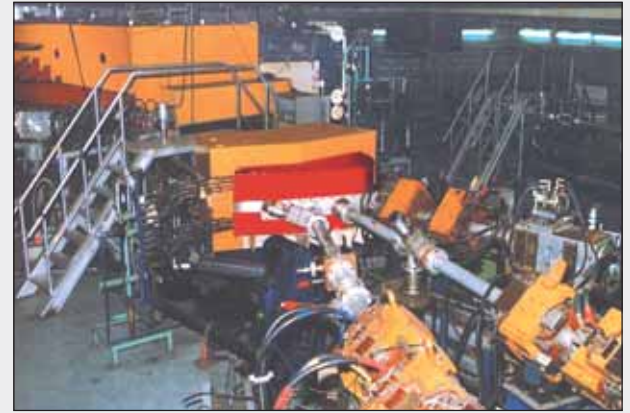




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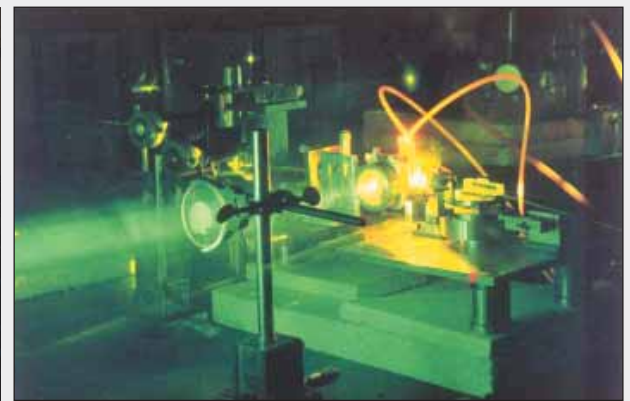
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## Chapter 6

### Advanced Technologies - Accelerator, Laser, Plasma, Fusion



4



5



6



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## Captions for Photo-Collage

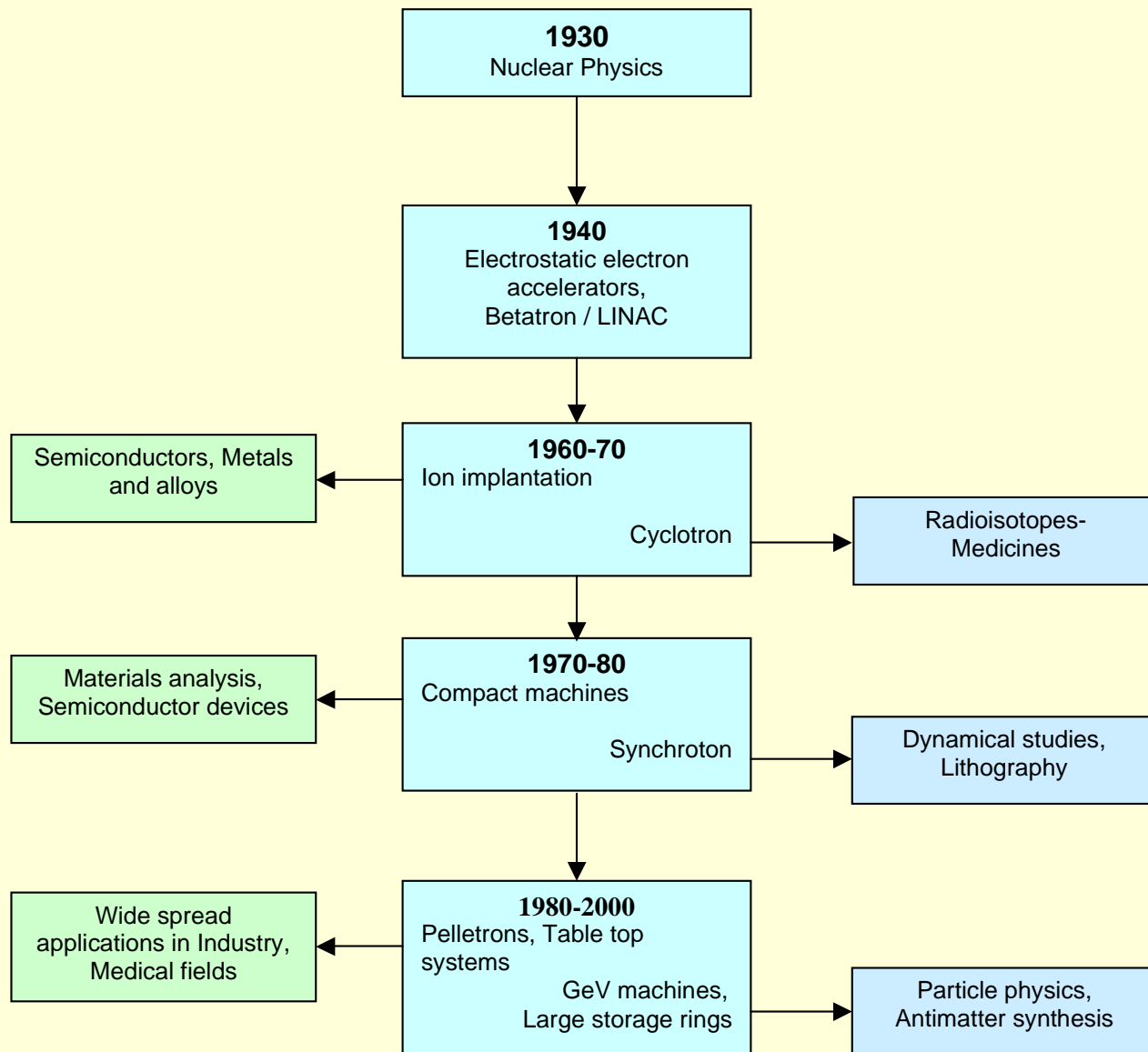
- 1 *Photograph of Folded Tandem Ion Accelerator (FOTIA) column and the tank developed at BARC, Mumbai.*
- 2 *Beam lines of Variable energy cyclotron centre (VECC) at Kolkata,*
3. *Lasers are being developed for various industrial applications at CAT, Indore – shown here is a laser being used for cutting operation.*
- 4 *Assembly of various parts of Steady State Tokamak (SST-1) at IPR, Gandhinagar.*
- 5 *Test bench set-up of prototype grazing-incidence-grating dye laser oscillator pumped by the green beam (left) from the copper vapour laser, developed at BARC, Mumbai.*
- 6 *Photograph of Photochemical reactor for laser separation of carbon isotopes at BARC, Mumbai.*
- 7 *INDUS -1 Storage ring at CAT, Indore.*

# ACCELERATORS

Particle accelerators are devices, which produce beams of energetic charged particles. Beginning as tools for exploration of the nucleus, accelerators today are being extensively used in various domains including industry and medicine. Accelerators can be broadly classified as (i) lower energy ion implantation machines (ii) Van de Graff generators, (iii) Tandem Van de Graffs (Pelletron) (iv) high energy Cyclotrons (v) very high energy Linear Accelerators (LINAC) and (vi) Synchrotrons. They are very ingenious machines, whose design and construction stretches the technologies involved to their limits. It is, in fact, said that the level of technological competence of

a country can be judged from the type of accelerator it can build. The development of accelerators has revolutionized scientific research and led to the development of a host of technologies, including ultrahigh vacuum systems, DC and AC magnets, high voltage and high current power supplies etc. It has also resulted in a number of applications for the benefit of human society. Thus, accelerators can be said to be an example of the unique interface between science and technology.

Around 1920, the first DC high voltage (100 kV) particle accelerator was conceived by Cockroft and Walton. Discovery of the Cyclotron (a device for accelerating nuclear particles to



*Evolution of various accelerator systems over the decades and their uses.*

high energies without the use of very high voltages) by Ernest Lawrence in the year 1929 made a big impact on nuclear physics research. It also revolutionized the nuclear energy scene through its role in the discovery of “man-made” transuranic elements/isotopes, of which plutonium is the most striking example. The bombardment of heavy element targets by energetic charged particles produced from accelerators was the main technique used for production of these transuranic elements. Over the years, higher and higher energy accelerators have been developed with the main objective of probing the deeper and deeper structure of matter. As a result, we have now learnt that the families of the six quarks and six leptons are the basic building blocks of matter, and have also gained knowledge about the nature of basic forces operating in nature. Today, we have synchrotrons up to a proton energy as high as 1 TeV and electron energy of 100 GeV. The world’s largest synchrotron based accelerator called the Large Hadron collider (LHC) is now coming up at CERN, Geneva, with a proton energy of 8 TeV.

Particle accelerators are not only unique as tools for exploration of the nucleus, but also find a variety of applications in fields such as medical sciences, material characterisation and materials processing. Production of radioisotopes using accelerators has today widened the ambit of medical applications of radioactivity. In our country, over 35 accelerators are used in hospitals, 4 being added each year. In the field of material sciences, about half of the world’s accelerators are being used for ion-implantation applications.

The approach to the development of accelerators in India is yet another example of the emphasis laid by Dr. Homi Bhabha, on the importance of building expertise in a variety of experimental areas and facilities. During the stay of Dr. Bhabha at Cambridge, Prof. Rutherford was active in studies on nuclear reactions. One of the requirements for experimental physicists at that time was to build various equipment such as detectors, amplifiers, power supplies, vacuum systems, etc, which left an important impression on Dr. Bhabha. Back in India, he took the bold step of nucleating an activity on production of such equipment in an institute of fundamental research – TIFR. Such equipment building was recognized to be the key to innovation and the foundation for futuristic technologies. The electronics group of TIFR was the nucleus from which the Electronics Division of

BARC grew. This led to the establishment of the Electronics Corporation of India (ECIL) at Hyderabad. Work on linear accelerators led to the development of microwave components and devices and contributed substantially to the design and supply of critical components and subsystems required by national agencies. This group has now been formed into a separate organisation, the Society for Applied Microwave Engineering and Electronics Research (SAMEER).

In 1950, a Cockroft-Walton generator for 1 MeV protons was set up at TIFR, which was used for neutron physics studies. A one foot size cyclotron was another piece of equipment built in the early days of TIFR.

A 38 inch cyclotron was set up at the Institute of Nuclear Physics, Kolkata (now called Saha Institute of Nuclear Physics-SINP), which was made operational in early 1960 with an internal beam of about 4 MeV protons. Later, several low energy D.C accelerators were also set up at other institutes/universities such as Bose Institute at Kolkata, Aligarh Muslim University at Aligarh, Banaras Hindu University at Varanasi, Andhra University at Waltair, and at IGCAR, Kalpakkam, for studies with neutrons and low energy charged particles. A 2 MV Van de Graff accelerator was set up and made operational in the early eighties at IIT, Kanpur, which was utilized for studies on neutron induced fission and application of nuclear methods to various disciplines. Around 1971, a small size cyclotron with acceleration radius of 28 cm, capable of giving primary proton beams of up to 5 MeV was also set up and made operational at Punjab University, Chandigarh. This was a gift to the Punjab University from University of Rochester, USA. In the beginning of 1990, a 3 MV pelletron accelerator capable of delivering a variety of ion beams in the MeV range was installed at the Institute of Physics, Bhubaneswar, which is finding important applications in diverse areas of basic and applied research. During 1990s, a 3 MV Tandatron accelerator was installed at the National Centre for Compositional Characterization of Materials to serve as state-of-the-art analytical tool for the characterization of materials. Also very recently, a 1.7 MV tandem accelerator has been put into operation at IGCAR, which is serving as an important tool for the radiation damage related studies.

