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

Michael Borland

Argonne National Laboratory

December 3, 2010

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

  M. Bei, M. Borland, Y. Cai, P. Elleaume, R. Gerig, K. Harkay, L. Emery, A. Hutton, R. Hettel, R. Nagaoka, D. Robin, C. Steier, "Report of the Ultimate Storage Ring Working Group of the Workshop on Accelerator Physics for Future Light Sources," NIM A 622, 518-535 (2010).

Strengths of Rings

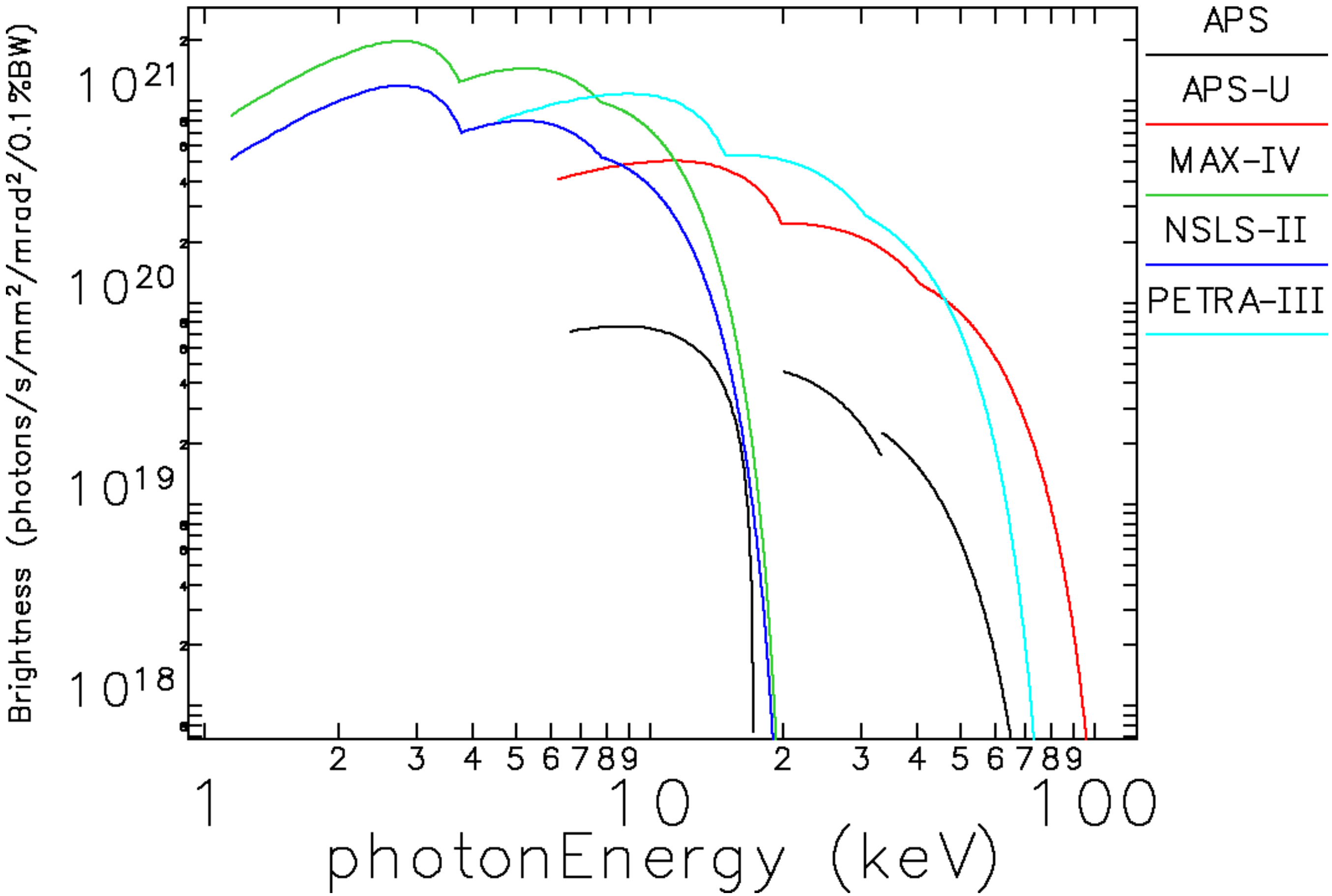
- Storage rings are extremely successful scientific facilities
  - Many thousands of users per year from dozens of scientific disciplines
- There is a good reason for this
  - Wide, easily-tunable spectrum from IR to x-rays
  - High average flux and brightness
  - Excellent stability
    - Position and 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

[1] K. Balewski *et al*, DESY 2004-035, 2004.
[2] J. Ablett *et al*, NSLS-II CDR, 2006.
[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

$$\left(\frac{d}{dt}\epsilon\right)_q \approx \frac{\langle \dot{N}_{ph} \langle u_\gamma^2 \rangle \mathcal{H}(s) \rangle_s}{2E_0^2}$$

$$\mathcal{H} = \beta_x \eta_x'^2 + 2\alpha_x \eta_x \eta_x' + \frac{1+\alpha_x^2}{\beta_x}\eta_x^2$$

- 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

$$\epsilon \propto \frac{E_0^2}{R}$$

Wrong!

