3.9 GHZ DEFLECTING CAVITY AS A BUNCH LENGTH DIAGNOSTIC

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ABSTRACT

A superconducting TM_{110} p mode cavity, initially designed for use in a fixed target beam line[1] has found application as a diagnostic to measure short electron bunch lengths, i.e. bunches traversing a point in a picosecond or less. The operating frequency of FNAL's TM_{110} cavity is 3.9GHz, three times the operating frequency of both the FNPL Photoinjector at Fermilab as well as that of the proposed International Linear Collider (ILC). We discuss the modeling of the TM_{110} cavity in a beamline during operation as well as in a "standby" mode. Additionally, we present prototype TM_{110} cavity vertical test performance results. Additionally, FNAL's TM_{110} cavity is an ideal candidate as a crab cavity for the ILC.

INTRODUCTION

The use of a transverse mode RF cavity to measure short bunch lengths is not a new concept [2], however the application of SCRF to the measurement is, and along with which are advantages as well as complications. SCRF enables a deflecting field of approximately 6 MV/m for a minimal expense in RF power, however, the potentially high Q of the structure's Higher Order Modes could have a significant impact on the beam. The operating TM_{110} mode also possesses a noticeable longitudinal electric field that is accelerating on one side of the vertical deflecting plane while decelerating on the other.

The theory of operation of the TM_{110} cavity as a longitudinal bunch length measurement is straight forward. A short, but finite bunch is injected into the TM_{110} cavity centered about the deflecting field's zero-crossing phase. The head of the electron bunch arrives shortly before zero crossing and is kicked transversely "down," while the tail of the bunch arrives after zero-crossing and feels a kick transversely "up," and of course everything in between is smeared out accordingly with the sweeping phase of the deflecting field. The total angular divergence is directly proportional to the bunch length. A viewing screen placed sufficiently down stream will intercept the crabbed bunch thereby displaying the bunch length. Taking this measurement one step further, a viewing screen capable of resolving incident beam intensity, time dependant structure in the bunch can be extrapolated.

One of FNPL's [3] beam physics program's goals is the generation of extremely short bunches as needed for Free Electron Lasers. To ensure short bunch lengths, the FNPL laboratory has decided to employ this time resolving crabbing technique of the TM_{110} cavity.

HFSS AND ASTRA SIMULATIONS

To understand how the TM_{110} cavity would operate in the Photoinjector beamline, a full 3-dimensional 13-cell TM_{110} cavity was modelled HFSS [3]. A solution for the desired p mode was solved, and its corresponding 3D field map was generated for the volume of the cavity that the beam could interact with. The field map was then formatted for use in ASTRA [4], the 3-dimensional beam tracking code. The field map was normalized for a peak deflection corresponding to an electric field 5MV/m.

The simulated injected charge bunch was composed of two Gaussian bunches of differing charge that were separated slightly in time. The use of two Gaussian bunches with encoded amplitude and time structures allowed us to test the time resolution of the deflecting structure. A viewing screen was placed 1 m downstream in the modelled beamline. Figure 1 shows the results of that simulation. The left, top and bottom plots are of the beam on the viewing screen. The top image is the beam with the TM_{110} cavity off, and the vertical projection of the beams intensity is shown on the plot directly to the right. The bottom left image is the same beam, but traversing the TM_{110} cavity while energized. Similarly, to the right is the vertical projection of the beam's intensity as a function of position, on top of which is plotted the beam's intensity time dependence as used in its generation. This clearly demonstrates the time to spatial correlation perseverance.

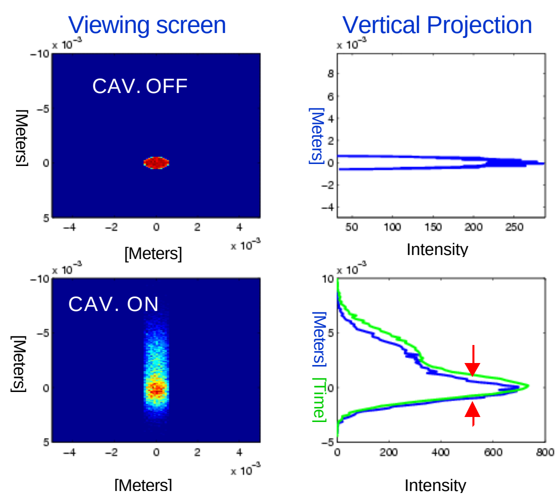

Figure 1. Transverse beam density 1 m downstream of the TM_{110} cavity (left plots) and associated vertical projection (right plots).

