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DOUBLE PASS LINEAR ACCELERATOR - REFLEXOTRON

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Summary

Measurements of energy spectra and percentage beam transmissions are given for an S-band linear accelerator through which the electron beam passes twice, in opposite directions. Results are presented for two magnet reflecting systems which have energy acceptance windows, $\Delta E/E$, of 2% and 16% where E is the output beam energy after the first pass through the accelerator. For a first pass beam energy of 8 MeV the second pass energy could be varied from 3 MeV to 16 MeV by changing the separation between the accelerator and the magnet system. The corresponding full-width half-maximum energy spreads were 1.6 MeV and 0.7 MeV respectively. The system transmission was 35% first pass (unbunched injected beam) and $\sim$ 100% second pass.

Introduction

Multiple passes of an electron beam through an accelerating cavity were achieved in the 1950's with microtron systems based on principles originally developed by Veksler[1]. Roberts[2] was the first to propose using a linear chain of cavities for acceleration with a system called a racetrack microtron. In a microtron the beam passes through the accelerating structure in the same direction each time. The "Linatron", a variant of multiple pass acceleration involving passing of the beam through a standing-wave linear accelerating structure in opposing directions, was proposed by Kolomensky[3] in 1967. Reflecting magnets are required for bending the beam at each end of the structure. A version of this type of accelerator with two electron beam passes through a 1 m, 0.1% duty factor, S-band, standing-wave structure has been built and tested. The accelerating structure had the added complication of a graded β injection portion. After first pass acceleration the electron beam was reflected (hence Reflexotron) by a compact magnet system which satisfied achromatic, isochronous and non-magnifying conditions over a specific energy acceptance window - 2% and 16% $\Delta E/E$ magnet systems were tested.

The double-pass linac can be an attractive alternative to single pass systems where for economic reasons an application requires a compact accelerator with low rf power consumption. In particular, for a 20 to 40 MeV accelerator the Reflexotron has the following additional features compared to a conventional multi-tank system:

(a) The single accelerating structure simplifies rf controls and assembly.
(b) The entire system is small enough to be baked-out as a unit package.
(c) Conversion of rf energy into beam energy is four times as efficient because the energy gain is doubled.
(d) Good energy spectra can be obtained for output energy variations in excess of a factor of five.
(e) Energy variability, by moving the reflecting magnet system with respect to the accelerator, is easy.

Based on experience gained, a 25 MeV Reflexotron is being built which uses a 1.6 m pancake-coupled[4] accelerating structure, a 2 MW, 0.1% duty factor magnetron and the 16% $\Delta E/E$ reflecting magnet. With a pulsed, co-axial, annular diode gun as the electron source, output currents of 90 mA at 8 MeV and 8 mA at 25 MeV are expected.

System Description

A block diagram of the system used for testing double-pass performance is shown in Figure 1. The side-coupled accelerating structure was fabricated by brazing OFHC copper segments and consists of 21 accelerating cells with grading in β limited to the first four cells (β_1= 0.79, β_2= 0.90, β_3= 0.94, β_4= 0.96). At the design field for this grading, first pass output energy was 8 MeV with a spectral full width at half height of less than 0.16 MeV.

Rf power was coupled to the structure via an iris in the central accelerating cell. Capacitive probes mounted close to the perimeter of the first, central and last accelerating cells monitored rf fields to give a measure of electric field gradients. The rf power source was a tuneable M-3056 Thomson-CSF magnetron with a nominal output rating of 2 MW at 0.1% duty factor. Isolation was provided by a 23 db circulator. Other high power rf components consisted of a power attenuator to vary the rf drive, a VSWR detector, a phase shifter and directional couplers.

The Pierce-geometry diode electron-gun using a 3 mm diameter dispenser cathode was mounted 90^o to the accelerator axis. It was driven by the magnetron HT pulse through a quadrifilar-wound pulse transformer at 40 kV. A 90^o magnet with 26.6^o pole face rotations was mounted between the gun and accelerating structure to inflect the low energy electrons. Deflection of the emergent double-pass beam by the 90^o magnet was calculated to be less than 3^o for 5 MeV electrons.

A 60 ℓ/sec noble-gas ion-pump maintained pressures less than 10^{-6} torr with rf and beam on. The pump, attached to the electron gun which was the major gas load, can be seen in Figure 2 which shows the Reflexotron mounted on the test frame.

