Impact of of Longitudinally Tilted Beams on BPM Performance at the Advanced Photon Source

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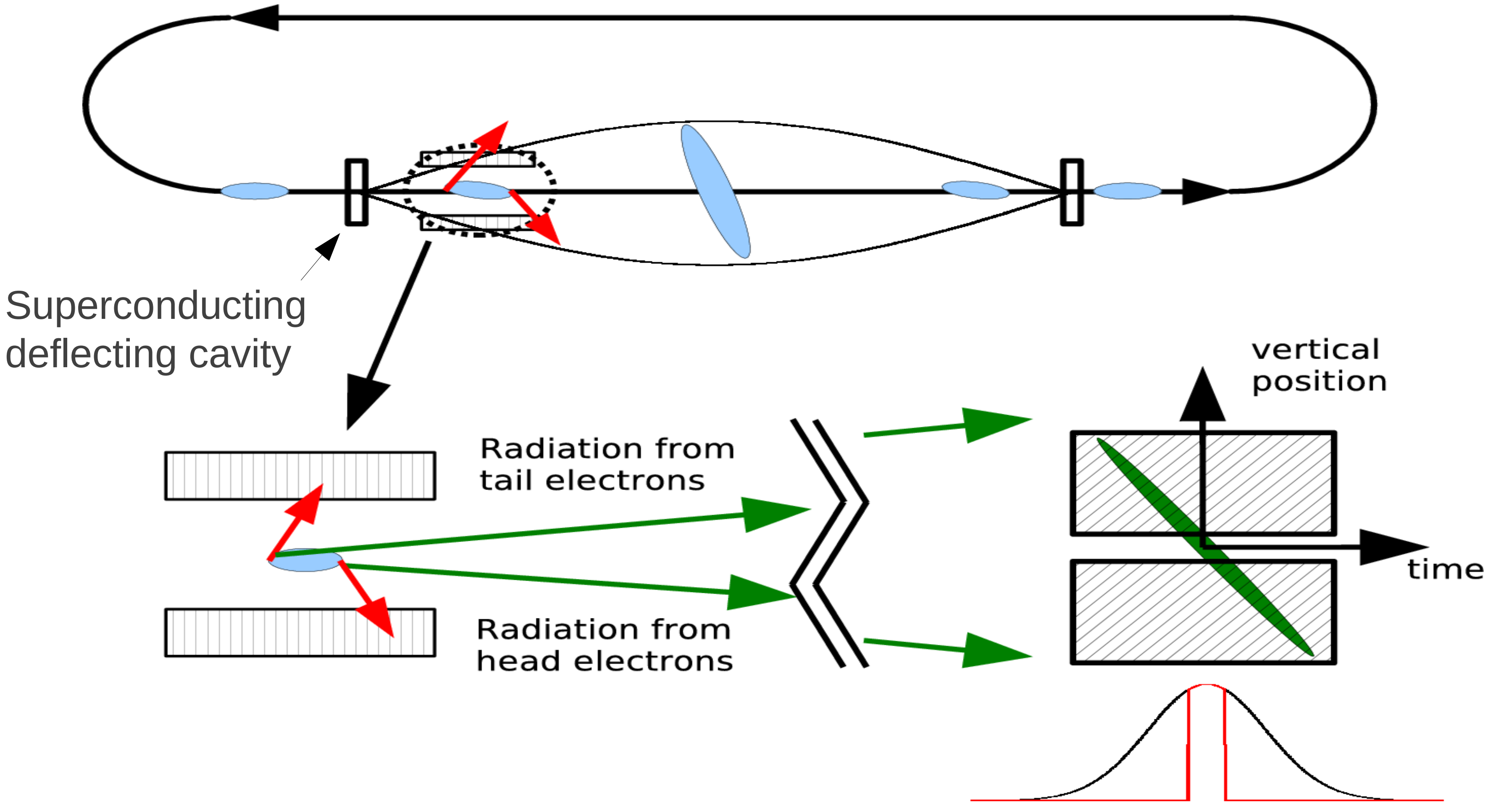
U.S. DEPARTMENT OF ENERGY

Outline

- Motivation: Tilted beams at the APS used to create short pulse X-rays (SPX)
- Tilted beams: Qualitative discussion
- Button signals from tilted beams
  - Delta and sum signals
  - Phase shift between buttons
- Impact on existing monopulse bpm system
- Experimental measurement of beam tilt using buttons
- Conclusion

Motivation: Short-Pulse X-ray Project at APS Using Zholents' scheme[1,2]

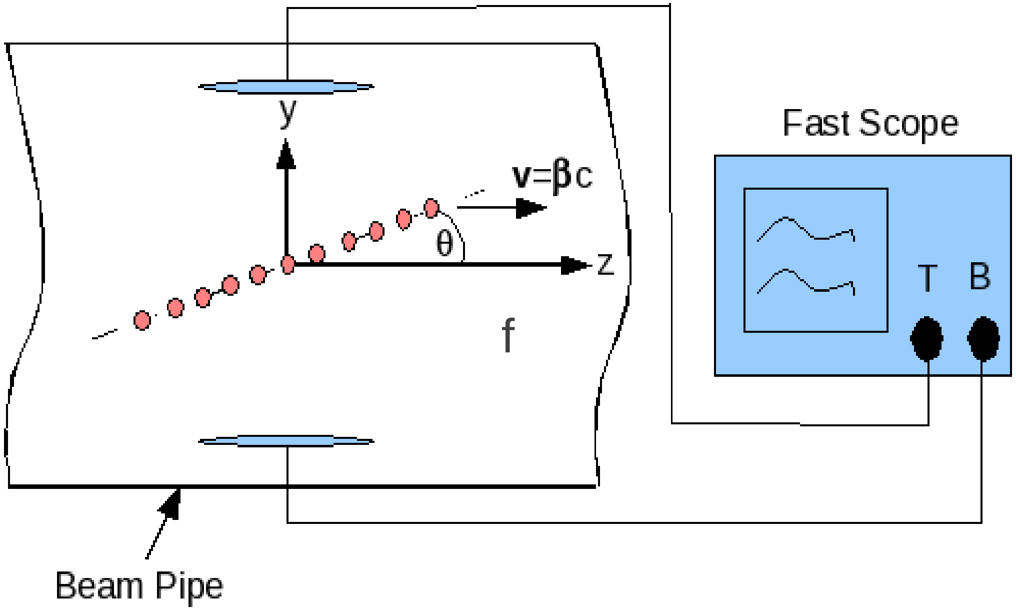


[1]A. Zholents *et al.*NIM A 425, 385 (1999).
[2]M. Borland, Phys. Rev. ST Accel Beams 8, 074001 (2006).

Button Signal Due to Tilt: Qualitative Discussion

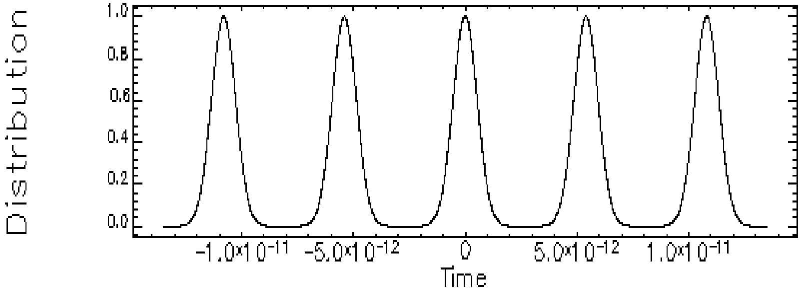
- Button signals to first order from offset beams
  - Large signal from beam current for a centered beam (cavity bpm signal does not have this offset)
  - Transverse beam displacement perturbs the signal with sensitivity $\kappa = (1 - 5 \times 10^{-4}\,\mu m^{-1})$
  - Consider a simple tilted beam consisting of point charges

