# Beam Dynamics Measurements with New Generation BPMs

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**BES Light Sources Beam Stability Workshop, ALS, LBNL**

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Office of Science
U.S. DEPARTMENT OF ENERGY

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# Motivation

Why (electron) beam dynamics at Beam Stability Workshop?

- Majority of users are happy with present stability levels.
- Looking into the future: diffraction-limited light sources with tiny beams.
- Plan on running above collective instability thresholds (counting on self-stabilizing or feedback-controlled instabilities).
- Understanding collective and nonlinear single-particle dynamics and, increasingly, their interplay, is crucial for stably running an advanced light source.
- Sophisticated measurements are need to confirm/refine machine model.
- Some of these measurements are done at low current, non-standard fill patterns and without feedbacks. Stability is often a limitation.
- Beam dynamics is reach and exciting subject.

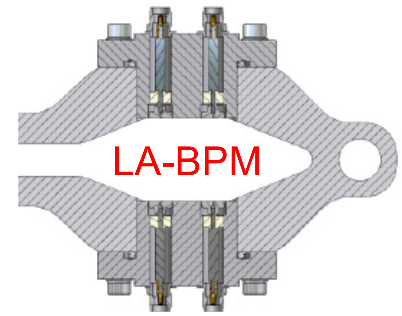
# Outline and References

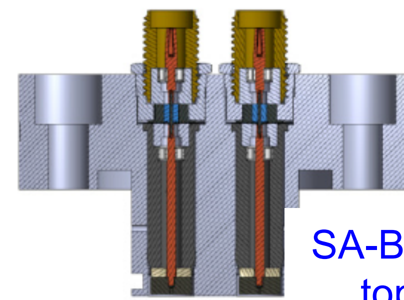
- A bit about NSLS-II BPMs
- How these enable delicate beam dynamics measurements
- Measurement examples
- Conclusions


- B. Podobedov, W. Cheng, K. Ha, Y. Hidaka, J. Mead, O. Singh, K. Vetter, IPAC2016, WEOBB01
- B. Podobedov, W. Cheng, Y. Hidaka, D. Teytelman, IBIC2016, TUCL02
- Y. Hidaka, W. Cheng, B. Podobedov. NAPAC2016, MOA2CO03

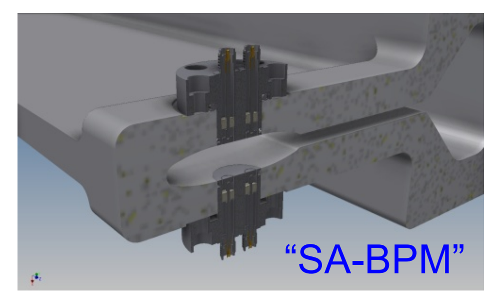
# NSLS-II BPM Pickups

- NSLS-II: 30 cell DBA 3 GeV ring with 1 nm / 8 pm design emittances, smallest beam size 3 $\mu$m rms (y)
- Beam stability of paramount importance for users
- NSLS-II is equipped with a large number of high-performance BPMs (~240 at present)



SA-BPM top

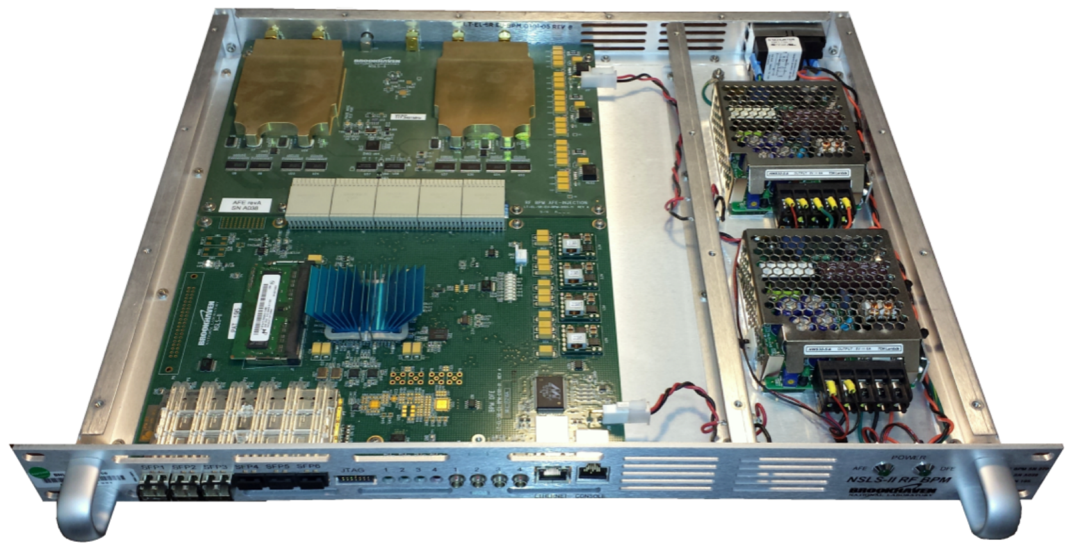



Real SA button assemblies are rotated around the vertical

| RF BPM Types | Quantity |
|---|---|
| Multi-Pole Chamber BPMs (LA)<br>Large Aperture (25 mm vert.) | 6 per cell<br>180 Total |
| Insertion Device (ID) Chamber BPMs (SA)<br>Small Aperture (8-11.5 mm vert.) | 2-4 per ID straight<br>~30 Total (now) |
| Special BPMs (injection, BxB fdbk, test, ...) | ~10 |

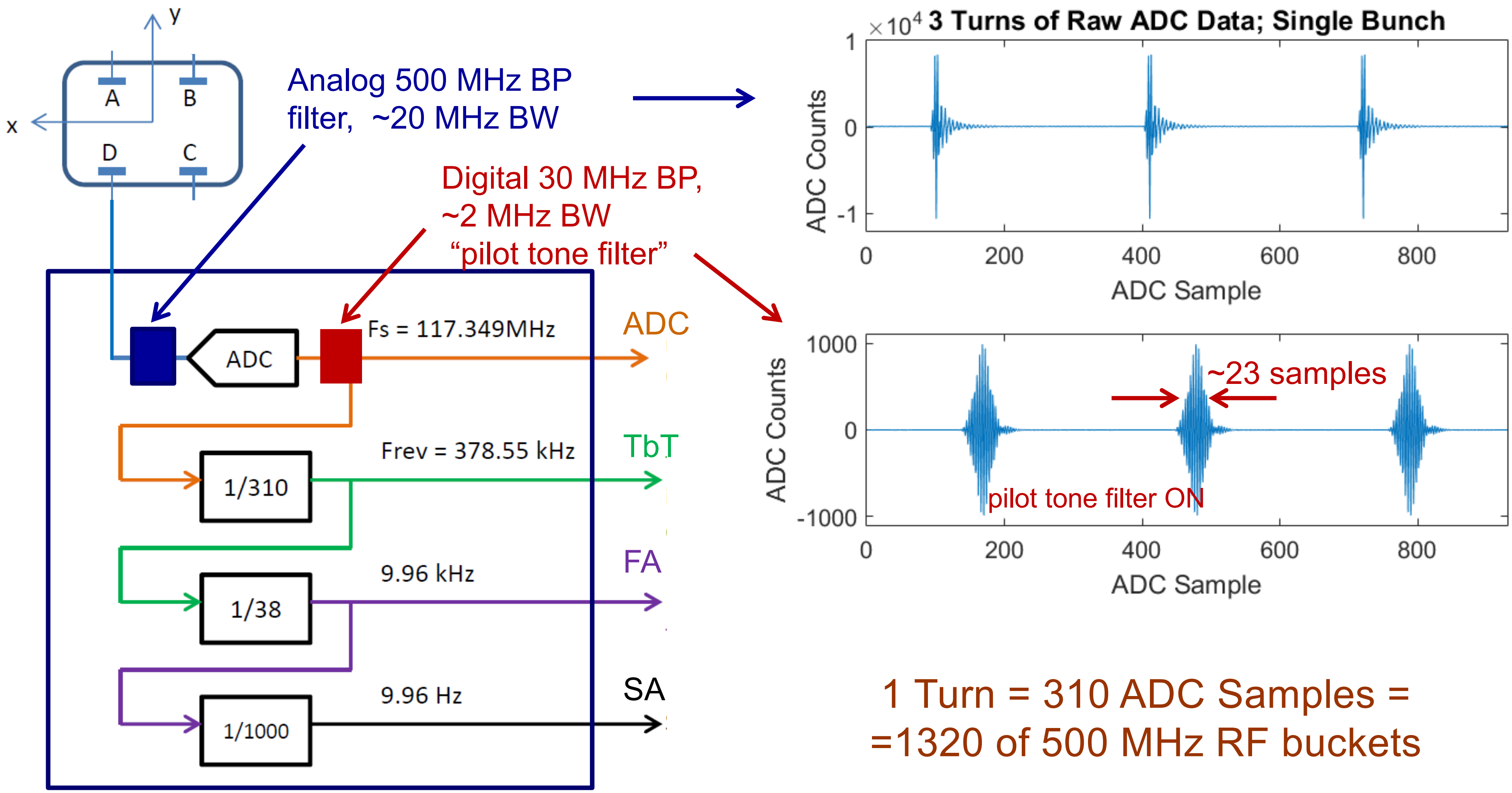
# NSLS-II BPM Receivers

| 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 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. 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 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 $\mu$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
- Recently added bunch-by-bunch capability (to resolve bunches within a turn)

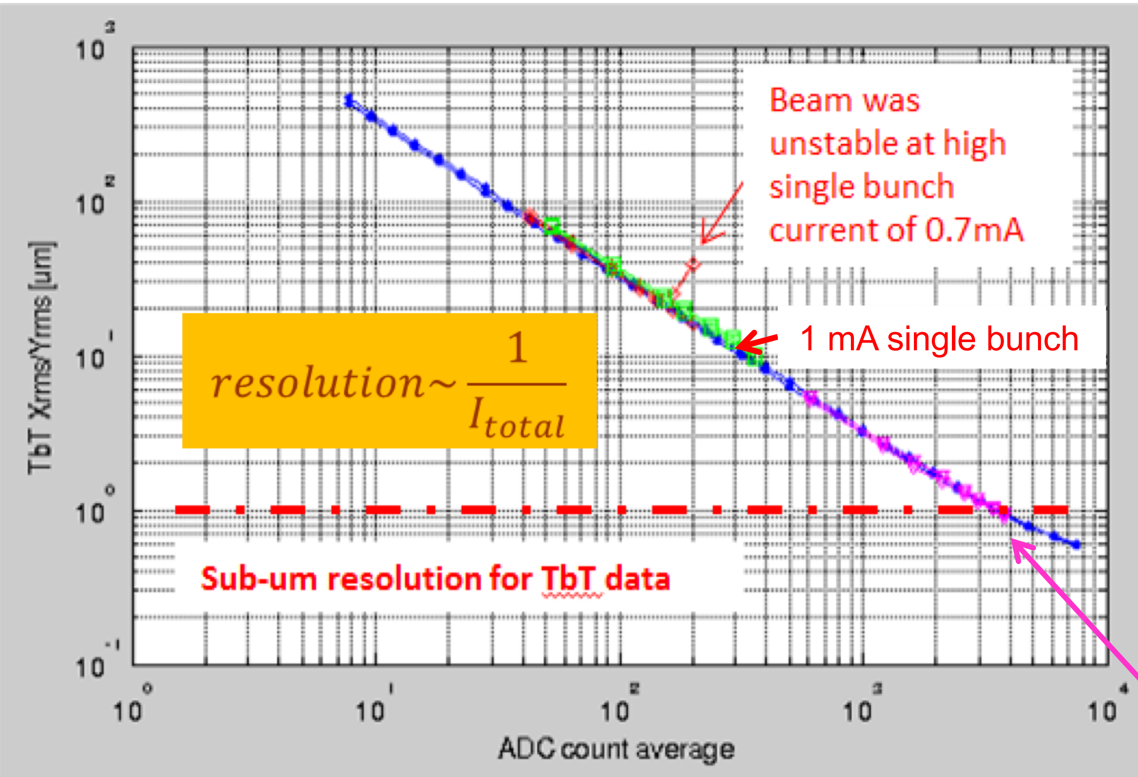
# NSLS-II BPM Signal Processing




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

- TbT X, Y, and Σ are obtained (in FPGA for Ops, or Matlab for studies) from ADC signals by coherent signal processing locked to revolution harmonic.

