Proceedings of the Eighth International Conference on Cyclotrons and their Applications, Bloomington, Indiana, USA

OPERATION OF THE VARIABLE ENERGY CYCLOTRON AT CALCUTTA

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Abstract

The 224 cm Variable Energy Cyclotron at Calcutta with design energies of 140 Q^2/A has been completed. An internal beam of 50 MeV alphas has been obtained in June, 1977. An external beam of 30 MeV alphas has been obtained in July, 1978. During the internal beam trials and the external beam trials, experience has been gained on the operation of various systems and the reliability tested. Results obtained are presented. Beam Transport and Data Processing Systems are being installed and plans for utilization are under way.

1. Introduction

At the time of the VIIth International Conference on Cyclotrons and their Applications, assembly of the 224 cm Variable Energy Cyclotron at Calcutta was nearly complete[1]. Subsequent progress has been reported at other Conferences[2,3]. An internal beam of 50 MeV alphas has been obtained in June, 1977 and an external beam of 30 MeV alphas has been obtained in July, 1978. At present beam optimization and beam development are in progress, and a study of the various systems is being carried out with the objective of achieving long term reliability. Simultaneously, Beam Transport and Data Processing Systems are being installed and utilization of the cyclotron is being planned. The basic design parameters of the cyclotron are given in Table 1.

Table 1

DESIGN PARAMETERS - VEC CALCUTTA

MAXIMUM ENERGY	:	140 Q^2/A MeV
INTERNAL BEAM CURRENT	:	1 mA
EXTERNAL BEAM CURRENT	:	100 μA
MAGNET POLE DIAMETER	:	224 cm
SPIRAL SECTORS	:	3
DEE	:	1, 180°
FREQUENCY RANGE	:	5.5 - 18.0 MHz
DEE VOLTAGE	:	70 kV (max)
ION SOURCE	:	PIG
ION SOURCE ARC CURRENT	:	2 A (max)
DEFLECTOR	:	ELECTROSTATIC
DEFLECTOR VOLTAGE	:	120 kV (max)

The cyclotron along with the beam line is shown in Figure 1 and the cyclotron with the resonator tank and RCA 6949 housing is shown in Figure 2.

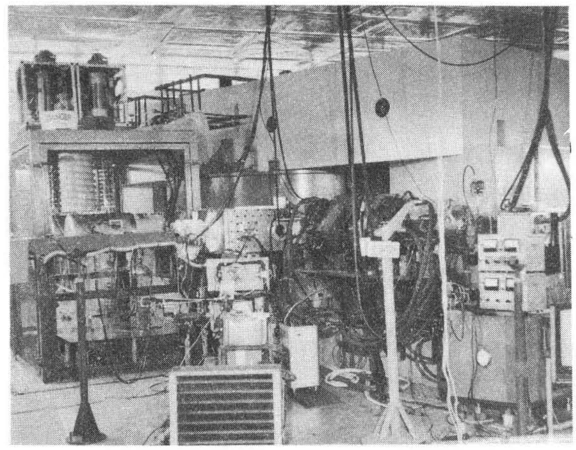

Figure 1. Cyclotron with the beam line

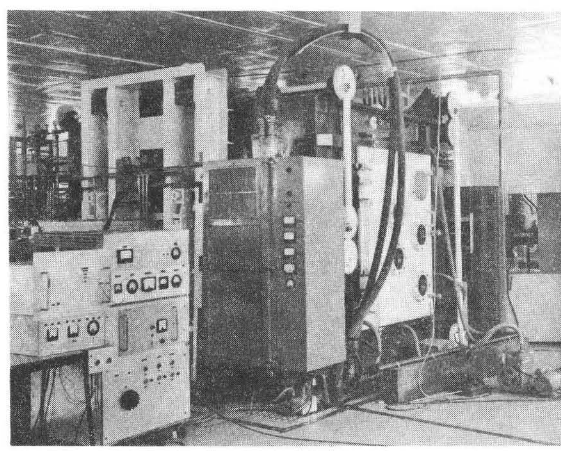

Figure 2. Cyclotron with the resonator tank and RCA 6949 housing

2. Magnetic Field

The 262 tonne VEC magnet has pole pieces made from upset forged steel and yoke and yoke blocks made from cast steel. Coils have been made using copper conductor and the trim and valley coils have been epoxy potted. The magnetic field obtained at the centre (R = 0) plotted as a function of the current in the main coils is shown in Figure 3. The magnetic field obtained compares well with the magnetic field obtained in the magnet at the Berkeley 88" cyclotron. The maximum difference, which occurs at high field values,

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is 1%. Average magnetic field B, as a function of the radius, at a current value of 1056 A for the VEC has also been shown.

