HIGH POWER, ON-AXIS COUPLED LINAC STRUCTURE

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Summary

A prototype linac structure with five accelerating cells and four on-axis coupling cells has been constructed and operated at 805 MHz with 100% duty factor. The structure is a favoured design for both a spallation breeder and a high power microtron. Magnetic coupling slots provide 10.4% first neighbour coupling, and two mechanical tuners cover the necessary frequency range for resonance control. Thermal detuning effects, controlled by independent radial and circumferential cooling circuits, are observed at power levels up to 100 kW/m with diagnostic probes in each cell. Results of experiments of beam blow-up mode excitation with current pulses in a thin conductor are reported.

Introduction

Structures optimized for use in linacs designed for fundamental research are not necessarily appropriate for high power applications. The large power dissipation and strong beam-cavity interactions can lead to unstable operation and loss of the beam. Such conditions are encountered when the accelerating structure is run in the cw mode and large currents are accelerated.

Operation of biperiodic structures at 100% duty factor has already been demonstrated[1]. Modified versions of the LAMPF side-coupled structure are presently operating at 0.7 MeV/m in the Electron Test Accelerator (ETA)[2] and stable operation up to 50% beam loading has been achieved. Beam loading up to 80% has been achieved at a lower gradient[3]. A more attractive design based on work by Schriber et al.[4] at S-band is possible when the coupling cells are placed on-axis. Simple assembly procedures and reduction in fabrication costs have already encouraged designers of electron storage rings to choose a coaxial design of single periodicity for cw operation. In these designs, the ingenuity and complexity of the segment cooling is motivated by a desire to decrease losses from the temperature-dependent variation in electrical conductivity[5].

The main parameters to be optimized for high current application and consequent heavy continuous beam loading are the field tilt and the system stability. This favours high intercavity coupling and biperiodicity. The structure to be described[6] has both and was built for tests at high field gradient. So far high power tests, limited only by the available power, have been done up to 105 kW/m at 804 MHz with energy gradients up to 1.8 MeV/m. High current operation in ETA is planned at a later time.

Design Description and Low Power Tests

A drawing of the copper, 930 mm long, β=1 structure is shown in Fig. 1. There are five accelerating cells and the rf power is fed to the centre cell through an iris which is demountable for ease of machining during matching tests at low power. Mechanical tuners in the end cells are used to keep the structure on resonance. They provide a range of 2.2 MHz which exceeds the frequency shift occurring during start-up. Magnetic field probes are provided in each cell for control and diagnostic purposes. The tank rests on a vacuum manifold with ports on the second and fourth accelerating cells. There is sufficient conductance through the beam hole and coupling slots to provide a vacuum in the 10^{-5} Pa range in the other cells.

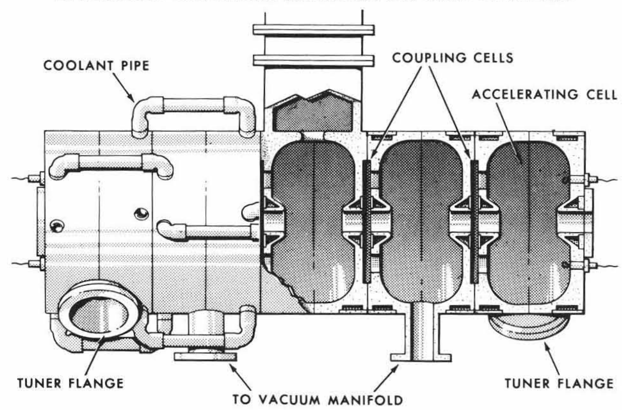

Fig. 1 On-axis coupled β=1 linac structure showing cooling channels, ports for resonance tuners, rf input and vacuum manifold.

The cavity profile has a flat portion which is convenient for two large magnetic coupling slots. Calculations using the coupled RLC-loop model[7] predict that at 90% beam loading the field tilts will be less than 1% for an intercavity coupling constant of 10%. These conditions were chosen as the design values. Fits to the measured dispersion curve gave a nearest neighbour coupling constants of 10.46% at the design frequency of 804.8 MHz. The coupling constant is independent of the tuners position.

A 5 mm (dia.) dielectric bead gave a frequency shift of 10.1 kHz and with a measured unloaded Q of 22,600 the shunt impedance is 28.5 MΩ/m. This is 35% less than that predicted by SUPERFISH[8] and is an indication of the penalty for the various slots and apertures necessary in a prototype structure.

