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Submicropulse Electron-Beam Dynamics Correlated with Short-range Wakefields in TESLA-type Superconducting RF Cavities

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Accelerator Physics and Technology Seminar

23 June 2020

Batavia, IL USA

OUTLINE

I. Introduction

II. Strategy to identify emittance dilution effects by steering beam off axis into TESLA Cavities to generate long range/Higher-order Mode (HOM) and short-range wakes.

III. Diagnostics: HOM Detectors, Bunch by Bunch rf BPMs, Streak camera, imaging screens, spectrometer.

IV. Previous long-range wakefield (LRW), HOM effects within macropulse will be presented as context. (PRAB-2018)

V. Initial observations of short-range wakefield (SRW) effects and head-tail kick *within* micropulses.(PRAB: May 4, 2020)

VI. Relevance to LCLS-II injector commissioning and others.

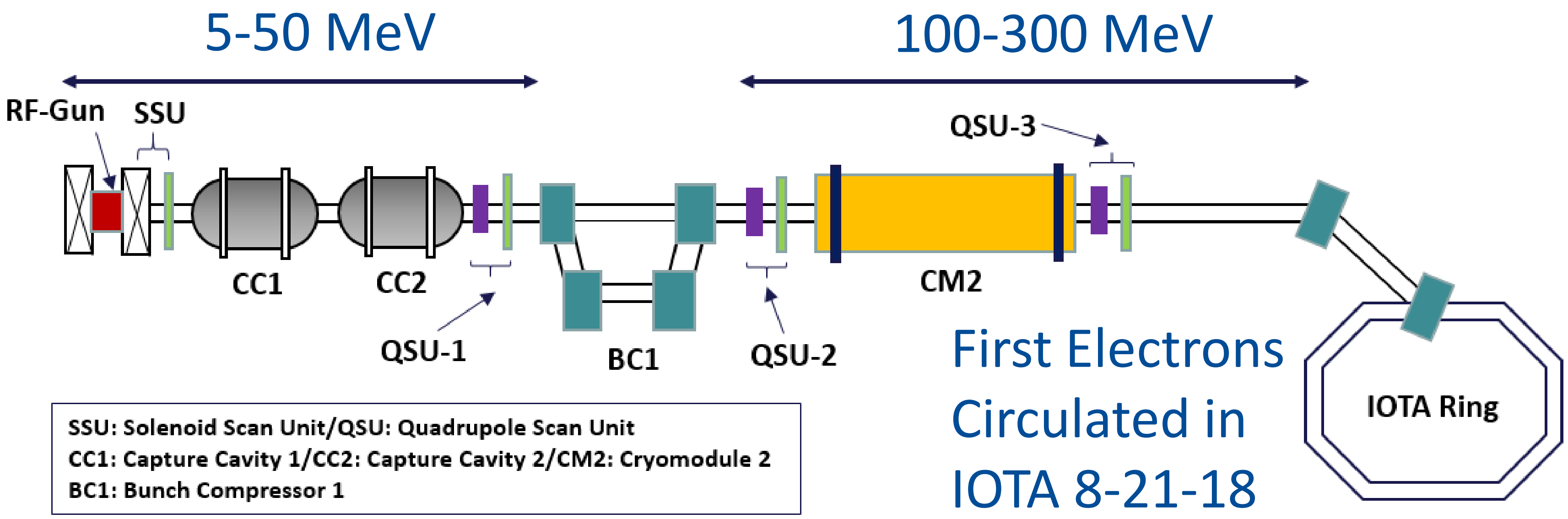
VII. Summary

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 long-range wakefields (e.g., higher-order modes (HOMs)) and short-range wakefields (SRWs) due to beam offsets in the accelerating cavities.
- We investigate effects in TESLA-type superconducting rf cavities which are the drive accelerator for major facilities such as the FLASH (FEL), European XFEL, the under construction LCLS-II, the STF in Japan, the proposed MARIE XFEL at Los Alamos, and the under-consideration ILC in Japan.
- Historically, many HOM studies at DESY have been related to determining cavity mode offsets from the beam axis within cryomodules, critical info also.
- We have asked whether we could measure LRW/SRW effects on beam dynamics directly using time-resolved diagnostics.
- The answer is "Yes" for both LRW/HOMs and SRWs with a PRAB published on each in the last two years. Today's seminar is focused on the SRWs.
- Our SLAC/FNAL collaboration continued these investigations this FY with a primary goal to inform LCLS-II injector commissioning.

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.



Integrable Optics Test Accelerator (IOTA)

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. HOMs guide to beam offsets.
- Streak camera views the X121 and X124 OTR screens and provides ~1-ps resolution so multiple time slices in 4 sigma-t.
- SRW Model indicates effects should be at 100-µm level for an offset of 3-5 mm, σ_t=10 ps, Q=0.5 nC (V. Lebedev calc.)

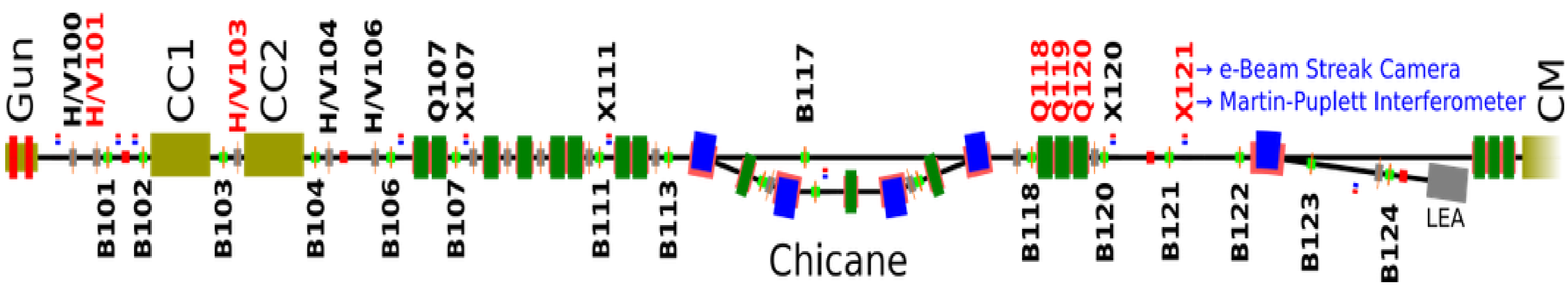


Table 1. FAST Electron Beam Parameters for Studies

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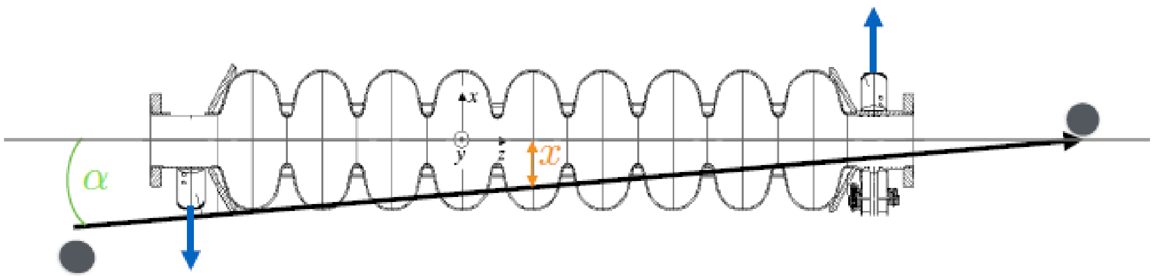
Beam Parameter	Units	Value		
Micropulse Charge (Q)	pC	100-2500		
Micropulse rep. rate	MHz	3		
Beam sizes, σ	µm	100-1200		
Emittance, σ norm	mm mrad	1-5		
Bunch length,σ Compressed	ps ps	4-20 1-3		
Total Energy	MeV	33, 41		
PC gun grad.	MV/m	40-45		
CC1 gradient	MV/m	14.2, 21		
CC2 gradient.	MV/m	14.2		

1-150 bunches used, 3000 max.

Experimental Setup

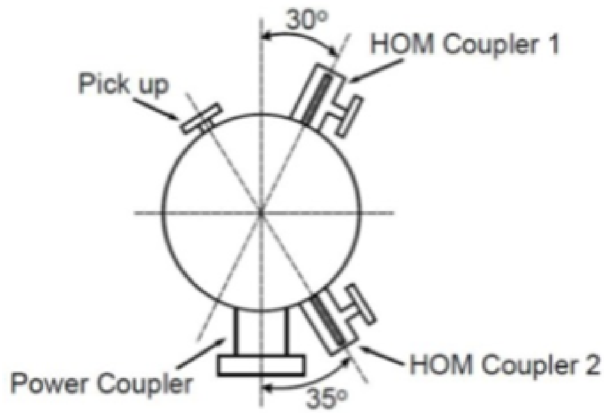
- TESLA cavity
  - 2 HOM couplers
- Dipole HOM
  - $V_x(t) \propto x \cdot e^{-\frac{t}{2\tau}} \sin(\omega t)$
  - $V_{x'}(t) \propto x' \cdot e^{-\frac{t}{2\tau}} \cos(\omega t)$

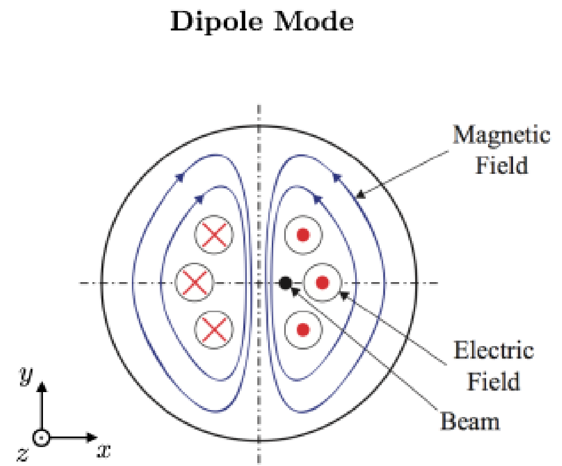


Expected HOMs in TESLA Cavities*

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





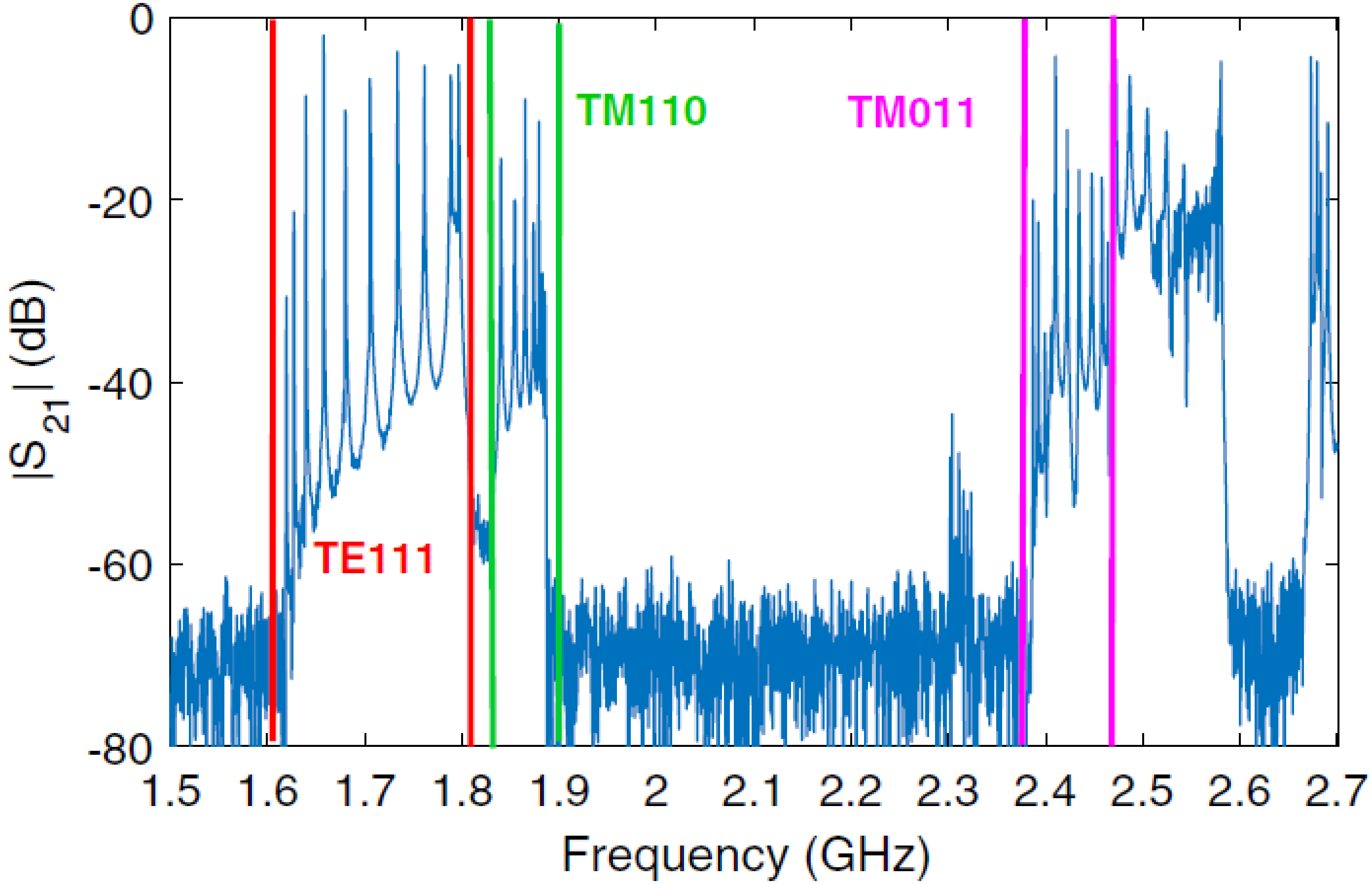
N.B. Modes excited in the cavities at frequencies Higher than the accelerating mode are HOMs. Amplitude of specific dipole mode, $A_d \sim q \times r \times (R/Q)$

Thorsten Hellert | FEL seminar | July 11 2017 | Page 12

T. Hellert 7/11/17 DESY Seminar

Complex Spectrum Recorded from a TESLA Cavity

- Three HOM bands are marked: TE111, TM110, TM011 from Wei et al.,PRAB 22,082804 (2019).



