EXPERIMENTAL INVESTIGATION OF LOW FREQUENCY MODES OF A SINGLE CELL RF CAVITY

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ABSTRACT

Low frequency modes of a single cell 500 MHz cavity are examined. All monopole, dipole, and quadrupole modes below 4 GHz are found. Of these, four modes are found to be trapped in the cavity in spite of being above the waveguide cut-off frequency of the beam tubes. The results are compared to URMEL[1] predictions.

Introduction

In designing a linear accelerator for a high average power free electron laser, one is driven to use high average currents since the beam energy is constrained by other considerations. Beam breakup instabilities (BBU) are likely to be the limiting factor in transporting high currents through an accelerator, so we are led to base our design on high gradient, low frequency, single cell cavities to raise the BBU threshhold[2]. BBU occurs as the beam interacts with higher order modes (HOMs) in the cavity, feeding energy into the modes and thereby increasing the strength of the interaction. If the amplitude of the HOMs can be suppressed, either by damping the modes as they grow or by preventing their growth in the first place, BBU can be prevented.

HOMs grow to large amplitudes in the cavity only when they are resonantly driven by the beam bunches. A resonance occurs whenever a HOM frequency falls on (or sufficiently near) a harmonic of the beam bunch frequency. This has an impact on how the accelerator is run: filling every N^{th} RF bucket will yield a basic bunch frequency of f_o/N, where f_o is the fundamental cavity frequency. N^{th} subharmonic bunching increases the number of potentially dangerous frequencies by a factor of N over the case when every RF bucket is filled.

The question arises as to how far out in frequency one must go before one can stop worrying about the HOMs. There are three approaches. First, one knows that the R/Qs of the modes must go to zero as the frequency increases. However, the rate at which the R/Qs approach zero is important. URMEL calculations show modes at 10 times the fundamental frequency with appreciable R/Qs, so this cannot be relied upon as a criterion for terminating the investigation. Second, one could assume that all modes above the waveguide cut-off of the beam tube simply propagate out to a load and can thus be ignored. Since this study shows the existance of trapped modes up to at least three times the cut-off frequncy, this is clearly a poor assumption. Finally, one can consider a Gaussian electron bunch with a temporal structure $\exp(-t^2/2T^2)$; such a bunch contains 99.5 percent of the charge in a length 4T. The induced fields fall off as $\exp(-\omega^2T^2/2)$, so that only frequencies below $f_{max} = (2^{1/2}\pi T)^{-1}$ are important. This is the criterion we have chosen to determine the upper limit for our HOM investigation. Even so, T must be quite large to keep fmax low and the number of modes to a reasonable number. Fortunately, in order to reduce the emittance growth of the beam due to space charge, we chose to design the accelerator around long beam bunches. To reduce the energy spread of the long bunches, we use harmonic acceleration[3]. For a bunch length of 250 ps (T=62.5 ps) f_{max} = 3.6 GHz, or about $7f_o$. Had we chosen a 30 ps bunch length and single frequency cavities, the investigation would have had to extend to 30 GHz, or $60f_o$.

Finally, one asks what type of modes are likely to be a problem. The coupling to the longitudinal motion of the beam goes as $(r/a)^m$, where r is the displacement from the cavity axis, a is a scale length, and m is the azimuthal mode number of the HOM. Once dipole modes are suppressed, eliminating BBU, quadrupoles and higher m-value modes can still cause undesired emittance growth of the beam. We have chosen to terminate the investigation at m=2 for the present, although it is clearly extendable to higher mode numbers.

Experiment Design

A simple system was chosen for diagnostic development. The basic cavity geometry is that of a right circular cylinder with beam tubes. The cavity radius is 23.6 cm, the cavity length is 25.0 cm, the beam tube radius is 9.0 cm, and the length of each beam tube is 15.0 cm. The cavity is constructed of 6061 aluminum alloy. The sidewalls are demountable, as are the beam tube end plates. Eight holes were drilled in the equator at 45 degree intervals to provide probe access.

Because the beam tube endplates are removable, we have the option of changing the boundary conditions at the end wall. The plate provides a reflecting boundary at which the electric field is normal. This is a "worst case" simulation of the cavity since the higher order modes cannot couple out of the cavity into waveguide modes. The second type of boundary is absorbing; power flowing out of the cavity is not reflected and the Qs of the untrapped modes drop. This boundary is formed by terminating the beam pipes in matched loads.

