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EXPERIMENTAL MEASUREMENTS ON A 25 MeV REFLEXOTRON

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Summary

A 25 MeV electron double-pass linac (reflexotron) has been built and tested in a medical-therapy configuration. It uses a 16% $\Delta E/E$ reflecting magnet and a pulsed coaxial annular diode gun. The electron beam passes through the S-band accelerating structure twice achieving second pass energies of 5 to 25 MeV depending on the position of the reflecting magnet relative to the accelerating structure. The 0.1% duty factor electron accelerator has many attractive features. The 1.6 m on-axis coupled accelerating structure has a ZT^2 of 82 MΩ/m and requires less than 2 MW of rf power for energies up to 25 MeV. Calculations of beam transmission, energy variability and double-pass spectra have been verified by experiment. Therapeutically useful radiation beams are achieved by suitable target and flattener combinations.

Introduction

The reflexotron[1] is one of a class of electron accelerators which increase the efficiency of converting rf power to beam power by multiple beam passes through the same accelerating structure. In this way, the structure length necessary to achieve a given final energy is reduced. Such compact, high efficiency and low cost accelerators have advantages for medical applications.

Two types of accelerators which employ multiple beam passes are the microtron[2] and the linatron[3]; in the former the beam passes through the structure in the same direction each time, while in the latter every alternate pass is in the opposite direction. The reflexotron is a linatron with only two passes.

Measurements on two 25 MeV reflexotrons to determine their operating characteristics and to confirm the advantages of the reflexotron as an X-ray source for medical therapy applications are reported here. In addition to its efficiency, small size and low cost, the reflexotron output energy is easily varied from 5 MeV to 25 MeV with acceptable energy spectra.

General Description

One of the two similar 25 MeV reflexotrons is shown in Fig. 1. One system had extra diagnostics to assist in beam measurements. This 2.8 m long accelerator can be mounted on the rotating arm of an isocentric therapy unit and can produce flattened treatment beams of 500 rads/min (5 Gy/min) over 40 cm x 40 cm fields at a one metre target to surface distance, (TSD), for photon end point energies from 8 to 25 MeV and for extracted electron beams with energies from 5 to 25 MeV. The 1.6 m on-axis coupled accelerating structure operates in the $\pi/2$ mode at 3 GHz. It is excited by a 0.1% duty factor 1.8 MW tunable M-5125 magnetron isolated by a 23 db circulator. Details of the accelerating structure have been published[4,5].

The 16% $\Delta E/E$ passband 180° reflecting magnet, also described earlier[6], consists of four dipoles with a maximum 1.5 T field. It is 0.4 m in length along the accelerator beam axis and is mounted on a rigid carriage designed to allow 5 cm travel of the magnet along the axis of the accelerating structure. Changing the position of the reflecting magnet relative to the accelerator changes the re-entray phase of the second pass beam, resulting in beam energy variability.

After second pass acceleration the beam is bent up 12° and down 102° for a net 90° bend prior to exit from the accelerator vacuum through a nickel window. This double magnet system is designed to be achromatic and have strong axial and radial focusing properties.

Focusing and steering elements at the entrance and exit of the structure are used to offset effects of space charge forces, rf defocusing and misalignment. Demountable nickel windows are installed at each end of the accelerator so that first pass and second pass beam characteristics could be measured.

Bremsstrahlung radiation is produced by electrons impinging on a fully stopping copper target placed at the focus of the exit magnet system. Copper is used because its neutron production is five times less than that from a high atomic number element such as tungsten, because its thermal conductivity is excellent and because the average energy of the output radiation is not reduced as it is by a high atomic number target.

Experimental Results

A twin cavity automatic frequency control[7] system, used to lock the magnetron operating frequency to the accelerating structure resonant frequency, maintained the accelerating fields associated with selected peak power levels to within 0.5% for average powers from 20 W to 2 kW. Similar field control was observed for average accelerating structure temperatures from 10°C to 100°C at 2 kW average rf power.

The high efficiency of the standing-wave accelerating structure with on-axis couplers has been reported earlier[4] - the measured effective shunt impedance was 82 MΩ/m (95% of the theoretical value).

An annular diode electron gun with a measured emittance of 50 π mm mrad at 600 mA has been tested and will be used on the accelerator soon. Its emittance matches the calculated requirement of the accelerator for optimum double pass beam transmission at high currents (> 25 mA). Beam measurements reported in this paper were done with an annular diode gun which had an emitter in only one quarter of the annulus. The accelerator does not have a buncher, limiting first pass transmission to 30%. Such transmissions were achieved for first pass currents up to 150 mA - at which point first pass energy had decreased to 8 MeV because of the limit on rf power.

Transmission through the reflecting magnet was measured by a toroid placed between the accelerator and the reflecting magnet. Beam losses in the reflecting magnet ranged from 10 to 15%; this agreed with calculations based on measured first pass energy spectra and magnet properties[6]. The lost beam was a low energy continuum with an upper bound determined by the energy acceptance "window" of the reflecting magnet. Radiation produced by the lost beam was not significant - the total dose rate without extra shielding and if all the lost beam was directed at one point was estimated to be less than 0.1% of that produced by the 25 MeV beam incident on the copper target.

Measurements with a bremsstrahlung beam monitor[8] showed that both first pass and reflected first pass beams had full widths at half maximum intensity of approximately 5 mm. These measurements confirmed the assumed beam cross sections used in transmission calculations.