# NSLS-II BPM Turn-by-Turn Resolution



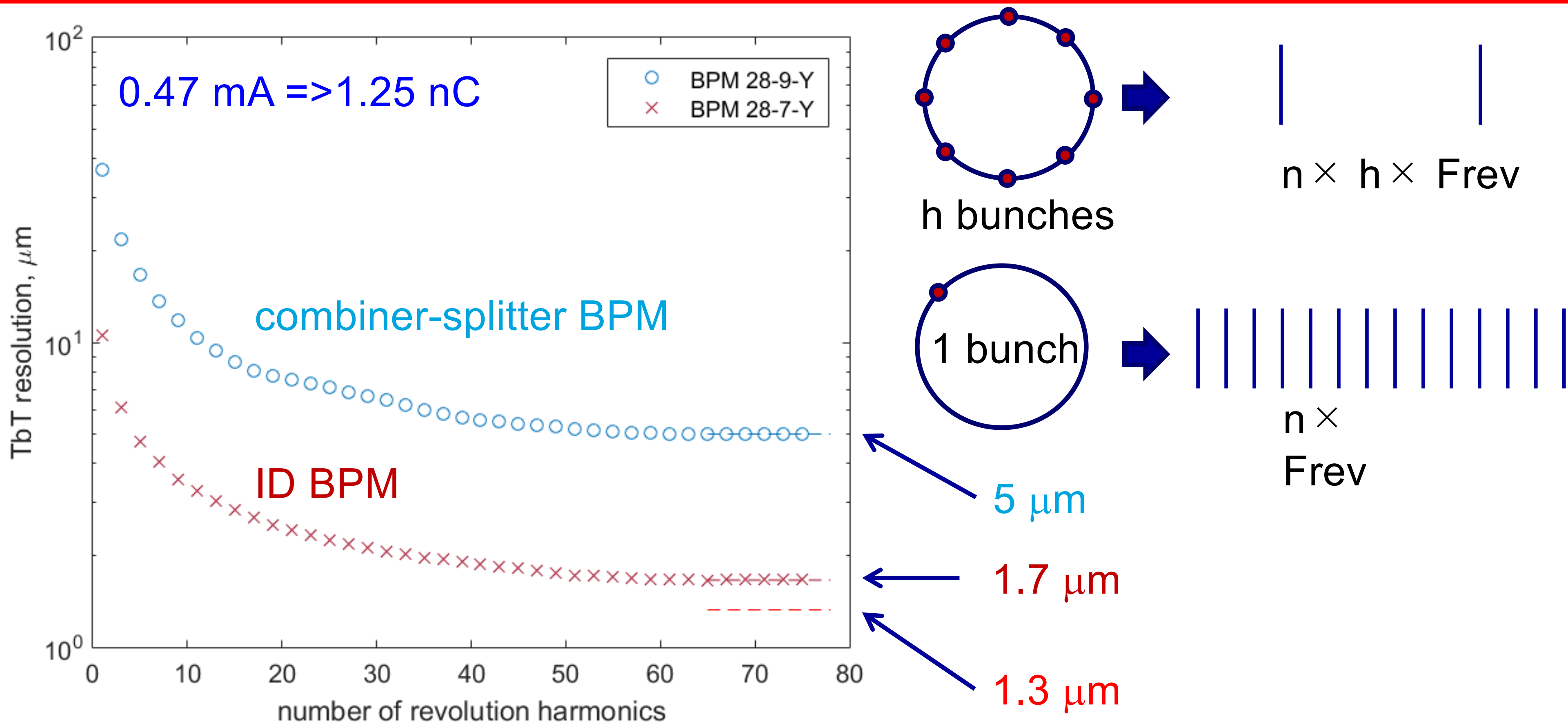

W. Cheng et al., IBIC'15

- 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

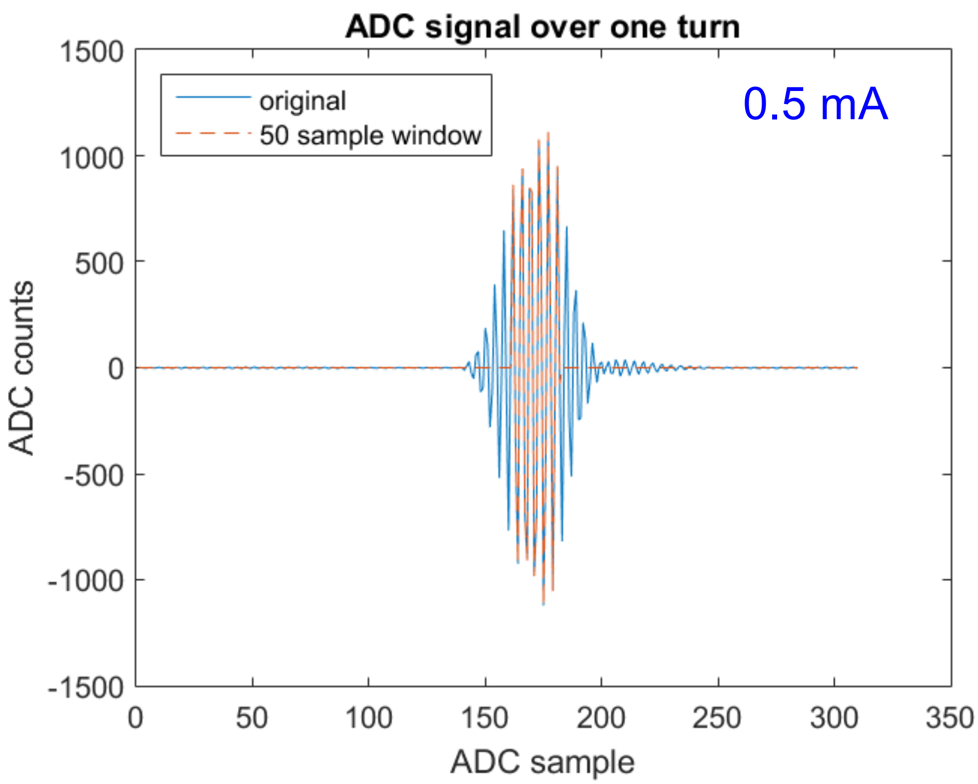
# Resolution Improvement by Including Multiple Revolution Harmonics

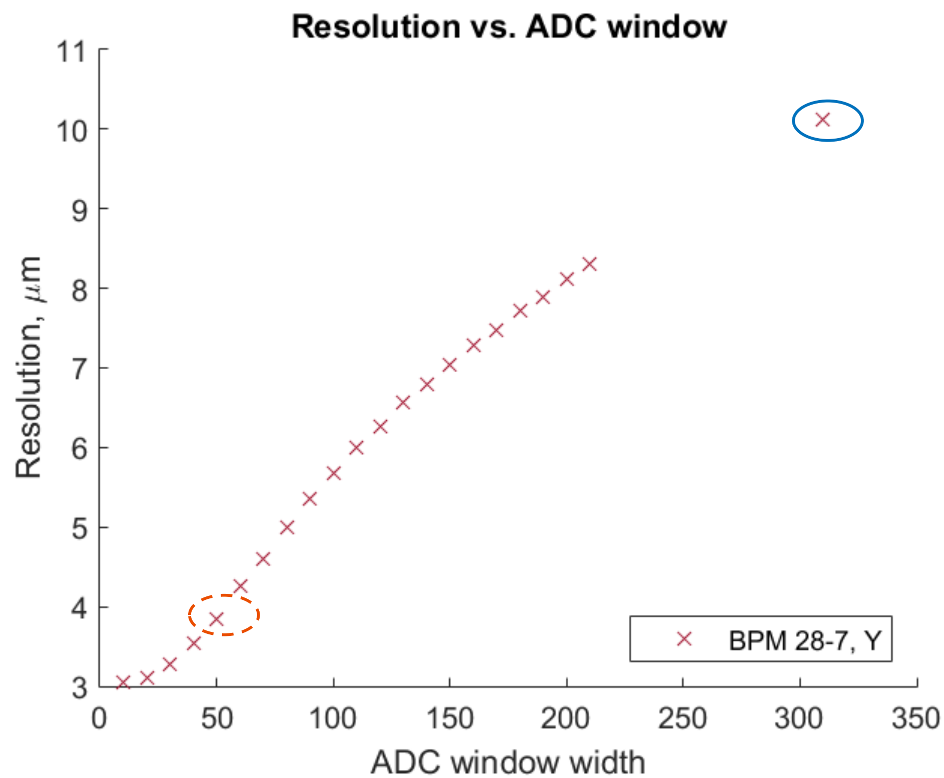



- Without pilot tone filter the number of in-band harmonics is higher =>resolution improvement of about factor of 7.
- On ID BPMs directly measured resolution reaches 1.7 μm, or 1.3 μm when scaled from combiner-splitter BPM.

# Resolution Improvement by Gating BPM ADC Signals

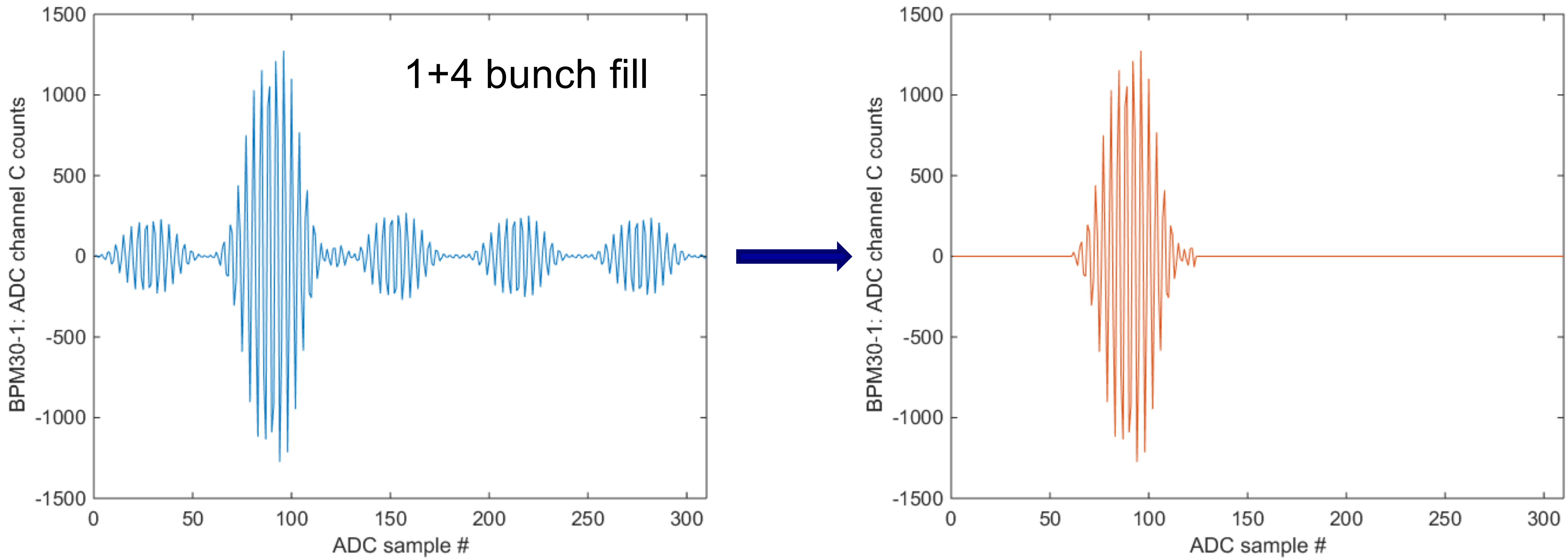
- Standard BPM processing looks at all 310 ADC channels (i.e. entire turn)
- Let's use only the ADC channels that contain most of the single bunch signal (i.e. apply a boxcar window on every turn)




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

# From Gating ADC Signals to Resolving Individual Bunches within a Turn



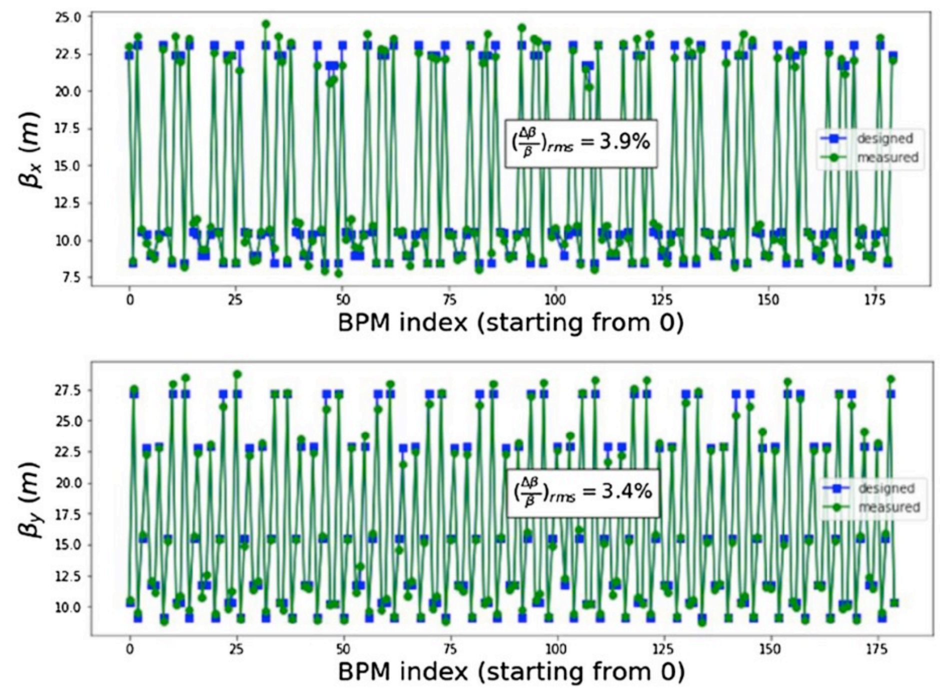

- Gate-out signals from all but one bunch (on every turn)
- Include enough harmonics of Frev
- Use standard processing to extract X, Y, Σ from these modified ADC data
- Repeat for each bunch
- We can resolve up to 8 bunches, depending on experiment

# We can resolve few separate bunches on every turn, with good resolution, so what?

- This enables precise beam dynamics measurements
- Two examples to follow:
  - Tune shift with current (for collective effects)
  - Tune shift with amplitude (for single-particle dynamics)

