Beam Dynamics Measurements with New Generation BPMs

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U.S. DEPARTMENT OF ENERGY | Office of Science
BROOKHAVEN NATIONAL LABORATORY

Outline

- NSLS-II BPMs
- BPM signal processing enhancements to enable sensitive beam dynamics measurements
- Measurement examples
- Summary

All measurement examples are from NSLS-II

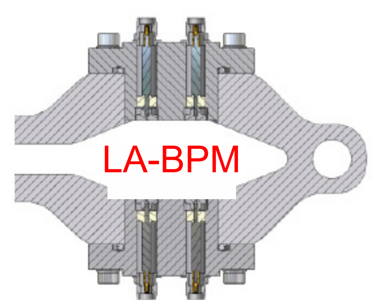
Motivation

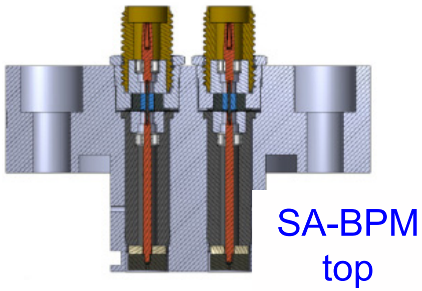
- Beam dynamics is rich and exciting subject.
- Understanding collective and nonlinear single-particle dynamics and, increasingly, their interplay, is crucial for stably running an advanced light source, as well as other accelerators.
- Sophisticated measurements are needed to confirm and refine machine models.
- Some of these measurements must be done at low current, non-standard fill patterns and without feedbacks. Machine stability as well as diagnostics capabilities in these regimes often present severe limitations.
- New ideas to overcome these limitations are often needed.

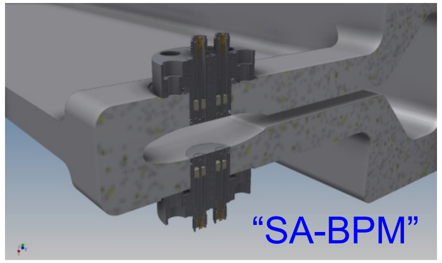
NSLS-II BPMs: Pickups

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

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







Real SA button assemblies are rotated around the vertical

NSLS-II RF BPM Electronics In-house Development

RFBPM Design(2009-2010)
- Established BPM Performance Requirements for Injector, Storage Ring

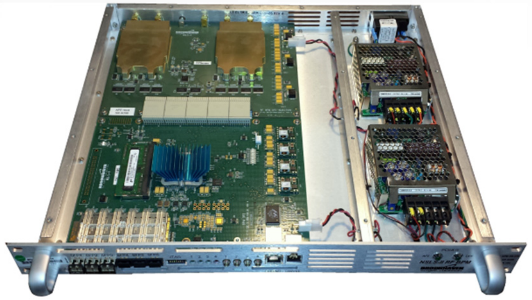
RFBPM Hardware Requirements(2009-2011)
- Architecture (AFE/DFE)
- FOFB/PS, Timing and EPICS interface
- FPGA selection adequate for calculations and signal processing
- Interface to Controls System Platform
- Software/firmware requirements
- Provision for adequate control of all required parameters
- Meet SR performance requirements
- Meet Long term stability requirements
- Adequately addresses maintainability and reliability
- Development of X-Ray BPM application
- Flexibility to meet future needs

RFBPM Design and Construction (2012-2014)
- Prototype AFE, DFE hardware/software/firmware/controls interface
- Perform Beam tests at sister facilities
- Analyze/evaluate/assess data
- Production build/test/install total 60 receiver assemblies for Injector
- Production build/test/install total 250 receiver assemblies for Storage Ring

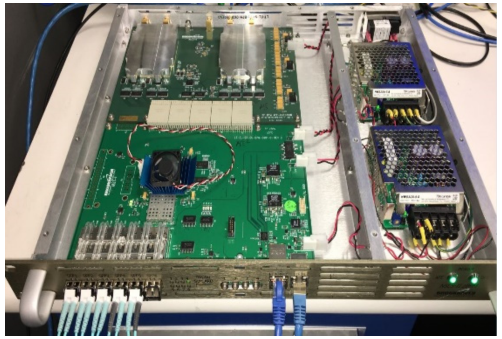
NSLS-II Operations (2015-Present)
- Completed 283, RFBPM receivers for operations, 10 spare assemblies
- Completed 4, X-Ray BPM receivers for operations, 2 spare assemblies

Next-Generation RFzBPM Development (2016-Present)
- Completed 20 pre-production next generation zDFE Developed/built/tested using existing AFE
- Completed Prototype next generation AFE developed/built, testing in progress
- Completed Prototype BbB BPM receiver(500Msps direct sampling) developed/built, testing in progress

