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Long-Range and Short-Range Wakefield Effects in TESLA-type Cavities (LRW/SRW)

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FAST/IOTA Users' Meeting

15 June 2020

Alex Lumpkin

Outline

I. Introduction

II. Long-range wakefield (LRW) and Higher-order mode (HOM) results

III. Beam Offset Monitor (BOM) results using HOMs

IV. Short-range wakefield (SRW) results

- Experiment
- Initial ASTRA simulations (Feng Zhou)

V. Run 3 strawman studies proposals, Machine learning added

VI. Proposed new optical transport line for SRW studies in CM2

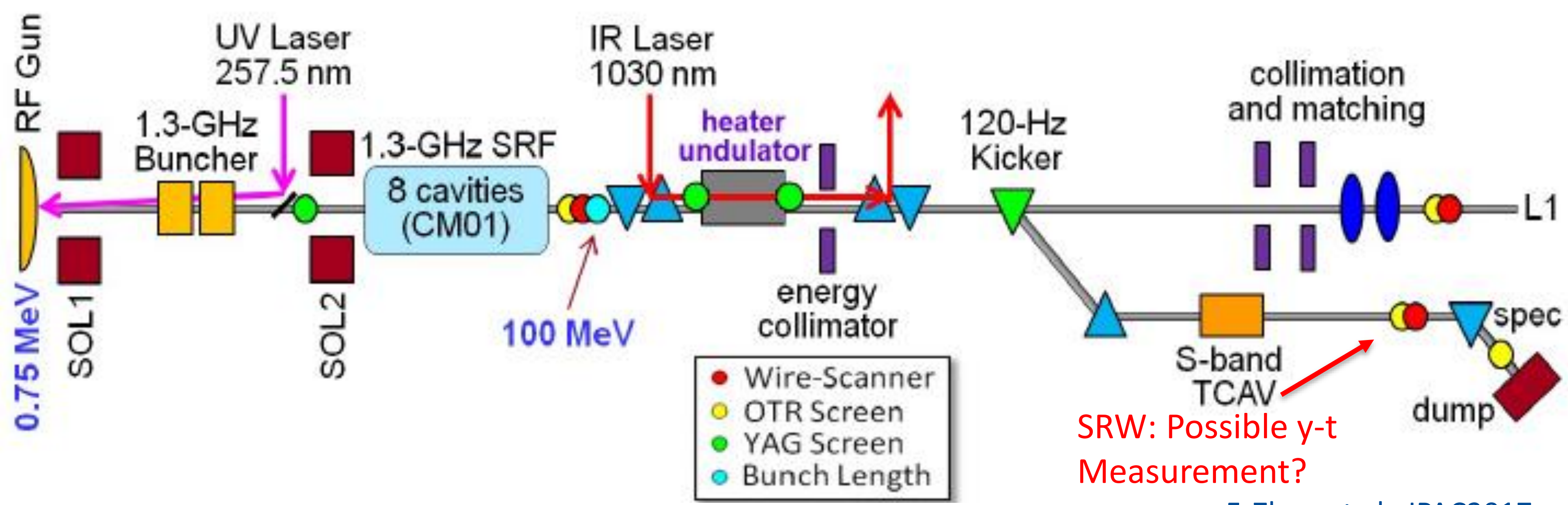
VII. Summary

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.
- Historically, many HOM studies have been related to determining cavity offsets from the beam axis, 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.
- In Run 2, our collaboration continued these investigations with a primary goal to inform LCLS-II injector commissioning.

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 FY21.



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.
- Primary objectives are to identify and mitigate beam size and emittance dilutions due to wakefield effects in the rf cavities.

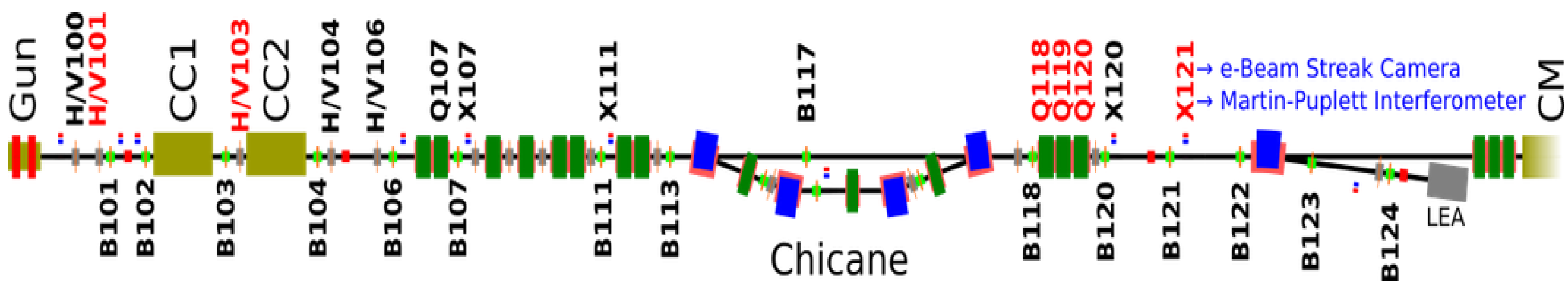


Table 1. FAST Electron Beam Parameters for Studies

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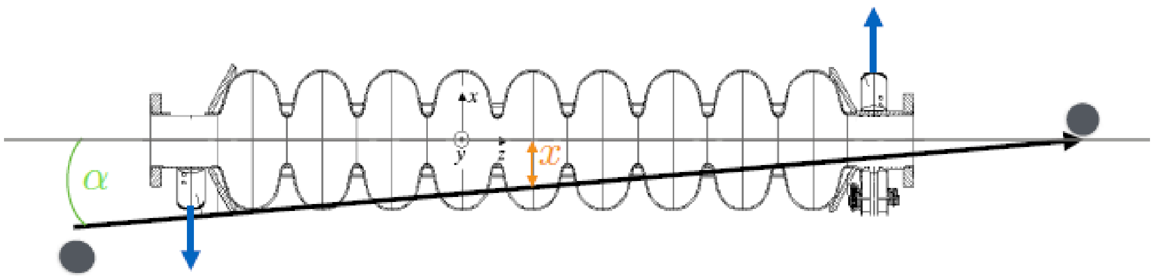
Beam Parameter	Units	Value		
Micropulse Charge (Q)	pC	100-2500		
Micropulse rep. rate	MHz	3		
Beam sizes, σ	µm	100-1200		
Emittance, σ norm	mm mrad	1-5		
Bunch length,σ Compressed	ps ps	4-20 1-3		
Total Energy	MeV	33, 41		
PC gun grad.	MV/m	40-45		
CC1 gradient	MV/m	14.2, 21		
CC2 gradient.	MV/m	14.2		

1-150 bunches used, 3000 max.

EXPERIMENTAL SETUP

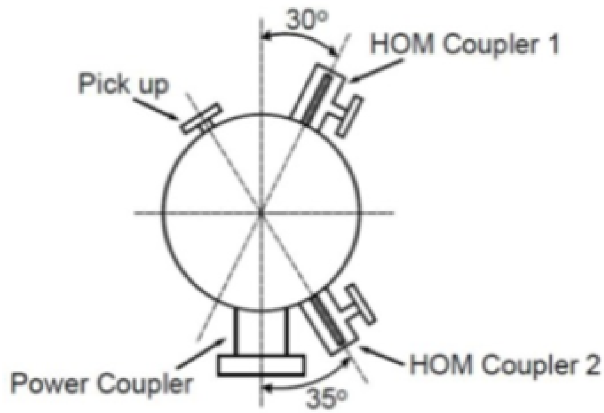
- TESLA CAVITY
  - 2 HOM couplers
- DIPOLE HOM
  - $V_x(t) \propto x \cdot e^{-\frac{t}{2\tau}} \sin(\omega t)$
  - $V_{x'}(t) \propto x' \cdot e^{-\frac{t}{2\tau}} \cos(\omega t)$



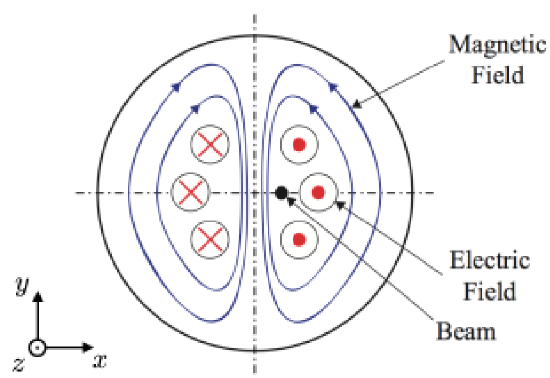
Expected HOMs in TESLA Cavities*

Mode #	Freq.(GHz)	R/Q (Ω/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



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

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

T. Hellert 7/11/17 DESY Seminar

Collaboration Objectives: Wakefield Assessments

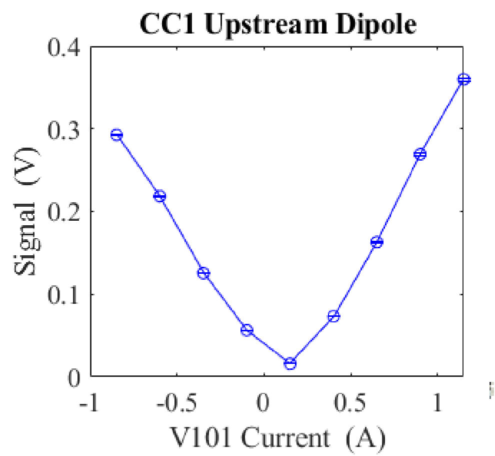
- Establish more comprehensive data sets on LRWs in TESLA-type cavities. Check trajectory centering in cavities with HOMs.
- Demonstrate a beam-offset monitor (BOM) based on HOMs.
- Evaluate a wideband amplifier for tests with 1 bunch at 100 pC/b for LCLS-II and to look for HOM quadrupole modes.
- Establish a more comprehensive set for SRW effects versus charge and offset. Used nine offsets with 4 charges.
- Use synchroscan streak camera for 50 b sums and 20- or 60-image sums for projected beam size, slice beam sizes, head-tail effects, and projected bunch lengths.
- Initiate ASTRA simulations for SRW effects and bunch lengths.
- Provide data bases for possible Machine Learning application.
- Inform LCLS-II injector commissioning plans.