- Many other applications, incl. some that directly benefit stability =>

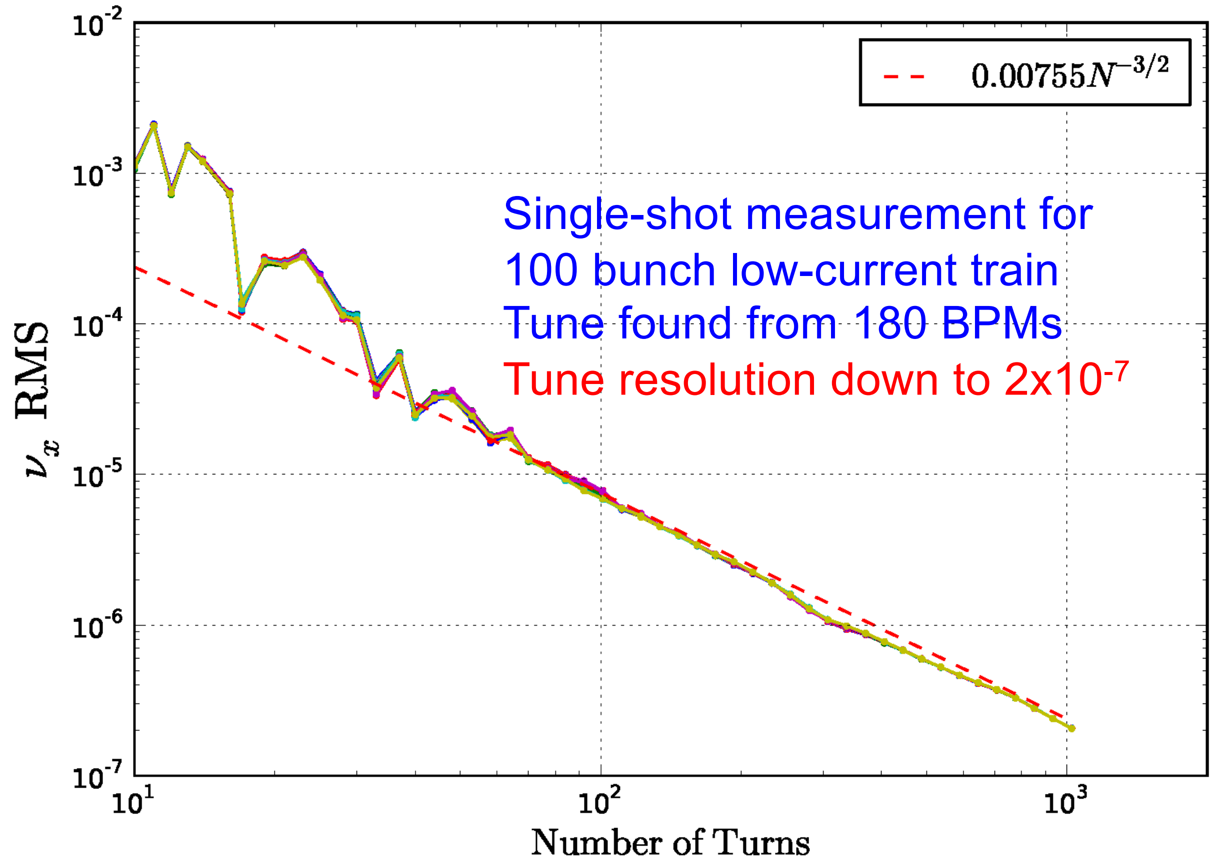
Lattice functions measured from camshaft bunch with user beam in the ring




Weixing Cheng*, Kiman Ha, Yongjun Li, Boris Podobedov

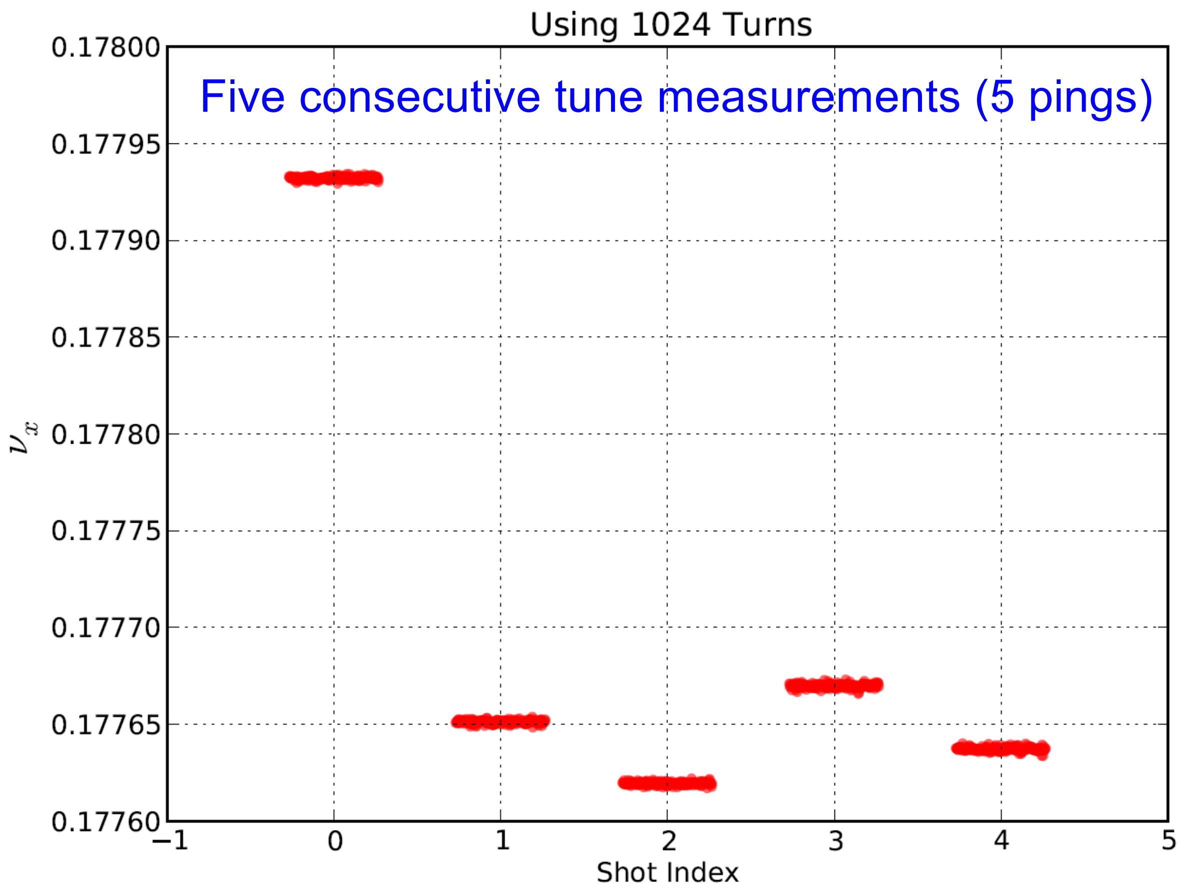
MethodsX 5 (2018) 626–634

# ~$10^{-7}$ Tune Resolution has been Demonstrated




**But only for a single-shot (and low-current bunch train)**

# Shot-to-Shot Tune Stability is Much Poorer



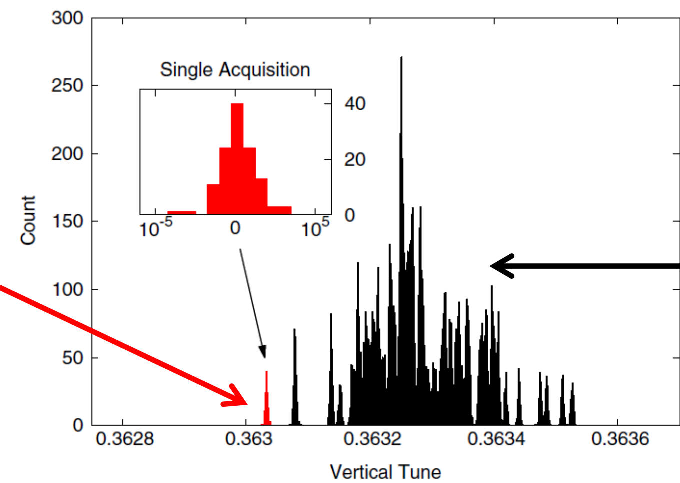

Tune jumps without anyone touching the pinger or anything else in the machine

- At NSLS-II typical (shot-to-shot) tune jitter is >10-4 (rms)
- This would normally preclude any sensitive measurements that rely on better tune resolution (including impedance)

# Shot-to-Shot Tune Jitter is a Common Obstacle for Impedance Measurements

Example from ALBA LS:
120 Libera BPMs
100 acquisitions (shots)

Single-shot tune rms=2.1 × 10$^{-6}$




100-shot tune rms=1.1 × 10$^{-4}$

FIG. 3. Histogram of the vertical tune measured by 120 BPMs for 100 acquisitions. The measurement shows an overall standard deviation of $1.1 \times 10^{-4}$, on the other hand looking at one single acquisition (in red) the spread is strongly reduced presenting a standard deviation of only $2.1 \times 10^{-6}$.

PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 121002 (2016)

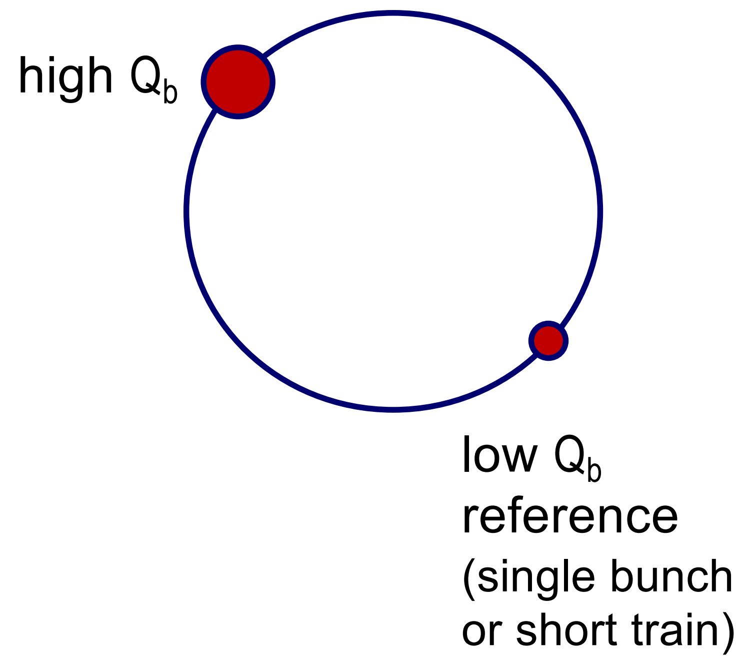
**Local transverse coupling impedance measurements in a synchrotron light source from turn-by-turn acquisitions**

Michele Carlà, Gabriele Benedetti, Thomas Günzel, Ubaldo Iriso, and Zeus Martí
*ALBA-CELLS Synchrotron Radiation Facility, Carrer de la Llum 2-26, 08290—Cerdanyola del Valles, Barcelona, Spain*
(Received 13 June 2016; published 19 December 2016)

# How to Overcome Tune Jitter and Drifts for Impedance Measurements

Use a reference measurement: simultaneously kick, record turn-by-turn BPM positions, then calculate the tunes of two (or more) bunches stored in the ring. Tune difference gives Z.

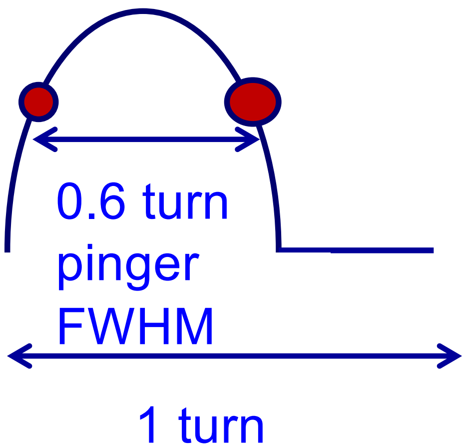
- Must have high-resolution BPMs that are capable of accurate tune measurements.
- Better to have many of these BPMs, to improve the resolution further.
- BPMs must capable of resolving turn-by-turn positions of two (or more) individual bunches, with low-current bunch(es) used as a reference.

