Ultimate Storage Ring
Light Sources

Michael Borland
Operations and Analysis Group
Accelerator Systems Division
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Outline

- Strengths of storage rings
- Performance of rings: present and near future
- "Ultimate" SR designs
- Operations concepts and issues for ultimate rings
- Outlook for further improvements
- Sub-picosecond pulses from storage rings
- Conclusion
Demonstrated Strength of Storage Rings\textsuperscript{1}

- High brightness (e.g., APS, ESRF, SPRing-8)
- High current
  - 100~200 mA is typical
  - Provides high flux
- Stable and reliable
  - Excellent position and angle stability
  - Top-up mode improves optics stability
  - 98% availability and ~100 hour MTBFs
- Well developed technology
  - Rings are relatively affordable
  - New rings commission very quickly
- Safety issues well understood and controlled.

\textsuperscript{1}L. Emery, “Overview of SR Upgrade Options,” APS MAC Review, 11/15/06.
Brightness of Present and Planned Rings

PETRA case uses hypothetical 5-m APS U27 undulator.
Approaches Used by Near-Future Rings

- **NSLS II**\(^1\): 0.6 nm emittance at 3 GeV
  - Double-bend achromat (DBA) lattice with 30 alternating long/short straights
  - Large ring (800m) for the beam energy (3 GeV)
  - Weak dipoles and damping wigglers

- **PETRA III**\(^2\): 1 nm emittance at 6 GeV
  - Retrofit of a high-energy physics ring
  - Existing FODO lattice in 7/8 of the ring
  - New DBA lattice in user section (1/8)
    - Alternating high/low betax
    - 13 beamlines, including one 20-m-long ID
  - Large circumference (2304m) leading to weak dipoles
  - Damping wigglers

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\(^1\)NSLS-II CDR, www.bnl.gov/nsls2/project/CDR

End of the Road for Rings?

- ERLs and FELs promise spectacular x-ray properties
- Can storage rings compete?
  - Weakness is the difficulty of improving emittance, energy spread
  - Cannot provide extremely short time resolution with high flux
- ESRF, APS, and SPRing-8 have looked at “Ultimate Storage Rings”\(^1\),\(^2\),\(^3\)

Possible approach
- Build a “large” ring
  - *E.g., a 2 km ring has \(~1/8\) the emittance of a 1 km ring*
  - Multi-bend achromats instead of double-bend\(^4\)
    - Potential improvement up to \(~100\)-fold
  - Use damping wigglers
    - Potential improvement \(~3\) fold (e.g., for NSLS-II)

Naively, a multi-kilometer ring could be several orders of magnitude better than APS.

## A 7-GeV, 40-Sector Ultimate Storage Ring: USR7

<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>
</tr>
<tr>
<td>Natural emittance</td>
<td>0.030</td>
<td>nm</td>
</tr>
<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>
<td></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>
</tbody>
</table>

- Similar to Tsumaki and Kumagai, but
  - Larger circumference (3.16 vs 2 km)
  - Higher energy (7 vs 6 GeV) to make hard x-rays easier
  - More sectors (40 vs 32)
  - Longer straight sections (10 vs ~5m)
Lattice Functions

- Uses conventional magnets with workable strengths
- For 200 mA in 4000 bunches, emittance is 16 pm in both planes with full coupling
- With ten 4-m-long PETRA III damping wigglers, drops to 11 pm
USR7 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 $\sim 10 \mu m$ beam size
- Momentum aperture about $\pm 2\%$
  - 2 hour Touschek lifetime
Brightness Predictions

- Better than ERL due to higher current (200 mA vs 25 mA)
- Might improve both with better beta matching, longer IDs
So What's Stopping Us?

- Ring is large and therefore expensive
  - Much smaller than Tevatron, LEP, LHC
- Very small dynamic aperture, small momentum aperture
  - Small momentum aperture makes lifetime poor
  - Small dynamic aperture makes accumulation of beam very difficult
- 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 large dynamic aperture ~10 mm
  - Partly driven by desire to reduce injector cost
- Doesn't top-up solve these problems?
  - No: even top-up injection relies on accumulation
- Fortunately, there appears to be a solution.
A Different Idea for Ring Operation\textsuperscript{1,2}

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

- Several possible modes
  - Full beam replacement in one shot
  - Bunch train replacement
  - Individual bunch replacement using fast kickers

- Allows us to operate on the coupling resonance
  - Provide round beams
  - Reduce intrabeam scattering

- Several possible injectors
  - Booster + Accumulator ring
  - Low-emittance booster
  - Full-energy linac.

