Wakefield Study for Superconducting Accelerator Cavities at the FAST Facility

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Outline

- Motivation and importance
- Wakefield estimates
- Summary of measurement plan and goals
  - 1, 3, and 4.5 or 9 MHz bunch trains
  - Charge 500 pC up to 3 nC (up to max beam power)
  - Up to 200 bunches in bunch train (up to max beam power)
  - Measure the energy/transverse position deviations for the first few bunches and then the envelope for the entire bunch train

Our current plan is to interleave the longitudinal/transverse shifts (i.e., do all 3-MHz shifts first)

These measurements may impact the design of future SRF accelerators at high repetition rates (1 of 2)

- We have preliminary evidence that long-range wakefields (10 nsec to 1 micro-sec) may impact the design of accelerators using SRF structures for
  a) future high-energy linear accelerators for high-energy physics research (e.g., the 0.5-TeV **International Linear Collider (ILC)**) and
  b) high repetition rate X-ray free-electron laser (XFEL) light sources (e.g., the 1-MHz **Linac Coherent Light Source II (LCLS-II)** at SLAC (especially LCLS-II HE) and the burst mode operating format of the future **MaRIE XFEL** at LANL).
- There is urgency to understand and quantify these wakefields because of the ILC, LCLS-II, and European XFEL projects. The ability of the MaRIE XFEL to sustain a burst mode is a critical part of its design.
- This project's leave-behind will be an experimentally benchmarked and verified simulation model for both the long-range longitudinal and transverse wakefields and which will have relevance for all current and future projects using ILC superconducting cavities.
- The collaborative experiment offers a high impact return on modest investments.

These measurements may impact the design of future SRF accelerators at high repetition rates (2 of 2)

These wakefields cause:

Longitudinal: Electron beam energy spread
Transverse: Electron beam emittance growth

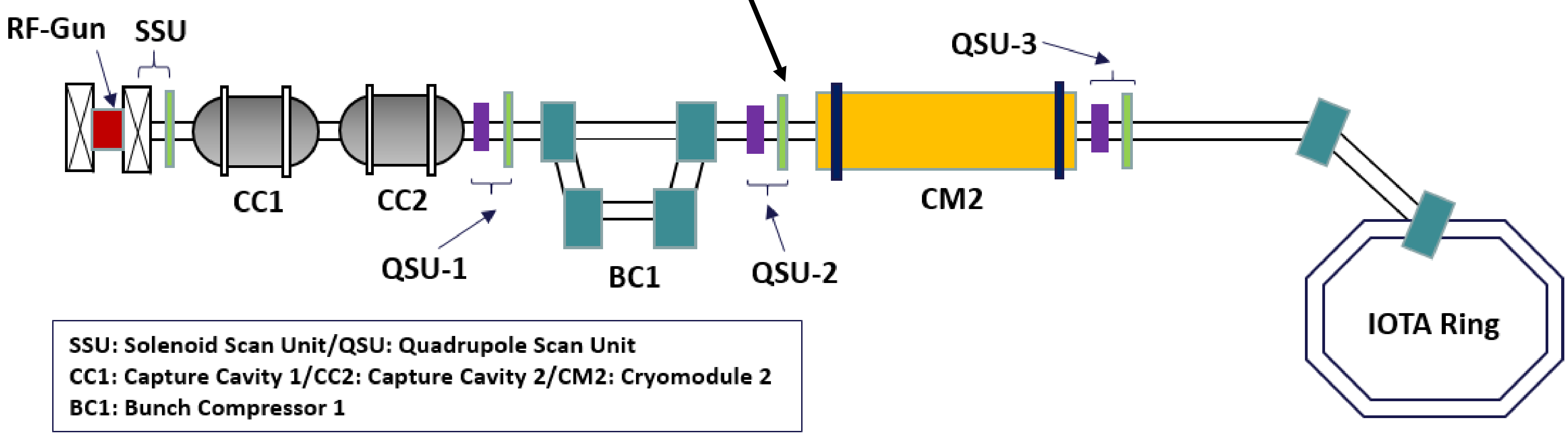
Longitudinal and transverse long-range wakes will lead to random energy spread and emittance jitter scaling as the square root of the number of bunches over some characteristic length

Our goals are to verify this scaling and determine the relevant amplitudes and characteristic lengths

