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Accelerator development in India

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Abstract. Accelerator development in India is reviewed with special emphasis on indigenous effort. It started with the 4 MeV cyclotron at the Saha Institute of Nuclear Physics, grew substantially with the installation of the Van de Graaff accelerators at Trombay and really came of age with the 224 cm Variable Energy Cyclotron at Calcutta, which resulted in considerable fall-out of technology. Simultaneously electron linac development has also taken place. Thus the stage is set for developing new types of accelerators such as the electron storage ring synchroton, and a proton/heavy ion synchrotron.

Keywords. Accelerators; cyclotron; Van de Graaff; Tandem; linac; technology fall-out.

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1. Introduction

Charged particle accelerator development in the world started in the late 1930s with the primary motivation of seeking fundamental understanding about the structure of the atom. In the last half a century there has been a phenomenal growth all over the world in the field of accelerator technology and a variety of accelerators have been developed for fundamental research as well as applications. It is, therefore, very important to review the development of accelerators and consider the future prospects of accelerator technology in India.

Accelerator development in India started in the 1940s, when a project was undertaken at the Saha Institute of Nuclear Physics, Calcutta to build a 38″ cyclotron modelled after the cyclotron at Berkeley (SINP, 1983). Except for the magnet yoke and pole pieces which were imported, all other components were fabricated indigenously. In 1960, it delivered an internal proton beam current of 50–70 μA at 4 MeV and later an external beam current of 0·1 μA.

At the Tata Institute of Fundamental Research, Bombay, some work was done towards building a 1 MeV cyclotron in the 1950s, though it was not made fully operational. At the same time, the 300 keV open air Van de Graaff accelerator was built and operated (George *et al* 1959) and development work on a 1 MeV electron linear accelerator was carried out.

Simultaneously 400 keV Cockroft-Walton accelerators were built at the Saha Institute and the Bose Institute, Calcutta, a 1 MeV Cockroft-Walton accelerator was bought and installed at the Tata Institute (TIFR 1945–70) and a 150 keV neutron generator was built at the Aligarh Muslim University, Aligarh.

For the first time a large accelerator was available in India when the 5·5 MeV Van de Graaff accelerator purchased from the High Voltage Engineering Corporation (HVEC, USA) was installed at the Bhabha Atomic Research Centre, Trombay in 1962 (Divatia *et al* 1962). Though the accelerator was purchased, the switching magnet and the beam transport system were built indigenously. Some time later, a 2 MeV Van de Graaff accelerator, also purchased from the HVEC, was installed at the Indian Institute of Technology (IIT), Kanpur, and a 2 MeV electron Van de Graaff accelerator was built indigenously at the Indian Institute of Science (IISC), Bangalore. Using these accelerators stimulated the scientists and a need for bigger accelerators was felt. H J Bhabha convened a meeting of scientists on 3 August 1964 at the IISC to consider this question. After the deliberations, he summed up as follows:

"I think the result of this meeting has been extremely instructive and very fruitful. I am convinced that there is a large field of operation in nuclear physics where fruitful work can be done with these machines. The following general situation seems to emerge in my mind. One is that the two machines the Tandem and the AVF accelerator are complimentary. It may be possible for an AVF machine with the help of elaborate equipment to do what a Tandem does. If we decide to go in for a Tandem, it seems clear that we should buy one. The technology of an AVF is entirely different and this is the field, except for the cyclotron at Calcutta, which has been neglected in India. This is the field which I think should now be developed. We are in a position now to enter in a new field of building of accelerators. Therefore, I myself favour the idea of going in for an AVF machine."

2. Variable energy cyclotron at Calcutta

The Atomic Energy Commission decided in 1968 to construct a 224 cm diameter Variable Energy Cyclotron (VEC) at Calcutta indigenously adopting the design of the 88 inch cyclotron at the Lawrence Berkeley Laboratory.

Specifications of the cyclotron are given in table 1. An overall view of the cyclotron and the beam transport lines after construction is seen in figure 1, and a close up of the cyclotron is seen in figure 2. Various stages of progress of the VEC have been reported at International Conferences on Cyclotrons and their applications (Divatia *et al* 1984; Chatterjee *et al* 1981; Divatia 1979). A brief description of various components of VEC and the technologies involved is presented here.

Table 1. Design parameters—VEC Calcutta.

Beam		Hill gap	19·05 cm
Maximum energy	130 Q^2/A MeV	Valley gap	29·97 cm
Internal beam current	1 mA	Maximum hill field	21·1 kGa
External beam current	100 μA	Maximum valley field	14·1 kGa
Energy resolution		*Acceleration system*	
a) Unanalysed beam	0·5% (FWHM)	Dee	1; 180°
b) Analysed beam (1 mm slit)	0·024% (FWHM)	Frequency range	5·5–16·5 MHz
		Dee voltage	70 kV (Max)
Magnet			
Pole diameter	224 cm	*Extraction system*	
Spiral sections	3	Deflector voltage	120 kV (Max)

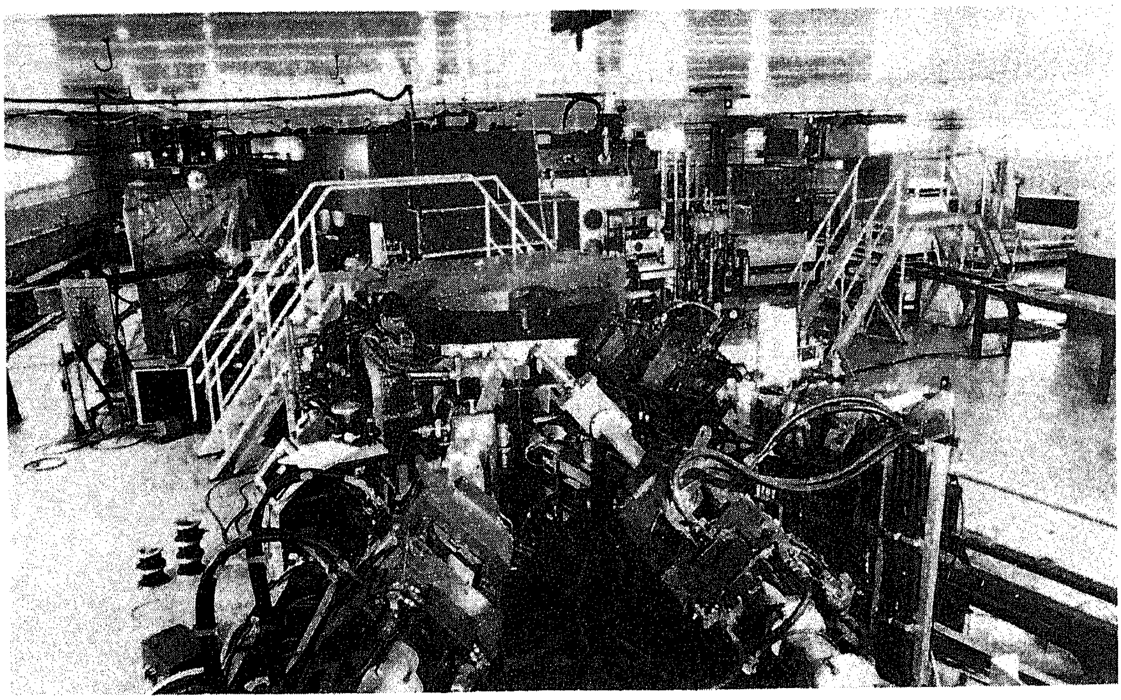

Figure 1. Overall view of the VEC, Calcutta and the high intensity beam transport lines in the vault.