V101 and H101 Scans for HOM Data Dec. 2019

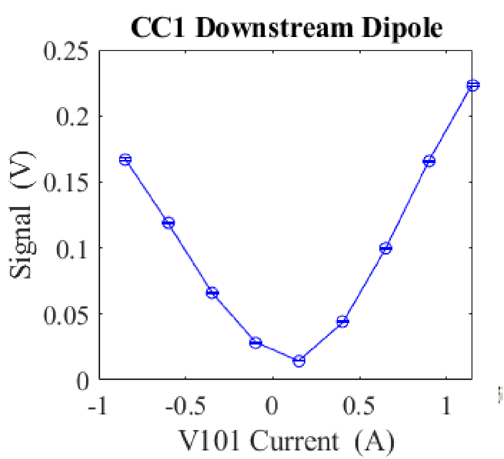
- CC1 HOMs, scans, 500 pC/b, 50 b, 100-shot averaging.

CC1 Dipolar

US

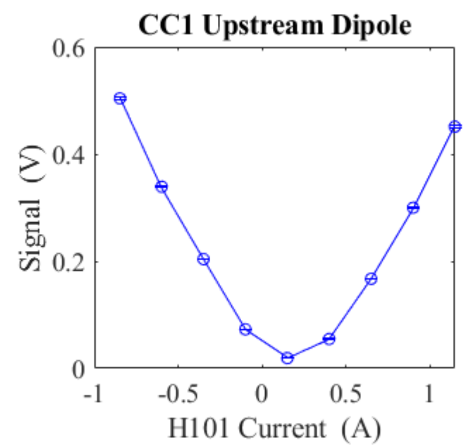


DS



CC1 Dipolar

US



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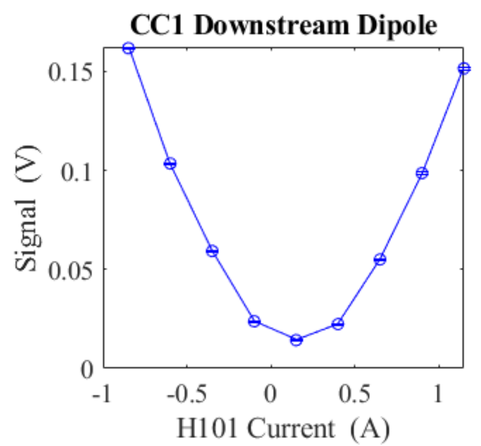
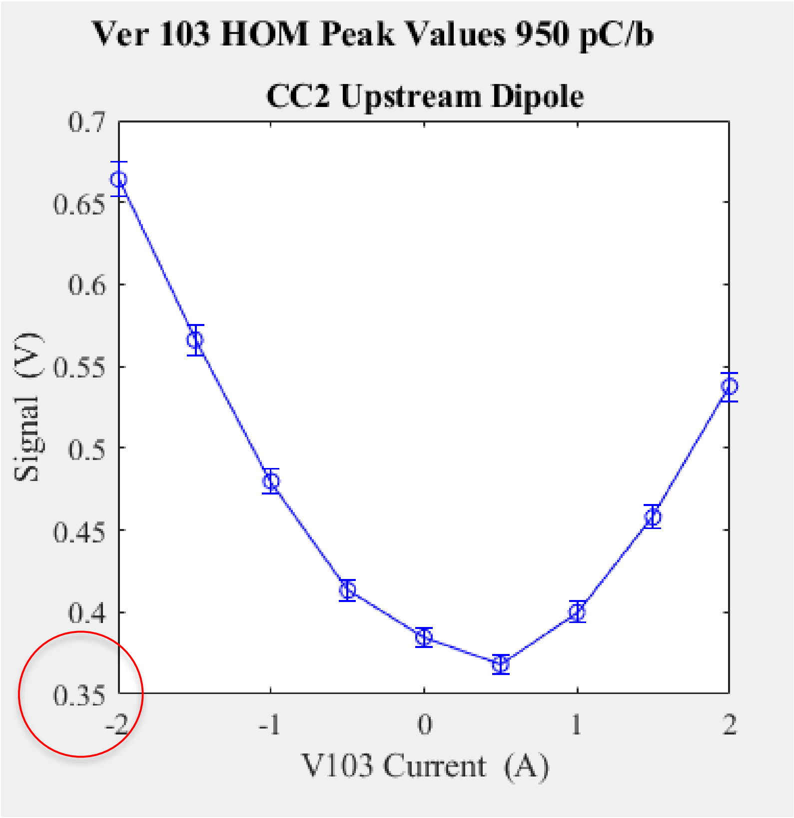
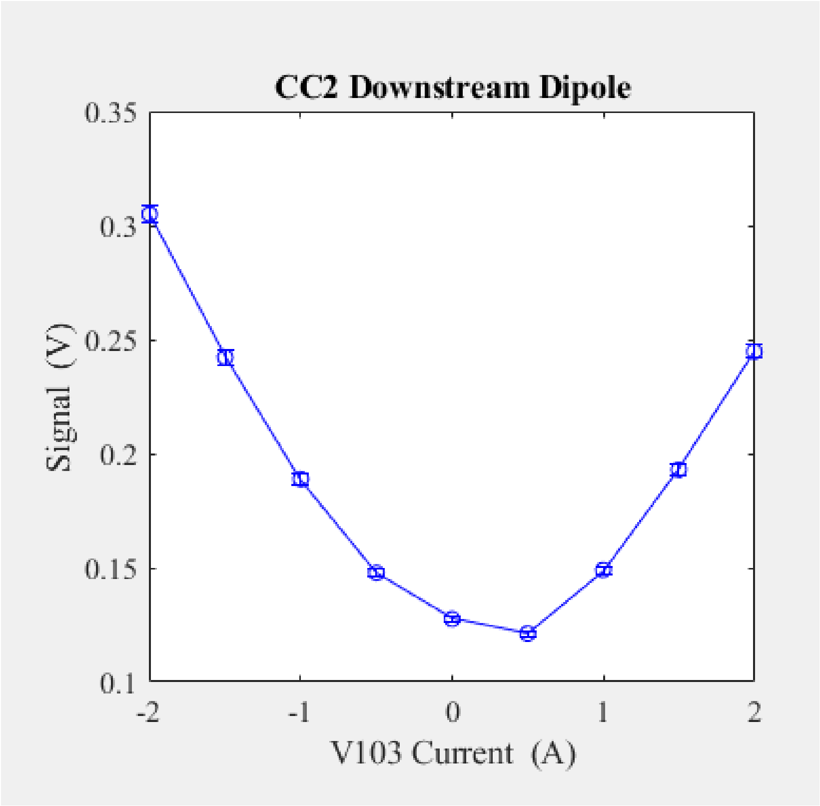


V103 Scan: CC2 HOMS

02-27-20

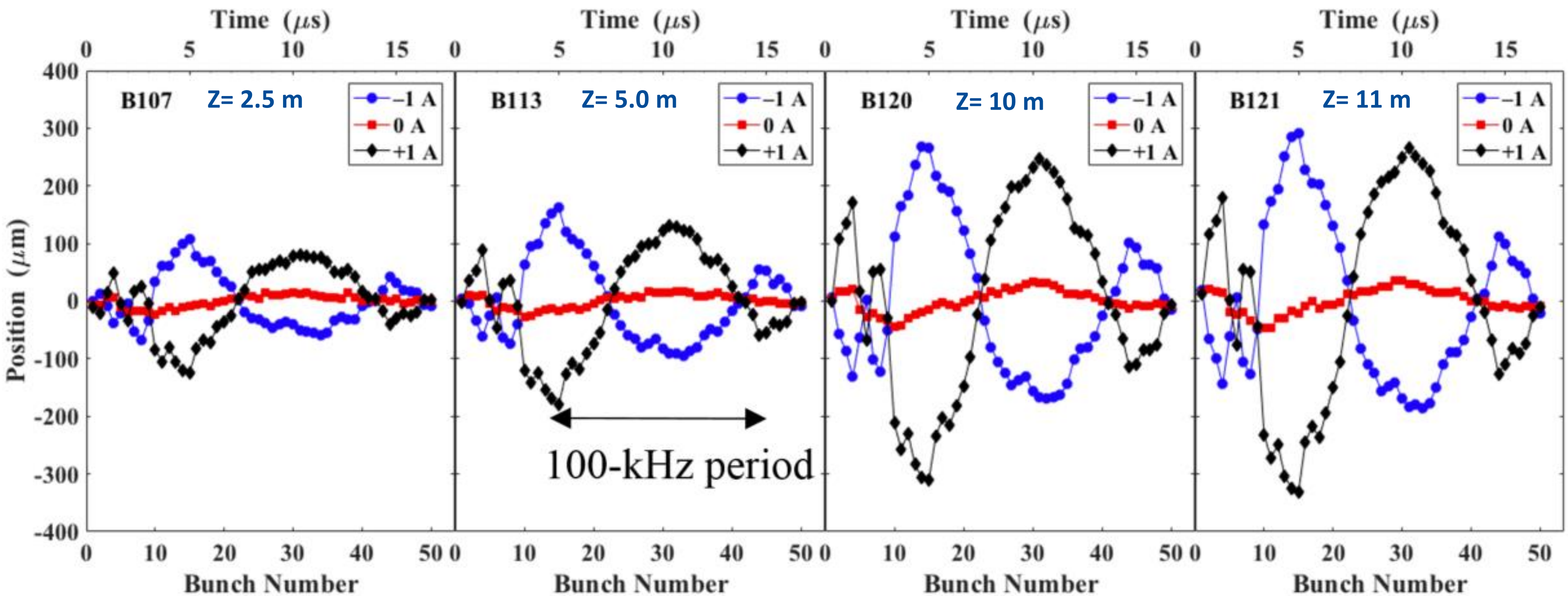
- HOMs in CC2 active. Relative Minimum at +0.5 A (+1 mrad). Q=950 pC/b, 50b. Scaled to 500 pC/b, US signal is too high.