[1] H. Wiedemann, Particle Accelerator Physics.

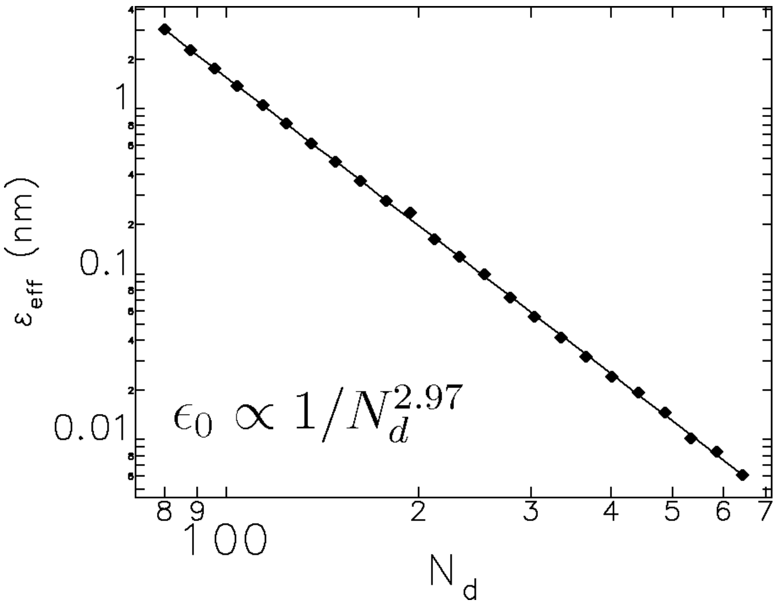
Methods of Decreasing Emittance

- 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

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

Used **elegant** to simulate scaling APS to larger circumference by adding more fixed-length cells.

Emittance scaling is as expected.



- A useful approximation[1]

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

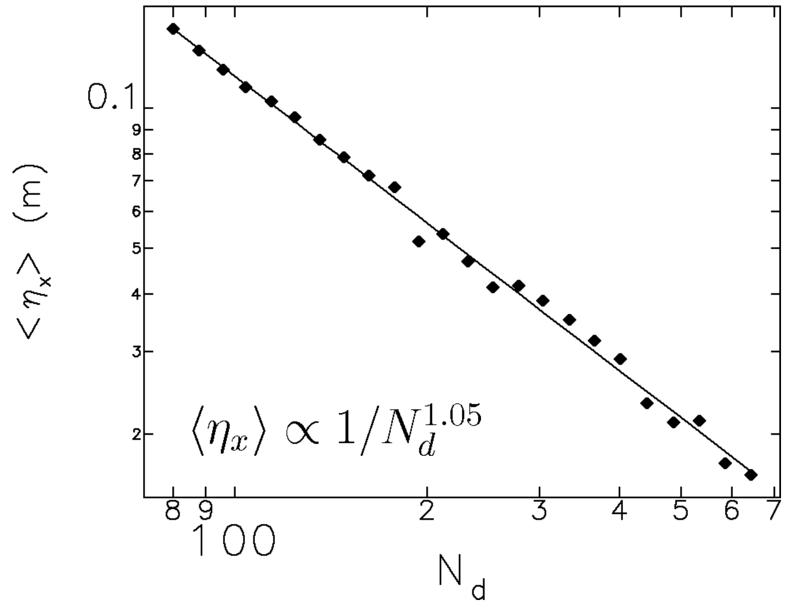
[1]J. Murphy, Light Source Data Book, BNL.