The effect of the tuners on the fields in a coupling cell is shown in Fig. 2. A frequency shift from the reference fully out position caused by one tuner must be balanced by a corresponding shift in the second tuner to reduce the coupler field. These observations are confirmed by the RLC-coupled loop model and indicate that even with the π/2-mode, a tuner located away from the structure centre can seriously imbalance the field distribution. The measurements also confirm that the tuned condition, i.e. minimum coupler field, is near the position of minimum penetration into the cavity.

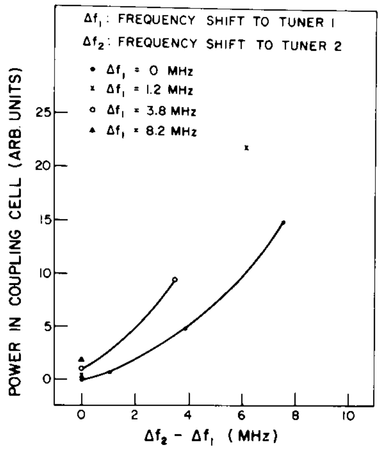

Fig. 2 Power in a coupling cell shown as function of the frequency shift and of the difference between frequency shifts of cells with tuners.

It is hoped to investigate structure stability at very high field gradients, hence considerable care was taken with the cooling design. Radial and circumferential cooling are separate circuits, each with counter flow as shown in Fig. 3. Flow tests confirm the design with a total flow rate of 4.5 ℓ/s for a pressure drop of 340 k Pa with both circuits operating simultaneously.

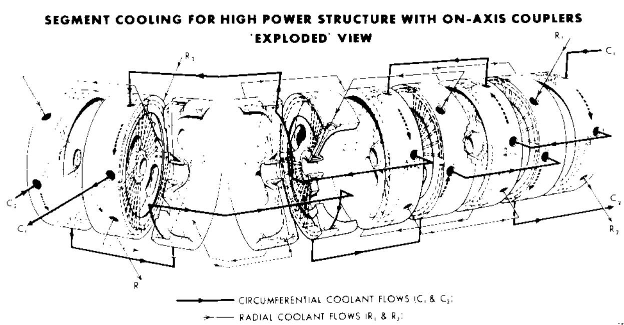

Fig. 3 Counter flow arrangment through the ten segments to reduce frequency shifts at high power.

Beam Blow-up Mode Excitations

In high current applications, and particularly in circular machines where beam disturbances may be regenerative, the excitation of the TM_{110}-like modes (beam blow-up modes) by an off-axis beam is important. These excitations were studied by simulating the off-axis beam by short pulses of current in a thin conducting wire (0.127 mm dia.) displaced from the structure symmetry axis[9]. Previous measurements[10] have shown that the field distribution of the TM_{110}-like modes are not perturbed by this technique for small wire displacements, provided the electric field lines of the modes are not intercepted by the wire.

The coupling slots in the cells resolve the azimuthal degeneracy of the TM_{110}-like mode into two modes of neighbouring frequency. The two modes have orthogonal symmetry planes, each running through a set of coupling slots. The frequency of the TM_{110}-like modes were first determined with a loop located on the structure symmetry axis. Rotation of the loop excites both orthogonal modes in the accelerating cell having frequencies of 1237 and 1238 MHz. The 90° orientation of the consecutive coupling slots restricts propagation of these modes beyond the first neighbour coupling cell, where the frequencies of the modes was 1240 and 1241 MHz, however their amplitudes in the accelerating cell and in the coupling cell where they are electrically coupled through the coupling slots are comparable.

With current pulses from an oscillator sweeping a frequency domain around the frequencies of the TM_{110}-like modes, the amplitudes of these modes in accelerating and in coupling cells are measured as a function of the wire's displacement from the structure symmetry axis. As shown in Fig. 4, a coupling cell is more sensitive to TM_{110}-like mode excitation than accelerating cells for a given wire displacement indicated by the steeper curve. Accelerating cells with tuners in the fully retracted position are less sensitive, suggesting that the electric field maximum is further displaced from the structure axis.