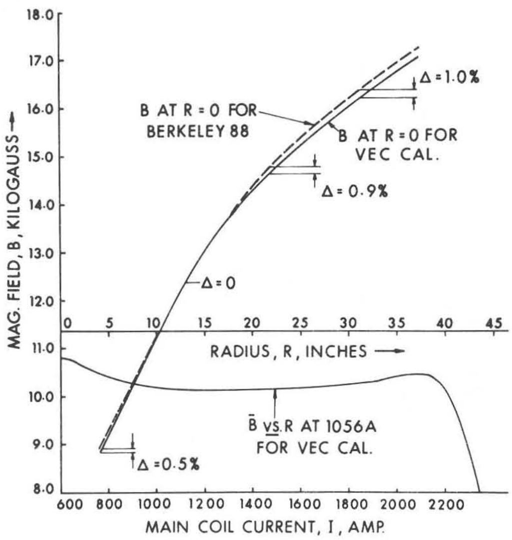

Figure 3. Magnetic field in VEC

Magnetic field measurements - Phase I for determining the first harmonic in the magnetic field were carried out using two search coils placed 120° apart on a rotating frame and measuring the differential output under rotation. Figure 4 shows the first harmonic as a function of the radius at two different positions of the ion source. The values of the first harmonic obtained are well within the expected values.

Magnetic field measurements - Phase II were carried out in the geometrical median plane using a search coil which could be positioned at equal radial (2.54 cm) and azimuthal (3°) intervals over a polar mesh. Automatic positioning and recording of data was done with the help of a NOVA computer and over 3,000,000 data points were obtained. The relative accuracy of the measurements was 0.03%. The magnetic field data was processed on a BESM-6 computer using codes CERTFY, OMNVEC and MAINCO. The iron field at any current and grid point was constructed with the help of control setting code CYDE using polynomial coefficients generated as functions of r, θ and I by the code COMPCO. The field was accurate to $\leq$0.1% of the central field.

The main magnet current supply, with an output of 150 V, 2800 A, is regulated to 1 part in 10^4, and it is continually adjustable from 10% to 100% of the rated output value. The characteristics of the magnet power supplies as well as other power supplies are shown in Table 2.

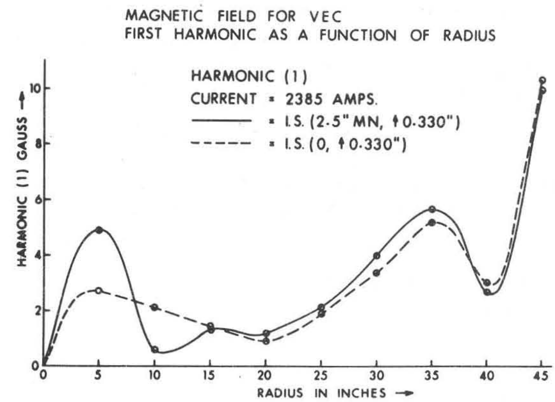

Figure 4. First harmonic

Table 2

POWER SUPPLIES

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 SENCING 0.001%
QUADRUPOLE MAGNET	5	30 V, 300 A	REGULATION 0.1%

3. Radio frequency

The radio frequency system consists of movable panels inside the resonator tank and a single dee.

The radio frequency system was initially tested in air using a low power oscillator. The capacitance of the dee-dee chamber system was 1800 pF and the Q of the system was 3000 at 5.5 MHz. During the initial tests as well as the internal beam trials, due to outgassing and multipactoring, it was difficult to get the RF system started as a self excited oscillator and therefore the grid line was decoupled and the system was made a driven system using a booster amplifier with RF drive capacity of 2 kW. A dee voltage of 22.5 kV could be sustained under these conditions. The frequency reached was 10 MHz; however, the capability of frequency variation was limited.

