Single Micron Single-Bunch Turn-by-Turn BPM Resolution Achieved at NSLS-II

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BROOKHAVEN NATIONAL LABORATORY
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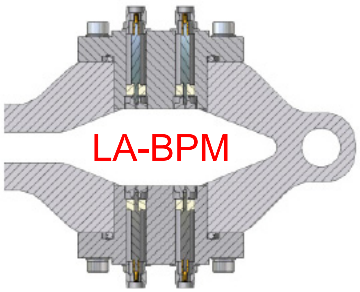
Outline

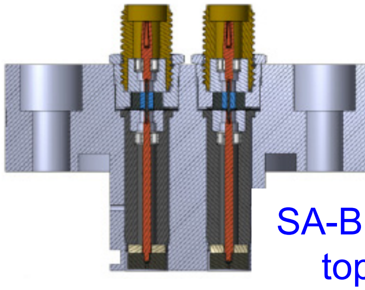
1. Introduce NSLS-II BPMs and resolution in standard configuration
2. Motivate resolution improvements for single- and few bunch fills and the need to resolve a few bunches within a ring turn
3. Show how this is done and the best resolution achieved
4. Give examples of beam physics measurements that benefit from these new BPM capabilities

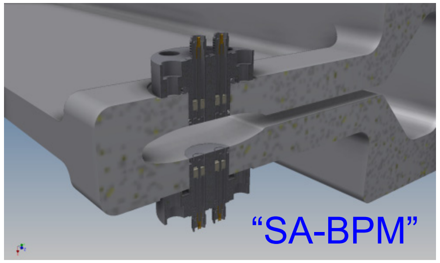
Introduction: NSLS-II BPM Types & Pickup Geometries

- NSLS-II: 30 cell DBA 3 GeV ring with 1 nm / 8 pm design x/y emittances (see WEPOY055 for more)
- NSLS-II BPMs differ in chamber and button geometry



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.)	2-3 per ID straight ~30 Total (now)
Special BPMs (injection, BxB fdbk, test, ...)	~10



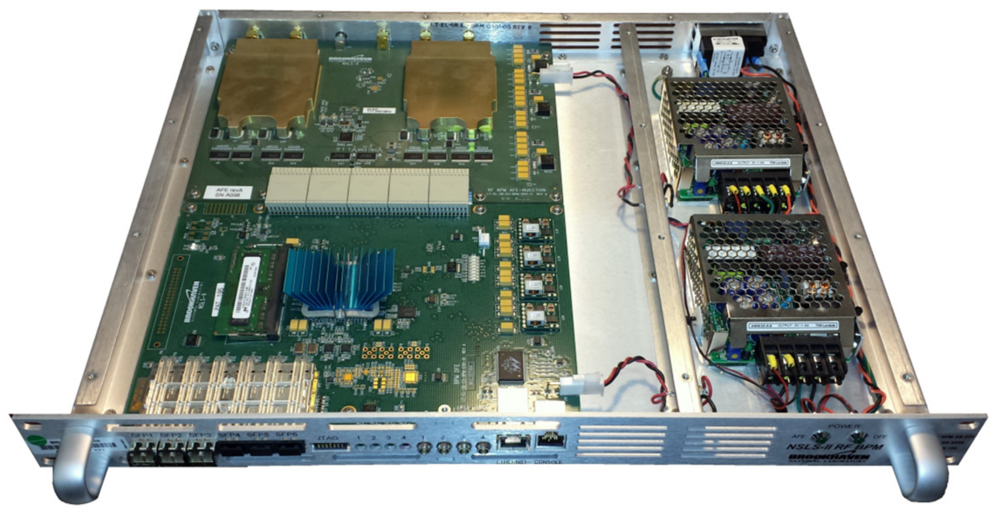


Real SA button assemblies are rotated around the vertical

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

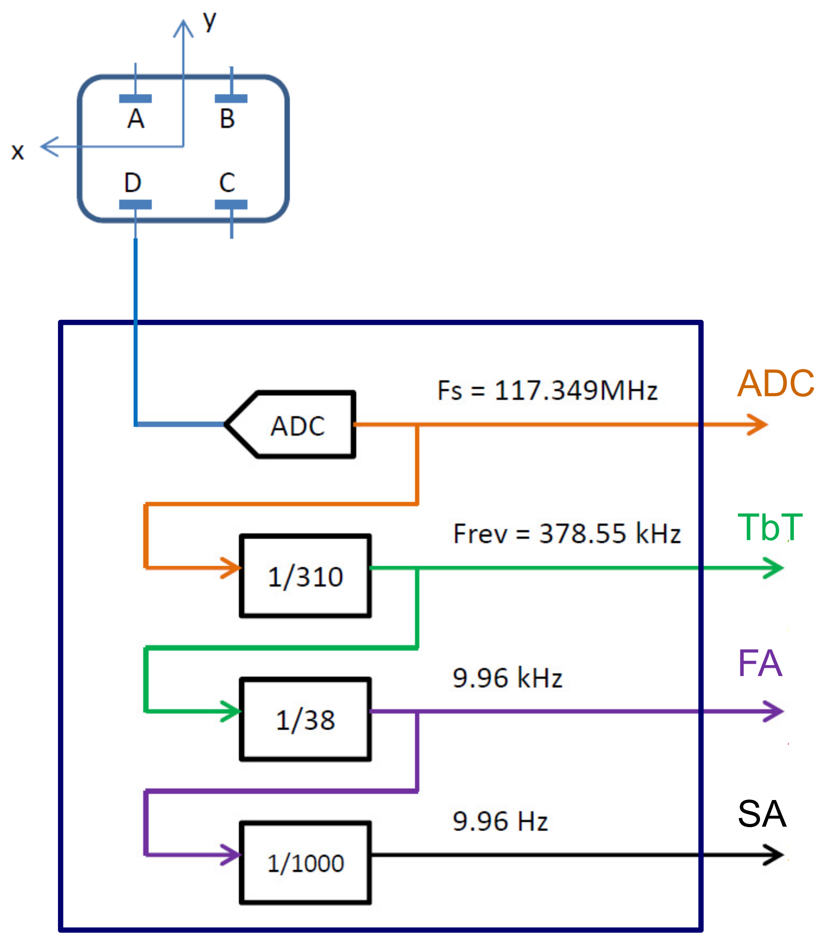
Introduction: NSLS-II BPM Receivers

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 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 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



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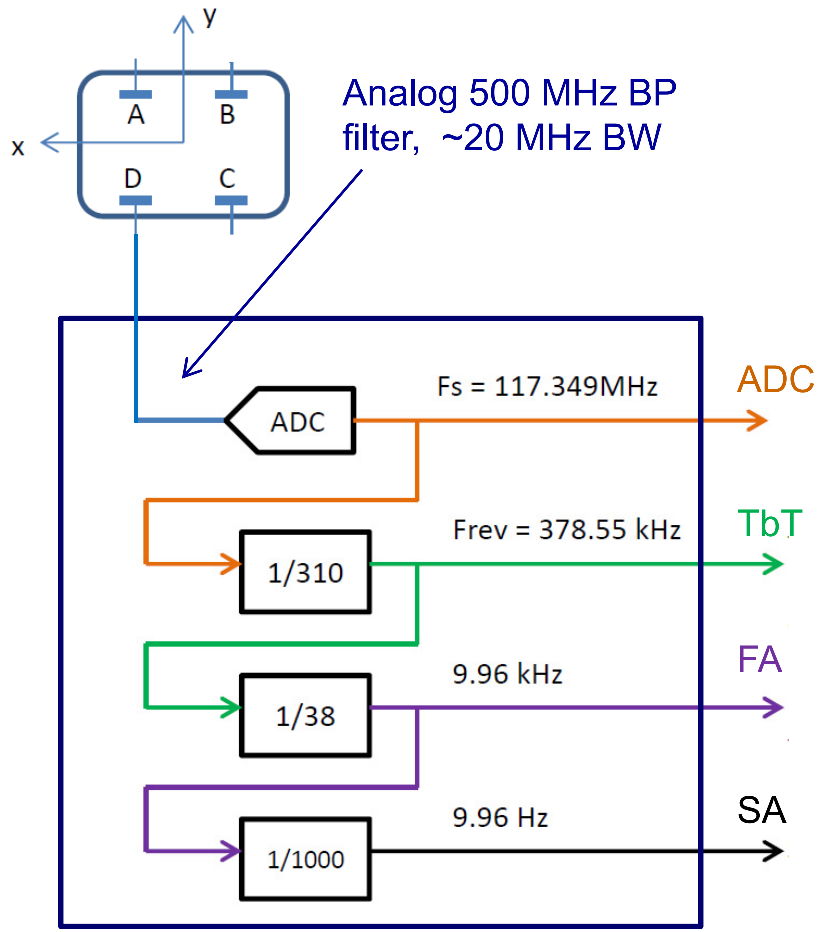

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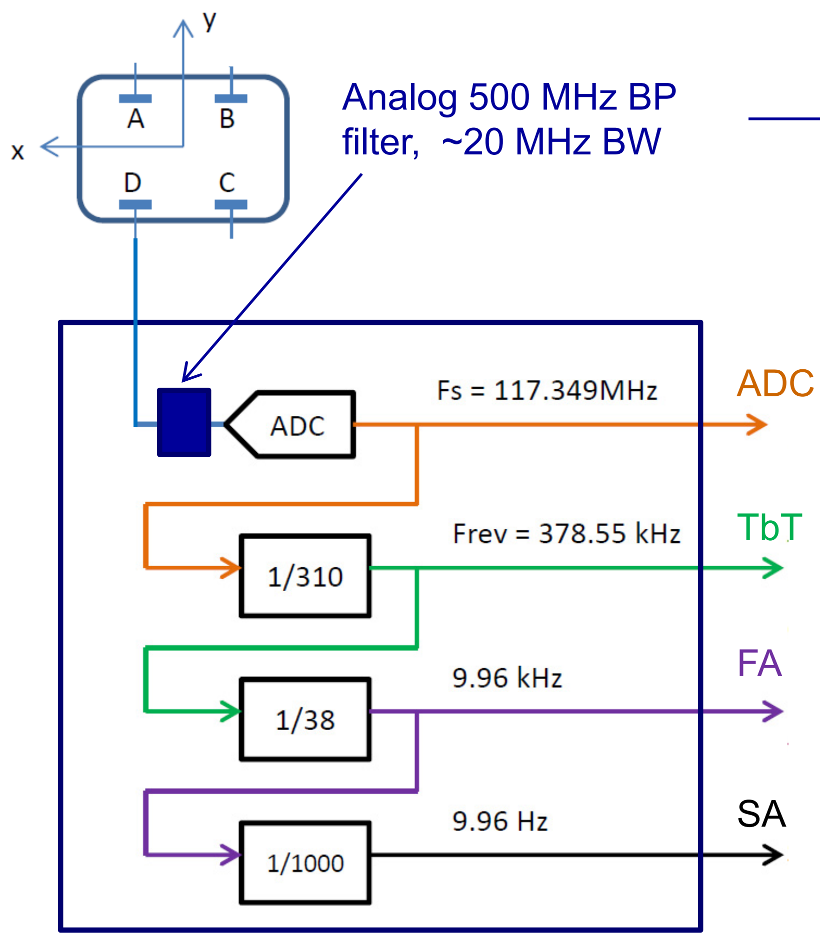

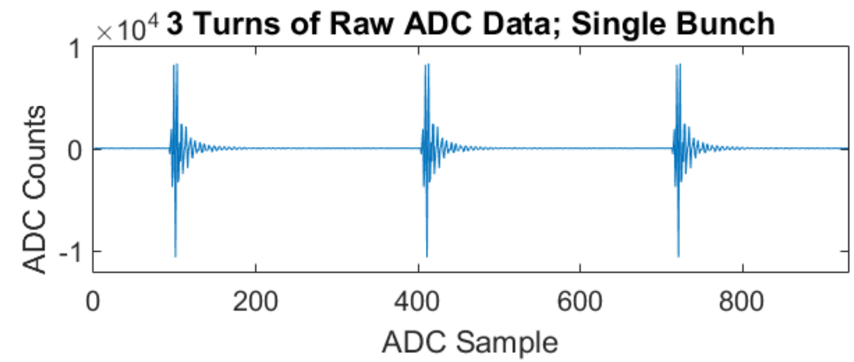

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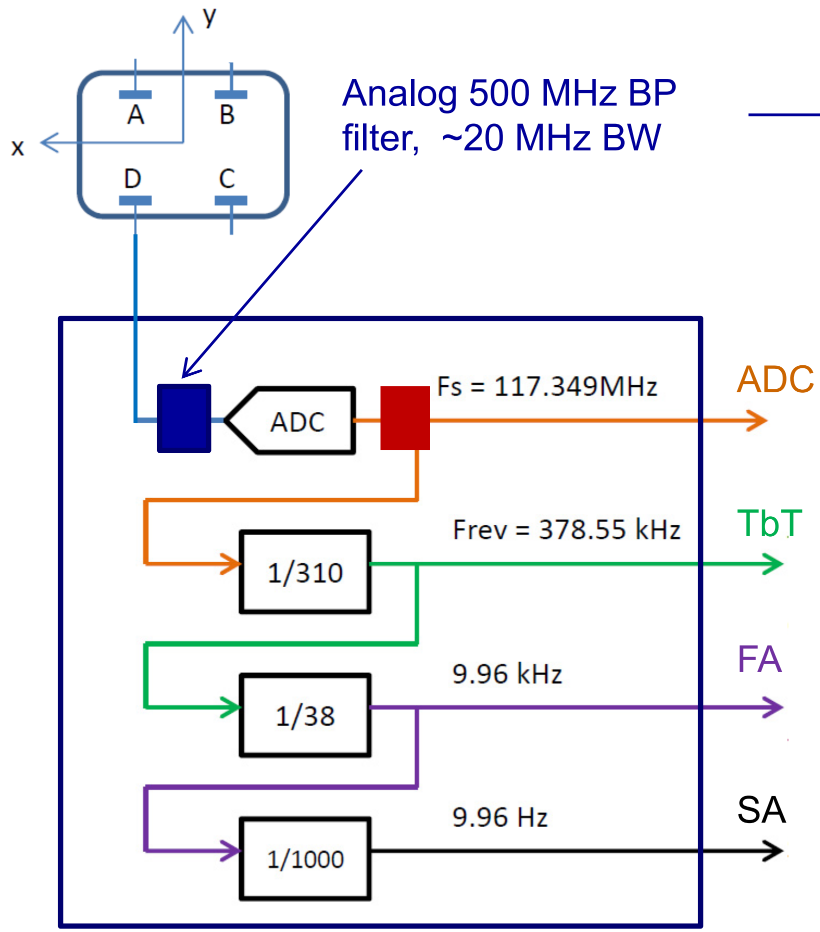

