Status of the APS Short X-ray Pulse Project

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APS/Users Monthly Operations Meeting
SPX Project Team Members

Outline

- Introduction
- Short x-ray pulse generation
- Beam dynamics issues
- Crab cavity design
- Timeline
- Summary
Excerpts from the 2004 Time-Domain Workshop (Aug29 –Sept 1)

**Summary**

“...by far the most exciting element of the workshop was exploring the possibility of shorter timescales at the APS, i.e. the generation of 1ps x-ray pulses whilst retaining high-flux.”

“... time domain from 1 ps to 100 ps will provide a unique bridge from hard x-ray science between capabilities at current storage rings and future x-ray FELs.”

“...this unique potential has generated substantial interest and technical activities both during and subsequent to the workshop, and we believe, is of primary strategic importance for future scientific directions for the Advanced Photon Source.”

**Recommendations**

“The APS should pursue the development of high-flux picosecond beamlines through the use of advanced accelerator techniques. Such beamlines could produce 1 ps x-ray pulses and would be complementary to future LCLS facilities.”
WORKSHOP ON TIME DOMAIN SCIENCE USING X-RAY TECHNIQUES, AUG 2004

Slide courtesy D. Reiss, U. Michigan

Period of Moon

Cell Division

Protein Folding

DNA Unfolding

Ex. State Fe$^{57}$

Bound Water Relaxation Rotations

Bond Breakage Phonon Frequency

Proton Transfer

Atomic Ex. States

$10^6$  $10^4$  $10^2$  $10^0$  $10^{-2}$  $10^{-4}$  $10^{-6}$  $10^{-8}$  $10^{-10}$  $10^{-12}$  $10^{-14}$  $10^{-16}$

Lasers

Ultrasonic

EPR

NMR

X-ray Techniques

Storage Ring Sources

X-ray FELs

APS ps source

A. Nassiri

Status of the APS SPX Project

APS/Users Monthly Operations Meeting
Strategic LDRD 2008 submitted†
Ultrafast x-ray tracking of laser-controlled molecular motions

Goal: Expand science and beamline capabilities to studies of laser-controlled motions in isolated molecule samples (gas or solution phase).

Science thrust: Photonic control of molecular motions
X-ray snapshots of transient molecular species

Beamline thrust: Enhance flux 100x - pink beam scattering and spectroscopy

Diverse Team: Unique SPX capability unites researchers from many parts of Argonne plus significant interest from outside Argonne.

LDRD team:
Linda Young (CHM)
Lin Chen (CHM)
Robert Dunford (CHM)
Elliot Kanter (CHM)
Bertold Krässig (CHM)
Robin Santra (CHM)
Stephen Southworth (CHM)
David Tiede (CHM)
Stefan Vajda (CHM and CNM)
Bernhard Adams (XSD)
Dohn Arms (XSD)
Klaus Attenkofer (XSD)
Eric Dufresne (XSD)
Eric Landahl (XSD)
Donald Walko (XSD)
Jin Wang (XSD)

†L. Young (CHM)
**Design approaches**

- We initially started with superconducting (SRF) deflecting cavity design to provide continuous wave (cw) mode of operation.
- In cw SRF scheme, the short-pulse repetition rate can be as high as the rf frequency of the APS SR, depending on the bunch spacing.
- While femtoslicing gives shorter x-ray pulses, this approach produces significantly higher flux at a much higher repetition rate.

- We concluded “room temperature” copper cavity design can be implemented in a shorter timeframe at much reduced cost.
- Phase I and II of the APS SPX project is based “room temperature” technology.
- CW SRF capabilities will be developed for the Phase III of the APS SPX project.
Crabbing Scheme

- Deflecting cavity introduces angle-time correlation into the electron bunch
  - “crabbing” the beam
- Electron oscillate along the orbit
- Bunch evolution through the lattice results in electron and photons correlated with vertical momentum along the bunch length
- Second cavity at $n\pi$ phase cancels “kick”; rest of the storage ring unaffected

† A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A 425(1999), 385
Short x-ray pulse generation

- Slitting, “streak”

- Compression

\[ \text{\sim 1\, \text{ps FWHM} } \]
Compressed pulse length (linear rf):\
\[
\sigma_{t,x-ray} = \frac{E}{2\pi hf_0 V} \sqrt{\sigma^2_{y',e} + \sigma^2_{y',rad}}
\]

Parameters for APS:

h=8, V=4 MV, \( \sigma_{y',e}=2.0 \ \mu\text{rad} \), \( \sigma_{y',rad}=5 \ \mu\text{rad} \)

Calculated compressed x-ray is \(~0.5 \text{ ps rms.}\)

\( ^\dagger \)S. Shastri, R. Dejus, L. Assoufid

\( ^\ddagger \) M. Borland, PRST-AB 8, 074001 (2005)
Technical challenges

- Crab cavities operation must be “transparent” to the APS normal operation outside the “crabbing sector.”
- Under normal operating modes, crab cavity-beam interaction must not induce beam instabilities (transverse and longitudinal) that cannot be controlled by normal acceleration means.

