# Observation of Polarization-Dependent Changes in Higher-Order Mode Responses as a Function of Transverse Beam Position in TESLA-Type Cavities at FAST

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# Introduction

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## Abstract

*Higher-order modes (HOMs) in superconducting rf cavities present problems for an electron bunch traversing the cavity in the form of long-range wakefields from previous bunches. These may dilute the emittance of the macropulse average, especially with low emittance beams at facilities such as the European X-ray Free-electron Laser (XFEL) and the upgraded Linac Coherent Light Source (LCLS-II). Here we present observations of HOMs driven by the beam at the Fermilab Accelerator Science and Technology (FAST) facility. The FAST facility features two independent TESLA-type cavities (CC1 and CC2) after a photocathode rf gun followed by an 8-cavity cryomodule. The HOM signals were acquired from cavities using bandpass filters of 1.75 ± 0.15 GHz, 2.5 ± 0.2 GHz, and 3.25 ± 0.2 GHz and recorded using an 8-GHz, 20 GSa/s oscilloscope. The frequency resolution obtained is sufficient to separate polarization components of many of the HOMs. These HOM signals were captured from CC1 and cavities 1 and 8 of the cryomodule for various initial trajectories through the cavities, and we observe correlations between trajectory, HOM signals, and which polarization component of a mode is affected.*

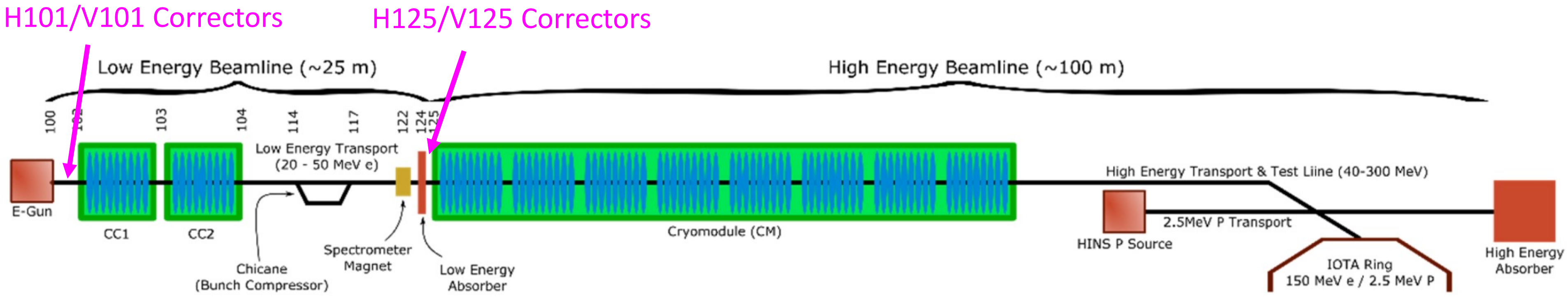
# Introduction

Beam traversing an accelerating cavity can induce higher order mode (HOM) responses in the cavity. These HOMs may impact the beam in the form of long-range wakefields. At high-brightness electron accelerator facilities such as the European XFEL at DESY [1] and the soon-to-be completed LCLS-II at SLAC [2], these wakefields may cause emittance dilution as the beam is transported down the beamline, particularly through the early cryomodules. In this paper, we focus on the dipole modes of TESLA-type 9-cell cavities [3-5] which are generated when the transverse position of the bunch does not align with the electromagnetic center of the mode. The response of the mode is then a linear function of the transverse distance of the bunch from the electromagnetic center. Each dipole mode has two polarizations which are orthogonal and typically split in frequency due to the cavity shape not being exactly cylindrical.

Previous efforts at DESY to reduce these HOM wakefields involved the use of a narrowband, down-converted signal filtered on the TE111-6 dipole mode at ~1.7 GHz to measure and correct the beam position through the cavities [6]. Here we look at some of the dipole modes from 1.6 GHz to 1.9 GHz in a standalone cavity and in 4 of the cavities of a cryomodule. We have used horizontal and vertical corrector magnets in front of the cavities to steer the beam and produce an average offset through the cavities. These offsets produce varying levels of HOM signals which we process through an oscilloscope to obtain the magnitude and phase of the modes including the two polarizations for some of them. Additionally, we identify modes that are close to beam harmonics which may induce larger effects in the later bunches due to harmonics. In the past [7,8], we have identified modes that caused motion along the bunch train at the difference frequency of the mode and a beam harmonic.

# FAST Beamline

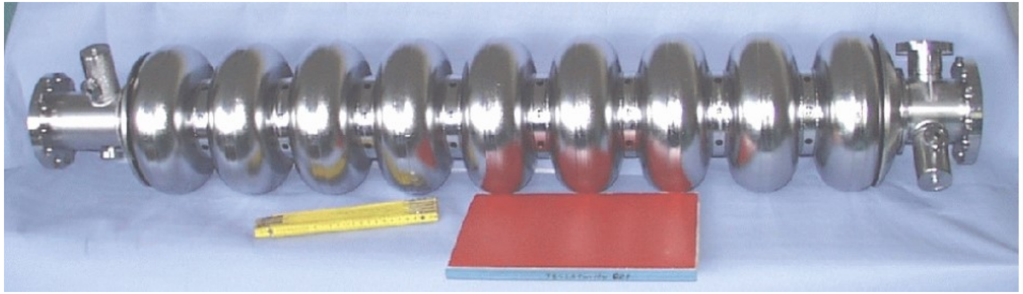
The FAST Linac [9] consists of a photocathode electron gun with a $Cs_2Te$-coated Mo cathode driven by a Nd:YLF laser. The photocathode is embedded in a 1.5 cell normal conducting rf cavity operating at 1.3 GHz and surrounded by 2 solenoids. The laser repetition rate is typically 3 MHz and can produce electron bunches from below 100 pC to several nC which exit the gun with ~<5 MeV of energy. Following the gun are two 9-cell Tesla-type superconducting rf cavities (CC1 and CC2) which can increase the energy up to 50 MeV. After the cavities is a section with quadrupoles and an optional chicane followed by an optional spectrometer magnet and low energy dump. This section has many diagnostic stations in it, including Al OTR foils, YAG:Ce single-crystal screens, and an Al-coated Si transition radiation screen leading to a THz interferometer and a streak camera for bunch length measurements. Beyond this section is the 8-cavity cryomodule (CM2) and the high-energy line ending at the absorber. The cavities all have a higher-order mode (HOM) coupler at each end to extract the HOMs generated by the passing beam. These signals from the couplers are used to determine some properties of the beam. The dipole correctors at location 125 are used to alter the trajectory through CM2 producing varying levels of HOMs.