During the external beam trials a better baking out of the RF system was obtained under good vacuum conditions. The lowest pressure achieved was 5 x 10^{-6} t. It was then possible to operate the system as a self-excited oscillator. In order to achieve this condition, an automatic drive system was incorporated for aligning the anode line coupling capacitance, the booster was disconnected and the grid feed back was reestablished. Fine tuning of the RF system in the self-excited mode was done by driving a trimmer capacitor and it was possible to tune the system within 100 cycles of the set frequency. A dee voltage of 40 kV was achieved at 8.5 MHz with a frequency stability of 1 in 10^5. The RF system operating characteristics are shown in Table 3.

Table 3

RF SYSTEM OPERATING CHARACTERISTICS

RCA 6949 | Filament Voltage = 6·3 V, Filament Current = 1100 Amp.

Energy MeV	Freq. MHz	D.C. Anode Voltage kV	D.C. Plate Current Amp.	Grid Fixed V	Bias Total V	Dee Voltage kV	Freq. Stability	Pressure Torr
51 ALPHA	8·001	7·4	3·6	−35	−120	22·5	1 in 10^5	$2{\cdot}4\times10^{-5}$
30 ALPHA	6·005	8·6	2·5	−91	−610	29·5	1 in 10^5	1×10^{-5}

Since the RCA 6949 oscillator tube is very costly, it is necessary to have a very fast protective crowbar in the high voltage anode power supply for the tube. Such a crowbar has been incorporated and, due to frequent multipactoring, put to very severe tests, particularly during the beam trials. Typical crowbar operating times are shown in Table 4.

Table 4

RF HIGH VOLTAGE POWER SUPPLY CROWBAR OPERATION

	Anode Voltage kV	Anode Current Amps.	Crowbar Operation Time μS
1.	5	6·4	1·6 1·0 1·5 1·2
2.	5·6	7·0	1·6 1·2 1·7 1·4 1·6
3.	6·6	8·4	1·2 1·2 1·3
4.	7·0	8·4	1·2 1·8 1·4

The entire system was pumped down by two 89 cm diffusion pumps on the resonator tank and one 30 cm diffusion pump on the dee chamber. Typical pump down characteristics are shown in Figure 5.

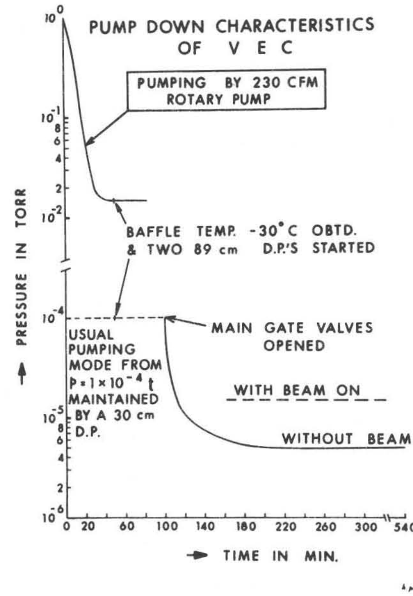

Figure 5. Pump down characteristics

The magnet coils, the radio frequency system and other components are cooled by a low conductivity water system of 1000 gpm at 200 psi. Operation data of this system is shown in Table 5.

Table 5

OPERATIONAL DATA OF LCW SYSTEM

1. Operation Since Installation	4000 h
2. Percentage Of Water Being Treated	2%
3. Average Conductivity	0·45-0·60 μmho/cm
4. Oxygen Content	4·5-7·0ppm
5. pH	~6·9

4. Cyclotron Operation

a. Internal beam

The internal beam trials of the cyclotron began in January 1977 and the internal beam was obtained on June 16, 1977, when a circulating current of about 120 nanoamperes was measured at an energy of 50 MeV for alphas. Later the beam was tuned to full radius at an energy of 52 MeV for alphas using calculated control settings. The tuning was done using both resonance and shadow techniques. For the shadow technique, three probes located strategically within the pole gap, about 120° apart, were used. The probes can move in and out along a radius of the cyclotron. The central region of the cyclotron is shown in Figure 6.

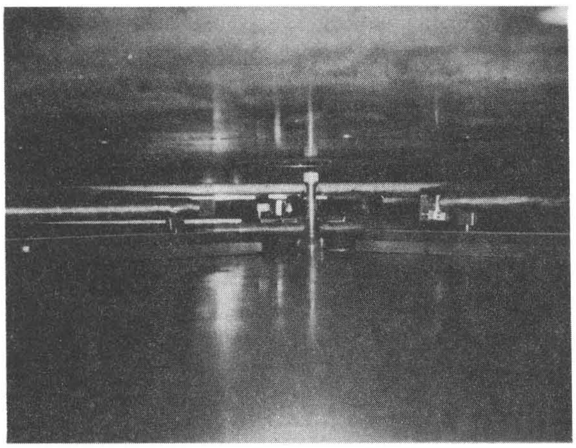

Figure 6

The internal beam current as a function of the cyclotron radius, measured by the shadow technique during the internal beam trials, is shown in Figure 7. During the internal beam trials, a fixed frequency and a low dee voltage were used in order to overcome the multipactoring problems.

