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Ultimate Storage Ring Light Sources

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January 29, 2008

U.S. Department of Energy

THE UNIVERSITY OF CHICAGO

Office of Science
U.S. DEPARTMENT OF ENERGY

Outline

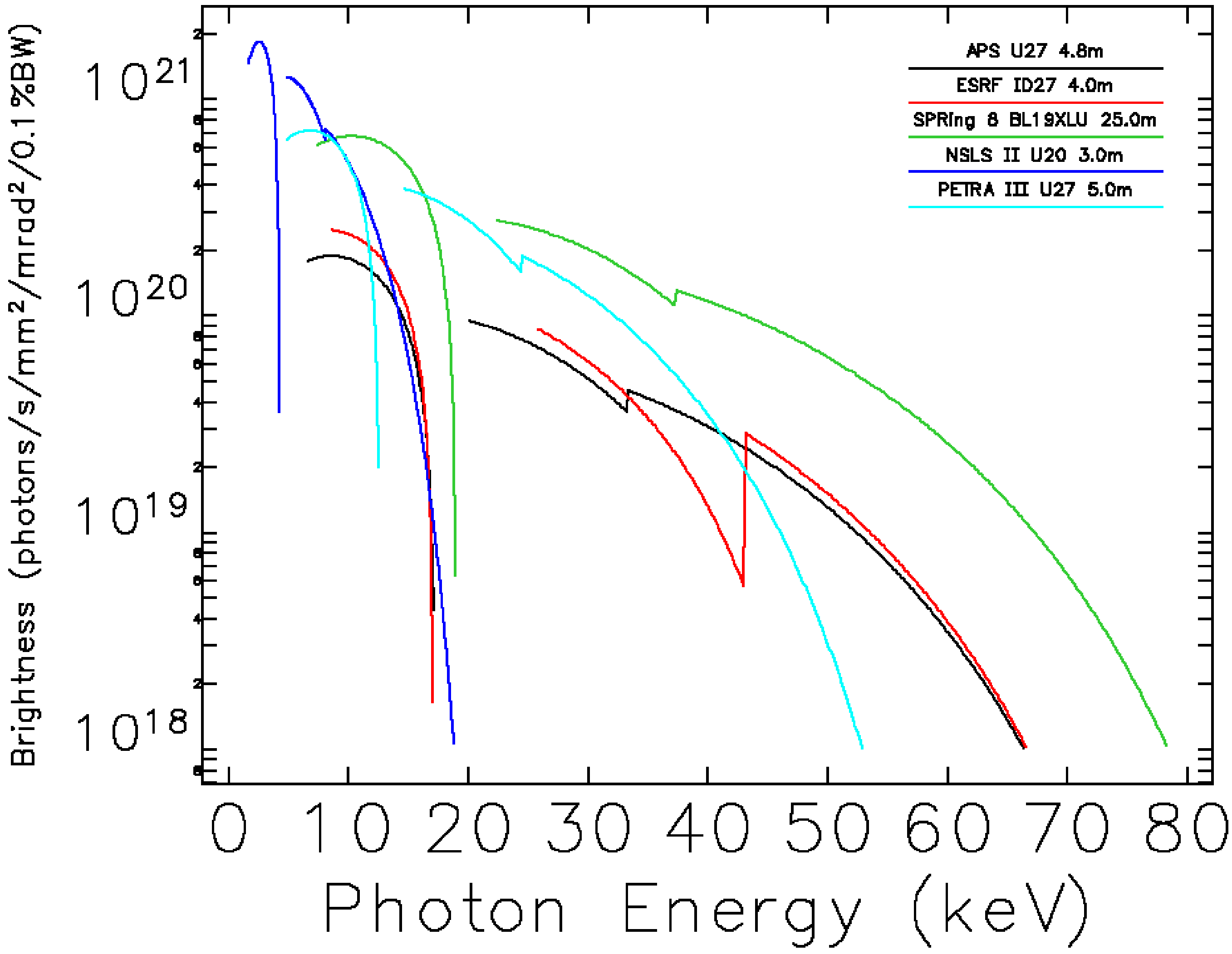
- Strengths of storage rings
- Performance of rings: present and near future
- "Ultimate" SR designs
- Operations concepts and issues for ultimate rings
- Outlook for further improvements
- Sub-picosecond pulses from storage rings
- Conclusion

Demonstrated Strength of Storage Rings[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.

