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DESIGN OF A SHUTTLE MICROTRON FOR RADIATION THERAPY

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Summary

A design proposal for a new type of electron accelerator for radiotherapy applications is presented. The three-pass, fixed-magnet shuttle microtron is designed to allow continuous variation of electron beam energy from 4 to 24 MeV, while providing maximum current levels for x-ray treatment at 6, 12, and 20 MeV. The reflector magnets are structured for both axial and radial beam focusing and the entire accelerator fits into the horizontal arm of a rotatable therapy gantry.

Introduction

Linear accelerators and betatrons are widely used as electron accelerators for radiation therapy at energies from a few MeV to about 30 MeV. In the lower part of this range, linacs are very suitable but at the higher energies there is still a search for improved accelerator designs which are smaller, less expensive, and more convenient than the betatrons and linacs now available. There is also demand[1] for an accelerator whose energy can be varied over the widest possible range, so that a single "universal" therapy unit can provide either electron or x-ray treatment at any desired energy from a few MeV to 20 MeV or more.

The performance of the University of Western Ontario (UWO) racetrack microtron, with a three-cavity linac accelerating section and with output energy continuously variable from 1.5 to 18 MeV,[2,3] has demonstrated that such factors as size, beam characteristics, rf power requirements, ease of energy variation, and overall convenience and dependability of operation, make the racetrack microtron well-suited for development in a therapy configuration. An even more promising design for a therapy accelerator, however, is the shuttle microtron proposed in this paper.

General Description

In a racetrack microtron, the electron beam makes repeated passes, always in the same direction, through the accelerating structure (which may be a short linac). After each pass the beam is steered around by the magnetic guide field in a racetrack type of orbit, so that the return portion of each orbit by-passes the accelerating structure. The guide field must be designed to maintain proper synchronism between the beam and the rf field in the accelerating structure and also to achieve proper beam focusing for stable orbits. In a shuttle microtron, electrons are shuttled back and forth through a linac repeatedly, first in one direction and then in the other, by means of a reflector magnet at each end of the linac. Microtron-type synchronism and phase stability conditions must be satisfied, but the phase at which the beam enters the linac while travelling in the reverse direction can be selected independently from the entrance phase in the forward direction and therefore the energy gains in the two directions may differ. It is also possible and sometimes desirable to allow the beam to lose energy to the rf field during certain traversals of the linac.

An earlier proposal for an accelerator with repeated back-and-forth passes through a linac has serious practical limitations because the focusing properties of the reflector magnets[4,5] make it very difficult to obtain stable electron orbits. In the shuttle microtron proposed here, proper focusing to ensure orbit stability is obtained by using reflector magnets whose pole-pieces are shaped, in a relatively simple way, into several distinct regions with different gap widths between pole-piece faces and different values of magnetic field strength. Focusing occurs in the transition fields which exist along the boundaries between adjoining regions of unequal field strengths. The shapes and the relative gap widths required for the different regions in each reflector magnet must be determined from detailed calculations of electron trajectories to give correct overall focusing for stability of both axial and radial modes of betatron oscillations. This method of maintaining beam focusing has been used very successfully in the UWO racetrack microtron,in which the pole-pieces have been shaped to produce a three-level field in each of the two 180° bending magnets.[3]

A shuttle microtron has several advantages that make it especially suitable as a therapy accelerator. (1) Constraints on linac design, which are usually imposed by the small size of the first orbit in a racetrack microtron, are eliminated. This makes it possible to accommodate a higher shunt impedance linac in a shuttle microtron and simplifies both the cooling and mechanical design of the linac assembly. It also allows the use of auxiliary focusing coils around the linac. (2) Output beam energy can be varied more conveniently. If the beam makes not more than three passes through the linac, the final energy can be varied continuously by changing only the rf power in the accelerating cavities and the magnetic field in the reflector magnets, without changing the magnet positions as is required in a variable energy racetrack machine.[3] (3) Even though it requires a somewhat larger magnet than a racetrack design with the same maximum energy, a shuttle microtron can be fitted more easily into the space available in a rotatable therapy gantry because the orbit planes in the two reflector magnets need not be coplanar.

Therapy Design

The basic design of a three-pass, fixed-magnet shuttle microtron for radiation therapy is shown in Fig.1 and the arrangement of the accelerator in a rotatable gantry is shown in Fig. 2. This design, which allows the final beam energy to be varied continuously from 4 to 24 MeV for electron treatment, is optimized for x-ray treatment at 6, 12, and 20 MeV. The two reflector magnets are mounted, at fixed distances from the linac, with their orbit planes at right angles to each other. An annular in-line electron gun[6] with a hollow center is mounted on one end of the standing wave linac and electrons are injected directly into the first accelerating cavity. After making either one or three passes through the linac, the electron beam is extracted through the smaller reflector magnet and is then focused and directed on target by means of the two deflecting magnets shown in Fig. 2.