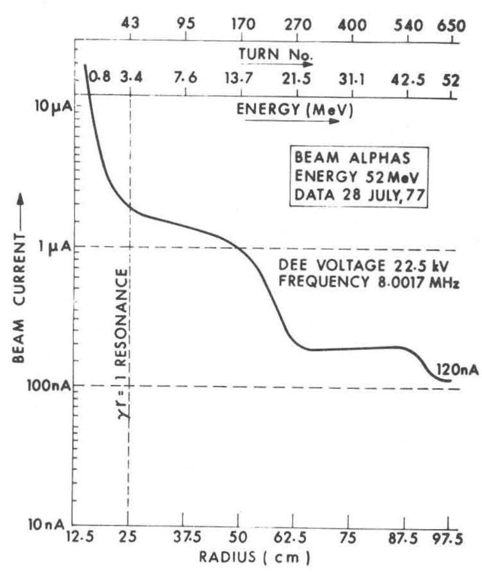

Figure 7. Beam Current vs. Radius

This resulted in an unusually larger number of turns, in excess of 650, corresponding to 52 MeV energy, and it took some effort to get the beam to clear the puller electrode in the first orbit, get the orbits centered and to overcome the $\nu_r = 1$ resonance which occurs at a radius of about 25 cm. These factors are responsible for the rapid beam loss in the central region. The central magnetic cone was adjusted to suit the conditions arising from the low value of the dee voltage, with the aid of the central trim coils.

The beam energy was confirmed by irradiating a stack of 19 copper foils mounted on the target area probe. Activation at the extraction radius of 99 cm confirmed that the penetrating power of the alphas was greater than 45 MeV. A gamma spectrum measured for the second irradiated Cu foil obtained with a Ge(Li) detector 11 hours after irradiation is shown in Figure 8.

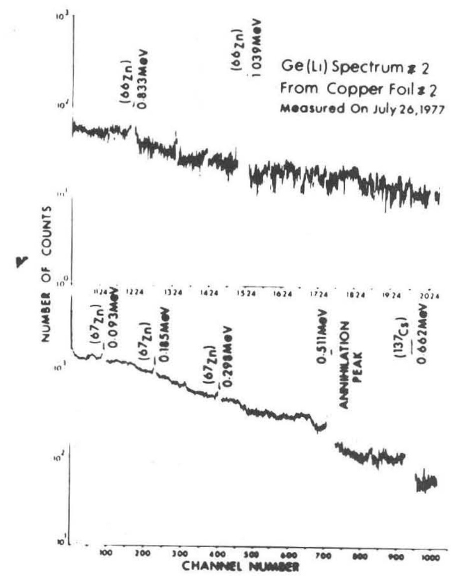

Figure 8. Ge(Li) Spectrum of Irradiated Cu Foil

To obtain the internal beam, such central region parameters as the ion source and the puller electrode positions were calculated in advance, and after optimization it was observed that the actual parameters were very close to the calculated values. The trim coil settings were calculated using the computer programme CYDE, and it was observed that the experimental settings achieved after optimization of the beam were very close to the calculated settings. Table 6 shows a comparison between the calculated and optimized experimental settings.

b. Deflector

The deflector was installed after the internal beam trials were completed. The deflector consists of four inconel electrodes, two ground electrodes joined together and two high voltage electrodes separated from each other. The septum, made of tungsten, fits into the ground electrode. Figure 9 shows the deflector design. Before installation, the

Table 6

MAGNET CURRENTS FOR 52 MeV ALPHAS

Trim Coil	Calculated current	EXPTL.	RANGE
1 2 3 4			Not used for isochronism but central field bump upto R=25cm
5	0	0	+750to-750
6	0	+14.5	±750
7	0	-24.5	±750
8	+26	+22.5	±750
9	0	0	±750
10	+240	+235	±750
11	0	0	±750
12	+396	+324	±2000
13	0	- 13.8	±2000
14	+1076	+1023	±2000
15	-1417	-1415	±2000
16	0	0	±2000
17	447Amps = 9 Amps. on main coil		Equivalent to main coil, presently used for fine tuning only
Main coil	979.2	979.2	±3000