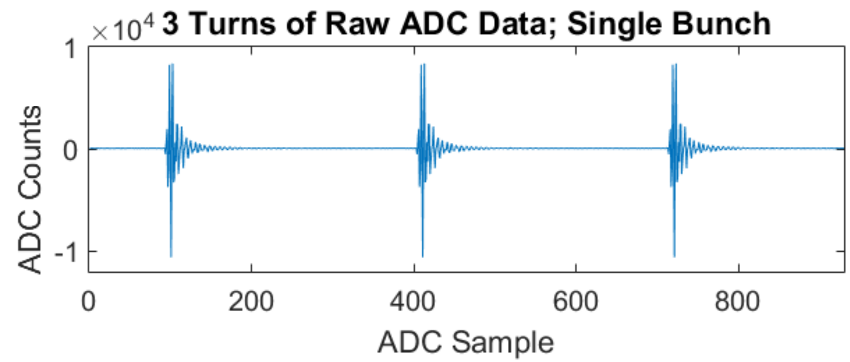

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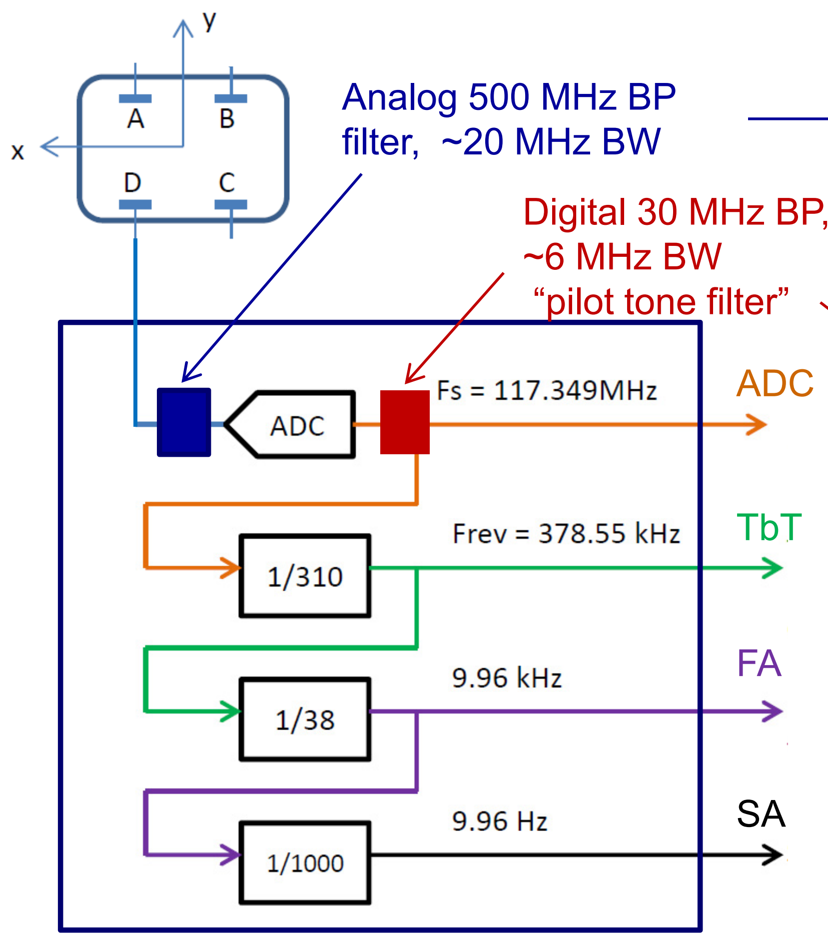

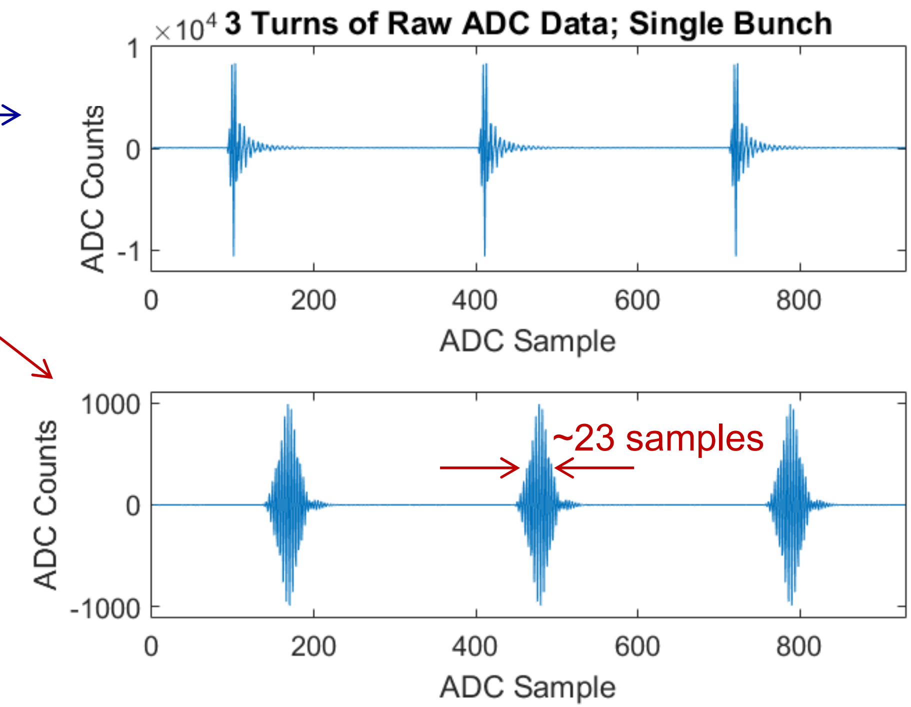

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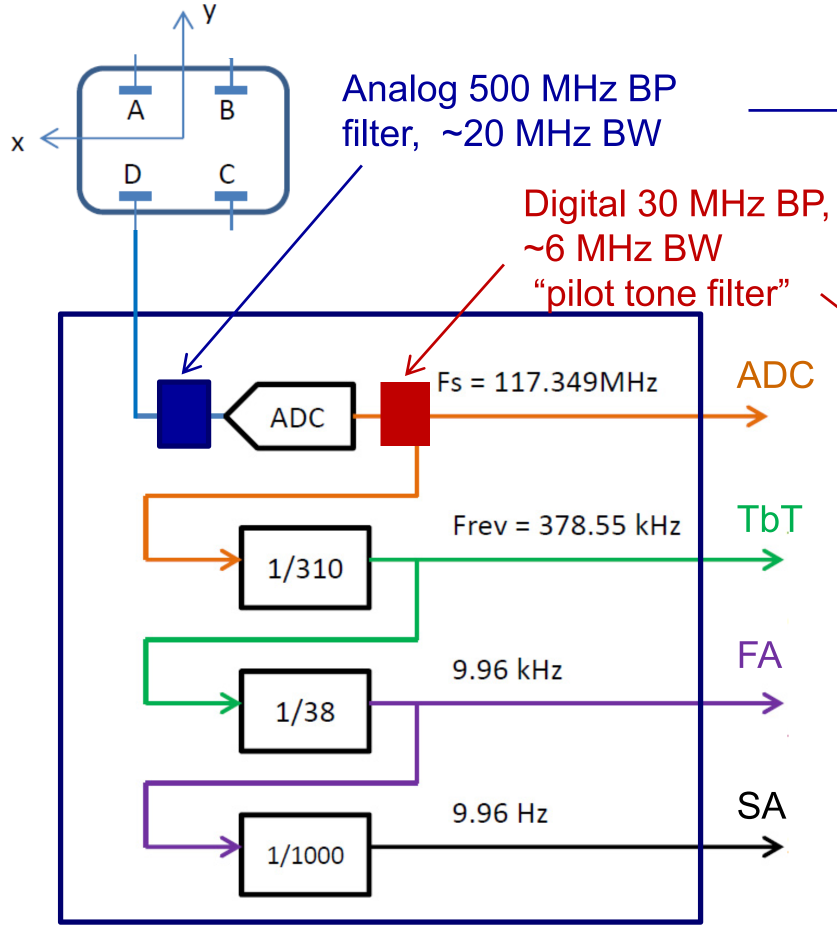

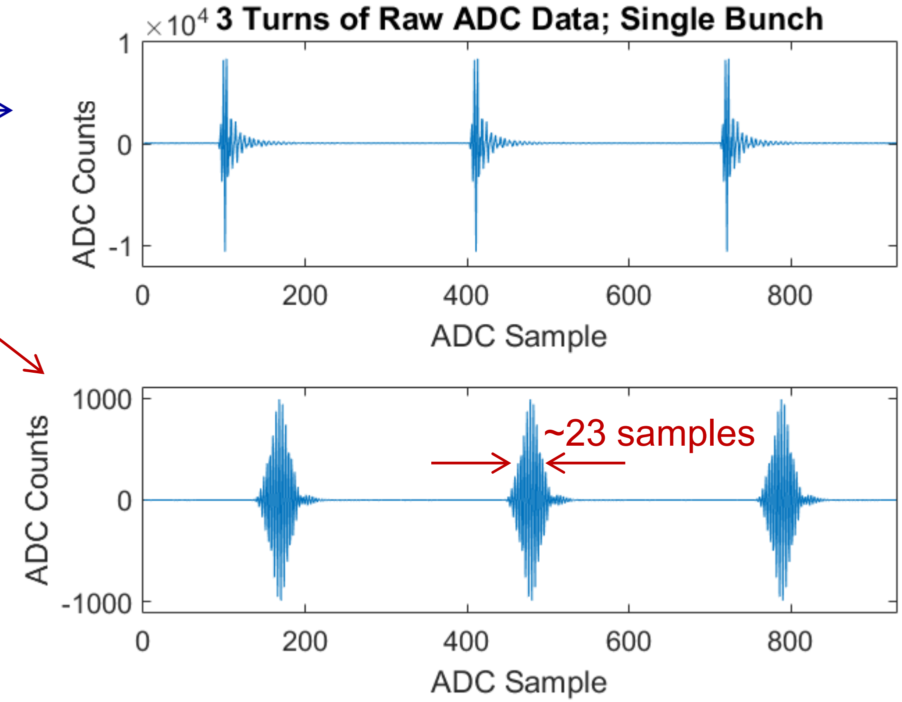

1 Turn = 310 ADC Samples =
=1320 of 500 MHz RF buckets

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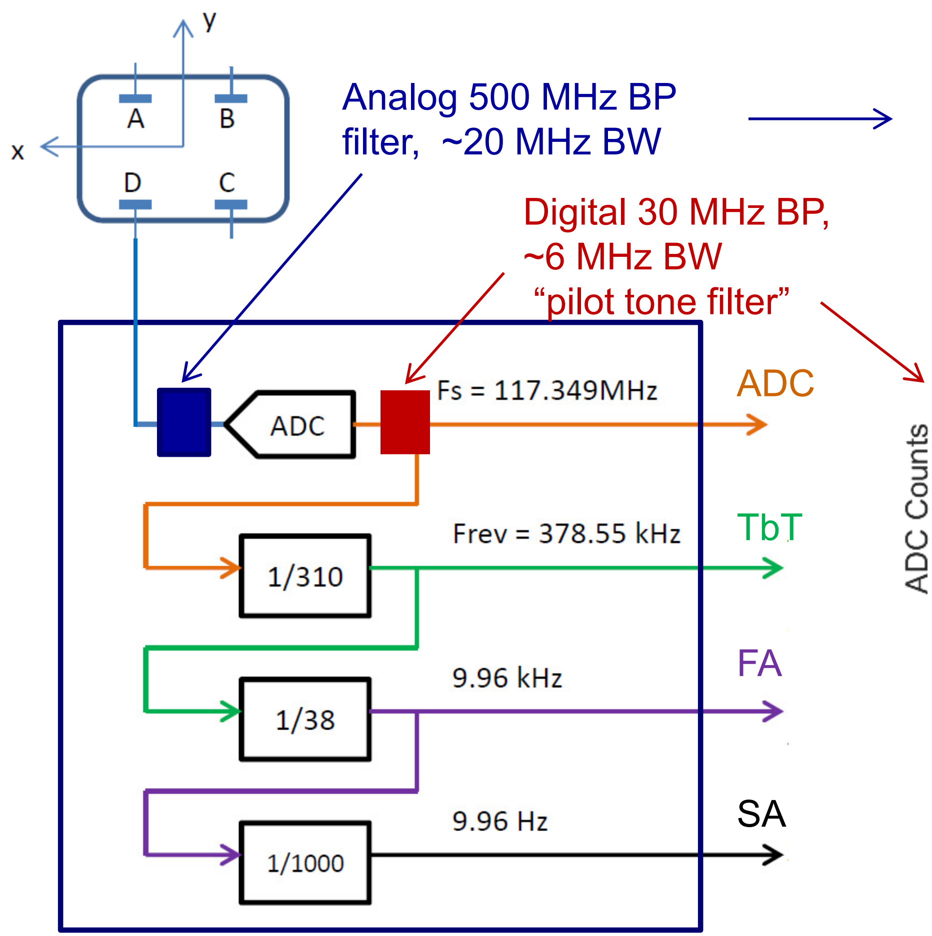

