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# Observations of Long- and Short-Range Wakefield Effects on e-Beam Dynamics in TESLA-type Superconducting RF Cavities

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Accelerator Physics Seminar at DESY

03 September 2019

Hamburg, Germany

# OUTLINE

I. Introduction

II. Strategy to measure 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 tests, HOM effects within macropulse will be presented as context. (PRAB-2018)

V. Initial observations of short-range wakefield effects and head-tail kick *within* micropulses.

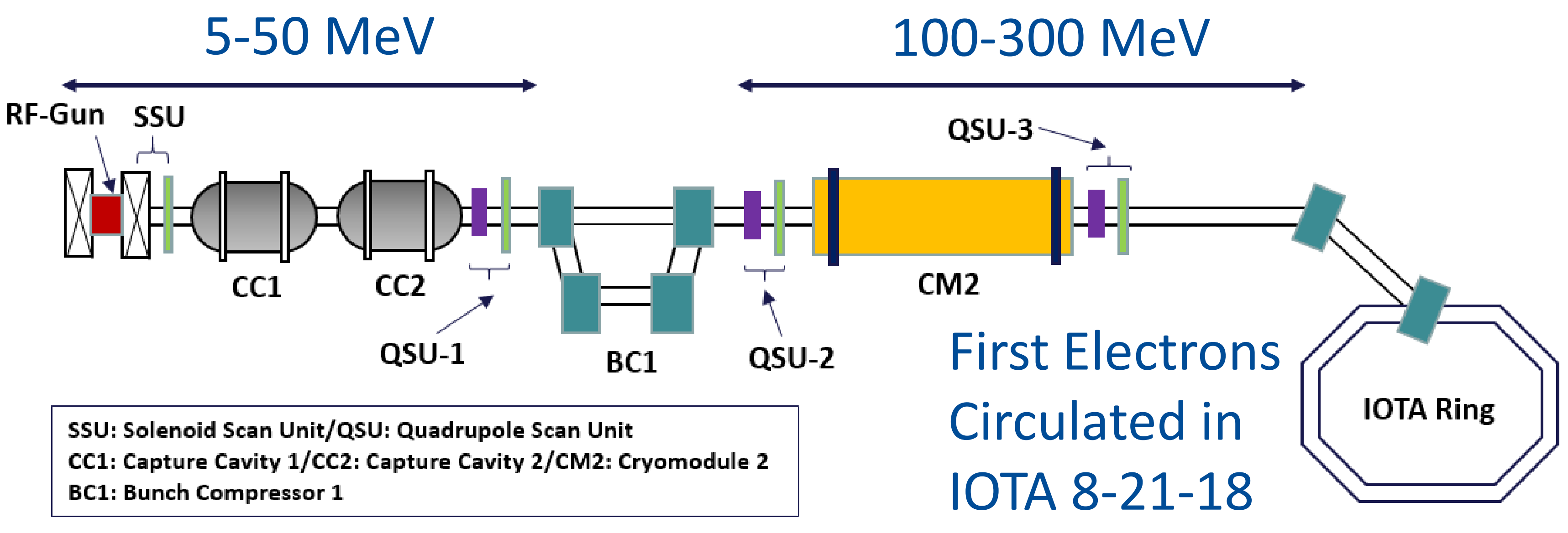
VI. Summary.

# I. 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 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 effects in L-band, 9-cell TESLA-type superconducting rf 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 and sub-micropulse effects on beam transverse position centroids correlated with off-axis beam steering in TESLA-type cavity at the Fermilab Accelerator Science and Technology (FAST) Facility.
- We used a unique two separated-single-cavity configuration, and targeted diagnostics (bunch by bunch rf BPMs, streak cam.) for these tests.

# FAST/IOTA Facility

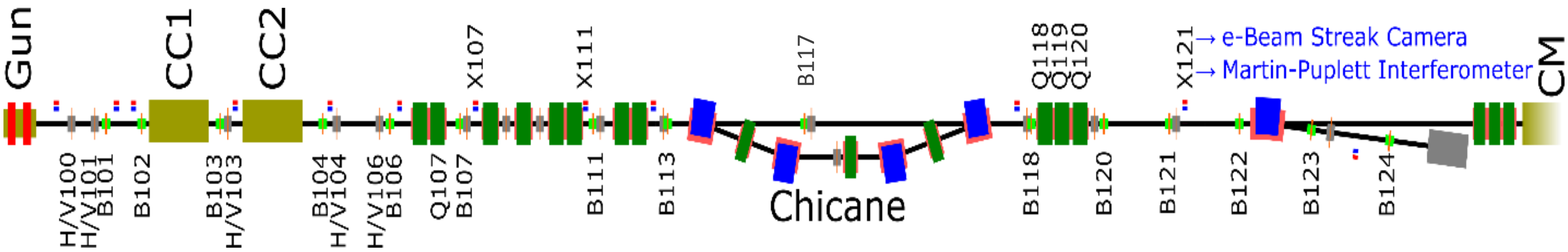
- The Fermilab Accelerator Science and Technology (FAST) Facility is based on a photocathode rf gun and TESLA-type superconducting rf accelerators.
- 300-MeV milestone with full 31.5 MV/m average gradients in cryomodule (CM) attained in November 2017.




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.
- 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, $\sigma_t$ =10ps, and Q~2.4 nC. (V. Lebedev calc.)



# Table 1. FAST Electron Beam Parameters for Studies

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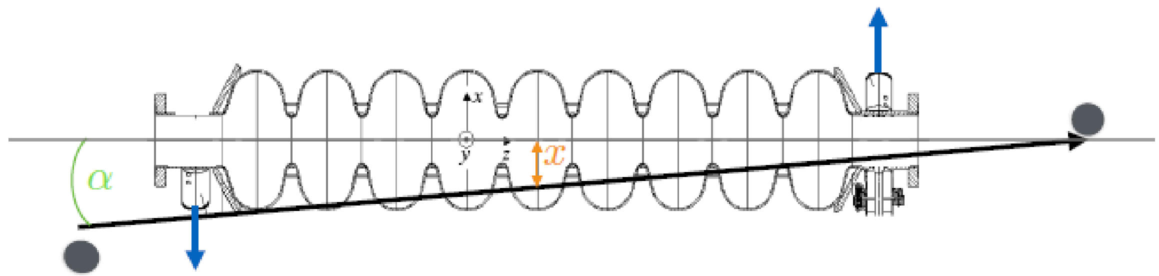
| Beam Parameter | Units | Value | | |
|---|---|---|---|---|
| Micropulse Charge (Q) | pC | 100-1000 | | |
| Micropulse rep. rate | MHz | 3 | | |
| Beam sizes, σ | µm | 100-1200 | | |
| Emittance, σ norm | mm mrad | 1-5 | | |
| Bunch length,σ<br>Compressed | ps<br>ps | 4-10<br>1-3 | | |
| Total Energy | 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

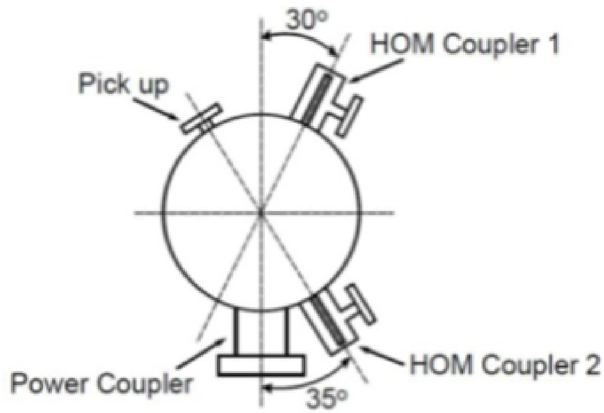
- **TESLA cavity**
  - 2 HOM couplers
- **Dipole HOM**
  - $V_x(t) \propto x \cdot e^{-\frac{t}{2\tau}} \sin(\omega t)$
  - $V_{x'}(t) \propto x' \cdot e^{-\frac{t}{2\tau}} \cos(\omega t)$



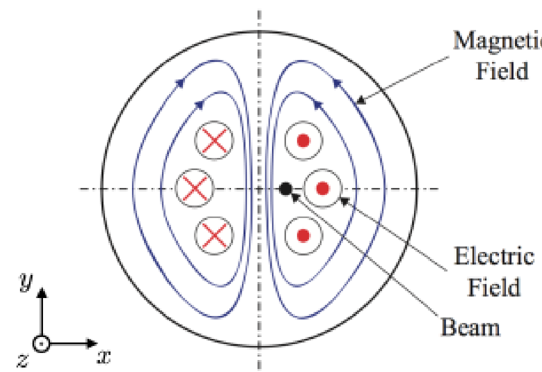

Expected HOMs in TESLA Cavities*

| Mode # | Freq.(GHz) | R/Q ($\Omega/cm^2$) |
|---|---|---|
| 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

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T. Hellert 7/11/17 DESY Seminar

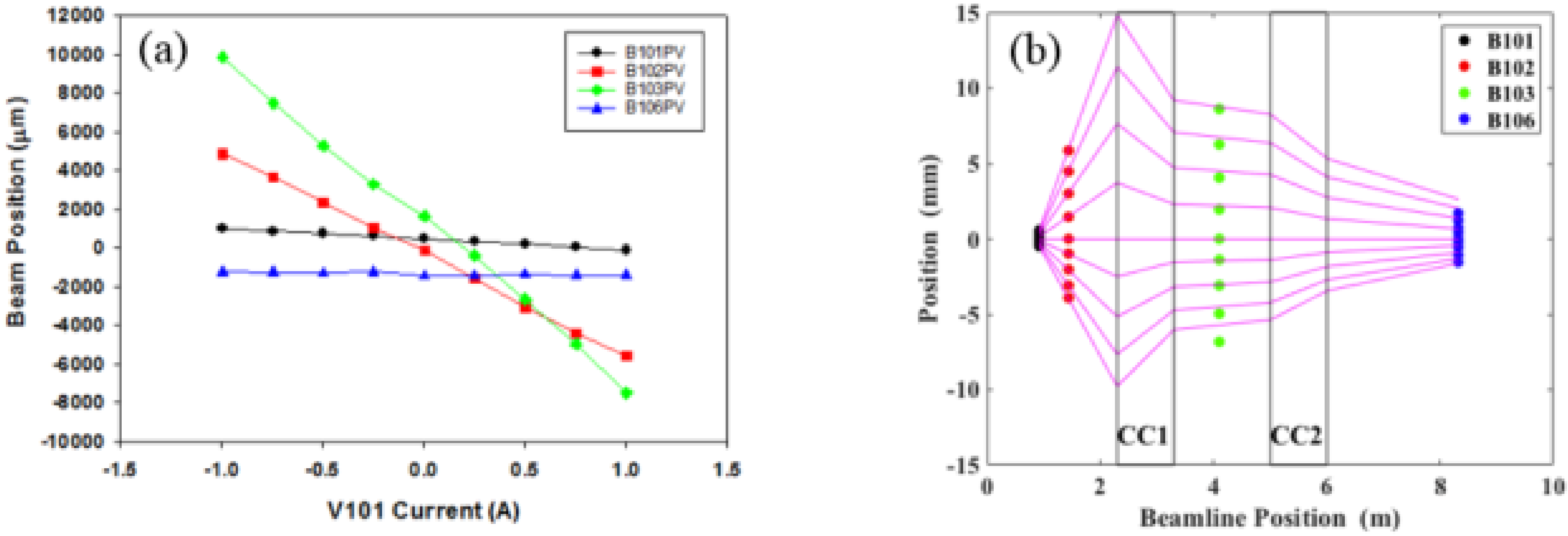
# IV. Initial tests for Long-range Wakefield Effects (HOMs)

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.

# V101 Current Scan Affects Beam Trajectories

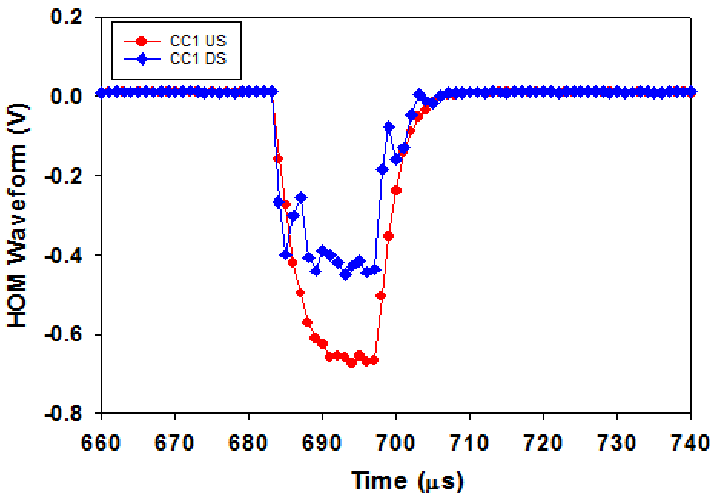
- Tracking of beam trajectories around CC1 and CC2.
- BPM data (a) and calculated trajectories using cavity transfer matrix (b) (ref. E. Chambers (1965))

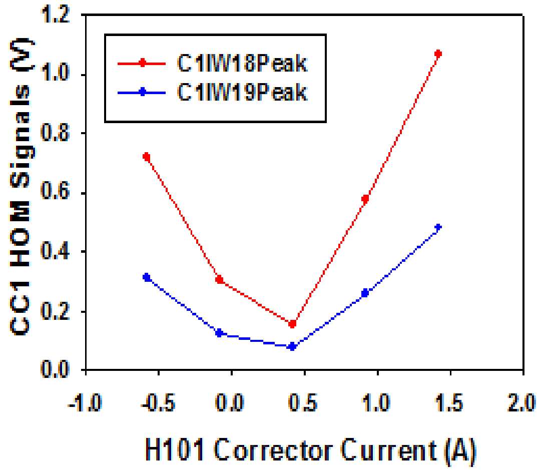


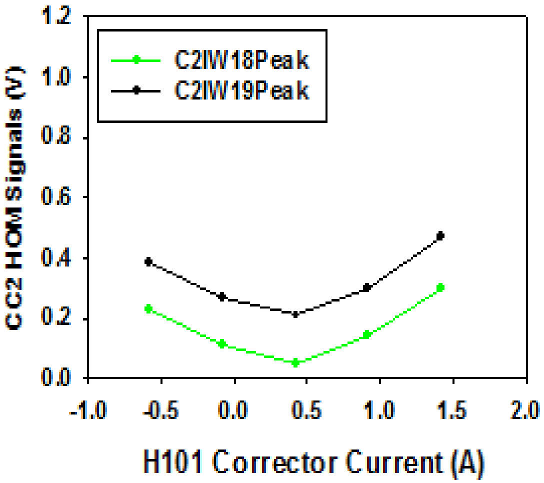
# H101 scan: HOM Signals Observed from CC1 and CC2