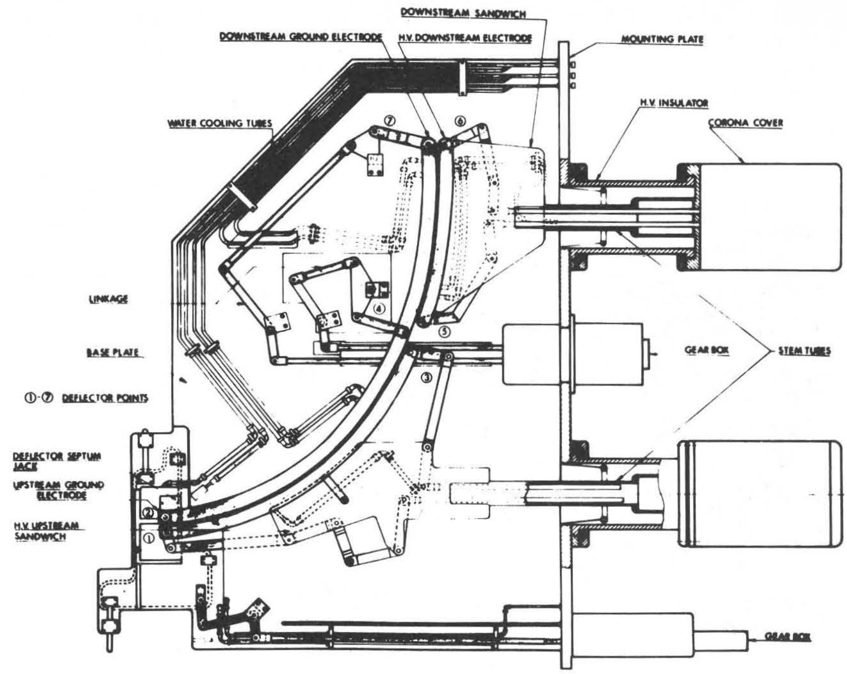

Figure 9. Deflector design

deflector was calibrated and the electrode movements were checked for backlash and reproducibility. The reproducibility was found to be better than 100 microns. A quarter scale model of the deflector, coupled to the main deflector by servomotors and placed in the control room, was also calibrated. Figure 10 shows the deflector. After installation, the deflector power supply was tested with resistive load up to 70 kV and the deflector was baked at a dee tank pressure of 2×10^{-5} t in a magnetic field of about 10 kG, and an electric field gradient of 7 kV/mm was achieved.

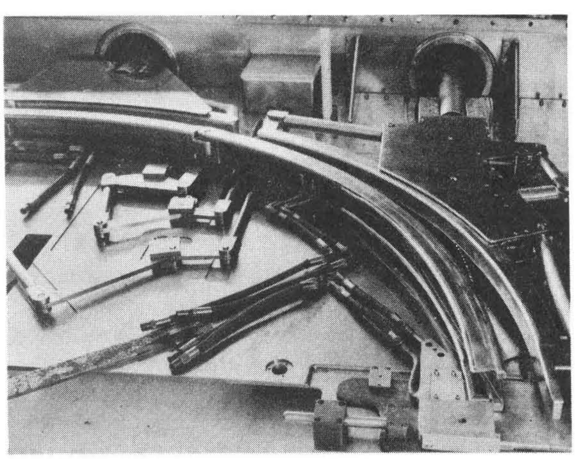

Figure 10. Deflector-Entrance channel view

Optimization of the deflector parameters was done with the help of computer programme DFLKTR, which calculated the channel positions and voltages from the magnetic field data calculated by means of the programme CYDE. For a dee voltage of 40 kV, the extraction efficiency of the deflector for 50 MeV alphas is estimated to be 48%.

c. External Beam

The external beam trials were started in April 1978, and an external beam of 30 MeV alphas was obtained on July 8, 1978. The alphas, after emerging from the deflector at the extraction radius of 99 cm, were brought out of the dee chamber into a beam transport line 2 meters long, passing through a quadrupole doublet. The beam transport line terminated in a copper flange having a 75 micron thick wall over a diameter of 5 mm at the centre, so that the alphas could pass through into air. These alphas were counted in a surface barrier detector located just in front of the copper flange. The extracted alphas could be shadowed by moving in the target area probe. The energy of about 18 MeV for the alphas, after accounting for the energy loss in the copper flange, was confirmed from the pulse height observed. During the external beam trials multipactoring was largely overcome, and it was possible to use higher dee voltages. The available internal beam intensity was about 2 μA. At such times, due to beam loading, the deflector draws 2.5 mA instead of the no-beam current of 0.5 mA.

