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EXPERIMENTAL COMPARISON OF BEAM EXCITED MODES IN BIPERIODIC STRUCTURES

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Summary

An experiment to study excitations of higher order modes in a coaxial coupled structure and an on-axis coupled structure is in progress. The tuning and assembly of these structures is complete. Calculations have shown that a coaxial coupled structure is 5% less sensitive to beam excitation of its axially symmetric modes than an on-axis coupled structure. Low power tests have identified mode frequencies above the accelerating mode passband showing that higher order modes propagate in an on-axis coupled structure and not in a coaxial coupled structure. High power beam tests are scheduled for later this year.

Introduction

Excitations of higher order modes in accelerating structures are important in considering beam loading, beam energy loss and beam breakup[1,2]. These excitations are being studied in an on-axis coupled structure and a coaxial coupled structure in order to obtain information on efficiency and beam stability, information that could lead to a preferred biperiodic structure for applications in storage rings and microtrons. The on-axis coupled structure was chosen because it has been used in the University of Mainz microtron[2] and the Electron Test Accelerator (ETA)[3] at the Chalk River Nuclear Laboratories (CRNL). The coaxial coupled structure was chosen because recently reported work showed promising results in reducing beam breakup effects[4]. The fundamental modes of these structures are the $\pi/2$ modes of the TM_{010} passbands.

In the proposed beam tests, the structures will be initially studied with a low duty cycle pulsed beam (4 MeV electrons from ETA) that has high enough charge per bunch (10^{11} electrons) to provide sufficient single bunch excitation in the rf cavities. This allows the energy loss parameters to be measured without the complication of an enhancement effect from closely spaced multiple bunches. The structures will then be studied with a cw beam from ETA. With their fundamental frequencies chosen to be the third harmonic of the ETA frequency (804.78 MHz) and with their TM_{110}-like mode frequencies at approximately 1.7 times that of the fundamental frequencies, the frequencies of the TM_{110} modes are in the vicinity of the fifth harmonic of the ETA frequency. This choice of frequencies provides an opportunity of resonantly exciting both the fundamental and the TM_{110}-like modes and, as a consequence, of studying the excitation of the fundamental mode and a typical beam breakup mode with enhanced sensitivities.

For simple cavity geometries, energy loss parameters and excitation levels of higher order modes can be calculated with computer programs like BCI[5] and MODE[6]. Results from the proposed beam tests when compared to these calculations can provide insight to the beam excitation process and validation for the computer programs.

This experiment is now in progress. The results of low power tests of structures and results from calculations are reported in this paper. High power beam tests are scheduled for later this year.

Calculation Method

The beam energy loss and excitation levels of higher order modes can be well described if the energy loss parameters of the cavities are known. The energy loss parameter is defined as the proportionality constant between the energy lost by a single bunch to an empty cavity and the square of the total bunch charge.

The total energy loss to exciting the axially symmetric modes can be calculated using the computer code BCI[5]. This code computes the induced axially symmetric electromagnetic fields, when a charge bunch traverses a cavity, by numerically integrating Maxwell's equations in the time domain. Another code, TBCI[7], which calculates the nonaxially symmetric electromagnetic fields has recently become available. With this code, the total energy loss parameter for the non-axially symmetric modes can be similarly calculated.

The above codes do not provide the energy loss in individual modes of the structure. The energy loss $p_m^2U_m$ of a single bunch to the mth mode is calculated with data from low power tests and by integrating the following differential equation:

$$\frac{d^2p_m}{dt^2} + \frac{\omega_m}{Q_m}\frac{dp_m}{dt} + \omega_m^2 p_m = \frac{\omega_m}{2U_m}\int \vec{J}\cdot\vec{E}_m d^3r$$

where p_m = eigenmode expansion coefficients
ω_m = mode frequency
E_m = mode electric field
J = beam current density
Q_m = mode quality factor
U_m = mode stored energy = $1/2\ \varepsilon_0 \int \vec{E}_m\cdot\vec{E}_m d^3r$