Both electric antennas and magnetic loops are used, depending on the axial symmetry properties of the modes launched and detected. The magnetic loops are balanced to eliminate coupling to radial electric fields. The electric probes couple to the antisymmetric TM modes and the antisymmetric TE $m\neq0$ modes. The loop probes couple to all symmetric modes. The antisymmetric TE modes can also be measured by rotating the loop probes 90 degrees to detect the H_z fields.

A single probe on the equator will launch or detect any mode of a given axial symmetry, irrespective of azimuthal or radial mode number. Because the number of modes is so large (there are 210 m=0,1,2 modes between 0.5 and 4 GHz, excluding TE_{onp} modes), it is desirable to excite and detect only specific m-valued modes. This is done by placing matched probes symmetrically around the equator and driving them with the proper phases using power splitters and 180 degree hybrid couplers. For example, consider four probes placed 90 degrees around the equator. Driven in phase, they will produce only m=0,4,8,... modes; if two adjacent probes are driven in phase with each other but with a 180 degree phase shift with respect to the remaining two, m=1,3,... modes are produced. If probes opposite to each other are driven in phase with each other but 180 degrees out of phase with respect to the remaining two, m=2,6,... modes are generated. Similar configurations can be used to combine the signals at the other four remaining probe positions, thereby discriminating against unwanted modes both in launching and detection. Typically, at least 20 dB attenuation of unwanted modes is achieved.

Experimental Results

Figure 1 demonstrates the advantage of using selectivity in isolating modes with specific m-values. The top trace shows a scan of the ratio of transmitted to incident power versus frequency, using just one launching probe and one detecting probe. The lower traces show the same frequency range, but selectivity has been used to substantially reduce the sensitivity to undesired modes. A larger number of probes around the equator would allow discrimination against higher m-value modes as well.

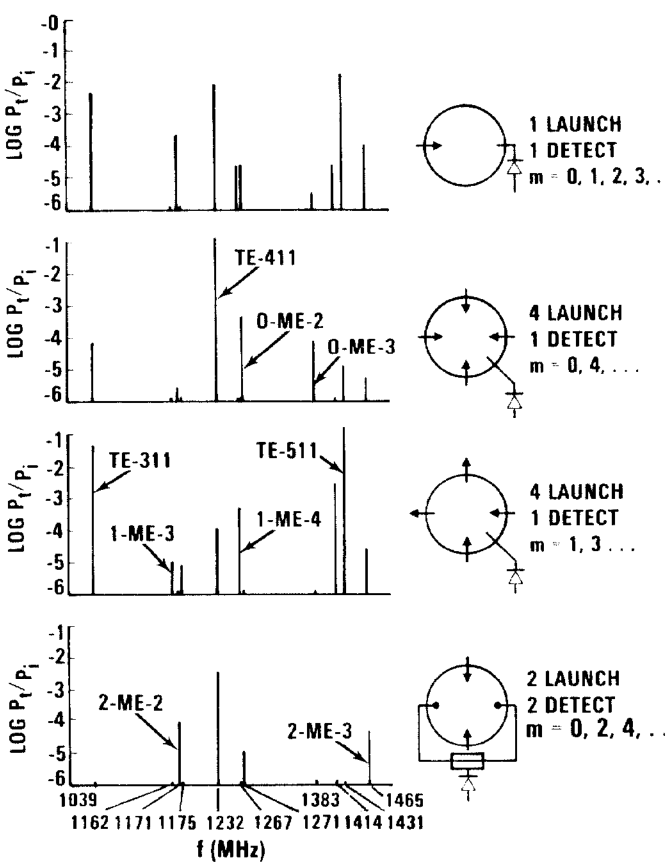

FIGURE 1: SELECTIVITY IS USED IN ISOLATING AND IDENTIFYING MODES

Figure 2 is a detailed comparison of P_t/P_i for the measured modes to the results predicted by URMEL for the antisymmetric m=0 modes. Figure 3 is the same, but for the antisymmetric m=1 modes. Both figures show only those modes detectable with electric probes on the equator; three m=0 modes and ten m=1 modes were below the detection threshhold (although they were easily detected with the loop probes) and are not included. P_t/P_i is not actually calculated by URMEL, since this is a number that is dependent upon the degree of coupling between the probes and the cavity, i.e. a geometric factor. The unknown probe coupling coefficient is found by using the computed electric field at the probe position, the computed stored energy, the measured Q and the measured P_t/P_i to calculate for each mode what should be a mode-independent quantity. The average of these values is used to compute a coupling coefficient. Given this coupling coefficient, P_t/P_i for each mode is computed using quantities calculated by URMEL.

