Field Profile and Loading Measurements on Higher Order Modes in a Two Cell 500 MHz Superconducting Structure*

W. Barry, J. Edighoffer, and S. Chattopadhyay
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720
and
S. Fornaca
TRW Space and Technology Group, Redondo Beach, CA

Abstract

The Infrared Free Electron Laser, being designed at LBL as part of the Chemical Dynamics Research Laboratory, is based on a 500 MHz superconducting linac driver that consists of five 4-cell structures of the CERN/DESY type. A 500 MHz, 2-cell version of this structure is being used in a joint Stanford/LBL/BNL program to study accelerator issues relevant to the FEL applications. As part of this study, field profile and loading measurements of higher order modes have been made on the prototype structure.

Introduction

As presently proposed, the LBL Chemical Dynamics Research Laboratory (CDRL) will incorporate a high-brightness, tunable, infrared free-electron laser (FEL) for the purpose of studying combustion dynamics at the molecular level.[1] In order to achieve the necessary wavelength stability and CW operation, the FEL makes use of superconducting RF cavity structures. Reported are the results of preliminary low level room temperature RF measurements of a 500 MHz two-cell structure for use in the FEL.

The prototype structure is a two-cell version of the CERN/DESY structure that was originally built by Interatom for TRW. The cavity components, made from high purity nobium sheet, were formed by spinning and then electron beam welding. The cavity pair, shown in Fig. 1, incorporates four higher order mode (HOM) couplers (two TE and two TM) mounted on the expanded beam tube sections. On each beam tube there is one TE and one TM coupler with an angle of 70^o between them. The TE (TM) couplers on opposite beam tubes are oriented with an angle of 110^o between them.

In addition to the measurements reported here, further evaluation of the two-cell structure will include RF measurements on the fundamental coupler and an improved HOM coupler, and detailed microphonics studies, both warm and at cryogenic temperature.

Cavity Measurements

Five basic measurements were performed on the two cell structure: Mode spectrum and identification, HOM coupler external Q's, on-axis field profiles, effects of tuning to flatten the field profile of the accelerating mode, and isolation of the accelerating mode from the HOM couplers. The results of the mode spectrum and Q measurements are given in Table 1. As indicated, a total of 21 longitudinal and dipole modes below the 1.28 GHz TM_{01} beam pipe cutoff were identified. The modes were identified by correlating their measured frequencies with those predicted by URMEL and by probing inside the cavity with directional electric and magnetic field perturbers (needles and disks).

In Table 1, HP and VP refer to horizontal or vertical electric field polarization where vertical is defined to be aligned with the axis of the fundamental coupling port. Nearly all of the dipole modes exhibit horizontal or vertical polarization. Exceptions are the TE dipole (TE_{111} Exp) modes that are trapped in the expanded beam tube sections. In these cases, the modes in each expanded beam tube section are completely uncoupled. As a result, the electric field directions for the two polarizations of each mode are determined by the $\bar{E}$ and $\bar{H}$ HOM couplers. The vertical and horizontal polarizations occur for all other dipole modes because the strong coupling between cells and the two sets of HOM couplers introduces symmetries with respect to these directions.

Mode	f_o (MHz)	Q_{ext} ($x10^3$)	R/Q (kΩ,kΩ/cm)	R (kΩ,kΩ/cm)
TM_{010}-0	494.2	> 2500	.001	> 2.5
TM_{010}-π (Accel)	500.0	$3x10^9$	115	$3.5x10^8$
TE_{111}-0 HP	618.4	11.1	4.24	47
TE_{111}-0 VP	620.2	1071.0	4.24	4500
TE_{111}-π HP	651.5	1.2	8.22	9.9
TE_{111}-π VP	655.4	44.6	8.22	370
TM_{110}-π HP	700.8	.15	15.75	2.4
TM_{110}-π VP	702.1	2.7	15.75	43
TM_{110}-0 HP	727.3	< .1	6.72	< .67
TM_{110}-0 VP	728.0	33.0	6.72	220
TM_{011}-π	887.3	2.1	2.77	5.8
TE_{111} Exp A⊥E	895.0	.28	---	---
TM_{011}-0	906.6	2.2	36.4	80
TE_{111} Exp B⊥E	918.0	.21	---	---
TE_{111} Exp B⊥H	924.0	< .1	---	---
TE_{111} Exp A⊥H	936.0	< .1	---	---
TM_{020}-0	1040	2.3	.05	.12
TM_{020}-π	1061	4.6	.72	3.3
Trapped	1174	42.0	.22	9.2
TM_{011}-0 Exp	1191	2.8	---	---
TM_{011}-π Exp	1195	3.5	---	---

Table 1: Mode Spectrum and HOM Damping Data.