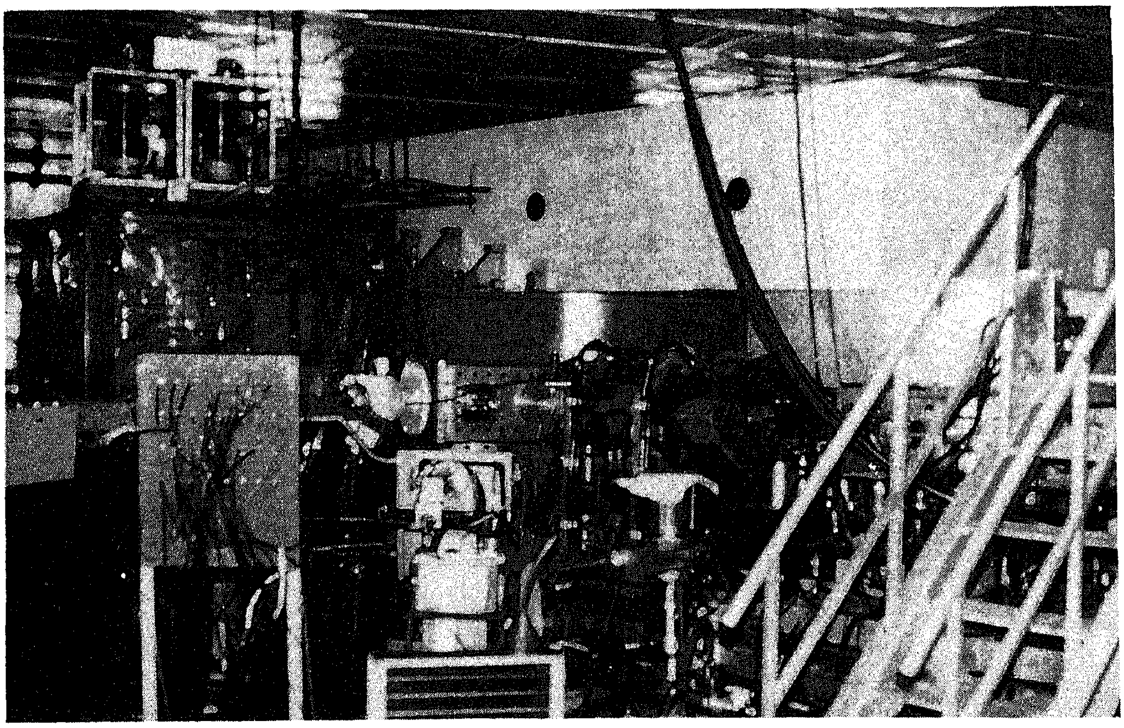

Figure 2. A close-up of the cyclotron showing the main magnet with the main coil and the first quadrupole magnet near the exit port on the dee chamber.

2.1 *Magnet*

The most challenging job from the standpoint of indigenous effort was that of constructing the 260 tonne magnet. Since large-sized rolled plates of the requisite quality and size were not available, it was decided to cast the necessary steel blocks, and machine them. The Heavy Engineering Corporation (HEC), Ranchi was the only agency capable of delivering the job, and they agreed to do it. They were highly successful in casting the magnet-quality steel, with carbon content less than 0·1 %. Table 2 shows a comparison of the steel composition achieved and that specified. The machining of the magnet, including the 3 spiral-shaped pole tips of the magnet was also carried out successfully to the required accuracy. Figure 3 shows the assembled magnet and figure 4 shows the accuracy achieved in the magnet gap.

Table 2. Comparison of specified and achieved steel composition for VEC magnet.

	Specified composition (%) (maximum)	Achieved composition (%) (typical)
Carbon	0·12	0·11
Silicon	0·35	0·25
Manganese	0·50	0·30
Phosphorous	0·04	0·011
Sulphur	0·05	0·023
Iron	Balance	Balance

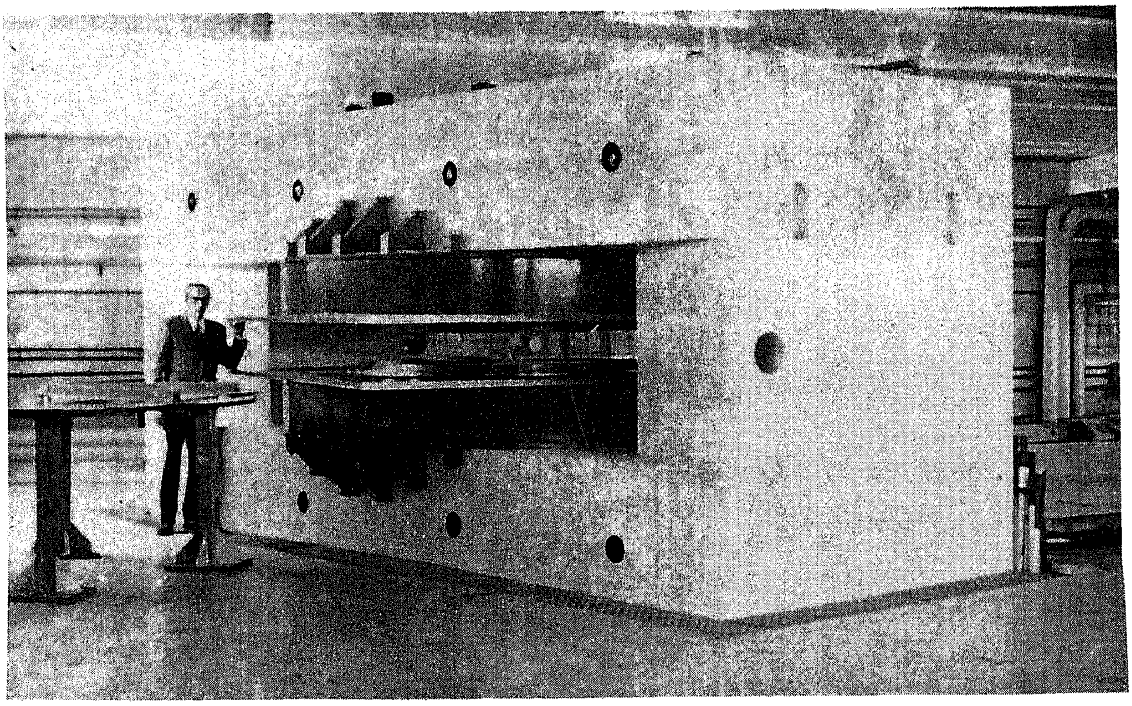

Figure 3. The assembled 260 tonne main magnet frame and the main coils during assembly stage.

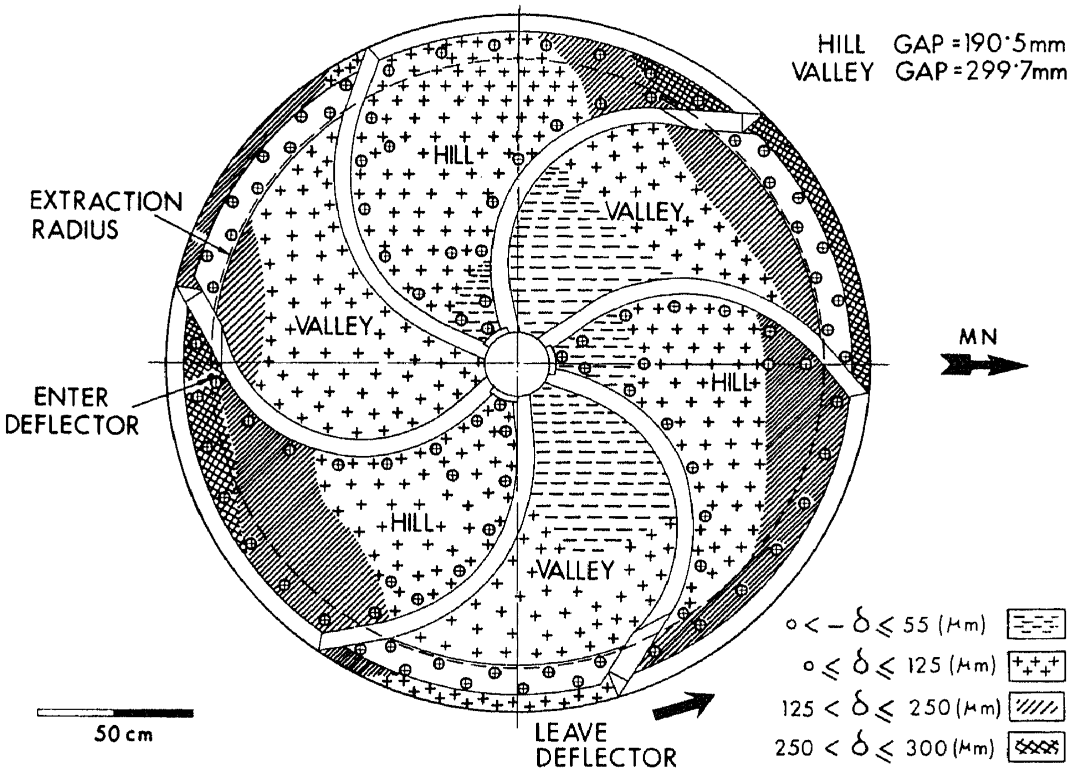

Figure 4. Deviation (δ) from the required magnet gap.