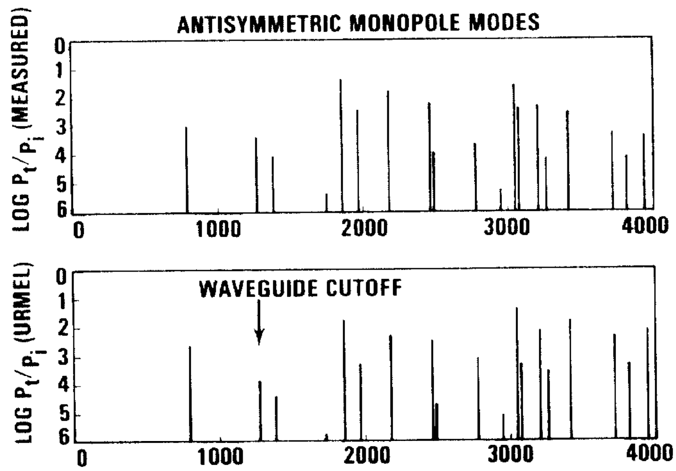

FIGURE 2: ANTISYMMETRIC MONOPOLE MODES, MEASURED AND CALCULATED

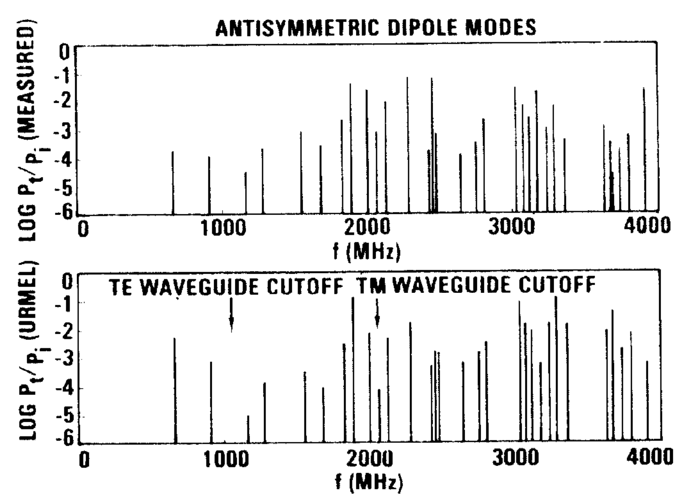

FIGURE 3: ANTISYMMETRIC DIPOLE MODES, MEASURED AND CALCULATED

Figure 4 shows P_t/P_i versus frequency for the m=0 antisymmetric modes, both with endplates and with the matched load termination. Only the trapped modes are left as the Q of the untrapped modes drops. The detection threshhold for these measurements was 1.2×10^{-6}; the transmitted power drops as Q^2 for weak coupling so a large drop in Q is not necessary to drop the signal below the limits of detection.

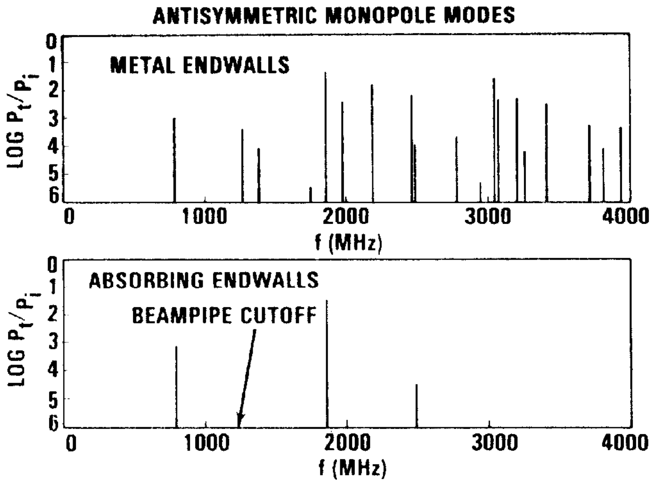

FIGURE 4: ANTISYMMETRIC MONOPOLE MODES, WITH CONDUCTING ENDWALLS AND ABSORBING ENDWALLS

Table 1 lists all trapped modes below 4 GHz that were found experimentally. Modes below cut-off are defined as trapped even though they coupled to the terminations in the experiment. Presumably longer beam pipes would greatly reduce this coupling. Note that power flow out the beam pipe can only limit the Q of the monopole mode at 3856 MHz to 150,000, in spite of the fact that its frequncy is three times cut-off.