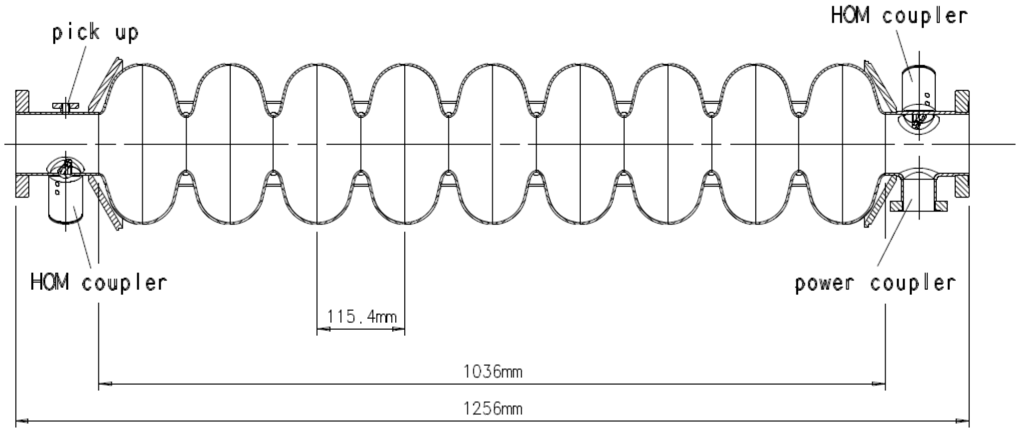


# TESLA-Type Cavities

Pictures and schematics of the superconducting 9-cell TESLA-type Niobium cavity found in CC1, CC2, and the cryomodule CM2. The diagram below shows the azimuthal angular offset between the two HOM couplers located at the ends of the cavity. The cavity is ~1 meter long.

from Ref. 4



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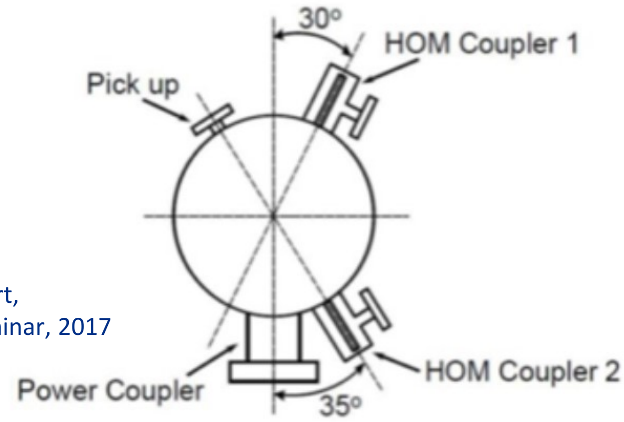
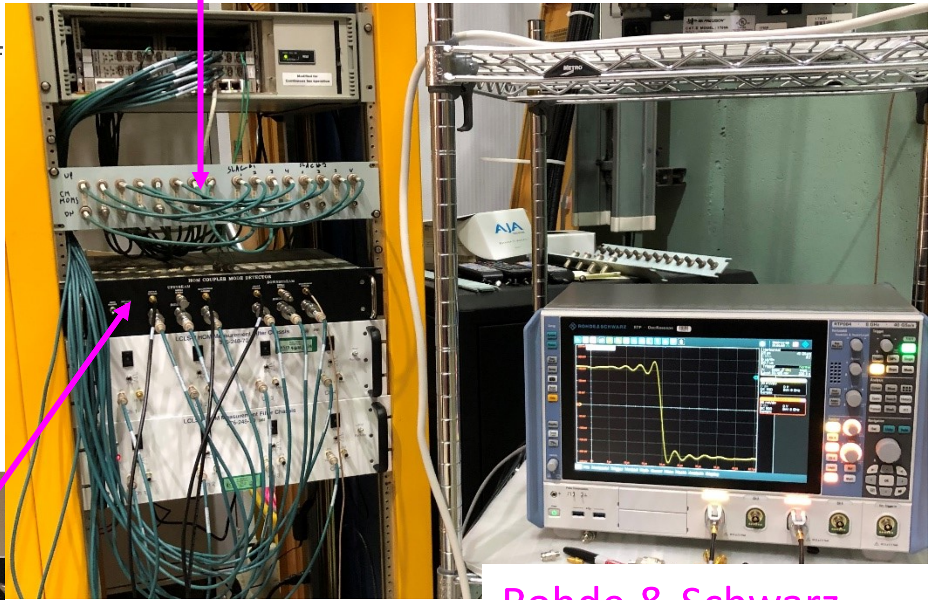