We have predictions on the amplitudes and we think the characteristic length is ~ 1 to 10 μsec

FAST beamline – CC1 and CC2 are the TESLA superconducting cavities

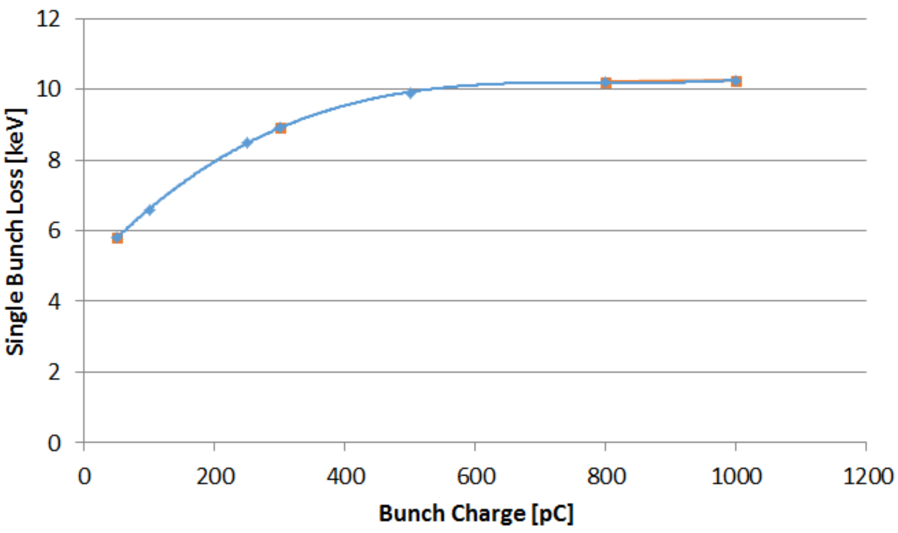
We will make wakefield measurements here



Short-range wakefields are essentially negligible

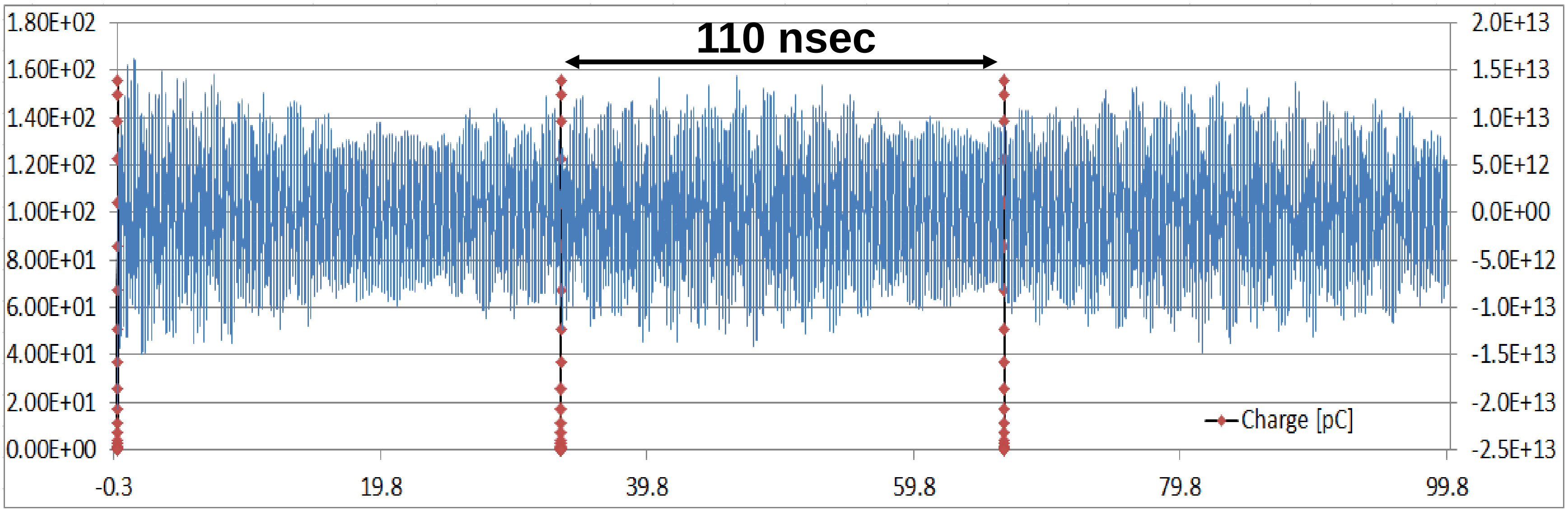
Short-range wakes are small in comparison (wakes for different charges and their bunch lengths; ~ 10 keV maximum)

