Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

HIGHER-ORDER-MODE EFFECTS IN TESLA-TYPE SCRF CAVITIES ON ELECTRON BEAM QUALITY

A.H. Lumpkin, R. Thurman-Keup, D. Edstrom Jr., J. Ruan,
P. Prieto, N. Eddy, Fermi National Accelerator Laboratory,
O. Napoly (TD/CEA-Saclay),
B. E. Carlsten, K. Bishofberger , Los Alamos National Laboratory.

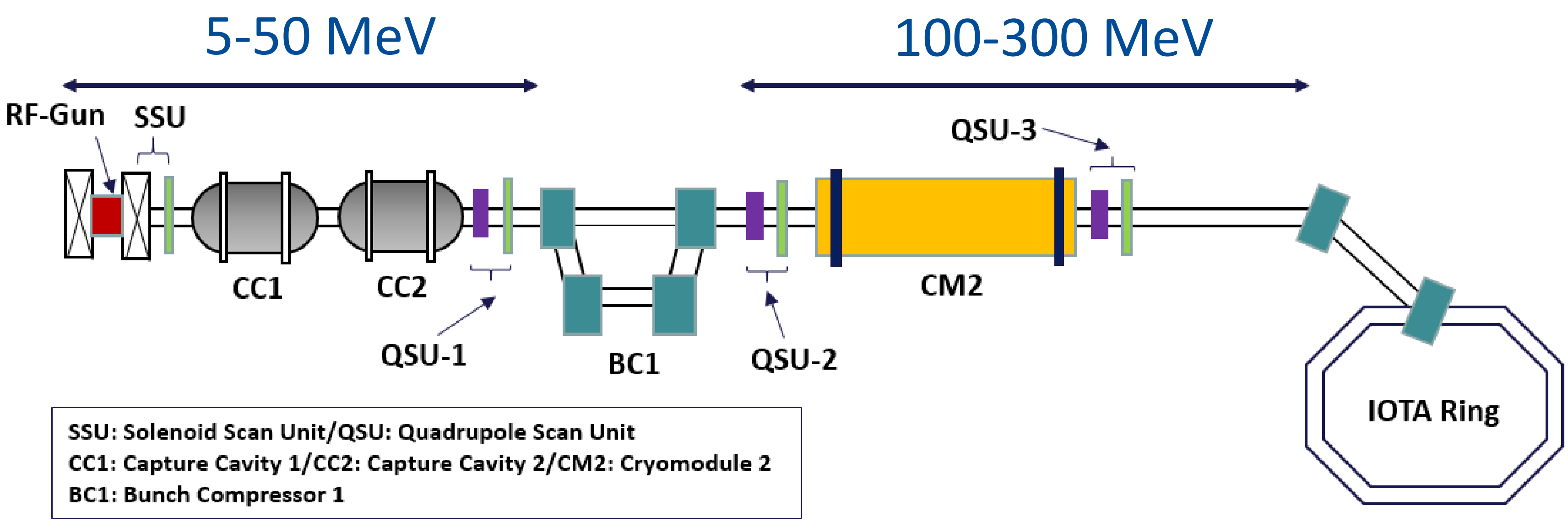
IPAC18 Conference
01 May 2018

Introduction

- Generation and preservation of bright electron beams are two of the challenges in the accelerator community given the inherent possibility of excitations of dipolar higher-order modes (HOMs) due to beam offsets in the accelerating cavities.
- Our primary goal is to investigate beam steering offsets and possible emittance dilution by monitoring and minimizing HOMs in L-band, 9-cell TESLA-type superconducting accelerating cavities.
- Such cavities form the drive accelerator for the FLASH FEL, the European XFEL, the under construction LCLS-II, the proposed MaRIE XFEL at Los Alamos, and the International Linear Collider under consideration in Japan.
- We report sub-macropulse effects on beam transverse position centroids correlated with HOMs at the Fermilab Accelerator Science and Technology (FAST) Facility.
- We used the 3-MHz micropulse repetition rate, a unique two separated single-cavity configuration, and targeted diagnostics for these tests.

FAST/IOTA Facility

- The Fermilab Accelerator Science and Technology (FAST) Facility is based on a photocathode rf gun and TESLA-type superconducting rf accelerators.
- 300-MeV milestone with full 31.5 MV/m average gradients in cryomodule (CM) attained in November 2017. (THPMF024)



Integrable Optics Test Accelerator (IOTA)

Table 1. FAST Electron Beam Parameters for HOM Studies

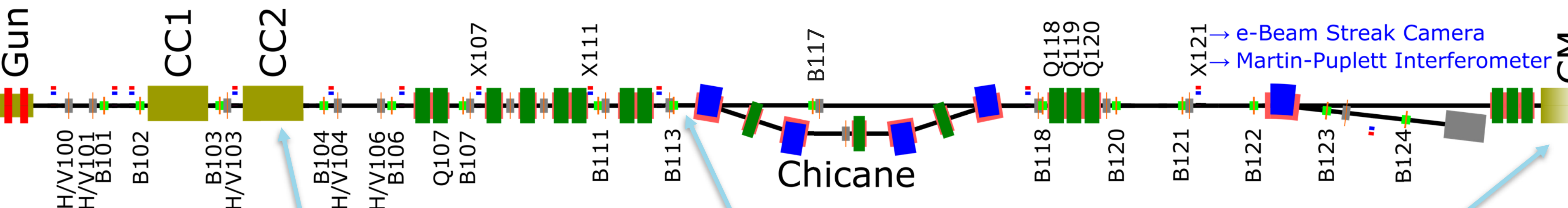
.

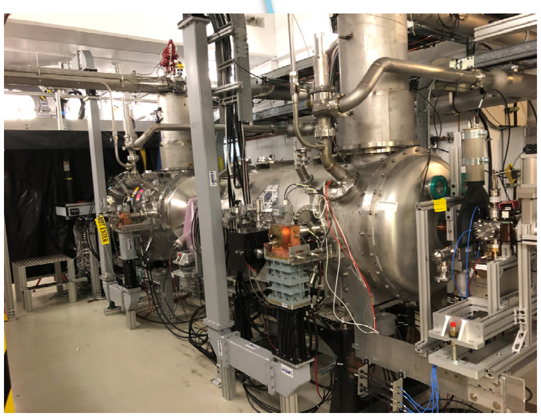
Beam Parameter	Units	Value		
Micropulse Charge (Q)	pC	100-1000		
Micropulse rep. rate	MHz	3		
Beam sizes, σ	μm	100-1200		
Emittance, σ norm	mm mrad	1-5		
Bunch length,σ Compressed	ps ps	4-8 1-3		
Total Energy	MeV	33		
PC gun grad.	MV/m	40-45		
CC1 gradient	MV/m	14.2		
CC2 gradient.	MV/m	14.2		

1-500 bunches used, 3000 max.

