Chromaticity: Measurement Techniques

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What is required

	Resolution		scenario
	on observable	on tunes	
Q	~ ± 3. 10^{-3}		Commissioning
	± .75 10^{-3}		Tune measurement and/or feedback in operation (injection,ramp, flat top during squeeze)
	±.25 10^{-3}		Nominal (pre-collision and collision)
	≤ ± 1. 10^{-3}		Bunch by bunch
	≤ 10^{-5}		Low-β non-linearities
	≤ 10^{-4}		Pilots, bunch by bunch (detunings)
Q′	±2.5	± 3. 10^{-3}	Commissioning
	±0.5 to ±1.5	±.35 10^{-3}	Nominal, 450 GeV to 7 TeV (measurement and/or feed-back)

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What is required (cont'd)

energy	Scenario	Maximum dc momentum offset	Maximum ac momentum offset
450 GeV (injection optics)	nominal	$\pm 0.5\ 10^{-3}$	$\pm 0.1\ 10^{-3}$
	Pilot, momentum collimators withdrawn	$\pm 2.5\ 10^{-3}$	
7TeV (squeezed optics)	Pilot and nominal	$\pm 0.15\ 10^{-3}$	
	Pilot, crossing angle suppressed, collimator setting scheme relaxed accordingly	$\pm\ 10^{-3}$	

Methods

- Traditional slow $\Delta p/p$ modulation method
  - This is the baseline.
- Phase modulation – McGinnis method
- Head-tail method
  - Strong kicks*
  - Weak kicks with 3D-BBQ as detector*
  - Continuous kicks with 3D-BBQ as detector
- 3 tone method

*Not part of TF task for ξ feedback

Some LHC Parameters

$$\omega_{RF} = 2\pi \times (400.8 \times 10^6)\, s^{-1}$$

$$h = 35640$$

$$\eta = 0.0003$$

$$\xi \approx 2$$

$$Q_0 \approx 0.28 - 0.32$$

$$\delta Q_0 < 1 \times 10^{-3}$$

$$\Delta p / p < 1 \times 10^{-4}$$

$$D < 3\,\mathrm{m}^{*}$$

$$\Delta r_{\max} < 50 - 200\,\mu\,\mathrm{m\ rms}^{**}$$

* "Measuring Beta Functions and Dispersion in the early LHC", F. Zimmerman et. al, Proc. EPAC 2002.

** "Feedbacks and Stabilization --- getting them going", J. Wenninger, LHC Performance Workshop, Chamonix XII.

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Traditional $\Delta p/p$ Modulation

- Slowly change $\Delta p/p$ by changing RF frequency
  - Relationship between chromaticity and RF frequency change:

$$\Delta Q_0 = \xi \frac{\Delta p}{p} = -\frac{\xi}{\eta} \frac{\Delta \omega_{RF}}{\omega_{RF}}$$

$$\Rightarrow \Delta \omega_{RF} = \left| \frac{\eta \, \delta Q_0 \, \omega_{RF}}{\xi} \right| \approx 6\,\mathrm{Hz}$$

using numbers from page 4 for LHC and setting $\Delta Q_0 = \delta Q_0$.

Traditional $\Delta p/p$ Modulation

- This method is well known
  - Slowly frequency modulate the RF frequency (typically < 5 Hz)
  - Maximum RF frequency change typically < 10Hz.
  - Use tune tracker to track the betatron tune execursions.
  - Calculate the chromaticity from here.

Traditional $\Delta p/p$ Modulation (cont'd)

- Must take care that the RF frequency modulation must not change the radial position too much

$$\Delta r_{max} = \left| D \frac{\Delta p}{p} \right| < 1.5\sigma(450\,GeV), 0.5\sigma(7\,TeV)$$

$$= \text{ or 50 to 200 } \mu\text{m rms}$$

- Also change in betatron tune δQ_0

$$\delta Q_0 = \left| \xi \frac{\Delta p}{p} \right| < 1 \times 10^{-3}$$

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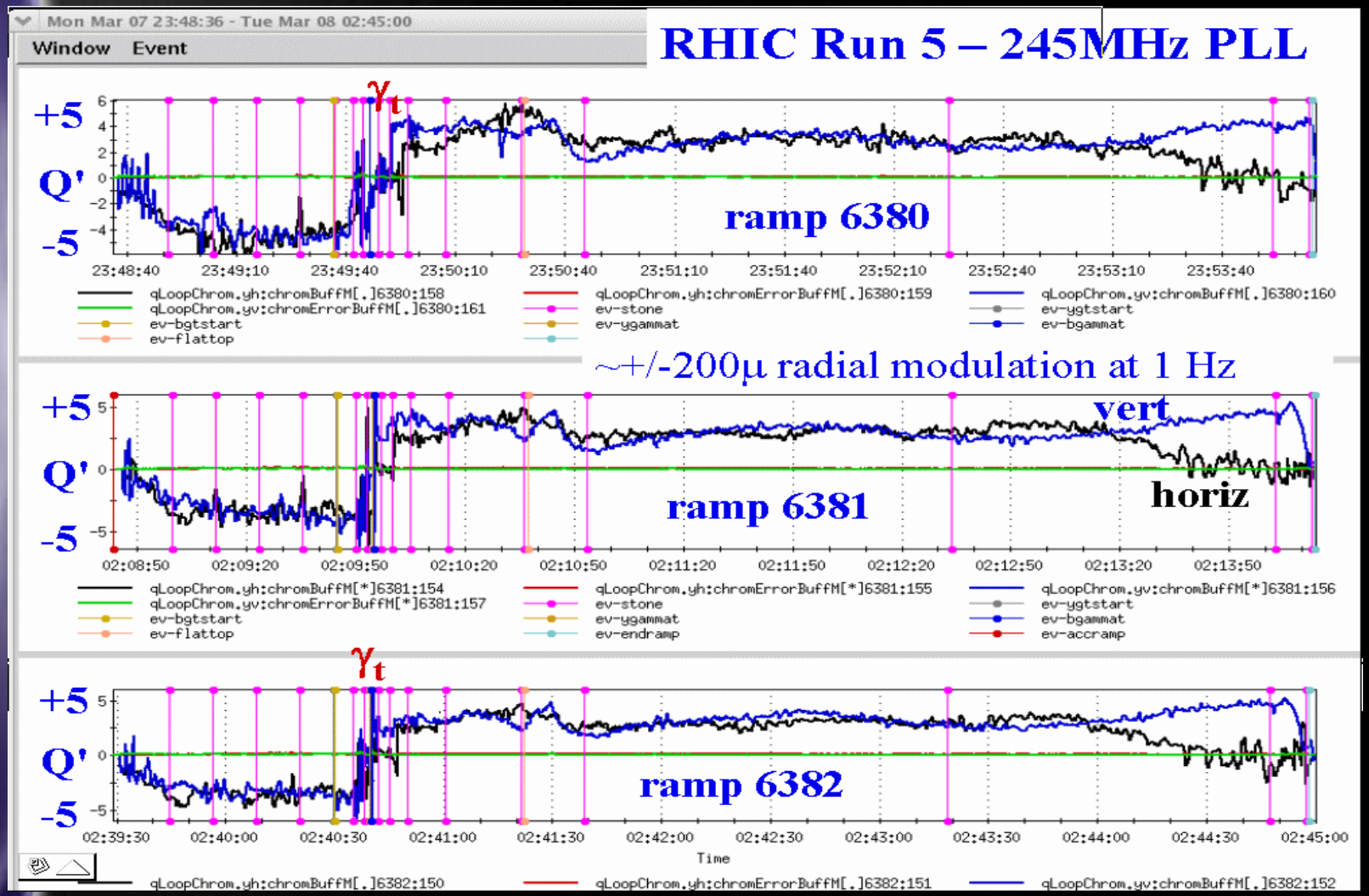
For Example in RHIC