T. Hellert,
FEL Seminar, 2017

# Experimental Setup

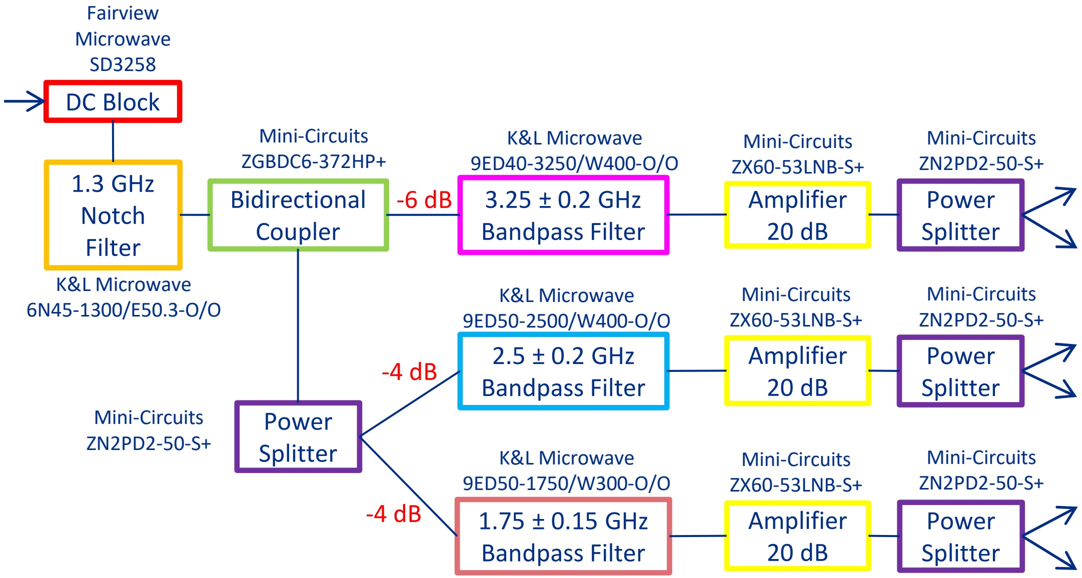
The HOM signals are transported to the electronics via 1/2” Heliax cables.  Once in the rack, they transition to BNC-terminated RG-58 cables for convenience before entering one of several analog filter boxes.  Since there were different filter boxes being tested, a patch panel was used to quickly switch between cavities and boxes.

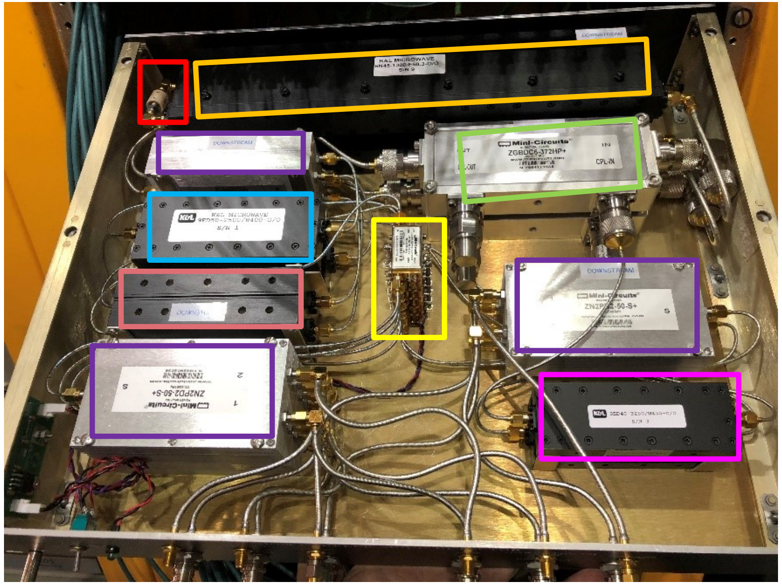
The HOM filter box used in this set of measurements is shown below.  It contains two channels, with each channel having three bandpass filters at 1.75 GHz, 2.5 GHz, and 3.25 GHz, and two outputs per filter enabling one to be used in an 8-GHz, 20 GS/s, Rohde & Schwarz RTP084 oscilloscope, and the other to be used in a peak detector.




# Experimental Setup

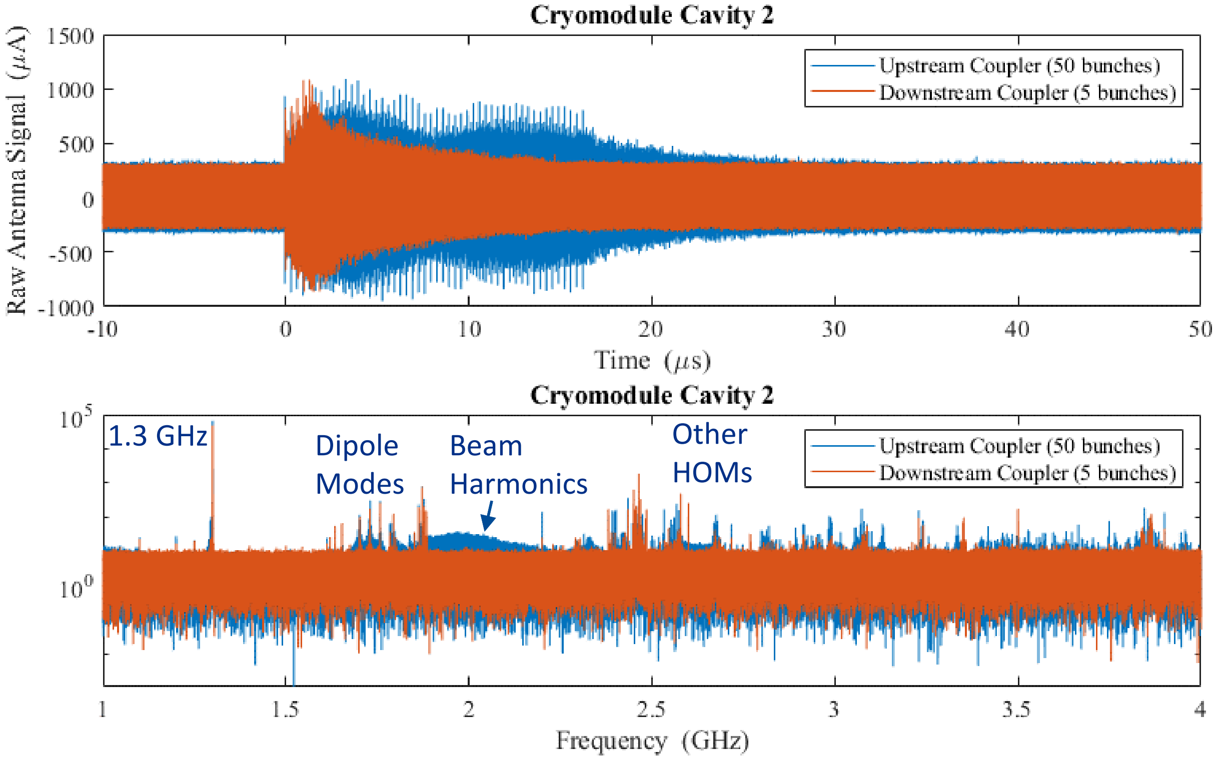
Below is a schematic of one of the two channels of the filter box showing the three bandpass filters and an optional 20 dB amplifier controlled by a switch on the front panel. Three of the outputs (one of each frequency band) pass through a Schottky diode to rectify the signal and send it to a digitizer. The other three outputs can be run to the oscilloscope. The initial DC block is to prevent any charge buildup from getting to the 1.3 GHz notch filter. The red dB numbers indicate the relative amplitudes of the three channels after the combined bidirectional coupler and power splitter.