[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

[1]NSLS-II CDR, www.bnl.gov/nsls2/project/CDR
[2]K. Balewski *et al.*, "PETRA III: A New High Brilliance Synchrotron Radiation Source at DESY," EPAC 2004, www.jacow.org.

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.

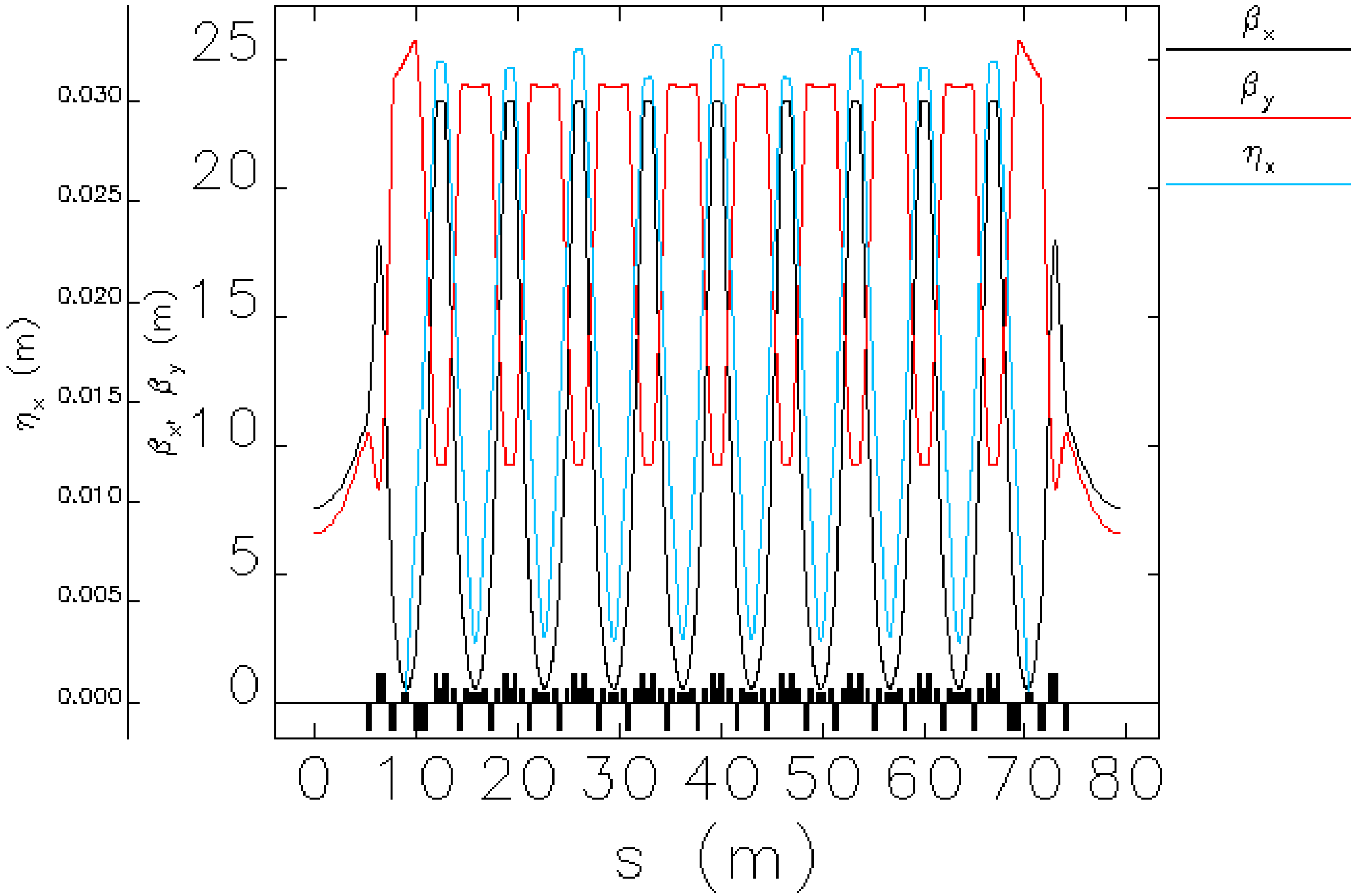
[1]A. Ropert, "Towards the ultimate storage-ring based light source," EPAC 2000, www.jacow.org.
[2]M. Borland, "A super-bright storage ring alternative to an energy recovery linac," NIM A 557 (2006) 230-235.
[3]K. Tsumaki and N. Kumagai, "Very low emittance light source storage ring," NIM A 565 (2006), p. 394
[4]D. Einfeld *et al.*, "A Lattice Design to Reach the Theoretical Minimum Emittance for a Storage Ring," EPAC 96, www.jacow.org.