- 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



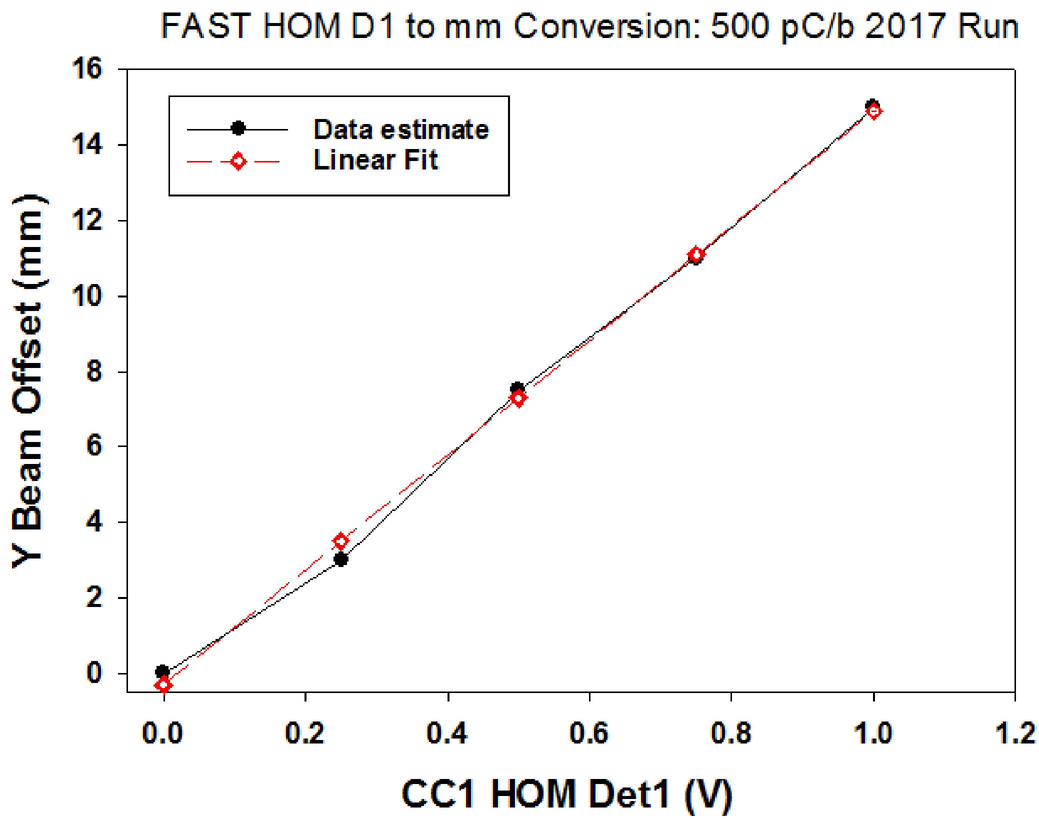



# Beam Offset Monitor (BOM) seems Feasible with HOMs

- 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.

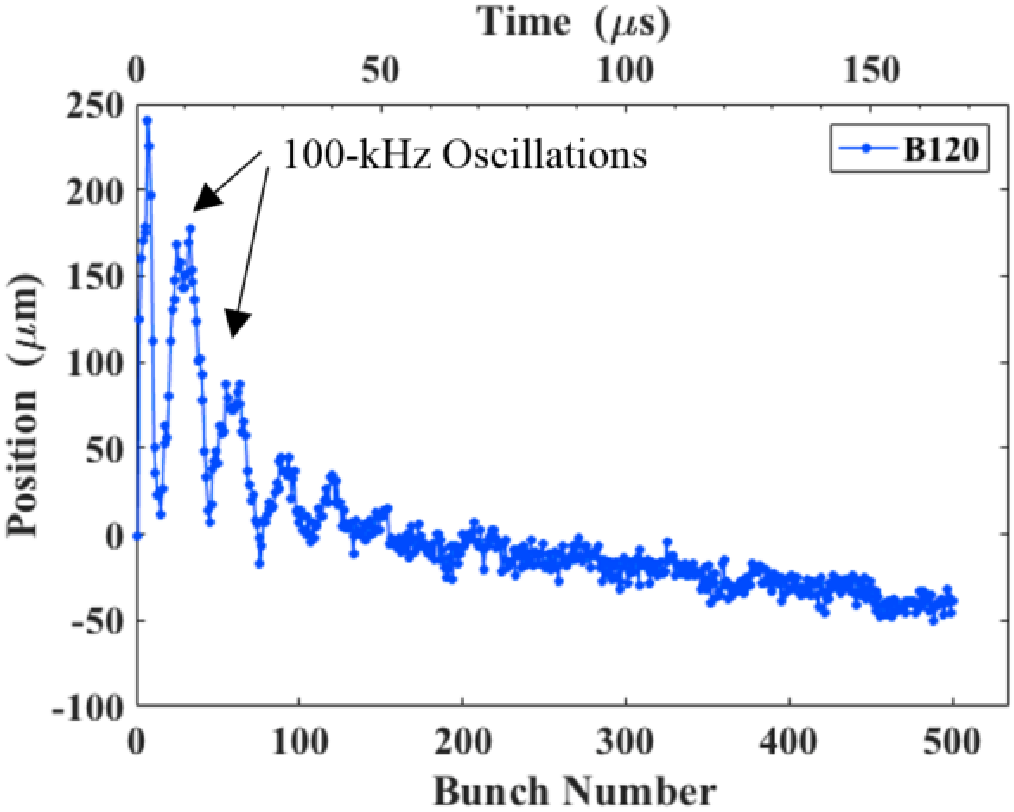
Preliminary




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

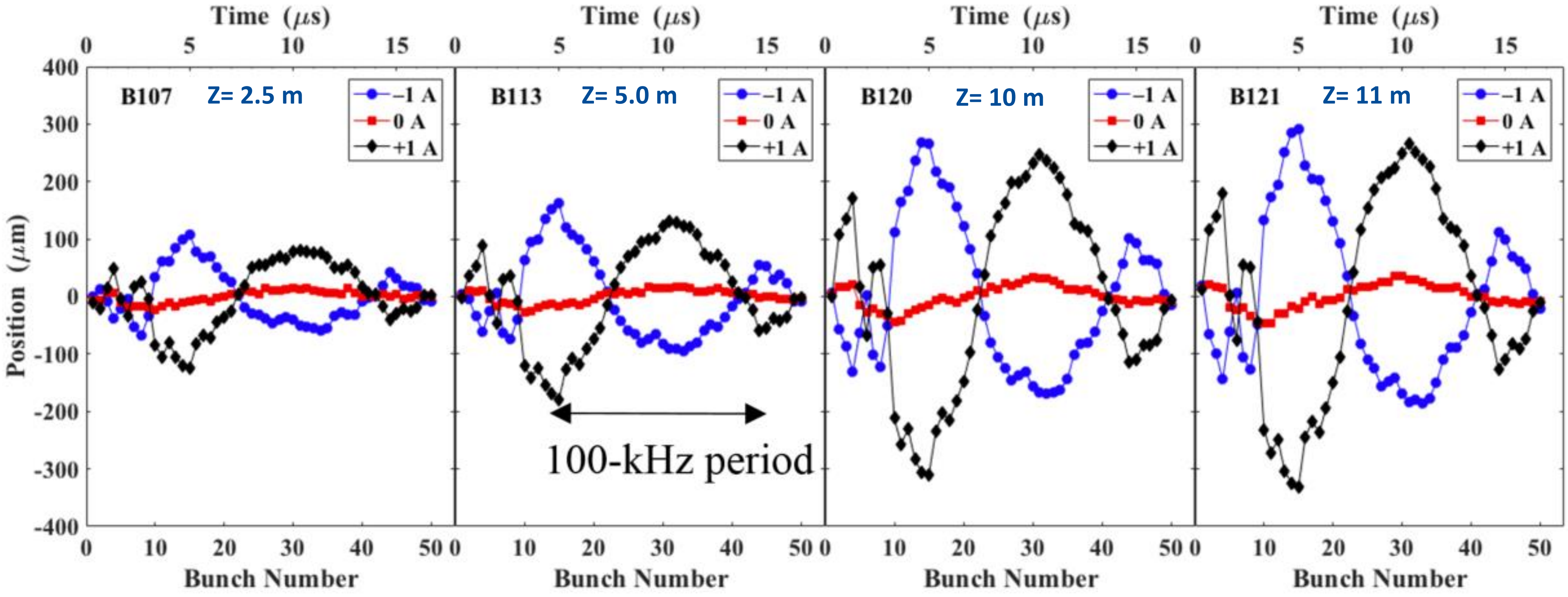
# V101 Scan: Vertical BPM Shows Damping Effect in 500b

- Centroid oscillation seen in first ~150 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
- Attributed to near resonance of beam harmonic and CC2 dipole mode 14 (A.H. Lumpkin et al., Phys. Rev. A-B **21**, June 2018).



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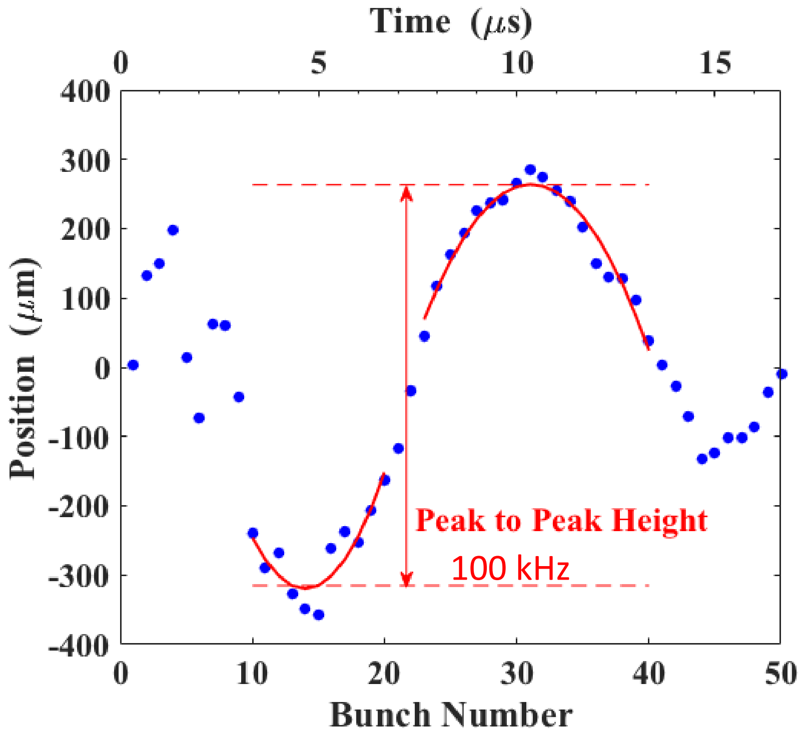
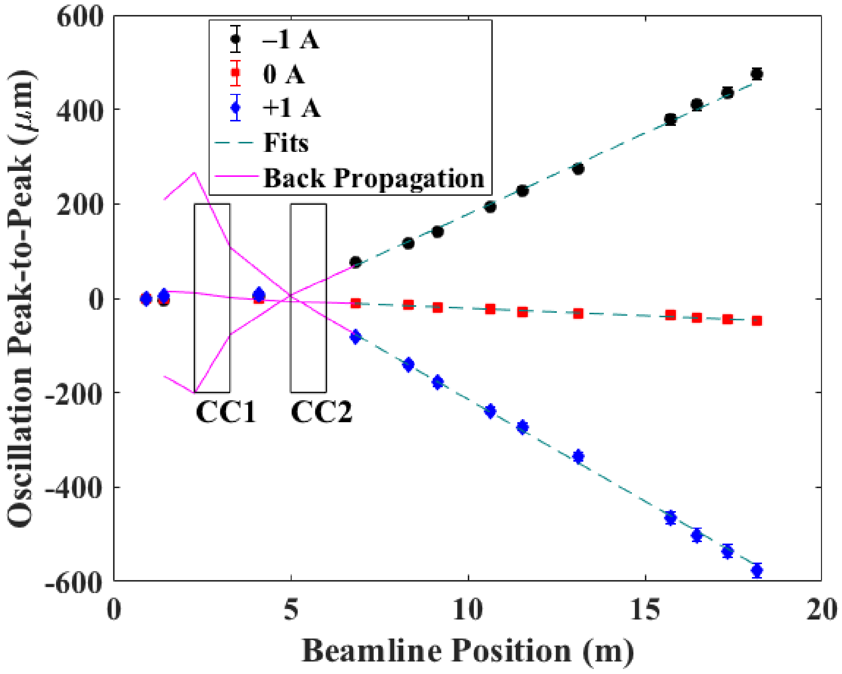
# Evaluation of HOM Vertical Kick Angles

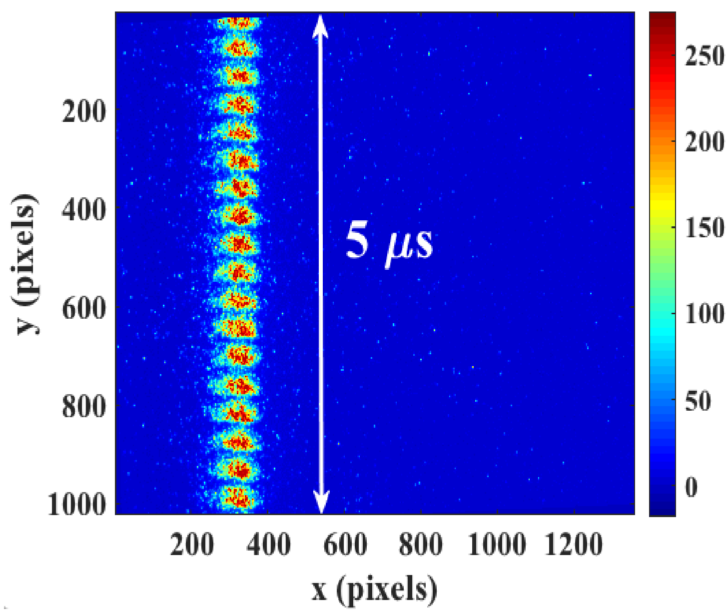
- V101 scan results with drift to B122. Kick deduced 84 µrad from CC2 at 1000 pC/b in vertical BPM readings.