FAST 50-MeV Beamline Schematic with Diagnostics

- FAST beamline up to the cryomodule (CM). Photocathode rf Gun, two capture cavities (CC1 and CC2), BPMs (B1xx), correctors (H/V1xx), and imaging station beamline crosses (X1yy) are indicated. Framing camera views X121.

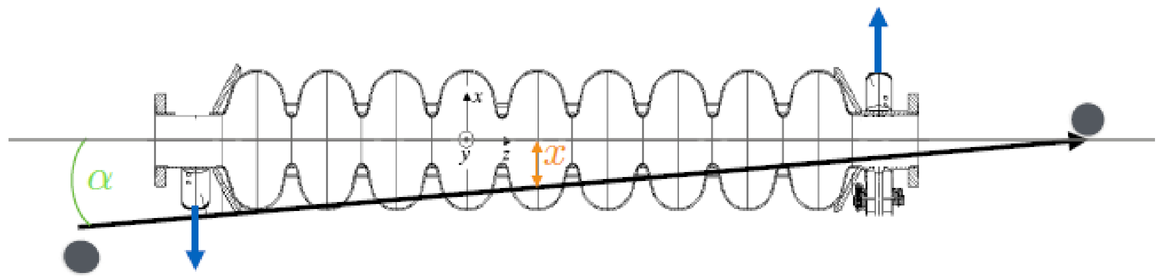




EXPERIMENTAL SETUP

> TESLA CAVITY
- 2 HOM couplers

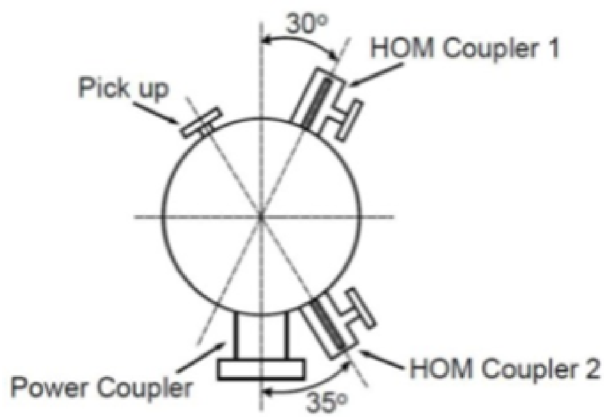
> DIPOLE HOM
- $V_x(t) \propto x \cdot e^{-\frac{t}{2\tau}} \sin(\omega t)$
- $V_{x'}(t) \propto x' \cdot e^{-\frac{t}{2\tau}} \cos(\omega t)$



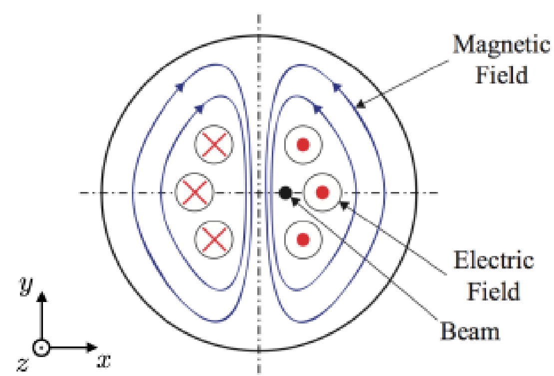
Expected HOMs in TESLA Cavities*

Mode #	Freq.(GHz)	R/Q (Ω/cm^2)
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

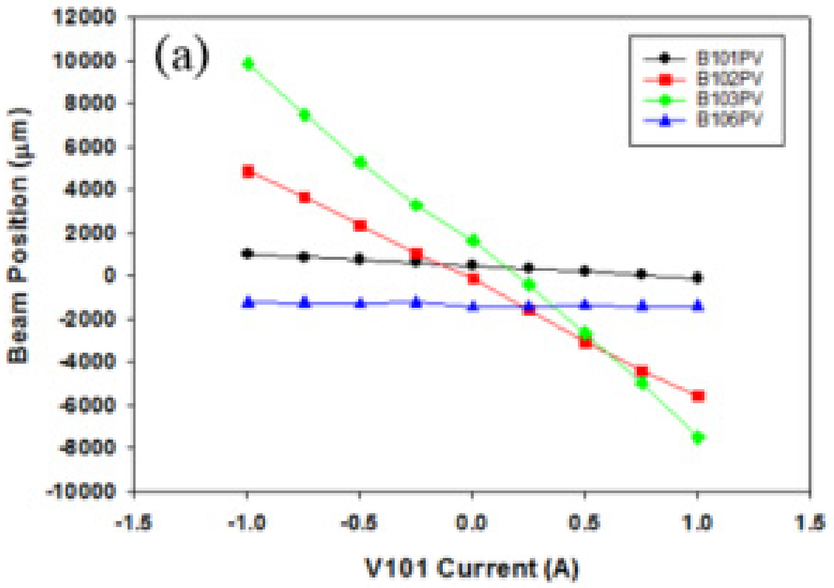


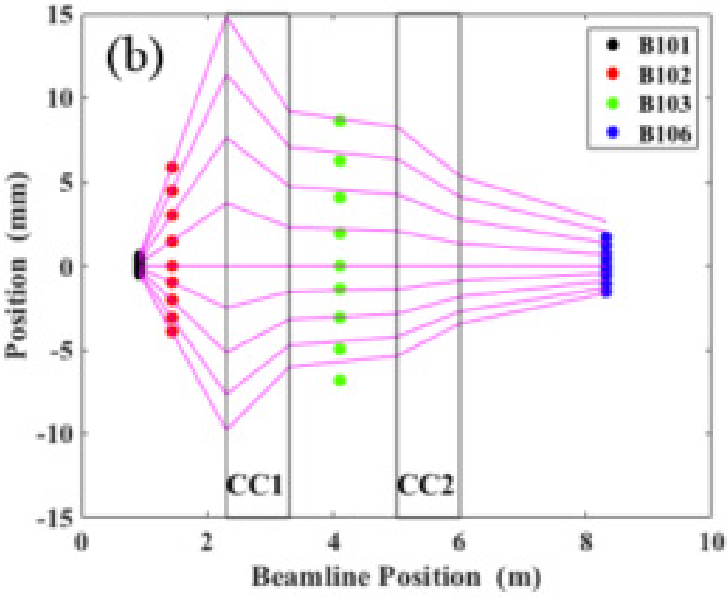
THORSTEN HELLERT | FEL SEMINAR | JULY 11, 2017 | PAGE 12

