Possible Upgrade of the Advanced Photon Source with an Energy Recovery Linac

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May 4, 2009

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Outline

- Why upgrade the APS?
- Ring replacement
- Advantages of linacs and rings
- ERL basics
- Concepts and options for an ERL upgrade
- Injector design
- Linac design
- High energy transport
- X-ray performance
- Other options
- Conclusion
Why Upgrade the APS?

- APS has been in operation since 1996
  - ~98% availability
  - ~70 hour MTBF
  - Thousands of users per year
- Source performance meets the demands of most users
  - 7 GeV
  - 3.1 nm horizontal emittance
  - ~50 pm vertical emittance
  - 100 mA
  - ~80% of time in top-up
  - Various bunch patterns to support timing experiments
- APS is presently state of the art, but can't remain so indefinitely
  - New rings, ERLs, and FELs promise higher coherence, brightness, and/or flux
  - An upgrade in the not-to-distant future is needed to stay relevant.
Ring Improvement or Replacement

- APS started out as a 8-nm light source
  - We've brought this down to 3.1 nm
  - We may be able to lower this ~15% more
- To go further requires replacing the ring itself
- Unfortunately, the up-side potential isn't that great\(^1\)
  - ~3 fold in transverse coherent fraction
  - ~40 fold in brightness
  - At least 1 year of dark time for users
- A different idea is needed for an eventual upgrade.

\(^1\)A. Xiao et al., PAC07, 3447-3449; V. Sajaev et al., PAC07, 1139-1141.
Importance of Emittance and Energy Spread

- Average spectral brightness is a primary measure of performance
  - The units of brightness are telling: photons/s/mm²/mrad²/0.1%BW
  - Hence, brightness benefits from high current, high energy, small emittance, and narrow energy spread

\[
B \sim \frac{I_{\text{beam}}}{E_x E_y \sqrt{4\sigma_x^2 + \left(\frac{0.4}{h N_u}\right)^2}}
\]

\[
E_x = \sqrt{\left(\epsilon_x \beta_x + \frac{\lambda L}{8\pi^2}\right) \left(\frac{\epsilon_x}{\beta_x} + \frac{\lambda}{2L}\right)} \geq \epsilon_x + \frac{\lambda}{4\pi} \quad \text{(Plus similar for y plane)}
\]

- Comparison of multi-GeV rings and linacs
  - Linac: Emittance comparable to 1Å/4π in both planes
  - Linac: Greater freedom in matching to ideal beta functions
  - Linac: Small energy spread allows capitalizing on long undulators
  - Ring: Easy to achieve high average current
Energy Recovery Linac X-ray Source Concept\textsuperscript{1,2,3}

- High-brightness, high average current 10 MeV injector
- "Merger"
- Multi-GeV output beam
- Multi-GeV return beam
- \textasciitilde10 MeV energy-recovered beam
- Turn-around arc with undulator beamlines

Energy recovery addresses the most significant advantage of rings over linacs.

\textsuperscript{2}I. Bazarov \textit{et al}., PAC 2001, 230.
\textsuperscript{3}I. Ben-Zvi \textit{et al}., PAC 2001, 350.
Simulations Give Promising Predictions for Injector

- Bazarov *et al.* performed optimizations\(^1\) for a ultra-bright photo-injector based on a high-voltage DC gun
- Litvinenko *et al.* have developed the “zig-zag” merger\(^2\), which maintains laminar beam motion and prevents emittance growth
- Sun *et al.* developed a design\(^3\) using an ellipsoidal electron beam that delivers similar performance
- We've combined these concepts into an injector design with a merger that gives the desired beam quality
  - See X. Dong *et al.*, MO6RFP044, this afternoon.

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\(^1\)I. Bazarov et al., PRSTAB 8, 034202 (2005).
\(^2\)V. Litvinenko et al., NIM A 557 (2006) 165.
\(^3\)Y. Sun et al., Proc. Linac08, TUP100.
Predictions for Injector with Zig-zag Merger\textsuperscript{1}

Beam properties scaled to 7 GeV and compared to APS today

<table>
<thead>
<tr>
<th>Quantity</th>
<th>APS today</th>
<th>Injector design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Current (mA)</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Repetition Rate (MHz)</td>
<td>6.5 to 352</td>
<td>1300</td>
</tr>
<tr>
<td>Bunch Charge (nC)</td>
<td>&lt;59</td>
<td>0.019</td>
</tr>
<tr>
<td>Horizontal Emittance (nm)</td>
<td>3.1</td>
<td>0.006</td>
</tr>
<tr>
<td>Vertical Emittance (pm)</td>
<td>25~50</td>
<td>6</td>
</tr>
<tr>
<td>Rms Bunch Length (ps)</td>
<td>&gt;20</td>
<td>2</td>
</tr>
<tr>
<td>Rms Energy Spread (%)</td>
<td>0.1</td>
<td>0.02</td>
</tr>
</tbody>
</table>

\textbullet{} These are equivalent to the High-Coherence and High-Flux parameter sets defined by Cornell.\textsuperscript{2}

\textbullet{} We'll concentrate on the High-Coherence parameters.