The main magnet coils, made of ETP copper of 29 cm square cross-section with a 1·9 cm hole in the centre for cooling water, providing 5,60,000 ampere turns, were made by the Bharat Heavy Electricals Limited (BHEL), Bhopal to the required accuracy. Similarly the technology of winding and epoxy potting the trim and valley coils was also evolved at the BHEL and fabrication completed to full satisfaction.

The main magnet coils, 17 trim coils and 5 sets of valley coils, all require independent power supplies with stabilized currents. The building of these power supplies was totally an in-house effort, undertaken by the personnel of the VEC Centre. For some of the power supplies special water cooled transformers were built. Table 3 shows the specifications of these power supplies and figure 5 shows the inside of a trim coil power supply. The peak power consumption for the main magnet alone is about 1 MW.

Table 3. Power supplies for VEC.

Unit	No.	Ratings	Remarks
Main coil	1	150 V, 2800 A	SCR controlled current regulated to 0·01 %
Trim coils	17	6–24 V, 750–2500 A	Series transistor current regulated to 0·01 %
Valley coils	5	15 V, 300 A	Unregulated
Oscillator	1	20 kV, 20 A	Series tube fast crowbar
Ion source	1	600 ARC Voltage 500 A filament current	Series tube SCR controlled
Deflector	2	120 kV, 5 mA	Voltage multiplier
Switching magnet	2	50 V, 300 A	SCR controlled 0·01 %
Analysing magnet	1	150 V, 500 A	SCR/transistor NMR sensing 0·001 %
Quadrupole magnet	5	30 V, 300 A	Regulation 0·1 %

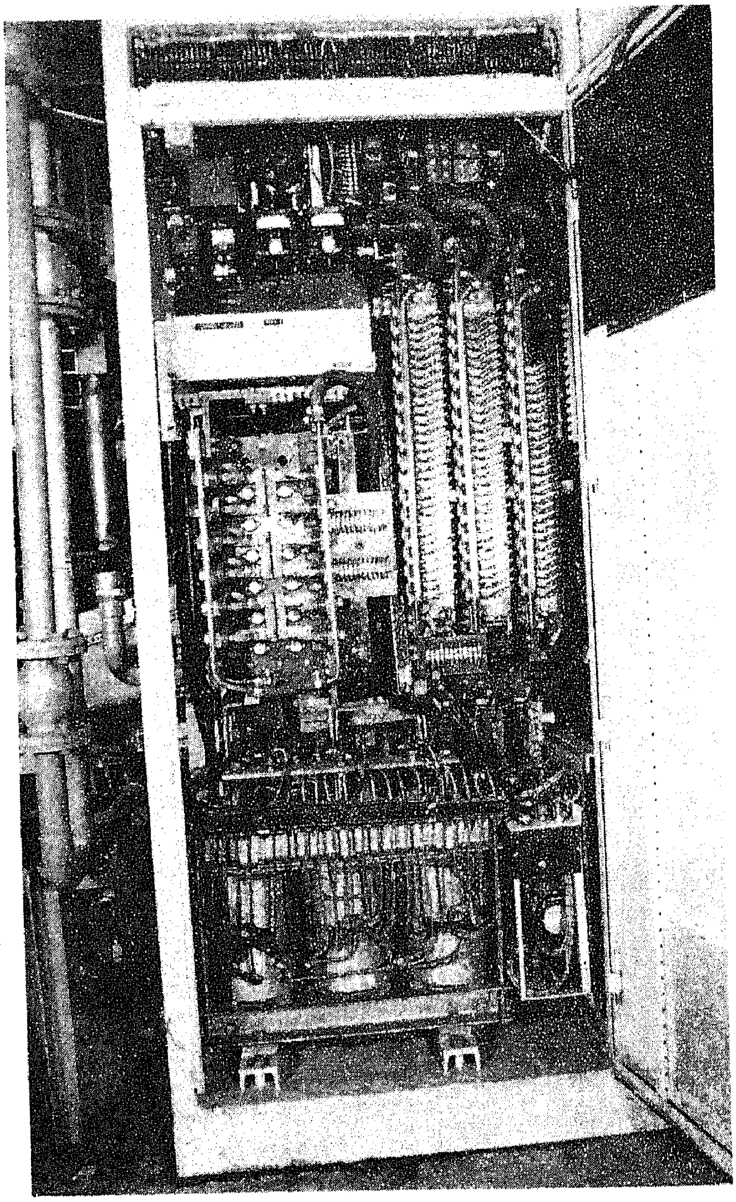

Figure 5. A typical inside view of a regulated power supply.

The total quality of the magnet can best be judged by examining the B *vs* I curve, shown in figure 6. It can be seen that the curve is in excellent agreement with a similar curve for the Berkeley cyclotron magnet.

2.2 *Radiofrequency system*

The radiofrequency system of the VEC is a 400 kW RF oscillator system in the frequency range 5·5–16·5 MHz, using panel movement for frequency variation. The resonator tank, made from 38 mm thick copper clad steel plates, measuring 2·36 m × 3·13 m × 2·39 m, was fabricated at the Garden Reach Shipbuilders and Engineers Ltd. Calcutta and the dee, dee stem and panels, made from ETP copper, were fabricated at the Central Workshops, BARC, Bombay. The RF panels inside the resonator tank are shown in figure 7.

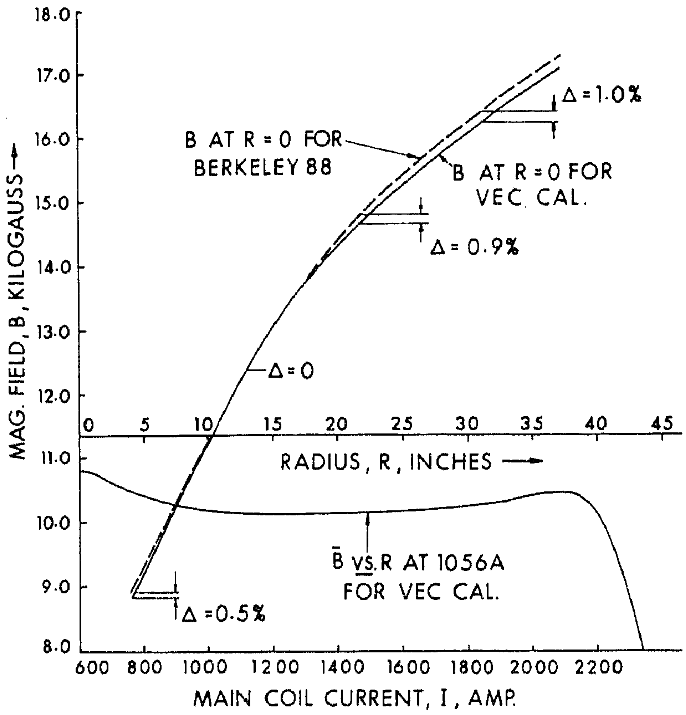

Figure 6. *B vs I* characteristics of the main magnet; lower portion shows average magnetic field $\bar{B}$ *vs* radius.