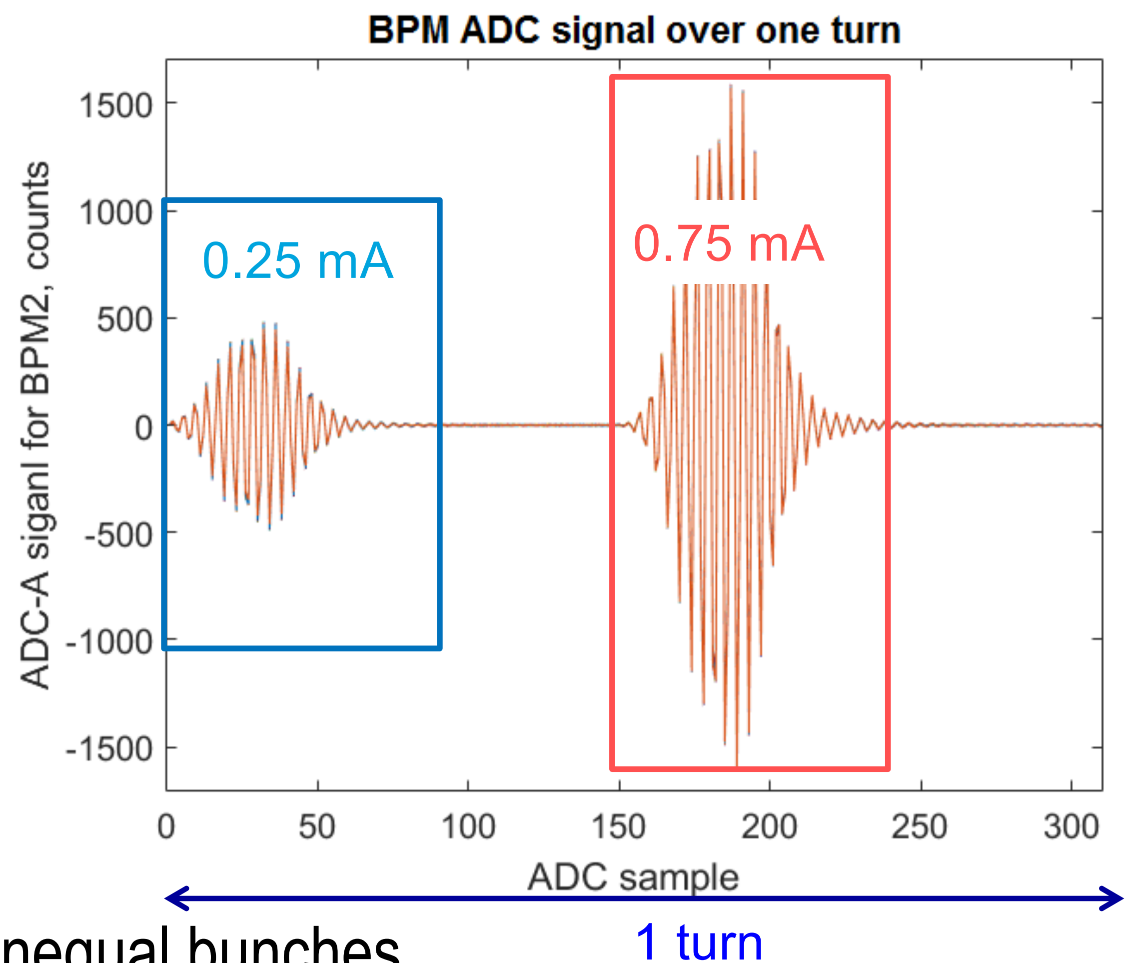



$$\delta k_{kick} = 4\pi\delta(\nu_{lowQ_b} - \nu_{hiQ_b})\frac{E/e}{\Delta Q_b < \beta >}$$

**NSLS-II has BPMs that make this possible**

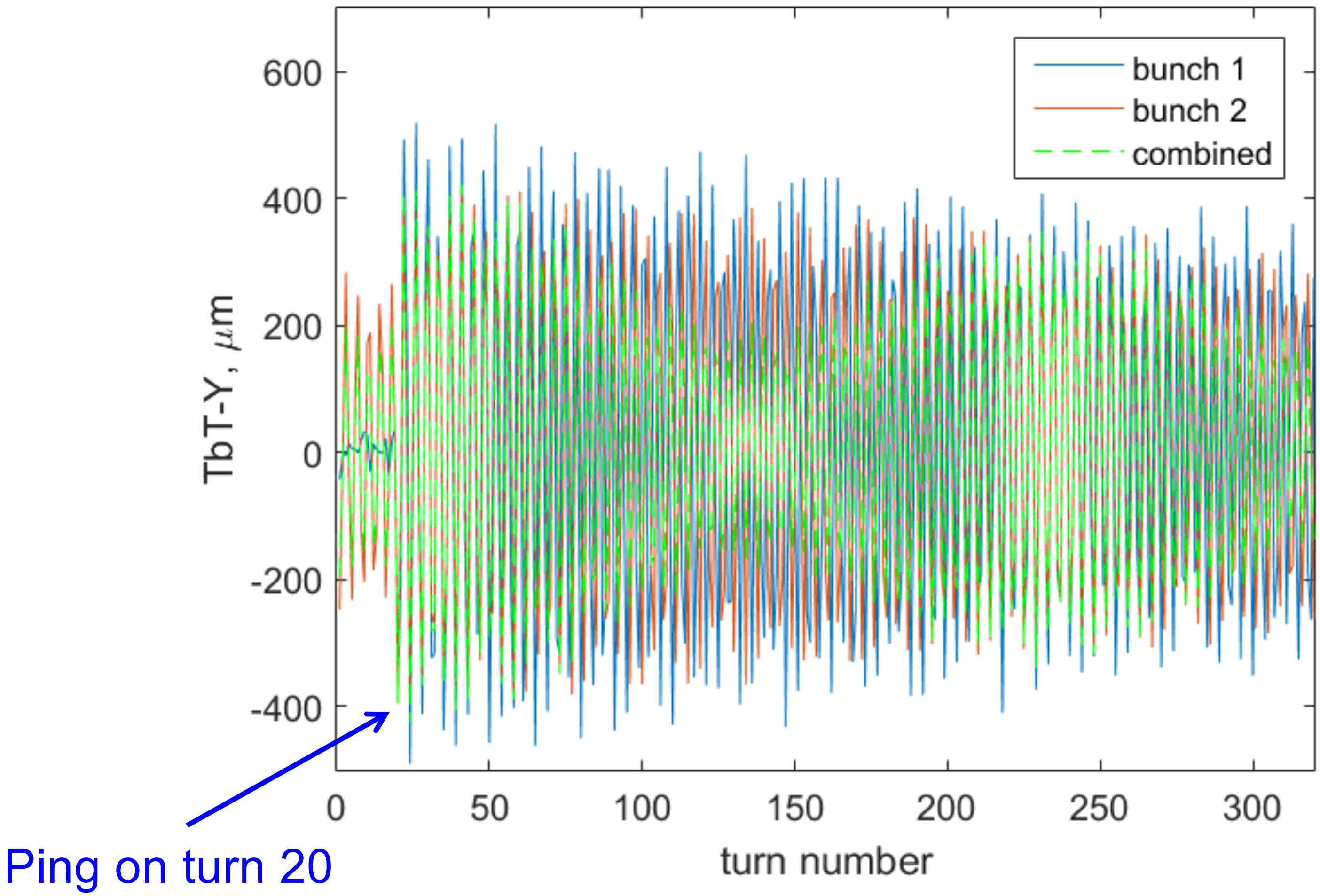
# Unequal Charge Bunches Kicked with a Pinger



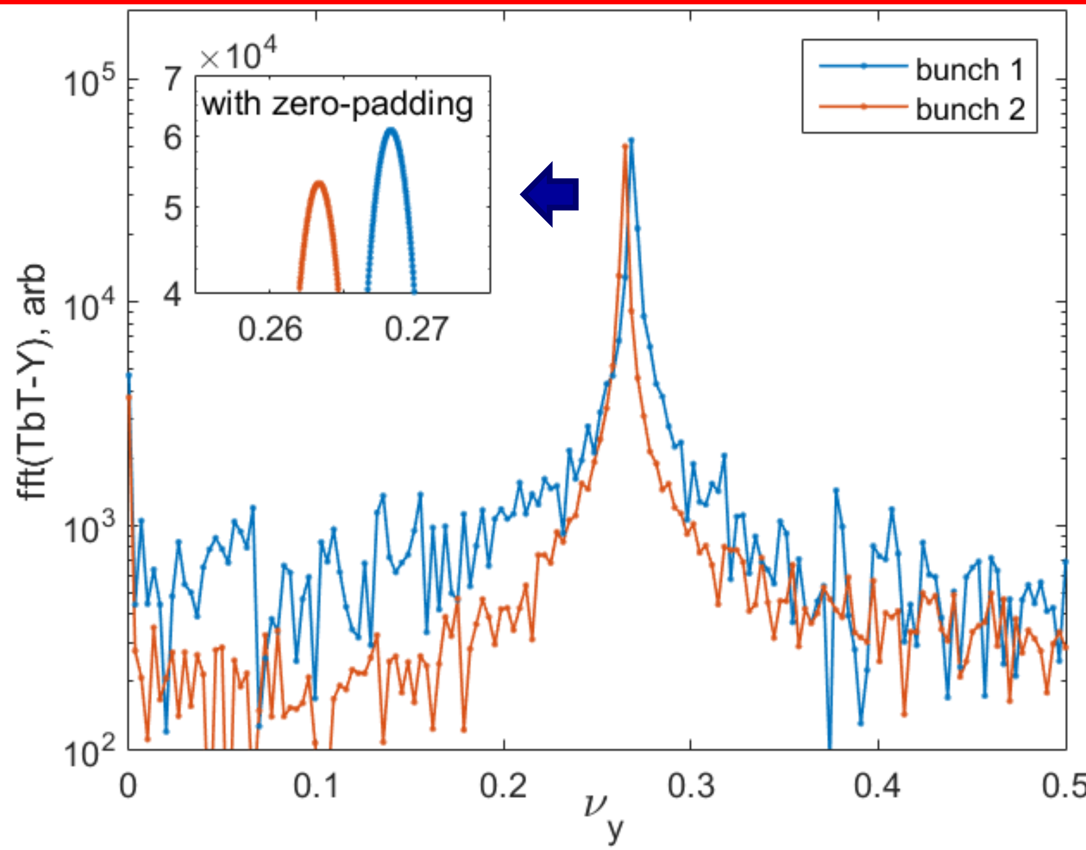

- Two-bunch fill with unequal bunches
- Pinger timing adjusted for equal vertical kick
- ADC data processed to get turn-by-turn positions for each bunch

# Turn-by-Turn Signals




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

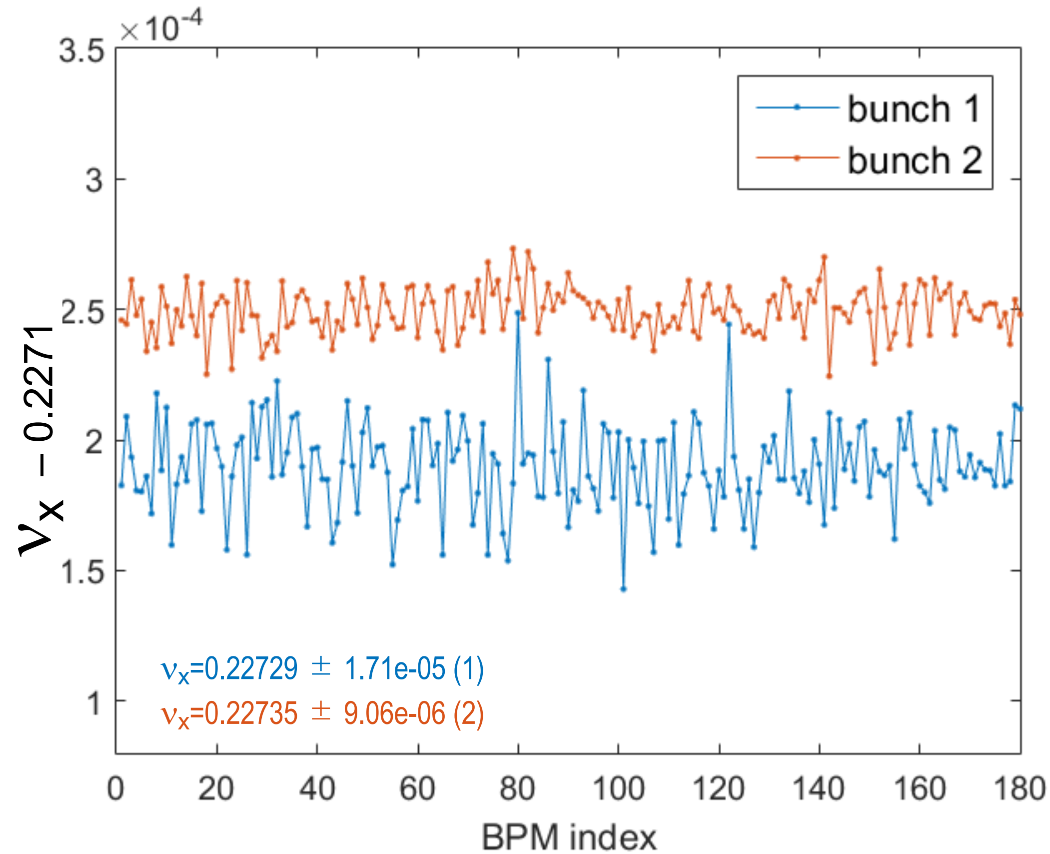
# Vertical Tunes are Distinctly Different




- 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 $\Delta\nu_{21}$ = -5e-3/(0.5 mA)=-0.01/ma agrees with measurements by other methods

# Same Measurement in the Horizontal

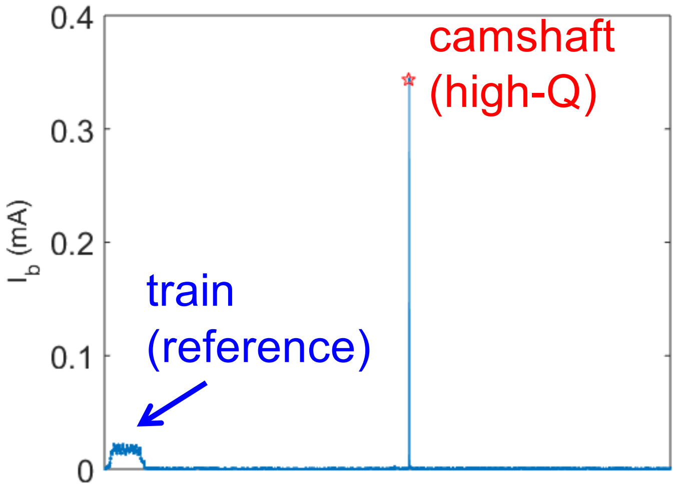
- Same two bunches, 0.25 mA (1) and 0.75 ma (2)
- Use horizontal pinger
- BPM ADC data processed to get separate TbTs for each bunch
- Use 25 revolution harmonics to increase the resolution