T. Hellert 7/11/17 DESY Seminar

V101 Current Scan Affects Beam Trajectories

- Tracking of beam trajectories around CC1 and CC2.
- BPM data (a) and calculated trajectories using cavity transfer matrix (b) (ref. E. Chambers (1965))

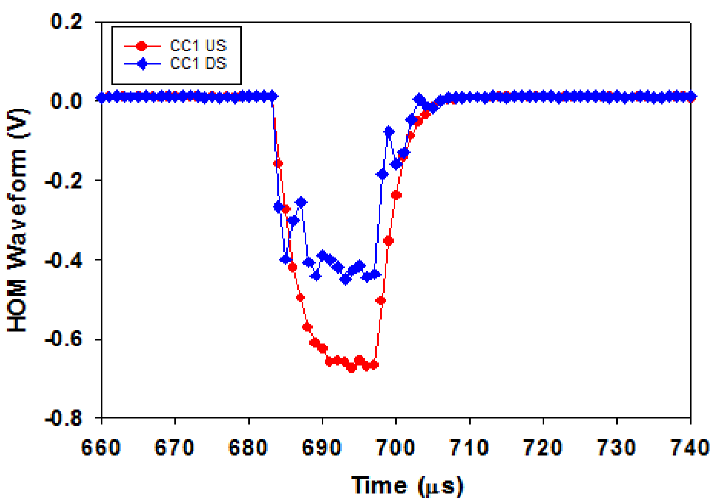


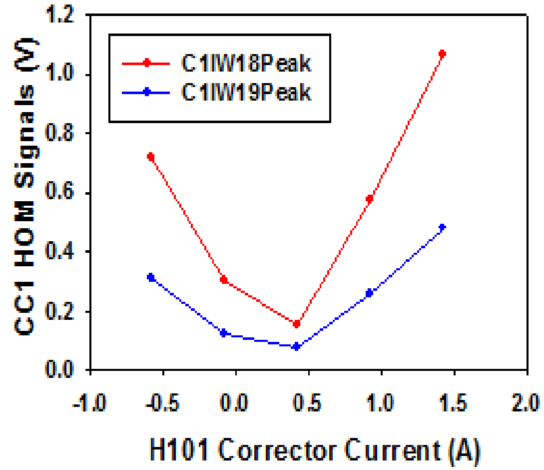


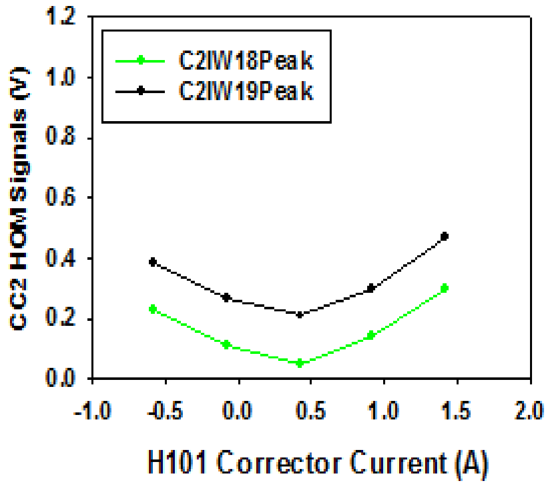
H101 scan: HOM Signals Observed from CC1 and CC2

- Example of HOM waveform signals (L) and peak signals at 500 pC/b, 50 b during H101 scan (R).

FAST HOM Detectors:
- 1.3-GHz notch Filter
- amplifier
- 1.6-1.9 GHz passband
- 2.2-GHz lowpass filter
- Zero-bias Schottky Detector