Maximum double pass beam currents obtained to date have been 30 mA at 25 MeV and 30 mA at 8 MeV. This current, at 300 pps, 2.7 μs pulse length will produce bremsstrahlung radiation of approximately 8000 rads/min (80 Gy/min) and 300 rads/min (3 Gy/min), respectively, at one metre from the target.

A 30° magnet with a radially focused, momentum dispersed image at a 0.5 mm slit, 0.18 m from the magnet was used to analyze the spectra of output beams with energies from 5 to 25 MeV. Spectra had negligible low energy "tails" because the reflecting magnet acts as an energy selector, eliminating low energy electrons. The average peak energy and the spectral full width at half maximum intensity are recorded in Table 1 with the predicted values determined from "impulse approximation" energy gain calculations. Full variation of output energy was obtained by a 2 cm movement of the reflecting magnet with respect to the accelerating structure.

Table 1

Comparison of Measured and Calculated Spectral Full Width at Half Maximum (FWHM)

Average Peak Energy (MeV)	Calculated FWHM (MeV)	Measured FWHM (MeV)
25	0.9	0.8 ± 0.1
20	0.8	0.9 ± 0.1
15	1.0	0.9 ± 0.1
10	1.2	1.0 ± 0.1
5	0.9	0.8 ± 0.1

Measurements of the 25 MeV end point bremsstrahlung beam with a lucite phantom at a TSD of one metre (using LiF thermoluminescent dosimeter chips) yielded 50% dose depths of 21.4 ± 1.0 cm for a 40 cm by 40 cm field and 22.5 ± 1.2 cm for a 10 cm by 10 cm field. (The different field sizes were defined by a movable-jaw tungsten collimator.) Similarly, the measured 50% dose depths with an 11.8 cm (47.2 g/cm^2) long conical Al_2O_3 flattening filter in the field were 28.4 ± 1.5 cm for a 40 cm by 40 cm field and 27.8 ± 1.9 cm for a 10 cm by 10 cm field. Attenuation measurements with the Al_2O_3 filter confirmed that a 20.5 cm thick cone would be required to flatten a 25 MeV bremsstrahlung beam whose intensity 12° from the central axis is 0.18 that of the central axis intensity.

Stable operation of the reflexotron at preselected set-points for electron beam energies from 5 to 25 MeV was achieved within one second of turn-on after bending magnet supplies, magnetron and gun high voltage had been off for periods up to an hour.

Discussion

A 25 MeV accelerator has been demonstrated which is compact (less than 2.8 m in length), uses rf power efficiently (< 2 MW required), provides useful electron and bremsstrahlung beams from 5 to 25 MeV and can be isocentrically mounted on a rotating therapy structure with a one metre target to surface distance.

First pass and second pass transmissions were approximately 30% and 26% respectively, of the injected beam current. These transmissions are as expected for an accelerator designed without a buncher or chopper.

No unexplained phenomena have been observed in the operation of the double pass accelerator. Measured energy spectra, beam transmissions and operating set points for the various components agree with calculated values. Easy energy variability has been demonstrated.

References

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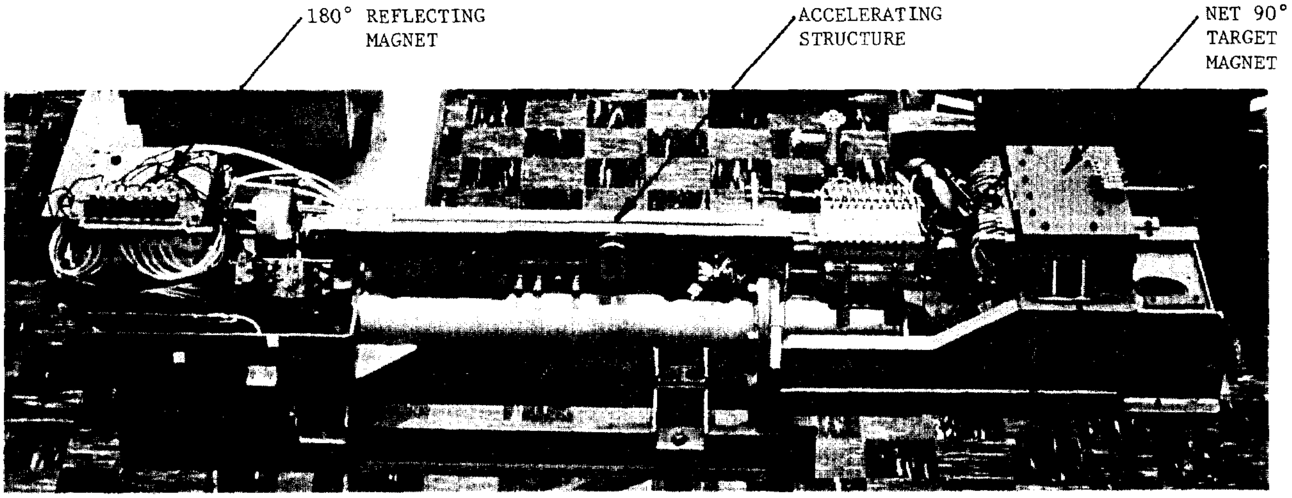

Figure 1. The 25 MeV electron accelerator attached to its strongback.