This equation is a modified version of the well known formula by Condon[8] that expands the vector potential in terms of eigenmodes using coefficients p_m. In this equation, the vector potential, $\vec{A}_m$, is replaced by the electric field, $\vec{E}_m$, using the fact that they are simply related in the Coulomb Gauge, i.e., $\vec{E}_m = (1/c)(\partial\vec{A}_m/\partial t)$ for $\nabla\cdot\vec{A}_m = 0$. The integration of the above differential equation with values for ω_m, Q, U_m and $\vec{E}_m$ obtained from low power tests is performed with a computer program, MODE, developed at CRNL.

To calculate the excitations in the cw case, the induced fields of the single bunch are multiplied by the resonance function F to account for the contributions from multiple bunches. The resonance function is given by:

$$F = F_R + jF_I \qquad \phi = \tan^{-1}(F_I/F_R)$$

$$F_R = \frac{1 - e^{-2T}}{2(1-2e^{-T}\cos\delta + e^{-2T})}$$

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$$F_I = \frac{e^{-2T}\sin\delta}{2(1-2e^{-T}\cos\delta + e^{-2T})}$$

where $\delta = 2\pi(f_m - f_b)/f_b$ $\quad f_m$ = mode frequency

$T = (f_m/f_b)(\pi/Q)$ $\quad f_b$ = beam frequency

The cw synchronous field will be $|F|$ times that of the single bunch value in magnitude and at a phase lag ϕ referring to the phase of the beam bunch.

Experimental Setup

A schematic of the experimental arrangement for testing beam excitations in rf structures is shown in Fig. 1. ETA will deliver electrons in cw or pulsed mode at energies between 1.5 MeV to 4 MeV. The beam will traverse the two structures at displacements from the structure axis controlled by steering magnets and measured by beam position monitors.

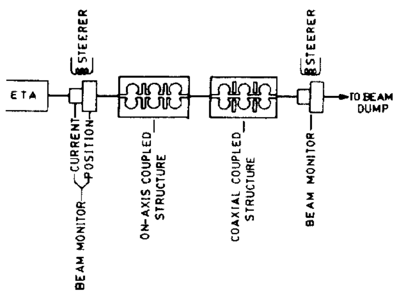

Fig. 1. Experimental arrangement.

The ETA pulsed electron gun is presently being commissioned. It is similar to the Collider Injector Gun employed on the Stanford Linear Collider[9]. It can produce electron pulses of 5 ns length which contain up to 10^{11} electrons (5 A peak current). Cavity excitation from this gun operating at low duty cycle (5 kHz) can be considered as that from a single bunch, and the energy loss parameters can be extracted without considering cw enhancement.

The ETA cw electron gun can provide accelerated currents up to 20 mA. With the energy loss parameters obtained from the pulsed beam and the measured excitations with the cw beam, the enhancement factors in cw operation can be determined.

Accelerating Structures and Low Power Testing

The structures have been tuned and assembled (Fig. 2). Dimensions for the unit cells are shown in Fig. 3. Table 1 lists the rf parameters for the copper structures made up of 3 accelerating cells and 2 coupling cells.

Table 1. Summary of parameters of the on-axis and coaxial structures.

	On-axis	Coaxial
$\pi/2$ Mode Frequency (MHz)	2415.0	2415.0
Q, Quality Factor	15800	18000
First Neighbour Coupling	3%	2.4%
Stopband (kHz)	60	2150
Estimated ZT^2 (MΩ/m)	74	74