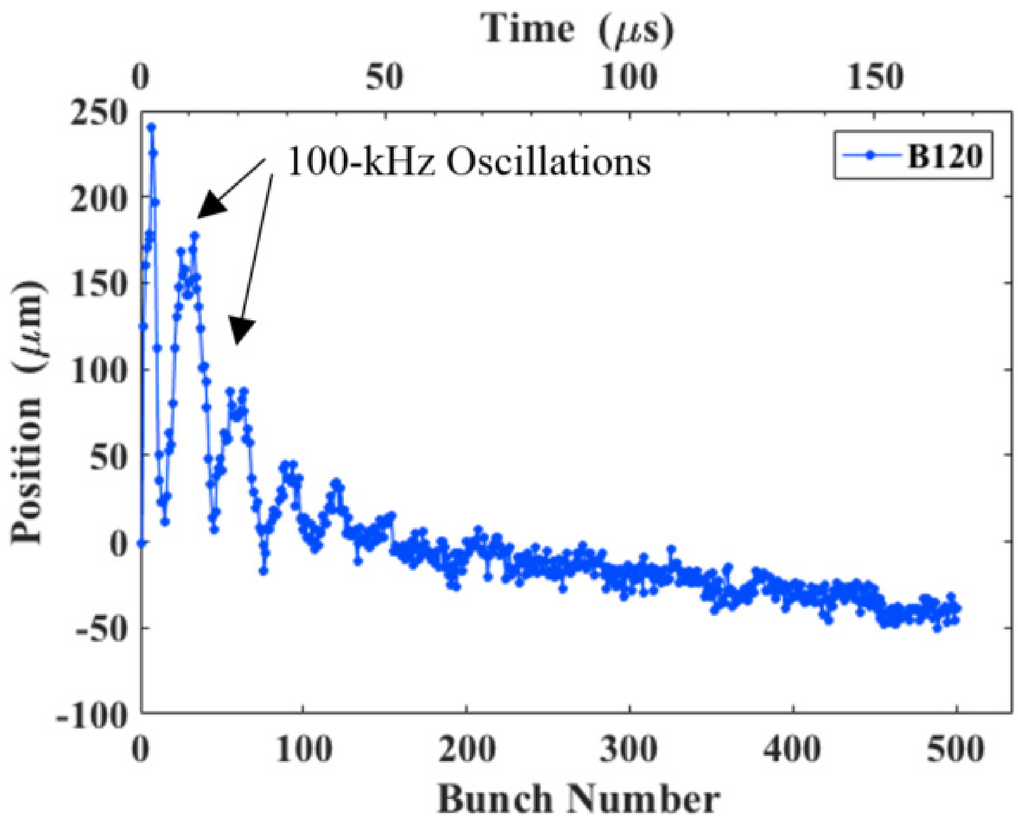






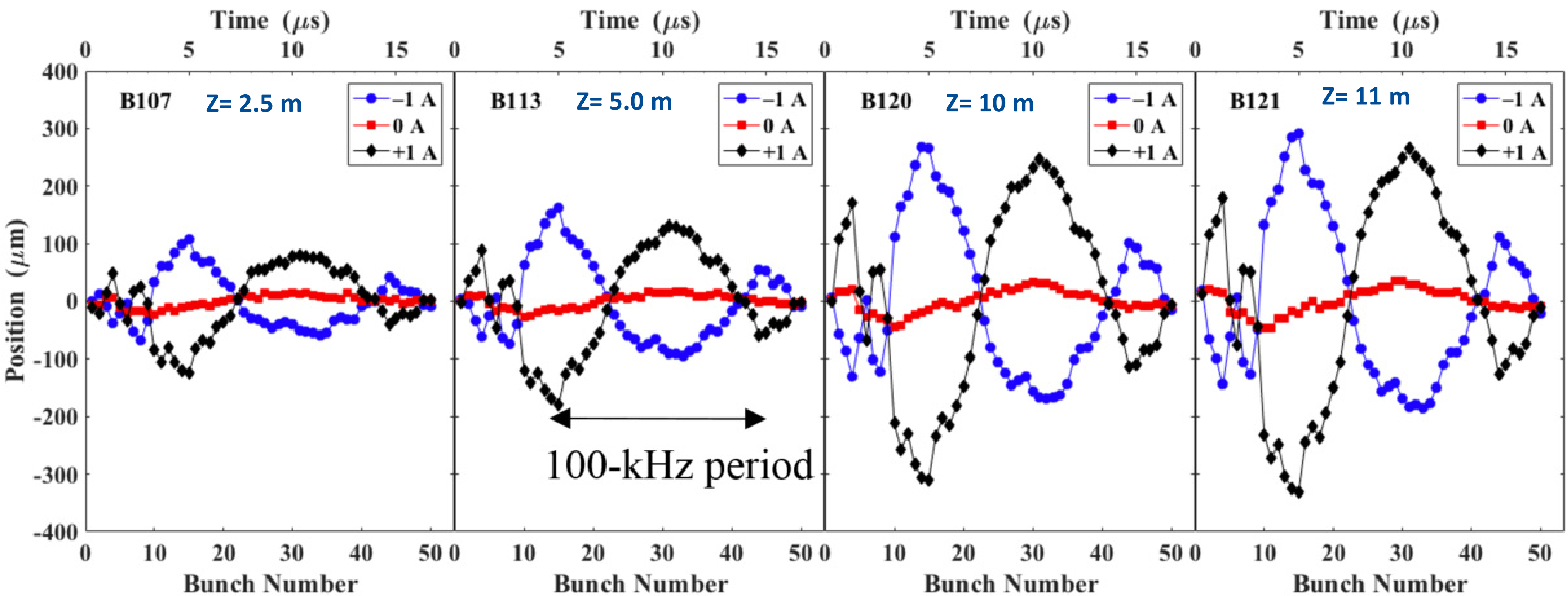
V101 Scan: Vertical BPM Shows Damping Effect in 500b

- Centroid oscillation seen in first ~100 b, then damps out. Centroid slew observed to end of pulse train. Q=500 pC/b.
- 100-macropulse average. V101= 1 A. z~ 10 m after CC2.



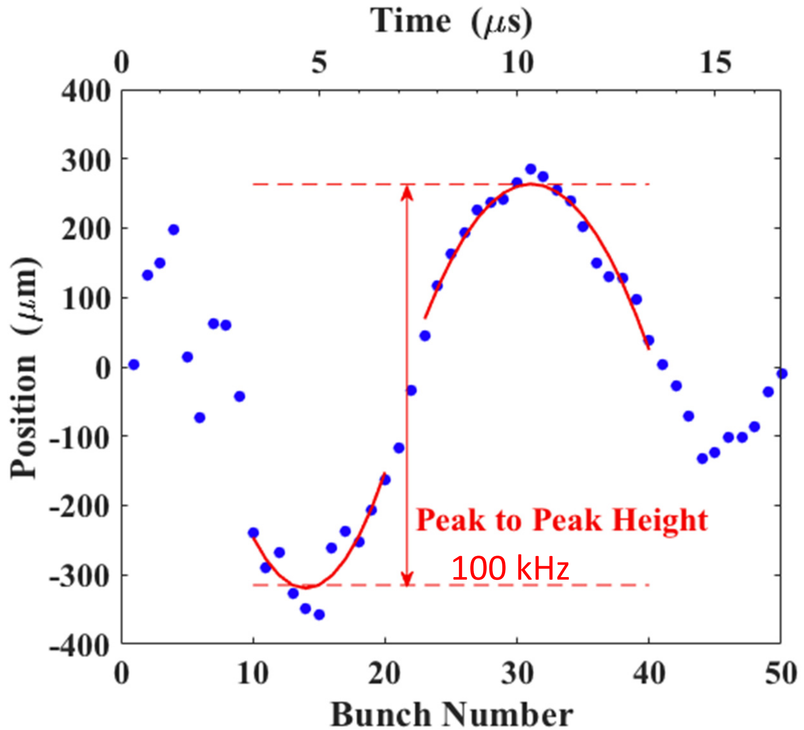
Centroid Vertical Oscillations Observed to Grow with Drift

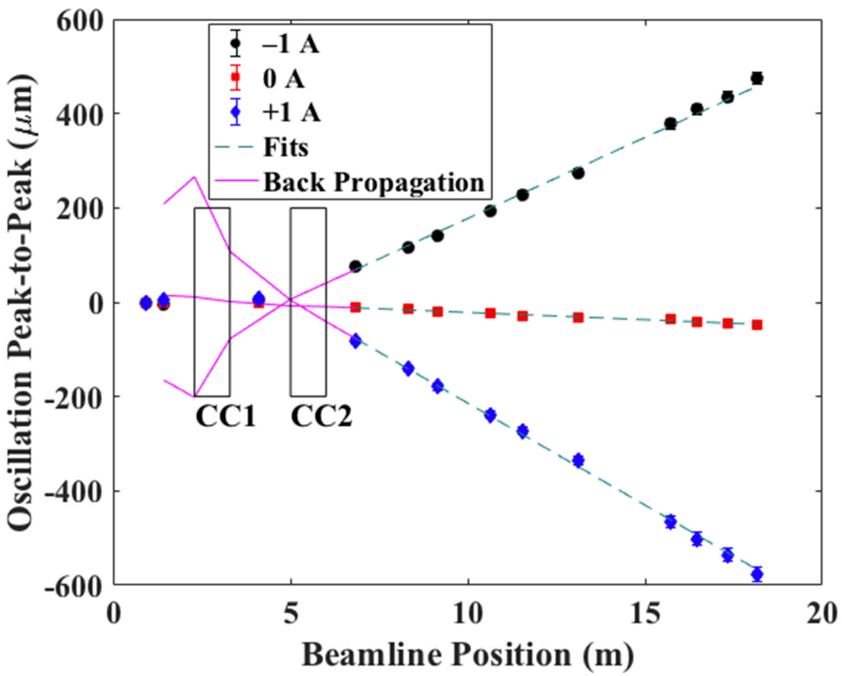
- Comparison of sub-macropulse motion with corrector currents at V101= -1, 0, +1 A. Correlation with excited HOMs. 1000 pC/b



Evaluation of HOM Vertical Kick Angles

- V101 scan results with drift to B122. Kick deduced 84 μrad from CC2 at 1000 pC/b in vertical BPM readings.

