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Observations of Short-Range Wakefield Effects in TESLA-type SCRF Cavities

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FAST/IOTA Collaboration Meeting

11 June 2019

OUTLINE

I. Introduction

II. Injector beamline and streak camera viewing optical transition radiation (OTR) screen at X121.
   -Strategy of beam steering off axis into TESLA Cavities to generate wakefields and beam effects.

III. Previous long-range wakefield test, Higher-order Modes (HOMs) context.

IV. Initial observations of short-range wakefield effects.

V. 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 short-range and long-range wakefields (e.g., 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 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-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 3-MHz micropulse repetition rate, a unique two separated-single-cavity configuration, and targeted diagnostics for these tests.

FAST Configuration and Unique Diagnostics Available

- Photocathode (PC) rf Gun beam injected into TESLA Cavities.
- Two single cavities allow localization of vertical effect to mostly second cavity using corrector H/V103 with HOMs minimized in CC1.
- 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.)

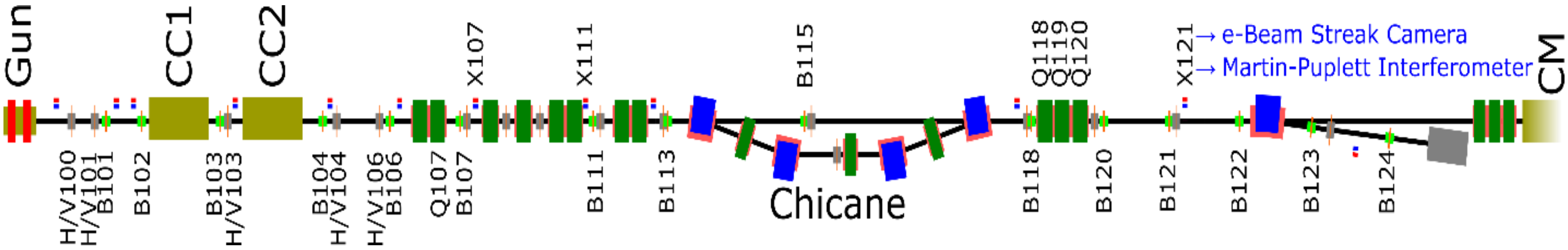

Table 1. FAST Electron Beam Parameters for Studies

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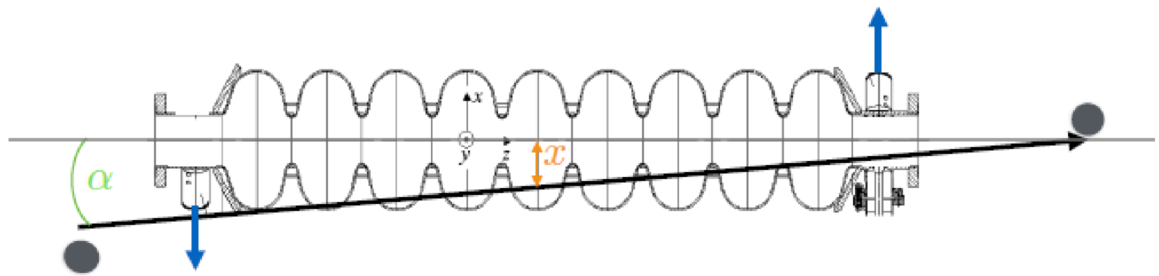
Beam Parameter	Units	Value		
Micropulse Charge (Q)	pC	100-1000		
Micropulse rep. rate	MHz	3		
Beam sizes, σ	µm	100-1200		
Emittance, σ norm	mm mrad	1-5		
Bunch length,σ Compressed	ps ps	4-10 1-3		
Total Energy	MeV	33, 41		
PC gun grad.	MV/m	40-45		
CC1 gradient	MV/m	14.2		
CC2 gradient.	MV/m	14.2		

1-150 bunches used, 3000 max.

Experimental Setup

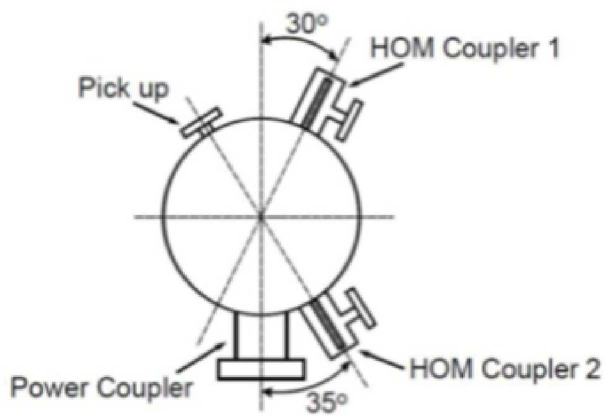


- > TESLA cavity
  - 2 HOM couplers
- > Dipole HOM
  - $V_x(t) \propto x \cdot e^{-\frac{t}{2\tau}} \sin(\omega t)$
  - $V_{x'}(t) \propto x' \cdot e^{-\frac{t}{2\tau}} \cos(\omega t)$

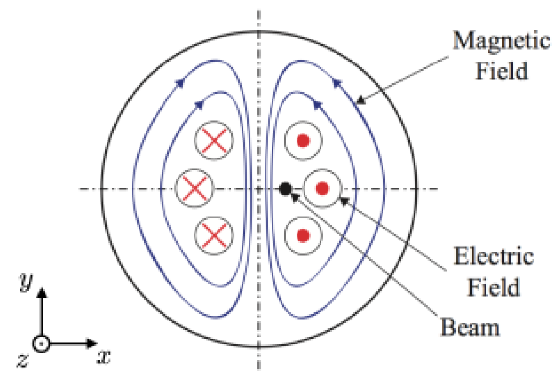
Expected HOMs in TESLA Cavities*

Mode #	Freq.(GHz)	R/Q (Ω/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

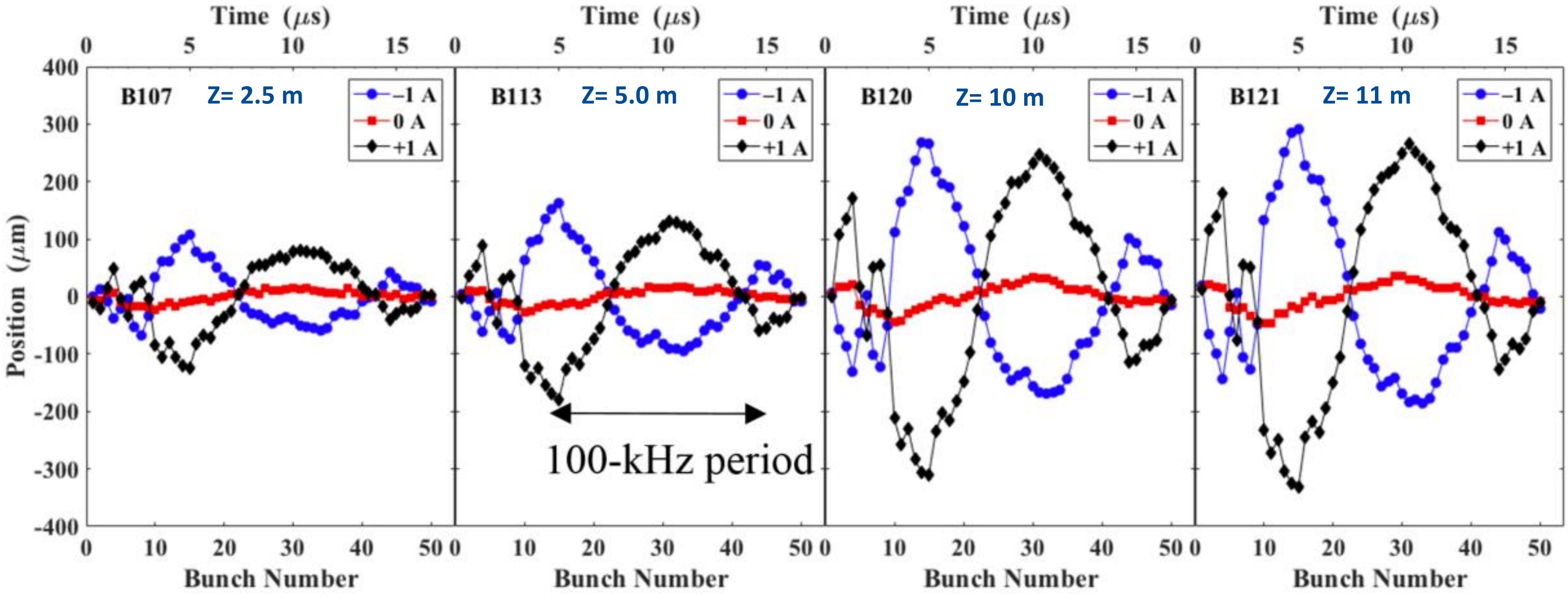


Thorsten Hellert | FEL Seminar | July 11 2017 | Page 12

T. Hellert 7/11/17 DESY Seminar

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).