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

Quantity	Value	Unit
Energy	7	GeV
Circumference	3.16	km
Natural emittance	0.030	nm
Energy spread	0.079	%
Maximum ID length	8	m
Number of dipoles	10	per sector
Horizontal/vertical tune	183.1/36.1	
Horizontal/vertical chromaticity	-495/-166	
Energy loss	3.6	MeV/turn
Beta functions (x/y) at ID	7.58/6.56	m

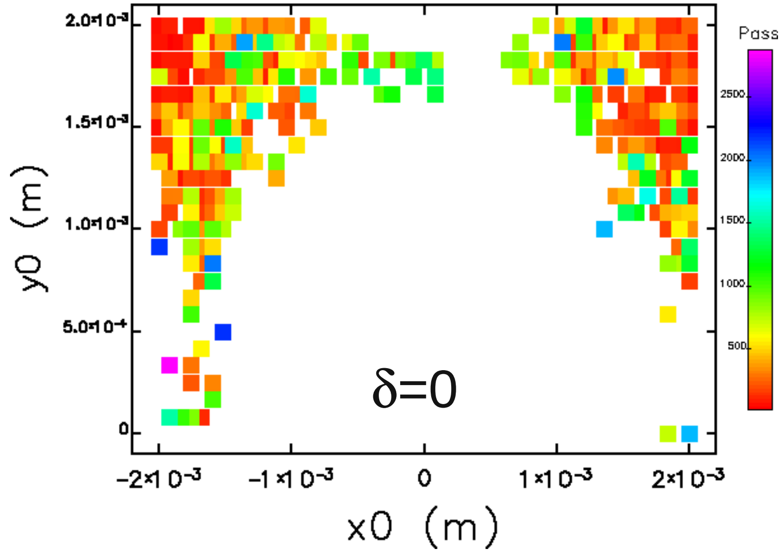
- Similar to Tsumaki and Kumagai, but
  - Larger circumference (3.16 vs 2 km)
  - Higher energy (7 vs 6 GeV) to make hard x-rays easier
  - More sectors (40 vs 32)
  - Longer straight sections (10 vs ~5m)

