

# Novel Accelerator Physics Measurements Enabled by NSLS-II RF BPM Receivers

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# Outline

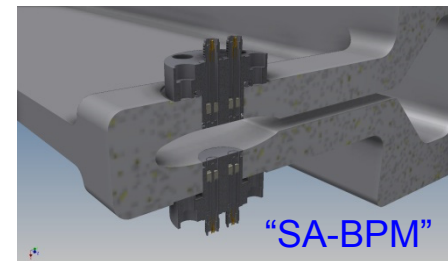
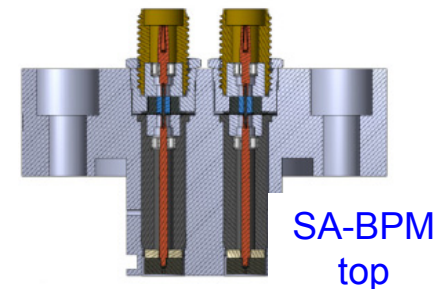
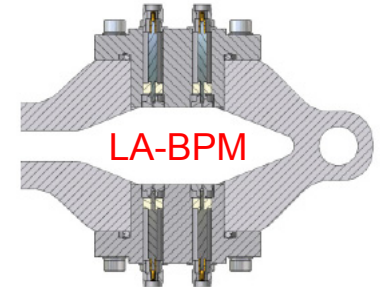
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1. NSLS-II BPM introduction
2. Recent resolution improvements for single- and few bunch fills
3. Added capability to resolve bunches within a ring turn
4. Beam physics measurements that benefit from these new BPM capabilities
  - Small, current-dependent tunes shifts  $\Rightarrow$  total ring impedance
  - Small, current-dependent tunes shifts  $\Rightarrow$  localized impedance components
  - Amplitude dependent tunes shift

# Introduction: NSLS-II BPM Types & Pickup Geometries

- NSLS-II: 30 cell DBA 3 GeV ring with 1 nm / 8 pm design x/y emittances
- NSLS-II BPMs differ in chamber and button geometry

| RF BPM Types                                                                                              | Quantity                                                       |
|-----------------------------------------------------------------------------------------------------------|----------------------------------------------------------------|
| <b>Multi-Pole Chamber BPMs (<u>LA</u>)</b><br><u>L</u> arge <u>A</u> perture (25 mm vert.)                | <b>6 per cell</b><br><b>180 Total</b>                          |
| <b>Insertion Device (ID) Chamber BPMs (<u>SA</u>)</b><br><u>S</u> mall <u>A</u> perture (8-11.5 mm vert.) | <b>2-4 per ID</b><br><b>straight</b><br><b>~30 Total (now)</b> |
| <b>Special BPMs (injection, BxB fdbk, test, ...)</b>                                                      | <b>~10</b>                                                     |

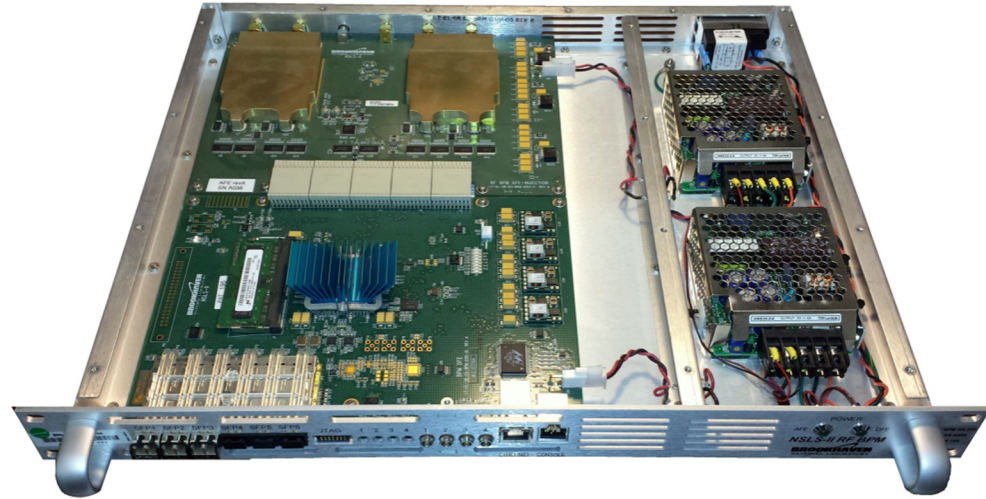


Real SA button assemblies are rotated around the vertical

- Different geometries result in different sensitivity/resolution by a factor of ~2
- Most sensitive (ID) BPMs are at the locations with small beam size

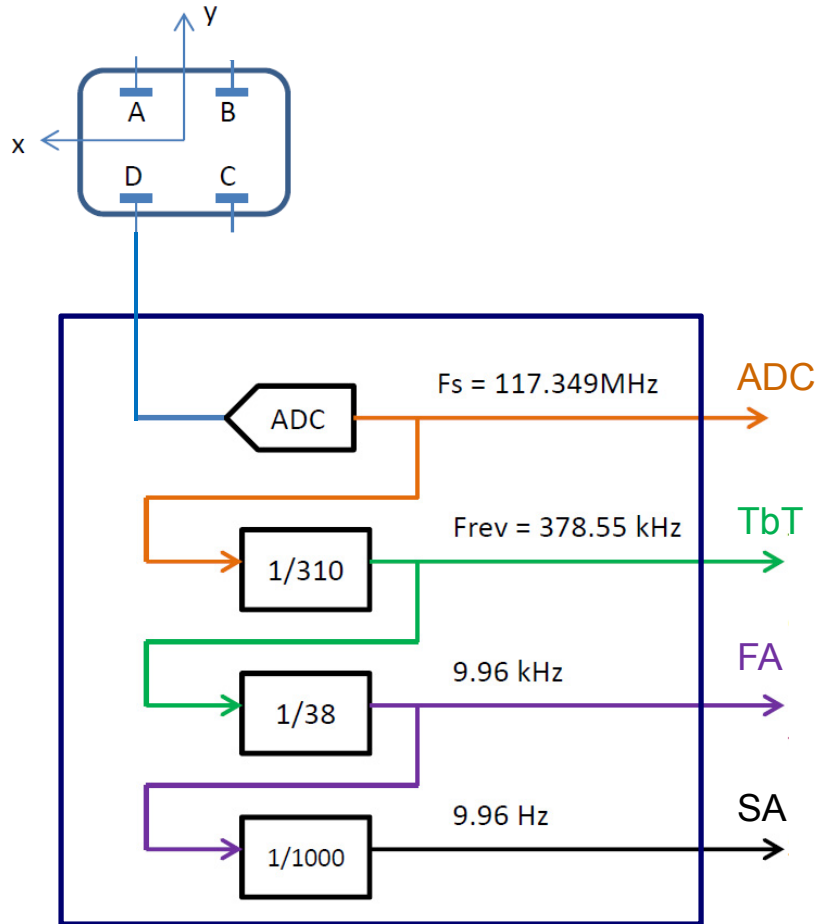
# Introduction: NSLS-II BPM Receivers

| Data Type                        | Mode                               | Max Length                                                                                                         |
|----------------------------------|------------------------------------|--------------------------------------------------------------------------------------------------------------------|
| ADC Data                         | On-demand                          | 256Mbytes or 32M samples per channel simultaneously                                                                |
| Turn-by-Turn (TbT), Frev=379 kHz | On-demand                          | 256Mbytes or 5 M samples<br>Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd                                       |
| Fast Acquisition (FA) , 10KHz    | Streaming via SDI Link & on demand | Streaming - X,Y,SUM; For on demand: 256 Mbytes or 5 Msamples.<br>Va,Vb,Vc,Vd, X,Y, SUM, Q, pt_va,pt_vb,pt_vc,pt_vd |
| Slow Acquisition (SA), 10Hz      | Streaming and On-demand            | 80hr circular buffer<br>Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd                                           |

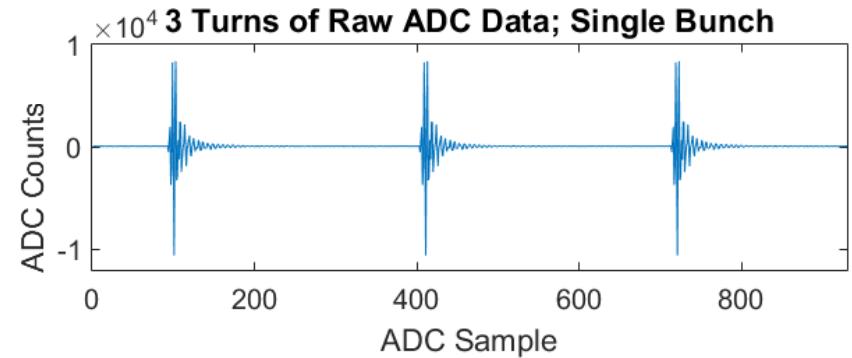
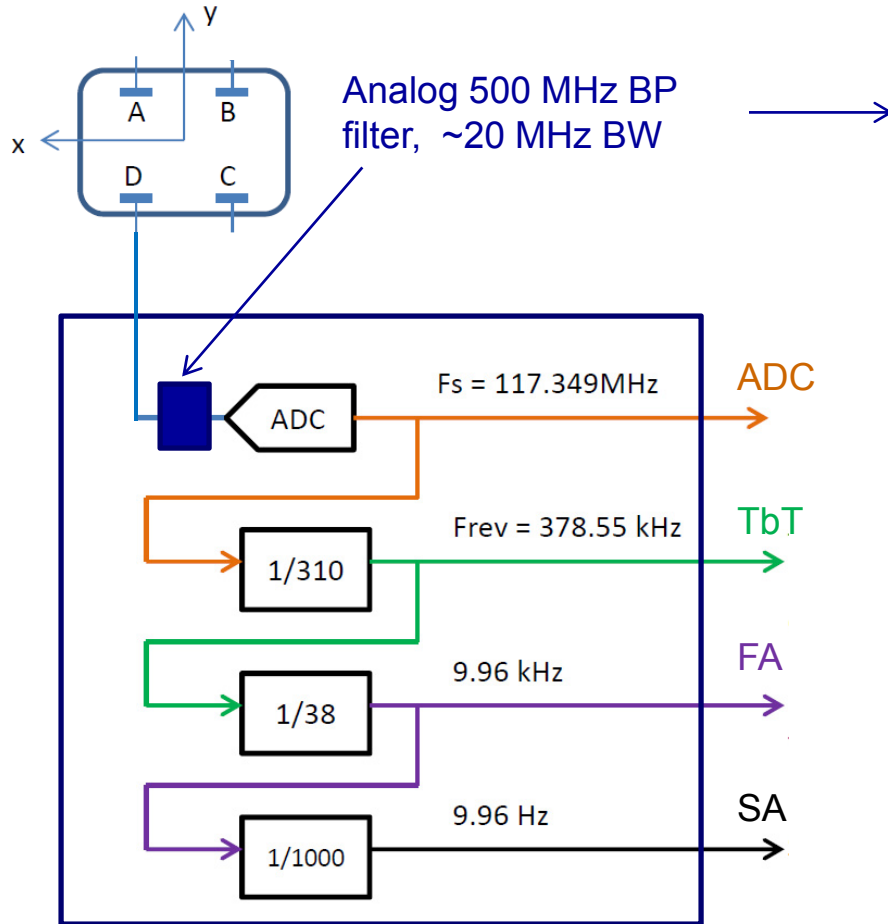


- Original NSLS-II development (by Kurt Vetter et al.)
- Resolution specs of 1  $\mu\text{m}$  turn-by-turn (TbT) and 200 nm in 10 kHz (FA) mode were verified with beam
- TbT used for injection & kicked beam studies, FA for fast orbit feedback & interlocks, SA for orbit measurements
- No bunch-by-bunch capability (cannot resolve bunches within a turn)