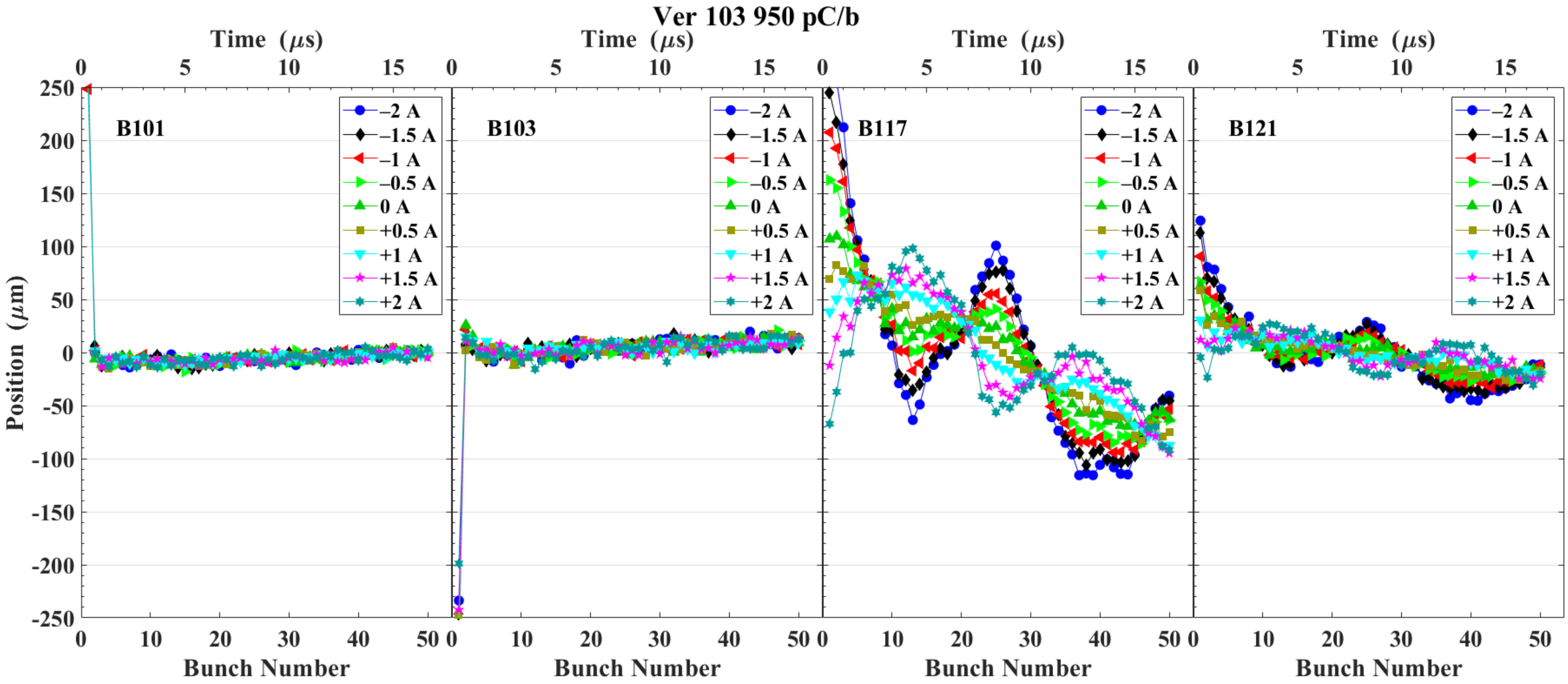
Centroid Vertical Oscillations Observed to Grow with Drift

- 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

- Quads Q118-120 ON. V103 Corrector 1 A=> 2 mrad



HOMs vs Beam Offset

- Use BPMs B101 and B102 as input vectors and propagate downstream via linear matrices
- Use cavity matrix of Chambers for CC1 and CC2

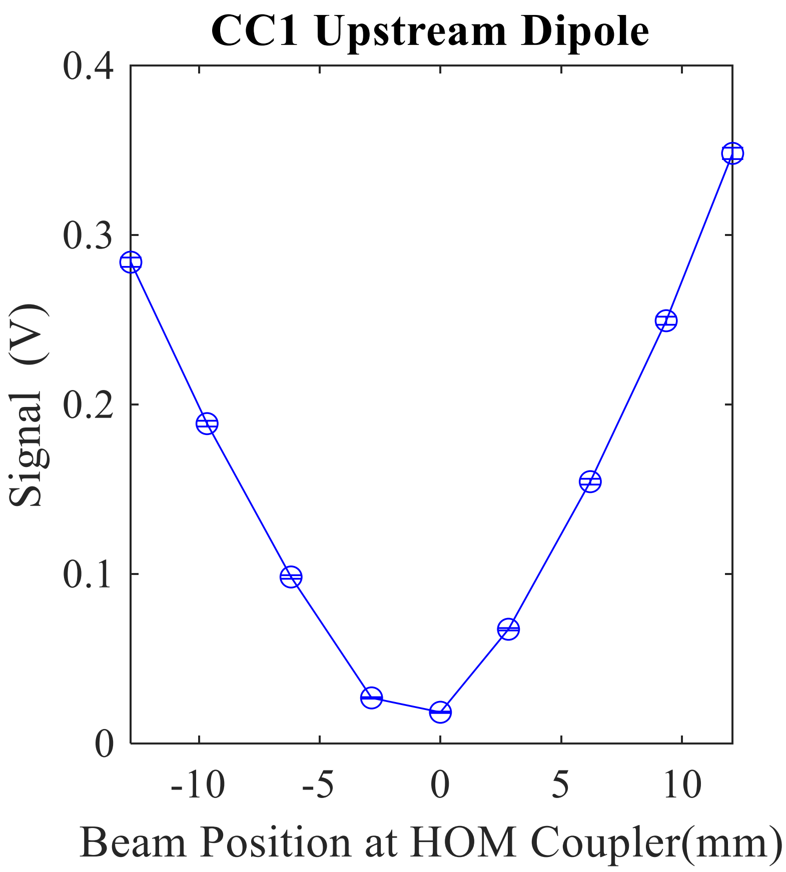
$$\begin{bmatrix} \cos\alpha - \sqrt{2}\sin\alpha & 2\sqrt{2}\dfrac{\gamma_i L}{\gamma_f - \gamma_i}\sin\alpha \\ -\dfrac{\gamma_f - \gamma_i}{\gamma_f L}\dfrac{3}{2\sqrt{2}}\sin\alpha & \dfrac{\gamma_i}{\gamma_f}\left(\cos\alpha + \sqrt{2}\sin\alpha\right) \end{bmatrix} \quad \alpha = \frac{\ln\gamma_f - \ln\gamma_i}{2\sqrt{2}}$$

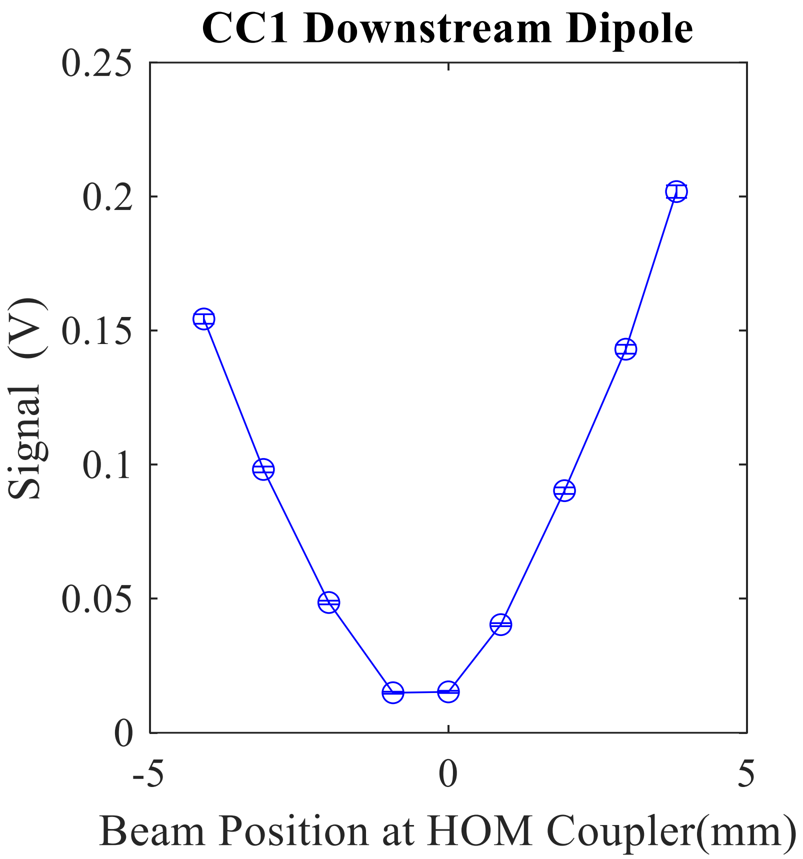
$$L = 1\ \mathrm{m}$$

- Upstream HOM is entrance to cavity
- Downstream HOM is exit of cavity
- BPM values are relative to zero kick data
- Initial and final gammas are γ_i and γ_f ,respectively