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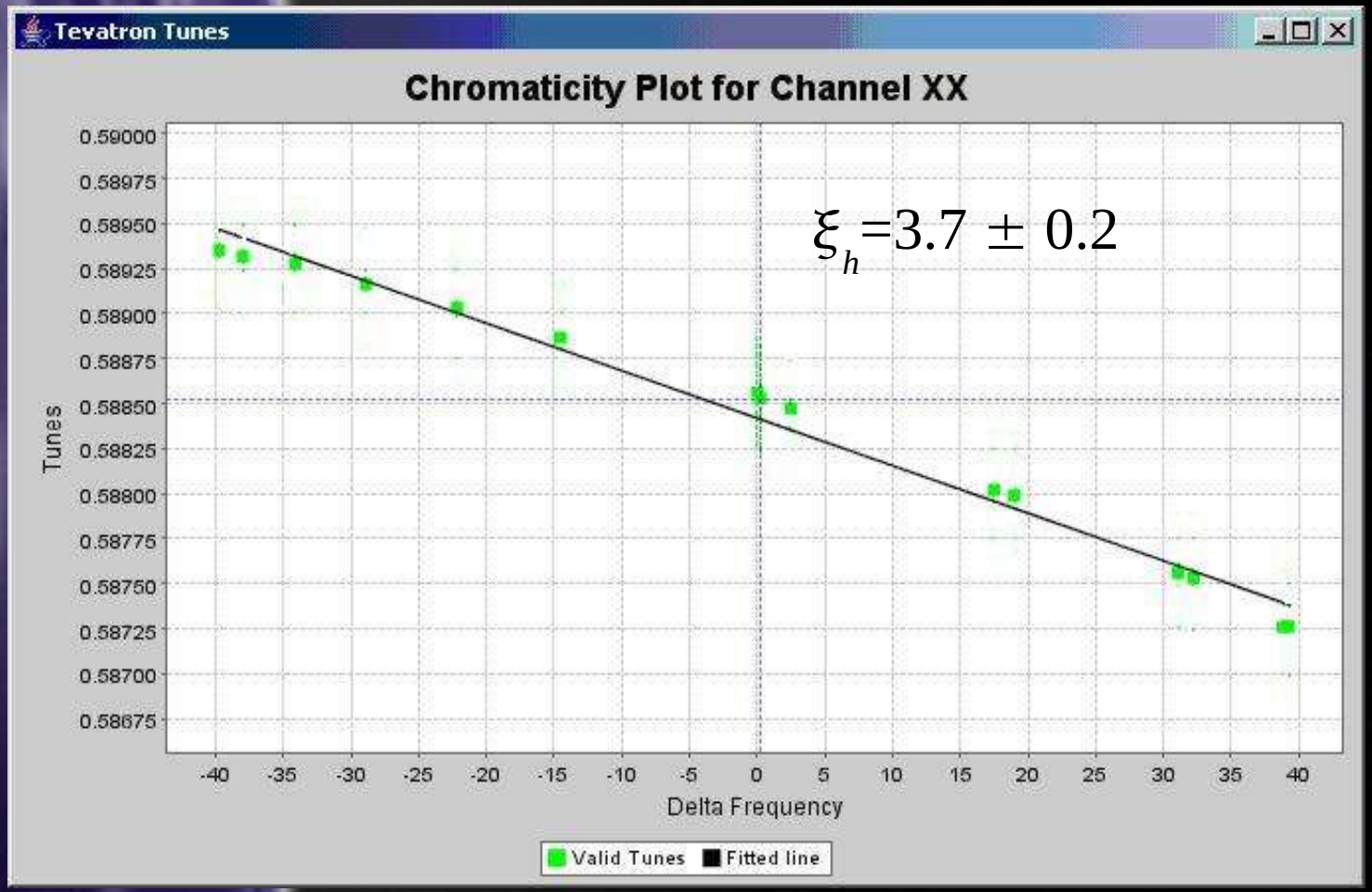
For Example in the Tevatron



$\Delta\omega_{RF} = \pm 20$Hz or $\Delta p/p = 1 \times 10^{-4}$ @ 2Hz rate.
(Can see non linear chromaticity)

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Method Comparison

	A	B	C	D
1	Summary of Chromaticities measured with various methods			
2				
3	Coalesced			
4	Method	Ch	Cv	Comments
5	C100	3.1	1.8	
6	Tune Tracker	0.84 +/- 0.2	2.22 +/- 0.23	VFKNOB=+/-40 Hz
7	C43	1.5	1.5	VFKNOB=+/-40 Hz
8				
9	Uncoalesced			
10	Method	Ch	Cv	Comments
11	C43	4	2	VFKNOB=+/-40 Hz
12	Tune Tracker	3.7 +/- 0.47	1.7 +/- 0.46	VFKNOB=+/- 20 Hz
13	Tune Tracker	3.61+/- 0.47	1.37+/- 0.46	VFKNOB=+/- 20 Hz
14	Tune Tracker	3.77 +/- 0.24	1.49 +/- 0.23	VFKNOB=+/- 40 Hz

Notes

- At least in the Tevatron with octupoles ON
  - Tune tracker measured horizontal ξ seems to depend on charge density (charge/bunch length)
  - Measurements only affect coalesced beam
    - Even when measured by hand
  - This effect is not well understood.

Phase Modulation Method (McGinnis Method)

- The phase modulation of the RF produces a phase modulation of the betatron tune due to chromaticity.
- The formula which relates ξ to demodulated phase amplitude ϕ_{demod} and modulated amplitude $\Delta\phi_{\text{mod}}$ is:

$$\xi = \eta \left(\frac{h\,\phi_{\text{demod}}}{\Delta\,\phi_{\text{mod}}} \right)$$

Formula is for 3D-BBQ

McGinnis Method

- Phase modulate the RF
  - Modulation frequency must be outside the closed loop bandwidth of the tune tracker.
  - It must also not be too close to the synchrotron frequency.
- Use tune tracker “locked” frequency as carrier for phase demodulation.
- Angle must be small
  - $< 10^{\circ}$ in the Tevatron to prevent beam from falling out.