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, 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 $\qquad \Delta x := 0.1$ cm

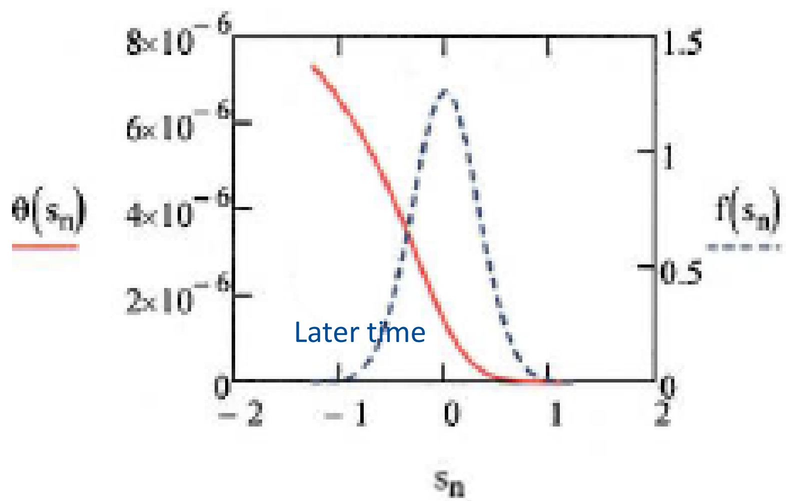
$$\theta(s) := \frac{e_{conv} \cdot e_{SGS} \cdot N_e}{P_0} \cdot \int_s^{10} \Delta x \cdot W_T(s_p - s) \cdot f(s_p)\, ds_p$$

$\beta x := 1000$ cm

Transverse wake

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

Wake numerically computed for ILC cavities



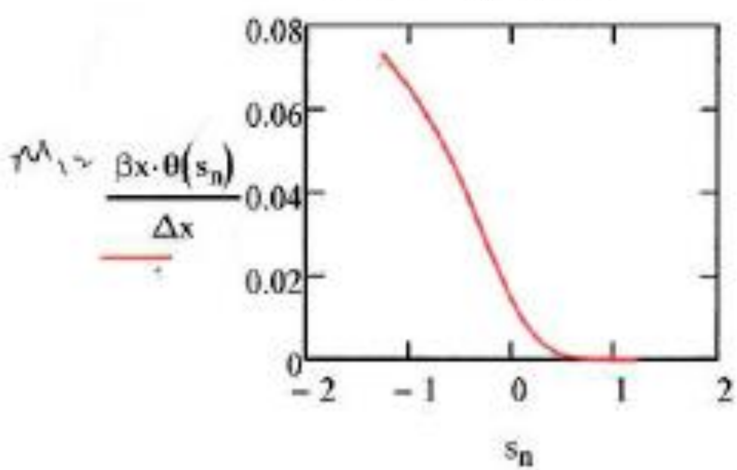


Table of Scaled Short-Range Wakefield Kick Angles

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 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	500	5	20	10	4	80	

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

IV. Initial tests for Short-range Wakefield Effects

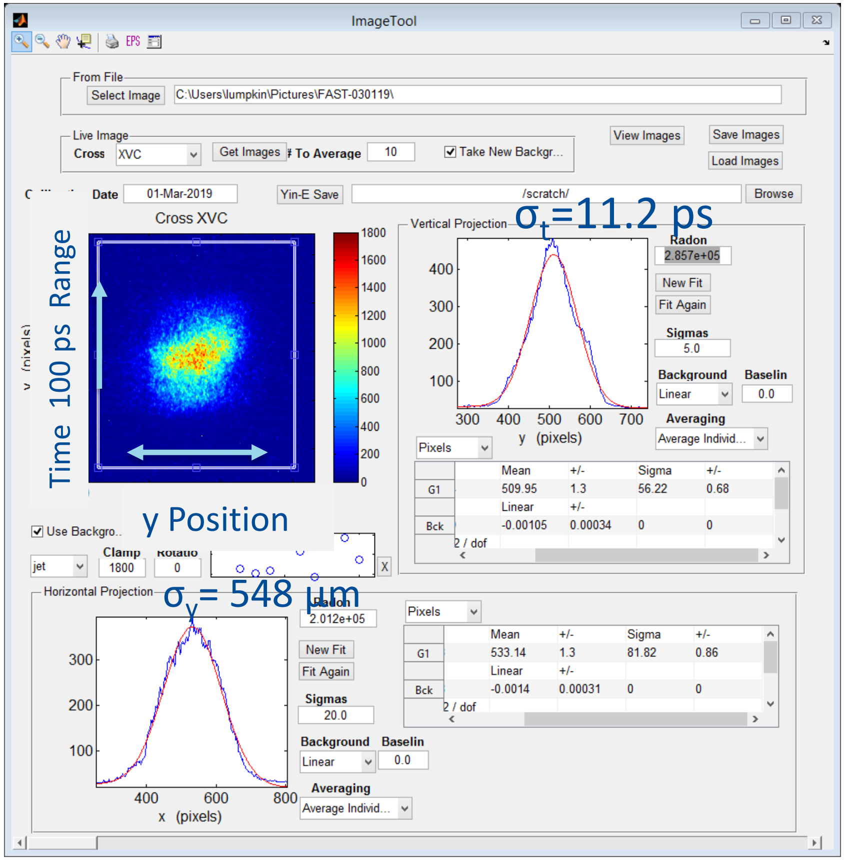
Initial tests for short-range wakefield effects generated by off-axis steering of the beam into CC1 and CC2. Localize to CC2 with V103 corrector.

- 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.

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

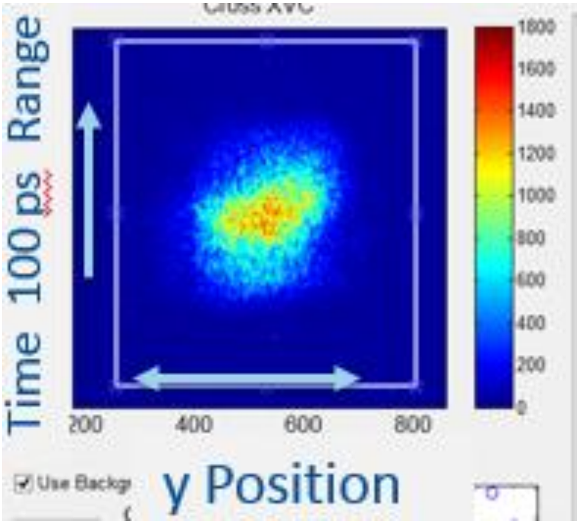


HOM Detectors
CC1[8]= -100 mV
CC1[9]= -60 mV
CC2[8]= -100 mV
CC2[9]= -50 mV

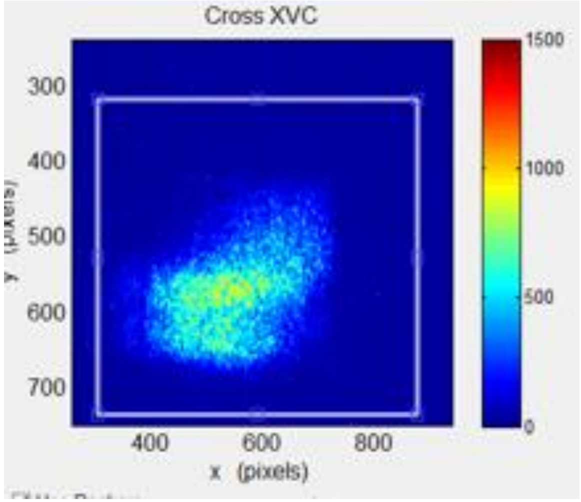
HOMs as Found: Effects of Steering Observed 3-01-19