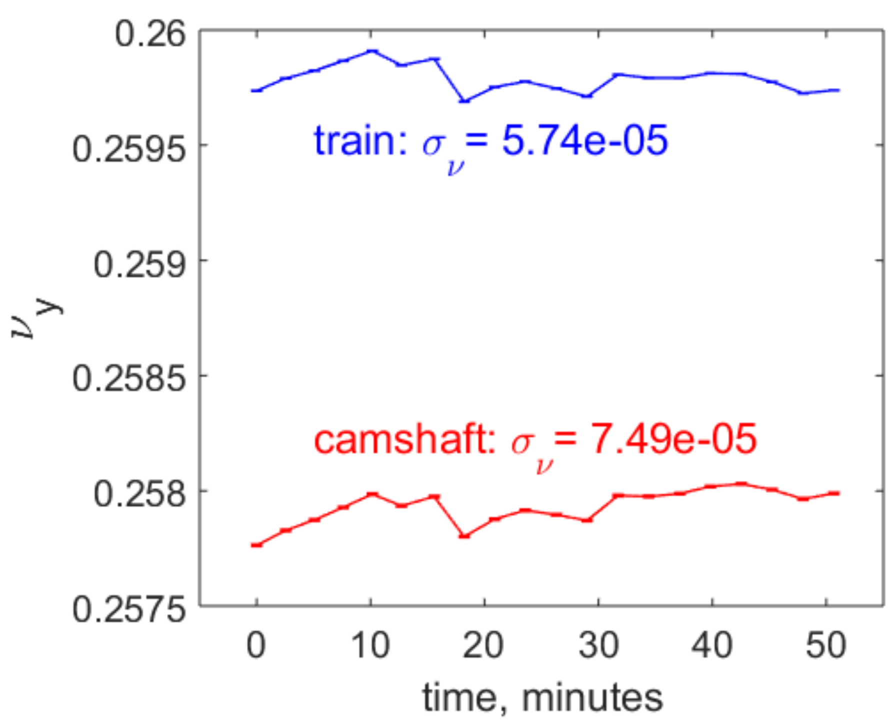

$\Delta\nu_{21}$ =(6.0 ± 1.9)*1e-5

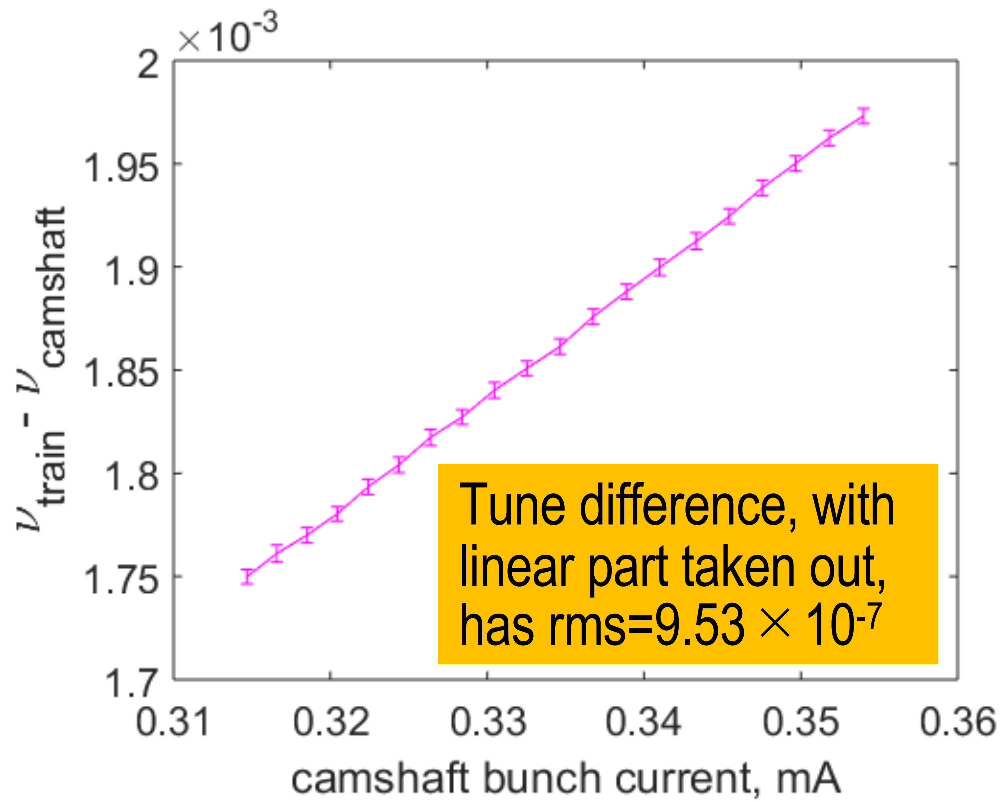
- This measurement convincingly shows that horizontal tune goes up with current (i.e. total wake is slightly focussing).

# $10^{-6}$ Tune Difference Resolution Achieved




- Hybrid fill pattern: 1.7 mA/80 bunches + 0.35 mA camshaft (initially)
- Measure vert. tunes every ~3 mins
- Over 50 mins tune rms $\sigma_\nu$~$10^{-4}$ for each
Also, camshaft bunch decays by ~40 uA



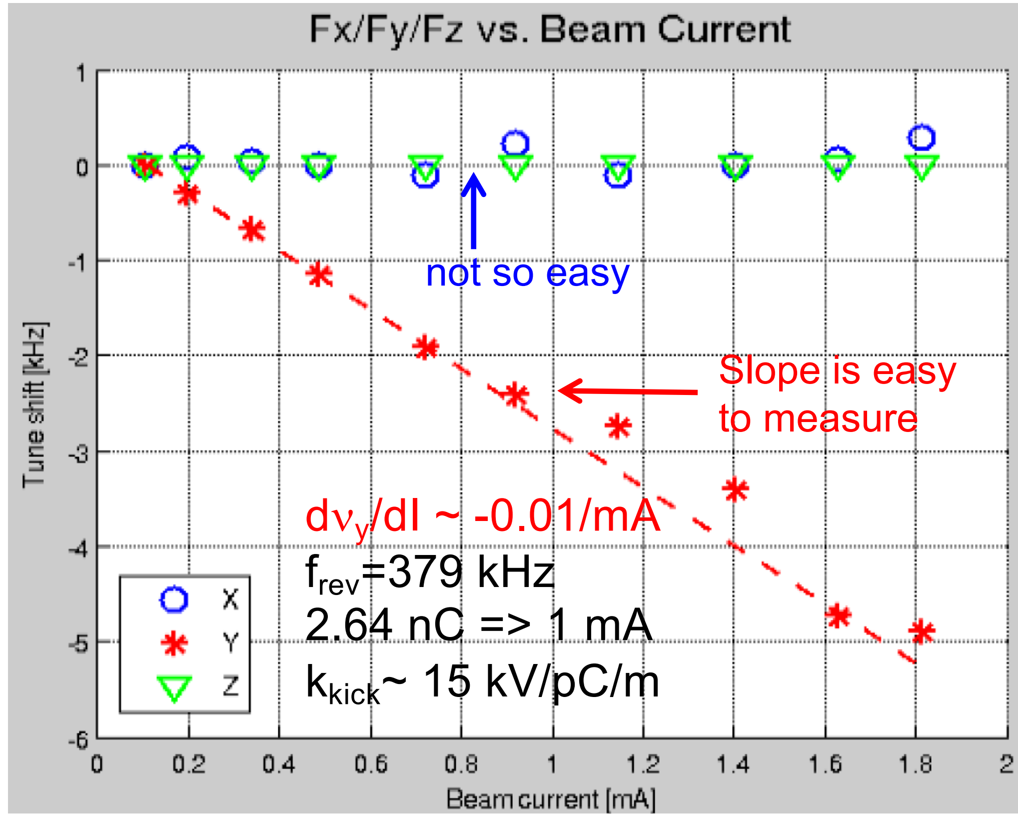
# From Tune Measurement to Coupling Impedance

Kick factor:

$$< y' >= \frac{Q_b}{E/e} k_{kick} < y_0 >$$ definition

$$k_{kick} \propto \int |\rho|^2 \operatorname{Im}[Z_y(\omega)] d\omega$$ relation to impedance

$$\delta \nu_y (Q_b) = -k_{kick} Q_b \frac{< \beta_y >}{4\pi \; E/e}$$ relation to tune shift with current




If we could resolve tunes to $10^{-6}$

$$\delta k_{kick} = 4\pi \delta(\nu_{lowQ_b} - \nu_{hiQ_b}) \frac{E/e}{\Delta Q_b < \beta >}$$

then we get kick factors as low as 10 V/pC/m

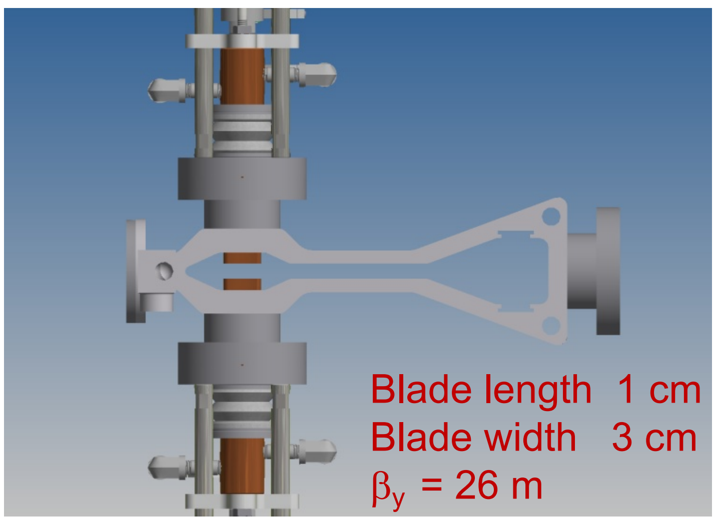
assumed 1 nC, $<\beta>$=4 m, 3 GeV

10 V/pC/m is a RW kick factor of a 1 m long Al pipe 12 mm in diameter ($\sigma_z$=5 mm)

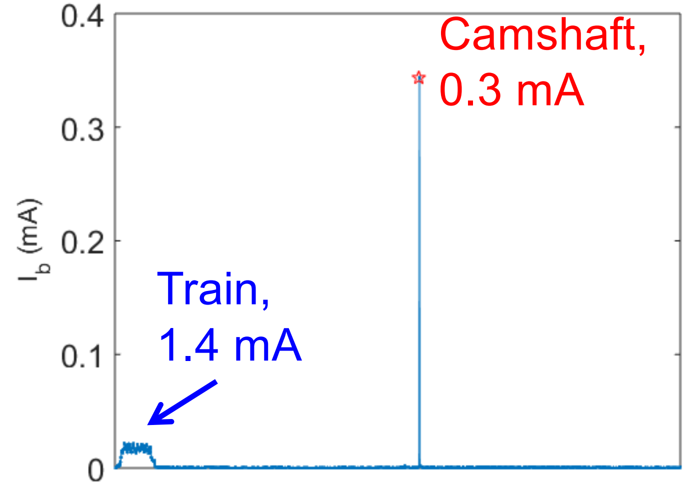
# Measurement Examples

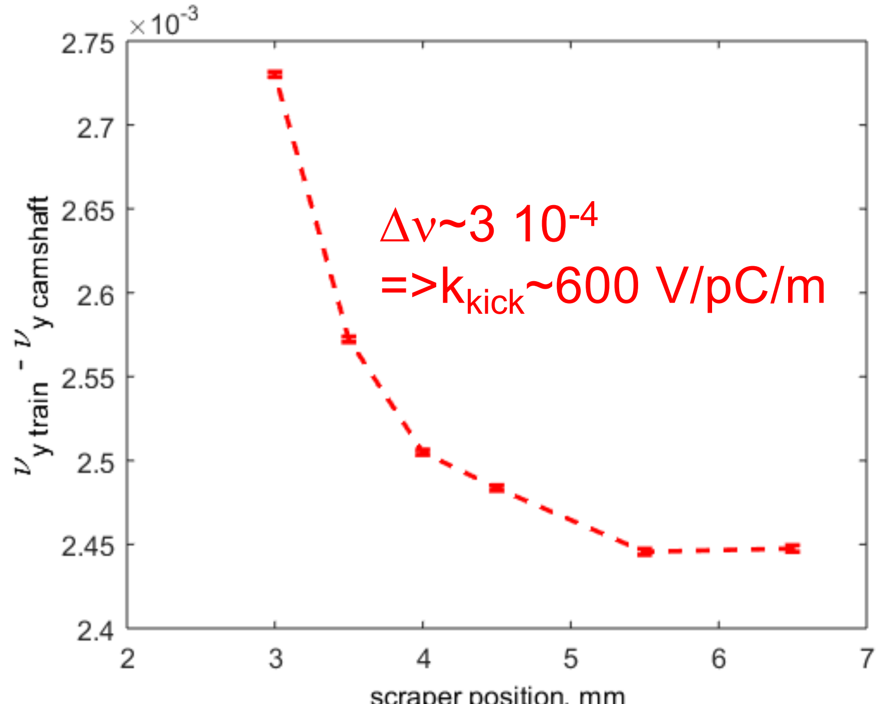
# Local Impedance Measurement: Vertical Scraper

- Measure tune difference high-Q bunch vs. reference train (low-Q / bunch)
- Repeat with the scraper inserted
- Change in the tune difference is due to added scraper impedance