\textsuperscript{1}X. Dong, MO6RFP044.
\textsuperscript{2}G. Hoffstaetter, "Status of the Cornell ERL Project," fls2006.desy.de
Energy Choice for ERL@APS

- Previously\(^1\), we showed the advantage of high beam energy
  - Initial geometric emittance decreases with energy
  - Photons more numerous and harder like \(E^2\)
  - Emittance and energy spread growth in arcs increases
  - We concluded that for photon energies over ~7 keV, we want a 7 GeV or higher electron beam

- Another consideration is energy spread growth due to undulators
  - A limiting factor in an ERL is how much energy spread can be tolerated after deceleration
  - This is a fixed value, independent of the linac energy

- For \(K\sim 1\) and keeping the photon energy fixed, we find
  \[
  \Delta \sigma^2_{E,u} \propto \frac{L_u}{E^2}
  \]
  where \(L_u\) is the total length of undulators.

- Hence, a higher energy electron beam can tolerate longer undulators.

\(^1\)M. Borland et al., PAC 2007, 1121 (2007).
Some Configuration Options for ERL@APS

Infield\textsuperscript{1,2}: Two 2.33 GeV linacs.

Outfield: Two 3.5 GeV linacs, budget turn-around system.

Ultimate: 7 GeV linac, new user arc, straight-ahead hall

\textsuperscript{1}M. White et al., SRF2003 (MoP42).
\textsuperscript{2}N. Sereno et al., PAC2007, 1145 (2007).

Based on ideas from M. Borland, G. Decker, N. Sereno.
An “Ultimate” ERL@APS Concept

- Single- or two-pass 7 GeV linac with 7 GeV turn-around arc
  - Two-pass linac shown as cost-reducing measure
  - Accelerate away from APS to put highest-quality beam into TAA
- TAA has nine 50-m straight sections
  - Accommodates 48-m undulators to get maximum benefit from beam quality
- Ability to store beam is unchanged, using existing injector
  - Envision a gradual change from 100% stored beam operation to 100% ERL operation.

\footnotesize
\textsuperscript{1}M. Borland et al., NIM A 582 (2007) 54-56.
\textsuperscript{2}G. Decker, private communication, September 2006.
Linac Design

- The linac will see four beams
  - Accelerating from 10 MeV to 3.5 GeV, and from 3.5 GeV to 7 GeV
  - Decelerating from 7 GeV to 3.5 GeV, and from 3.5 GeV to 10 MeV
- Started with the graded gradient concept\(^1\) to develop the optics
  - Constant focal lengths for the lowest energy beam at any location
- Used ELEGANT to optimize individual quads for four beams at once
  - Doublet configuration found to give good control of beam sizes

\(^1\)D. Douglas, JLab-TN-00-27 (2000).
Linac Layout

1-m, 9-cell, 1.3 GHz cavities (TESLA-like\textsuperscript{1}) with independent klystrons, @ 20 MV/m

\textsuperscript{1}B. Aune et al., PRSTAB 3, 092001 (2000).
Beam Evolution Through the Linac (Acceleration)

TBA-based arcs with 50-m average radius
Turn Around Arc (TAA) Design

- Our previous TAA designs provided a large number of additional straights
  - 48 TBA or DBA cells
  - 230m average radius
  - 10m straight sections to accommodate 8m undulators
  - This gave ~140 fold brightness increase over APS today
  - About 80% of present flux (HC mode)

- For this work, we sought to push the brightness and flux higher
  - Emphasize fewer, much-longer undulators
  - Room for “booster cavities” to restore energy lost to each undulator
  - Use TME cells to reduce emittance growth
  - 190m average radius (100m in arcs)

- Design was done with ELEGANT, which allows simultaneously optimizing floor coordinates, linear optics, emittance growth, and energy spread growth.
**TAA Optics**

- **Optimum beta functions for brightness and coherence**
- **15 TME cells per superperiod**
- **48m undulator**
- **Booster cavity**

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Possible Upgrade of the APS with an ERL