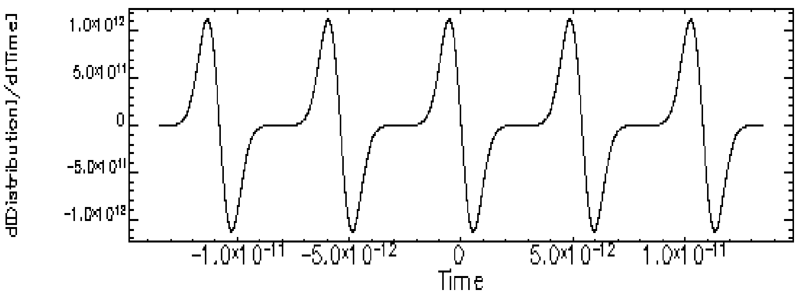
$$V_{T,B}(t) = Z\frac{dI_b(t)}{dt}(1 \pm \kappa\, y)$$

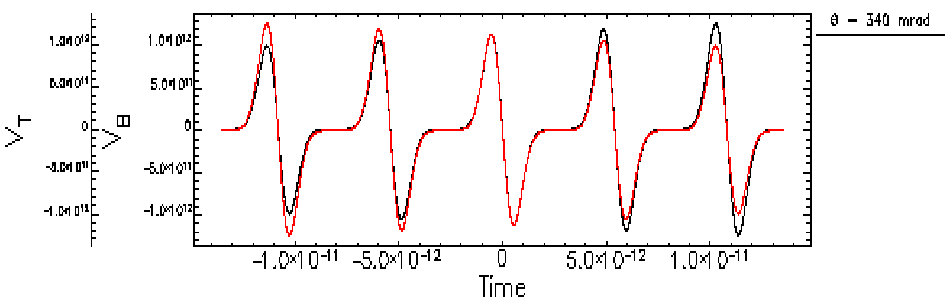


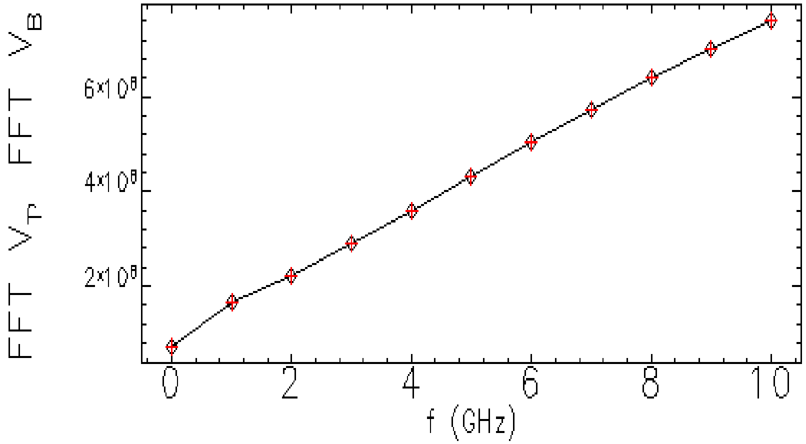
Longitudinal View

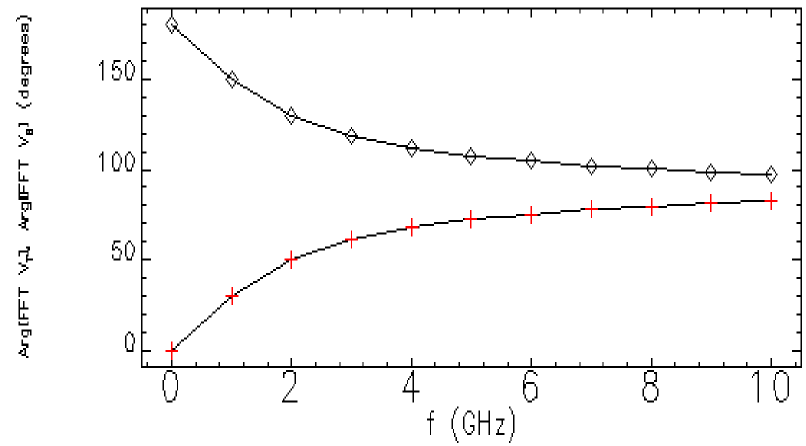
Button Signal Due to Tilt: Qualitative Discussion





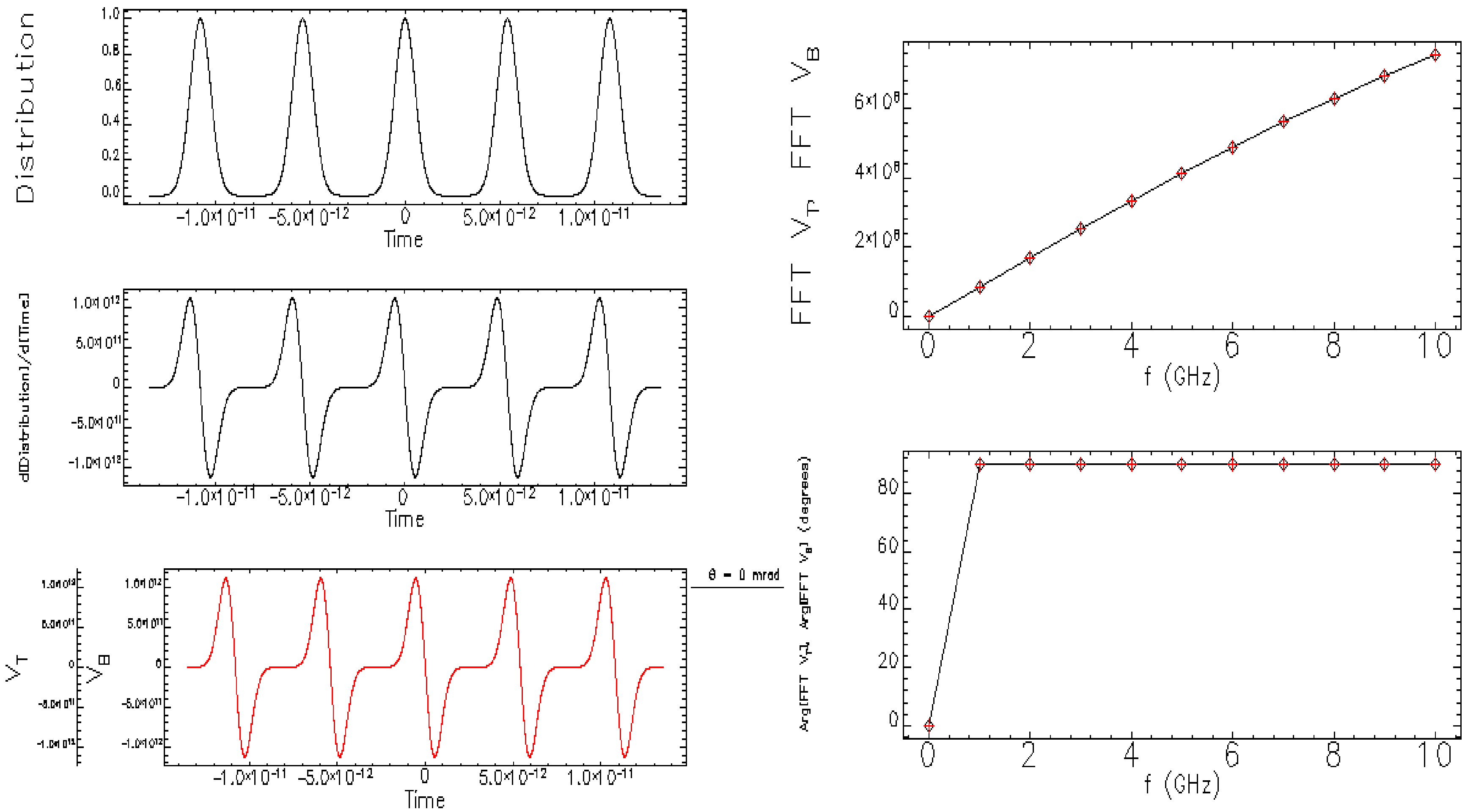






- Time and frequency domain button signals for tilt = 340 mrad

Button Signal Due to Tilt: Qualitative Discussion



- Time and frequency domain button signals for tilt = 0 mrad

Button Signal Due to Tilt

- Calculate the button signals in time and frequency domains for an arbitrary distribution
  - Construct the time domain button signals:
    - Start with expression for button signal to first order in transverse displacement
    - Integrate differential current x displacement elements along the tilted distribution
    - Convert particle position in the distribution to time by using $z=\beta ct$
  - Transform button signals to the frequency domain
    - Compute phase difference between buttons
    - Compute Delta and Sum signals
- Use these results to analyze:
  - performance of monopulse bpm system when there is beam tilt
  - Button phase measurement of a tilted beam using an Sband phase detector

