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PERFORMANCE OF A MULTICAVITY RACETRACK MICROTRON

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Summary

Measured characteristics of both the extracted beam and the beam within the accelerator are given for a racetrack microtron with a three-cavity accelerating structure. Final beam energies of 9 to 15 MeV with currents up to 30 mA have been achieved by passing the beam six times through the cavities and beam energies of 4.5 to 7.5 MeV with currents up to 60 mA have been obtained after three traversals of the cavities. An improved injection system and magnetic guide field design are described, and the suitability of this type of machine for radiation therapy is considered.

Introduction

Considerations such as size, cost, flexibility and beam characteristics make the racetrack, or split-magnet, microtron very attractive as an electron accelerator. Its advantages have not been widely appreciated, however, and as a result the considerable potential of this type of accelerator has not yet been fully developed. Some advances in this direction have been made at the University of Western Ontario with the design and successful operation over the past few years of a multicavity racetrack microtron which produces an output beam variable in energy from 1.5 to 15 MeV.

Description of the Microtron

The main features of the accelerator were described previously[1], but some important changes in the design of the injection system and the magnetic guide field have been made more recently. Fig. 1 shows a schematic drawing of the accelerator proper. The basic components are an electron gun, an accelerating structure, and two 180° bending magnets.

The electron gun consists of an annular emitting filament, a focusing electrode with an aperture in the centre and an anode. The gun is mounted directly on the accelerating structure and has its axis of symmetry coincident with the axis of the cavities. The electron beam in the returning orbits can pass freely through the centre of the gun. The gun voltage can be varied up to 50 kV and the gun pulse can be delayed with respect to the rf pulse. The emitted current can be varied up to 1 A by adjusting the filament heating current.

The accelerating structure consists of three identical accelerating cavities which are coupled by means of two klystron-type coupling cavities positioned off the accelerator axis. Each accelerating cavity has a length of .45λ and a radius of .31λ. This radius was chosen so that the cavity would not interfere with the return portion of the first orbit. The choice of length, radius and resonant frequency largely determine the internal shape of each cavity.

The polepieces of the 180° bending magnets are structured in such a way that stability of both modes of betatron oscillations is ensured and that adequate phase acceptance is obtained over the complete range of final energies. Stability of betatron oscillations is maintained by the focusing effects of transition fields between regions of different field strength. Since transition fields that are focusing axially will be defocusing radially and vice versa, overall focusing for both the axial and radial modes must be achieved by alternating the two types of transition fields. These requirements are met by substructuring the field as shown in Fig. 2. First orbit focusing is achieved by a ridge at the boundary of each field sector. The inside slope of this ridge produces axial focusing, while the outside slope gives radial focusing. Since the effectiveness of the ridge diminishes with increasing orbit radius, orbits other than the first also traverse a three level field. Radial focusing occurs at the transition between the plateau region and the valley and axial focusing at the transition between the valley and the ridge. At a distance of 1.5 cm from the pole piece a magnetic shield reduces the magnetic field strength to zero. The beam optical properties of the guide field were determined by tracing electron trajectories through the field.

Resonant operation of the accelerator has been achieved over a wide range of final energies. This is done by adjusting the average magnetic field strength in the 180° magnets, the distance between the two magnets (drift space length) and the electric field strength in the cavities to satisfy specific resonance conditions. The drift space length is changed by moving only the polepieces and this adjustment can be made quickly and easily while the accelerator is in operation.

Performance Characteristics of the Microtron

At the present time the energy gain of electrons in the accelerating structure is limited to the range from 1.5 to 2.5 MeV. Energy gains of up to 3 MeV were obtained without difficulty during the first few months after assembly of the accelerating structure. Since then the surfaces of the cavity reentrant cones have deteriorated because of adverse vacuum conditions. As a result, excessive field emission and secondary emission of electrons now occur at energy gains above 2.5 MeV. With the 1.5 to 2.5 MeV energy gains the following ranges of final energies can be obtained by operating in different modes characterized by the number n (where the beam traverses every n^{th} orbit): 1.5 to 2.5 MeV for n = 6, 3 to 5 MeV for n = 3, 4.5 to 7.5 MeV for n = 2 and 9 to 15 MeV for n = 1.