IV. Initial tests for Long-range Wakefield Effects (or HOMs)

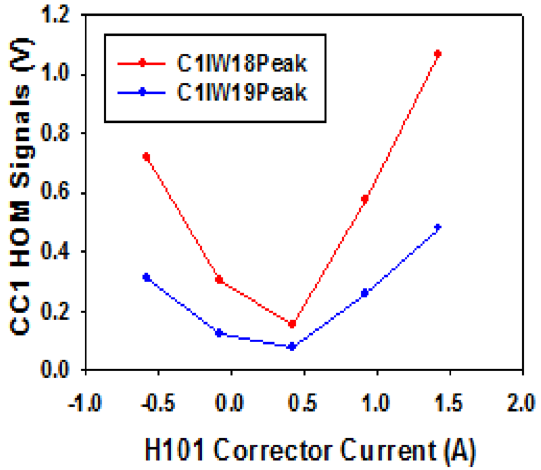
Initial tests for long-range wakefield effects generated by off-axis steering of the beam into CC1 and CC2. Can Localize to CC2 with V103 corrector in principle, used in short-range wake tests.

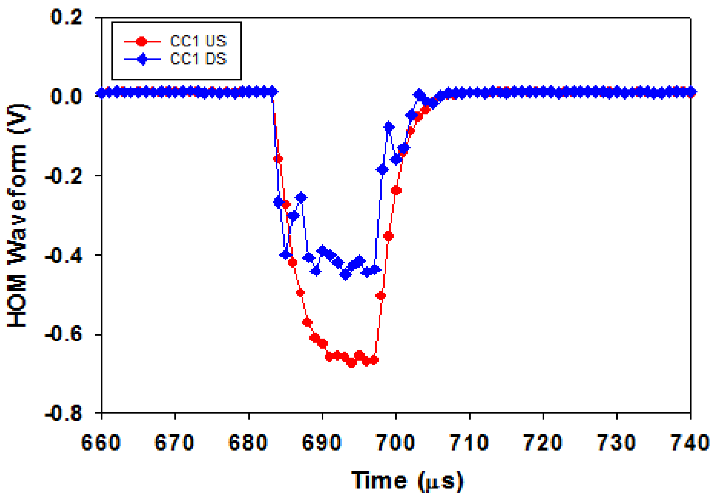
- Characterize beam steering effects on beam position.
- Search for effects of beam steering on HOM detector signals.
- Search for corrector settings to minimize all four HOM detectors at same time? Can we?
- Search for centroid shifts within the 16-μs long macropulse.
- Search for possible near-resonance effect with HOMs.
- Search for possible time-averaged emittance-dilution effect.
- Compare basic model (O. Napoly) to observations.
- Identify and mitigate beam size growth due to LRWs.

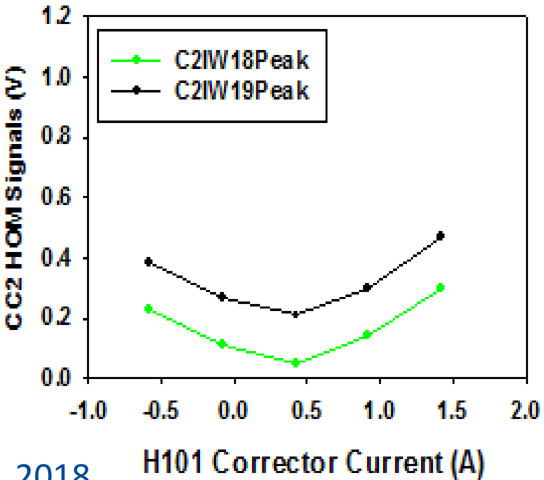
H101 scan: HOM Signals Observed from CC1 and CC2

- 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



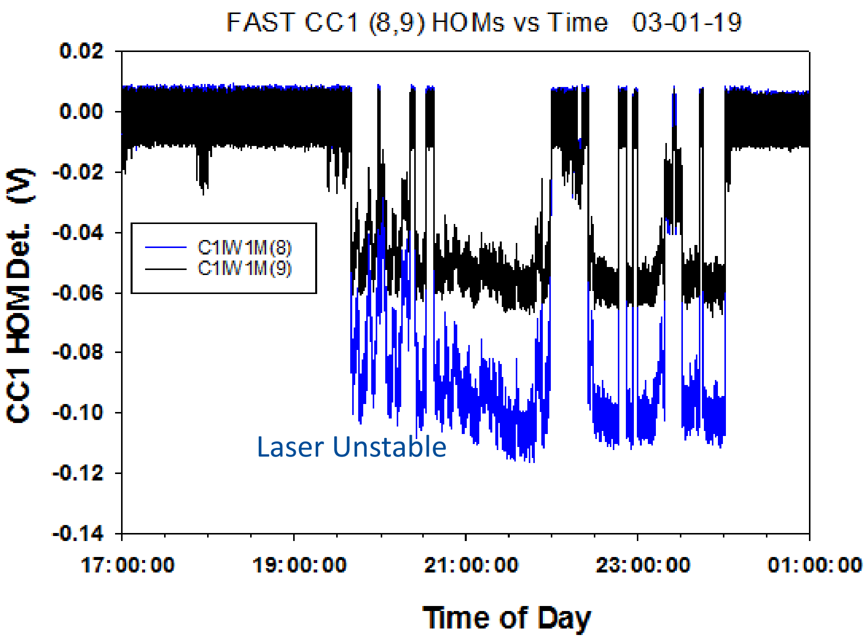


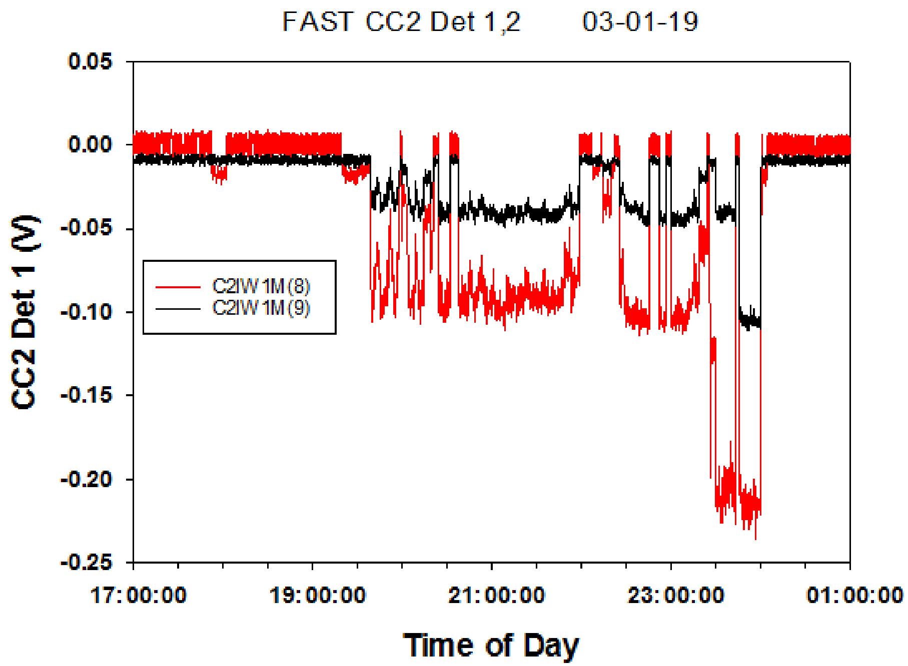


A.H. Lumpkin et al., PRAB, 2018

HOM Detector Signals Tracked During Run 03-01-19

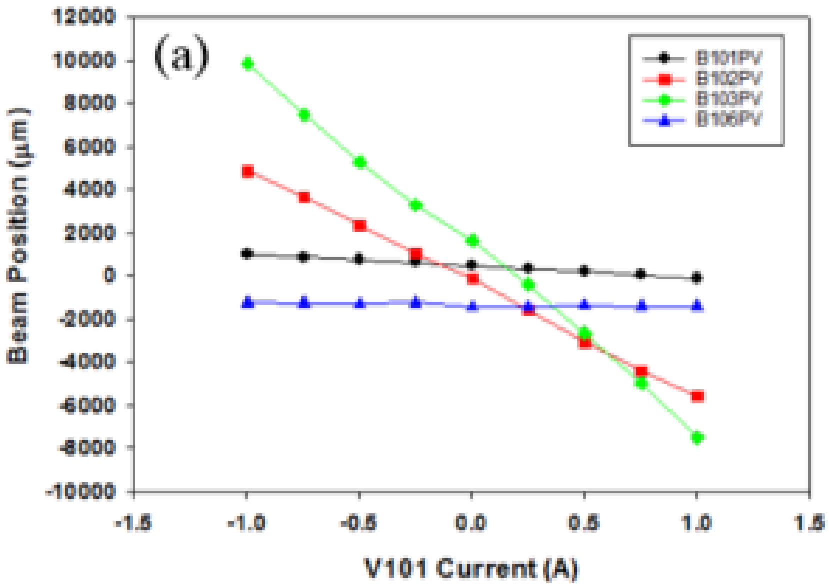
- CC1 detector signals stable after 21:00 when laser stabilized.
- CC2 detectors show effects of V103 current changes.

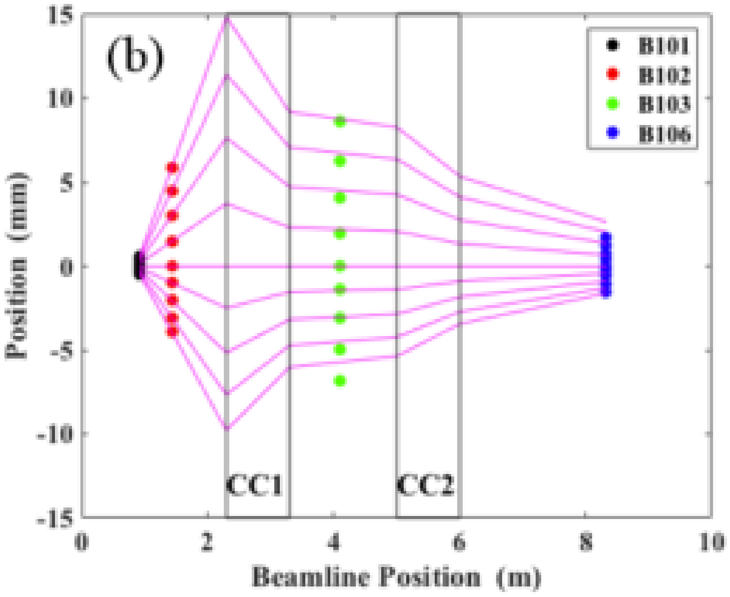




V101 Current Scan Affects Beam Trajectories

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



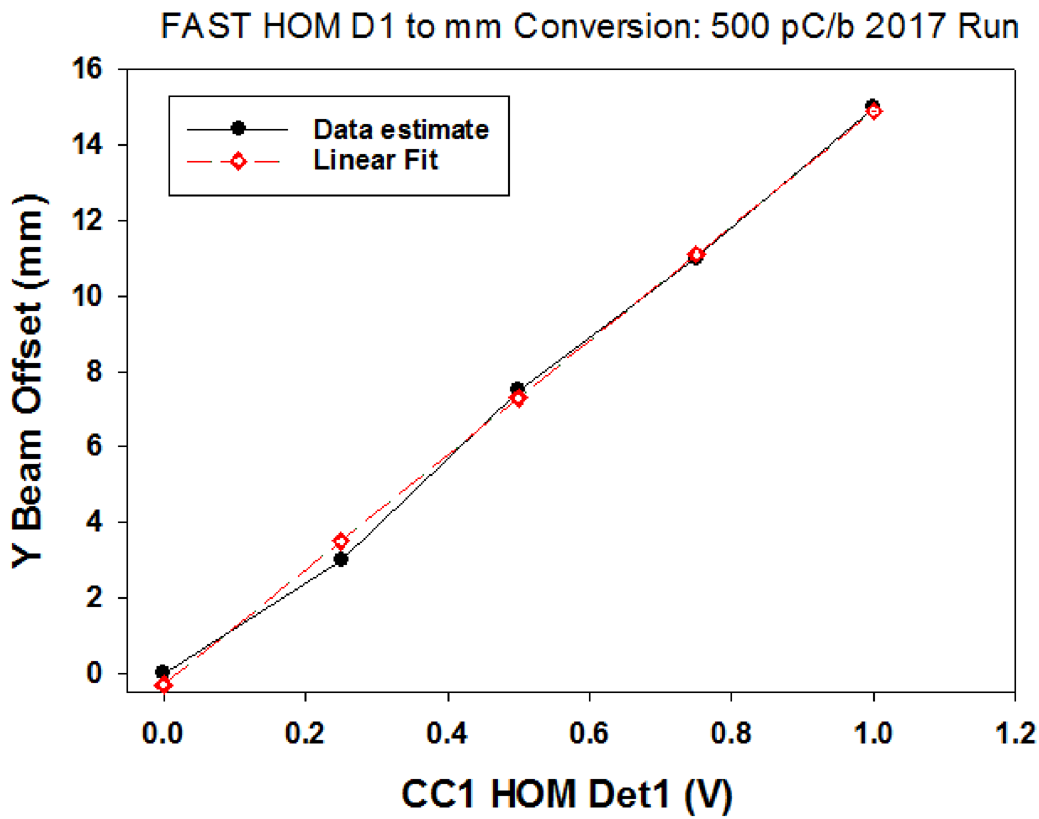


A.H. Lumpkin et al., PRAB, 2018

Beam Offset Monitor (BOM) is 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.

