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Single-cavity 8 MeV race-track microtron

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Abstract. This paper describes the operational details of the single-cavity race track microtron of this laboratory. The machine is capable of providing electrons of 8 MeV energy at 1 mA peak current. Important parameters of the machine and beam handling system are studied and the results are reported.

Keywords. electron; beam; microtron; orbit; pulse.

1. Introduction

The microtron, an electron accelerator, falls into two main categories of design, (i) conventional and (ii) race-track. In a conventional microtron the uniform magnetic field exists throughout the region of cavity and orbits, whereas in a race track, it is limited to sectors allowing the cavity to be accommodated in the field-free region.

In earlier designs of conventional microtrons (Redhead *et al* 1948; Henderson *et al* 1953) the walls of the accelerating cavity which served as the source of electrons restricted the beam current to very low values ($\approx 10^{-8}$ A). This limitation is because of the strong magnetic field at the cavity, disallowing injection of electrons from an external source. The beam current was later increased by Wernholm (1964) and Kapitza (1969) and this resulted in the operation of conventional microtron with relatively large beam currents of about 20 mA (pulsed).

The concept of race-track design came into existence after a sector magnet approach to microtron was first suggested independently by Moroz (1958) and Roberts (1958). In this type of machine, electrons from the gun are injected into the cavity and beam currents of about 60 mA (pulsed) can be obtained.

An 8 MeV race-track microtron has been put into operation in this laboratory and the results on the measurement of its various operational parameters are reported. To establish a framework of describing the 8 MeV race track microtron, the general characteristics are also briefly discussed.

2. General characteristics of microtrons

The electrons in the conventional microtron are bent in circular orbits of increasing radius by a fixed and uniform magnetic field. In each turn, they cross the accelerating cavity and gain energy. To allow the electrons to enter the cavity at proper phase, the following synchronism conditions should be satisfied (Redhead *et al* 1948)

$$B = \frac{2\pi}{ec^2}\frac{\Delta E}{n\tau}, \tag{1}$$

and

$$\Delta E = \frac{m_0 c^2 + eV_i}{\frac{n_0}{n} - 1}, \tag{2}$$

where B is the magnetic field, ΔE is the gain per turn, τ is the period of the microwave field and V_i is the injection voltage. The integers n and n_0 specify the operating mode of the microtron. The transit time for the kth orbit is

$$T_k = \frac{2\pi}{ec^2 B}(eV_i + m_0\, c^2 + k\Delta E). \tag{3}$$

In the race track microtron, electron orbits are no longer circular but are elongated by straight sections in the field-free regions created between the sectors of each module.

The total length of each orbit in the field-free region is then an additional parameter which can be used to control the time required to complete each orbit. Equation (1) remains valid for race-track microtron; however, the second synchronism condition becomes (Froelich 1962)

$$n\tau\,\frac{eV_i + m_0\, c^2}{\Delta E} + \frac{s_k}{v_k} = n_0\,\tau \tag{4}$$

where s_k and v_k are the total field free space length and the velocity of the electrons respectively in the kth orbit. The transit time for the kth orbit is then

$$T_k = \frac{2\pi}{ec^2 B}(eV_i + m_0 c^2 + k\,\Delta\, E) + \frac{s_k}{v_k}. \tag{5}$$

The typical characteristics of the race-track microtron include good energy resolution, ease of beam extraction, efficient use of microwave power and small pole gap all of which give the race track microtron a significant size and cost advantage over a conventional microtron.

3. Description of the machine

As shown in figure 1, the two magnet modules are placed inside the stainless steel chamber. Each module is made of two 90° sector magnets aligned in the horizontal plane to obtain a uniform pole gap of 0·70 cm. Rectangular strips of mild steel, with holes at appropriate locations are fitted between the sectors of each

