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Long-Range and Short-Range Wakefield Effects in TESLA-type Cavities (LRW/SRW)

Alex Lumpkin, Randy Thurman-Keup, Dean Edstrom, Jinhao Ruan, Peter Prieto, (Fermi National Accelerator Lab)
Bryce Jacobson, John Sikora, Jorge Diaz-Cruz, Feng Zhou, Auralee Edelen, (SLAC National Accelerator Lab)

LRW/SRW Collaboration

FAST/IOTA Collaboration Mtg

27 October 2021

Long-range wakefields (LRWs)

Short-range wakefields (SRWs)

Motivation: Assessment of HOM Effects on Beam Dynamics

- Investigate higher-order-modes (HOMs) in a TESLA-type cryomodule (CM) and their effects on beam dynamics using bunch-by-bunch rf BPM data taken downstream of CM2.
- It is known that off-axis steering in accelerator cavities can lead to dipolar HOMs that can cause submacropulse centroid slewing and oscillations. (A.H. Lumpkin *et al*., PRAB 2018).
- Experiments were enabled by using 8-channels of the SLAC prototype HOM detectors (Sikora) for the LCLS-II Injector and the hybrid FNAL detector, all with wide-band amplifiers.
- Recorded HOMs as found in 8 cavities, using the upstream (US) and downstream (DS) couplers in sequence.
- Acquired complementary high-resolution HOM spectral data.
- Beam dynamics that lead to emittance dilution were observed and mitigated. (Relevant to LCLS-II injector and TESSA FEL)

LRW/SRW 8-hr Studies Shifts Executed in Run 3

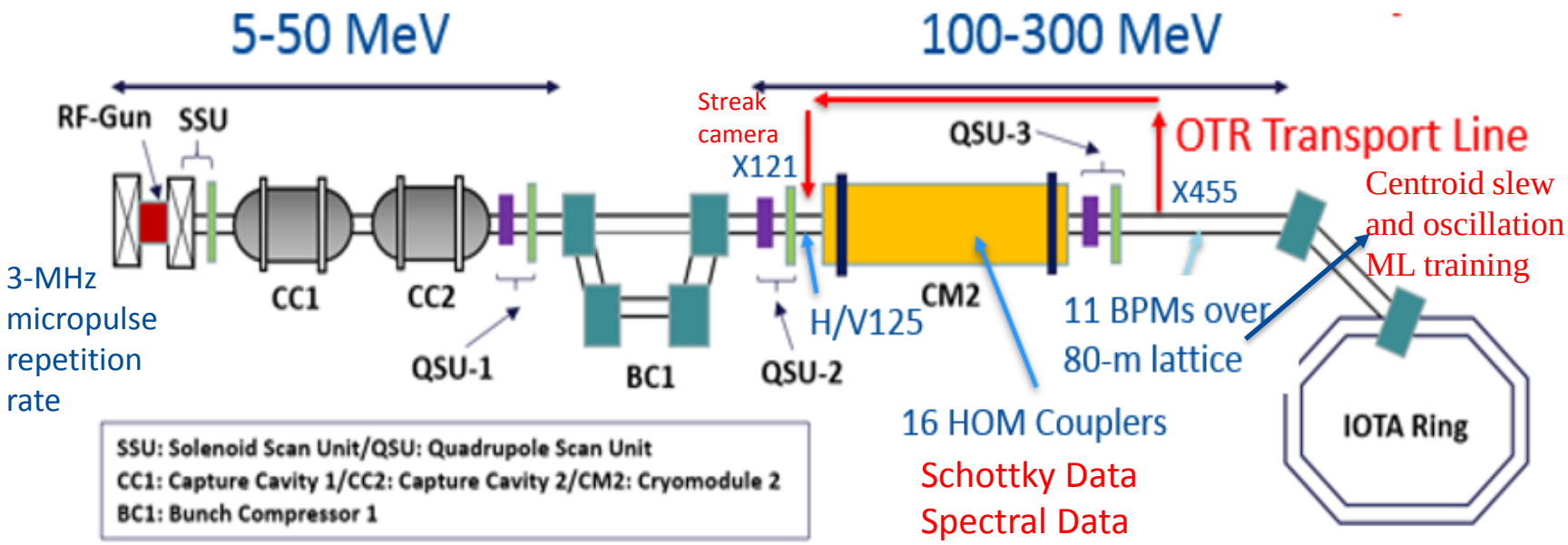
- Commissioning of the two SLAC Prototype HOM chassis on CC1 and CC2. Direct comparison to FNAL chassis data done. (2 shifts in Nov. 2020).
- Application to the cryomodule for emittance-dilution reduction. HOMs (Schottky integrated data and high-resolution spectral processing), rf BPMs, ML training data. (3 shifts: 1 each in Nov., Dec. 2020 and Feb. 2021). Needed 1 more for H125.
- Evaluation of the off-resonance CC2 effects and SRW test.