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

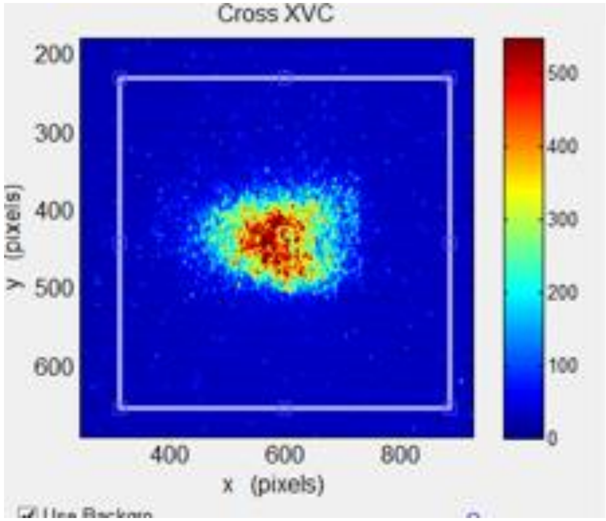
V103=-0.43 A as found



Δ V103= +2.4 A

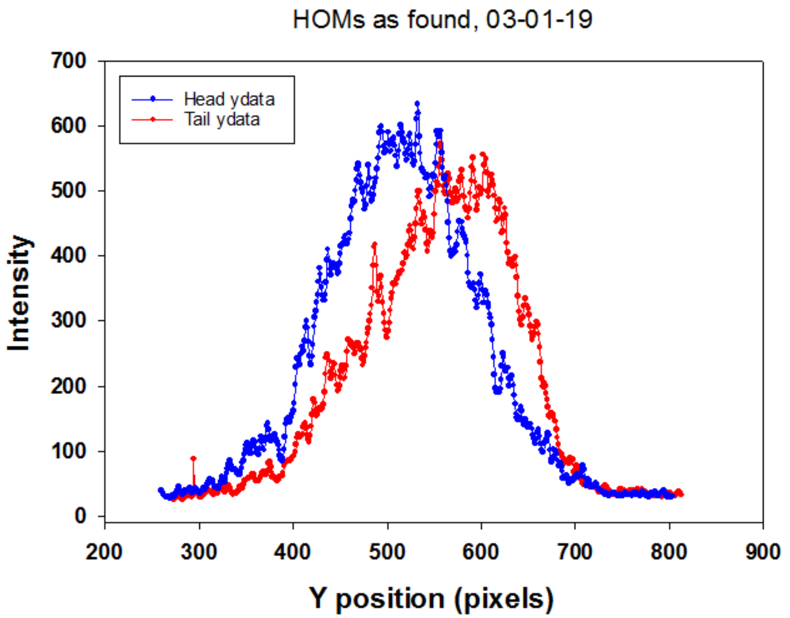


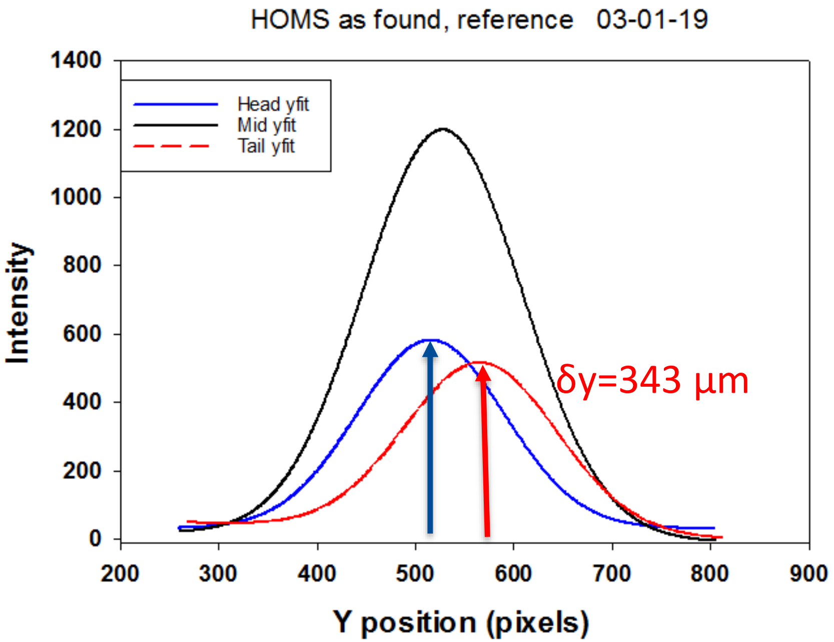
Δ V103= -2.4 A



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

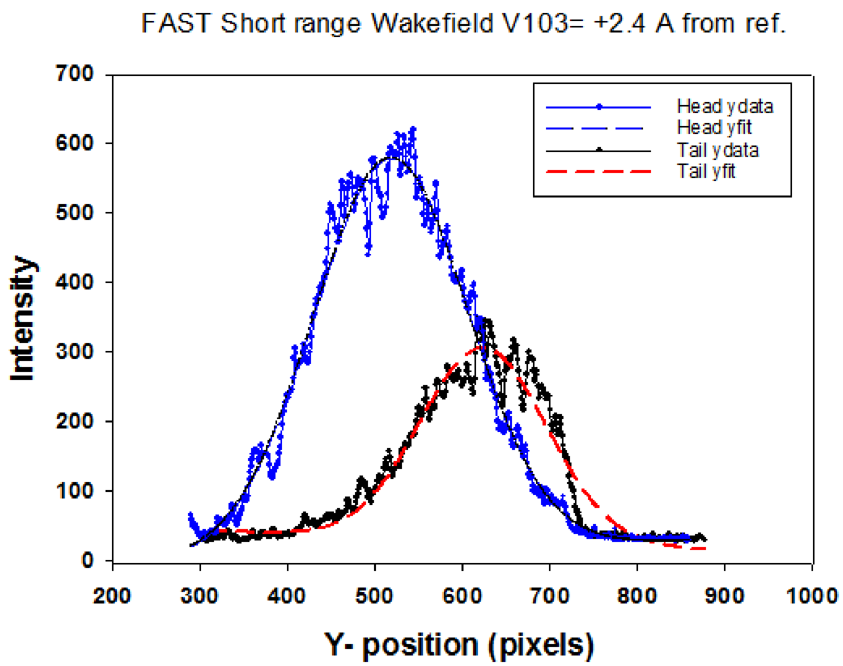
- Estimate mm+ off axis, angle with CC1 HOMs;100 mV, 60 mV
- Estimate mm+ off axis, angle with CC2 HOMs;100 mV, 50 mV