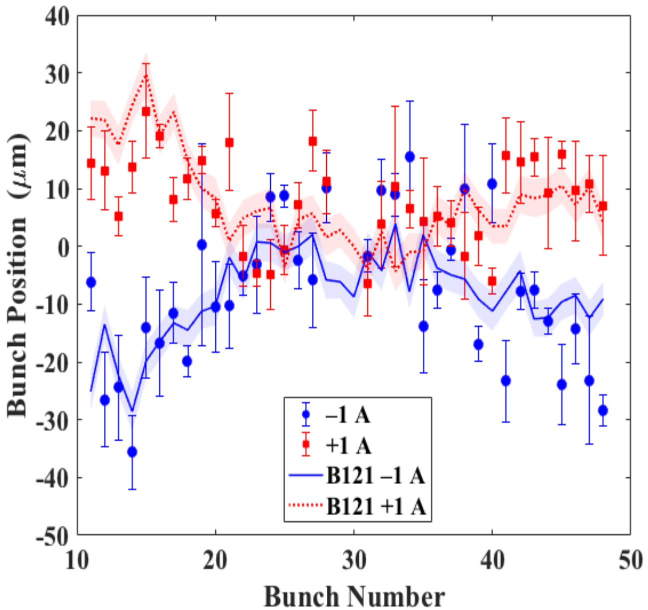


# V101 Scan: Framing Camera Mode Shows HOM Effects

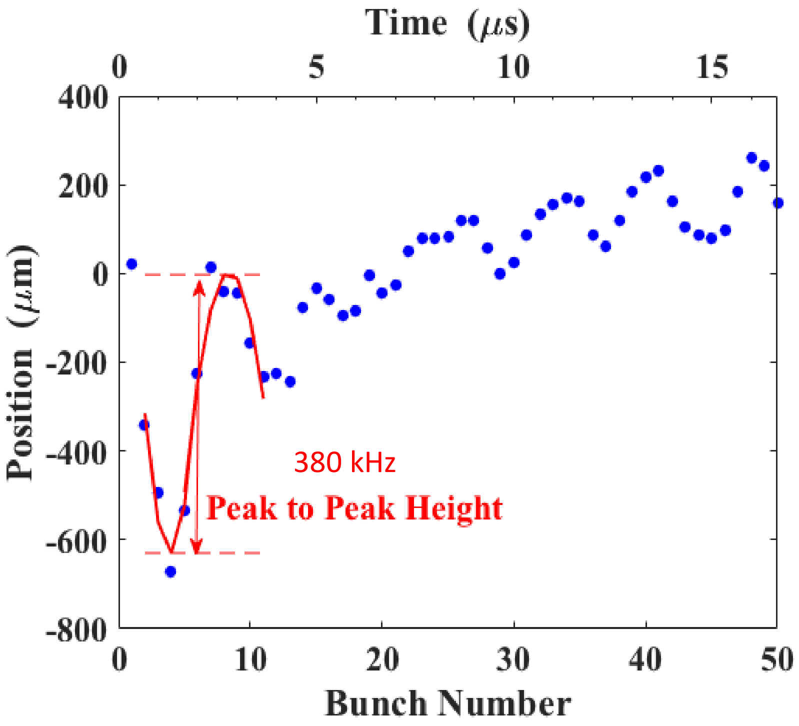
- 50b, 1000 pC/b, 5 µs vertical, 100 µs Horiz., ~16 µs gap.
- Bunches #31-48 shown in image (L). Second set of bunches #11-28 also taken. Later time is down and leftward on axes.
- Centroid motion comparison to rf BPMs shown at right (R).

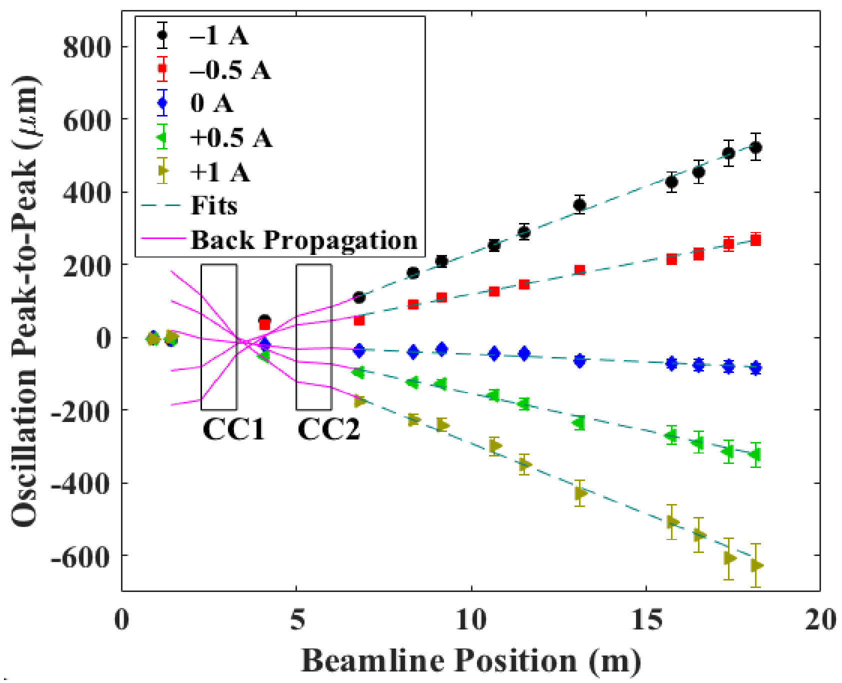


# Evaluation of HOM Horizontal Kick Angles

- 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

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

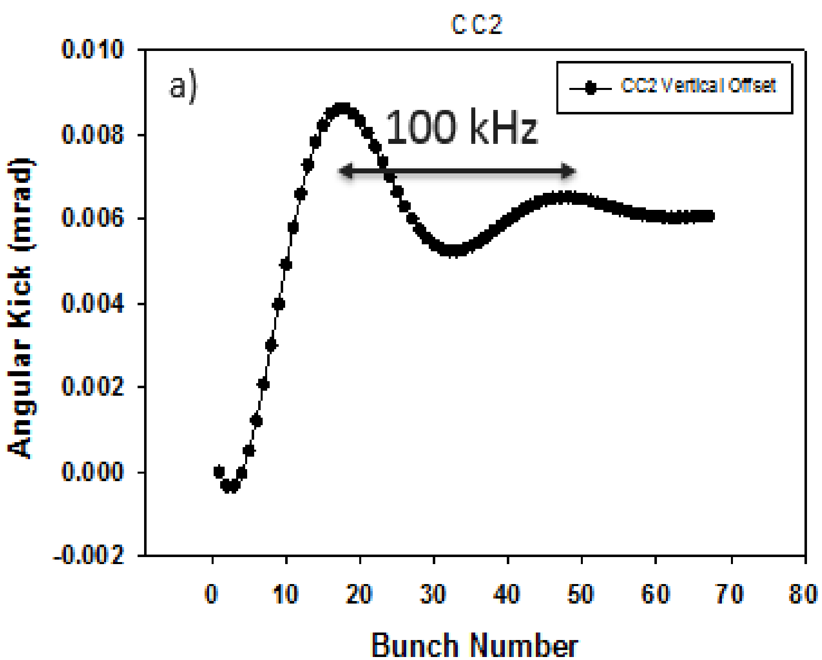
- where $\vec{B}$ and $\vec{E}_\perp$ are the magnetic and transverse electric fields generated by the HOM-exciting bunch, the integral is over the electron path, and *c* is the speed of light. For a series of $m$ bunches, the wake potential at the $m^{\text{th}}$ bunch, $\overrightarrow{W}_\perp(s_m)$,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

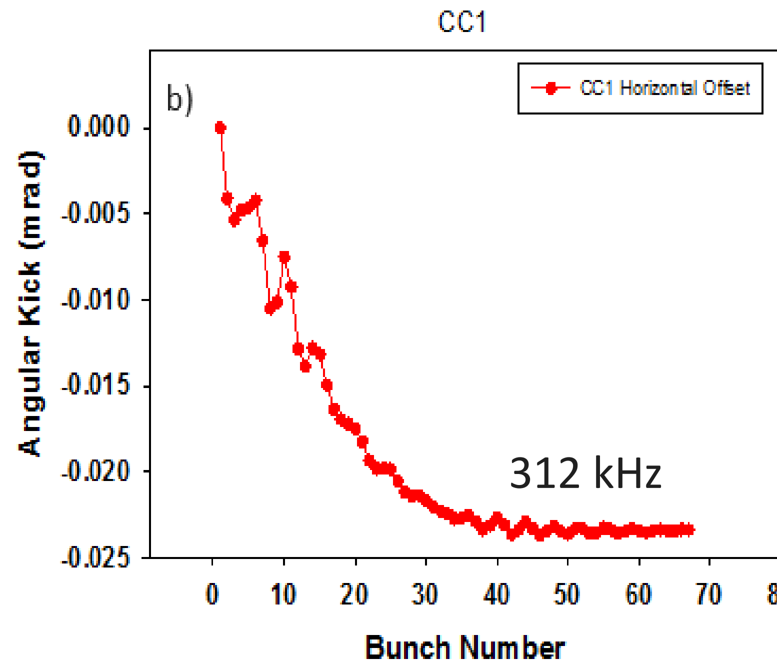
$$\overrightarrow{W}_\perp(s_m) = \vec{r}_0\frac{c}{2}\sum_{k=1}^{m-1}\sum_n\left(\frac{R_\perp}{Q}\right)_n e^{-\frac{\omega_n^2\sigma_z^2}{2c^2}}\sin\left(\frac{\omega_n(s_m-s_k)}{c}\right)e^{-\frac{\omega_n(s_m-s_k)}{2Q_n c}}\cos^2(\varphi_n), \quad (2)$$

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

O. Napoly Source

# CC2 and CC1 Generated Dipole HOM Kicks (Calculations)



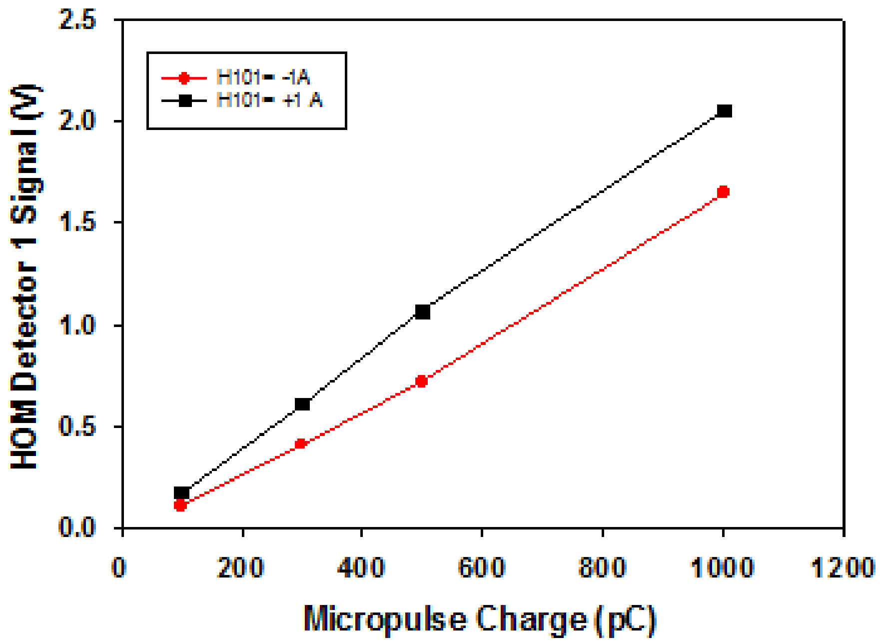

CC2: MM-14 with vertical polarization, 5 mm translation, 500 pC/b. Beam sampling at 3.008 MHz, harmonic # 623 within 100 kHz of the HOM frequency.

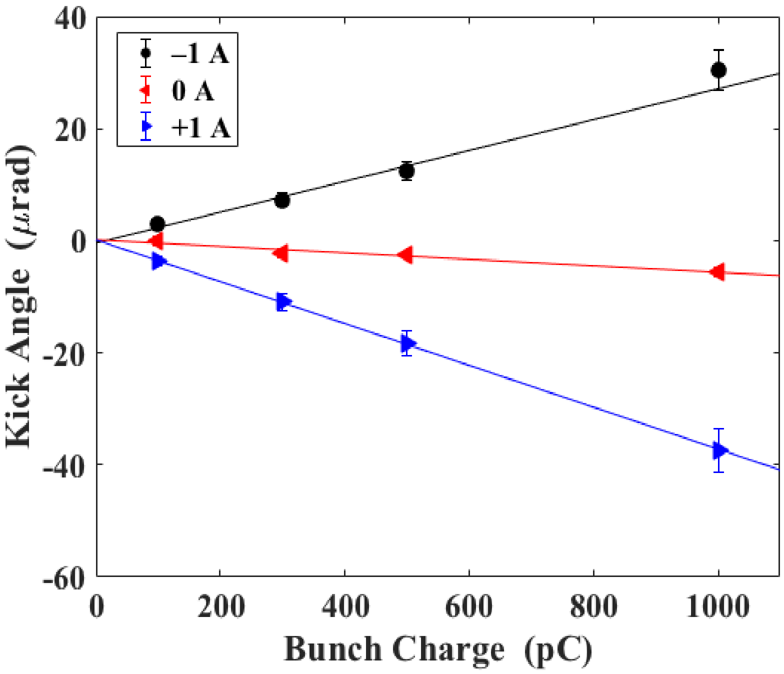
CC1: MM-7 plus MM-30;
5 mm translation, 500 pC/b.