Energy spectra of the output beam have been measured at different energies in the n = 1 and n = 2 modes[2]. Typically the energy width at half maximum was less than 1.5% in the n = 1 mode and less than 2.5% in the n = 2 mode. The spectra given in Ref. 2 are compared with calculated values in Fig. 3.

Current profiles measured by scanning a Faraday cup across the orbits in the drift space are given in Fig. 4 for two final energies. These profiles show the positions of the various orbits and the relative currents in the obits. Maximum pulse currents obtained in the output beam with the full 1 μ sec pulse width are as follows: 30 mA at 4.5 MeV and 60 mA at 7.5 MeV in the n = 2 mode, 20 mA at 9 MeV and 30 mA at 15 MeV in the n = 1 mode. The currents are limited by the amount of rf power that can be delivered to the accelerating structure under stable operating conditions[3] with the present coupling of the accelerating structure to the wave guide (VSWR = 1.6 overcoupled). Higher currents of up to 80 mA in n = 2 and 40 mA in n = 1 can be obtained with reduced pulse widths. In that regime of operation, energy stored in the electromagnetic field in the cavities is transferred to the beam. An output beam is then obtained only during the time (typically a few hundred nanoseconds) in which the electric field strength in the cavities is high enough to ensure phase stable operation.

For this accelerator the following approximate relations can be derived. They have been verified by both numerical calculations and experiment. The final beam energy E can be calculated from the average magnetic field B_{av} in the 180° magnets and the effective length of the drift space S using:

$$E = (12\,\lambda - S)\,\frac{B_{av}\,ce}{2\pi} \tag{1}$$

where λ is the wavelength of the rf, c the velocity of light and -e the charge of the electron. If E is given in MeV, B in Tesla and λ and S in meters (1) can be written as

$$E = 47.71\,(12\,\lambda - S)\,B_{av} \tag{2}$$

Using these equations the beam energy can be determined directly from the accelerator settings to within ±0.1 MeV. Optimum phase acceptance is obtained if the following relations hold between the average magnetic field and the effective drift space length

$$S = 6\,\lambda - \frac{3\pi\,m_o c}{eB_{av}} \tag{3}$$

for the n = 1 mode, and

$$S = 6\,\lambda - \frac{8\pi\,m_o c}{3eB_{av}} \tag{4}$$

for the n = 2 mode.

Electron depth absorbed dose distributions have been measured for different output energies using a solid polystyrene phantom and thermoluminescent dosimeters. The electron beam emerged from the accelerator through a thin .006" Al window and no other electron scattering material was used except for the air in the 1 m long path. The measurements were done at two energies (14.5 and 10.2 MeV) in the n = 1 mode and one energy (7.3 MeV) in the n = 2 mode of microtron operation. The results are shown in Fig. 5. For comparison the curve for monoenergetic 10 MeV electrons calculated by Berger and Seltzer[4] is also given. The energies recalculated from the practical range of electrons were 14.45, 10.31 and 7.4 MeV respectively. These curves are similar to the depth absorbed dose distributions of beams from other types of accelerators except near the surface of the phantom where the dose is lower due to the narrower energy spectrum of the microtron.

Radiation Therapy Applications

A number of features of the racetrack microtron make it particularly suitable for use in radiation therapy.

Racetrack microtrons can be made sufficiently compact that an accelerator of up to 40 MeV can be fitted into an isocentric therapy unit of normal size. Rf power requirements for such a unit can be satisfied with a magnetron as microwave generator, thus making it possible to place the rf supply on the rotating part of the unit.

By selecting different modes of microtron operation the final beam energy can be varied continuously from a few MeV to the maximum energy of the accelerator. This makes it possible to build a universal unit that can be used for both x-ray and electron therapy of any desired energy with dose rates of up to a few hundred rads per minute.

The small energy spread of the microtron facilitates the design of a treatment head, particularly the bending magnet that directs the beam in the direction of the isocentre. It also results in electron depth dose distributions which are close to the theoretical values with more pronounced peaks and smaller surface doses than are obtained using other types of accelerators.