M. Borland *et al.*, PAC09, 5/4/09
Need for Booster Cavities

- Users must vary undulator gaps, causing energy variation downstream
  - With long devices, variation may exceed the energy spread (1.4 MeV)
  - If uncompensated, will adversely impact downstream users
  - We also need to limit variation in
    - *Time of flight through the TAA and APS*
    - *Energy offset in the 3.5 GeV arcs*
    - *Energy of recovered beam*

- We used a representative set of APS undulator designs
  - Assess impact on beam dynamics
  - Estimate booster cavity parameters

- Booster cavities may be needed in the APS ring portion as well
  - Want to use 8m undulators
  - Could devote every N\textsuperscript{th} straight section to a cavity

<table>
<thead>
<tr>
<th>Undulator Period mm</th>
<th>K max.</th>
<th>Booster cavity Voltage MV</th>
<th>Power kW</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>0.45</td>
<td>0.11</td>
<td>2.7</td>
<td>1</td>
</tr>
<tr>
<td>23</td>
<td>1.20</td>
<td>0.46</td>
<td>11.6</td>
<td>1</td>
</tr>
<tr>
<td>27</td>
<td>1.78</td>
<td>0.74</td>
<td>18.5</td>
<td>2</td>
</tr>
<tr>
<td>30</td>
<td>2.20</td>
<td>0.92</td>
<td>22.9</td>
<td>1</td>
</tr>
<tr>
<td>33</td>
<td>2.74</td>
<td>1.18</td>
<td>29.4</td>
<td>2</td>
</tr>
<tr>
<td>35</td>
<td>3.08</td>
<td>1.32</td>
<td>33.0</td>
<td>1</td>
</tr>
<tr>
<td>55</td>
<td>4.97</td>
<td>1.39</td>
<td>34.8</td>
<td>1</td>
</tr>
</tbody>
</table>
**Beam Evolution in the TAA and APS Portion (19 pC)**

\[ \epsilon_{nx} (\mu m) \]

\[ \sigma_\delta (10^{-4}) \]

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Possible Upgrade of the APS with an ERL

M. Borland et al., PAC09, 5/4/09
Final Longitudinal Phase Space

Nominal

+IDs

+IDs +CSR
X-Ray Performance: Transverse Coherence

\[ F_c = \left( \frac{\lambda}{4\pi} \right)^2 \frac{1}{E_x E_y} \]

Fraction coherent vs. photon energy
**X-ray Performance: Brightness**

Computed with sddsbrightness (H. Shang, R. Dejus, M. Borland).

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Possible Upgrade of the APS with an ERL

M. Borland et al., PAC09, 5/4/09
**X-ray Performance: Flux**

Computed with sddsfluxcurve (M. Borland, R. Dejus).
Other Options: XFEL-O

- X-ray FEL oscillator using x-ray crystals as mirrors
- Extremely high average brightness
- Fully coherent
- ERL-like beam requirements, but no recovery
- Serves fewer beamlines and less tunable than ERL
- See Ostroumov et al. (MO6RFP046), Lindberg et al. (TU5RFP049), Borland (TU5RFP048).

1K.-J. Kim et al., PRL 100, 244802 (2008)
Other Options: USR7

- “Ultimate” storage rings (USRs) have been proposed several times\textsuperscript{1,2,3}
- An APS design concept\textsuperscript{4} approaches ERL performance
  - 7 GeV, 200 mA
  - 40 MBA\textsuperscript{5} sectors, 3.1 km circumference, damping wigglers
  - Fully coupled beam, on-axis swap-out operation
  - Technology apparently not challenging

\textsuperscript{1}A. Ropert et al., EPAC2000, 83.
\textsuperscript{3}K. Tusmaki et al., NIM A 556 (2006) 394.
\textsuperscript{4}M. Borland, LSU Grand Challenge Workshop.
\textsuperscript{5}D. Einfeld et al., EPAC 96, jacow.org.
Conclusions

- An ERL upgrade appears to be a viable option for APS
  - In-tunnel storage ring replacement can't compete with next-generation sources
  - Injector modeling is very promising
  - Several system designs have been developed

- Latest design incorporates nine 48m undulators
  - 3+ orders of magnitude higher brightness
  - Higher flux than APS today
  - Use of booster cavities seems necessary, looks feasible
  - Energy spread after deceleration seems workable

- Other upgrades are still on the table
  - Greenfield ERL (similar performance)
  - XFEL oscillator
  - Ultimate storage ring

- Meanwhile, we are developing an APS “renewal” plan to better serve users through the intervening years
Acknowledgements

We are grateful to many of our colleagues for stimulating discussions and suggestions, including:

- Cornell University: G. Hoffstaetter, I. Bazarov
- FNAL: Y. Sun
- LBNL: J. Qiang
- TJNAF: D. Douglas, G. Krafft
- TRIUMF: L. Merminga