Also contained in Table 1 are the Q_{ext} values of the four HOM couplers combined for each mode. These values were calculated from Q measurements of the unloaded cavity and the cavity loaded with 50Ω terminations on the HOM couplers. The loaded and unloaded Q values for all modes except the TM_{010}-π accelerating mode were determined by finding the 3dB width of each resonance in a weakly coupled transmission measurement through the cavity structure. The TM_{010}-π mode is well isolated from the HOM couplers resulting in a high Q_{ext} and a small difference between Q_{loaded} and $Q_{unloaded}$ which is difficult to

* This work is supported in part by the Office of Energy Research, Contract No. DE-AC03-76SF00098 and by the Office of Naval Research, Contract No. N00014-91-J-4152.

measure by the 3dB resonance method. In this case, Q_{ext} was found by measuring β for each HOM coupler via power transmission measurements through each HOM coupler. Using this technique, $Q_{ext} = 3x10^9$ for the accelerating mode was measured. This value is of the same order as the superconducting cavity Q_0.

In order to assess the accuracy of the Q_{ext} values in Table 1, a brief qualitative explanation of the HOM couplers is necessary.[2] Both the TE and TM couplers consist of coaxial transmission lines with various shunt inductances and capacitances. In addition, the HOM couplers incorporate a resonant shunt filter tuned to 500 MHz for the purpose of isolating the accelerating mode from the external 50 Ω load. The locations of the shunt reactances are configured so as to obtain a spectrum of real damping impedances that is aligned with the spectrum of HOM's in the cavity. The HOM couplers are constructed of niobium and are essentially lossless at liquid helium temperature. In this case, all of the coupled power is delivered to the external load.

At room temperature, the niobium has finite loss and because of the resonant characteristics of the HOM couplers, real impedances are presented to the cavity at the HOM frequencies resulting in mode damping even in the absence of the external terminations . By adding the resistive termination and as a consequence, removing the existing reactive termination at the output port of the HOM coupler, both the resonant frequencies and impedances of the HOM coupler spectrum are altered in a rather complex way. Thus, in general, at room temperature, the addition of the resistive termination can cause an increase, decrease or even no change at all in the Q of a given HOM in the cavity. For this reason, it becomes difficult to infer values for Q_{ext} at liquid helium temperature from measurements made at room temperature.

However, in light of the room temperature characteristics of the HOM coupler structures, it is not unreasonable to believe that, at least on average, the Q_{ext} values obtained at room temperature will be higher than the true Q_{ext} values when the cavity and damping structures are superconducting. In effect, the room temperature impedances of the HOM couplers in the absence of the external loads hides the true effectiveness of them. Of course, the only definitive measurement of Q_{ext} is when the structure is superconducting.This testing will take place at Stanford over the next several months.

The only troublesome HOM as far as damping is concerned is $TE_{111\text{-}0}$VP mode. This mode has a history of being difficult to damp in this structure and has typically been addressed by adding spheres to the coupling tips of the TE HOM couplers. The effect of the spheres is to increase the coupling to the transverse electric field in the cavity through an increase in the surface area of the probe. Following this lead, the effect of adding 1.5" diameter disks to the ends of the TE probes was investigated. The result was a reduction in Q for the $TE_{111\text{-}0}$mode by a factor of three yielding a Q_{ext} of $5.2x10^3$. Further investigations into HOM coupler modifications will be made over the next several months.

Finally, Table 1 lists R/Q as calculated by URMEL for each of the higher order modes. In addition, the shunt impedances, assuming the measured Q_{ext} values are listed. Although URMEL computes R/Q for an ideal symmetric structure, the values are believed to be accurate to within a factor of two or three based on the measured asymmetries in the cavity field profiles. Except for the $TE_{111\text{-}0}$ mode, all shunt impedances are under 1000 kΩ (kΩ/cm) which is acceptable for the expected beam current levels in the FEL. The impedance of the $TE_{111\text{-}0}$mode also becomes acceptable with the simple HOM coupler tip modifications.