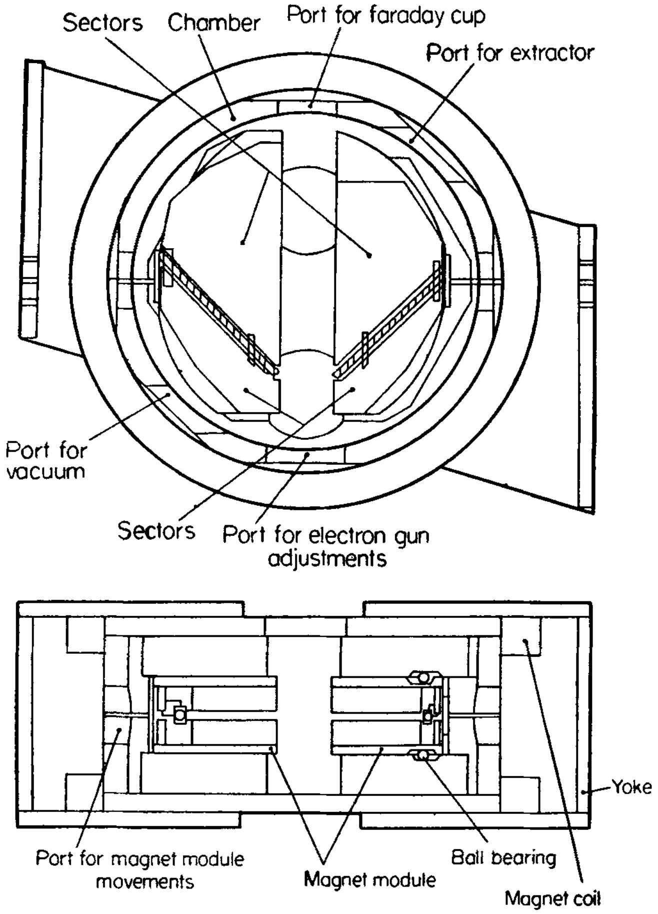

Figure 1. Schematic view of the 8 MeV race-track microtron.

module to act as the magnetic shield. The top and bottom flanges of the chamber are made of mild steel to provide magnetic contact between the modules and the yoke fitted to complete the magnetic circuit. A pair of coils, each containing 8000 turns is fitted around the vacuum chamber. A current of 0·3A through the coils produces a magnetic field of 0·15T in the pole gaps of both the modules. The cavity, the electron gun and the Faraday cup are located in the field-free region between the two magnet modules. The module situated on the side of the electron gun is cut at its other edge to accommodate a mild steel pipe for the beam extraction. The separation between the two magnet modules can be varied with electric motors.

A 500 litres/sec oil diffusion pump with cold traps coupled to a 200 litres/min rotary pump provides a vacuum better than 10^{-6} torr in the chamber in 3 hr. A number of microwave systems based on parameters like insertion loss, frequency stability, stabilisation factor and resonance standing wave ratio were studied for this machine (Bhalla 1978). The one assembled and presently in use with the machine consists of a cavity, mica window, ferrite isolator, phase shifter, tunable S-band magnetron and various S-band wave guide couplings. The cavity with 4.15 cm

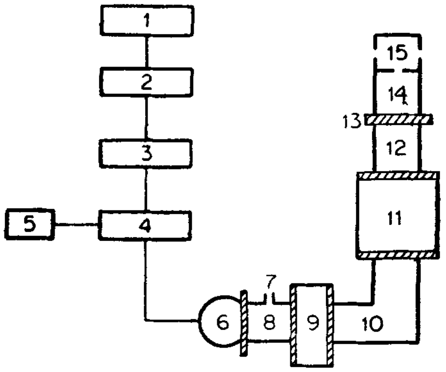

Figure 2. Block diagram of the microwave system.
1. Sub resonant charging power supply; 2. Pulse forming network; 3. Hydrogen thyratron switch–5C22; 4. Pulse transformer; 5. Magnetron filament; 6. Magnetron M5083; 7. Pressure port, 8. 10. 12. 14. Wave guide; 9. Ferric isolator (14db) 11. Phase shifter; 13. Vacuum window; 15. Accelerating cavity.

diameter and 3.43 cm length is made from OFHC copper and has a tuning frequency of 2780 MHz. The theoretical values of Q and the shunt impedance are 15363 and 1.56 M ohms/cm respectively. The magnetron of 1 MW power (English Electric M 5083) is driven by a line-type modulator. The pulse forming network provides a 1.6 μ sec pulse at a repetition rate of 50 pps. The wave guide feed from the magnetron to the mica window is filled with dry nitrogen gas at a pressure of one atmosphere, whereas the feed on the other side of the window is in vacuum.

