisotopes like ^{67}Ga and ^{201}Tl required for accurate diagnosis of soft-tissue tumour and analysis of the functioning of the heart, respectively, can be produced only through nuclear reactions induced by charged particles from accelerators. Small quantities of ^{67}Ga are now routinely produced at VECC and used for diagnosis work in hospitals. Using the proton beam from VECC it is expected that the first batch of ^{201}Tl will be produced soon. A high-current captive cyclotron will be ideal to produce these isotopes at a reasonable cost. Trace element analysis of biological tissues, blood, etc., is another important area of investigation carried out using small-size accelerators.

The technique of radiation sterilization nowadays is used on a commercial scale in the manufacture of such products as disposable hypodermic syringes, blood transfusion kits, blood oxygenerators, Petri dishes, gloves, surgeon's needles and scalpels, besides some pharmaceutical products. Other areas include hygienization of sewage sludge and preservation of perishable food items. Electrons offer a substitute for gamma rays with the advantage of flexibility and inherent safety through on/off switching of the beam. A 10 MeV electron beam has been found to be suitable for this type of work. In India we are building a machine for this purpose. From economic considerations, a gamma ray source is favourable for industrial processing if source requirement does not exceed 1 million curies of ^{60}Co. The electrons complement the gamma rays from radioactive sources in many areas.

Radiation processing technology using electron accelerators has a pivotal role in an industrial environment. Low-energy electron accelerators having high beam intensity are being increasingly used in the radiation processing industry for a variety of applications.

At BARC, using the electron accelerator the following programmes are being pursued:

- Crosslinking of polythene 'O' rings for drum fittings – MOU with a Bombay firm for this application has been signed.
- Crosslinking of PVC/PE cables and wires for high performance and speciality applications.

There are plans to develop electron accelerators indigenously in BARC for this type of work.

For the radiation processing industry, plans are also under way at CAT to build a 750 keV, 20 kW electron accelerator mainly for the following items:

1. Radiation-processed crosslinked polyethylene cables and wires required by TV and computer manufacturers. Railways also import Rs 100 crores worth of these cables per annum.

2. Development of heat-shrinkable tubes. Telecommunication industry imports this item costing annually more than Rs 30 crores. CAT is also developing a 10 MeV, 15 kW electron Linac for industrial applications such as sterilization of medical products, irradiation of food products, etc. The dose rate available from such accelerators will be an order of magnitude higher than that from a typical ^{60}Co facility used for this purpose.

In order to demonstrate the economic viability of these various applications of accelerators in our country, CAT is thinking in terms of a medical and industrial accelerator centre which will be available to potential users for developing radiation-processing technology.

Use of radioactive sources like ^{60}Co for treatment of tumours is a well-known method. Recently, the electrons from low-energy electron accelerators are also being used for such treatment, particularly for superficial tumours. In India the radiation therapy based on accelerators is growing rapidly and at present there are about 20 odd electron accelerators operational in the country for this purpose. CAT has developed and operated a 20 MeV microtron as injector to a 700 MeV booster. Based on the experience gained on microtron, a 12 MeV microtron has been designed for applications like radiation physics studies and non-destructive testing and the same has been installed at Mangalore university. With addition of a Gantry, it is possible to make a radio therapy machine using the 12 MeV microtron. CAT is also at an advanced stage of building a 11 MeV cyclotron to produce short lived radio isotopes for positron emission tomography.

There exist also possibilities for use of accelerators in the nuclear fuel cycle, both for disposal of radioactive waste and for use as an 'energy amplifier' by introducing neutrons produced in spallation reactions into a subcritical assembly.

Summary

A possible strategy for accelerator-based research and applications can be summarized as follows:

- Research with existing facilities and utilization of the facilities for applied areas.
- Building new accelerator facilities for research and applications. Concentrating on reasonably large-size accelerators involving high technology but at moderate cost, which will enable work to be carried out in many frontier areas.
- International collaborations – physics research, participation in building accelerators and detector set-ups.

It is being realized that at least for research using big accelerators, cooperation amongst countries is very much needed not only for building expensive facilities but also for using the same. As we said before, no nation can any longer afford to go at such activities alone. However, our own national base has to be sufficiently strong and several national accelerator facilities are essential to provide this base. Our success in the international arena depends crucially on our expertise and competence built around our national facilities and development of manpower required to build and use the facilities both in India and abroad. A strong synthesis of the two programmes, national and international, should be the vision for our accelerator programme.

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Recent fertility trends and prospects in India

K. Srinivasan

There is an increasing pace of fertility decline in large parts of the country in the recent years. Among the proximate determinants, the variables that have played a dominant role in fertility changes directly, in the Indian context are natural fertility and contraceptive use and indirectly, female literacy and infant mortality. For future, we can expect the TFR to be in the range of 2.9 to 3.0 by the year 2001 and 2.00 to 2.13 by the year 2011. The spurt in the female literacy rate will have a major impact on the future fertility levels.

THE most recent census[1] conducted in India in March 1991 placed her total population at 846.30 million, including an estimated figure of 7.72 million for the state of Jammu & Kashmir, where the census could not be conducted owing to political disturbances. Since 1951, when the first post-independence census was taken, the population of the country has increased by 485.22 million, more than twice the population that lived in the country in 1901, which was 238.40 million. During the decade 1981–1991 we have added to the country a whopping 162.97 million people, which is equal to the combined populations of France, Poland and the United Kingdom.

In terms of the rate of growth rather than numbers, during the decade 1981–91 the population has increased by 23.85%, or 2.12% annually, compared to 24.80%, or 2.20% annually, during the decade 1961–71. During the year 1991 the growth rate was 1.97%, almost the same as the average annual growth rate of 1.96% experienced 40 years earlier during the decade 1951–61. However, while the earlier growth rate was the result of a difference of an average crude birth of 42.4 and

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