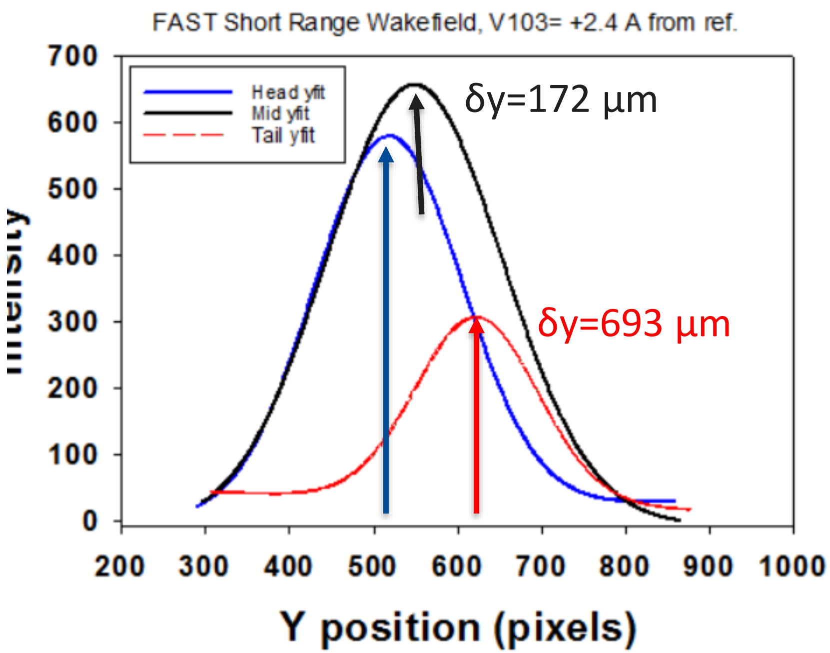




Centroid Shifts within Micropulse Time: y-t   03-01-19

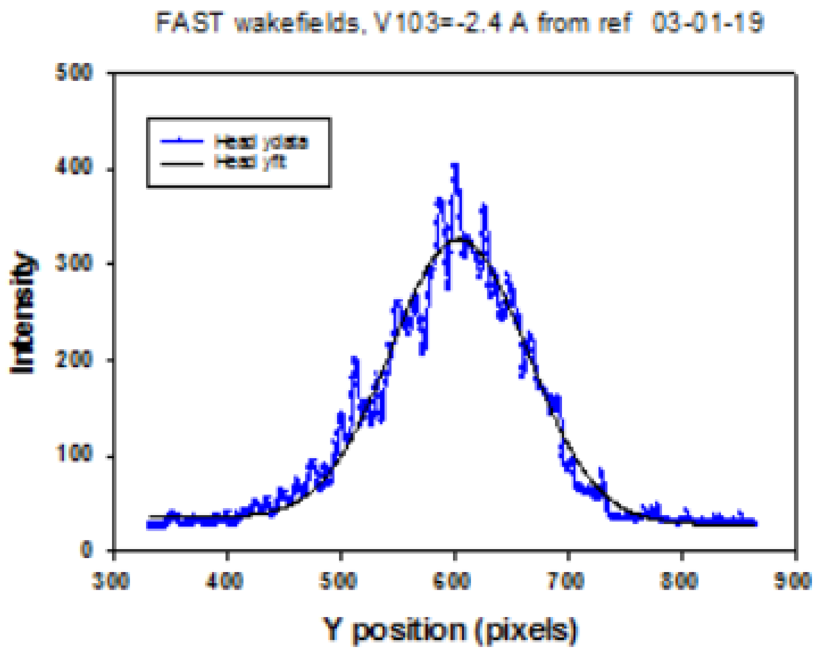
- V103= +2.4 A from ref, 500pC/b, 150b, MCP=61
- Time samples of y profile at Head, Mid, and Tail of micropulse.

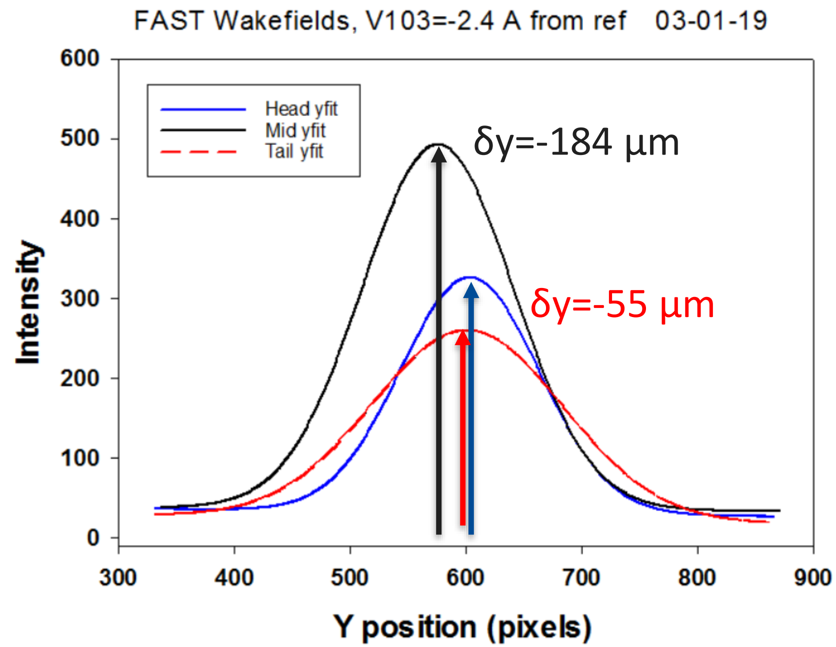




Centroid Shifts within Micropulse Time: y-t 03-01-19

- 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

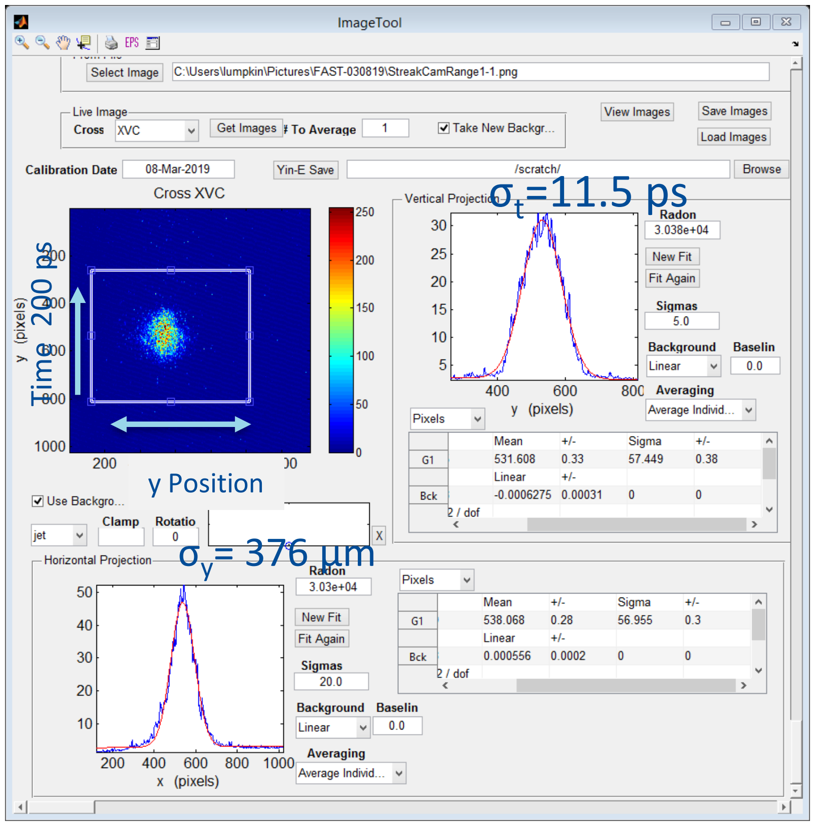
Cases 1-3: 16% size reduction, Cases 2-3: 38 % reduction.

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

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

- V103= 0.054 A , sig-t=57.4 $\pm$0.5 pixels => 11.5 ps with 0.20 ps/pix, 50b, 500 pC/b, Sigma-y = 57 $\pm$1 pixels. No y-t tilt.

No y-t tilt: Ellipsoidal beam



HOM Detectors

CC1[8] = -13 mV

CC1[9] = -10 mV

CC2[8] = -5 mV

CC2[9] = -7 mV

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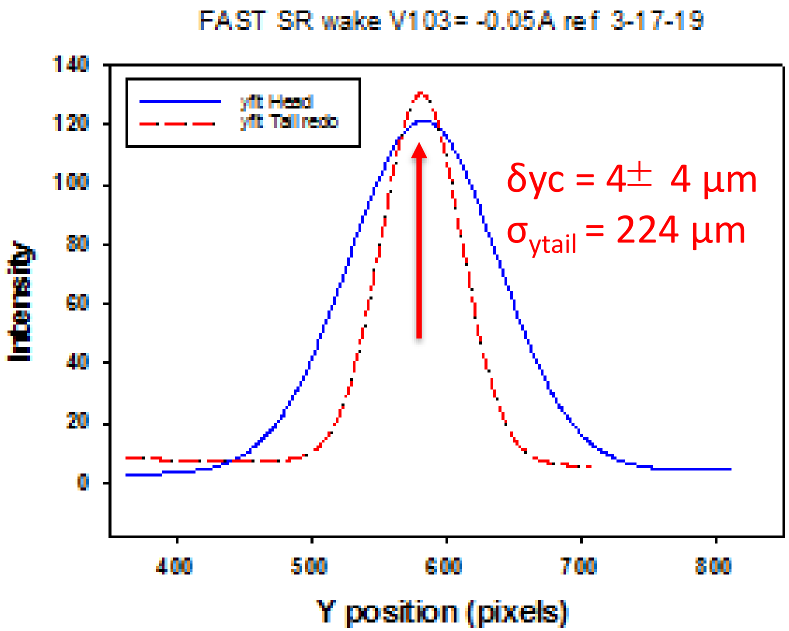
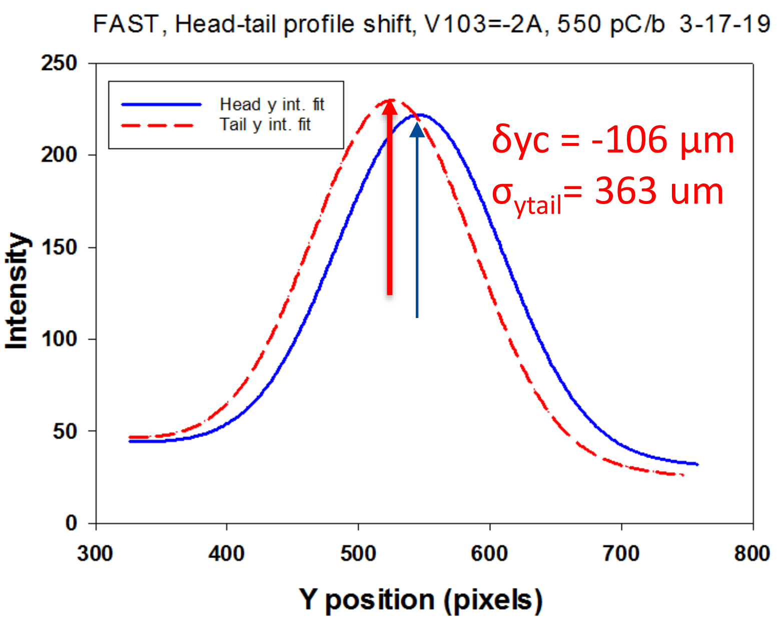
y(t) Centroid Shift and Slice Profile Growth Seen 3-17-19