Beam Offset Monitors for CC1 (and LCLS-II Injector)

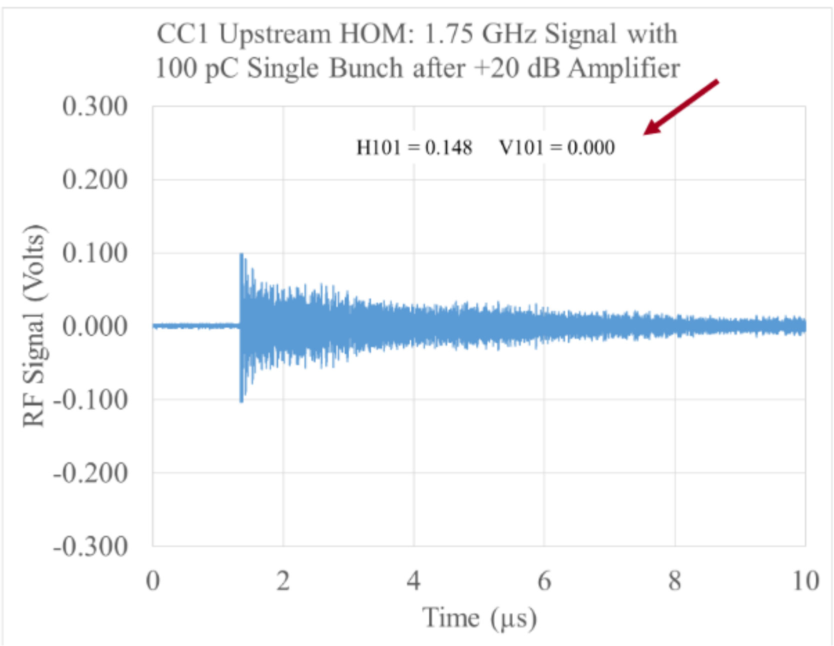
- 480 pC/b, 50 b, 15 MeV in center of CC1.   41 MeV total.
- Curves done for 4 charges.

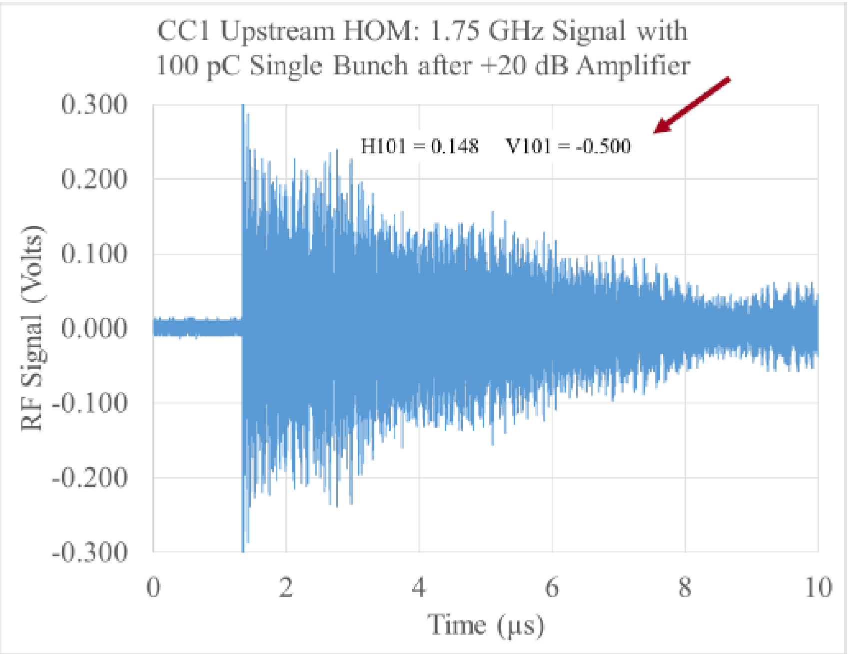




See Raw HOM Waveforms from Single bunch at 100 pC/b

- Wideband amplifier (20 db) added to the dipole channel raw output. Signal changes with offset due to V101 corrector current changes at FAST. (J. Sikora, P. Prieto)
- Signal persists for several µs.





Initial tests for Short-range Wakefield Effects

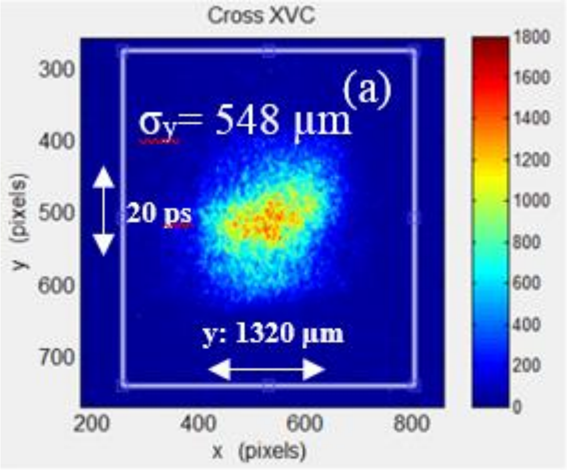
Initial tests for short-range wakefield effects generated by off-axis steering of the beam into CC1 and CC2. Localize to CC2 with V103 corrector. Use streak camera viewing X121 OTR screen.

Used Prosilica 1.3 Mpix digital camera as readout camera.

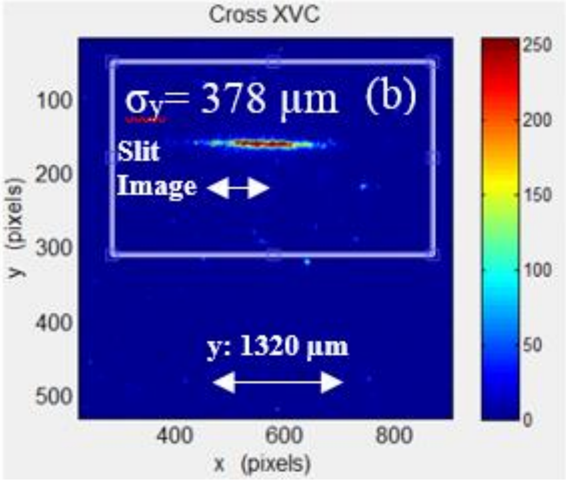
- Search for centroid shift *within* the 10-ps long micropulse.
- Search for possible kick compensation by CC2.
- Search for possible slice emittance effect.
- Detect space-charge dominated regime and ellipsoidal beam.
- Distinguish short-range wakefield centroid effect from HOMs' effect.
- Compare to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

“As found” Steering Shows Submicropulse SRW Effects

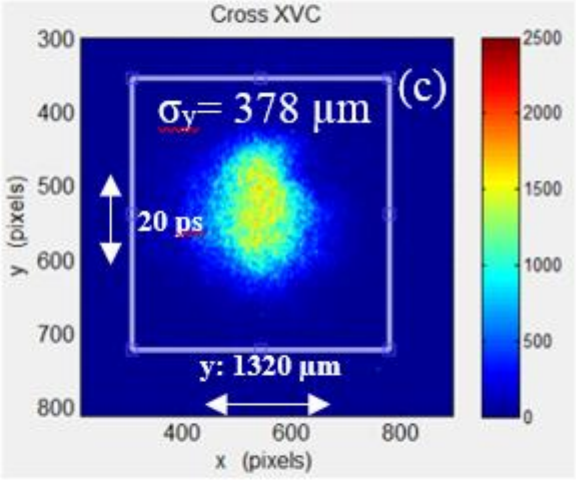
- Beam size dilution due to SRW quantified at >40% in streak camera images (Range 1) at X121 in FAST beamline.
- Laser spot 0.2 mm RMS, Q=500 pC/b, E=41 MeV after CC2.
- Later time is upward in streak image.



HOMs As Found: Machine Learning Opportunity



Focus Image HOMs min.

