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Long-range Wakefields and HOMs at FAST

Alex Lumpkin, Chip Edstrom, Jinhao Ruan, Randy Thurman-Keup, Peter Prieto, Nathan Eddy, Olivier Napoly (TD), Kip Bishofberger (LANL), Frank Krawczyk (LANL), Bruce Carlsten (LANL)

FAST Retreat

21 December 2017

Outline

I. Introduction
II. Lessons learned and proposed future studies
    -Transverse wakes and HOMs.
III. Examples of 11/20 and 11/29 studies results
IV. Lessons learned and proposed future studies
    - Longitudinal wakes (Bruce, Kip, et al.)
V. Summary-1

VI. Other Observations (Randy Thurman-Keup).
VII. Beam-based cavity alignment proposed (Olivier Napoly)

Introduction

- Primary goal is to reduce beam steering offsets and possible emittance dilution by monitoring and minimizing higher order modes (HOMs) in the cavities.
- Two HOM couplers are installed in both CC1 and CC2: upstream (US) and downstream (DS).
- Signals can be processed for TM110 dipole modes using 1.6-1.9 GHz filters covering first two dipole passbands.
- Filters also used to reject 1.3 GHz and >2.2 GHz.
- Used scripts for stepping corrector currents while tracking HOM signals, rf BPMs, beam images, framing camera, etc. and MATLAB script for 100-shot BPM array acquisitions.
- Searched for sub-macropulse effects on beam centroids related to transverse position and to energy.

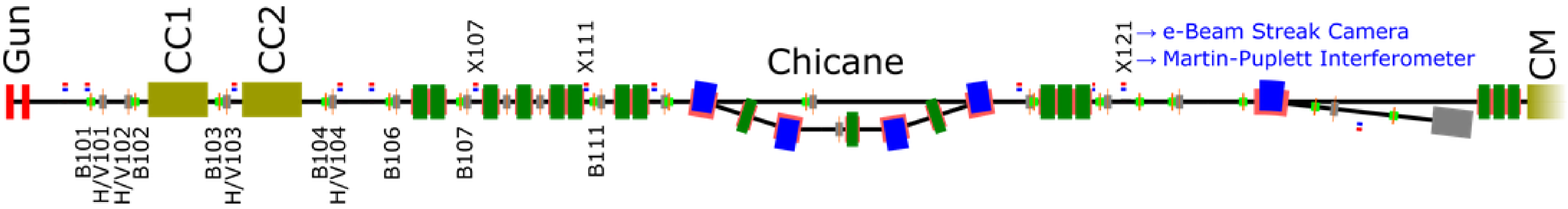
Nominal FAST Electron Beam Parameters for Studies

- Table 1.

Beam Parameter	Units	Value		
Micropulse Charge	pC	100-1000		
Micropulse rep. rate	MHz	1,3		
Beam sizes, σ	µm	100-1200		
Emittance, norm	mm mrad	1-5		
Bunch length,σ Compressed	ps ps	4-8 1-3		
Energy	MeV	32-34		
PC gun grad.	MV/m	40-45		
CC1 grad.	MV/m	12-15		
CC2 grad.	MV/m	12-15		

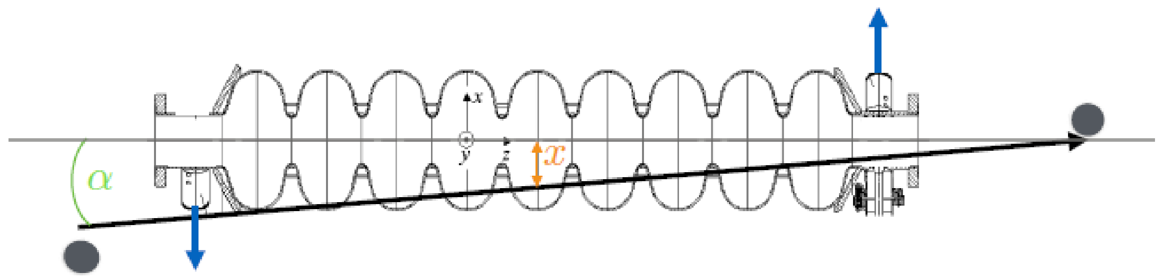
FAST 50-MeV Beamline Schematic

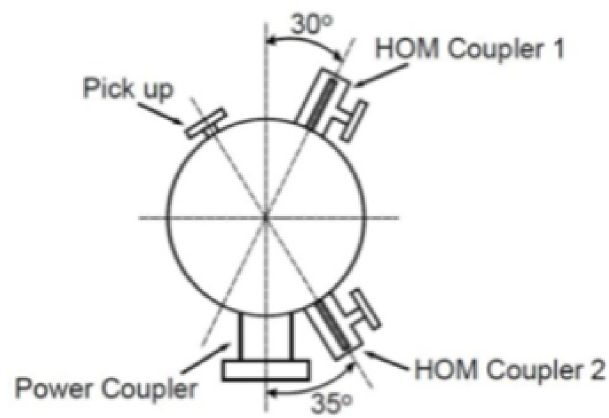
- FAST beamline up to CM2. Photocathode rf Gun, two capture cavities, BPMs (B1xx), correctors (H/V1xx), and imaging station beamline crosses (X1yy) are indicated.

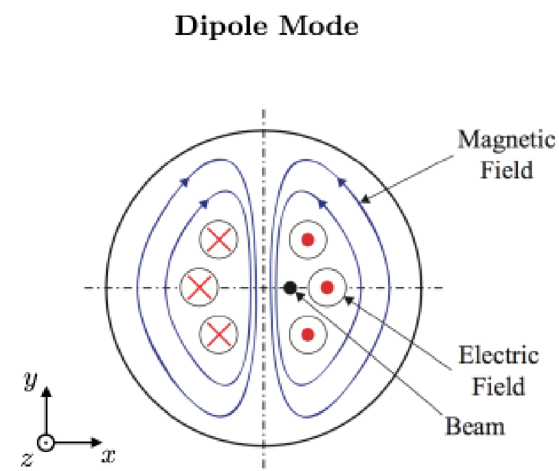


EXPERIMENTAL SETUP

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







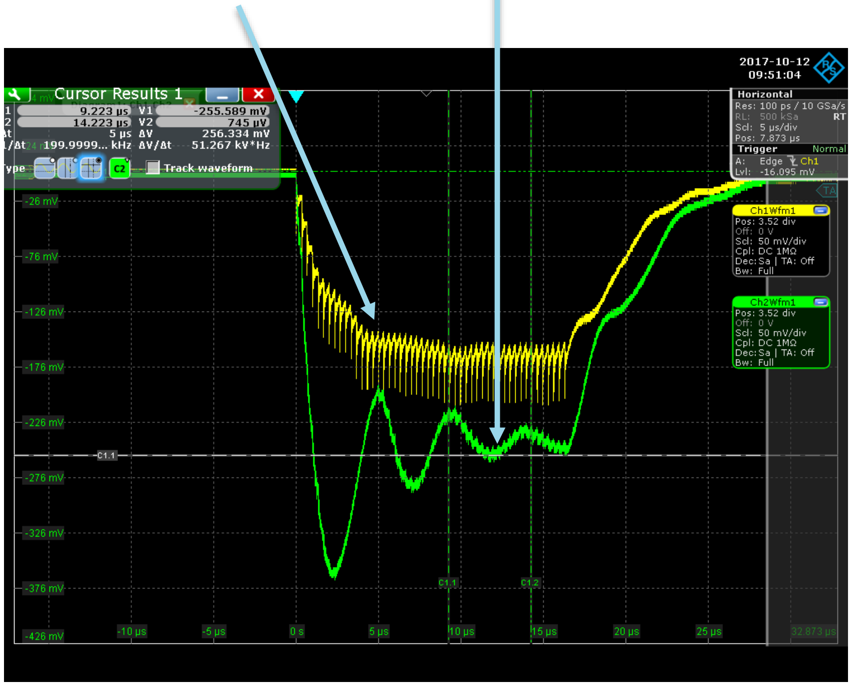
Initial looks at HOM signals on Oscilloscope

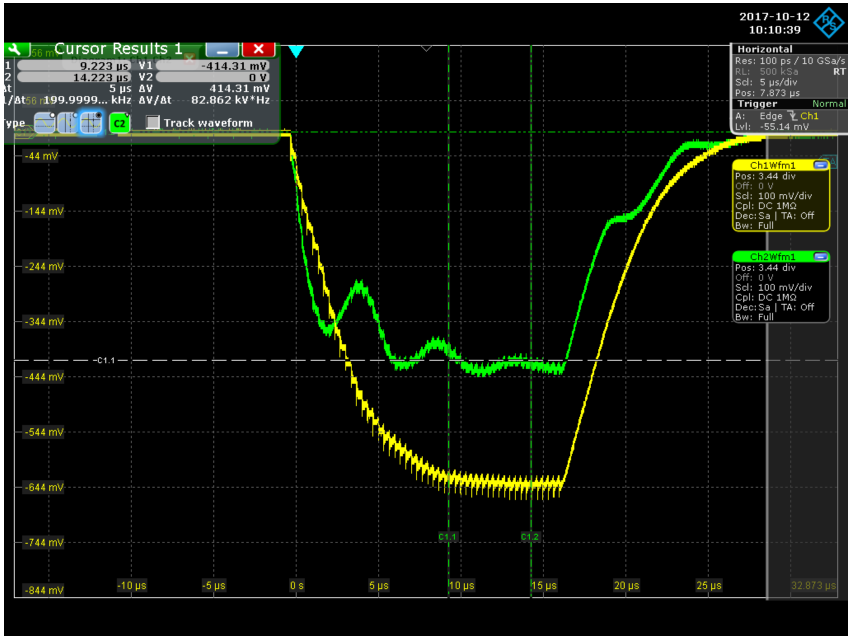
- Beam: 500 pC/b, 50 b,31 MeV
- H101=0.75 A, V101=0.89A

H101=1.25 A

CC1 US=-173 mV, DS=-256 mV

CC1 US=-628 mV, DS=-415 mV

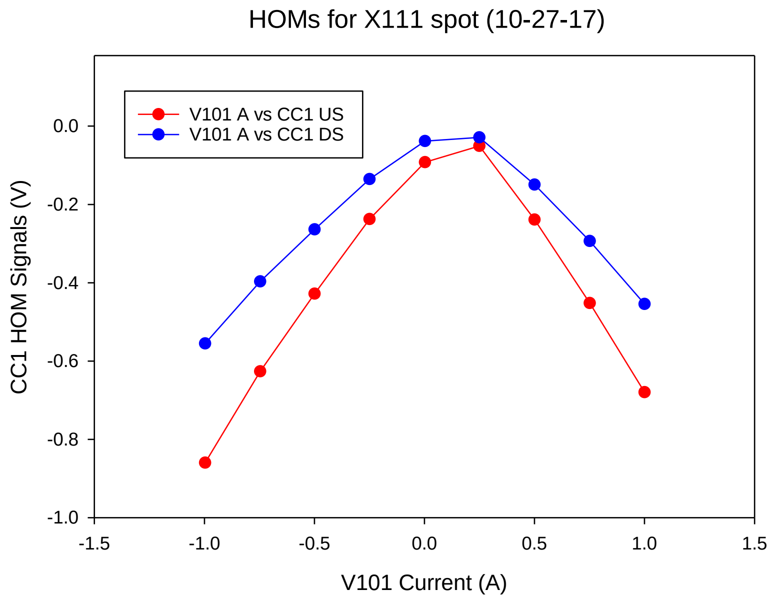


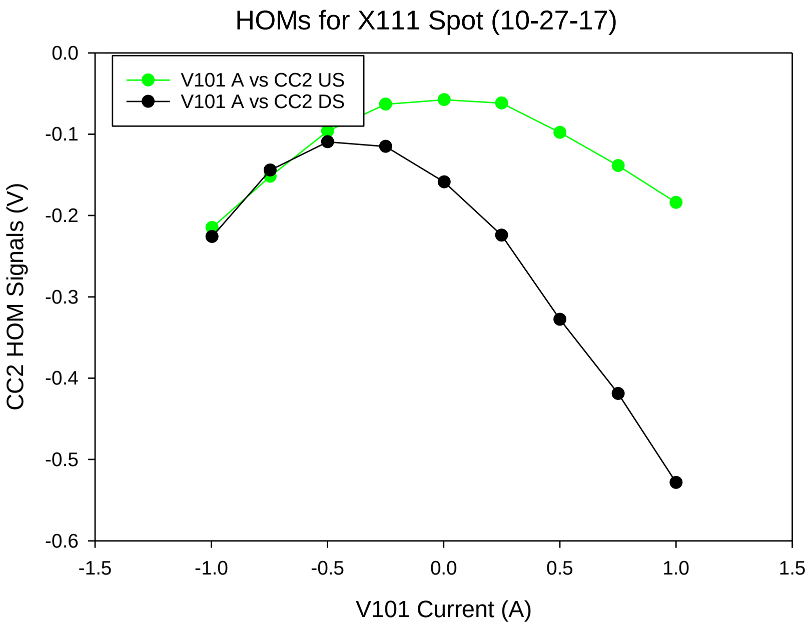


US detector-yellow, DS detector-green

V101 scan 4, HOMs

- Example of HOM peak signals at 500 pC/b, 50 b during V101 scan.