Button Signal Due to Tilt (cont.)

$$V_{T,B}(\omega)=ZQ\omega\{iI_c(\omega)(1\pm\kappa\delta y)\mp\kappa I_s(\omega)\theta\}$$

$$I_c(\omega)=\int_{-\infty}^{\infty} f(z)\cos\left(\frac{\omega z}{\beta c}\right)dz$$

$$I_s(\omega)=\int_{-\infty}^{\infty} zf(z)\sin\left(\frac{\omega z}{\beta c}\right)dz$$

$$\Delta(\omega)=\Delta_o(\omega)-2ZQ\omega\kappa I_s(\omega)\theta$$

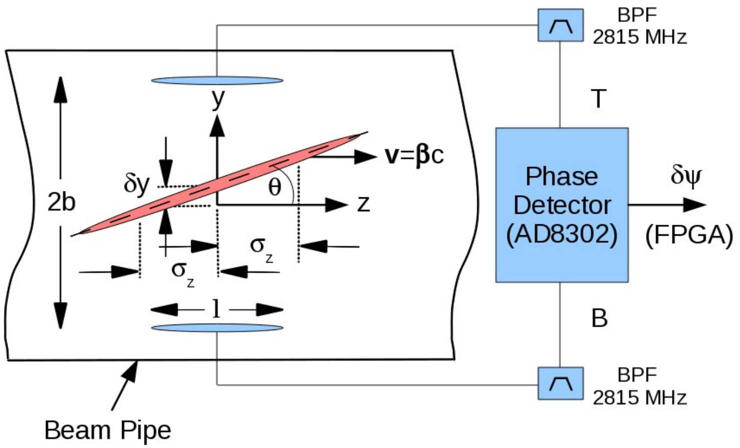
$$\Delta_o(\omega)\equiv 2iZQ\omega\kappa I_c(\omega)\delta y$$

$$\Sigma(\omega)=2iZQ\omega I_c(\omega)$$

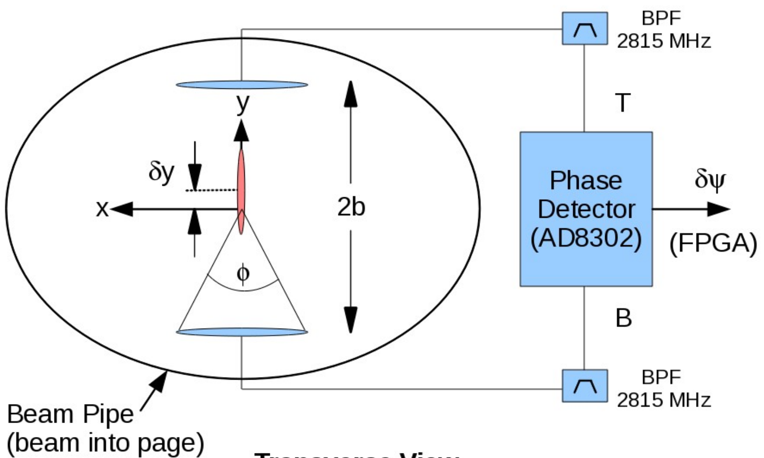
$$\frac{\Delta(\omega)}{\Sigma(\omega)}=\frac{\Delta_o(\omega)}{\Sigma(\omega)}+i\kappa\frac{I_s(\omega)}{I_c(\omega)}\theta$$

$$\frac{\Delta_o(\omega)}{\Sigma(\omega)}=\kappa\delta y$$

$$\delta\Psi\equiv\Phi_T-\Phi_B\approx 2\kappa\frac{I_s(\omega)}{I_c(\omega)}\{1-O(\kappa^2\delta y^2)\}^{-1}\theta\approx 2\kappa\beta c\omega\sigma_t^2\theta$$

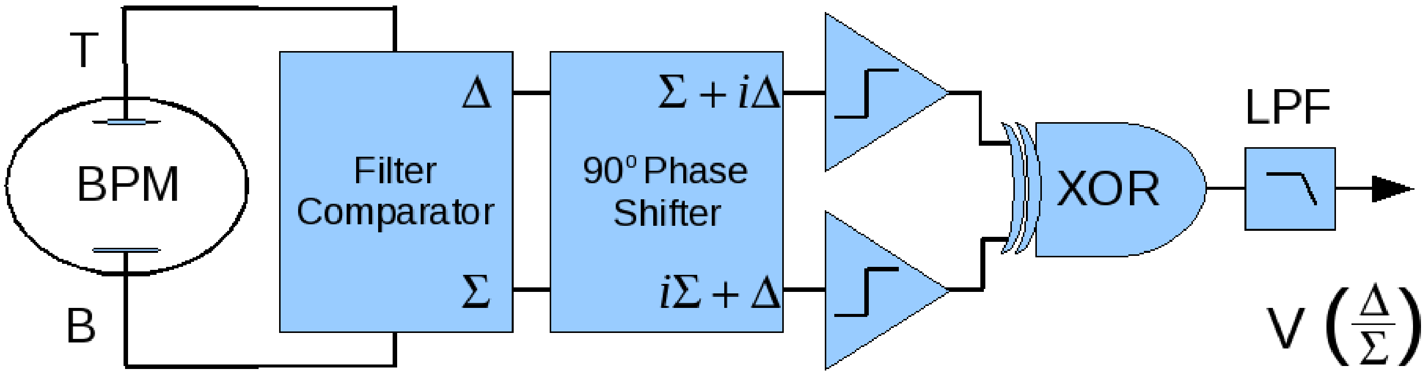


Longitudinal View



Transverse View

Tilt Impact on Monopulse BPM System



- Converts position information in Delta signal to phase
- Compares the phase of two equal amplitude signals created from the Delta and Sum signals
- For no tilt $\theta = 0$:

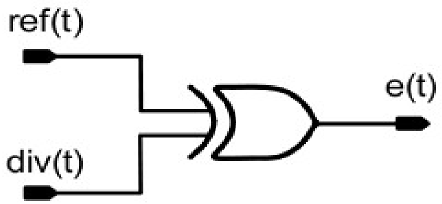
$$V\left(\frac{\Delta(\omega)}{\Sigma(\omega)}\right) \approx \frac{4}{\pi}\left|\frac{\Delta_o(\omega)}{\Sigma(\omega)}\right| \cos(\phi_\Delta - \phi_\Sigma) = \frac{4}{\pi}\kappa\,\delta\,y$$

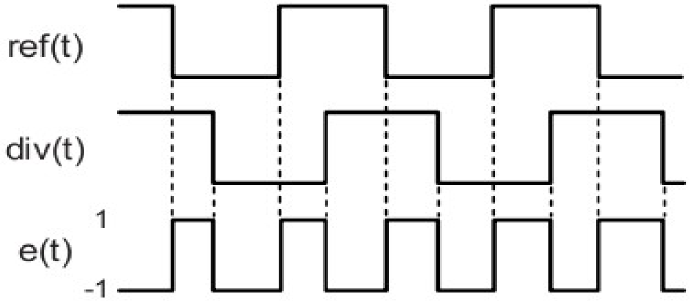
$$\phi_\Delta = sign(\delta\,y)\frac{\pi}{2}$$