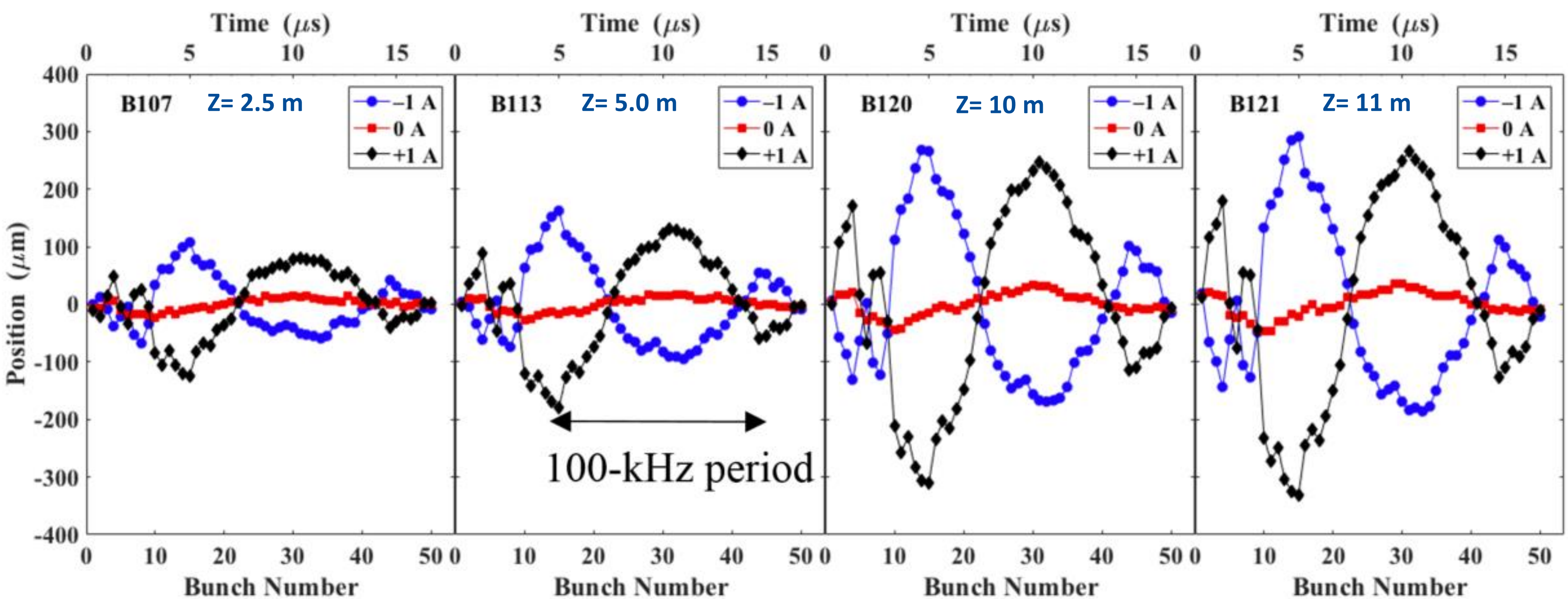
Preliminary



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

Centroid Vertical Oscillations Observed to Grow with Drift

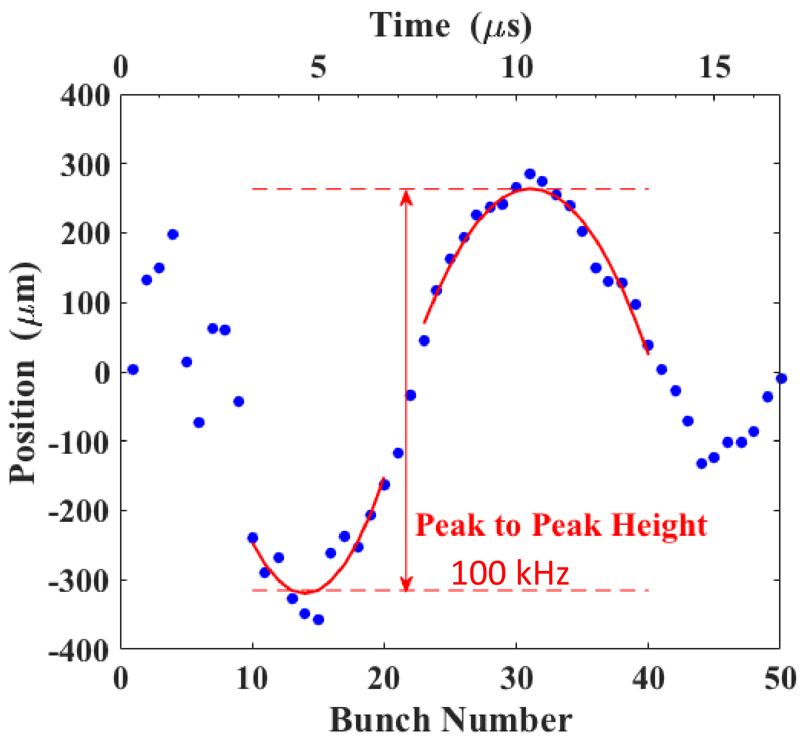
- Comparison of sub-macropulse motion with corrector currents at V101= -1, 0, +1 A. Correlation with excited HOMs. 1000 pC/b
- Attributed to near resonance of beam harmonic and CC2 dipole mode 14 (A.H. Lumpkin et al., Phys. Rev. A-B **21**, June 2018).

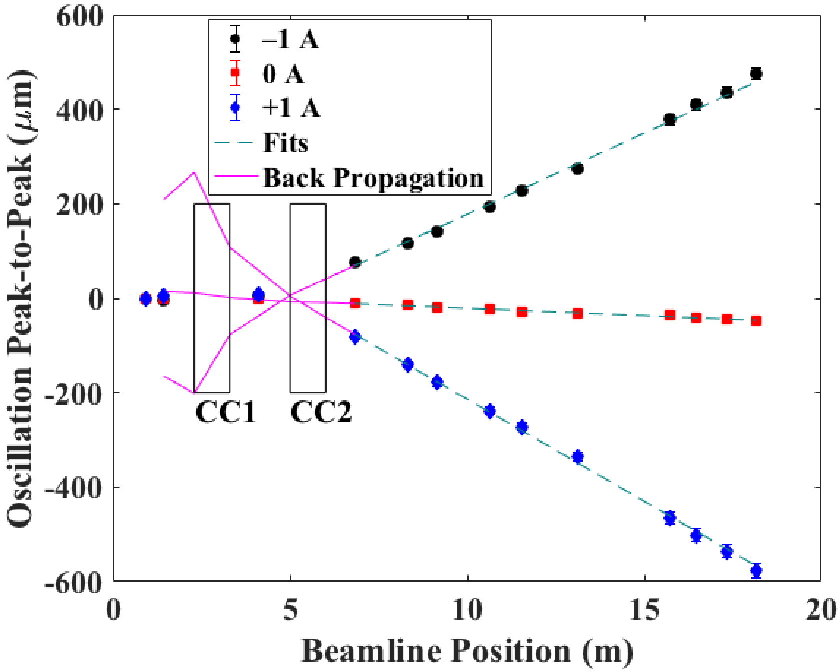


A.H. Lumpkin et al., PRAB, 2018

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.





A.H. Lumpkin et al., PRAB, 2018

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

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

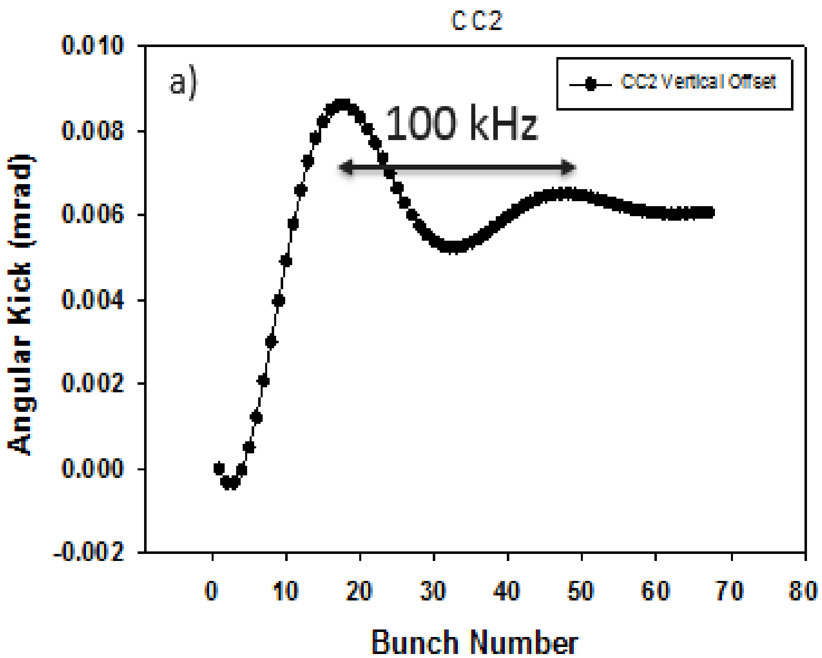
- where $\vec{B}$ and $\vec{E}_\perp$ are the magnetic and transverse electric fields generated by the HOM-exciting bunch, the integral is over the electron path, and *c* is the speed of light. For a series of m bunches, the wake potential at the m^{th} bunch, $\overrightarrow{W}_\perp(s_m)$, is given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

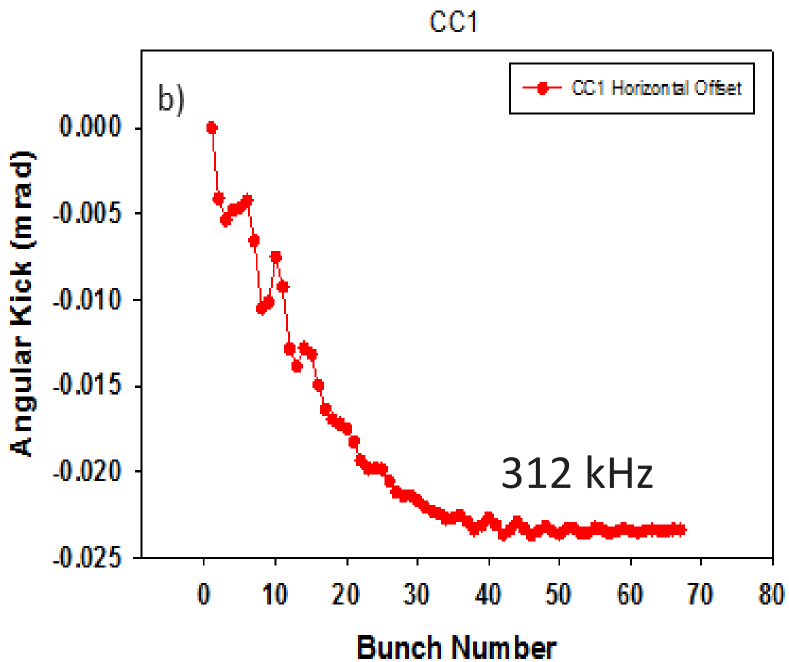
$$\overrightarrow{W}_\perp(s_m) = \vec{r}_0\frac{c}{2}\sum_{k=1}^{m-1}\sum_n\left(\frac{R_\perp}{Q}\right)_n e^{-\frac{\omega_n^2\sigma_z^2}{2c^2}}\sin\left(\frac{\omega_n(s_m-s_k)}{c}\right)e^{-\frac{\omega_n(s_m-s_k)}{2Q_nc}}\cos^2(\varphi_n), \quad (2)$$

- 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.

O. Napoly Source

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.

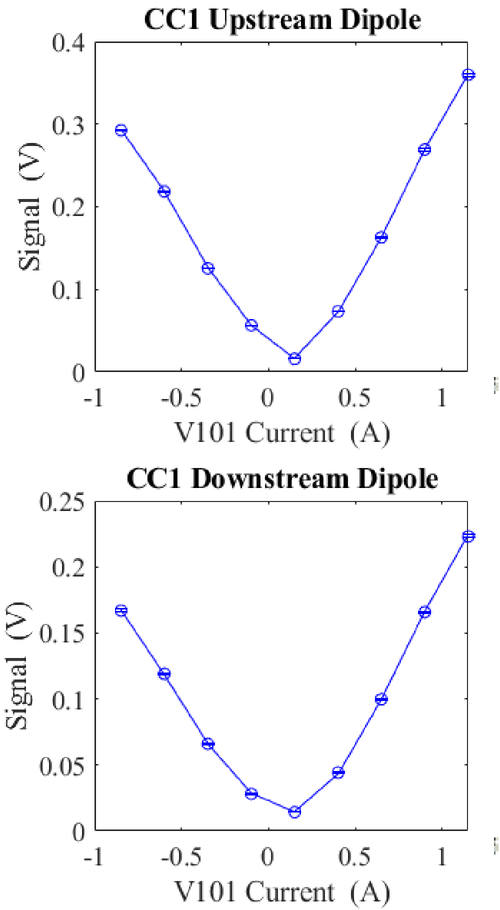
SLAC NATIONAL ACCELERATOR LABORATORY

- CC1 HOMs, scans, 500 pC/b, 50 b, 100-shot averaging.