The S-band linac, which is 0.73m long and consists of 15 side-coupled cavities of the Los Alamos type,[7] is designed for optimum operation with an energy gain of 6 to 7 MeV per traversal. Rf power from a tunable 2 MW magnetron is coupled into the linac through the middle accelerating cavity. The rf design is similar to that used in the UWO variable energy racetrack microtron[3] and includes a power splitter to adjust the rf power supplied to the linac and thus the energy gain in the linac.

The pole-pieces of the reflector magnets are shaped to give essentially a two-level field in each magnet, with some additional structuring along the boundaries between the high and low field regions for beam focusing. The field is symmetric about the orbit plane and bilaterally symmetric with respect to the extended beam axis of the linac. Field strengths in the high and low field regions are in the ratio 4.5 to 1, with a maximum field strength in the high field region of 1.2 T. The beam is deflected a total of 540° during each reflection. This magnet design allows the beam to be focused both axially and radially and also allows on-axis electrons of different energies to return to the linac on-axis.

Two mechanisms are available for energy variation. Electron energies from 4 to 8 MeV can be obtained by passing the beam only once through the linac and adjusting the energy gain by means of the rf power splitter. The magnetic field in the small reflector magnet is adjusted to maintain the proper extraction position for different beam energies. In this single-pass mode, maximum beam current is available at 6 MeV for x-ray treatment. For higher electron energies, three passes through the linac are needed. Continuous variation of electron energy up to 24 MeV is possible by varying both the energy gain in the linac and the phase at which the beam re-enters the linac. The entrance phases for the second and third passes can be adjusted, independently of each other, by changing the magnetic field in the small and large reflectors respectively. For 12 MeV x-rays, the electron beam is accelerated with an energy gain of 6 MeV in each of the first two passes and is then allowed to drift through the linac in the final pass.

Since this therapy design involves only three passes through the linac and since the schematic arrangement and orbit shapes given in Fig.1 show little resemblance to any previously known microtron design, it is not obvious why this type of accelerator should be regarded as a microtron rather than simply as a multiple-pass linac. Justification for the name "microtron" comes not from the physical appearance but from a consideration of the phase behaviour. In a multiple-pass design with this type of reflector magnets, phase oscillations occur, with periods which are of the order of the time required for one linac traversal plus one reflection. These phase oscillations, together with the existence of a phase-stable region that determines the acceptance of the accelerator, characterize this design as a microtron and make it fundamentally different from a multiple-pass linac with isochronous reflector magnets.[8]

Discussion

The shuttle microtron concept proposed here opens new possibilities in accelerator design for radiotherapy. This new type of microtron, just as its racetrack counterpart, offers considerable design flexibility which can be adapted to suit the needs of a particular application. The proposed three-pass, fixed-magnet design satisfies the specific objective of allowing very convenient energy variation over a wide continuous range, in a unit small enough to fit into a rotatable gantry. The same range of energies can be obtained with a shorter linac and/or more modest rf system by using a modified reflector magnet design and more passes through the linac; this, however, requires a movable magnet design to allow the distance between each magnet and the linac to be adjusted as the energy is varied. A simpler version of the three-pass, fixed-magnet design is possible if an electron beam is required only at several discrete energies in the range, rather than over the continuous range. Energy variation over a series of discrete energies can be accomplished by adjusting only the magnetic field in the reflector magnets, to change the entrance phase for the final two traversals, without changing the rf power in the linac. The present design is optimized for x-rays at 6, 12, and 20 MeV, but a design for other x-ray energies in this range is also possible.

Although a side-coupled linac has been used in the present design study, other types of accelerating structures, with or without focusing coils, can be accommodated and may in fact prove to be more suitable in a shuttle microtron.