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





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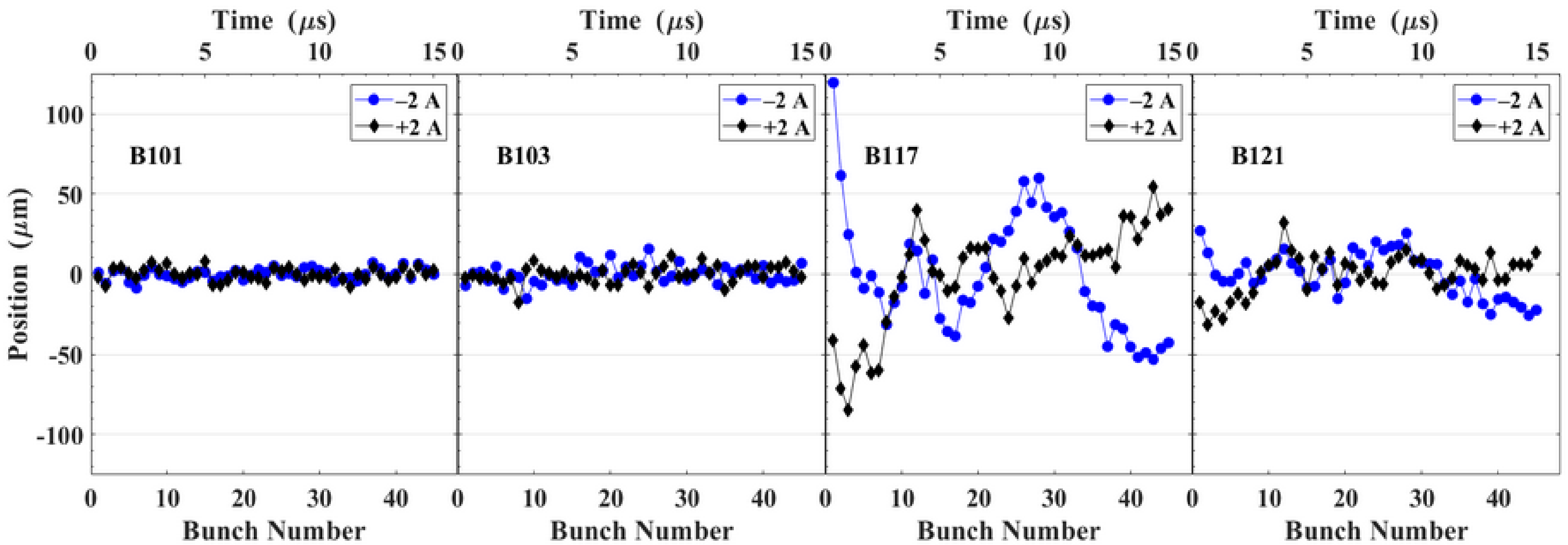
100-shot Average rf BPM for HOM-induced motion at B121

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



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

*Data has 50-b mean subtracted.

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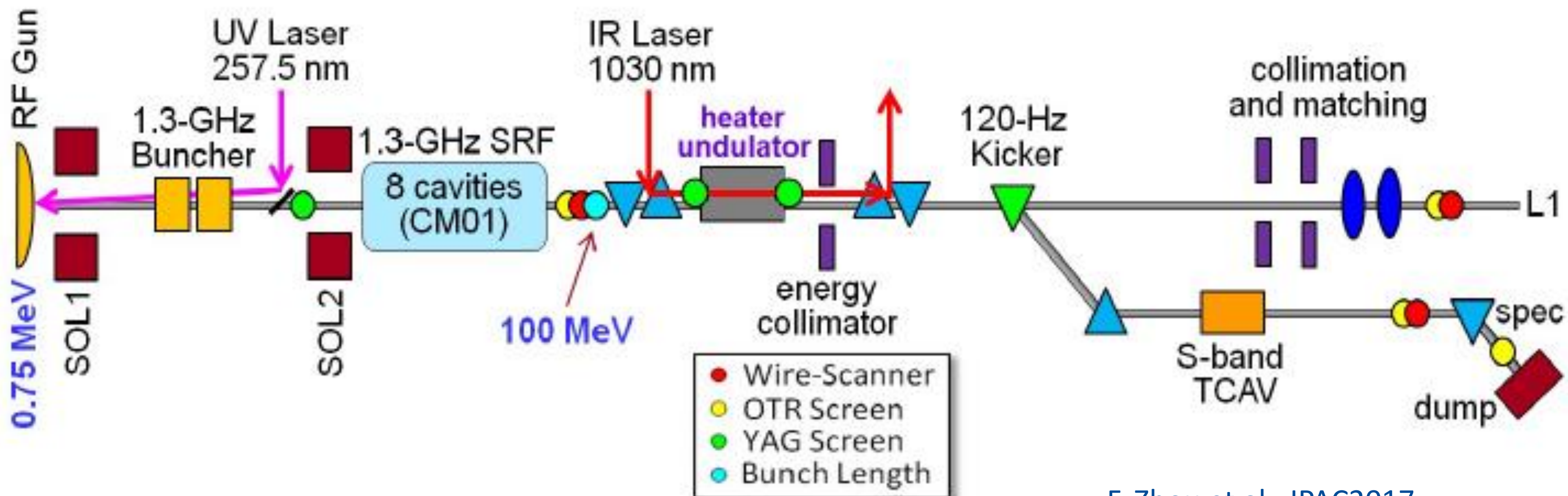
Schematic of the Planned Full LCLS-II Injector

- 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 Fall 2020.



F. Zhou et al., IPAC2017

V. SUMMARY

- 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.