Lessons Learned -1

- HOM detectors after commissioning worked well in support of our wakefield studies. Scripts worked well in most cases.
- Minimized HOMs for the long range longitudinal wakes studies reasonably well. Need to properly set correctors.
- We controlled HOM strength over two orders of magnitude with charge variation and beam offsets into CC1.
- X107 Multi-slits emittance technique showed some effects but not deemed robust by some against beam steering.
- X107 imaging camera only functional for 500 pC/b on last shift. Small correlation with HOMs probably detected (6%) with +-150-µm centroid oscillations seen in B107.
- X111 images showed a probable shoulder effect with corrector polarity consistent with HOM buildup on one side.

X107 Multi-slits Emittance Measurements Tests 10-26-17

- Technique in commissioning. 100 pC/b Delta-V101=+1A

Prel. calc. eps-y= 0.8 mm mrad eps-y= 1.7 mm mrad

Multislit Emittance Summary ---- 2017-10-26 17:38:16

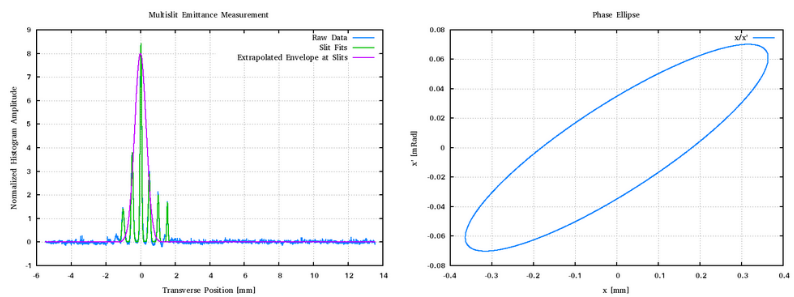
```
Emittance & System Params:
    Emittance (Un-Norm) :  1.268e-02 µm
    Dist to Screen (L)  :  1.538e+00 m
    Slit Width (w)      :  4.000e-05 m
    Slit Spacing (s)    :  4.000e-04 m
    Histogram Amplitude :  8.39 ArbU
    Histogram Width     :  2049 px
    Camera Resolution   :  9.300e-06 m/px
```

Second Moments:
- <x^2> : 1.325e-07 m^2
- <x`^2> : 4.922e-09 rad^2
- <xx`> : 2.216e-08 m*rad

Checks:
- Full χ^2 : 4.989e-03
- σ_{Env}^2 : 1.109e-07 m^2
- <x^2> / σ_{Env}^2 : 1.195

Twiss Parameters:
- α : -1.748
- β : 10.447
- γ : 0.388

Full Final Fit:
--> 28 Parameters



6 Gaussians Detected (Threshold = 1.502 | Noise = 0.491)

Gaussian	Amplitude	Centroid [m]	Sigma [m]	LinOff	Integral [m]	Div [Rad]
1	1.382e+00	-1.000e-03	6.627e-05	--	2.295e-04	-1.436e-04
2	3.770e+00	-4.751e-04	5.490e-05	--	5.189e-04	-6.216e-05
3	8.395e+00	2.568e-05	4.801e-05	--	1.010e-03	3.359e-06
4	2.860e+00	5.102e-04	5.792e-05	--	4.153e-04	5.831e-05
5	1.974e+00	1.025e-03	4.683e-05	--	1.138e-13	1.332e-04
6	1.675e+00	1.555e-03	3.697e-05	--	9.795e-11	2.173e-04
Baseline	2.006e-02	2.163e-05	1.345e-03	-1.094e-03	4.678e-05	
Proj Env	7.997e+00	0.000e+00	3.330e-04	0.000e+00	6.676e-03	

Projected Sigma=333 µm

Multislit Emittance Summary ---- 2017-10-26 17:43:56

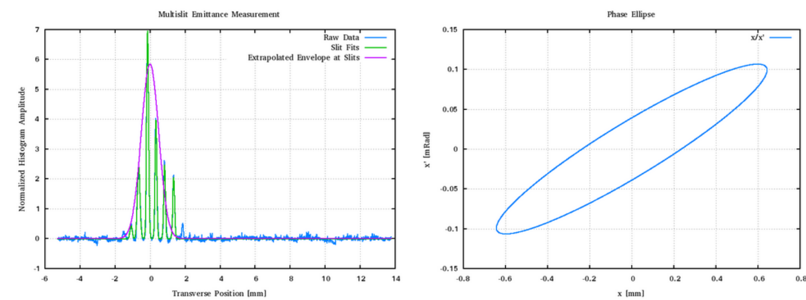
```
Emittance & System Params:
    Emittance (Un-Norm) :  2.515e-02 µm
    Dist to Screen (L)  :  1.538e+00 m
    Slit Width (w)      :  4.000e-05 m
    Slit Spacing (s)    :  4.000e-04 m
    Histogram Amplitude :  6.85 ArbU
    Histogram Width     :  2049 px
    Camera Resolution   :  9.300e-06 m/px
```

Second Moments:
- <x^2> : 4.135e-07 m^2
- <x`^2> : 1.136e-08 rad^2
- <xx`> : 6.374e-08 m*rad

Checks:
- Full χ^2 : 5.016e-03
- σ_{Env}^2 : 2.483e-07 m^2
- <x^2> / σ_{Env}^2 : 1.665

Twiss Parameters:
- α : -2.535
- β : 16.440
- γ : 0.452

Full Final Fit:
--> 24 Parameters



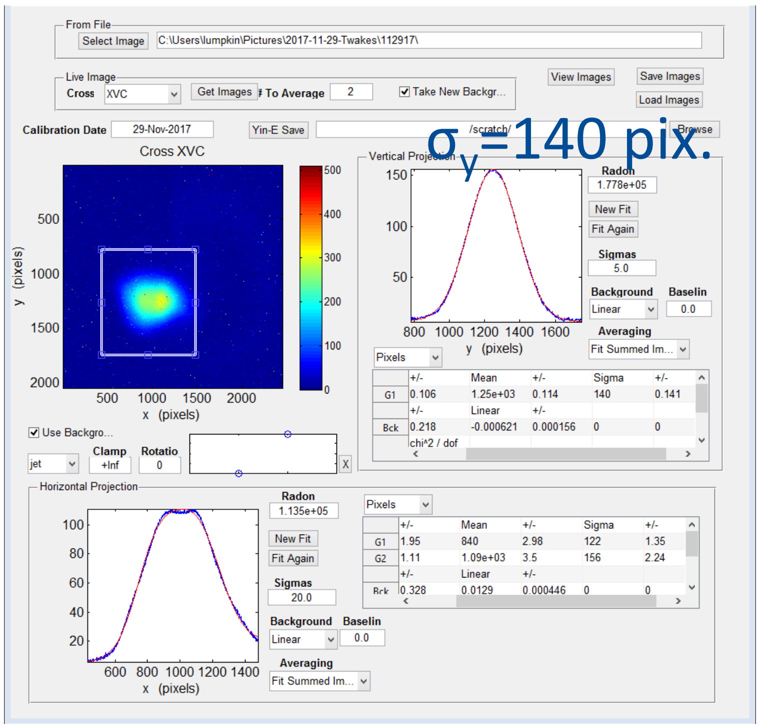
5 Gaussians Detected (Threshold = 1.534 | Noise = 0.567)

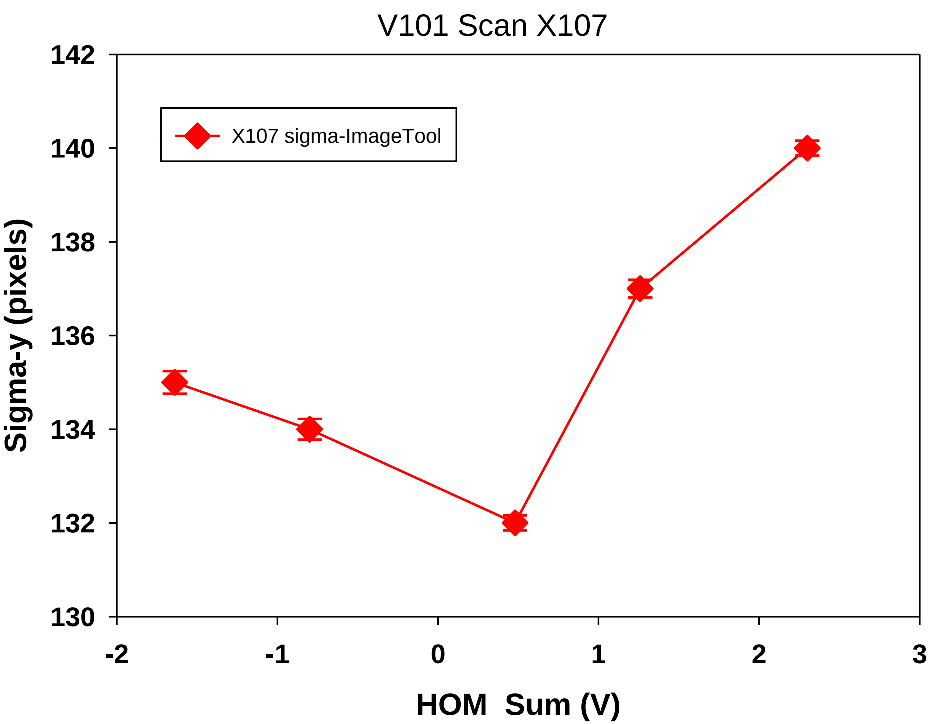
Gaussian	Amplitude	Centroid [m]	Sigma [m]	LinOff	Integral [m]	Div [Rad]
1	2.405e+00	-6.468e-04	7.670e-05	--	4.624e-04	-8.484e-05
2	6.949e+00	-1.383e-04	5.830e-05	--	3.625e-10	-1.434e-05
3	3.977e+00	3.375e-04	4.929e-05	--	4.914e-04	3.500e-05
4	2.471e+00	8.293e-04	5.067e-05	--	3.139e-04	9.468e-05
5	2.045e+00	1.352e-03	5.501e-05	--	2.820e-04	1.745e-04
Baseline	4.237e-01	-1.080e-03	6.214e-05	-2.158e-04	6.189e-05	
Proj Env	5.843e+00	0.000e+00	4.983e-04	0.000e+00	7.299e-03	

Projected Sigma= 498 µm

X107 Images and Possible HOM correlation 11-29-17

- Images and V101 scan using HOM sums for correlation.