O. Napoly's calc.

# HOM Signals and Deduced Kick Angles Vary with Charge

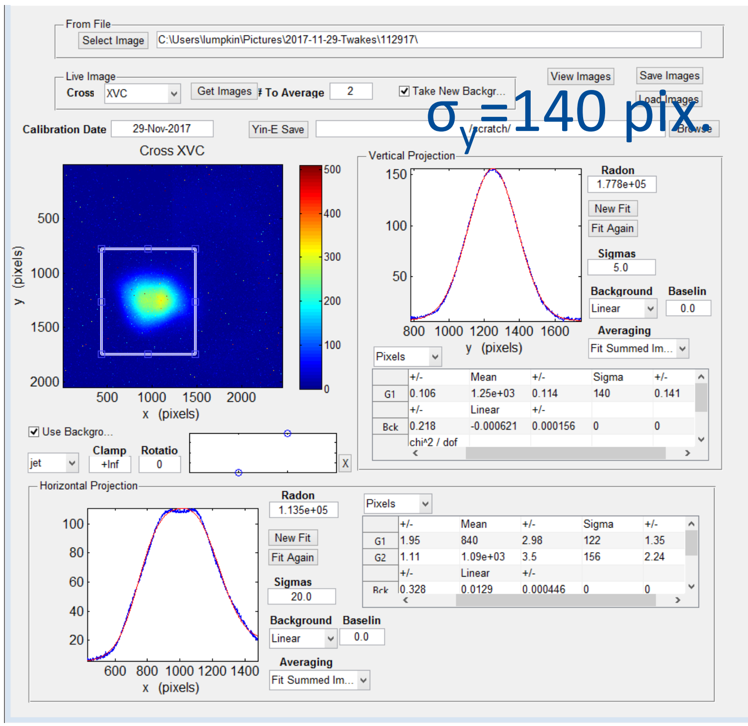
- HOM Detector Signals (L) and Horizontal Kick Angle (R) vary linearly with micropulse charge as expected.

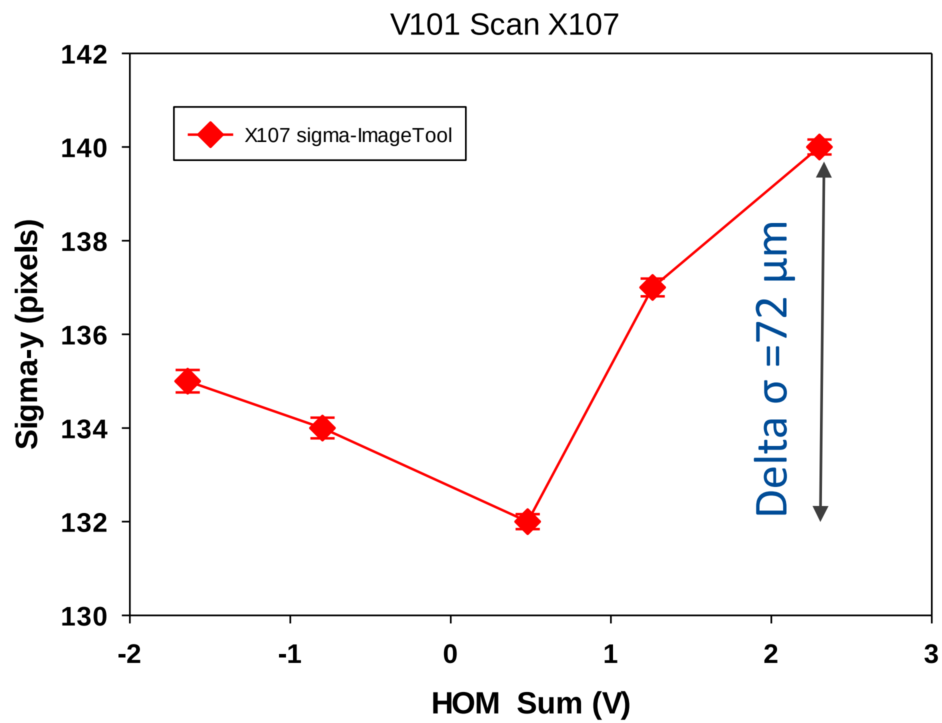


# X107 Images and Probable HOM correlation with Beam Size

- Images and V101 scan using HOM sums for correlation.
- Recall X107 is 2 m drift after CC2. 6% maximal effect.

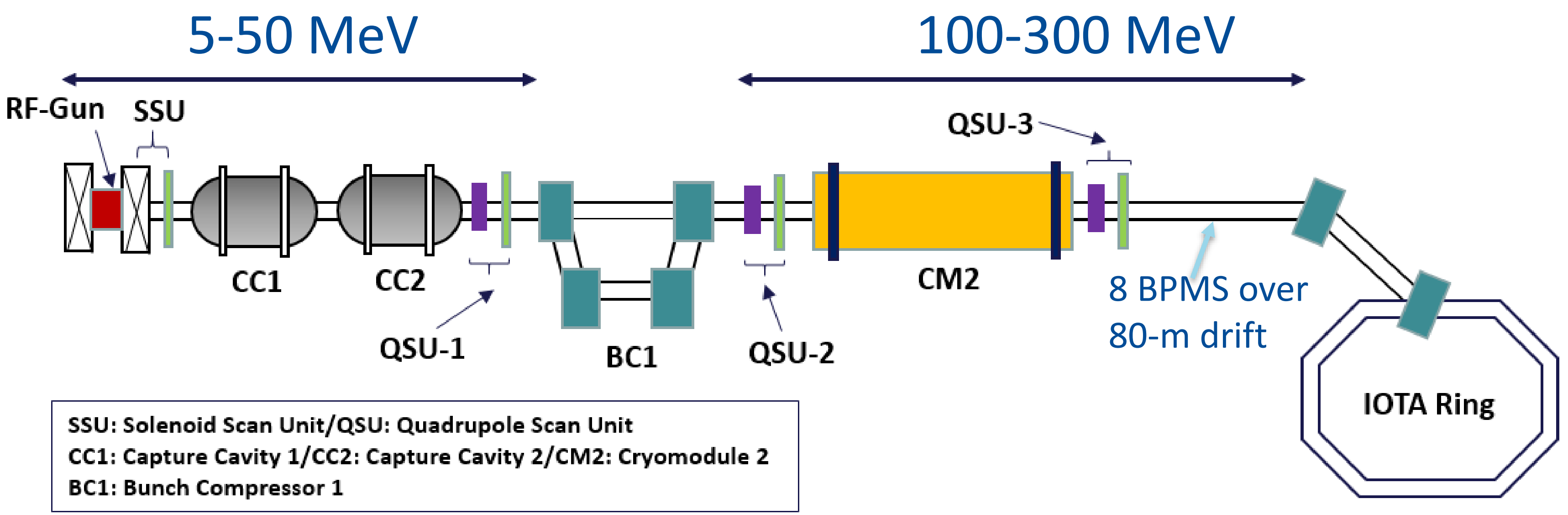



Spatial Calibration= 8.9 µm/pixel

# 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. See O. Napoly's talk.




Revised YMS

# V. Initial tests for Short-range Wakefield Effects

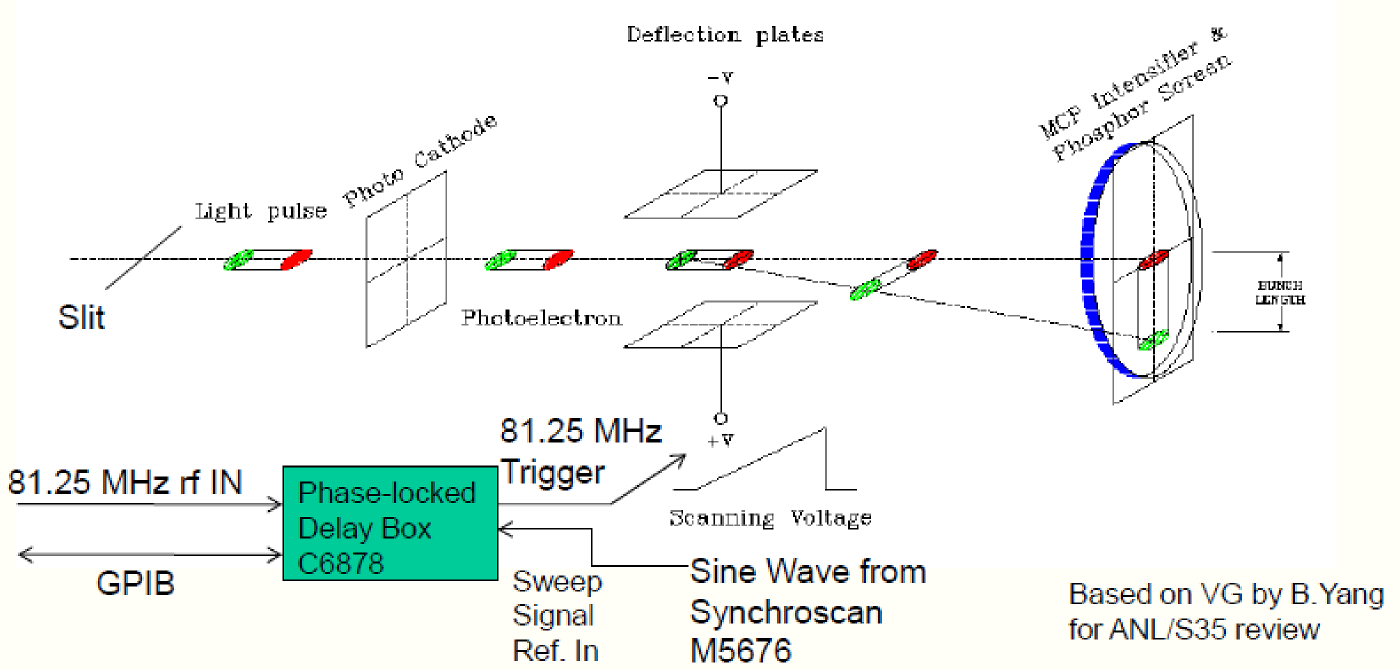
Initial tests for short-range wakefield effects generated by off-axis steering of the beam into CC1 and CC2. Localize to CC2 with V103 corrector. Use streak camera viewing X121 OTR screen.

- 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 short-range wakefield centroid effect from HOMs' effect.
- Compare to numerical model for short range, transverse effects.

# 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.

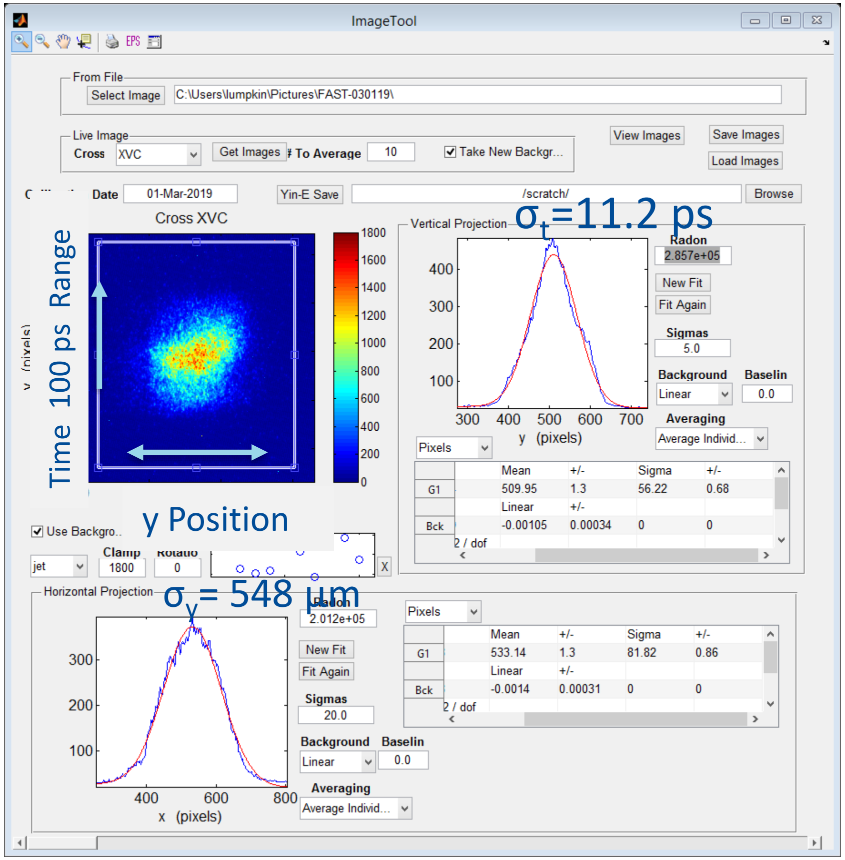
- **Addition of synchroscan plugin module and the C6878 phase-locked delay box enabled new series of experiments**



# 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.
+9% beam
size effect
@ 495 µm

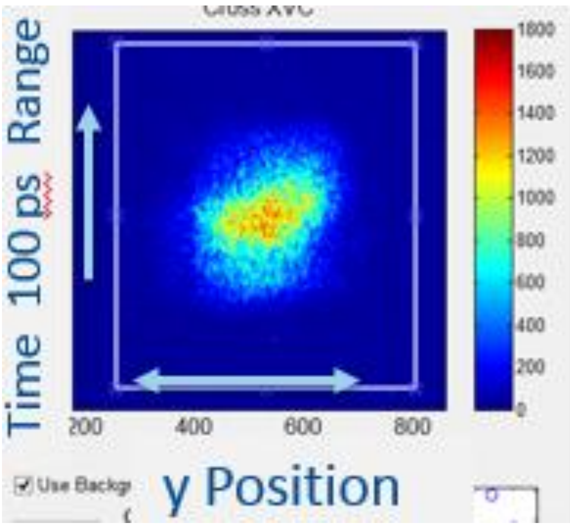



HOM Detectors
CC1[8]= -100 mV
CC1[9]= -60 mV
CC2[8]= -100 mV
CC2[9]= -50 mV

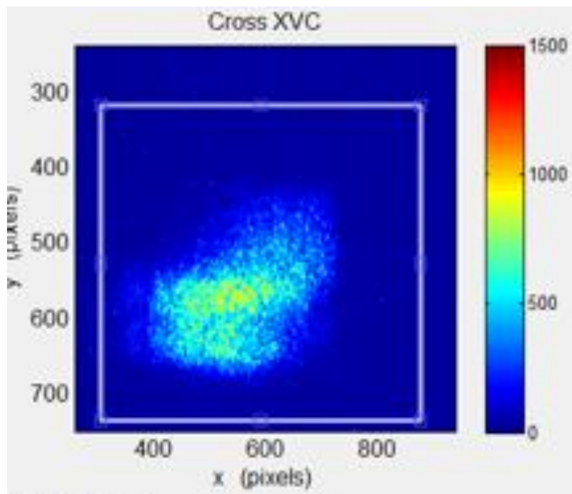
# HOMs as Found: Effects of Steering Observed 3-01-19

- It appears one can compensate the sub-micropulse scale kick in CC1 with one in CC2.