CC1 Dipolar

US

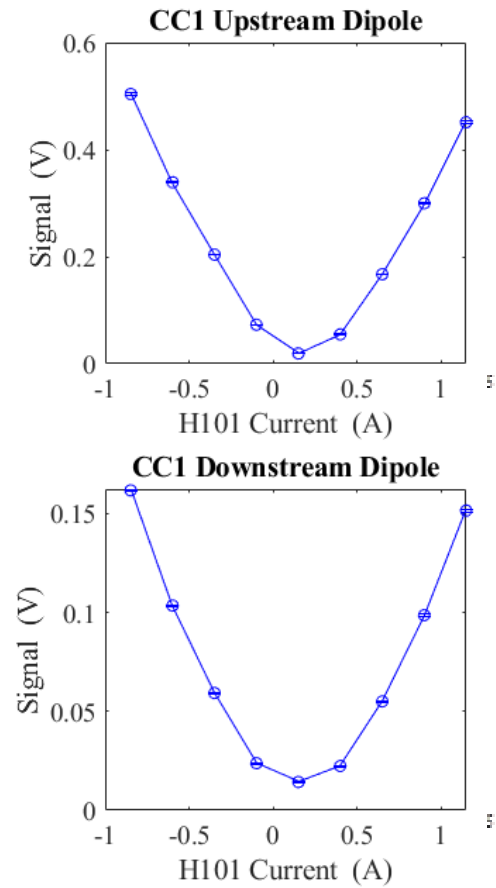
DS



CC1 Dipolar

US

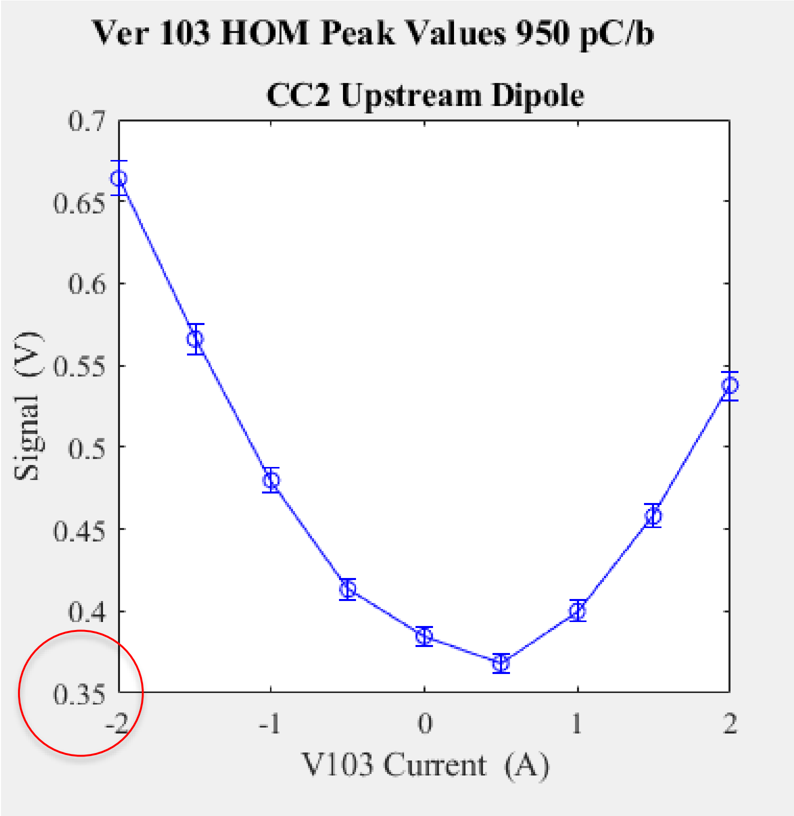
DS

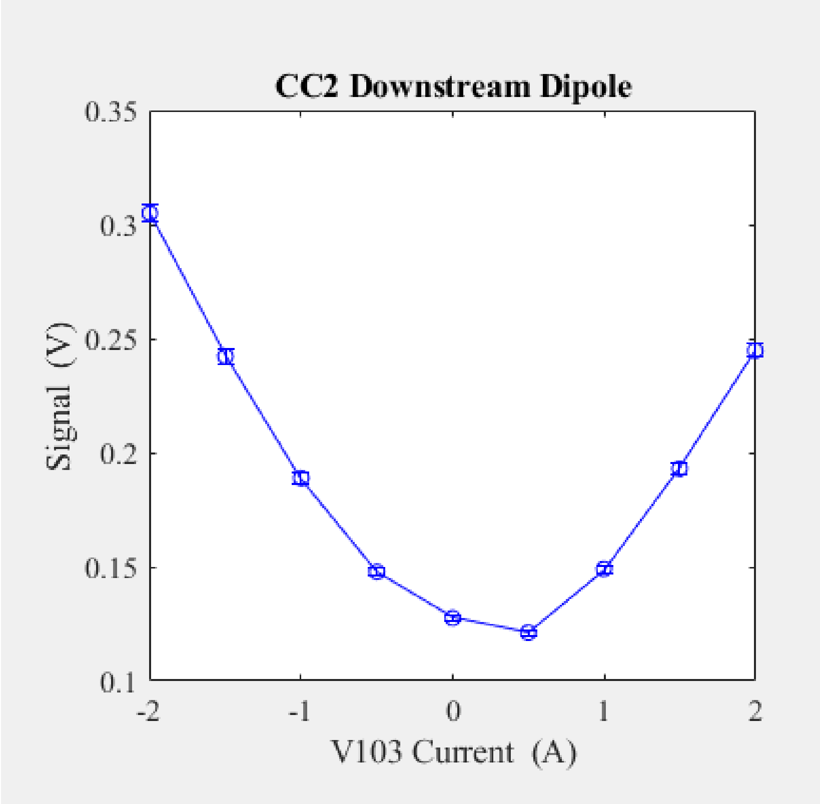


V103 Scan: CC2 HOMS

02-27-20

- HOMs in CC2 active. Relative Minimum at +0.5 A (+1 mrad). Q=950 pC/b, 50b. Scaled to 500 pC/b, US signal is too high.





V. Initial tests for Short-range Wakefield Effects

Initial tests for short-range wakefield effects generated by off-axis steering of the beam into CC1 and CC2. Localize to CC2 with V103 corrector. Use streak camera viewing X121 OTR screen.

Used Prosilica 1.3 Mpix digital camera as readout camera.

- Search for centroid shift *within* the 10-ps long micropulse.
- Search for possible kick compensation by CC2.
- Search for possible slice emittance effect.
- Detect space-charge dominated regime and ellipsoidal beam.
- Distinguish SRW centroid effect from HOMs' effect.
- Compare to numerical model for SRW, transverse effects.
- Compare to ASTRA simulation for SRW, transverse effects.
- Identify and mitigate beam-size growth due to SRWs.

Short-range Wakefield Experiment on LANL Linac 1993

- Streak camera diagnostic showed head-tail kick and observed emittance growth and reduction with steering through normal conducting L-band cavity #4 with 24-mm diam. Iris.
- Q=5 nC/b, ~12 ps sigma,
- Pulse train length 20 µs.
- E =37 MeV.
- Camera in tunnel on lead-shielded optical table.
- AWA and APS/ANL linac relevant.

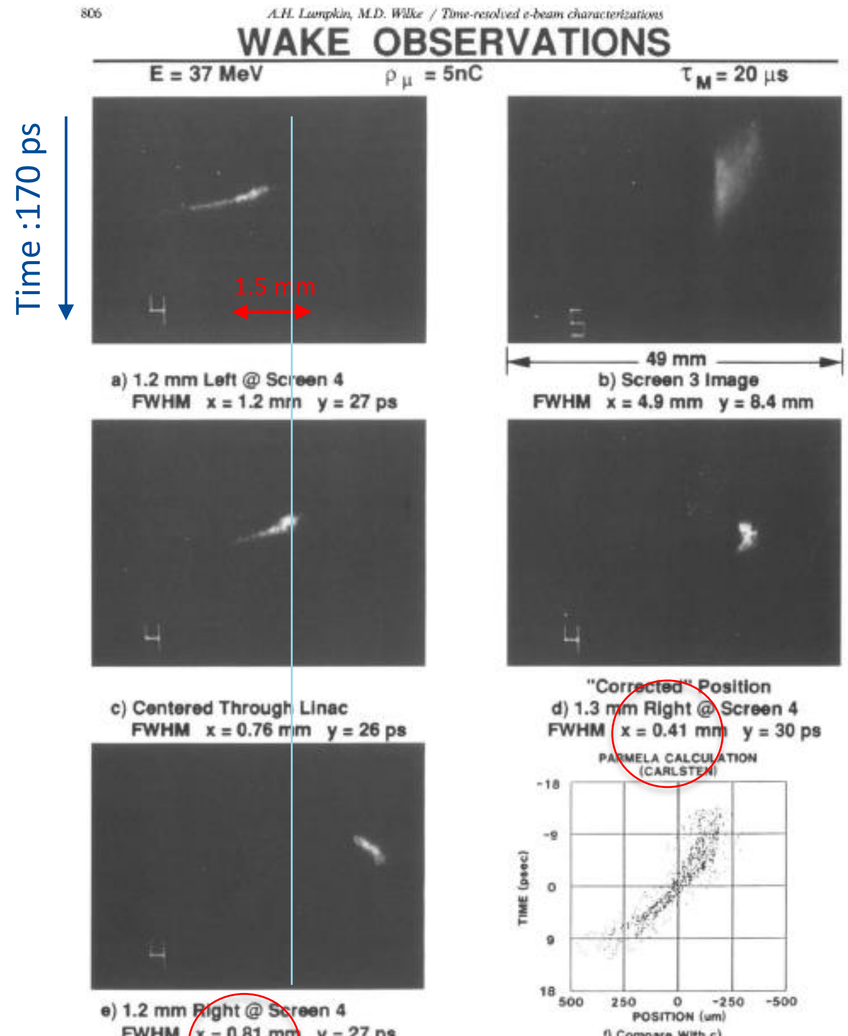
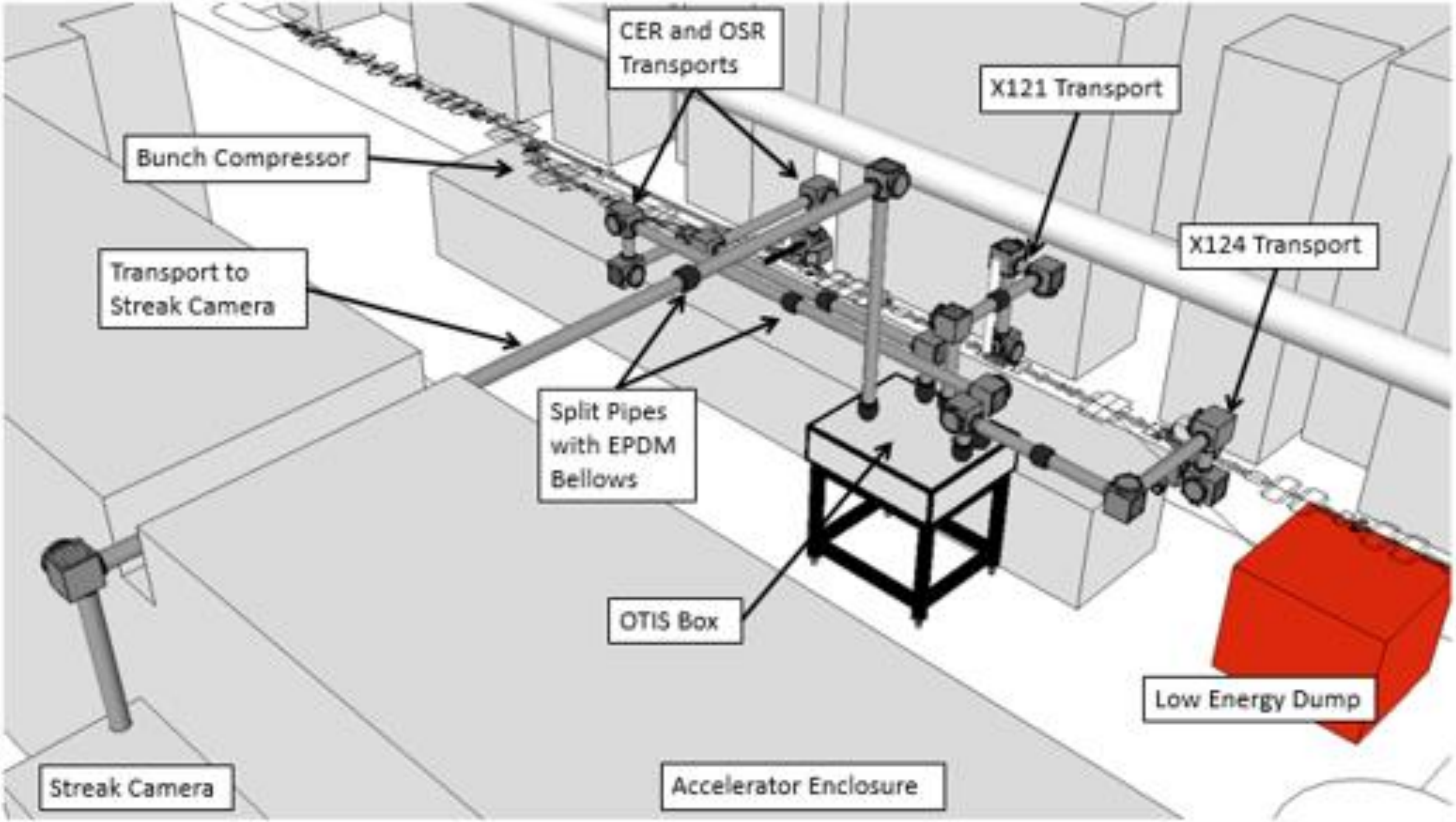


Fig. 6. A composite of streak images at station 4 for steering horizontally "left to right" across the scene. Note the flip in the direction of the head-to-tail kick. Time increases going down on the vertical axis.