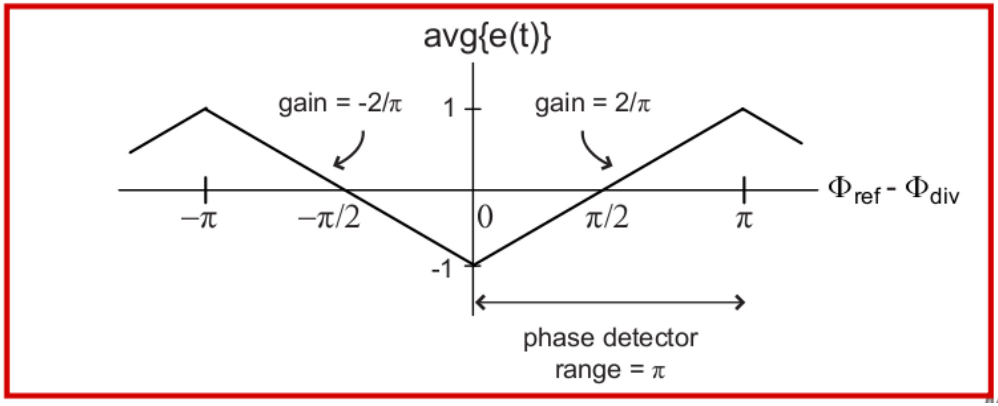
$$\phi_\Sigma = \frac{\pi}{2}$$

Tilt Impact on Monopulse BPM System cont.

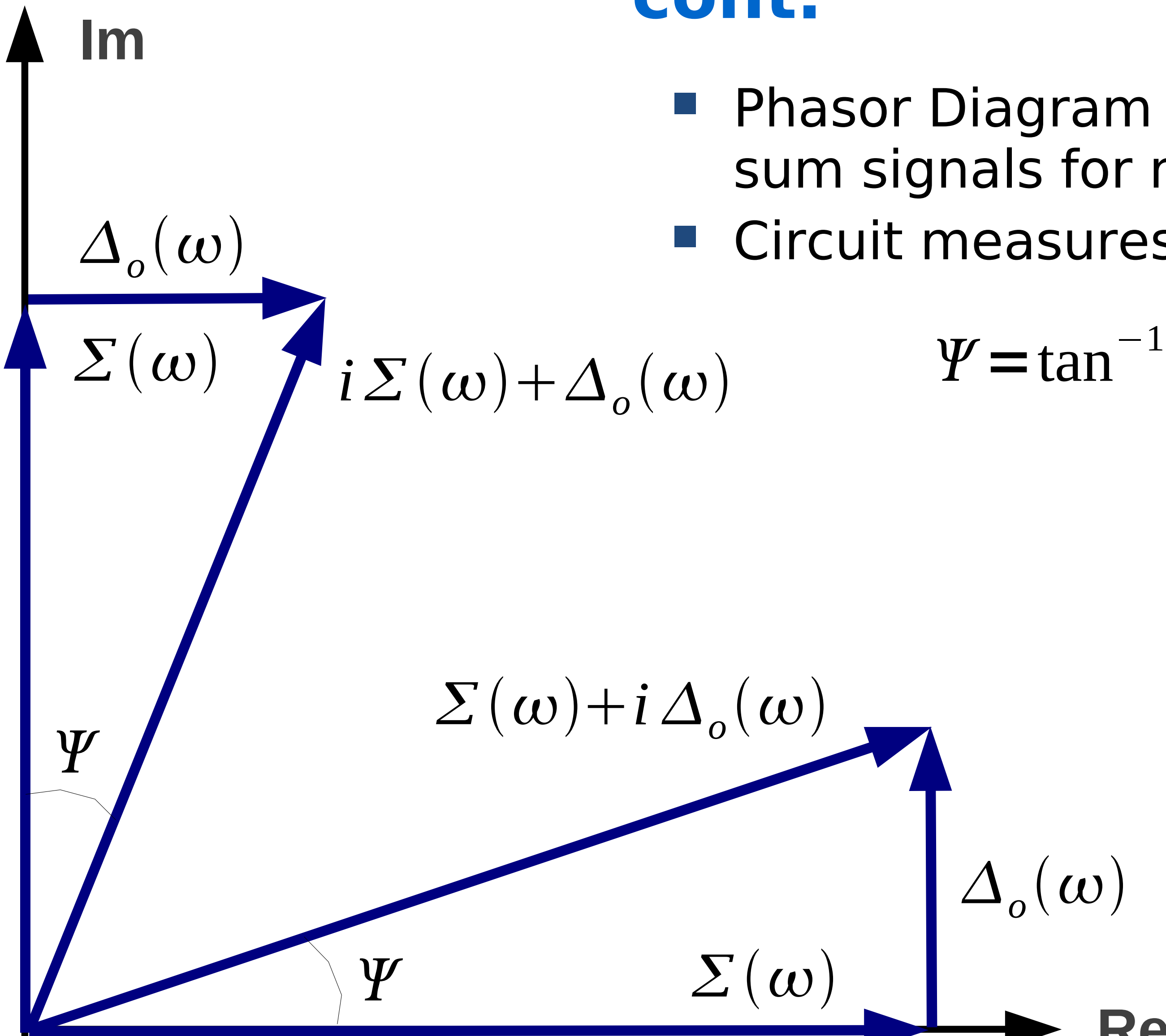
- XOR output
  - High state if both inputs have different states
  - Low state if both inputs have the same state
- DC component of XOR output proportional to phase
- 180 degree linear range
- Monopulse system operates near 90 degree phase point







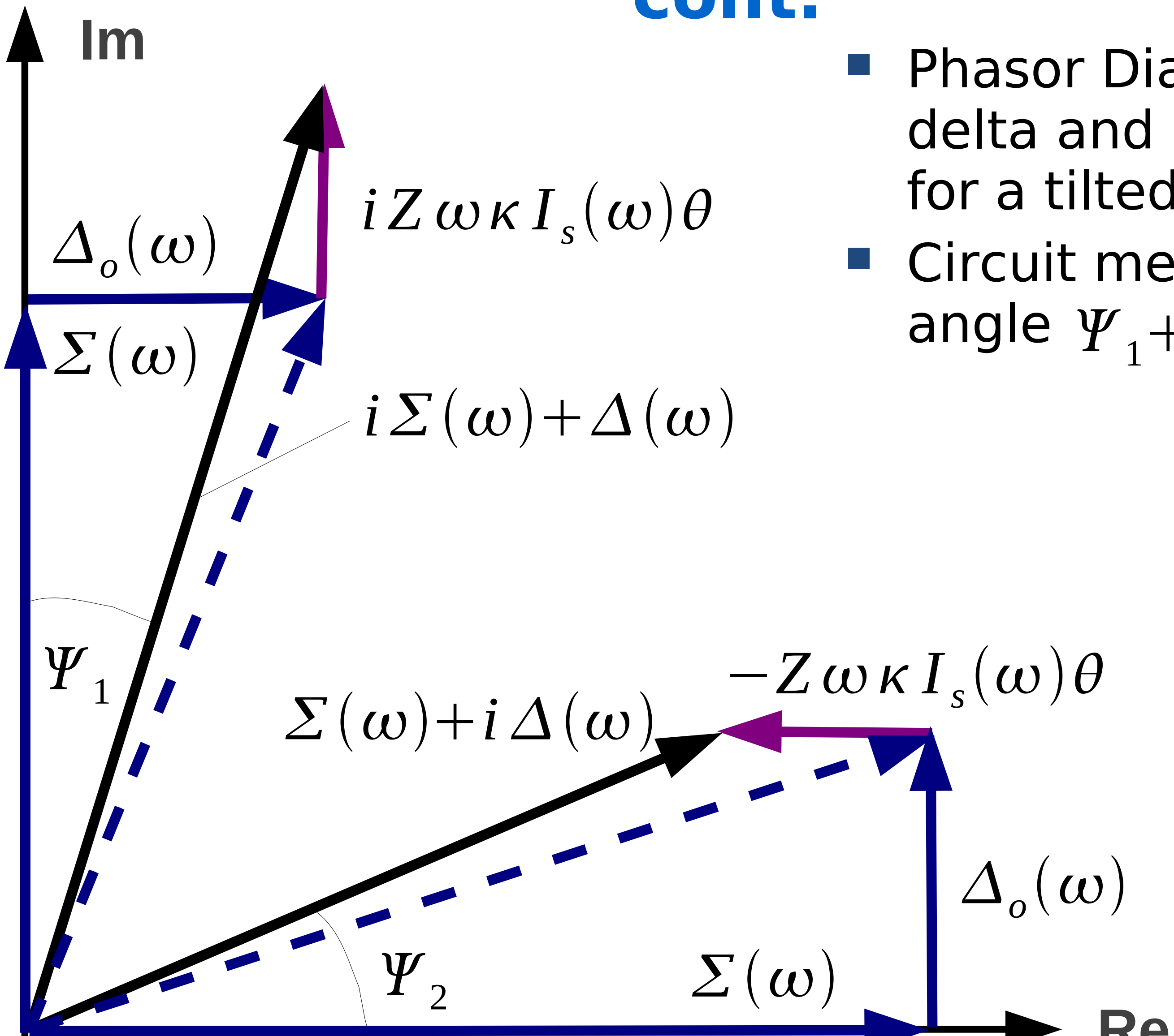
Tilt Impact on Monopulse BPM System cont.