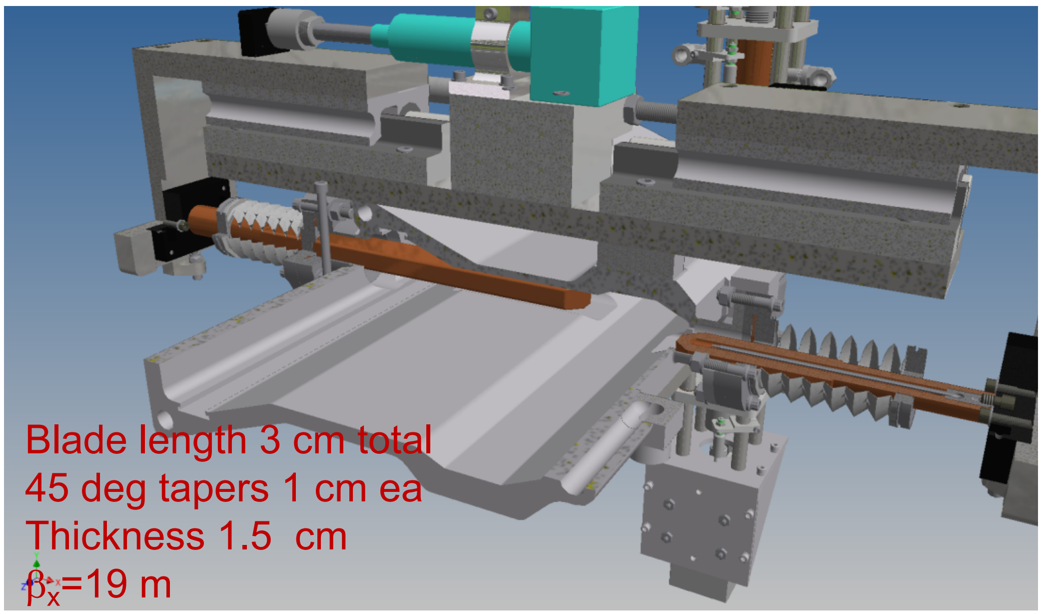

- Complimentary measurement would be from closed orbits (no kick), TBD

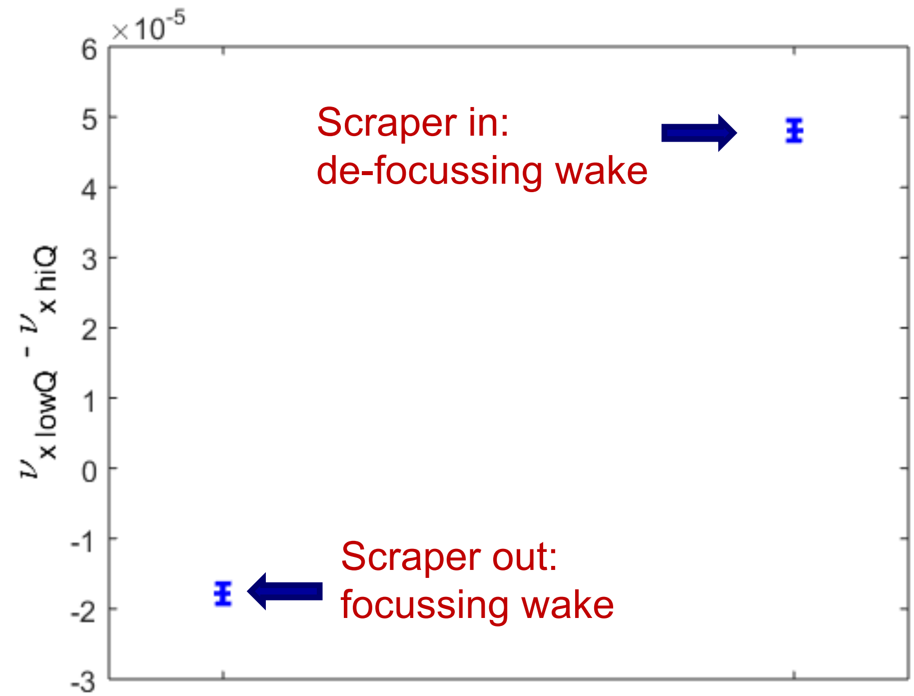


# Horizontal Scraper

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

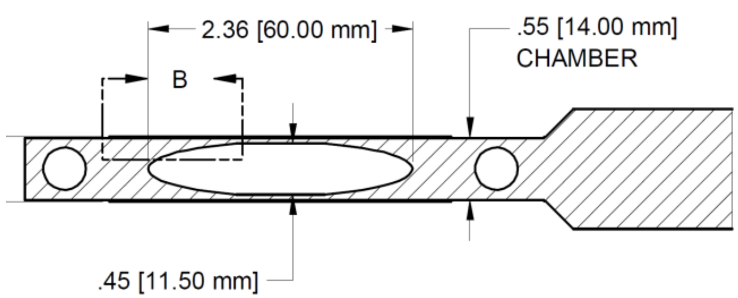


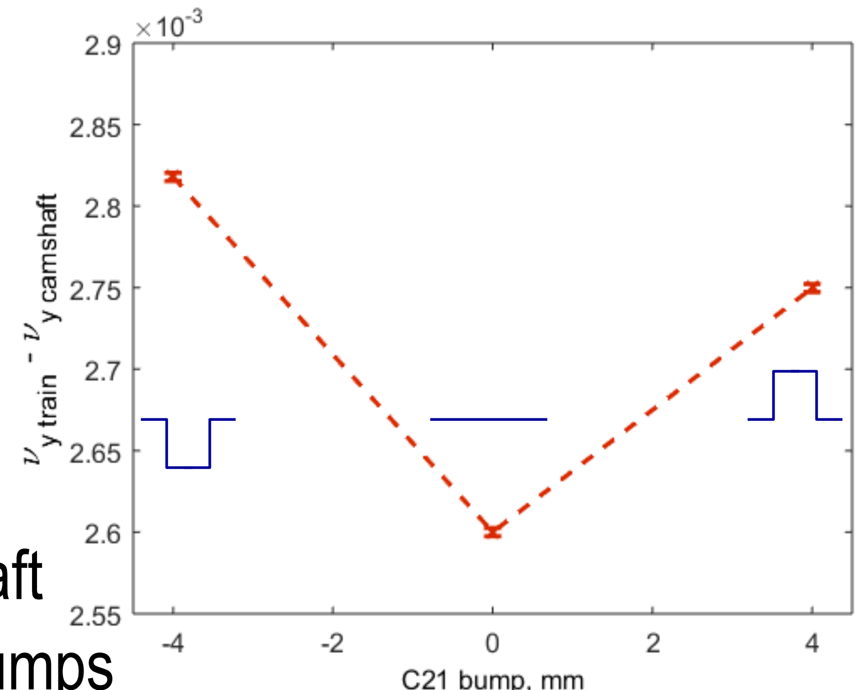




- With scraper blade close to the beam, tune-current slope changes to negative (agrees with expectation)

# Measure Low-β Insertion Device Chamber

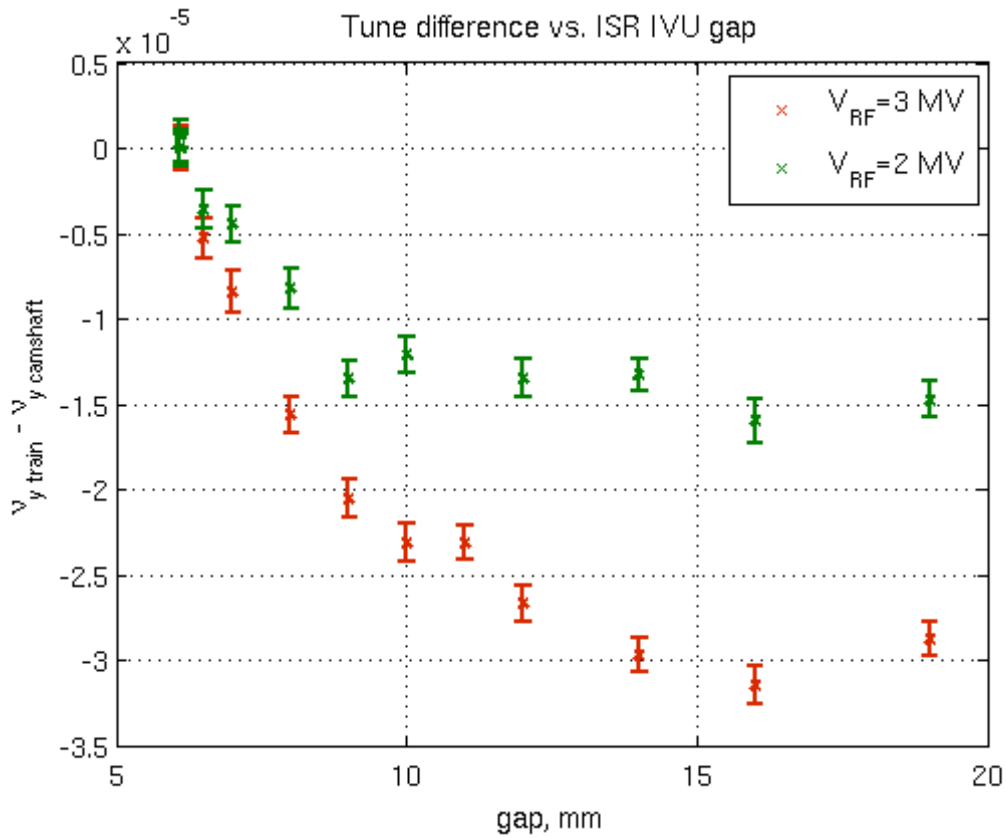
- Example of a fixed impedance component, use local bumps to probe Z
- Cell 21 has two EPUs (out-of-vacuum)
- Vacuum chamber is Al pipe, 4.8 m length, $\beta_{y0}$=1.2 m, resistive wall is dominates, RW kick factor 56 V/pC/m at $\sigma_\tau$(0.3mA)=16.2 ps measured separately




- 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 and addl'l taper impedance

# ISR In-Vacuum Undulator Tunehifts vs. Gap

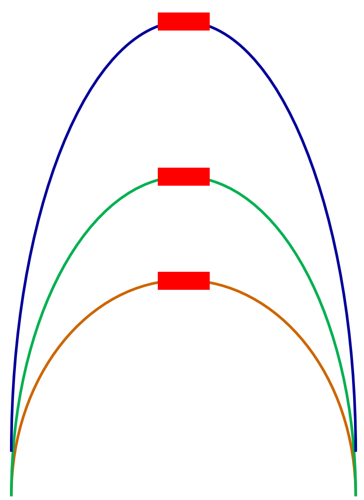


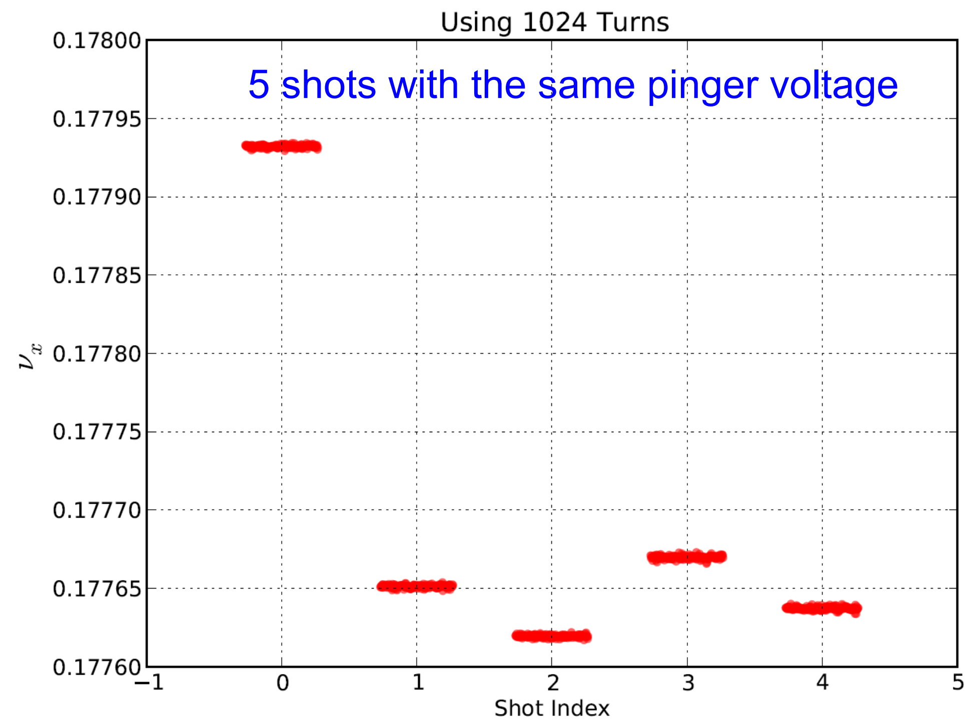

- Performed on C4-ID (ISR, IVU23, L=2.8 m). Tune difference between the train and camshaft bunches measured vs. gap.
- ~$10^{-6}$ tune relative tune resolution easily achieved at <1000 turns, 0.3 mA camshaft bunch current.
- Effect is smaller for longer bunch, as expected.