A.H. Lumpkin and M. Wilke NIMA (1993)

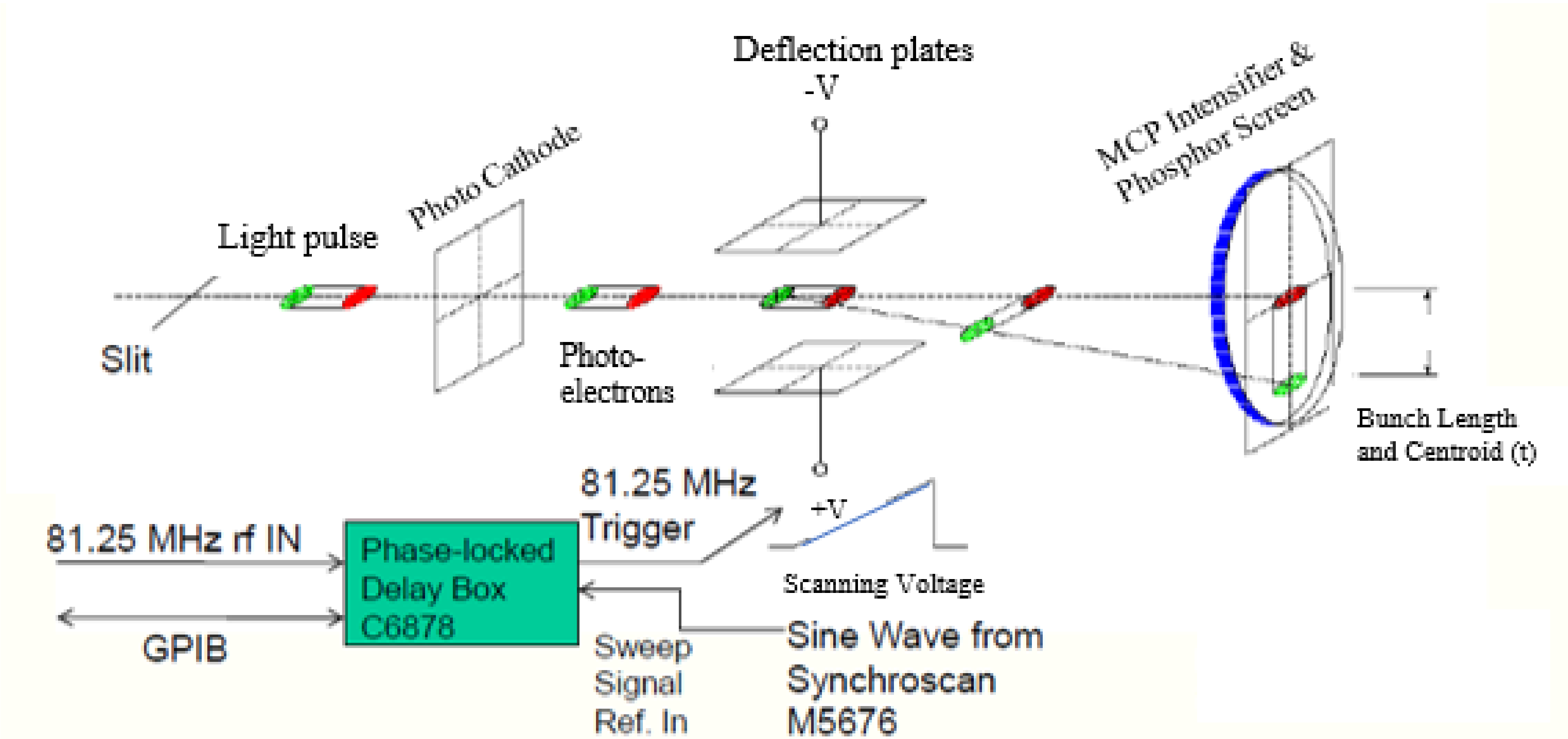
Schematic of Optical transport from X121 to Streak Camera

- All mirror optics used to transport OTR in enclosed line.



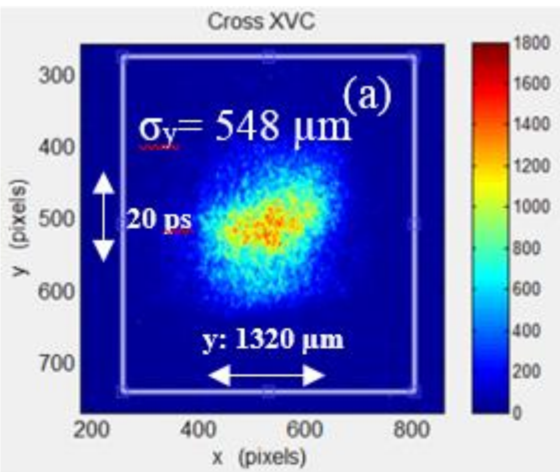
Synchroscan Deflection unit is Phase locked to 81.25 MHz

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.

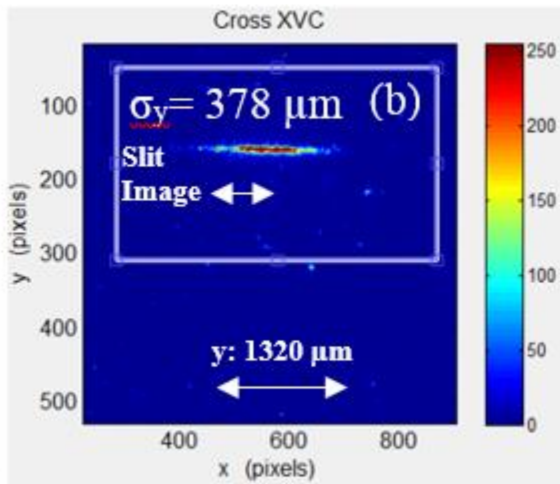


“As found” Steering Shows Submicropulse SRW Effects!

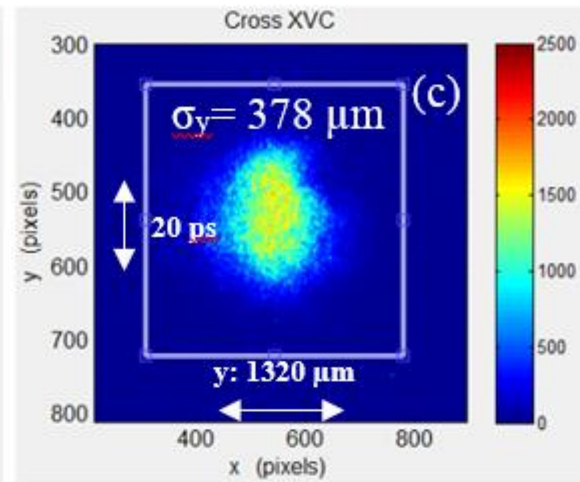
- Beam size dilution due to SRW quantified at >40% in streak camera images (Range 1) at X121 in FAST beamline.
- Laser spot 0.2 mm RMS, Q=500 pC/b, E=41 MeV after CC2.
- Later time is upward in streak image.



HOMs As Found: Machine Learning Opportunity



Focus Image HOMs min.



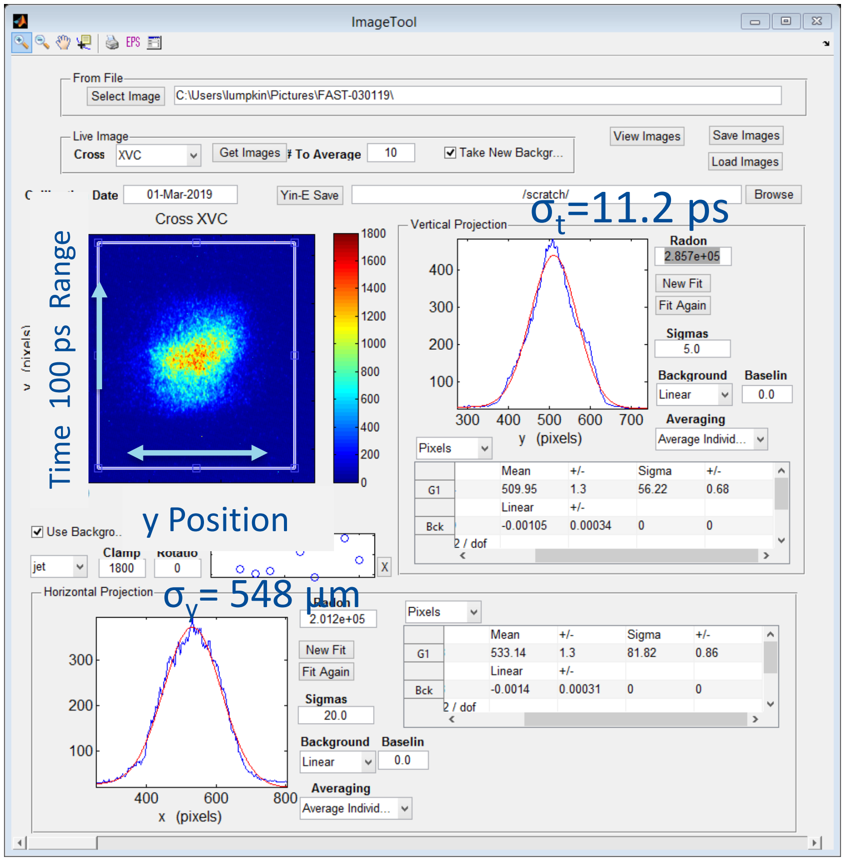
Streak: HOMs Minimized Elliptical y-t shape.

PRAB, publ. 5/4/2020

Initial conditions: HOMs as found, not minimized (03-01-19)

- V103=-0.30 A , sig-t=56.2 ±0.7 pixels => 11.2 ps with 0.20 ps/pix, 150b, 500 pC/b Sigma-y = 82 ±1 pixels. y-t tilt. 10 ave.

y-t tilt:
+343-µm
Shift, H-T.
+40% beam
size effect
@ 378 µm

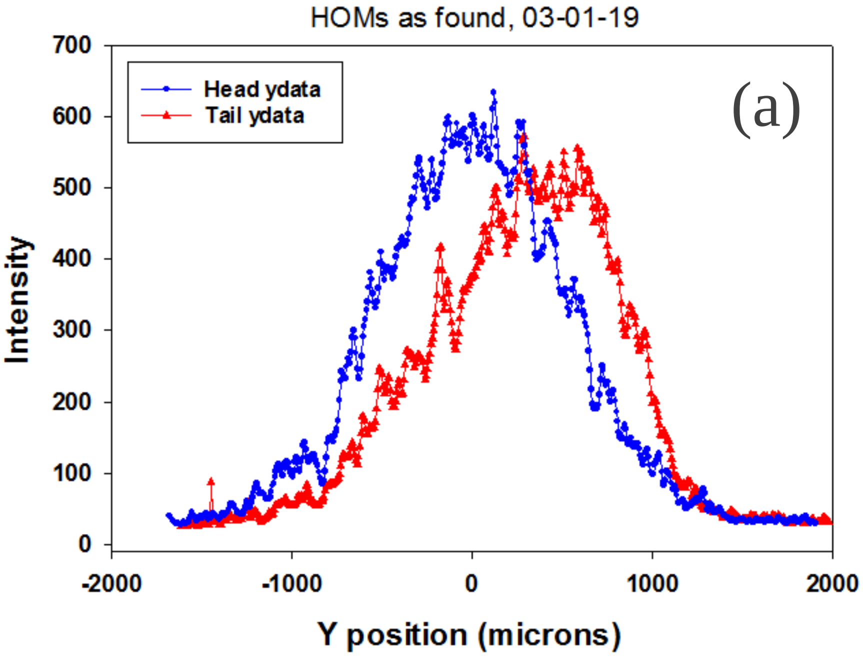


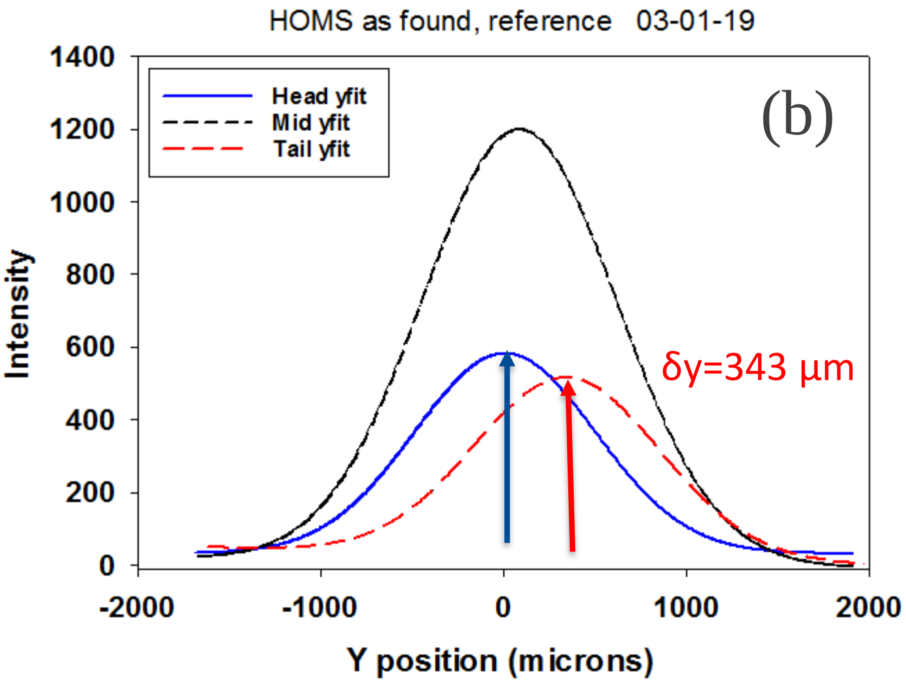
Process Images for:
- Projected y size
- Projected Bunch length
- Slice y size
- Head-tail kick

HOM Detectors
CC1[8]= -100 mV
CC1[9]= -60 mV
CC2[8]= -100 mV
CC2[9]= -50 mV
Offset of 1.5-1.0 mm

HOMS as found, reference, y-t 500 pC/b 03-01-19

- Estimate mm+ off axis, angle with CC1 HOMs;100 mV, 60 mV
- Estimate mm+ off axis, angle with CC2 HOMs;100 mV, 50 mV