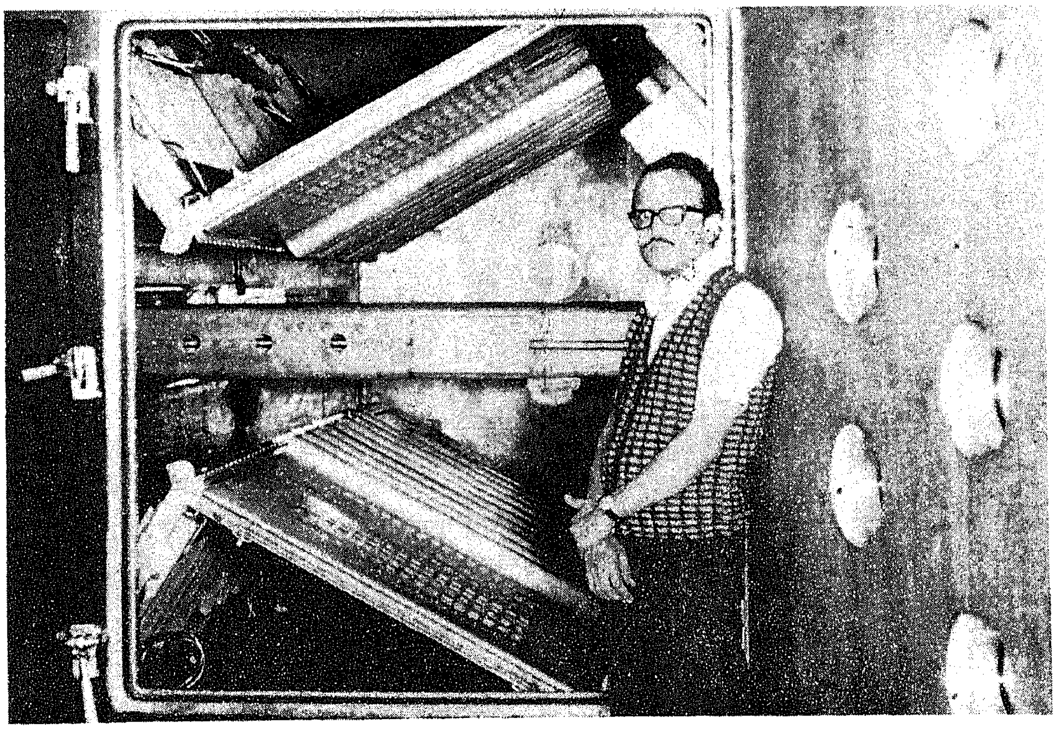

Figure 7. Radiofrequency movable panels and the dee stem inside the resonator tank.

In the earlier stages, an RF self-excited oscillator system based around the RCA 6949 triode was used. Later on, for reasons of economy and more reliable and stable operation, an RF system of MOPA configuration with the RCA 4648 tetrode has been used. Figure 8 shows a block diagram of the system. The high voltage anode power supply for the RF system was built by the in-house VECC group.

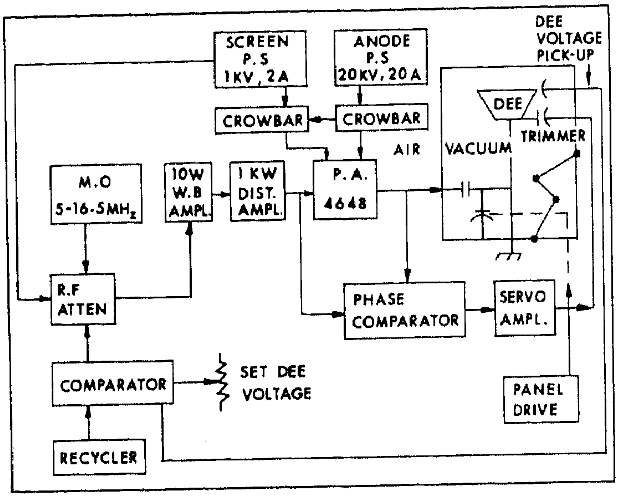

Figure 8. Block diagram of the radiofrequency system.

2.3 *Vacuum system*

The combined volume of the dee chamber and the resonator tank is 23 m^3, and when the vacuum system for evacuating this volume to a pressure in the range of 10^{-6} torr was built, it was the largest one built indigenously. There are two 89 cm oil diffusion pumps, backed by roots and rotary pumps, with proper arrangements of freon cooled chevron baffles and gate valves. The unbaffled pumping speed of each pump is 42,000 litres per second. This pump under initial testing is shown in figure 9. The pumps, baffles and the gate valves were made at the Technical Physics Division, BARC. Subsequently, this technology has been transferred to the Indo-Burma Petroleum Co. and many large vacuum systems have been built by them for the Indian Space Research Organisation (ISRO) and other agencies.

2.4 *Ion source, probes and deflector*

The ion source is a hot cathode PIG type and it is mounted on a 3·6 m long shaft which is inserted through a central hole at the bottom of the magnet. There is an air-lock so that the ion source can be pulled out for filament replacement without disturbing the main vacuum. A view of the ion source assembly below the magnet is shown in figure 10. There are three water-cooled copper probes—the target probe, the dee probe and the deflector probe, for monitoring the beam current as a function of the radius, as well as for measuring the radial and vertical characteristics of the beam. All these components are remote controlled from the control room.

The electrostatic deflector has three water-cooled cylindrical electrodes and a tungsten septum. The electrodes can be moved to vary the gap by remote control,

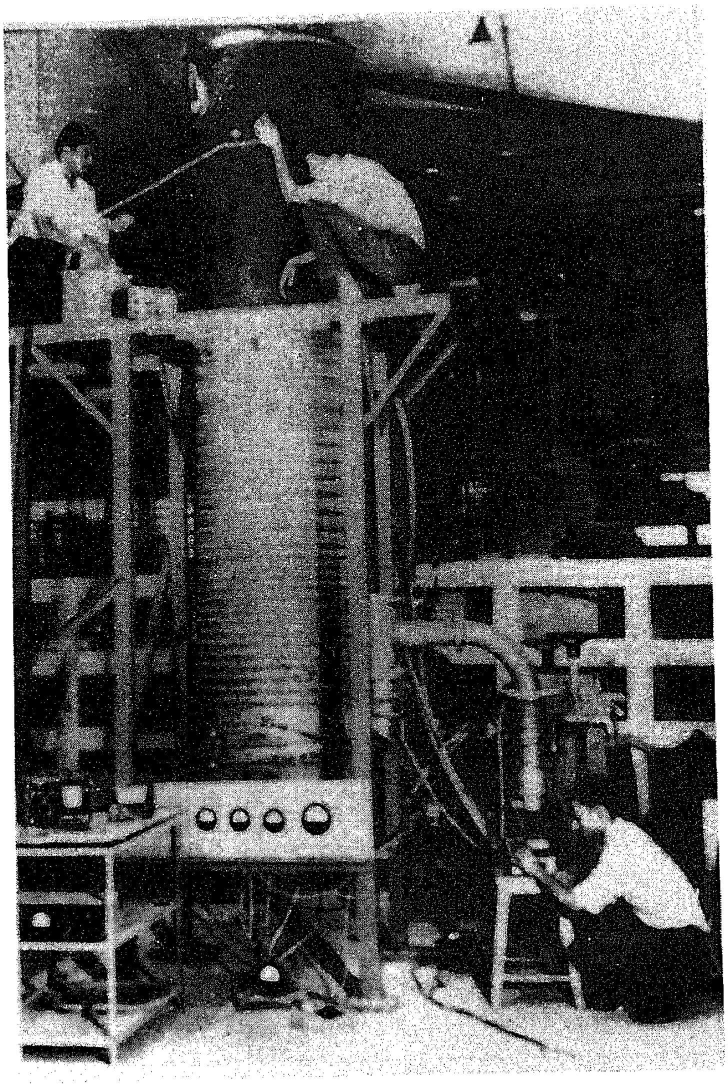

Figure 9. 89 cm oil diffusion pump under initial testing.

through servo-motors. A 120 kV, 5 mA power supply provides the necessary electrical field in the deflector gap.