  (1 shift: Feb 2021)
- Data saved in \\beamssrv1\iota-fast.bd\Data\<runfolder>

  and a server at SLAC.
- Used Zoom in shifts, Chip in CR, Randy at oscilloscope and HOM chassis in Electronics Racks Gallery.

Techniques Will be Applied to FAST Cryomodule

- Possible to extend HOM studies techniques to higher charges and to the cryomodule using an 80-m lattice and 11 rf BPMs distributed in z downstream of it, 8 SLAC HOM det., 2 hybrid.
- Fermilab Accelerator Science and Technology (FAST) Facility.

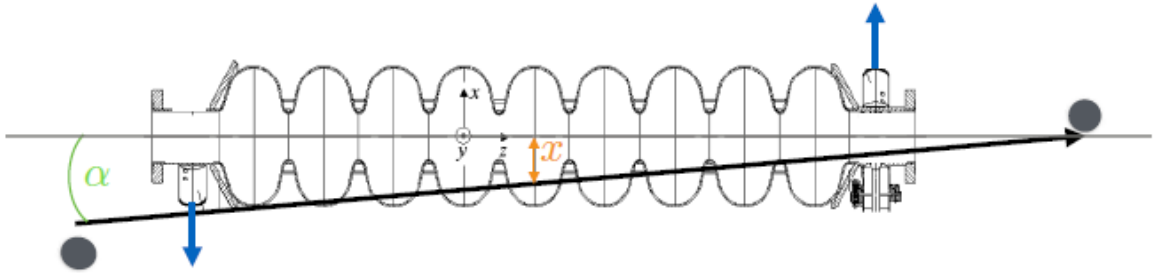


Revised YMS

EXPERIMENTAL SETUP

HIGHER ORDER MODES

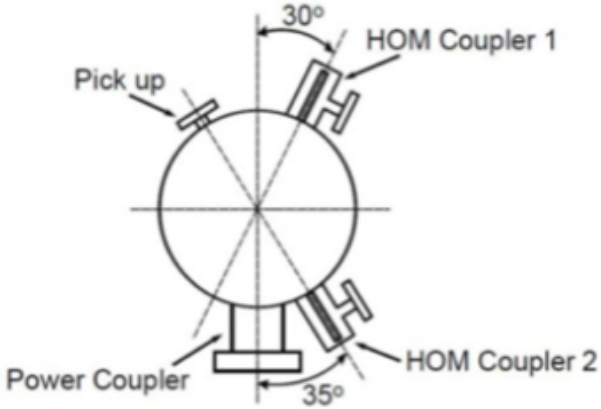
- TESLA CAVITY
  - 2 HOM couplers
- DIPOLE HOM
  - $V_x(t) \propto x \cdot e^{-\frac{t}{2\tau}} \sin(\omega t)$
  - $V_{x'}(t) \propto x' \cdot e^{-\frac{t}{2\tau}} \cos(\omega t)$



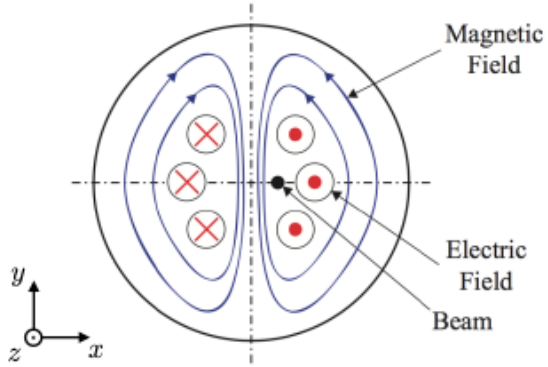
Expected HOMs in TESLA Cavities*

Mode #	Freq.(GHz)	R/Q (Ω/cm²)
MM-6	1.71	5.53
MM-7	1.73	7.78
MM-13	1.86	3.18
MM-14	1.87	4.48
MM-30	2.58	13.16

*R. Wanzenberg, DESY 2001-33



Dipole Mode



N.B. Modes excited in the cavities at frequencies Higher than the accelerating mode are HOMs.