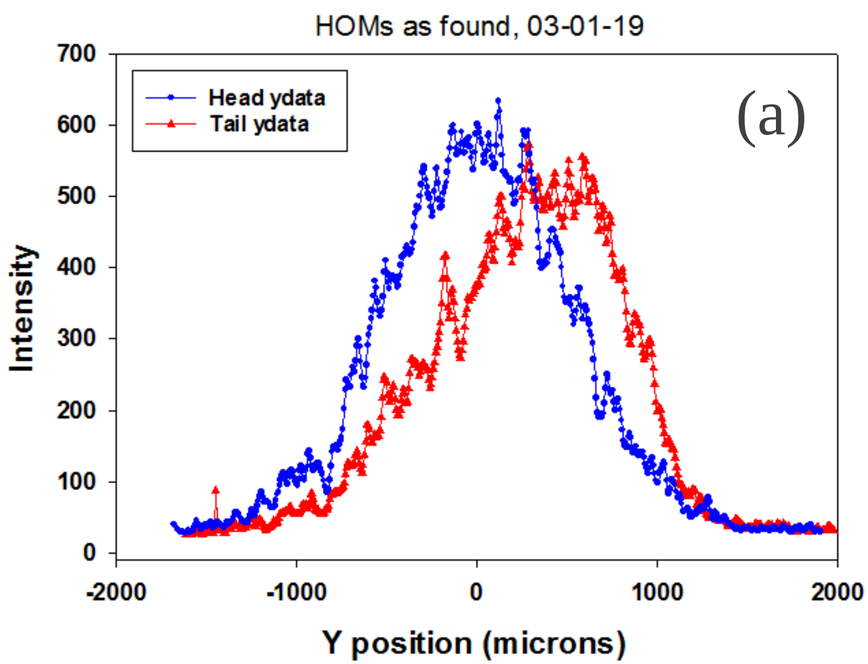


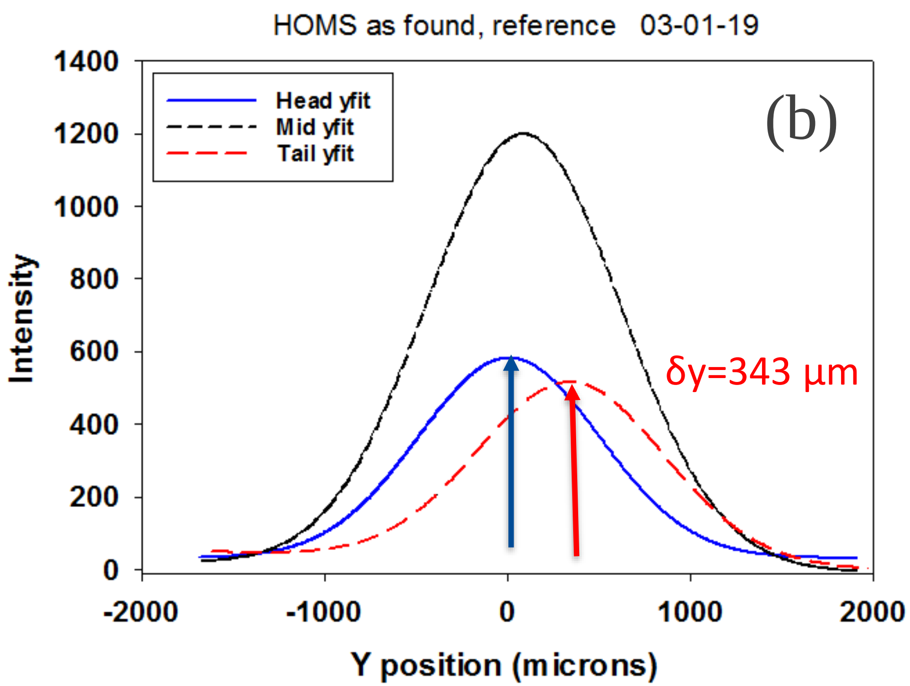
Streak: HOMs Minimized

PRAB, publ. 5/4/2020

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

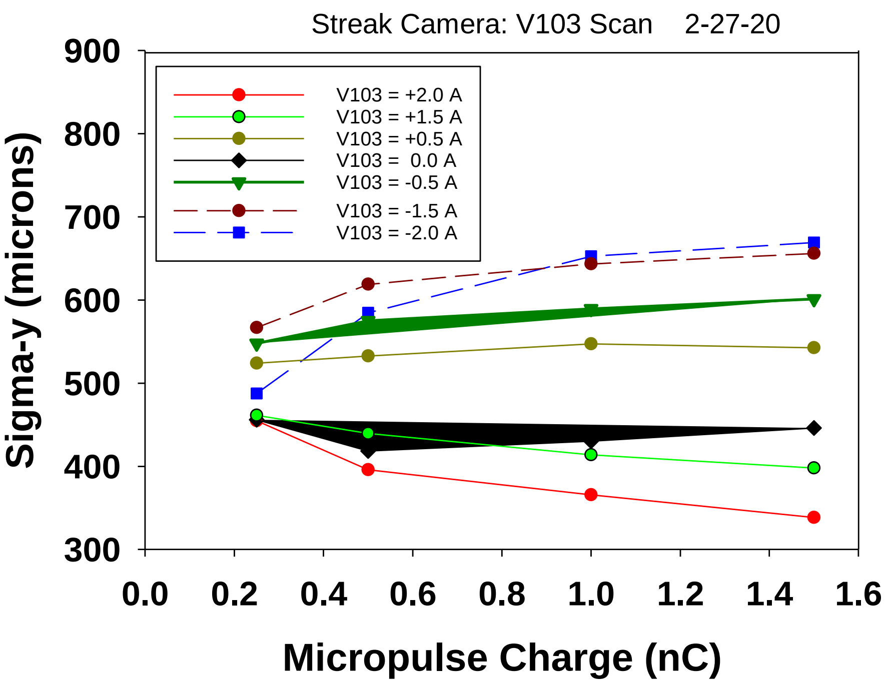


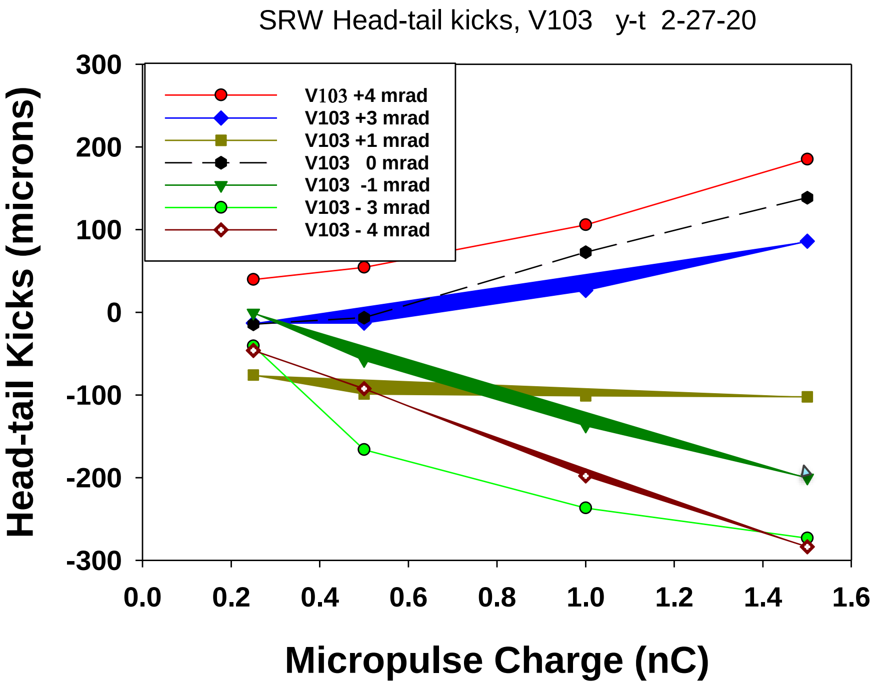


PRAB accepted, 4/2020

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

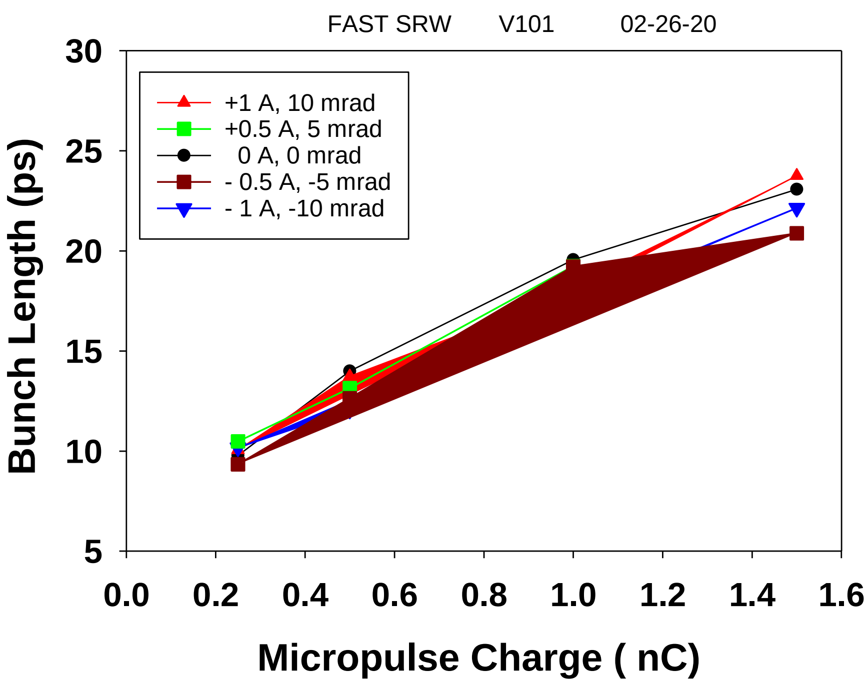
- V103 scan confirms +0.5 A,+1 mrad is better steering for HOM.
- Projected beam y size lower for + 2A (+4 mrad) steering?
- Proposed data for machine learning training. (Auralee E.)

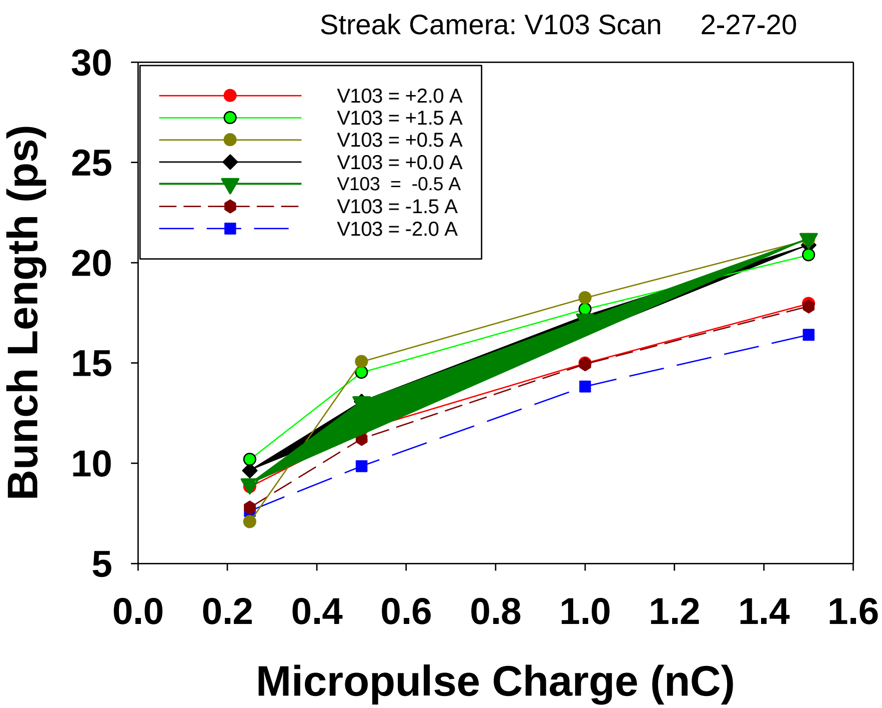




Streak Camera Data Provide Temporal Info 02-26,27-20

- 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?