Beam energy and spectral measurements were made after both passes using a 30° analysing magnet with a radially focussed, momentum dispersed image at a 0.5 mm slit. Currents transmitted through the slit were measured using a Faraday cup. Faraday cups were also employed to measure currents directly from the gun and at the first and second pass beam exits. Toroidal pulsed current monitors were used at both ends of the tank to give additional transmission information.

Focussing elements were mounted between the accelerating structure and inflection magnet and between the structure and reflecting magnet. Calculations, which considered off-axis beam dynamics related to space charge forces and rf focussing effects, showed that lenses with focal lengths of 0.05 m and 2 m were required at the two locations respectively. The latter requirement compensated for rf defocussing effects on the second pass beam in the graded β portion of the structure.

Two magnet systems shown schematically in Figure 3 were used in tests of the double pass system. They had to satisfy stringent achromatic (radial dispersion after reflection < 0.2 mm/%$\Delta E/E$), isochronous (change in path length between -0.15 mm/%$\Delta E/E$ and 0.2 mm/%$\Delta E/E$ to not degrade the output spectra), and non-magnifying (absolute radial and axial magnifications of < 1.0 and < 1.0 respectively) requirements over a 2% and 16% $\Delta E/E$ window, respectively.

The 2% magnet system consisted of two magnets - the initial 5° magnet approximately 27 cm from the 190° magnet. This system was designed for accelerator operation with a fixed first pass energy gain of 8 MeV where the spectrum ΔE is a minimum (hence a small window). Second pass energy changes required adjustments to the rf power as well as to the magnet-structure separation to compensate for changing beam loadings. Rf power variation would not be required for a system with very small beam loading.

The 16% $\Delta E/E$ magnet consisted of four elements and although more complicated than the 2% system, it was shorter - 11 cm separate the near and far pole pieces with respect to the structure. Details of its design are given in reference 5. This magnet was designed for studying system operation at variable beam loading with constant rf power; under these conditions first pass acceleration departs from optimum conditions and narrow first pass spectra are not always achieved.

Previously described magnet systems of Kolomensky[3], Gapanovich[6] and Hortig[7] do not meet the stringent requirements of the reflector.

Calculations

On-axis calculations of double-pass energy gains in the accelerator using an "impulse approximation" are shown in Figure 4 for a wide range of average electric field gradients (12 MV/m corresponds to the design gradient). Corresponding rf powers, shown in parenthesis, assumed an effective shunt impedance of 70 MΩ/m. Modal energies are plotted as a function of the reflecting magnet-accelerating structure separation, with "0" corresponding to a path length of 1 m from the centre of the last accelerating cell, through the reflecting magnet and back to the centre of the same cell. Note that energy variability can be achieved for both positive and negative magnet displacements. But narrower spectra are obtained for positive displacements; Figure 5 shows the calculated spectral widths corresponding to the various energy gains plotted in Figure 4.

Calculations for a positive-displacement output energy range of 3 to 16 MeV, which considered both transverse and longitudinal beam losses, showed that double-pass output currents would be 20-25% of the inflected gun current for the output spectral width at 10% of the maximum height (FW10%M). First pass spectra were calculated to determine the fraction of the first pass spectra falling within the energy band-pass of the particular magnet in use. Over the 3 to 16 MeV range only 6 to 15% of first pass current (2 to 5% of inflected gun current) is outside the 16% $\Delta E/E$ magnet window and this current is lost in the reflecting magnet.

Experimental Results

No unexplained phenomena were observed with double-pass operation of the accelerator using either magnet system. For the 2% $\Delta E/E$ system, experimentally determined peak energies, transmissions and spectral shapes as a function of magnet-structure gap were in reasonable agreement with calculations. One example of measurements with the 2% $\Delta E/E$ system, double-pass energies, is shown in Figure 6.

Selected double-pass energy data near an average electric field gradient of 12 MV/m are shown in Figure 7 as a function of magnet-structure gap for the 16% $\Delta E/E$ reflecting magnet. Measured energies at other gradients were also in reasonable agreement with calculated values.

Some measured beam transmissions are compared with calculations in Table 1. The calculated second pass current, in good agreement with the measured value, was determined using the fraction of first pass electrons (based on measured spectra) which are transmitted by the 16% $\Delta E/E$ magnet window and using calculated second pass beam transmission through the structure ($\sim$ 100% for the 16% $\Delta E/E$ system). Other results with the 2% magnet (which returned less current for the second pass) are in equally good agreement.