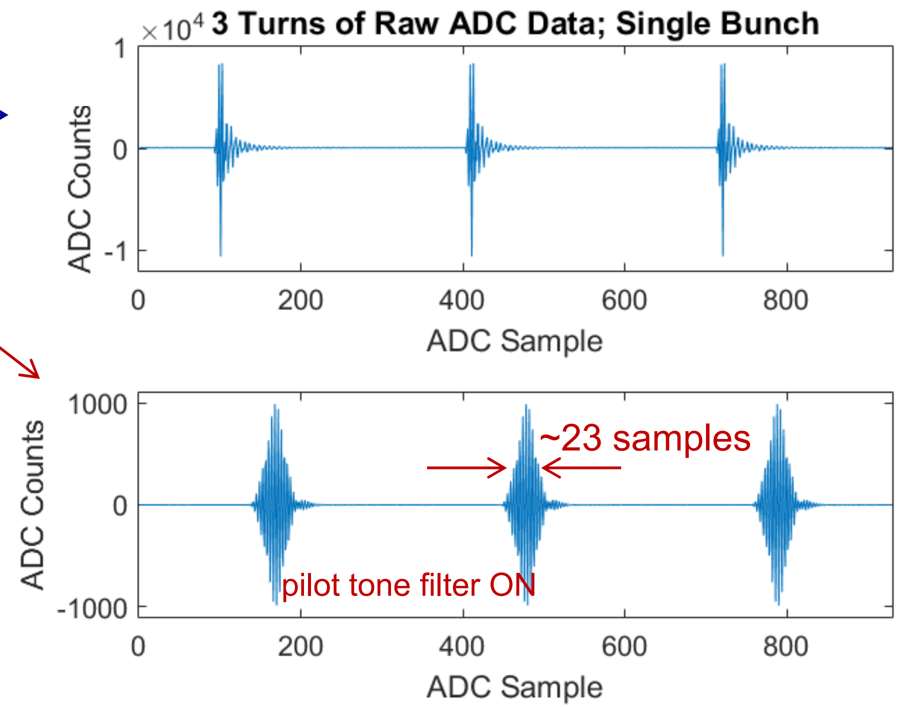

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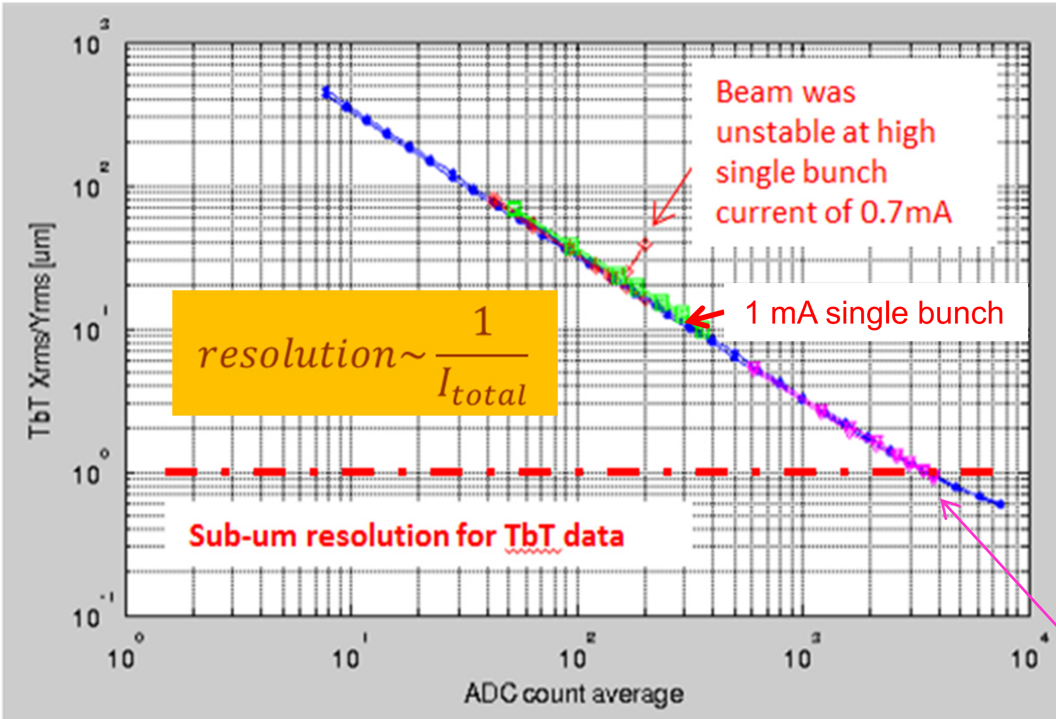
- TbT X, Y, and Σ are obtained (in FPGA) from ADC signals by coherent signal processing locked to revolution harmonic.

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 is 1-2 magnitude orders worse
- The goal of present work is to improve it, and enhance BPM capabilities for single and few-bunch fills

Motivation

- 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

- 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

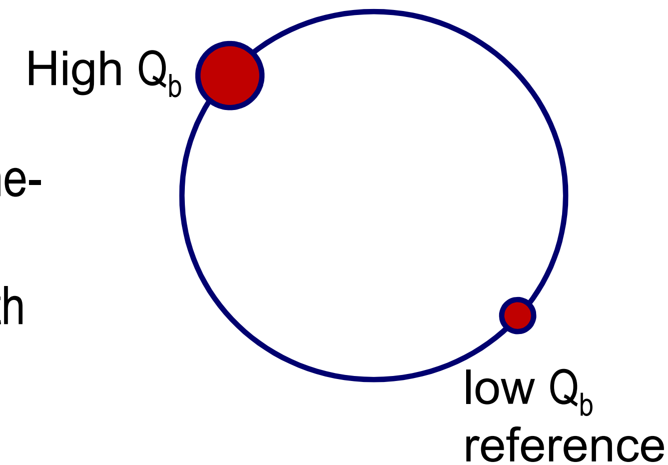
- Apart from resolution why special BPM signal processing?

  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 undulator or a wiggler?
- By design, these are small.
- Impedance is not directly measured, but Z-related effects ~Q_b are.
- Take Q_b=1 nC, β_y=3 m, k_y=500 V/pC/m
  - Tune shift ~4×10^{-5}
  - Closed orbit shift ~0.7 μm rms per Δy=1 mm
  - Local betatron phase jump of ~4×10^{-5}
- These are hard to measure!
- The standard approach, via multiple injections or time-decay, is virtually impossible due to machine drifts
- Can be overcome by the relative measurements, with high-Q_b and low-Q_b bunches



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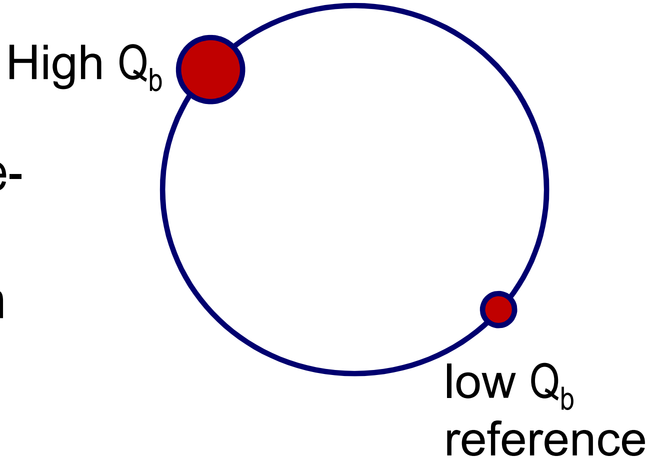
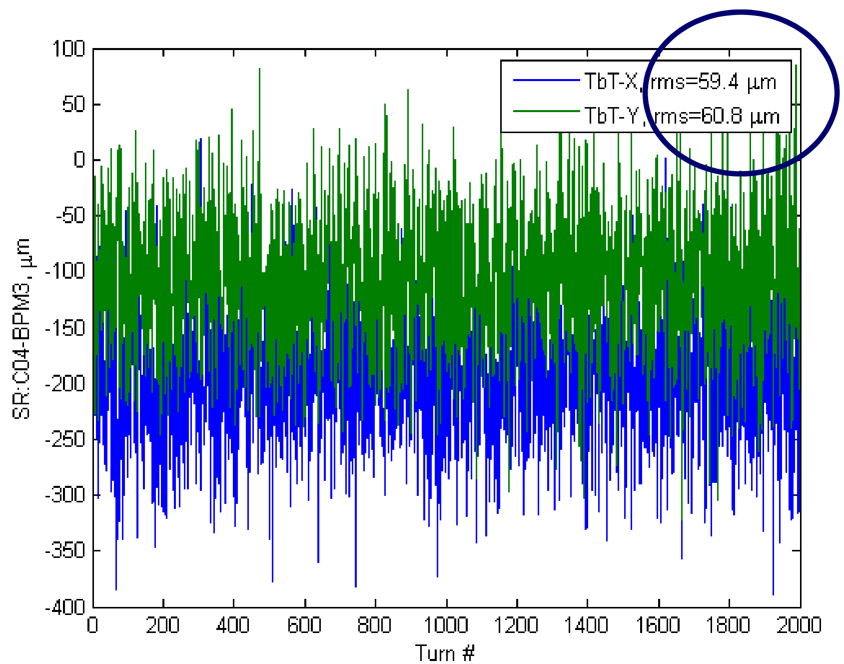


Need good resolution at low current, and many BPMs capable of resolving the orbits of at least two bunches

BPM Resolution Defined

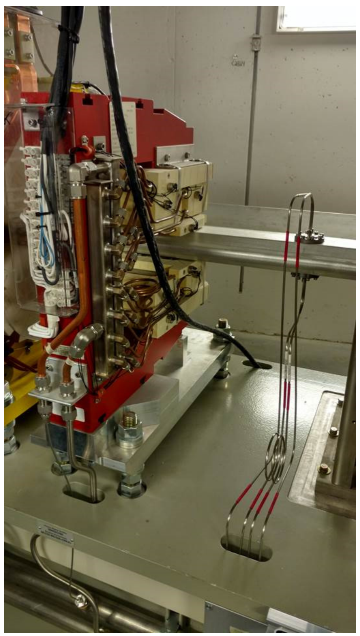
- TbT resolution is defined as the beam position standard deviation over a few thousand turns (typically 2-3 k)
- Example: resolution at 0.1 mA single bunch is ~60 microns in X or Y

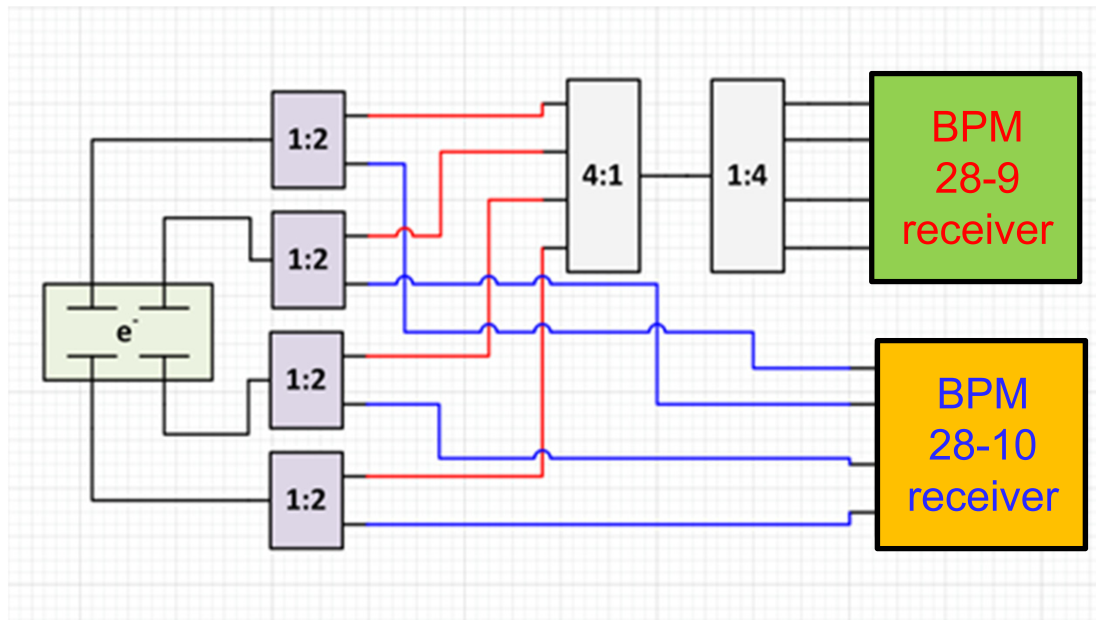


- Problem: this includes true beam motion, esp. at higher current
- Solution: splitter-combiner test BPM config on BPM28-9

Combiner-Splitter Test BPM Setup in Cell 28

- Dedicated LA BPM in Cell 28 with two BPM receivers
- True beam motion is excluded for 28-9, but not 28-10