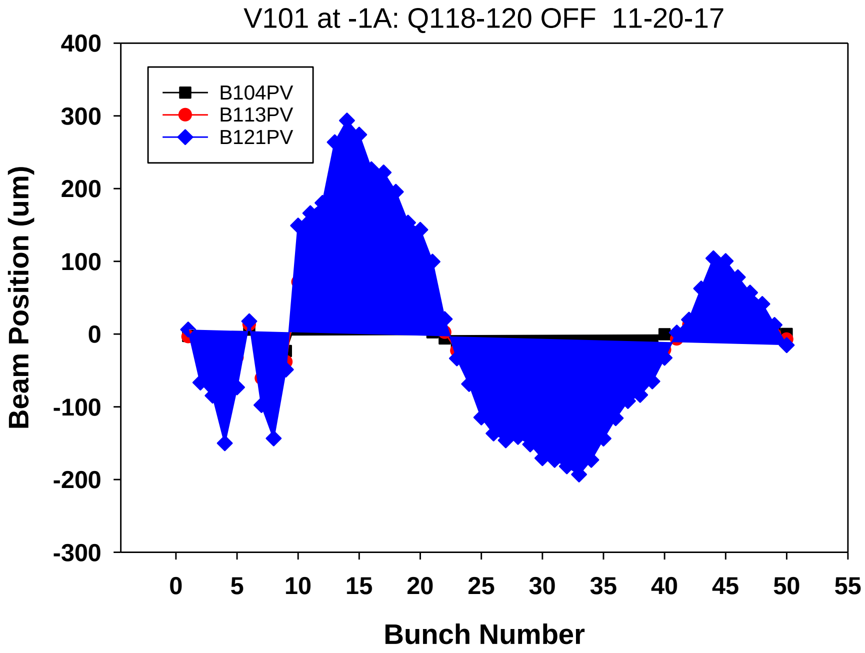


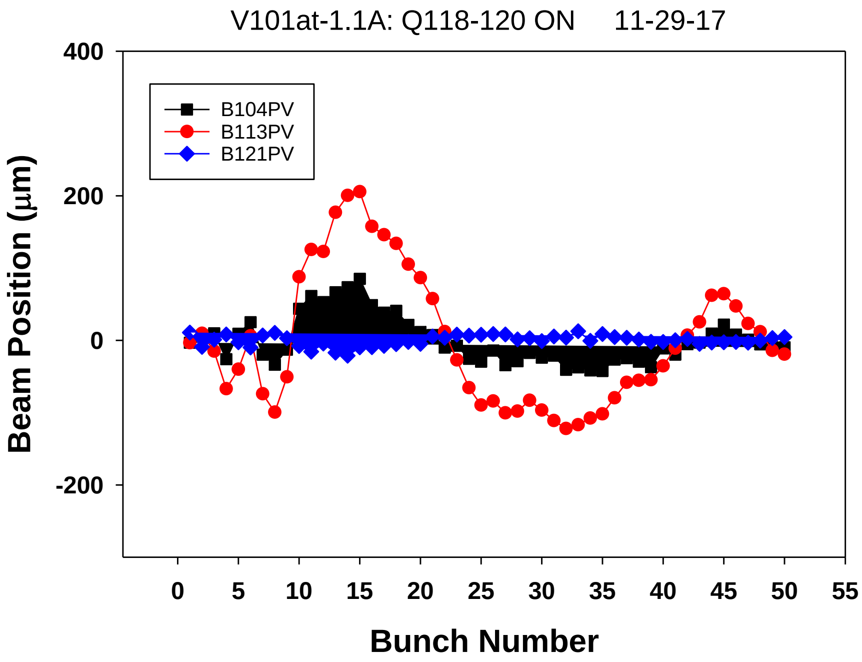
Lessons Learned -2

- X121 images for framing camera showed reduced centroid motion effects when Q118-120 powered on. Needed post processing to see in 3-image averages. Probably should consider averaging more images and higher charges of 2,3 nC/b. Single micropulses observed successfully with OTR.
- Bunch-by-bunch rf BPM capability was useful in experiments as foreseen, but 100- to 1000-shot averages proved critical.
- Using the 10 BPMs after CC2 in a 12-m drift was quite useful in deducing kick angles and the estimated source points.
- Effects on beam energy seen from CC2 LLRF feedback circuit. (Randy's talk)
- Understanding of the beam-driven modes in the cavities benefited from Olivier Napoly's assessments. (Talk follows)
- .

X121 Framing Camera Practical Issue with Beam Focus

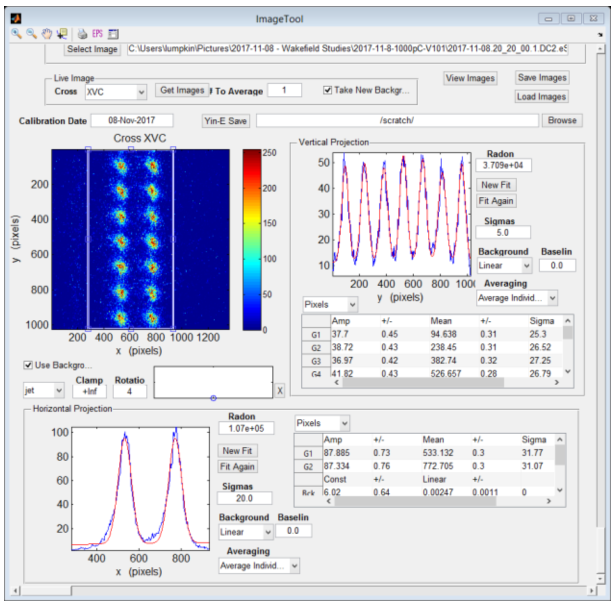
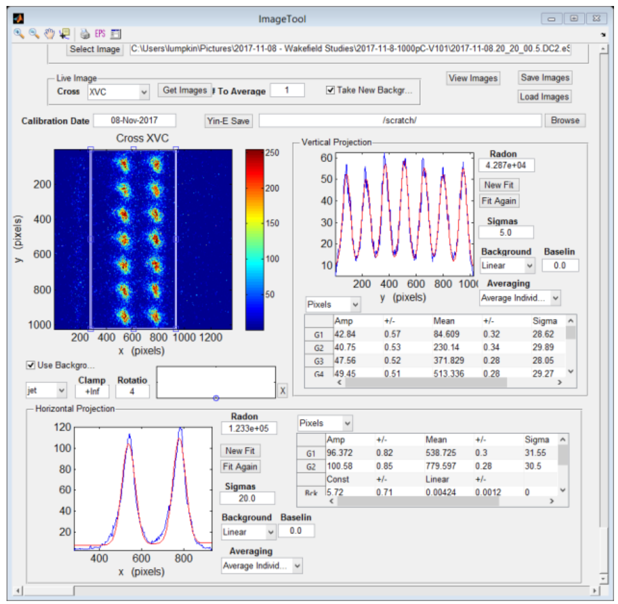
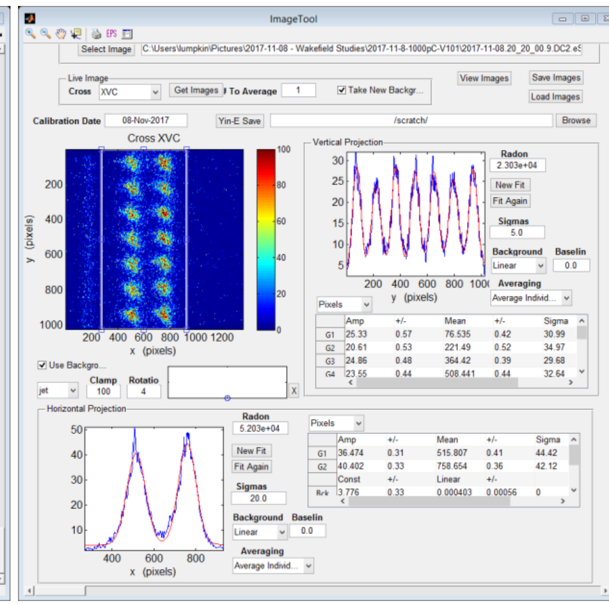
- Focus beam at X121 to match into framing camera, but this results in smaller beta function and beam centroid motion.
- Still about 30 μm effect with 7 μm resolution at 1000 pC/b.





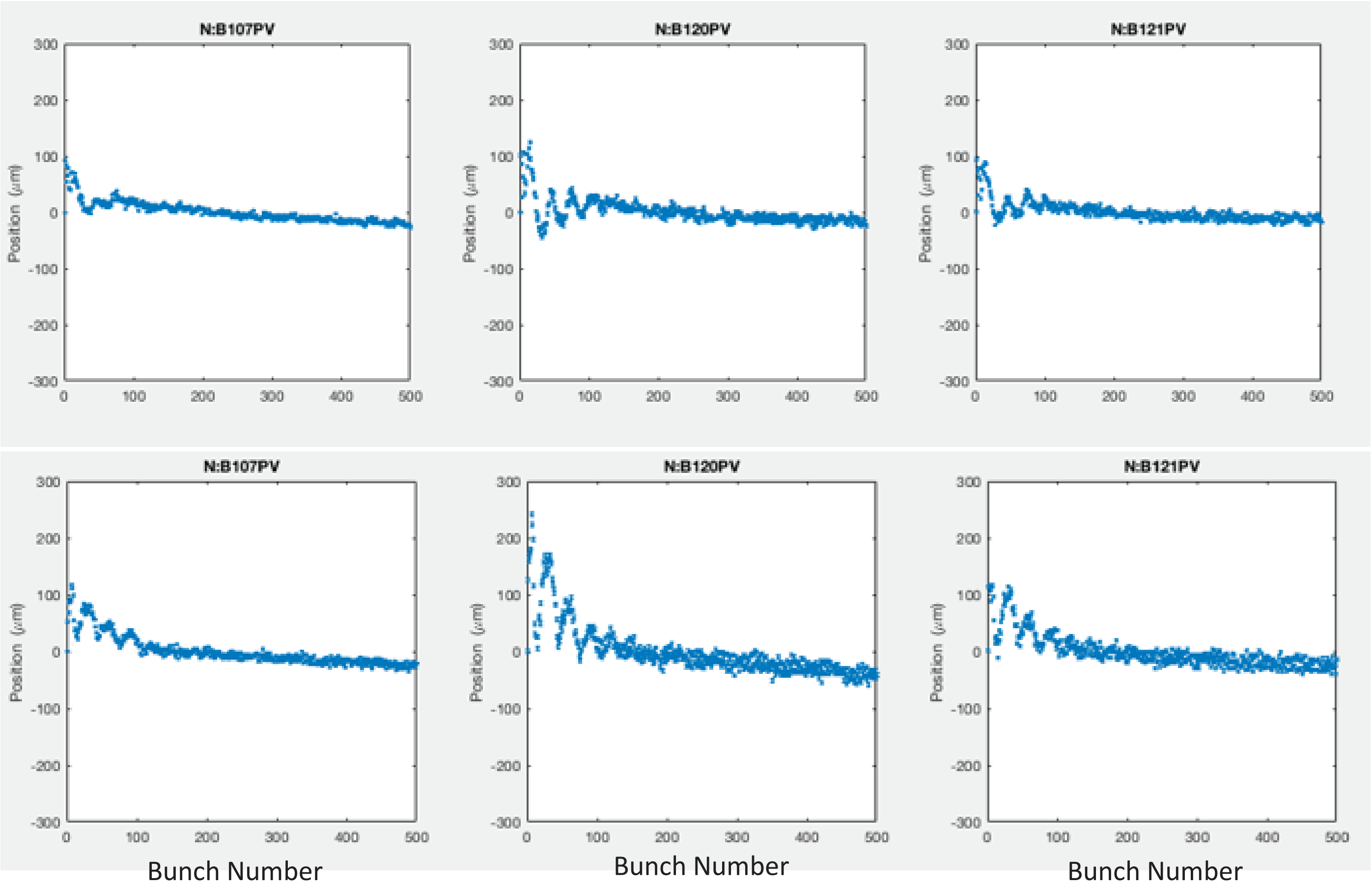
V101 Scan: Framing Camera Mode Test 11-08-17

- 61b, 1000 pC/b, 2 µs vertical, 100 µs Horiz., ~16 µs gap.
- Bunches 3-9, 55-61. Later time is down and leftward on axes.