Typical operating conditions of the cyclotron are shown in Table 7.

Table 7

VEC OPERATING CHARACTERISTICS FOR 30 MeV ALPHAS	
1. PRESSURE	Pressure In Resonator Tank : 1×10^{-5} torr
2. RESONANCE	Main Coil Current : 683·5 A Radio Frequency : 6·005 MHz Dee Voltage : 29·3 kV
3. ION SOURCE	Filament Current : 399 A Arc Voltage : 420 V Arc Current : 300 mA Gas Flow : 3 cc/min.
4. DEFLECTOR	Entrance Voltage : 45 kV Exit Voltage : 0 kV Extraction Radius : 99 cm
5. BEAM OPTICS	Quadrupole Magnet Current - I : 55A Quadrupole Magnet Current - II : 50 A
6. BEAM	Internal Beam At Extraction Radius : 2·4 μA External Beam (Estimate) : 0·1 nA

d. Neutron Flux

The neutron flux produced during the beam trials was monitored at a number of places, in order to collect data for health physics purposes. The neutron flux measured with the internal beam hitting the target probe was also used to corroborate the beam intensity variations. Table 8 shows the neutron flux at various locations in the vault and the pit for different internal beam conditions.

e. Availability of power

The commissioning of the Variable Energy Cyclotron at Calcutta has involved the facing of an unusual problem, in addition to the usual scientific and technical problems of commissioning an accelerator. The

Table 8

VEC Neutron Flux Data

Position Of The Neutron Detector	Fast Neutron Flux – $n/cm^2/sec$	
	Internal Beam Current 160 nA	Internal Beam Current 1 μA
1. Near Dee Tank Exit Port	5000	~30,000
2. About 3 Meters From The Deflector	200	2000
3. In The High Intensity Cave, Along 0° Line	2	50
4. In The Pit	18	100

availability of electrical power has been very erratic. There have been frequent power failures which have interrupted the testing of various systems of the cyclotron as well as the testing of the cyclotron itself. Since cyclotron testing requires prolonged operation of the vacuum system, RF system, magnet power supplies and services, it has been difficult and time consuming to carry out the cyclotron testing. Since the power has been somewhat better at nights, the internal beam trials as well as the external beam trials have been carried out at nights, working on a schedule of 9 PM to 7 AM. As a partial short term solution to this problem, plans are underway to instal a diesel generator so that the entire vacuum system can be operated without break. As a long range solution, arrangements are being worked out to have a special power connection with priority for VEC.

5. Experimental Facilities

The experimental area of the VEC

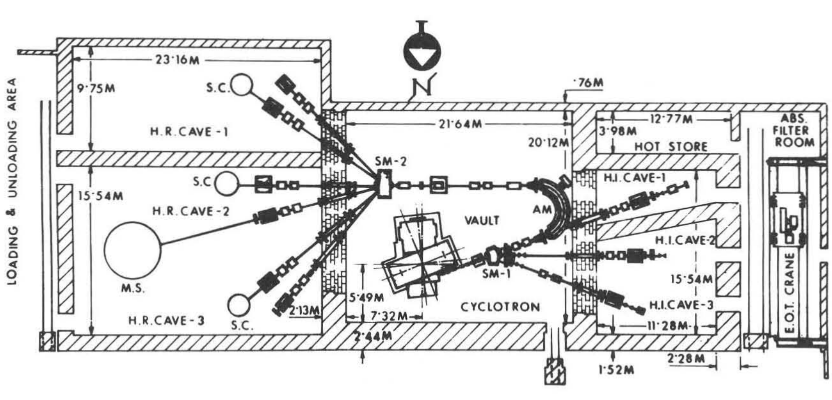

Figure 11. VEC Experimental area

laboratory is shown schematically in Figure 11. The first switching magnet makes available three beam channels for high intensity (100 uA), low resolution (ΔE = 300 keV for 60 MeV) experiments in two different experimental caves. The 0° channel passes through a 159.5°, n = 1/2 analyzing magnet which makes available a high resolution (ΔE = 15 keV for 60 MeV), low intensity (1-2 uA) beam. Another switching magnet makes available six high resolution channels in two different experimental caves. The first switching magnet, which is under installation, is shown in Figure 12.