The first accelerator based neutron generator was commissioned as early as 1957 at SINP. It produced  $10^9$  neutrons per second (n/s), and has been extensively used in nuclear experi-

ments. The neutrons were produced by the T (d, n) nuclear reaction ( ${}^3\text{H}_1 + {}^2\text{H}_1 \rightarrow {}^1\text{n}_0 + {}^4\text{He}_2 + 17.6 \text{ MeV}$ ). In the early 70s, a similar neutron generator was built indigenously for fusion related research activities in BARC. All the components of the neutron generator were developed locally. In the continuous mode of operation, the maximum neutron yield was  $5 \times 10^9$  n/s. In early 90's, the generator was upgraded for higher neutron yield at PURNIMA.

At Trombay, research work in nuclear physics using particle accelerators started with the setting up of a 5.5 MV Van de Graff (VDG) generator in 1961. It was utilized for nuclear reaction and other studies till about 1990s after which it was retro-fitted as an innovative folded tandem accelerator with 6 MV terminal voltage (Folded Tandem Ion Accelerator-FOTIA), capable of delivering heavy ion beams up to A~40 and energy ~60 MeV. FOTIA was commissioned in April 2000, when the first beam of C-12 ions with an energy of 12 MeV was delivered. These beams are being used for research in several interdisciplinary areas.

In the early sixties, a committee under the Chairmanship of Dr. R. Ramanna was appointed by Dr. Bhabha to review all



*Folded Tandem Ion Accelerator (FOTIA) column and the tank developed at BARC*

aspects pertaining to accelerators to make recommendations on the types of accelerators worth setting up in India. Based on the detailed discussions, seminars and report of the Committee, Dr. Bhabha proposed that the country should indigenously set up a Cyclotron and also later procure a Tandem Van de Graff machine. The development of accelerator technology took a big leap with the decision to set up a Variable Energy Cyclotron Centre (VECC) at Bidhan Nagar, Kolkata. Work on the fabrication and installation of the VEC was started in 1967 under the leadership of Dr. D.Y. Phadke, TIFR, and later by Sri C. Ambasankaran and Dr. A.S. Divatia of BARC, with active participation of scientists and engineers from BARC, SINP and TIFR.

The design of the Variable Energy Cyclotron (VEC) is based on the 88-inch cyclotrons at the Lawrence Berkeley National



*224 cm variable energy cyclotron machine at Kolkata*

Laboratory and at the Texas A&M University in USA, with modifications incorporated for facilitating indigenous fabrication. The 224 cm cyclotron (K=130) the first of its kind in India, became operational in June 1977, with the production of the first internal beam of alpha particles. The machine is capable of giving up to 60 MeV protons and 130 MeV alpha particles and is in regular operation since 1981.

A cyclotron is an assembly of a large number of sub-systems such as a magnet, RF oscillator, power supplies, ion injection and extraction systems, vacuum and control systems,



Main magnet fabrication completed at Heavy Engineering Corporation (HEC), Ranchi

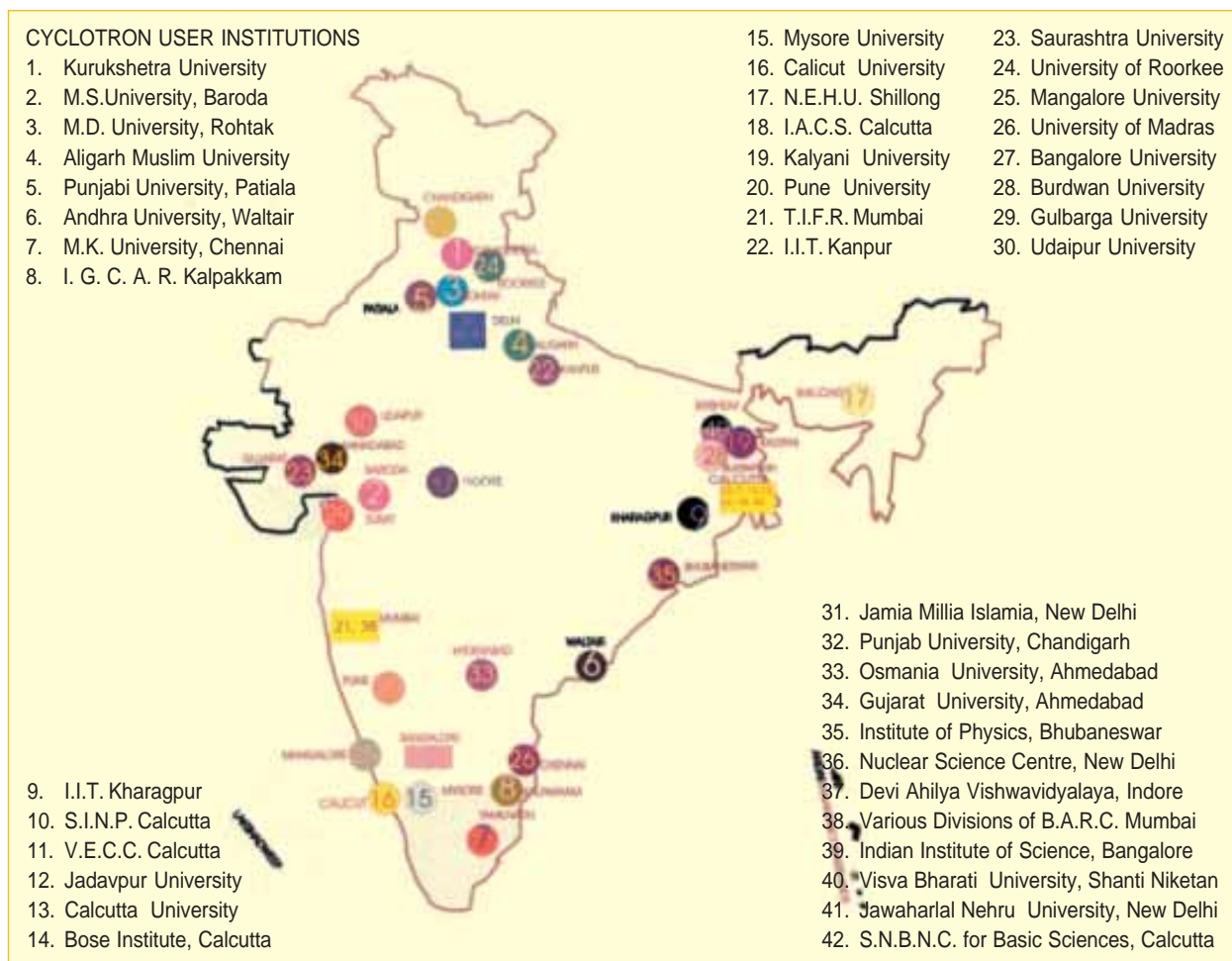
beam transport and data processing systems. Thus, the design, construction and operation of the cyclotron involved a large multidisciplinary activity. In the case of VECC, a number of institutions besides BARC were involved in the manufacture of the subsystems, including Heavy engineering corporation, Ranchi, BHEL, Bhopal, ECIL, Hyderabad, Garden Reach Workshops, Calcutta, Variety engineers, Baroda and Indian Telephone industries, Bangalore. For instance, the magnet, weighing 262 tonnes, was fabricated at Heavy Engineering Corporation, Ranchi. Thus, the cyclotron programme stimulated indigenous production of a number of sophisticated accelerator equipment within the country. VECC has made available high energy beams of protons, deuterons and heavy ions for a number of research and development activities undertaken by various groups in the country. This

cyclotron produced  $^{67}\text{Ga}$  radioisotope for the first time in the country. This isotope is used extensively for the diagnosis of soft tissue tumours.

VECC is now setting up a superconducting cyclotron for delivering intermediate energy heavy ion beams. The design of this machine is based on the Cyclotrons at MSU and Texas A&M, USA. It is expected to be completed by 2007. When completed, its operation will extend the maximum available energy to 200 MeV/nucleon, which is well above the velocity of sound in nuclear matter. There are only four such machines in the world. This machine will be a boon to nuclear physicists to study complex nuclear phenomenon. Apart from utility in basic sciences, it will find applications in diverse fields such as radiation damage studies related to reactor materials, proton and heavy ion induced radiation therapy, etc. Extensive basic research has been carried out using various accelerators in DAE.

For pursuing nuclear physics research, a 14 MV Pelletron Medium Energy Heavy Ion Accelerator (MEHIA) – was com-

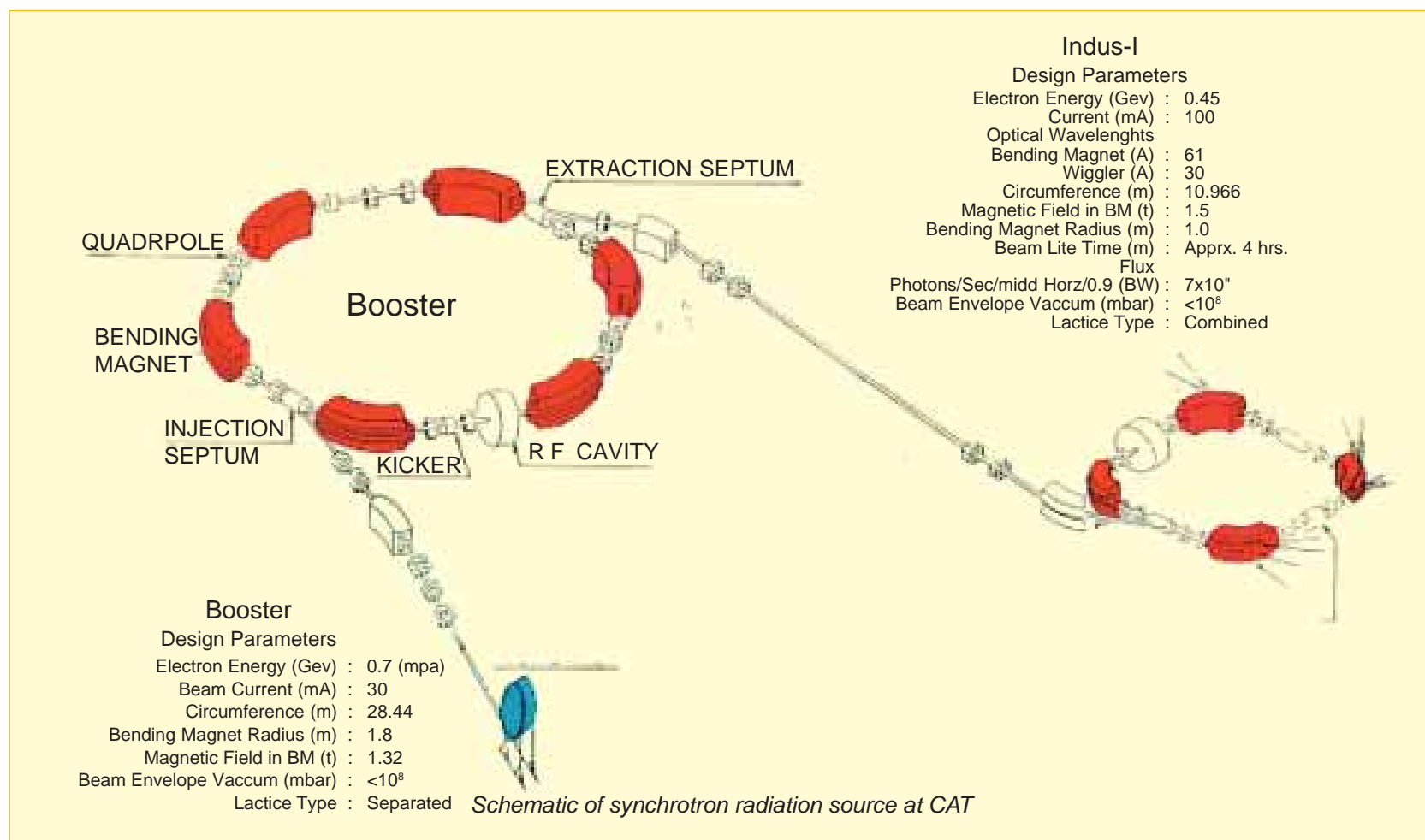
#### Various accelerator facilities in India



