BEAM EXCITED MODES IN LINEAR ACCELERATOR STRUCTURES

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Summary

Excitations of higher order modes in linac structures are important in considering beam loading, power losses and beam breakup. Eigenmodes in accelerator structures driven by a bunched relativistic electron beam have been measured in two biperiodic structures. These were an on-axis and a coaxial coupled structure, operating at the third harmonic of the beam frequency. The structures were excited by both cw and pulsed beams to examine their steady state and transient behaviour. The measured shunt impedance and energy loss parameter of beam excited modes are compared with theoretical predictions.

Introduction

The energy lost by a charged particle beam to eigenmodes in rf cavities is an important design parameter for heavily beam loaded structures such as those used in high power microtrons and storage rings. The study of heavily beam loaded cw linear accelerator structures is one of the research programs undertaken at the Chalk River Nuclear Laboratories (CRNL). Previous experiments have been performed where 80% of the rf power was transferred to an electron beam[1].

This paper describes results of measurements of the rf power deposited by cw and pulsed electron beams in coaxial[2] and on-axis[3] coupled structures. Beams were accelerated with the CRNL Electron Test Accelerator (ETA) and drifted through the structures under study. Transient excitation of the structures' eigenmodes with high current beam pulses was used to compare the beam-excited mode spectrum of coaxial and on-axis coupled structures.

Experimental Arrangement

A schematic representation of the experimental arrangement for measuring the beam excitation of modes in linac structures is shown in Fig. 1. The 4 MeV electron beam from the ETA was used for the experiments with the transmitted beam's energy spread restricted to less than 1% by high power apertures in the 90° achromatic bending system. The beam was drifted through three test structures in series. The first two were an on-axis and a coaxial coupled structure having a fundamental π/2-mode frequency of 2414.34 MHz, which is the third harmonic of the beam frequency. The third structure was an on-axis coupled structure operating at 804.78 MHz, the fundamental of the beam frequency. (This third structure was used to obtain the beam bunch length by measuring the ratio of power deposited in the accelerating mode of this structure to that in the third harmonic on-axis coupled structure.) The power deposited by the beam in the structures' eigenmodes was measured with a spectrum analyzer. Field probes were installed in all of the structures' accelerating and coupling cavities.

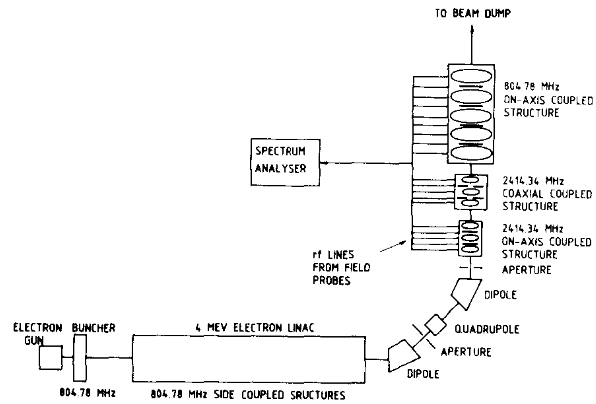

Fig. 1 Experimental arrangement.

Details of the structures' mechanical design and lower power rf tests are published elsewhere[5,6]. The two third harmonic structures are composed of three full accelerating and two coupling cavities. The resonant frequencies of these structures were controlled by varying the temperature of water coolant to the cavities. The structures operate at 60°C and the tuning range of TM_{mno}-like modes is ± 0.05% for a temperature change of ± 30°C.

The 804.78 MHz structure is composed of five full accelerating and four coupling cavities. Mechanical tuners in the end cavity are used to change the structure's resonant frequency.

Low Power RF Measurements for the Third Harmonic Structures

Eigenmodes were excited in the third harmonic structures with a magnetically coupled loop driven with a sweep oscillator. Table 1 lists the eigenmode frequencies and unloaded Q values measured in the on-axis and coaxial coupled structure. A cavity mode was assigned if the mode was excited in one cavity and the excitation was not detected by probe insertion in other cavities. Higher order modes in the coaxial coupled structure, unlike those in the on-axis coupled structure, did not propagate because the coaxial couplers and the accelerating cavities have fundamentally different boundary conditions and hence different frequency spectra. Also shown in Table 1 are the individual cavity mode frequencies and Q values calculated with the computer codes SUPERFISH[7] and URMEL[8]. Coupling slots cannot be modeled correctly in computer codes assuming cylindrical symmetry. This results in incorrect model values for the mode frequencies of the coupling cells. As a result the observed unloaded Q values are generally smaller than the predicted individual cavity Q values.

