Overview of Ring-Based X-ray Sources and Their Future

Michael Borland

Argonne National Laboratory

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Outline

- Strengths of storage rings
- Near-term outlook
- Scaling of ring performance
- Next-generation ring sources
  - Potential
  - Challenges
  - Comparison to alternatives

- This talk draws heavily on a recent paper

Strengths of Rings

- Storage rings are extremely successful scientific facilities
  - Many thousands of users per year from dozens of scientific disciplines

- There is a good reason for this
  - Wide, easily-tunable spectrum from IR to x-rays
  - High average flux and brightness
  - Excellent stability
    - Position and angle
    - Energy and intensity
    - Size and divergence
  - Pulse repetition rates from ~300 kHz to ~500 MHz
  - Large number of simultaneous users
  - Excellent reliability and availability
  - Well-understood technology
Near-Term Outlook

- From 1990's onward, increasing number of rings offered emittance of few nm
- New rings pushing to 1 nm and below
  - Design emphasis is usually average brightness, micro-focusing
- PETRA III\(^1\)
  - 6 GeV, 1 nm ring now in early operation
  - Large circumference with damping wigglers
- NSLS-II\(^2\)
  - 3 GeV, 0.5 nm ring under construction
  - Large circumference DBA with damping wigglers
- MAX IV\(^3\)
  - Planned 3 GeV, 0.24 nm ring, just funded
  - 7BA with damping wigglers

\(^3\)S.C. Leeman et al., PRSTAB 12, 120701 (2009).
Brightness of a Few Present and Planned Rings

- APS curve assumes existing 2.4m long U27
- Assume maximum length SCU20 (future 1.25T device\(^1\))
- Used best published electron beam parameters, with 1% coupling
- First three harmonics shown only

\(^1\)R. Dejus, private communication.
Emittance of Storage Rings\(^1\)

- Quantum excitation causes emittance growth in any bending system

\[
\left( \frac{d}{dt} \epsilon \right)_q \approx \frac{\langle N_p \rho \langle u^2 \rangle \mathcal{H}(s) \rangle_s}{2E_0^2} \\
\mathcal{H} = \beta_x \eta_x^2 + 2\alpha_x \eta_x \eta_x' + \frac{1+\alpha_x^2}{\beta_x} \eta_x^2
\]

- Fortunately, in rings there is also damping

\[
\left( \frac{d}{dt} \epsilon \right)_d \approx -\frac{\langle P_\gamma \rangle}{E_0} \epsilon
\]

- Giving the equilibrium emittance

\[
\epsilon \propto E_0^2 \frac{\langle \mathcal{H}/\rho^3 \rangle}{\langle 1/\rho^2 \rangle}
\]

- A common mistake

\[
\epsilon \propto \frac{E_0^2}{R} \quad \text{Wrong!}
\]

\(^1\)H. Wiedemann, Particle Accelerator Physics.
Methods of Decreasing Emittance

- To decrease the natural emittance, we can
  - Reduce the energy
  - Increase the bending radius
    - Larger circumference
  - Decrease $\mathcal{H}$
    - Stronger focusing
    - More frequent focusing
  - Increase damping
    - Damping wigglers

- A useful approximation\(^1\)

$$\epsilon = F(\nu_x, \text{lattice}) \frac{E_0^2}{J_x N_d^3}$$

$$\epsilon \propto \frac{E_0^2}{\langle \mathcal{H}/\rho^3 \rangle} \frac{\langle 1/\rho^2 \rangle}{\langle 1/\rho^2 \rangle}$$

\(^1\)J. Murphy, Light Source Data Book, BNL.
Nonlinear Dynamics

- Weaker dipoles and/or stronger focusing → smaller dispersion
  - Emittance smaller (good)
  - Chromaticity sextupoles are less effective (bad)

- Stronger sextupoles means
  - Transverse motion is less linear
  - Smaller dynamic aperture → injection problems
  - Smaller momentum aperture → lifetime problems

- We have to add more sextupoles to compensate the aberrations

More data from the scaling simulation. Again no surprise.