The cavity modes were further characterized through on axis field profile measurements. The field profiles were measured using the standard technique of pulling a small metal bead along the axis of the cavity and measuring the resulting frequency shift of the mode as a function of bead position. Due to space constraints, only the accelerating mode and most unusual higher order mode profiles are shown in Figures 2. In Figure 2a, the fundamental accelerating mode profile is shown for the cavity as delivered from Interatom (solid) and after differential tuning of the two cells (dashed) to equalize (flatten) the field amplitudes. The cells were plastically tuned by compressing one and expanding the other along the axis of the cavity. The total deformation of the cells was estimated to be on the order of 1-2 mm. Although not shown in Figures 2, the in phase version of the fundamental mode, the $TM_{010\text{-}0}$, was also flattened simultaneously.

The field profiles for the higher order modes basically matched the profiles predicted by URMEL except for flatness from cell to cell. The mode with the worst cell to cell field asymmetry was the TM_{011} mode shown in figure 2b. In this case, the field asymmetry was 6dB and is attributed to the techniques used to fabricate the structure. This can be compared to a 1300 MHz two-cell structure fabricated by die forming where the fields of the HOMs were flat to a few percent.[3] The following characteristics for all the profiles were measured: The field profiles did not change with tuning of the fundamental mode nor in the presence of mode damping, and the two polarizations of the dipole modes, except for the TE expanded beampipe modes, all had identical profiles. An important consequence of the first of these conditions is that tuning of the fundamental mode has no effect on HOM damping. This fact was confirmed by measuring the damped Q of each HOM before and after tuning.

Several of the more unusual higher order modes are shown in figures 2c, 2d and 2e. Figure 2c shows the field profile for the "trapped" mode which is a TE dipole mode with strong electric field concentrated near the iris between the two cells. However, this mode does have some field content in the expanded beam tube on the fundamental coupler side affording adequate damping by the HOM couplers in this region. The field profile shown in figure 2d is for a TE_{111} mode trapped in the expanded beam tube region. In this case, the fields in the left and right beam tube regions are uncoupled resulting in separate modes in each expanded region rather than a zero and pi version the of the same mode. In contrast, figure 2e gives the profile for a TM_{011} mode in the expanded regions. In this case the mode is coupled though the cavity structure resulting in zero and pi variations.

Summary

Room temperature RF tests were performed on a 500 MHz two cell superconducting cavity structure for the LBL CDRL FEL. The studies indicate that the HOM couplers perform well for all HOMs except the TE_{111} mode. Modifications to the TE HOM couplers bring the damping of the TE_{111} HOM into specification.

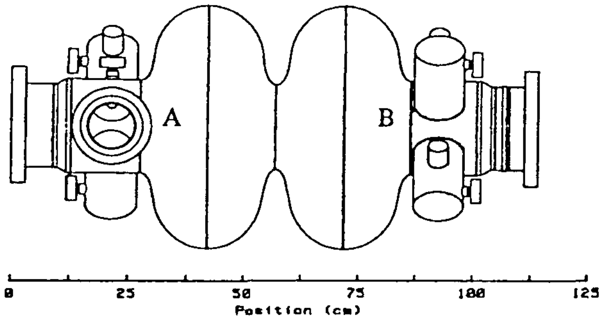

Figure 1: Cavity Geometry.

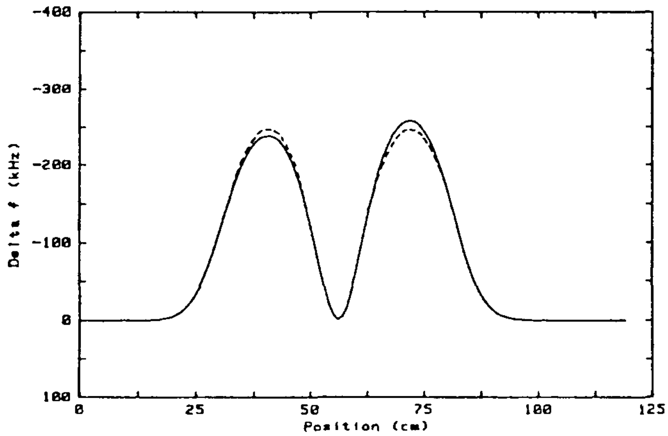

Figure 2a: Fundamental Mode.

