BEAM LOADING EXPERIMENTS WITH A SIDE-COUPLED STRUCTURE

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Summary

Experiments to investigate the performance of side-coupled structures under heavy beam loading have been carried out with the Electron Test Accelerator at Chalk River. Initially, an 18-cell structure was excited at 805 MHz by a 1.4 MeV cw beam. The induced power dissipated in the structure shows a square-law dependence upon beam current (0.013 kW/mA^2) up to 12 mA. With an externally applied field to give an energy gain of 0.1 to 0.2 MeV/m, beam was accelerated under conditions designed to achieve greater than 80% beam loading, i.e. more than 80% of the klystron applied power was converted into beam power. These conditions are important in applications of accelerators to nuclear breeding.

Introduction

In electro-nuclear breeding and other applications of high duty factor linacs, heavy beam loading of the structure is anticipated. In long accelerators with high duty factors, where the cost of rf power is a dominant factor, it is important not only that the structure have a high shunt impedance, but to an even greater extent, that the power from the generator be delivered to the beam with maximum efficiency. In the general case of high reactive beam loading,[1] which occurs when the synchronous phase is not zero, maximum energy transfer is obtained when the complex generator admittance is matched to the cavity admittance, as seen by the generator.

Most theoretical studies on beam loading have been carried out for pulsed linacs[2] or cyclic machines,[3] and the representations are not directly applicable to control systems developed for a high-power cw linac. There is a considerable imbalance between theory and experiment in this field,[4] and experimental data on the behavior of standing-wave systems at very high beam loading have not been previously reported.

An approximation to the principle of maximum energy transfer is employed in the combined resonance, amplitude and phase control circuits[5] of the Chalk River Electron Test Accelerator (ETA), by minimizing the reflected power. Ultimately, a dynamic matching device might be employed to reduce the reflected power to zero. With the first of the two accelerator structures delivering an electron beam of up to 22 mA at 1.4 MeV, beam loading experiments have been carried out in the second structure, with widely varying field amplitude and phase.

Experimental Arrangement

The Chalk River Electron Test Accelerator (Fig. 1) is dedicated to the study of the various accelerator properties which are important in the understanding of the behavior of a proton linac that might be used for breeding nuclear fuel. The ETA is comprised of an electron gun, a buncher, a graded-β structure, and a β=1 side-coupled structure modelled on the LAMPF design. Beams up to 22 mA cw have been accelerated so far. The energy is continuously variable between 1.4 MeV and 4.0 MeV.

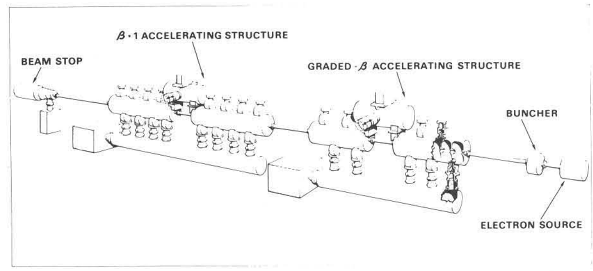

Fig. 1 Chalk River Electron Test Accelerator - 1.4 to 4 MeV, 0 to 25 mA cw.

The control system has been described previously[5,6] and differs somewhat from those of other machines. There are three separate control loops for amplitude, phase and resonance control, as shown in Fig. 2. Phase control is accomplished by varying the phase of the klystron drive. A mechanical tuner is used to keep each resonant structure at minimum reverse power. In this way reactive beam loading is not compensated by cavity detuning but rather by changing the impedance of the source.

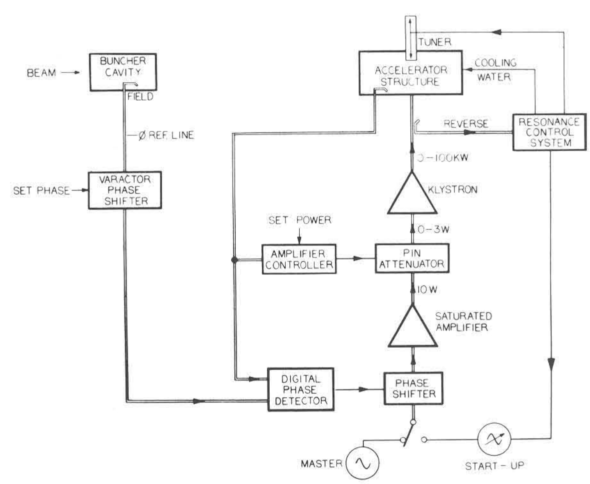

Fig. 2 Accelerator Structure Control System Block Diagram

The 18 accelerating cell, β=1 structure is powered by a 100-kW cw, 805-MHz klystron and dissipates 60 kW when a 4-MeV beam is required (accelerating gradient ≈ 0.8 MeV/m). Under these conditions, there is only sufficient power available to reach 40% beam loading. Beam loading in excess of 80% can, however, be achieved with the available rf power supply by reducing the accelerating gradient to between 0.1 MeV/m and 0.2 MeV/m.

