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Investigations of Long-range and Short-range Wakefields on Beam Dynamics in TESLA-Type Superconducting rf Cavities

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IOTA/FAST Mtg

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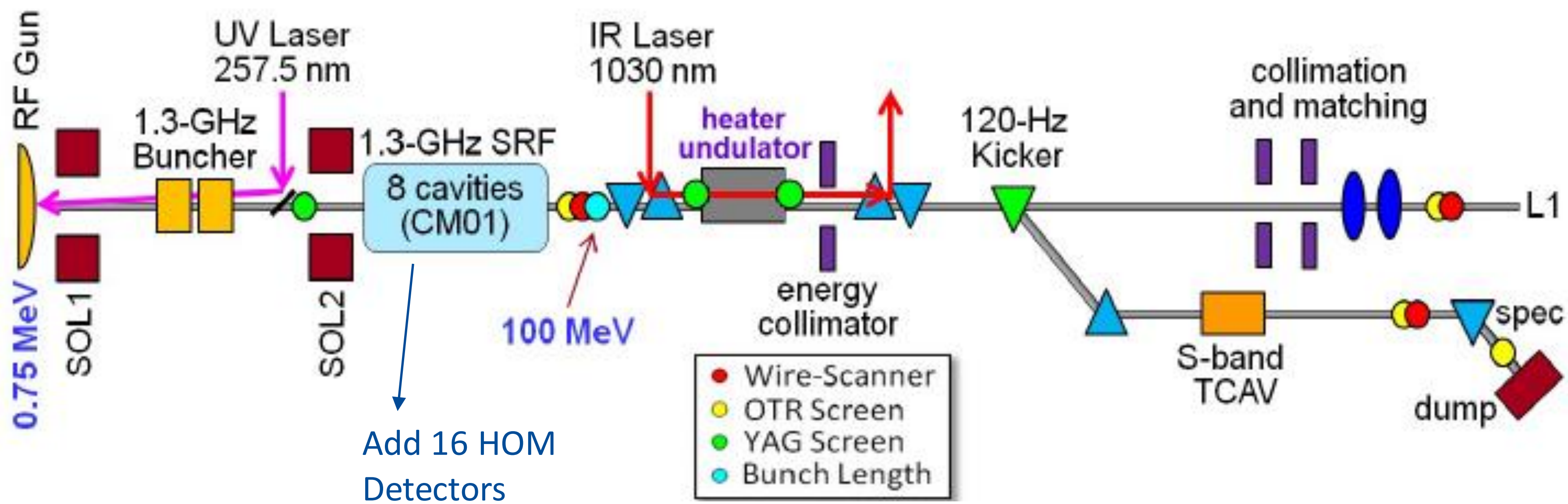
Fast Studies Proposal on Long-range (LRW) and Short-range Wakefields (SRW) on Beam Dynamics: Motivation

- TESLA cavities are being used in major projects around the world and merit full understanding of effects on the beam.
- Proposal to measure emittance dilution effects by steering beam off axis into TESLA-type Cavities to generate long range/Higher-order Mode (HOM) and short-range wakes.
- Diagnostics: HOM Detectors, Bunch by Bunch rf BPMs, Streak camera, imaging screens, spectrometers: e^- and GHz.
- Relevance to LCLS-II Injector commissioning noted with their <1 MeV beam injection into a cryomodule. Dec. 2020 target.
- Transverse LRW and SRW kicks go inversely with Energy.
- This proposal is in collaboration with SLAC staff to investigate LRW and SRW in TESLA cavities, to inform HOM detector designs for LCLS-II, and to inform their commissioning plans.