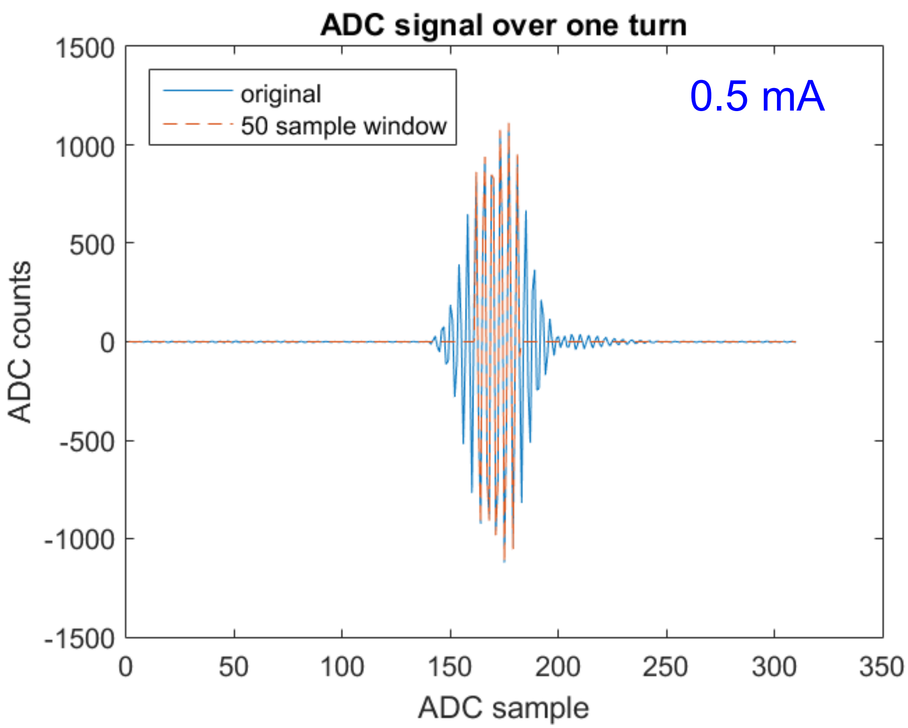


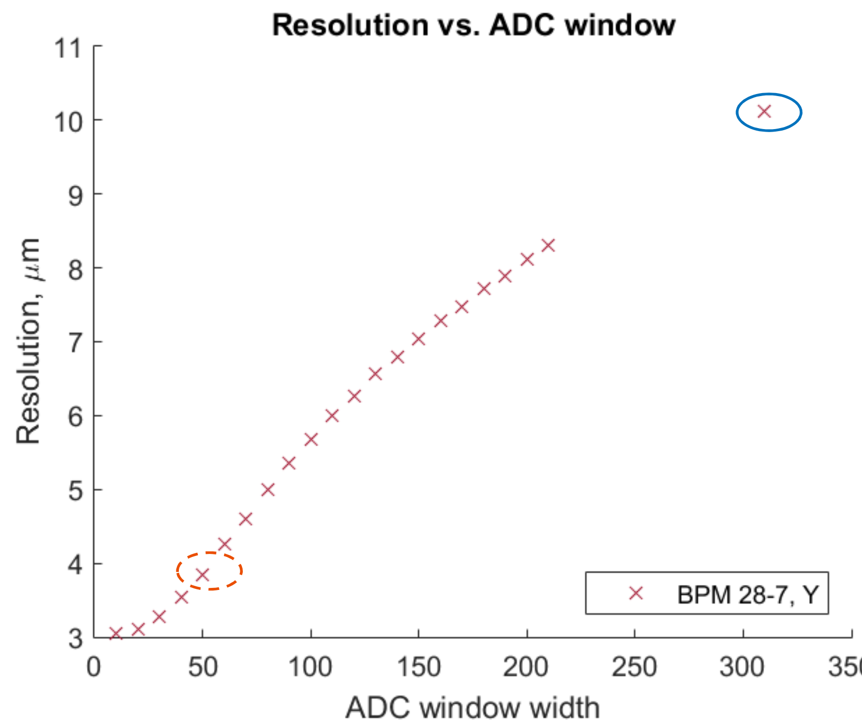


- Power splitters introduce 3 dB loss => measured resolution is √2 higher than that for a regular LA BPM

Resolution Improvement: Time-Domain

- 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)

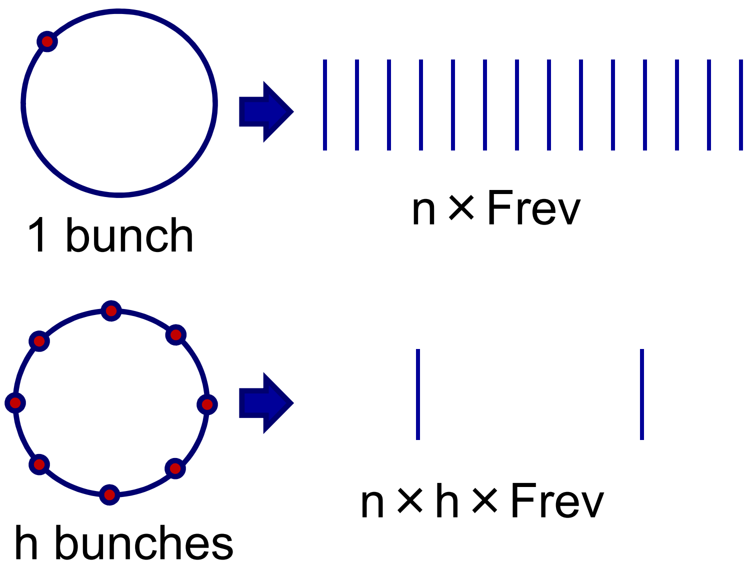


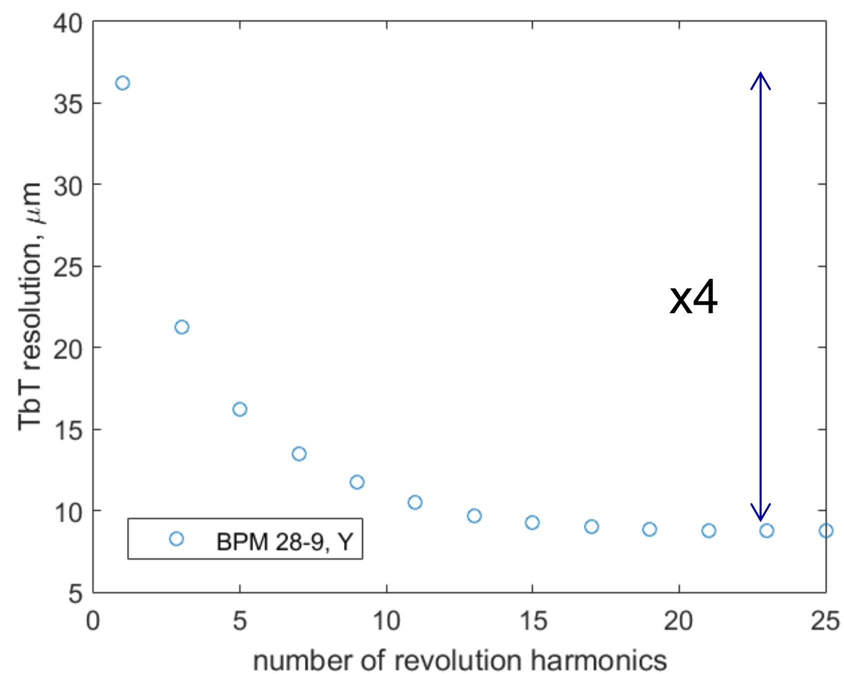


- This results in resolution improvement by factor of 3 to 4.

Resolution Improvement: Frequency Domain

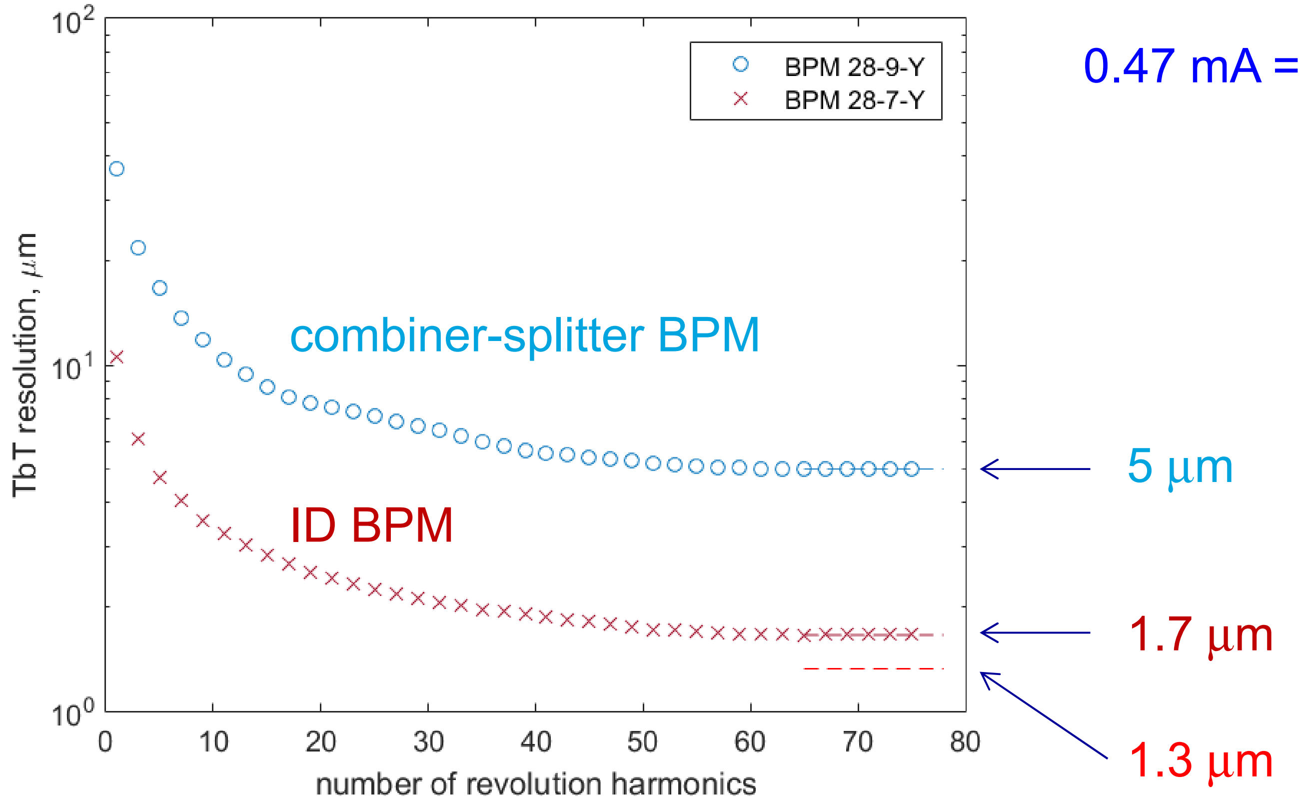
- Standard processing looks at a single revolution harmonic, f = 1320 Frev, which is fine for long trains used in user operations
- Single bunch fills have BPM signals at every multiple of Frev (before filters)





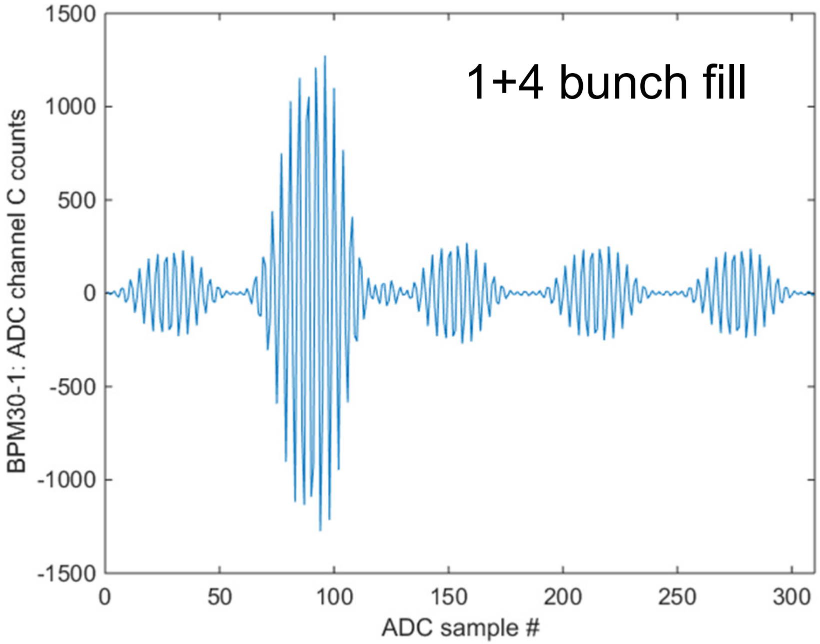
- Let's include multiple harmonics to increase the signal and resolution
- Resolution improvement of ~4 (for 23 rev. harmonics)

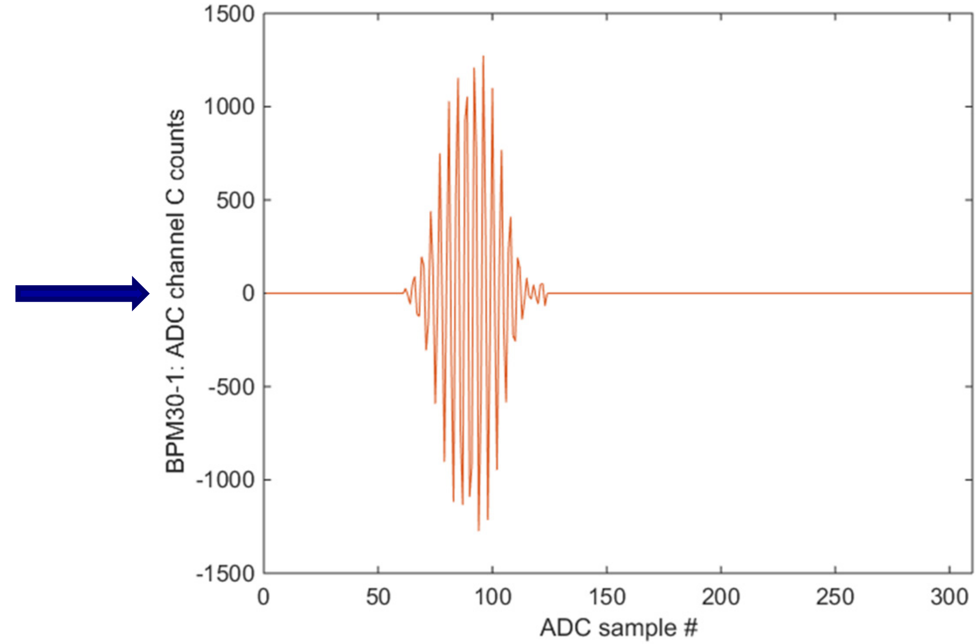
Including Multiple Harmonics We Approach single micron @ 0.5 mA on ID BPMs



- 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.