-1.0 A	0.0 A	1.0 A
		

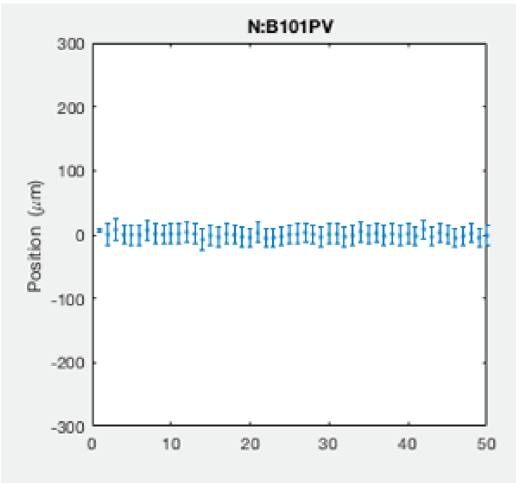
V101 Scan, 500b, Vert. BPMs Show Damping Effect 11-09-17

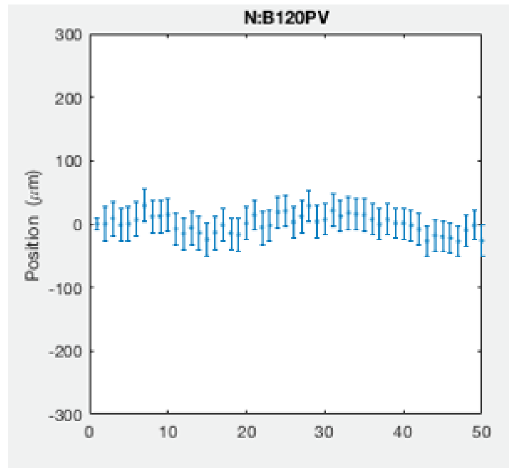
- Centroid oscillation seen in first ~100 b, then damps out. V101= -1A (T) and 1A (B), but HOMs are different. 500 pC/b.

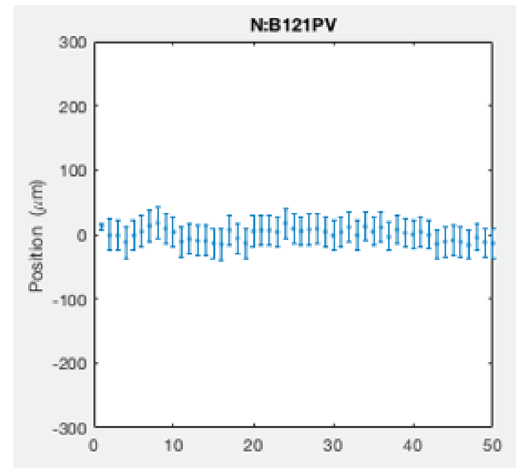


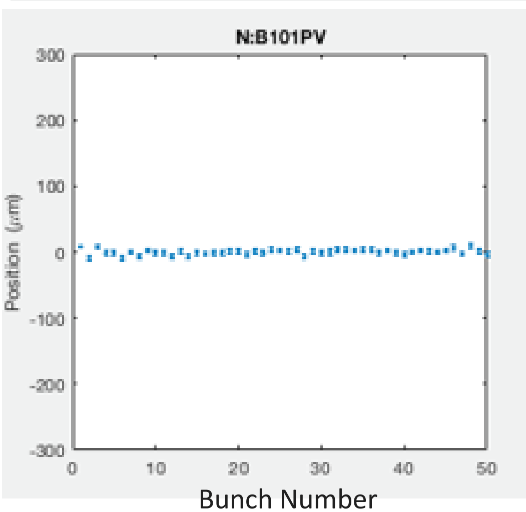
Comparison at V101=1A 11-08,09-17: Dramatic Effects Seen

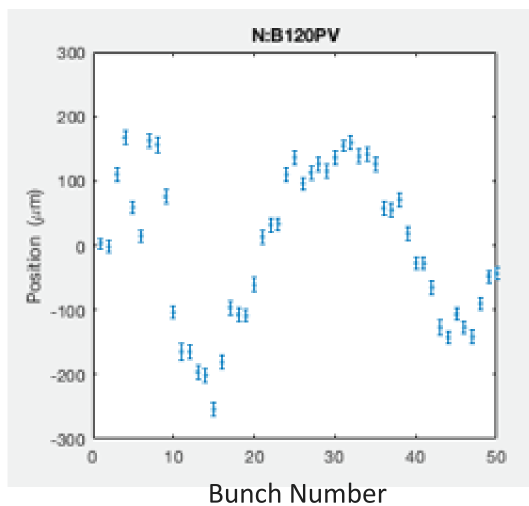
- 100 pC/b,1000 shots (Top row) 500 pC/b,50b,100sh (Bottom)

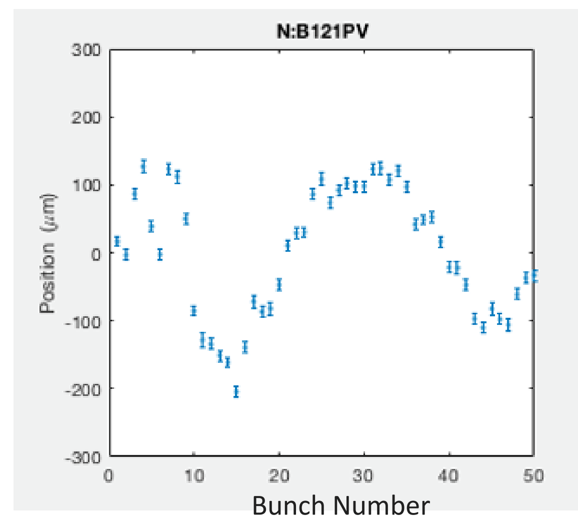








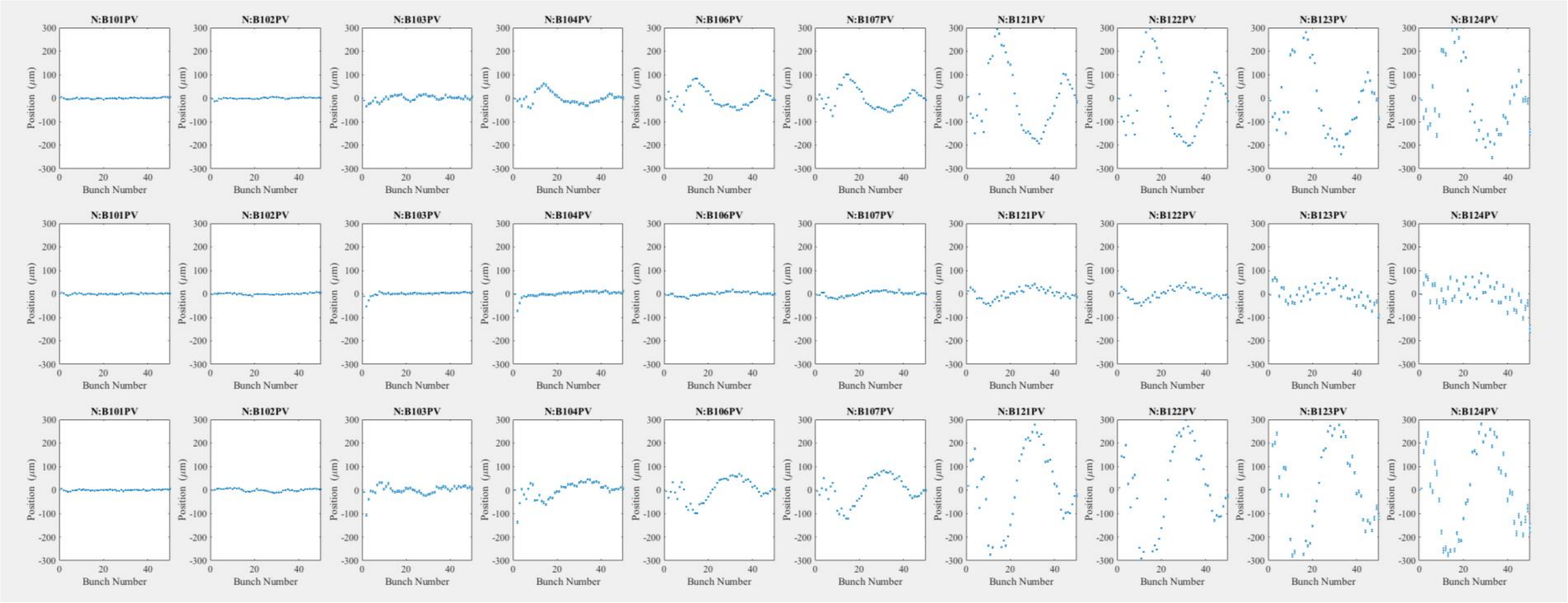




Fermilab

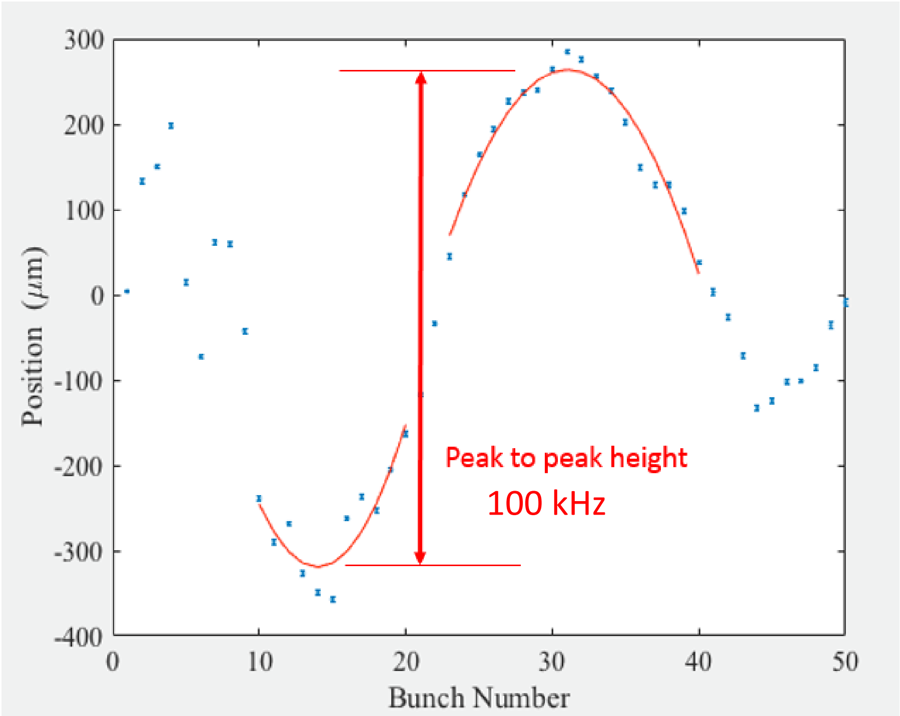
V101 Scan, 1000 pC/b, 50 b   B101-124   11-20-17

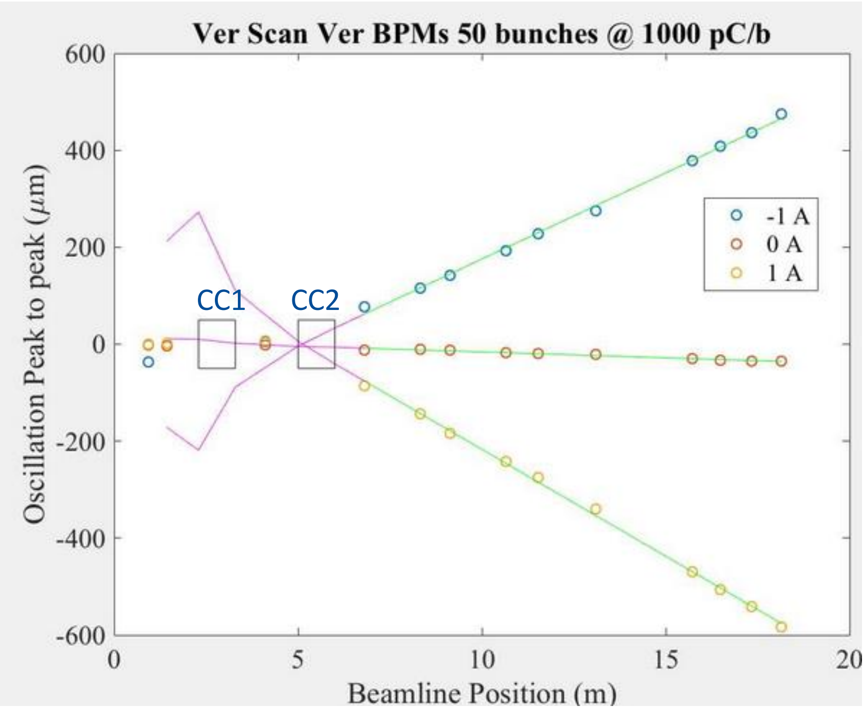
- BPMs Vertical, -1,0,1 A Top to bottom rows. Note flip of first oscillation. Quads off.



Evaluation of HOM Vertical Kick Angles 11-20-17

- V101 scan results with drift to B122. Kick deduced 84 µrad from CC2.