- Phasor Diagram for delta and sum signals for no tilt ($\theta=0$)
- Circuit measures the angle 2Ψ

$$\Psi=\tan^{-1}\frac{\Delta_o(\omega)}{\Sigma(\omega)}\approx\kappa\,\delta\,y$$

Tilt Impact on Monopulse BPM System cont.



- Phasor Diagram for delta and sum signals for a tilted beam
- Circuit measures the angle $\Psi_1+\Psi_2$

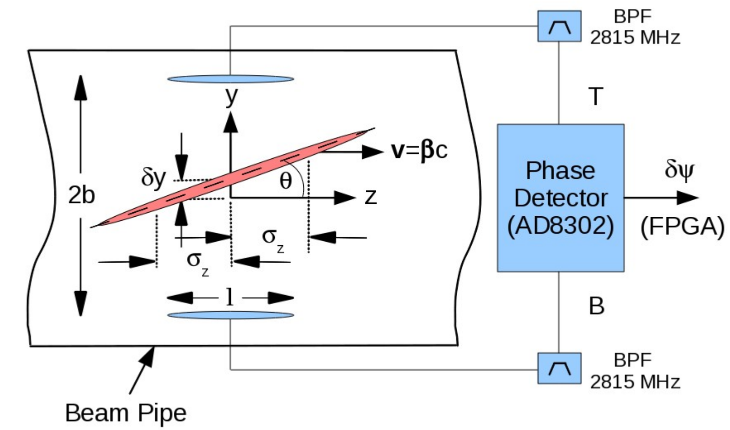
Tilt Impact on Monopulse BPM System cont.

$$\Psi_1+\Psi_2=\tan^{-1}\left(\frac{\Delta_o(\omega)}{\Sigma_o(\omega)+Z\,\omega\,\kappa\,I_s(\omega)\,\theta}\right)+\tan^{-1}\left(\frac{\Delta_o(\omega)}{\Sigma_o(\omega)-Z\,\omega\,\kappa\,I_s(\omega)\,\theta}\right)$$

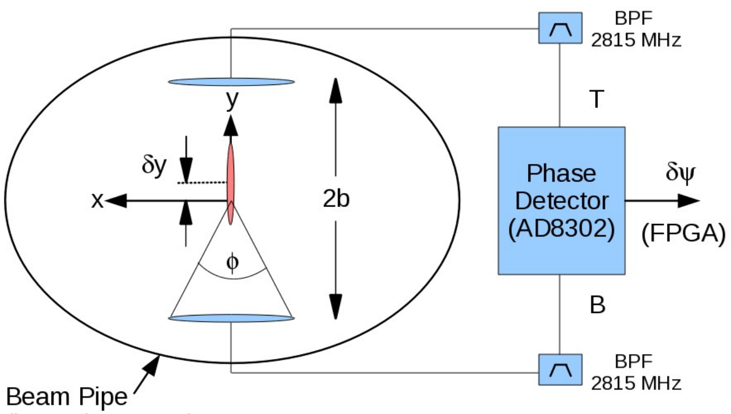
$$\Psi_1+\Psi_2\approx 2\frac{\Delta_o(\omega)}{\Sigma_o(\omega)}\left(1+O\left(\frac{\kappa\,I_s(\omega)}{I_c(\omega)}\theta\right)^2\right)=2\,\kappa\,\delta\,y\left(1+O\left(\frac{\kappa\,I_s(\omega)}{I_c(\omega)}\theta\right)^2\right)$$

- Centroid position error is second order in tilt angle
- Reduced sensitivity to tilt at the 352 MHz monopulse processing frequency due to transform ratio
- For largest SPX tilt of 340 mrad (BM source point) the beam centroid position error would be
- ~0.03 % for large aperture bpms
- ~0.75 % for small aperture bpms (P0's) (however tilt is nearly zero at the small aperture bpms

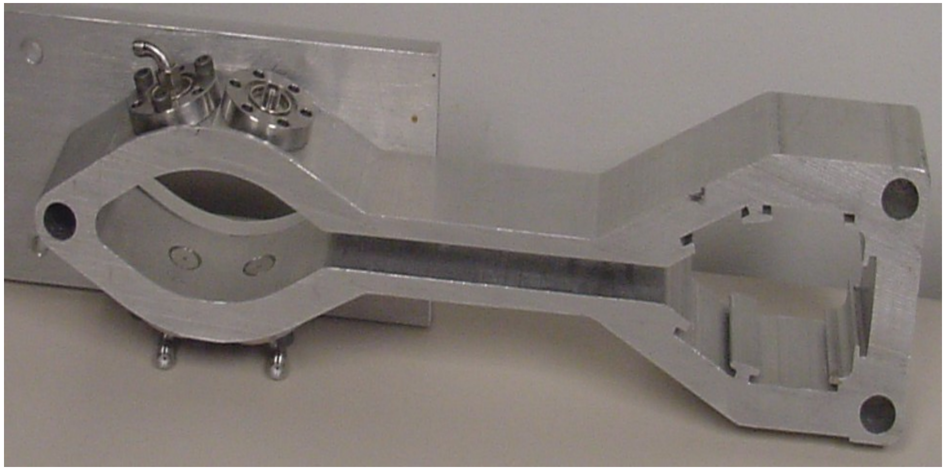
Tilt Measurement Using Buttons and Sband Phase Detector



