Proceedings of the 1984 Linear Accelerator Conference, Seeheim, Germany

COAXIAL-COUPLED LINAC STRUCTURE FOR LOW GRADIENT APPLICATIONS

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Summary

The most cost effective mode of operation for the accelerating structure in a cascade microtron occurs when the linac sections are run at relatively low power and low gradient (~1.0 MeV/m). A prototype 2.45 GHz coaxial-coupled structure optimized for low power operation was fabricated and tested. The prototype was found to have a shunt impedance of over 90 MΩ/m with a cell to cell coupling of 3.5%.

Introduction

As part of the room temperature CW electron-microtron development project at the University of Illinois we have been interested in determining ways in which the characteristics of accelerating structures can be optimized in the context of our particular cascade microtron application.[1] Some recent work on structure development[2,3] has tended to emphasize high power, high gradient operation and large cell to cell coupling. For machines of the cascade microtron type however, a better course of optimization may lie in the direction of low power, low gradient operation with only modest demands on the coupling. In the following we examine these considerations and describe the results of tests on a short copper section of 2.45 GHz coaxial-coupled structure optimized for low gradient applications.

Cascade Microtron

In a racetrack microtron dipole return magnets are used to recirculate electrons many times through a relatively short length of linear accelerator.[4] General stability considerations tend to limit the desirable overall energy gain to about a factor of ten above the injection energy.[5] For higher final beam energies, successive independent microtron stages can be linked together in a cascade. The maximum energy gain required in each of the embedded sections of linac tends to be rather narrowly fixed by the recirculation scheme and by the size of the return dipole magnets. For the case of the 750 MeV machine proposed at Illinois,[1] the injection energy is 4.5 MeV with subsequent single pass gains of 1.0, 5.55, and 8.33 MeV required respectively in the three following stages.

Because these individual energy gains are relatively modest the actual physical length of structure that is used to provide the acceleration is not a very strong constraint on the design of the machine. It is interesting to look at both the cost of the structure itself and the cost of the power required to operate it as functions of the accelerating gradient. In simple terms the length of an accelerating section can be estimated from

$$L \sim \frac{\Delta E}{\varepsilon \cos\phi}$$

where ΔE(MeV) is the total energy gained by a relativistic electron injected at a phase ϕ, and ε(MeV/m) is the gradient. Similarly, the power required to maintain this gradient in the section is

$$P_s \sim \frac{\varepsilon^2 L}{ZT^2} = \frac{\varepsilon}{ZT^2}\,\frac{\Delta E}{\cos\phi}$$

where ZT^2(MΩ/m) is the shunt impedance of the structure. From these simple expressions it is evident that for a very high gradient structure the total length of accelerator will be small and that the cost of power will tend to dominate the total cost. For very low gradient structures the reverse tends to be true, and one might expect that the most cost effective configuration would lie somewhere between the two extemes.

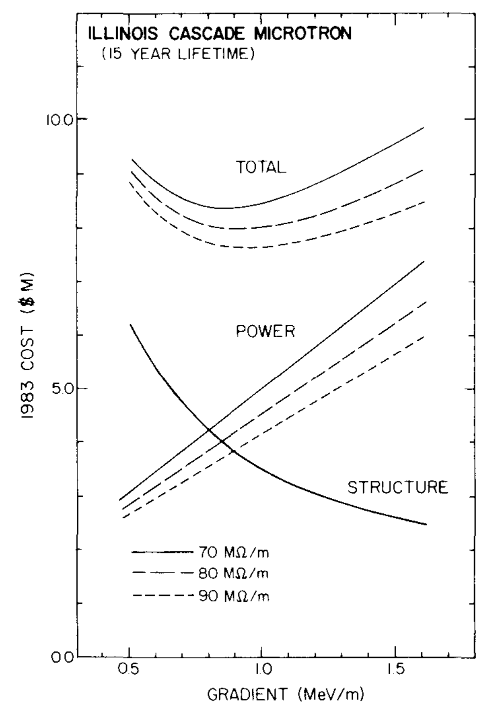

Figure 1. Structure cost, lifetime power cost, and total cost as a function of accelerator gradient. Three different assumptions for the shunt impedance of the structure are shown.

We have investigated the cost trade-off described above in great detail for the particular case of the proposed 750 MeV Illinois machine. An attempt was made to include all costs for klystrons, power supplies, RF distribution, vacuum, cooling and control as well as fabrication and material costs in the numbers used for the accelerating structure. Similarly, power expended in all of the contributing elements and in the beam itself has gone into the total power cost. The results are summarized in Figure 1 for three different assumptions about the shunt impedance of the accelerating structure. The power expenditure is based on an average operation of 5000 hours per year over a 15 year facility lifetime. The total cost curves of Figure 1 suggest that there is little to be gained by operating a cascade microtron at gradients much above 1.0 MeV/m. This result is quite insensitive to rather large variations in the cost per meter of linac fabrication, and should apply generally to machines of this type.

