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

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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\textsuperscript{1,2}

Superconducting deflecting cavity

Radiation from tail electrons

Radiation from head electrons

vertical position

time

\textsuperscript{1}A. Zholents \textit{et al.} NIM A 425, 385 (1999).
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 $\kappa = (1 - 5 \times 10^{-4} \text{\mu m}^{-1})$
  - Consider a simple tilted beam consisting of point charges

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

\[ V_{T,B}(\omega) = ZQ \omega \left\{ i I_c(\omega) (1 \pm \kappa \delta y) \mp \kappa I_s(\omega) \theta \right\} \]

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

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

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

\[ \Delta_o(\omega) = 2i ZQ \omega \kappa I_c(\omega) \delta y \]

\[ \Sigma(\omega) = 2i ZQ \omega I_c(\omega) \]

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

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

\[ \delta \Psi \equiv \Phi_T - \Phi_B \approx 2 \kappa \frac{I_s(\omega)}{I_c(\omega)} \left\{ 1 - O(\kappa^2 \delta y^2) \right\}^{-1} \theta \approx 2 \kappa \beta c \omega \sigma_t^2 \theta \]
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 $\theta = 0$:

$$V \left( \frac{\Delta(\omega)}{\Sigma(\omega)} \right) \approx \frac{4}{\pi} \left| \frac{\Delta_0(\omega)}{\Sigma(\omega)} \right| \cos (\phi_\Delta - \phi_\Sigma) = \frac{4}{\pi} \kappa \delta y$$

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

$$\phi_\Sigma = \frac{\pi}{2}$$
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 \( 2\Psi \)

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

\[
\Delta_o(\omega)
\]

\[
\Sigma(\omega)
\]

\[
i \Sigma(\omega) + \Delta_o(\omega)
\]
Tilt Impact on Monopulse BPM System cont.

- Phasor Diagram for delta and sum signals for a tilted beam
- Circuit measures the angle $\psi_1 + \psi_2$

Phasor Diagram for delta and sum signals for a tilted beam.
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

\[ \approx 0.03\% \text{ for large aperture bpms} \]

\[ \approx 0.75\% \text{ for small aperture bpms (P0's) (however tilt is nearly zero at the small aperture bpms} \]
Tilt Measurement Using Buttons and Sband Phase Detector

- Button geometry used in the experiment
- Small-gap button geometry

*X. Sun, these proceedings*
Tilt Measurement Using Buttons and S-band Phase Detector\textsuperscript{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 \textasciitilde100 turns

\textsuperscript{1} W. Guo et al., PRST-AB, 10, 020701 (2007)
\textsuperscript{2} B.X. Yang et al., PAC 2005
Tilt Measurement Using Buttons and Sband Phase Detector

1 B.X. Yang et al., PAC 2005

N. Sereno
2012 BIW, Newport News Va,
Filtered and amplified S37A:P4 TI and BI button signals
Tilt Measurement Using Buttons and Sband Phase Detector

- Raw phase detector phase output measured on a scope

Pinger Fires
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 bpmms 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

Low chromaticity ensures linear tilt oscillations over ~100 turns

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b, l$</td>
<td>18.7 mm, 12.5 mm</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$2\tan^{-1} \frac{L}{2b} = 0.645 \text{ rad} = 36.96^\circ$</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>$1.05 \times 10^{-4} \text{ } \mu\text{m}^{-1}$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$2\pi \times 2815 \text{ MHz}$</td>
</tr>
<tr>
<td>$\sigma_t = \sigma_x / \beta c$</td>
<td>27 ps @ 1 mA</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$\approx 1 \times 7 \text{ GeV}$</td>
</tr>
<tr>
<td>$\nu_y, \nu_z, \xi$</td>
<td>0.241, 0.008, 4.00</td>
</tr>
<tr>
<td>$\alpha_c, \sigma_5$</td>
<td>2.82e-4, 0.00096</td>
</tr>
<tr>
<td>$\lambda, f_{rev}, \omega_{rf}$</td>
<td>1296, 271.555 kHz, $2\pi \times 351.9 \text{ MHz}$</td>
</tr>
<tr>
<td>(Kick angle) $\Theta$</td>
<td>$\approx 0.1 \text{ mrad}$</td>
</tr>
<tr>
<td>$\beta_{kicker}, \beta_{S37A:P4}$</td>
<td>5.4 m, 26.7 m</td>
</tr>
</tbody>
</table>
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 into 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