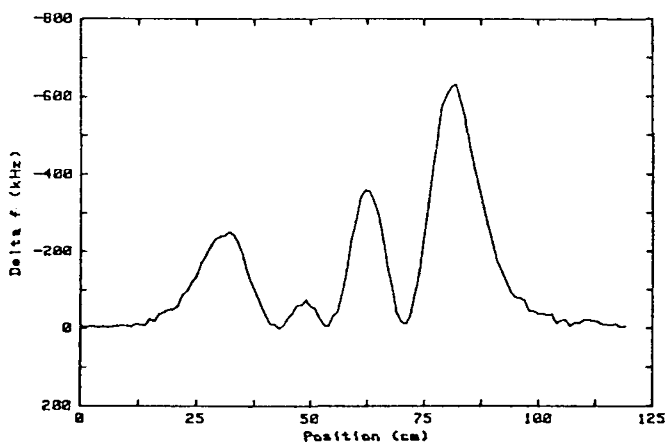

Figure 2b: TM_{011} Mode.

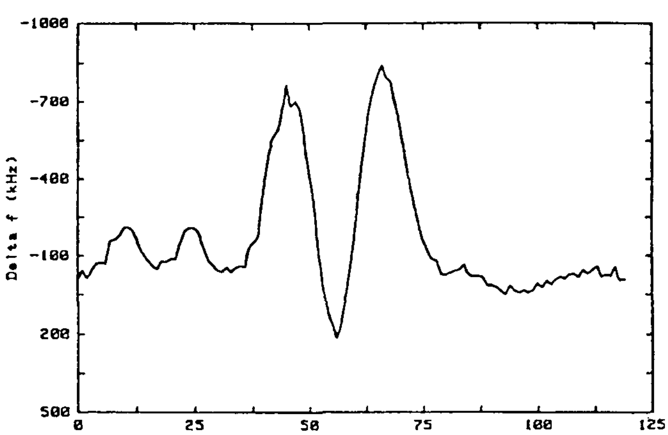

Figure 2c: Trapped Dipole.

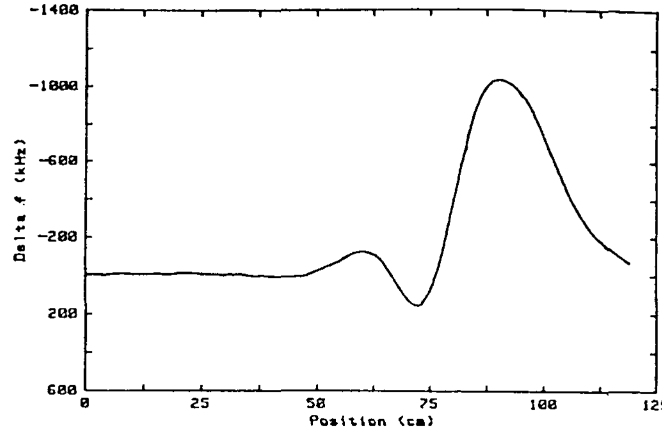

Figure 2d: TE_{111} Exp B⊥H.

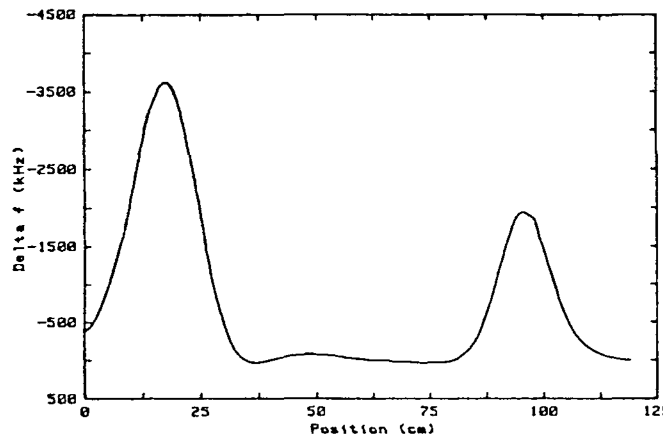

Figure 2e: $TM_{011\text{-}0}$Exp Mode.

Field flattening of the fundamental mode did not affect any of the HOMs. It appears that the spinning technique used to fabricate this two-cell structure lead to significant non-uniformity of the HOM field profiles compared to a similar structure built by die-forming. The effect of this is on beam dynamics is yet to be determined.

Acknowledgments

The authors wish to thank A. Schwettman and A. Marziali of Stanford for many fruitful discussions.

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