Schematic of the Planned Full LCLS-II Injector

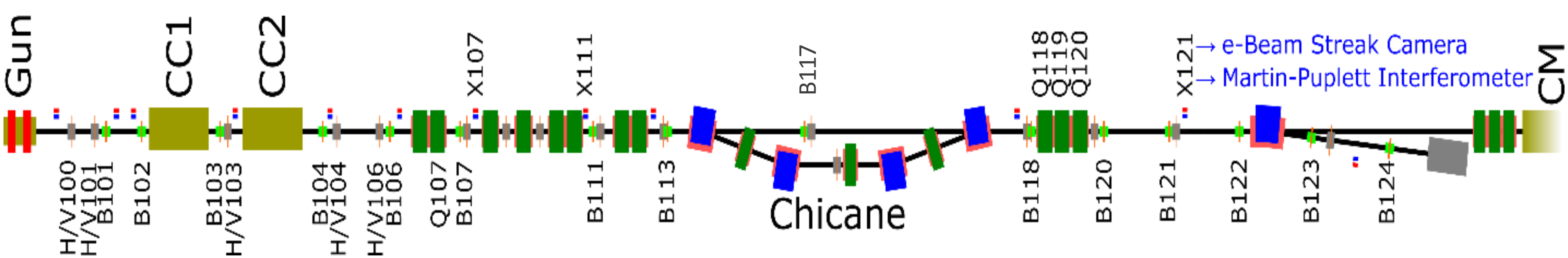
- Potential long-range and short-range wakefields due to off-axis beam in cavities need to be minimized to preserve emittance.
- HOMs in CM01 tracked. Steering at 1-9 MeV critical in first 3 cavities. Cavity 1 at 8 MV/m; Cavities 2,3 at 0 MV/m; Cavities 4-8 at 16 MV/m. Commissioning expected in late 2020.



F. Zhou et al., IPAC2017

FAST Configuration and Unique Diagnostics Available

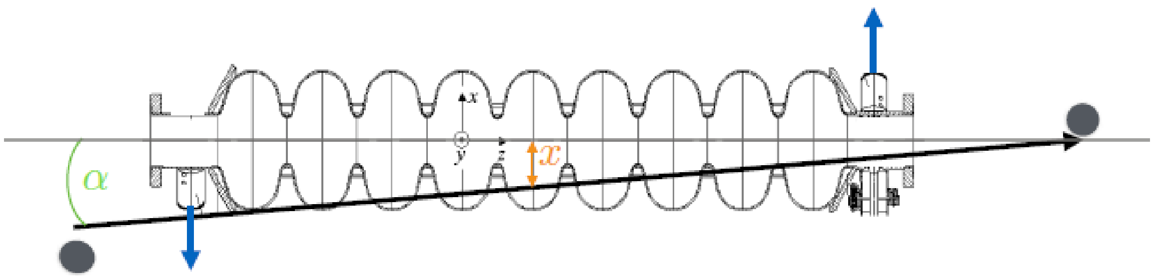
- Photocathode (PC) rf Gun beam injected into TESLA Cavities at 3 MHz micropulse repetition rate.
- Two single cavities with two corrector sets before CC1 and one set before CC2 allow localization of vertical effect to mostly second cavity using corrector H/V103 with HOMs minimized in CC1 for the tests.
- Streak camera views the X121 and X124 OTR screens and provides ~1-ps resolution so multiple time slices in 4 sigma-t.
- Wakefield Model indicates effects should be at 50-µm level for an offset of 1 mm, σ_t =10ps, and Q~2.4 nC. (V. Lebedev calc.)



EXPERIMENTAL SETUP

> TESLA CAVITY
  - 2 HOM couplers

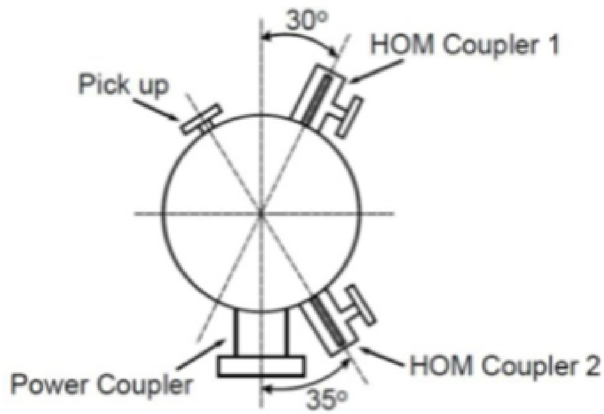
> DIPOLE HOM
  - $V_x(t) \propto x \cdot e^{-\frac{t}{2\tau}} \sin(\omega t)$
  - $V_{x'}(t) \propto x' \cdot e^{-\frac{t}{2\tau}} \cos(\omega t)$