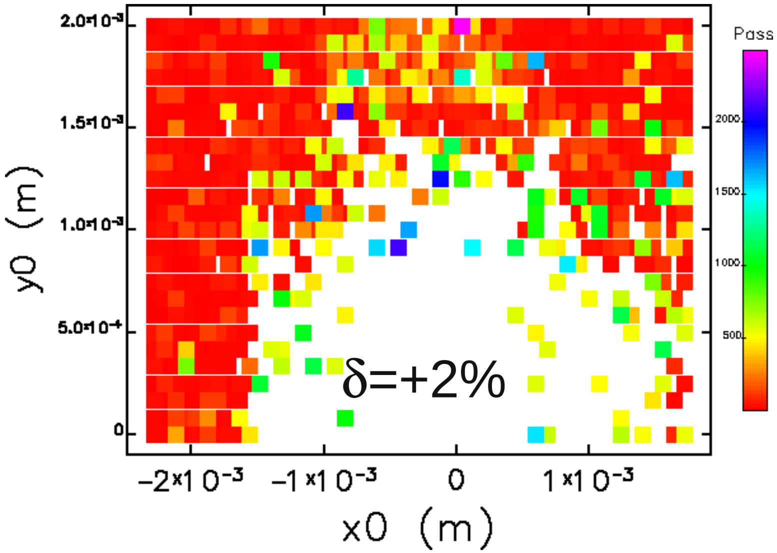
Lattice Functions

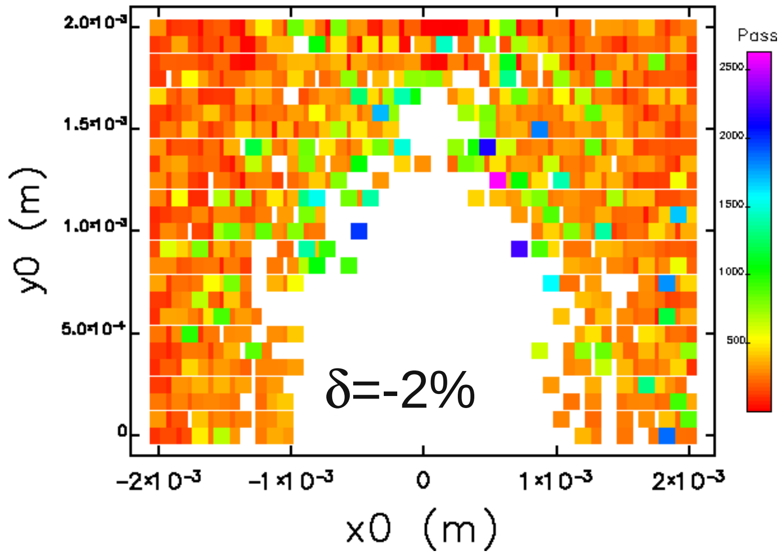


- Uses conventional magnets with workable strengths
- For 200 mA in 4000 bunches, emittance is 16 pm in both planes with full coupling
- With ten 4-m-long PETRA III damping wigglers, drops to 11 pm