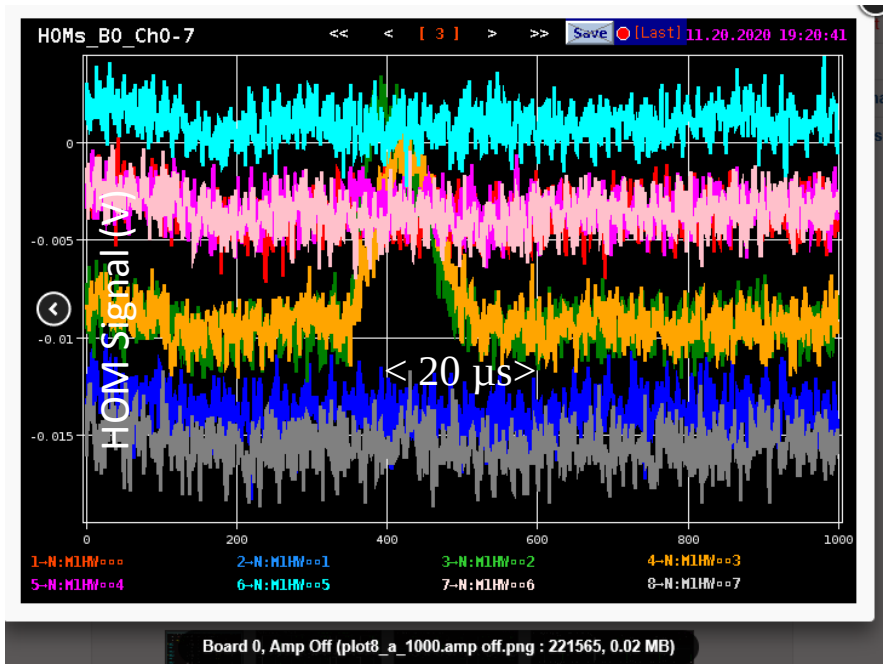
Amplitude of specific dipole mode, $A_d \sim q \times r \times (R/Q)$

T. Hellert 7/11/17 DESY Seminar

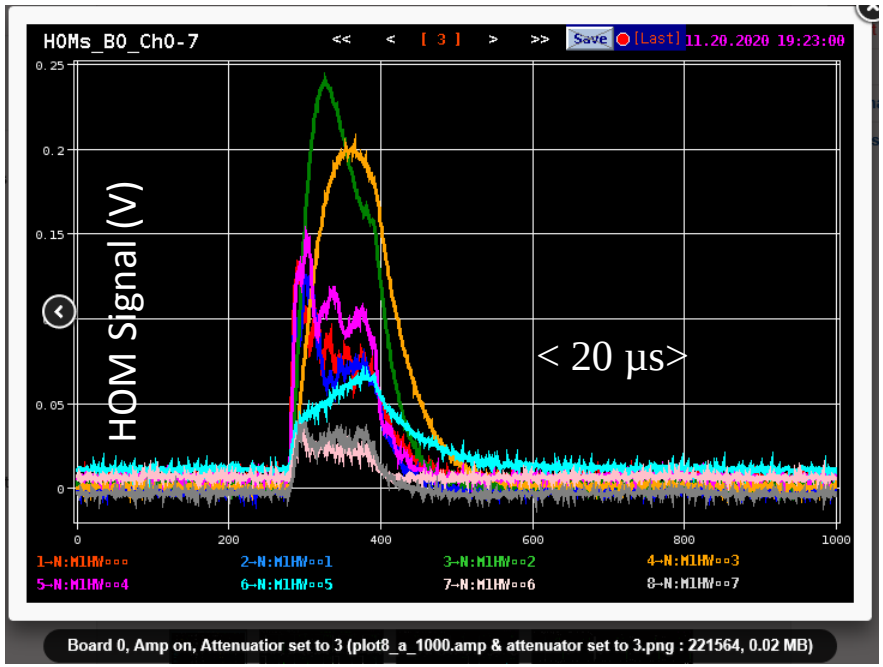
CM2 HOMs As Found with Beam to HE Abs. 19:25 11-20-20

- Encountered lower signals on HOMs at box. CM2 couplers or cables or well centered? Required 1 Ampl ON for all detectors.
- C3 and C4 upstream (US) HOMs highest.