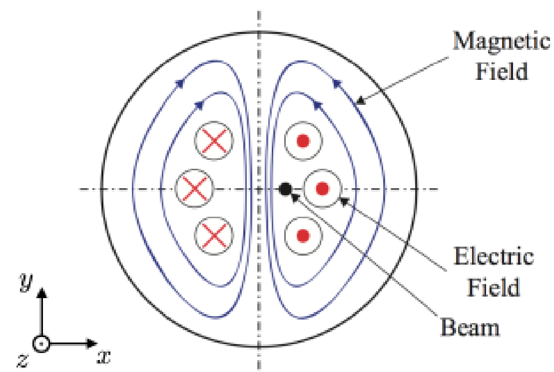
Expected HOMs in TESLA Cavities*

Mode #	Freq.(GHz)	R/Q (Ω/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



T. Hellert 7/11/17 DESY Seminar

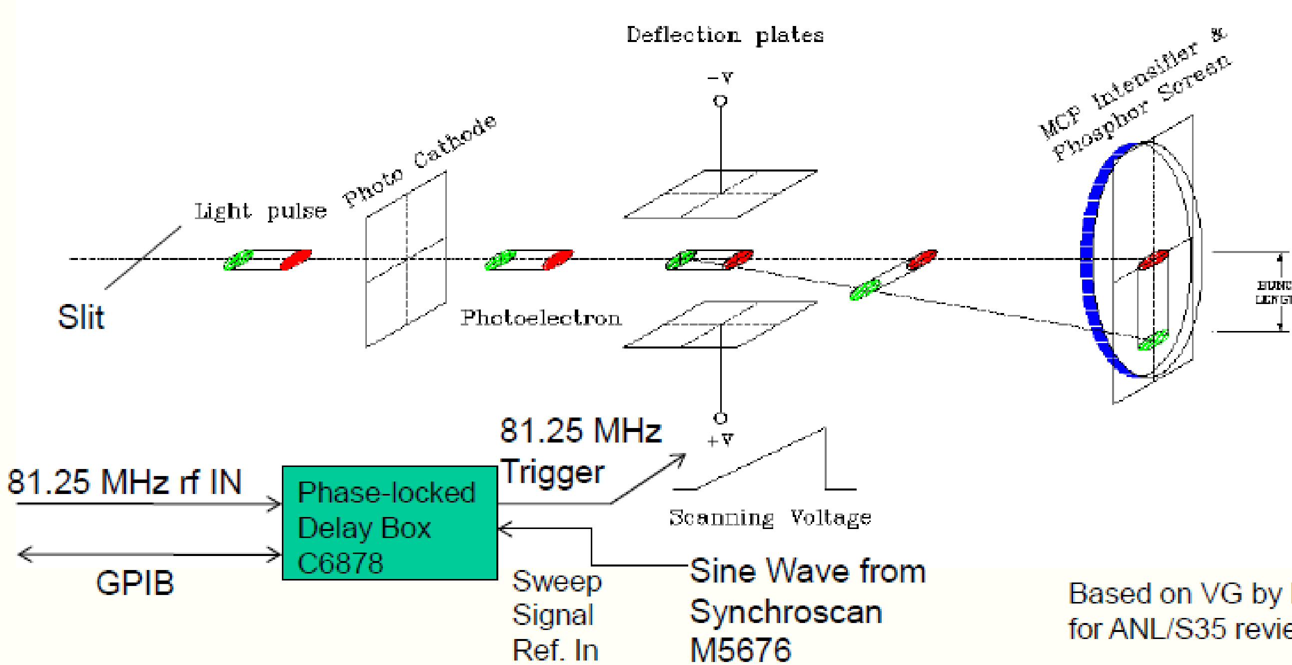
Run 1 Provided Initial results; Run 2 to Extend Studies.