Fig. 6 shows the schematic diagram of a 25 MeV microtron that would be suitable for radiation therapy applications. The accelerating structure consists of 5 accelerating cavities and four coupling cavities allowing electrons to be accelerated from 1.5 to 3.2 MeV per passage. Output beam energies from 1.5 to 25 MeV can be obtained in the following ranges: 1.5 to 3 MeV for n = 8, 3 to 6 MeV for n = 4, 6 to 12 MeV for n = 2 and 12 to 25 MeV for n = 1.

References

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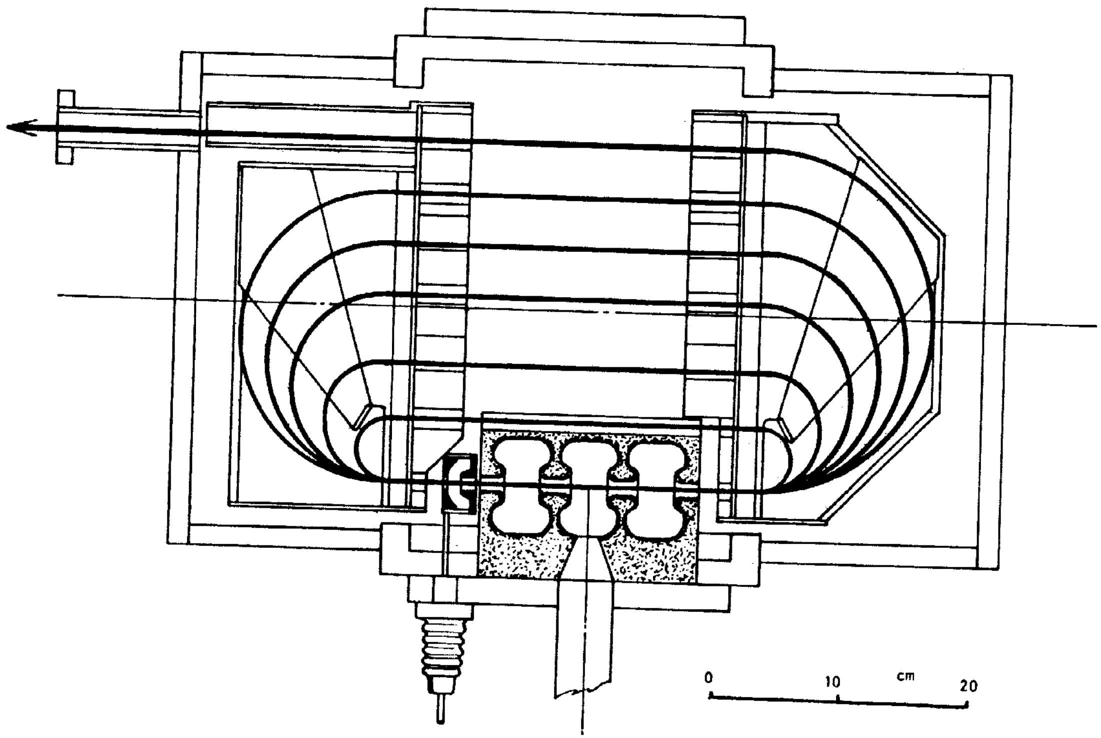

Fig. 1. Schematic diagram of the 6-orbit racetrack microtron.