The microwave system shown in figure 2 is mounted on the bottom flange of the chamber such that the centres of the cavity hole and magnet gap lie in the horizontal plane. A maximum beam current of 63 mA can be accelerated by this microwave system. In the electron gun attached to the cavity, electrons are emitted from the indirecty heated cathode (Type 104 Spectra Mat.), accelerated by the anode structure and finally turned into the cavity by the small pole pieces. The gun and the magnetron are operated in the pulsed mode at 50 pps.

The Faraday cup is moved inside the chamber to intercept any desired orbit for beam current measurement. Figure 3 shows the details of the machine and figure 4 shows its block diagram. The whole machine is housed behind a 45 cm thick wall made from concrete blocks. The machine is operated remotely from the control panel shown in figure 5.

4. Performance of the machine

All the variable parameters of the machine are to be adjusted to the optimum values to satisfy the resonance condition given by equation (5). The current profiles of the circulating beam in the field-free space are shown in figure 6 when the machine was operated at 1 mA (pulsed) current and 8 MeV energy. The results show that almost 50% of the beam is lost in the first two orbits and the subsequent reduction in the beam current is very small. A narrow width of the orbit current profile demonstrates a characteristic orbit separation in the microtron. The dimensions of

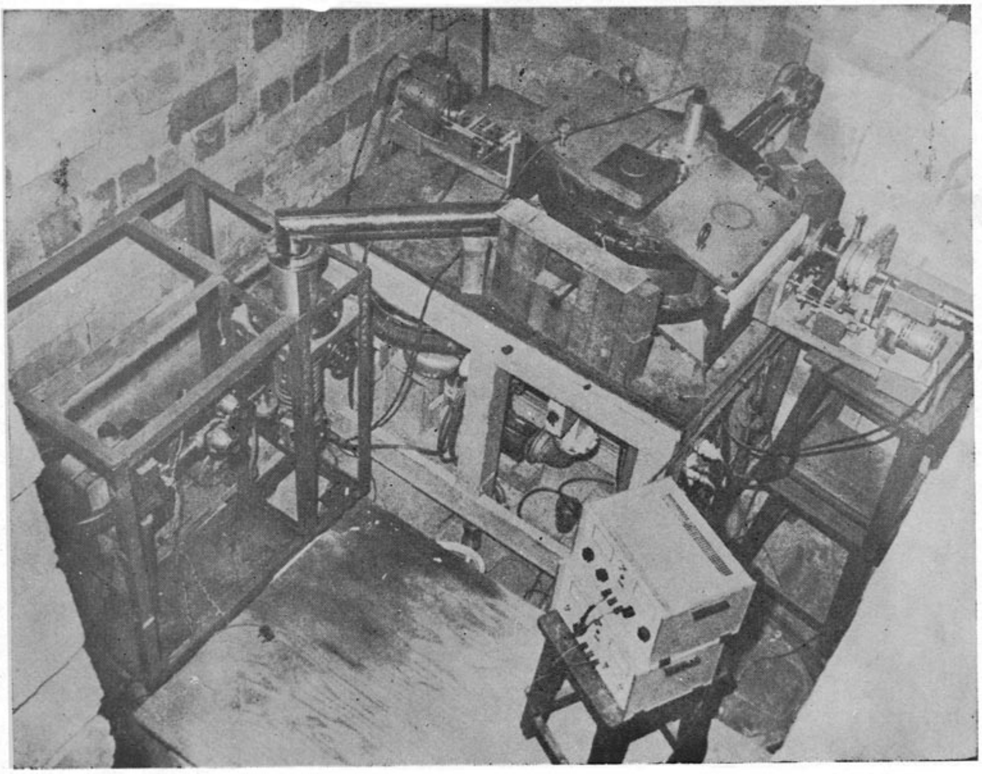

Figure 3. View of the microtron accelerator.