Table 1: Measured and Calculated Performance with the 16% $\Delta E/E$ Reflecting Magnet

First Pass Energy	First Pass Current	Second Pass Current	Calculated Second Pass Current
8.3 MeV	20 mA	16.6 mA	16.1 mA
8.2 MeV	20 mA	14.8 mA	17 mA

Figure 8 gives a few comparisons of measured double pass spectra with calculated spectra as a function of displacement, z. There is good agreement over a wide range of output energy.

Conclusions

An accelerating system has been described which increases the efficiency of converting rf power into beam power by the simple expedient of reflecting the beam and passing it through the accelerating structure again, in the opposite direction. Calculations and experimental measurements which are in good agreement have been presented for an 1 m S-band linear accelerator coupled to a reflecting magnet with either a 2% or a 16% $\Delta E/E$ energy acceptance window. Magnet characteristics which must be met have also been given.

No unexplained beam performance related to counterflowing currents has been observed for double pass currents up to 20 mA. Experiments are continuing and hopefully pulsed currents of 100 mA will be accelerated without complications in the future. The experiments have demonstrated the ease with which energy variability can be achieved in a relatively small and compact accelerator. Based on these results this type of accelerator could be useful in future applications where economies in physical space and rf power are important.

Acknowledgements

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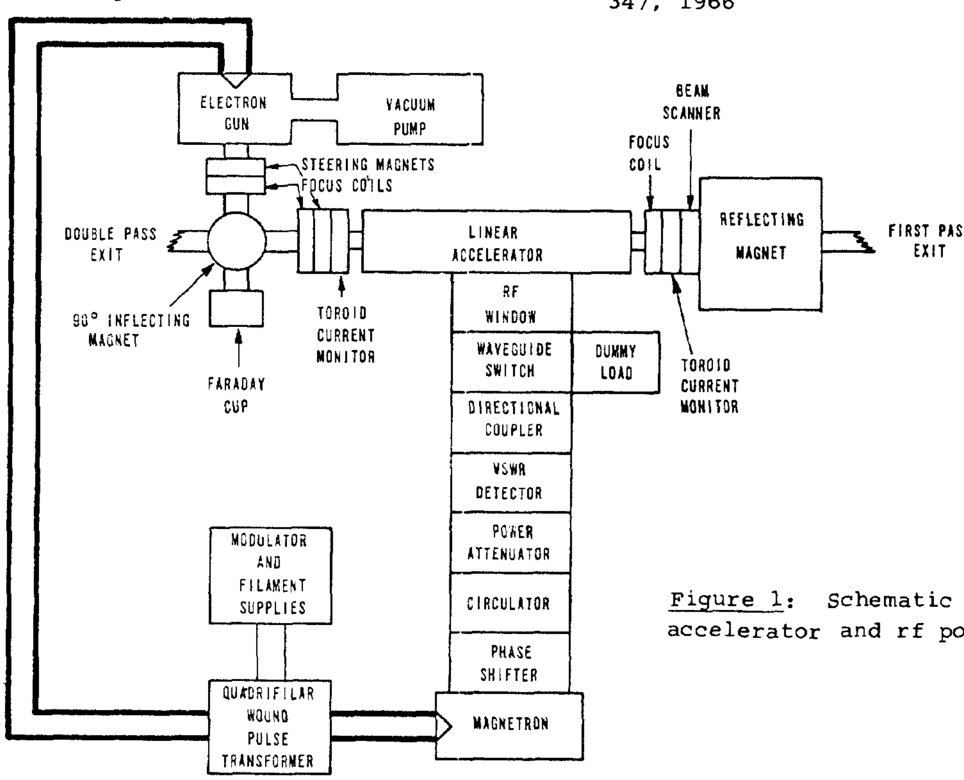

Figure 1: Schematic layout of accelerator and rf power system.