Sextupole strengths are proportional to average dispersion.

\[
\langle \eta_x \rangle \propto 1/N_d^{1.05}
\]
Collective Effects

- Smaller dispersion $\Rightarrow$ smaller momentum compaction $\alpha_c$
  $\Rightarrow$ shorter bunch, reduced synchrotron tune $\Rightarrow$
  increased collective effects

Simulations assume rf voltage adjusted for constant rf acceptance.
Collective Effects

- Touschek scattering
  \[ \frac{1}{\tau} \sim \frac{N_b N_d^{1.8}}{E^{4.1}} \]

- Intrabeam scattering
  \[ \frac{1}{\tau} \sim \frac{N_b N_d^{5.5}}{E^{8.1}} \]

- TMCI
  \[ I_{\text{thres}} \sim \frac{E}{\langle \beta \rangle N_d^{1.5}} \]

- Microwave instability
  \[ I_{\text{thres}} \sim \frac{E^{3.3}}{N^{5.5}} \]

\[ \rightarrow \] High-energy ring with many weak bunches, bunch lengthening, feedback systems

Computed with \texttt{toushekLifetime} and \texttt{ibsEmittance} (A. Xiao \textit{et al.})
Ultimate Storage Rings

- ESRF, APS, Spring-8, and SLAC have looked at “Ultimate Storage Rings”\(^1,2,3\)

- A possible way forward includes
  - Build a “large” ring
    - E.g., a 2 km ring has \(\sim 1/8\) the emittance of a 1 km ring
  - Use multi-bend achromats\(^4\)
    - Potential improvement of \(\sim 100\)-fold (10BA vs DBA)
  - Use damping wigglers
    - Potential improvement \(\sim 2\)-fold (e.g., for NSLS-II)

- A multi-km ring could be several orders of magnitude brighter than APS
  - Will show that many problems are less serious than generally thought

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**USR7: A 7 GeV, 40 Sector Ultimate Ring\textsuperscript{1,2}**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>3.16</td>
<td>km</td>
</tr>
<tr>
<td>Natural emittance</td>
<td>0.028</td>
<td>nm</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.079</td>
<td>%</td>
</tr>
<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>183.18/36.18</td>
<td></td>
</tr>
<tr>
<td>Natural chromaticities</td>
<td>-535/-175</td>
<td></td>
</tr>
<tr>
<td>Energy loss</td>
<td>3.7</td>
<td>MeV/turn</td>
</tr>
<tr>
<td>Beta functions (x/y) at ID</td>
<td>4.4/5.5</td>
<td>m</td>
</tr>
</tbody>
</table>

\textsuperscript{1}M. Borland, LSU Grand Challenge Workshop, 2008.  
\textsuperscript{2}M. Borland, Proc. SRI09, to be published.
Sextupole Optimization

- Targeted chromaticity of 1 in both planes
- Used parallel genetic optimizer\(^1,2,3\) to tune sextupoles
  - 21 independent sextupoles
  - Also varied fractional tune
- Direct optimization of
  - Dynamic aperture
  - Touschek lifetime
- One evaluation takes about 10 hours
- Typically use 100~300 processors

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\(^1\)M. Borland, H. Shang, \texttt{geneticOptimizer}.
\(^2\)M. Borland \textit{et al.}, Proc. PAC09, to be published
\(^3\)M. Borland \textit{et al.}, Proc. ICAP09, to be published.
Magnet Strengths

- Nothing remarkable here: only slightly stronger than APS quadrupoles
- About 4x stronger than APS sextupoles
- Preliminary design shows this is feasible with 20mm bore radius\(^1\)

\(^1\)A. Xiao et al, Proc. PAC07, THPAN096.
USR7 Momentum Aperture (5 Ensembles)

- Local momentum aperture exceeds ±2.2%
- This is about what APS runs with today

Computed with elegant (M. Borland, et al.)