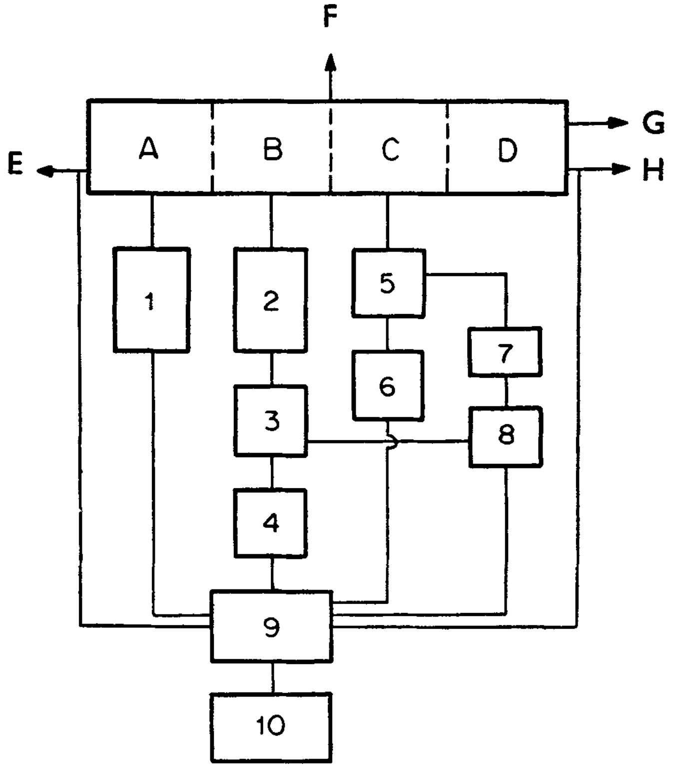

Figure 4. Block diagram of the machine.

A. Magnet, B. Microwave cavity, C. Electron gun and D. Magnet E & H, Pole piece drive; F. Faraday cup drive G. Beam out;
1. Magnet power supply; 2. Microwave system; 3, 5. Modulator; 4, 6. Sub resonant power supply; 7. Delay line; 8. Trigger generator, 9. Interlock; 10. Controls.

Table 1. Maximum values of excursion (x) and divergence (x') of the electron beam at the cavity entrance for various values of perveance.

Perveance (μ)	x (mm)	x'
0·01	1·8447	—0·0118
0·02	1·9217	—0·0182
0·03	1·9833	—0·0227
0·04	2·0361	—0·0264
0·05	2·0845	—0·0300
0·06	2·1296	—0·0336
0·07	2·1714	—0·0364
0·08	2·2110	—0·0391
0·09	2·2484	—0·0427
0·10	2·2847	—0·0455
0·11	2·3199	—0·0473
0·12	2·3540	—0·0500
0·13	2·3870	—0·0527
0·14	2·4189	—0·0555
0·15	2·4497	—0·0573
0·16	2·4805	—0·0600
0·17	2·5102	—0·0618
0·18	2·5399	—0·0645
0·19	2·5685	—0·0664
0·20	2·5971	—0·0682

the beam spot in various orbits have been calculated by the transfer matrix method (Livingood 1961) and the values given in table 1 are in agreement with the experimentally measured values. The calculated values of the acceptance and the emittance for all the orbits are shown in table 2. The amplitudes of the radial and vertical betatron oscillations have been calculated in the guide field (Raye 1980) by using the transfer matrices for this machine and the results are shown in figures 7 and 8 respectively. It can be seen that the amplitudes of these oscillations are less than 0·7 cm indicating almost no loss of beam current due to these oscillations.

Further experiments were carried out to study the effect of variations in the field-free space, magnetic field and gun voltage, on the beam current. Out of these three parameters only one was varied at a time, keeping all other parameters to their original values required to obtain 1 mA beam current. Figures 9, 10, and 11 show the variations in the output beam current with the variation in the field-free space, magnetic field and gun voltage respectively. The results show that if any one of these parameters deviates from its specified value, it reduces the beam current. Performance characteristics are given in table 3.

Table 2. Acceptances and emittances at the cavity entrance for various orbits except for the 8th orbit. The emittances for the 8th orbit correspond to the extractor position.

Orbit No.	Acceptances (mm-mradians)		Emittances (mm-mradians)	
	Radial plane	Vertical plane	Radial plane	Vertical plane
2	1293·61	325·95	85·50	24·19
3	1051·06	264·83	30·08	9·45
4	970·21	244·46	23·62	8·91
5	929·78	232·24	17·83	5·35
6	889·36	224·09	12·99	4·63
7	848·93	215·94	7·26	3·06
8	808·51	207·79	13·62	9·37

Table 3. Performance characteristics of the Poona University Microtron.