# HOM Data

Here is a time plot and spectrum of the upstream and downstream couplers of cavity 2 in CM2. These are the raw coupler signals without the filter box. One can see that the cavity fundamental line at 1.3 GHz is about 100 times larger than the HOM lines. One can also see the beam harmonics in the spectra since the upstream signal was captured with 50 bunches in the pulse.



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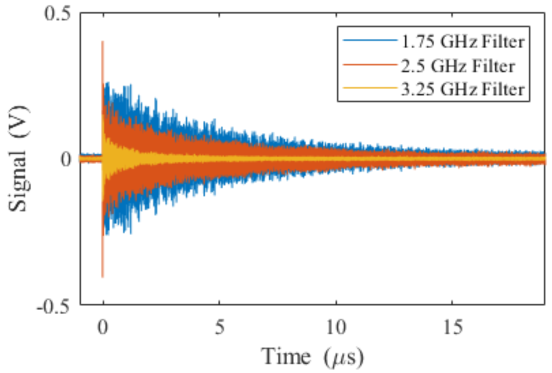
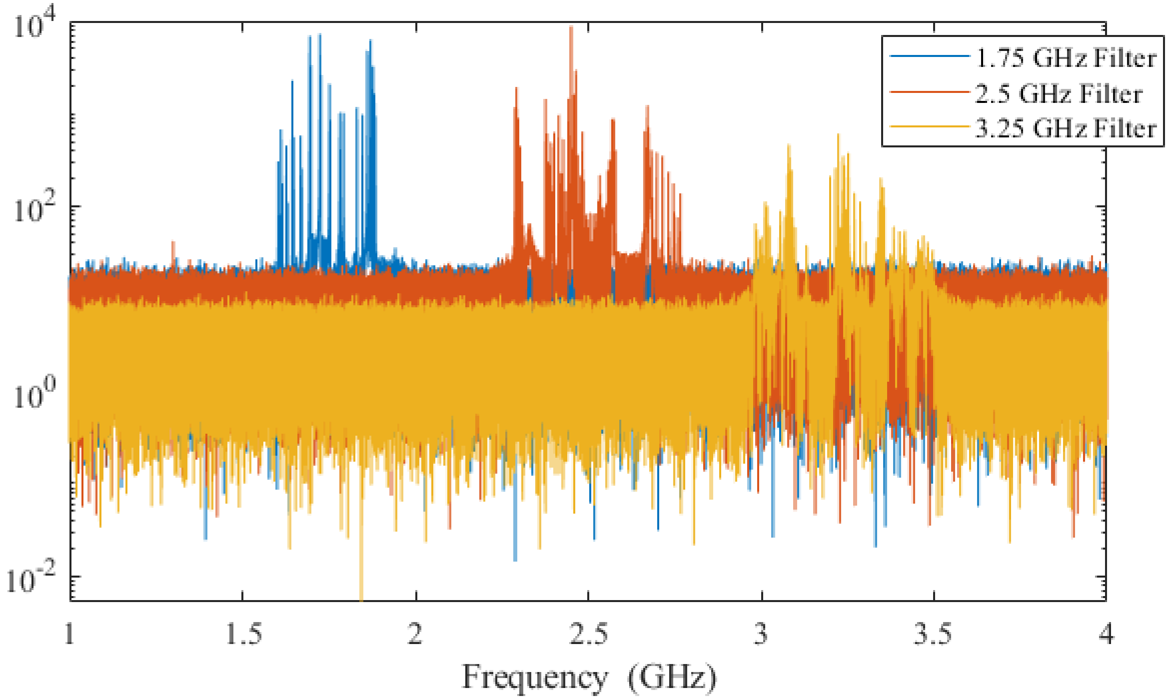
# HOM Filter Box Outputs