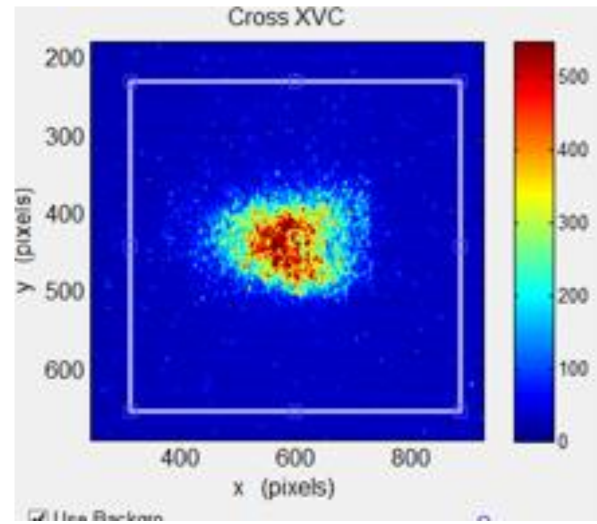
V103=-0.43 A as found




Δ V103= +2.4 A

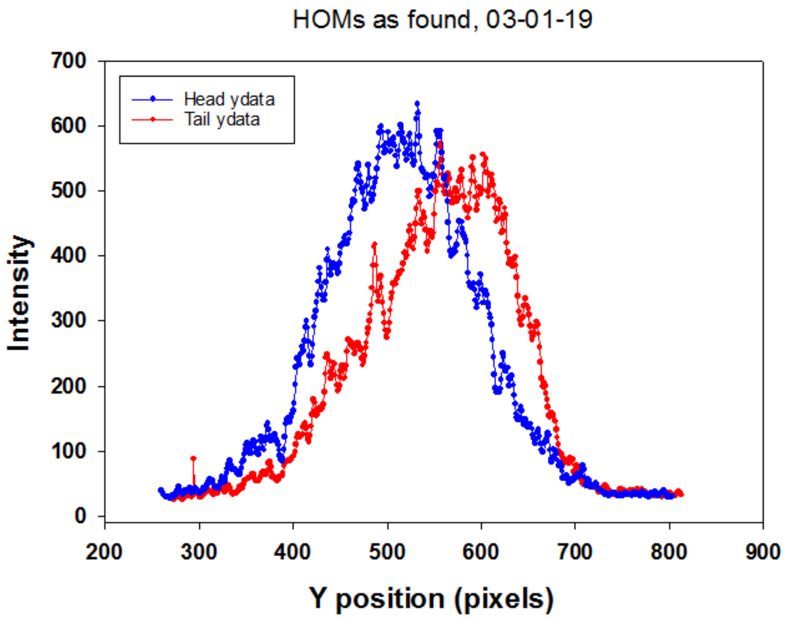


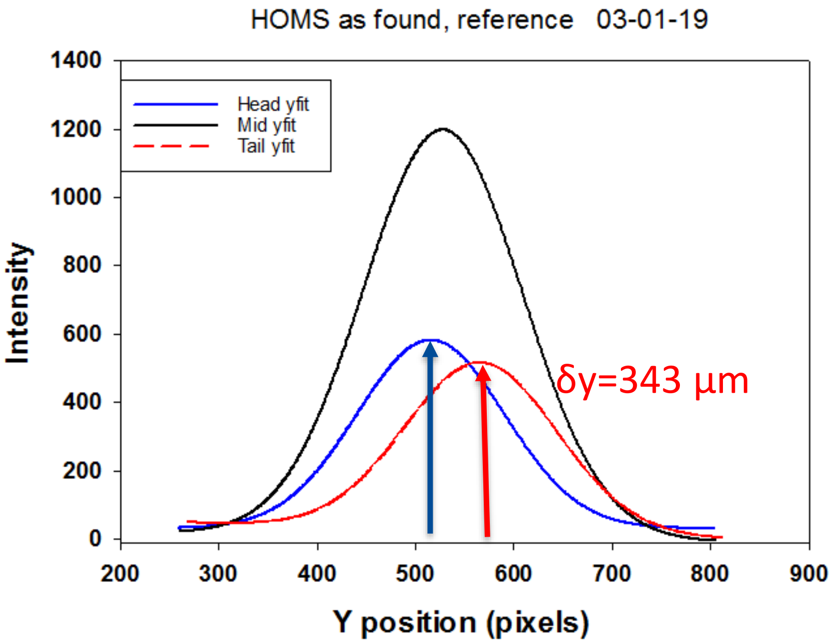

Δ V103= -2.4 A



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

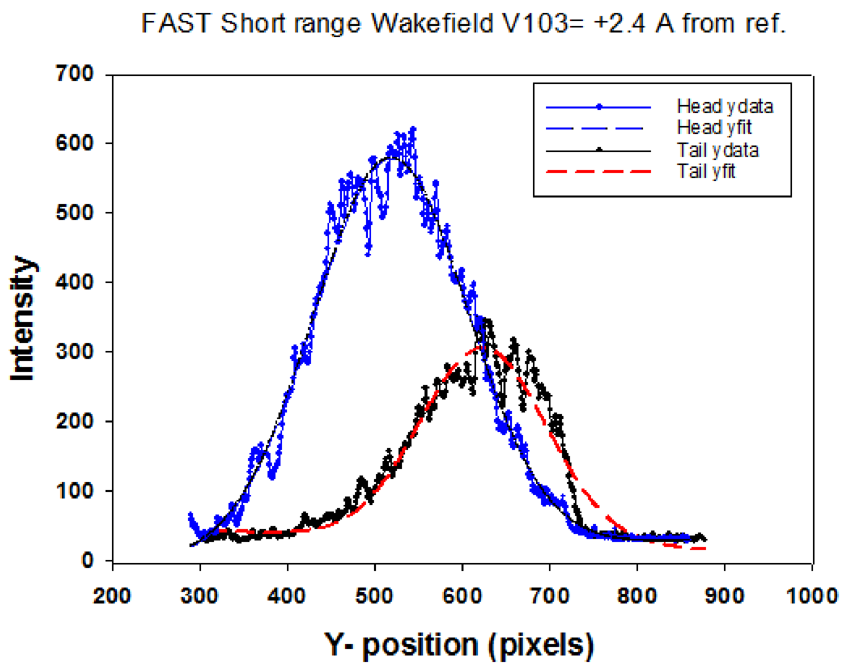
- Estimate mm+ off axis, angle with CC1 HOMs;100 mV, 60 mV
- Estimate mm+ off axis, angle with CC2 HOMs;100 mV, 50 mV

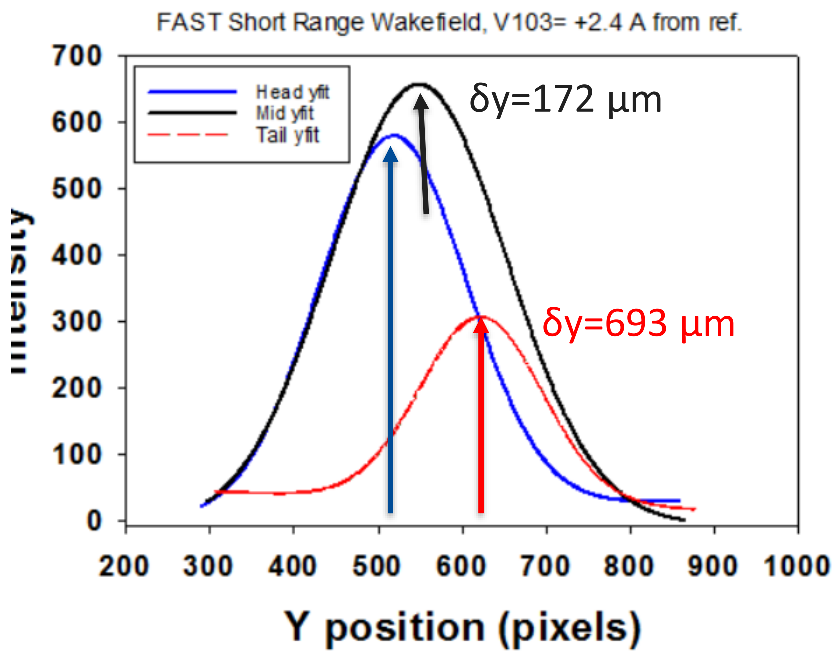


# Centroid Shifts within Micropulse Time: y-t 03-01-19

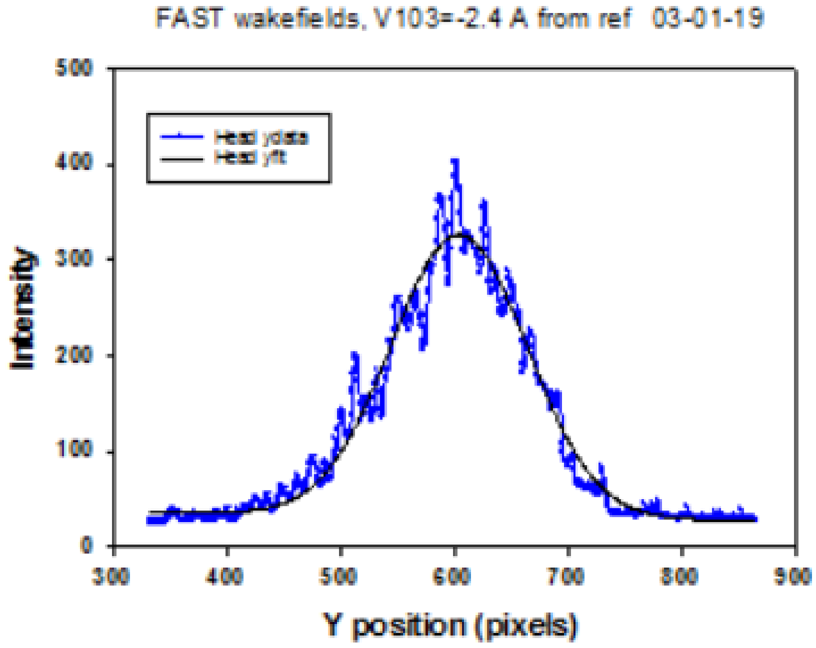
- V103= +2.4 A from ref, 500pC/b, 150b, MCP=61
- Time samples of y profile at Head, Mid, and Tail of micropulse.

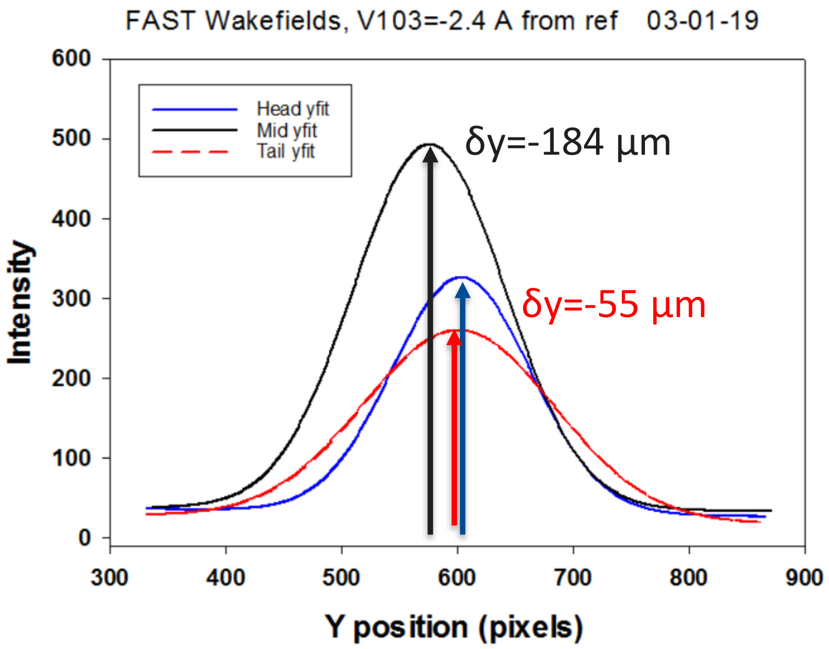


# Centroid Shifts within Micropulse Time: y-t 03-01-19

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



# Combined Wakefield Effects of CC1 and CC2 Observed (03-01-19)

- 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

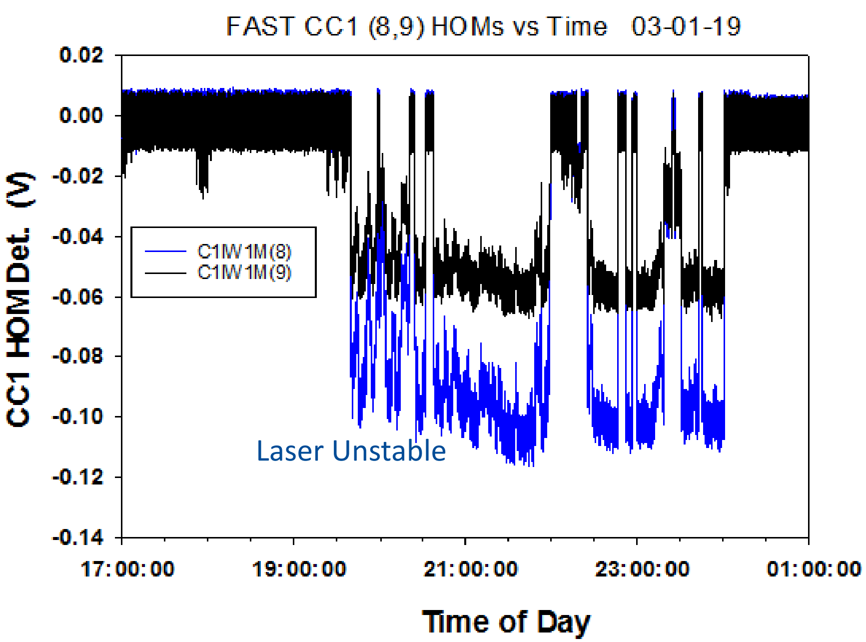
| Case # | V103 (A) | Head-tail y centroid shift (µm) | Projected y size (µm) | CC1 D1 (mV) | CC1 D2 (mV) | CC2 D1 (mV) | CC2 D2 (mV) |
|---|---|---|---|---|---|---|---|
| 1 | Ref (-0.43) | 343 | 548 | -100 | -60 | -100 | -45 |
| 2 | + 2.4 delta | 681 | 643 | -100 | -55 | -204 | -40 |
| 3 | - 2.4 delta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