- Run 1: on March 8, 2019 we obtained minimal HOMs in all 4 detectors (10 $\pm$ 5 mV) and observed the space-charge dominated elliptical y-t shape with the streak camera at X121.
- Laser spot was characterized as 0.2 mm rms for this date.
- However, only the reference streak image and one steering change were recorded due to the image server crash.
- We want to reproduce this condition in Run 2, and steer the beam before and after CC1 to map out the HOM signal effects from this base reference line. Our shift 1. BOM data.
- We determined that the laser spot size and spatial distribution can affect the HOM signal minimization. We want to control and study this in Run 2, our shifts 1-3.
- We will look at CC1,2 HOM quadrupole modes in Run 2, new.
- Extend the SRW studies in shifts 4-6 with better reference.

Synchroscan Streak Camera Displays y-t effects.

Combined phase locking steps allow synchronous summing of micropulses and of multiple images (10-100 typically for improved statistics). Slow sweep vertical unit gives framing camera capability.

- **Addition of synchroscan plugin module and the C6878 phase-locked delay box enabled new series of experiments**

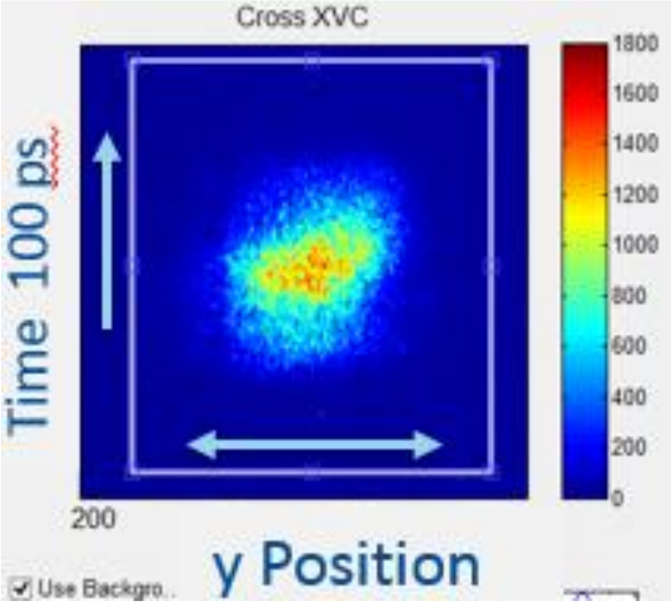


Look for head-tail centroid shift of beam distribution: SRW

Based on VG by B.Yang for ANL/S35 review

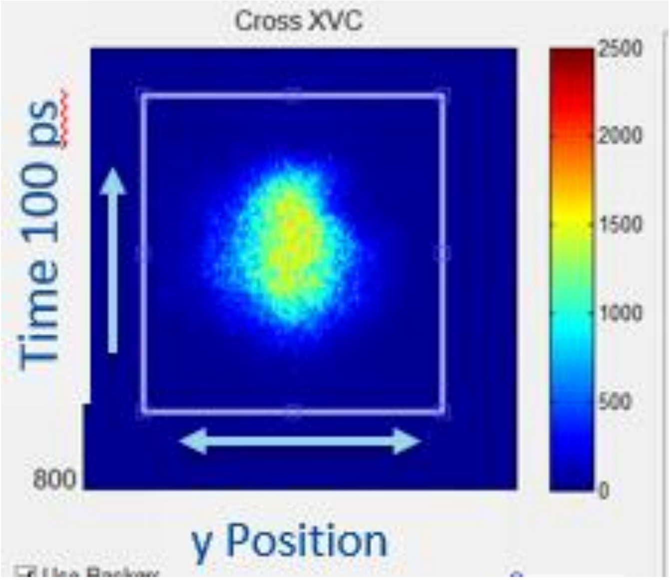
SRW Effects Observed in Run 1 with HOMs as found 3-01-19

- Streak images show the head-tail centroid shift with higher HOM readings. Projected y size is 46 % larger than reference.