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**



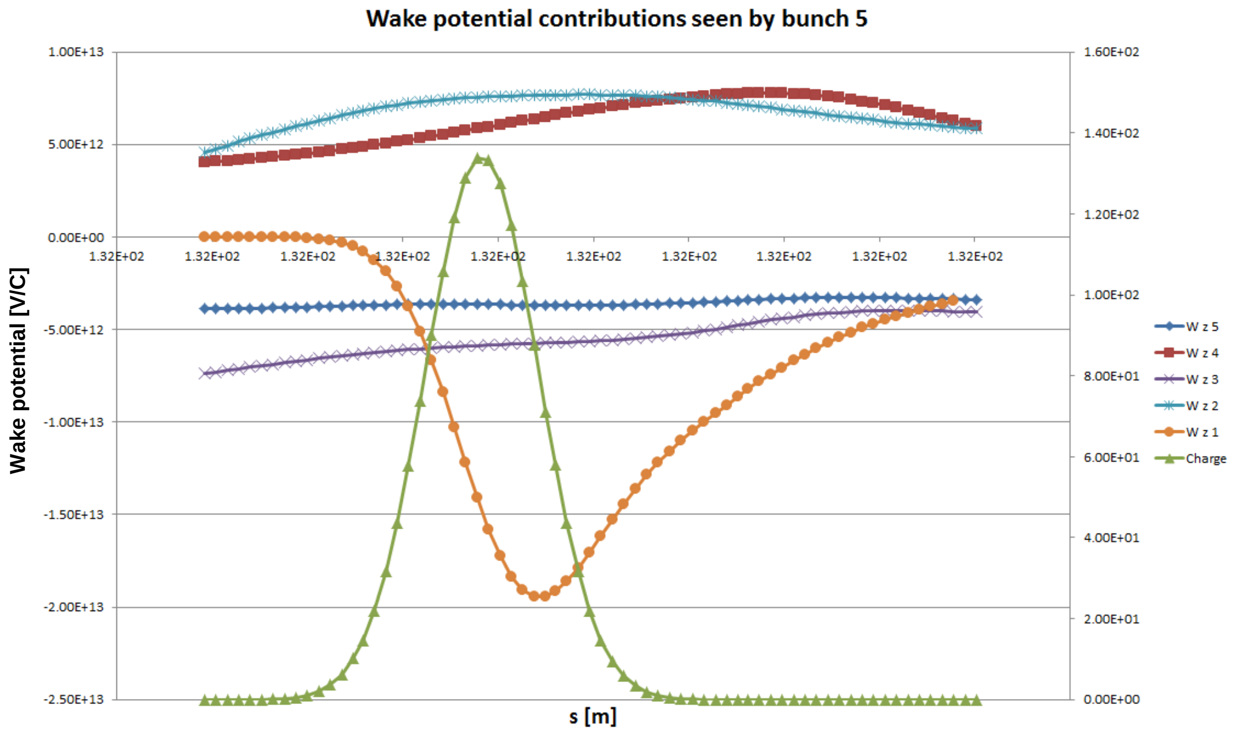
Motivation – simulations

The longitudinal wakes persist for a long time



Snapshot of the longitudinal wake potential of the first bunch at the location of the first 3 bunches (9 MHz). The interaction will change "randomly" even with smaller changes in bunch spacing. (Note qualitatively same as at a couple GHz.)