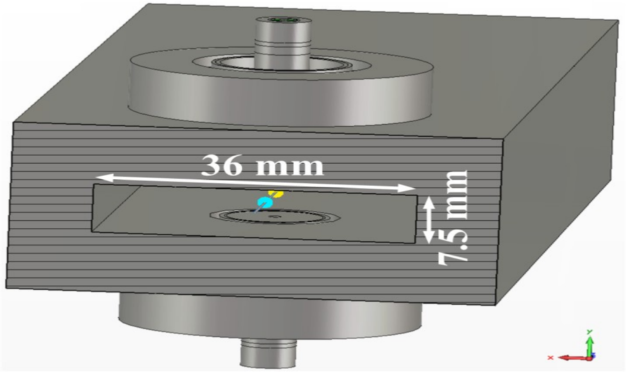
Longitudinal View



Transverse View



- Button geometry used in the experiment

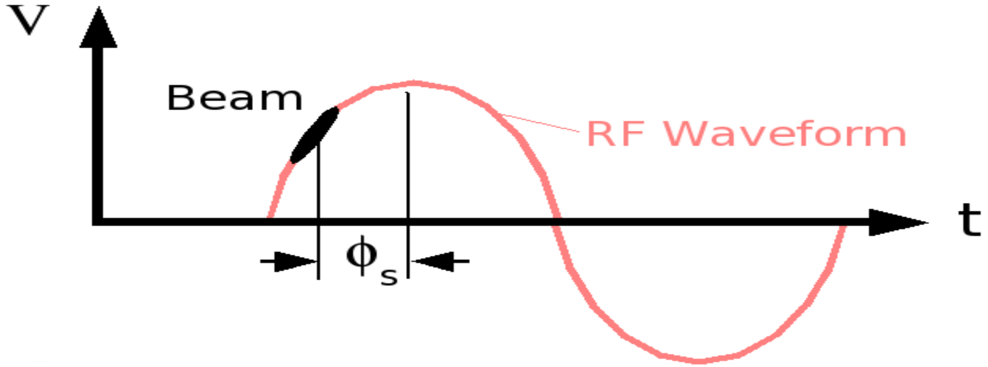


- [1]Small-gap button geometry

[1]X. Sun, these proceedings

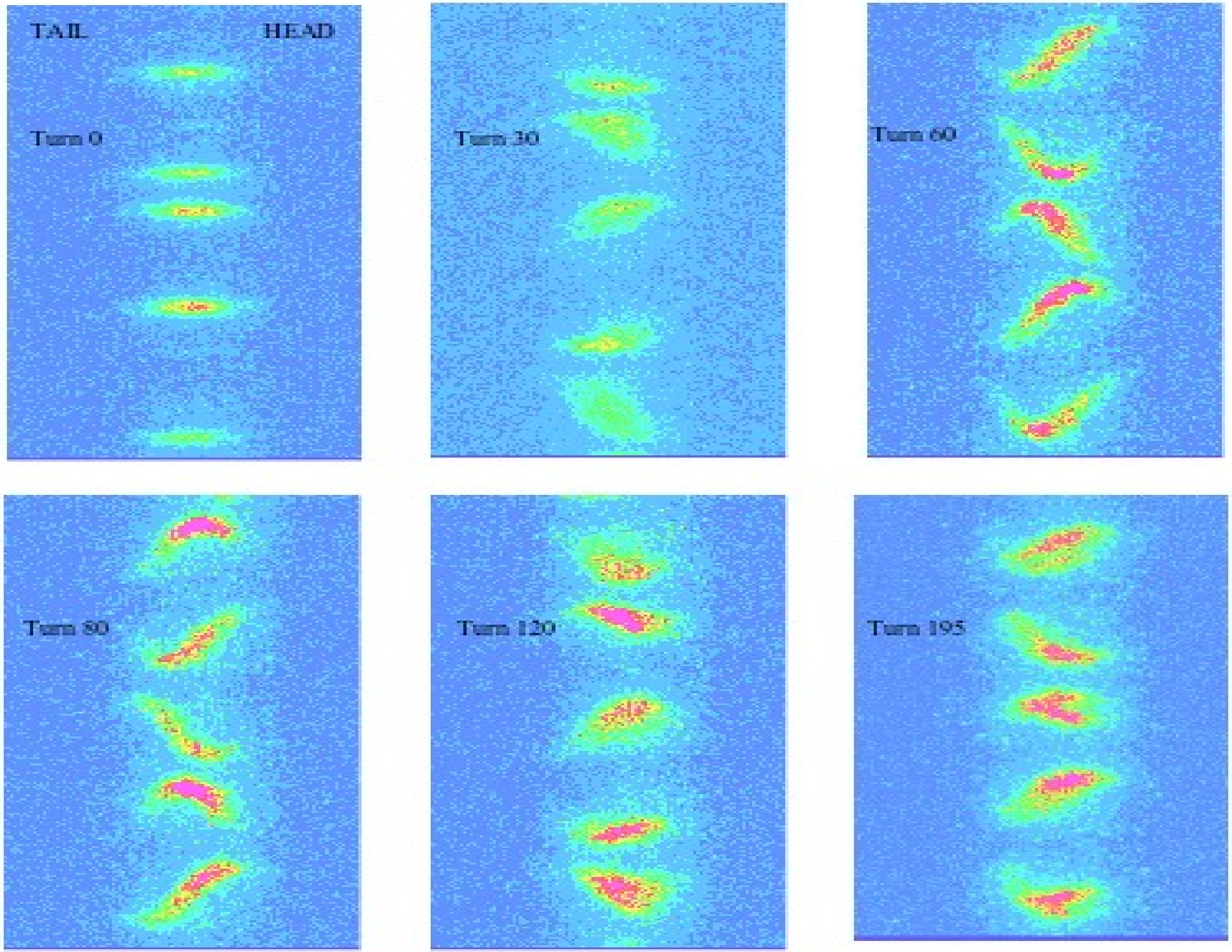
Tilt Measurement Using Buttons and Sband Phase Detector[1,2]

- Experiment relies on coupling between synchrotron and betatron motion via chromaticity: $\Delta\nu = \xi\frac{\delta E}{E}$
  - Head of the bunch is at higher energy (tune)
  - Tail of the bunch is at lower energy (tune)
- Fast betatron frequency differs between head and tail
- After half a synchrotron period betatron phase difference between head and tail reaches maximum for maximum tilt (at least in the linear regime)
- Transient experiment: Kick the beam and observe over ~100 turns



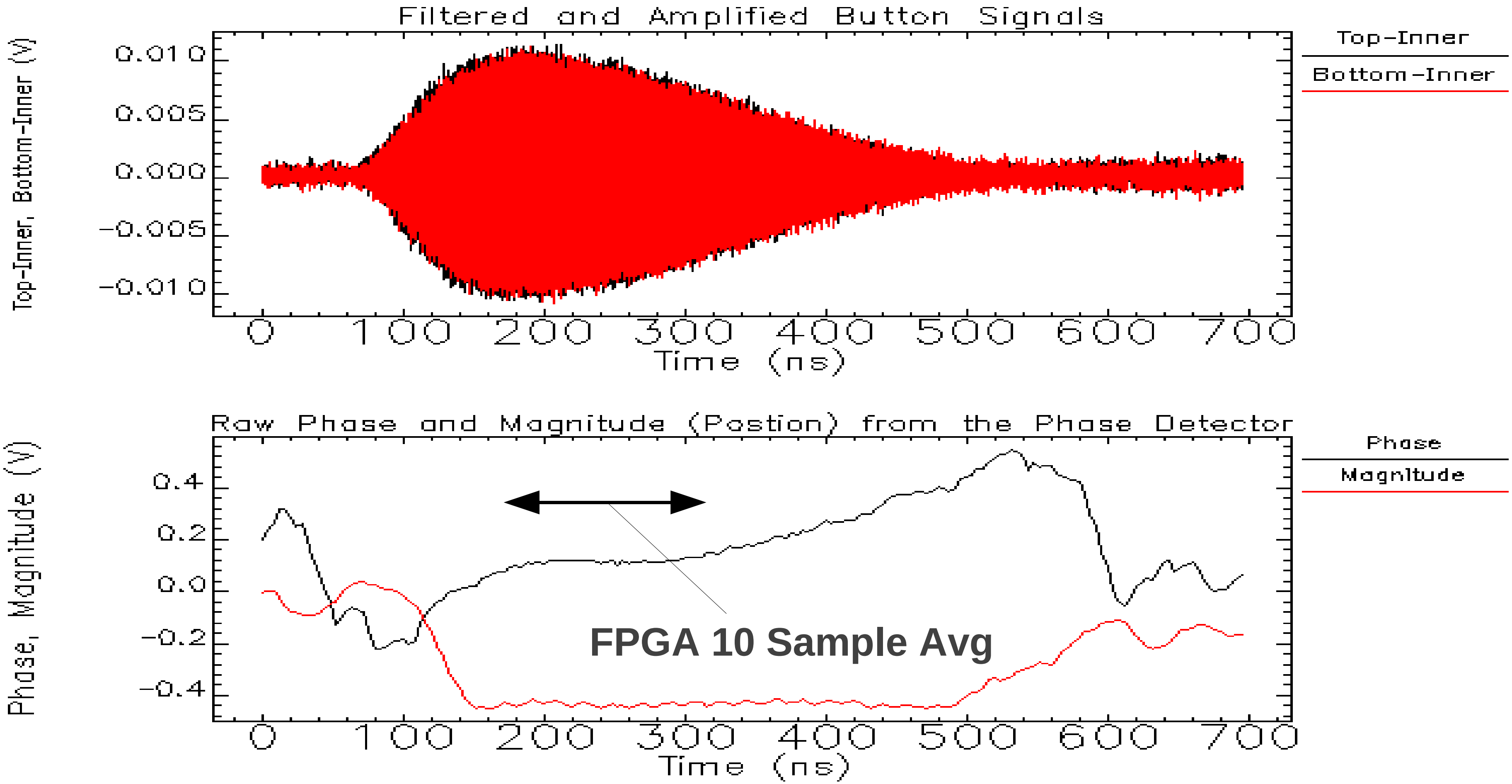
[1] W. Guo etal, PRST-AB, **10**, 020701 (2007)
[2] B.X. Yang etal., PAC 2005