No AMPL

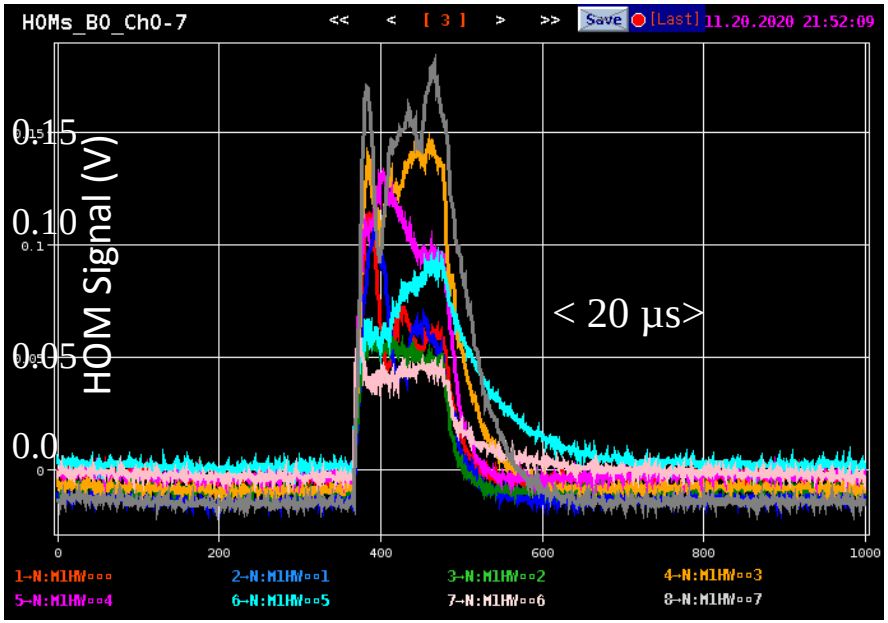


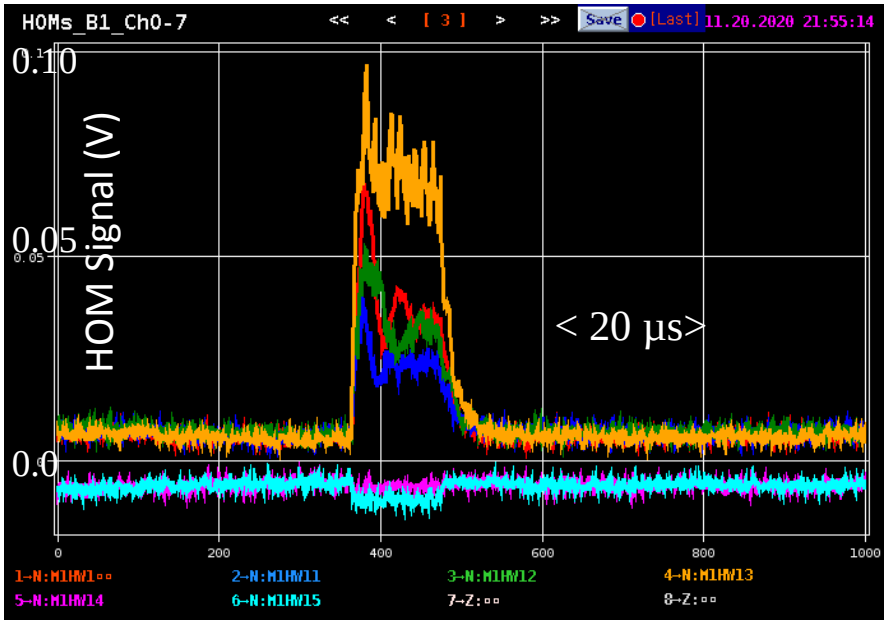
1 AMPL, with attenuation of 2



Reduced US HOMs by Adjusting H/V125; See 2.5 & 3.25 GHz

- Steered in $\theta_{x,y}$ to H/V125 =0.96, 4.3 A to reduce most US HOMs
- 125 pC/b, 50 b. Board 1 has C1-DS and C8-DS with Mode 30.
- Board 0, C1-8 US 21:51 Board 1, C1,8 DS