RFBPM

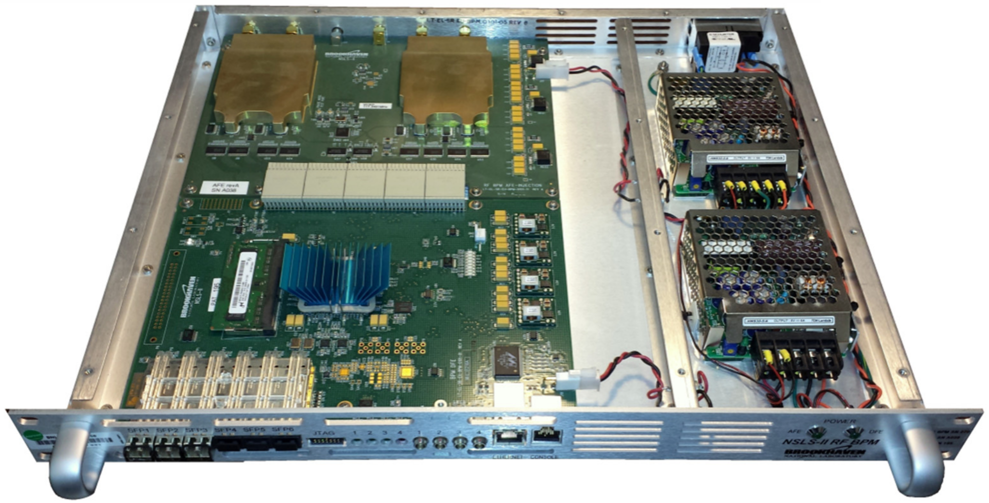


Next-Gen RFzBPM



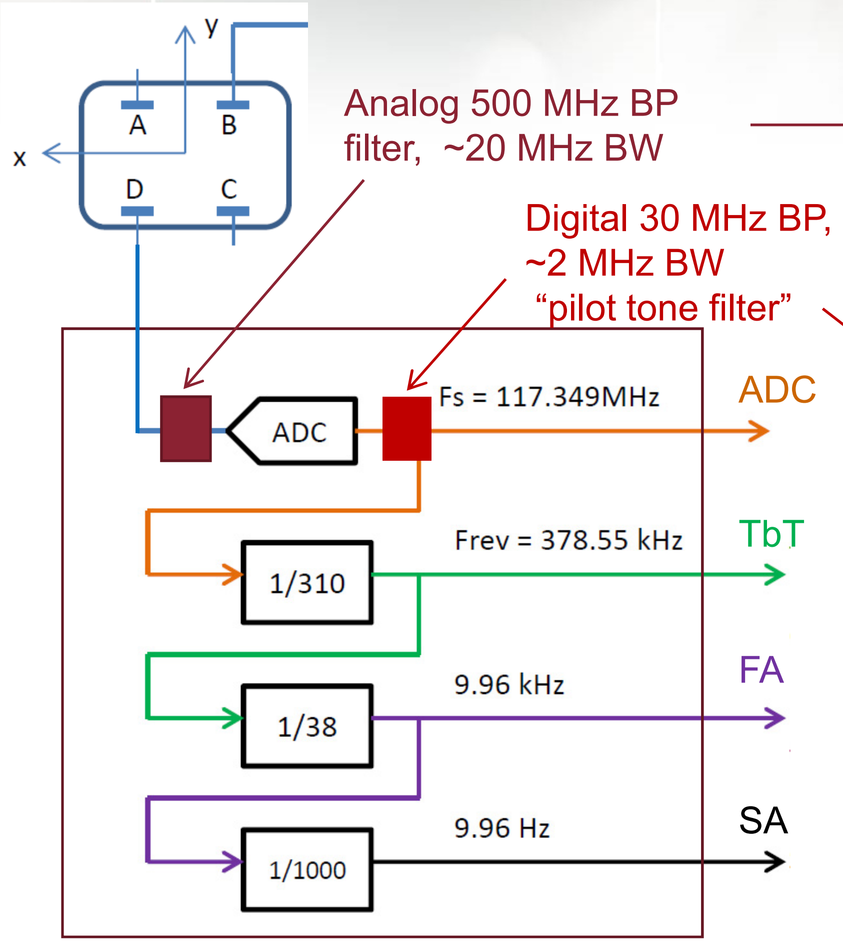
NSLS-II BPMs: Receivers

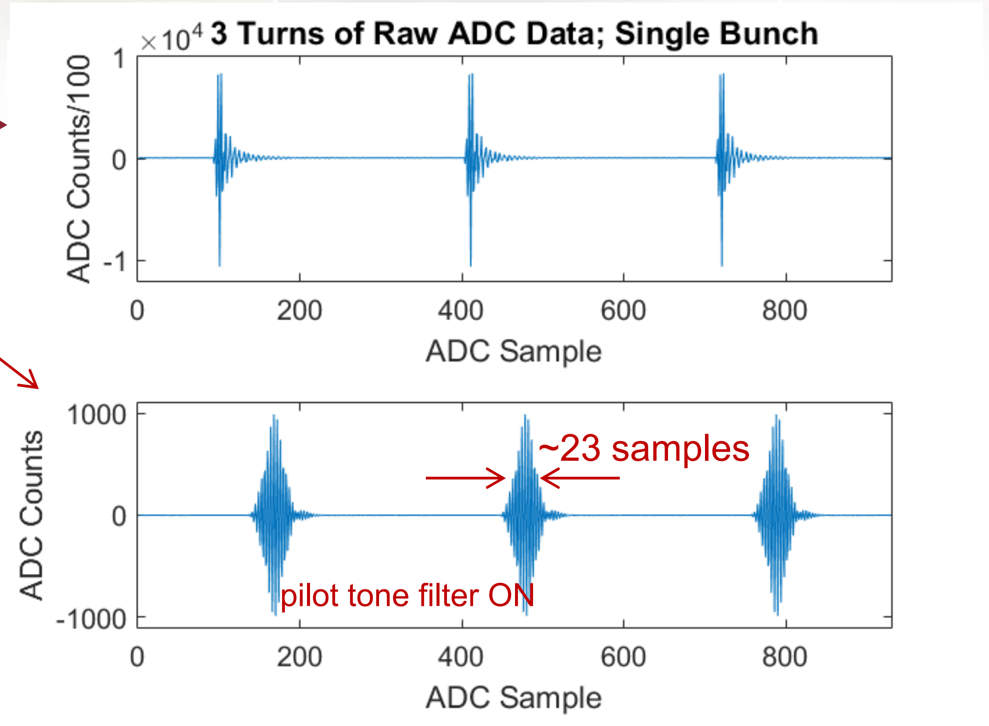
Data Type	Mode	Max Length
ADC Data	On-demand	256Mbytes or 32M samples per channel simultaneously
Turn-by-Turn (TbT), Frev=379 kHz	On-demand	256Mbytes or 5 M samples Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd
Fast Acquisition (FA) , 10KHz	Streaming via SDI Link & on demand	Streaming - X,Y,SUM; For 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 μm turn-by-turn (TbT) and 200 nm in 10 kHz (FA) mode were verified during beam commissioning in 2014
- TbT used for injection & kicked beam studies, FA for fast orbit feedback & interlocks, SA for orbit measurements
- Do not have bunch-by-bunch capability (and could not, until recently, resolve bunches within a turn)

NSLS-II BPM Signal Processing

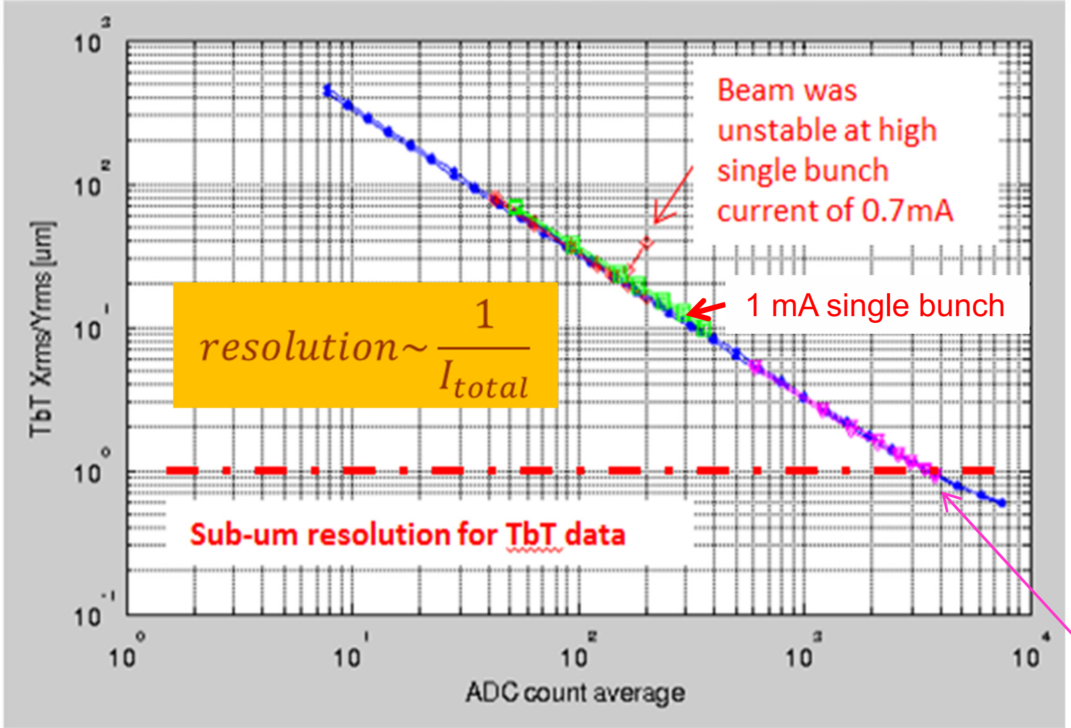




1 Turn = 310 ADC Samples =
=1320 of 500 MHz RF buckets

- 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 Positional Resolution



W. Cheng et al., IBIC'15

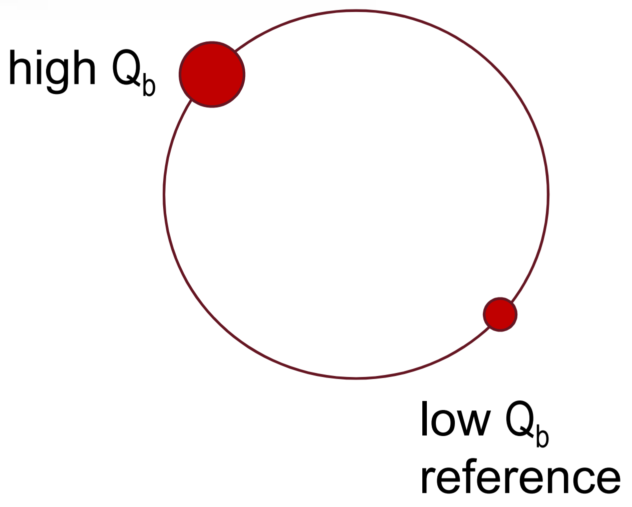
- pilot tone test
- 20 bunch train
- 1000 bunch train
- single bunch

~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

BPMs have Good Positional Resolution and now We Can Resolve Few Separate Bunches on Every Turn, so What?

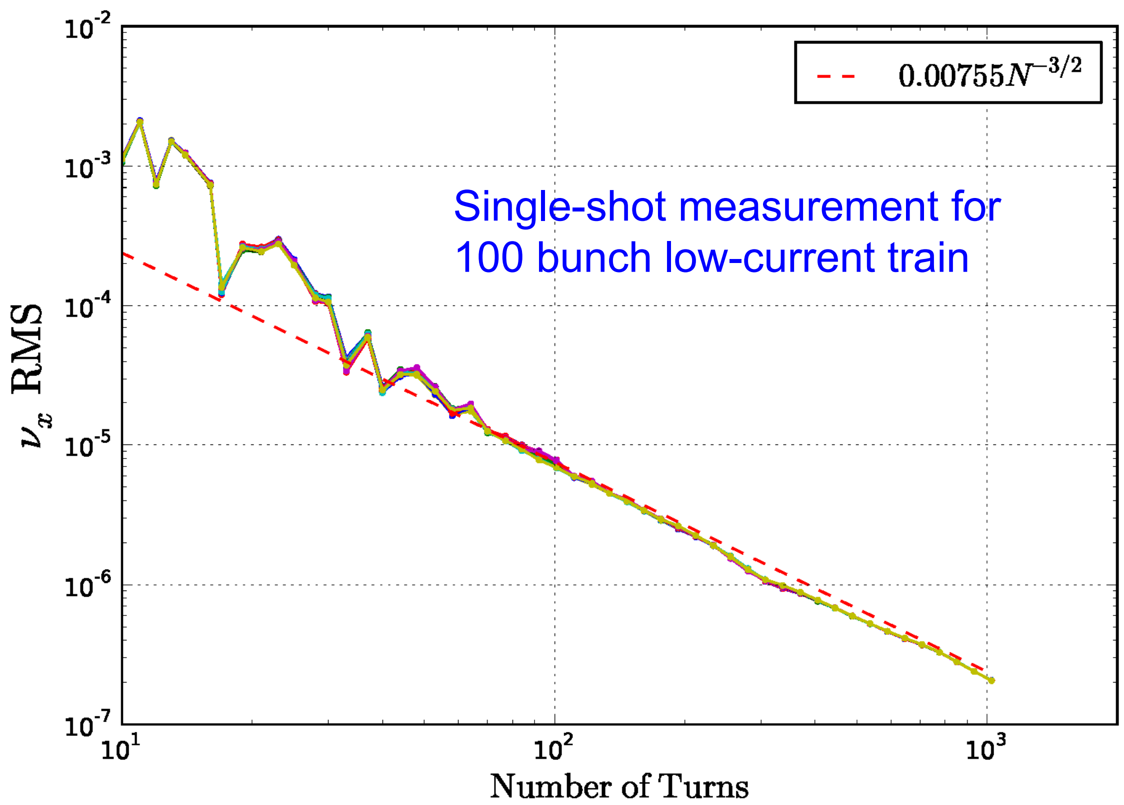
- This enables precise beam dynamics measurements
  - Good positional resolution gives good tune resolution
  - Separate bunches measured simultaneously allow for precise reference measurements
- Must have high-resolution BPMs that are capable of accurate tune measurements.
- Better to have many of these BPMs, to improve the resolution further and to quantify it.
- BPMs must capable of resolving turn-by-turn positions of two (or more) individual bunches, with low-current bunch(es) used as a reference.