McGinnis Method (cont'd)

- We must be careful that
  - Modulation must not be in the bandwidth of the longitudinal dampers.
  - Modulation will cause radial excursion. Formula is

$$\Delta r_{max} = \left| \frac{D}{\eta} \times \frac{\Omega_{mod} \Delta \phi_{mod}}{\omega_{RF}} \right| < 1.5\sigma(450\,GeV), 0.5\sigma(7\,TeV)$$

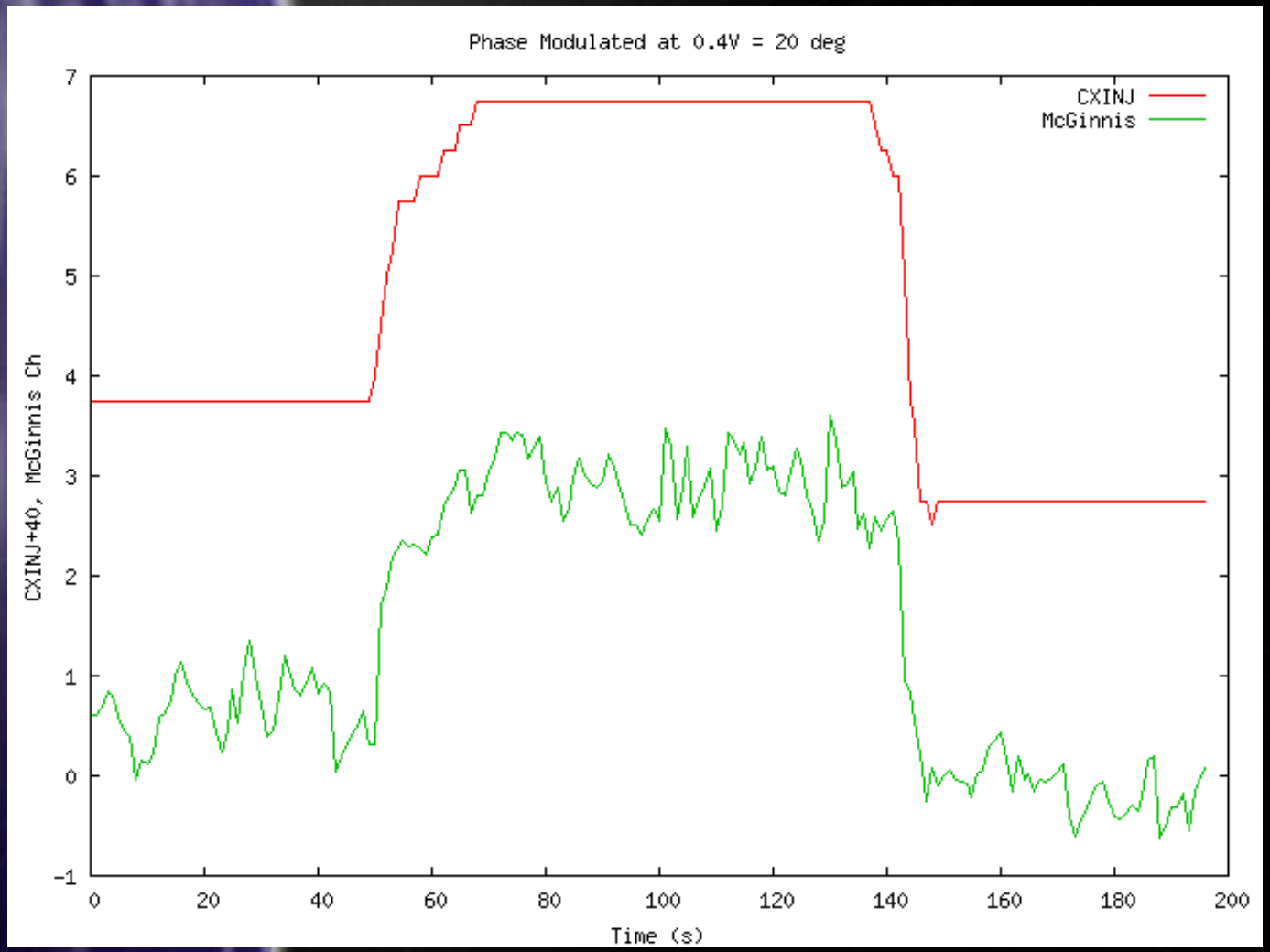
$$= \text{or } 50 \text{ to } 200\,\mu\text{m rms}$$

McGinnis Method (cont'd)

- Phase modulation will also cause betatron tune excursion

$$\delta Q_0 = \frac{\Delta \phi_{\mathrm{mod}} \times \Omega_{\mathrm{mod}}}{\omega_{RF}} \left(Q_0 - \frac{\xi}{\eta} \right) < 1 \times 10^{-3}$$

Example



Note that this is done with a phase detector with problems.
Even so, ξ measured to ± 0.5 unit.

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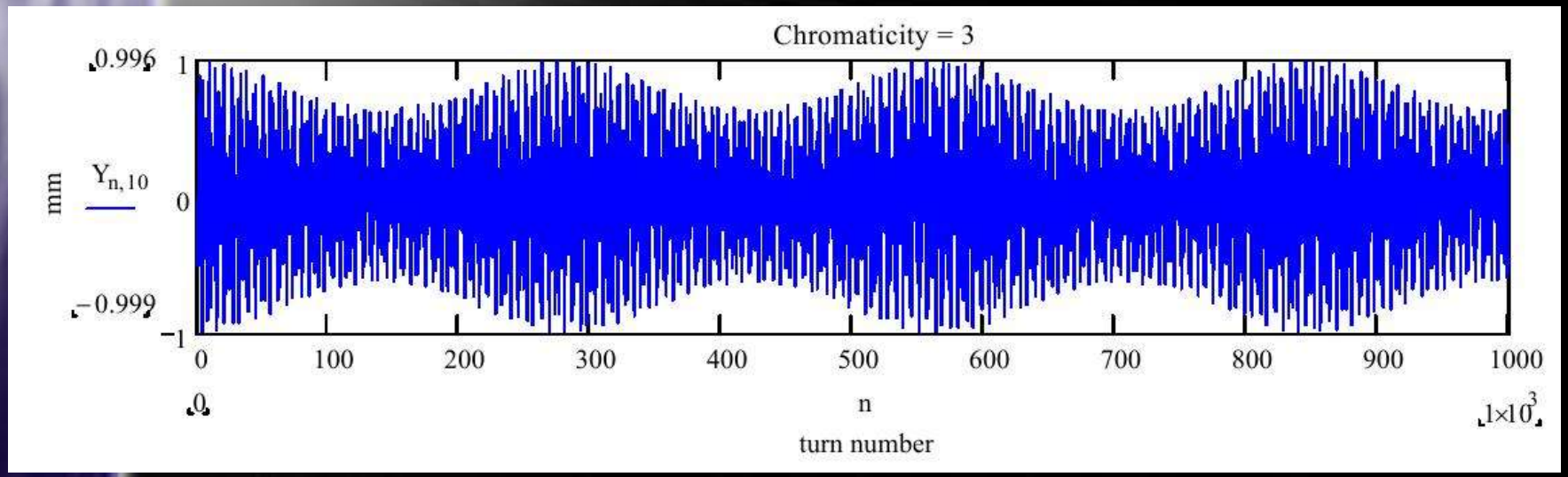
Notes

- Although not seen in the Tevatron, RHIC was unable to keep the beam in the machine even with 1° modulation.
  - Beam also did not fall out in SPS.
- Advantage is that it does not tax the tune tracker.
- Not yet demonstrated to work up the ramp.
- Still more machine studies needed to determine if method is feasible.

Strong Head-Tail Method

- Head-tail method relates ξ to the phase of head and tail oscillation from kick impulse.
- After the kick impulse, the head and tail oscillates at the betatron frequency but at different phases. Maximum at ½ sync. period.



Not part of TF task for ξ feedback

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Strong Head-Tail (cont'd)

- Formula which relates ξ to head-tail phase $\Delta\Psi$ is

$$\xi = -\eta \frac{\Delta\Psi}{\omega_0 \Delta\tau \left(\cos(2\pi n q_s) - 1\right)}$$

$\Delta\Psi =$ phase diff. head & tail $\quad \omega_0 =$ rev. freq.