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

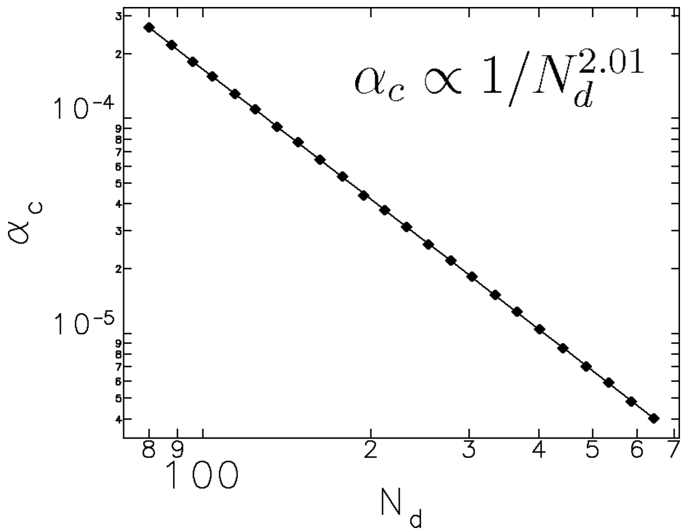
More data from the scaling simulation. Again no surprise.

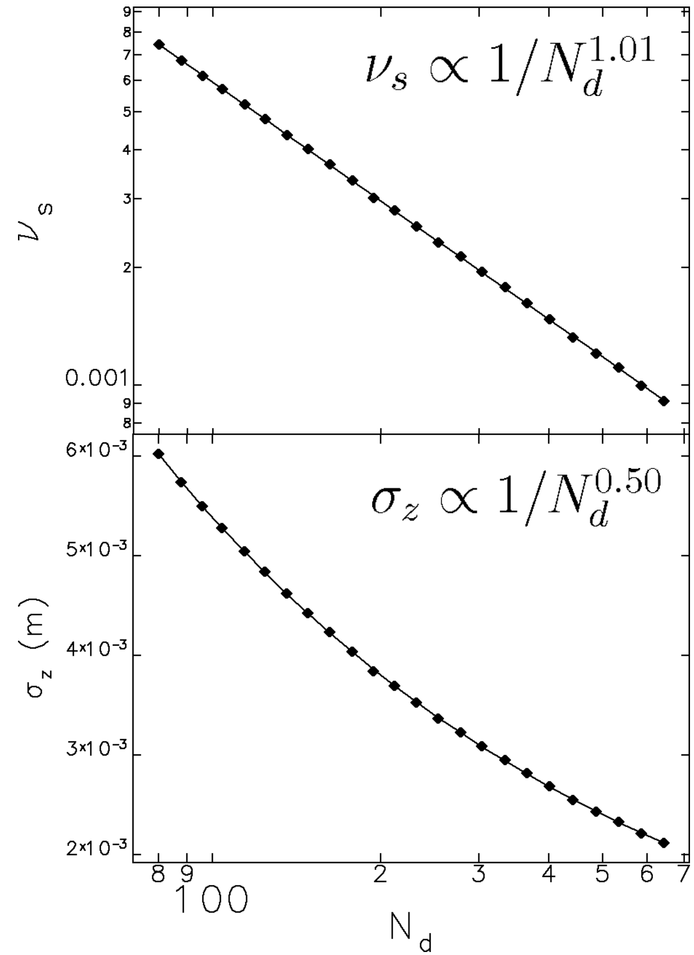
Sextupole strengths are proportional to average dispersion.



Collective Effects

- Smaller dispersion ➔ smaller momentum compaction α_c ➔ shorter bunch, reduced synchrotron tune ➔ 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

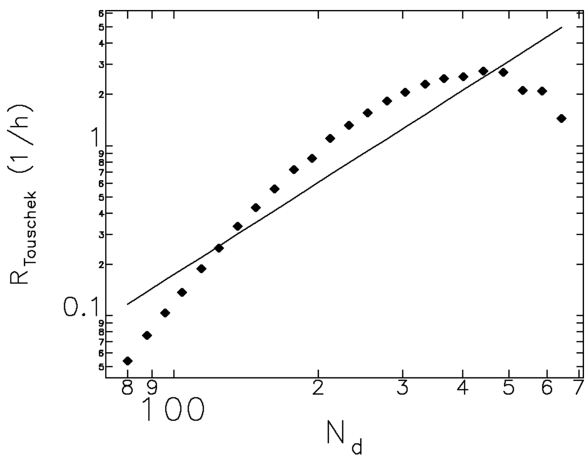
$$\frac{1}{\tau} \sim \frac{N_b N_d^{5.5}}{E^{8.1}}$$