HOM Detectors
CC1[8]= -100 mV
CC1[9]= -60 mV
CC2[8]= -100 mV
CC2[9]= -50 mV

σ_y= 548 μm
y-t shift 343 μm
σ_t=11.2 ps
HOMs as found 3/1/19

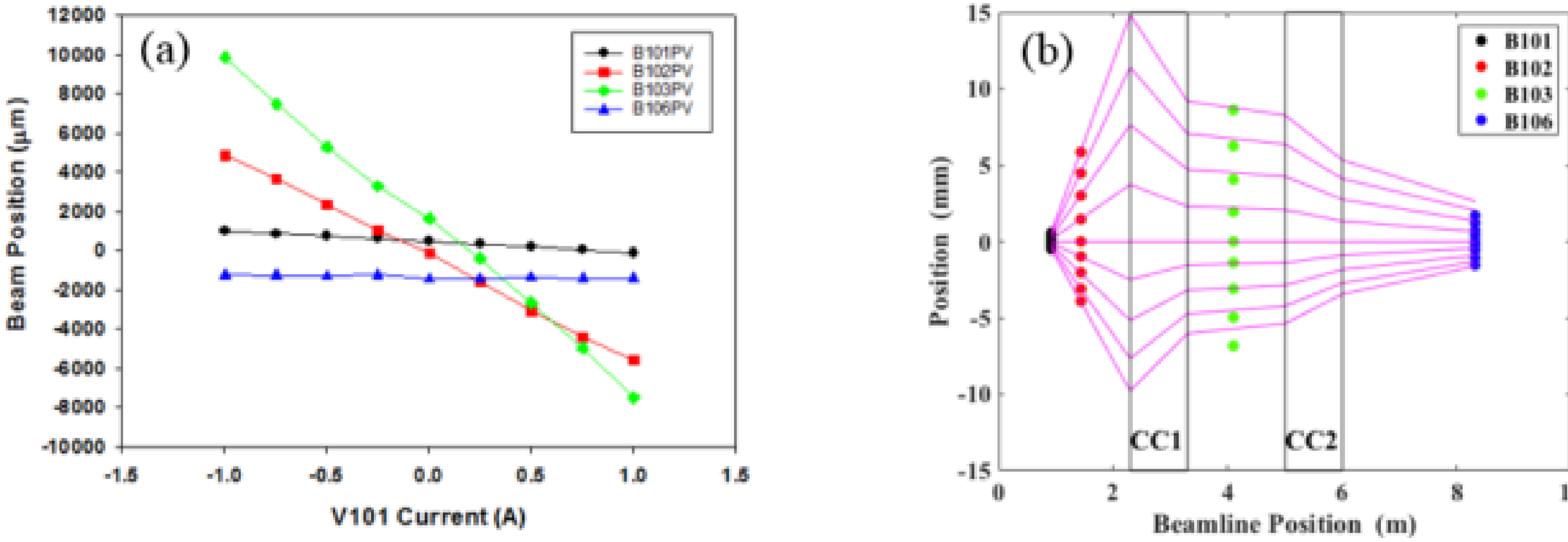


HOM Detectors
CC1[8] = -13 mV
CC1[9] = -10 mV
CC2[8] = -5 mV
CC2[9] = -7 mV

σ_y= 376 μm
y-t shift <4 μm
σ_t=11.5 ps
HOMs minimized

V101 Current Scan Affects Beam Trajectories

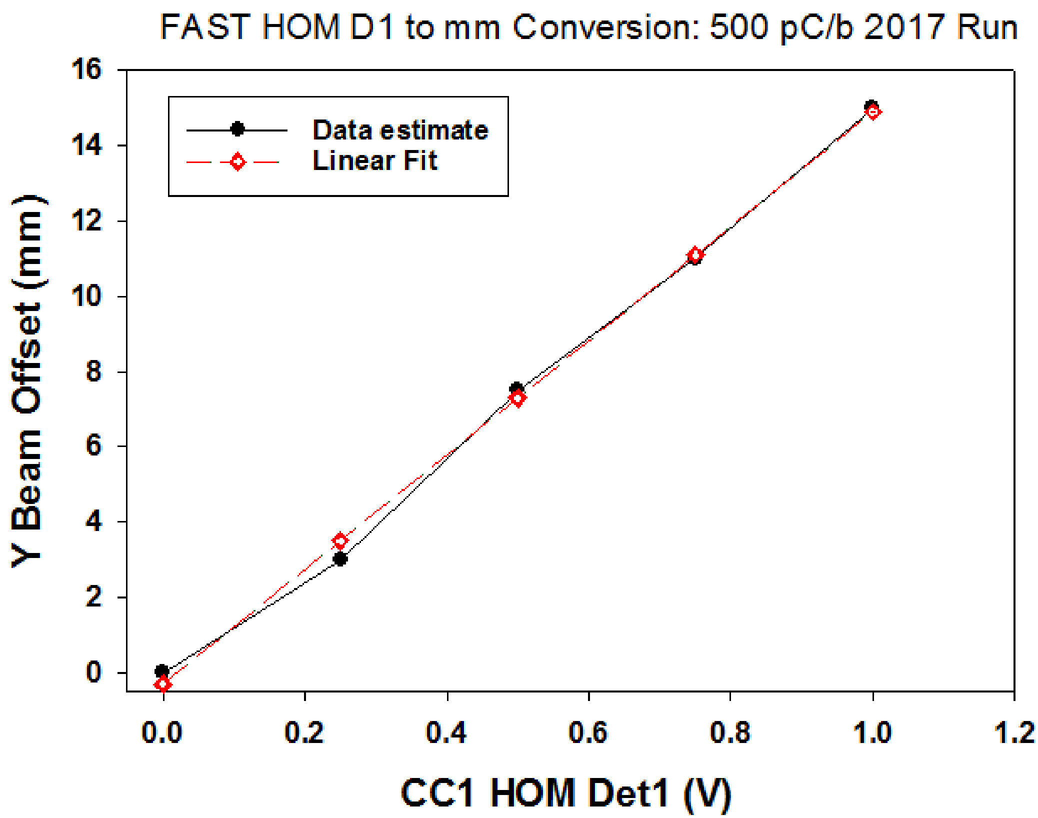
- Tracking of beam trajectories around CC1 and CC2.
- BPM data (a) and calculated trajectories using cavity transfer matrix (b) (ref. E. Chambers (1965)) PRAB (2018)



Beam Offset Monitor (BOM) seems Feasible with HOMs

- Using the corrector to HOMs and corrector to BPM values a coarse BOM was constructed. The Chambers model trajectories were used that matched the rf BPM readings.

Preliminary



Need –y and ± x offset curves too For HOM Det1

Studies Request Run 2: 3 Shifts (8 hr) for LRW/HOM Effects

- Investigators: Wang, Lumpkin, Maxwell, Edstrom, Ruan, et al.
- Machine: FAST Injector Linac:
- Parameters: 41 MeV total energy, Charges Q=0.2-3 nC,1-50 b. Uncompressed beam-No chicane. HOM detectors, rf BPMs, cameras, LE spectrometer, GHz spectrometer on Shift 0 (4hrs)
- Shift 1:
  - Setup steering for minimum HOMs in CC1 and CC2.
  - Develop table for V104,106 correctors to compensate for H/V10n, changes: Verify beam trajectory to LE beam dump.
  - H/V101 steps 0.25 A for -1 to +1 A : H/V103, -2 to +2A.
- Shifts 2,3: Vary laser spot size, then solenoid settings. Record virtual cathode, 9-way, X107 images, and HOMs. Different charges, 0.2 to 3 nC. Bunches for X107,Evaluate during shifts.

Studies Request Run 2: 3 Shifts (8hr) for SRW Effects (streak camera)

- Investigators: Lumpkin, Wang, Maxwell, Edstrom, Ruan, et al.
- Machine: FAST Injector Linac:
- Parameters: 41 MeV total energy, Charges Q=0.5-3 nC,1-50 b. Uncompressed beam-No chicane. HOM detectors, X121 station, streak camera, BPMS, LE spectrometer.
- Shift 4:

  - Setup steering for minimum HOMs in CC1 and CC2.