A time width sampling, indicated by arrows, of the greater peak in the bottom right plot is 730 femtoseconds, this corresponds to a 2.0 mm width on the viewing screen. An imagining system capable of resolving 50µm would correspond to a resolution of approximately 20femtoseconds.

"OTHER" MODES

In addition to the nuisance of Higher Order Modes [HOMs], a TM_{110} cavity is faced with Lower and Same Order Modes, denoted as LOMs and SOMs respectively. The lower order modes are the TM_{010} passband of accelerating modes and the SOMs are indeed the same TM_{110} modes, but of orthogonal polarization

To identify potentially problematic LOMs, the MAFIA[5] code was used to determine the phase of the 13 modes comprising the TM_{010} passband. Those nearest a phase velocity of *c* pose the greatest threat. R/Q values for the thirteen modes were calculated. Of the thirteen the three of greatest concern are listed in table 1.

Mode	Phase Advance	R/Q
TM_{010}	9p/13	187?
TM_{010}	10p/13	354?
TM_{010}	11p/13	129?
TM_{020}	7p/13	14?
TM_{110}	p 2nd polarization	$2.3\text{x}10^{6}$? /m

Table 1 LOMs, SOMs, and HOMs of concern.

A LOM coupler is located on the beam tube opposite of the main power input coupler, its placement at the opposite avoids capacitive coupling to the input coupler. The LOM coupler is designed to have a Q_{ext} of 10^{10} at the 3.9GHz operating frequency, while a much lower Q_{ext} of the order 10^{5} in the TM_{010} passband. An undesirable characteristic of the LOM coupler is the need for its antenna to penetrate into the beam pipe, the tip of which is about 11mm from the cavity's center, to sufficiently couple to the TM_{010} modes.

The SOM coupler, also located on the same end as LOM coupler, is comparatively simple. With the exception of being a fixed length, the SOM coupler follows a similar geometry of the input power coupler. After its manufacture a slight bend will be introduced into the center conductor of the SOM coupler to allow transverse adjustment via its procession when spun about its rotatable mounting flange. The transverse adjustment will be required to locate the null of the operating polarization, hence offering the greatest rejection to the operating mode. Of the band of undesired polarization TM_{110} modes, by far the p advance mode is of greatest concern, as its phase velocity is the speed of light and has an R/Q value of $2.3\text{x}10^{6}$?/m.

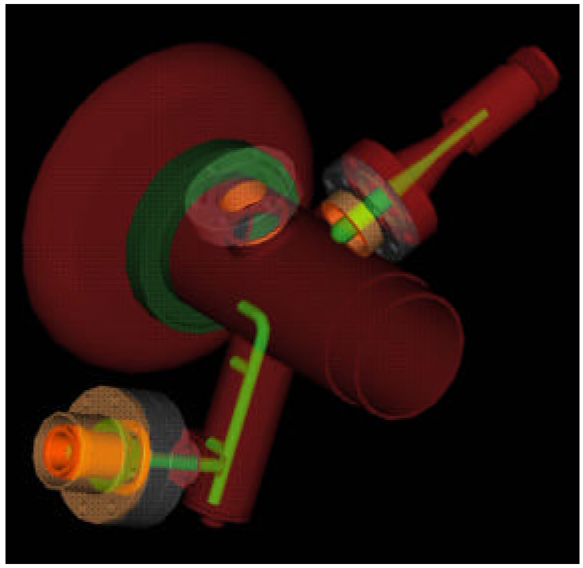

Figure 2 LOM (bottom left) and SOM couplers.

We have also investigated HOM's from the monopole, dipole and quadruple modes up to and slightly beyond cut-off wavelength of the beam tubes. Similar to the LOM studies, modes with phase velocities near the speed of light have been identified, see Figure 3 for example of the m=1 modes, and their R/Q values established by MAFIA simulation. Using the following definition for R/Q:

$$R^{(m)}/Q = \frac{1}{r^{2m}}\frac{2k^{(m)}(r)}{w} = \frac{2}{r^{2m}w}\frac{\left|\int dz\tilde{E}_z^{(m)}(r,z)e^{-iwz/c}\right|^2}{4U^{(m)}}$$

we plot the R/Q values, where the units are ? for m=0, ? /m^2 for m=2 and ?/m^4 for m=2