ACKNOWLEDGEMENTS

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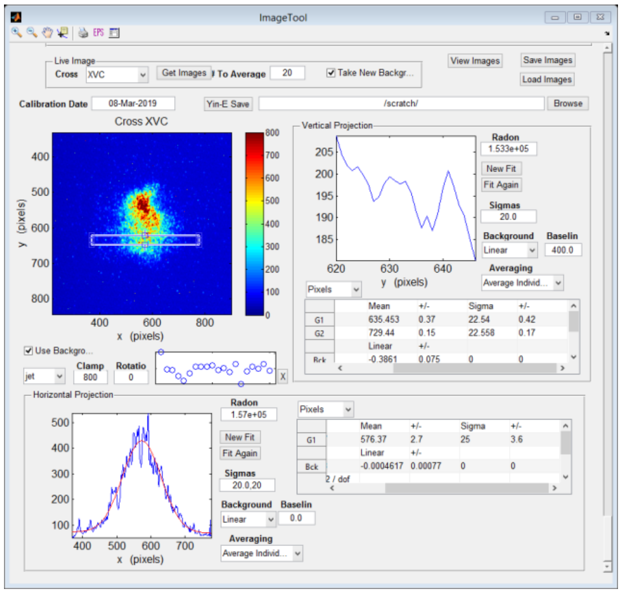
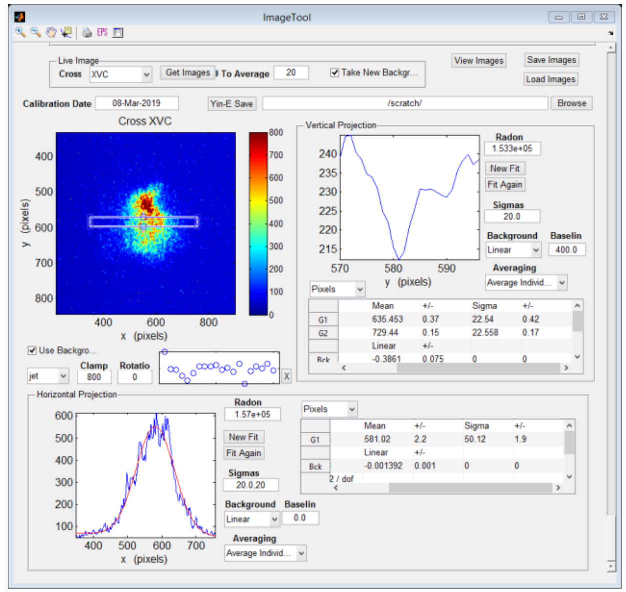
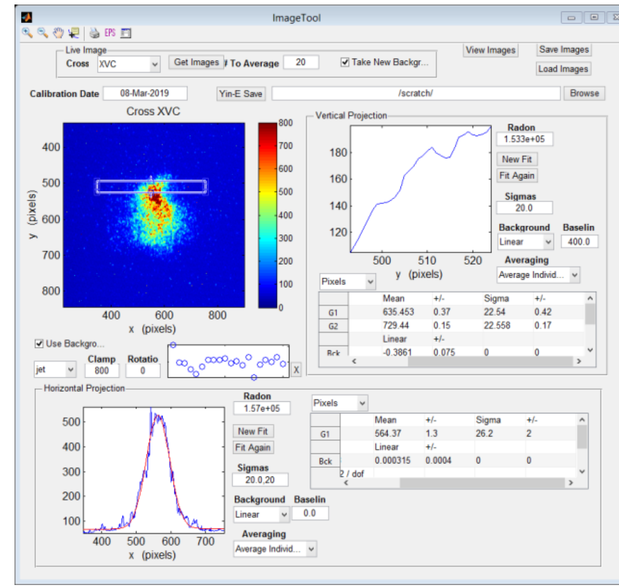
Backup and Extra Slides

- Ellipsoidal beam
- Source images for different conditions.
- LANL short-range wakefield data, NC L-band.
- HOM data logger
- HOM model results
- etc.

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

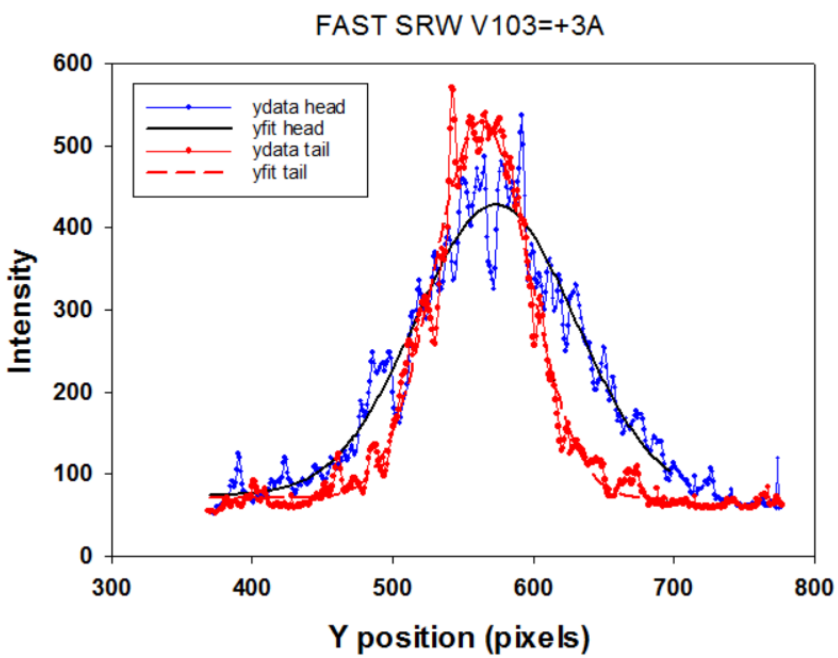
- V103=+3A head to tail centroids: 576.4, 581.0,564.4 pix
- sigmas 25, 50.1,26.2 pix

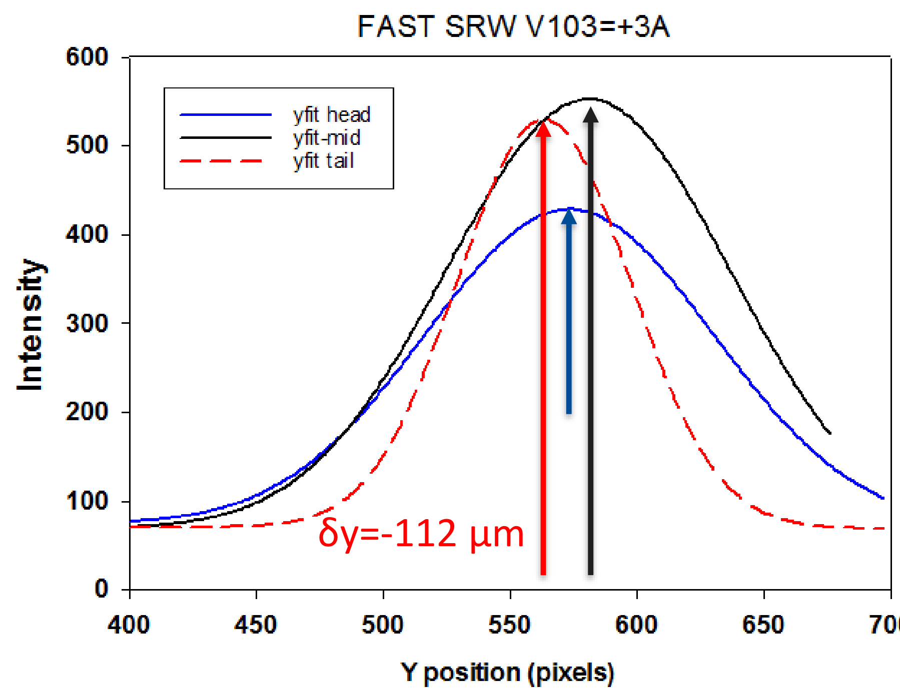




Ellipsoidal shape perturbed by short range wakefields.
HOMs only 20 µm oscillation generally at Q and V103 setting