missioned in 1989, at the TIFR complex. Pelletron is a tandem electrostatic accelerator capable of providing beams of accelerated nuclear particles such as alpha particles, protons and different types of heavy ions. While the main accelerator was procured from National Electrostatic Corporation, USA, the large pressure vessel (weighing 120 tonnes) needed for housing the accelerator in an atmosphere of pressurized SF<sub>6</sub> gas was fabricated at Mumbai. The transport of the huge vessel across the metropolis and its erection on a 40 feet high pedestal were quite challenging jobs. In addition, several other items, such as beam line components, optical-fibre data telemetry system, UHV components, buncher-sweeper system etc. were indigenously set up. Also, five beam lines as well as experimental stations involving a variety of detectors were also set up and developed, which have been extensively used by a number of institutions. A similar machine with a 15 MV terminal voltage was also installed at the Nuclear Science Centre, Delhi and commissioned around 1991 under UGC, which has been extensively used by the University researchers.

Realising the importance of development of accelerator technology, DAE set up a committee led by Dr. P.K.Iyengar, in early 1979, to recommend a long term programme in the field of accelerators. This committee recommended that in the first phase a synchrotron facility should be set up to cater to the needs of a much larger scientific community. In the next phase, it was planned to set up a proton accelerator of several GeV energy for nuclear physics research. As these accelerators would require large facilities and involve sustained developments in many a new technology, a new research center was set up in 1984 at Indore in Madhya Pradesh. This was named as Center for Advanced Technology (CAT) and had the specific objective of development of accelerators, lasers and related technologies, and began its scientific activities in 1987.

It was decided to build two synchrotron radiation sources of 450 MeV and 2.5 GeV electron energy (later named as Indus-I and Indus-II respectively). The reason for selecting the Synchrotron Radiation Source (SRS) in the first phase was that synchrotron radiation finds many applications in studies related



to a number of areas such as solid state physics, crystallography, surface physics, molecular biology, lithography etc.

Synchrotron radiation is the electromagnetic radiation emitted, when electrons traveling at almost the speed of light are bent under the influence of magnetic field and travel in a circular path of the accelerator. They radiate at frequencies in the visible, ultraviolet and X-ray regions of the spectrum. The synchrotron radiation has some unique properties. It is very bright and has continuous spectrum of wavelength. It is also polarized and pulsed with useful time structure. It has a strong concentration of radiation in horizontal plane, small source size, low divergence and precisely calculable radiation characteristics. Thus, brightness enhanced intense UV and X-ray beams provide a unique means of materials characterization in terms of probing dynamical features occurring over short time scales in materials.

The first Indian SRS named as Indus –I essentially consists of three accelerators- a 20 MeV microtron, a 700 MeV booster synchrotron and a 450 MeV storage ring. In each cycle 20 MeV electron beam from the microtron is injected into the booster ring, wherein the beam energy is ramped up and boosted to 450 MeV. This beam is then extracted from the booster synchrotron, using pulsed magnets and injected into the storage ring. The cyclic operations are continued till sufficient beam is stored in the storage ring. The filling time is typically a few minutes and the beam lifetime in Indus-I is 1-2 hrs. The construction of Indus-I is a totally indigenous effort. A number of technologies, for example, ultra-high vacuum systems (pressures less than  $10^{-9}$  torr), RF cavities and large electromagnets along with their power supplies, pulse magnets etc., were developed within the country in the course of construction of Indus-I.

Indus-I is a 450 MeV synchrotron radiation source, with a critical wavelength of 61 Å. It was commissioned in 1999 and a maximum stored beam current of 200 mA was achieved against the designed current of 100 mA. At present four beam lines are operational for reflectivity, angle-integrated PES, angle-resolved PES and photophysics applications and two are under construction for high resolution VUV and Photo-absorption (PASS) applications.

Indus –II will be a synchrotron radiation source of electron energy 2.5 GeV and a critical wavelength of about 2 Å. Its ring



*INDUS storage ring at CAT*

is almost 10 times larger than Indus-1 and has a circumference of 172.5 m. It is so designed as to give low beam emittance with high brightness. The design of Indus-II was totally the responsibility of CAT. Indus-II is in an advanced stage of construction and is expected to be available to users in the next few years. With the commissioning of both these facilities, Indian scientists will have powerful sources of light with wavelengths in the visible as well as ultraviolet regions, soft x-rays and hard x-rays.

For accelerator based research in the universities, a 8 MeV, 50 mA electron accelerator (Microtron) was installed and com-

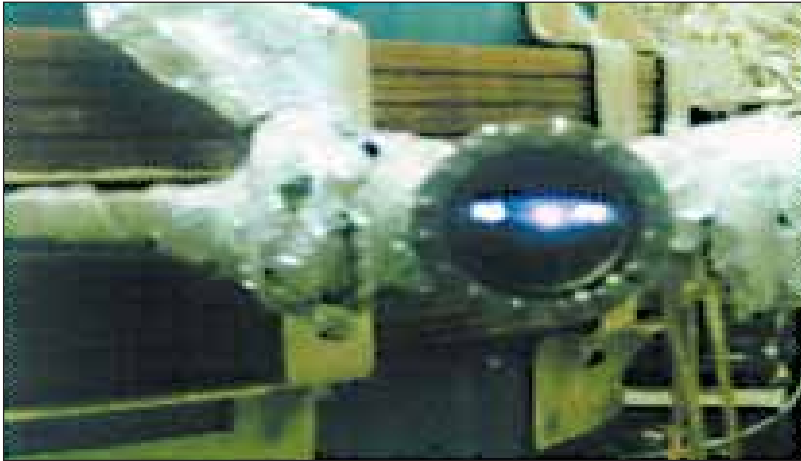


*Angle resolved photoelectron spectroscopy beam line at INDUS-1*

missioned at Mangalore University, Mangalore in 1995. This accelerator is now being extensively used for educational as well as research purposes.

To build a base in developing a high current proton accelerator in the country, a programme for designing and develop-





*First light from INDUS-1*



*Bending magnet with vacuum chamber and pumps for INDUS-II*

ing high current based ion sources and RFQ based accelerator programme was initiated at BARC. As a proof of the underlying principle, prototype development of a low energy and low power radiofrequency quadrupole (LPRFQ) was also initiated around 1988. A Duoplasmatron ion source delivering proton beams was commissioned in 1990, followed by a compact permanent magnet based microwave ion source. The beam tests on LPRFQ were performed in 1996. This was totally designed and developed for the first time in the country.

At present, BARC is developing a 50 keV, 50 mA proton source, which will be used for various high current applications, including generation of neutrons. Activities have also started towards design and development of a high current (~ 30 mA)



*INDUS-II mock up assembly in tunnel*



*Sextupole magnet in INDUS - II*



*Inner view of the Low Power RFQ (LPRFQ). BARC was the first to develop this technology in the country*



*A View of LPRFQ in the commissioning phase*

proton LINAC of 10 MeV, as a part of development for high power accelerators, to be used in Accelerator-Driven Sub-critical (ADS) reactor systems.

### **Development of High Power Pulsed Electron Accelerators for Strategic and Industrial Applications**

Pulsed high power electron beams with peak power of several Gigawatts are useful for generating Flash X-rays (FLX), High Power Microwaves (HPM), Pulsed Neutron Sources (PNS) and Pulsed Ion Sources. In addition, they have potential applications in thermonuclear fusion devices for energy generation. BARC has been involved in the development of pulse power technology since 1970. The pulse power systems



*KALI-5000 Pulse Power System : It is the most powerful pulsed electron source designed and built indigenously in the country*

developed for REB (Relativistic Electron Beam) generation are KALI-75, KALI-200, KALI-1000, KALI-5000 and Induction Linac (LIA). These are all electron beam based high power pulsed accelerators, capable of delivering pulsed beams (50 ns – 100 ns) with energies from 200 keV to 1 MeV and powers ranging from 0.5 GW to 50 GW. KALI-60 is now in use at TBRL (Terminal Ballistic Research Lab), Chandigarh, for their Flash X-ray development; KALI-75 was delivered to Dept. of Electrical Engg., I.I.T., Madras, for research in insulation material studies. KALI 200 (300kV, 20kA, 200J, 50ns) was delivered to MTRDC/LRDE, Bangalore for HPM related activity. KALI-5000 was recently commissioned at 600 kV, 25 GW. LIA with parameters as 150 keV, 0.5 GW, is in an advanced stage of fabrication.

Most of the systems described above are quite bulky and massive, because of which the flexibility of using them for the fields, strategic and industrial sectors gets severely limited. To make the accelerators more compact and light weight, a long range programme is being conceived and implemented.