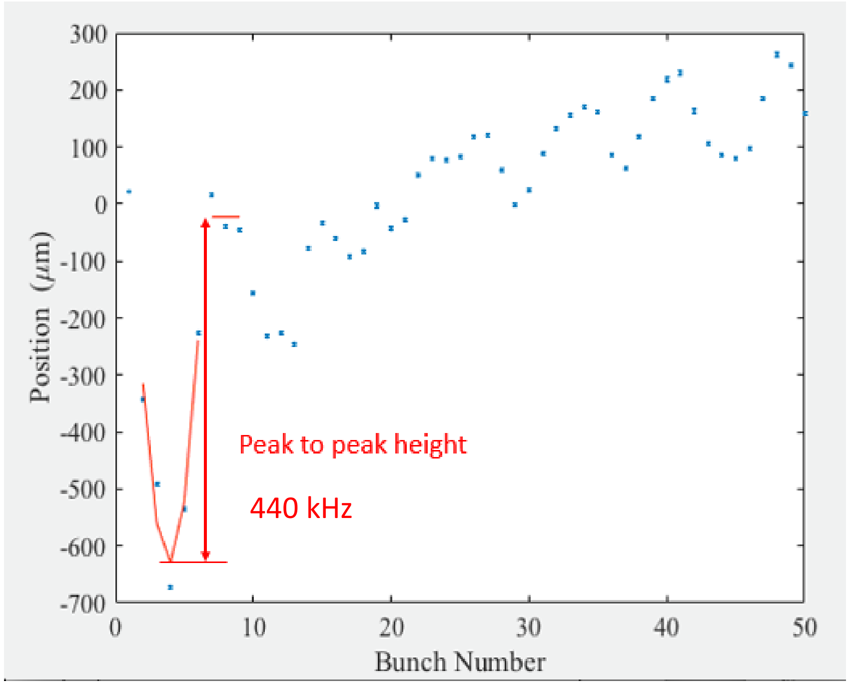


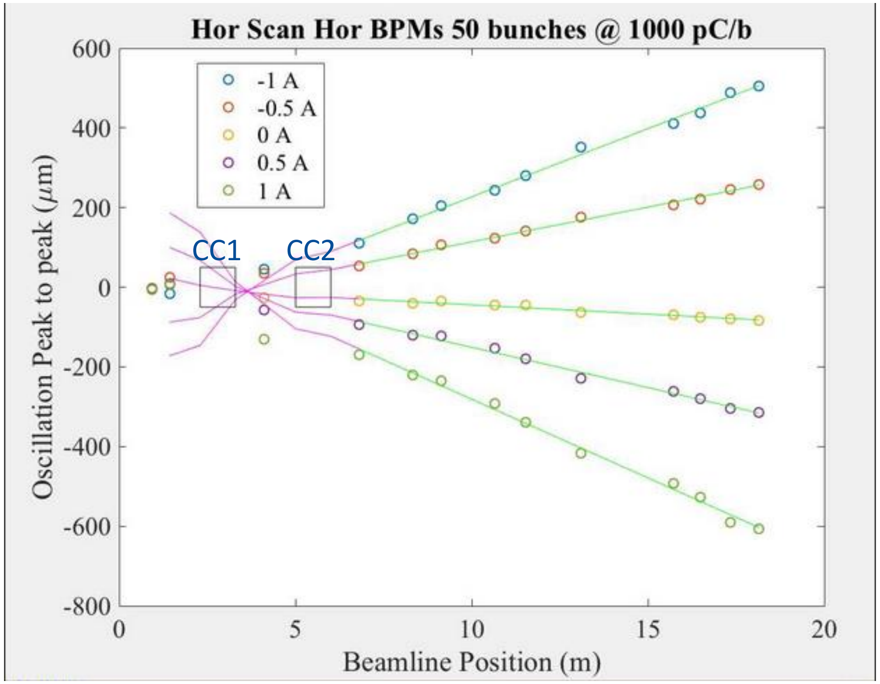


Fermilab

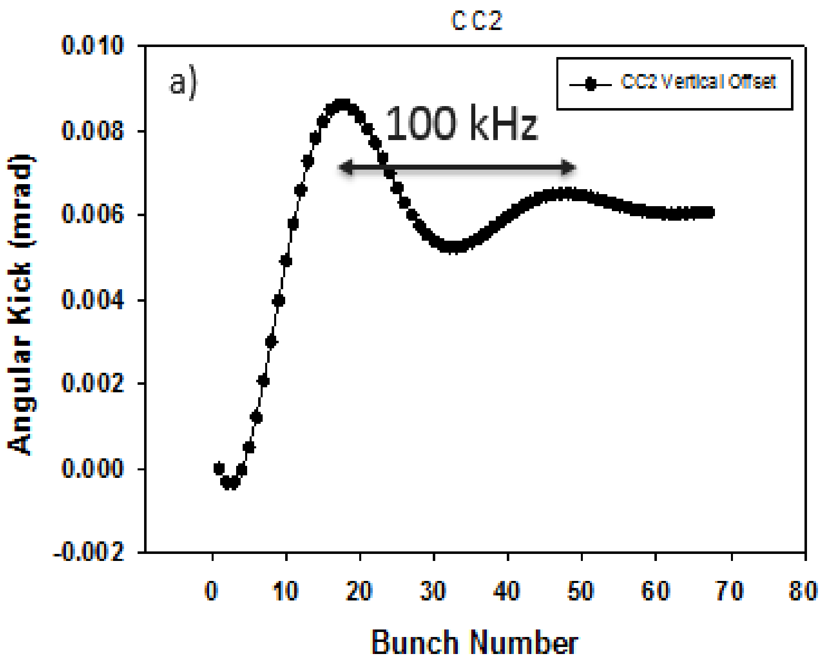
Evaluation of HOM Horizontal Kick Angles 11-29-17

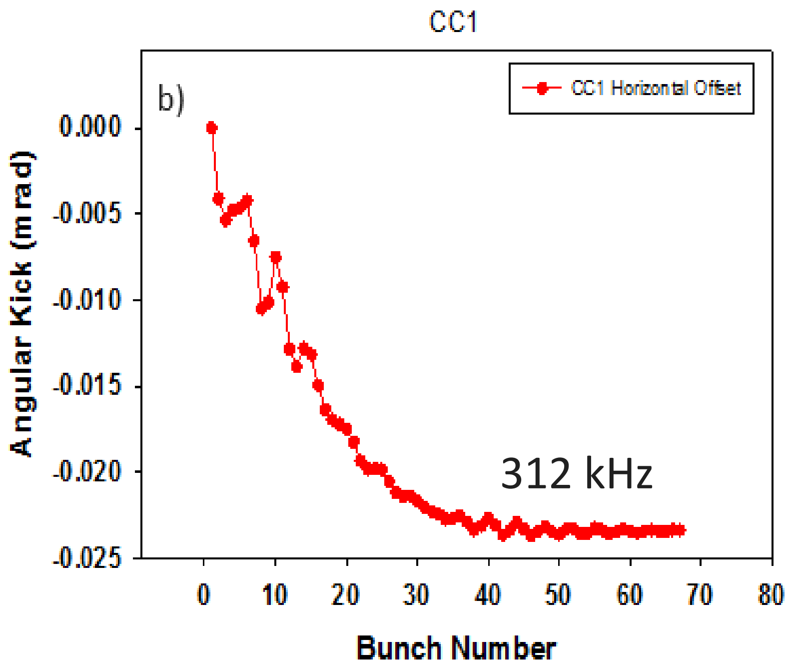
- H101 scan results with drift to B122. Deduced kick ~40 μrad from CC1 for largest input offset.





CC2 and CC1 Generated Dipole HOM Kicks (Preliminary)



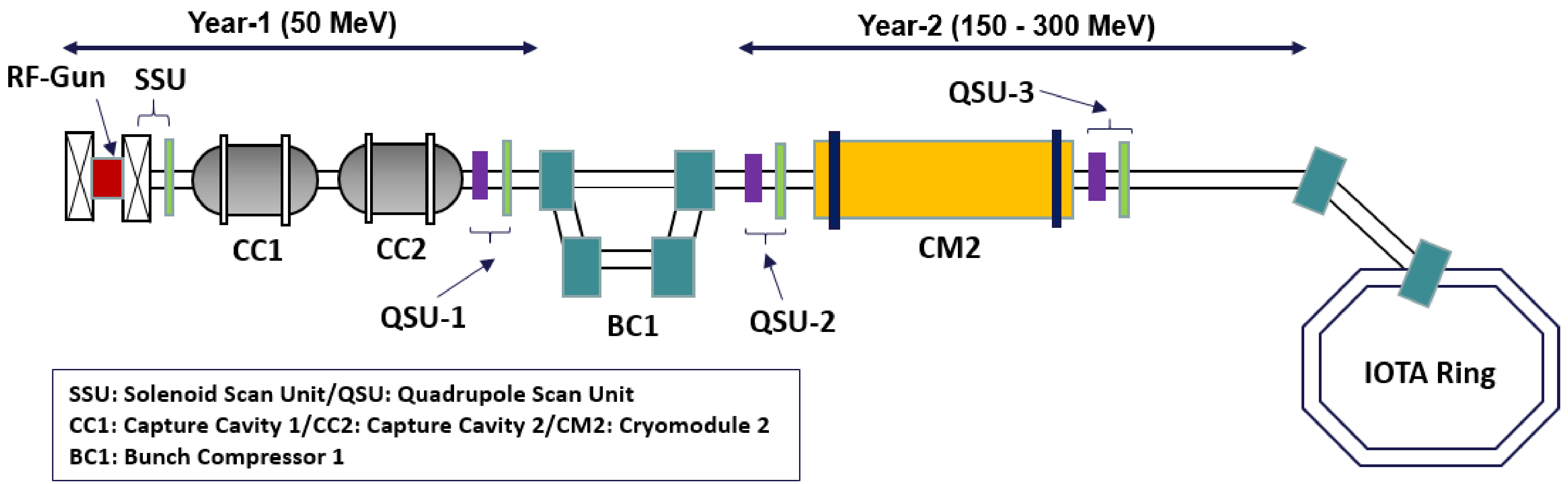


O. Napoly

Lessons Learned -3

- These techniques should be applied to CM2 in next run.
- BPMs and long drift already in place in 300-MeV line.
- Propose the 16 HOM coupler lines should be instrumented with detectors similar to those of CC1 and CC2.
- Studies could continue up to 3.2 nC/b, the ILC specification.
- The corrector values used to minimize HOMs indicate CC1 and CC2 are not well aligned to reference axis. Also CC2 DS does not reach as low of a minimum as other 3 channels?
- Olivier proposes efforts to determine HOM field centers in all ten cavities at FAST. (More details in his talk)
- Propose to check arrival time of HOM detector signals to determine US and DS couplers in each cavity.