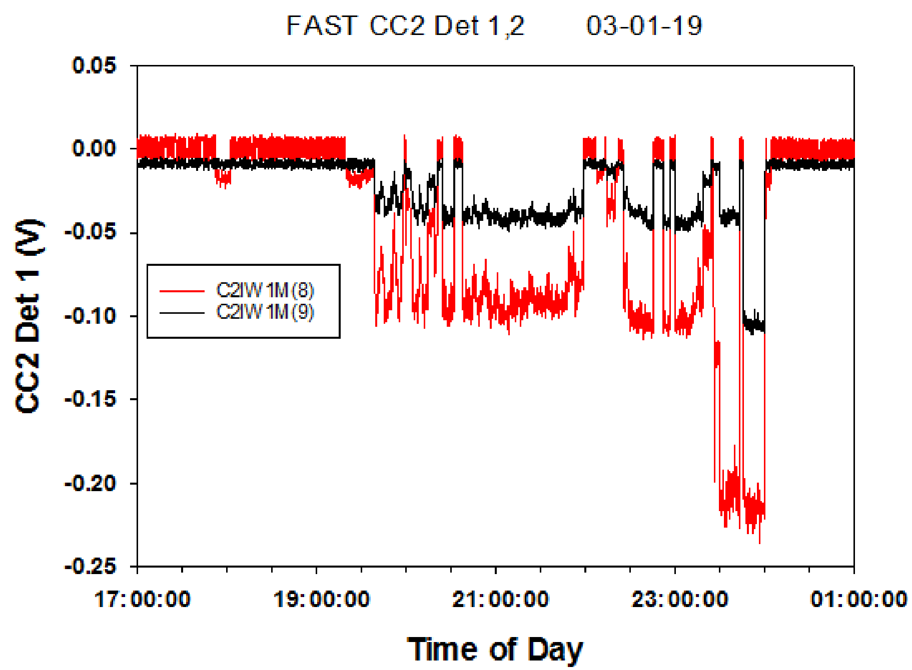
Cases 1-3: 16% size reduction, Cases 2-3: 38 % reduction.

After CC2, rf BPM B104 = +7.4 mm for case 2, -12.4 mm for case 3

# 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.

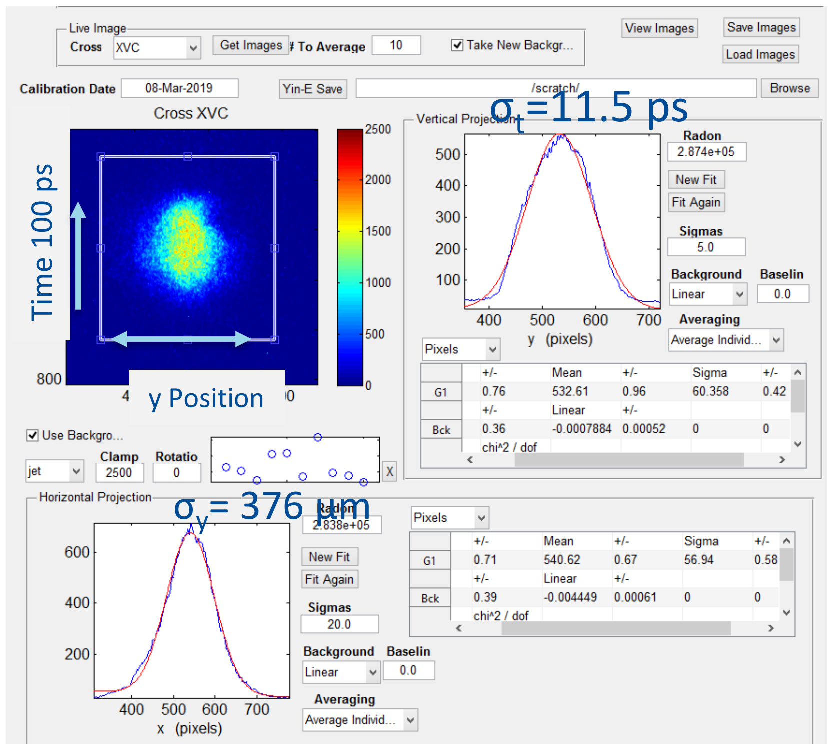


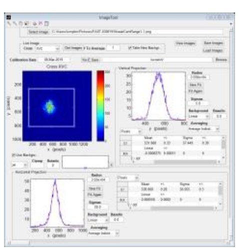
# Initial conditions: HOMs minimized (03-08-19)

- V103= 0.054 A , sig-t=60.3 ±0.5 pixels => 11.8 ps with 0.20 ps/pix, 50b, 500 pC/b, Sigma-y = 57 ±1 pixels. No y-t tilt. 10i.
- Laser spot size 0.2 mm rms.

No y-t tilt: Ellipsoidal beam

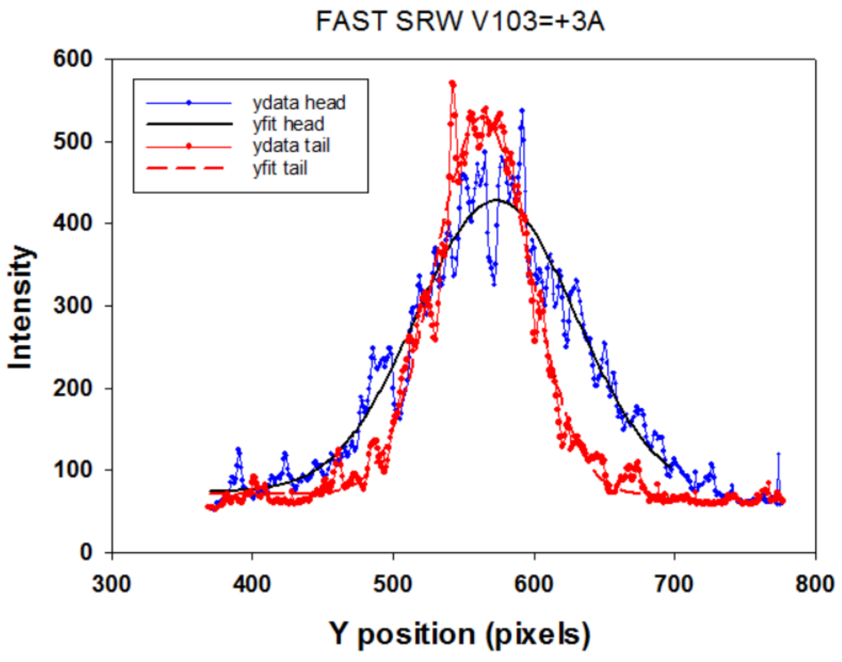


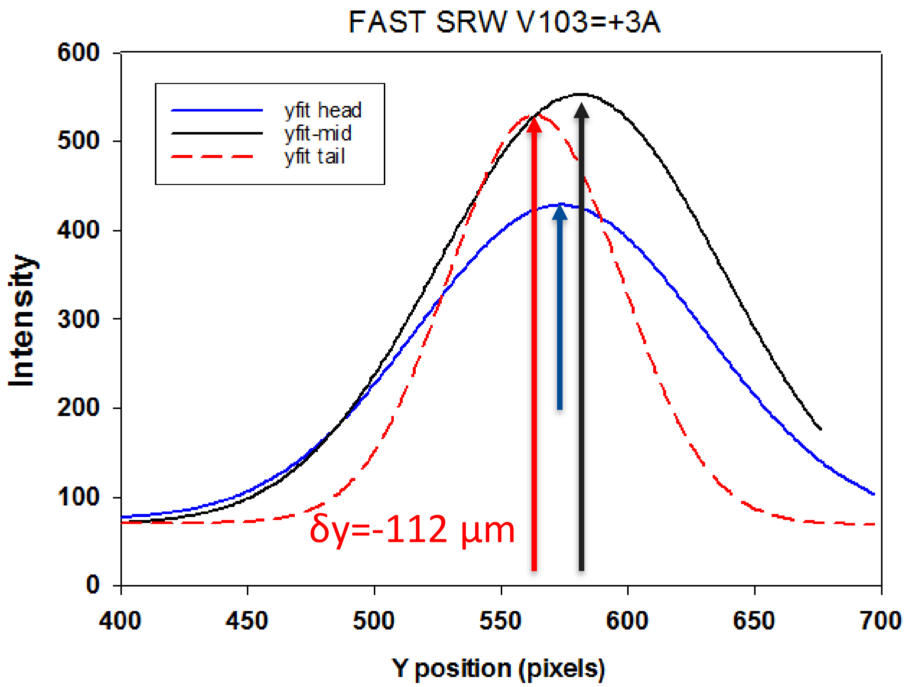

HOM Detectors
CC1[8] = -13 mV
CC1[9] = -10 mV
CC2[8] = -5 mV
CC2[9] = -7 mV



# Head tail kick at V103=+3A from reference  20 Image ave

- Centroid shift observed from head to tail: -79 µm.
- Centroid shift observed from midpoint to tail: -112 µm



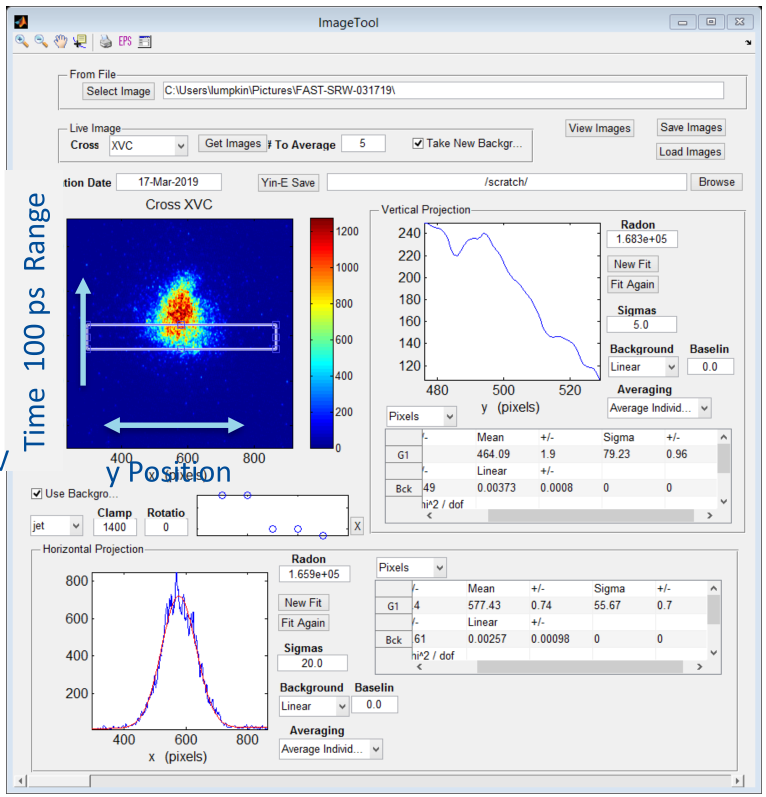



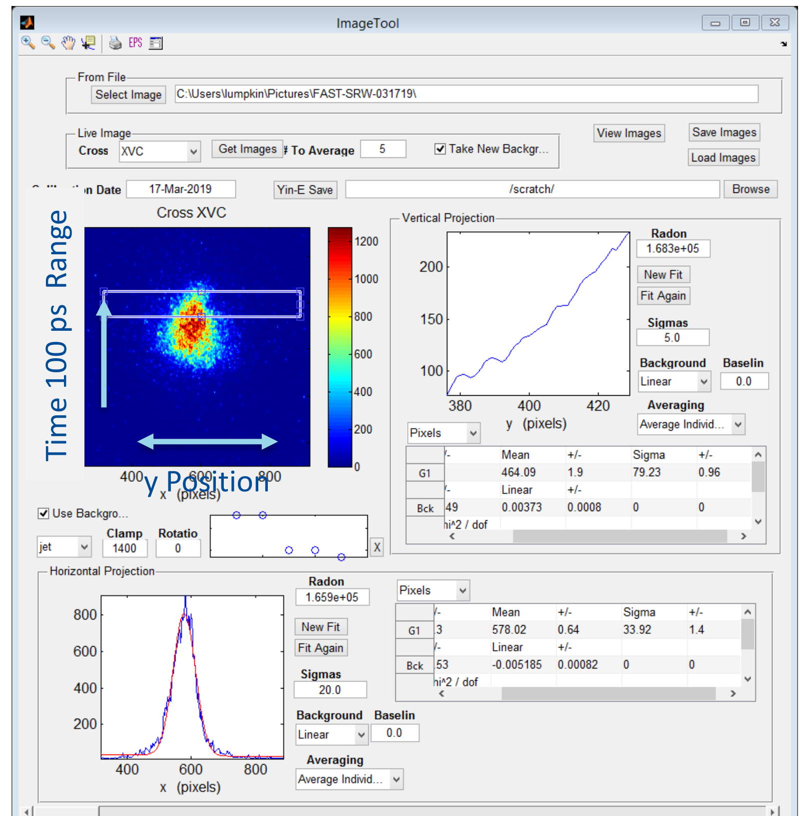
# Search for Short Range y-t effect in Streak Camera Images

