Concepts and performance for a next-generation storage ring hard x-ray source

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Outline

- Introduction
- An Ultimate Storage Ring design
- Operations issues
- Outlook and conclusion
Demonstrated Strengths of Storage Rings

- High brightness and flux
  - >100 mA is typical
  - Low emittance (1~10 nm)

- Highly stable
  - Excellent position and angle stability
  - Top-up mode improves optics stability

- ~98% availability and ~100 hour MTBFs

- Many independent, simultaneous users

- Well developed technology
  - Extensive R&D not required
  - New rings commission very quickly

- Safety issues well understood and controlled

- Other sources don't share all these features

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Can Storage Rings Compete with ERLs?

- Major weakness: difficulty of improving emittance

\[ \epsilon_o \sim \frac{E^2}{N^3_d} \]

- Possible approach\(^1,2,3\)
  - Build a “large” ring
  - Multi-bend achromats instead of double-bend\(^4\)
  - Use damping wigglers

- A multi-kilometer ring could be several orders of magnitude better than APS

- Could compete with an ERL, but
  - Much less risk
  - Much less R&D.

USR7: A 7-GeV Ultimate Storage Ring

- MBA-based with 10 dipoles per sector
- 40 sectors
- 8 m insertion devices
- 30 pm natural emittance

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>7</td>
<td>GeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>3.16</td>
<td>km</td>
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<tr>
<td>Natural emittance</td>
<td>0.030</td>
<td>nm</td>
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<tr>
<td>Energy spread</td>
<td>0.079</td>
<td>%</td>
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<tr>
<td>Maximum ID length</td>
<td>8</td>
<td>m</td>
</tr>
<tr>
<td>Number of dipoles</td>
<td>10</td>
<td>per sector</td>
</tr>
<tr>
<td>Horizontal/vertical tune</td>
<td>183.1/36.1</td>
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<tr>
<td>Horizontal/vertical chromaticity</td>
<td>-495/-166</td>
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<tr>
<td>Energy loss</td>
<td>3.6</td>
<td>MeV/turn</td>
</tr>
<tr>
<td>Beta functions (x/y) at ID</td>
<td>7.58/6.56</td>
<td>m</td>
</tr>
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</table>
Uses conventional magnets with workable strengths assuming reasonable 20mm bore radius

Lattice designed with *elegant* (M. Borland, *et al.*).
**Dynamic Aperture with Errors**

- Nonlinear elements tuned using genetic optimization technique
- 4000-turn tracking with damping and synchrotron oscillations
- Dynamic aperture is small, but very large compared to ~10 μm rms beam size

Modeled with elegant (M. Borland, et al.)
Large momentum aperture is important for Touschek lifetime

We computed momentum aperture at exit of sextupoles for first five sectors

Modeled with elegant (M. Borland, et al.)
**Touschek Lifetime Predictions**

- Lifetime is a workable 4 hours for $50 \mu$A/bunch and full coupling ($\epsilon_y = \epsilon_x$).

Computed with `touschekLifetime` (A. Xiao).
Intrabeam Scattering Impacts Emittance

- IBS effects greatly reduced for full coupling and low current/bunch
- For 200 mA, need 4000 bunches at 50 μA/bunch

Computed with ibsEmittance (L. Emery, A. Xiao, M. Borland)
Brightness Predictions Compared to APS

Computed with sddsbrightness (H. Shang, R. Dejus, M. Borland).
Can We Operate with Full Coupling?¹,²

- Present-day rings all use accumulation
  - Requires large dynamic aperture (off-axis injection)
  - Prevents working on coupling resonance
  - Charge is added via repeated injections into each bucket
  - Top up replenishes the charge when it decays

- Need to abandon accumulation in favor of “swap-out”
  - Inject on-axis
  - Kick out depleted bunch or bunch train
  - Simultaneously kick in fresh bunch or bunch train

- Many benefits
  - Can tune for very low emittance
  - Provide round beams
  - Reduce intrabeam scattering and improve lifetime

¹M. Borland, “Can APS Compete with the Next Generation?”, APS Strategic Retreat, May 2002.
Bunch Pattern and Fill Rate

- If we inject bunch trains, the fractional droop in intensity among trains is
  \[ D \approx \Delta T_{\text{inj}} N_{\text{trains}} \frac{1}{\tau} \]

- The required injector current is
  \[ I_{\text{inj}} \approx \frac{I_{\text{ring}} L_{\text{ring}}}{c \tau D} \]

- We probably want \( D < 0.1 \)
- For 4000-bunch beam, 20 bunches per train, and 4 hour lifetime
  - Replace a bunch train every 7.2 s
  - 1.5 nA average current from the injector (APS injector: 4 nA)
  - Each train has 11 nC (APS injector: 3 nC/bunch)
- Shorter lifetimes should be acceptable
Radiation Issues (For Example Parameters)

- We worry about radiation from two sources
  - Extracted beam
  - Losses in the ring
- The beam dump power is only \( \sim 20\) W for a 7 GeV beam
- The losses in the ring are \( \sim 1\) W
  - In APS today, have 0.1 W
  - Can design a collimation system to intercept these losses
Outlook for Further Improvement

- Increase the beam current above 200 mA
  - Lifetime will drop as we can't easily have more bunches
  - Emittance will increase for same reason
  - Beamlines/front-ends may not be feasible
  - Need to evaluate beam instabilities

- Add damping wigglers
  - ~30% reduction in emittance from 10 DWs

- Decrease the beam energy
  - Only slight improvement at ~6 GeV

- Ring DA is ~20x larger than needed
  - Push lattice harder to get lower emittance
  - Adding geometric sextupoles will also help
Conclusion

- We've developed an ultimate storage ring design with ultra-low emittance
  - 7 GeV
  - 40-sector MBA lattice
  - 16 pm emittance in both planes
- Dynamic aperture and lifetime are workable
- Swap-out injection is key
  - Injector requirements not difficult
- Ultimate ring is very competitive with ERL
  - Modest risk and R&D
- May be possible to further increase brightness
Acknowledgements

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  - Louis Emery (ANL)
  - Vadim Sajaev (ANL)
  - Aimin Xiao (ANL)