# Measurement of Tune Shift with Amplitude

Conventional measurement:

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



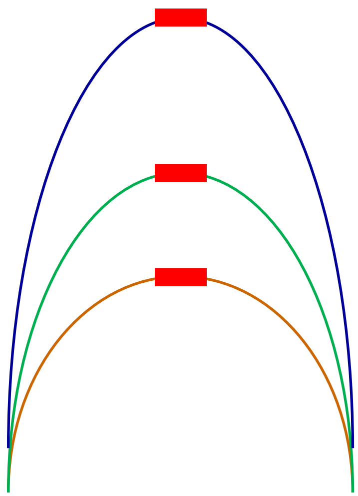



Issues: kicker jitter, machine drifts

Shot-to-shot tune jitter

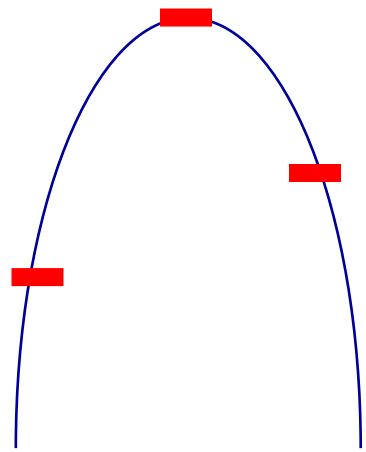
# Single Shot Measurement of Tune Shift With Amplitude

Conventional measurement



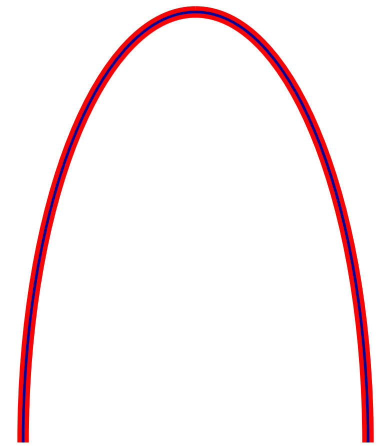
Kicker jitter, machine drifts

New option



Max. # of trains / turn

Alternative new option

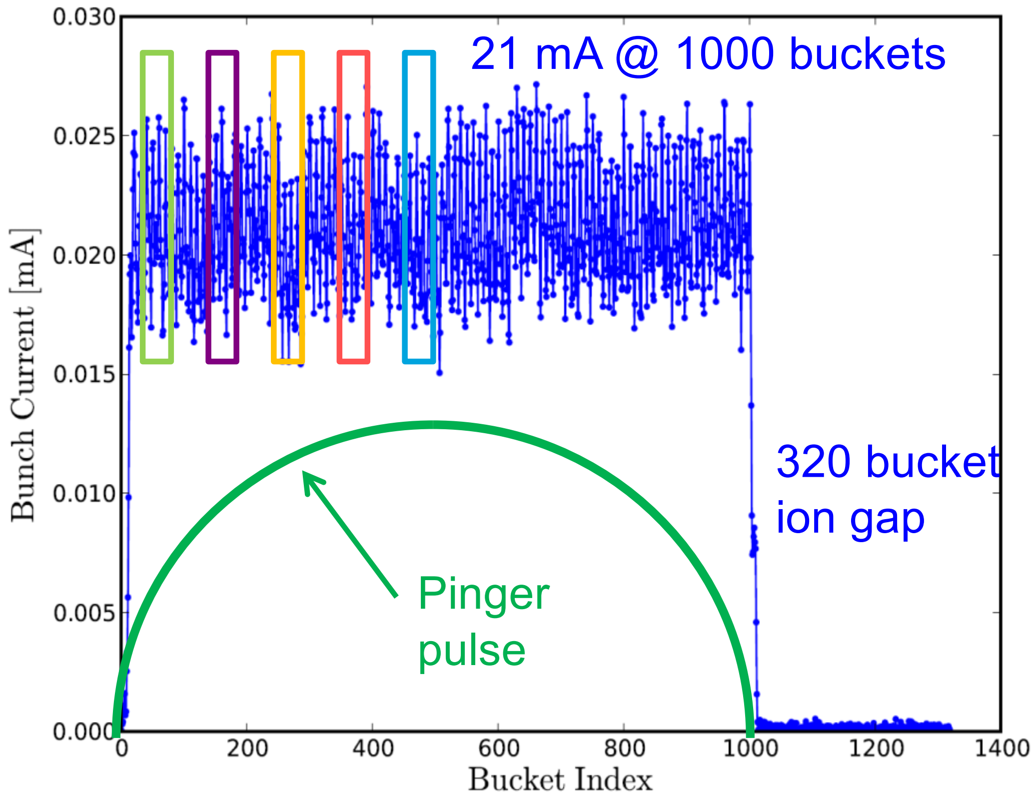


?