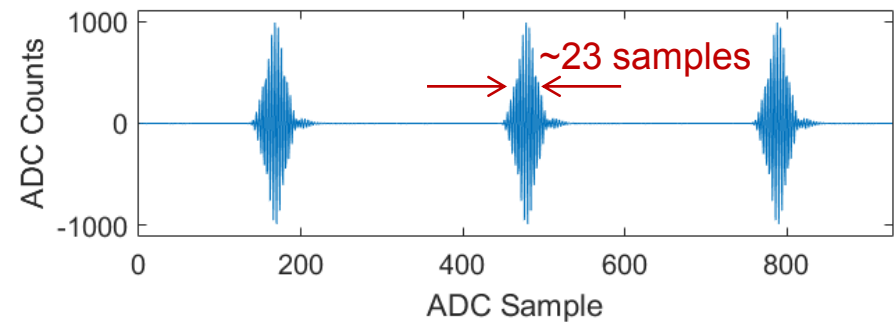
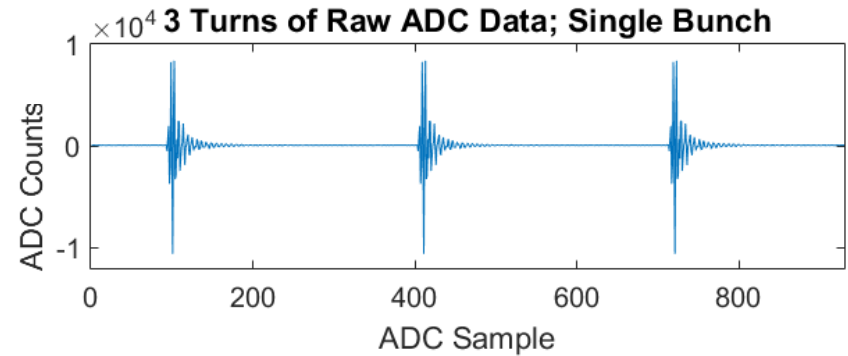
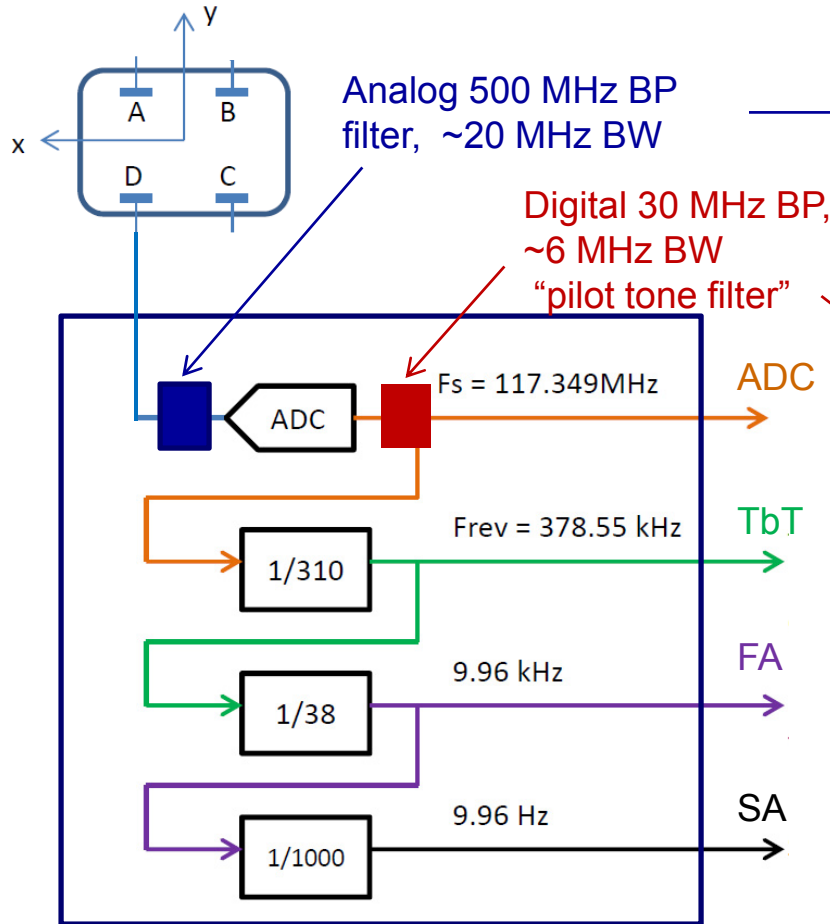
# Introduction: BPM Signal Processing



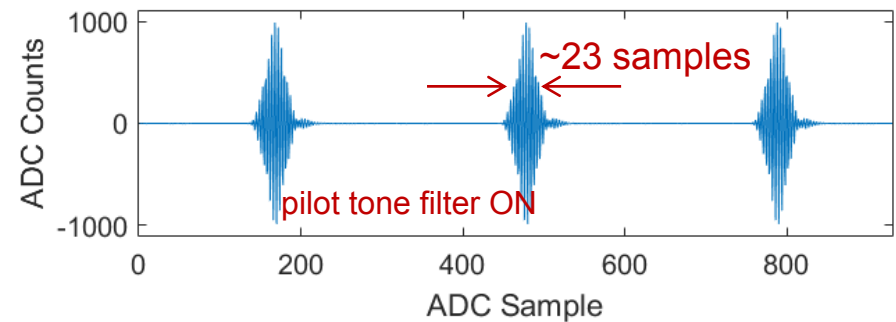
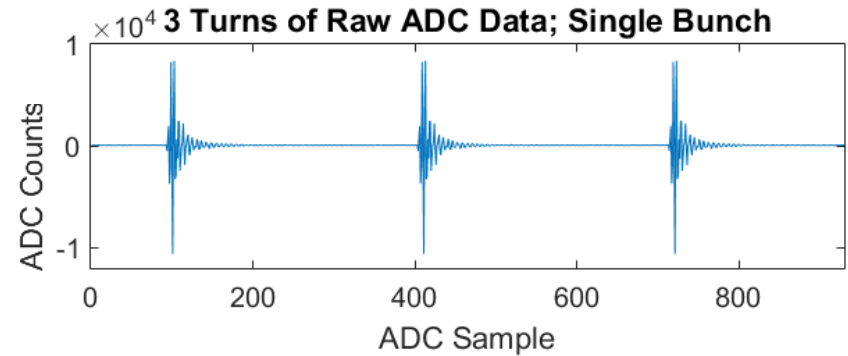
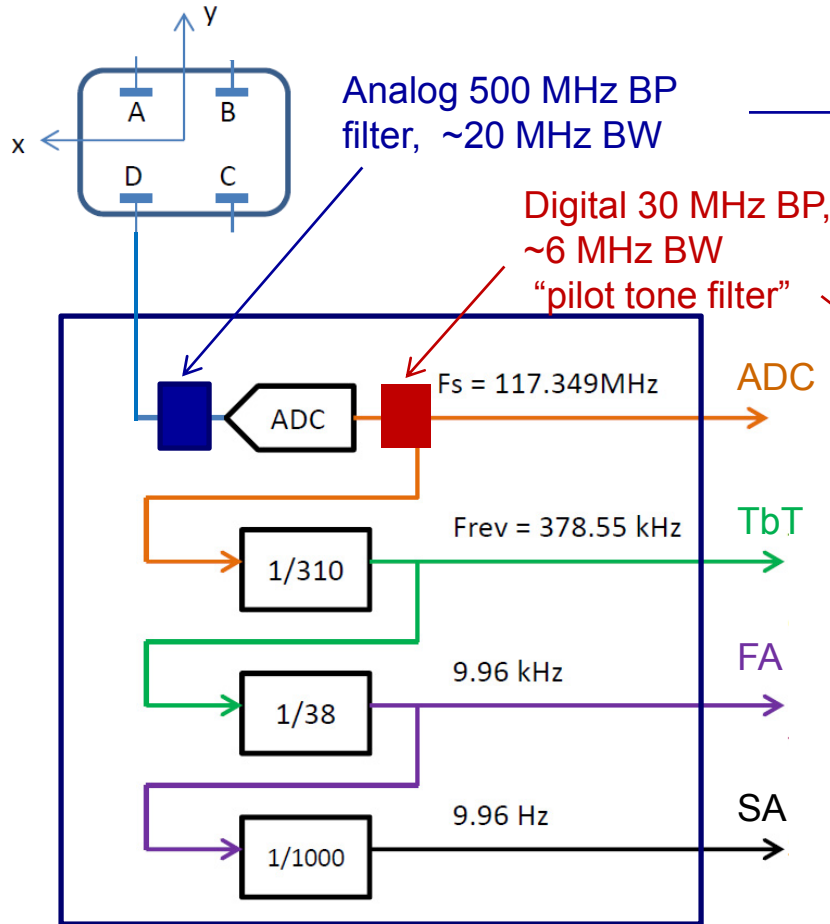
# Introduction: BPM Signal Processing



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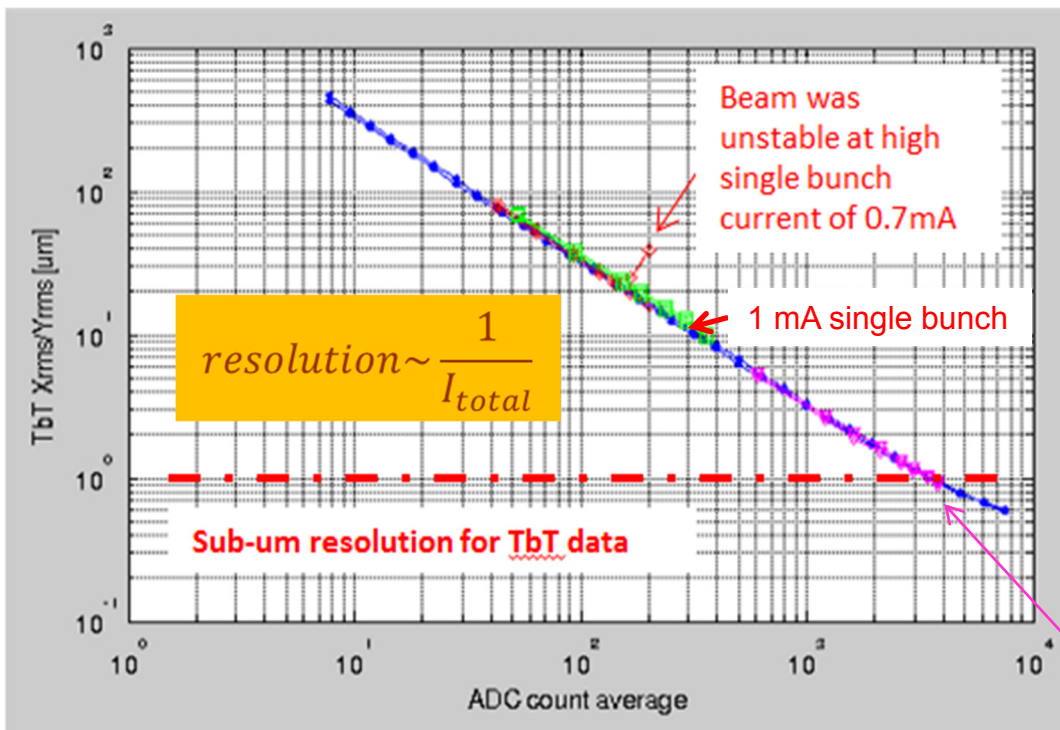


**1 Turn = 310 ADC Samples =  
=1320 of 500 MHz RF buckets**

- TbT X, Y, and  $\Sigma$  are obtained (in FPGA) from ADC signals by coherent signal processing locked to revolution harmonic.