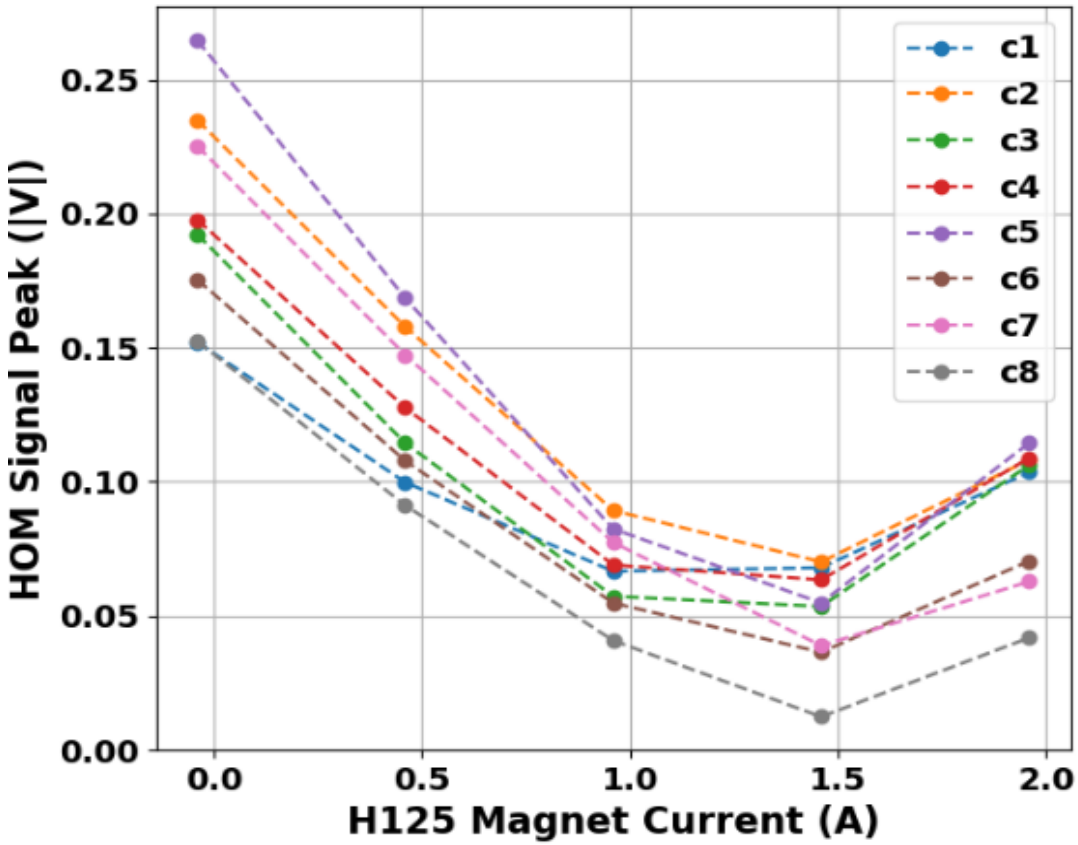


1 red	C1 US 1.75 GHz	5 purple	C5 US 1.75 GHz	1 red	C1 DS 1.75 GHz
2 blue	C2 US 1.75 GHz	6 lt blue	C6 US 1.75 GHz	2 blue	C8 DS 1.75 GHz
3 green	C3 US 1.75 GHz	7 pink	C7 US 1.75 GHz	3 green	C1 DS 2.50 GHz
4 yellow	C4 US 1.75 GHz	8 grey	C8 US 1.75 GHz	4 yellow	C8 DS 2.50 GHz

5 purple	C1 DS 3.25 GHz		
6 lt blue	C8 DS 3.25 GHz		
7 pink	---		
8 grey	---		

H125 scan Data for US HOMs Show Local Minimum 12-03-20

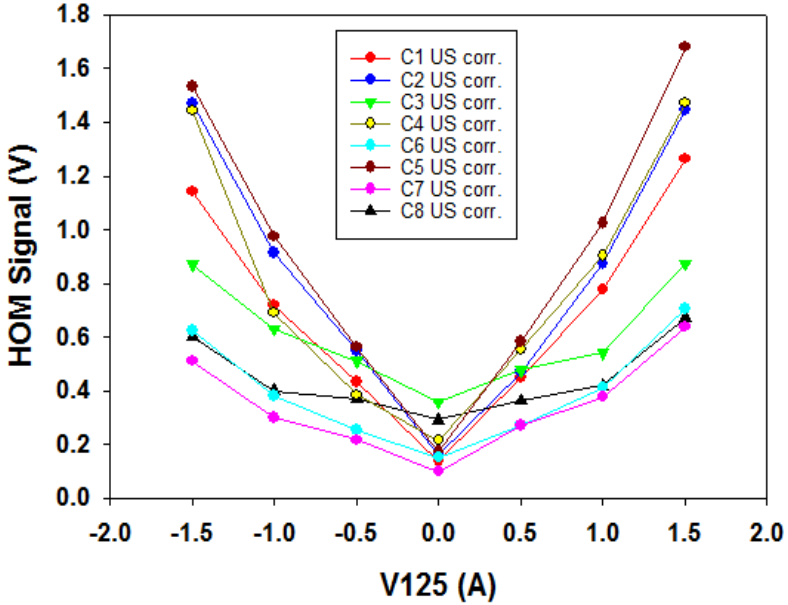
- Relative min. at +0.5 A from first reference on 11-20-20. Coordinates at B125 were different for two runs in post look.

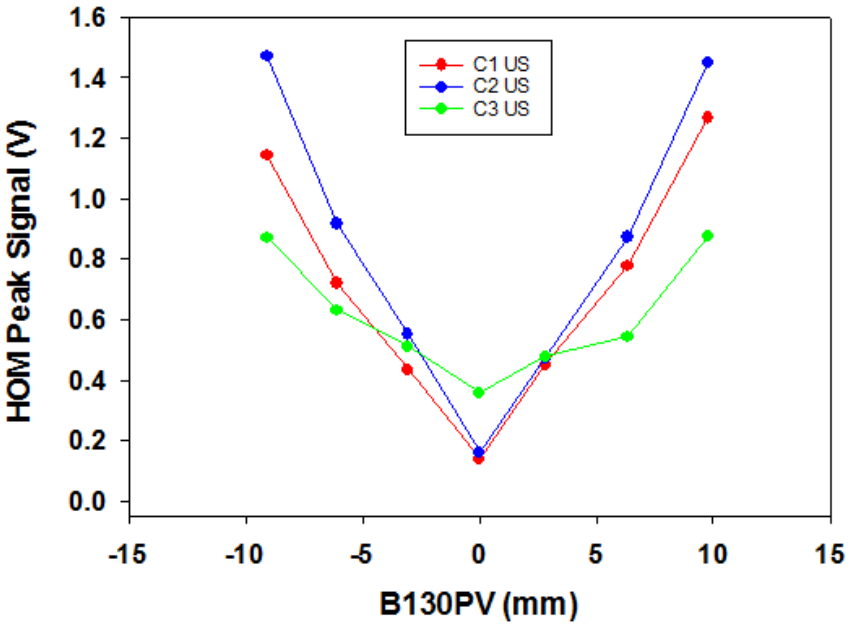


Jorge's Plot

V125 Scan Data Provide Beam Offset Monitor (BOM)