The ion source, probes and the deflector were made by the joint efforts of the Central Workshops, BARC and the VECC Workshop.

2.5 *Beam transport and data processing systems*

The beam transport system consists of three high intensity, low resolution experimental channels which are operational and six high resolution, low intensity experimental channels, which are under installation. There is one switching magnet giving the three high intensity channels, and, after an analysing magnet, another switching magnet giving the six high resolution channels. The steel for the switching and analysing magnets was cast at the HEC, Ranchi and machining has been done in various engineering firms. The coils for the analysing magnet have been fabricated by the BHEL, Bhopal, whereas the coils for the first switching magnet have been made at the VECC

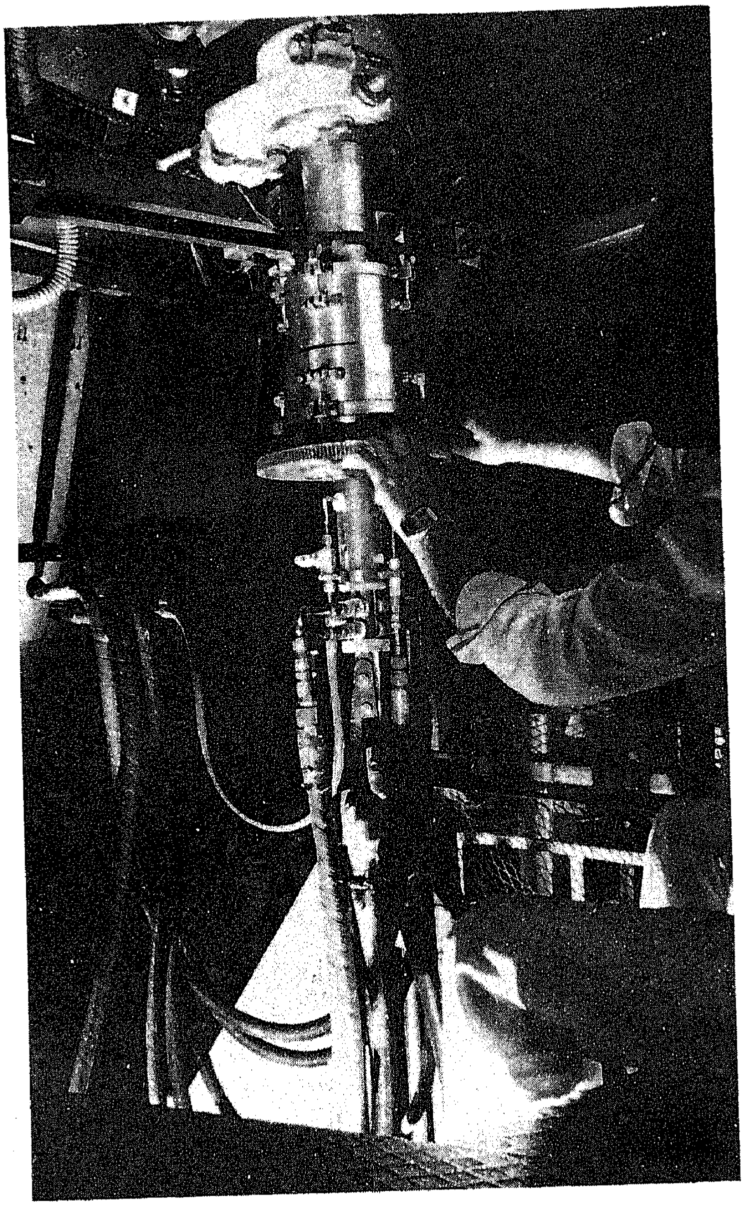

Figure 10. A view of the ion source assembly below the magnet.

Workshop. Figure 11 shows the first switching magnet under installation. A large number of quadrupole magnets are required for focussing the beam at various stages of the beam transport system. A typical quadrupole magnet is shown in figure 12. The design and fabrication of some quadrupole magnets has been done at VECC and a large number have been fabricated at commercial workshops, under VECC supervision. Many elements of the beam transport system, such as collimating slits, beam viewers, faraday cups, etc have been fabricated entirely at VECC. Figure 13 shows a completed beam transport line in the experimental area.

Facilities for research at VECC include a 915 mm scattering chamber fabricated at VECC, a target facility for making a variety of targets, a detector facility for fabricating various surface barriers and Si(Li) detectors and an electronics facility for producing nuclear instrument modules.

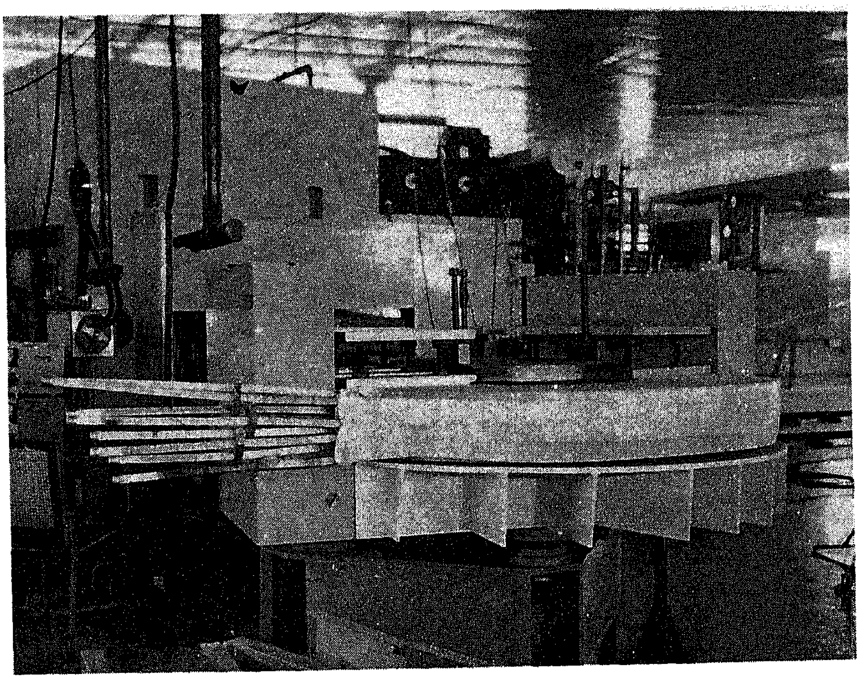

Figure 11. The first switching magnet under installation; the main magnet is seen in the background.

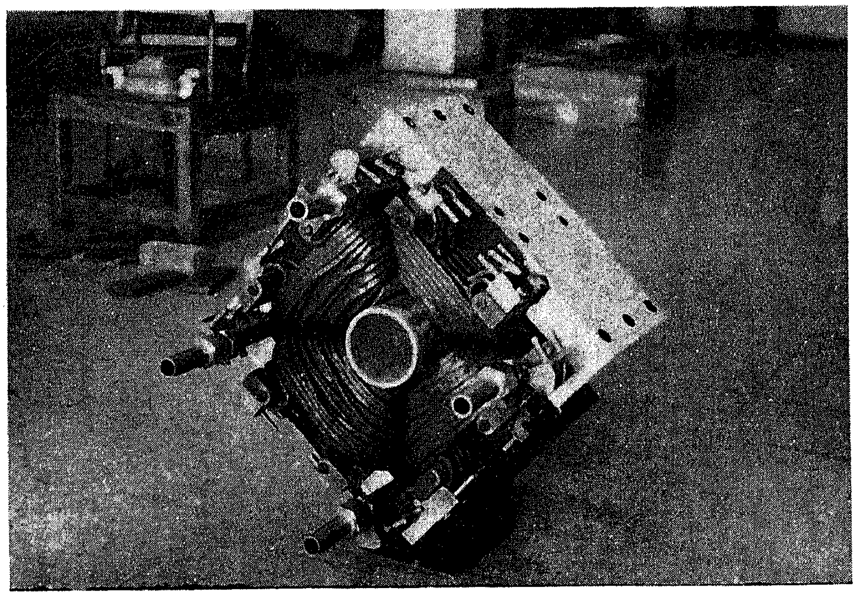

Figure 12. A typical quadrupole magnet.