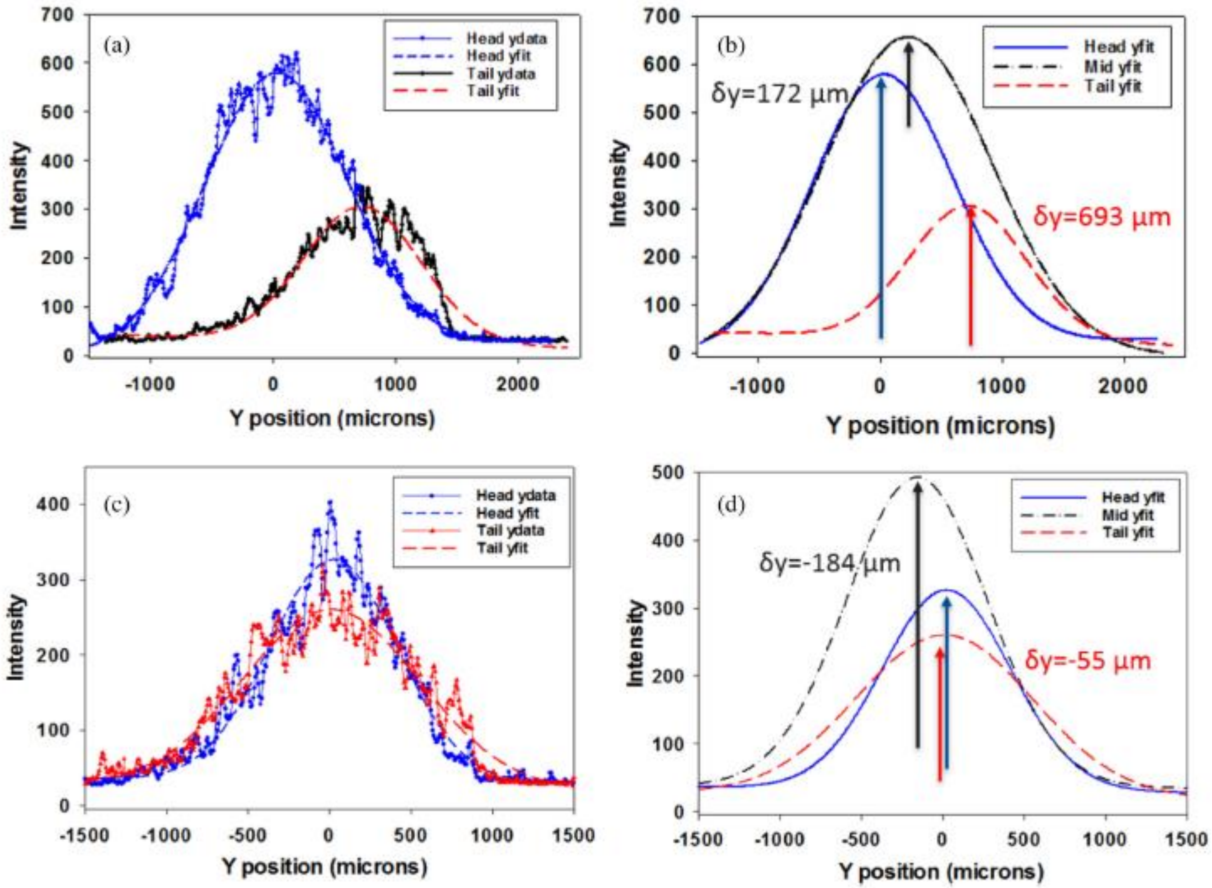
PRAB publ., 5/4/2020

Observed Centroid Shifts within Micropulse Time 03-01-19

- V103= ±2.4 A (±5 mrad) from ref., 500 pC/b, 150b, MCP=61
- Time samples of y profile at Head, Mid, and Tail of micropulse.

+ 5 mrad
Kick enhanced

-5 mrad
Kick Compen-
sated



A.H. Lumpkin et al., PRAB, publ. 5/4/2020

Combined Wakefield Effects of CC1 and CC2 Observed (03-1,8-19)

- Can one compensate kicks within micropulse time scale? Yes.
- Observations in X121 streak camera images 10 m downstream HOMs as found on 03-01-19: 500 pC/b, 150 b, 41 MeV Total.

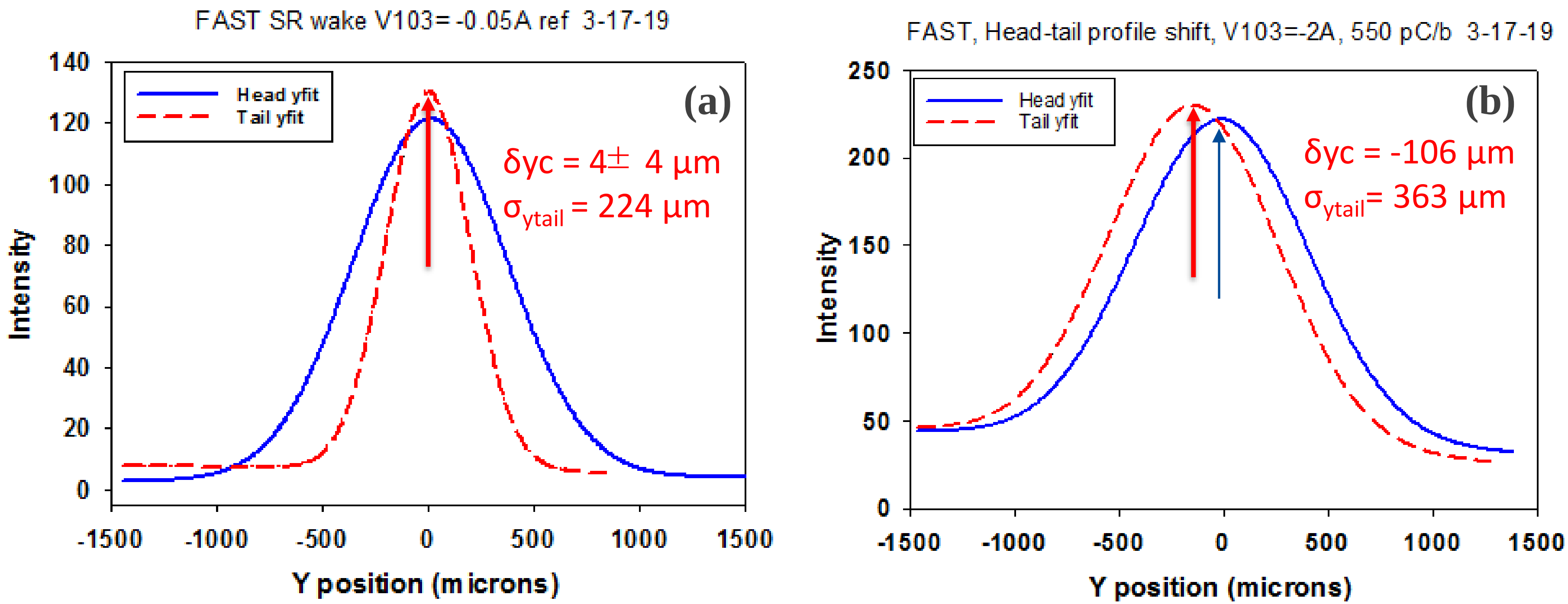
Table 1: Summary of V103, Beam Image parameters, HOMs

Case #	V103 (A)	Head-tail y centroid shift (µm)	Projected y size (µm)	CC1 D1 (mV)	CC1 D2 (mV)	CC2 D1 (mV)	CC2 D2 (mV)
1	Ref (-0.43)	343	548	-100	-60	-100	-45
2	+ 2.4 delta	681	643	-100	-55	-204	-40
3	- 2.4 delta	-55	466	-100	-58	-214	-105
4	"0.0"	4±4	378	-13	-10	-5	-7

Cases 1-3: 16% size reduction, Cases 2-3: 38 % reduction, Cases 1-4: 30 % reduction.
After CC2, rf BPM B104 = +7.4 mm for case 2, -12.4 mm for case 3

y(t) Centroid Shift and Slice Profile Growth Seen 3-17-19

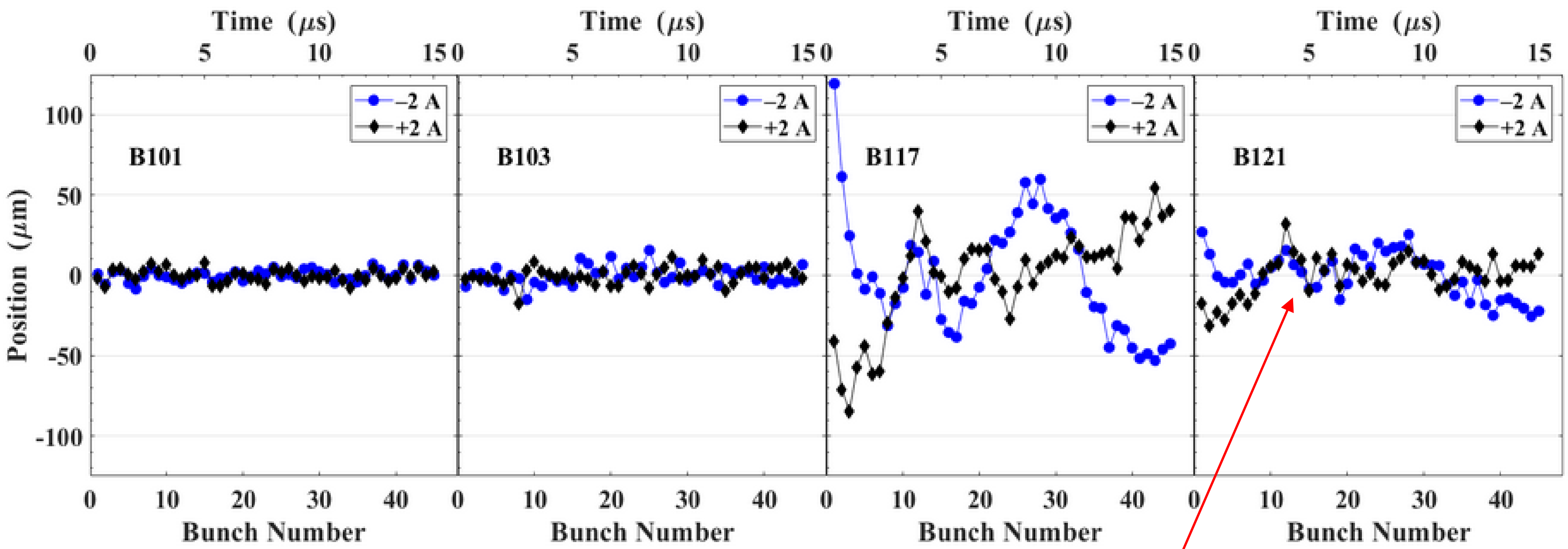
- Comparison of V103= -0.05, delta-2A images shows a -106 µm centroid shift and width change of +140 µm at tail. 1.2 mm VC.
- Observed changes would be slice emittance effect.



A.H. Lumpkin et al., PRAB, publ. 5/4/2020

100-shot Average rf BPM for HOM-induced motion at B121

- 550 pC/b, 50 b, V103= -2A, +2A. ~4-mrad kick angle into CC2.
- 3-17-19 Data.



<20 μm centroid motion at B121, average effect even smaller.

*Data has 50-b mean subtracted.

A.H. Lumpkin et al., PRAB, publ. 5/4/2020

Model of TESLA Cavity for Transverse SRWs used to Predict Effect Scale (Calculations by V. Lebedev)

For Q= 0.5nC, sigma-t=10 ps, 5-mm offset, M_{12}=20 m, 33 MeV, get 100- to 150-µm kick within the micropulse from 1 TESLA cavity's wakefield. We are at 33 MeV in middle of CC2.

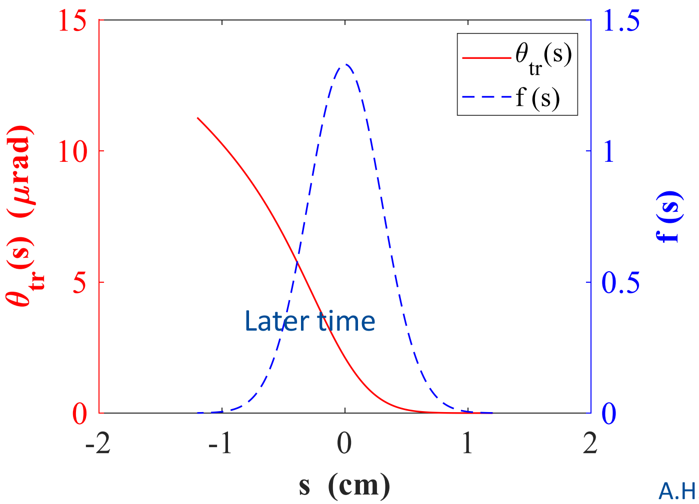
N_{cell} is the number of cells in a cavity, a is the cavity bore radius, g is the cell length, the longitudinal wake γ_{eff} is a fitting parameter, and s is the distance between leading and trailing charges. Parameters for our model cavity are: N_{cell} = 9, a = 3.1 cm, g = 11.511 cm, and γ_{eff} = 0.9 x 10^2.