This Works on Few Bunch Fills as Well





- Blank-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

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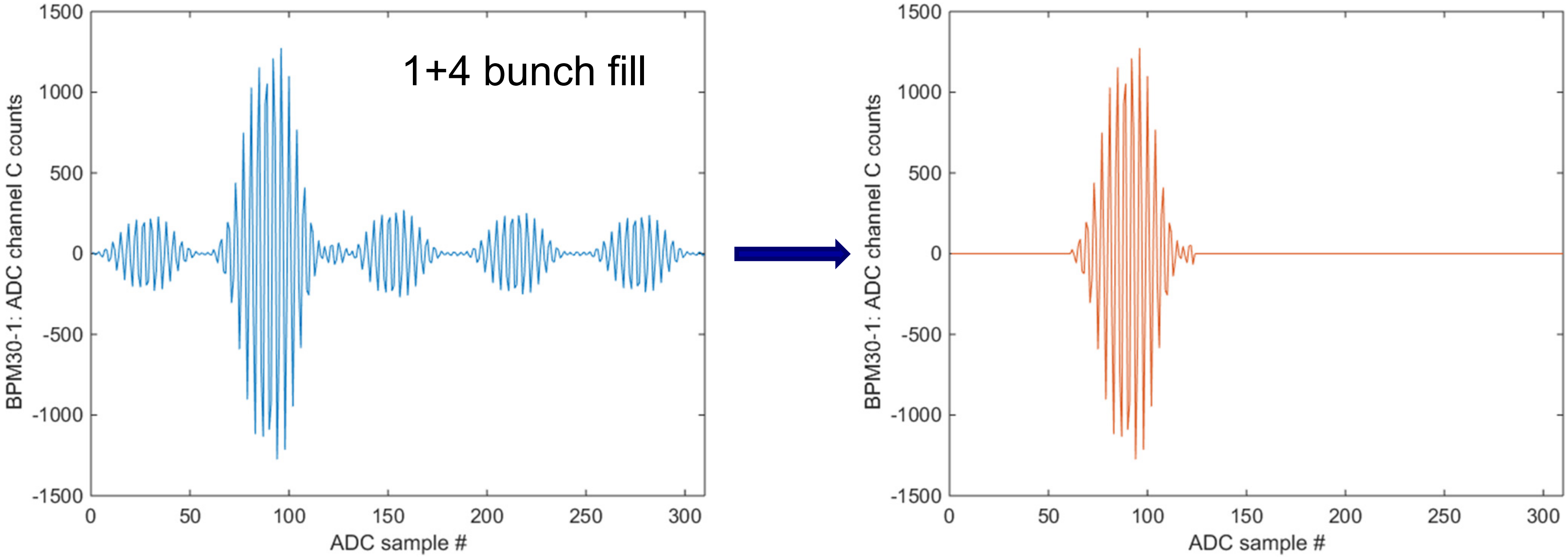

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As long as bunches are well separated (up to 8 for equally spaced)

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

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

More are in the works …

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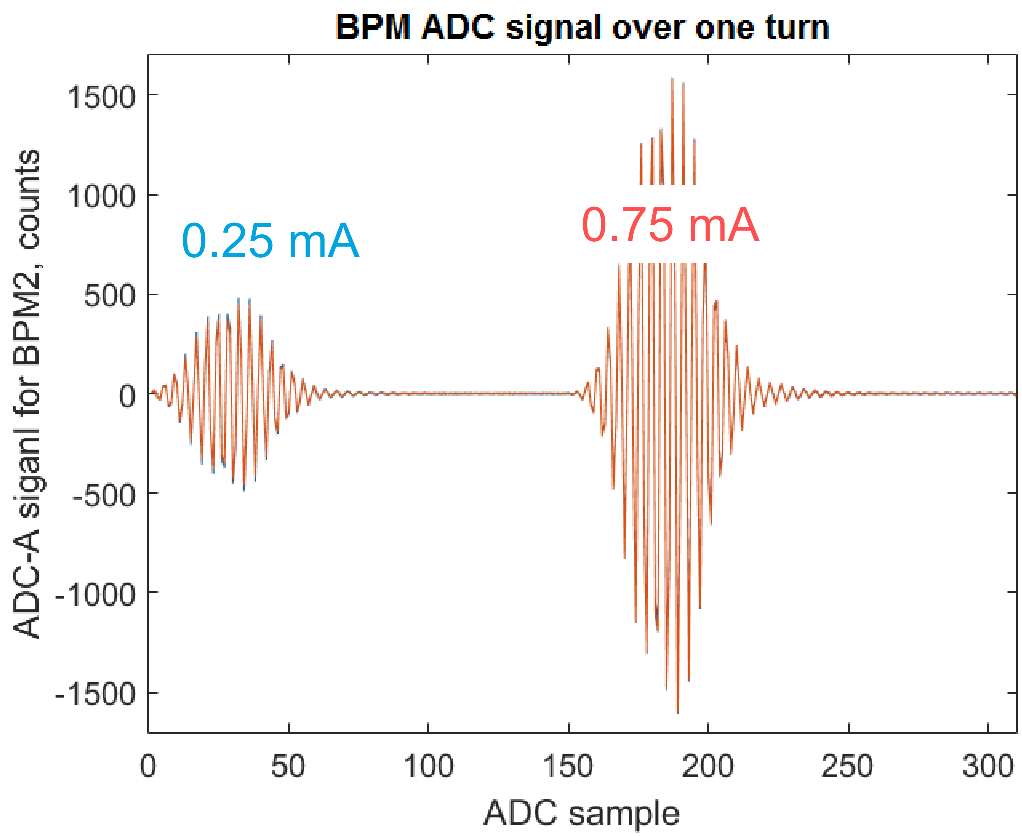
Unequal Charge Bunches Kicked with a Pinger



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

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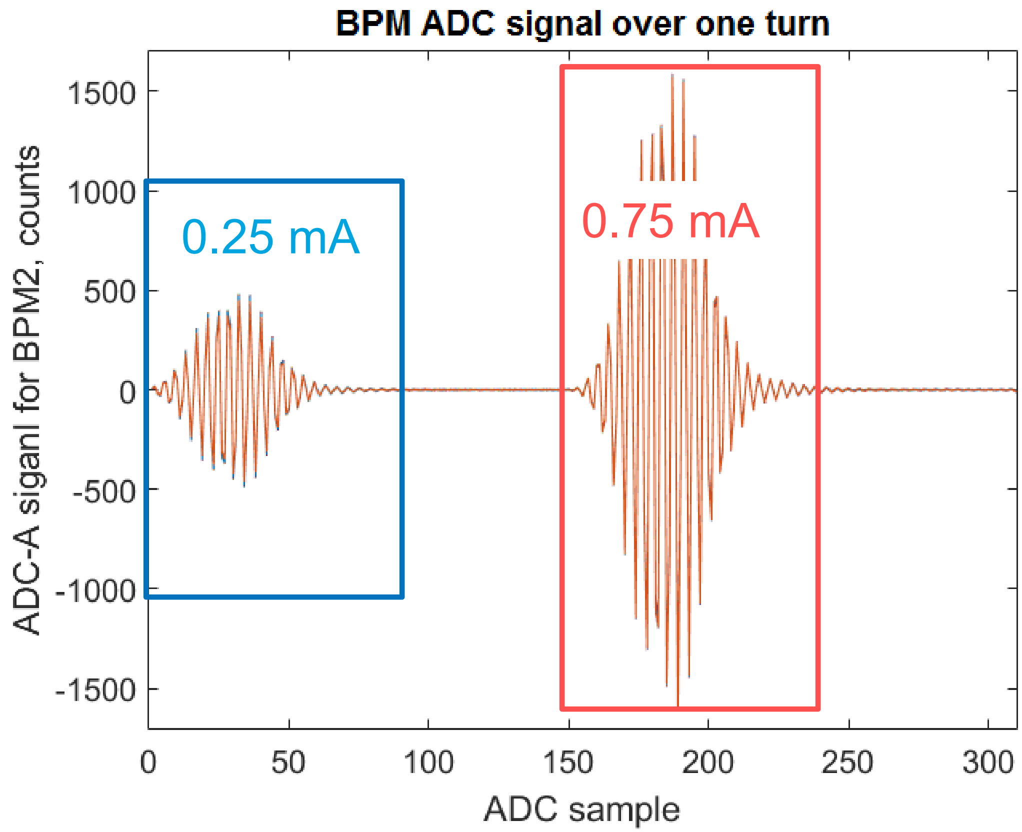

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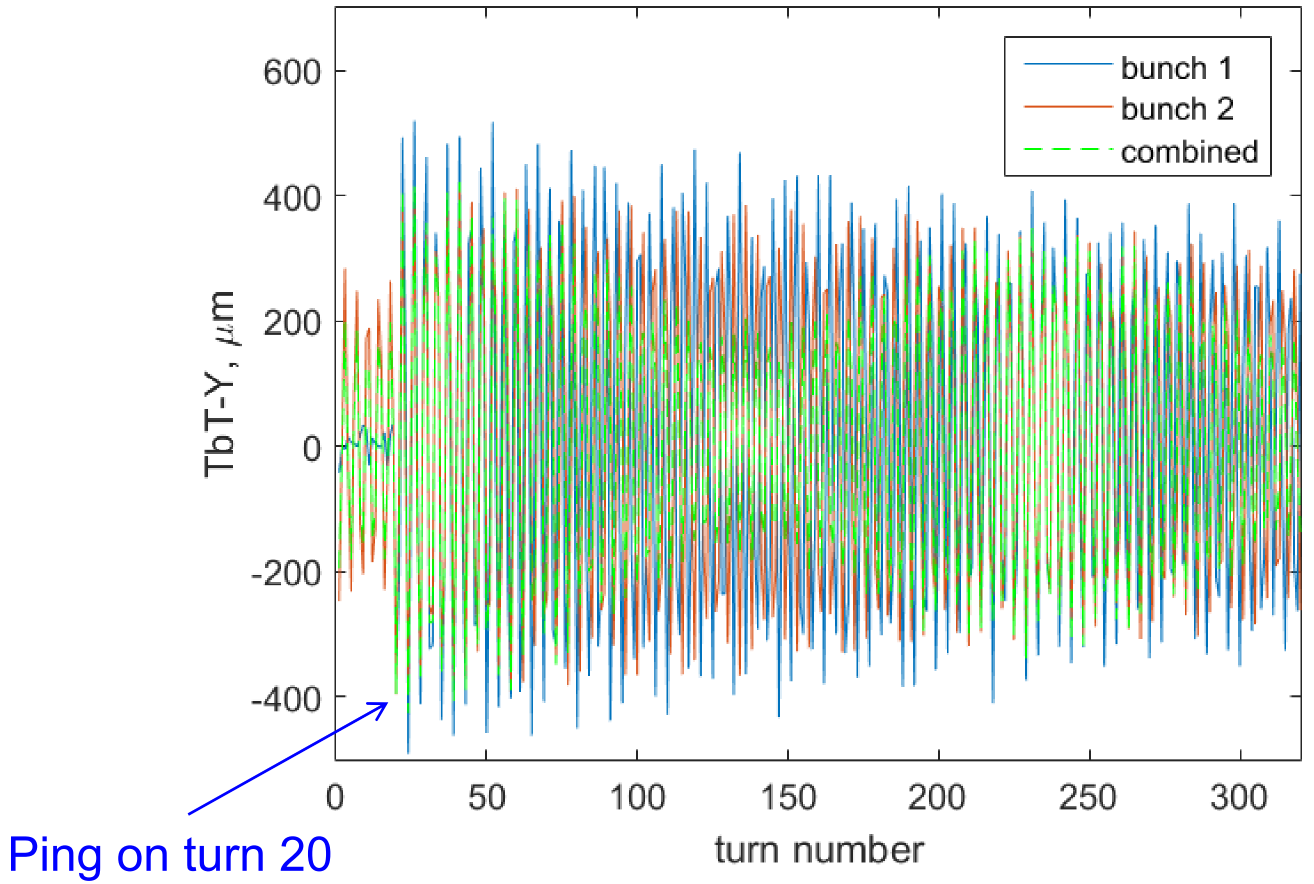
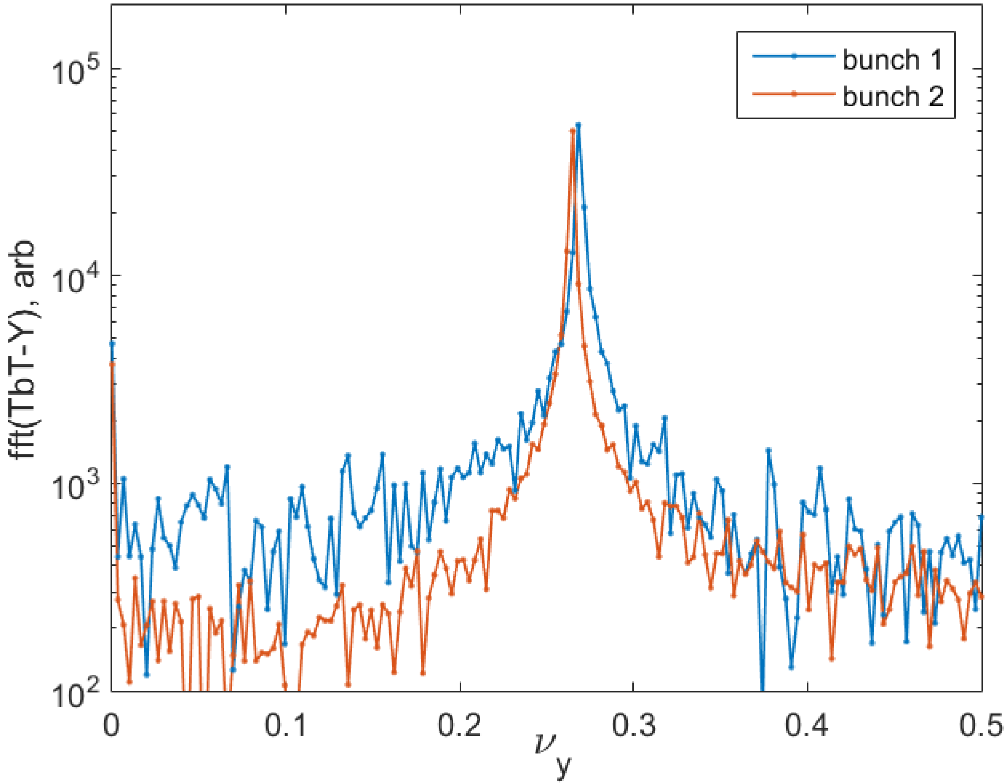
Turn-by-Turn Signals