2.6 *Low conductivity water system*

Since the many magnet coils, power supplies and the RF system, all require extensive cooling, a 1000 gpm, 200 psi, low conductivity (conductivity 1 μmho-cm) water cooling system has been installed. Figure 14 shows the storage tanks and the heat exchangers of the cooling system.

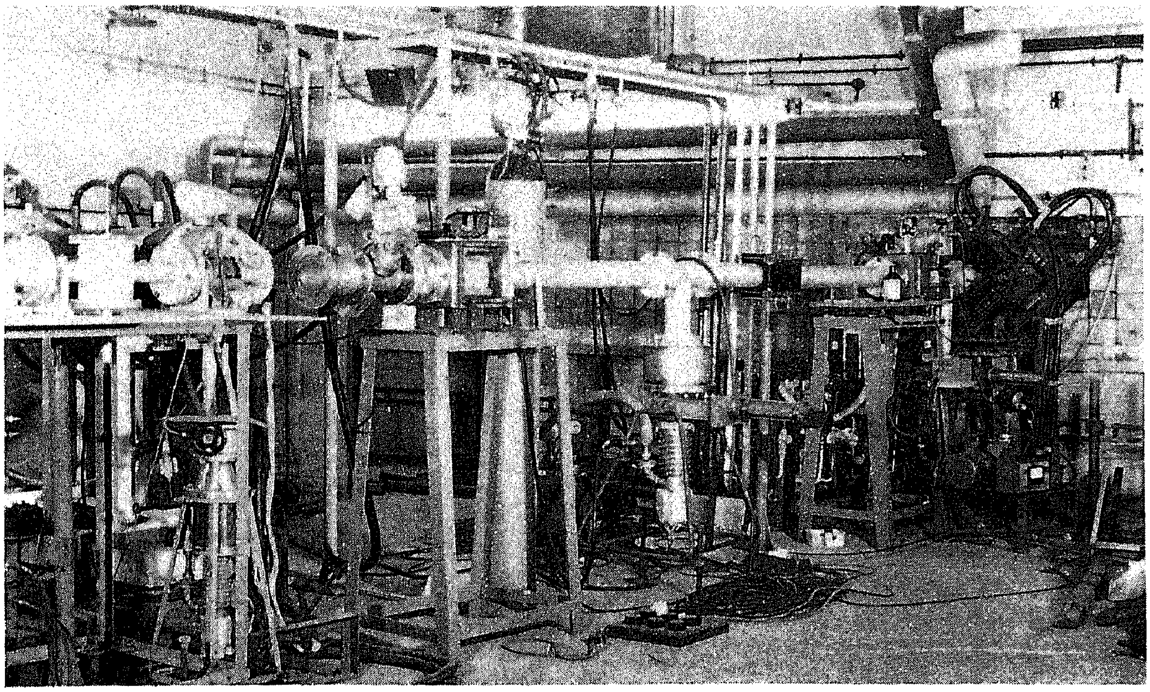

Figure 13. A completed beam transport line in the experimental area.

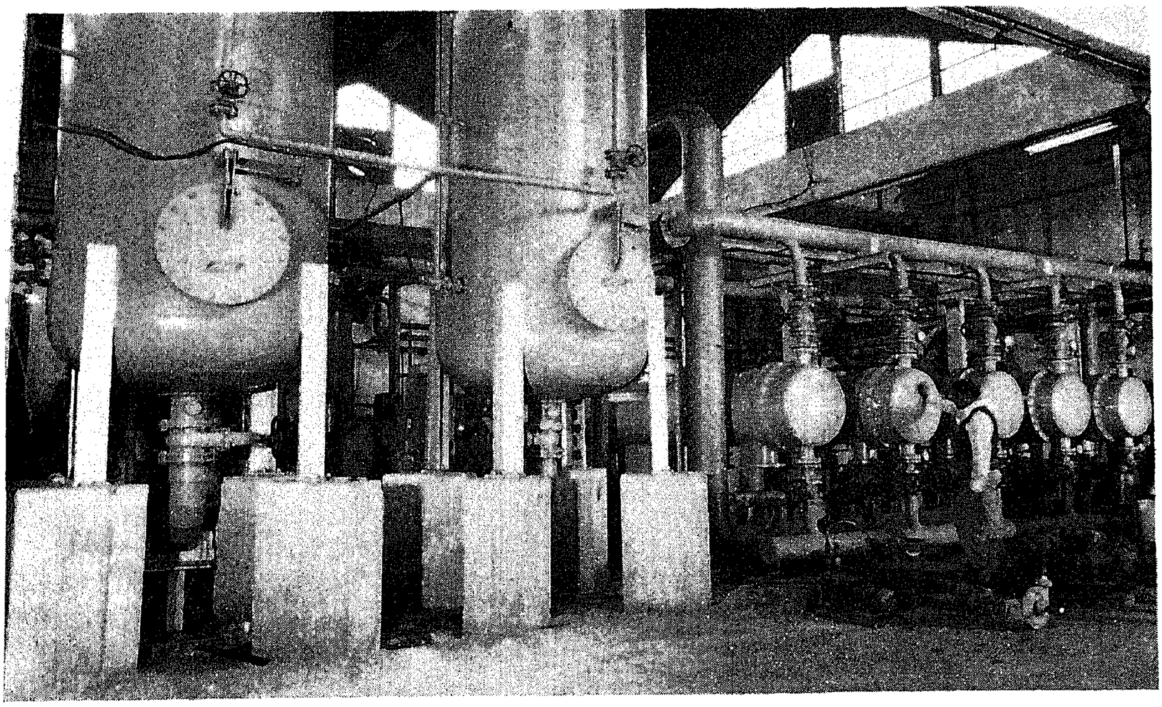

Figure 14. Low conductivity water system.

2.7 *Control system*

Control and monitoring of all the cyclotron systems is done remotely from the control console in the control room, shielded by adequately thick concrete. A view of the control console is shown in figure 15.