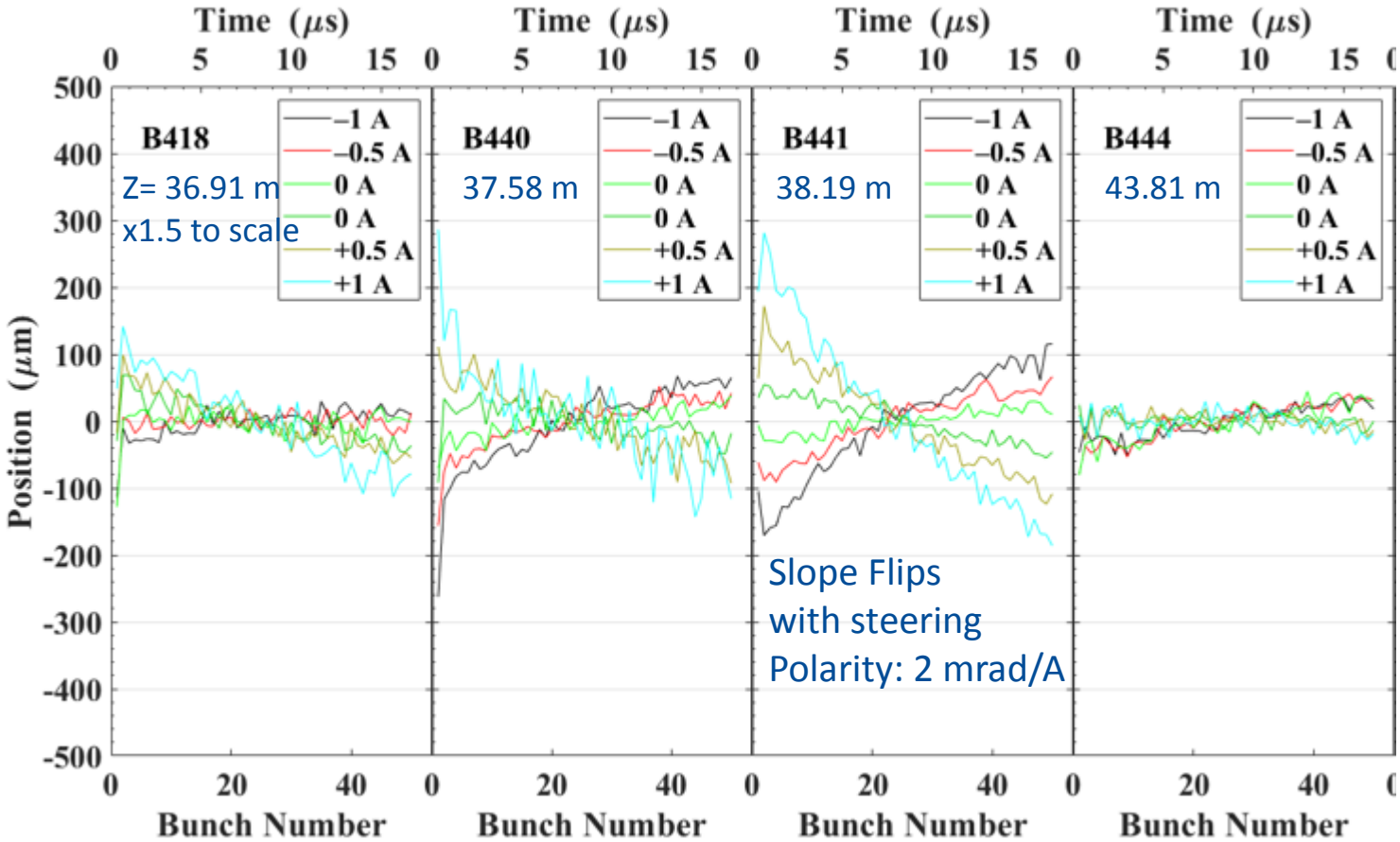
- Combination of the corrector scan, US HOM data, B130 rf BPM data at CM2 give BOM. 400 pC/b, 50 b. (Feb. 2021).
- C3 and C8 seem misaligned compared to others.
- H/V125 corrector values at reference indicate CM2 off axis.





BPM Vertical Array Data Downstream of CM2 Show Slew!