# Introduction: NSLS-II BPM TbT Resolution

W. Cheng et al., IBIC'15

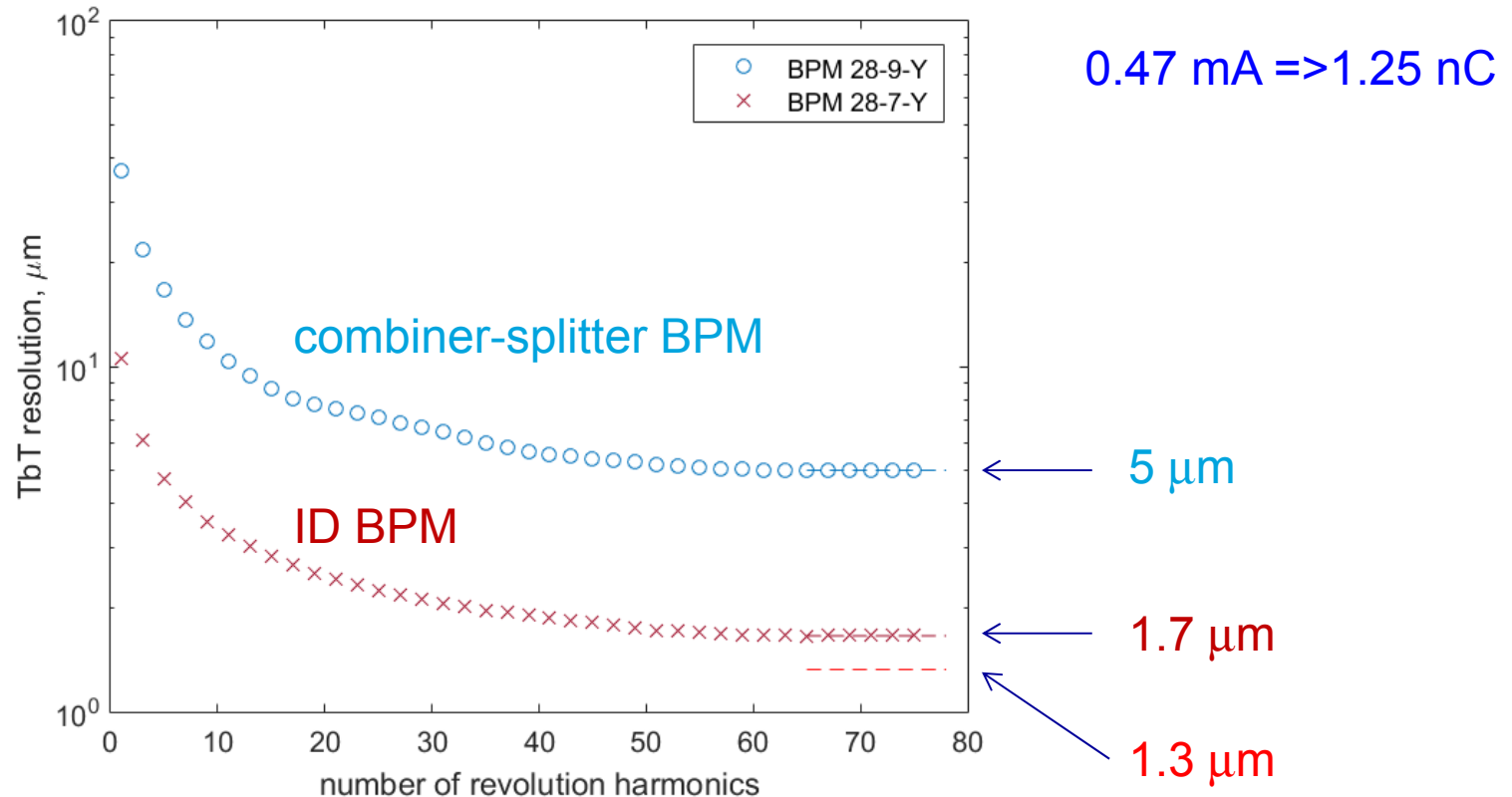


- pilot tone test
- 20 bunch train
- 1000 bunch train
- single bunch

~10 mA / 1000 bunches

- Sub-micron TbT resolution is routinely available for long bunch trains
- However, single bunch resolution was 1-2 magnitude orders worse
- It was recently improved [B. Podobedov et. al., IPAC'16] by order of magnitude plus BPM capabilities were enhanced to resolve multiple bunches within a ring turn

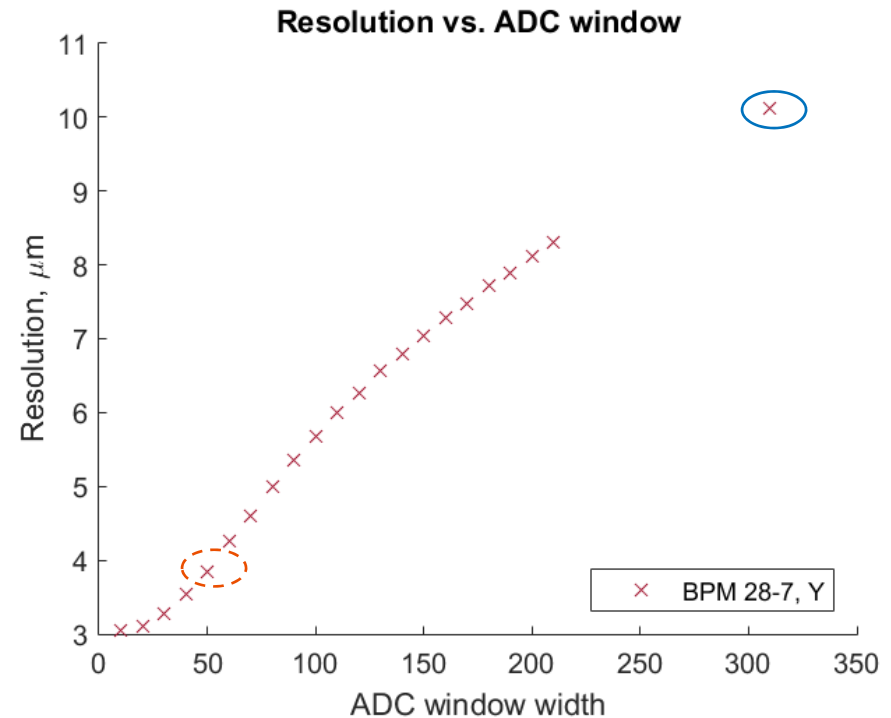
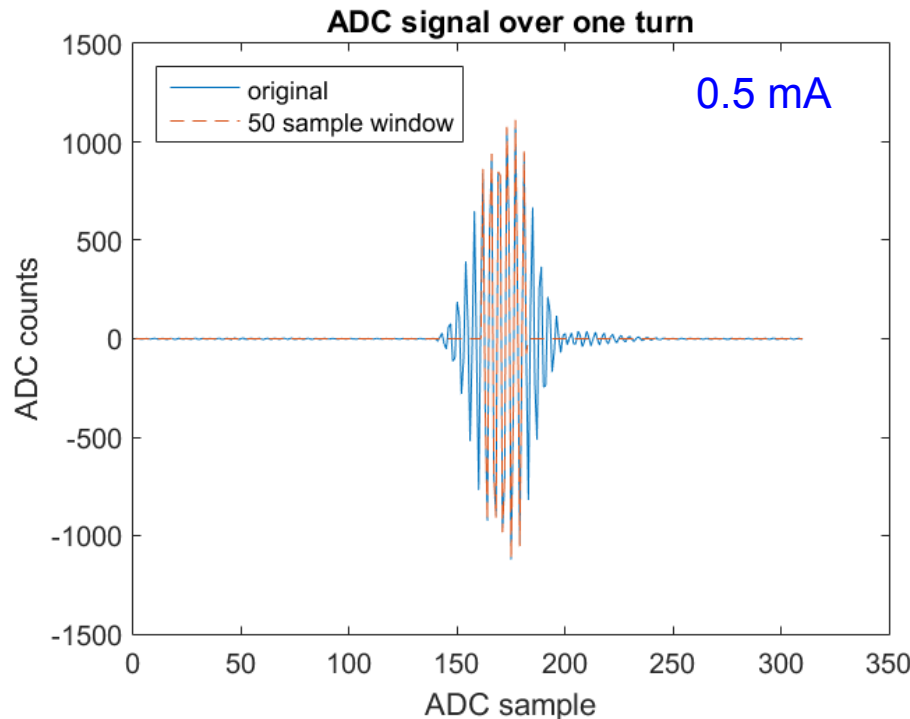
# Resolution Improvement by Including Multiple Revolution Harmonics



- Without pilot tone filter the number of in-band harmonics is higher => resolution improvement of about factor of 7.
- On ID BPMs directly measured resolution reaches 1.7  $\mu\text{m}$ , or 1.3  $\mu\text{m}$  when scaled from combiner-splitter BPM.

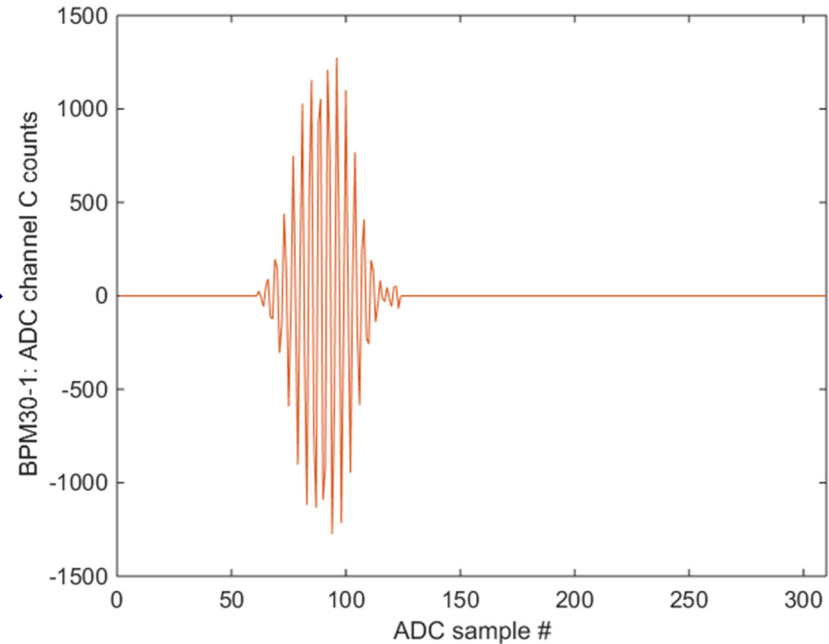
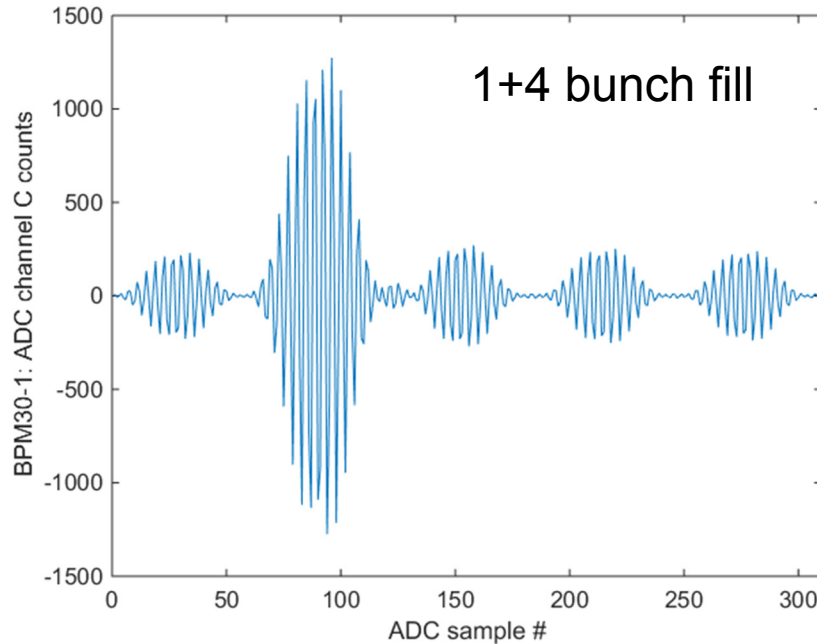
# Resolution Improvement by Gating BPM ADC Signals

- Standard BPM processing looks at all 310 ADC channels (i.e. entire turn)
- Let's use only the ADC channels that contain most of the single bunch signal (i.e. apply a boxcar window on every turn)



- This results in resolution improvement by factor of 3 to 4.

# Resolving Individual Bunches within Ring Turn



- Blank-out signals from all but one bunch (on every turn)
- Include enough harmonics of  $F_{rev}$
- Use standard processing to extract  $X$ ,  $Y$ ,  $\Sigma$  from these modified ADC data
- Repeat for each bunch
- We can resolve up to 8 bunches, depending on experiment

# Motivation for Recent BPM Capability Enhancements

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- Why single- or few bunch fills?