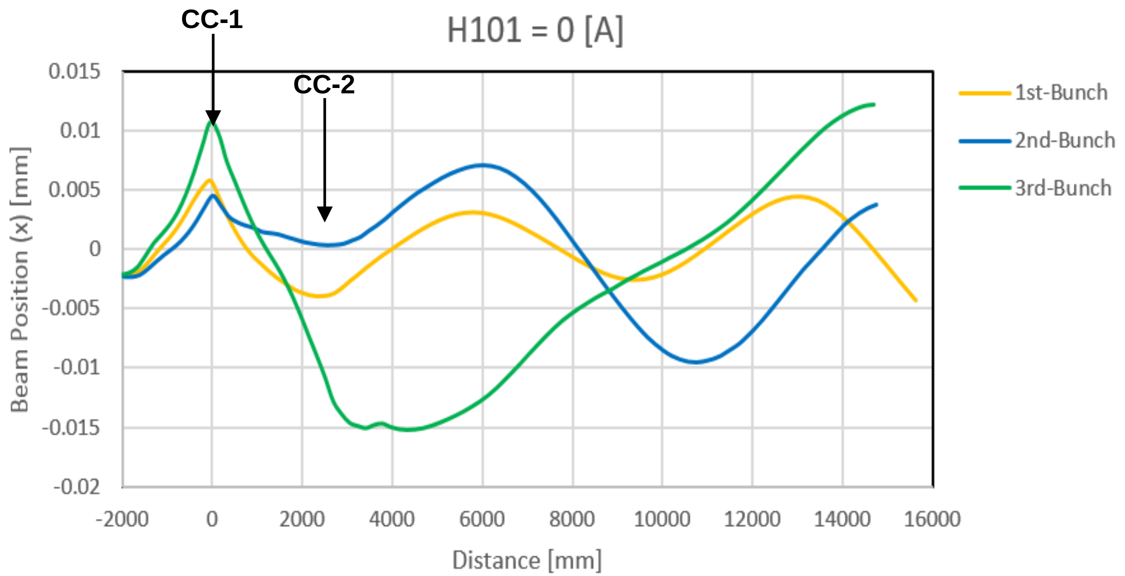
Motivation – simulations



ECHO2D simulation – CST simulations indicate an order of magnitude larger longitudinal wakes

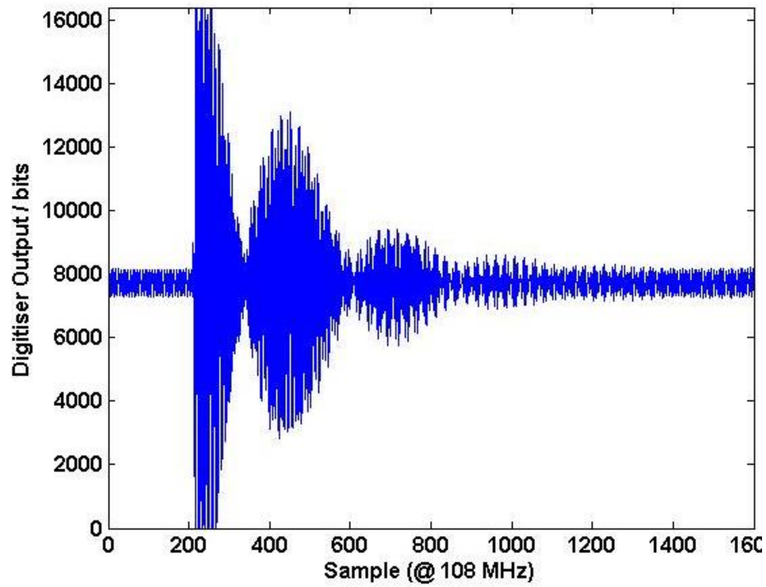
Wake potentials seen by bunches at a 9 MHz rep rate. Energy change is on the order of 10 keV for nC bunches. *Energy centroid jitter prediction is about 0.02% times square root of number of bunches, so about 0.2% for 100 bunches.*

Motivation - simulations



Transport simulations through CC1 and CC2 show the effect of CC1 and CC2 steering and transverse wakefield steering (note the difference between the yellow and the blue/green lines). Both effects are linear with offset (***so a 1 mm offset leads to ~5 mrad steering from the transverse wakes***)