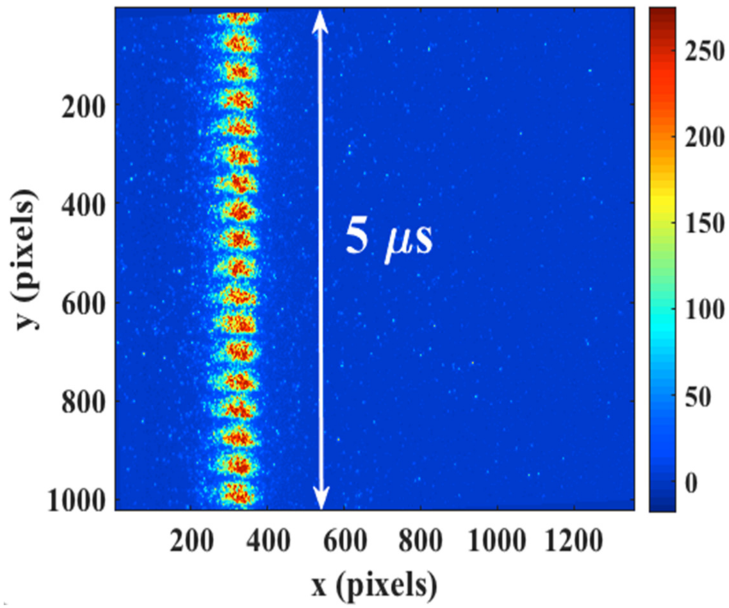


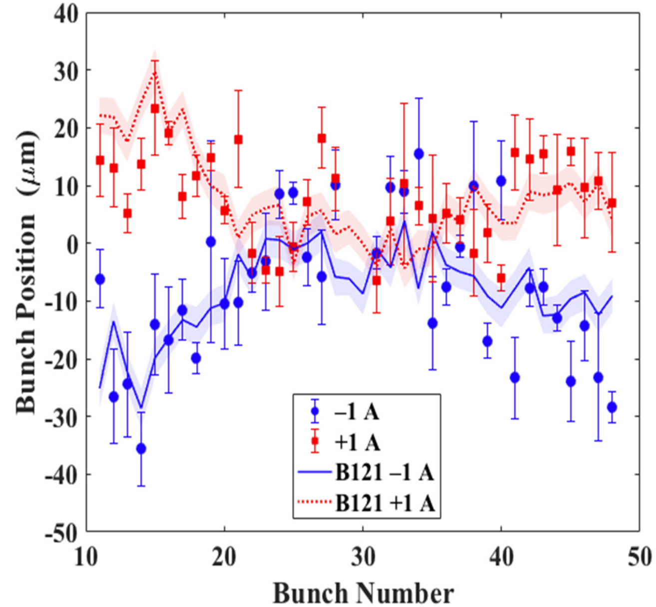


Fermilab

V101 Scan: Framing Camera Mode Shows HOM Effects

- 50b, 1000 pC/b, 5 μs vertical, 100 μs Horiz., ~16 μs gap.
- Bunches #31-48 shown in image (L). Second set of bunches #11-28 also taken. Later time is down and leftward on axes.
- Centroid motion comparison to rf BPMs shown at right (R).