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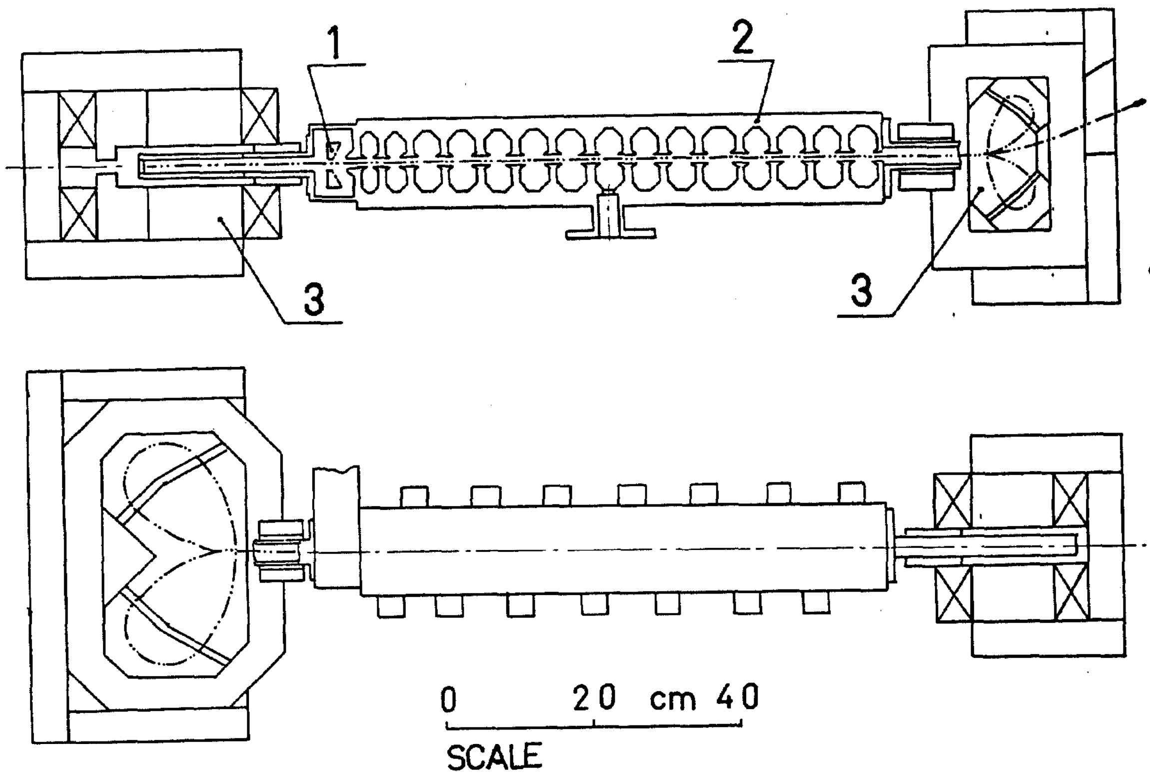

Fig. 1. Schematic diagram of a three pass fixed magnet shuttle microtron. 1. Annular electron gun. 2. Accelerating structure. 3. Reflector magnet.

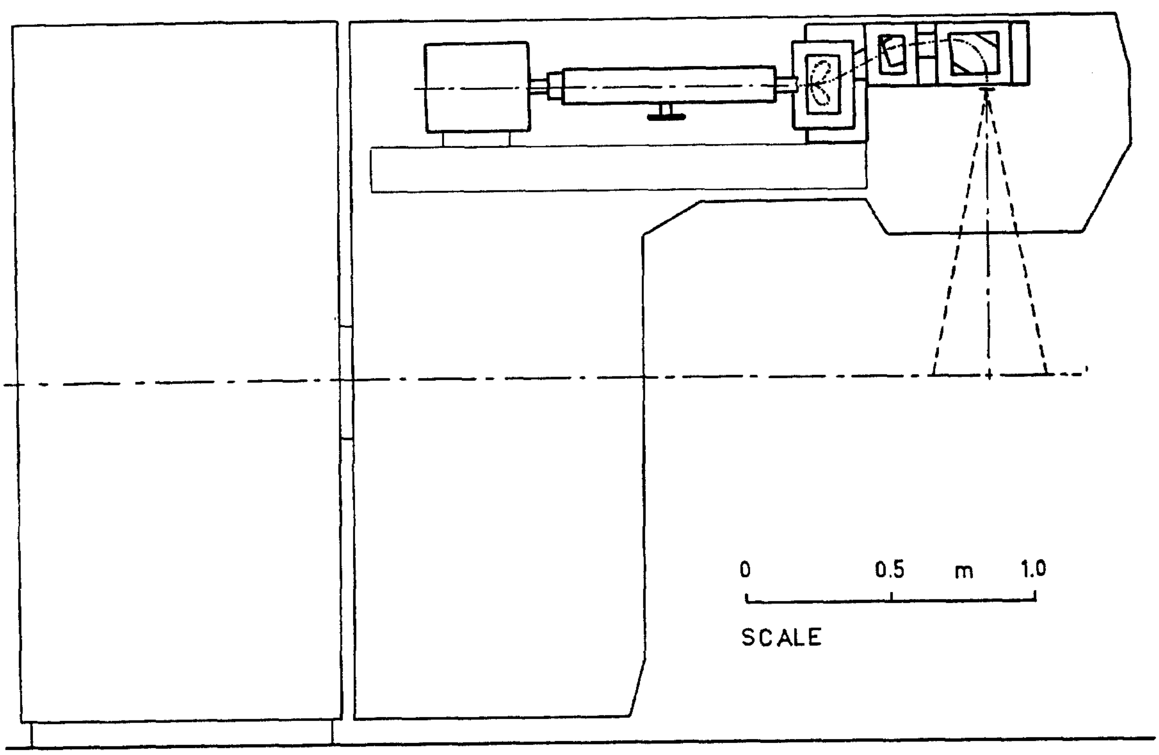

Fig. 2. A possible arrangement of a shuttle microtron in a rotatable radiotherapy gantry.