### **Electron Accelerators for Medical, Industrial and Agricultural Applications**

Electron beams are potential tools for a variety of applications. They are gradually replacing the old methods of curing of coatings, adhesive and paints. Electron beam processing of cables and sheets vastly improves their thermal and mechanical properties. Irradiation of semiconductor devices has brought in a total transformation in IC and microchip industry. Sterilization of the disposable medical products and food preservation are other areas, where electron beams have made a big impact. Electron beams are also used to produce exotic colours in gems and stones. Several thousand accelerators are used in industry all over the world. In India, a 500 keV industrial electron accelerator was indigenously developed by BARC and commissioned at Vashi, Navi Mumbai in Aug. 1998. It is a Cockroft-Walton based DC accelerator. The accelerator is in regular operation at a power level of about 3.5 kW and is used by industries as well as research organisations. Industries such as Reliance India Ltd. are using this accelerator for crosslinking of plastic sheets and granules. As a result of the work carried out in this facility, electronic beam processing facilities are being set up by some industries for processing cables and wires. One plant of 3 MeV, 150 kW was



An exploded view of 500 keV DC accelerator, developed at BARC



A complete view of 500 keV Industrial accelerator facility, operational at Kharghar, Navi Mumbai

set up by M/s NICCO cables at Kolkata and another of 3 MeV, 50 kW was established at Hyderabad by Radiant Cable Industries.

To meet diverse needs of the industry, BARC is also designing and building two more machines - a 3 MeV, 30 kW DC and a 10 MeV, 10 kW RF Linac, for the same purpose. Both these machines are full of technological challenges. The 45 kW, 120 kHz oscillator is being designed and built for the first time in the

country. A coupled cavity Linac, capable of giving 10 MeV beam with a power of 10 kW is now under installation. The Linac technology is among the most sophisticated technologies, consisting of intricate subsystems. The cavity of Linac should exhibit highest possible Q, the field uniformity and proper dispersion at the operating frequency. The geometrical deviations have to be confined within a few tens of microns. Similarly, the microwave source ought to show highest possible stability at the maximum power level. All the microwave components of this accelerator will be handling very high average power, a task being attempted for the first time in the country. After fully perfecting the RF Linac technology, the same will be duplicated for various applications such as baggage scanning, Cancer therapy, etc.

Accelerator development for industrial use has also been a thrust area at CAT, Indore. A 750 kV DC accelerator was designed and developed and is in regular operation since 2002, for R & D on radiation processing of food materials, curing of coatings, treatment of seeds etc. This system is used for surface irradiation of potatoes for sprout inhibition. Successful surface irradiation using low energy electron accelerator is a major milestone in food irradiation technology, as it will keep the bulk material, unaffected by the irradiation and we can increase the throughput many folds, as compared to irradiation by gamma rays.

In addition, work on two more electron accelerators is in progress. One of them is a self-shielded 400 kV system, which can be installed in any industrial shed for curing applications



Surface radiation processing of potatoes using DC accelerator prevented sprouting for 3 months. Unprocessed (left) and radiation processed (right) potatoes

and another is a 2.5 MeV, 100 kW based on air core transformer design for high power applications in radiation processing. A 10 MeV, 10 kW electron linac is installed at CAT and undergoing commissioning trials. Based on this, a radiation processing facility is being built for irradiation of agriculture products.

India has presently 36 accelerator-based and 231 isotope-based radiation therapy machines. As per an assessment by WHO and IAEA, a developing country like India would need one radiation therapy machine per million population. One can thus infer that India needs about 1000 machines for radiation therapy. Considering the exorbitant cost of imported machines and difficulty in maintaining them, DAE had initiated development of radiation therapy machines based on accelerators. The machine, based on a 12 MeV electron accelerator (Microtron), is in advanced stage of completion and commissioning.

The maturing of the accelerator technology and associated fields in the country is evident from the fact that India has participated in the world's largest particle accelerator The Large Hadron Collider (LHC) being set up by CERN. A protocol agreement to develop and supply superconducting sextupole, decapole and octopole magnets, quench protection heater power supply (QPS), precision magnets positioning system jacks (PMPS), control electronics for high current circuit breakers, large capacity liquid nitrogen tanks, etc., and to provide services such as magnetic measurements for a period of about 8 years was signed between AEC and CERN in 1996. The Magnet Technology Lab at CAT embarked on an ambitious project of developing and supplying 4500 nos. of superconducting sextupole and decapole corrector magnets required for LHC project of which a pre-series of eight superconducting sextupole magnets (MCS) were supplied in 2001. These magnets passed all the specified tests and measurements at room temperature and at 1.8 K under super-fluid helium at CERN. Two units of 50,000 litre capacity liquid nitrogen tanks were also delivered, which have performed well at the two main installations at CERN.

## LASER TECHNOLOGY

The importance of lasers was recognized early in India, and many Indian laboratories started working on lasers in the early sixties. BARC was one of the first laboratories in the country to develop a semiconductor laser, which was used for setting up an optical communication link over a distance of 20 km. Since then, the laser programme has expanded to include development of other lasers and to take up research in diverse fields such as non-linear optics, laser-plasma interactions, resonance ionization spectroscopy, material processing, etc. With the establishment of Center for Advanced Technology (CAT) at Indore in 1986, many of the laser activities have now been shifted from BARC to CAT.

Although laser is a tool of great power and precision, its use in industry and medicine is limited in India because of the high cost of imported lasers. The high power continuous wave (CW) CO<sub>2</sub> laser is a versatile tool of high precision for carrying out various material processing operations such as cutting of me-



*20 kW CW CO<sub>2</sub> laser system*



*Laser cutting operation*



*Laser cladding operation*

allic and non-metallic materials, welding, surface hardening, surface alloying, cladding, glazing, engraving, and metal forming. The country's highest power CW CO<sub>2</sub> and high repetition rate pulsed TEA (Transversely Excited Atmospheric pressure) CO<sub>2</sub> lasers were indigenously developed at CAT. CW CO<sub>2</sub> lasers of different output powers ranging from 3.5 kW to 20 kW are now operational for different applications such as CNC aided profile cutting of metal and non-metal sheets, welding, surface engineering, rapid manufacturing and thermal testing of materials for Synchrotron as well as TOKAMAK. A few specific examples are profile cutting of CRNGO sheets for developing magnets for particle accelerator, laser welding of end-plug of nuclear reactor fuel clad tube, development of graded overlay of stellite on AISI304 stainless steel, refurbishing Ni-superalloy based turbine blades by laser cladding and cutting of thick concrete blocks for possible decommissioning and decontamina-

tion of radioactive facility. The high repetition rate (500 Hz) pulsed TEA CO<sub>2</sub> laser, producing pulses with several MW (with an average power of 500 W) is being used for paint stripping and selective photochemical reaction studies.

### **Fiber Coupled Industrial Nd:YAG Laser**

Industrial use of laser sources requires special techniques for delivery of the high power laser output to work pieces with typical intensity more than 10<sup>6</sup> W/cm<sup>2</sup> at a specific location on the work piece. CAT has developed an Industrial Nd:YAG laser with fiber optic beam delivery unit, with a maximum pulse energy of 50 Joules per pulse and an average power of up to 200W.

This system is able to cut up to 8 mm steel sheets at a speed of 60mm/min with oxygen as assist gas, and to carry out welding of steel and titanium with welding depths up to 0.8mm. Fibre optic beam delivery helps in locating the laser system, associated power conditioning systems and heat exchanger units far away from the processing site, and is thus attractive in terms of flexibility, robotic handling, power sharing and time sharing capability, as well as for processing in hazardous nuclear environments. Other possible applications include slitting of zircaloy fuel pins for extraction of fuel pellets, cutting of end plates of irradiated fuel bundles, welding of miniature radiotherapy capsule etc.



*Industrial YAG laser with power supply and controls unit  
(Top right: Laser cutting of Zircaloy tube)*

## Medical Applications

Lasers have distinct advantages over conventional surgery. Their use reduces operative complications and minimizes post-operative bleeding, oedema and pain. Laser cuts are precise and controllable with minimal damage to surrounding tissue. The non-contact nature further minimizes chances of infection. Several complicated operation procedures have been changed to outpatient clinical procedures using laser treatment. This translates to more number of patient being able to receive the treatment, a great boon for India, where the the ratio of number of hospital beds to patients is dismally low. In this context, surgical carbon dioxide laser, Model C-40 developed by CAT, can be used for a range of surgical modalities, such as ENT, Gynaecology, General Surgery, Dermatology, Plastic Surgery etc. Fourteen such laser systems have so far been supplied to various hospitals across the country, including AIIMS (All India Institute of Medical Sciences), New Delhi and Choitram Hospital and Research Centre, Indore.

## Other Applications

Precision laser welding is a solution for welding of small thin-walled capsules, and intricate, small devices such as a cardiac pacemaker. A Nd:YAG laser based welding machine was designed and developed by CAT for welding of radiation source capsules in a hot cell. One such machine has been installed at BRIT, Mumbai, where regular laser welding of capsules is being carried out. Similarly, an automated laser work-

station with four degrees of freedom was developed for welding titanium shells of the pacemaker, achieving a leak rate of the order of  $10^{-10}$  torr litre/sec. Two such machines were installed at Shree Pacetronix Ltd., Pithampur. The machine has been in operation for the last four years in the production line and has given very good performance.

In addition to the above, CAT had also developed a variety of Q-switched Nd:YAG laser systems, capable of producing peak power in excess of 50 MW in a few nsec pulse duration for R & D applications, The Nd:YAG lasers find application in Plasma Physics, pumping optical parametric oscillator (OPO), Pulsed laser deposition, atmospheric studies, Thomson Scattering etc. For studying non-linear optics at ultrahigh speed, a laser capable of giving pulses at a few picoseconds ( $10^{-12}$  sec) has also been developed.

Under a National Laser Programme several projects on 'Medical Application of Lasers' and 'Industrial Application of Lasers' are funded at several academic institutions and hospitals. Under the first project, several doctors from Choithram Hospital and Research Centre, Indore and Sri Chitra Tirunal Centre, Thiruvananthapuram. were sent to Russia to gain hands-on-experience with medical lasers. Subsequently, surgical CO<sub>2</sub> lasers were supplied to several hospitals in the country. Similarly, through a project on 'Industrial Application of Lasers' with Jadavpur University, Kolkata and PSG College, Coimbatore, several industries in around Kolkata and Coimbatore have benefitted.

## Development of Intense Laser Technology:

High peak power lasers have reached record levels of Petwatts ( $10^{15}$ ) in the world today. Ultra short pulse, high peak power solid state lasers capable of producing focused laser intensity in the range of  $10^{13}$ - $10^{15}$  W/cm<sup>2</sup> have assumed great importance in the field of High Pressure Physics and Laser-Plasma interactions. The technology of high peak power solid-state lasers has been under development for the past three decades in BARC. Starting in the 70s with Q-switched, Nd:YAG/Glass lasers capable of producing  $10^8$  to  $10^9$  Watts (Gigawatts) peak power in a few nanosecond pulse duration, presently peak powers more than  $10^{10}$  Watts in sub-nanosecond (hundred picosecond) pulse duration have been achieved. Nd:Glass laser systems providing 50 Gigawatt, 75 picosecond pulses, 1 to 5



*Automated pace maker welding station. Inset shows a welded pace maker*

Joules in 200 picosecond pulses have been indigenously developed at BARC and CAT for applications such as generation of laser driven shocks in the range of ~10 Mega bars and studies on their propagation through various materials. During the last decade, a 100 GW ( $10^{11}$  watt) 27 picosecond Nd:glass laser system was built at CAT to study laser-plasma interaction in the short pulse regime. This laser is used for investigations on high order harmonic generation from solid surfaces, intense x-ray emission from gas cluster targets and applications in x-ray contact microscopic imaging, and setting up of a  $K_{\alpha}$  monochromatic x-ray source. Further, in order to extend the investigations to ultrahigh intensity, ultrashort pulse regime, a table top Terrawatt ( $10^{12}$  watt) laser system, providing 1 J, 1 ps laser pulses, has also been developed using chirp-pulse amplification scheme. A beam delivery system has also been set up to irradiate different targets to a laser intensity of  $\sim 10^{17}$  W/cm<sup>2</sup>.