The transverse wakefield, $W_T(s)$ is given by,

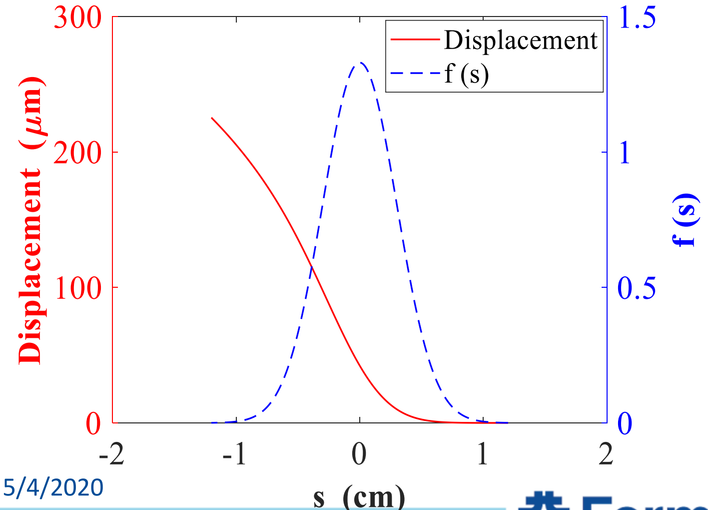
$$W_T(s) = \frac{4N_{\text{cell}}}{\pi a^3}\left\{\frac{5}{4}\left[\sqrt{2g\left(s+\frac{a}{\gamma_{\text{eff}}}\right)} - \sqrt{2g\frac{a}{\gamma_{\text{eff}}}}\right] - s\right\}$$

The transverse kick angle $\theta_{tr}(s)$ is then given by,

$$\theta_{tr}(s) = \frac{e_{conv} e_{SGS} N_e}{P_0} d \int_s^{10} W_T(s_p - s)\, f(s_p)\, ds_p$$



33 MeV,
Δx=5mm
M_{12}= 20 m



A.H. Lumpkin et al., PRAB, publ. 5/4/2020

Table of Scaled Short-Range Wakefield Kick Angles

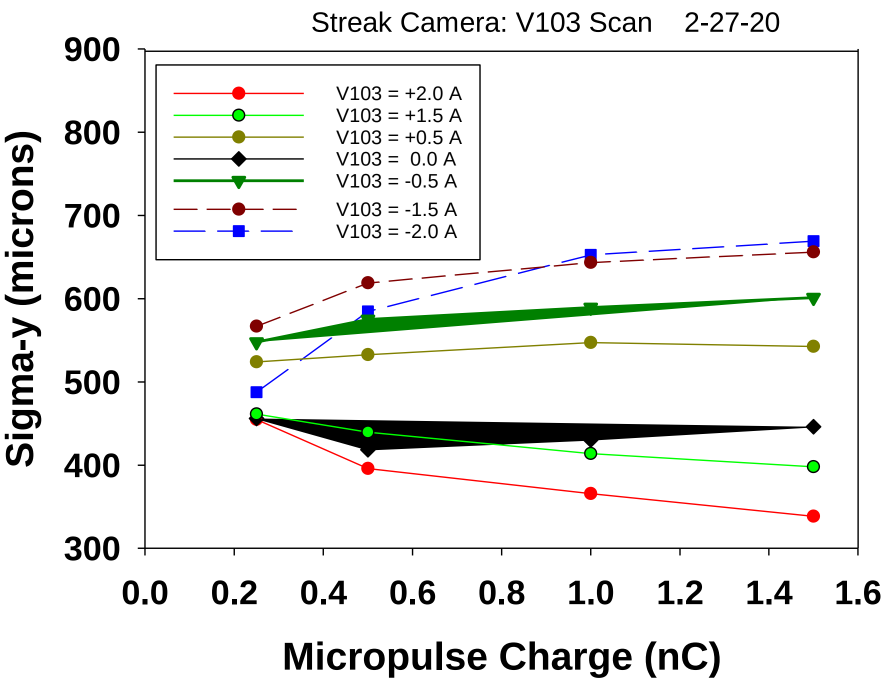
Table 1: Comparison of kicks vs Q and offset referenced to Lebedev case 1 in one cavity at ~50 MeV so 1.5 x for 33 MeV in middle of CC2

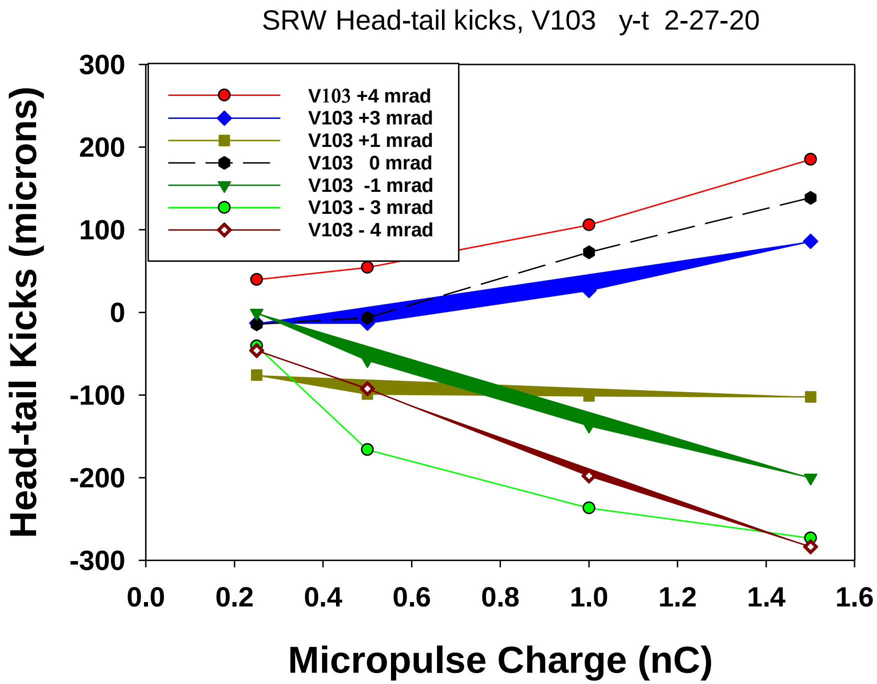
Case. No	Charge (pC)	Offset (mm)	M_{12} (m)	Sigma-t (ps)	Kick θ (μrad)	Offset @ FWHM-point 2 (μm) z=10m	
1 (ref.)	2400	1	10	10	4	40	
2	2400	5	10	10	20	200	
3	1000	10	10	8	16	160	
4	3000	10	10	10	48	480	
5 (33MeV)	500	5	20	10	4	80	

Such effects should be measurable with X121 OTR source and Synchroscan streak camera.

SRW Head-tail kicks from CC2: Streak Camera 02-27-20

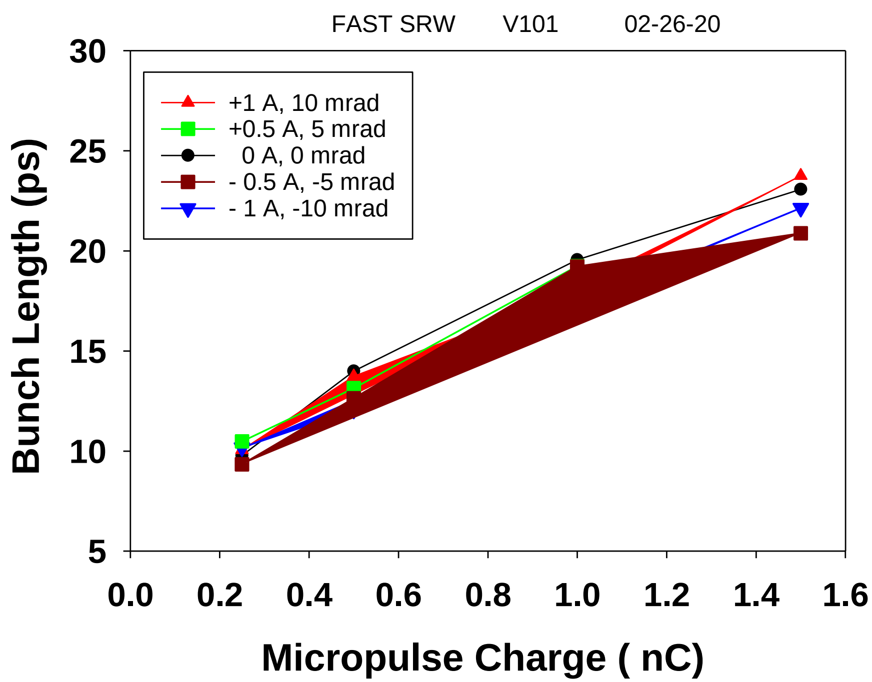
- V103 scan confirms +0.5 A(+1 mrad) is better steering for HOM.
- Projected beam y size lower for +2A (+4 mrad) steering? Cavity focusing effects?

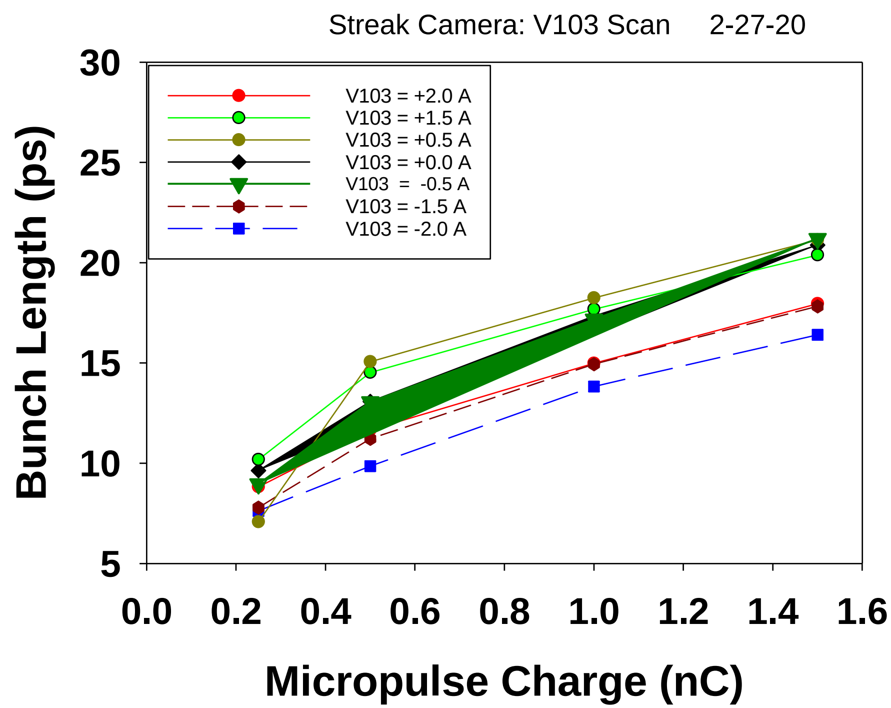




Streak Camera Data Provide Temporal Info 02-26,27-20

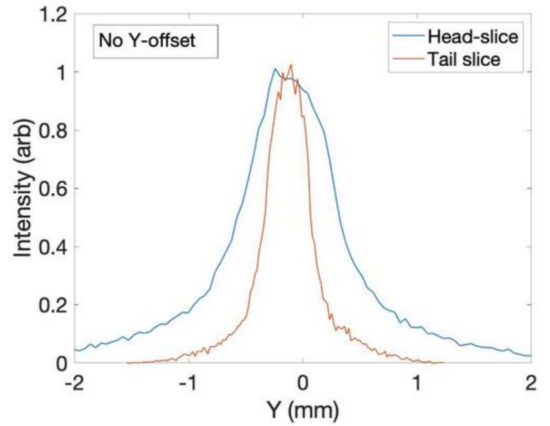
- Clear charge-dependent growth in bunch length for fixed laser spot size: H/V about 450 ± 25 µm x 590 µm on 2 days.
- Curious relatively shorter bunch lengths at higher Q for larger V103 steering. Net dispersion from Correctors or ?

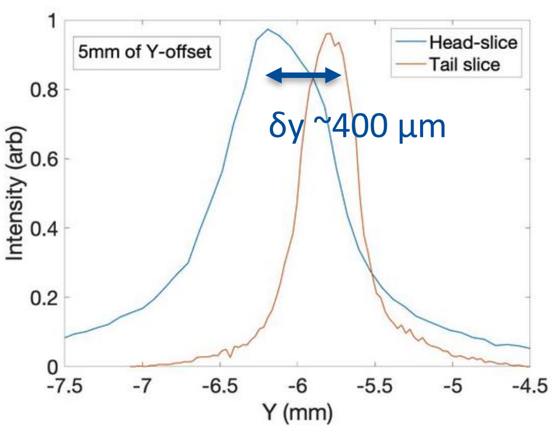




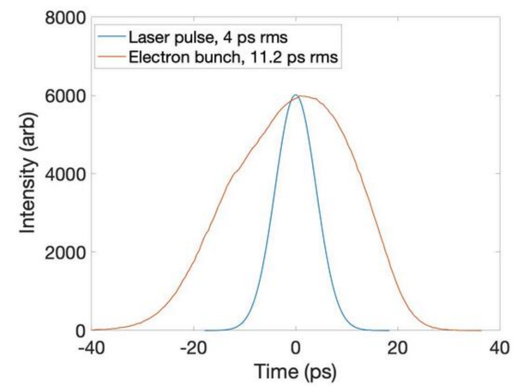
Initial ASTRA Simulation Results for FAST Linac

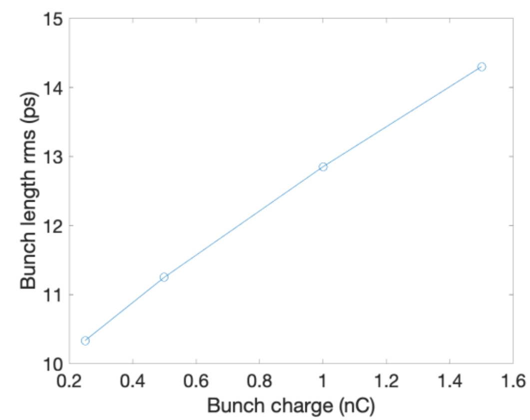
- Preliminary runs show the SRW head-tail kick after CC2 when there is a beam offset of 5 mm into cavities.(Feng Zhou: SLAC)





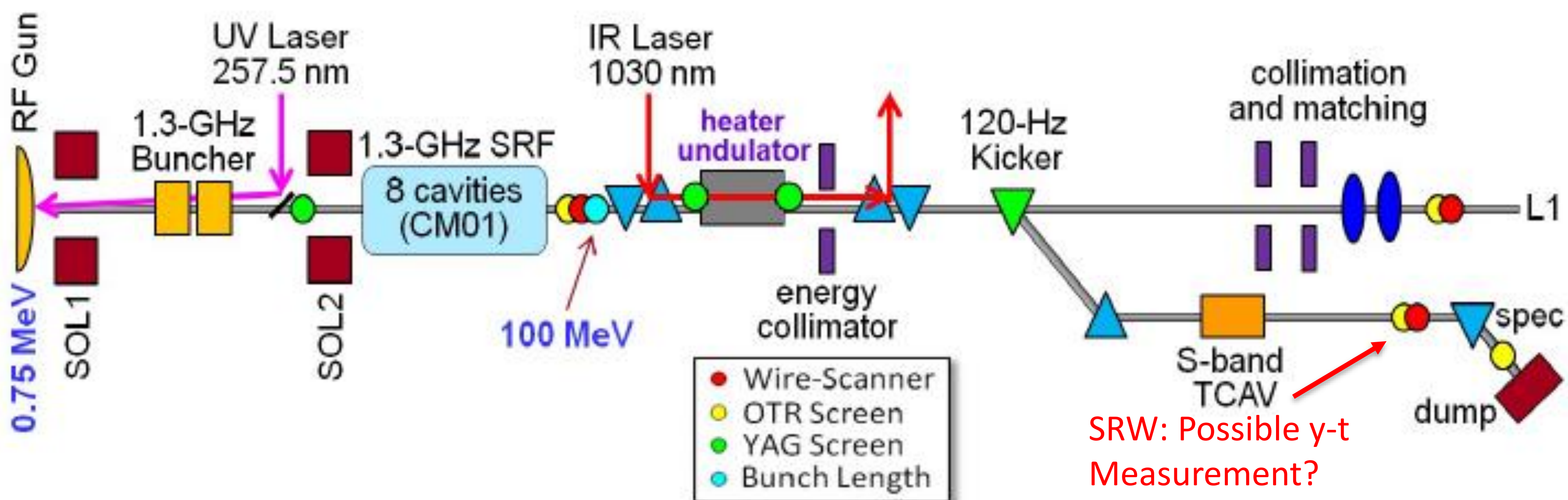
ASTRA Input for FAST case:
Laser spot size =1.2 mm
Laser sigma-t = 4 ps
Laser phase 45^0
Q= 500 pC/b
E=43 MeV
3D fields of TESLA Cavities





Planned Full LCLS-II Injector with Low-energy rf Gun

- Potential short-range and long-range wakefields due to off-axis beam in cavities need to be minimized to preserve emittance.
- HOMs in CM01 tracked. Steering at 1-8 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 CY21.