For various beam dynamics studies, especially

- 1) single bunch collective effects, incl. impedance measurement
- 2) single particle non-linear dynamics
- 3) beam lifetime and instability diagnostics

- Why resolution improvement is beneficial for these?

Measurements are very sensitive (effects are small, and could be masked by machine drifts)

Need to be done at low currents

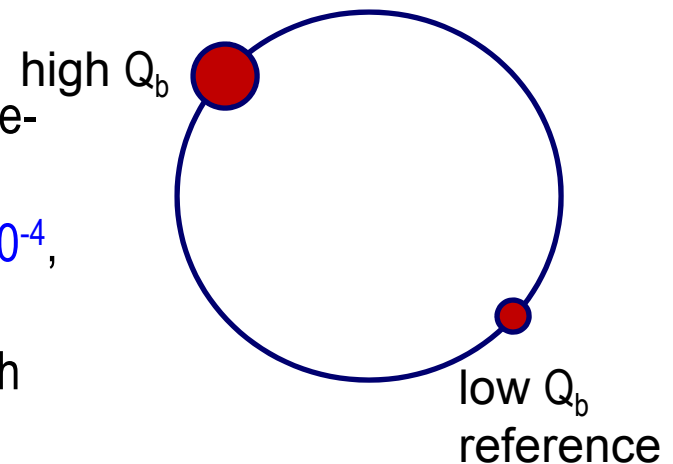
- Apart from resolution why special BPM signal processing?

To provide “bunch-by-bunch capability”\* for overcoming the machine drifts

\* For at least a few, well separated, bunches

# Motivation Example: Transverse Impedance Measurement

- What is the impedance (or kick factor) of an accelerator component, i.e. an insertion device chamber?
- By design, these are small.
- Impedance is not directly measured, but Z-related effects  $\sim Q_b$  are.
- Take  $Q_b=1$  nC,  $\beta_y=3$  m,  $k_y=500$  V/pC/m
  - Tune shift  $\sim 4 \times 10^{-5}$
  - Closed orbit shift  $\sim 0.7 \mu\text{m rms per } \Delta y=1 \text{ mm}$
- These are hard to measure!
- The standard approach, via multiple injections or time-decay, is virtually impossible due to “machine drifts”  
typically at low current and no fdbk.:  $\text{tune jitter} > 10^{-4}$ ,  
 $\text{rms orbit drift} > 1 \mu\text{m/min}$
- Can be overcome by the relative measurements, with high- $Q_b$  and low- $Q_b$  bunches

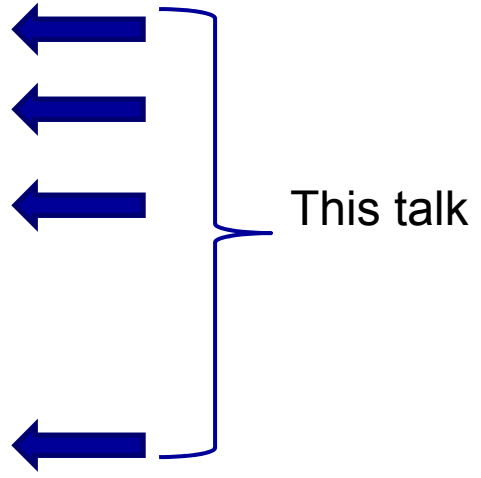


**Need good resolution at low current, and many BPMs capable of resolving the orbits of at least two bunches**

# Beam Physics Studies that Benefit from New BPM Capabilities at NSLS-II

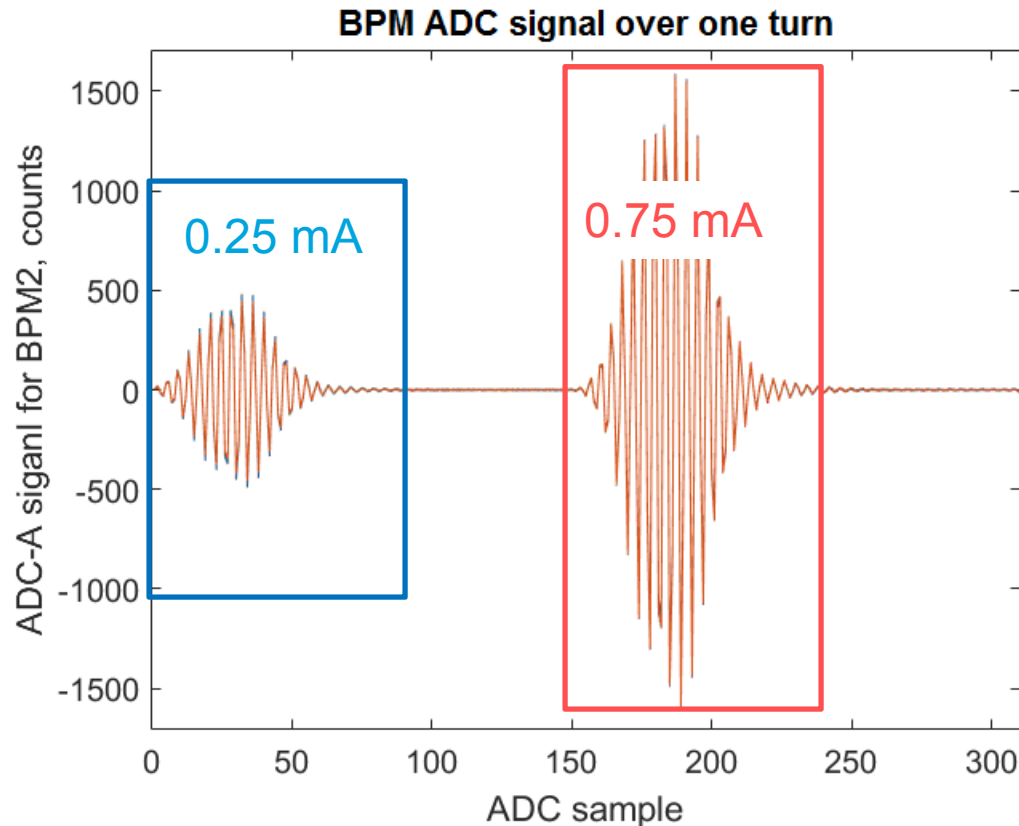
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Several measurements have been tried with promising results:

- ✓ Tune shift with current
  - ✓ Probing impedance of a scraper
  - ✓ Synchrotron tune shift with current with “RF-ping”
  - ✓ Instability studies
  - ✓ Beam lifetime studies
  - ✓ Tune shift with amplitude
- 
- The diagram consists of five horizontal blue arrows pointing to the left, arranged vertically. A blue bracket on the right side groups the first three arrows together, with the text 'This talk' to its right. The last two arrows are not grouped.

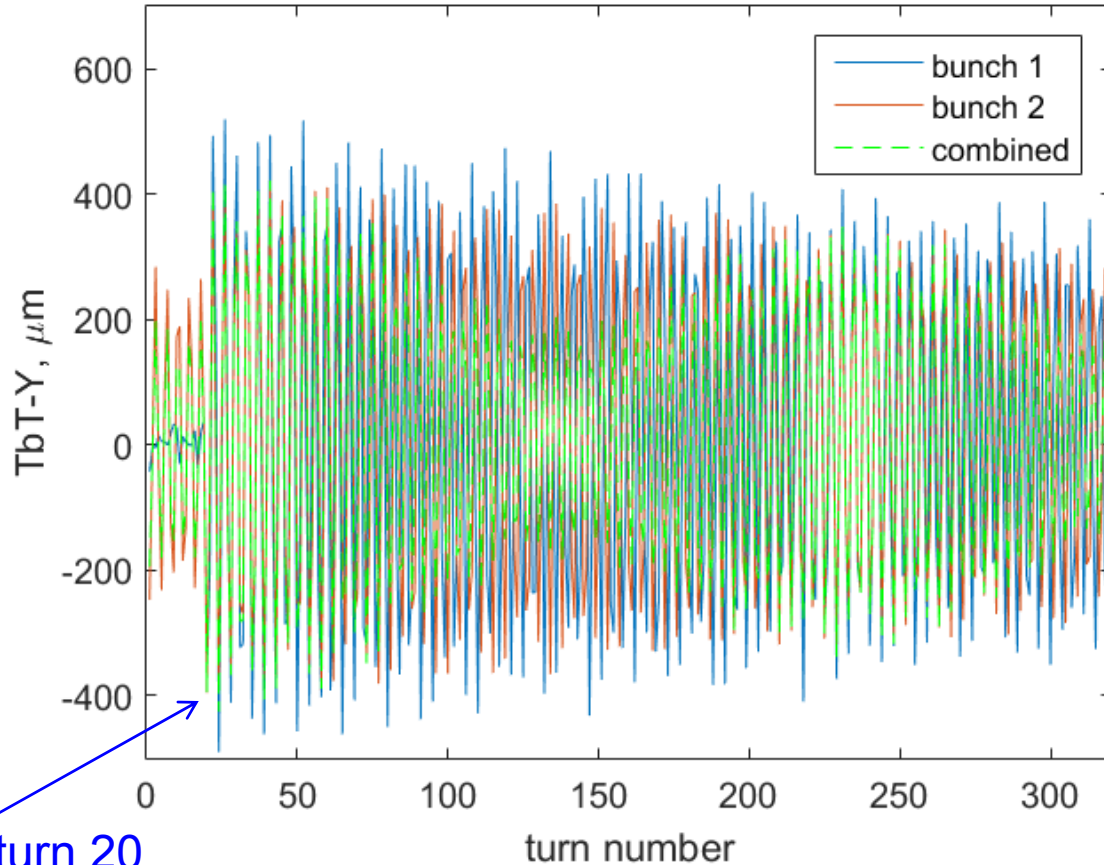
More are in the works ...

# Unequal Charge Bunches Kicked with a Pinger



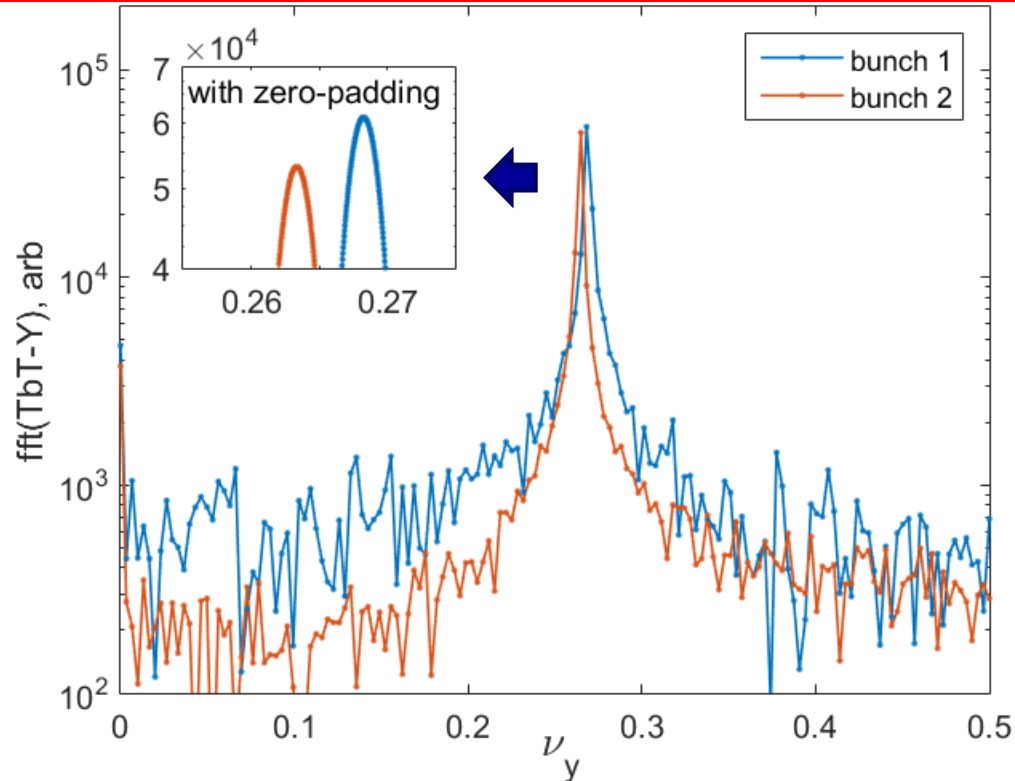
- Two bunch fill with unequal bunches
- Pinger timing adjusted for equal vertical kick
- ADC data processed to get separate TbTs for each bunch