Hybrid fill pattern

† J. Carwardine, L. Emery

Deflecting cavity RF voltage

† † G. Waldschmidt

Rise/fall times limited by crab cavity fill time (~800 ns)

~ 2 μs
Beam dynamics issues – collective effects

- The cavity operates in TM\textsubscript{110} mode (main deflecting mode, vertical polarization)
  - 2815 MHz (8\textsuperscript{th} harmonics of the SR frequency, 351.93 MHz)
- In addition to the main deflecting mode, other frequencies are also present and could be excited by the beam. These are LOM and HOM non-deflecting modes
  - These frequencies are populated in various “passbands”
    - Monopole
    - Dipole
    - And higher poles
- The cavity main design challenge is to reduce the modes growth rate in these passbands for stable SR operation for hybrid fill and 24 singlets.\textsuperscript{†}

<table>
<thead>
<tr>
<th>Plane</th>
<th>Growth Rate</th>
<th>Synchrotron radiation Damping Rate</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>60 s\textsuperscript{-1}</td>
<td>208 s\textsuperscript{-1}</td>
<td>Stable</td>
</tr>
<tr>
<td>Horizontal</td>
<td>5 s\textsuperscript{-1}</td>
<td>104 s\textsuperscript{-1}</td>
<td>Stable</td>
</tr>
<tr>
<td>Vertical</td>
<td>200 s\textsuperscript{-1}</td>
<td>104 s\textsuperscript{-1}</td>
<td>Stable only at 100 mA</td>
</tr>
</tbody>
</table>

- Single bunch: broadband\textsuperscript{++}
  - Single bunch limit reduced by 1-2 mA (horiz wake)
  - Present limit 20 mA, deliver 16 mA for hybrid mode is okay

\textsuperscript{†}L. Emery, PAC07

\textsuperscript{++} Y.-C. Chae, K. Harkay
“Room temperature” Cavity design evolution†

†V. Dolgashev, SLAC
**Crab cavity mechanical design**

RF Cavity Design

**Thermal analysis**

- Analysis was performed on the cavity
- A complete analysis of rf heat loss, thermal, stress and frequency shift was performed for various iris thickness and radii
- The analysis concluded that the frequency shift due to rf heat loss can be controlled with cooling water temperature.

† Courtesy: M. Givens and L. Morrison

‡‡ P. Den Hartog
## Design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>2815 MHz</td>
</tr>
<tr>
<td>Nominal RF pulse length</td>
<td>1.3 μs</td>
</tr>
<tr>
<td>Number of cell per cavity</td>
<td>3</td>
</tr>
<tr>
<td>Cavities layout</td>
<td>2 downstream of S6 ID 2 downstream of S7 ID</td>
</tr>
<tr>
<td>Nominal operating deflecting voltage per cavity</td>
<td>2 MV</td>
</tr>
<tr>
<td>Nominal operating rep. rate</td>
<td>Phase I ≥ 120 Hz  Phase II 1 kHz</td>
</tr>
<tr>
<td>Max operating rep. rate for thermal load and mechanical stress analysis</td>
<td>1 kHz</td>
</tr>
<tr>
<td>Single bunch threshold</td>
<td>19 mA</td>
</tr>
<tr>
<td>Nominal SR beam current</td>
<td>102 mA</td>
</tr>
<tr>
<td>Max SR beam current ( stability criteria)</td>
<td>202 mA</td>
</tr>
<tr>
<td>Longitudinal single-particle damping rate</td>
<td>208 s⁻¹†</td>
</tr>
<tr>
<td>Transverse single-particle damping rate</td>
<td>104 s⁻¹†</td>
</tr>
<tr>
<td>RMS bunch length ( for 56 singlets in 202 mA hybrid mode)</td>
<td>37 ps †</td>
</tr>
</tbody>
</table>

† L. Emery, OAG-TN-2007-023
Two sectors layout

Components Layout
(Typical Sector)

†Courtesy: L. Morrison
New two-sector layout

![Diagram of two-sector layout]

**Sector 6 Section 6**
- 5590 mm Max
- Drift Space ~1786 mm
- Bellows (90 mm)
- (SR Elliptical Aperture)
- Bellows (90 mm)
- (42 mm dia. Aperture)
- T1: Upstream End Box Transition Mask
  - 41.7 mm SR ellipse to 8 mm ID ellipse
- T2: Downstream End Box Transition Mask
  - 8 mm ID ellipse to 42 mm dia. B2 aperture
- T3: Transition (100 mm)
  - 42 mm dia to 41.7 mm SR ellipse

**Sector 7 Section 6**
- 5590 mm Max
- Drift Space ~1786 mm
- Bellows (90 mm)
- (SR Elliptical Aperture)
- Bellows (90 mm)
- (42 mm dia. Aperture)
- T1: Upstream End Box Transition Mask
  - 41.7 mm SR ellipse to 8 mm ID ellipse
- T2: Downstream End Box Transition Mask
  - 8 mm ID ellipse to 42 mm dia. B2 aperture
- T3: Transition (100 mm)
  - 42 mm dia to 41.7 mm SR ellipse

*Courtesy: L. Morrison, P. Den Hartog*
Timeline

- External crab cavity design review August 07
- Begin SPX infield construction August 07
- Place the order for 2815 MHz klystron August 07
- Final cavity mechanical design September 07
- Order cavities (5) October 07
- SPX infield building Beneficial Occupancy December 07

- Receive prototype cavities (2x 3-cell) March 08
- Install 2x3-cell cavities in S7 (passive) May 08 SD
- Receive remaining cavities (3) June 08
- Receive klystron July 08
- Begin cavity power test and characterization in ITS July 08
- Install cavities and start system commissioning September 08 SD
Summary

- SPX implementation will provide a unique opportunity to conduct experiments using high-flux picoseconds x-rays.
- We started this project fully aware of all the challenges and technical difficulties.
- We have worked hard to successfully address many critical accelerator physics, rf, thermal, mechanical, controls issues that have been very challenging and unique in nature. Our baseline design reflects this collective work.
- There are few cavity design issues remaining to be addressed in weeks time.
- We are working toward meeting Phase I milestones for September 08.
- We will pursue design and implementation of SRF deflecting cavities system in phase III to provide cw capabilities.