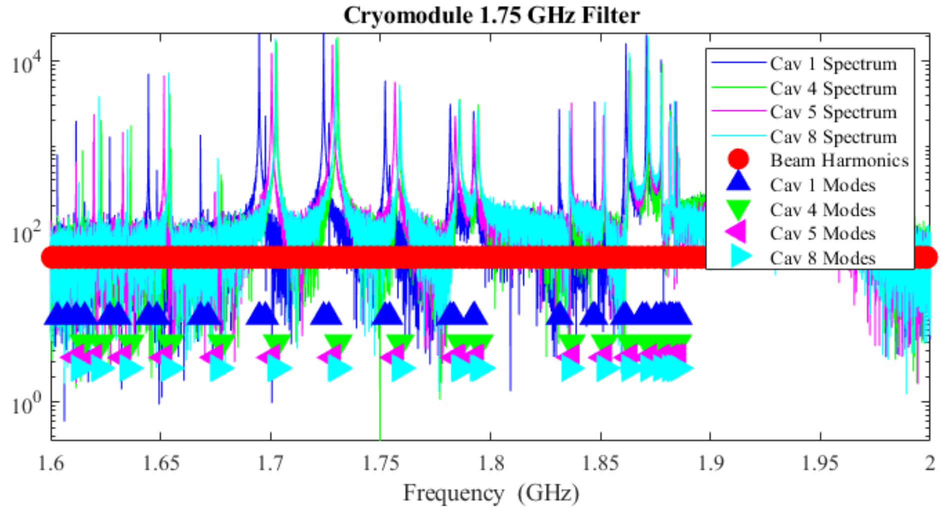
Here are the overlayed waveforms (below) and spectra (right) of all three filtered outputs for a single bunch in CC1. One can see the slightly smaller 3.25 GHz signal due to the bidirectional coupler. The measurements in this paper focus on the 1.75 GHz region which is the blue and contains the first 18 dipole HOM modes.

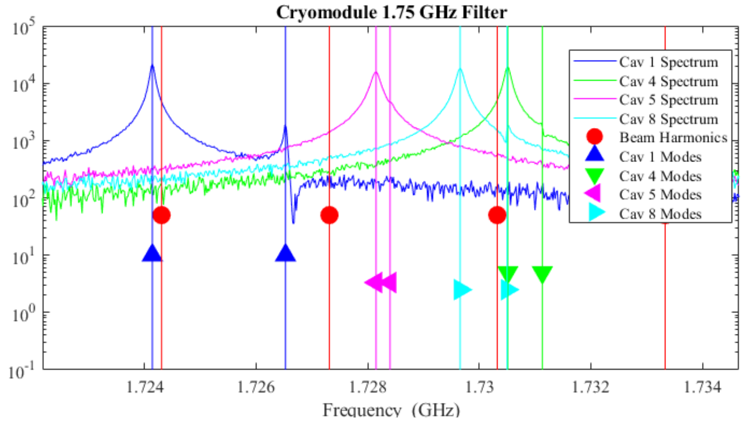


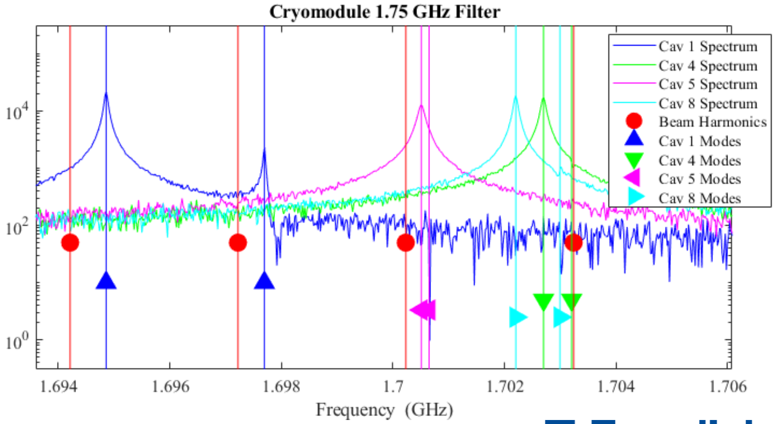



# Spectral Mode Data

Below are spectra for the downstream coupler of 4 of the 8 cavities in CM2 in the 1.6 – 1.9 GHz dipole mode region. One can see the variation in the mode frequencies. Also shown are the measured mode values using a network analyzer between the two couplers of the cavity, and the beam harmonics. Right are two specific modes at ~1.7 GHz and ~1.73 GHz where the agreement with the network analyzer and proximity to beam harmonics can be more easily seen.

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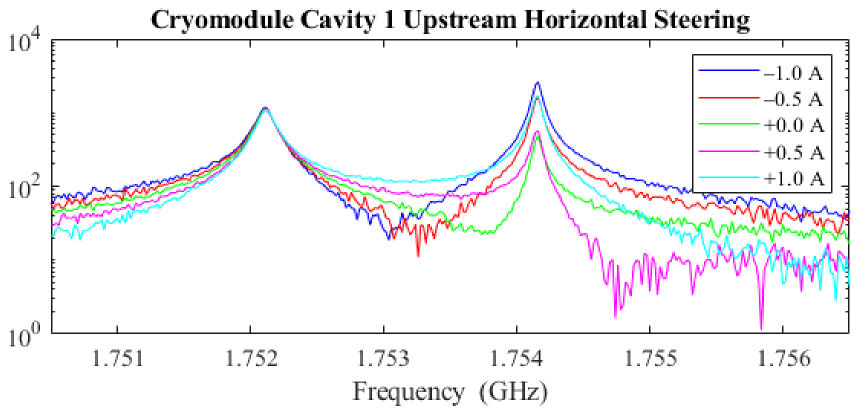
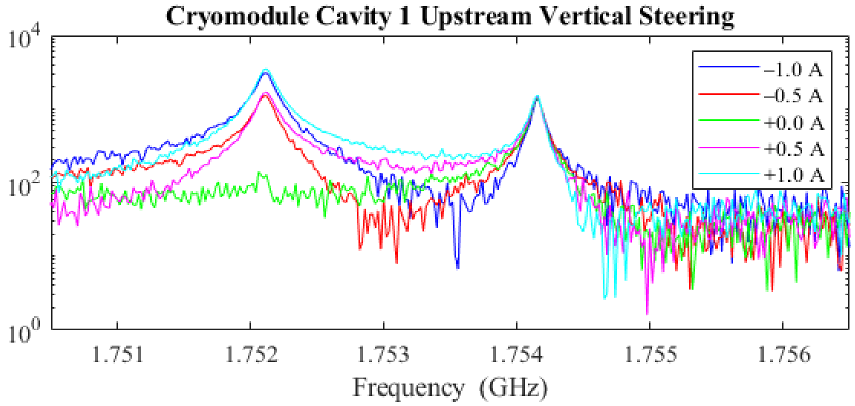
# Mode Polarization Spectral Data

As part of the study of the effect of HOMs on the beam [10,11], the beam was steered by corrector magnets upstream of the cavities.  Here are the HOM spectra showing the two polarizations for the ~1.75 GHz mode of cavity 1 of CM2 for various corrector magnet currents.  We can see that for this mode, the polarizations seem to coincide with horizontal and vertical as shown by the fact that only one polarization changes for each steering direction.