Collective effect measurement (measure tunes, or other charge-dependent effects)

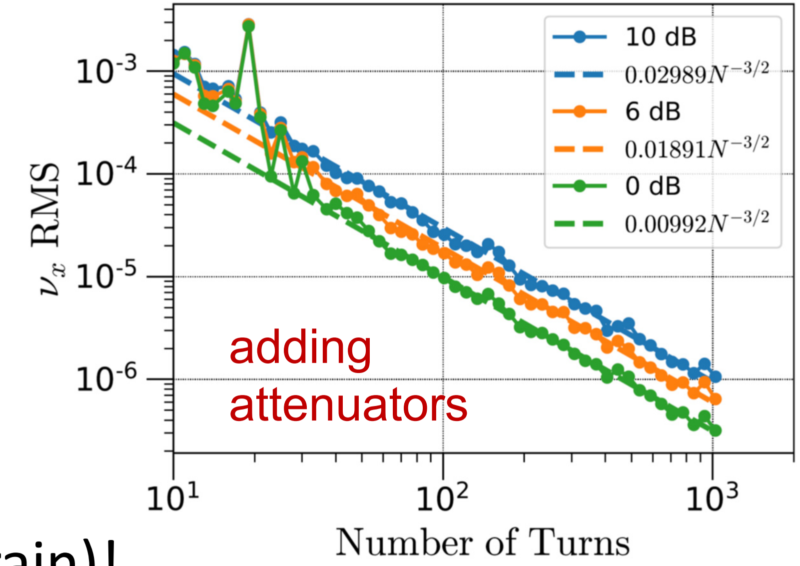
~10^{-7} Tune Resolution has been Demonstrated

- Ping the beam
- Measure 180 tunes from 180 BPMs
- Average gives the tune value (not shown)
- RMS gives the tune resolution, plotted



$N^{-3/2}$ scaling agrees with theory*
Coefficient ~(signal/noise)$^{-1}$

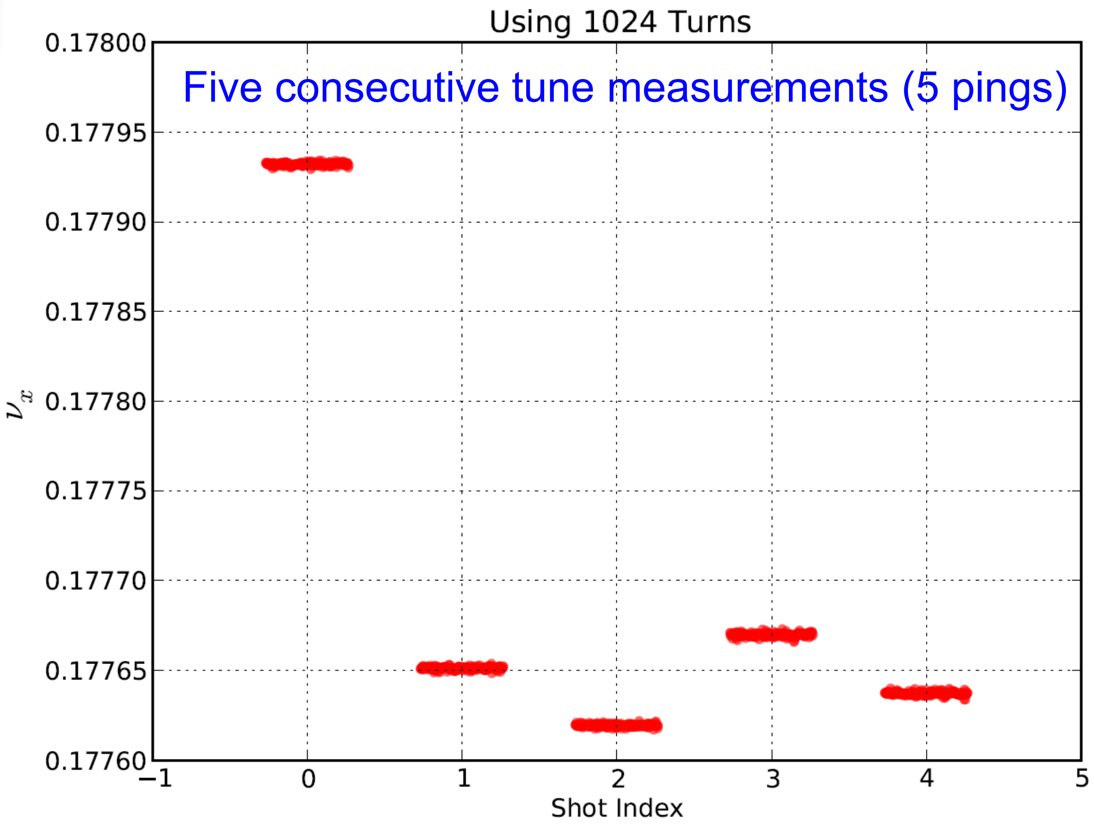
*R. Bartolini et al., Part. Accel. 55, 1 (1996).



Y. Hidaka

- Tune resolution down to $2\text{x}10^{-7}$ at 1000 turns
- But only for a single-shot (and short, 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 tune jitter is ~10-4 rms (this tune stability is well within specs)
- This would normally preclude any measurements which require better tune resolution

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

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

Single-shot tune rms=2.1×10^{-6}

100-shot tune rms=1.1×10^{-4}

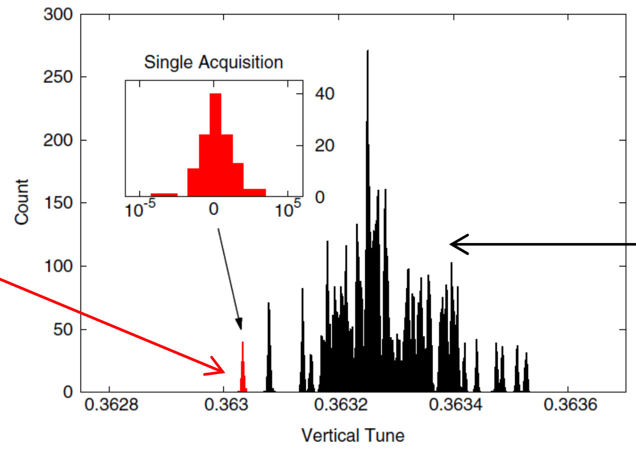


FIG. 3. Histogram of the vertical tune measured by 120 BPMs for 100 acquisitions. The measurement shows an overall standard deviation of 1.1×10^{-4}, on the other hand looking at one single acquisition (in red) the spread is strongly reduced presenting a standard deviation of only 2.1×10^{-6}.

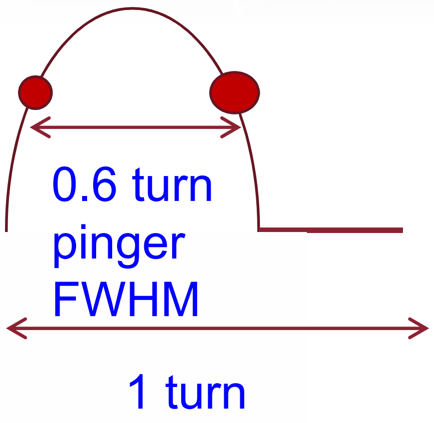
PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 121002 (2016)

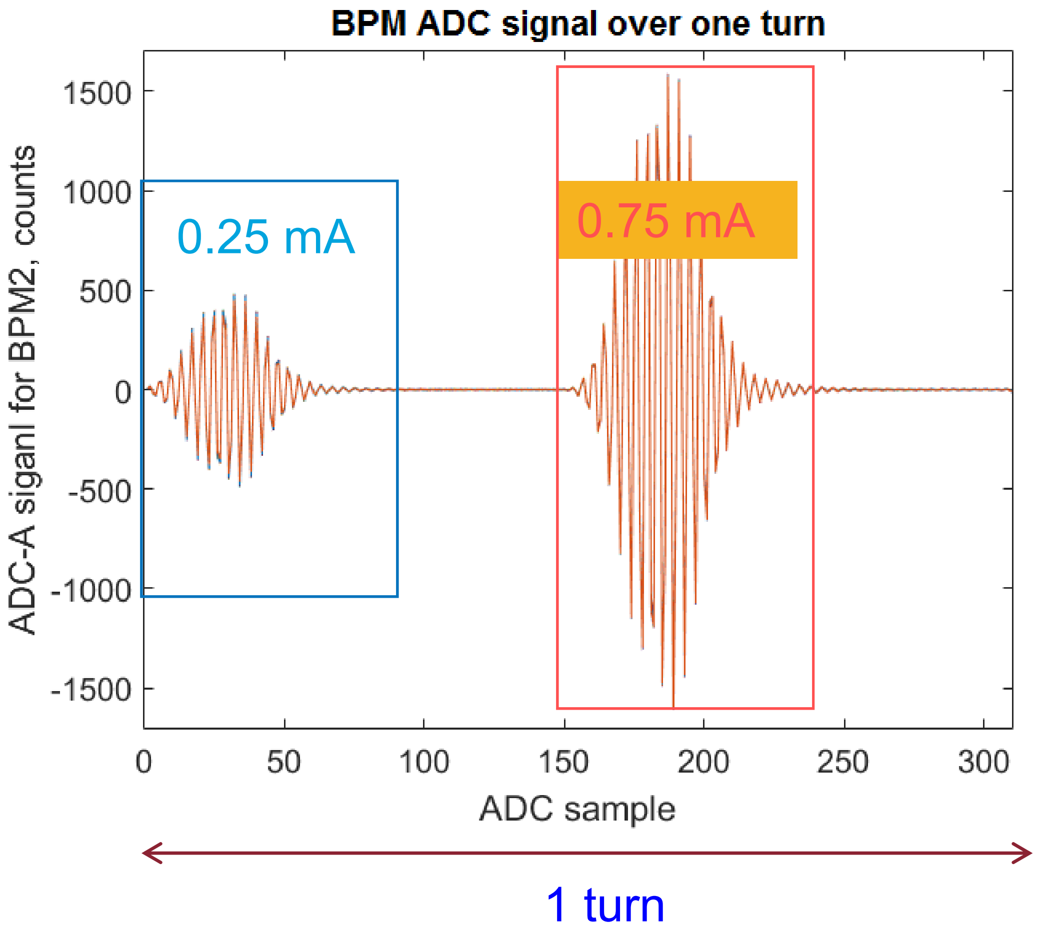
Local transverse coupling impedance measurements in a synchrotron light source from turn-by-turn acquisitions

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)