Structure Optimization

At present there are three room temperature CW electron accelerating structure designs that can be considered seriously for use in a cascade microtron. The three are the on-axis coupled structure,[6] the co-axial-coupled structure,[7] and the side coupled structure;[2,8] all of which are operated in the $\pi/2$ mode and have biperiodic cell configurations. As the names indicate, and as can be seen from the profile comparsion in Figure 2, the most obvious differences among them are in the arrangement of the unexcited coupling cells. The excited cells can be virtually the same in each of the cases.

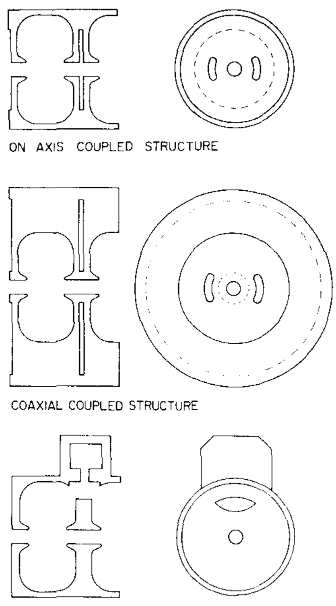

Figure 2. Comparison of the profiles of three accelerating structures suitable for recirculating CW room temperature electron machines.

In general the efficiency of a structure depends on the shunt impedance and on the Q which tends to be degraded somewhat as the cell to cell coupling is increased. The maximum power level at which a structure can be operated is constrained by the susceptibility of the design to thermal detuning and by the physical potential for the introduction of cooling. Interrelations among the shunt impedance, the operating power, and cavity shape parameters related to radial cooling are shown in Figure 3 for an accelerating cell geometry that is essentially common to all three structure designs. The power scale on the figure corresponds to the assumption that the structure is operated at the optimum gradient of 1.0 MeV/m discussed in the previous section. Below a web thickness of about 0.6 cm, which is a dimension typical of the Mainz and CRNL s-band structures, it is not physically practical to introduce radial cooling channels. The dashed curves on the figure correspond to constant web temperature gradients assuming only conductive cooling. For example a structure that could be powered up to a level of 18 kW/m with a 0.6 cm web might be expected to be constrained to operate below about 11 kW/m with a 0.4 cm web. The Mainz structure has been taken to more than 20 kW/m with only conductive cooling through a 0.61 cm web.[9]

The real interest of Figure 3 is that it shows that low power 1 MeV/m gradient operation eliminates the necessity for radial water cooling channels in the on-axis and coaxial geometries and allows the thickness of the cavity wall to be reduced. This in turn has the effect of significantly increasing the

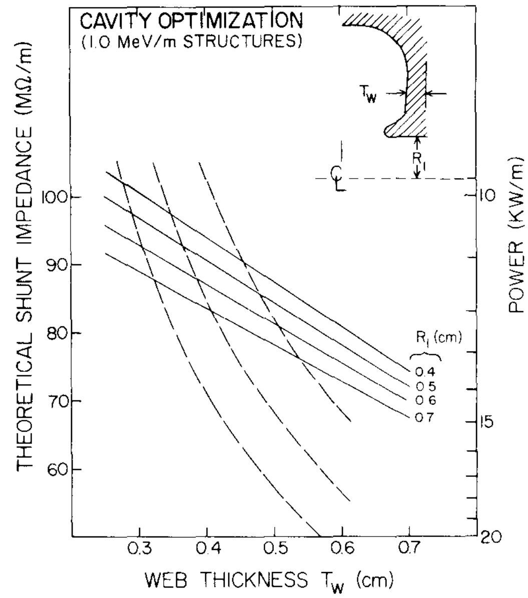

Figure 3. Interrelations among the shunt impedance and two cavity-shape parameters related to radial cooling. The power scale corresponds to a gradient of 1.0 MeV/m and the dashed lines correspond to constant web temperature gradients assuming only conductive cooling.

shunt impedance of the structure which further reduces the heat load associated with a given gradient. From the Figure, one expects that a structure with a 0.3 cm web and 1.0 cm beam aperture would have a shunt impedance well in excess of 90 MΩ/m.