# Turn-by-Turn Signals



- Each bunch decays a long time, but the combined shows beating
- Also instability for high current bunch before the ping

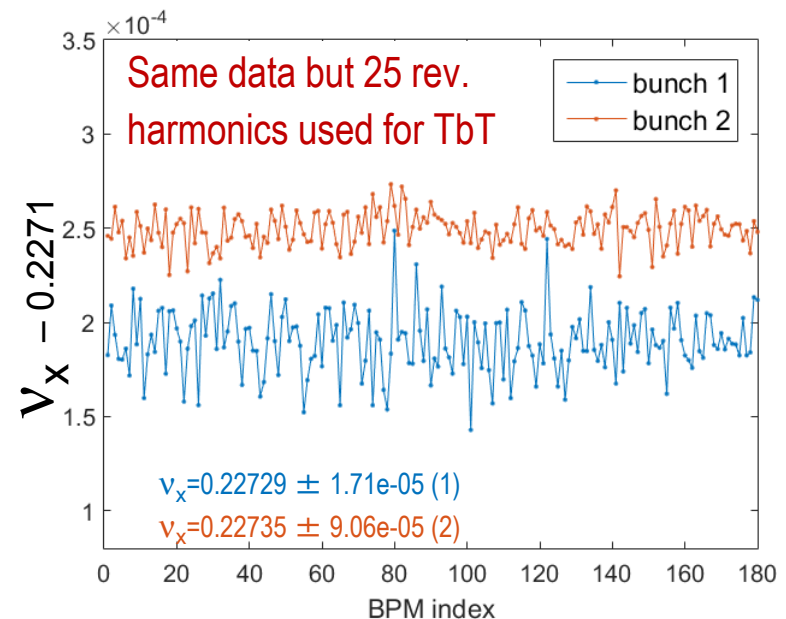
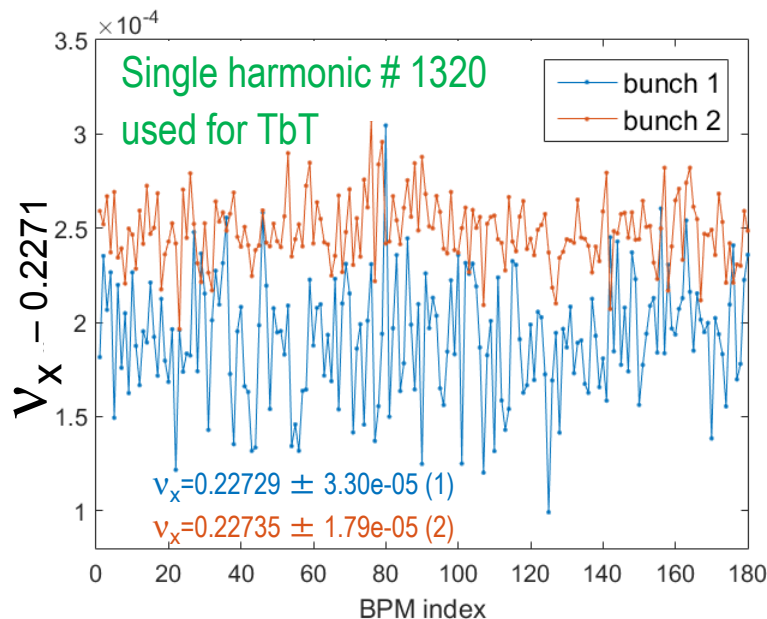
# Tunes are Distinctly Different



- Single BPM FFT shows tunes are clearly unequal
- Detailed analysis with interp'd FFT for 180 BPMs gives  
 $\nu_y = 0.26833 \pm 1.93e-5$  (bunch 1) and  $\nu_y = 0.26334 \pm 6.90e-6$  (bunch 2)
- Tune difference of  $5e-3/(0.5 \text{ mA})$  is consistent with other measurements

# Same Measurement in the Horizontal

- Same two bunches, 0.25 mA (1) and 0.75 ma (2), use hor. pinger
- ADC data processed to get separate TbTs for each bunch



$$\Delta v_{21} = (6.0 \pm 3.8) \cdot 1e-5$$



$$\Delta v_{21} = (6.0 \pm 0.9) \cdot 1e-5$$

- Resolution improvement (est. x4) has helped; now convincingly show that hor. tune goes up with current (i.e. total wake is slightly focussing).

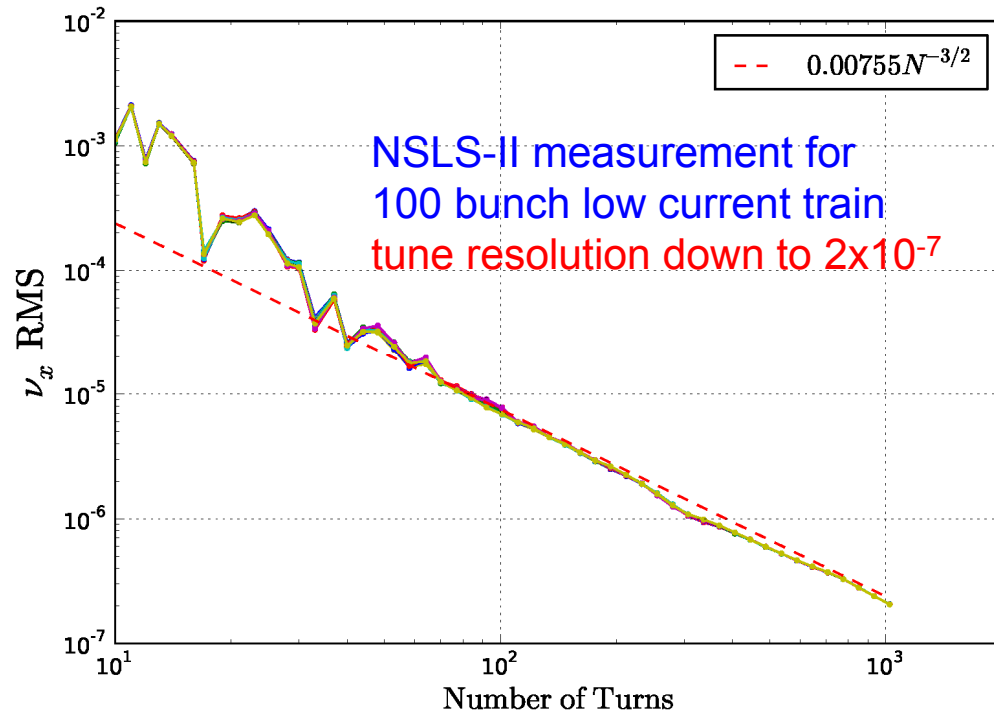
# From Accurate Tune Difference Measurement to Coupling Impedance

Kick factor definition, relation to effective coupling impedance and measurement via tuneshift with current:

$$\langle x' \rangle = \frac{Q_b}{E/e} k_{kick} \langle x_0 \rangle$$

$$k_{kick} \propto \int |\tilde{\rho}|^2 \text{Im}[Z_x(\omega)] d\omega$$

$$\delta\nu(Q_b) = -k_{kick} Q_b \frac{\langle \beta_x \rangle}{4\pi E/e}$$



resolve tunes to  $10^{-6}$

$$\delta k_{kick} = 4\pi \overbrace{\delta(\nu_{low Q_b} - \nu_{hi Q_b})}^{\text{resolve tunes to } 10^{-6}} \frac{E/e}{\Delta Q_b \langle \beta_x \rangle}$$

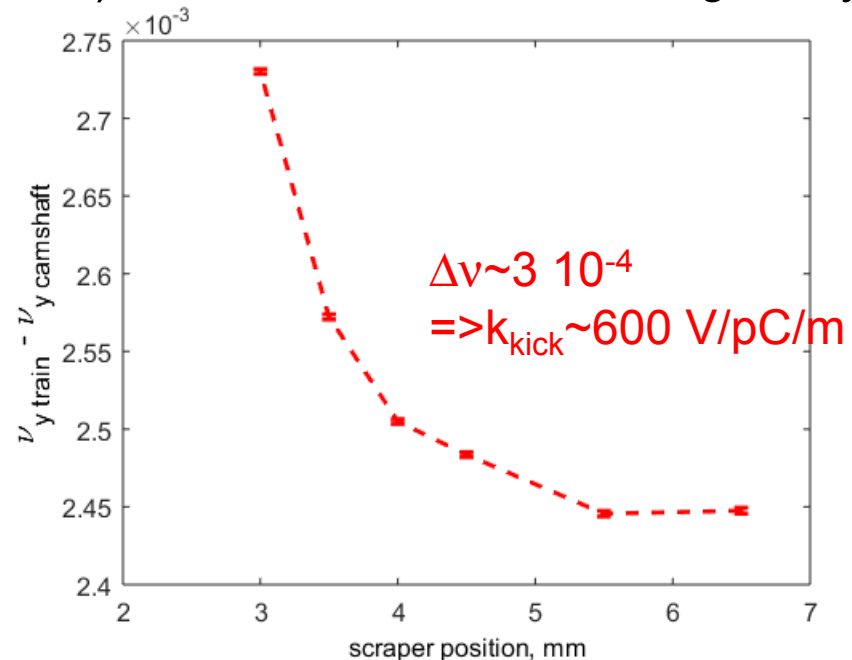
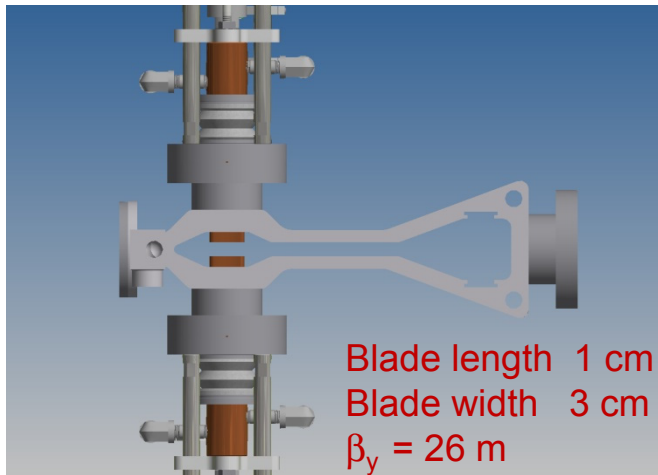