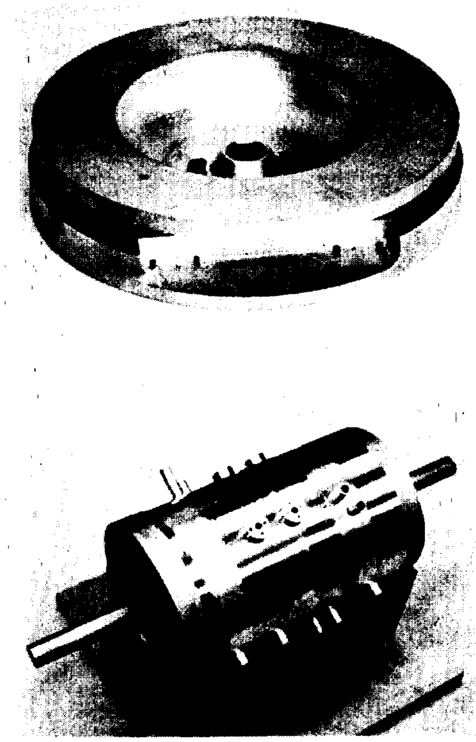

Fig. 2. A half cell and the assembled coaxial coupled structure.

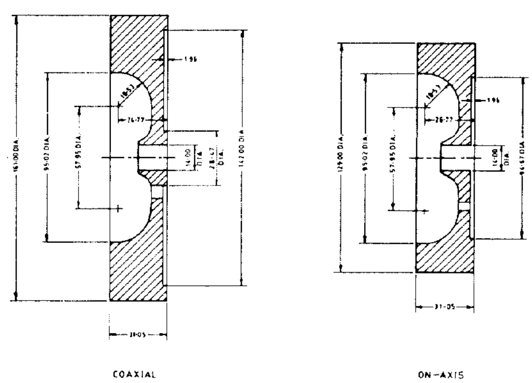

Fig. 3. Dimensions of the half cells of coaxial and on-axis coupled structures. All dimensions are in mm.

Low power testing of the structures is underway. Table 2 lists the mode frequencies in the coaxial and on-axis coupled structures measured to the TM_{110} passband. The assignments of structure and cavity modes are tentative. Cavity mode is assigned if the mode is excited in one cavity and the excitation is not detected by probe insertion in other cavities. Data show that the higher order modes in the coaxial coupled structure, unlike those in the on-axis coupled structure, do not propagate because the coaxial couplers and the accelerating cavities have relatively different frequency spectra.

Results of Calculations

Beam bunches were assumed to be Gaussian with σ_{rms}'s of 0.0155 m or 15°. An average current of 2 mA was assumed for the cw beam and total charge of 1.6×10^{-8} C per pulse for the pulsed beam.

Table 2. Modes observed between frequencies 2300 and 4200 MHz for the on-axis and coaxial structures. The mode assignments are tentative.

On-Axis		Coaxial		Mode Assignment
Frequency	Q	Frequency	Q	
2374	5300	2391	5100	
2391	4700	2401	5500	TM_{010} structure passband
2415	15800	2415	18000	
2439	4700	2431	6800	
2457	6200	2442	5100	
		2733	3500	TM_{110} coupling cavity mode
		2737		
		3408	3600	TM_{210} coupling cavity mode
3908	9600			
3912	9500			TE_{111} structure passband
3914	9100			
3933	9200			
3942	9200			
		3966	16000	TE_{111} accelerating cavity mode
		3973		
4033				
4035				
4046	∿ 6000			TM_{011} structure passband
4047				
4047				
		4117	20300	TM_{110} accelerating cavity mode
		4118		
4123.1	18000			
4124.6	20000			
4125	18000			
4125.3	17000			
4127.4	19000			TM_{110} structure passband
4132.5	5000			
4134.7	5000			
4135.4	16000			
4139.7	5000			
4140.7,	5000			

The energy loss parameter calculated by MODE for the $\pi/2$ mode was 1.73 $V \cdot pC^{-1}$ for the entire structure (i.e., 9.44 $V \cdot pC^{-1} \cdot m^{-1}$ which is in agreement with the fields calculated by SUPERFISH[10]. The synchronous field induced by the cw beam was 70 $kV \cdot m^{-1}$ and the maximum field by the pulsed beam was 300 $kV \cdot m^{-1}$. The resonance function calculated for the cw beam was 1500 by using a Q value of 14200 and resonant excitation at the third harmonic of the beam frequency. Energy loss parameters for 0 and π modes were only 3.91 x 10^{-3} and 1.11 x 10^{-3} $V \cdot pC^{-1}$ for the entire structure. They are small compared to that of the $\pi/2$ mode because of the effects of transit time factors and field level differences in various cells in the structure. These results are applicable to both the coaxial and on-axis coupled structures because the differences calculated with SUPERFISH[10] are approximately 5%, which is comparable to the error of the bead pull data used.