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Table 1

Eigenmodes observed between Frequencies 2300 and 4200 MHz for the On-axis and Coaxial Structures

On-Axis		Coaxial		Mode Assignment	SUPERFISH and URMEL Results	
Frequency	Q	Frequency	Q		Frequency	Q
2374	5300	2391	5100			
2391	4700	2401	5500	TM_{010} structure		
2415	15800	2415	18000	passband	2415	18250
2439	4700	2431	6800			
2457	6200	2442	5100			
		2733	3500	TM_{110} coupling	2848	2848
		2737		cavity mode		
		3408	3600	TM_{210} coupling	3509	3273
				cavity mode		
3908	9600					
3912	9500			TE_{111} structure		
3914	9100			passband		
3933	9200					
3942	9200					
		3966	16000	TE_{111} accelerating	4042	19488
		3973		cavity mode		
4033						
4035						
4046	≈ 6000			TM_{110} structure	4116	24485
4047				passband		
4047						
4123.1	18000					
4124.6	20000	4117	20300	TM_{110} accelerating	4253	16000
4125	18000	4118		cavity mode		
4125.3	17000					
4127.4	19000					
4132.5	5000			TM_{011} structure		
4134.7	5000			passband		
4135.4	16000					
4139.7	5000					
4140.7	5000					

CW Electron Beam Tests

The accelerating mode effective shunt impedance of the structures was obtained from a measurement of the power deposited in the fundamental π/2 mode at resonance. The power deposited by the beam in the π/2 mode of the third harmonic and fundamental frequency structures is shown in Fig. 2(a) as a function of beam current. For a longitudinal Gaussian bunch shape, the effective shunt impedance is given by[9]

$$ZT^2 = \frac{P(1+\beta)}{i_o^2 L} \exp\left(\frac{\omega\sigma}{c}\right)^2$$

where P is the power extracted from the beam to excite the π/2 mode, β is the probe coupling, i_o is the average beam current, L is the length of the structure, ω is the mode frequency, σ is the beam bunch length and c is the speed of light. The effective shunt impedance of the third harmonic on-axis and coaxial coupled structure calculated from the measured power deposited by the beam is 66 MΩ/m. The result agrees well with the measured shunt impedance of on-axis coupled structures with the same cavity profile constructed at the University of Mainz for the MAMI racetrack microtron[4]. This value when scaled by the square root of the resonant frequency agrees with the measured shunt impedance of 36 MΩ/m for the 804.78 MHz on-axis coupled structure. This is expected since the geometrical dimensions of the 804.78 MHz on-axis coupled cavities almost scale with the third harmonic cavity dimensions. The measured shunt impedances are 14% less than the SUPERFISH predictions for the same cavity profiles without coupling slots.

The Q value of the beam excited π/2 mode in the third harmonic structure was obtained from a measurement of the power deposited as a function of the beam bunch frequency. Results, shown in Fig. 2(b), indicate that the on-axis and coaxial structures have a similar Q value of 14600. The Q values measured with beam are smaller than the results given in Table 1 for the low power rf tests because for the former, additional field probes were inserted in the structures which contributed to the rf power losses.

The energy loss parameter for the π/2 mode of the third harmonic structures was obtained from the measured shunt impedance and Q value. The measured accelerating mode energy loss parameter was 15 $V \cdot pC^{-1} \cdot m$ for both structures, in agreement with the value calculated with the computer code BCI[10] for the measured ETA beam bunch length of 14 mm[5].

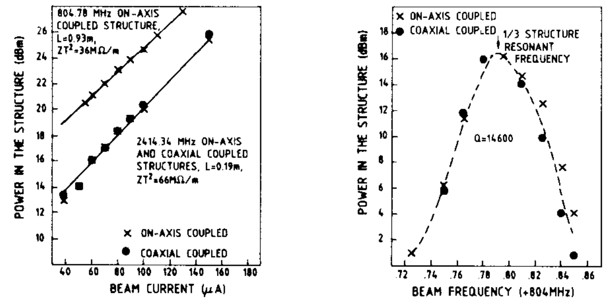

Fig. 2(a) Power deposited by a cw electron beam in the π/2 fundamental mode of third harmonic on-axis and coaxial coupled structures and on-axis coupled structure operating at the beam frequency.
(b) Q value of the third harmonic structures measured with beam.

Pulsed Electron Beam Tests

The rf power deposited in a structure's eigenmodes increases as the square of the beam current. In order to observe non-resonant beam-excited modes without large beam spills, the transient excitation of the structures eigenmodes was obtained with 4 MeV beam pulses. A pulsed thermionic electron gun was operated at a repetition frequency of 5 kHz and produced 2.2×10^{-8} C in 5 ns beam pulses. Because space-charge forces changed the beam emittance as a function of current, the measurements were made at a constant pulse width and peak current. For each beam pulse, four beam bunches separated by 1.24 ns were obtained at the ETA output. The voltage induced by a beam pulse in a structure eigenmode was the resultant of the vector summation of the contribution of individual beam bunches.

As verified analytically, the vector summation of the contribution of each beam bunch within a beam pulse did not affect the relative amplitude of the excitation of the fundamental passband modes in the third harmonic structures. The phase of the beam-induced rf voltage with respect to the beam bunches has however a significant effect on the relative amplitude of the fundamental passband modes. The 0 and π modes have the least excitation because the beam-induced rf voltage is 180° out of phase with respect to the beam in every second accelerating cavity.