The resonance control system is sufficiently flexible to allow the structure to run at any arbitrary power dissipation level. In the beam loading experiments, the amplitude and phase of the accelerating fields were kept constant to within 1% and 1° respectively.

Resistive Beam Loading Experiments

Effect on Impedance Match

To first order, if the centroid of a symmetrical beam bunch reaches the center of an accelerator cell gap when the field is maximum (beam phase $\phi_B = 0$), the beam acts as a purely resistive load on the cavity. The ETA accelerator structures are iris coupled to the waveguides; for the β=1 structure, the iris was machined to provide critical coupling at zero beam current. The progressive undercoupling as the beam current is increased at different accelerating gradients is shown in Fig. 3. The match changes with beam loading as follows[7]:

$$\sigma = \text{VSWR} = \frac{P_S + P_C}{P_S + P_B} \quad \text{(overcoupled)}$$

$$= \frac{P_S + P_B}{P_S + P_C} \quad \text{(undercoupled)}$$

$$P_C = P_S(\sigma_o - 1)$$

where: P_S= power dissipated in the structure, P_B= power added to the beam, P_C = power added to the beam to critically couple the structure to the transmission line, and σ_o is the VSWR with zero beam loading.

A key component in the resonance controller is a mechanical tuner in the bridge coupling cell. Because of the proximity of the tuning plunger to the iris coupler, the impedance match at zero beam current changes with tuner position such that σ_o varies from 1.0 to 1.2. A value of σ_o = 1.16 gives good agreement between theory and experiment.

Change in Q

When the structure is driven at a frequency ddiffering by Δf from the resonant frequency f_o, the admittance phase angle, ϕ_A, is given by

$$\phi_A = \tan^{-1} 2Q_L \frac{\Delta f}{f_o}$$

where Q_L ≡ loaded quality factor for the structure. For small perturbations about the tuner

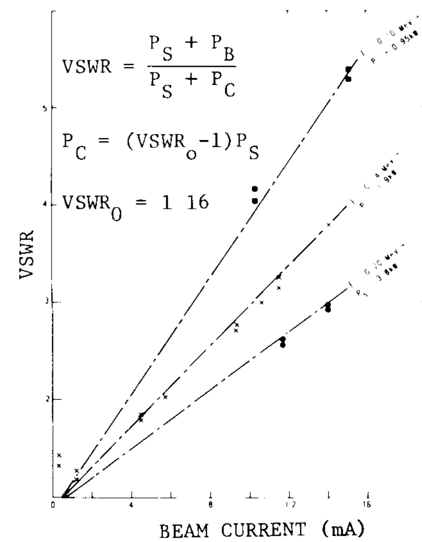

Fig. 3 Resistive Beam Loading - Impedance Match Changes

mid-position,

$$\Delta f = 80\ S\ (\text{kHz})$$

where S is the linear tuner motion expressed as a fraction of its full range. ϕ_A was measured by connecting the inputs of a vector voltmeter to a field probe in an accelerator cell, and to a directional coupler in the waveguide. The cavity was detuned manually with the tuner and Q_L was calculated for beam loading factors up to 85% (see Fig. 4).

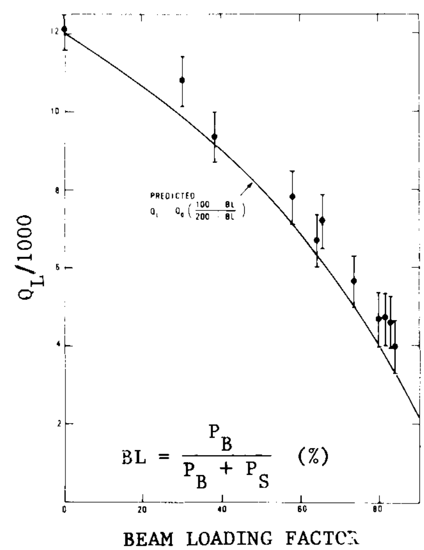

Fig. 4 Resistive Beam Loading - Q_L Changes

Beam loading affects Q_L in two ways. Let Q_o ≡ unloaded Q with no beam (for the β=1 structure, Q_o = 24000). Beam loading has no effect on the energy stored in the cavity (the amplitude controller maintains constant field), but the internal energy loss per cycle is proportional to $P_S + P_B$. Therefore the "unloaded" Q with beam is given by