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



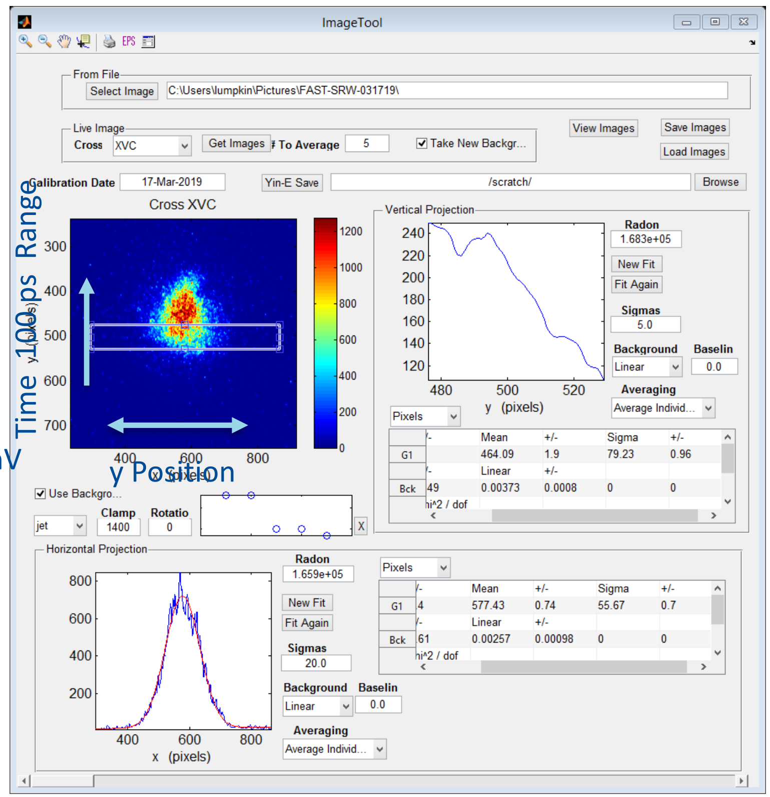


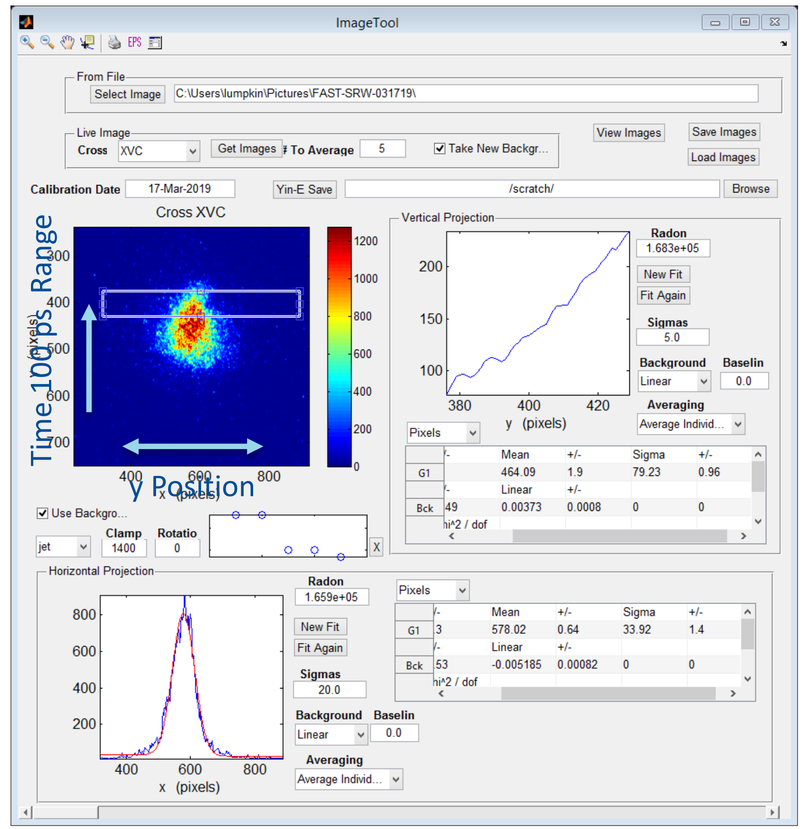
Search for Short Range y-t effect in Streak Camera Images

- 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





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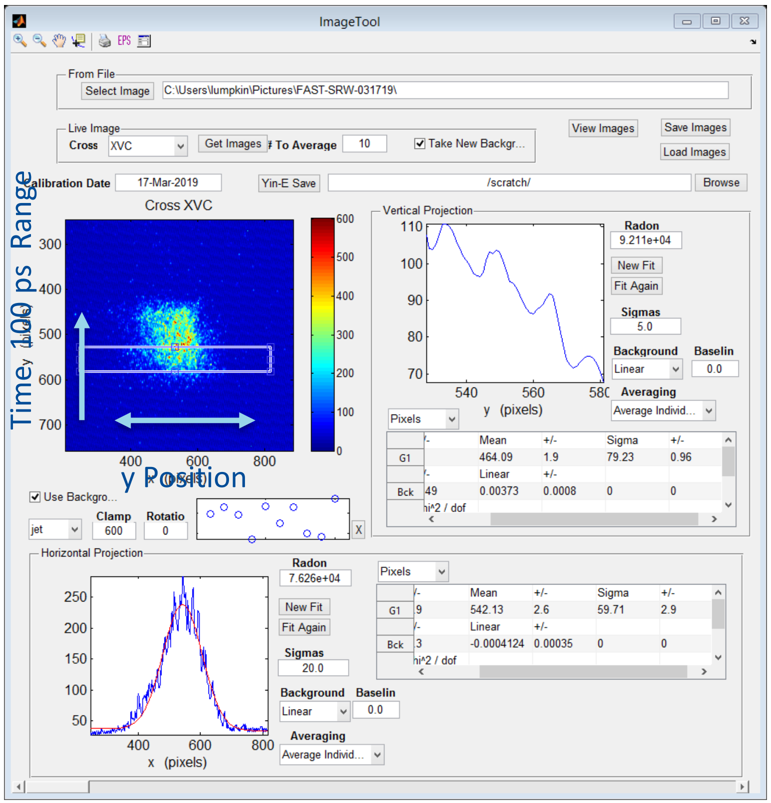
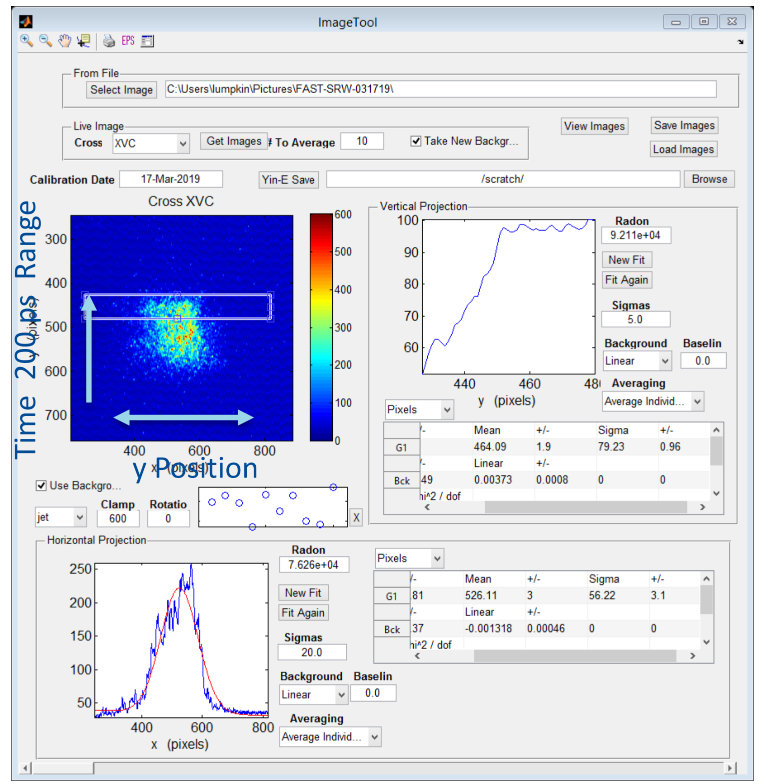
Search for Short Range y-t effect in Streak Camera Images