- 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 DFT for 180 BPMs gives

  ν_y=0.26833 ± 1.93e-5 (bunch 1) and ν_y=0.26334 ± 6.90e-6 (bunch 2)
- Tune difference of 5e-3/(0.5 mA) is consistent with other measurements

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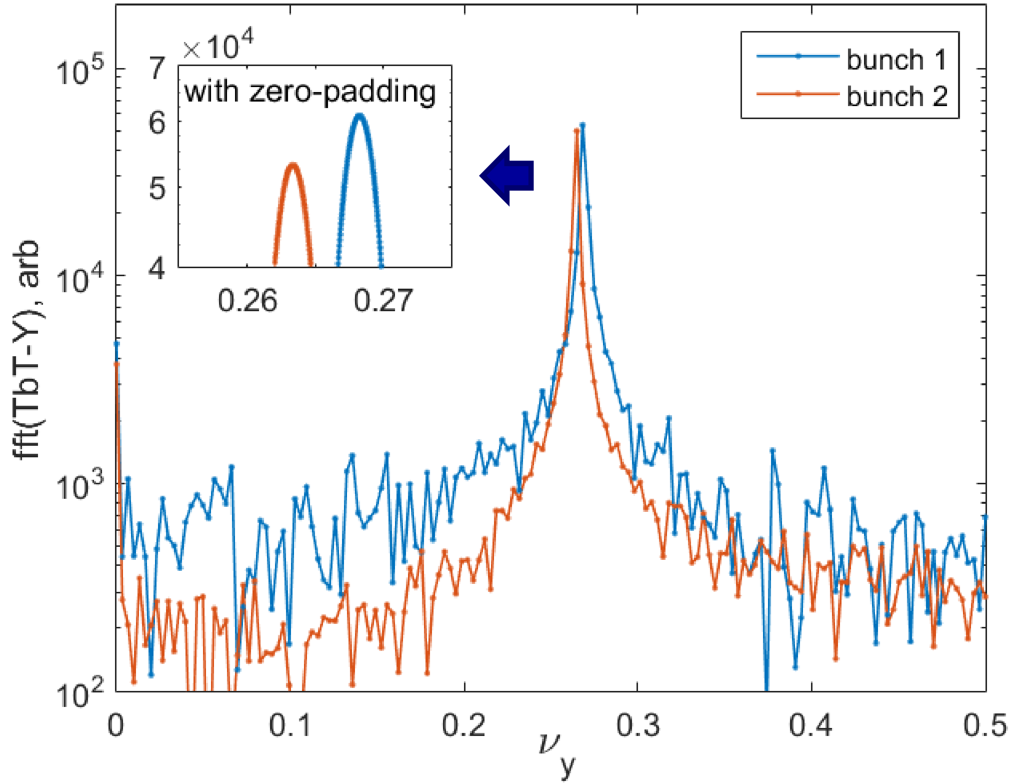

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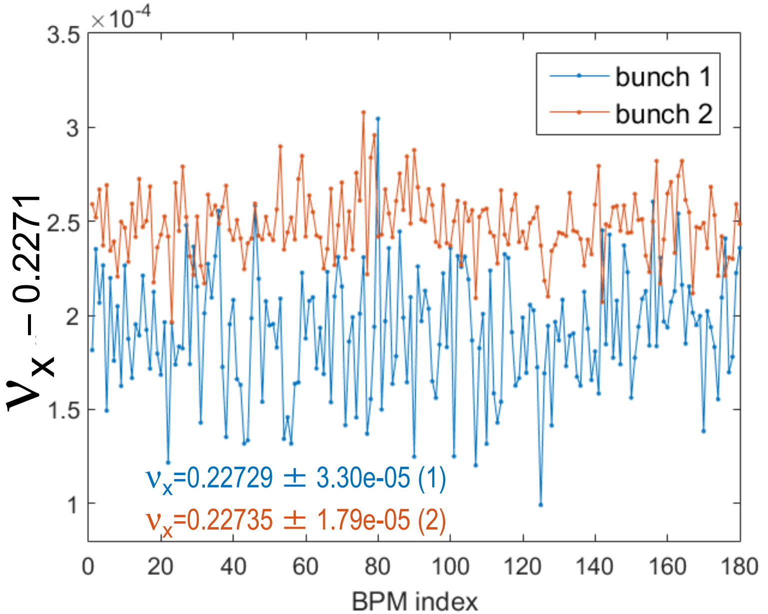
Same Measurement in the Horizontal

- 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



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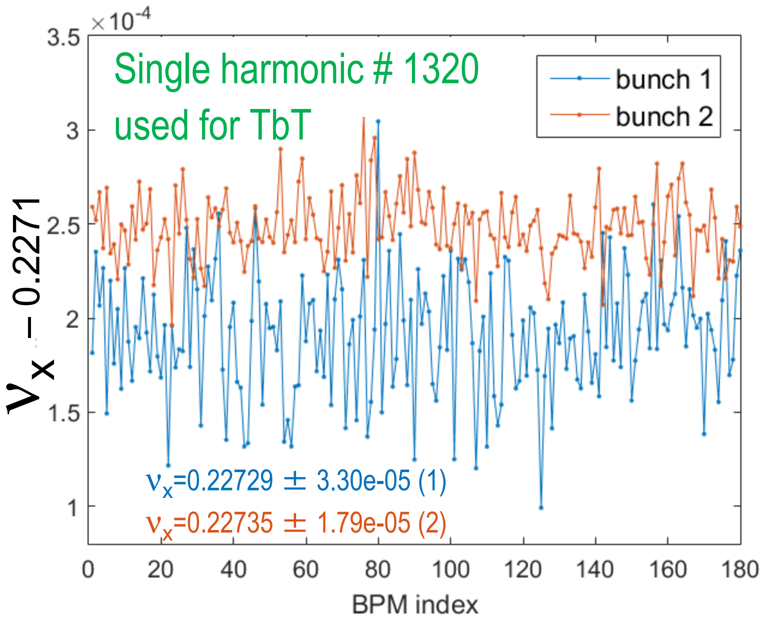

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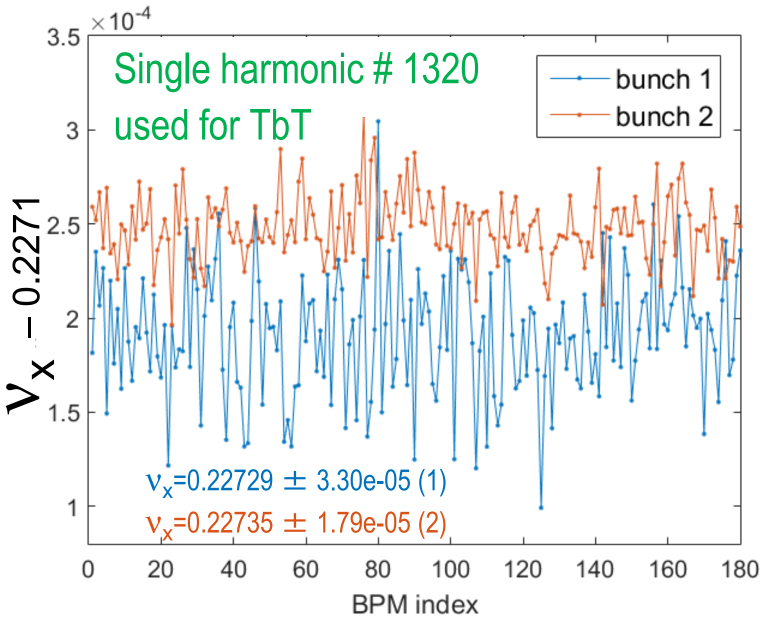

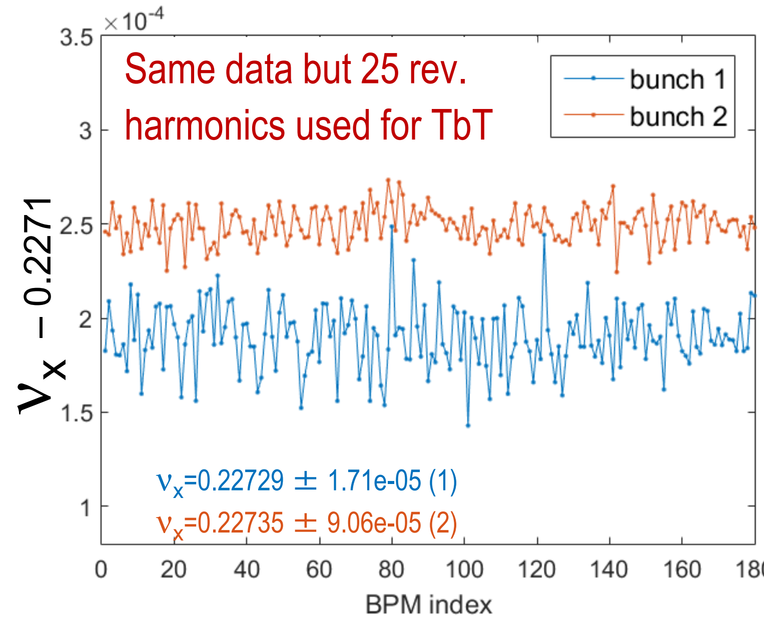

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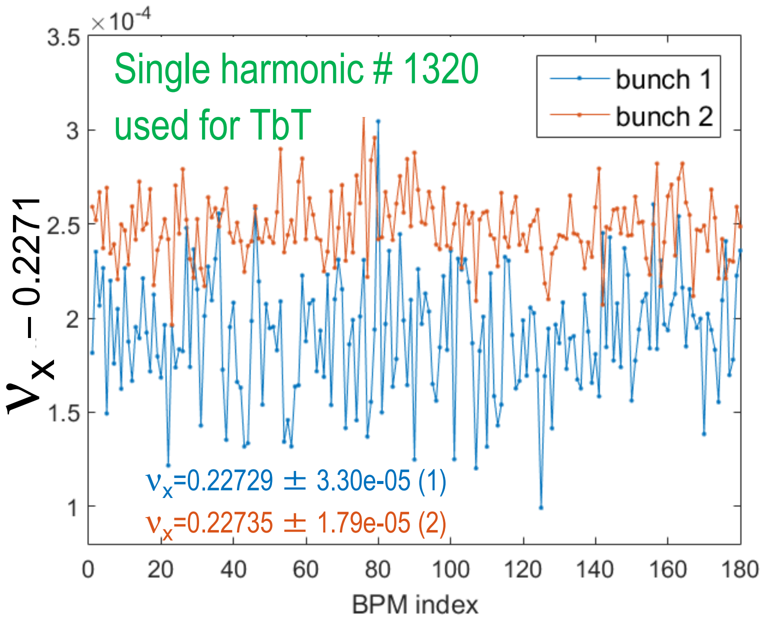

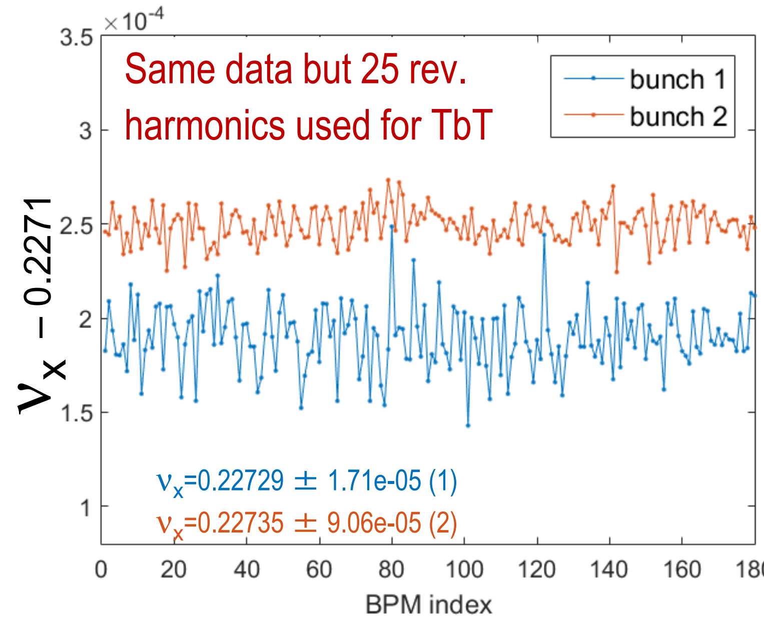

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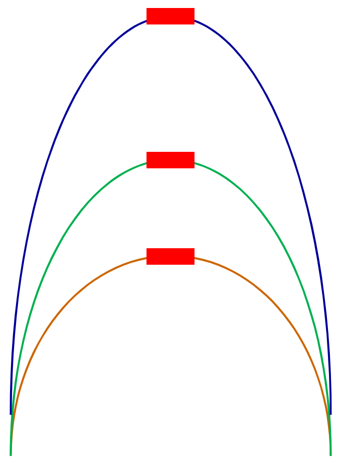
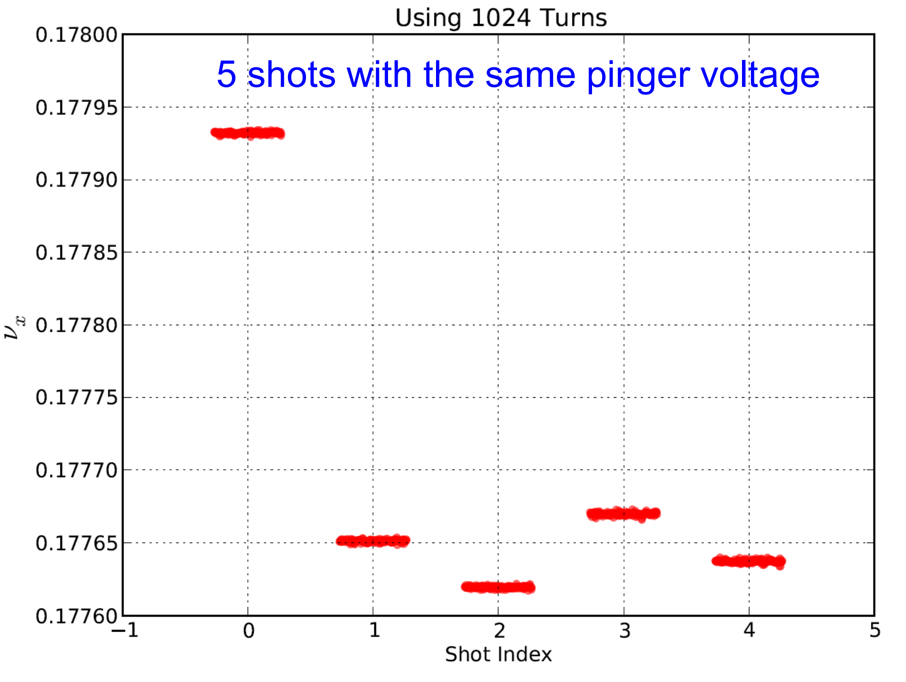
- Resolution improvement (est. x4) has helped; now convincingly show that hor. tune goes up with current.