USR7 Dynamic Aperture with Errors

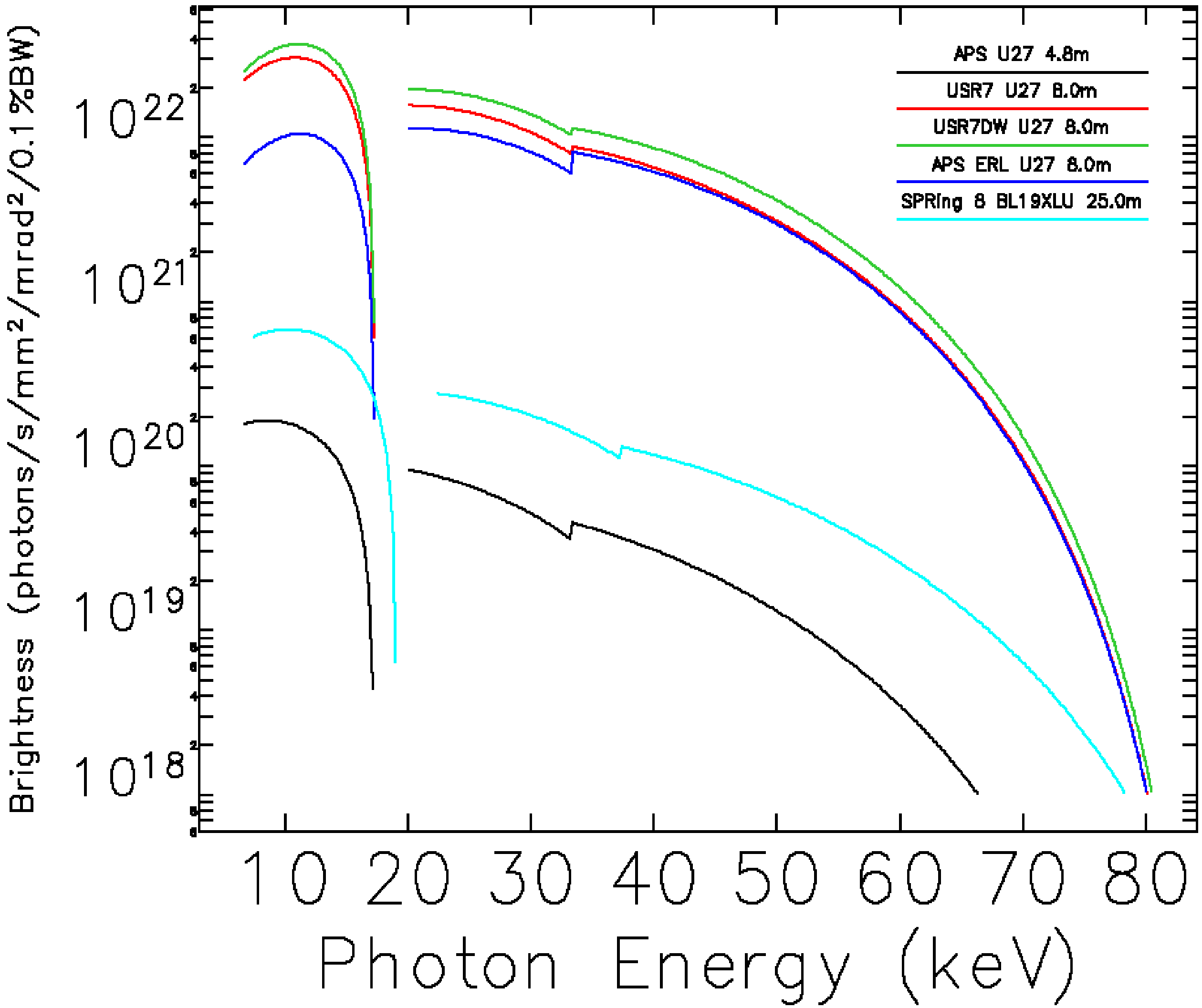






- Nonlinear elements tuned using genetic optimization technique
- 4000-turn tracking with damping and synchrotron oscillations
- Dynamic aperture is small, but very large compared to ~10 μm beam size
- Momentum aperture about ±2%
  - 2 hour Touschek lifetime

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?

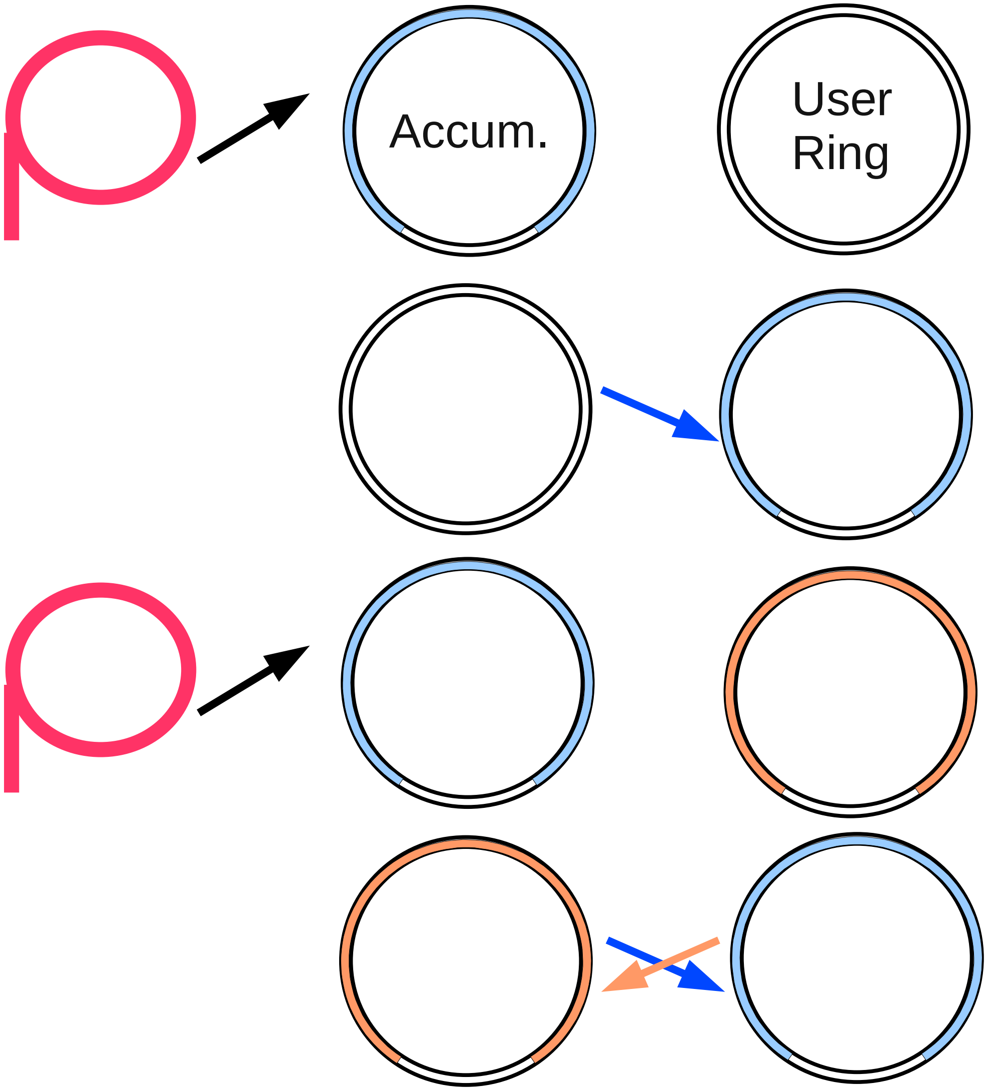
- Ring is large and therefore expensive
  - Much smaller than Tevatron, LEP, LHC
- Very small dynamic aperture, small momentum aperture
  - Small momentum aperture makes lifetime poor
  - Small dynamic aperture makes accumulation of beam very difficult
- All ring light sources use beam accumulation
  - 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[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.