$\Delta\tau =$ dist. between head & tail $\quad q_s =$ sync. tune

$n =$ turn number

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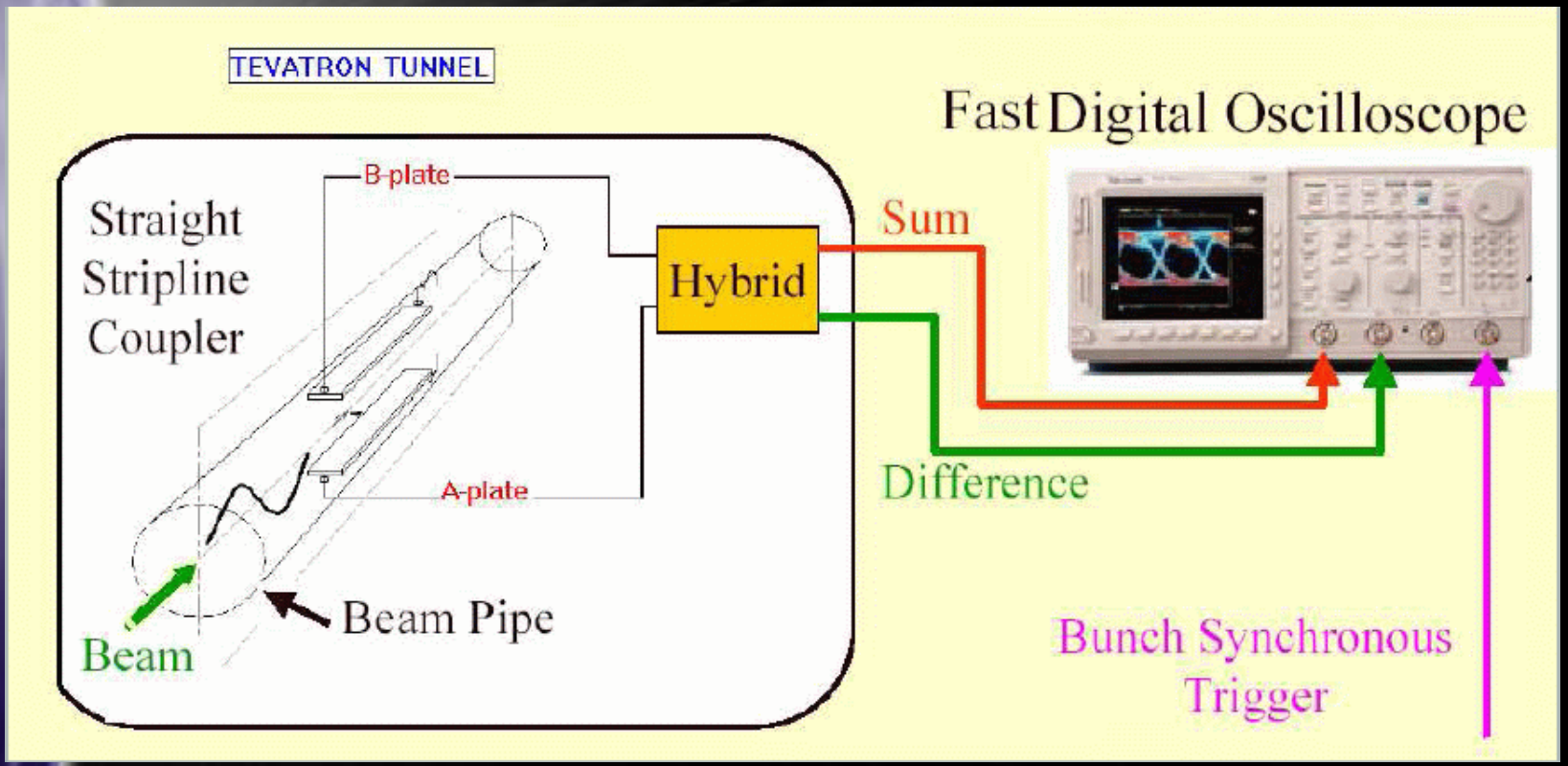
Strong Head-Tail (cont'd)

- Usually uses stripline and difference signals, fast sampling oscilloscope.



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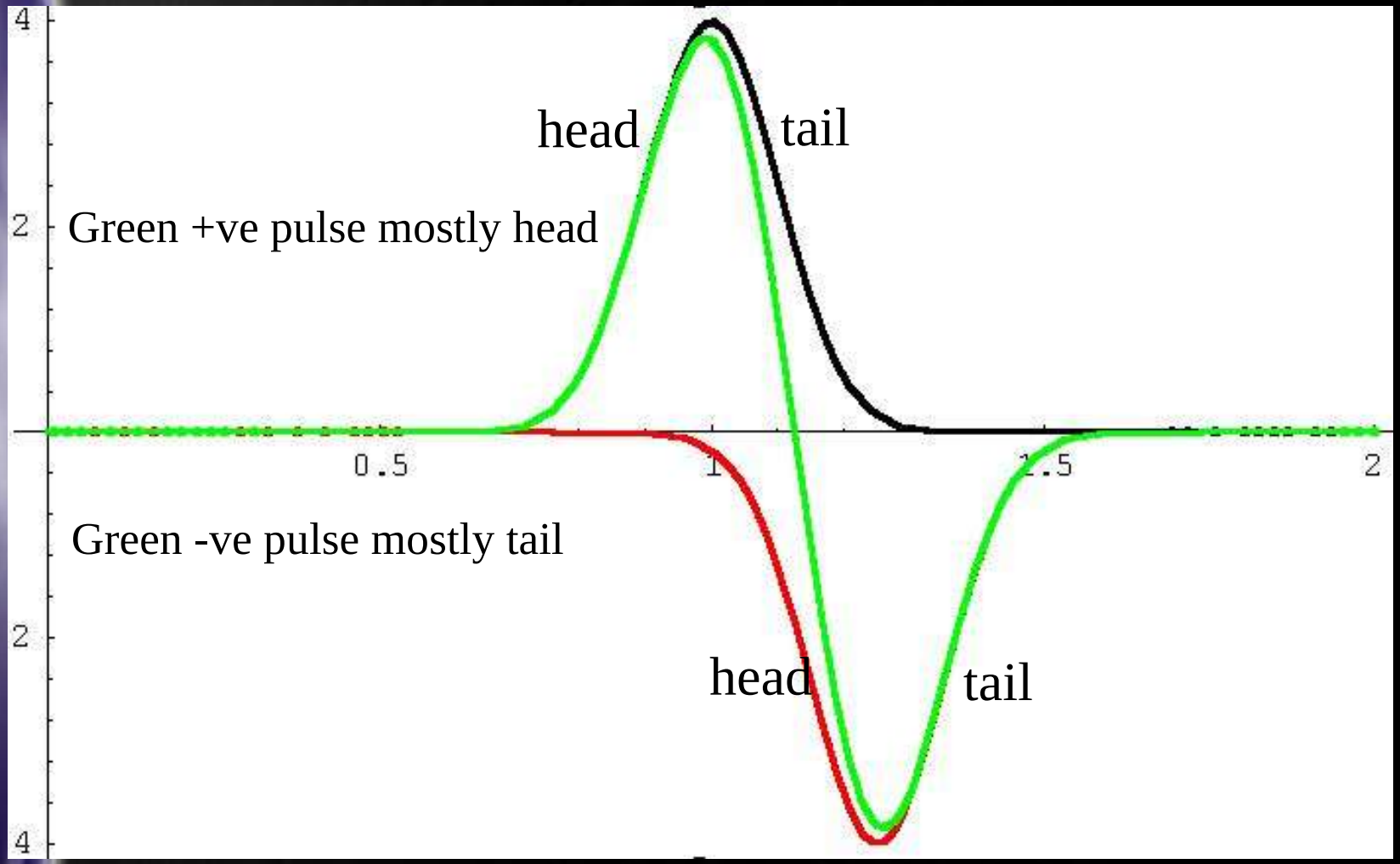
The Doublet