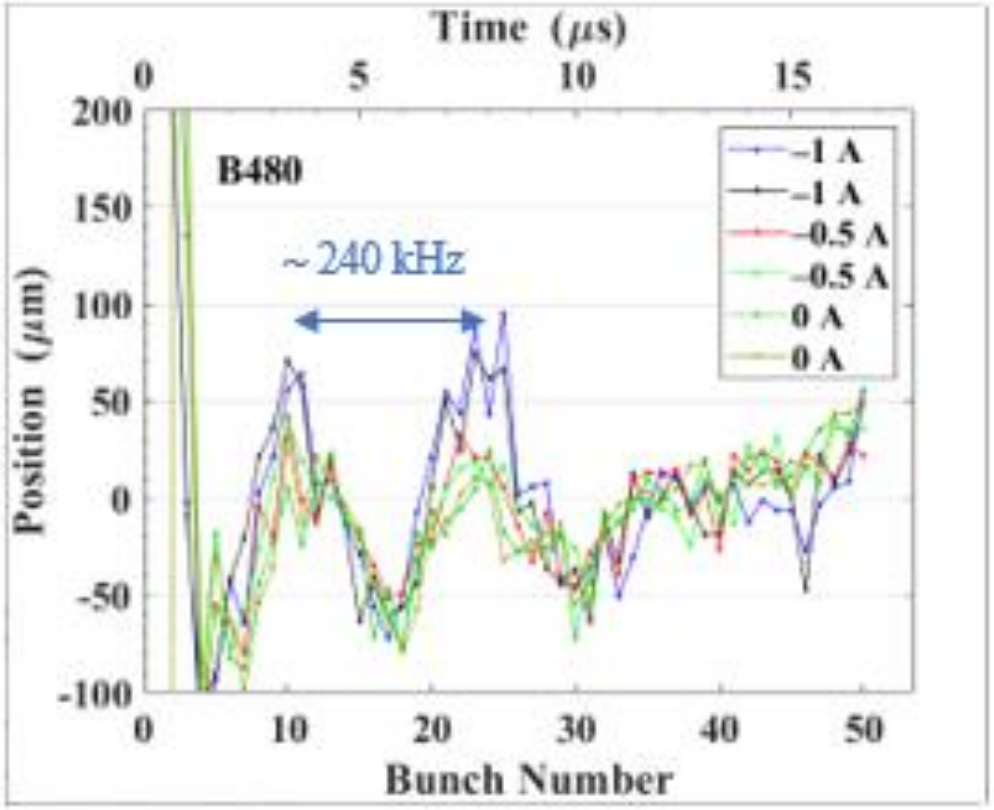
- Cold B418V data and others show offset dependence in scan. V125 corrector is 4 m before CM2. 11-20-20 +12-03-20



RTK Plot

BPM Array Data Downstream of CM2 Show Oscillation!

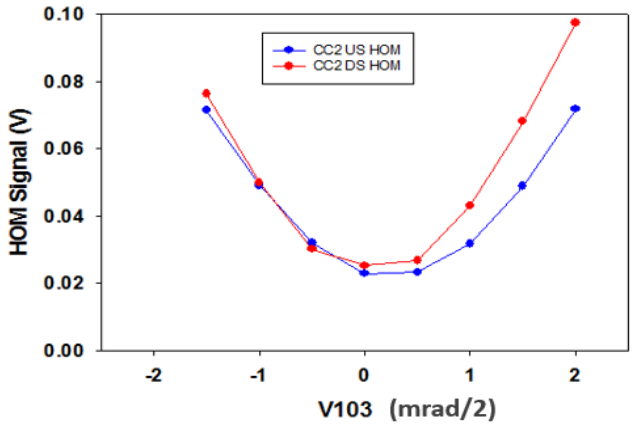
- B480V data show ~240-kHz Vertical Oscillation with offset dependence. V125 corrector is 4 m before CM2. 11-20-20
- We subtracted a linear slew for each data set. 50b used.