Tilt Measurement Using Buttons and Sband Phase Detector[1]



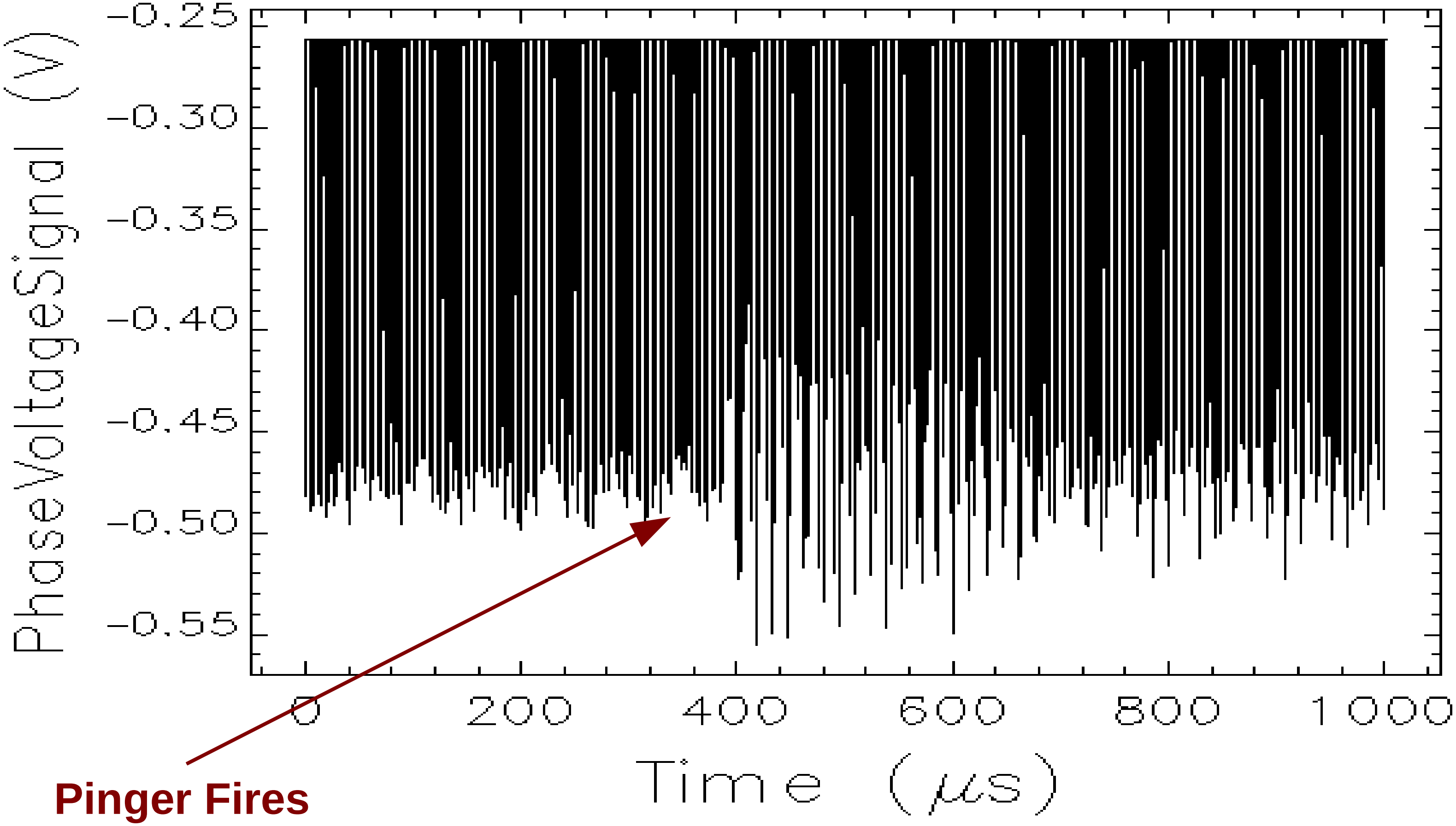
[1] B.X. Yang etal., PAC 2005

Tilt Measurement Using Buttons and Sband Phase Detector



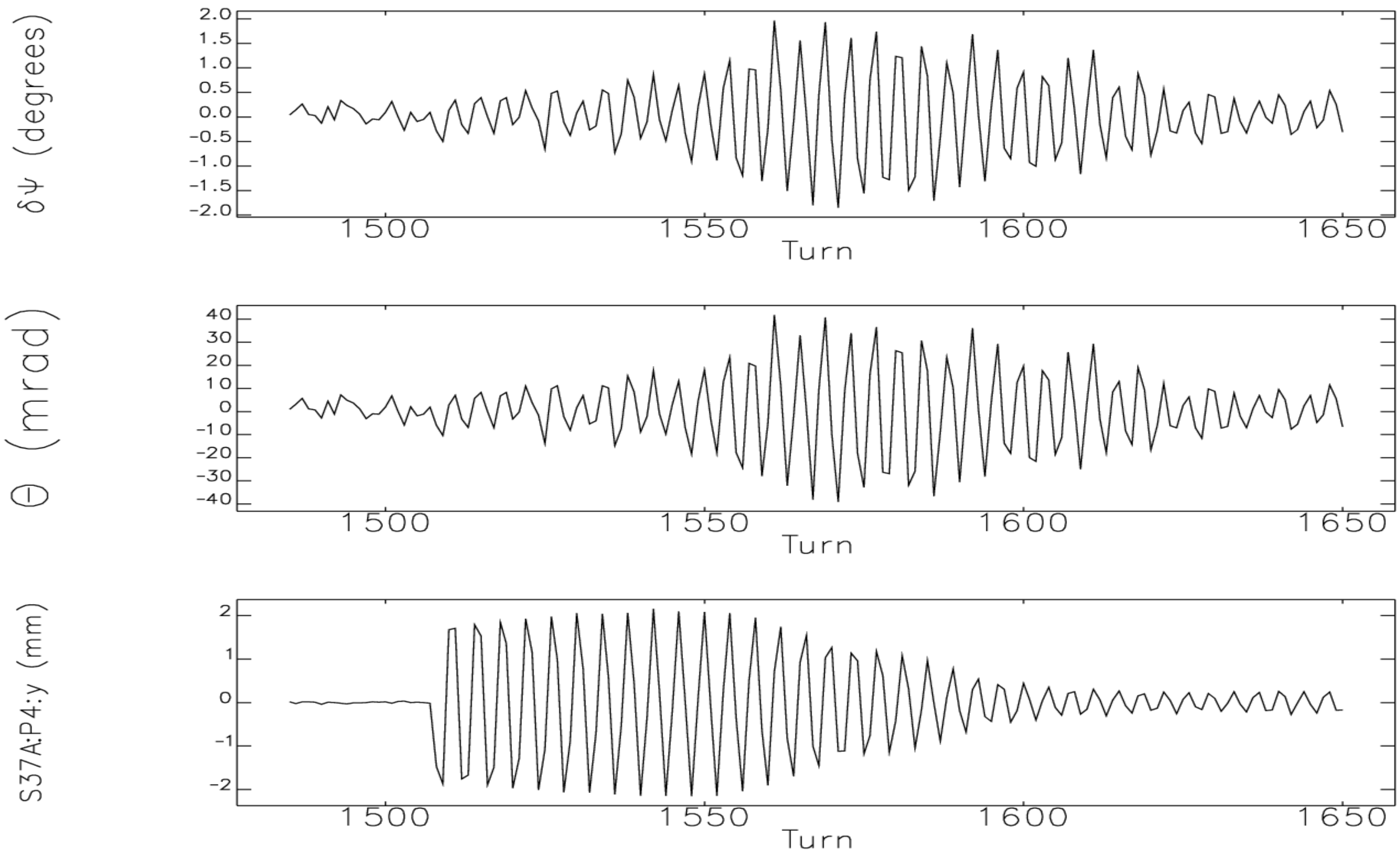
- Filtered and amplified S37A:P4 TI an BI button signals