- Conservative lifetime calculation
  - Use ±2.2% aperture
  - Ignore bunch lengthening (PWD)
  - Ignore IBS
- If we have full coupling
  - 50 µA/bunch: ~4 hours
  - 75 µA/bunch: ~3 hours

Computed with touschekLifetime (A. Xiao, M. Borland)
USR7 Dynamic Aperture

- Evaluated 5 ensembles to check robustness
- Dynamic aperture is small, but very large compared to ~10 μm beam size

Computed with elegant (M. Borland, et al.)
Injection Issues

- All ring light sources use beam accumulation
  - Each stored bunch/train is built up from several shots from the injector
  - Incoming beam has a large residual oscillation after injection
    - Requires DA of ~10 mm or more
  - Because of x-y coupling, residual oscillations result in loss on vertical small-gap chambers
    - Incompatible with large x-y coupling

- For USR7, we must use “swap-out” injection\(^1\),\(^2\)
  - Kick out depleted bunch or bunch train
  - Simultaneously kick in fresh bunch or bunch train
  - Injector requirements and radiation issues seem manageable\(^3\)
  - See L. Emery's talk in the ring working group

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\(^1\) M. Borland, “Can APS Compete with the Next Generation?”, APS Strategic Retreat, May 2002.
\(^3\) M. Borland, Proc. SRI09, to be published.
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 \( D < 0.1 \)
- We are considering a very large ring (3.16 km) with up to 300 mA
- For 4000-bunch beam, 20 bunches per train, and 3 hour lifetime
  - Inject a bunch train every 5 s
  - 2.9 nA average current from the injector (APS injector: 4 nA)
  - Each train has 16 nC (APS injector: 3 nC/bunch).
Intra-Beam Scattering

- IBS is modest for full coupling

- Even with full coupling, little advantage to reducing the beam energy (assuming 50 μA/bunch)

Computed with ibsEmittance (A. Xiao, L. Emery, M. Borland)
Collective Effects
(A Very Rough Look)

- **TMCI**
  - 400 dipoles (USR7) vs 80 (APS)
  - Similar average beta functions
  - APS threshold\(^1\) is \(\sim 4\) mA
  - USR7 may be \(\sim 360\) \(\mu\)A

- **Microwave instability**
  - APS threshold\(^1\) is \(\sim 5\) mA
  - USR7 may be \(\sim 1\) \(\mu\)A
  - For 50 \(\mu\)A need significant bunch lengthening (4x)
  - APS runs well above threshold (20 mA or more)

\[ I_{thres} \sim \frac{E}{\langle \beta \rangle N_{d}^{1.5}} \]
\[ I_{thres} \sim \frac{E^{3.3}}{N^{5.5}} \]

Other Challenges and Issues

- **Ion trapping**
  - Already need gaps in beam for bunch train swap-out

- **Kickers to support swap-out**
  - Fast rise/fall times for bunch train swap-out
  - Flat-top length and uniformity (~1% required?)

- **Alignment and tolerances**
  - Sextupoles are strong, need good alignment
  - Need to carefully correct residual dispersion

- **Size and cost**
  - Still smaller than HEP rings
  - Magnets can be small
  - Hybrid EM/PM magnets would have cheaper PS

- See Bei et al. for more detailed discussion
Brightness Comparison

Maximum-length SCU20 (Nb₃Sn wire)

- APS: 100mA, 1.3% coupling, 3.8 m device
- USR7: 300mA, 100% coupling, 8.0 m device
- ERL7: 25mA, “high-coherence” parameters, 48m device

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

\[ F_{\text{coh}} = \frac{(\lambda/4\pi)^2}{(E_x E_y)} \]

- APS
- ERL7
- USR7

\(F_{\text{coh}}\) vs. Photon Energy (eV)
Flux Comparison

Maximum-length SCU20 (Nb$_3$Sn wire)
APS: 100mA, 1.3% coupling, 3.8 m device
USR7: 300mA, 100% coupling, 8.0 m device
ERL7: 25mA, “high-coherence” parameters, 48m device