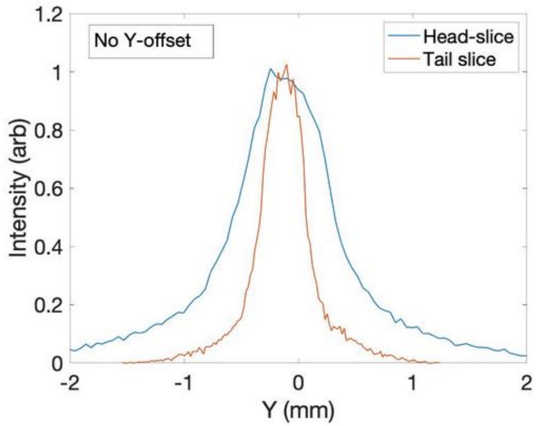


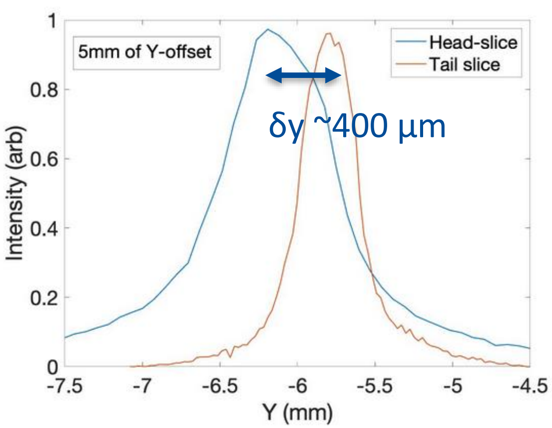


Initial ASTRA Simulation Results for FAST Linac

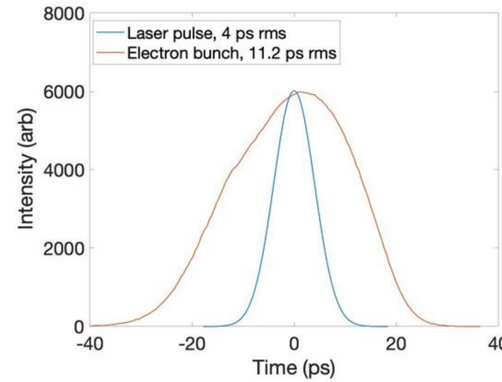
SLAC NATIONAL ACCELERATOR LABORATORY

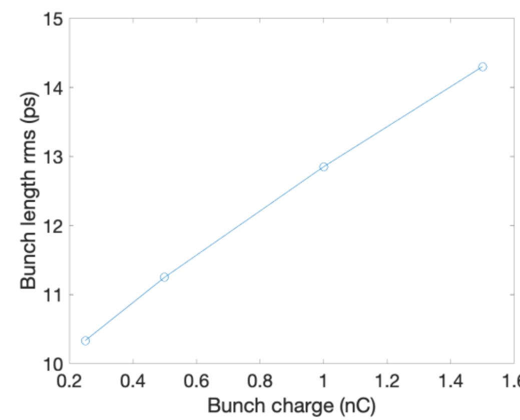
- Preliminary runs show the SRW head-tail kick after CC2 when there is a beam offset of 5 mm into cavities.(Feng Zhou:SLAC)





ASTRA Input:
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 Cavity



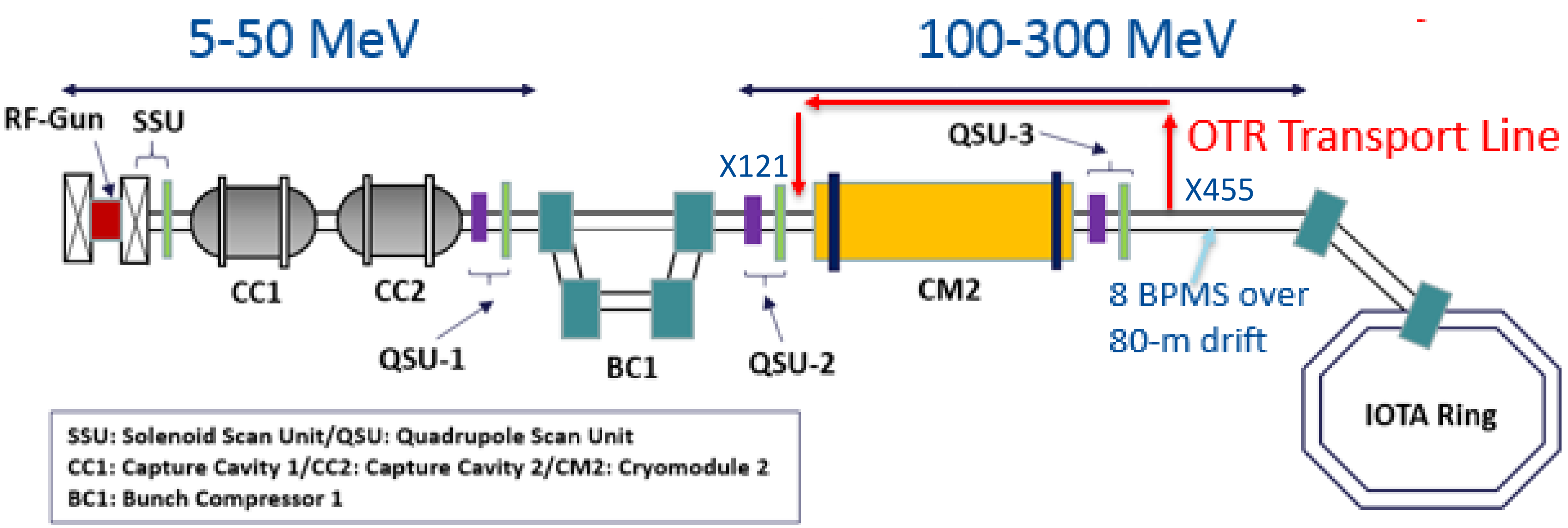


Strawman Run 3 LRW/SRW Studies

- LRW: Test prototype SLAC 4-channel HOM box(es) with CC1 and CC2, upstream and downstream channels.41 MeV, 1 shift
- SRW: Lower Energy: Gun=4.5, CC1=8 MeV, CC2=8 MeV, 20.5 MeV tot; V101,3 scan, Kick x2 from 41 MeV case 2 shifts
- SRW: SLAC Special: Gun=4.5, CC1=8 MeV, CC2=0 MeV 12.5 MeV tot. V101,3 scan, Kick x3 from 41-MeV case. 2 shifts
- LRW: Also take rf BPM, HOM data at same time for the low energy cases with FNAL HOM boxes as above up to B121.
- LRW: CM2, set up SLAC's two,4-ch boxes on 8 US channels; then 8 DS channels for "as found" signals. 41 MeV input and 100 MeV output. 50 b, 500 pC/b. Then minimize HOMs by steering correctors H/V125 and scan from reference. Use Jinhao's scaling downstream and ML, HE dump use   3 shifts
- SLAC specials: Sikora, Auralee (ML), CM2,SRWs   4-6 shifts

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

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.

Documentation of the Wakefield Studies Results

- Run 1: Spring 2019 initial short-range wakefield tests.
- FEL19 conference paper on SRW effect. August, 2019
- IBIC19 Conference paper on LRW/SRW effects Sept., 2019
- PRAB article on SRWs published. Selected as Editors' Suggestion for cross-field interest. May 4, 2020

- Run 2: Dec. 2019 – Feb. 2020. SLAC/FNAL Collaboration
- IBIC2020 abstract on SRWs submitted March 3, 2020.
- IBIC2020 is going to be a virtual meeting in September with normal JACoW proceedings plan (announced on June 5). Option for augmented paper in PRAB special issue.

Summary

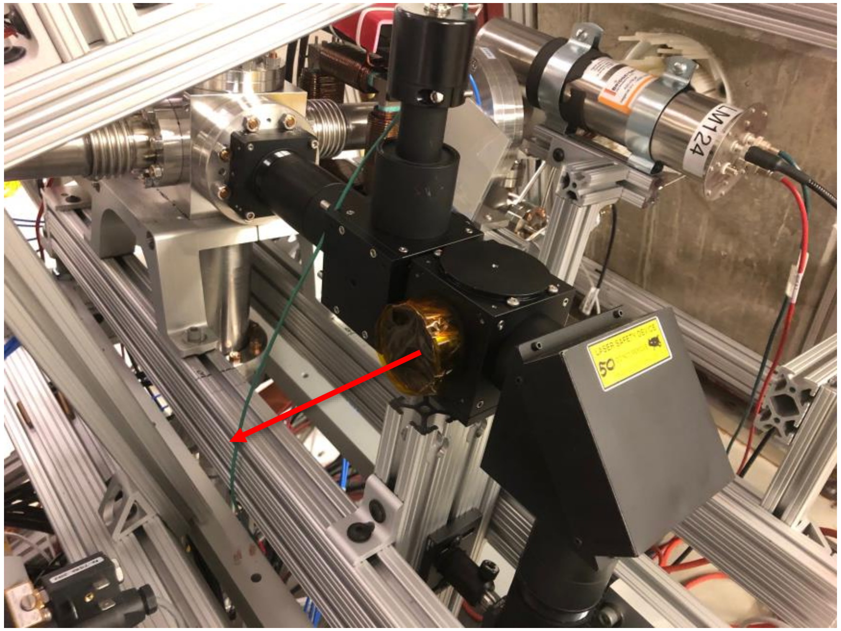
- Noticeable correlations of the V103= +0.5 A (1 mrad) steering giving CC2 US and DS HOM relative minima, a reduced centroid oscillation at B117, and reduced head-tail kick at X121.
- The CC2 US value scales to ~180 mV, implies 1-2 mm offset.
- Beam offset monitor demonstrated for cavity quench protection: LCLS-II interest. Single-bunch sensitivity also shown.
- Bunch length trends are another aspect. The V101 scan data are similar in charge dependence, but the V103 scan data seem to have a “compression” effect at ± 4 mrad with shorter bunches.
- Observed trends in the CC2 SRW-related submicropulse kicks.
- 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).