We were interested in pursuing an optimization of the coaxial-coupled structure design developed at CRNL because it could be shown to be more stable against thermal detuning than the Mainz on-axis structure[3] and could be much more easily fabricated than the LANL side coupled structure. Questions about a possible coupling of the accelerating mode of this structure to higher modes in the coupling cells have been investigated in an earlier paper.[10] The profile for the 2.45 GHz cavity was determined by using SUPERFISH[11] to maximize the theoretical ZT^2 and Q, and the final configuration is shown in Figure 4. Thermal detuning sensitivity and stop band changes were calculated for this structure at CRNL using MARC and SUPERFISH. For a 2m long section of this structure operating at a gradient of 1 MV/m the thermal detuning of the stop band is expected to be 262 KHZ[12] which compares favorably with the "standard" on-axis and co-axial structures which have corresponding values of 632 KHZ and 371 KHZ respectively.[3]

Test Procedures and Results

Four cavity segments were fabricated from OFHC copper plate on an analogue tracer lathe. Following the experience of Euteneuer,[9] integral diamond tooling was used at 1600 RPM for the final shallow surface cuts. Coupling slots were milled into the segments with a standard 3/16" carbide cutter. This operation was carried out in two stages so that some measure of both the coupling and the Q dependence on the slot opening angle could be obtained as described below.

TABLE I

COMPARISON OF THEORETICAL CAVITY PARAMETERS WITH EXPERIMENTAL MEASUREMENTS

	ZT^2/Q_o	Q_o	ZT^2(MΩ/m)	k(%)
Theoretical values:	.00532	18.2 k	96.6	-
Measured values:	.00527			
no slots		18.3 k	96.4	-
45° slots		17.8 k	93.8	1.9
60° slots		17.3 k	91.2	3.5

The cavity segments could be stacked vertically in a specially designed pneumatic cavity press. The mating surfaces of the segments were relieved, leaving edges only 3 mm wide which were then carefully lapped to ensure optimum contact. The mode frequencies were

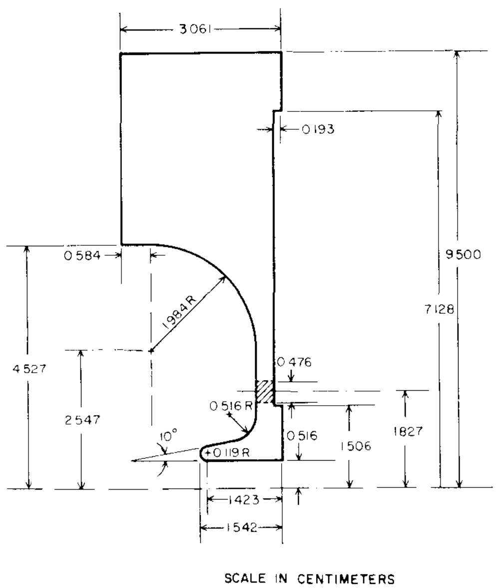

Figure 4. 2.45 GHz coaxial coupled structure optimized for 1.0 MeV gradient operation.

measured, and the coupling and accelerating cell frequencies as well as coupling constants were obtained with the code DISPER.[13]

The characteristic quantity ZT^2/Q was obtained for this structure by the usual means of perturbing the cavity fields with a metal bead. A computer-controlled stepping motor was used to move a 4.3 mm diameter copper bead along the structure axis, and the perturbed frequency at each point was read directly by an interfaced Racal-Dana frequency counter which measured the frequency of an oscillator that was phase locked to the $\pi/2$ mode. The computer then could display the data either as frequency or as electric field, and could perform the field integration.

The Q of the structure was measured using a method of Euteneuer.[9] The structure Q_o is determined from

$$\frac{1}{Q_o} = \frac{2}{Q_2} - \frac{1}{Q_1}$$

where Q_1 is the Q of a two segment stack consisting of a coupling cell terminated in two half accelerating cells, and Q_2 is the Q of a four segment stack also terminated in two half accelerating cells. We found this method to give very consistent results as long as particular care was taken in making the accelerating cell joints.

In Table I the results of our measurements are compared with the theoretical predictions for ZT^2/Q and Q given by SUPERFISH. Before the coupling slots were cut the measured values were found to be very close to the theoretical values. As the slots were opened and the coupling increased, the Q and hence the ZT^2 were degraded somewhat as expected. However, even with 3.5% cell to cell coupling the shunt impedance was found to be 91.2 MΩ/m.

Conclusion

In terms of overall efficiency the optimum gradient for the accelerating structure in a cascade microtron appears to be about 1 MeV/m. Structure that is intended specifically for such low power operation can be designed to have a rather large RF efficiency. We have demonstrated a prototype coaxial structure suitable for operation at a gradient of 1 MeV/m that has a cell to cell coupling of 3.5% and a shunt impedance in excess of 90 MΩ/m.

This work was supported by the National Science Foundation grant NSF PHY 83-11717.

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