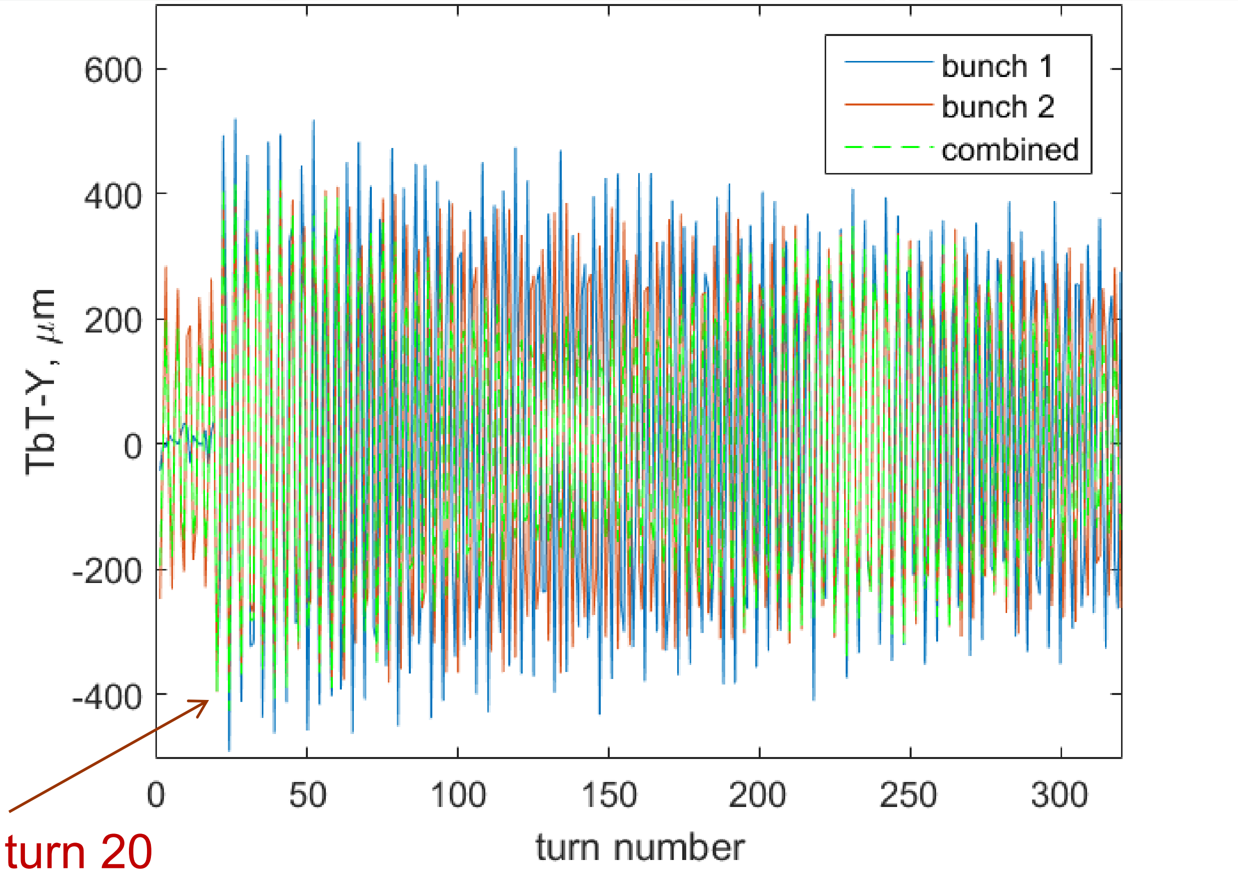
Solution to Overcome Tune Jitter: Reference Measurements





- Two-bunch fill with unequal bunches kicked with a pinger (timed for equal kick)
- ADC data processed to get turn-by-turn positions for each bunch

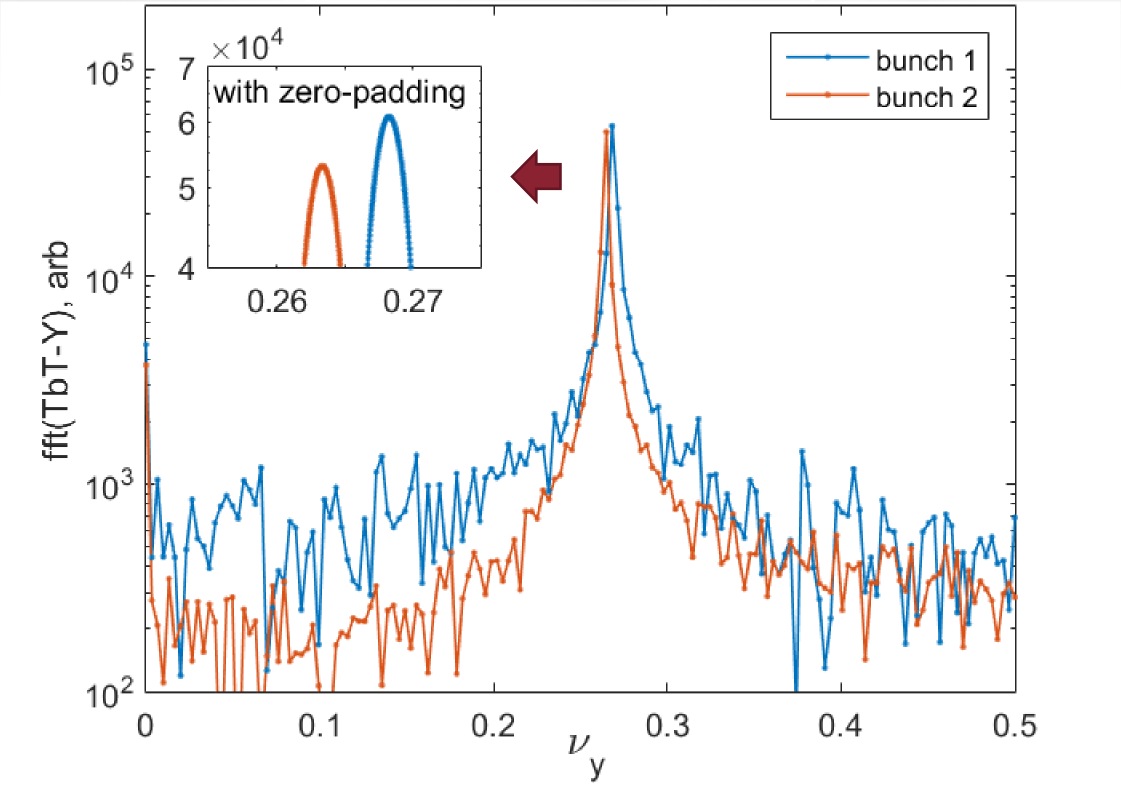
Turn-by-Turn Signals



Ping on turn 20

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

Vertical Tunes are Distinctly Different



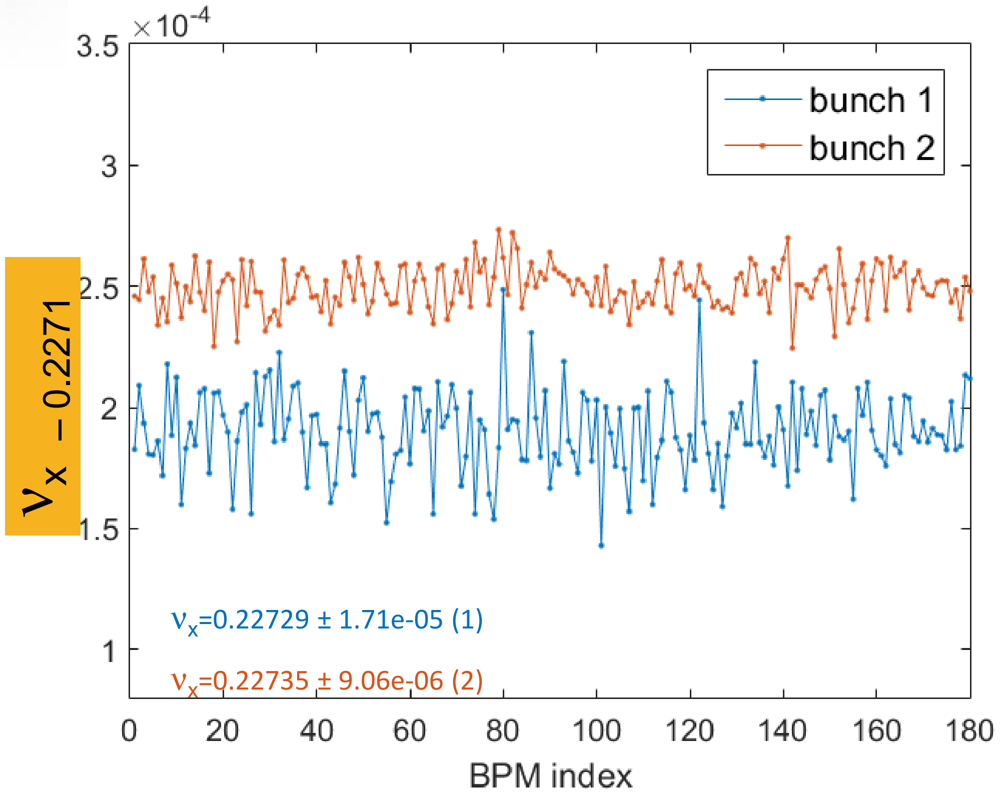
- Single BPM FFT shows tunes are clearly unequal
- Detailed analysis with interp'd FFT for 180 BPMs gives

$$\begin{cases} \nu_y = 0.26833 \pm 1.93\text{e-}5 \text{ (bunch 1)} \\ \nu_y = 0.26334 \pm 6.90\text{e-}6 \text{ (bunch 2)} \end{cases}$$