[1]M. Borland, "Can APS Compete with the Next Generation?", APS Strategic Retreat, May 2002.
[2]M. Borland, L. Emery,"Possible Long-term Improvements to the APS," Proc. PAC 2003, 256-258 (2003).

Swap-Out Concept Using an Accumulator[1,2]



Fill accumulator from linac/booster.

Transfer on-axis from accumulator to UR.

Fill accumulator, use top-up to maintain fill.

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.
[2] M. Borland, L. Emery,"Possible Long-term Improvements to the APS," Proc. PAC 2003, 256-258 (2003).

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

$$D \approx \Delta T_{inj} N_{trains} \frac{1}{\tau}$$

- The required injector current is

$$I_{inj} \approx \frac{I_{ring} L_{ring}}{c \tau D}$$

- 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

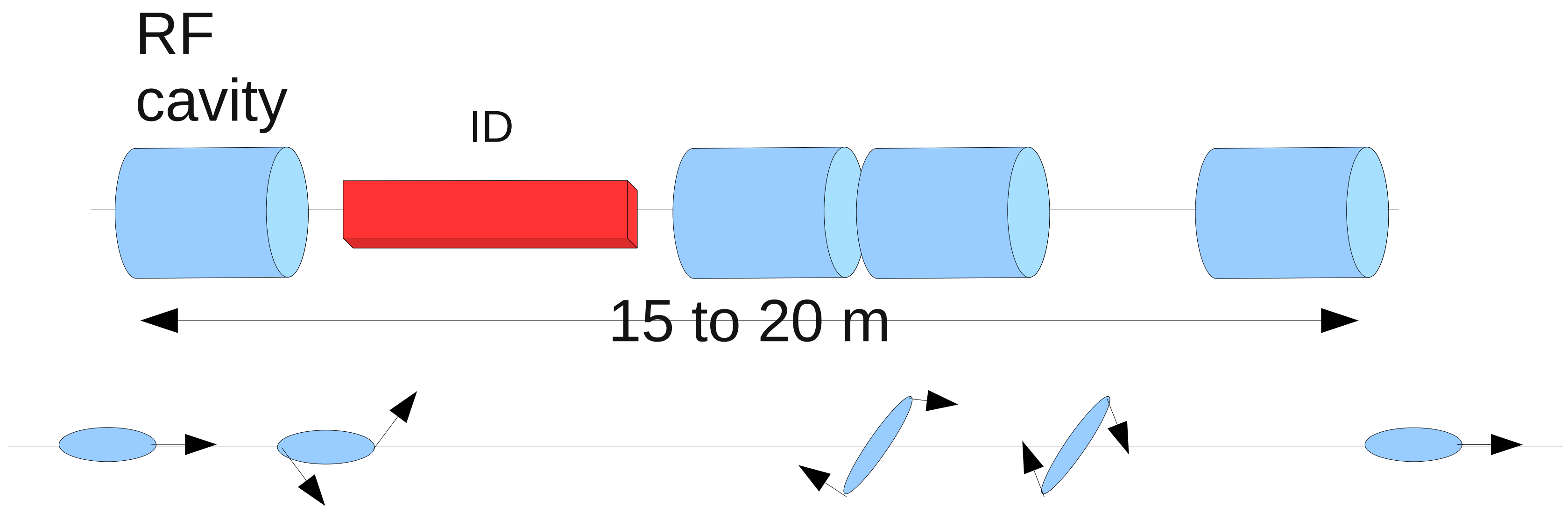
- It may be possible to increase the beam current above 200 mA
  - Lifetime will drop as we can't easily have more bunches
  - Emittance will increase for same reason
  - Beamlines/front-ends may not be feasible
- 7 GeV is not the optimum energy for emittance
  - Natural emittance drops with energy ($\sim E^2$)
  - Intra-beam scattering worse at lower energy
  - Optimum seems to be ~5 GeV (25% less than 7 GeV value)
- Ring DA is ~20x larger than needed: can push lattice harder.
- Ring is not fully optimized for damping wigglers
  - Reducing beta functions in straights will help ($\sim\beta_x$)
- ~5-fold gain in brightness with optimized beta functions at IDs
  - Very difficult with long straight sections
  - Could explore alternating long/short straight sections

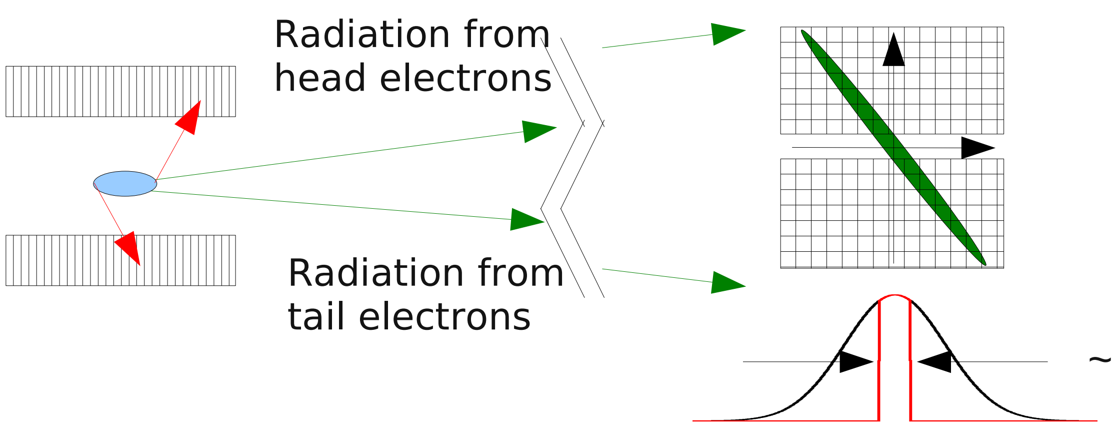
Supporting Time-Resolved Studies

- Rings have inherent difficulties supporting time-resolved studies
  - Electron bunch duration ~40 ps FWHM
  - ~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.

[1]A. Zholents *et al*., NIM A 425 (1999) 385-389.

Zholents' Scheme in a Long Straight Section





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

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.

Acknowledgements

- We acknowledge valuable discussions with and information from
  - Klaus Balewski (DESY)
  - Roger Dejus (ANL)
  - Louis Emery (ANL)
  - Efim Gluskin (ANL)
  - James Murphy (BNL)
  - Vadim Sajaev (ANL)
  - Aimin Xiao (ANL)