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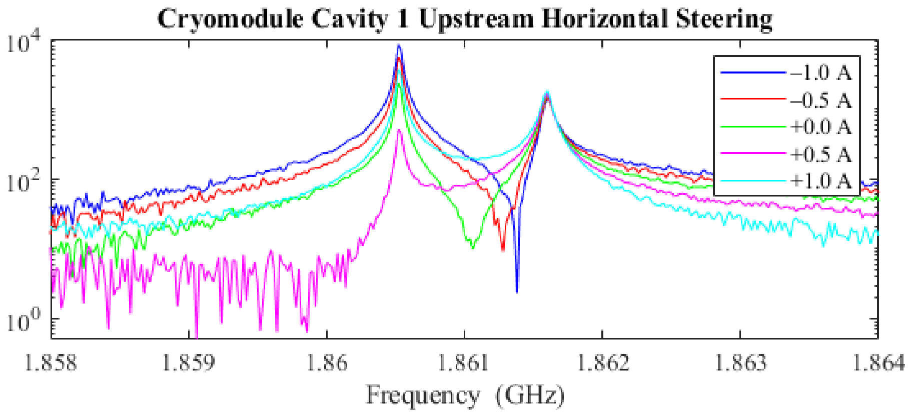
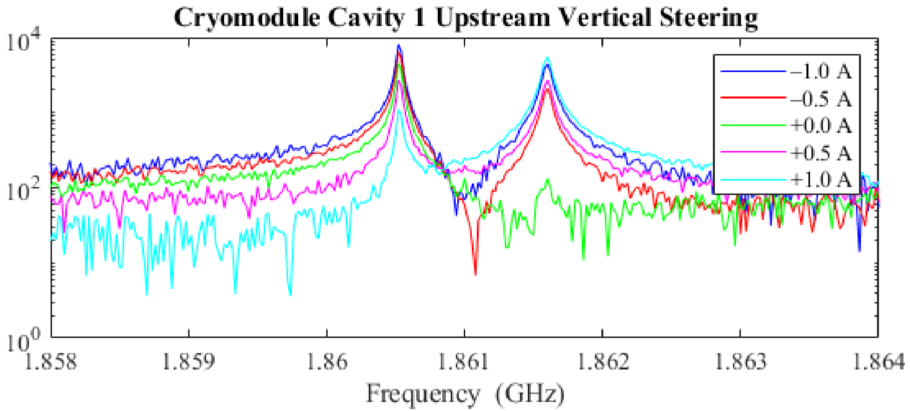
# Mode Polarization Spectral Data

Here is another pair of polarizations for the mode at ~1.86 GHz. For this mode, the horizontal steering changed one polarization, while the vertical steering changed both polarizations.



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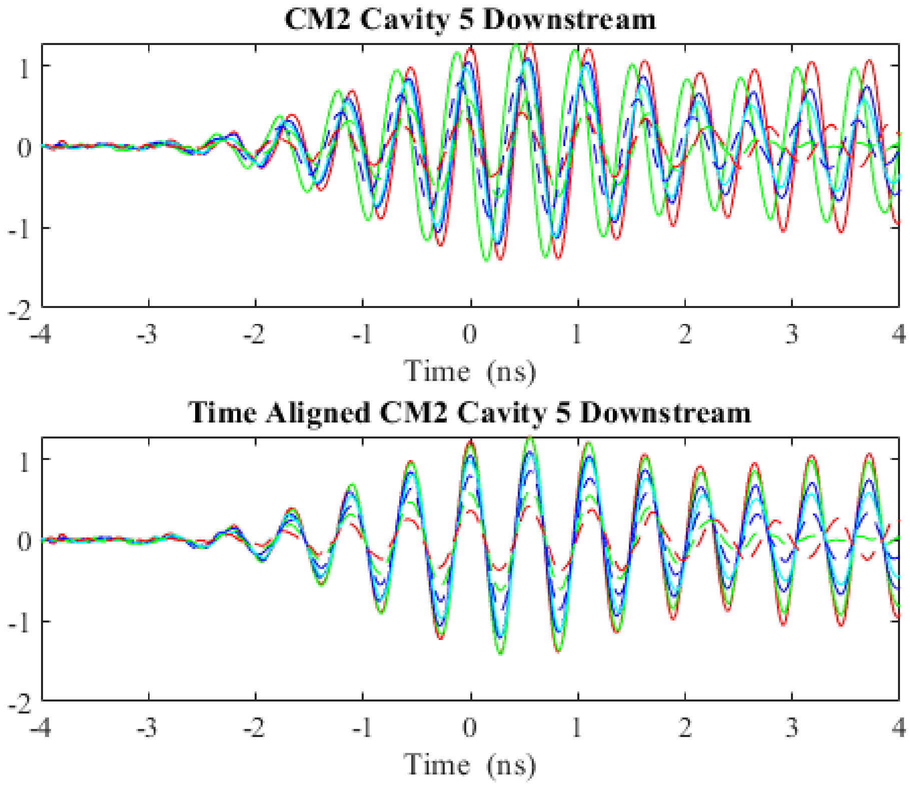
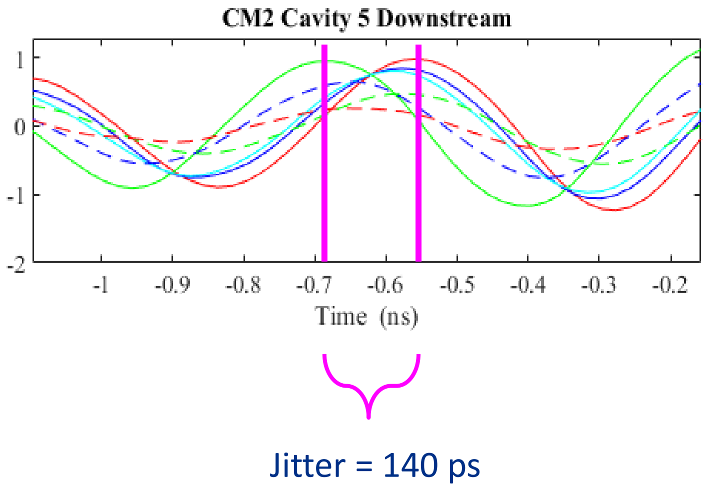
# Phase Alignment