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

Same Measurement in the Horizontal

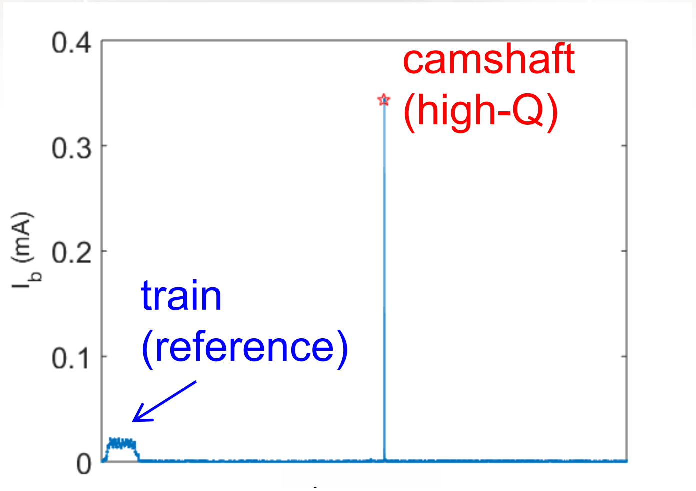
- The same pair of bunches, 0.25 mA (1) and 0.75 ma (2)
- Use horizontal pinger
- BPM ADC data processed to get separate TbT positions for each bunch
- Use 25 revolution harmonics to increase the resolution



$\Delta\nu_{21}$ =(6.0 ± 1.9)*1e-5

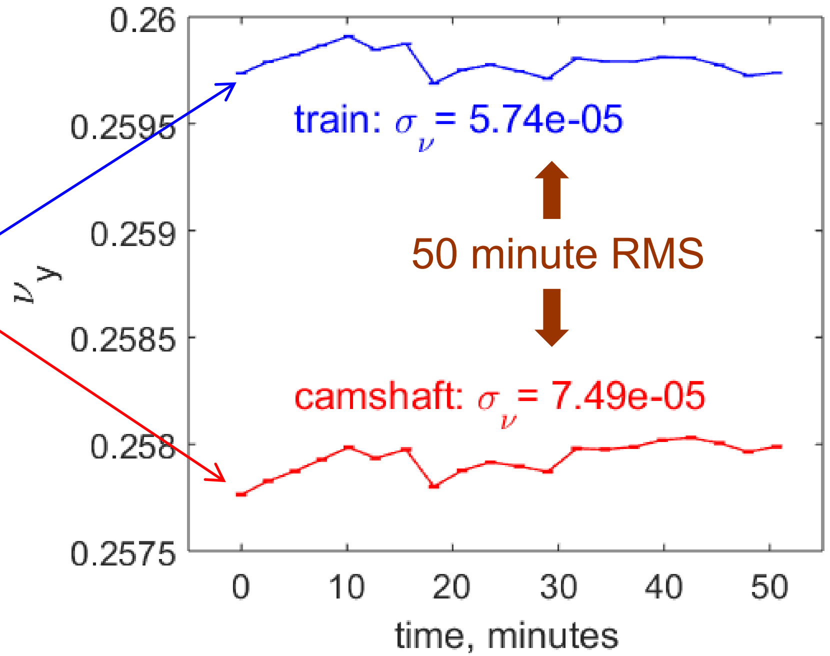
- This measurement convincingly shows that horizontal tune goes up with current (i.e. total wake is slightly focussing).

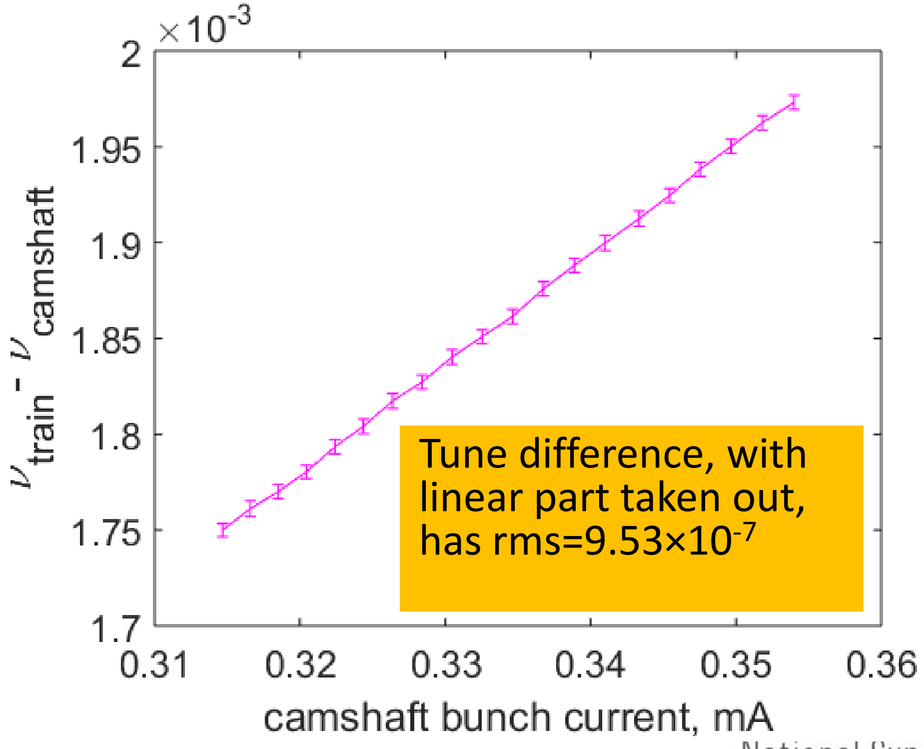
10^{-6} Tune Difference Resolution Achieved



- Initial fill pattern: 1.7 mA/80 bunches train + 0.35 mA camshaft bunch
- Measure vertical tunes every ~3 mins
- Over 50 mins tune rms σ_ν~10^{-4} for each
  Also, camshaft bunch decays by ~40 μA

Error-bars show single-shot RMS:
~10^{-7} train
~10^{-6} camshaft





More Advanced Measurement Examples

Three examples to follow:

- Tune shift with current (for collective effects/impedance)
- Tune shift with amplitude (for single-particle dynamics)
- Non-invasive lattice function measurement during user operations (for stability)

Many more applications are possible

From Tune Slope with Current to Kick Factor and Coupling Impedance

Kick factor:

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

definition

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

relation to impedance

(ρ or, at least, σ_z are measured separately)

$$\delta\nu_y(Q_b) = -k_{kick} Q_b \frac{< \beta_y >}{4\pi \; E/e}$$

relation to tune slope with charge

$$k_{kick} = -\frac{4\pi \; E/e}{<\beta_y> T_{rev}} \frac{d\nu_y}{dI_b}$$

or with beam current

- Typically measuring the kick factor of the entire machine is straightforward, because tune slopes are large (at least in y)
- For NSLS-II (bare lattice ~2014)

k_{kick} ~15 kV/pC/m, $\frac{d\nu_y}{dI_b}$ ~ - 0.075/ma

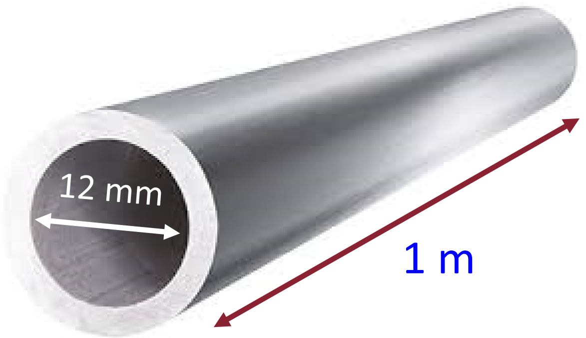
A. Blednykh et al., IPAC'14

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

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

then we can measure kick factors as low as10 V/pC/m

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



10 V/pC/m is a resistive wall kick factor of a smooth 1 m long Al pipe 12 mm in diameter (σ_z=5 mm)

From Tune Slope with Current to Kick Factor and Coupling Impedance

Kick factor:

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

$$k_{kick} \propto \int |\tilde{\rho}|^2 \, \mathrm{Im}[Z_y(\omega)] d\omega$$ relation to impedance (ρ or, at least, σ_z are measured separately)

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

$$k_{kick} = -\frac{4\pi \; E/e}{<\beta_y> T_{rev}} \frac{d\nu_y}{dI_b}$$ or with beam current

Reference technique allows for repeated measurements, while moving small impedance components or making local orbit bumps[1] around them, so we can resolve small impedances on top of relatively large total impedance of the ring.

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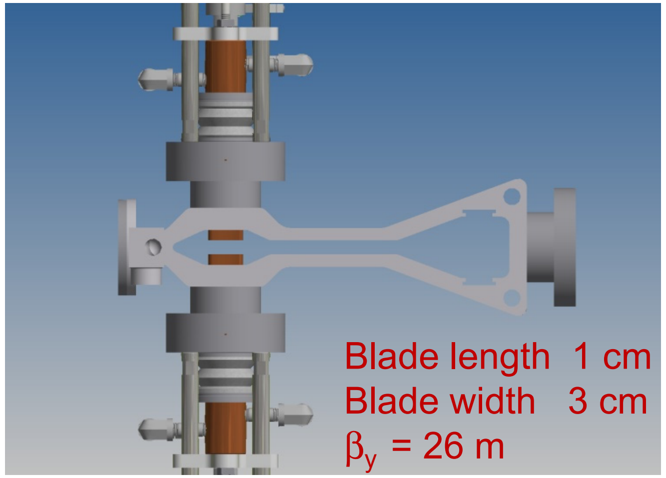
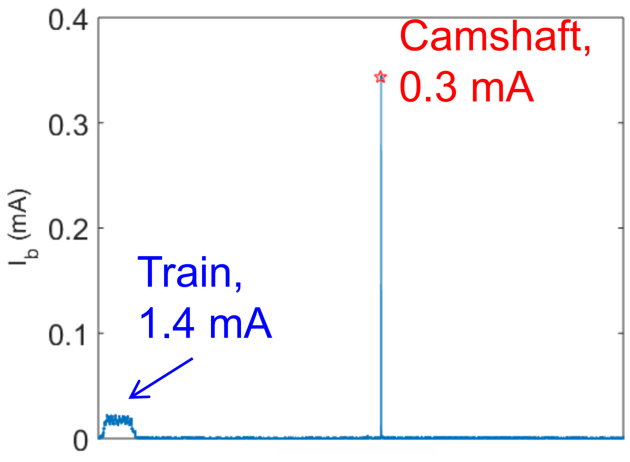
[1]V. Kiselev, V. Smaluk, DIPAC 1999
L. Emery, G. Decker, and J. Galayda, PAC'2001