#### **Inexpensive-Pulsed Driven, Helium-Free, Versatile Transversely Excited Atmospheric-Pressure (TEA) CO<sub>2</sub> Laser**

The major role of helium in the pulsed atmospheric pressure operation of a transversely excited CO<sub>2</sub> laser, commonly termed as TEA CO<sub>2</sub> laser, is to stabilise the discharge. Helium is expensive and scarce. In large systems and in repetitive systems, where the flow rate of helium is high, a recirculatory loop incorporating heat exchanger and catalytic reconverter is incorporated to enable recycling of helium. This adds enormously to the cost of the system in addition to making it bulky. Helium-free operation of TEA CO<sub>2</sub> lasers has been achieved by making use of a pulser based on a spiker-sustainer excitation scheme.

#### **Development of Copper Vapour Lasers**

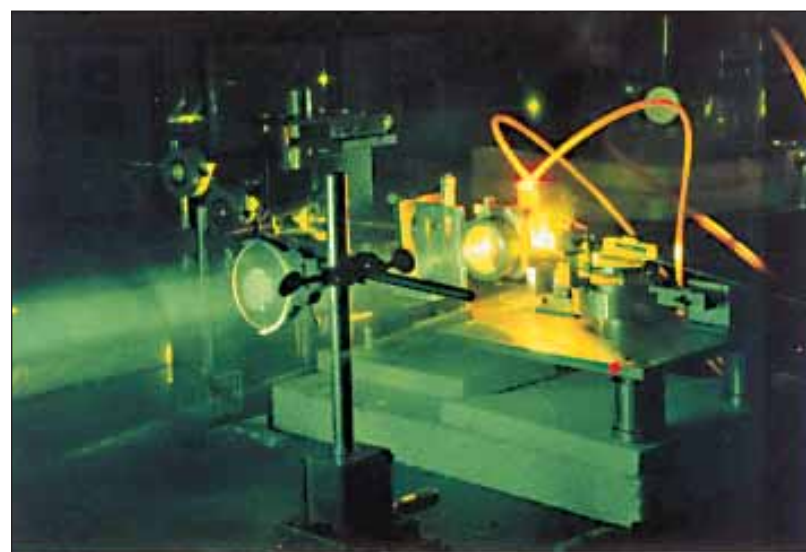
Copper Vapour Lasers (CVL) are a special class of lasers that produce short duration (few tens of nanosec) pulsed output at a high repetition rate (a few kHz to several tens of kHz), and with scalable average powers (tens to hundreds of Watts) in the visible wavelength region. These lasers are used in diverse applications for precision machining, cutting and drilling of materials, as drivers for frequency tunable lasers, as well as for high speed photography of fast moving objects. Development

of CVLs was initiated at BARC and has reached an advanced level of product maturity at CAT.

#### **High Repetition Rate Dye Lasers**

Dye lasers are the most versatile class of lasers, producing highly monochromatic output beams, which can be precisely tuned over large wavelength regions (UV to near IR), scaled to high powers by circulation cooling, and can be designed to produce continuous (CW) or intermittent pulsed beams, with pulse duration ranging from microseconds to femtoseconds. Nuclear energy establishments of several nations have actively pursued development of dye lasers for diverse applications in the nuclear fuel cycle, ranging from large-scale material processing to monitoring of process streams and effluents.

BARC has been playing a leading role in the indigenous development of high-repetition-rate (several kHz), high-average power, pulsed dye lasers pumped by CVLs with an aim to exploit its capabilities in the nuclear energy sector. Based on investigations carried out with CVL pumping, the prototype dye laser was demonstrated in the early 80s. The laser produced highly efficient (>10%), pulsed output at 5 kHz, with a bandwidth of 2 - 2.4 GHz with good short-term spectral stability. This was later improved to a long-term frequency stability of better than 300 MHz using active wavelength locking techniques. A number of these indigenous lasers have been profitably employed in an extensive range of experiments useful to DAE.



*Test bench set-up of prototype grazing-incidence-grating dye laser oscillator pumped by the green beam (left) from the copper vapour laser*

Special efforts are required for handling, storage, disposal, and recovery of commonly used organic dye solvents and dye solutions because of associated hazards and toxicity. An indigenous technology for synthesis and bulk production of high purity laser dyes was successfully developed under a collaborative programme at UDCT, Mumbai (now MUICT), under a BRNS project, and bulk quantities of Rhodamine 6G and Rhodamine 101 have been synthesized.

### Advanced tunable lasers

In order to seek better technology for the envisaged applications, BARC has initiated activities on advanced solid state coherent sources of tunable radiation, based on widely tunable media, such as the Ti:Sapphire laser and the optical parametric oscillator, which do not have the limitations associated with dye lasers, such as flow instabilities, material degradation, chemical hazards, etc. A third option, viz., organic solid-state laser, has already produced encouraging results with in-house synthesis of dye doped polymers.

### Laser Photo-Chemical Separation of Carbon Isotopes

The naturally occurring carbon isotope  $^{13}\text{C}$  (1.11%) is widely used in environmental science, biochemical science, healthcare, and industry. The current technology for separation of  $^{13}\text{C}$  isotope by low-temperature distillation has inherent drawbacks arising from low separation factor, high energy consumption,



*Photochemical reactor for laser separation of carbon isotopes*

and huge distillation tower leading to a high production cost. In order to meet a projected hundredfold increase in demand at lower cost, BARC has developed energy-efficient isotope selective infrared multiphoton dissociation (IRMPD) techniques for several halogenated methanes using pulsed  $\text{CO}_2$  laser, which are designed to produce 50% and 90% enrichment in single and two stage processes, respectively. A prototype facility has been built for demonstrating plant scale technology, consisting of a 5 Joule commercial laser, photo-chemical reactor, and product separator, with computerized process monitoring and control.

### INDUSTRIAL PLASMA TECHNOLOGIES

Industrial Plasma Technology is an advanced materials processing tool with many unique capabilities. Exotic properties of the plasma medium such as high temperature, high enthalpy and energy density, steep temperature gradient and presence of reactive species make it adaptable for a wide variety of material synthesis and surface engineering. The unique properties of the plasma such as high energy of the ions, which can sputter atoms from surfaces, have resulted in a host of non-equilibrium materials processing techniques. The technology is environmentally benign and economical with respect to material and energy inputs.

A comprehensive R&D programme on Plasma Science and Technology, which was initiated during the formative years of DAE has metamorphosed into a major activity contributing significantly to various stages of the advanced nuclear Fuel cycle programmess. As early as 1970, air and underwater plasma cutting systems were developed for cutting 50 mm thick 2 meter diameter steel plates for the Variable Energy Cyclotron (VEC) Project. This culminated in the development of a whole range of plasma cutting torches of 40 – 100 kW capacity operating in argon, nitrogen and hydrogen that could routinely cut 100 mm thick steel plates in air and 50 mm thick plates underwater.

In 1996, the Institute for Plasma Research (IPR), Gandhinagar, which was originally established as an autonomous institute under Department of Science and Technology (DST), in 1986, was brought under the umbrella of Department of Atomic Energy. IPR has been carrying out extensive experimental and theoretical research in plasma





*Plasma cutting Torch at BARC*

physics with special emphasis on applications to magnetically confined fusion research and industrial plasma. IPR has set up a Facilitation Centre for Industrial Plasma Technologies (FCIPT) in the Gandhinagar industrial estate to consolidate all activities related to development, demonstration, incubation and commercialisation of plasma technologies. Industry, research establishments and universities extensively use the advanced material characterisation facility to support their in-house research activities. Manufacture and supply of complete reactors to industries and research institutions is an integral part of the technology transfer activity.

### **Plasma MHD Generators**

The 1970's and 80's saw the evolution of the Indian Open Cycle Magneto Hydrodynamic Power Generation jointly executed by BARC and BHEL with Soviet collaboration, resulting in a gasified coal based pilot plant at Tiruchirapalli. Apart from MHD Generator technology, there have been a large number of spin-offs from this program to the Department. These include development of high temperature materials for plasma

processes, generalized MHD flow codes and a two phase liquid metal MHD generator that has greatly contributed to the development of the target for the ADS programme.

### **Plasma Surface Engineering**

A comprehensive plasma spray program was initiated in the seventies at BARC, that helped to overcome a large spectrum



*Controlled environment plasma spray unit at BARC*



*Microwave-ECR large volume plasma system*

of surface engineering barriers in the nuclear program. Several process innovations have been developed, such as reactive plasma processing for mineral processing and nano particle synthesis.

A wide spectrum of surface engineering systems including 40 kW plasma spray system, 2.45 GHz, 1.5 kW Microwave plasma processing system and Wire arc and plasma spray torch systems for depositing metals, alloys, ceramics and



*Wire arc spray unit at BARC*

composites has been developed in-house to meet the specialized requirements of the Department. Corrosion resistant ceramic-alloy duplex coatings for handling corrosive melt and ceramic-alloy composite coatings for strategic and specialized nuclear applications are some of the significant contributions in this area.

### **High Power Plasma Devices**

An array of high power plasma torches and test stands ranging from 40 kW to 300 kW have been developed at BARC for applications like cutting, plasma spray, alloy melting, waste processing, mineral processing etc. The expertise developed



*"Segmented arc plasma torch" developed at BARC*



at BARC has been particularly demonstrated in a joint program with ISRO for design, test and establishment of a segmented arc Thermal protection Test Facility (250 kW & 1 MW) at Vikram Sarabhai Space Centre (VSSC), Trivandrum.

### **Pulsed Plasma Nitriding**

Production and productivity loss due to wear and tear is a major industrial problem. Plasma nitriding is a medium temperature, low distortion surface engineering process capable of producing wear resistant material with tailored microstructure and hardness profile. IPR has developed state-of-the-art systems capable of extended unmanned operations. A number of plasma nitriding applications have been developed by FICPT on an industrial scale. For example, cavities and core inserts made of P20 material used in manufacturing toothpaste caps were nitrided to a surface hardness of ~850 HV and a case depth of ~300 microns with excellent surface finish and minimal distortion, in collaboration with Indo-German Tool Room, Ahmedabad. In field operations, the plasma nitrided components survived more than one million shots as against half a million shots of the untreated components. Other strategic applications include indigenisation of the nitriding of solar panel drive gear of ISRO satellites.