FAST beamline – CC1 and CC2 are the TESLA superconducting cavities

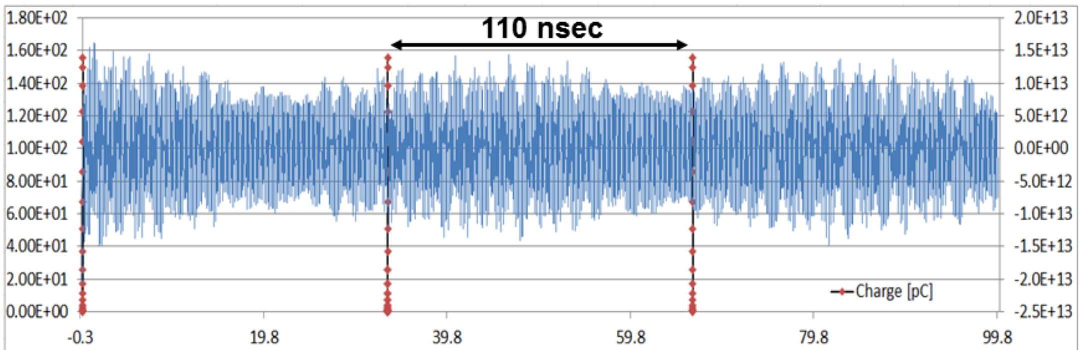


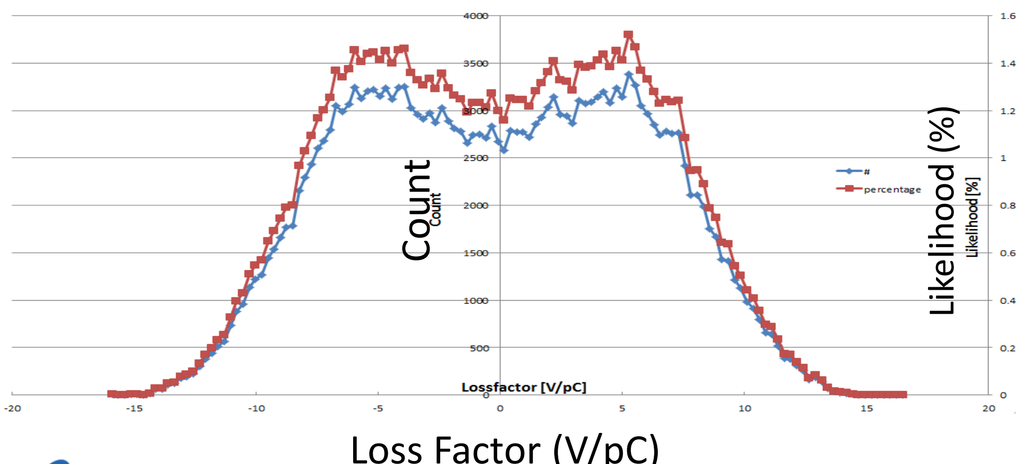
SSU: Solenoid Scan Unit/QSU: Quadrupole Scan Unit
CC1: Capture Cavity 1/CC2: Capture Cavity 2/CM2: Cryomodule 2
BC1: Bunch Compressor 1

Lessons Learned -4

- Longitudinal effects are difficult to diagnose with present diagnostics and effect magnitude, but upper limits set.
- Even 100-shot data did not reveal a distinct effect. Propose 2,3 nC/b data still needed. Also 9-MHz micropulse rep. rate.
- Potential to augment diagnostics by using framing camera viewing X124 screen in the spectrometer. Minimal Beta-y OK.
- Option to use YAG:Ce screen with ~100x more light emitted per electron than OTR.
- Mirror boxes and mirrors in hand, need beam splitter and Thorlabs holder. Need 80-20 frame to hold hardware.
- May need image rotator in the optical hut for streak camera so energy direction is mapped along the entrance slit axis.
- Both ACL and MATLAB scripts were critical to our studies.

Scoping simulations





The longitudinal wake has a stochastic appearance (top). Binning of the loss-factors over a distance of 5 bunches at 9 MHz rep rate (bottom), max/min are -15.9 V/pC to +16.5 V/pC. The most likely loss-factors are in the range of -8V/pC to +8V/pC. Not clear why this isn't a normal distribution; we still based analysis on RMS approximation

The single-bunch wake is 19.6 V/pC for comparison

Estimates on how many bunches sum before HOM damping saturates effect

Q ext	damping between bunches	n where damping dominates
1e5	0.995	715
1e4	**0.956**	**41**
5e3	0.913	15
1e3	0.635	1

$$e^{-\frac{\omega n \Delta t}{2Q}} \times \sqrt{n} < 1$$

9 MHz rep rate

Our plan was to expect a nominal 100 keV longitudinal wake over ~50 bunches at 3 nC (0.2% effect at 50 MeV)

Q ext	damping between bunches	n where damping dominates
1e5	0.986	193
1e4	0.873	7
5e3	0.762	2
1e3	0.256	1

3 MHz rep rate

Estimate of energy spread effect of longitudinal space charge may lead to competing effect

$$E_{s-c} = \frac{Z_0}{2\pi\gamma^2}\frac{dI}{dz}\ln\left(\frac{b}{a}\right)$$

Longitudinal space-charge force

$$\Delta V_{s-c} = \frac{Z_0}{2\pi\gamma(d\gamma/ds)}\frac{dI}{dz}\ln\left(\frac{b}{a}\right)$$

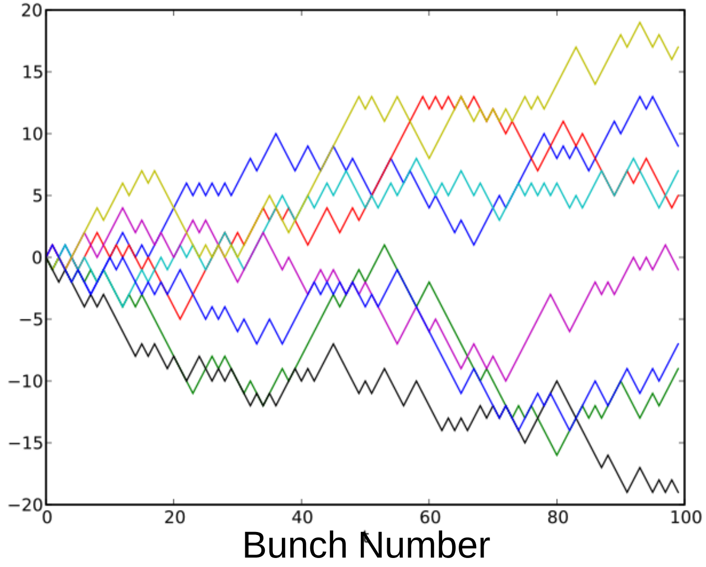
Work on particles due to LSC for first 7 m ($d\gamma/dz \sim 10\ \mathrm{m}^{-1}$): 10 to 20 keV rms

$$\Delta V_{s-c} = \frac{Z_0}{2\pi\gamma^2}\frac{dI}{dz}\ln\left(\frac{b}{a}\right)\Delta s$$

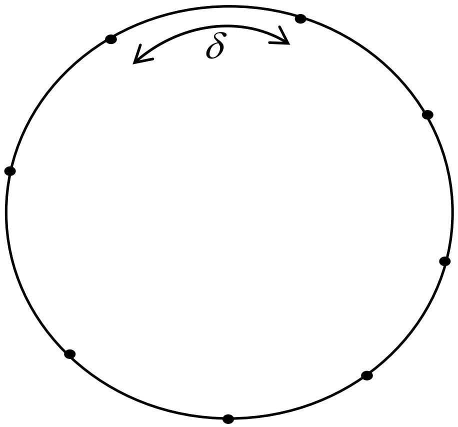
Work on particles due to LSC for next 10 m: about 5 keV rms

Note: Longitudinal wakes shift the energy centroids within the pulse train. LSC affects the energy spread of the individual micropulses.

What we expected to see



Considering at the bunch-to-bunch energies, we expected to see a random walk ~ 5 keV/100 pC * sqrt(bunches)

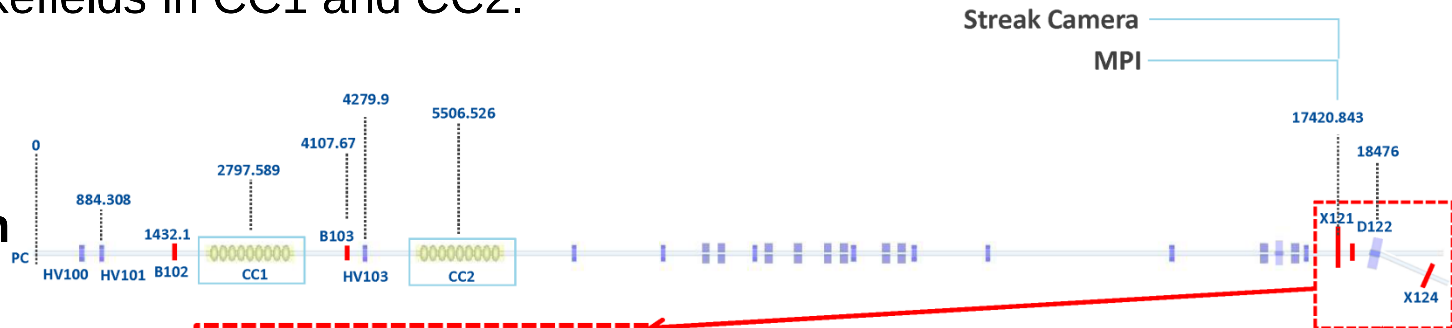


However, we have *learned* from the TWs that we should expect the LWs are also going to be deterministic and not stochastic as one or a couple high-Q modes will dominate. Contributions sum at regularly spaced phases and may cancel out; ***every bunch will see the same net wake***

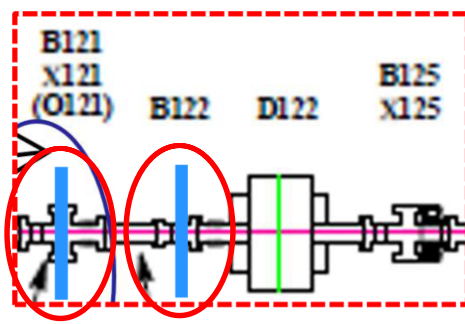
$V_{sum}=NW_1 sin(\theta_0) sinc(N\delta/2)$

Measurement 1: Measure bunch-to-bunch energy centroid shifts from change of angle in spectrometer

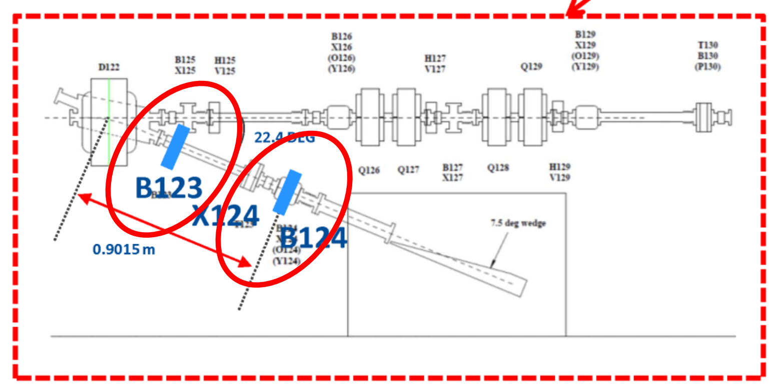
Measure vertical bunch angle before dipole with B121 and B122 and after dipole D122 with B123 and B124 (all circled in red below). The difference in bend angle is attributed to a different in bunch centroid energy due to longitudinal wakefields in CC1 and CC2.



Distance between B121 and B122 is 811.6 mm



Distance between B123 and B124 is 440.3 mm



Energy normalization: 22.5^o deflection for 32.6 MeV electron

BPM resolution (B123, B124):
~ 20 microns (10 – 50 keV @ 50 MeV)

Original data was very noisy (due to several effects including 858 kHz oscillation)

	RMS energy deviation
1. 1000 pC at 1 MHz	25.4 keV
2. 1000 pC at 3 MHz	26.1 keV
3. 500 pC at 3 MHz	39.3 keV
4. 250 pC at 3 MHz	79.1 keV