$$Q_b = Q_o \frac{P_S}{P_S + P_B}$$

However, beam loading also changes the impedance match or coupling to the transmission line so that

$$Q_L = \frac{Q_b}{1 + \frac{1}{\sigma}} = Q_o \cdot \frac{P_B}{2P_S + P_B}$$

for a structure critically coupled with zero beam. Or, in terms of the beam loading factor

$$BL \equiv \left(\frac{P_B}{P_S + P_B}\right)100 \quad \text{(percent)}$$

$$Q_L = Q_o\left(\frac{100 - BL}{200 - BL}\right).$$

In Fig. 4, this relation is shown to be in good agreement with the experimental data.

Field Tilts and Shunt Impedance

The amplitude of the field in the accelerating cells was found to tilt along the structure less than 2% (field depressed in the cells remote from the drive point at the bridge coupler) as beam loading was increased from 0 to 85%.

Calorimetric measurements of beam power delivered to the beam dump at the output of the β=1 structure and of structure dissipation power imply an effective shunt impedance of 33.6 ± 1 MΩ/m (35.4 ± 1 MΩ/m if the bridge coupler dissipation is excluded). A similar value was obtained when the beam energy was determined from neutron threshold measurements (γ,n) using a D_2O target after the beam stop. No change in shunt impedance was observed for accelerating gradients of 0.1 to 0.81 MeV/m and beam loading factors of 10 to 85%. The theoretical effective shunt impedance for this structure is 47.6 MΩ/m (excluding the bridge).

Reactive Beam Loading Experiments

For the beam phase angle $\phi_B \neq 0$, the beam admittance is complex. The admittance phase angle ϕ_A was measured while ϕ_B was varied (Fig. 5). A strong dependence on beam loading was noted. The resonance controller permits small variations of the structure resonant frequency about the accelerator frequency during an experimental run, causing a scatter in the measured values. Corrections for this effect have been made and the data shown in Fig. 5 are accurate to ± 2° for the 85%, and ± 1° for the 67% beam loading cases.

The impedance match of the accelerator to the transmission line was examined as the beam phase was varied. The complex admittance of the beam[1], $(I/V)e^{j\phi_B}$, combined with the conductance of

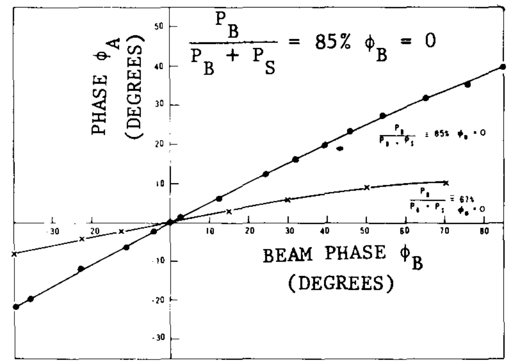

Fig. 5 Reactive Beam Loading - Transmitted Phase Angle Changes

the tuned cavity gives, to first order,

$$\sigma = \left(\frac{P_S + P_B}{P_S + P_C}\right)\left|1 + j\,\frac{P_B}{P_B + P_C}\tan\phi_B\right|.$$

In second order, $\tan\phi_B$ and P_B averaged over the beam phase distribution, should be used. The experimental data (Fig. 6) for two runs agree well with the predicted VSWR, the match varying relatively slowly while the incremental beam power changes by more than a factor of two.

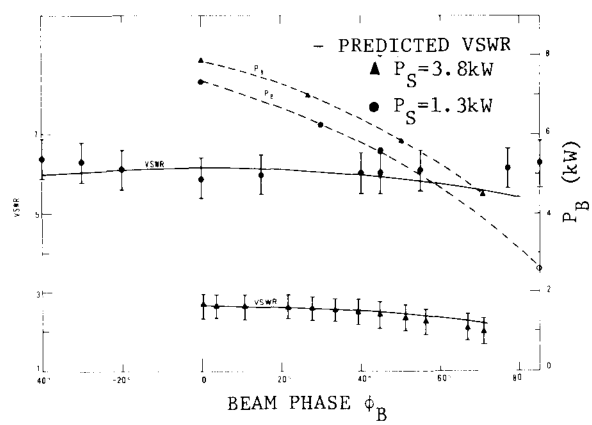

Fig. 6 Reactive Beam Loading - Impedance Match Changes

Cavity Excitation by a Bunched Beam

Under normal operation, an accelerator structure is driven by two sources: the external generator (klystron in the present work) and the bunched beam itself. To investigate the coupling between the beam and structure, the external generator for the β=1 structure was operated with zero drive. Up to 22 mA from the graded-β structure (1.4 MeV) was drifted through the β=1 structures and the mechanical tuner manually adjusted to keep the structure resonant at the accelerator frequency (tuner adjusted to maximize the induced field in the structure). The phase and amplitude of the induced field were measured. As expected, the phase was shifted 180° from the normal accelerating case, indicating that the structure appears as a resistive load to the beam.