### **Plasma Ion Implantation**

Plasma ion implantation (PII) on metal surfaces by high voltage acceleration of ions from a conformal sheath is an inexpensive and less complex technique for surface modification to improve wear and corrosion resistance. FCIPT has developed

a 1-meter diameter 2-meter long ion implanter using 50 kV hard tube pulser and DC and inductively coupled radiofrequency plasma source. Processes developed include nitriding of aluminum, titanium and chromium for increased corrosion resistance and hardness. The PII facilities have promoted research collaboration with a number of institutions such as IIT, Kharagpur and National Metallurgical Laboratory.

### **Plasma-Enhanced Chemical Vapour Deposition and Polymerisation**

Plasma enhanced Chemical Vapour Deposition (CVD) and polymerisation can provide thin films on metals and polymers, with surface hardness, wettability, good optical properties and corrosion protection. Glass-like Barrier Coating (basically consisting of polymerised silicon based thin films), anti-reflection Coating on Solar Cells, optical coating of metal mirrors and fluorocarbon coatings on surfaces are some important applications developed at IPR.

### **Plasma Etching and Cleaning of Surfaces**

Plasma cleaning is an environmentally benign cleaning process for removing 1 to 5 micron thick organic contamination on metal, polymer and ceramic surfaces and for removal of metal residue from hybrid circuit, PCB, etc. Applications developed for industry include etching of plastic perfume bottles to enhance the adhesion of glossy colour coating, etching of printed circuit boards for improved soldering, etching of polypropylene scooter parts for paint adhesion, etc.

### **Plasma Pyrolysis of Medical Waste**

Safe disposal of medical waste is an important and topical problem due to rapid growth in health care facilities. Oil fired incineration produces harmful products due to insufficient temperature in the process chamber. Due to the high temperatures reached in plasma pyrolysis (more than 10,000 degrees), the intense plasma heat causes the molecules to disintegrate, forming fragments of compounds, such as methane, carbon monoxide, hydrogen, carbon dioxide and water. The recombination of the plasma also produces intense ultraviolet radiation, which can destroy pathogens completely. This is an advantage unique to plasma pyrolysis. The volume reduction can be as high as 95 %.

In collaboration with TIFAC, IPR has developed a pyrolysis system for safe destruction of medical waste. The technology has been validated in field trials of a prototype system at the Gujarat Cancer Research Institute, Ahmedabad. Bacterial destruction has been confirmed. Emissions meet CPCB norms. Pyrolysis technology has been adapted for safe disposal of plastic carry bags for ecologically sensitive locations like Andamans and Nicobar Islands, Sikkim, Goa and Himachal Pradesh under a DST sponsored project. The first unit was commissioned in Goa in March, 2004.

### **Destruction of Volatile Organic Contaminants**

Non-thermal plasma environments exploit the high chemical reactivity of radicals and energetic electrons to dissociate toxic molecules and defragment them into non-toxic compounds. A number of types of atmospheric pressure and non-equilibrium plasma sources have been developed by IPR for treatment of volatile organic compounds from vehicular and industrial sources, which is a major source of atmospheric pollution.

### **Plasma Sources, Power Systems and Diagnostics**

A spin-off from the basic research carried out at IPR is the development of a variety of plasma sources, specialized power drivers and diagnostic instruments. The growing research activity in plasma physics and plasma processing in universities and the prohibitive cost of imported systems makes a good case for indigenous development and supply of these systems.

ECR-plasma sources have been extensively applied to numerous low-pressure plasma processing applications such as etching, deposition and ion implantation. To meet the indigenous demand for this system for research applications, IPR has developed an ECR microwave plasma system using a

*A number of patent applications including one PCT application on Constricted Anode Plasma Source (CAPS) have been filed. Four patents have been awarded.*

2.45 GHz 800 Watt commercial magnetron. FCIPT has also designed and developed a variety of power sources ( a few hundred watts to more than 100 kW) based on solid state and hard tube devices for such plasma loads as abnormal glow

discharges, magnetron sputter sources, RF capacitive and inductive sources, vacuum and atmospheric arcs, pulsed corona discharges etc. Electronically swept Langmuir probes with radiofrequency compensation and vacuum drives for automated positioning have been developed by IPR. Simpler probe systems for basic plasma research are now being supplied to universities and research institutions.

FCIPT has also supplied research and industrial grade nitriding systems to a number of national laboratories and research institutions. Plasma nitriding technology has been transferred to M/S Fluidtherm Technologies, Chennai, an established manufacturer of heat treatment systems. M/S Bhagwati Spherocast Ltd. has been licensed for commercialising the medical waste pyrolysis technology. Under DST funding, the company is building commercial prototypes for demonstration of the technology in major hospitals dispersed around the country.

### Minerals and Ceramic Processing

DC non-transferred arc plasma torch based reactors have been developed at BARC for processing of minerals. The experimental system has been successfully used for plasma dissociation of zircon and processing of ilmenite. FCIPT has also developed a number of small and medium power capacity non-transferred plasma torches for ceramic and mineral processing for similar applications. Successful in-flight dissociation of zircon sands was demonstrated by IPR in collaboration with M/S C. Z. Zircon Ltd., Himachal Pradesh under a DSIR project. Other developments include spheroidization of alumina and chromia ceramic powders to produce free flowing particles, with high yield and low specific energy consumption.

### Other Applications:

BARC has developed a 450 kW Plasma Cold Hearth Melter (PACHM) for melt refining of scrap as well as primary metals and alloys like uranium, zircalloy, titanium, Tantalum, Niobium etc.

The adoption of plasma melting technology has the potential of producing premium grade metal in less number of process steps than vacuum arc melting, resulting in great improvement in process economy.

A plasma torch based aerosol generator has been developed at BARC, which has now been integrated with the



*Plasma melters developed at BARC*



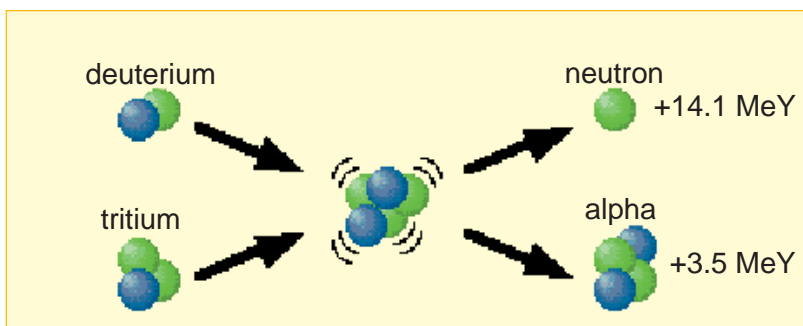
Plasma aerosol generator

Nuclear Aerosol Test Facility(NATF). The facility is being used to generate nuclear aerosols and to study their onward transport and settling behavior. The system has been adapted to generate ceramic nanoparticles using reactive plasma processing technique.

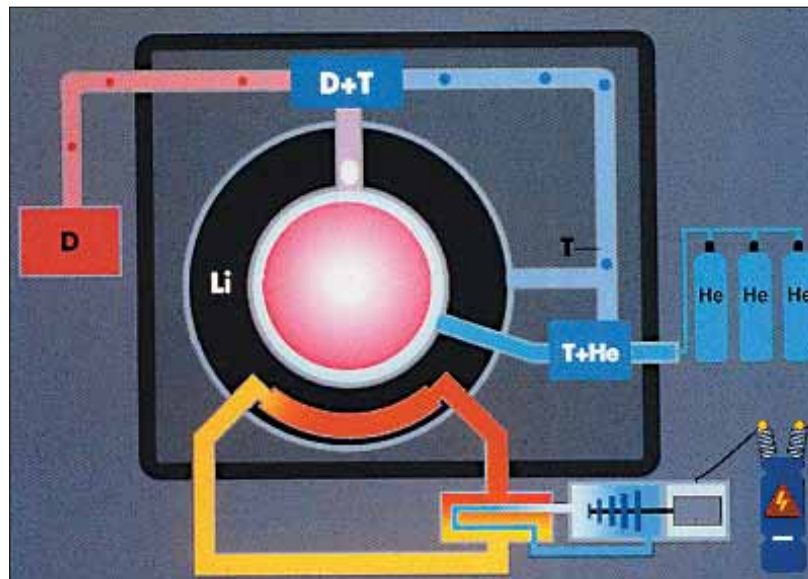
### Computer Simulation and Diagnostics

The development of plasma technology is critically dependent on a good theoretical understanding of the processes taking place in a plasma. At BARC, a variety of codes related to Computational plasma dynamics, Plasma particle interaction, Non-linear arc dynamics, arc thermophysics, particle nucleation and growth and radiation hydrodynamics have been developed to simulate the industrial plasma as close to reality as possible.

Thus, basic infrastructure and methodology has been established for converting the knowledgebase in plasma physics into products and processes. With the increasing awareness of the critical role of plasma techniques in strategic applications,



Schematic of fusion reaction between deuterium (D) and tritium (T) atoms



Artistic view of a futuristic fusion reactor, using D and T as inlet fuel gases for the plasma. Blanket in the form of Li wall, which breeds further tritium in to the reactor is also shown

it is believed that these applications would grow rapidly.

### FUSION RESEARCH

Fusion research is mainly carried out at IPR, Ahmedabad. It is presently based on Tokamak device. Tokamak is an experimental device comprising of a toroidal doughnut shaped metal vacuum vessel surrounded by a large number of magnetic field coils . TOKAMAK is the acronym for Russian word “Toroidalnya Kamera Magnetrnaya Katushka” meaning the toroidal chamber and magnetic coils. This device is used to produce, confine and heat the plasma. The plasma is confined in the vacuum chamber using toroidal magnetic field produced by external toroidal field magnets, placed around the vacuum chamber, and the poloidal magnetic field produced by internal plasma current. The plasma is produced in the toroidal vacuum vessel by gas breakdown using Ohmic transformer, which is also used to drive current in the plasma and thus heat the plasma for a period fixed by the flux stored in the Ohmic transformer. The vacuum vessel, the magnetic field coils and the Ohmic transformer are, thus, the essential components of a tokamak device.

### TOKAMAK - ADITYA

Major experimental work in the field of magnetically confined hot plasma, at IPR, is currently being carried out in tokamak



*A view of first indigenous experimental tokamak ADITYA at IPR, shown along with the associated subsystems*

“ADITYA”. ADITYA is the first Indian tokamak, conceived, designed, largely indigenously fabricated and erected at IPR. Commissioned in 1989, it has a plasma of circular cross-section with major radius 0.75 m and minor radius of 0.25 m. A 100 kA plasma current can be sustained for about 100 ms. This current confines the plasma as well as heats it through resistive heating. In order to further heat the plasma, auxiliary heating system using radio frequency waves has been incorporated. A large number of diagnostics are deployed to measure various plasma parameters.

### Magnets

Special machining, grit blasting and insulation bonding techniques were developed for fabrication of the large volume, large field, and high current magnets for ADITYA with the help of Indian industries. All the coils for ADITYA were fabricated by M/S BHEL, Bhopal under close supervision of IPR.