\textsuperscript{1} M. Borland, “Can APS Compete with the Next Generation?”, APS Strategic Retreat, May 2002.
Swap-Out Concept Using an Accumulator$^{1,2}$

1. Fill accumulator from linac/booster.
2. Transfer on-axis from accumulator to UR.
3. Fill accumulator, use top-up to maintain fill.
4. Swap beams when UR beam decays. Repeat from last step.

$^1$M. Borland, “Can APS Compete with the Next Generation?”, APS Strategic Retreat, May 2002.
Discussion

- Accumulation ring (AR) and user ring (UR) would occupy the same tunnel to reduce cost
- AR design easier than UR design
  - No user straight sections
  - May have comparable emittance and still allow accumulation
  - Damping wigglers in AR could be SR sources
- Need not swap the entire beam from ring-to-ring
  - Swapping a bunch train reduces transients seen by users and AR/UR systems
  - Would require increased swapping frequency
  - Would reduce need for a long kicker flat-top.
Low-Emittance Booster Injector

- A large-circumference booster emittance can be close to that of the ring (e.g., SLS booster)
  - Optics is “easy” since there are no user straights
  - Can occupy the same tunnel as the user ring to reduce cost
  - Can fill bunch trains at few Hz repetition rates

- This has advantages over accumulator concept
  - Booster emittance is lower since we needn't accumulate in it
  - Less costly since accumulator still needs booster to fill it

- Use “bunch train swap out” operating cycle rather than one-shot swap out

- Could also flat-top the booster ramp and transfer individual bunches using very fast (e.g., ILC-like) kickers.
**Full-Energy Linac Injector**

- In principle, could fill the ring in one shot or using trains
  - Single-shot filling promises better bunch pattern stability
  - Single-shot filling would result in a large emittance transient

- Probably not the optimum choice
  - Emittance would be ~70 nm for typical ~0.5 nC bunches
  - Short bunches are not desirable
  - Long linac requires a separate tunnel, driving up cost
  - Linac structures, rf systems more costly and less reliable than booster
  - Full energy extracted beam must be dumped, increasing radiation
    - *Could perhaps use the linac to decelerate the extracted beam*
**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 200 mA
- For 4000-bunch beam, 20 bunches per train, and 2 hour lifetime
  - Inject a bunch train every 3.6 s
  - 3 nA average current from the injector (APS injector: 4 nA)
  - Each train has 11 nC (APS injector: 3 nC/bunch).
Radiation Issues (For Example Parameters)

- We worry about radiation from two sources
  - Extracted beam (if not decelerated)
  - Losses in the ring

- The beam dump power is only ~20W for a 7 GeV beam

- The losses in the ring are ~2 W total
  - In APS today, have 0.1 W
  - Can design collimation system to intercept these losses
Outlook for Further Improvements

- It may be possible to 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

- 7 GeV is not the optimum energy for emittance
  - Natural emittance drops with energy ($\sim E^2$)
  - Intra-beam scattering worse at lower energy
  - Optimum seems to be $\sim$5 GeV (25% less than 7 GeV value)

- Ring DA is $\sim$20x larger than needed: can push lattice harder.

- Ring is not fully optimized for damping wigglers
  - Reducing beta functions in straights will help ($\sim \beta_x$)

- $\sim$5-fold gain in brightness with optimized beta functions at IDs
  - Very difficult with long straight sections
  - Could explore alternating long/short straight sections
Supporting Time-Resolved Studies

- Rings have inherent difficulties supporting time-resolved studies
  - Electron bunch duration $\sim 40$ ps FWHM
  - $\sim 500$ MHz bunch repetition rate
    - *Fill almost all rf buckets to get low emittance, acceptable lifetime*
  - Hybrid or camshaft modes problematic

- A concept$^1$ by Zholents *et al.* promises a means of providing picosecond x-ray pulses with good intensity
  - Uses superconducting deflecting rf cavities
  - Requires insertion of a long straight section into ring.

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Zholents' Scheme in a Long Straight Section

Radiation from tail electrons

Radiation from head electrons

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

~1ps FWHM
Conclusion

- Storage rings appear to have a bright future using
  - Large circumference
  - Multi-bend achromat lattice with conventional magnets
  - Operation on coupling resonance

- Swap-out operation must be used
  - Allows operation on coupling resonance
  - Allows pushing ring further into low-emittance territory
  - Injector requirements not dramatically harder than top-up

- Results are very promising
  - Brightness increase of about two orders of magnitude
  - Very competitive with proposed ERLs
  - Like ERL, high repetition rate (~500 MHz)
  - Zholents' scheme provides CW short x-ray pulses

- Two examples of comparable, workable ring designs
  - Tsumaki and Kumagai: 2-km, 32-sector ring
  - Present contribution: 3.2-km, 40-sector ring

- Improvements beyond those shown here are conceivable.
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