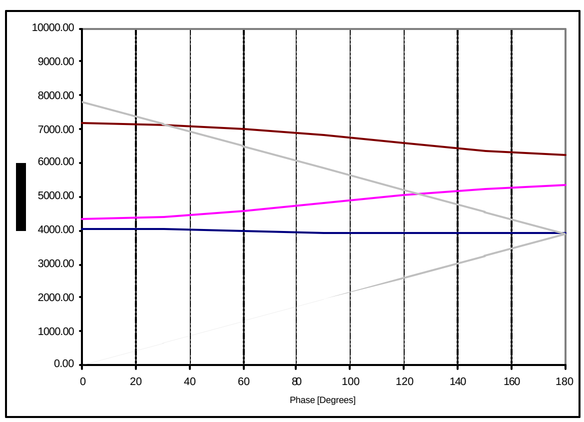

Figure 3 m=1 (dipole) modes phase plot

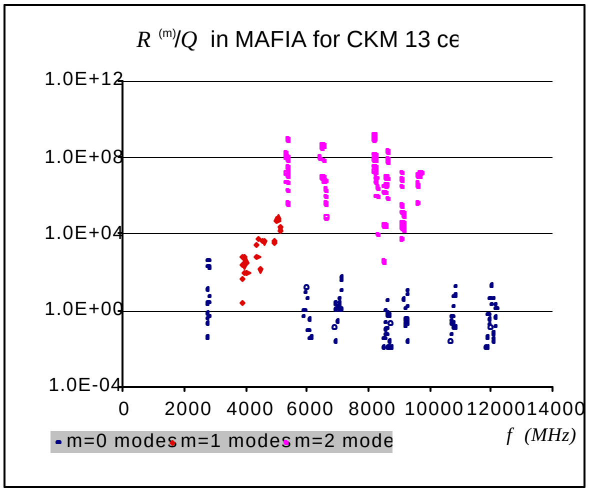

Figure 4. R/Q for m=0, 1, and 2 modes

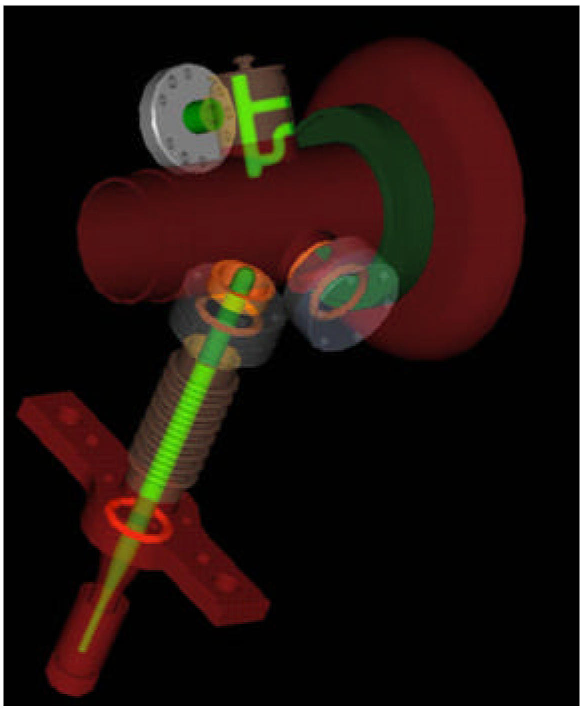

Figure 5 Input coupler (bottom left) and HOM coupler.

WAKE FIELD SIMULATIONS

Since the intended use of the TM_{110} cavity in the FNPL Photoinjector beamline is as a diagnostic, it will normally reside in the beamline in a "standby" mode, i.e. at 4.5K. Table 2 shows the typical operating parameters of the FNPL Photoinjector.

A study is currently underway to calculate the wake fields setup by typical bunches entering the cavity, both on and off axis. This study is utilizing the R/Q values generated by MAFIA. While the beam can generate wakefields from entering the cavity at any transverse location, only when the leading bunch is off set from the TM_{110} electrical axis are the dipole wake fields generated. The monopole wakefield will modulate the longitudinal energy while the excited dipole modes obviously impart a transverse kick to subsequent bunches. One must note that resonant excitation of the various wakefields can be enhanced or destroyed by careful selection of the macropulse time structure. This is a work in progress.