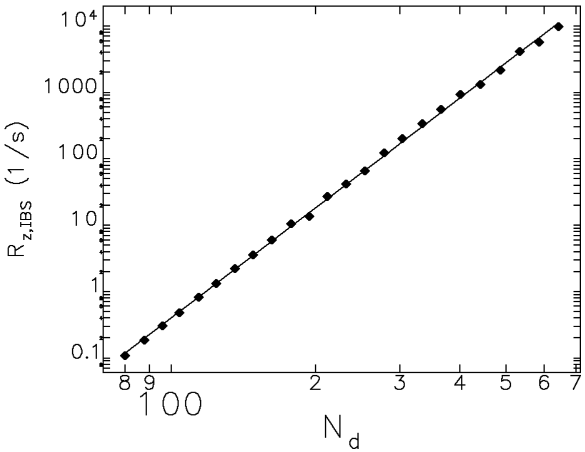
- TMCI

$$I_{thres} \sim \frac{E}{\langle\beta\rangle N_d^{1.5}}$$

- Microwave instability

$$I_{thres} \sim \frac{E^{3.3}}{N^{5.5}}$$





➔ High-energy ring with many weak bunches, bunch lengthening, feedback systems

Computed with **toushekLifetime** and **ibsEmittance** (A. Xiao *et al.*)

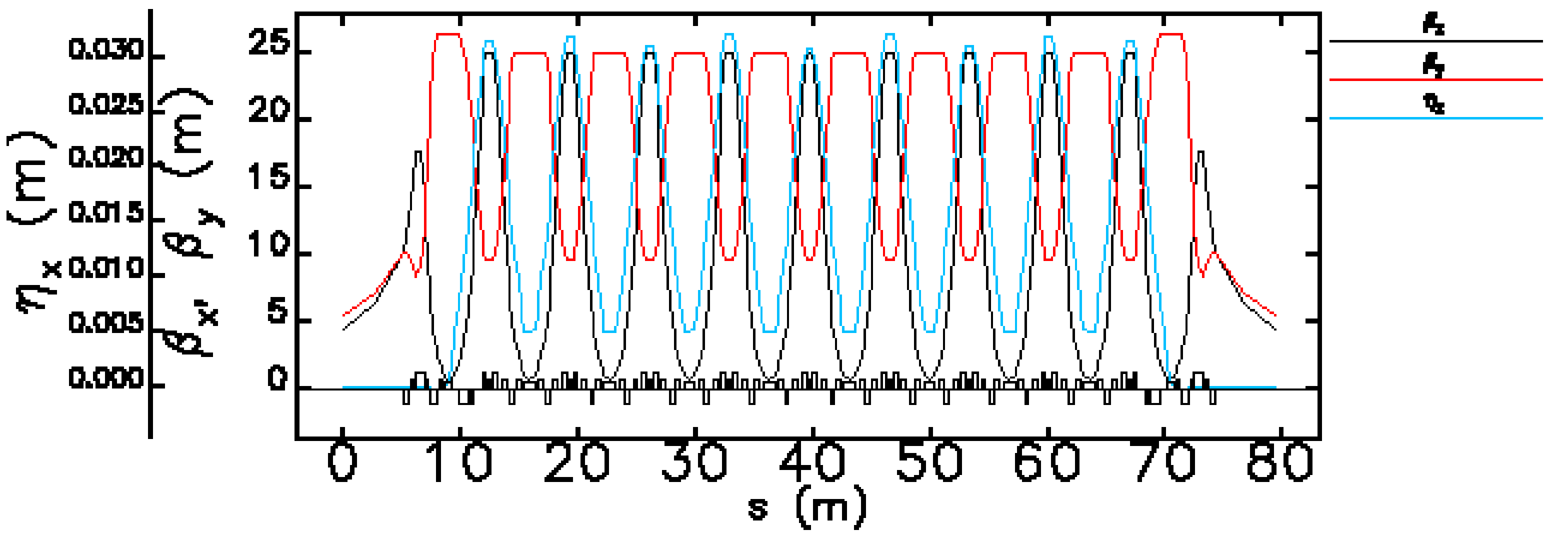
Ultimate Storage Rings

- 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 ~1/8 the emittance of a 1 km ring
  - Use multi-bend achromats[4]
    - Potential improvement of ~100-fold (10BA vs DBA)
  - Use damping wigglers
    - Potential improvement ~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

[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.