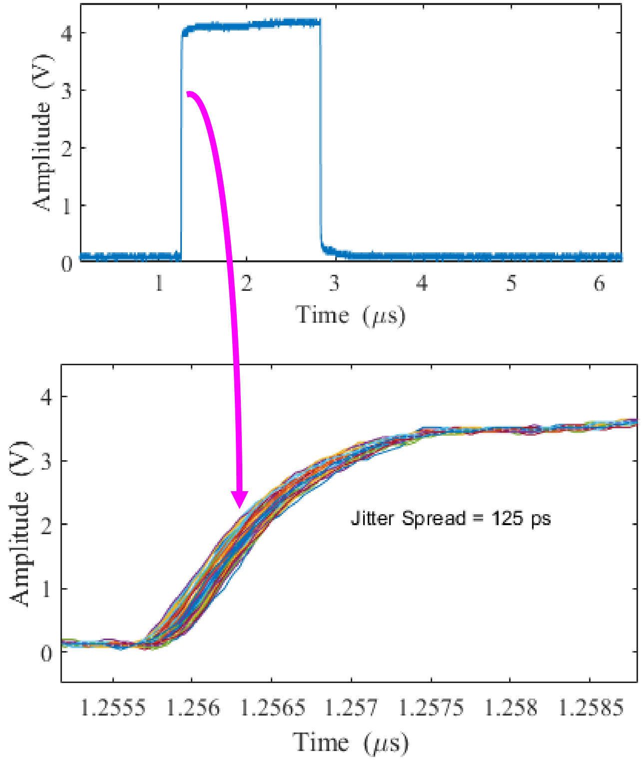
While the magnitude of a HOM spectrum can indicate whether or not you are at the electromagnetic center of a particular HOM, it doesn't tell you which direction you are displaced. For that you need the phase of the mode. The oscilloscope is triggered by a TTL signal timed with the first bunch. The top plot here, shows the start of the HOM signals which should be dominated by the arrival time of the bunch at the HOM pickup. One can see variation in the arrival time which needs to be corrected to get the correct phase of the HOMs. The bottom plot shows the signals after adjusting for the jitter using the peak located at $t = 0$ ns.



# Trigger Jitter

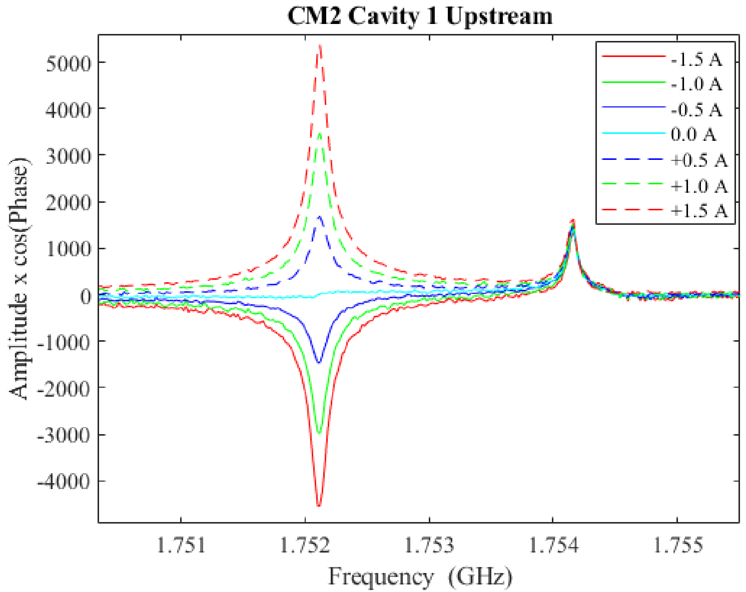
The bottom plot is an enlarged section of one peak in the top plot of the previous slide. The range of peak locations is about 140 ps. The right plots show the first-bunch trigger signal collected in the oscilloscope by triggering on a different version of the signal. The maximum spread in that trigger signal is about 125 ps (after dividing by sqrt(2)), which is very close to the observed spread in the HOM signals. Thus we concluded that the spread was mostly a trigger jitter issue and could be removed as demonstrated in the previous slide.