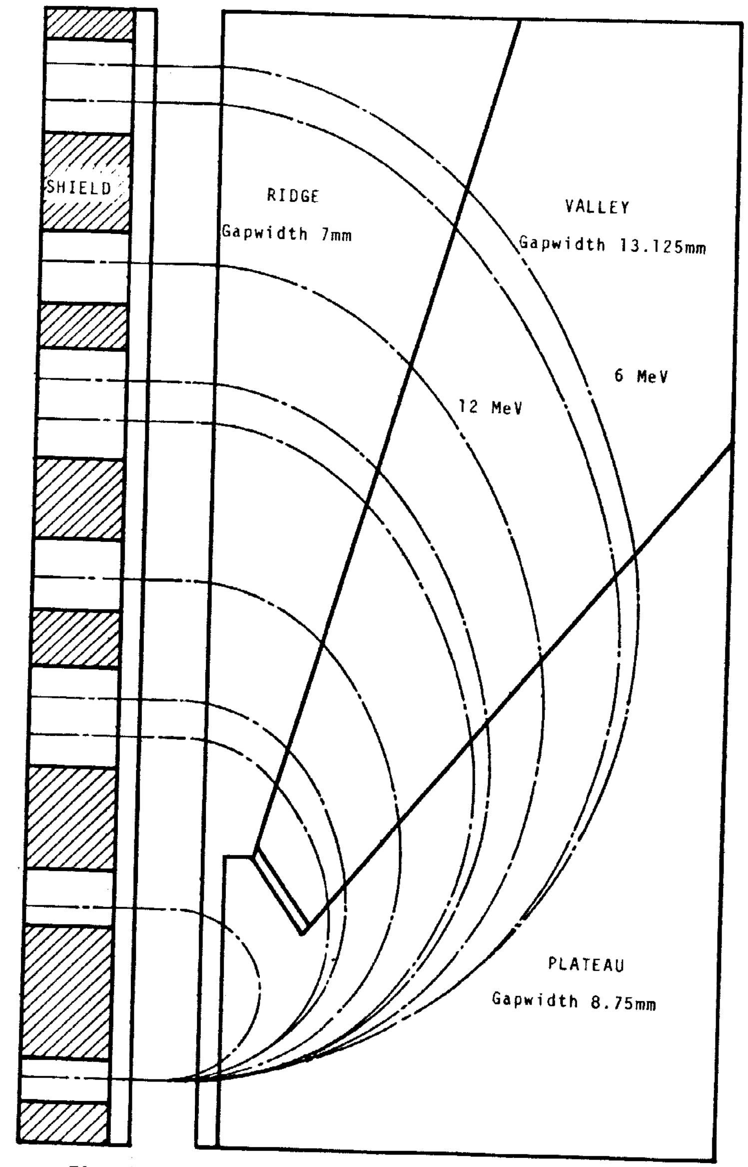

Fig. 2. Diagram of the 180° magnet configuration.