The relative amplitude of modes excited in the third harmonic structures with the pulsed electron beam is shown in Fig. 3. Only the fundamental TM_{010}-like modes and the TM_{110}-like modes observed in the accelerating and coupling cavities of the structures are shown.

The TM_{010}-like modes observed in the accelerating cavities of the on-axis and coaxial coupled structures are shown in Fig. 3(a) and (b) respectively. In both type of accelerating cavities, the excitation of the $\pi/2$ mode was dominant and, as expected, the 0 and π modes had the least excitation and could not be detected. The field distribution of the $\pi/4$ and $3\pi/4$ modes result in minimum power in the center accelerating cavity and in the on-axis coupled structure, these modes were observed in the coupling (Fig. 3(c)) and end accelerating cavities. In the coaxial coupled structure these modes were not detected either in the accelerating or coupling cavities (Fig. 3(a)). This is because the coaxial couplers do not interact with the beam, whereas in the on-axis coupled structure, the modes are enhanced by beam-induced rf voltage in the coupling cavities. The $\pi/2$ mode could be observed in the coupling cavities of both structures because of small tuning errors introduced during the structures' fabrication.

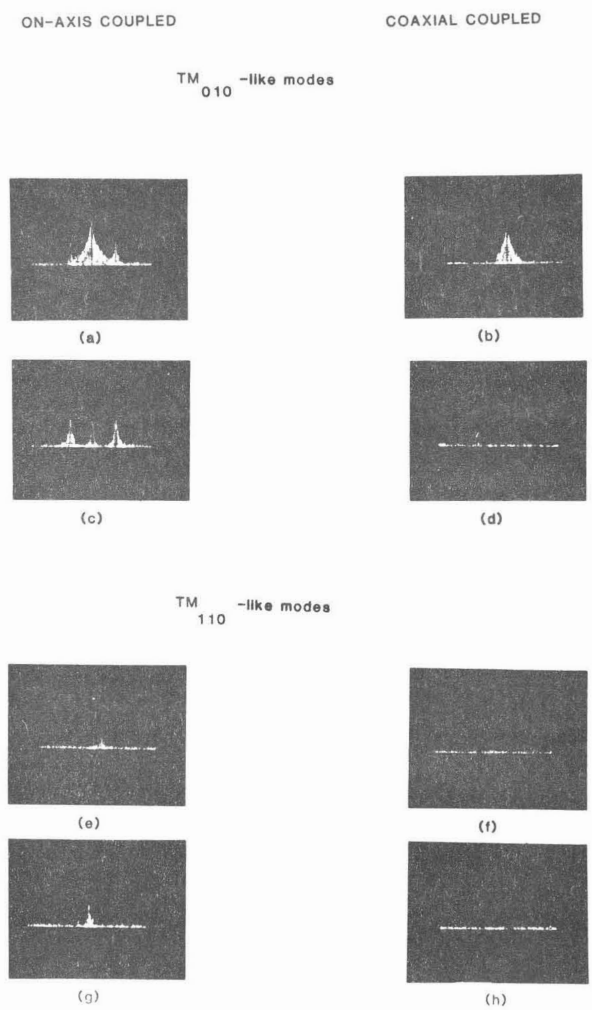

Fig. 3 Beam excited TM_{010}-like and TM_{110}-like modes in
- on-axis coupled accelerating cavities a) and e)
- coaxial coupled accelerating cavities b) and f)
- on-axis coupling cavities c) and g)
- coaxial coupling cavities d) and h)

respectively. Mode amplitudes are shown on a logarithmic scale.

The beam blowup TM_{110}-like modes were observed in the accelerating cavities of both the on-axis (Fig. 3(e)) and coaxial (Fig. 3(f)) structures but in the coupling cavities of only the on-axis (Fig. 3(g)) coupled structure. The beam cannot excite these modes in the coaxial couplers (Fig. 3(h)). The observation of the TM_{110}-like modes in both the accelerating and coupling cavities of the on-axis coupled structure (Table 1) indicated some propagation of these modes through that structure.

Several modes with resonant frequencies above the TM_{110}-like modes were excited by the beam pulses. The total number of modes observed in the coaxial coupled structure was significantly less than in the on-axis coupled structure.

Conclusions

The accelerating mode effective shunt impedance for an on-axis and a coaxial coupled structure with identical accelerating cavity profiles were found to be the same. Low power rf measurements and the excitation of the structures' eigenmodes with a pulsed electron beam indicate that the density of higher order modes is significantly less for a coaxial coupled structure. The possibility for excitation of beam breakup modes is therefore reduced and coaxial coupled structures are preferred for heavily beam loaded structures.

Acknowledgements

Mr. R.T.F. Bird was responsible for the operation of ETA during the beam tests, his participation is gratefully acknowledged. This work is supported in part the Natural Sciences and Engineering Research Council of Canada and by the National Science Foundation of the United States under grant NSF PHY 83-11717 to the Nuclear Physics Laboratory of the University of Illinois at Urbana-Champaign, USA.

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