Parameter	Value	Units
Energy	15 (upgrading to 40)	MeV
Charge/bunch	10	nC
Bunches per pulses	20	(max 50)
Bunch Spacing	1	μS
Repetition Rate	1	Hz

Table 2. Typical FNPL operating values.

VERTICAL DEWAR TEST RESULTS

Three 3-cell cavities, nick-named *shorty*, *softy*, and *thick* for their unique characteristics, have been through a battery of vertical dewar tests. A typical sample of their results are reported in the Tables below:

Cavity: "Shorty"

Date	Rres(nO)	Peak Field (MV/m)
Early 2003	250	5.1
Feb, 2003	120	3.6
Feb, 2004	1300	5.4
Dec, 2004	1000	5.4
April, 2005	200	3.3
June, 2005	10,000	N/A

Cavity: "softy"

Date	Rres(nO)	Peak Field (MV/m)
June, 2005	190	N/A
March, 2005	220	3.3

Cavity: "Thick"

Date	Rres(nO)	Peak Field (MV/m)
August, 2004	60	7.5 !

The thick walled cavity is shown to have exceeded the design specification of a P- of 5MV/m by 50%, achieving a deflecting field of 7.5MV/m. A deflecting field of 7.5MV/m corresponds to a peak surface magnetic field of 120mT, which is reasonable for BCP etched fine grain Niobium. Routine operation at 6MV/m deflection can be expected.

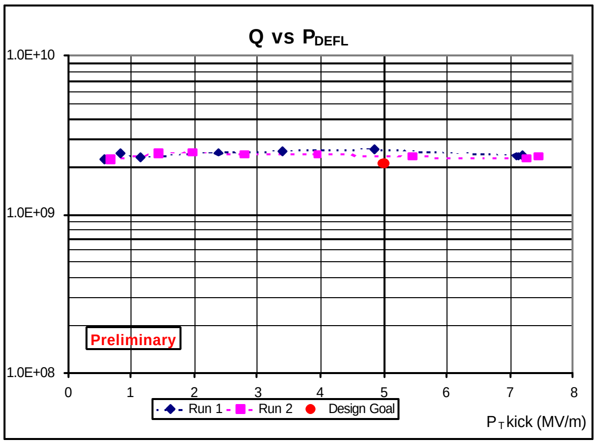

Figure 6. Q vs. P-

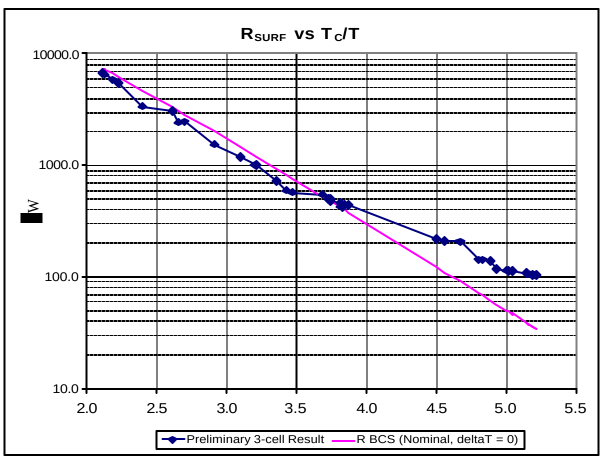

Figure 7. R_{surf} vs. T_c/T

Remarkably, the thick walled cavity's Q vs. P- does not fall off at high fields as would be expected (see Figure 6), but rather, continues to perform at peak field before quenching. Interestingly, as seen in Figure 7, R_s of the thick walled cavity only approached 100n?, which is considered to be fairly high. A value of 40n ? would be a more satisfactory goal. The reason for this rather high R_s is not well understood, but may be due to the magnetic field's interaction with the Vertical Test Stand input coupler antenna tip.

INFRASTRUCTURE

The FNPL group has begun to procure necessary support equipment for the operation of the TM_{110} cavity. Already, a tested horizontal cyrovessel, capable of hosting two 13 cell TM_{110} cavities is in hand. A 2600 watt CW. Klystron, intended for use in the original fixed target beamline application of the TM_{110} already exists and will be more than adequate for the present use. Finally, the Low Level RF automation will be executed by a system currently being developed at Deutsches Elektronen-Synchrotron (DESY) and is currently being tested at FNAL and DESY. A fast piezo-electric tuner which has been built by FNAL has successfully demonstrated microphonics reduction at room temperature on one of our 13-cell prototype TM_{110} mode cavities [6].

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