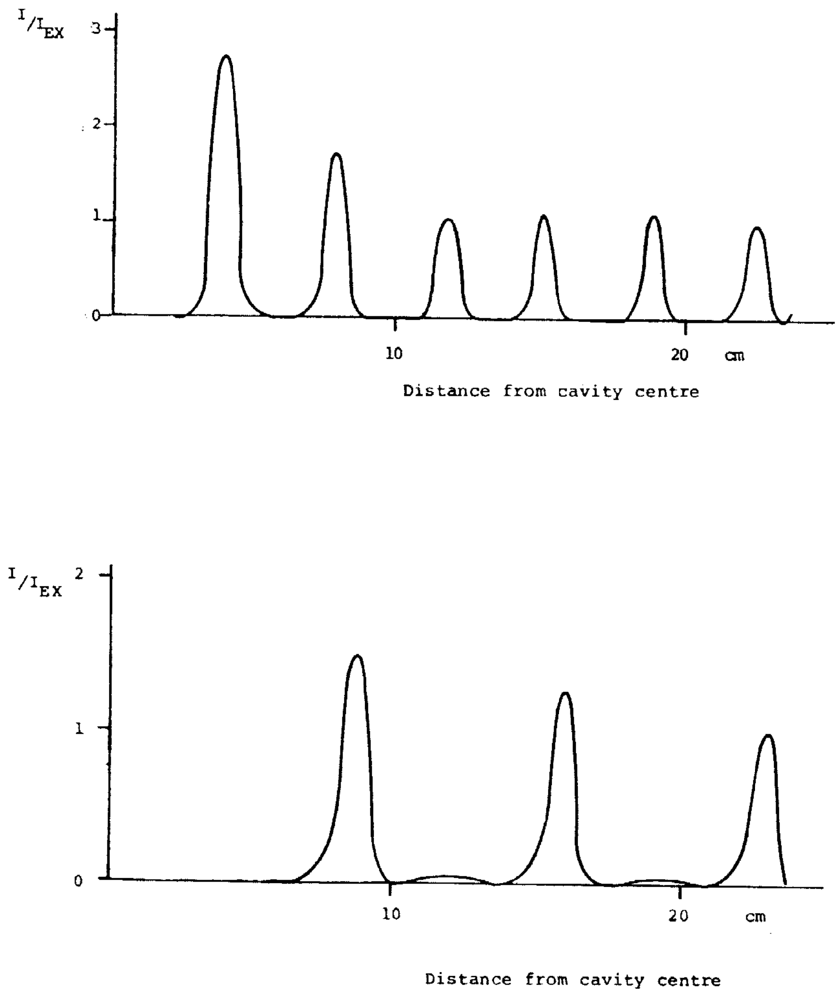

Fig. 3. Distribution of currents in the microtron orbits.

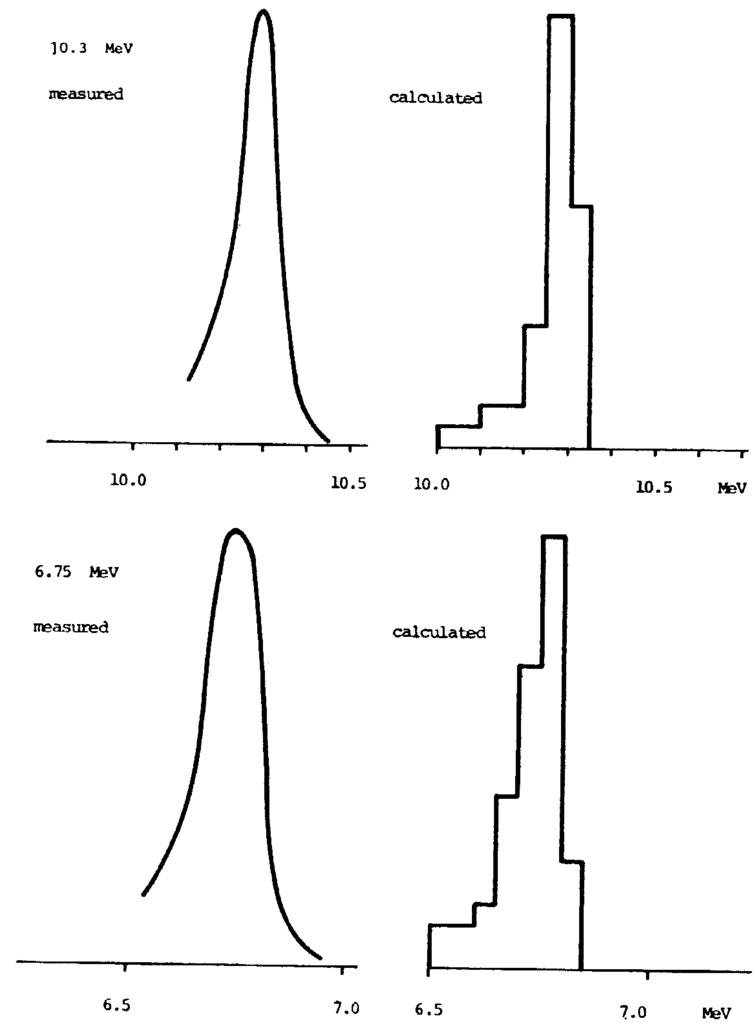

Fig. 4. Measured and calculated energy spectra of the extracted beam.