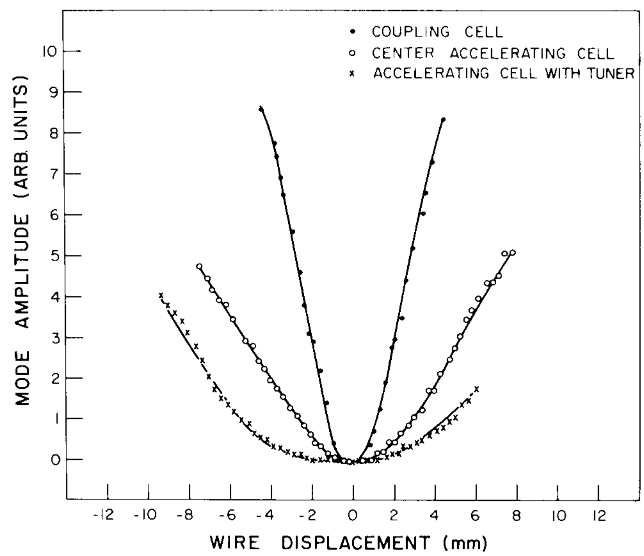

Fig. 4. Beam blow-up mode dependence on wire displacement from the structure symmetry axis.

High Power Test Procedure

All four cooling circuits were instrumented with Resistance Temperature Devices (RTD's) and annular flow meters. Rf power from the field probes was sent to individual crystal detectors. Thermocouples were used to measure the outer surface copper temperature only, as the radial cooling design precluded access near the beam aperture. An ionization chamber placed on-axis recorded the radiation level. All analog lines were read by a computer and were available for on-line analysis.

The tank was powered with a 100 kW cw klystron, Varian type VR-853M. A 3 dB isolator with a forward-to-backward ratio of fourteen was used to attenuate the reverse power. The field control loops described previously[11] were used in the tests except that the transmitted phase and not reverse power was the controlled variable for resonance control of the tuners. The water temperature, controlled by a task activated in the computer every ten seconds, keeps the electrically ganged tuners within range.

Several problems, including sparking at the coupler probes, excessive heating of the tuner stems and burning of the tuner fingers were encountered during the four-week commissioning period. Stable operation at 100 kW is now routine. The radiation level on axis was monitored as the power increased and initially, at 100 kW, it was 10 R/h. The level correlates well with the structure vacuum and less with the forward power.

The only hot spots are to be found at the uncooled interface between brazed stainless steel appendages and the main structure body. There is no evidence of circumferential gradients.

Performance at High Power

Thermal detuning of the structure manifests itself as a redistribution of the field. This effect was examined by withdrawing the tuners and allowing the master oscillator frequency to follow the tank resonant frequency as power increased. The results taken with constant inlet water temperature are shown in Table 1. All fields are normalized to 100 kW. Accelerating cell field amplitude, which varies by less than 1% as shown by bead pull measurements at room temperature does not vary systematically with power within experimental error showing that little imbalance has arisen from thermal effects.

Table 1: Cell Output Power Normalized to 100 kW Power

Power	Accelerating Cells					Coupling Cells			
kW	1	3	5	7	9	2	4	6	8
20	5.91	5.92	6.02	6.02	5.93	6.22	6.31	5.25	6.22
40	7.54	7.59	7.67	7.60	7.60	7.71	7.83	7.48	7.68
60	8.65	8.70	8.73	8.69	8.69	8.73	8.73	8.71	8.75
80	9.45	9.50	9.50	9.48	9.44	9.45	9.41	9.50	9.45
100	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0

Radial and circumferential cooling of our structure were compared at 50 kW by closing either the circumferential or radial flows and keeping the inlet water temperature constant. In the two cases, radial flow increases by 39% and circumferential by 25% respectively when one circuit is closed because of the increased pressure. The frequency shift with radial flow closed is 280 kHz, 5 times as much as that by closing circumferential flow. This indicates that, although calorimetric measurements show radial cooling is carrying away only 34% of the total power, it is superior for keeping copper surfaces within tolerable limits for high gradient work.

The rapid increase in frequency of 15 kHz/s when the radial flow is turned on is comparable to thermal transients on first power turn-on, and could have significant implications in control. Two cooling circuits could be envisaged, one for bulk cooling and the other would serve to eliminate stub tuners with the attendant advantage of tuning all cells simultaneously.

Conclusions

Average energy gradients of 1.8 MeV/m present no difficulty for biperiodic structures at 804 MHz. Magnetic slots can provide sufficient coupling for very heavy beam loading and the mechanical simplicity of on-axis coupled structure and its proven high power performance makes it attractive for high current applications. Beam tests are needed to examine its performance in circular machines where excitation of beam blow-up modes is regenerative. A cooling system has been designed and tested which could reduce the cooling needs of large machines and gives good prospects for the elimination of troublesome and costly stub tuners in future designs.

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