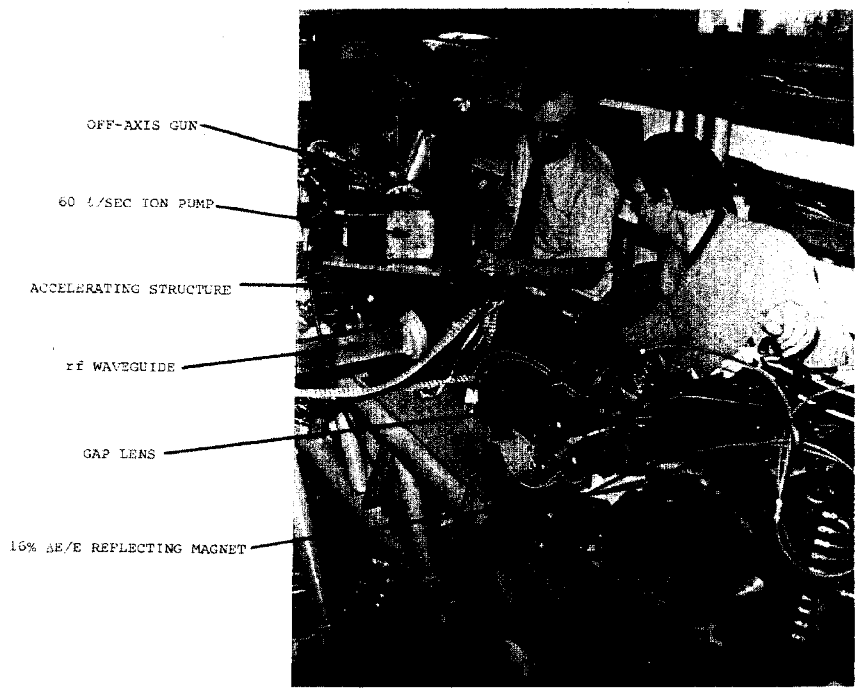

Figure 2: The experimental double pass accelerator.

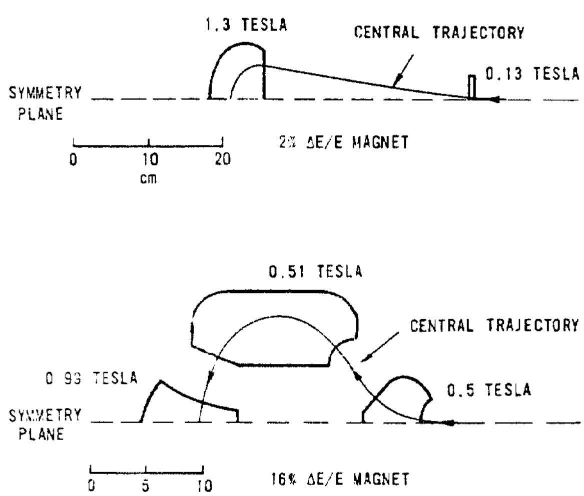

Figure 3: Layout of the two magnet systems (scales approximate). Magnetic fields in Tesla are given for 8 MeV first pass energy.

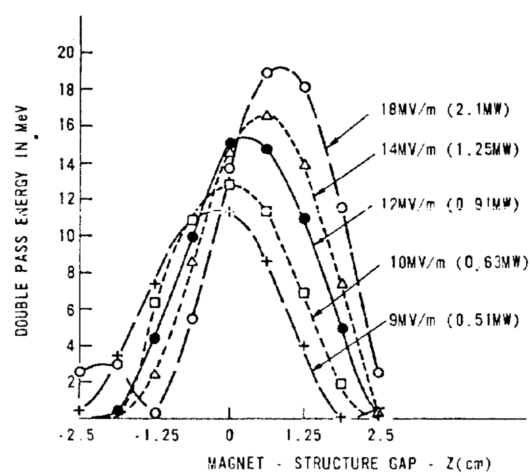

Figure 4: Calculated modal energy in MeV vs. magnet to accelerating structure gap for different field gradients and rf powers (z=0 corresponds to a 1 m drift through the reflecting magnet and back to the structure).

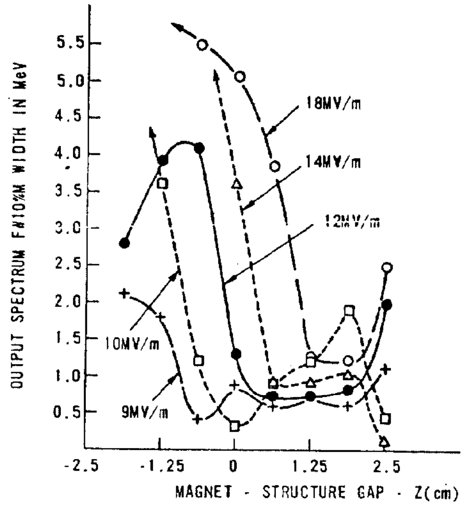

Figure 5: Calculated full spectral width at 10% of the maximum peak height (in MeV) of the double pass energy spectra vs. magnet to accelerating structure gap for different field gradients.