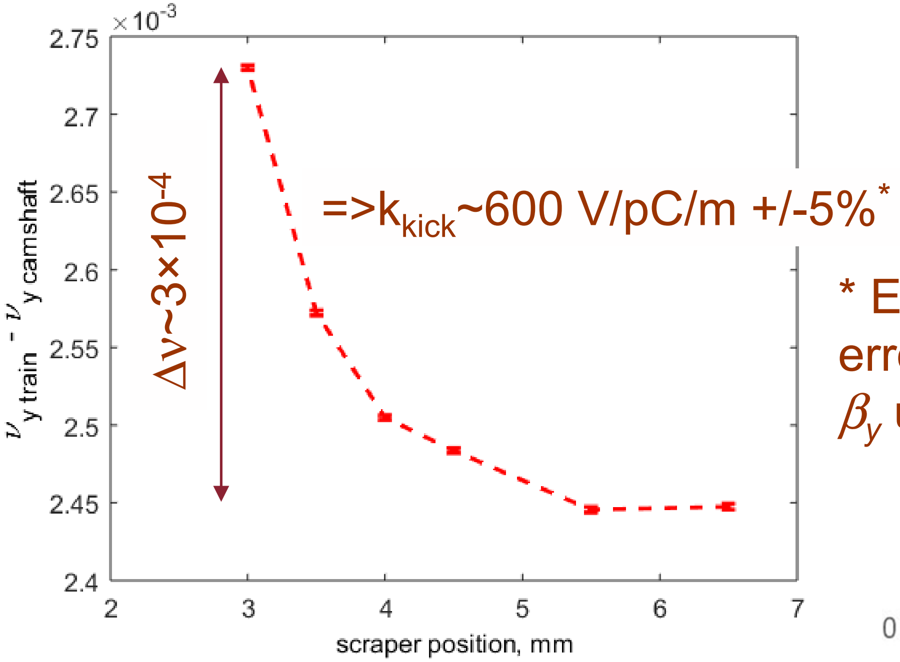
Local Impedance Measurement: Vertical Scraper

- 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

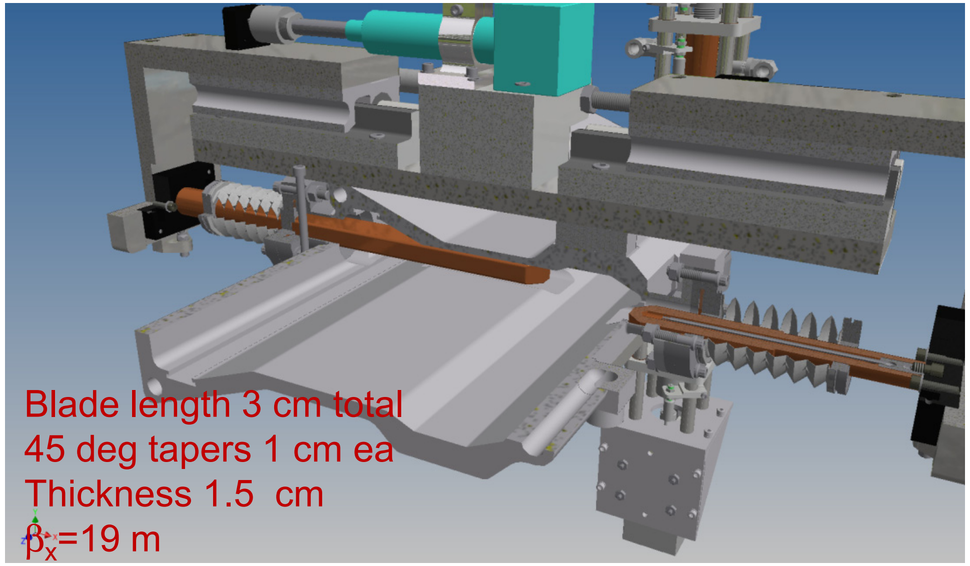


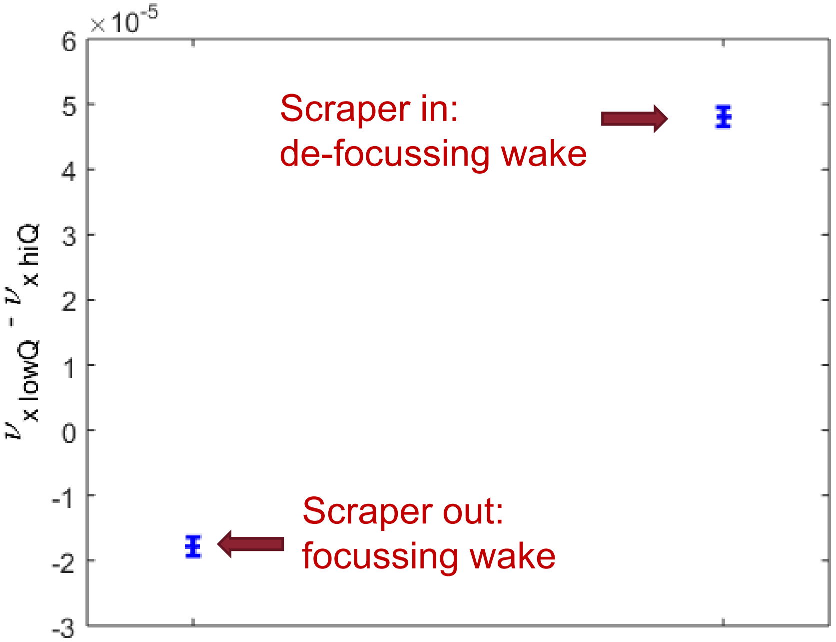


* Estimated error due to β_y uncertainty

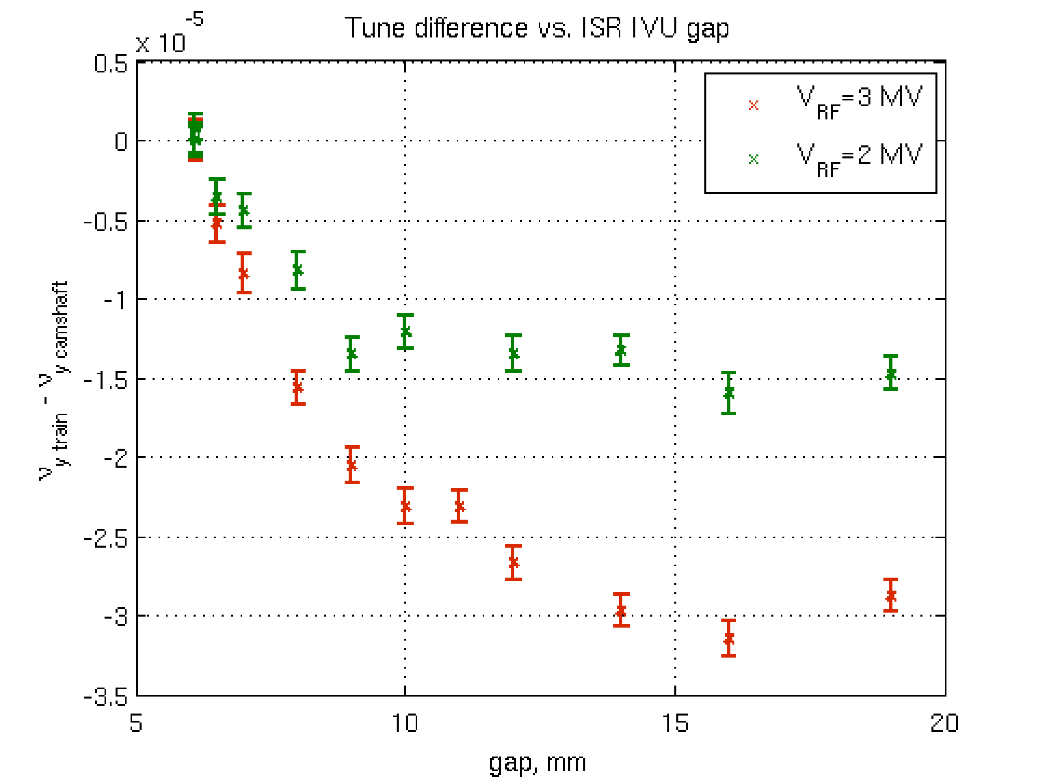
Same for the Horizontal Scraper

- Two bunches stored, inner scraper blade moved in
- Change in the tune difference is due to (added) scraper impedance
- As expected, wake effect becomes de-focussing as the scraper moves in





In-Vacuum Undulator Tuneshifts vs. Gap

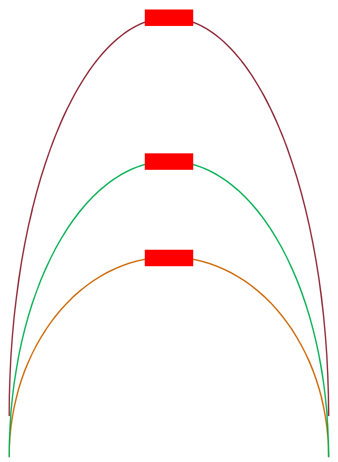


- Performed on C4-ID (ISR, IVU23, L=2.8 m). Tune difference between the train and camshaft bunches measured vs. gap.
- ~10^{-6} tune relative tune resolution at <1000 turns, 0.3 mA camshaft bunch current, adequate to see the effect
- Measured current-dependent tuneshifts are two orders of magnitude smaller than the tuneshift induced by the natural focusing of the undulator => reference technique is a key

For alternative method see e.g. V. Smaluk et al., NIM A, 871 (2017)

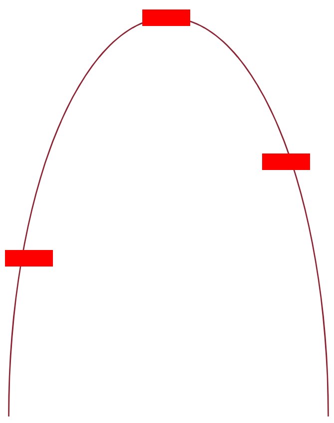
Single Shot Measurement of Tune Shift with Amplitude