- V103=0.05 A, 550 pC/b, 150 b, 5 images, Reference. 3-17-19
- Head-tail delta Gaussian peaks ~+0.6 ±0.5 pix=> +4 ±4 µm
- beam size changes in t, Head= 370 µm, tail= 224* µm

No Tilt

HOMs:
-20,-35;
-50, -15mV
Laser spot
1.2 mm



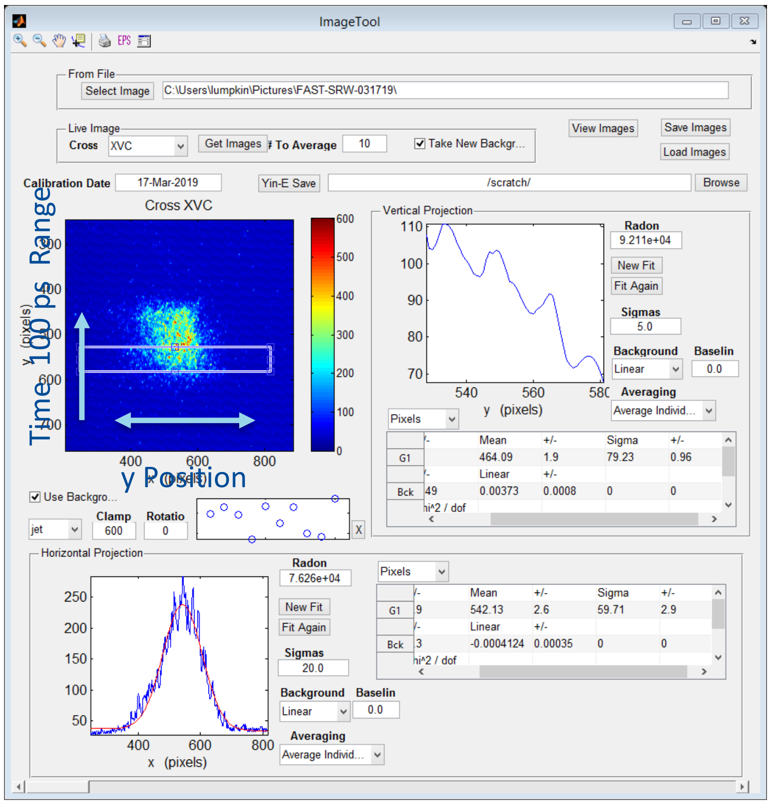


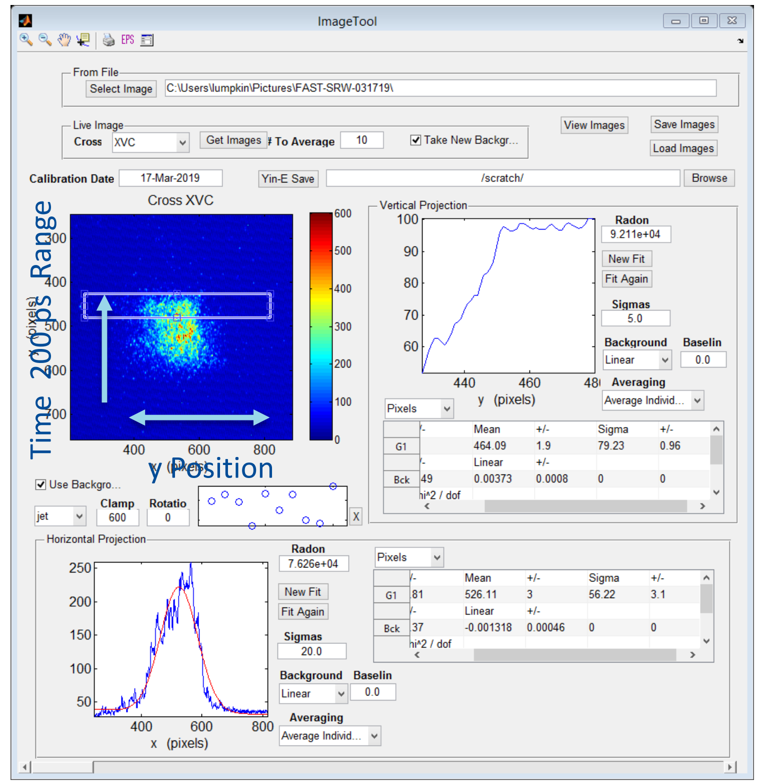

Fermilab

# Search for Short Range y-t effect in Streak Camera Images

- V103 = -2A, 500 pC/b, 50 b, 10 images                    3-17-19
- Head-tail delta Gaussian peaks ~-16 pixels => -106 µm
- Min. beam size changes in t, Head= 389 µm, tail= 363 µm,
- 

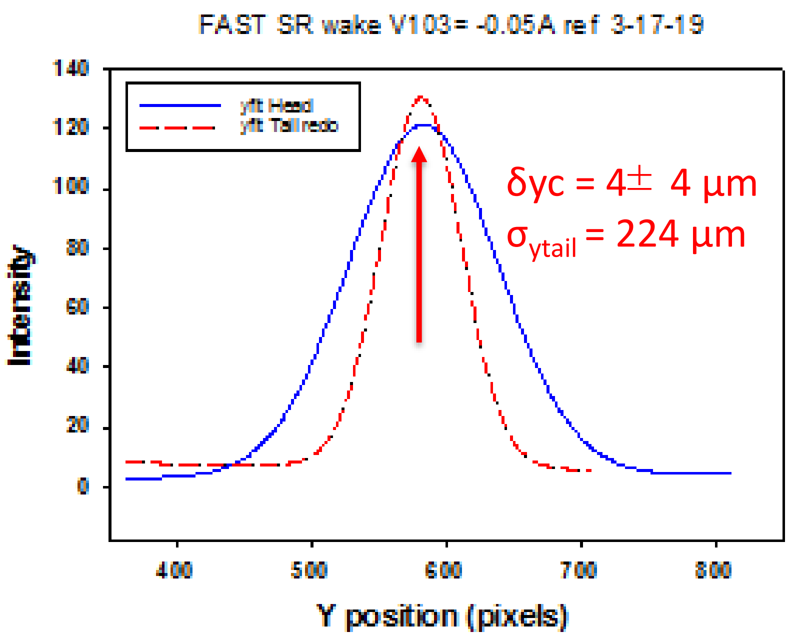
y-t tilt

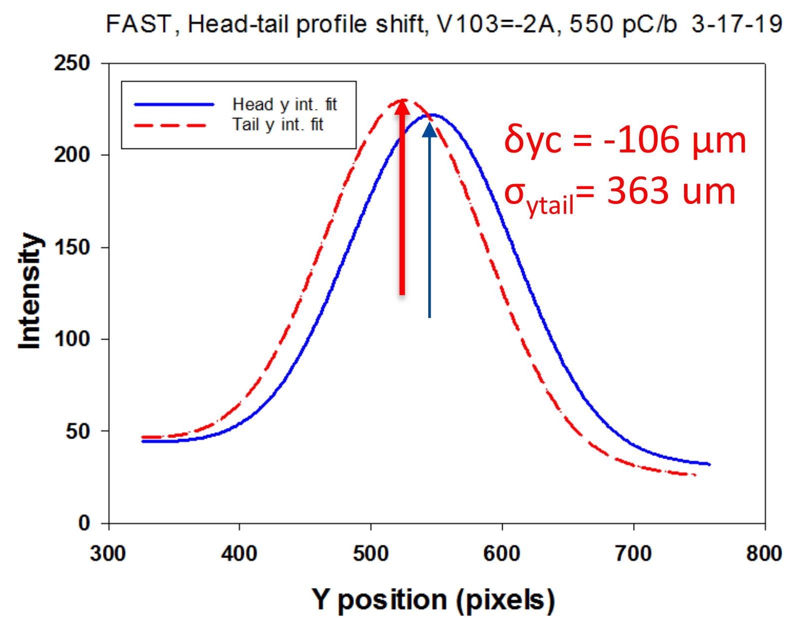


# y(t) Centroid Shift and Slice Profile Growth Seen 3-17-19

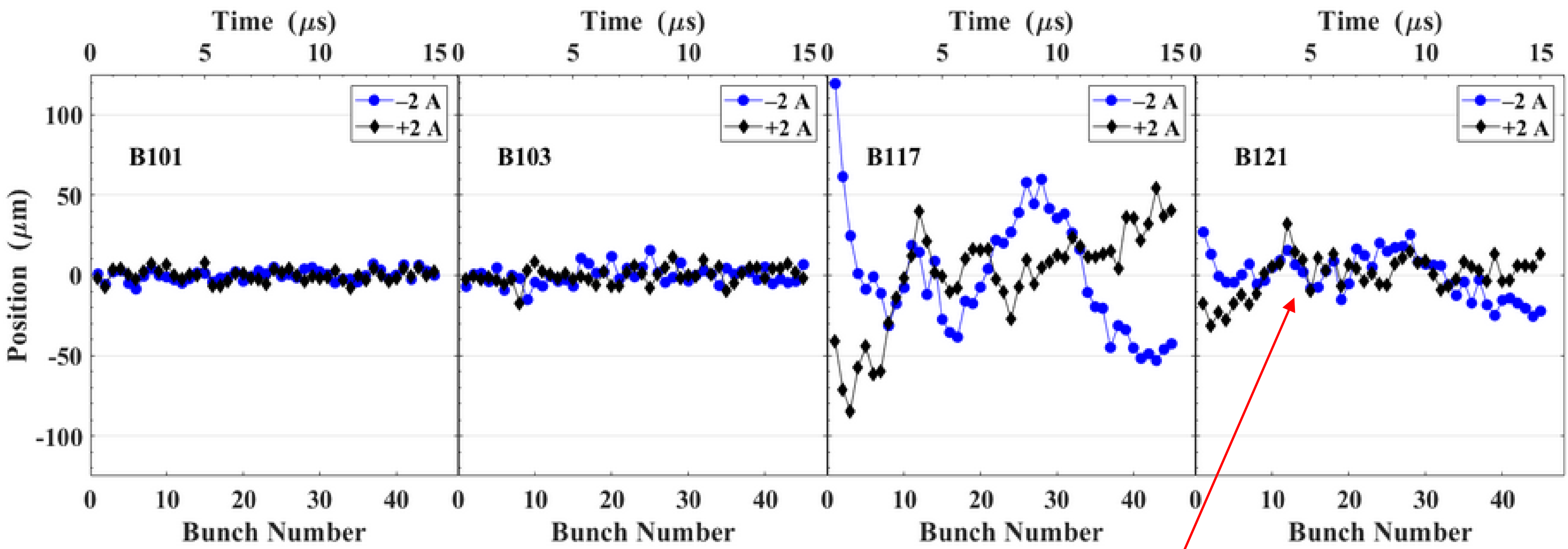
- Comparison of V103= -0.05, delta-2A images shows a -106 µm centroid shift and width change of +140 µm at tail.
- Observed changes would be 260% slice emittance effect.



# 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.

# Model of TESLA cavity for short-range transverse wakefields used to predict effect scale (Calculations by V. Lebedev)

For Q=2.4 nC, sigma-t=10 ps, 1-mm offset, Beta-x=10 m, 50 MeV, get 40- to 50-µm kick within the micropulse from 1 TESLA cavity's wakefield. We are at 33 MeV in middle of CC2 so scales up 50%.

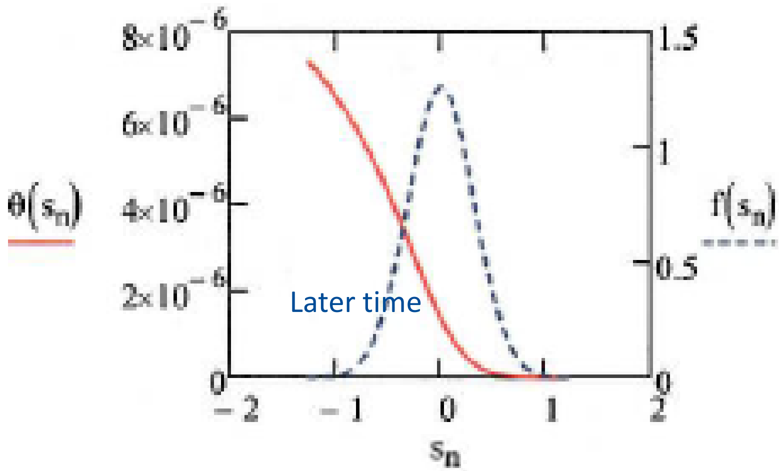
Lebedev Case:

***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 $\Delta x := 0.1$ cm

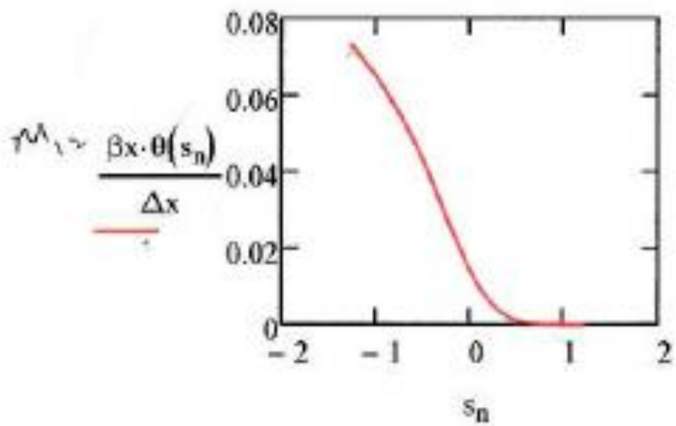
$$\theta(s) := \frac{e_{conv} \cdot e_{SGS} \cdot N_e}{P_0} \cdot \int^{10} \Delta x \cdot W_T(s_n - s) \cdot f(s_n)\, ds_n$$