Measurement of Tune Shift with Amplitude

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



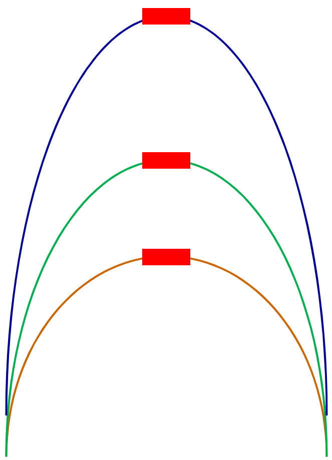


Issues: kicker jitter, machine drifts

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

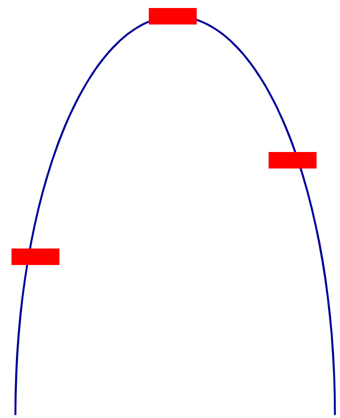
Single Shot Measurement of Tune Shift With Amplitude

Conventional measurement



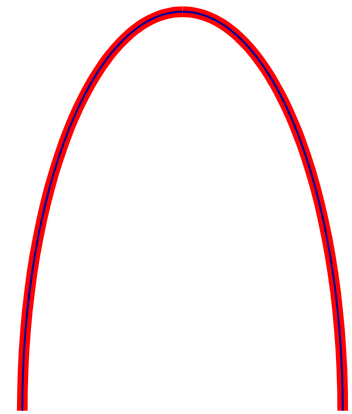
Kicker jitter, machine drifts

New option



Max. # of trains / turn

Alternative new option



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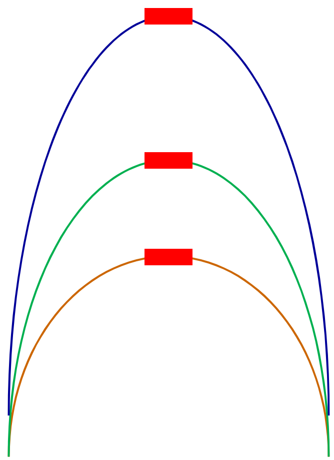
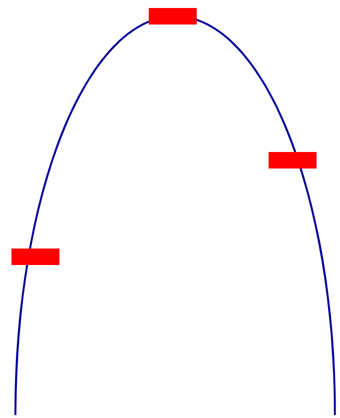


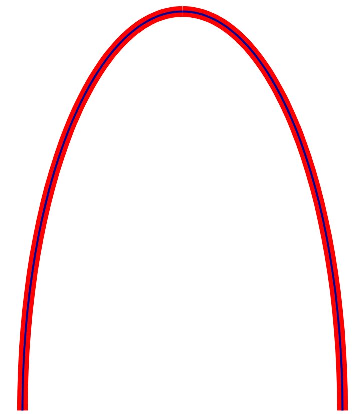
Kicker jitter, machine drifts

New option



Max. # of trains / turn

Alternative new option

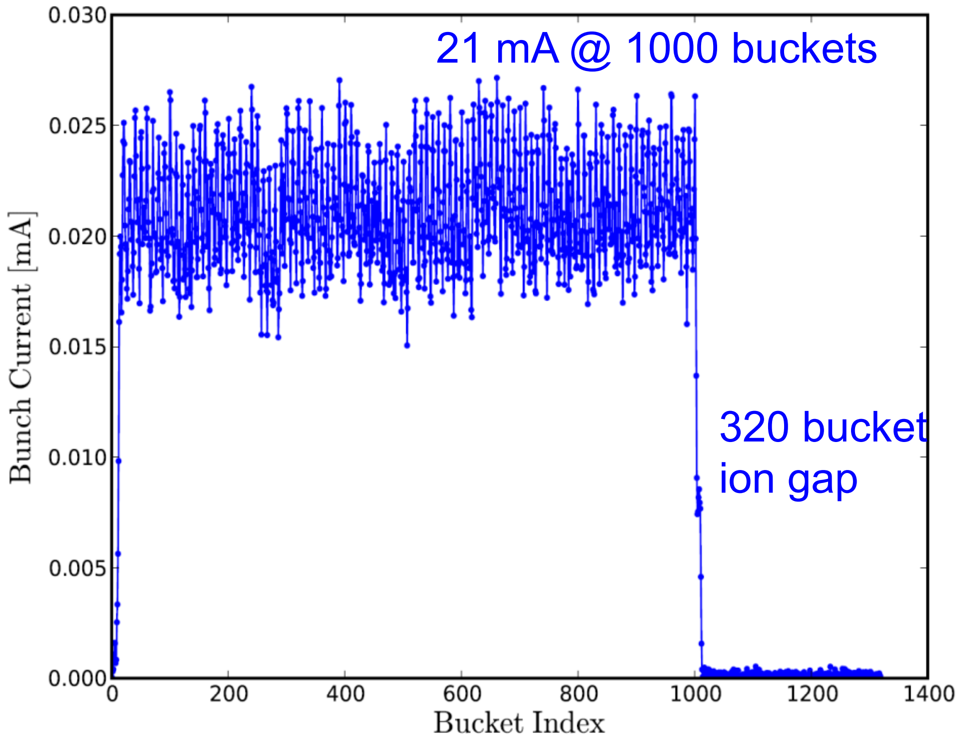


?

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

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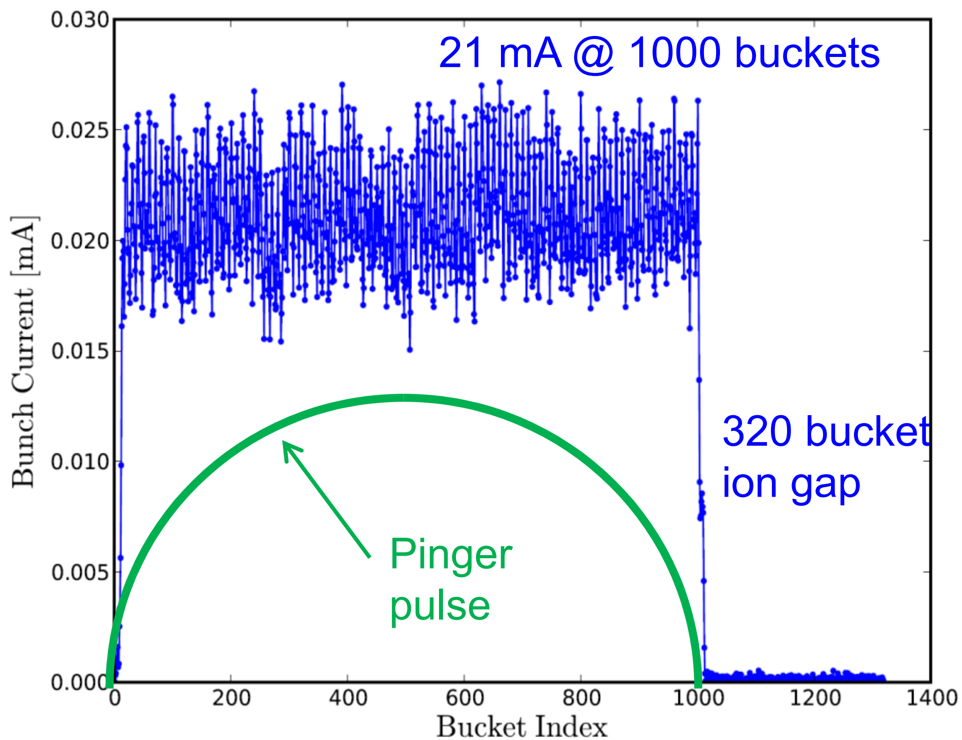

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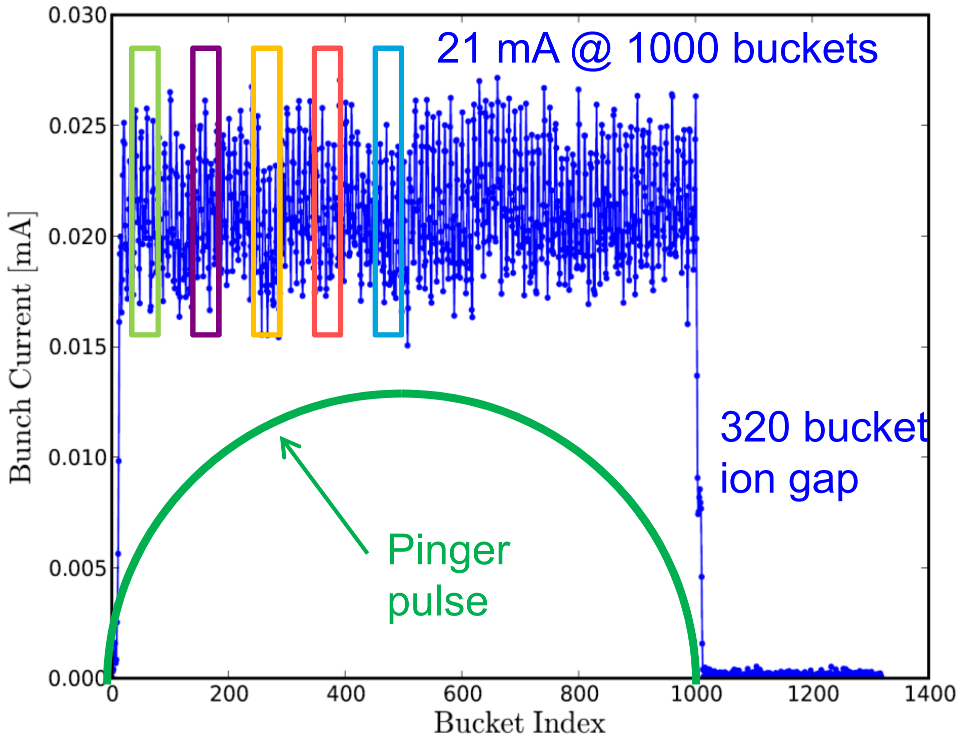