Conventional measurement



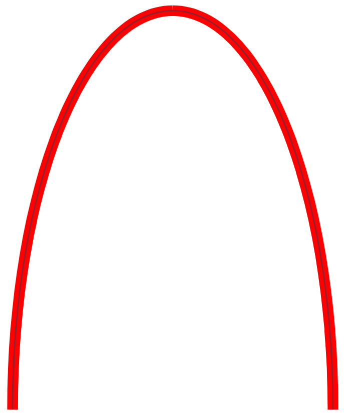
Limited by kicker jitter and machine drifts

New option



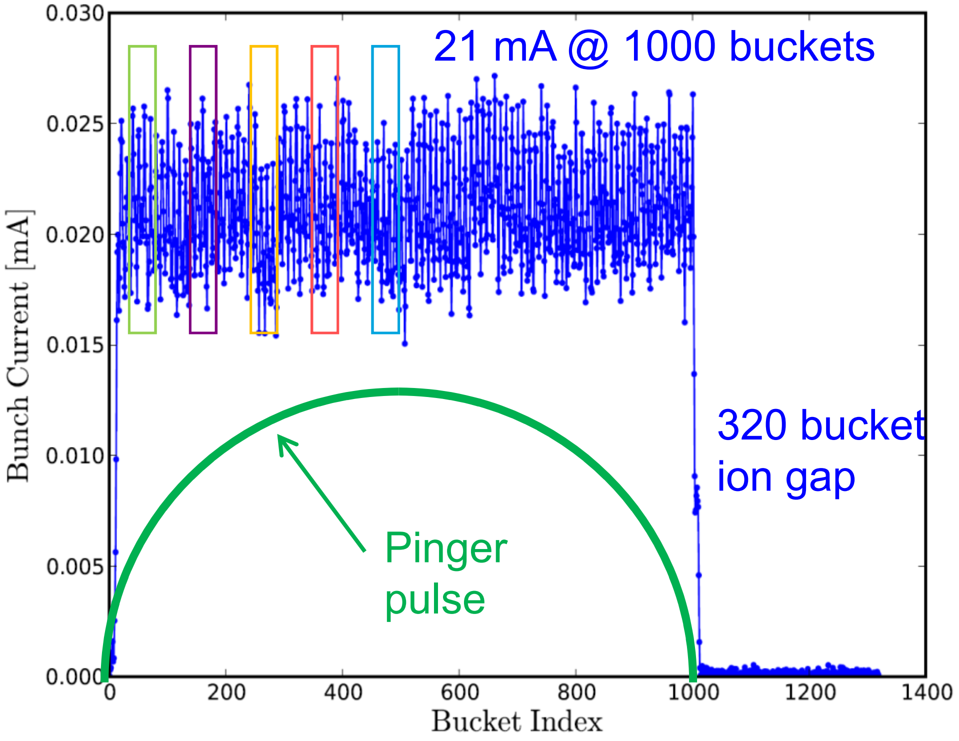
Limited number of trains / turn => few data points only

Alternative new option



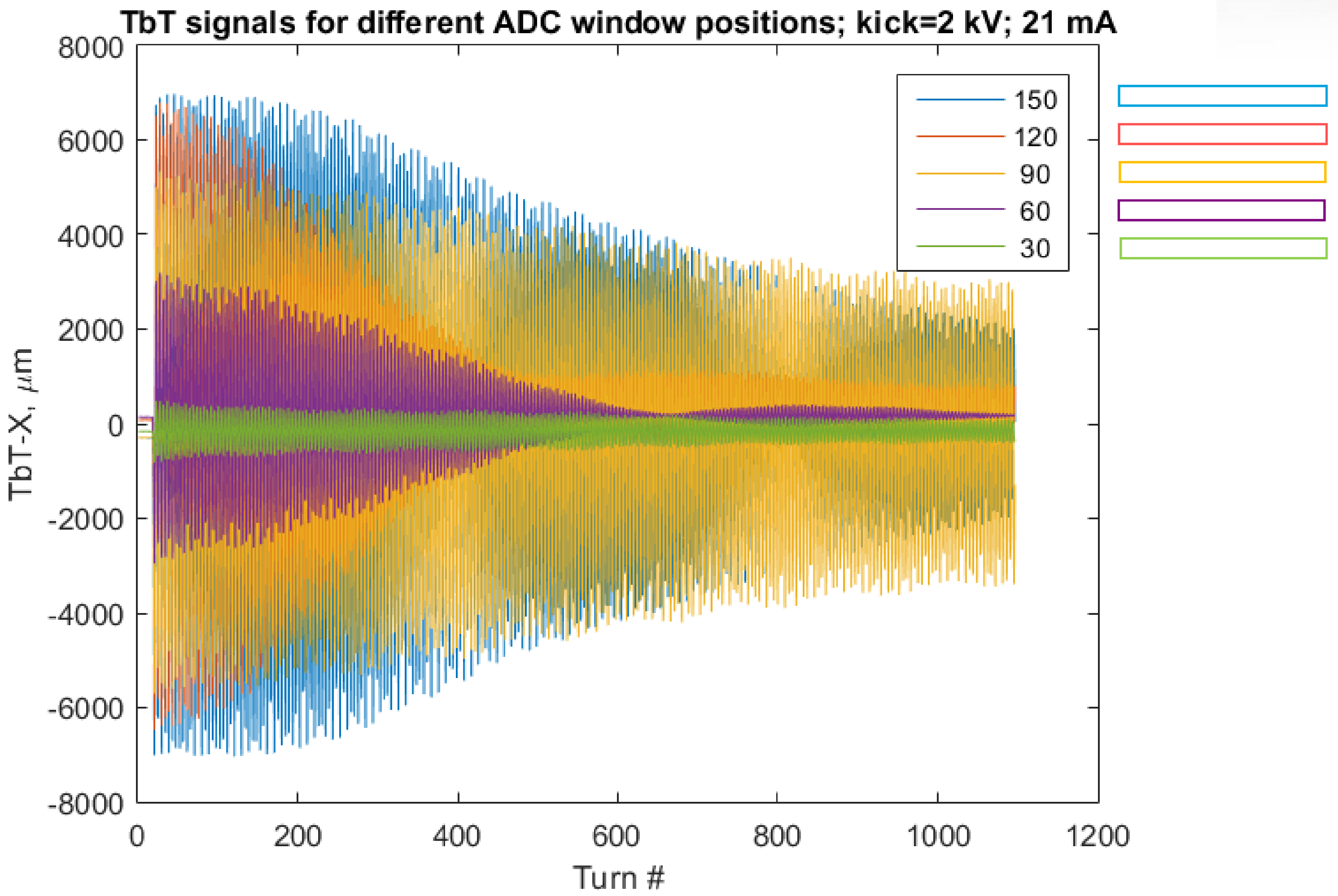
Worked for us

Measurement Setup



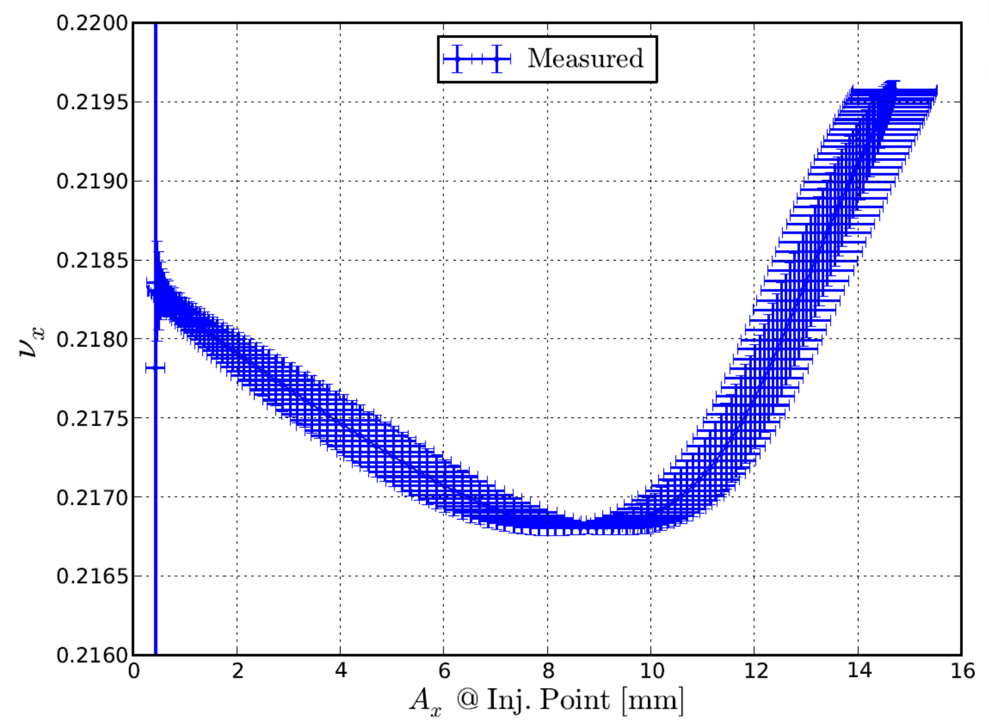
- Fairly uniform fill pattern at low current (no collective effects)
- Adjust pinger timing to center maximum kick in the middle
- 11 sample ADC bin (~47 RF buckets); slide over the turn (results independent of bin size when << than kicker rise time)