  - Transport beam to YAG screen at X121.

  - Commission light transport from X121 with OTR.

  - Verify beam trajectory to X121 preserved. Q118-120 adj.

  - streak image at reference steering, R1. Evaluate status.
- Shifts 5,6. Obtain y-t streak images, different offsets, different charges, 1-50-100 b, 0.5 to 3nC.

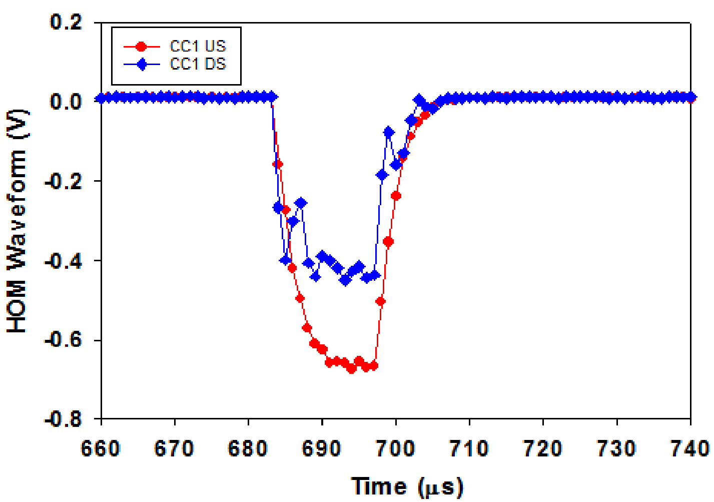
Summary

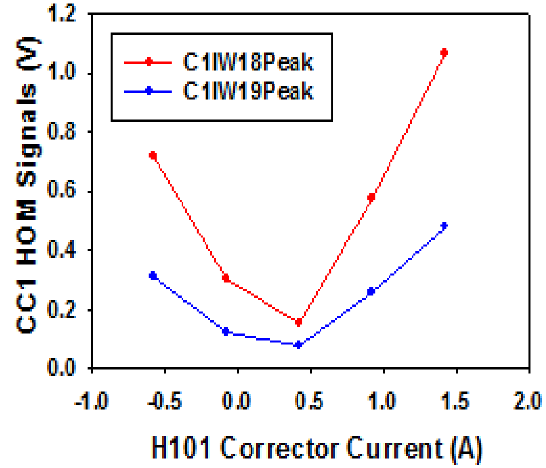
- Opportunity at FAST/IOTA to elucidate wakefield effects in TESLA-type Superconducting rf cavities in these studies.
- Opportunity to inform the steering setups for the FAST TESLA-type cavities to minimize emittance dilution.
- Opportunity to compare results to transverse wakefield models.
- Opportunity to inform the LCLS-II HOM detector designs, test the prototypes in Run 3, and inform the LCLS-II commissioning plans.
- Details in the proposal.

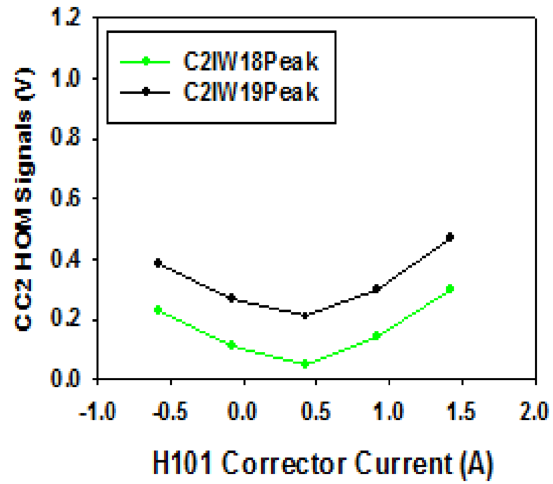
H101 scan: HOM Signals Observed from CC1 and CC2

- 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







Model of TESLA cavity for transverse wakefields used to predict effects. (V. Lebedev)

For Q=2.4 nC, sigma-t=10 ps, 1-mm offset, Beta-x=10 m, get 40- to 50-µm kick within the micropulse from 1 TESLA cavity's wakefield.