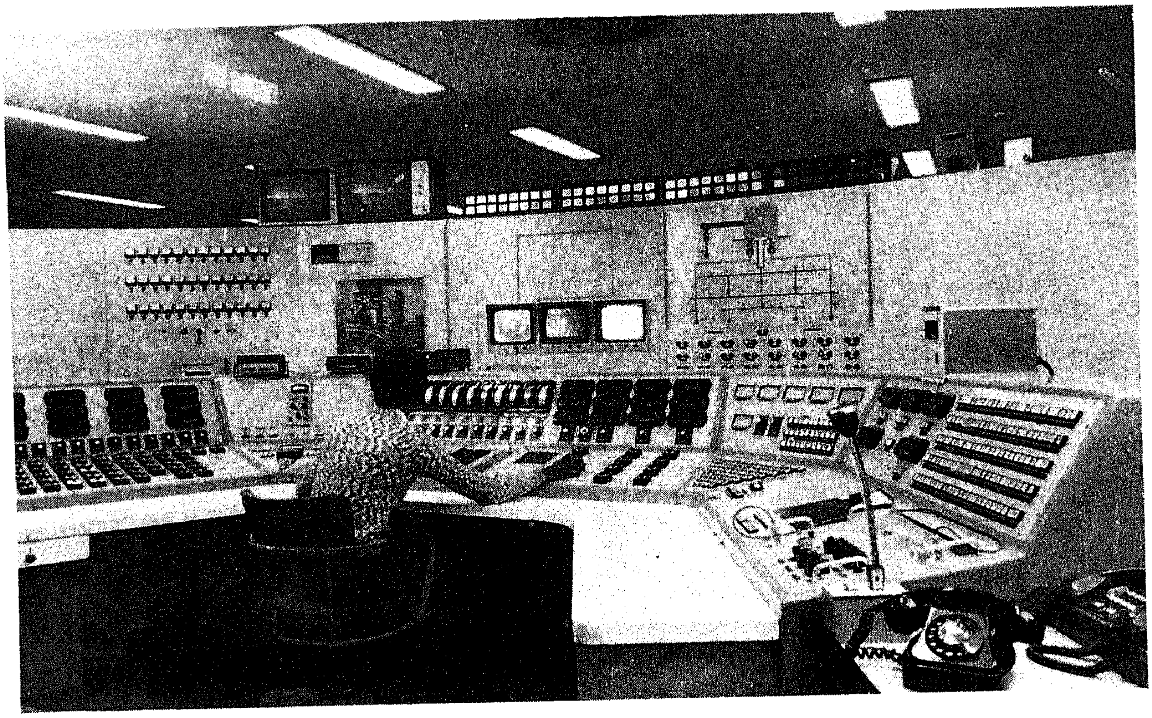

Figure 15. A view of the control room with various controls and instrumentation panels; the video monitors display the beam spot on an alumina beam viewer and the cyclotron central region.

2.8 *Cyclotron operation and utilization*

Regular cyclotron operation has been possible only after the availability of uninterrupted power at VECC from September 1981. The utilization programme has been gradually stepped up. During 1983, the cyclotron was scheduled for operation for 3626 hours; 41 % of this time was available for experiments and 17 % was available for beam development and tuning; the rest of the time comprised on-line repairs, machine start-up and stopping and grid power failure. He^{++} beams in the range of 30 MeV to 75 MeV were utilized. Details regarding beams obtained and utilized are given in table 4. During 1984 the cycle time of cyclotron operation has been further increased.

The utilization of the cyclotron has covered various fields, such as nuclear physics, solid state physics, radiation damage, chemistry and analytical chemistry, radiochemistry, isotope production, biophysics and metallurgy.

As many as 17 research institutions and universities all over the country have already utilized the cyclotron for experiments. They are the Saha Institute of Nuclear Physics, Tata Institute of Fundamental Research, Bhabha Atomic Research Centre, VEC Centre, Reactor Research Centre, Indian Association for the Cultivation of Science, Bangalore University, Mohanlal Sukhadia University, Udaipur, Mysore University, Banaras Hindu University, Aligarh Muslim University, Calcutta University, Kalyani University, Punjab University, Burdwan University, Jadavpur University and IIT, Kanpur.

2.9 *Technology fall-out from* VECC

There has been considerable fall-out of technology from the project of constructing the Variable Energy Cyclotron indigenously as summarised in table 5. Large industries,

Table 4. Alpha beam information.

Energy (MeV)	Beam current (μA)
30	14
35	11
40	11
45	10
50	7·5
55	5
60	5
65	4
70	2
75	2
80	2
85	1
100*	2

Energy resolution : 0·5% (FWHM)
Emittance, horizontal : 30π mm-mrad
vertical : 20π mm-mrad
Pulse width : 10° RF (optimized at 40 MeV)
Status—external in all cases, except where marked with an *.

Table 5. Fall out of technology from VECC.

Casting of steel with 0·1% carbon content at HEC, Ranchi for achieving high magnetic fields.
Epoxy potting of main, trim and valley coils (Cu conductors) of cyclotron at BHEL, Bhopal.
Precision machining of main magnet at HEC, Ranchi.
Fabrication of 89 cm dia diffusion pumps with their chevron baffles for the first time in India.
Fabrication of high voltage, high current, high frequency epoxy cast transformers for use in VECC and other DAE units.
Fabrication of water-cooled high current transformers.
Fabrication of high current (3000 A), stabilised (1 in 10^5) power supplies for cyclotron magnet.
Fabrication of high power (300 kW), wide band (5–20 MHz) amplifiers.
Fabrication of precision, high current sensing transformers.
Fabrication of special magnets such as quadrupole magnets, switching magnets, analysing magnet and steering magnets.
Development of semiconductor detectors.
Development of nuclear instrument modules for nuclear physics experiments.

both public and private sector, as well as small industries have been involved in the process, and in-house technological capabilities have been increased while developing new processes.

3. Variable energy cyclotron at Chandigarh

The 66 cm Variable Energy Cyclotron at Punjab University, Chandigarh is one of the earlier cyclotrons made, operating around 1953–54 at the University of Rochester,

Rochester, NY, USA (Punjab University 1979). It was transferred first to the Kurukshetra University and then to the Punjab University, where it was installed after modifications and made operational in 1973.

This is a classical single dee cyclotron with arrangements for frequency variation from 10 to 20 MHz and magnetic field upto 14 kiloGauss. Typical external beams available on target are

Protons	:	2 μA (max),	1–5 MeV
Deuterons	:	1 μA (max),	1–4 MeV
$^4He^{++}$	:	100 nA (max),	1–2 MeV
$^3He^{++}$	:	100 nA (max),	4–11 MeV

4. 2 MV Tandem Van de Graaff accelerator

Operation, maintenance and development of the 5·5 MeV Van de Graaff accelerator at Trombay has generated experience in the technology of electrostatic accelerators. Using this experience, a fully indigenous 2 MV Tandem accelerator has been designed and constructed at Trombay, (Betigiri *et al* 1982; Singh *et al* 1982).

There are two support columns, each consisting of 49 sections, each section being separated by 9 unglazed ceramic insulators of 25 mm thickness, bonded by a commercially available two-component adhesive. The pressure vessel contains a N_2