*“...An unique feature of our Department is its nurturing of fundamental science and associated technology development, while maintaining strong focus on applications which are making a significant impact on the everyday life of many Indians. Let us march with vigour on this twin-pronged road towards future...”*

**- P. K. Kaw, Director, IPR**

### Vacuum System

The vacuum vessel is a torus of major radius 75 cm with a square cross-section of side 60 cm, with a volume of  $\sim 16 \text{ m}^3$  and total surface area of  $\sim 75 \text{ m}^2$ . The vessel was subjected to various wall treatment procedures including electropolishing, ultrasonic cleaning, and baking, in order to be compatible for ultra high vacuum (UHV)  $\sim 10^{-8}$  torr. For obtaining plasmas with low impurity content as well as for achieving low desorption rate from vacuum vessel wall, a combination of glow discharge cleaning and low temperature pulsed discharge cleaning is used. Techniques for large volume UHV systems were developed for the first time in the country, during the fabrication and commissioning of ADITYA vacuum system.

### Pulsed Power System

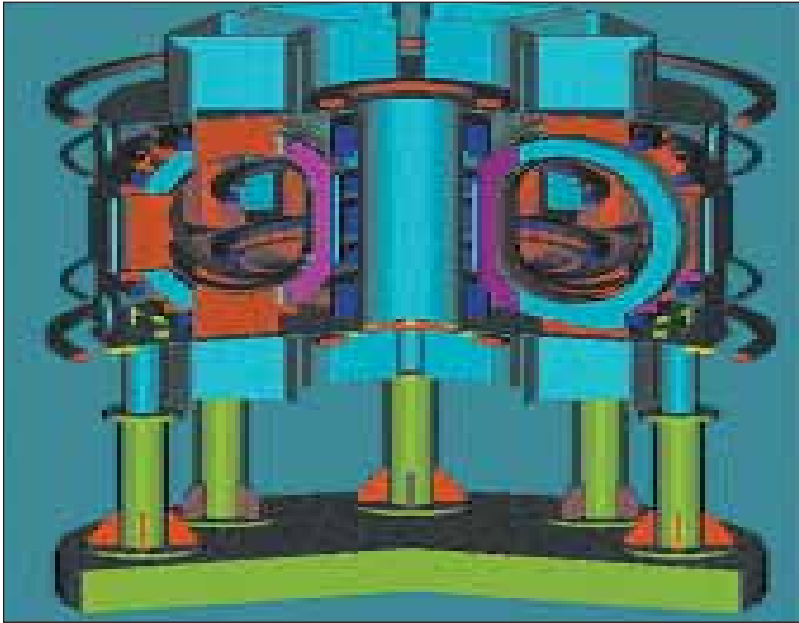
Pulsed power is required to energise the magnetic field coils of ADITYA. Due to the high peak power and energy requirements of each of the coils per pulse, the overall demand for all loads exceeds a peak power level of 50 MW per pulse. A complex and sophisticated power system, called ADITYA Pulsed Power System (APPS), extracts electrical energy from the Gujarat Electricity Board (GEB) grid and generates the current pulses of specified shapes, amplitude and duration.

### ADITYA Upgrade

ADITYA has been upgraded recently to obtain better performance. A 20 – 40 MHz, 200 kW Ion Cyclotron Resonance Heating (ICRH) system has been integrated to the vacuum vessel. A 28 GHz, 200 kW gyrotron based electron cyclotron resonance heating (ECRH) system has been successfully commissioned on the tokamak. ADITYA is regularly being operated with the transformer-converter power system with  $\sim 100$  msec 80 - 100 kA plasma discharges at a toroidal field of 8.0 kG.

### Steady State Superconducting Tokamak (SST-1)

A steady state superconducting tokamak SST-1 is presently in the final stage of assembly at IPR. SST-1 is a large aspect ratio Tokamak, configured to run elongated plasma with pulse duration of 1000 s. It has a major radius of 1.1 m and minor radius of 0.20 m. A plasma current of 200 kA will be produced



*Cross-sectional view of Tokamak SST-1*



*A view of SST-1 tokamak under erection & assembly at IPR*

in a toroidal field of 3 T. Radio frequency waves in different frequency bands will be used to drive the current and heat the plasma for 1000s. Superconducting magnetic field coils are deployed to produce the toroidal and poloidal fields in SST-1.

### **Magnet System**

Sixteen superconducting Toroidal Field (TF) magnets and nine superconducting Poloidal Field (PF) magnets, are used in SST-1. Several technologies and processes involving the winding of large volume large size superconducting and resistive

magnets, control of the spring-back behavior of non-circular D-shaped TF coils, consolidation of the winding packs and vacuum pressure impregnation (VPI) of large volume coils have been established. A superconducting Cable-in-Conduit Conductor (CICC), based on NbTi superconductor with high copper to SC ratio in the strands has been designed and manufactured, for the first time, for use in Tokamak Magnets. The CICC was manufactured by M/S Hitachi Cables Ltd, Japan, under close supervision of IPR. A total of ~ 15 km of the cable, in single lengths of 600 m each, has been manufactured and used in the SST-1.

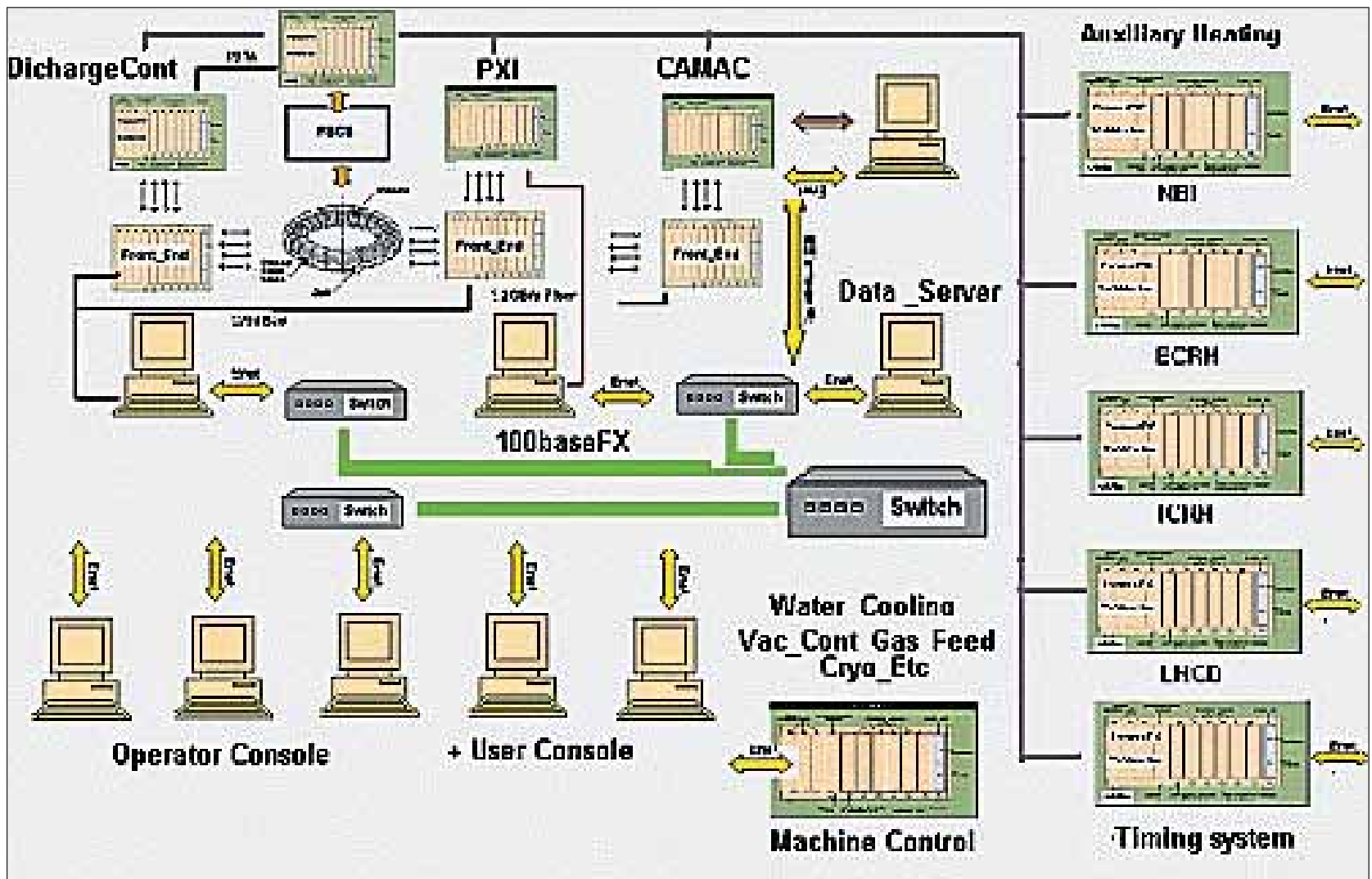
The insulation system for all the superconducting winding packs, as well as for the resistive magnets was developed by M/S Bharat Heavy Electricals Ltd. (BHEL), Bhopal in close collaboration with IPR. M/S BHEL developed a set of new raw materials e.g. specially treated glass fiber tape and *BHELMAT-G*, which is a porous glass fabric and chopped strand mat product, for this purpose. It is for the first time that such large volume specially shaped superconducting coils are made in the country.

### **Cryogenic System**

The superconducting magnet system (SCMS) in SST-1 has to be maintained at 4.5 K in presence of steady state heat loads. The magnets will be cooled using forced flow of supercritical helium (SHe). For meeting this objective, a Liquid Helium plant with a capacity of 400 W refrigeration at 4.5 K and 200 l/h liquefaction at the pressure 1.2 bar has been designed and fabricated by M/S Air Liquide DTA, France and installed at IPR. A cold circulation system, for the flow of SHe through the SC coils in a closed cycle, forms part of the Liquid Helium plant. A total He gas inventory of ~ 3100 m<sup>3</sup> is required for the refrigerator/liquefier and SCMS. Two high-pressure tanks, each of 25 m<sup>3</sup> capacity at 150 bar provide storage equivalent to twice of the required inventory. A medium pressure storage system (MPSS) at 14 bar with a total capacity of 272 m<sup>3</sup>, provides capacity to store total inventory as pure gas.

### **Neutral Beam Injection System**

A steady state Neutral Beam Injection (NBI) system is envisaged for SST-1. The Steady state Neutral beam injector capable of delivering neutral beam power of 1.7 MW at 80 KeV



Control system lay-out for SST-1

has a stringent requirement of a beam line which imposes not more than 5% reionization loss during the power delivery period of 1000 s. This necessitates making a provision of in-situ pumping at the rate  $10^6$  l/s. In the present case, use is made of a set of 10 Cryocondensation pumps at 3.8 K, dispersed along the beam line. The prototype pump was initially tested for its performance with  $\text{CO}_2$  and the pumping speed determined as 35,000 l/s. In the second stage the pump was tested for its performance with  $\text{D}_2$  and the corresponding speed determined as 100,000 l/s.