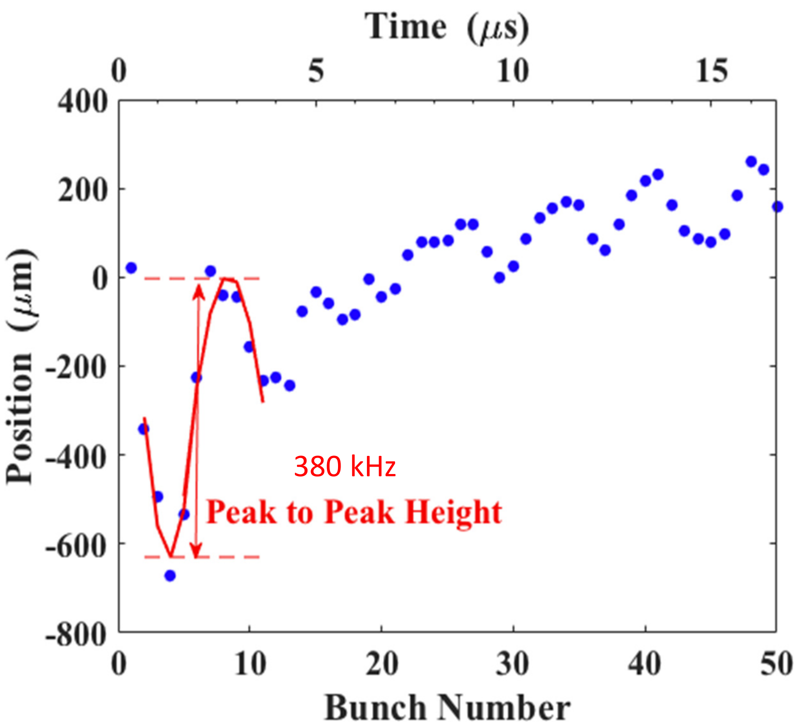


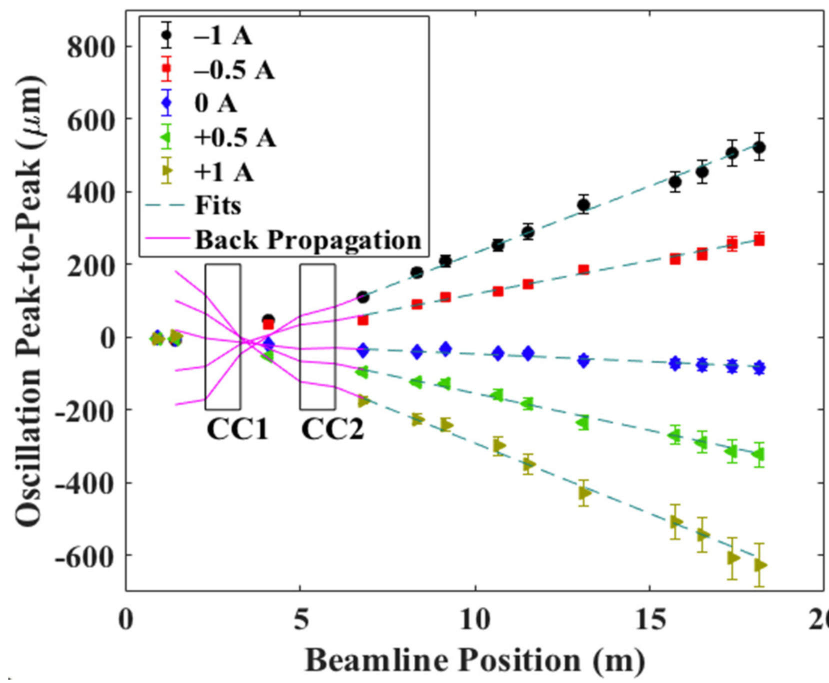


Fermilab

Evaluation of HOM Horizontal Kick Angles

- H101 scan results with drift to B122. Deduced kick ~40 μrad from CC1 in horizontal BPM readings at 1000 pC/b.





Basic Calculations of HOM Kick Angles Performed

- The angular kick $\delta\vec{r}'(s)$ experienced by a trailing electron of charge *e*, velocity $\vec{v}$, and momentum $\vec{p}$ at a distance s from the HOM-exciting bunch of charge Q_b and transverse offset $\vec{r}_0$ is given by

$$\delta\vec{r}'(s) = \frac{\Delta\vec{p}_\perp(s)}{p} = \frac{e}{pc}\int\left(\vec{E}_\perp + \vec{v}\times\vec{B}\right)(s)\cdot dl = \frac{e}{pc}Q_b\overrightarrow{W}_\perp(s), \qquad (1)$$

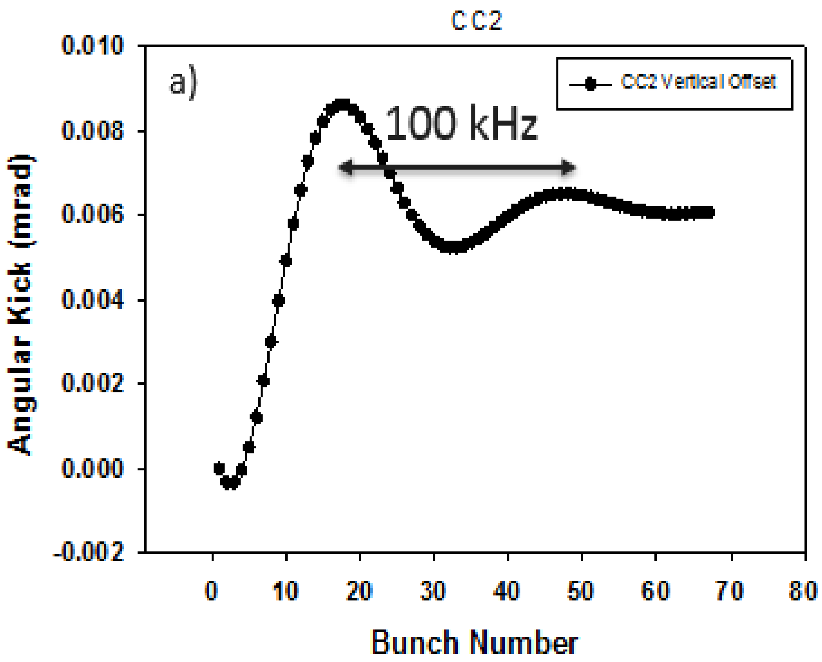
- where $\vec{B}$ and $\vec{E}_\perp$ are the magnetic and transverse electric fields generated by the HOM-exciting bunch, the integral is over the electron path, and *c* is the speed of light. For a series of m bunches, the wake potential at the m^{th} bunch, $\overrightarrow{W}_\perp(s_m)$, is given by the following summations over the resonant dipole modes, n, and the previous bunches, k:

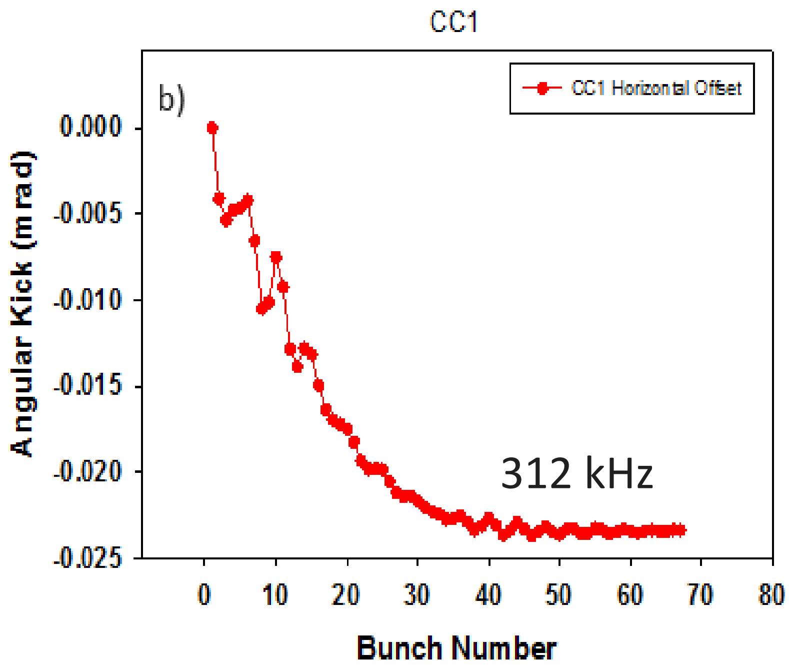
$$\overrightarrow{W}_\perp(s_m) = \vec{r}_0\frac{c}{2}\sum_{k=1}^{m-1}\sum_n\left(\frac{R_\perp}{Q}\right)_n e^{-\frac{\omega_n^2\sigma_z^2}{2c^2}}\sin\left(\frac{\omega_n(s_m-s_k)}{c}\right)e^{-\frac{\omega_n(s_m-s_k)}{2Q_nc}}\cos^2(\varphi_n),$$

(2)

- where ω_n is the angular frequency, $\left(\frac{R_\perp}{Q}\right)_n$ the transverse impedance, φ_n the polarization angle, and Q_n the damping factor of mode n.

