IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

OPERATIONAL EXPERIENCE WITH COUPLED-CAVITY STRUCTURES IN A HIGH DUTY FACTOR ACCELERATOR

Gerald E. McMichael* and Joseph McKeown*

Abstract

The Chalk River Electron Test Accelerator is a facility to study beam behaviour in a multi-tank accelerator and to develop control systems for high power operation. Two standing-wave structures have been operated at energy gradients of 0.75 MeV/m and their accelerating fields held constant under 50% beam loading. During start-up, the control systems must accommodate resonant frequency shifts exceeding ten bandwidths in both of the dissimilar structures and their resonant frequencies must differ by less than a tenth of a bandwidth before locking to the accelerator frequency. The central mini-computer controls the run-up and among other things controls the structure temperature.

Introduction

The Chalk River Electron Test Accelerator[1] (ETA) comprises an electron gun and buncher cavity as the injector, a graded-β and a β=1 structure, all operating at 100% duty factor. Operation of the graded-β structure at up to 50% beam loading has been described previously[2]. In the last two years the problems of multi-structure operation have been solved and 16 mA has been accelerated to 4 MeV without fundamental difficulty.

This paper describes the operation of the two dissimilar structures at 100% duty factor and the modular control systems which should permit straightforward expansion to a much larger accelerator.

Accelerating Structures

Model 4 (graded-β structure) and Model 3 (β=1 structure) have 11 and 18 accelerating cells respectively and each consists of two almost equal, (identical in the case of Model 3), sections joined by a bridge coupler. Both are adaptations of the LAMPF side-coupled structure with improved cooling for the increased power dissipation associated with 100% duty factor operation. A movable slug tuner in the bridge coupler of each structure provides a convenient means of varying the resonant frequency as shown in Fig. 1.

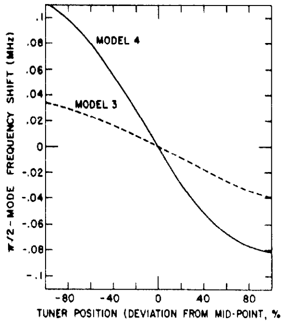
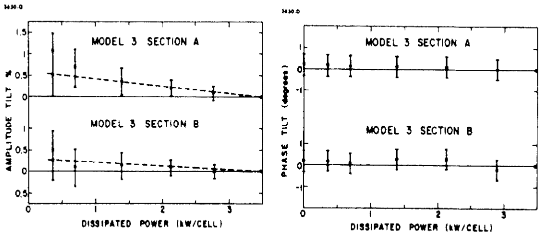


Fig. 1 π/2-mode Frequency Shifts Caused by Tuner Movement

The resonant frequency also depends on the temperature of the structure and the rf power dissipation. Because of different cavity profiles, small differences are found between the two structures, but on average the resonant frequency changes 0.014 MHz/°C for changes in structure temperature, and 0.070 MHz/kW/cell for changes in rf field. During accelerator operation, all structures must be excited from a single oscillator and the resonant frequencies of the individual structures must not deviate by more than a few kHz from the accelerator frequency. The control systems to meet this requirement have been described previously[3]. More recently, improvements to our instrumentation have allowed us to further investigate the behaviour of the structures under cw conditions.

Ignoring beam loading effects, there are two main perturbations to the structures - the temperature gradients between the cooling water and various parts of the structure due to the power dissipation of several kW/cell, and the detuning of the bridge by the tuner. Except for machining tolerances, all cells in Model 3 are of identical profile, thus it is a simpler structure than Model 4. After final tuning, bead pull measurements showed the fields in all Model 3 accelerating cells were equal at low power. Amplitude and phase tilts induced when the power is varied from 0 to 3.5 kW/cell are shown in Figs. 2 and 3. Within the uncertainty of the measurements, no phase tilts were found and the amplitude tilts are less than + or -1%.



Figs. 2 and 3 Model 3 Amplitude and Phase Tilts

Measurements made while the tuner was moved over its full range show that the tuner also does not cause a detectable phase tilt, however it has an appreciable effect on amplitude as shown in Fig. 4. Calculations with a coupled circuit model predicted that a 1% amplitude tilt would be induced in each section when the bridge was detuned so as to shift the π/2-mode frequency by 75 kHz. (These calculations assumed that the structure was perfectly tuned to begin with.) The observed tilts (2.5% in Section B and 1.5% in Section A) are roughly in agreement with this prediction, however the fact that they differ, plus the 2% shift from A to B indicates some asymmetry in the tuning. The observed bridge coupler-to-section tilt however, (18%), is an order of magnitude larger and of the opposite sign to that predicted. While not a problem for ETA, the large effect of the tuner on the cell being detuned could be important for accelerator structures with tuners in one or more of the accelerating cells. It is probable that in addition to the frequency shift, the tuner causes a change in the coupling. This is not taken into account in the model. Further investigations are planned to account for the magnitude of this effect and find ways to reduce it.