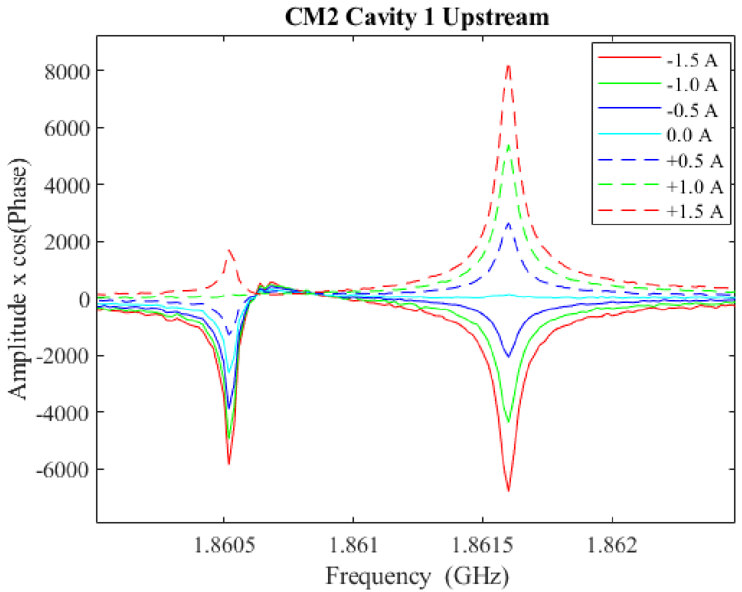


# ‘Signed’ Spectral Data

Below are plots of the spectra of cavity 1 of CM2 for two modes and for various vertical corrector currents . The spectra are multiplied by the cosine of the phase angle relative to the + 1.5 A current case. The phases are obtained after removing the trigger jitter. One sees the expected behavior, where trajectories on opposite sides of the center produce HOMs that are 180 degrees out of phase. For the mode at ~1.75 GHz (left plot), as we saw previously, only one of the polarizations is affected by the vertical trajectory offsets, whereas for the mode at ~1.86 GHz, the polarization angles do not coincide with horizontal and vertical.



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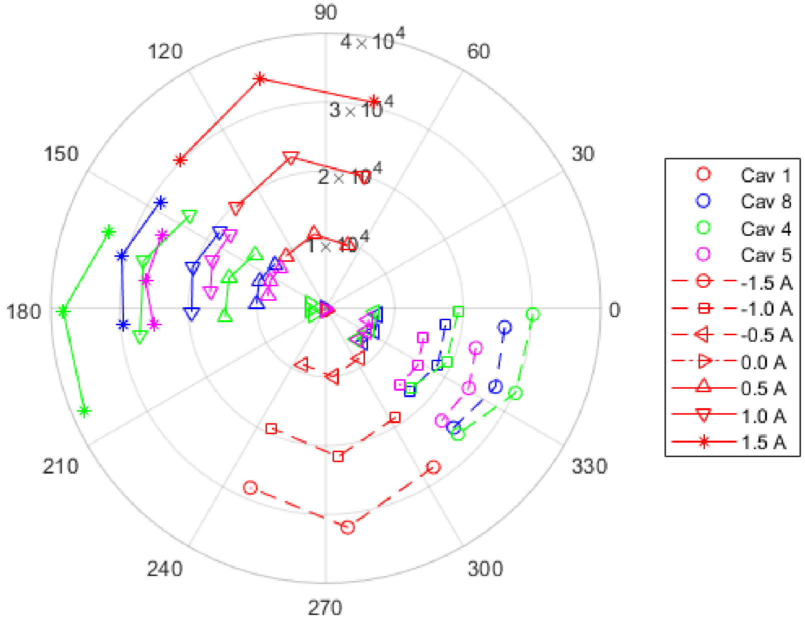
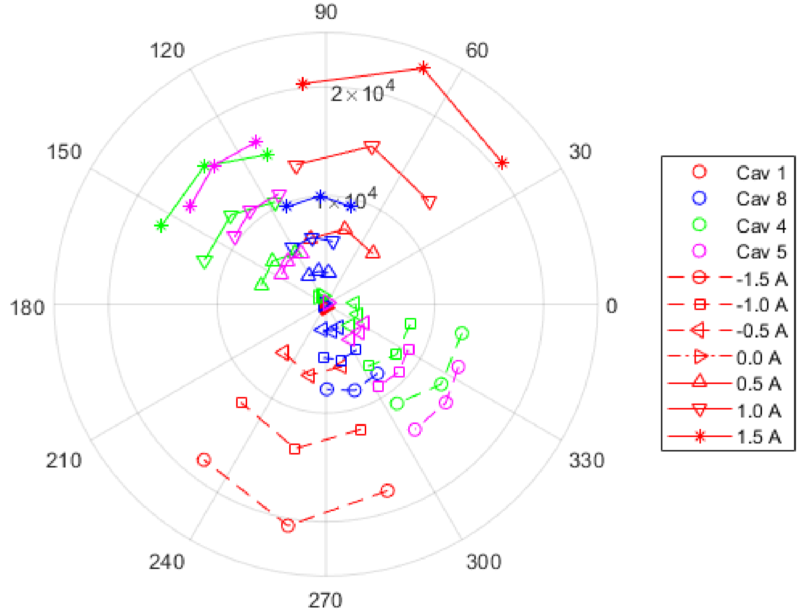
# Magnitude and Phase Spectral Data

Here we plot the full magnitude and phase of the peak and adjacent spectral values of the 1.73 GHz mode for cavities 1,4,5, and 8 of CM2, for various vertical corrector currents.  There is an interesting feature here and in other modes. The phase of cavity 1 is noticeably different from the other cavities.  It is not clear what causes this.

**Downstream 1.73 GHz HOM**




**Upstream 1.73 GHz HOM**



# Summary

Using a high bandwidth oscilloscope, we have recorded the dipole HOM signals from TESLA-type 9-cell superconducting rf cavities in an 8-cavity cryomodule and reconstructed the phase and magnitude of certain modes. The reconstruction allows one to ascertain the relative position of the beam with respect to the mode axis. We have used dipole correctors upstream of the cavities to steer the beam and produce a beam offset in the cavity to produce HOMs of varying amplitudes. We have produced changes in particular HOM polarizations dependent on the direction of beam steering. We also find a difference in the phase values in the first cavity of the cryomodule that we don't have an explanation for.

## References

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# Summary


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