get kick factors as low as 10 V/pC/m\*

\*assumed 1 nC,  $\beta=4$  m, 3 GeV

# Local Impedance Measurement: Vertical Scraper

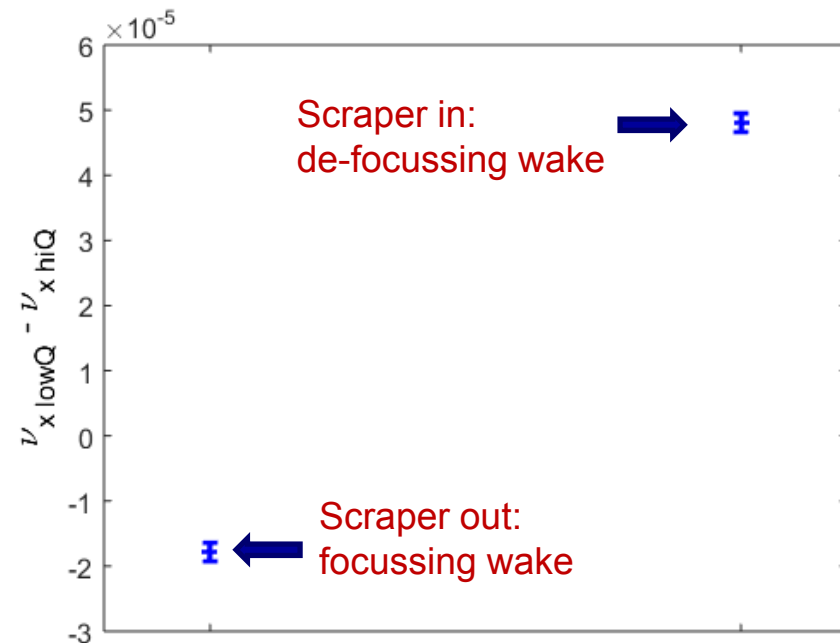
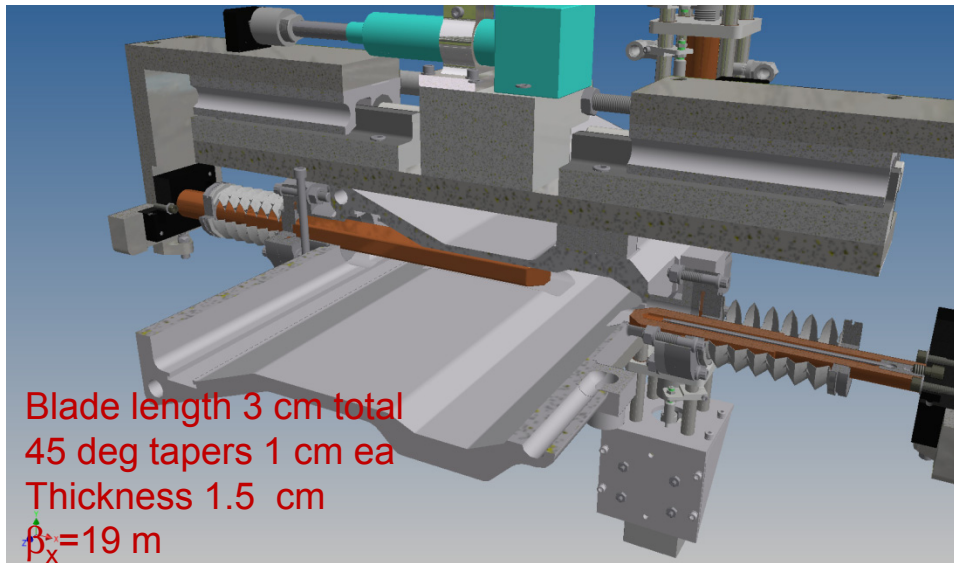
- Measure tune difference between low- and high-Q bunches
- Repeat with the scraper inserted
- Change in the tune difference is due to (added) scraper impedance
- 1.4 mA 100 bucket train (reference) + 0.3 mA camshaft ½ ring away



- Complimentary measurement would be from closed orbits (no kick), TBD

# Horizontal Scraper

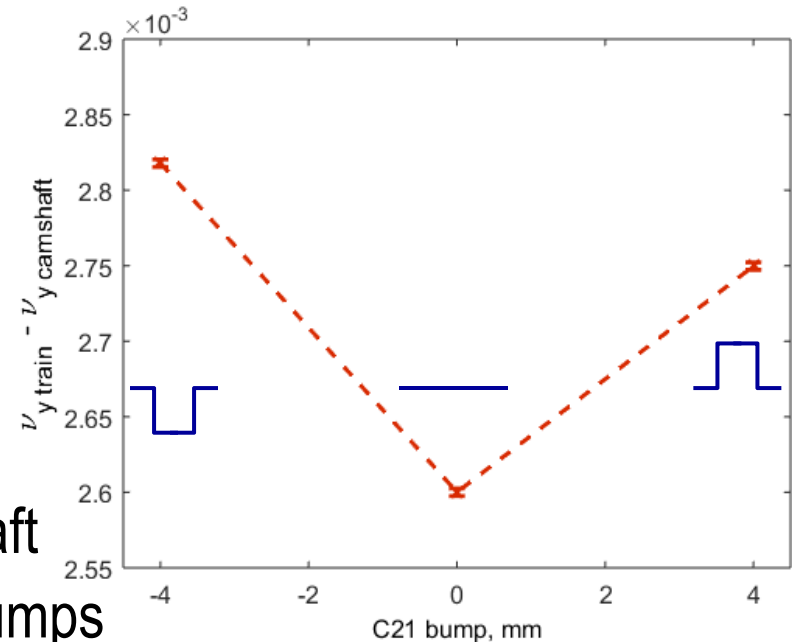
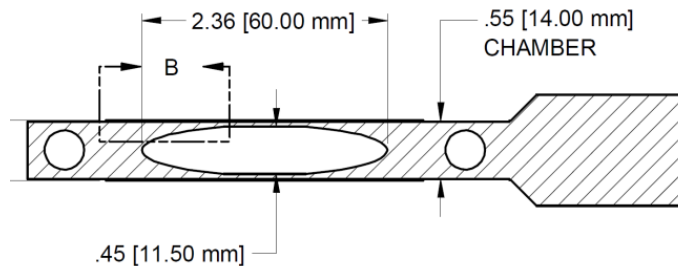
- Two bunches stored, inner blade moved in
- Change in the tune difference is due to (added) scraper impedance



- With scraper blade close to the beam, tune-current slope changes to negative (agrees with expectation)

# Measure Low- $\beta$ Insertion Device Chamber

- Example of a fixed impedance component, use local bumps to probe  $Z$
- Cell 21 has two EPU's (out-of-vacuum)
- Vacuum chamber is Al pipe, 4.8 m length,  $\beta_{y0}=1.2$  m, resistive wall is expected to dominate, RW kick factor **56 V/pC/m** at  $\sigma_{\tau}(0.3\text{mA})=16.2$  ps measured separately

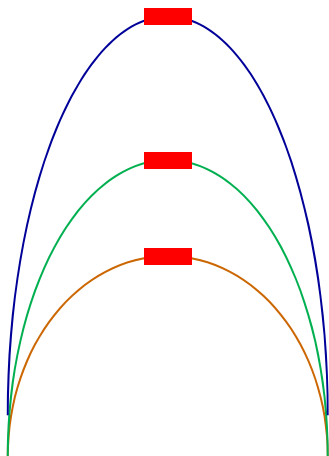


- Injected 1.4 mA train + 0.3 mA camshaft
- Camshaft decayed some during the bumps
- Measured kick factor of **210 V/pC/m** tune is about x4 higher than the theory for Al but is likely due to NEG coating

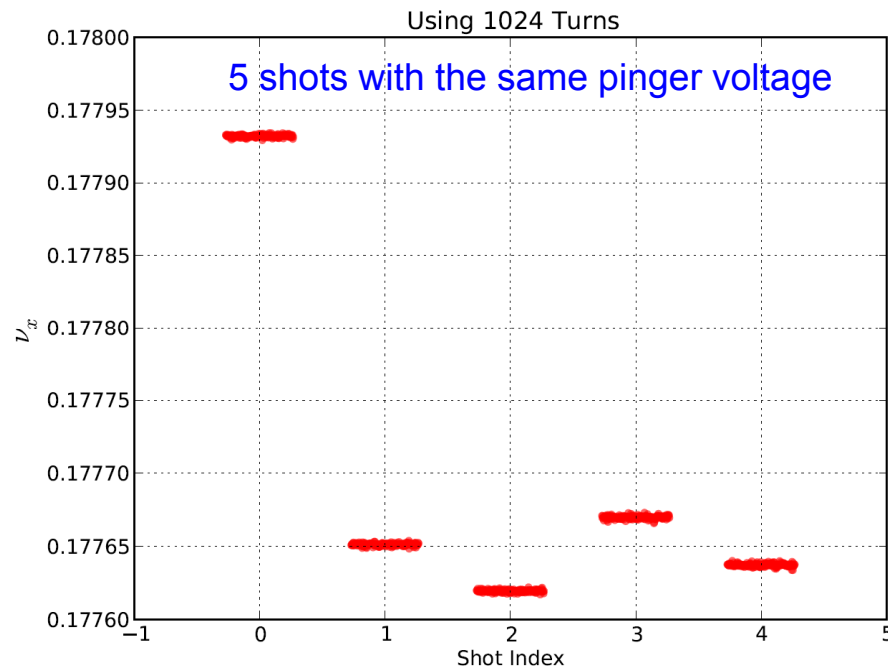
# Measurement of Tune Shift with Amplitude

## Conventional measurement:

- Use short bunch train at low current
- Vary pinger voltage
- Record multiple TbT data sets



Issues: kicker jitter, machine drifts

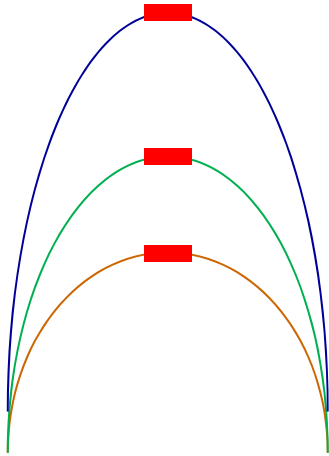


Tune jumps without anyone touching the pinger or anything else in the machine

# Single Shot Measurement of Tune Shift With Amplitude

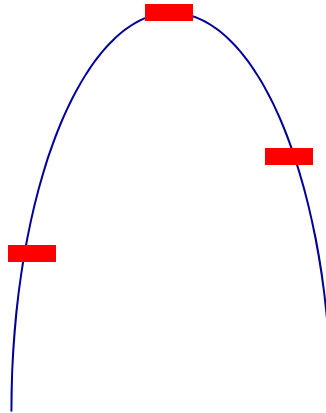
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Conventional measurement



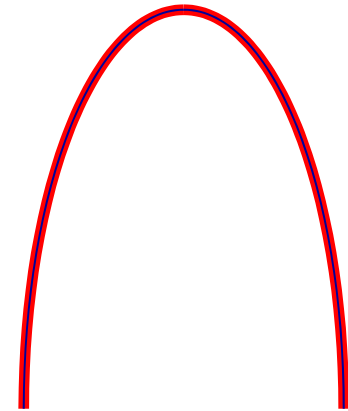
Kicker jitter, machine drifts

New option



Max. # of trains / turn

Alternative new option

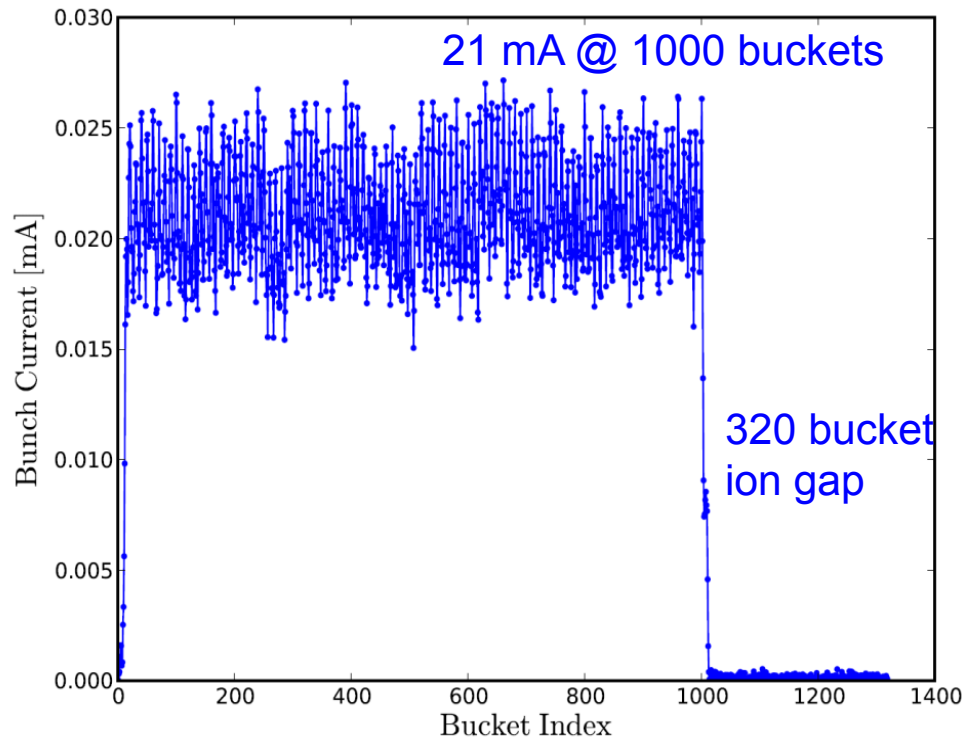


?