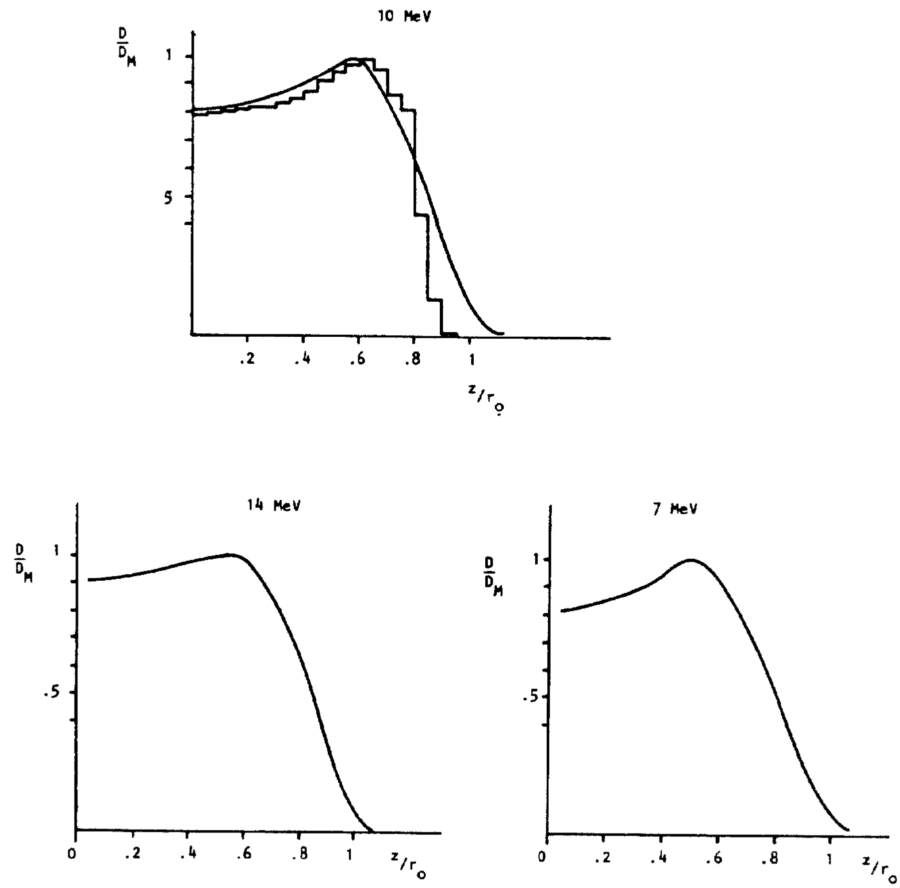

Fig. 5. Electron depth absorbed dose distribution.

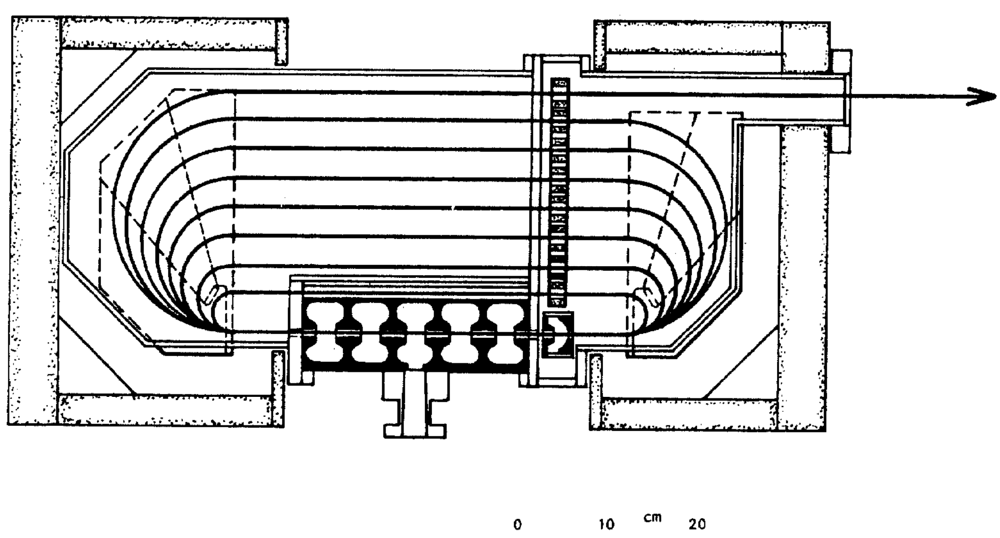

Fig. 6. Schematic diagram of a 25 MeV racetrack microtron.