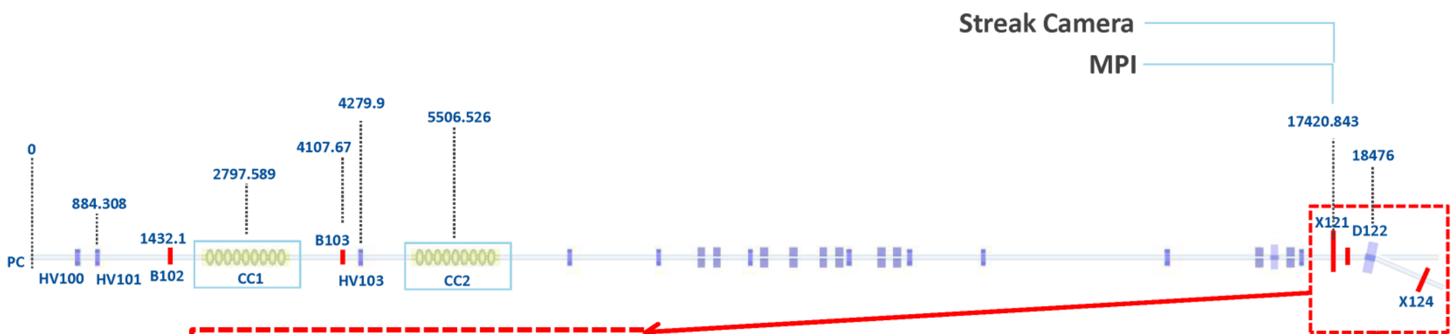
Motivation - measurements



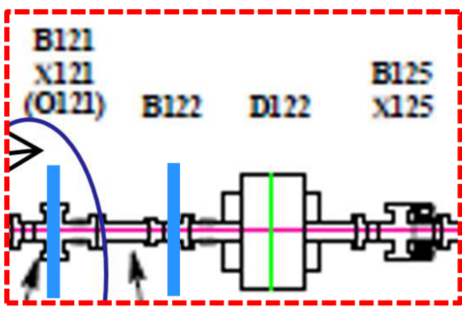
-HOM measurements at DESY clearly show presence of long-term transverse wakefields. HOM power can be measured if beam is off-axis in cavities.

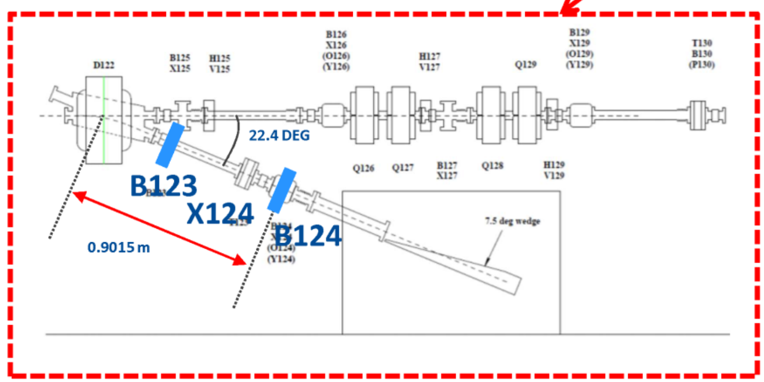
-When HOM power is minimized by transport steering, measured beam emittance was reduced by 30% at FAST at low charge and 3 MHz.

Longitudinal wake measurements



Centroid energy of each bunch in bunch train (up to 200 bunches or 15 W at 1/3/9 MHz) will be measured by BPM 123 and 124 after spectrometer magnet





BPM resolution (B123, B124):
25 μm (corresponds to 5 keV)

Measured BPM resolutions:

25 μm at 2 nC

60 μm at ~0.3 nC

(estimates were:
72 μm at 1 nC and
290 μm at 0.25 nC)

Longitudinal wake measurement is straightforward; feed forward removed beam loading; goal is to identify range of wake effects

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New rf BPM results (8-29-16)