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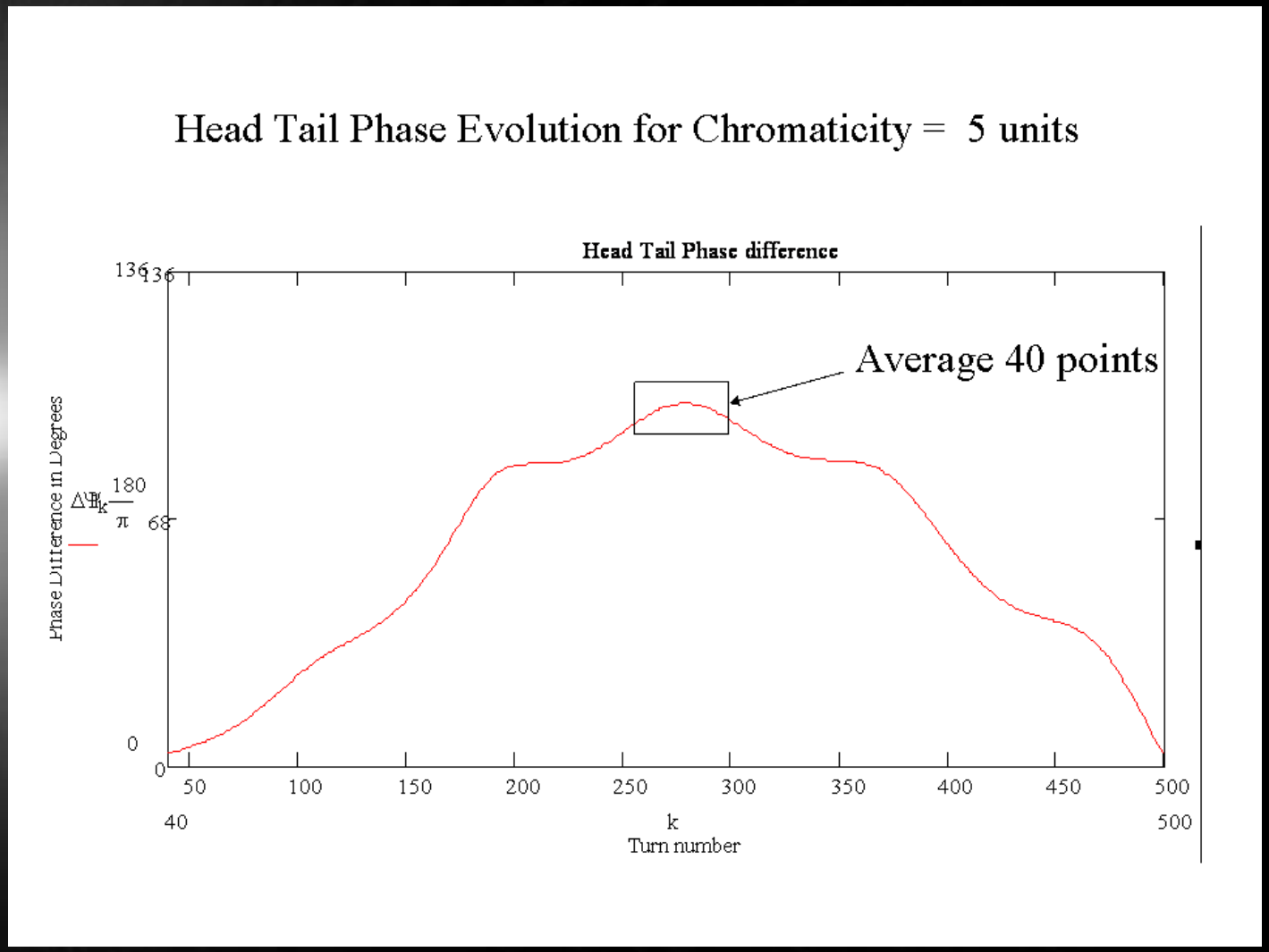
Example



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Notes

- This method works in the Tevatron and SPS
  - Error is ± 1 unit in the Tevatron.
- Strong kicks are used and emittance is blown up considerably. In the Tevatron causes 1 mm $\gg$ 100 μm beam motion.
- Beam lifetime is also affected.
- Does not work with uncoalesced bunches.