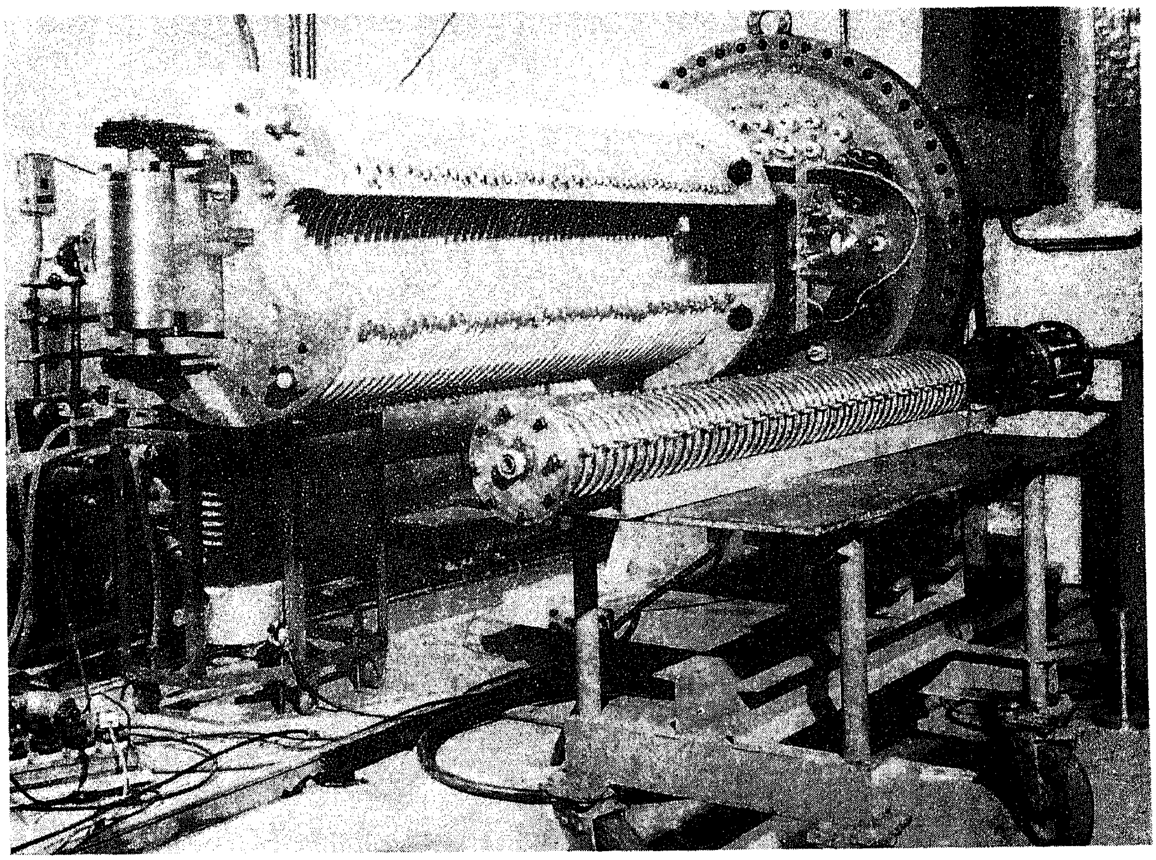

Figure 16. Column structure details and the accelerating tube of 2 MV Tandem Van de Graaff at Trombay.

and CO_2 gas mixture at 17·6 kg/cm. A nylon endless belt is used for carrying charge The accelerating tube consists of index glass rings and stainless steel electrodes. A negative ion source, an einzel lens, a pre-selector magnet, a quadrupole magnet and an analysing magnet, in conjunction with the accelerating tube, comprise the beam handling system. Figure 16 shows the column structure details and the accelerating tube.

The beams obtained are protons: 1 μA; $^{16}O^{2+}$: 200 nA; and $^{16}O^{3+}$: 40 nA.

5. 4 MeV 400 Rad standing wave linac at Bombay

A 4 MeV 400 Rad standing wave linac has been designed, developed and fabricated at the Tata Institute of Fundamental Research; it has been installed at the Vikram Sarabhai Space Centre (VSSC), Trivandrum for x-ray radiography and is in operation since August 1983 (Syunry 1983). A side view of the linac is given in figure 17. The x-ray head is manouverable in all directions so that the x-ray beam can be directed at any part of the heavy fabricated items such as large castings and rocket motors. The operational parameters of the linac are given in table 6.

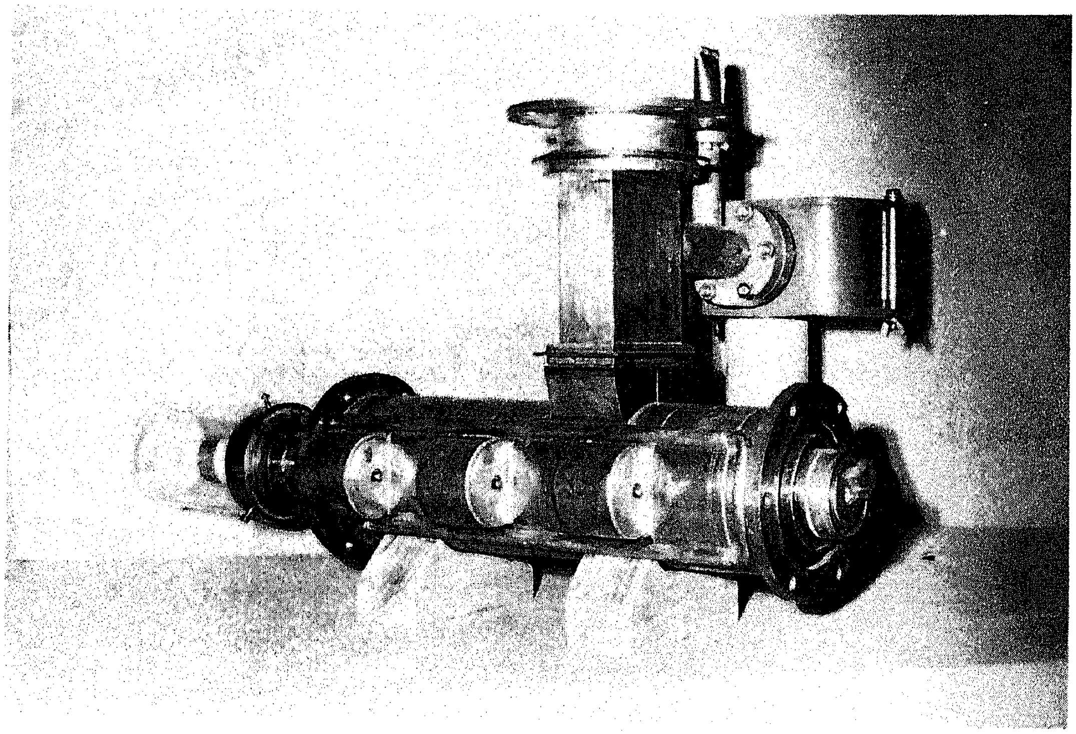

Figure 17. A side view of the 4 MeV standing wave linac at TIFR.

6. 8 MeV microtron accelerator, Pune

An 8 MeV microtron has been built and installed at the University of Poona (Asgekar 1980). It gives an internal electron beam current of 10 μA, and an external beam current of 1 μA at an extraction radius of 40 cm. The electron pulses are of 2 μsec duration, and the repetition rate is 50 sec^{-1}.

Table 6. Operational parameters of the 4 MeV standing wave linac at TIFR.

Maximum energy of x-rays	: 4 MeV
Dose rate (max)	: 250 Rad/min at one metre
Focal spot size	: 2 mm dia
Collimator angle	: 30°
Field size at one metre	: 560 mm dia
Half value thickness	: 25 mm of steel
Size of x-ray head	: 760 × 760 × 1700 mm
Weight of x-ray head	: 1000 kg
Beam centering	: By laser beam direction finder
Movement of x-ray head	: Telescopic vertical upto 5 m; ± 175° about vertical axis; + 45° to − 95° about horizontal axis; Long and cross travel by EOT crane

7. Future accelerators

A 2 MV Tandem accelerator, exactly similar to the 2 MV Tandem accelerator at Trombay, is being fabricated at the Reactor Research Centre, Kalpakkam, and it is expected to be commissioned in 1985.

A 14 UD Pelletron purchased from the National Electrostatic Company (NEC), USA, is being installed at the Tata Institute of Fundamental Research, Bombay by BARC and TIFR. It will accelerate protons to 28 MeV, alphas to 42 MeV and heavy ions such as ^{28}Si, ^{32}S, ^{40}A and ^{64}Ni. This accelerator is expected to be operational in 1985. A superconducting linac booster is planned as a post-accelerator.

A major programme of accelerator development is envisaged at the Centre for Advanced Technology, BARC, Indore. Proposals are being studied for an electron storage ring synchrotron, a proton/heavy ion synchrotron (Jain and Divatia 1977) and a medical cyclotron.

8. Conclusion

A variety of accelerators have been designed, developed and built in India. Wherever accelerators have been purchased, associated development work has been necessary. Construction of the Variable Energy Cyclotron at Calcutta has given a major boost to the accelerator technology and established a strong liaison between Research Institutes and the Industry.

Besides the accelerators discussed here, there are a number of accelerators, with energy less than 1 MeV, in Research Institutes and universities, which are used as Neutron Sources or for ion implantation. Quite a few medical institutes and hospitals have procured electron accelerators for radiation therapy. The need for accelerators and development of accelerator technology is growing.

Accelerator development in India has been pioneered by Meghnad Saha, given a major thrust with a vision by Homi J Bhabha, encouraged by Vikram A Sarabhai and brought to a high technology level with a promise for the future by Raja Ramanna.

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