Beam energy	8 MeV (variable from 6·5 to 8 MeV)
Beam current (peak)	1 mA
Beam emittance	5 mm-milliradians
Maximum pulse rate	50 pps
Maximum pulse length	1·6 μ sec
Number of orbits	8
Beam extraction	100%
Microwave cavity	Right circular cylinder
RF mode	TM_{010}
Operating frequency	2780 MHz
Electron injection voltage	17·6 kV
Magnetic field	0·136 T
Magnet gap	0·70 cm
Central field-free space	6·6 cm (variable)

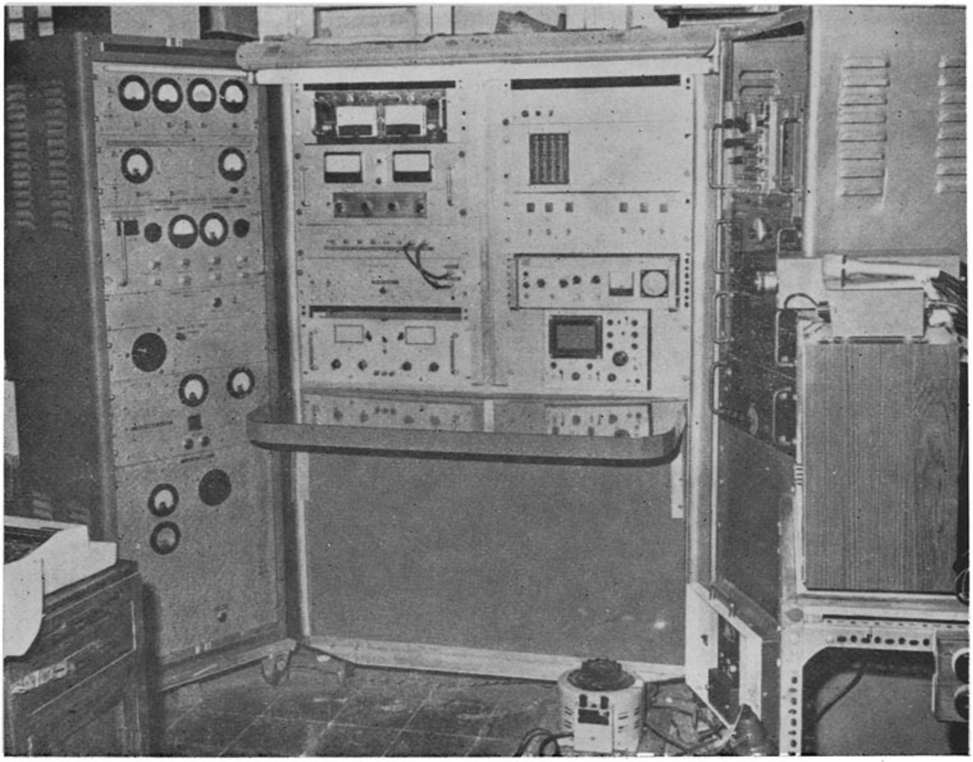

Figure 5. View of the accelerator control panel.

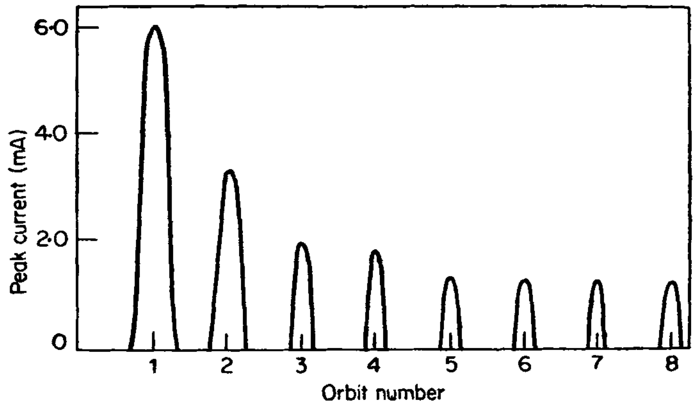

Figure 6. Peak currents in the various orbits.