Not part of TF task for ξ feedback

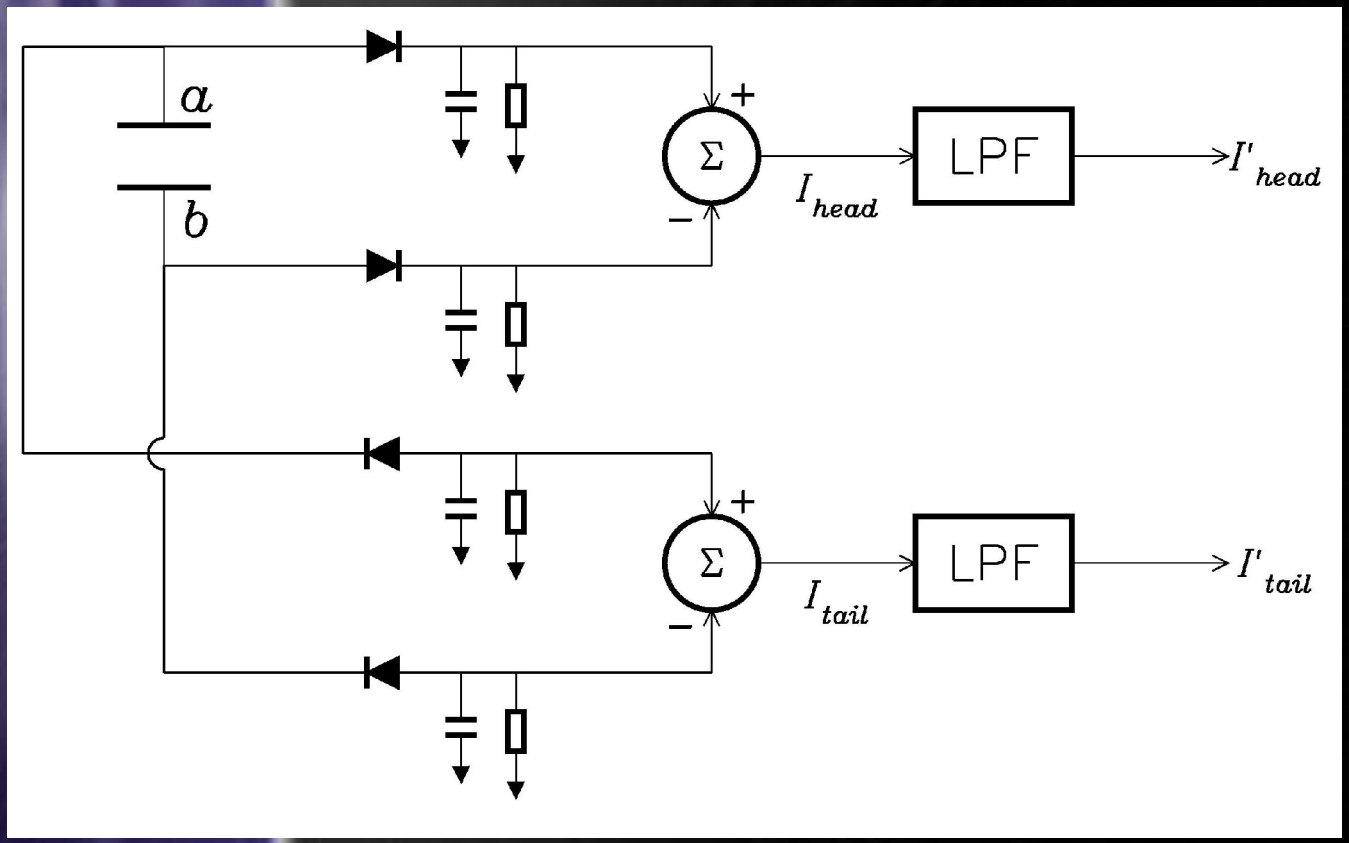
Weak Head-Tail Method

- Do the same thing as with the strong head-tail method except using much lower the kick amplitude.
- 3D-BBQ is very sensitive. Can measure changes ~10 nm in beam position.*
- If the kick can be reduced, beam lifetime and transverse emittance can be preserved.

* "High Sensitivity Tune Measurement by Direct Diode Detection", M. Gasior, 7th DIPAC 2005.

Not part of TF task for ξ feedback

3D-BBQ setup for head-tail



The diodes are oriented so that they pick out either the head or the tail.

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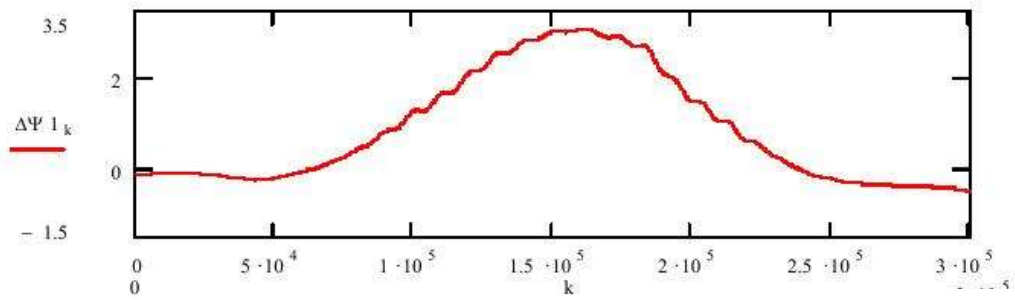
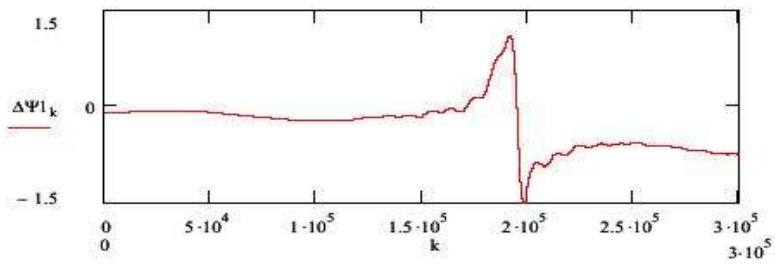
Example

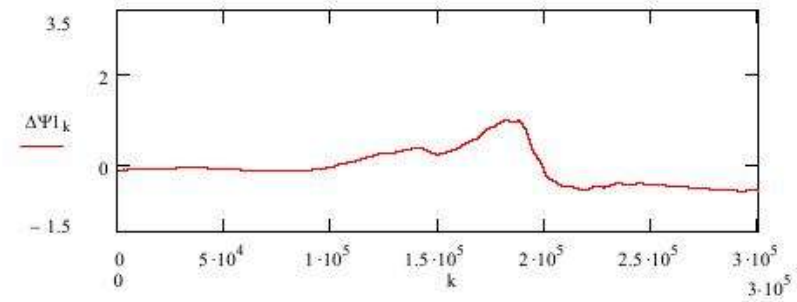


Chrom = 7.24 by C100 7.83

From Tevatron: strong kicks, 3D-BBQ with stripline



Peak chromaticity 3.4 units occurs ~ 60 turns later than It should. By C100 3.4



Peak chromaticity 3.05 units occurs ~ 60 turns later than It should. By C100 4.23

Method yields results which look pathological and yield ξ which is inconsistent.

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Notes

- Using the 3D-BBQ as the pickup in the Tevatron gives ambiguous results
  - 3D-BBQ is a peak detector and so there is some uncertainty as to where the actual position of the head, tail is detected. Thus $\Delta\tau$ is not pinned down.
  - There may be an effects from the closed orbit, kick amplitude and rms bunch length on the 3D-BBQ.

Not part of TF task for ξ feedback

Notes (cont'd)

- At the SPS, button pickups were used and not striplines. Results not good.
  - Repeat with stripline pickups.

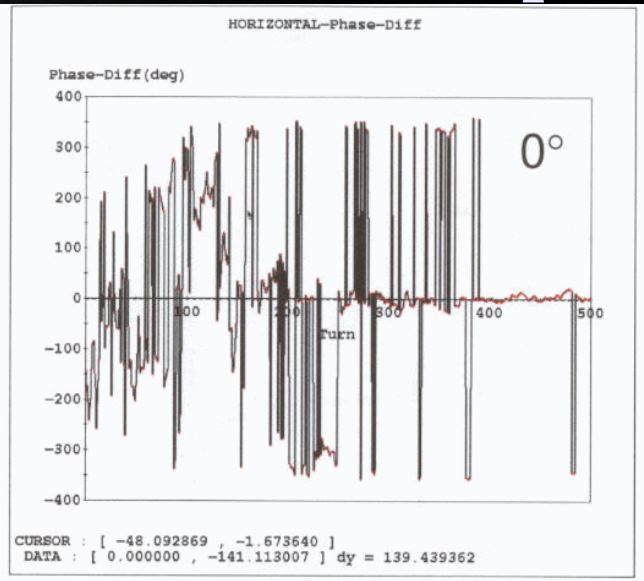
Not part of TF task for ξ feedback

Continuous Head-Tail

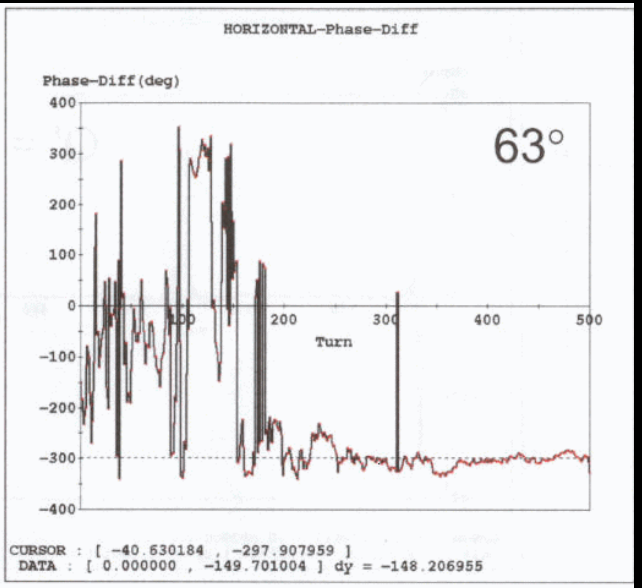
- Continuously kicking the beam transversely and using 3D-BBQ as detector to measure phase between head and tail.
- Computer simulations show that there is a phase difference between head and tail due to ξ.
- Continuous kick comes for free from tune tracker PLL.