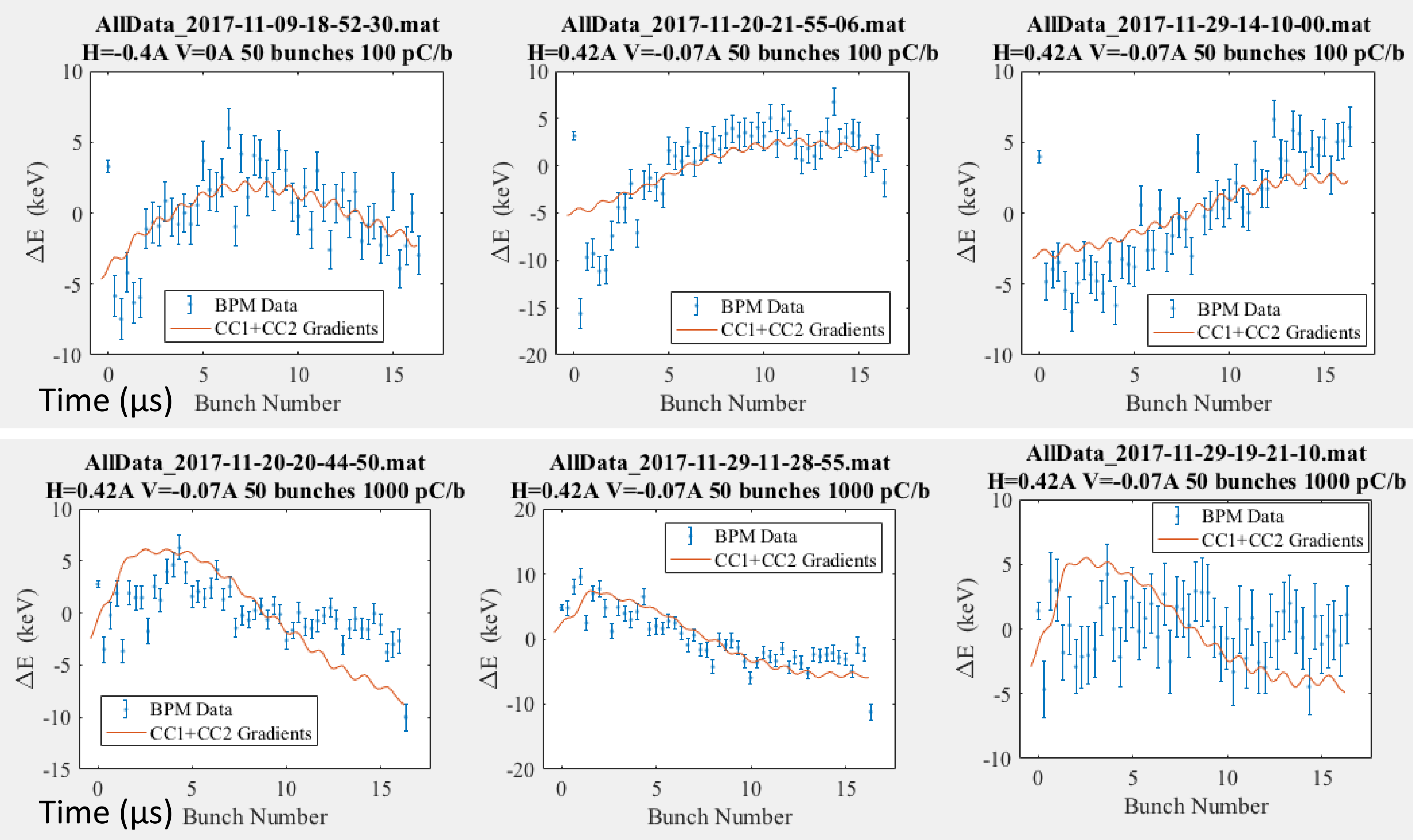
RMS deviation decreases with increasing charge due to decreased noise

Results at best brackets longitudinal wakefield; noise swamps expected wakefield, especially at the lower charges. Cannot infer bunch-to-bunch data

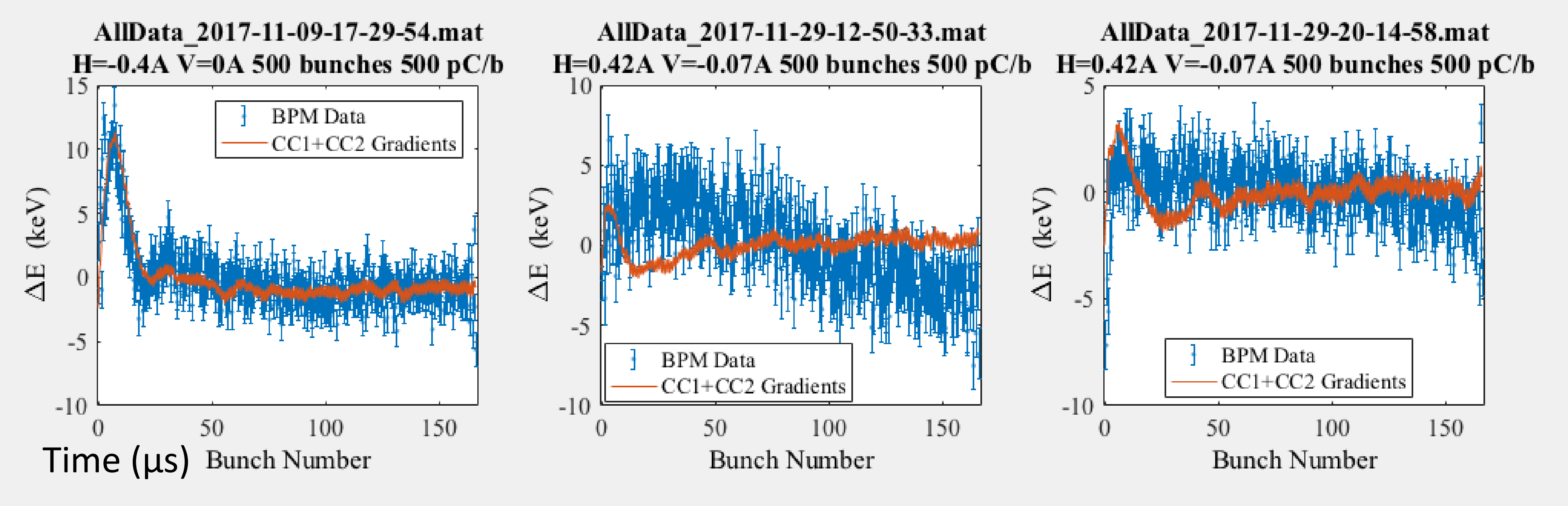
BPM angular noise was significantly lower in B121/B122 than in B123/B124 because of longer separation

Needed: Either increase charge (ideally 3 nC) or decrease BPM noise in B123 and B124

Data with 858 kHz removed – 100 pC and 1000 pc comparison



Data with 858 kHz removed – long term behavior at 500 pC



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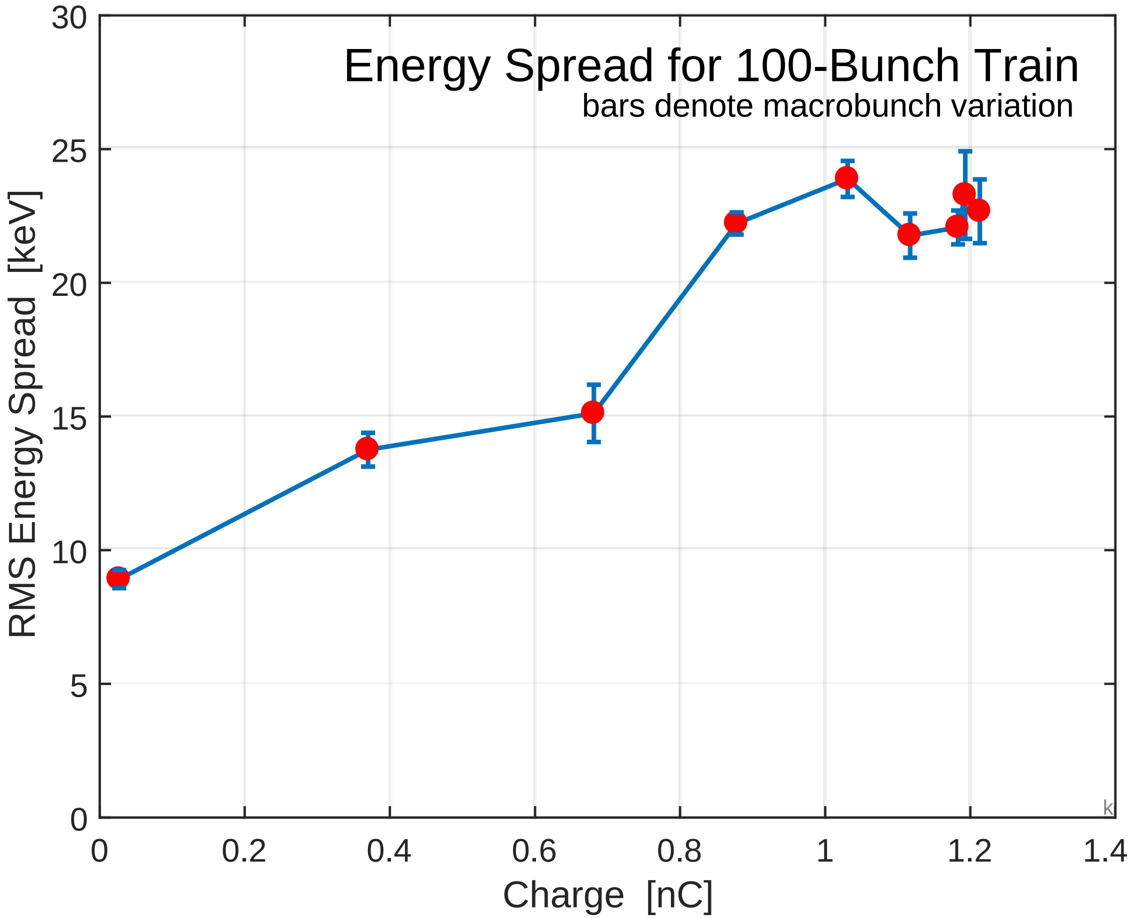
Integrated energy spread is consistent with LSC effects, but may contain longitudinal wake info also.



At each bunch charge, the rms energy spread was calculated. An error bar is also included to show the bunch-to-bunch fluctuations.

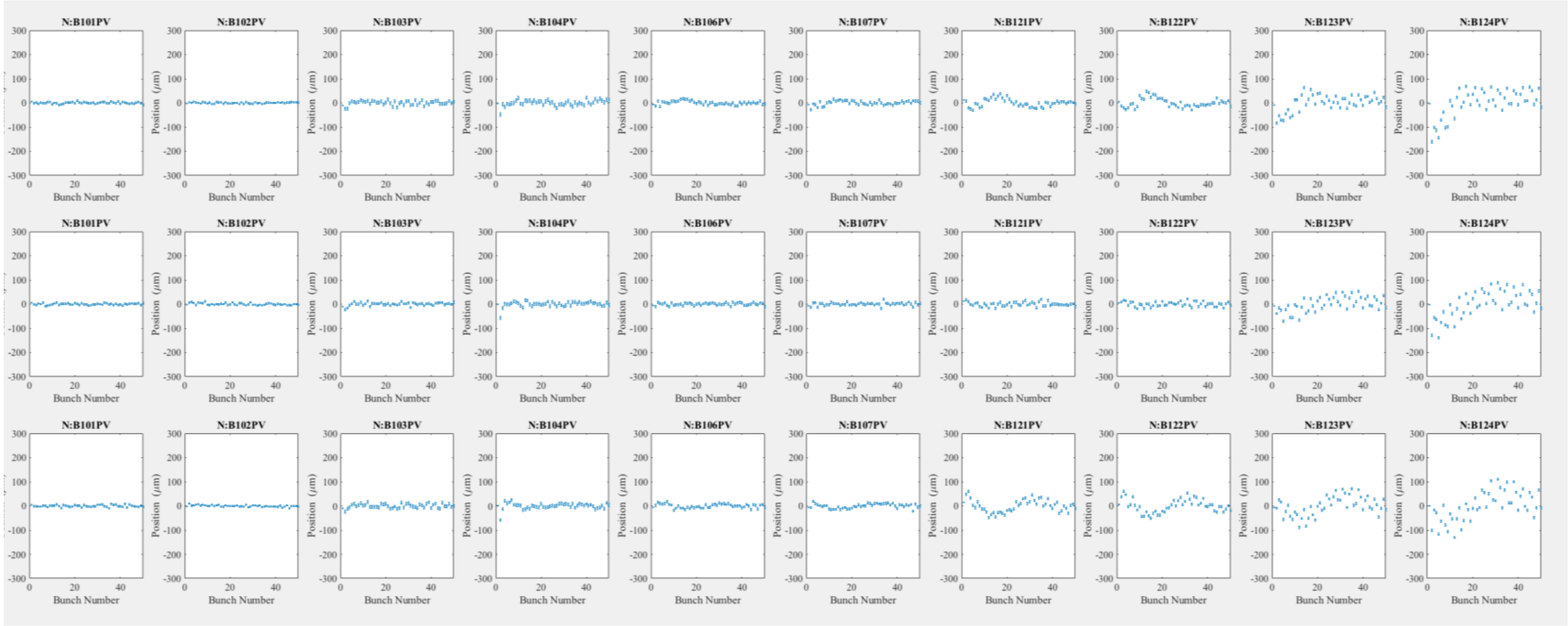
We are currently reducing the data for integrated energy spread with fewer bunches to see if there is a measurable difference.