The total energy loss parameter of all axially symmetric modes for the on-axis coupled structure was calculated to be 2.04 $V \cdot pC^{-1}$ over the entire structure with the computer code BCI. The parameter calculated for the coaxial coupled structure was 5% lower. Since the energy loss parameter for the $\pi/2$ mode is 1.73 $V \cdot pC^{-1}$, it accounts for more than 80% of the beam bunch excitations of the axially symmetric modes.

The excitation of the TM_{110} mode was estimated for a shaped cavity by using MODE and fields of an equivalent cylindrical cavity. The energy loss parameter was found to be one order of magnitude smaller than that of the $\pi/2$ mode when the beam traversed the cavity 4.7 mm off axis.

The magnitude and phase of the resonance function, F, for the TM_{110} mode excitation by the fifth harmonic of the ETA beam are shown in Fig. 4, indicating that the TM_{110} mode frequency has to be within 10 MHz of the fifth harmonic of beam frequency to obtain significant enhancement. This condition can be satisfied during future beam experiments by either adjusting the beam frequency or adjusting the mode frequency by means of the temperature of the water in the cooling channel. The latter has a sensitivity of ∿ 70 kHz/°C.

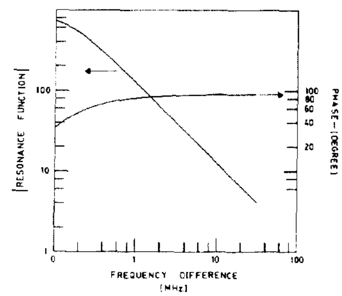

Fig. 4. The magnitude of the resonance function and its phase with respect to the beam is shown as a function of the frequency difference between the TM_{110}-like mode frequency and the frequency of the fifth harmonic.

Acknowledgement

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References

1. R.H. Helm and G.A. Loew, "Beam Breakup" in Linear Accelerators, eds., P.M. Lapostolle and A.L. Septier, North Holland Publ. Co., Amsterdam, (1970) 173.

2. H. Herminghaus and H. Euteneuer, "Beam Blowup in Race Track Microtron", Nucl. Inst. Meth. 163 (1979) 299-308.

3. J. McKeown, R.T.F. Bird, K.C.D. Chan, S.H. Kidner and J.-P. Labrie, "High Power, On-Axis Coupled Linac Structure", Proc. 1981 Linac Conf., Los Alamos Laboratory Report No. LA-9234-C, 334.

4. J.-P. Labrie and J. McKeown, "The Coaxial Coupled Linac Structure", Nucl. Inst. Meth. 193 (1982) 437-444.

5. T. Weiland, "On the Computation of Electromagnetic Fields Excited by Relativistic Bunches of Charged Particles in Accelerating Structures", CERN Laboratory Report No. CERN/ISR-TH/80-07 (1980).

6. K.C.D. Chan, Internal CRNL report, to be published.

7. T. Weiland, "TBCI and URMEL - New Computer Codes for Wake Field and Cavity Mode Calculations", proceedings of this conference.

8. E.V. Condon, "Forced Oscillations in Cavity Resonators", J. Appl. Phys. 12 (1941) 129.

9. R.F. Koontz, "CID Thermionic Gun System", Proc. 1981 Linac Conf., Los Alamos Laboratory Report No. LA-9234-C, 62.

10. K. Halbach and R.F. Holsinger, "SUPERFISH, A Computer Program for Evaluation of rf Cavities with Cylindrical Asymmetry", Particle Accelerators 7 (1976) 213.