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 \textit{et al.}, PAC07, 3447-3449; V. Sajaev \textit{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/mm$^2$/mrad$^2$/0.1%BW
  - Hence, brightness benefits from high current, high energy, small emittance, and narrow energy spread

$$B \sim \frac{I_{beam}}{E_x E_y \sqrt{4\sigma_x^2 + \left(\frac{0.4}{hN_u}\right)^2}}$$

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

- 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 addresses the most significant advantage of rings over linacs.

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.

\(^1\)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**

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>

- These are equivalent to the High-Coherence and High-Flux parameter sets defined by Cornell.
- We'll concentrate on the High-Coherence parameters.

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1. X. Dong, MO6RFP044.
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 \(~7 \text{ keV}\), 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 \(K\sim1\) 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

Based on ideas from M. Borland, G. Decker, N. Sereno.

\textsuperscript{1}M. White et al., SRF2003 (MoP42).
\textsuperscript{2}N. Sereno et al., PAC2007, 1145 (2007).
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\(^2\)
  - Envision a gradual change from 100% stored beam operation to 100% ERL operation.

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\(^1\)M. Borland *et al.*, NIM A 582 (2007) 54-56.
\(^2\)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\(^1\)) with independent klystrons, @ 20 MV/m

\(^1\)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
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>
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<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)

\[ \varepsilon_{nx} \text{ (\textmu m)} \]

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

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).

TAA 1.8cm
TAA 2.7cm
TAA 3.3cm
APS 3.3cm
present
X-ray Performance: Flux

Computed with sddsfluxcurve (M. Borland, R. Dejus).
Other Options: XFEL-O\(^1\)

- 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).

\(^1\)K.-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 \textit{et al.}, EPAC2000, 83.
\textsuperscript{3}K. Tusmaki \textit{et al.}, NIM A 556 (2006) 394.
\textsuperscript{4}M. Borland, LSU Grand Challenge Workshop.
\textsuperscript{5}D. Einfeld \textit{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