Summary-1

- Transverse wakefield studies' results are consistent with a sub-macropulse centroid motion correlated to HOM strength.
- Vertical position bunch-by-bunch data show 100 kHz oscillation whose amplitude increases with charge and offset.
- Effect seems to be related to CC2 dipole HOM and directional with beam offset.
- Horizontal position bunch-by-bunch data with 100-shot averages show centroid oscillation at about 440 kHz (CC1).
- Longitudinal wakefield effects at these charges are not seen.
- Complementary data with X107 YAG images, emittances, framing camera are being processed. Small effects.
- Both ACL and MATLAB scripts were critical to studies.
- Relevant data set for benchmarking HOM calculations and simulations in Tesla-type cavities remains objective.

V101 Scan, 100 pC/b, 50 b 1000 shots B101-124 11-20-17

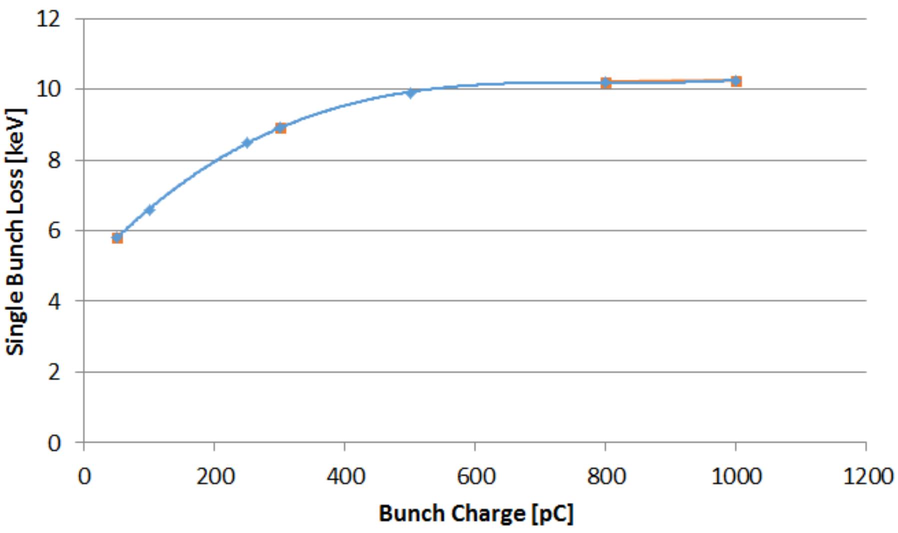
- BPMs Vertical, -1,0,1 A Top to bottom rows. Note flip of first oscillation. Quads off.



Energy spread from short-range wakefields should be relatively small

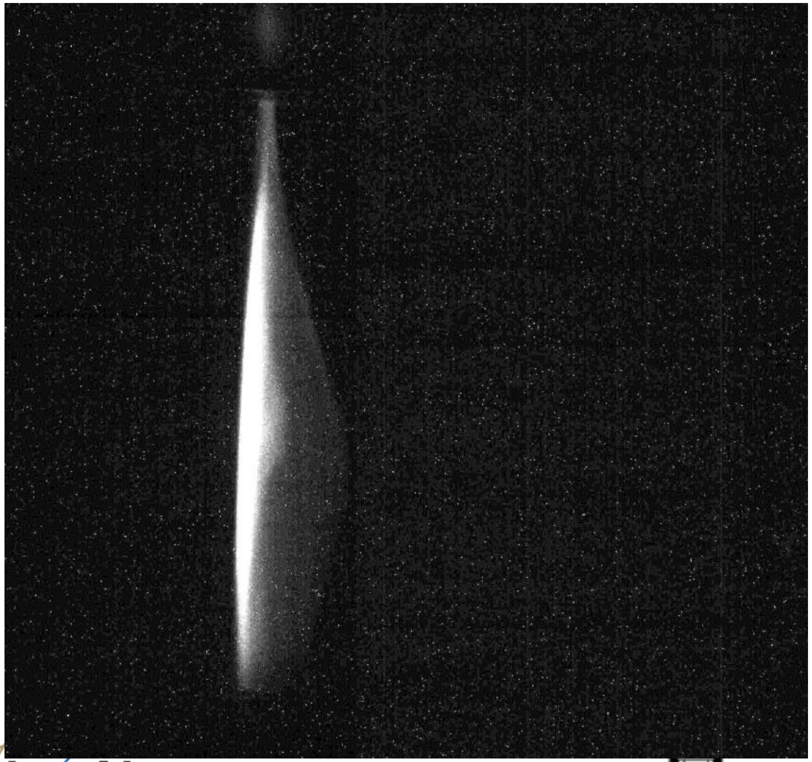
Centroid energy loss if ~ 10 keV at 1 nC; rms energy spread should be a few keV

Charge [pC]	σ [ps]	dE [keV]
50	**5.8**	**0.80**
100	6.6	1.54
250	8.5	3.50
300	**8.9**	**4.13**
500	9.9	6.60
800	**10.2**	**10.43**



Measurement 2: Measure integrated energy spread of bunch

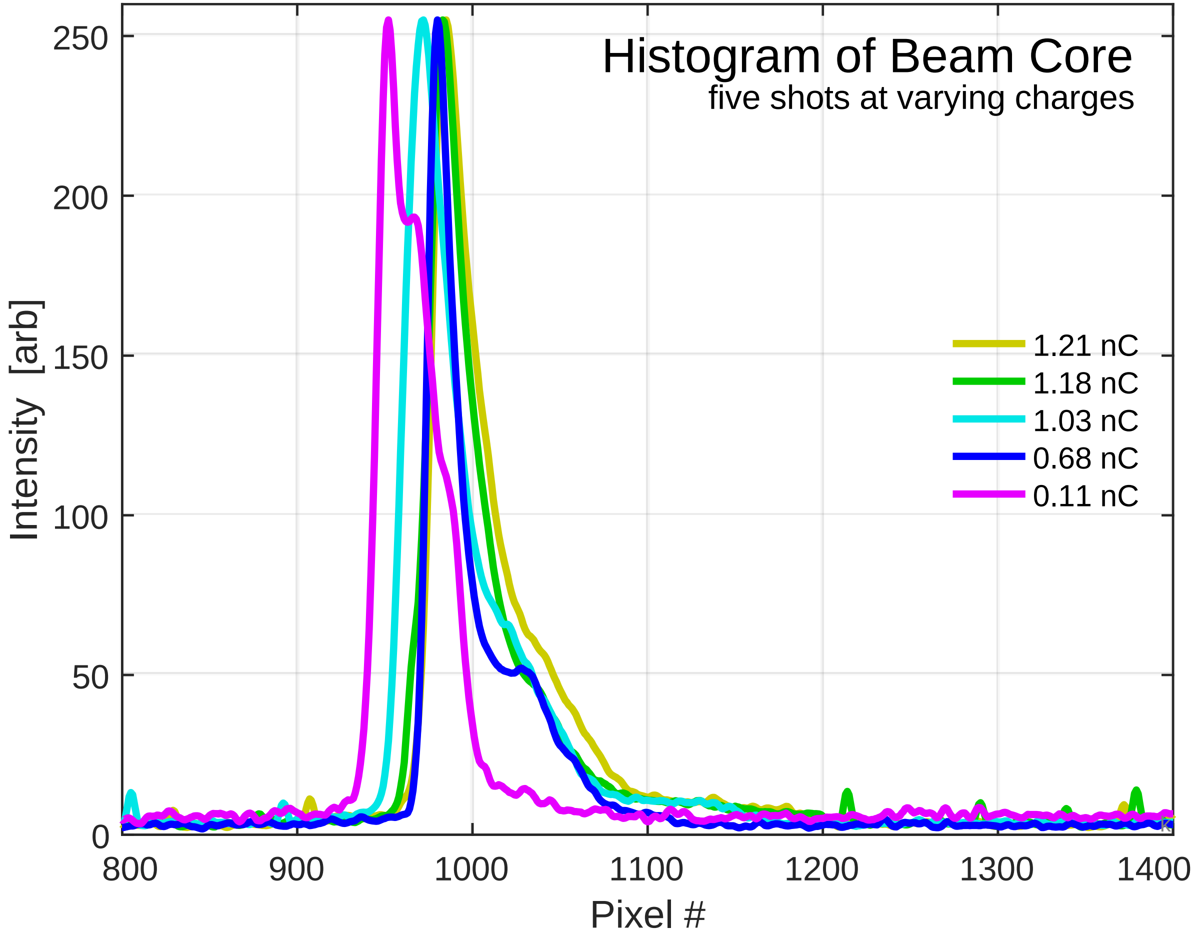
We calibrated and used an energy spectrometer to measure the macropulse's energy spread. We took data over a wide range of charges, and multiple beam shots to quantify variations.



At left is a typical raw image on spectrometer.

The camera's gain was adjusted for lower-charge levels, and for each image, a background image was subtracted. The image's tilt was adjusted, and a slice from the central portion was analyzed.

Real differences in energy profile at different charges

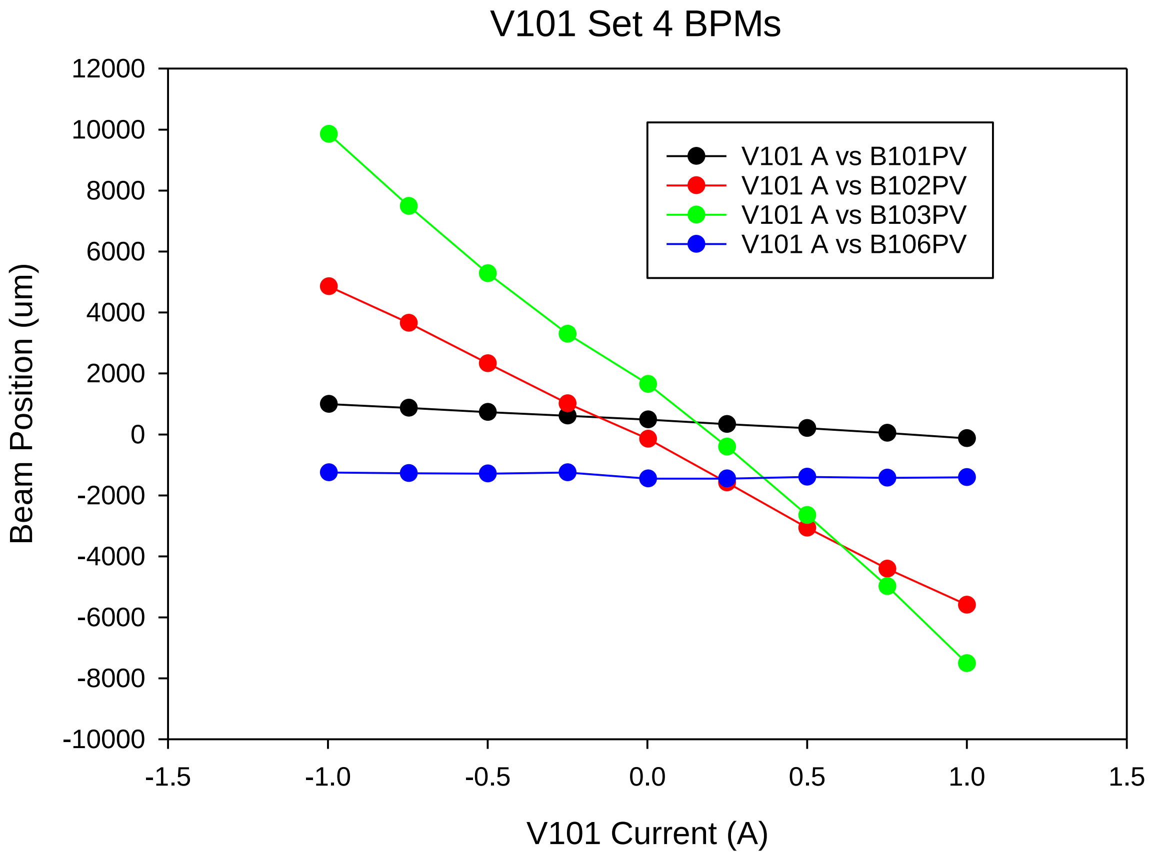


As the bunch charge varies, the beam energy fluctuated, but is not a significant problem.

Some structure became apparent (and charge dependent), at lower charges. Nevertheless, the energy spread is easily calculable.

V101 Scan 4, BPMs 10-27-17

- Tracking of beam trajectories around CC1 and CC2.



V101 Scan 4a, X111 images Show Profile Shoulder Shift

- 50b, 500 pC/b, nominal V101 at 0.0 A.   10-27-17

-1.0 A,   0.0 A,   1.0 A