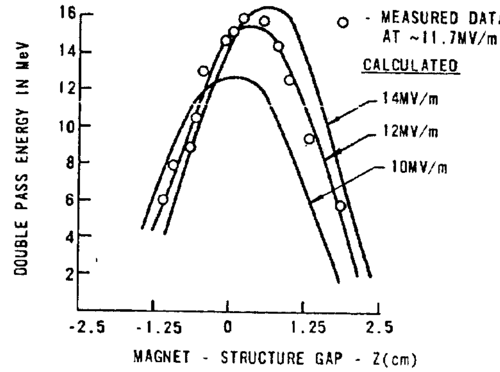

Figure 7: Measured double pass modal energy in MeV vs. magnet to accelerating structure gap.

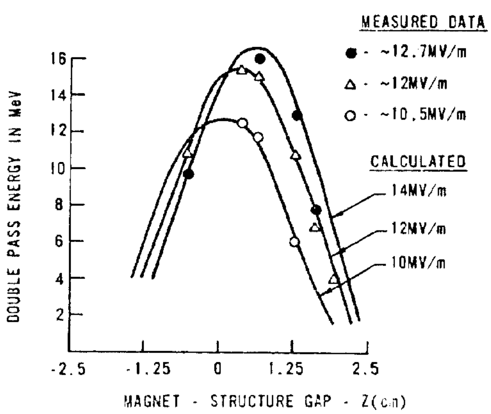

Figure 6: Measured double pass modal energy in MeV vs. magnet to accelerating structure gap for different field gradients.

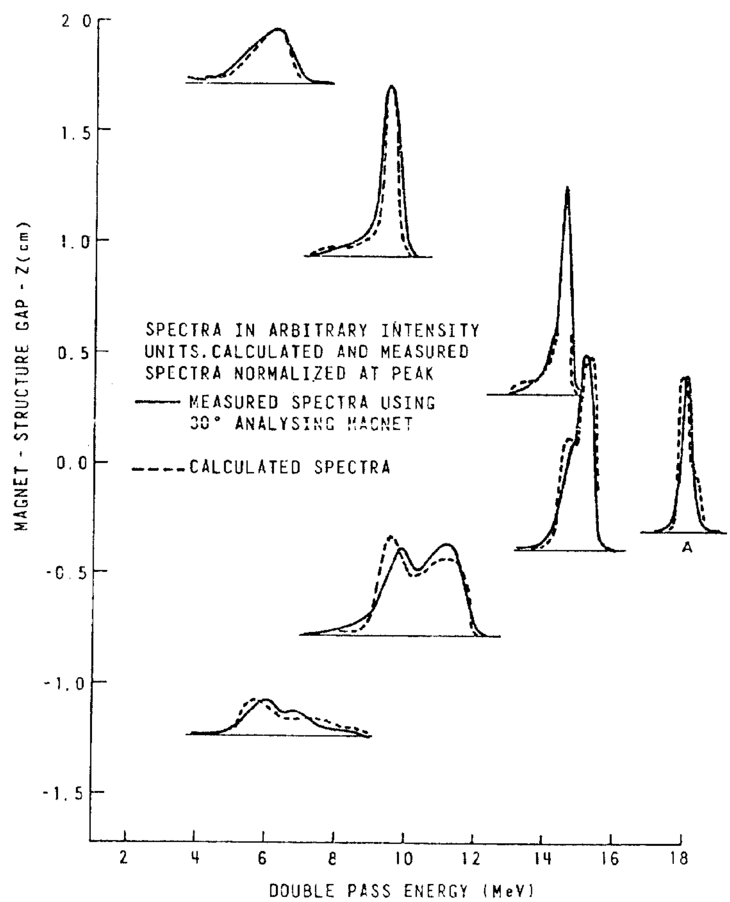

Figure 8: Comparison of measured and calculated energy spectra vs. magnet to accelerating structure gap for a gradient of $\sim$ 12 MV/m (Spectra A at $\sim$ 16 MV/m).