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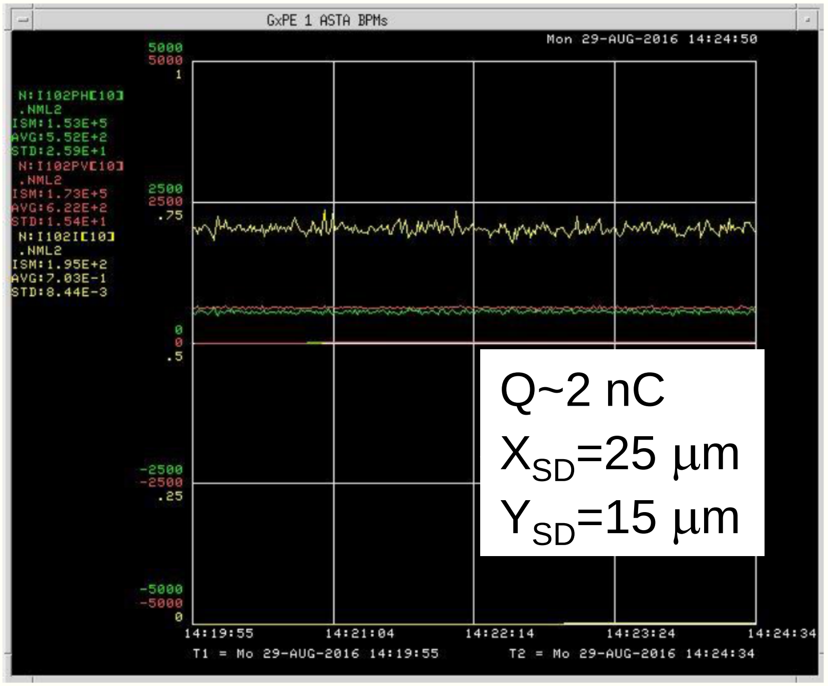
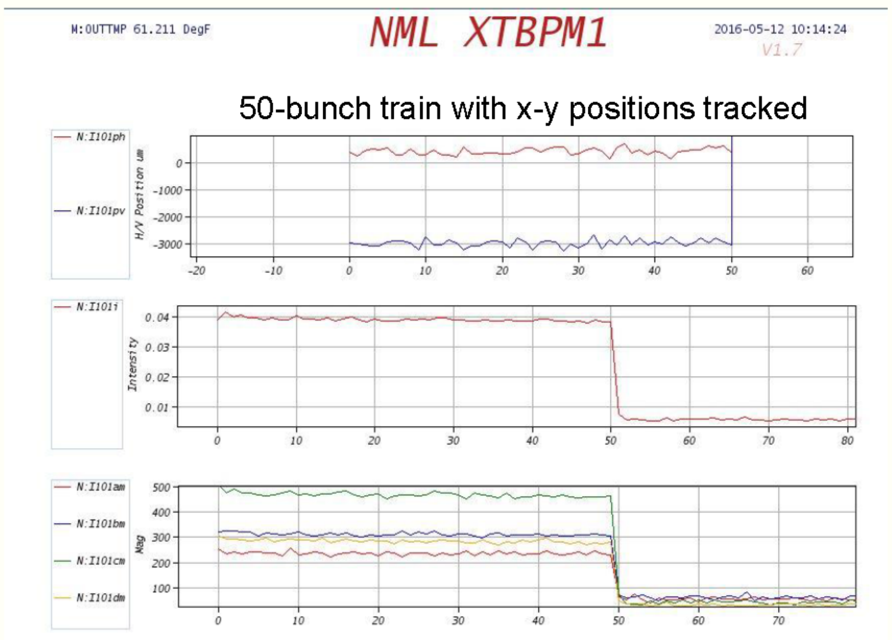
- **Using the 4-MeV beam from the gun, the new lower noise BPM board was shown to significantly reduce noise at high and low charge.**
- **The firmware was also revised to allow bunch-by-bunch position plots through ACNET for 50 bunches (Right).**
- **Need several (all) injector rf BPM stations upgraded for HOM studies.**





Courtesy of N. Eddy

Summary of longitudinal measurement plan

Longitudinal wakes (Y. M. Shin, B. Carlsten, et. al.)

- Measure change in bunch energies for a train of bunches at 1, 3, and 9 MHz (4.5 MHz if 9 cannot be achieved) using B123 and B124
- Measurement is bunch-by-bunch centroid shift from established baseline transport in spectrometer with BPMs (low charge: measurement is centroid position integrated over a bunch train)
- Feedforward used to compensate for single bunch beam loading at different charges
- Compare with simulations; publish results
- 5 shifts requested