In an attempt to understand why these trapped modes above cut-off were not coupling to the beampipe, we expanded the the fields at the entrance to the beampipe (as calculated by URMEL) in the eigenvectors of circular waveguide. Figure 5 shows the field pattern and the result of the decomposition of the fields into the waveguide basis for both an untrapped mode and a trapped mode. The untrapped cavity mode couples strongly to a propagating waveguide mode. The trapped cavity mode couples poorly to the propagating waveguide mode: the amplitudes of the evanescent modes are comparable in the two cases. When the total power associated with the propagating waveguide modes is calculated, it is found that for trapped modes the power flowing toward the endplates is small compared to the power dissipated in the cavity walls. For the untrapped modes the wall losses are only a small fraction of the propagating power. When the cavity Qs are recalculated assuming that the axially flowing power is lost, thereby modelling the absorbing boundary, the experimental results are reproduced. These investigations are continuing.

Conclusions

A mode-selective technique was used to isolate and examine 210 modes below 4 GHz: 48 m=0 modes (3 trapped above cut-off), 83 m=1 modes (1 trapped), and 79 m=2 modes (none trapped). All the modes were predicted by URMEL, with no more than 0.5 percent difference between the calculated and the measured frequencies; this difference is probably due to the uncertainties in the cavity dimensions as much as to any inaccuracies associated with URMEL. The existance of trapped modes above the waveguide cut-off frequencies has been clearly demonstrated. These modes, which occur over a wide range of frequencies, must be accounted for when designing cavities to handle high average beam current.

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References

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3. C.E. Hess, H.A. Schwettman, T.I. Smith, IEEE Trans. Nucl. Sci., **NS-32**, 2927 (1985)

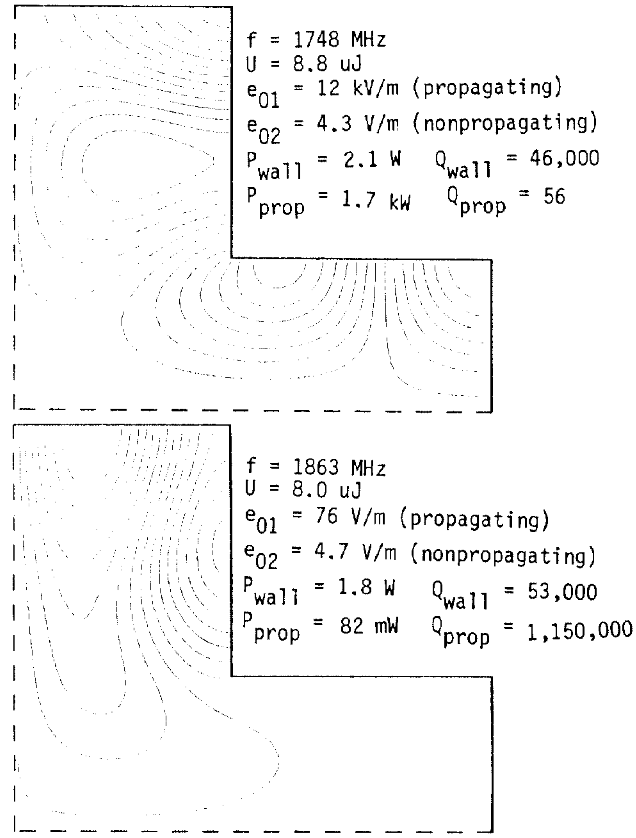

FIGURE 5: UNTRAPPED AND TRAPPED CAVITY MODES. AMPLITUDES OF WAVEGUIDE MODES, PROPAGATING POWER AND Q_s ARE SHOWN

URMEL DESIG	RCC DESIG	URMEL f (MHz)	URMEL R/Q (R/Q')	URMEL Q_{EP}	MEASURED f (MHz)	MEASURED Q_{EP}	MEASURED Q_{ML}
0EE1	TM010	500	133	33,200	501	16,200	16,700
1ME1	TE111	661	(5)	38,000	661	17,900	4,700
1EE1	TM110	747	(23)	35,900	748	15,900	3,200
0ME1	TM011	787	40	27,400	788	15,100	14,600
1ME2	TM111	910	(27)	27,100	911	12,500	******
DIPOLE TE	CUT-OFF	976					
0EE2	TM020	1137	0.16	56,600	1140	33,900	4,400
0ME2	TM021	1270	3	36,300	1271	17,900	******
MONOPOLE	CUT-OFF	1275					
1ME7	TE131	1822	(0.2)	61,100	1825	57,000	16,800
0ME5	TM013	1863	2.4	42,500	1864	10,400	9,400
DIPOLE TM	CUT-OFF	2031					
0ME9	TM041	2483	0.08	69,093	2486	50,000	40,000
0EE25	TM062	3856	0.71	62,200	3843	29,400	25,000

TABLE 1: SUMMARY OF TRAPPED MODES UP TO 4 GHz