TbT Signals from Selected ADC Bins



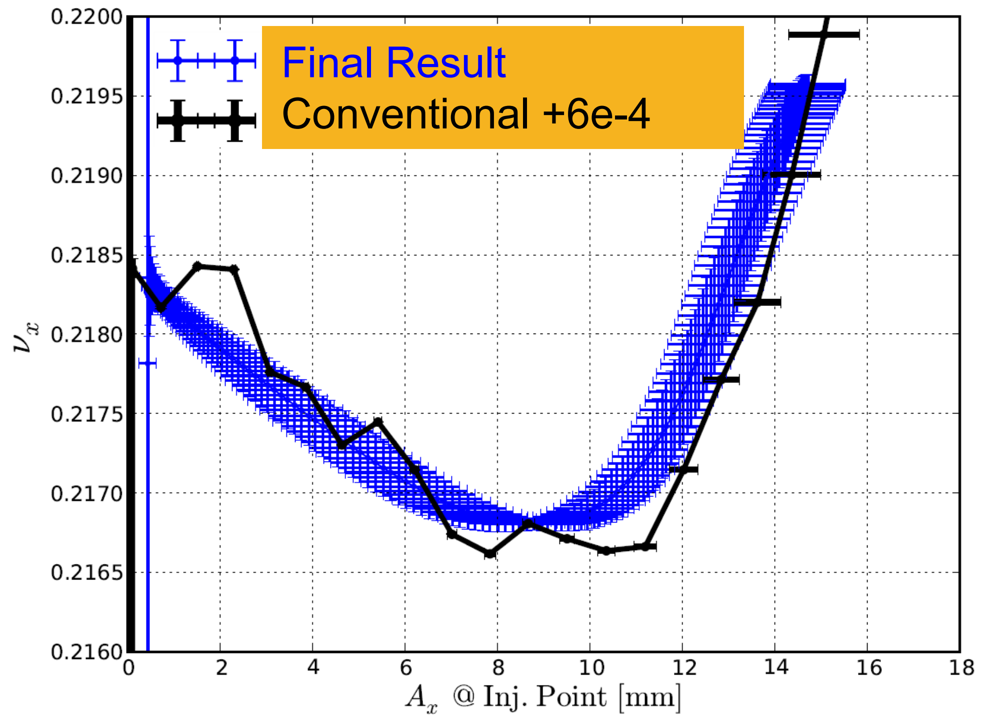
- Induced amplitudes vary according to bin position with respect to pinger
- Short chunks of the bunch train can be resolved!

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

Final Results: Horizontal



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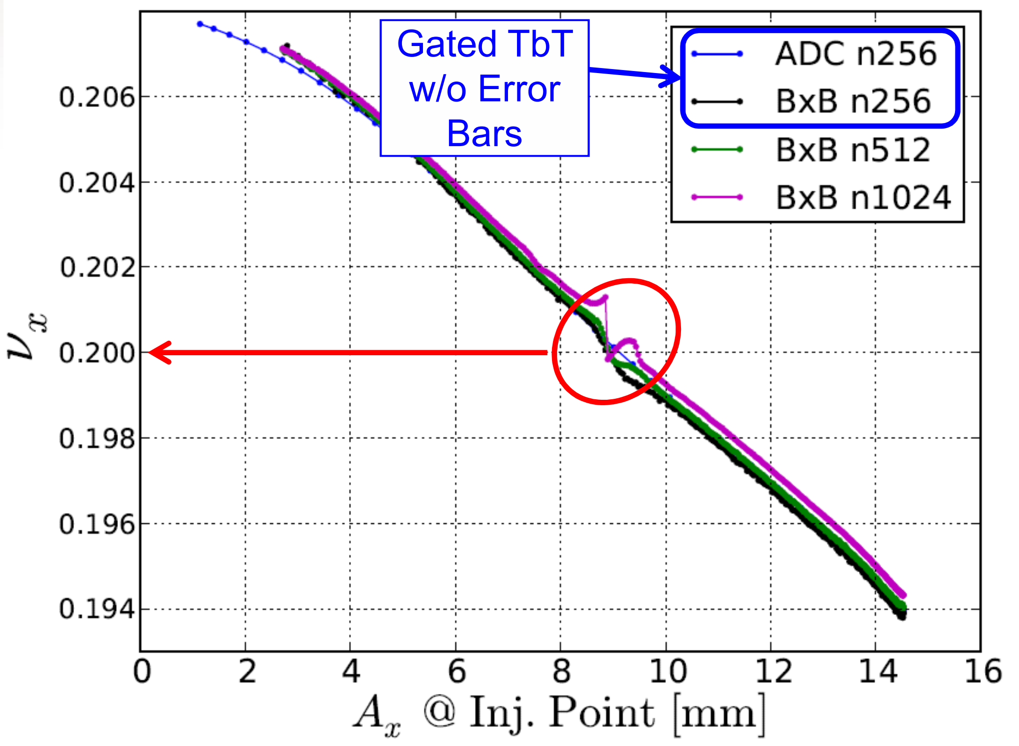
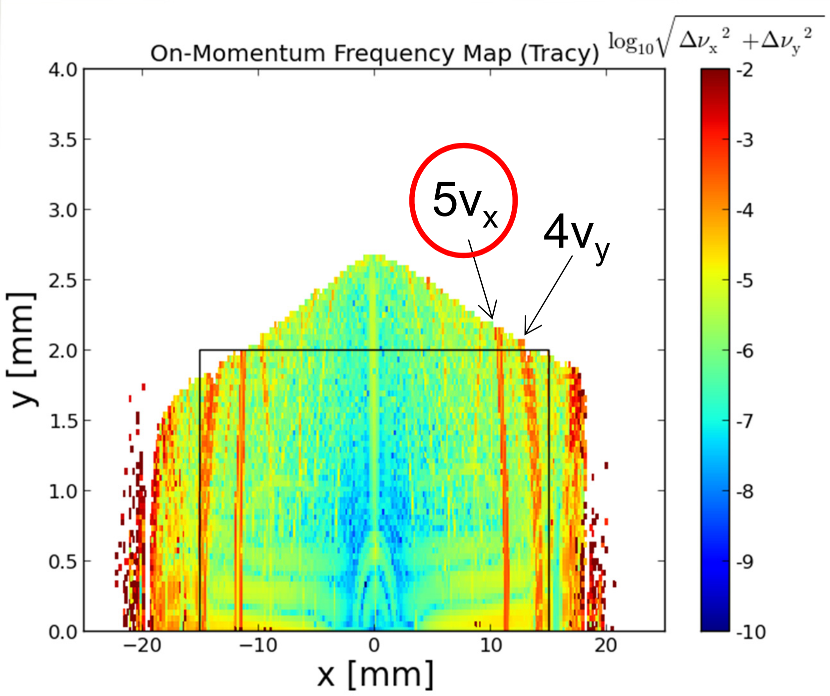
Example of Further Optimized Measurement



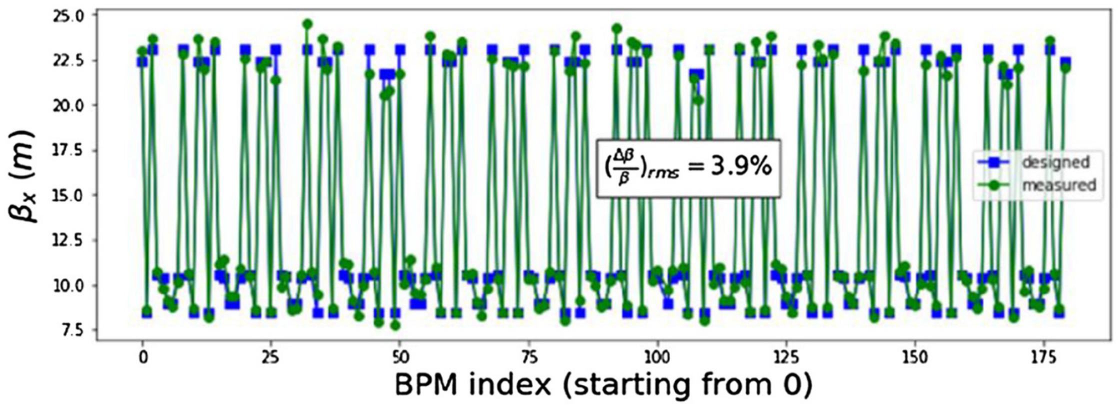


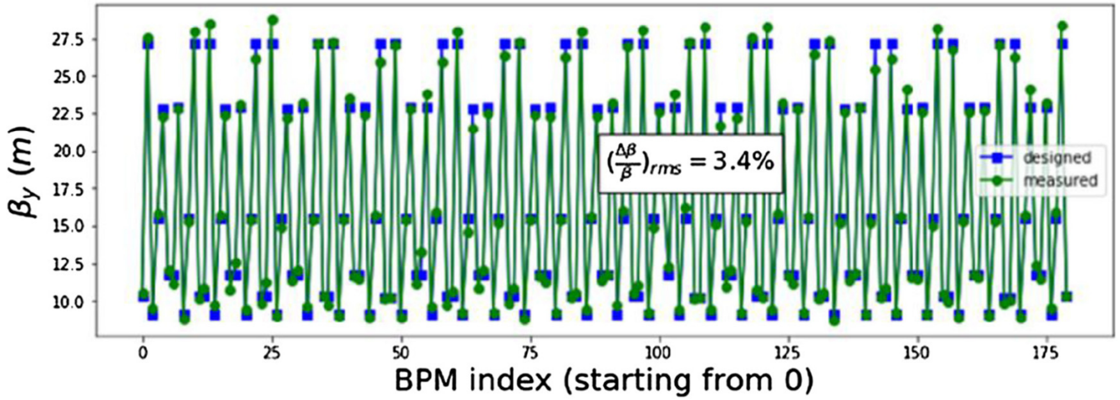
Y. Hidaka et al., NAPAC 2016

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

Lattice Functions Measured from Camshaft Train during User Operations

- Motivation: user beam stability
- Constraints: user beam stability
- Small perturbation on a small fraction of the train is driven by transverse bunch-by-bunch feedback
- Use gated signal from 180 BPMs to measure lattice functions
- Need good TbT resolution and ability to discriminate between the camshaft and the main train





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Conclusions

- State-of-the-art NSLS-II BPM receivers enable advanced beam dynamics measurements, which rely on resolving individual (or groups of) bunches within a turn.
- 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 reference technique for measuring the transverse impedance (kick factor) of storage ring elements.
- This 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.
- Other applications include single-shot measurements of tune-shift with amplitude, non-invasive lattice characterization during user operations and more.
- Looking forward to on-going NSLS-II R&D for “real” bunch-by-bunch BPM
- We are confident that new applications will come up and are looking forward for stimulating discussions at this conference

Thank you

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