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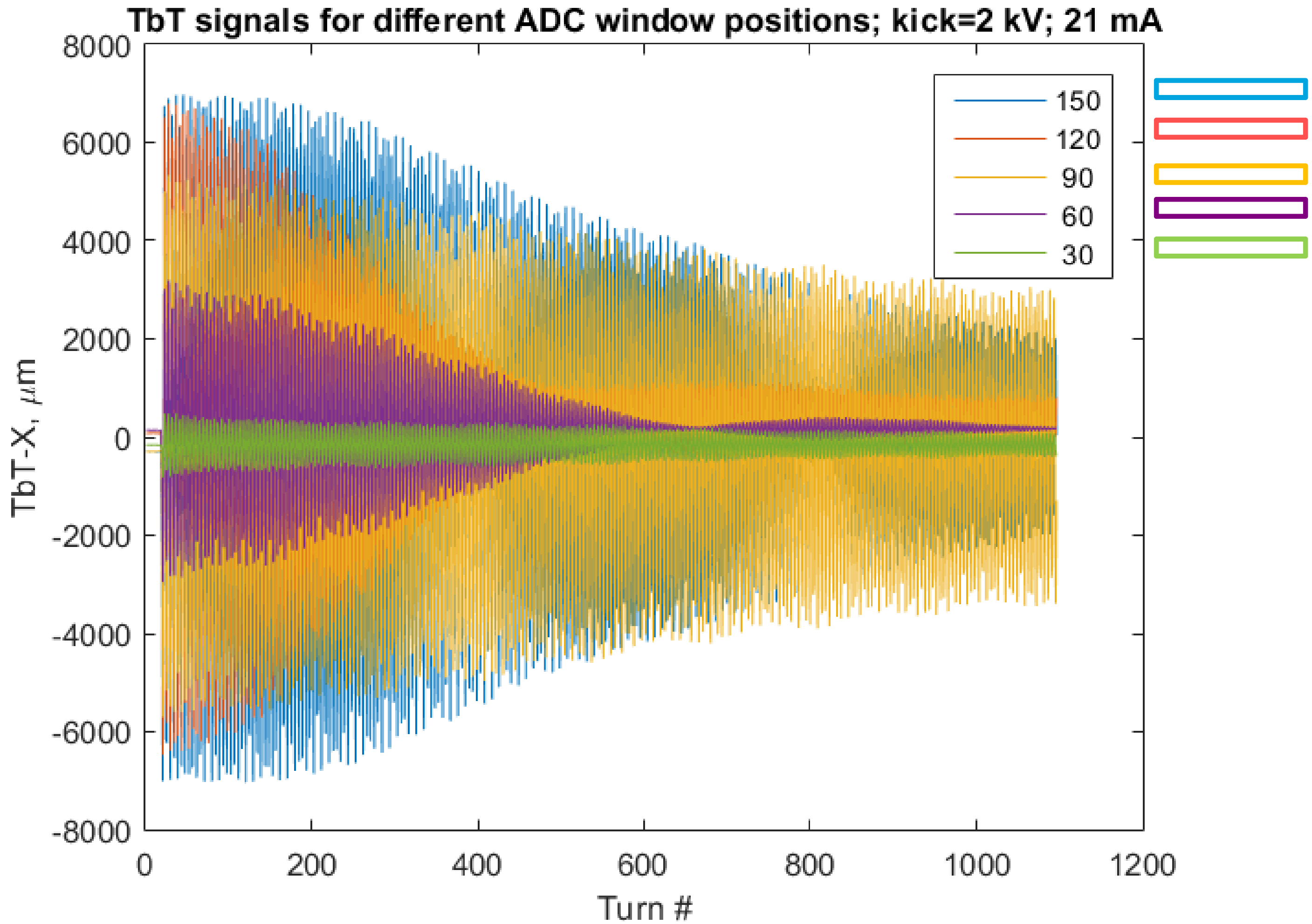
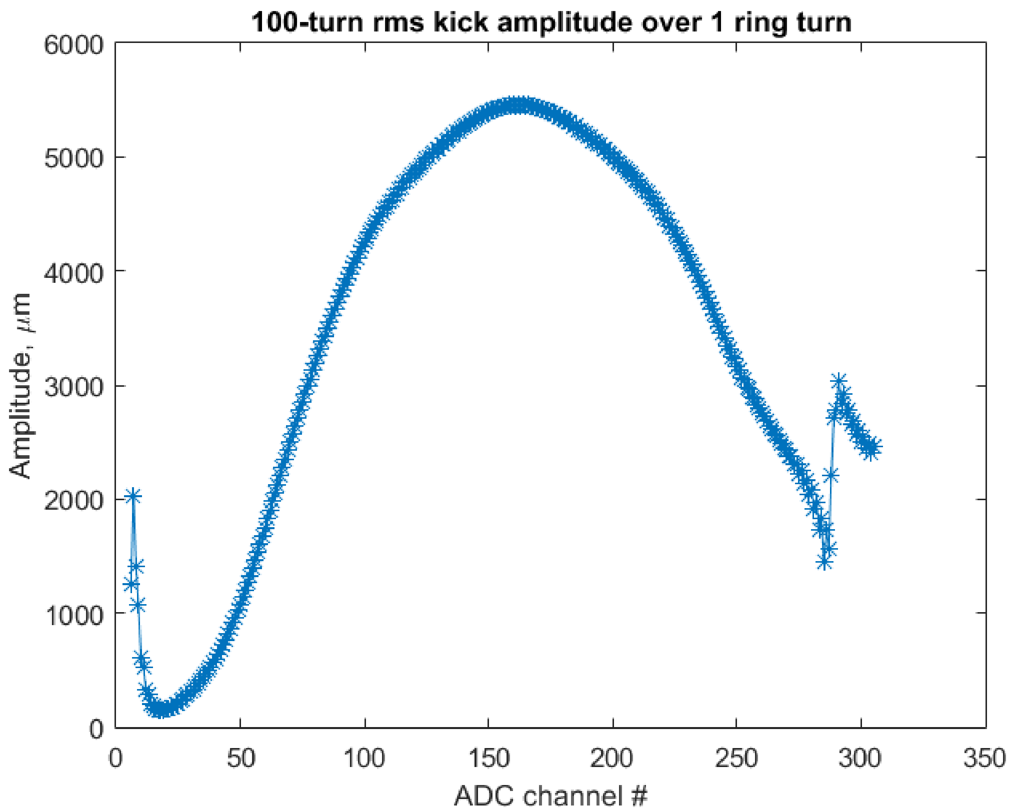
TbT Signals from Selected ADC Bins



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

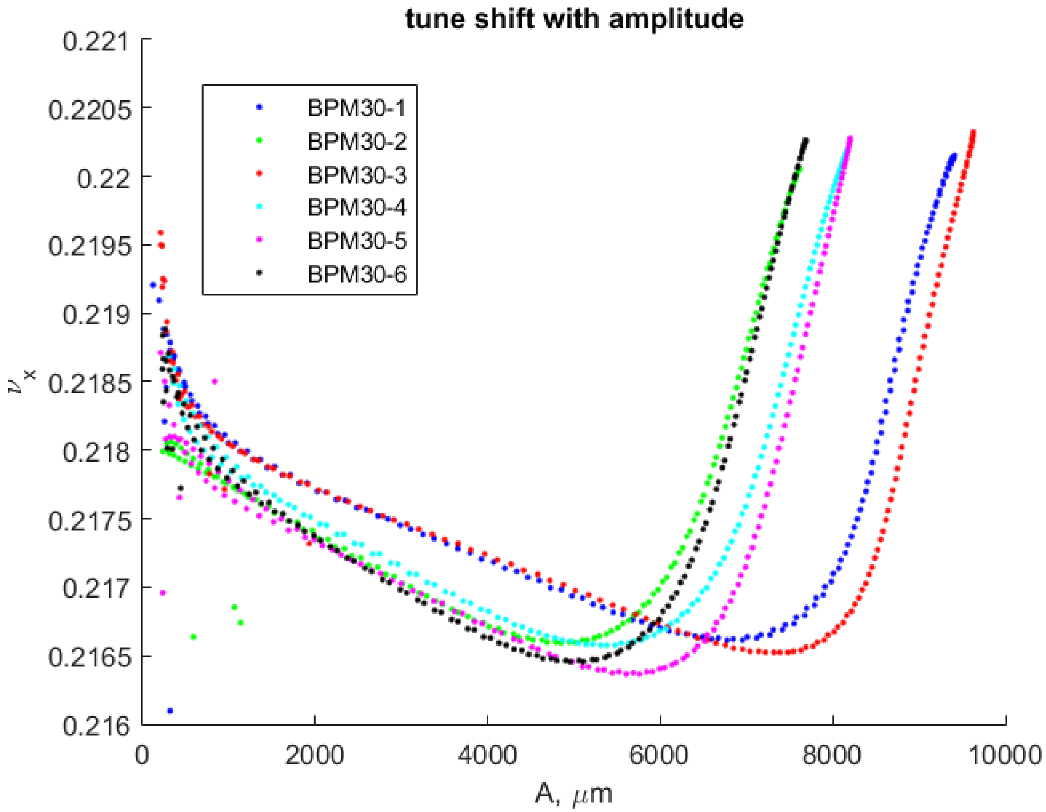
Amplitudes for All ADC Bins Together

- Recover the shape of pinger pulse



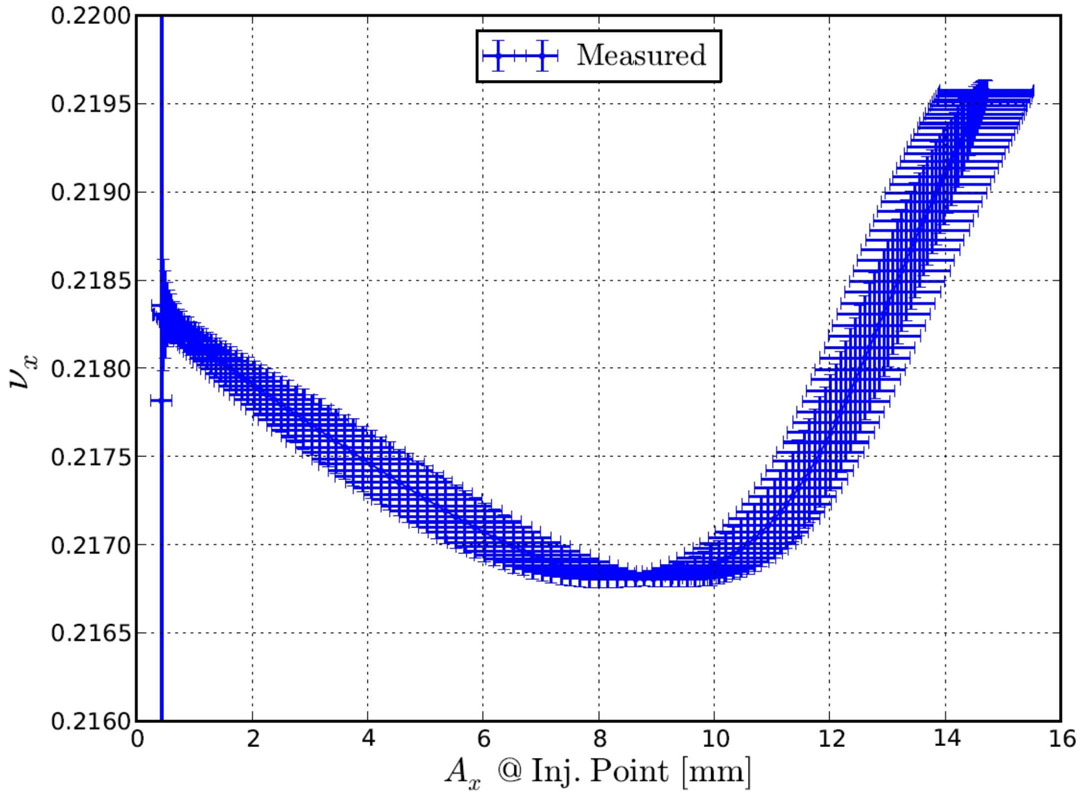
- Except at the head (there is no kick) and near the ion gap

Tune Shift with Amplitude: 6 BPMs



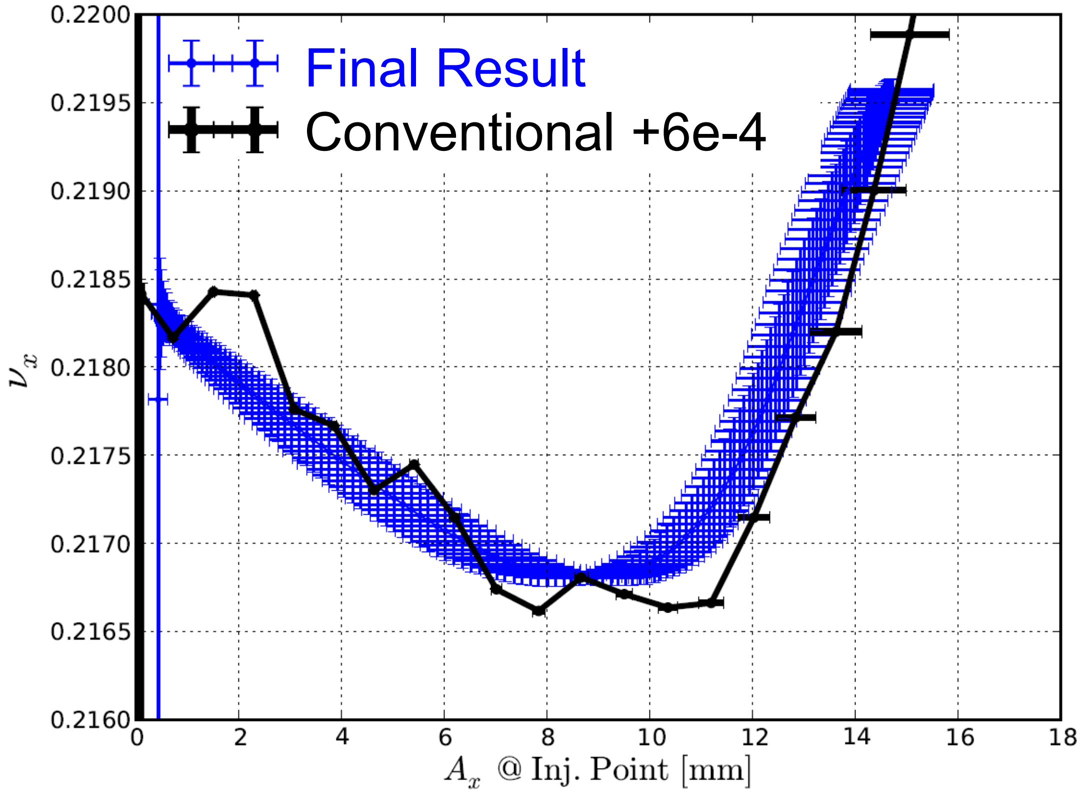
- Smooth curves except at very low amplitudes
- Other cells look very similar
- From here: scale to injection point; error-bars from all 180 BPMs

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

Final Results: Horizontal



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Conclusions and Future Plans

- Single-bunch resolution of NSLS-II BPMs was improved by an order of magnitude to about one micron TbT at ~1 nC/bunch.
- This improvement was achieved through special processing of ADC signals which additionally provides the new capability of resolving TbT signals from up to 8 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.
- ADC processing is presently done off-line but will be implemented in FPGA, so that improved resolution will be available through EPICS.
- Novel accelerator physics measurements enabled by improved resolution and new BPM capabilities will continue.

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Thank you