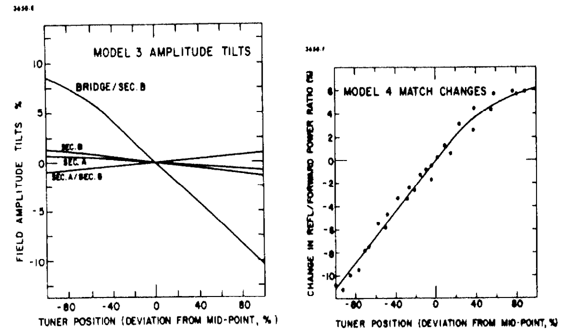
Unlike the Model 3 structure, which is critically coupled without beam, Model 4 is overcoupled (VSWR = 1.36) and becomes critically coupled with a beam power of 11.7 kW. The Model 4 tuner has a similar effect to that observed in Model 3, but the tilt from bridge to section is only about 8%. Whether this is due to the different coupling or the different number of cells in the structures has not been determined. The reflected/forward power ratio for Model 4 was measured

---

* Atomic Energy of Canada Limited
Physics Division, Chalk River Nuclear Laboratories
Chalk River, Ontario, Canada K0J 1J0

0018-9499/79/0600-4108$00.75 © 1979 IEEE

as a function of tuner position and is shown in Fig. 5. This change in reflected/forward power ratio represents a change in the match to the transmission line from a VSWR of 1.33 to 1.37.



Figs. 4 and 5 Effects of Tuner Movement

Structure Start-up and Control

Three control loops[3] provide the required accelerating field amplitude and phase stability and maintain the structure resonant frequency sufficiently close to the accelerator frequency. As shown in Fig. 6, the amplitude and phase controllers adjust the drive to the klystron, while the structure resonance (Fig. 7) is controlled by adjustments to the tuner and the cooling system. The cooling system is a closed loop with a heat exchanger through which a fraction of the structure cooling water may be passed.

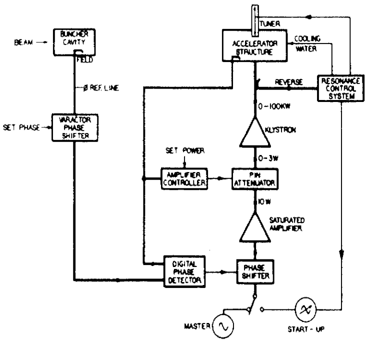


Fig. 6 Accelerator Structure Control System Block Diagram

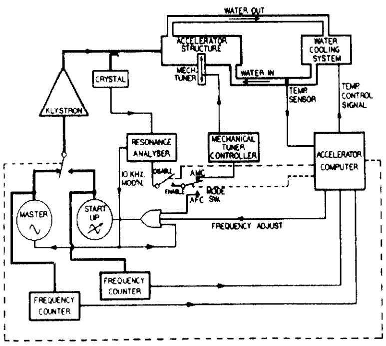


Fig. 7 ETA Resonance Control System

As can be seen in Fig. 7, start-up oscillators which can track the structure resonant frequency are provided for each structure. This simplifies the start-up procedure and also permits rf heating to be used to bring the structures up to operating temperature. The alternatives of a hot water system for heating, or tuners with sufficient range to accommodate the frequency shift of start-up are therefore not required, provided, as will be explained later, the beam can be shut down while the start-up oscillator is in use.

Although ETA is a two-structure accelerator, one of the purposes of the project is to develop equipment and techniques applicable to accelerators with many structures. For this reason, a control computer[4] was obtained early in the project, to develop hardware and software which could be useful for a multi-tank accelerator. At present, both structure temperature and start-up are completely controlled by the system computer but with hardware and software to permit future transference of the tasks to dedicated microprocessors.

The use of separate oscillators and mechanical tuners makes the start-up of the ETA structures simple and straightforward. To illustrate this, the time history of several parameters during computer start-up of Model 4 from an initial temperature of 5°C is shown in Fig. 8.