***Transverse wake***

$\beta x := 1000$ cm

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

Wake numerically computed for ILC cavities



# Table of Scaled Short-Range Wakefield Kick Angles

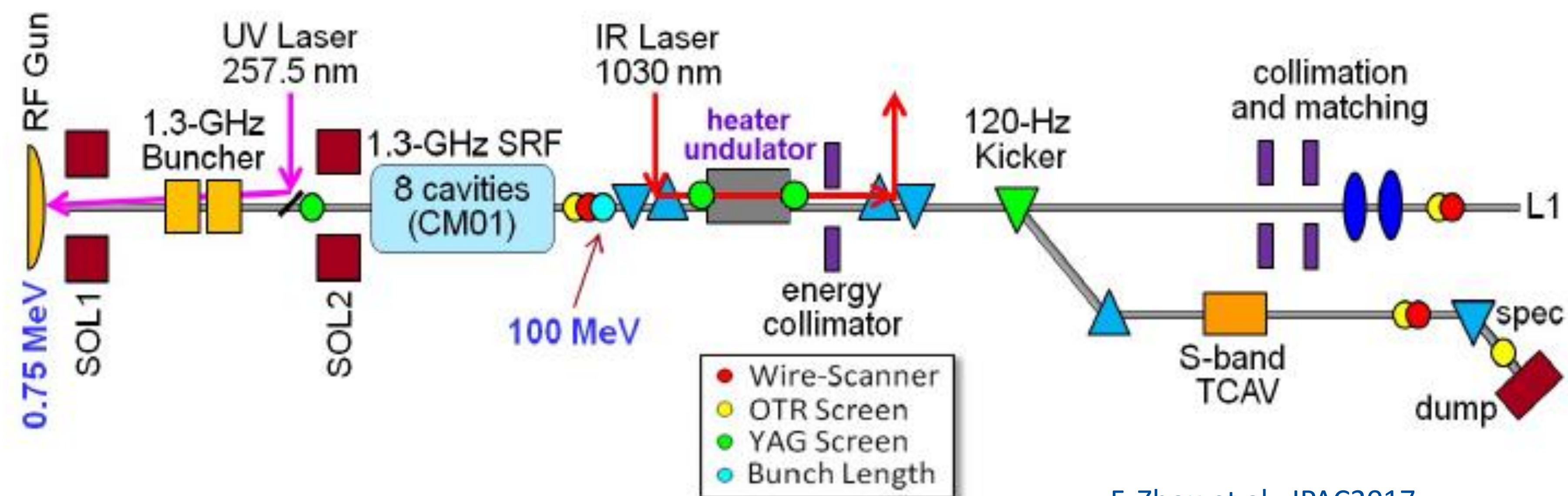
Table 1: Comparison of kicks vs Q and offset referenced to Lebedev case 1 in one cavity at ~50 MeV so 1.5 x for 33 MeV in middle of CC2

| Case. No | Charge (pC) | Offset (mm) | Beta-x (m) | Sigma-t (ps) | Kick $\theta$ (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 | 500 | 5 | 20 | 10 | 4 | 80 | |

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

# Schematic of the Planned Full LCLS-II Injector

- 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 late 2020.




F. Zhou et al., IPAC2017

# VI. SUMMARY-1   Long-range Wakefields

- 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. Difference frequency observed.
- 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. This system scales to higher micropulse repetition frequencies.
- Relevant, unique data sets for benchmarking HOM calculations and simulations in Tesla-type cavities remain objective.
- Transient beam centroid oscillations at near-resonance conditions could be issue for ultra-low emittance beams and ERLs.
- Full article published in Phys. Rev. Accel. and Beams, June 2018

# VI. SUMMARY-2 Short-Range Wakefields

- Generated and measured y-t effects consistent with short range wakefields calculated with a numerical model.
- Evidence for sub-micropulse centroid shifts and slice emittance effects. Unique results for TESLA-type cavity.
- Demonstrated kick compensation in CC2 within micropulses.
- Further studies with laser spot size and the position on cathode under control needed and with single bunches.
- Coordinated data with laser control, rf BPMs, HOMs, streak camera, etc. needed. Establish/monitor minimum HOM setup.
- Relevance to LCLS-II injector commissioning noted with their <1 MeV beam injection into a buncher and a cryomodule. Preliminary discussions on possible collaboration held in May for tests at FAST using our techniques. Plus FEL19 contacts.

# SUMMARY-3

- Note that under near-resonance conditions of an HOM mode frequency and a beam frequency harmonic, noticeable sub-macropulse centroid oscillations occur that can dilute emittance.
- Surprisingly to me, the short range-wakefields at 500 pC/b, ~1 mm offset in one cavity, and 33 MeV at FAST cause more emittance dilution than the HOMs (in general in TESLA cavity?). LCLS-II staff take note at 1 MeV into their first CM.
- The short-range wakefield can degrade the slice emittance in the last third (temporally) of an x,y-t elliptical micropulse.
- We will be minimizing the HOM signals more carefully at FAST in CC1,CC2, and CM2 (hopefully) and pursuing the BOM in the next run.

# ACKNOWLEDGEMENTS

The author acknowledges collaborations with R.Thurman-Keup, J. Ruan, D. Edstrom, P. Prieto, N. Eddy, B. Carlsten, K. Bishofberger; the wakefield calculations of O. Napoly and of V. Lebedev; 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; 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.

# LANL Short range Wakefield Experiment

- Streak camera diagnostic shows head-tail kick and observed emittance growth and reduction with steering through cavity 4.

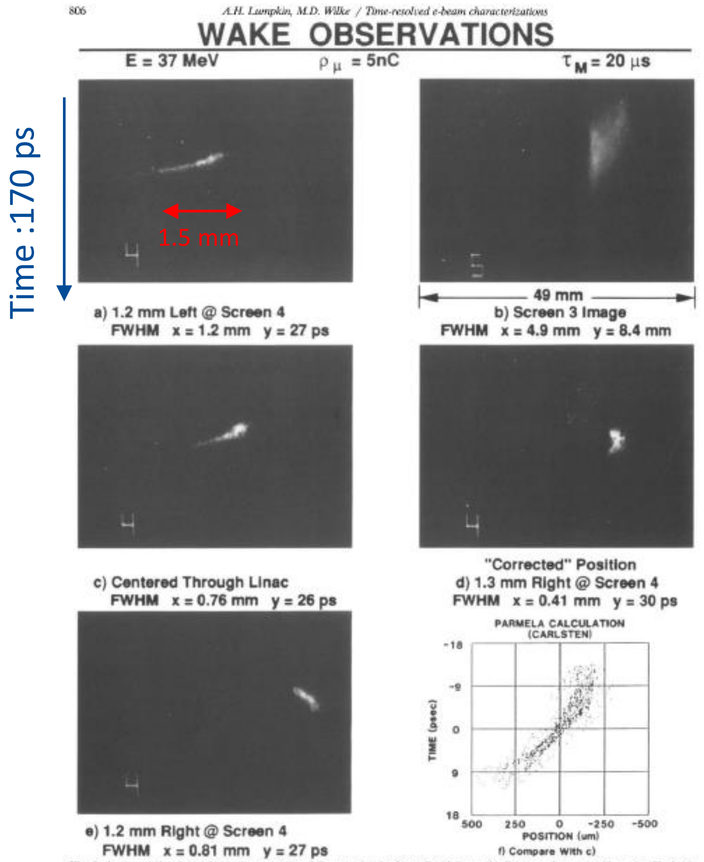
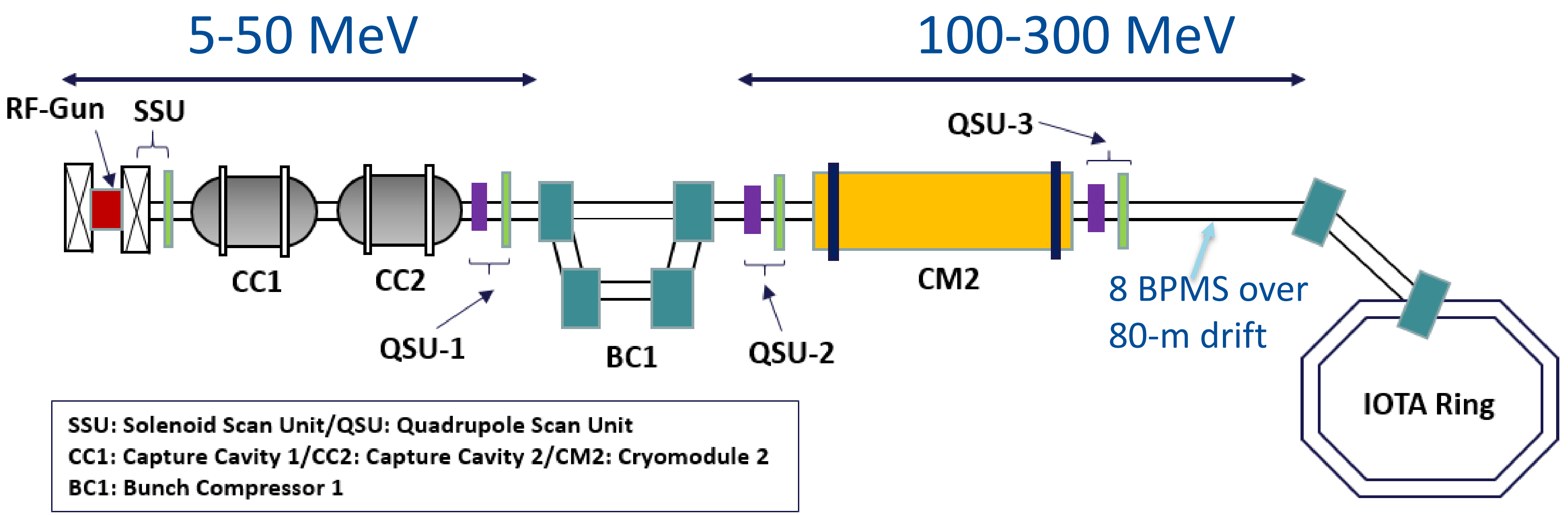


Fig. 6. A composite of streak images at station 4 for steering horizontally "left to right" across the scene. Note the flip in the direction of the head-to-tail kick. Time increases going down on the vertical axis.

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

# Techniques May be Applied to FAST Cryomodule

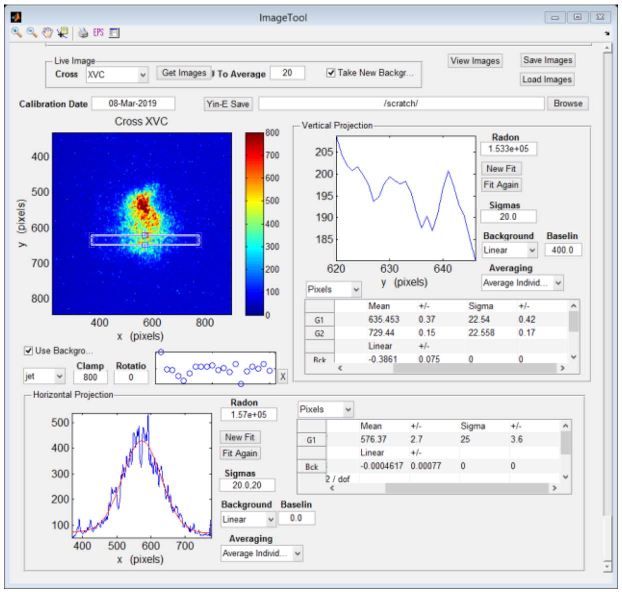
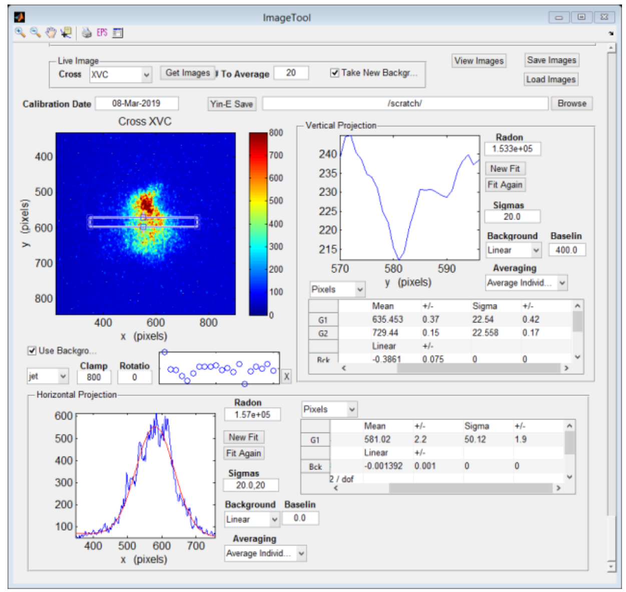
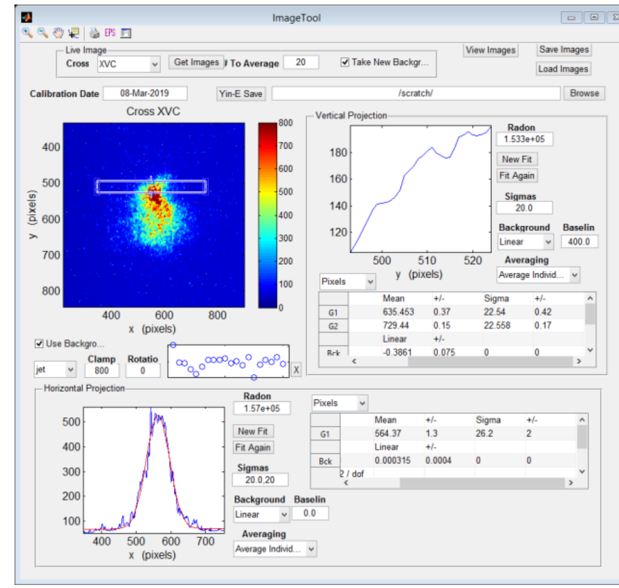
- Possible to extend HOM studies techniques to higher charges and to the cryomodule using an 80-m drift and 8 rf BPMs distributed in z downstream of it.




Revised YMS

# Head-tail Effect at V103= +3 A 500pC/b 03-08-19

- V103=+3A head to tail centroids: 576.4, 581.0,564.4 pix
- sigmas 25, 50.1,26.2 pix

Ellipsoidal shape perturbed by short range wakefields.
HOMs only 20 µm oscillation generally at Q and V103 setting

# 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.