An important system in the NBI program is the power supply and the data acquisition and control system. The development of regulated high voltage power supply (14kV/ 450kW, fast transient, continuous duty) was initiated in 1997. High power multi-secondary transformers with HV insulations & switched

power modules have been designed, manufactured, tested and erected at site.

Other technological achievements in the SST-1 project include the Ion Cyclotron Resonance Heating system, the Lower Hybrid Current Drive system, and Electron Cyclotron Resonance Heating system, to additionally heat and non-inductively drive plasma current to sustain the plasma in steady state for duration of up to 1000 sec. A high power transmission line has been indigenously fabricated and commissioned to deliver the power to the antenna, positioned inside the Tokamak vacuum vessel, through a sophisticated UHV compatible interface.

A host of control electronic subsystems have been developed and implemented using PC control bus logic, along with CAMAC & PCI interfacing architecture.



The Indian industry has played an important role in the development of technology and for the manufacture of the components of SST-1 as well as Aditya. These include magnet technology for copper and superconducting magnets, cryogenic technology, high vacuum and ultra high vacuum techniques, high heat flux removal techniques, high power RF technology and energetic neutral beams production and injection technologies. Some of the examples of the sophisticated products of such development are regulated HV power supplies, in the range of 10-120 kV, up to 10 MW output with fast transient response (mS) and the country's first large area (~1.4 m<sup>2</sup>) cryopump with a pumping speed of ~ 10<sup>5</sup> l/s for D<sub>2</sub> at 4.2 K (Liquid He temperature).

### Accelerator Driven Sub-critical Reactor System

Accelerator Driven Sub-critical reactor system (ADS) is one of the emerging technologies, which can have a major impact on the nuclear energy scenario. It is a sub-critical reactor device for producing nuclear power, which would operate with high neutron economy and safety. This can be used for a variety of nuclear applications such as power production, fuel breeding and incineration of the troublesome long-lived actinide and fission product waste. In an ADS system, an intense proton beam of energy of about 1 GeV bombards a heavy element target such as lead to produce neutrons by the "spallation" reaction. These are called "external" neutrons in contrast to those resulting from fission in a conventional critical reactor. These external neutrons impinge on the sub-critical core of the fissile fuel and get multiplied by the terminating fission chains. With a continuous feed of proton beam on to a spallation target, a steady fission rate in the sub-critical reactor can be maintained, at a thermal power level which is determined by the value of the multiplication factor (k) and the external neutron source strength.

The capability of spallation reactions was recognized long time ago as a possible way to create copious neutrons and breed new fissile materials. Programmes were indeed initiated during 1950s in USA and Canada with Material Test Accelerator (MTA) and Intense Neutron Generator (ING). But these could not be really exploited as such, mainly for economic reasons. In the recent years, however, there has been increasing concern over the management of the spent reactor fuel, particularly with

regard to the troublesome long-lived radiotoxic transuranic elements (TRUs). The disposal of such long-lived actinides in the deep underground geological repositories is yet to be established as an environmentally benign technology. Moreover, actinide nuclei, being fissionable, are also reservoirs of nuclear energy and it would be economically desirable to use them as nuclear fuels rather than throw away as waste. Therefore, a robust disposal option seems to be the partitioning and transmutation (P&T) of the offending isotopes of long-lived TRUs and fission products in a nuclear reactor. However, due to nuclear and other physical characteristics of the TRU-based fuels, this scheme has its own problems related reactor safety and fission power controllability. This is where the ADS technology seems to score over other options. In a sub-critical system (ADS), the fission rate is controlled by a neutron source triggered by externally supplied beam of high-energy protons incident on a non-fissile element such as lead. The fission power can be regulated by changing the intensity of proton beam (i.e., the beam current). Being always sub-critical, this system obviates the need for parasitic capture of neutrons to control reactivity and its implications on reactor safety. Since the ADS concept does not rely on fuel properties (e.g. the effective delayed neutron fraction and Doppler coefficient of fuel, void coefficient for the coolant/moderator etc.) for its intrinsic safety, TRU incineration would be safer in sub-critical rather than conventional critical reactor (fast or thermal) designs. This fact has prompted several R&D programmes worldwide on various scientific and technology development aspects of the ADS.

A typical full scale ADS, generating fission power of the order of several hundreds of MW, shall consist of the following technologically distinct sub-systems.

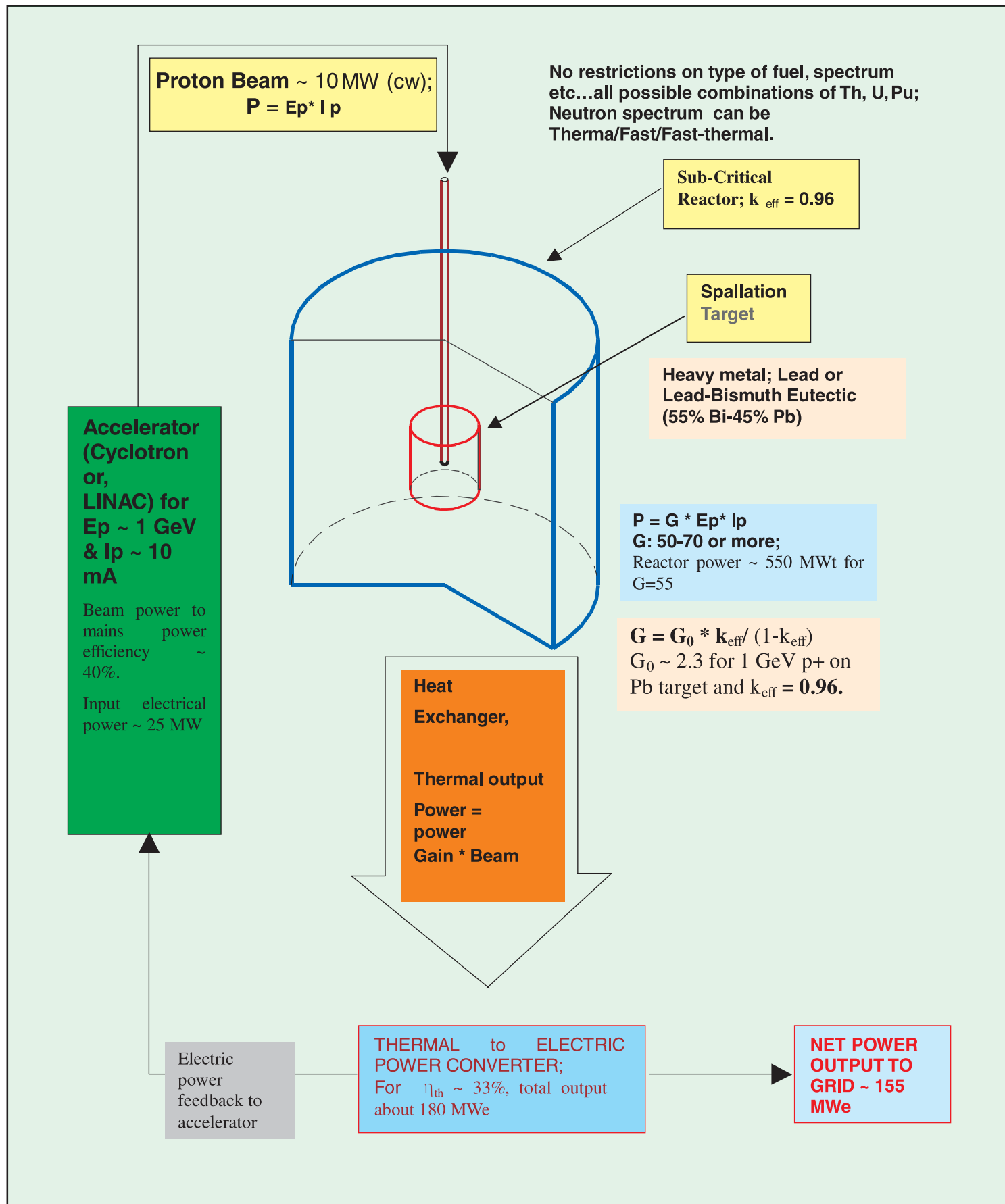
(a) High-Intensity Proton Accelerator (HIPA) delivering 1 GeV and, typically, 10 mA (cw) proton beam on a heavy element target/s which is physically located within a sub-critical core.

(b) High-power spallation neutron source in the form of heavy element target/s stopping the proton beam which would deposit heat energy of ~10 MW in a small volume of the order of tens of liters.

(c) Sub-critical reactor – the power generating part in ADS that is very similar to a conventional reactor but incorporating one or more spallation targets.

For the Indian nuclear programme, which involves utilization of its vast thorium reserves, the concept of ADS appears to be quite relevant and attractive. Therefore, the feasibility of ADS in the Indian context has been the subject of detailed studies at BARC from the mid-nineties, when a renewed thrust to the concept of ADS, as an energy amplifier was given by the CERN team led by Prof. Carlo Rubbia. In view of the existing gaps and technological challenges in achieving 1 GeV proton beams with beam currents of the order of 10 mA or more, BARC studies were focused on ways to achieve large thermal fission power with a lower accelerator beam power. The study indicated that the proton beam current of the driver accelerator could be substantially reduced by way of one-way coupled design of the sub-critical reactor of hundreds of MW of fission power. In view of the importance of ADS for thorium utilization, a roadmap for the development of ADS in India was evolved during 1999-2001, by an expert team chaired by Dr. S.S. Kapoor, at the initiative of Dr. Anil Kakodkar, then Director, BARC. The simultaneous development of scientific and technological aspects of main ADS sub-systems of accelerator, target and reactor in stage-wise manner, was the main recommendation of this study group. It was also realized that many new innovations and improvements were required in the existing state-of-art accelerator technologies.

Following this roadmap, major activities in ADS have started in BARC and some other units of DAE, notably in CAT, Indore and VECC, Kolkata. The design and development of a high current (~30mA) proton Linac of 10-MeV Radio-frequency quadrupole (RFQ) and Drift-tube Linac and the required 1-MW RF power supplies, has been progressing at BARC. Design studies on a 1GeV proton synchrotron for spallation neutrons have been initiated at CAT, Indore. Studies on interactions and particle transport in the spallation target bombarded with a high-energy proton beam have also started. An experimental development programme has been initiated for utilizing the attractive nuclear and physical properties of the heavy elements such as lead and bismuth as a spallation target. In addition, conceptual reactor physics and system studies are being carried out for innovative possibilities with the ADS. These include one-way coupled booster reactor concept, thorium burner concept, enhancement of fuel burn-up before discharge and maximization of power from thorium in a hybrid thorium-fissile fuel core. This is currently an area of intense research with interdisciplinary and inter-institutional collaborations, which has promising technological applications.



Schematic diagram of Accelerator Driven Sub-critical System (ADS) with relevant technical details