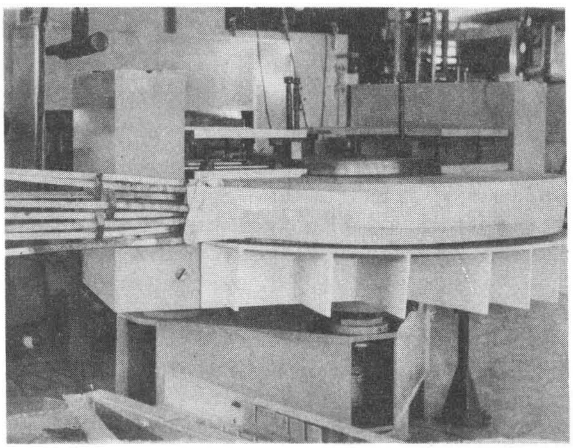

Figure 12. First Switching Magnet

The steel core of the analyzing magnet has been machined and the coils and the vacuum chamber are under fabrication. Assembly of the analyzing magnet will begin soon. Design of the second switching magnet is ready. Other components of the beam transport system--such as quadrupole magnets, beam steerers, collimating slit pairs, faraday cups, beam viewers and shield wall plugs--are nearly ready. The three high intensity beam channels are expected to be ready in early 1979.

A 915 mm scattering chamber which is being assembled is shown in Figure 13. Detector, target and electronics facilities have been set up. A PDP-15/76 on line computer system has been installed and it is operating. Software development for this computer is in progress. An IRIS-80 (one million byte) computer has been ordered and it is expected to be installed soon.

Work has started on a QSD magnetic spectrometer. Facilities for isotope production, radiation damage studies, activation analysis and radio chemistry studies are also being prepared.

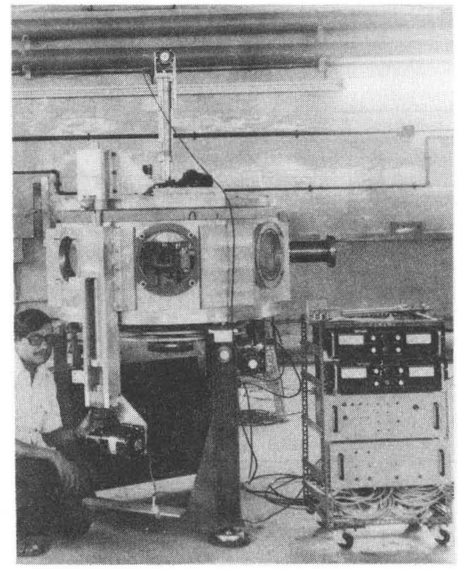

Figure 13. Scattering Chamber

6. Utilization

The Variable Energy Cyclotron will be used as a multidisciplinary national facility. Scientists from research institutions and universities from all over India will participate in its utilization.

References

1. C. Ambasankaran et al., Proc. VIIth Int. Conf. on Cyclotrons and their Applications (Birkhauser, Basel, 1975) pp. 84-87.
2. A.S. Divatia, Proc. VII Int. Conf. on Few Body Problems in Nucl. and Part. Phys., Delhi, 1976 (North-Holland) pp. 1-13.
3. VEC Staff - Presented by A.S. Divatia, Proc, Int. Symp. on Nucl. Phys. at Cyclotron Energies, Calcutta 1977 (to be published)

** DISCUSSION **

H. BLOSSER: Your slide showed "unregulated" power supplies on your valley coils. What are these coils used for?

A. DIVATIA: "Unregulated" power supplies for valley coils means 1% regulation only from the motor control centre. We haven't done enough beam development to use them. We will use them for introducing first harmonics in the magnetic field.

J.R. RICHARDSON: Is there a user's group of physicists interested in using your cyclotron? Have they participated in any of the design of the beam lines or supplemental facilities?

A. DIVATIA: Yes. The user institutions have been identified and a user's committee has been formed. The University Grants Commission, funding body for the Universities, has agreed to fund some of the research facilities.