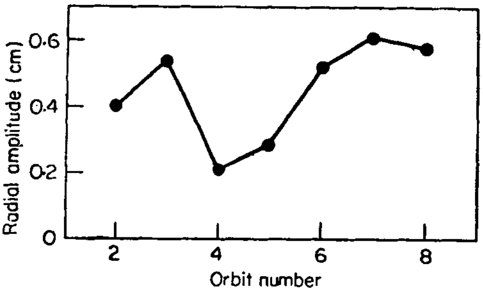

Figure 7. Radial oscillations of the electron orbits.

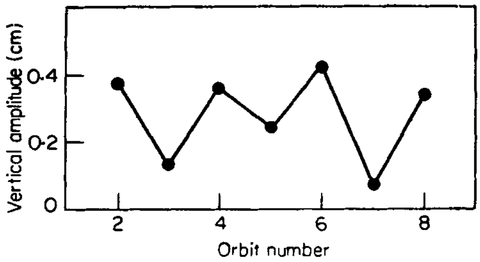

Figure 8. Axial oscillations of the electron orbits.

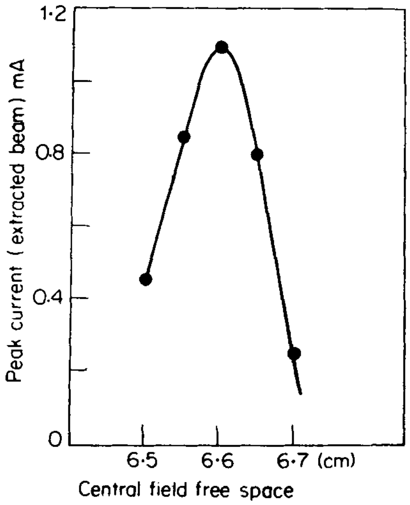

Figure 9. Variation of electron current with extent of central field-free gap.

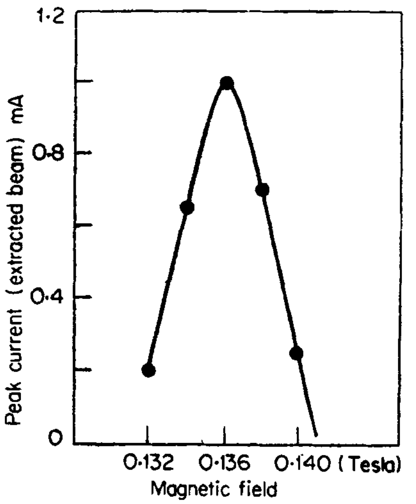

Figure 10. Variation of electron current with magnetic field in the sectors.

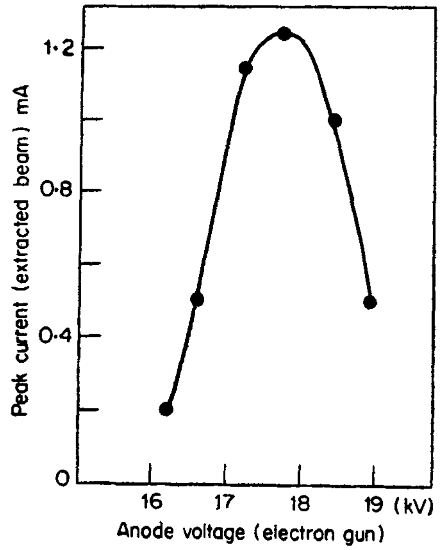

Figure 11. Variation of electron current with anode voltage of electron gun.

5. The beam transport system

The beam transport system for the microtron is based on a 90° double focusing bending magnet. The magnet parameters have been calculated on the basis of the output beam characteristics of the microtron. An analysis of the microtron beam using the transfer matrix method (Raye 1980) gives dimensions of the beam in the radial and axial directions of 0·4 cm and 0·6 cm respectively. The development of this beam inside a 90° sector magnetic field with a field index of 0·5 gives a maximum dimension of 0·46 cm and 0·66 cm respectively in the radial and axial directions (figures 12 and 13).