CC2 and CC1 Generated Dipole HOM Kicks (Calculations)





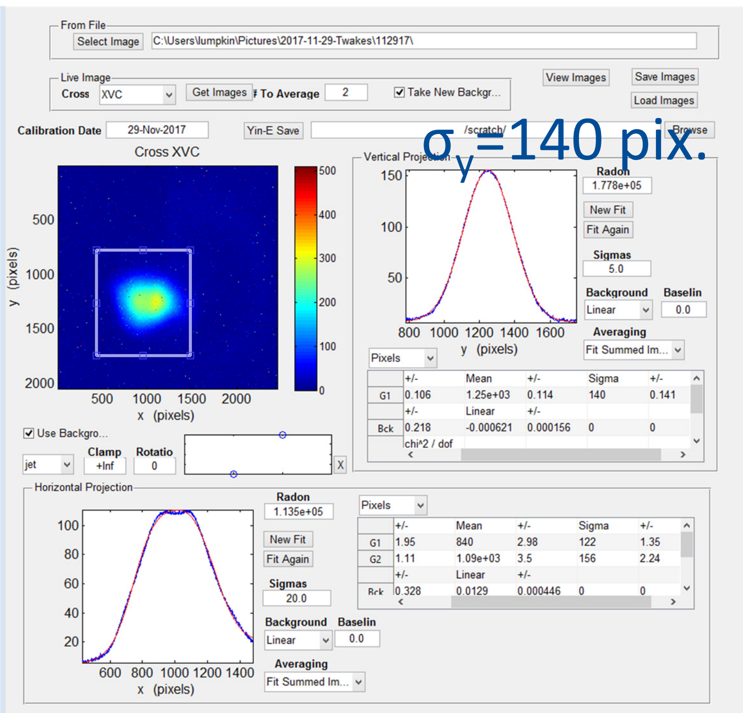
CC2: MM-14 with vertical polarization, 5 mm translation, 500 pC/b. Beam sampling at 3.008 MHz, harmonic # 623 within 100 kHz of the HOM frequency.

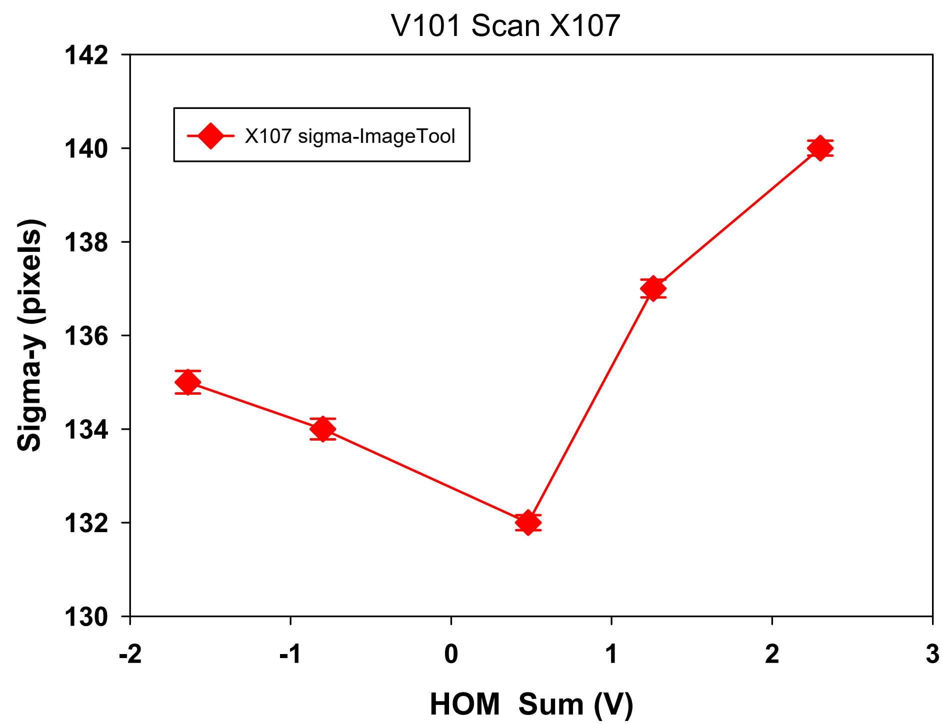
CC1: MM-7 plus MM-30; 5 mm translation, 500 pC/b.

O. Napoly's calc.

X107 Images and Possible HOM correlation with Beam Size

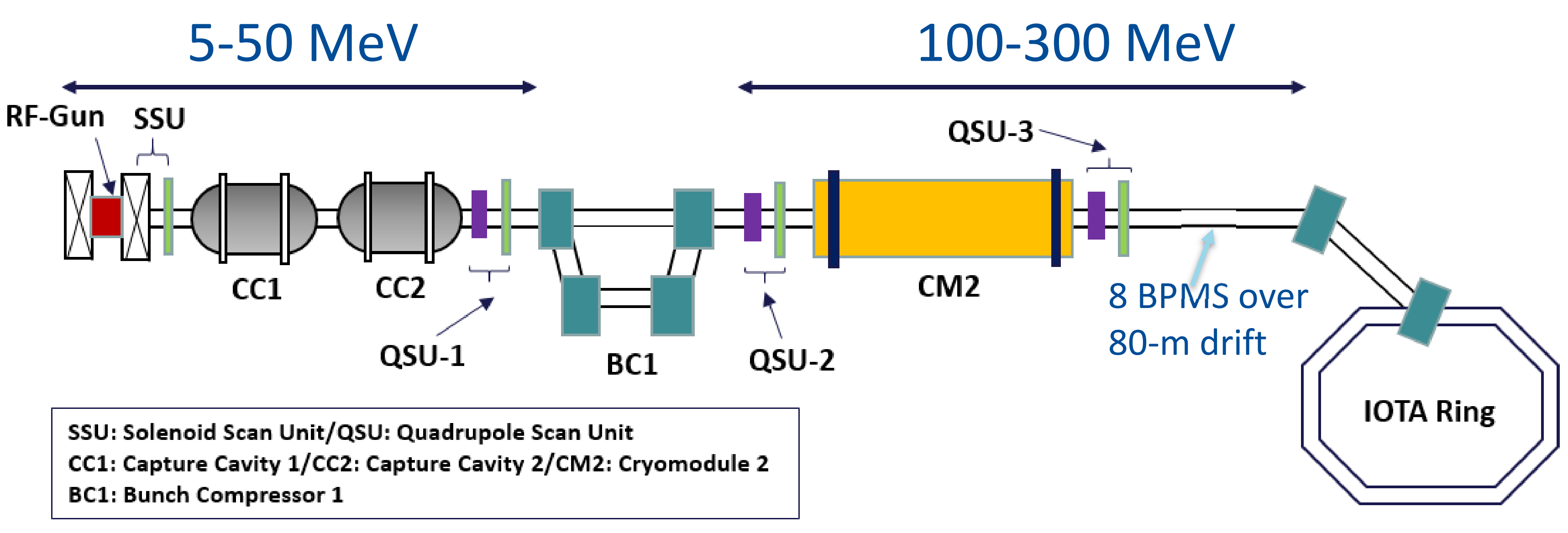
- Images and V101 scan using HOM sums for correlation.