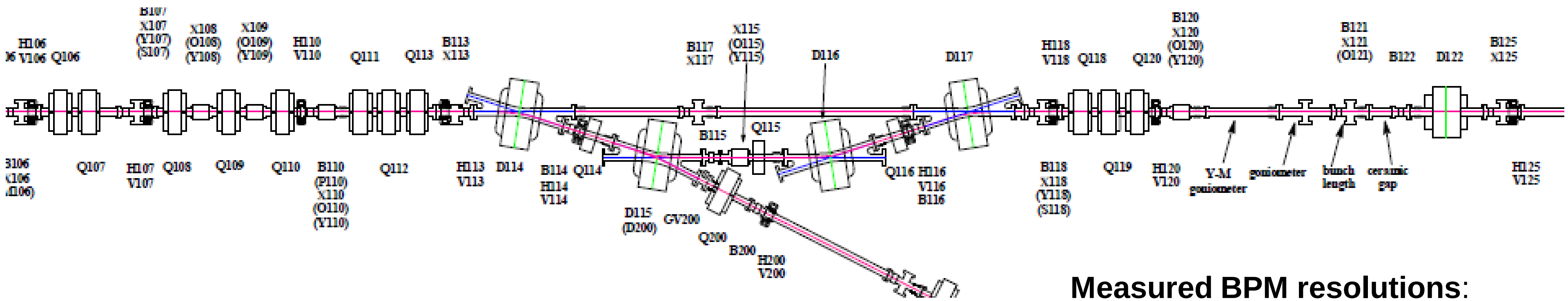
1 Baseline transmission (centroid measurement in BPMs, integrating bunch train with low charge at 3 MHz)

2 3 MHz, 500 pC (if possible), 1 nC, 2 nC, 3 nC with CC1/CC2 phase-scans

3 1 MHz, 500 pC (if possible), 1 nC, 2 nC, 3 nC with CC1/CC2 phase-scans

4/5 9 or 4.5 MHz, 500 pC (if possible), 1 nC, 2 nC, 3 nC with CC1/CC2 phase scans (up to 15 W peak beam power)

Transverse wake measurements



Measured BPM resolutions:

25 μm at 2 nC

60 μm at ~0.3 nC

(estimates were: 72 μm at 1 nC and 290 μm at 0.25 nC)

Streak camera resolution (in framing mode):

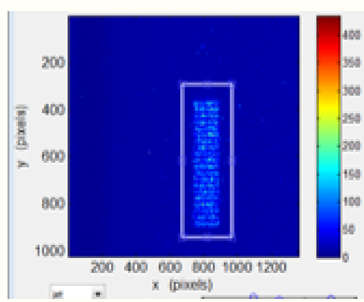
20 μm at 250 pC

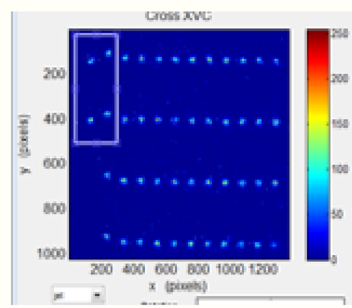
Required hardware: revised HOM detectors; low noise, bunch-by-bunch rf BPMs in injector; Correctors (H/V 100, H/V101/103/104/106/107/120); X107,X108, X111,X121,X124, X121 Streak camera, LE-spectrometer, E=40-45 MeV, on crest, no chicane.

With slow vertical unit, streak camera operates in framing mode

Effect	Mode	Temporal resolution	Spatial res. (µm, est.*)	Wake Range
Sub-Micropulse, y-t	Synchroscan,V	1ps	25-50	short
Sub-macropulse, y-t,T	dual sweep,H,V	1ps, H axis selectable	25-50	short
Sub-macropulse, y-T	Slow sweep,V	100 ps	25-50	long
Sub-macropulse, x,y-T	Framing Mode	100 ps	25-50	long

UV laser pulse train demos





*Bunch-by-bunch techniques can be applied to IOTA beam turn by turn.

* Spatial effects will be referenced to effects seen on the X121 YAG screen.