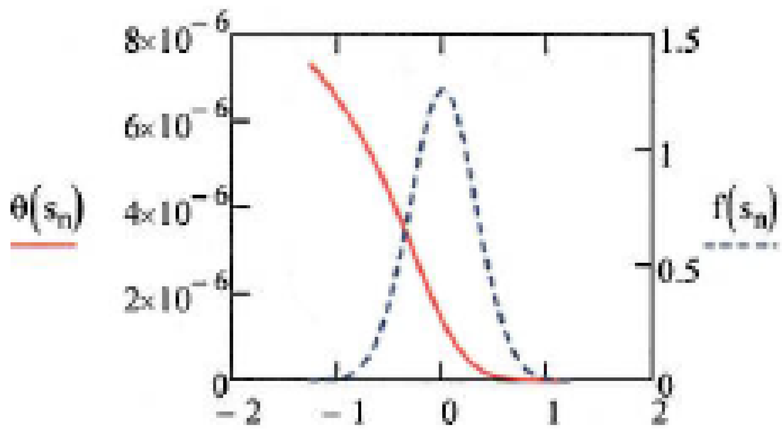
Lebedev Case:

Cavity parameters

$\lambda_{RF} := 23.022219$ cm

$N_{cell} := 9$ cells per cavity

$a := 3.1$ cm



Transverse kick

$P_0 := 50 \cdot 10^6$ eV $\quad \Delta x := 0.1$ cm

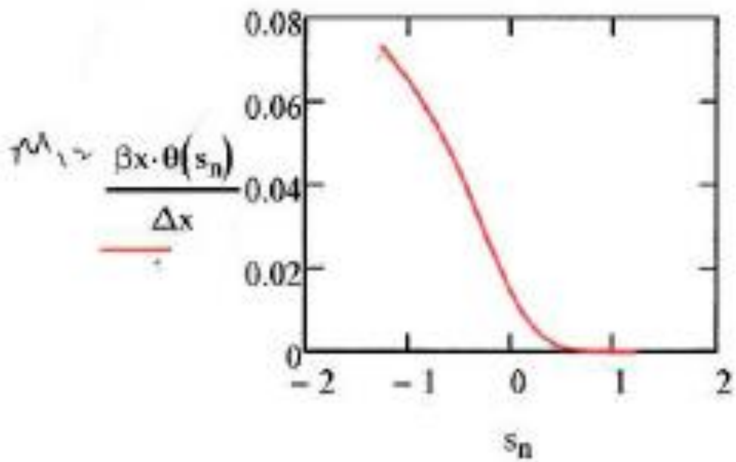
$$\theta(s) := \frac{e_{conv} \cdot e_{SGS} \cdot N_e}{P_0} \cdot \int^{10} \Delta x \cdot W_T(s_p - s) \cdot f(s_p)\, ds_p$$

Transverse wake

$$W_T(s) := \frac{4 \cdot N_{cell}}{\pi \cdot a^3} \cdot \left[\frac{5}{4} \cdot \left[\sqrt{2 \cdot g \cdot \left(s + \frac{a}{\gamma_{eff}}\right)} - \sqrt{2 \cdot g \cdot \frac{a}{\gamma_{eff}}}\right] - s\right]$$

$\beta x := 1000$ cm

Wake numerically computed for ILC cavities



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X121 Streak Camera with OTR Source Provides y-t Data

- C5680 Synchroscan vertical deflection unit provides submicropulse centroid information in ps slices, y-t.
- Spatial resolution demonstrated at 10 micron level.
- Vertical steering through CC2 will be varied to generate short range wakefields in CC2.
- CC2 HOM detectors will give supplementary data on offsets.
- Strongest kick angle for late in micropulse, but measurable kick at later FWHM point.
- Single micropulse tests possible, but can use synchroscan to sum and dual-sweep feature to track in pulse train.
- Averaging of images can be used for better statistics.