The rest of this talk

# Measurement Setup

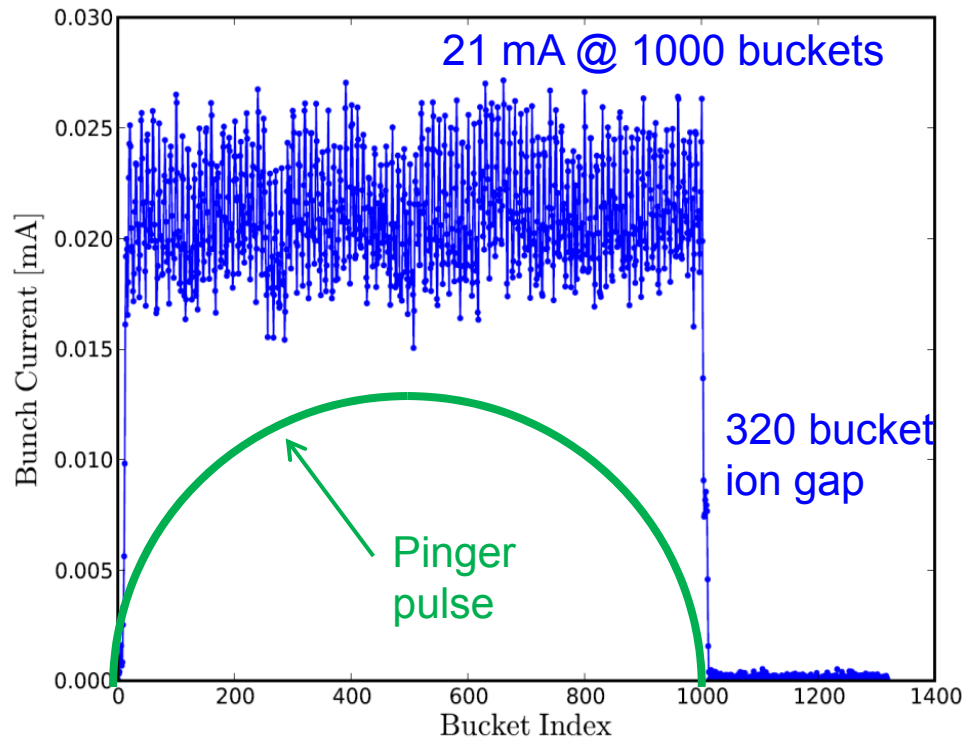
- Fairly uniform fill pattern at low current (no collective effects !)



- Adjust pinger timing to center maximum kick in the middle
- 11 sample wide ADC window (~47 RF buckets); slide over the turn
- Results independent of window width when it's  $\ll$  kicker rise time

# Measurement Setup

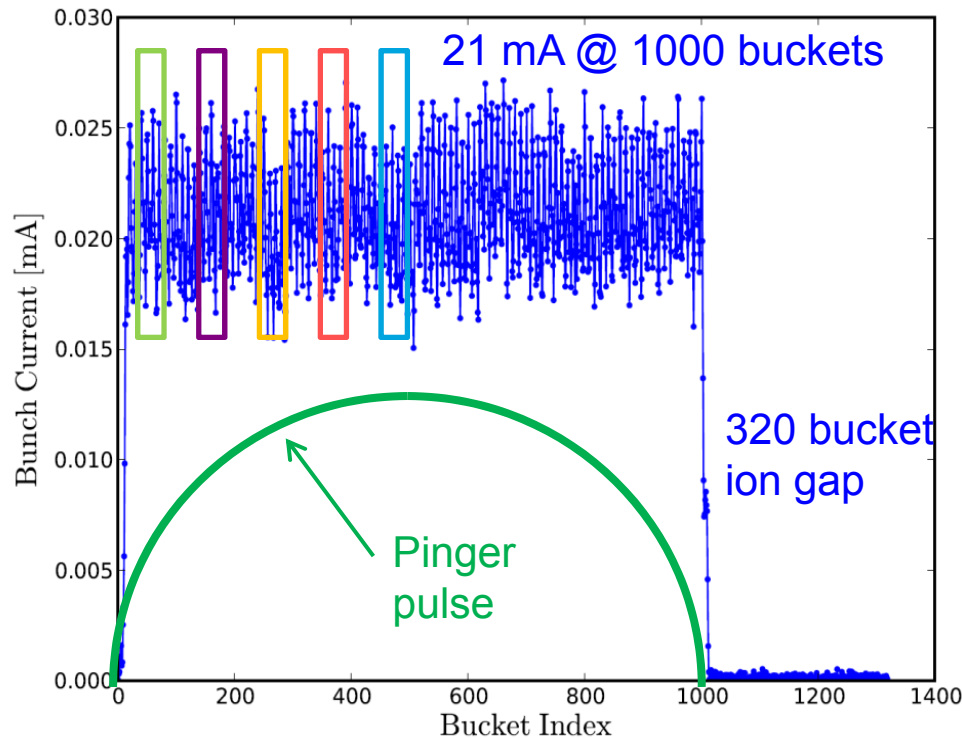
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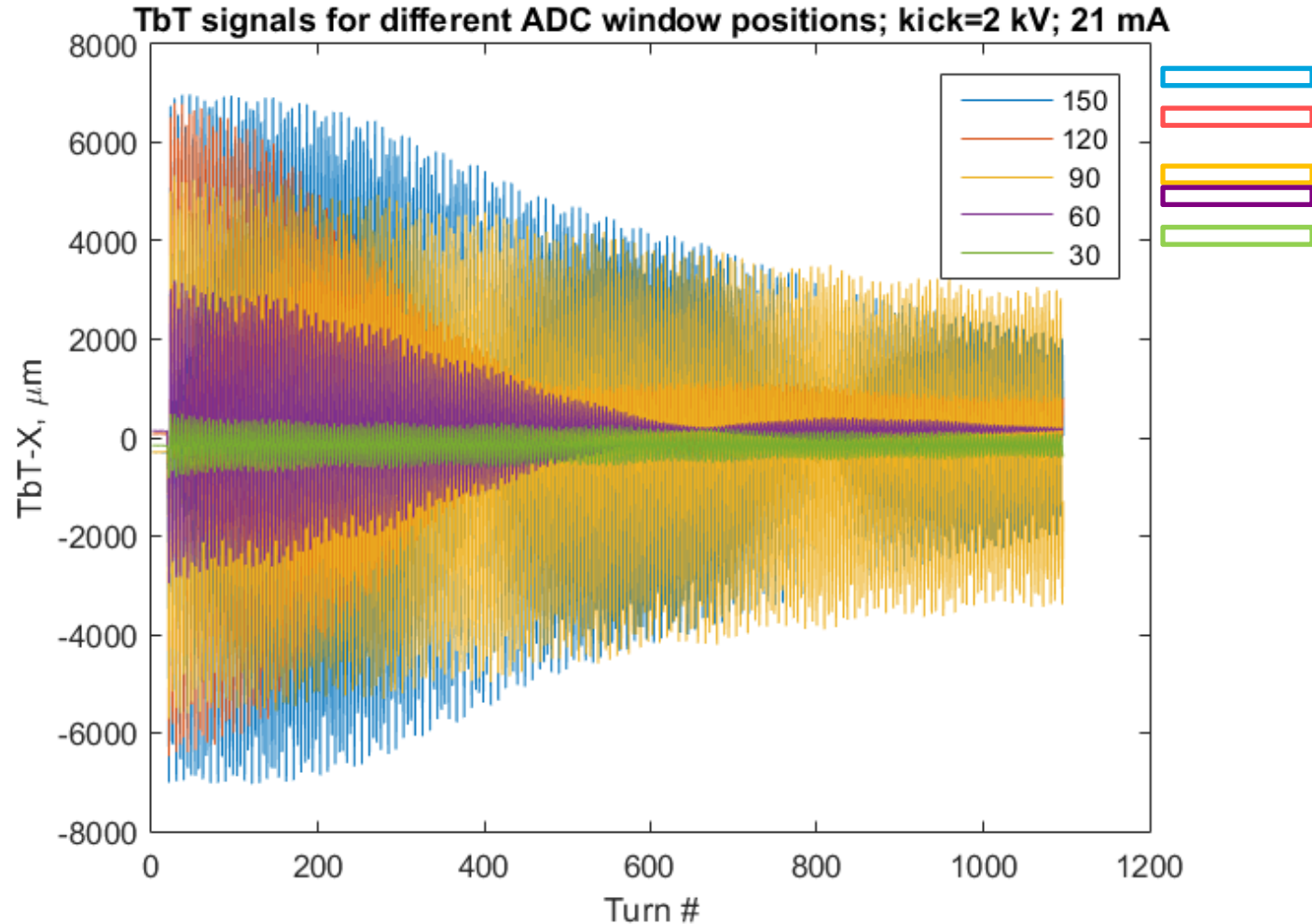
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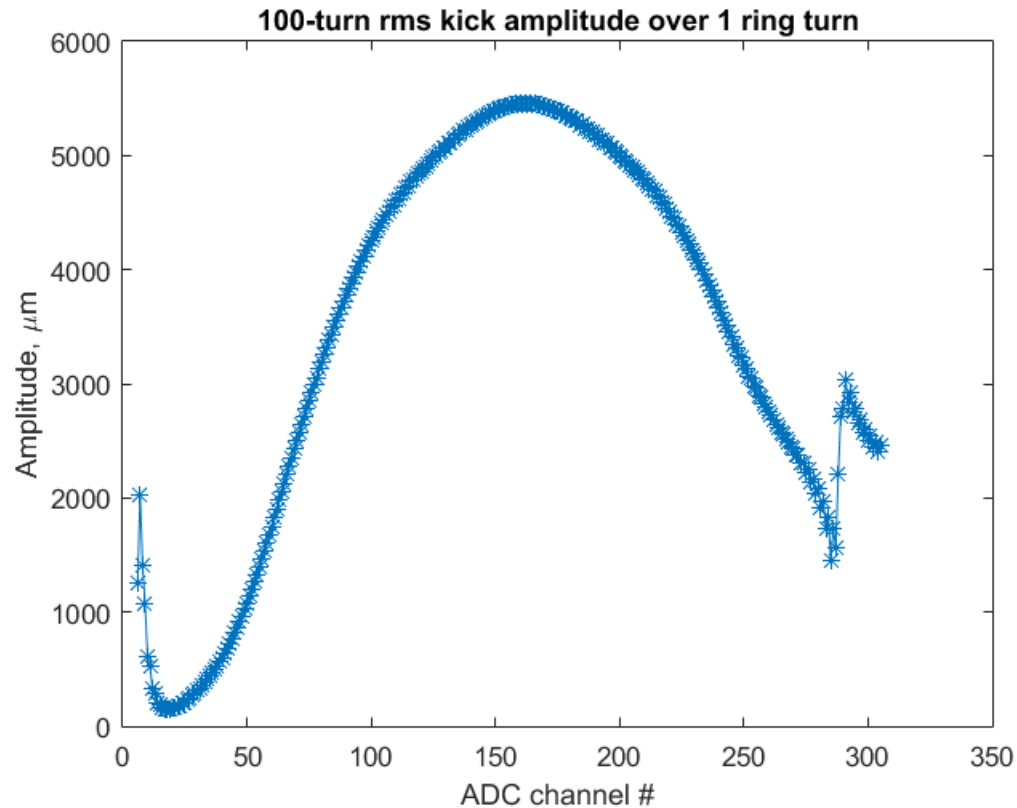
# TbT Signals from Selected ADC Bins



- Induced amplitudes vary according to bin position wrt. pinger
- Short chunks of the bunch train can be resolved!