The rest of this talk

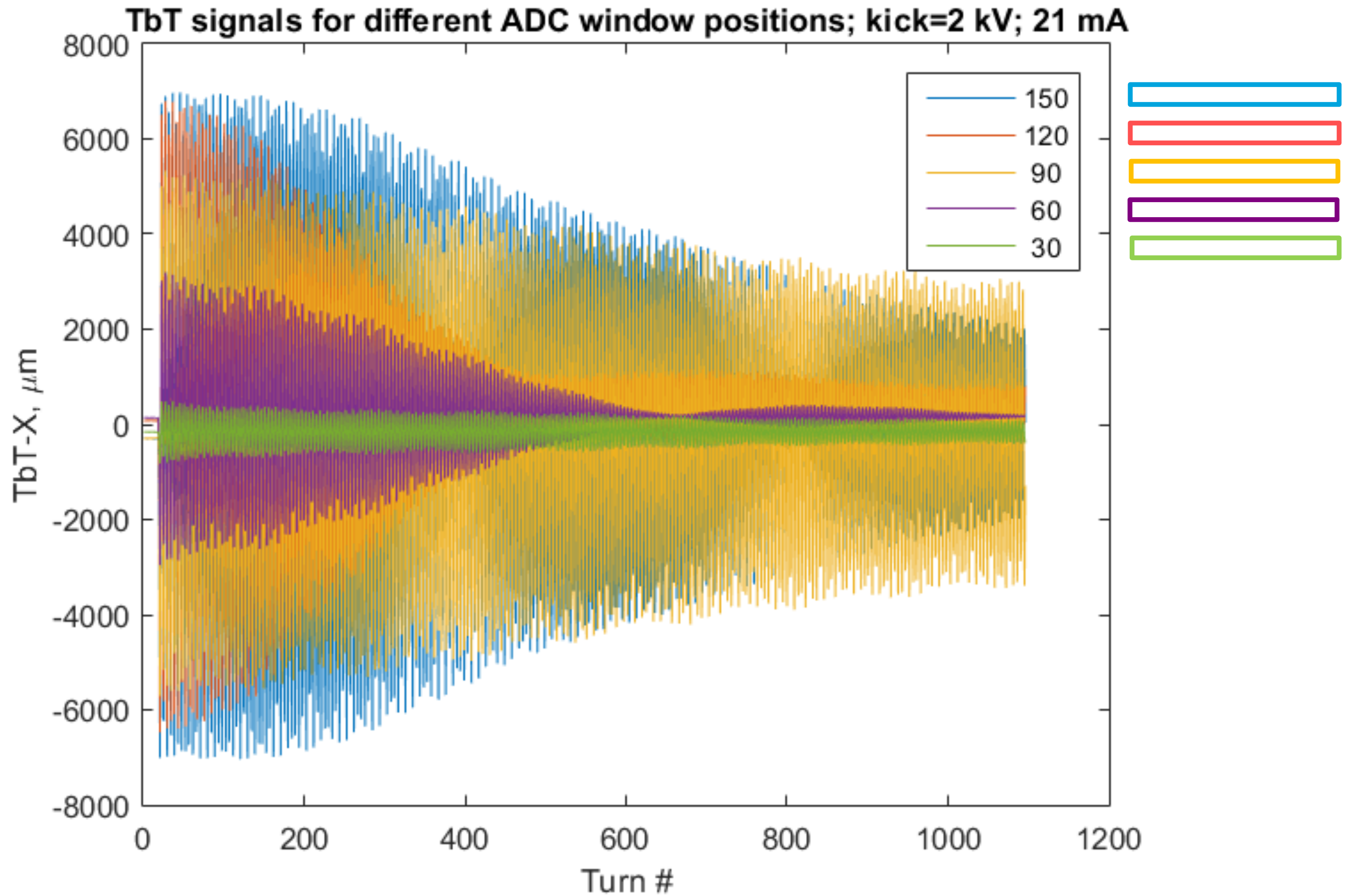
# Measurement Setup

- 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 << kicker rise time

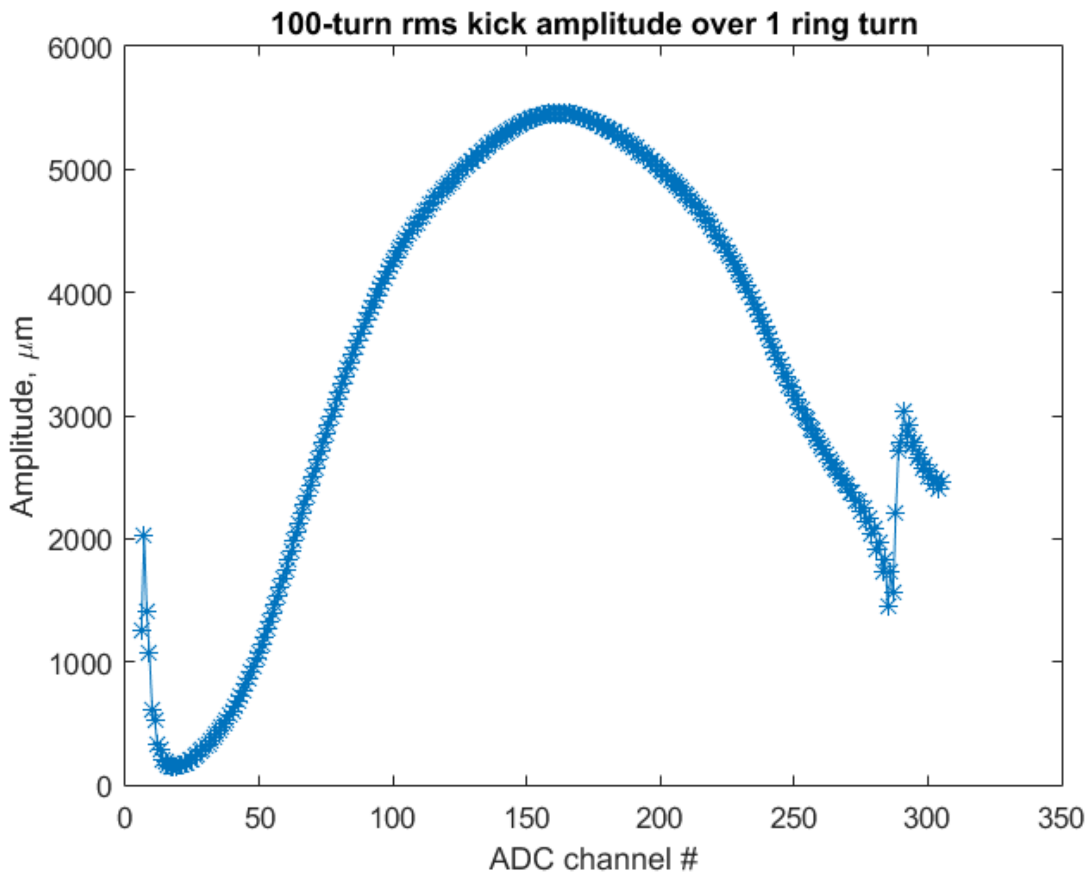
# TbT Signals from Selected ADC Bins




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

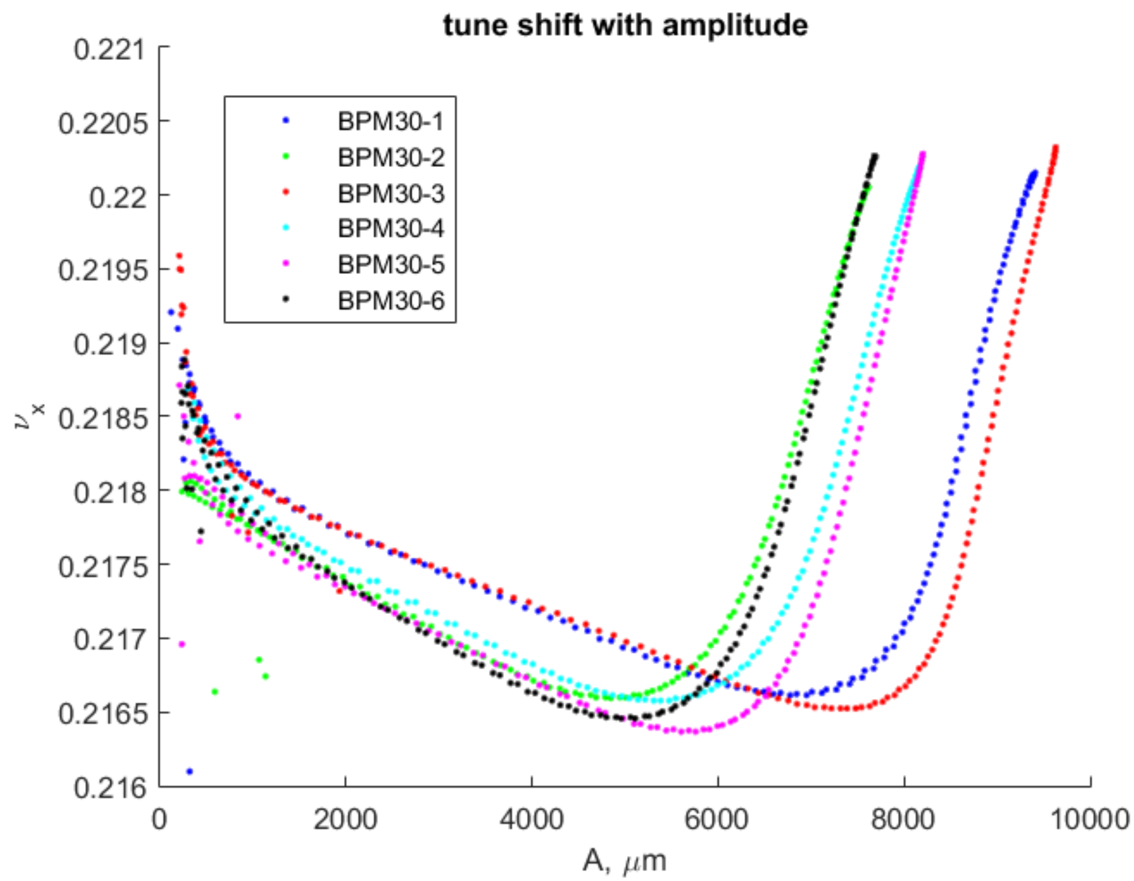
# Amplitudes for All ADC Bins Together

- Recover the shape of pinger pulse



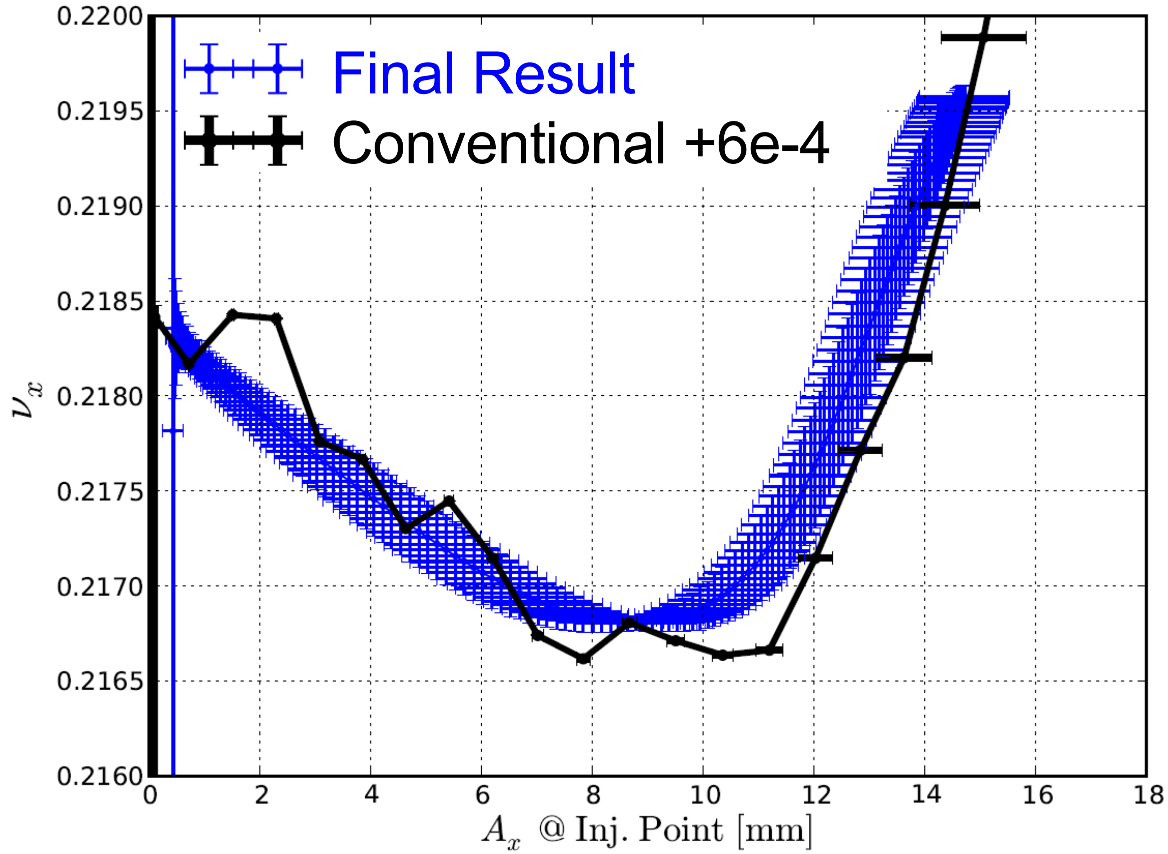

- Except at the head (there is no kick) and near the ion gap

# Tune Shift with Amplitude: 6 BPMs



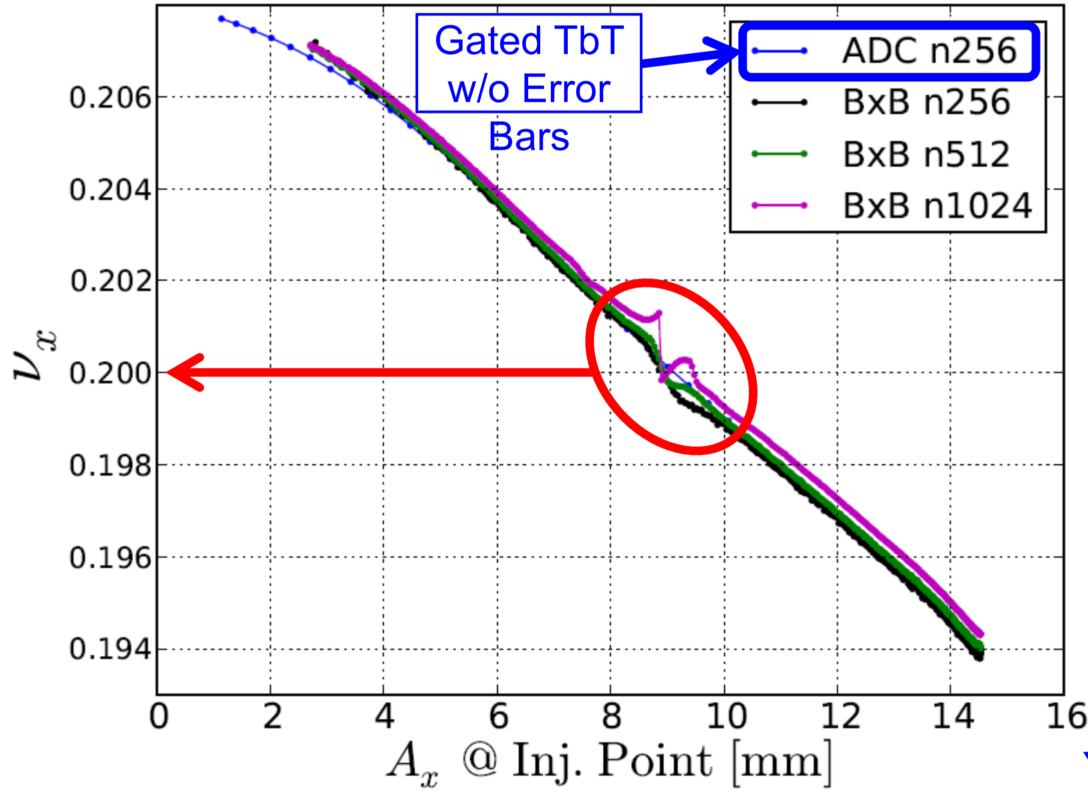

- Smooth curves except at very low amplitudes
- Other cells look very similar
- From here: scale to injection point; error-bars from all 180 BPMs

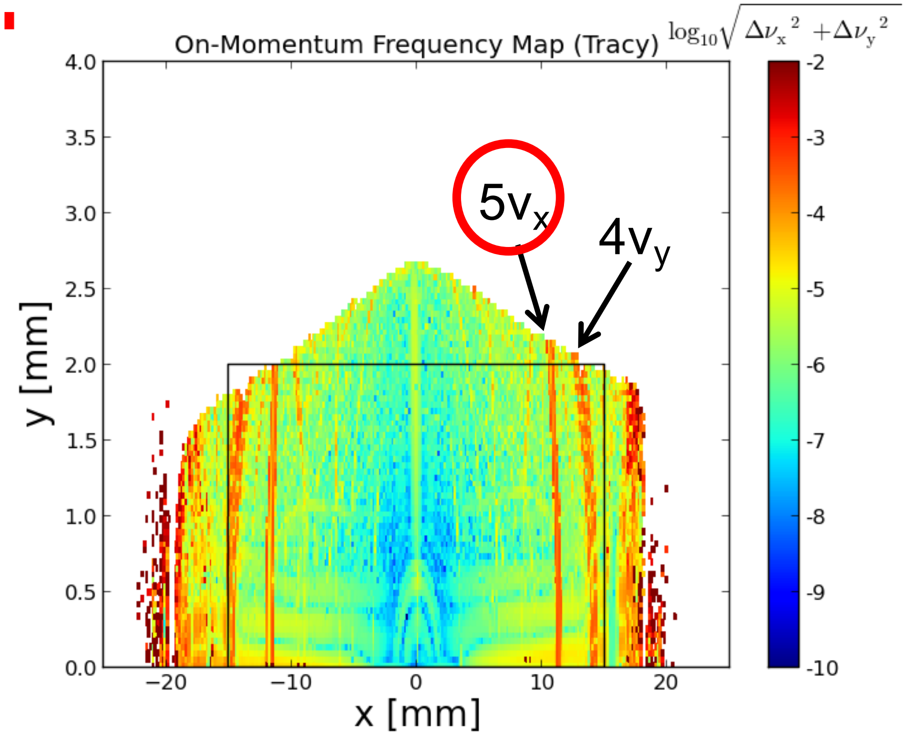
# Final Results: Horizontal




- Final result for 5mA/1000 bunches, single pulse of 2 kV ("bare" lattice)
- 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

# Example of Further Optimized Measurement




**Yoshiteru Hidaka et al., NAPAC 2016**

- “3 DW” lattice
- Gated turn-by-turn 180 BPMs for amplitude, BxB feedback for tune
- Distortion around $\nu_x$ = 0.2 (5$\nu_x$ resonance) from BxB (more pronounced with more number of turns used for tune extraction)
- Simulated frequency map analysis (w/ engineering tolerance) predicted this resonance!

# Conclusions

**Thank you**

- State-of-the-art NSLS-II BPM receivers enable advanced beam dynamics measurements.
- For instance, we can resolve the tunes of several individual bunches stored in the ring with very high accuracy. $10^{-6}$ tune resolution has been demonstrated.
- This enables a fast and precise technique for measuring the transverse impedance (kick factor) of storage ring elements.
- This reference technique eliminates harmful effects of machine drifts. It also eliminates other large systematic effects, unrelated to the impedance, i.e. singe particle tune change due to undulator gap closure.
- Another useful application is for single-shot measurements of tune-shift with amplitude. Many more were not mentioned in this talk.
- BPM signal processing for the examples presented in this talk was done off-line but it is being implemented in FPGA. This should greatly speed up these measurements as well as enable orbit-based Z-measurements.

# Acknowledgements

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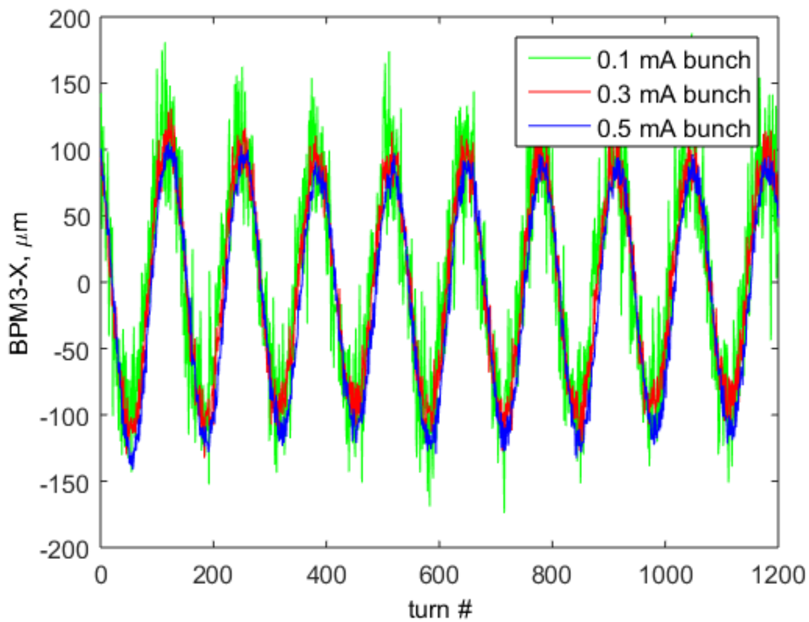
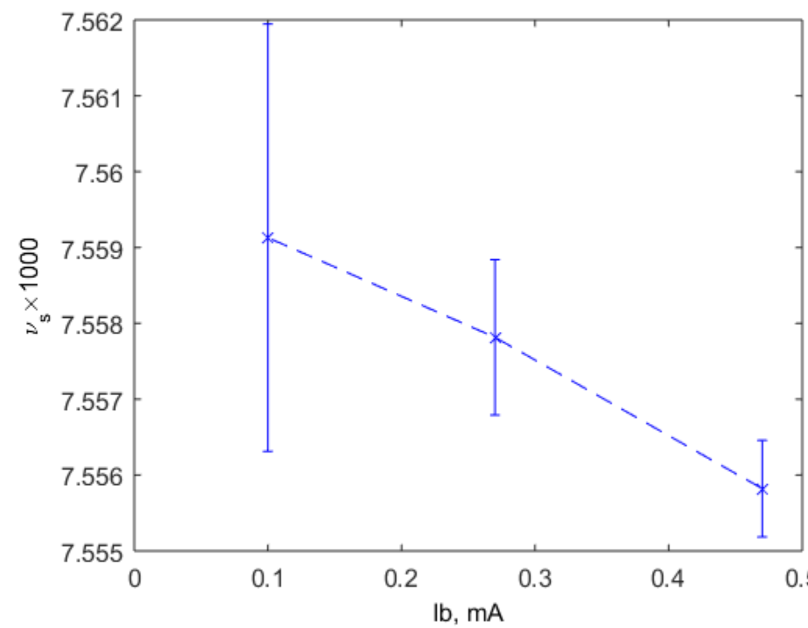
as well as from Dmitry Teytelman, from Dimtel, (everything)

# Extras

# Synchrotron Tune Shift with Current

- RF cavity feedforward provides short (<1/$f_s$) RF amplitude jump
- Beam (3 bunches, 1/3 ring apart each) is kicked longitudinally, synchrotron tune detected on dispersive BPMs (60 total)




- As expected, tune change with current is miniscule (imperfect cancellation of coherent and incoherent tuneshifts), yet measurable to be around $10^{-5}$/mA with this method ...