The Computer Simulations

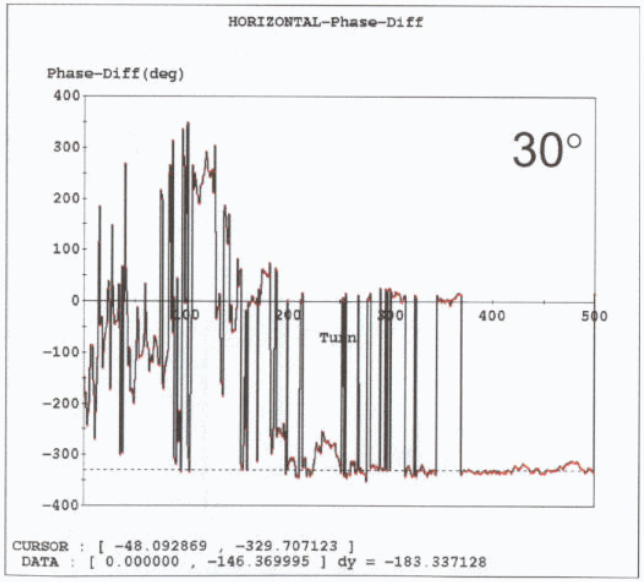
Q' ~ 0



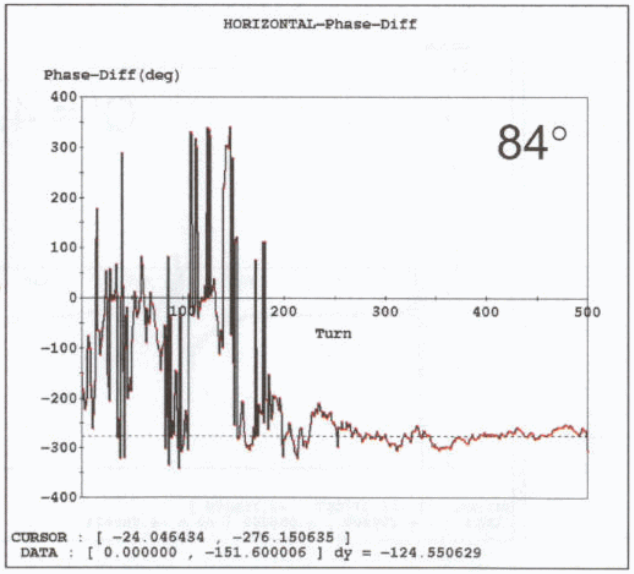
Q' ~ 10



Q' ~ 5



Q' ~ 15



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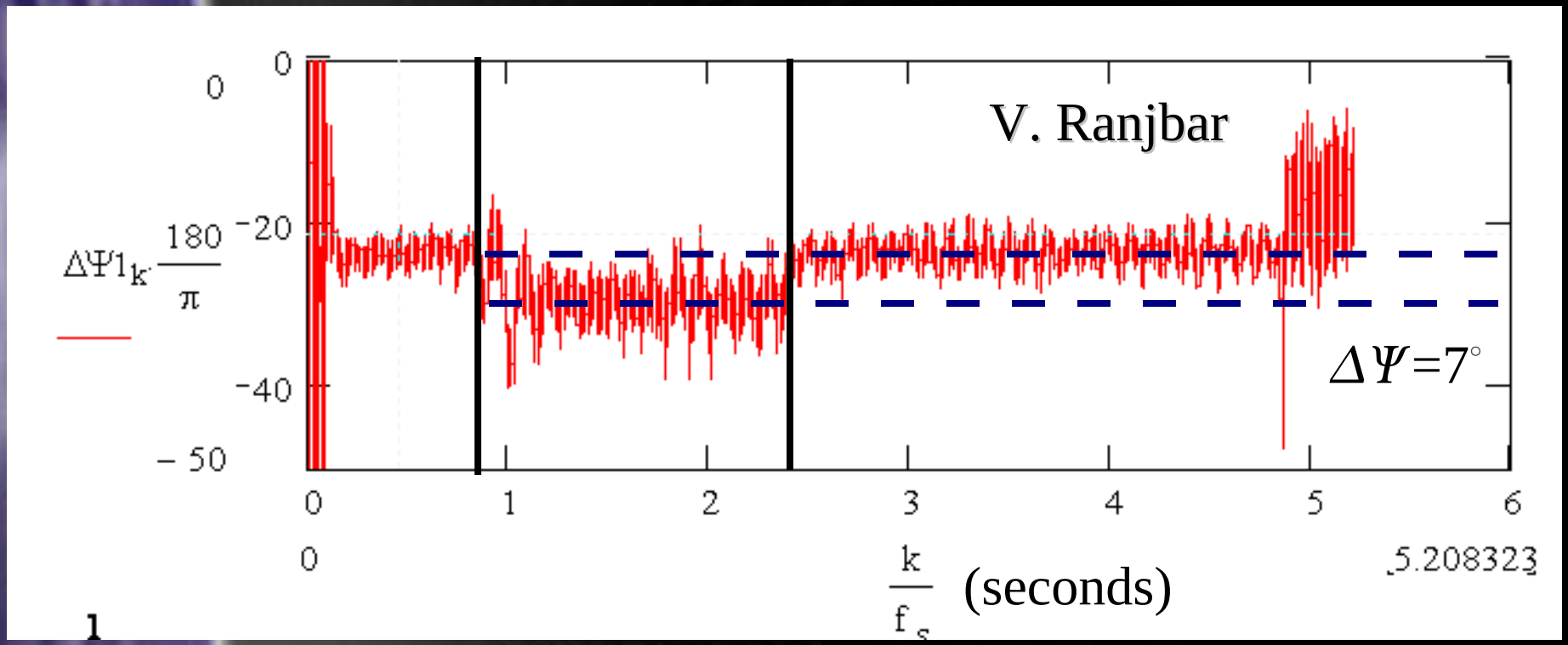
The SPS Measurements