- 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





LANL Short range Wakefield Experiment

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

806 A.H. Lumpkin, M.D. Wilke / Time-resolved e-beam characterizations

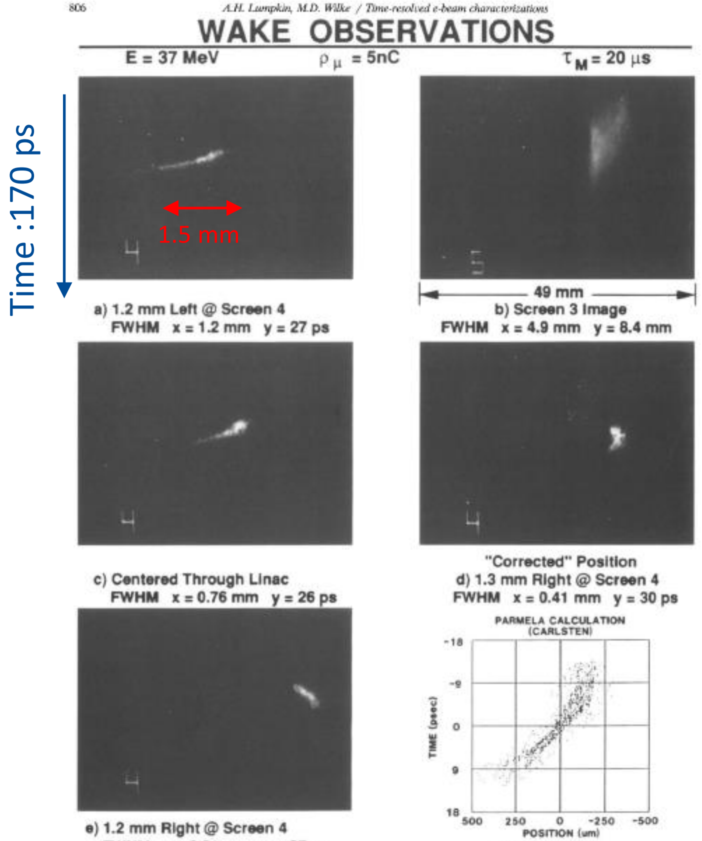
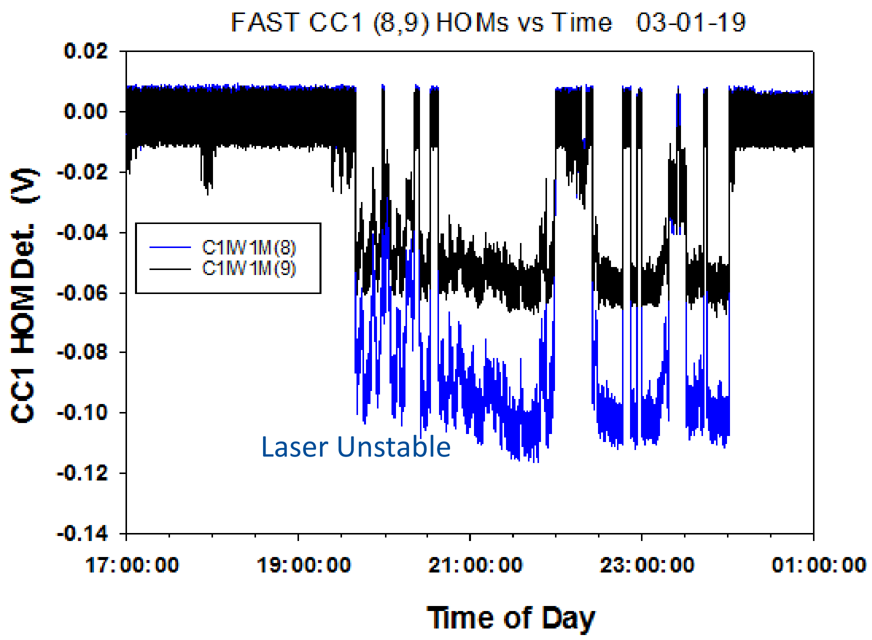


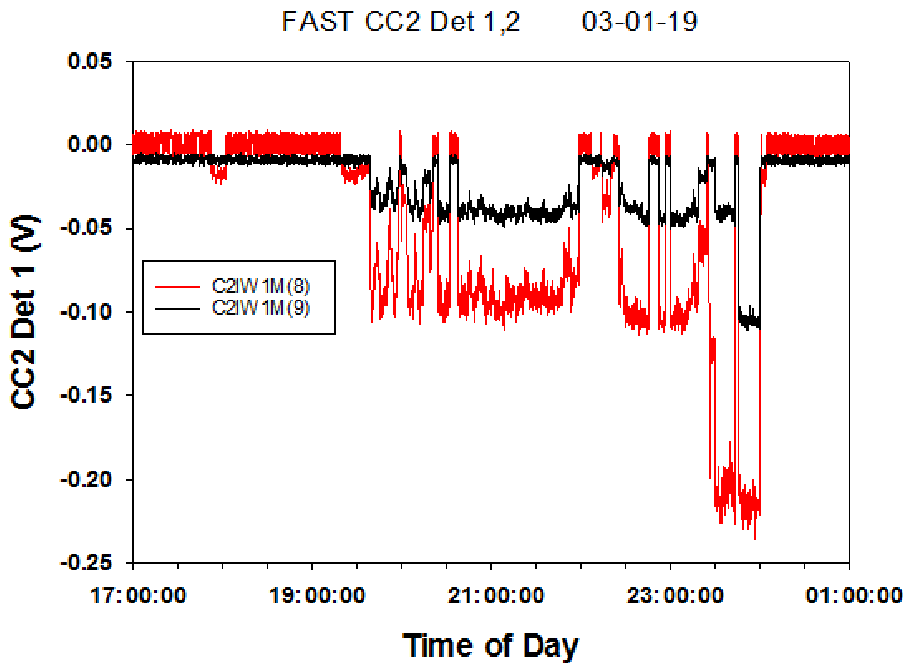
Fig. 6. A composite of streak images at station 4 for steering horizontally "left to right" across the scene. Note the flip in the direction of the head-to-tail kick. Time increases going down on the vertical axis.

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

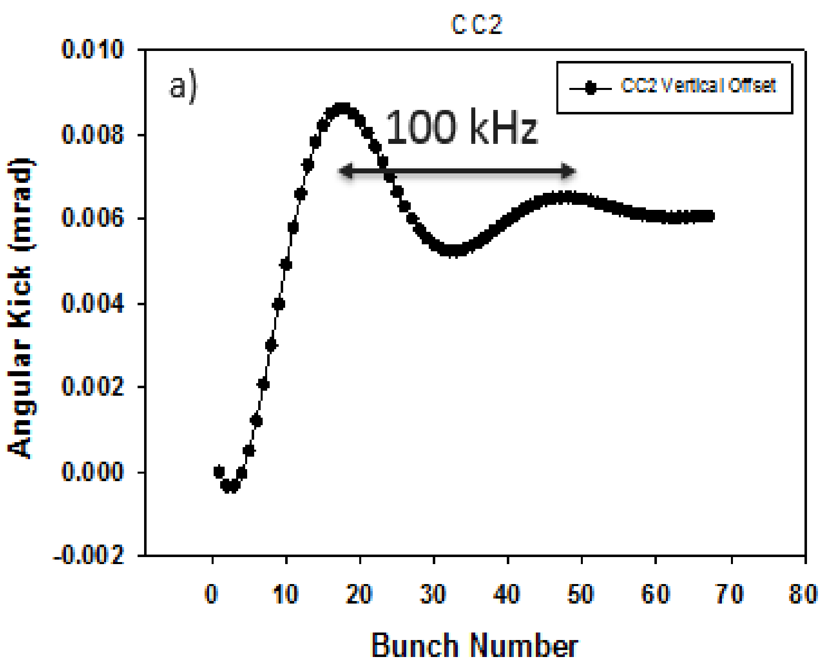
HOM Detector Signals tracked during run 03-01-19

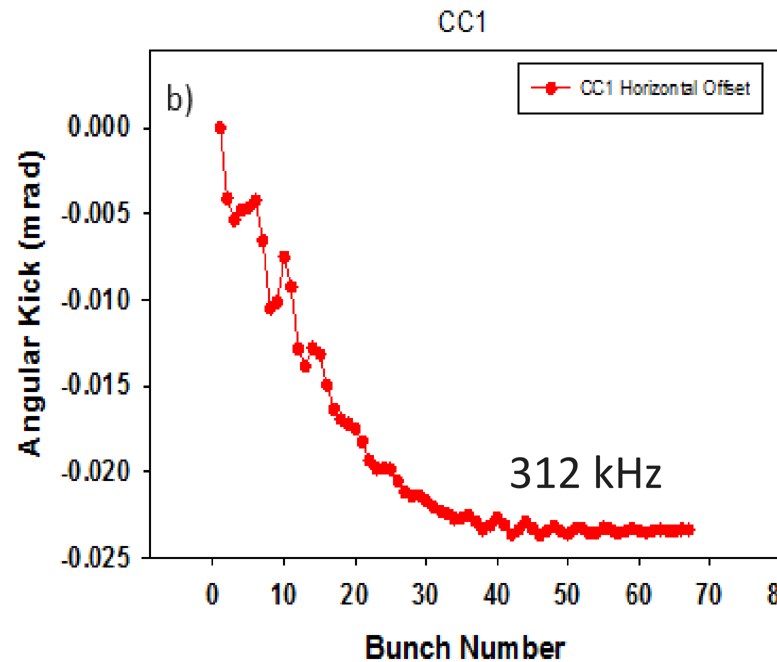
- CC1 detector signals stable after 21:00 when laser stabilized.
- CC2 detectors show effects of V103 current changes.





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.