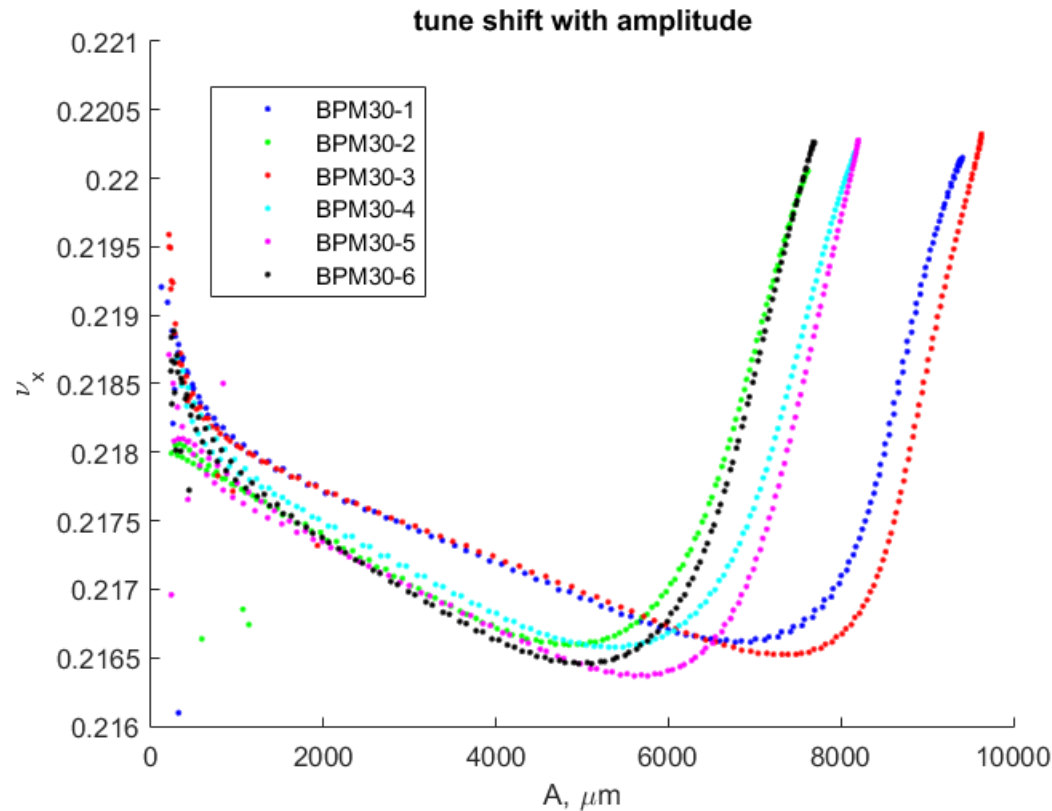
# Amplitudes for All ADC Bins Together

- Recover the shape of pinger pulse



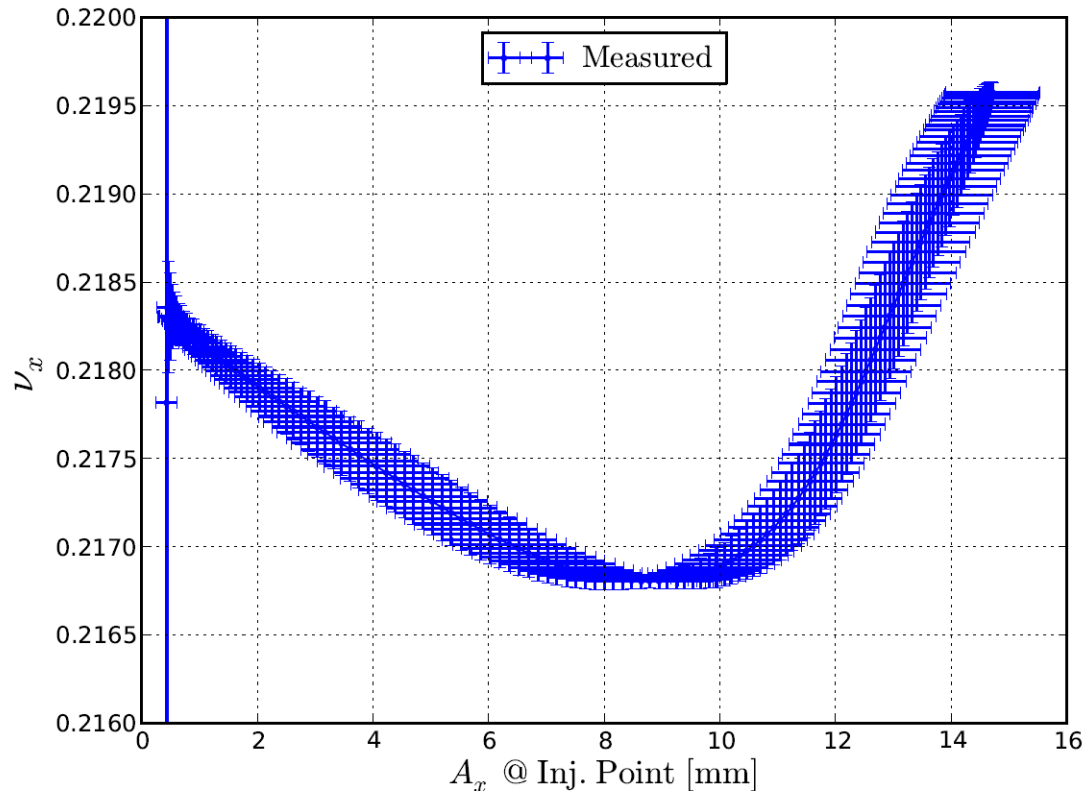
- Except at the head (there is no kick) and near the ion gap

# Tune Shift with Amplitude: 6 BPMs



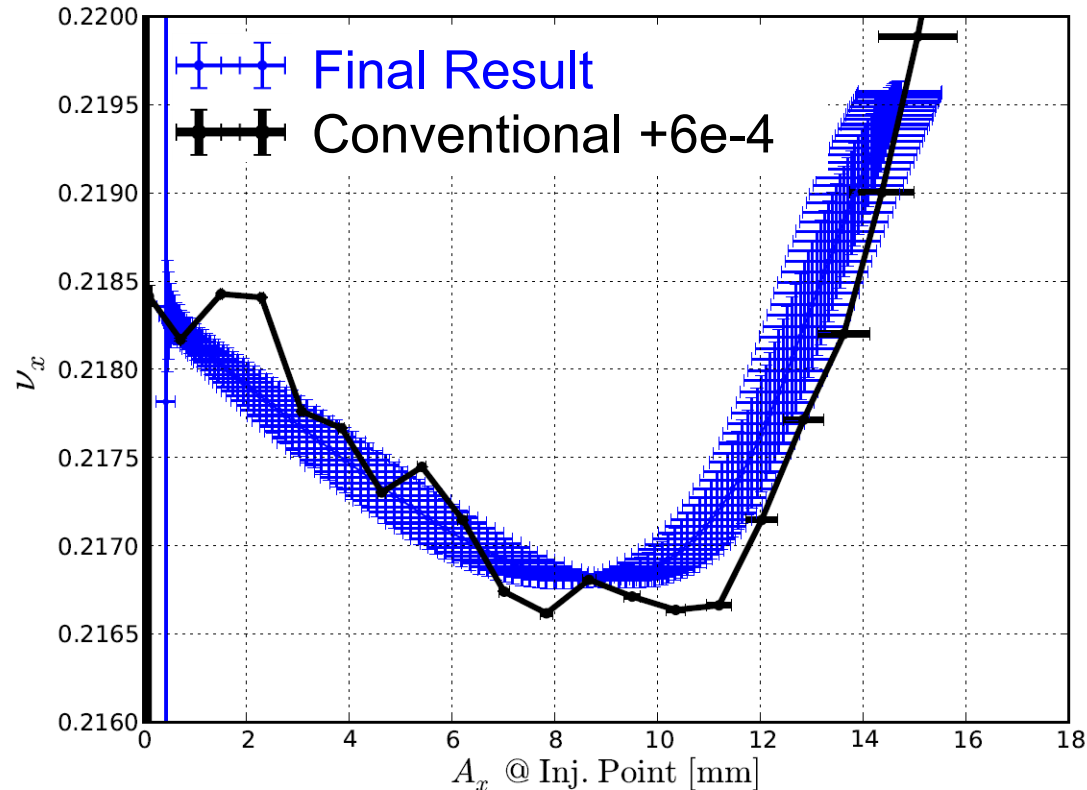
- Smooth curves except at very low amplitudes
- Other cells look very similar
- From here: scale to injection point; error-bars from all 180 BPMs

# Final Results: Horizontal



- Final result for 5mA/1000 bunches, single pulse of 2 kV
- Conventional measurement: 2 mA/100 bunches; 20 separate “pings”; clear pulse-to-pulse jitter, longer term drifts are likely
- Further optimization of new technique possible

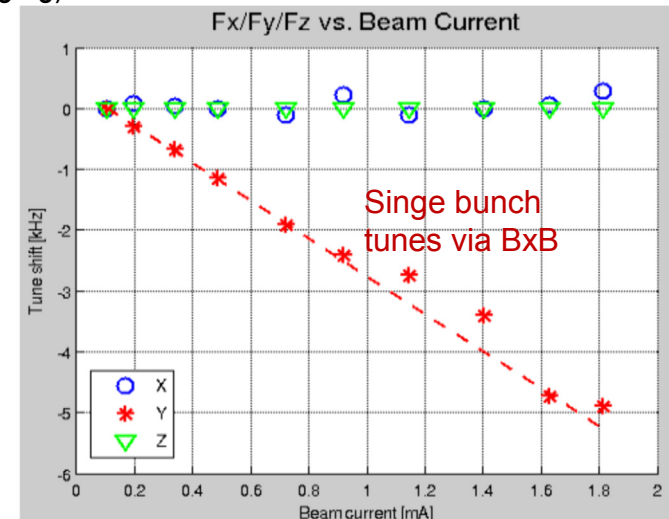
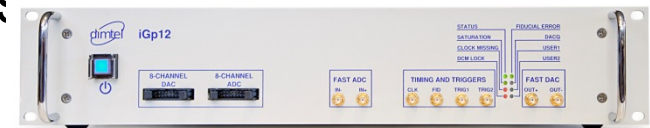
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# Can These Measurements be Improved by Bunch-by-Bunch Feedback?

- NSLS-II uses commercial bunch-by-bunch (BxB) feedback system
- Some of the measurements presented are also possible through this system or in combination with gated RF BPMs
- BxB Cons (for these measurements)
  - Single BPM (no closed orbit, etc., no gains from BPM-to-BPM averaging)
  - Less accurate tune measurements so far ...
  - Lower BPM positional resolution (due to higher BW)
  - Stripline kick strength is limited, no longitudinal kicker
- BxB Pros
  - True bunch-by-bunch TbT
  - Potentially more accurate tune measurement
  - Better sensitivity at low beam current
  - Direct longitudinal position measurement
- Combined measurements (i.e. external kick + BxB tune or BxB single bunch PLL tune tracker + gated RF BPM TbT) are in the works.



# Conclusions and Future Plans

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- Single-bunch resolution of NSLS-II BPMs was recently improved by an order of magnitude to about one micron TbT at  $\sim 1$  nC/bunch. Plus we can now resolve TbT signals from several bunches stored in the ring.
- Having this capability on all NSLS-II RF BPMs is extremely valuable for sensitive collective effect or single particle dynamics measurements. It allows us to simultaneously measure bunches with different charges (or kick amplitudes) thus eliminating harmful effects of machine drifts.
- We presented some novel accelerator physics measurements enabled by these new BPM capabilities. These include a new technique of probing the ring impedance, single-shot tunes shifts with amplitude, etc.
- More studies are in progress; some will include BxB feedback system.
- ADC processing is presently done off-line but is being implemented in FPGA, so that improved resolution, and multi-bunch capability will be available in real time.

# Conclusions and Future Plans

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- Single-bunch resolution of NSLS-II BPMs was recently improved by an order of magnitude to about one micron TbT at  $\sim 1$  nC/bunch. Plus we can now resolve TbT signals from several bunches stored in the ring.
- Having this capability on all NSLS-II RF BPMs is extremely valuable for sensitive collective effect or single particle dynamics measurements. It allows us to simultaneously measure bunches with different charges (or kick amplitudes) thus eliminating harmful effects of machine drifts.
- We presented some novel accelerator physics measurements enabled by these new BPM capabilities. These include a new technique of probing the ring impedance, single-shot tunes shifts with amplitude, etc.
- More studies are in progress; some will include BxB feedback system.
- ADC processing is presently done off-line but is being implemented in FPGA, so that improved resolution, and multi-bunch capability will be available in real time.

**Thank you**

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