Techniques May be Applied to FAST Cryomodule

- Plan to extend HOM studies techniques to higher charges and to the cryomodule using an 80-m drift and 8 rf BPMs distributed in z downstream of it.



Revised YMS

Summary

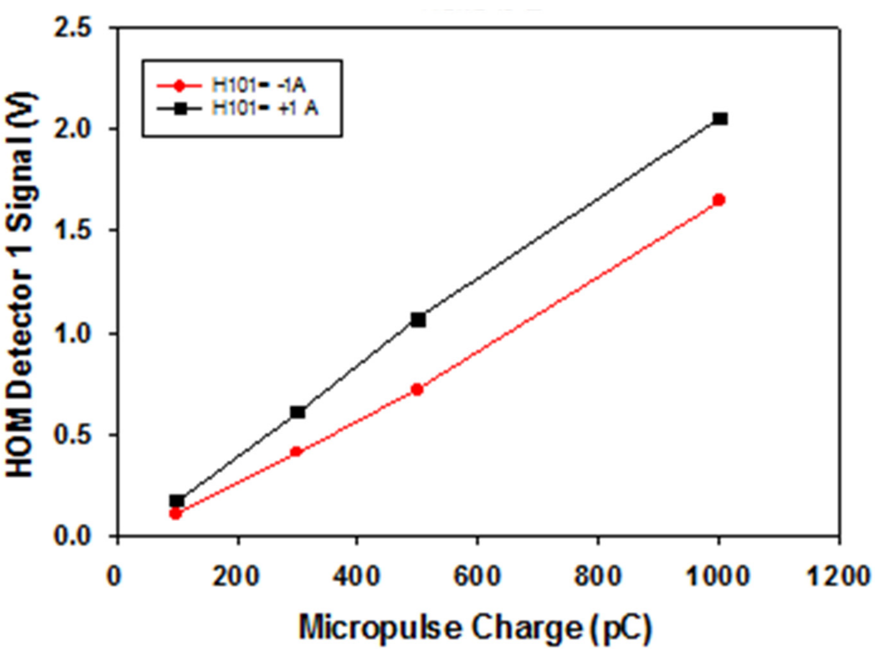
- Transverse wakefield studies' results are consistent with a sub-macropulse centroid motion correlated with HOM strength. Calculations supported this.
- Vertical position bunch-by-bunch data show 100-kHz oscillation whose amplitude increases with charge and offset. Unexpected frequency.
- Horizontal position bunch-by-bunch data show 380-kHz oscillation whose amplitude increases with charge and offset. Unexpected frequency.
- HOM signals and HOM kick angles vary linearly with charge as expected.
- Unique complementary data with framing camera show centroid oscillation at 25-μm level. YAG:Ce images, emittances, smaller effects for these beam parameters.
- Relevant, unique data sets for benchmarking HOM calculations and simulations in Tesla-type cavities remain objective. Such beam centroid oscillations could be issue for ultra-low emittance beams.
- Plan to apply techniques to the FAST cryomodule next run to evaluate further the relevancy of effects to accelerator community.
- Full article accepted for Phys. Rev. Accel. and Beams, 4/5/2018

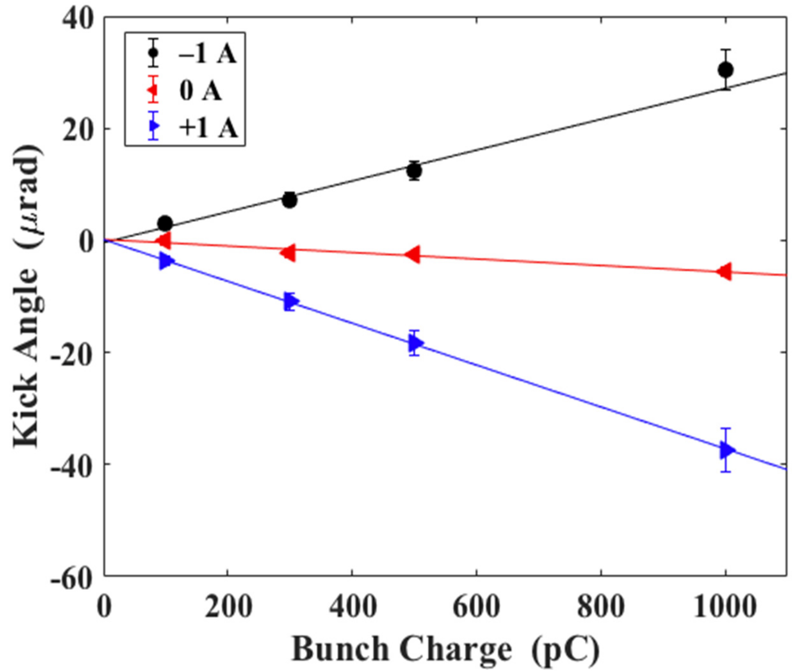
ACKNOWLEDGEMENTS

The authors acknowledge the technical support of J. Santucci, D. Crawford, and B. Fellenz; the project support of J. Liebfritz; the mechanical support of C. Baffes; the lattice assistance of S. Romanov; the cold cavity HOM measurements of A. Lunin and T. Khabiboulline of the Technical Division, the SCRF support of E. Harms; discussions with S. Yakovlev and Y. Shin; as well as the discussions with and/or support of A.Valishev, D. Broemmelsiek, V. Shiltsev, and S. Nagaitsev of the Accelerator Division at Fermilab. The Fermilab authors acknowledge the support of Fermi Research Alliance, LLC under Contract No. DE-AC02- 07CH11359 with the United States Department of Energy. The Los Alamos authors gratefully acknowledge the support of the US Department of Energy through the LANL/LDRD Program for this work.

HOM Signals and Deduced Kick Angles Vary with Charge

- HOM Detector Signals (L) and Horizontal Kick Angle (R) vary linearly with micropulse charge as expected.





Fermilab

X121 Framing Camera Practical Issue with Beam Focus

- Focus beam at X121 to match into framing camera, but this results in smaller beta function and beam centroid motion.
- Still about 30 μm effect with 7 μm resolution at 1000 pC/b.