Field amplitude was measured using probes in the accelerating cells and a directional coupler in the waveguide. The waveguide was left connected to the klystron through a 3 dB ferrite isolator in the waveguide. The power dissipated in the structure (Fig. 7) was shown to vary as the square of the beam current for currents up to 10 mA, and approximately linearly with beam current above 12 mA. A roughly equivalent power flow was observed in the waveguide with a negligible amount reflected back from the isolator/klystron combination. Thus the power lost by the beam was roughly twice the power dissipated in the structure, a fact that was confirmed by calorimetric measurements at the beam stop after the β=1 structure.

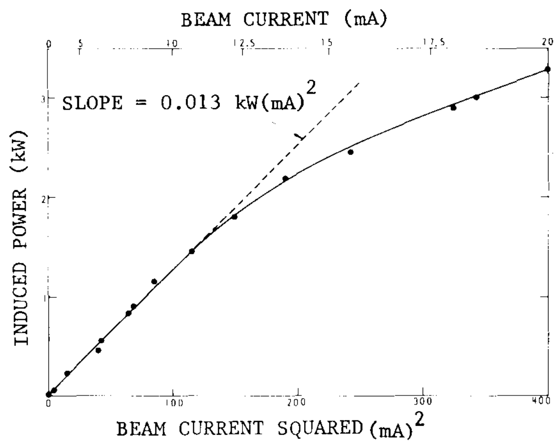

Fig. 7 Cavity Excitation by Bunched 1.4 MeV Beam - Structure Dissipated Power

Using the fact that the power lost by the beam is approximately twice the power dissipated in the structure, the fractional energy loss as a function of beam current can be plotted (solid curve in Fig. 8). Little additional deceleration occurs above 12 mA which contrasts sharply with the situation under 10 mA where the fractional energy loss is proportional to the current. Calculating shunt impedance in the same manner as for the accelerating case,

$$Z_{SH} = \frac{(\text{Energy change per meter})^2}{\text{Power in structure per meter}}$$

gives the dashed curve in Fig. 8.

The proportionality of induced power to beam current squared, and energy loss to beam current, observed here for currents up to 10 mA, has been reported by others.[9] Obviously with a finite input energy beam, these relations must fail before all the energy has been extracted from the beam. We are unable to significantly vary the energy of the input beam to the β=1 structure, so cannot confirm our suspicion that the 10 mA break-point in the curves is beam energy dependent. The shunt impedance value below 10 mA is surprisingly low; at 15.2 MΩ/m it is less than half the value (33.4 MΩ/m) measured when the structure was externally powered.

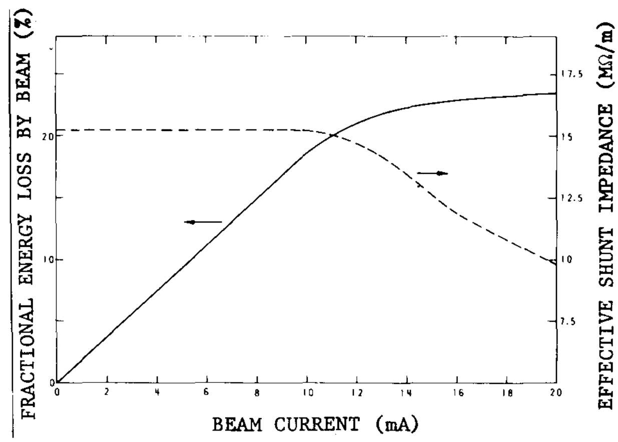

Fig. 8 Cavity Excitation by Bunched 1.4 MeV Beam - Power Lost by Beam and Structure Shunt Impedance

The excitation of spurious modes, a possible explanation for this discrepancy, is under study.

Attempts to represent beam loading with the vector model favored by many theoretical studies have so far been unsuccessful. However an equivalent circuit model is successful in predicting changes in VSWR with beam current and beam phase. Fundamental considerations are adequate to understand the observed changes in Q with beam loading. For a more complete understanding of the beam-cavity interaction further experiments are necessary.

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