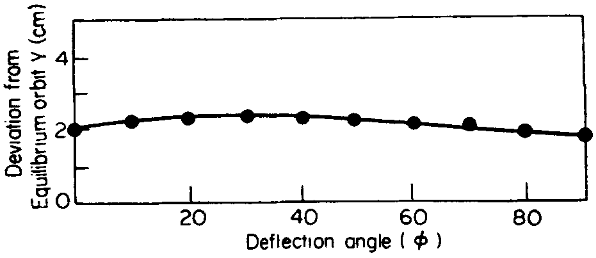

Figure 12. Limiting trajectory of electron beam in bending magnet (radial).

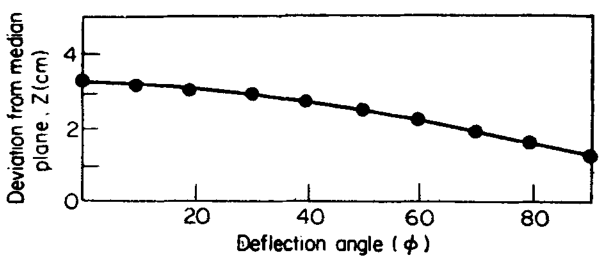

Figure 13. Limiting trajectory of electron beam in bending magnet (axial).

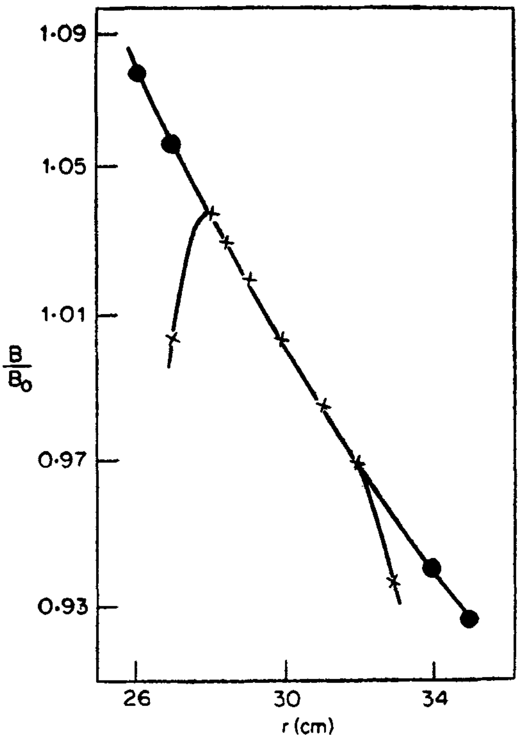

Figure 14. Variation of magnetic field in bending magnet as a function of distance from centre of curvature. Closed circles denote calculated values, crosses denote measured values.

The bending magnet was designed to have an equilibrium orbit of 30 cm. This value was chosen to provide the maximum dispersion (27 cm/MeV) at readily obtainable field values (0·1 T approximately). The field index was obtained by shaping the pole faces of the magnet in the form of truncated cones. The radial extent of the pole-faces was chosen to be 9 cm which gave a region of 4 cm about the equilibrium orbit in which the variation of the magnetic field was in accordance with theoretical values as shown in figure 14. This region is thus appreciably greater than the expected dimensions of the electron beam inside the magnet.

Performance tests of the transport system were done by photographing the electron beam at various points along the system. The dimensions of the beam at the image position of the bending magnet are 4 cm and 0·1 cm in the radial and axial directions respectively. These values agree well with the calculated focusing properties of the magnet and the energy dispersion of the microtron beam.

6. Discussion

The 8 MeV race-track microron has already been used as a source of electrons in experiments on Cerenkov radiation, electron-electron scattering and elastic electron-nuclear sattering. There are also plans to utilise the high energy bremsstrahlung from this machine to study various problems in photon activation analysis and sub-threshold photo fission in ^{238}U and ^{232}Th isotopes. In addition the microtron is being used as an electron and photon irradiation facility for the materials science programme of this Department.

Work is also in hand to improve the performance of the machine with regard to increase in beam current and reliability of operation. An annular cathode electron gun has already been developed for direct injection into the microwave cavity. Bench tests have indicated a possibility of injecting more than 300 mA of electron current per pulse. The microwave and gun pulses are also being redesigned to replace the hydrogen thyratron switches with silicon controlled rectifiers.

Acknowledgements

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