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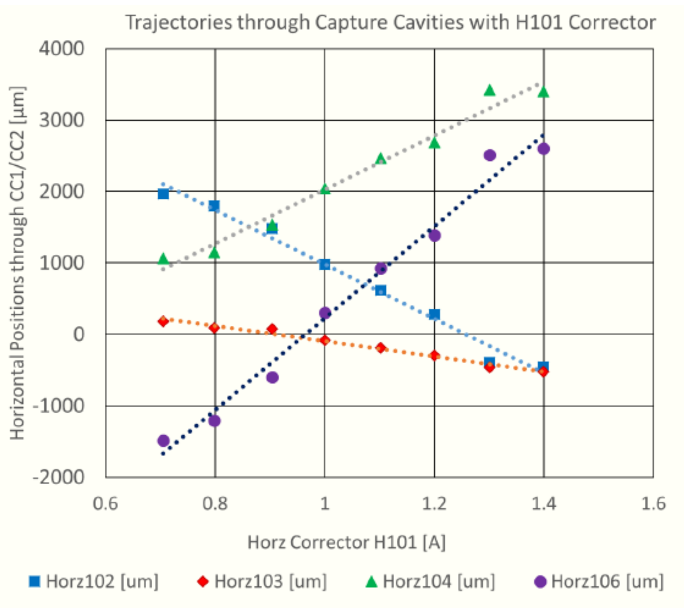
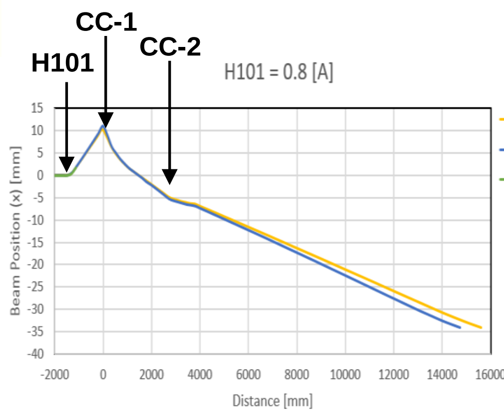
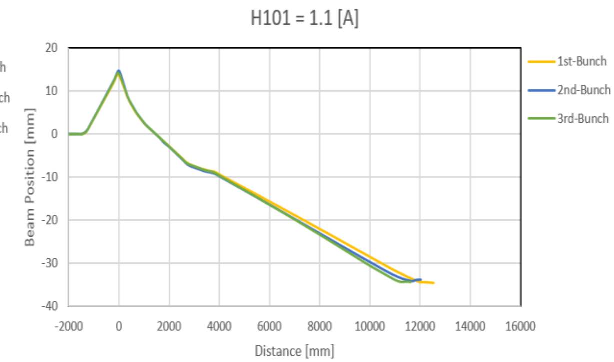
Simulations will help us determine the transfer matrix between BPMs so we can differentiate the effect of the transverse wakefields







Preliminary data showing our ability to generate arbitrary steering through CC1 and CC2. Here beam position monitor (BPM) 102 is before CC1, BPM 103 is between CC1 and CC2, and BPMs 104 and 106 are after CC2. These horizontal offsets are changed by varying steering magnet H101, located before CC1. Simulations can model these effects; will need to optimize CC1 and CC2 offsets to match experimental data.

Summary of transverse measurement plan

Transverse wakes (A. Lumpkin, B. Carlsten, et. al.)

- Measure bunch transverse shifts, average beam size effects, and average beam emittance for a train of bunches at 1, 3, and 9 MHz (4.5 MHz if 9 cannot be achieved)
- Measurement is bunch-by-bunch centroid shifts using RF BPMs B101 to B124) and integrated beam envelope size. Variations from established baseline transport (centroid and beam size) will be compared to simulations to infer transverse wakes
- Feedforward used to compensate for single bunch beam loading at different charges
- Publish results
- 5 shifts requested

  1/2 Baseline transmission (integrating bunch train with low charge) at 3 MHz; measure bunch centroid shifts with RF BPMs at 500 pC (if possible), 1 nC, 2 nC, 3 nC

  3/4 Measure bunch centroid shifts with framing camera at 3 MHz at X121 at 250 pC (if possible), 500 pC, 1 nC, 2 nC, 3 nC

  5 (Long shift) measure bunch centroid shifts with RF BPMs at 250 pC (if possible), 500 pC, 1 nC, 2 nC, 3 nC at 9 or 4.5 MHz (up to 15 W peak beam power)

Summary

- The effects from the transverse and longitudinal wakefields can be large enough to degrade beam quality (effective energy spread and emittance increases)
- Numerical estimates are hard to make – we need experimental data
- Order-of-magnitude estimates indicate that the BPM and streak camera resolutions should be good enough to see wakefield effects
- We will need to compensate for beam loading for the longitudinal wakefields
- We will need to back out the CC1 and CC2 transfer matrices for the transverse wakefields
- In addition to measuring the magnitude of these effects, we will verify the form of these effects (bunch-by-bunch and envelope)