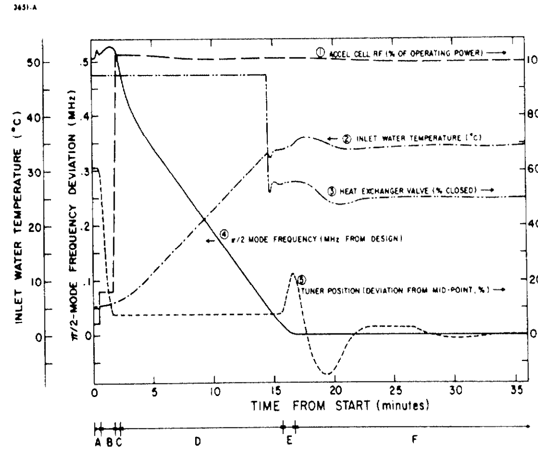


Fig. 8 Computer Controlled Start-up of Model 4

Time Interval	Comments
A.	Resonance control loop is disabled (Fig. 7), minimum drive applied to the klystron, and the frequency ④ (Fig. 8) swept until resonance (minimum reflected/forward power ratio) found.
B.	Rf field ① is increased to a level at which the resonance controller can operate, tuner control engaged and the frequency ④ adjusted to move the tuner ⑤ to within 10% of the mid-point of its travel.
C.	AFC mode (frequency slaved to structure resonance) is selected and the rf field ① increased to operating level.
D.	Heat exchanger valve ③ is kept closed so that the structure (and water in the cooling system ②) is brought to operating temperature is quickly as possible. With the increasing structure temperature, and the temperature gradient due to the power dissipation, the frequency ④ approaches the accelerator frequency. By about the 15 minute mark, the temperature ② has approached the calculated optimum temperature for that power and frequency and the heat exchanger valve ③ is rapidly adjusted to slow the temperature rise.

E. Both frequency and temperature have approached operating levels and the tuner control is engaged, leaving the start-up oscillator controlled only by the computer. The frequency is then adjusted to within 1 kHz of the accelerator frequency, and the klystron drive switched from "start-up" to "master" oscillator. At this point the structure is ready to accelerate the beam and the start-up program terminates.

F. The temperature control program (which is always running) continues to make valve adjustments ③ until the tuner is returned to the mid-point of its range.

Under normal circumstances, the cooling system pump provides sufficient power to the system (3 to 4 kW) to keep it close to operating temperature even when the rf is off. As shown in Fig. 9, for a restart under these conditions, both the frequency shift and time until the structure is ready to accelerate a beam are reduced by about a factor of 3, with the structure ready for beam in about 5 minutes.

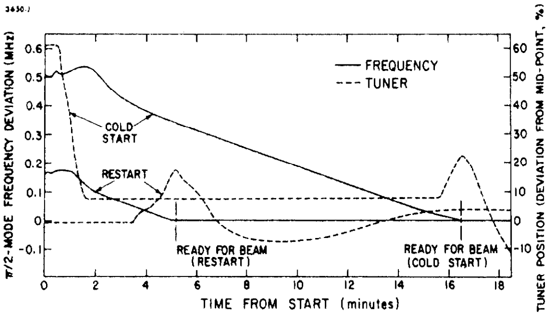


Fig. 9 Model 4 Start-ups from 5 and 33°C

Although the system described here would be relatively inexpensive to implement with microprocessors for a large multi-structure accelerator, it is suitable only for those cases (such as ETA) where the beam is off until all structures are ready. For electron rings, or a recently proposed 12 MeV accelerator for radiation processing[5], the beam must be drifted through an unpowered module. The accelerating module is brought into service with the beam on, and therefore would have to be at the accelerator frequency. This requires tuners with sufficient range to handle the frequency shift on start-up and/or a source of hot water, which could possibly be economically provided by tapping into the outlet of the klystron collector cooling system. These alternatives are being investigated.

Conclusions

The ETA program has demonstrated that accelerator structures and control systems are available which can accelerate high intensity electron beams in cw mode. The phase and amplitude tilts of the accelerating field due to power dissipation up to 3.5 kW/cell are less than ± 0.5 degrees and ± 1% respectively. Start-up and operation are greatly simplified by using a movable slug tuner in one cell to adjust the resonance of the coupled-cavity system, however this can introduce appreciable field amplitude tilts. A hardware and software system for automated start-up of accelerator structures, has been developed. Such a system could be easily and inexpensively expanded for a many-structure accelerator.

References

1. J.S. Fraser, S.H. Kidner, J. McKeown and G.E. McMichael, "The Chalk River Electron Test Accelerator", Proc. 1972 Proton Linear Accelerator Conf., LA-5115, 226 (1972).
2. J.S. Fraser, J. McKeown, G.E. McMichael and W.T. Diamond, "Operation of the Graded-β Electron Test Accelerator", Proc. 1976 Proton Linear Accel. Conf., Atomic Energy of Canada Limited, Report AECL-5677, 166 (1976).
3. J. McKeown, J.S. Fraser and G.E. McMichael, "Field Control in a Standing Wave Structure at High Average Beam Power", ibid. 291.
4. G.E. McMichael, J.S. Fraser and J. McKeown, "The Control Computer for the Chalk River Electron Test Accelerator", Atomic Energy of Canada Limited, Report AECL-5720 (February 1978).
5. J.S. Fraser, "High Power, Low Energy Linac for Radiation Processing", Proc. of 5th Conf. on Applications of Small Accelerators to be published in February 1977 IEEE Trans. on Nucl. Sci.