Tilt Measurement Using Buttons and Sband Phase Detector



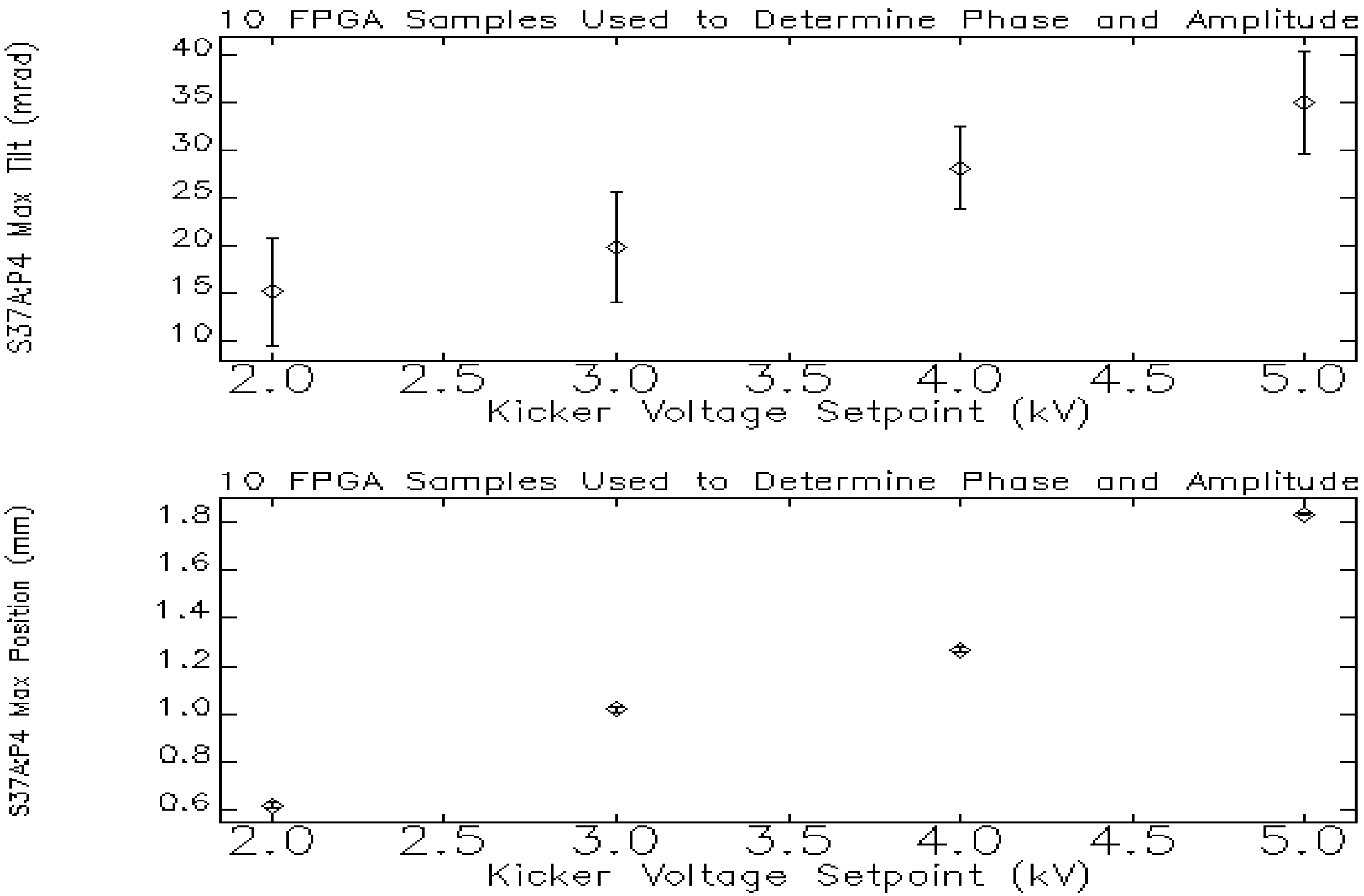
- Raw phase detector phase output measured on a scope

Tilt Measurement Using Buttons and Sband Phase Detector



- FPGA phase detector output scaled to get tilt (final equation slide 8) and position offset (using adjacent bpms and fitting a betatron oscillation)

Tilt Measurement Using Buttons and Sband Phase Detector



- Maximum tilt and position as a function of kicker (pinger) setpoint

Tilt Measurement Using Buttons and Sband Phase Detector

Table 1: APS SR machine and S37A:P4 "inner" BPM button parameters for large vacuum chamber buttons. Small gap chambers have b a factor of 5 lower.

Parameter	Value
b, l	18.7 mm, 12.5 mm
ϕ	$2\tan^{-1}\frac{l}{2b} = 0.645\ \mathrm{rad} = 36.96^\circ$
κ	$1.05\times10^{-4}\ \mu\mathrm{m}^{-1}$
ω	$2\pi\times$ 2815 MHz
$\sigma_t = \sigma_z/\beta c$	27 ps @ 1 mA
β	≈ 1 @ 7 GeV
ν_y, ν_s, ξ	0.241, 0.008, 4.00
α_c, σ_δ	2.82e-4, 0.00096
h, f_{rev}, ω_{rf}	1296, 271.555 kHz, $2\pi\times$ 351.9 MHz
(Kick angle) Θ	$\approx$ 0.1 mrad
$\beta_{\mathrm{kicker}}, \beta_{\mathrm{S37A:P4}}$	5.4 m, 26.7 m

- Low chromaticity ensures linear tilt oscillations over ~100 turns

Tilt Measurement Using Buttons and Sband Phase Detector

- Performed a transient experiment where tilt was generated using a kicker to induce centroid betatron oscillations which transform in to tilt oscillations
- Tilt generated was measured using buttons and an Sband phase detector (AD8302)
- For the transient measurement, large tilt angles can be measured >~ 3-5 mrad (final calibration yet to be done using streak camera)
- Tilt measurement verified central features of tilt build-up during first ½ synchrotron period for linear theory
- For APS SPX project, will have a CW signal and ability to average up to 324 samples per turn using FPGA
- Averaging over 1000 turns could give tilt measurement resolution down to perhaps 30 μrad up to 200 Hz

Conclusion

- APS SPX project requires:
  - Evaluation of existing monopulse bpm system sensitivity in the presence of large beam tilt
  - Measurement of the beam tilt between SPX cavities
- Monopulse bpm system centroid position measurement resolution calculated to be insensitive to beam tilt
  - Centroid correction is second order in beam tilt angle
  - For largest tilt present between SPX cavities beam centroid position measurement error is 0.03 %
- Performed a transient tilt experiment by kicking a single bunch in the APS storage ring
  - Using Sband phase detector measured tilt and position for transient experiment
  - With averaging should be able to measure tilt angles down to perhaps 30 μrad up to 200 Hz
  - Phase detector can provide simultaneous tilt and position information
  - Design of a tilt measurement system based on phase detector has commenced