Change in phase seen when chromaticity changed by 2.5 units

Data set sc33578-30.wav

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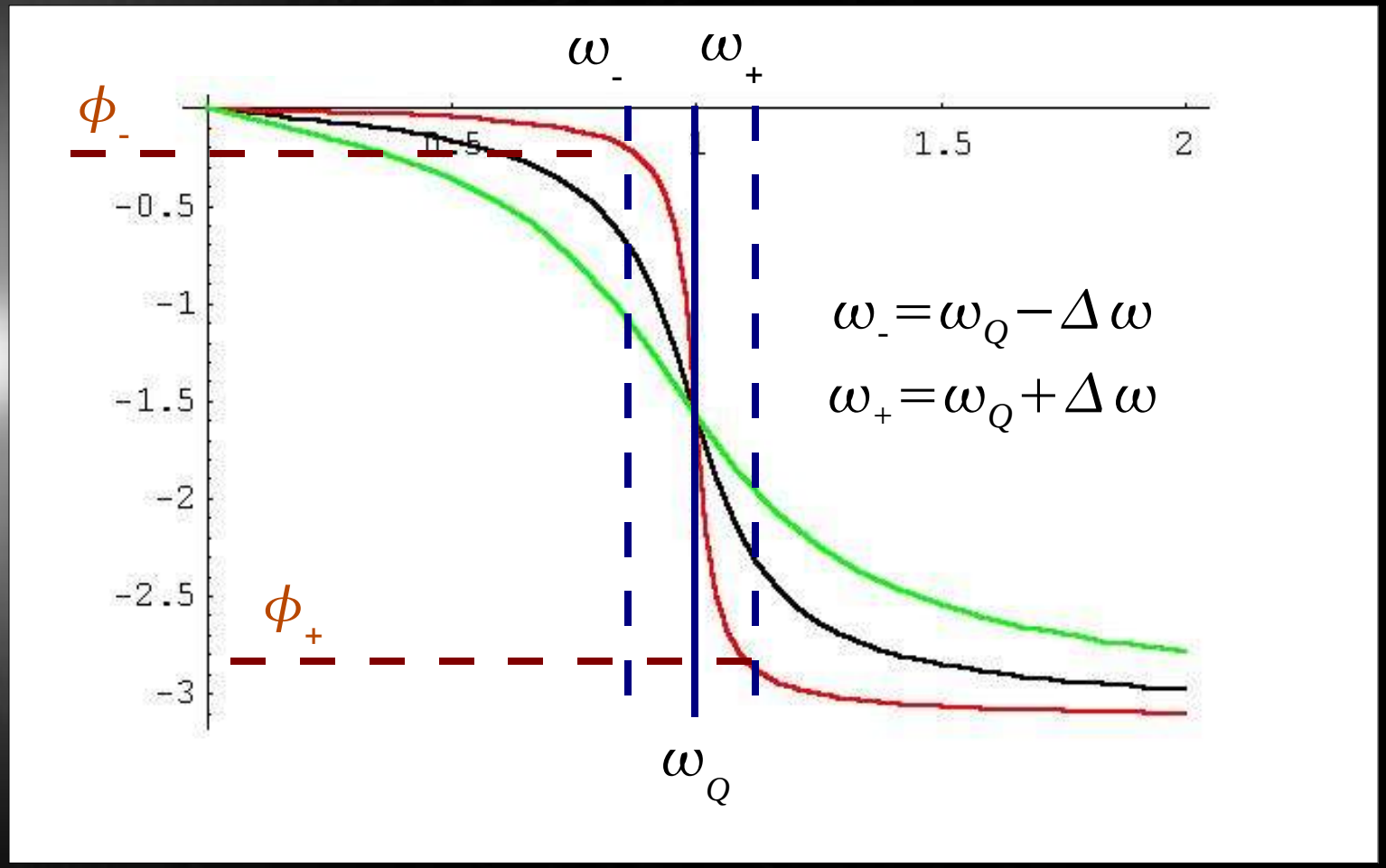
Notes

- First try at SPS gave some indication that there is a phase change from chromaticity
  - However, some data sets did not show this change.
  - Also sensitivity might be better if stripline pickups are used.
- This will be repeated more systematically in the SPS, RHIC and Tevatron.
- The advantage is that no extra kicks on the beam is required. Just use the continuous kicks from the tune tracker PLL.

3 Tone Method

- 3 tone method
  - Use the tune tracker to lock to phase null.
  - Use 2 tones at fixed distance $\pm\Delta\omega$ w.r.t. to locked tune ω_Q
  - $\Delta\omega < \omega_s$ the synchrotron frequency.

Measure the slope of the phase response which depends on ξ



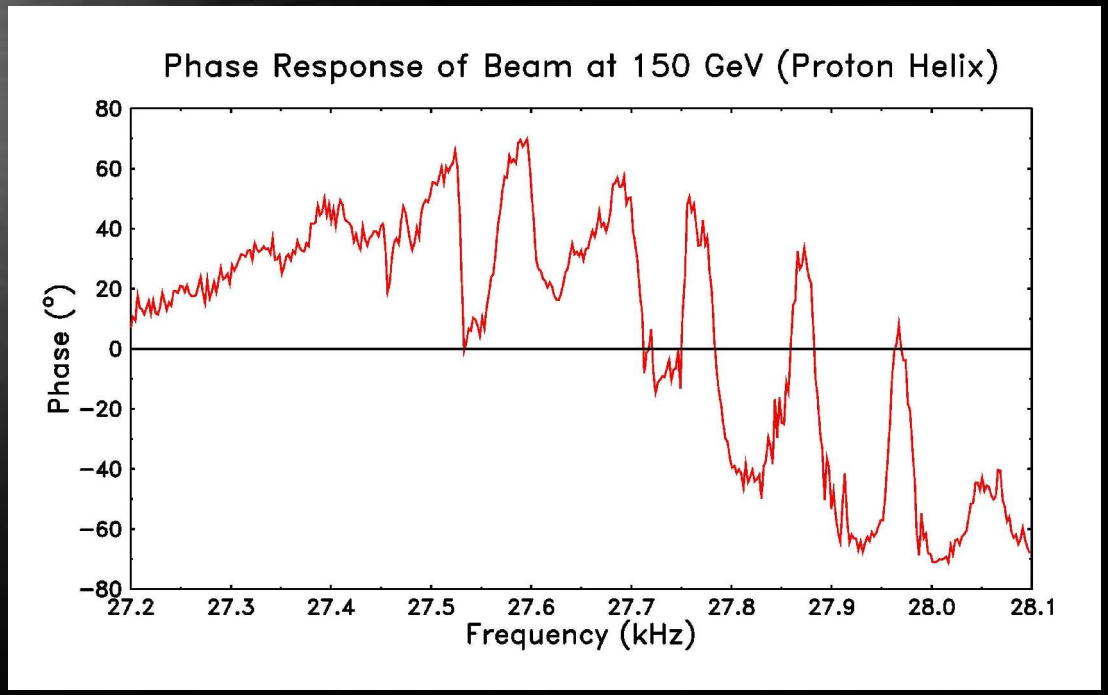
The 3 tone formula

$$\phi_+ - \phi_- = -2\tan^{-1}\left(\frac{\kappa\,\xi\sqrt{3}\,\omega_{\mathrm{rev}}\,\Delta p/p}{\Delta\omega}\right)$$

where κ is a constant which is found by calibration

Notes

- Requires calibration to find κ.
- May have problems if the synchrotron lines have a large width



Notes (cont'd)

- Low synchrotron frequency ~23 Hz at 7TeV and possibly 50Hz mains lines might also make this method non-feasible.

Comparing Methods

Method	Extra Excitation	Notes
Slow RF freq. Mod.	Y	Baseline
McGinnis Method	Y	Works in Tevatron
Strong Head-tail*	Y	Standard method
Weak Head-tail*	Y	Not demonstrated
Cont. Head-tail	N	Some Prelim. Results
3 tone	Y	Not demonstrated

*Not part of TF task for ξ feedback

Action Item

- Since the LHC will start up in 2007/2008, this may be the last opportunity to pin down the chromaticity tracking and feedback methods
  - RHIC, SPS and Tevatron will divide up the methods to look at.
  - RHIC will close the loop for chromaticity feedback.
  - Study plan at http://larpdocs.fnal.gov/
    - LARP-DOC-383

Conclusion

- Continuous chromaticity measurement and control is very important for the LHC.
- At least 6 methods to accomplish the same thing
  - Maturity of methods are not the same
    - Slow RF frequency modulation and strong head-tail are the most mature.
    - McGinnis method actively pursued at Fermilab.

Conclusion (cont'd)

- Clearly more machine studies needed to evaluate all the other methods.
  - Testing to be done at RHIC, SPS and Tevatron.
  - Chromaticity feedback attempt at RHIC.
- **Last chance to get chromaticity tracking/feedback working before LHC turn on in 2007/2008.**