Computed with sddsfuxcurve (M. Borland, R. Dejus, H. Shang)
Support for Timing Experiments

- Ultra-low emittance rings not well suited to timing experiments
  - Many weak, closely-spaced bunches
  - Bunch is naturally short, but deliberately lengthened to mitigate collective effects

- Zholents’ crab cavity scheme\(^1\) hard to apply
  - Nonlinear dynamics won’t permit use of sextupole optimization
  - Would have to incorporate long straights for the entire system
  - Even so, the repetition rate will be very high (e.g., 500 MHz)

\(^1\)A. Zholents et al., NIM A 425, 385 (1999).
Zholents' Scheme in a Long Straight Section

RF cavity

ID

15 to 20 m

Radiation from head electrons

Radiation from tail electrons

Slits can be used to clip out a short pulse. Can also use asymmetric cut crystal to compress the pulse.

~1ps FWHM
Isn't an ERL Better?

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Advantage</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>High transverse coherence</td>
<td>ERL</td>
<td>ERL has emittance and matching advantage</td>
</tr>
<tr>
<td>High average flux</td>
<td>USR7</td>
<td>ERL needs very long undulators and high current, not very plausible</td>
</tr>
<tr>
<td>High average brightness</td>
<td>Similar</td>
<td>Assuming 48m undulators in ERL, extremely small emittances</td>
</tr>
<tr>
<td>Wide tunability</td>
<td>ERL?</td>
<td>Can gaps really be smaller in ERL (impedance)?</td>
</tr>
<tr>
<td>Short bunch length</td>
<td>ERL++</td>
<td>Who cares at 1.3 GHz?</td>
</tr>
<tr>
<td>Useful repetition rate</td>
<td>Similar</td>
<td>USR7 slightly more flexible</td>
</tr>
<tr>
<td>High stability</td>
<td>USR7</td>
<td>ERL has additional sources of jitter</td>
</tr>
<tr>
<td>Less R&amp;D</td>
<td>USR7++</td>
<td></td>
</tr>
<tr>
<td>Less risk</td>
<td>USR7++</td>
<td></td>
</tr>
<tr>
<td>Lower construction cost</td>
<td>USR7</td>
<td>For same number of beamlines</td>
</tr>
<tr>
<td>Lower operating cost</td>
<td>USR7+</td>
<td>Large cryoplant for ERL</td>
</tr>
<tr>
<td>Higher reliability</td>
<td>USR7++</td>
<td>Large cryoplant, many rf systems for ERL</td>
</tr>
</tbody>
</table>

USR+FELs is a better strategy than ERL+FELs
Alternative Approaches

- MBA lattice is effective, but there are other options
- PETRA-III illustrates one possibility
  - Most of the ring is left-over from a HEP collider
  - Damping wigglers in former detector straights
  - Only $\frac{1}{8}$th of ring replaced
  - Resulting 1 nm emittance at 6 GeV is world-leading
- SLAC is considering\textsuperscript{1} similar concepts for PEP-II
  - Target emittance 10x less than PETRA-III
  - PEP-X would require replacing the entire ring
  - To optimize emittance, lattice would not necessarily be the same in all areas
- Could a similar approach be used with other large collider tunnels?
  - Major concern is the depth of the tunnel (and beamlines)

\textsuperscript{1}Y. Cai et al., IPAC10, WEPEA074, 2010.
Conclusions

- Storage rings are extremely successful scientific facilities
- There is a real possibility of dramatically smaller emittances in rings
  - NSLS-II, PETRA III, and MAX IV are paving the way
- USR7 provides an example of a possible new generation
  - Comparable to ERL in performance
  - R&D needed, but no obvious show-stoppers
    - Attention needed to instability evaluation
  - In contrast
    - ERL needs extensive R&D
    - Faces multiple show-stoppers
- Rings have the track-record to make the performance promises plausible