F. Zhou et al., IPAC2017

Scaling Short-Range Wakefield Effects to LCLS-II Injector

- Angular kick is inverse with energy and linear with charge, offset, M_{12}, cavity number N_{cav}.
- Can approximate effect in LCLS–II CM1 with injection at 1 MeV and cavity 1 at 8 mV/m, Cavities 2,3 at 0 mV/m.

LCLS-II CM1	Fast	$(R_E)^{-1}$	R_Q (pC)	R_{offset}	N_{cav}

- Kick at 5 MeV = 100 µm x 33/5 x 300/500 x 0.5 mm/3mm x1/1
  = 65 µm
- Kick at 8 MeV = 100 µm x 33/8 x 300/500 x 0.5 mm/3 mm x3/1
  = 120 µm
- Kick at 8 MeV = 100 µm x 33/8 x 100/500 x 0.5 mm/3 mm x3/1
  = 40 µm

Need scaling info for M_{12} term. Lower emittance in LCLS-II case.

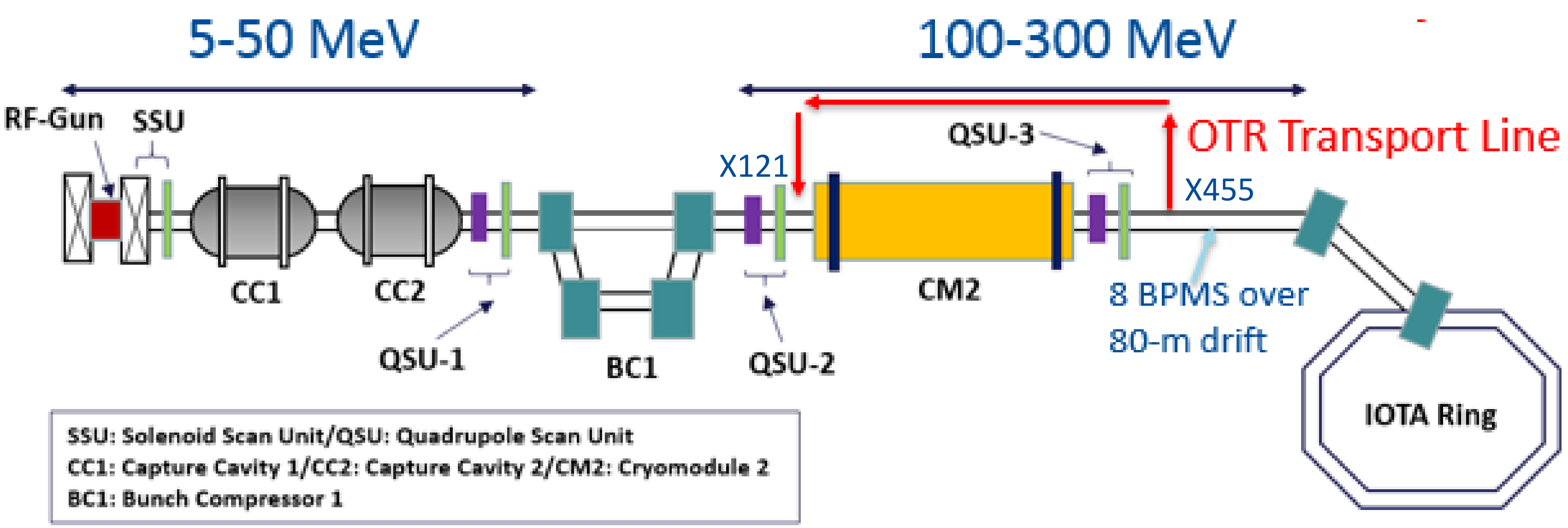
Could use S-band TCAV to look for SRW effects and mitigate?

Proposed New OTR Transport Line from X455 after CM2: R3

- Proposed to repurpose optical transport line hardware for OTR transport from screen X455 located 12 m after CM2.
- This light would be directed to the OTIS box near X121 and then on to the streak camera outside the tunnel.
- The images would be used to identify and mitigate SRWs in CM2 for the first time.
- Such data would inform the LCLS-II injector commissioning.
- OTR foils in X455 screen holder would be sources. 4x Intens.
- Additional beam splitter and port would be added to the Thorlabs optical transport line as done at X124. Need a lens.
- Alignment laser beam could be injected at illumination light port with its beam splitter rotated 90 deg.
- No beamline vacuum entry if thin OTR foils are flat enough.

Techniques May be Applied to FAST Cryomodule

- Possible 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, 8 SLAC HOM det., Run 3
- Add OTR transport line from X455 to X121 for SRW study of CM2 in Run 3 extended.



Revised YMS

Machine Learning Application: Emittance Dilution Mitigation

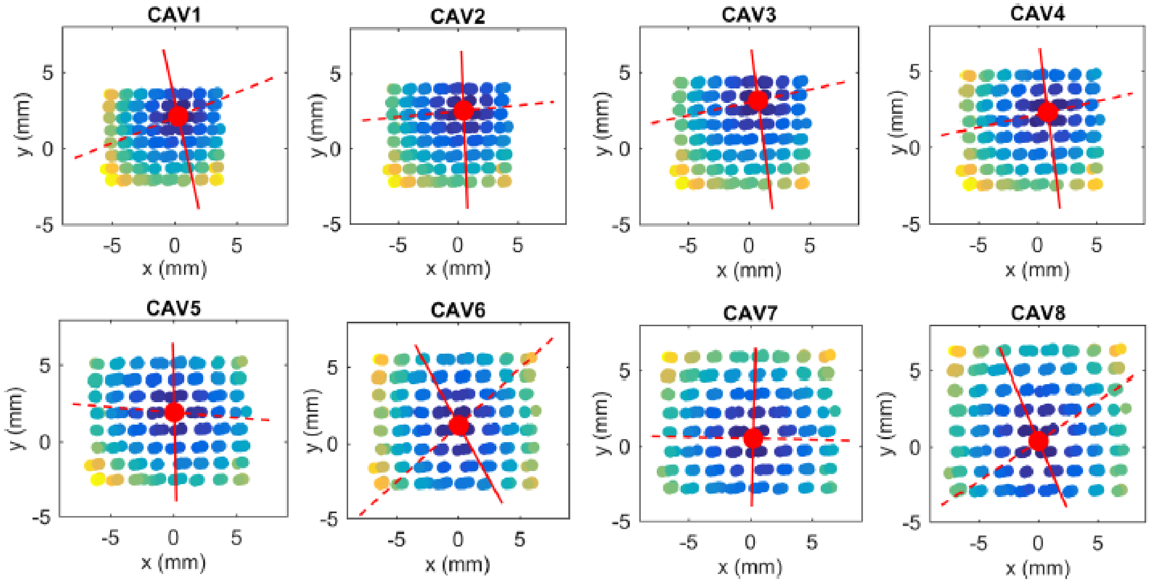
- FAST: 3 H/V correctors, 4 HOM detectors, 10 rf BPMs, Streak camera, Imaging screen, Injection at 4.5 MeV into first of two cavities. We already have a data base for training ML app.?
- LCLS-II injector: 4 H/V correctors, Sol. 1,2, 16 HOM channels, imaging screen, TCAV beam line with OTR or YAG screen. Injection at <1 MeV into CM first cavity.
- There is demonstrated emittance dilution from both LRW and SRW, although SRWs had bigger effect at FAST linac.
- Simplest objective is to minimize the HOM signals in all detectors by steering, but there could be special cases in a CM.
- May want to choose CM01 carefully on its cell/cavity centering rms value for LCLS-II injector.

FLASH Cryomodule Cavity Misalignments Measured

- Down converter electronics applied TE_{111}-6 mode at ~1.7 GHz
- FLASH ACC5 cavity misalignments were measured.

"The dots are color coded by the relative signal strength, giving a bright yellow point at 1 and dark blue at 0. The red dots indicate the fitted cavity centers. Polarization axes are indicated."

Cryomodule axis determined with upstream BPM and CM downstream cold BPM and beam drift with rf off.



Wei et al., PRAB (2019)

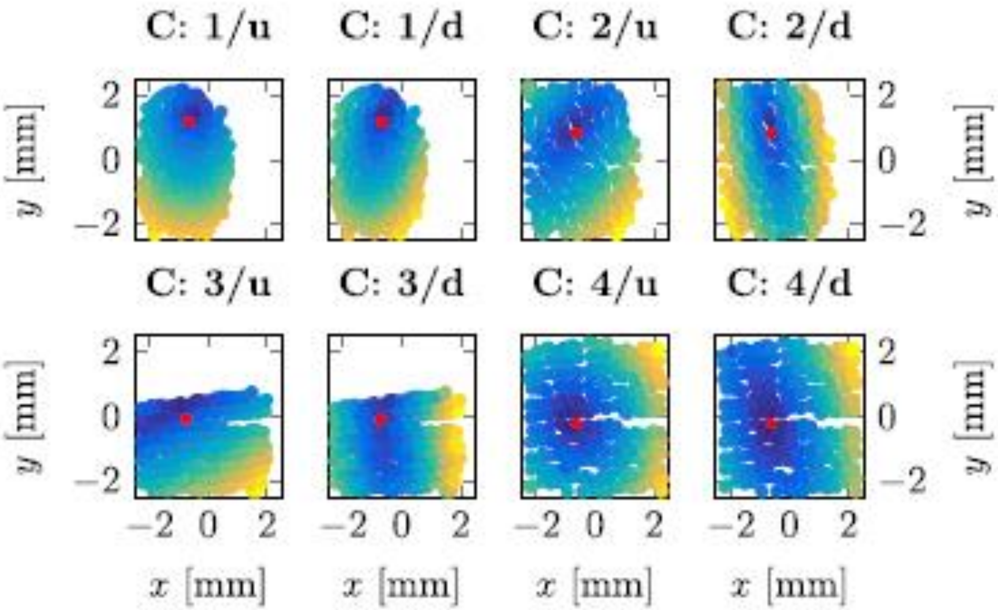
FLASH Injector Cryomodule Misalignments Measured

- Down converter electronics at TE_{111}-6 mode at 1.7 GHz.
- Injection cryomodule, AAC1 cavity misalignments measured at 1+mm level vertically in two ,-1 mm horizontally in first four.
- Our data at CC1 and CC2 appear very relevant to FLASH.

Cavity#, Upstream (u) and downstream (d) detectors are indicated.

"The dots are color coded by the relative signal strength, giving a bright yellow point at 1 and dark blue at 0. The red dots indicate the fitted cavity centers."

Cryomodule axis determined with upstream BPM and CM downstream cold BPM and beam drift with rf off.



T. Hellert et al., PRAB (2017)

VII. SUMMARY-1 Short-Range Wakefields

- Generated, measured, and mitigated y-t effects consistent with SRWs calculated with a numerical model and ASTRA.
- Evidence for submicropulse centroid shifts and slice emittance effects. Unique results for TESLA-type cavity.
- Demonstrated kick compensation in CC2 within micropulses.
- Relevance to LCLS-II injector commissioning noted with their <1 MeV beam injection into a buncher and a cryomodule.
- FEL19 and earlier contacts led to collaboration with SLAC staff on studies shifts at FAST/FNAL in FY20.
- Plan to run with lower cavity gradients in FAST Run 3 this Fall to obtain larger kick angles for same charge and offset.
- Full article accepted in Phys. Rev. Accel. and Beams, April 2020 on FY19 experiments presented today.

VII. SUMMARY-2

- Noticeable correlations of the V103= +0.5 A (1 mrad) steering giving CC2 US and DS HOM relative minima, a reduced centroid oscillation at B117, and reduced head-tail kick at X121.
- The CC2 HOM value scales to ~180 mV, implies 2-3 mm offset.
- Beam offset monitor demonstrated for cavity quench protection: LCLS-II interest. Single-bunch sensitivity also shown.
- Discussions ongoing with DESY on the relevance of the SRWs for the FLASH and European XFEL injector cryomodules.
- Plan to explore SRW relevance to the Superconducting Test Facility (STF) in Japan and the conceptual ILC injector.
- Tremendous opportunity exists to extend SRW studies to CM2 in particular, and cryomodules in general, if a critical optical transport line is installed this year. (Request submitted).

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- B. Jacobson, J. Sikora, F. Zhou, A. Edelen (SLAC) on LRWs/SRWs in FY20

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