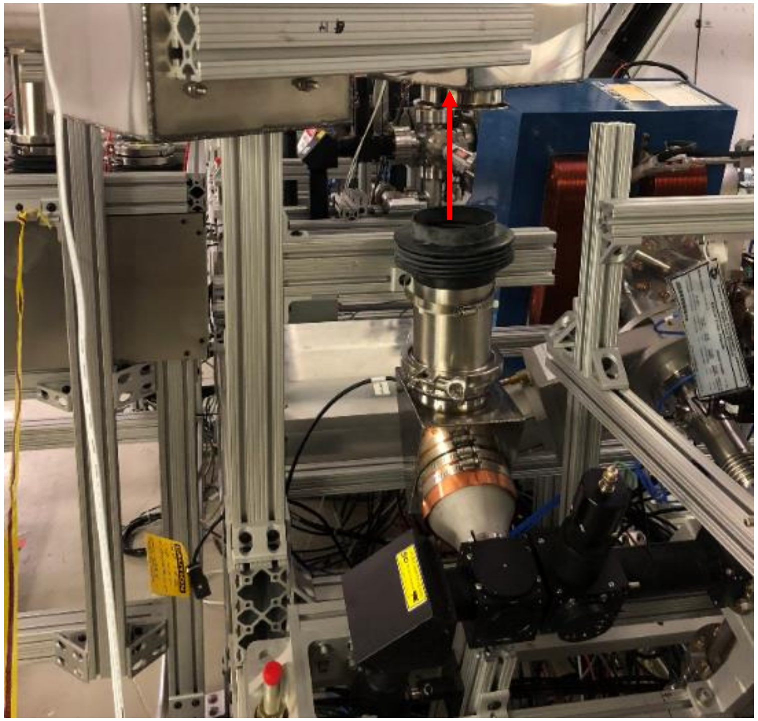
Machine Learning Application: Emittance Dilution Mitigation

- 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 due to cavity misalignments and near resonances.
- May want to choose CM01 carefully on its cell/cavity centering rms value for LCLS-II injector.

Propose to Add Beam splitter at X455 like X124

- Second Beam splitter has 50/50 ratio for OTR in X124.

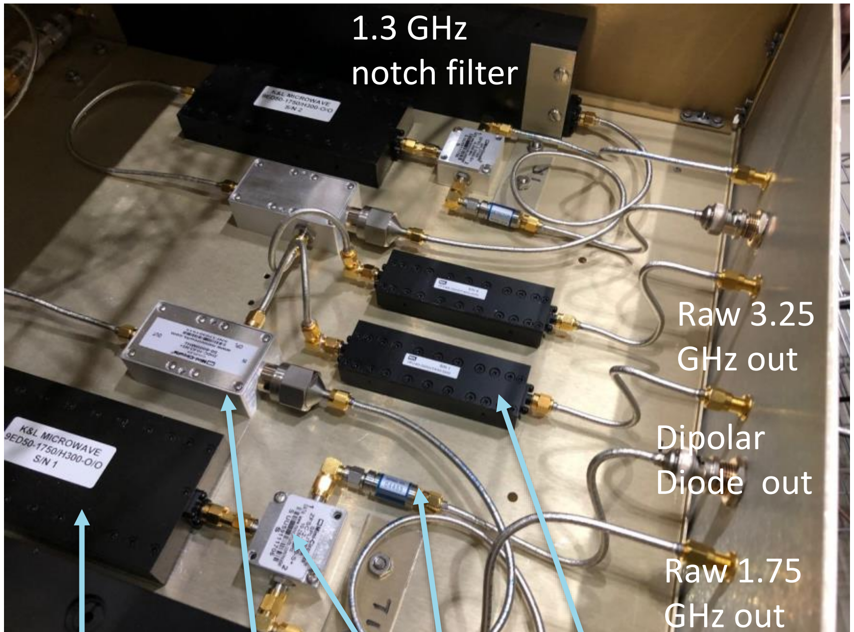




Photos by RTK

HOM revised electronics for CC1

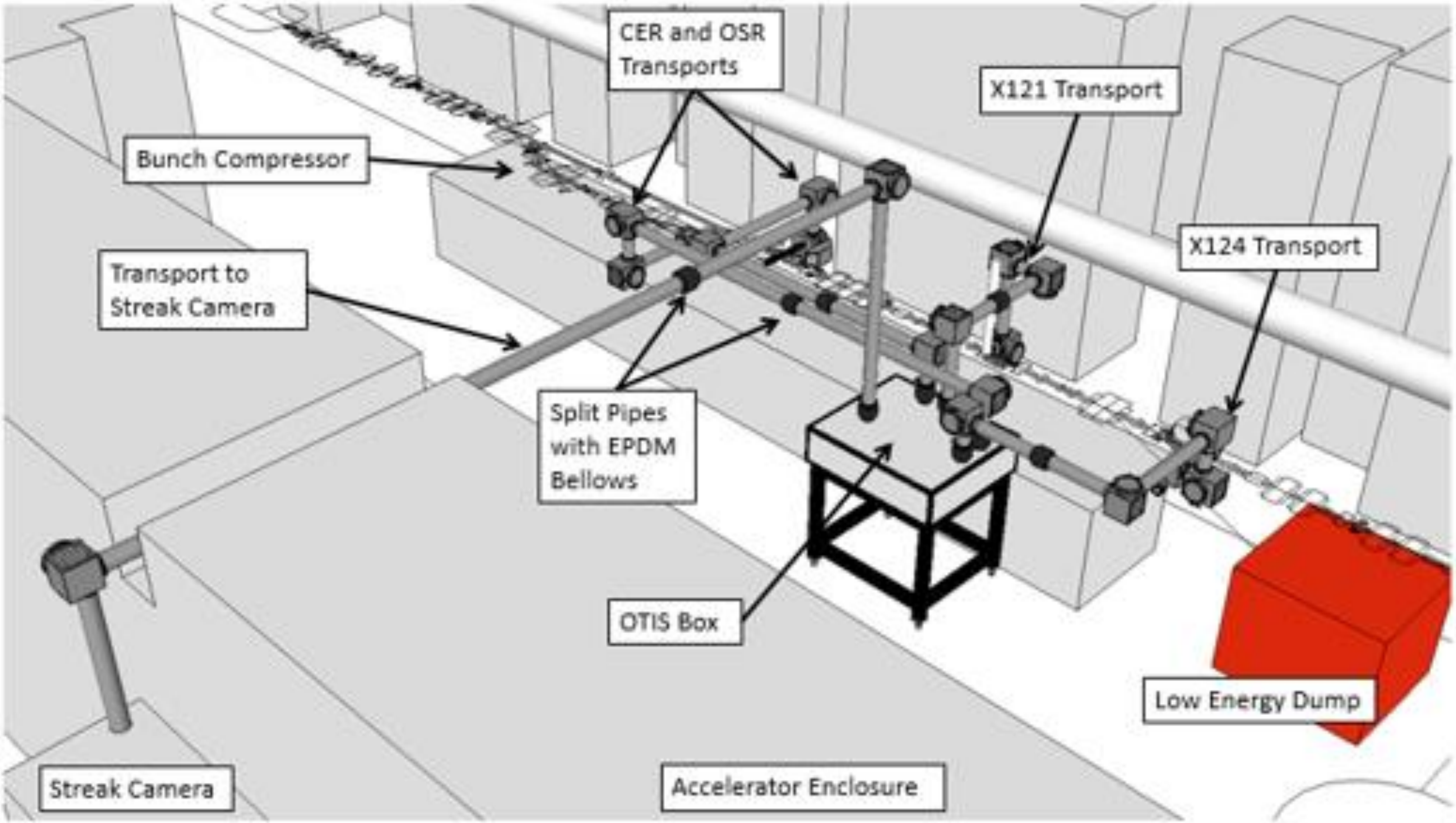
- Dipole and Quadrupole modes filtered then Schottky diodes