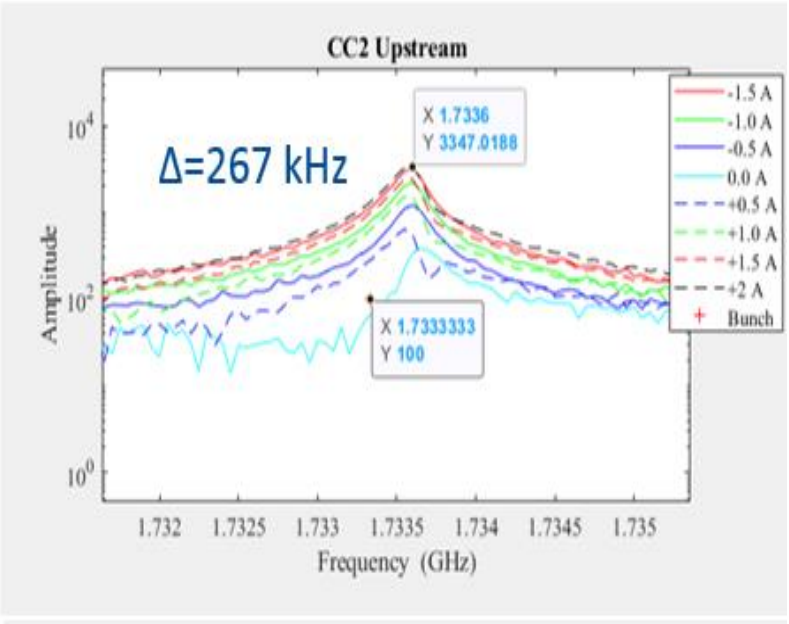


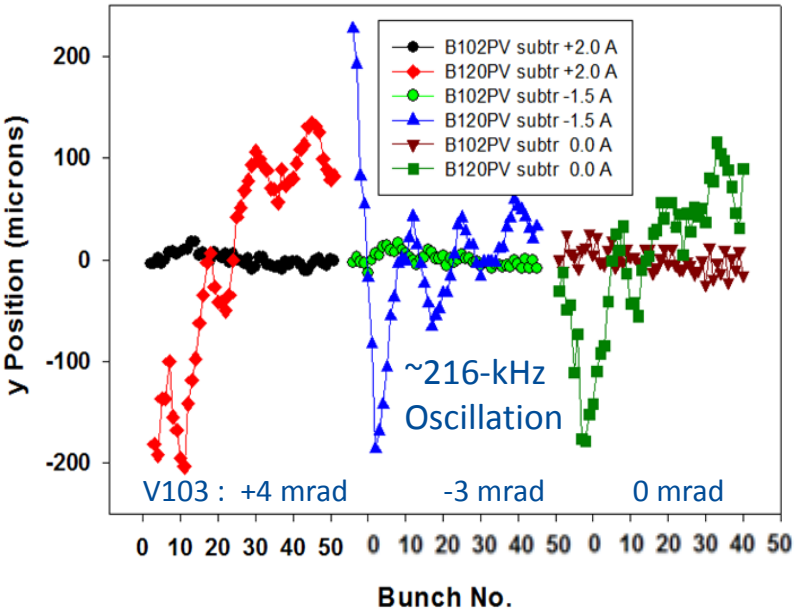
RTK Plot

Off-resonance CC2 Cavity Linked to Beam Dynamics Effects

- CC2 ended up 15-kHz off-resonance due to the stuck cavity tuner. Consequently, CC2 was not rf powered for Run 3.
- However, centroid oscillation still generated at minimum offsets. ~216 kHz DS of CC2 at B120PV.
- Near-resonances at dipolar Modes 7 and 14 were involved with difference frequencies at 267 and 181 kHz, respectively.







Summary

- The HOM detectors and rf BPMs were used to evaluate off-axis steering effects in a cryomodule at FAST for the first time.
- US HOM signals seemed reduced compared to those of CC1 and CC2, even when minimized in the latter. Used Amplifiers.
- Significant submacropulse centroid slewing and oscillations were observed downstream of CM2. (25 MeV in, 100 MeV out)
- These emittance dilution effects were mitigated by minimizing the HOMs and the observed slewing. (LCLS-II injects <1 MeV)
- Spectral data are rich in C1 (AES) and C8 (RI) info. Cavity asymmetry effects from two vendors. (Randy's talk)
- These combined effects were evaluated for machine learning (ML) training and to inform LCLS-II startup. (Jorge, Bryce)
- Results Documented in 6 IPAC21 papers, 1 Subm. to PRAB.

Run 3 Results Summarized in 6 IPAC21 papers

- ISC-required Documentation of Run 3 studies were provided in 6 IPAC21 papers in May 2021, 4 related to CM2 investigations.
- J. Sikora *et al*., Commissioning of SLAC Prototype HOM Chassis at FAST MOPAB-323
- A. Lumpkin *et al.,* Investigations of LRWs in CM2 TUPAB-274
- R. Thurman-Keup, *et al. HOM Spectral Analyses* MOPAB-232
- J. Diaz-Cruz *et al.,* ML Training on CM2 Data MOPAB-289
- A. Lumpkin *et al.,* SRW effects in TESLA cavity TUPAB-273
- A. Lumpkin *et al.,* CC2 off-resonance Effects TUPAB-272

- Augmented paper submitted to Phys. Rev. A-B, 10-16-21.
- Future SRW paper needs more simulations and CM2 data.

HOM Spectral Data Are Rich in Information on Modes

- Within the three passbands of the FNAL box, we cover the first two dipolar passbands (1.75 GHz), the third dipolar passband (2.58 GHz), and the quadrupole band (3.25 GHz). (Centers of the pass band)
- Cavity 1 and 8 are examples of the two vendors AES and RI whose cavities have different axial symmetries. This leads to differences in the frequency splits of the polarization modes. (A. Lunin and O. Napoly)
- We also can excite each polarization with our horizontal (L) or vertical (R) steering and map steering effects of H/V125 for the individual modes. 12-03-20