Photos by RTK

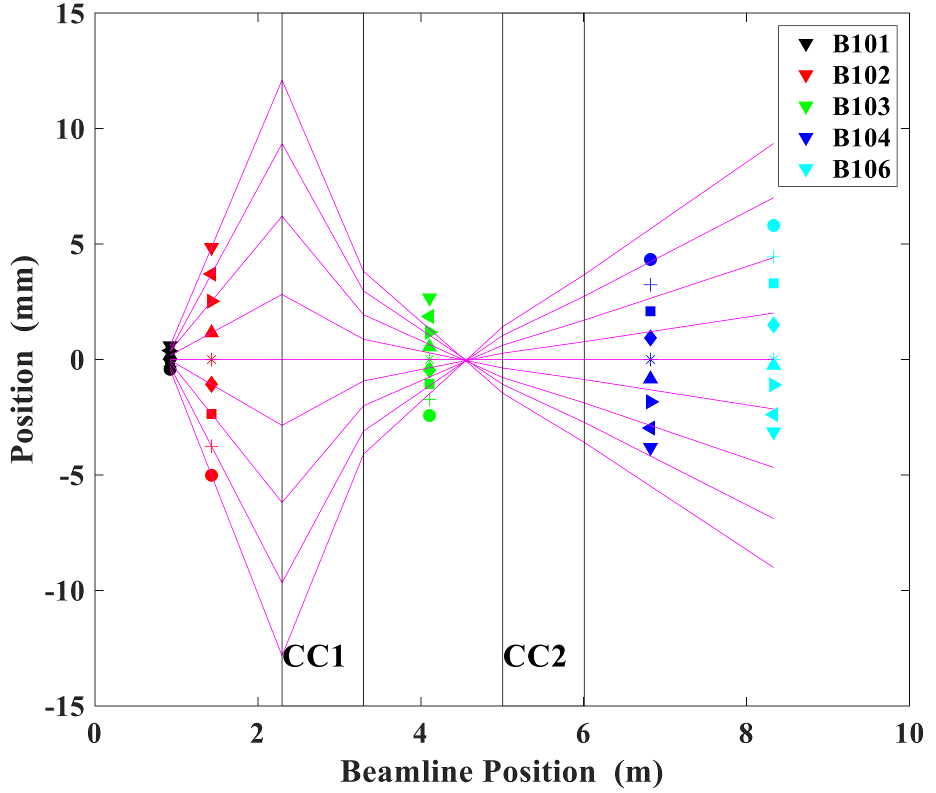
Schematic of Optical transport from X121 to Streak Camera

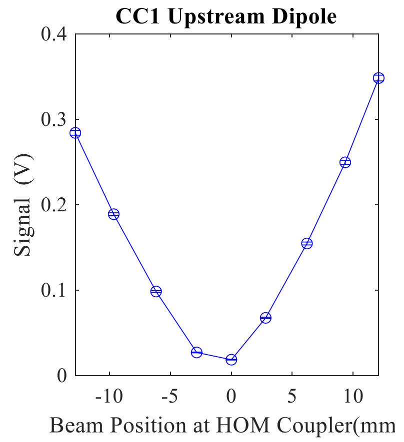
- All mirror optics used to transport OTR in enclosed line.

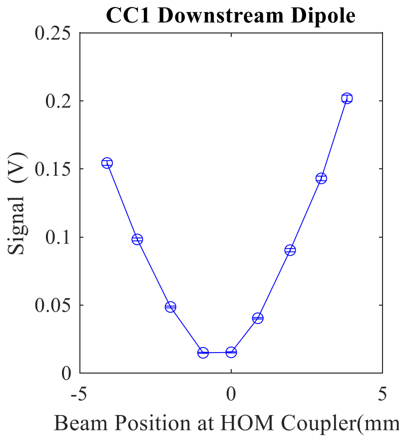


Beam Offset Monitor (BOM) Developed from Combined V101 Scan Data For rf BPMs and HOMs

Vertical 101 scan: 2-24-20
H101=0.15A V101=0A H103=-0.6A V103=-0.1A 50 bunches 480 pC/b

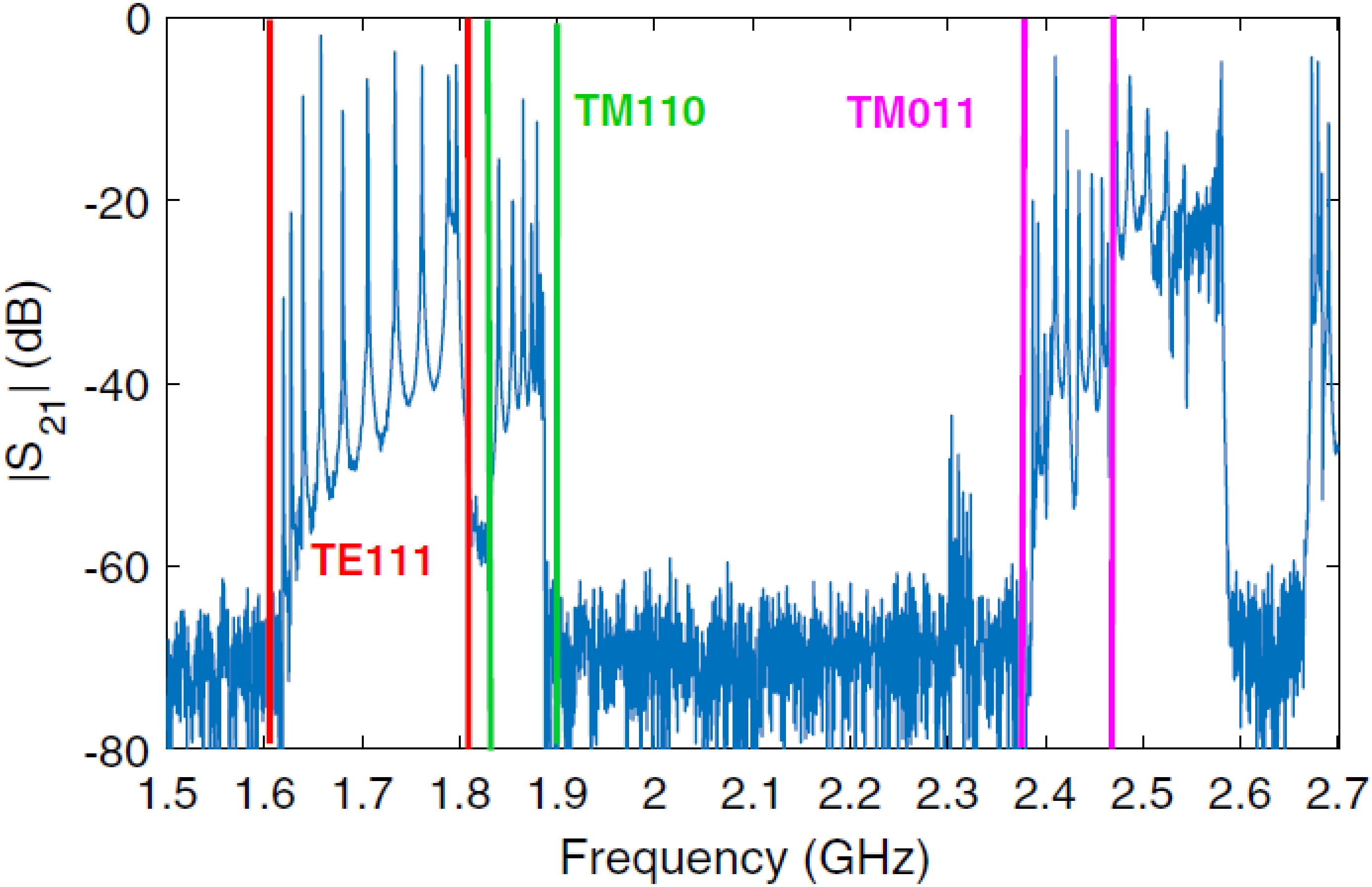






Complex Spectrum Recorded from a TESLA Cavity

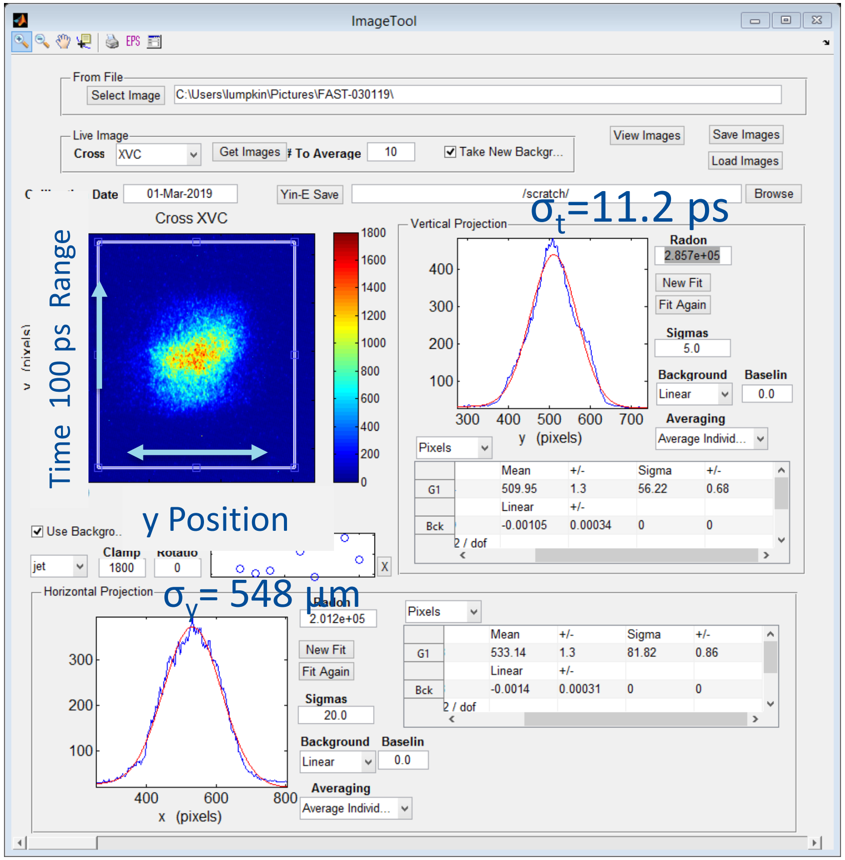
- Three HOM bands are marked: TE111, TM110, TM011 from Wei et al.,PRAB 22,082804 (2019).



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