USR7: A 7 GeV, 40 Sector Ultimate Ring[1,2]

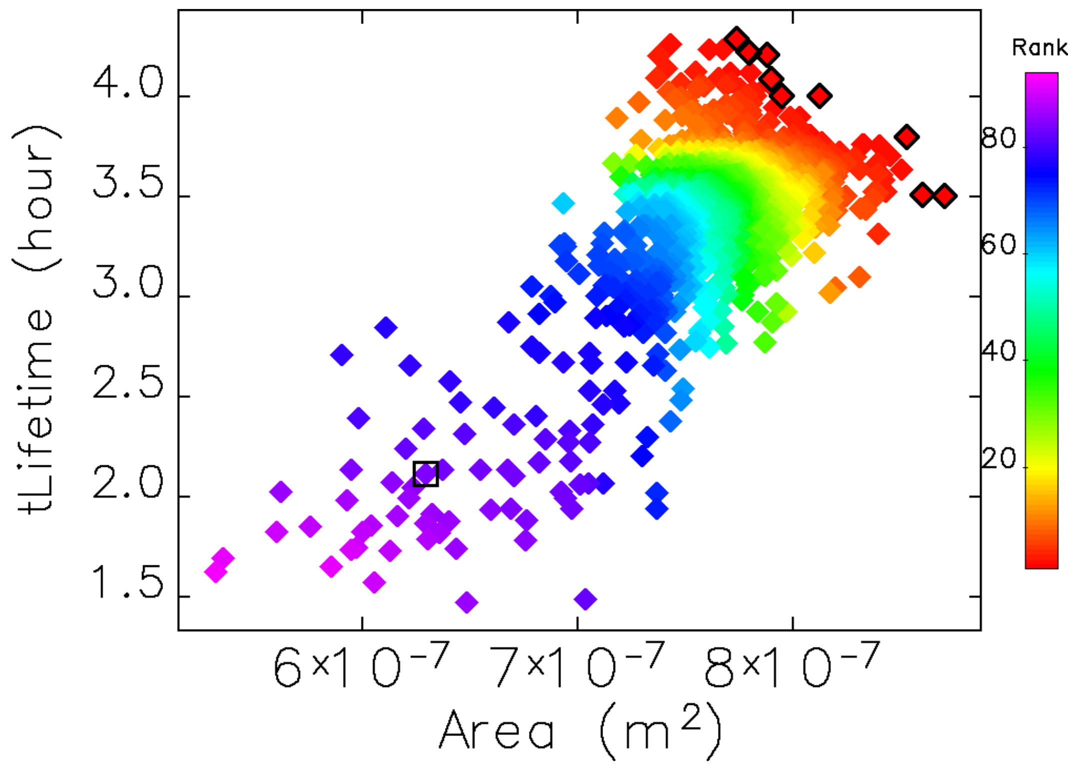
Quantity	Value	Unit
Circumference	3.16	km
Natural emittance	0.028	nm
Energy spread	0.079	%
Maximum ID length	8	m
Number of dipoles	10	per sector
Horizontal/vertical tune	183.18/36.18	
Natural chromaticities	-535/-175	
Energy loss	3.7	MeV/turn
Beta functions (x/y) at ID	4.4/5.5	m



[1]M. Borland, LSU Grand Challenge Workshop, 2008.
[2]M. Borland, Proc. SRI09, to be published.

Sextupole Optimization

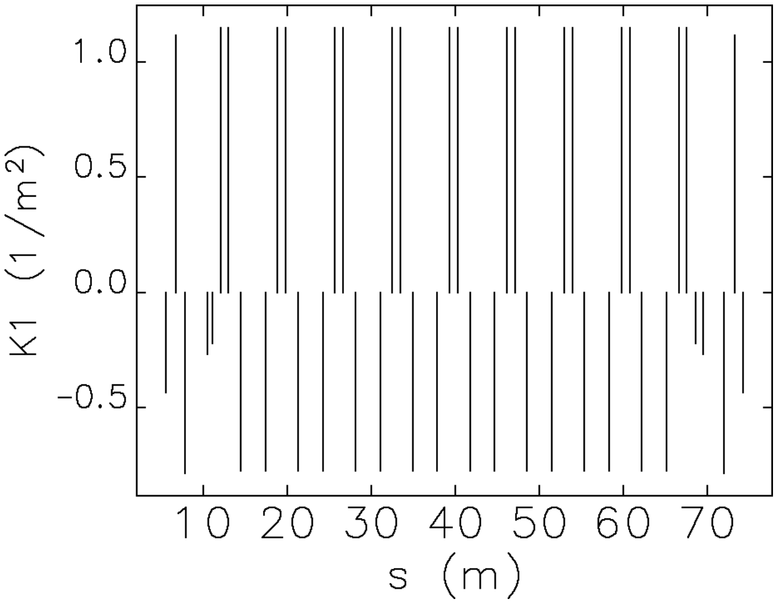
- Targeted chromaticity of 1 in both planes
- Used parallel genetic optimizer[1,2,3] to tune sextupoles
  - 21 independent sextupoles
  - Also varied fractional tune
- Direct optimization of
  - Dynamic aperture
  - Touschek lifetime
- One evaluation takes about 10 hours
- Typically use 100~300 processors

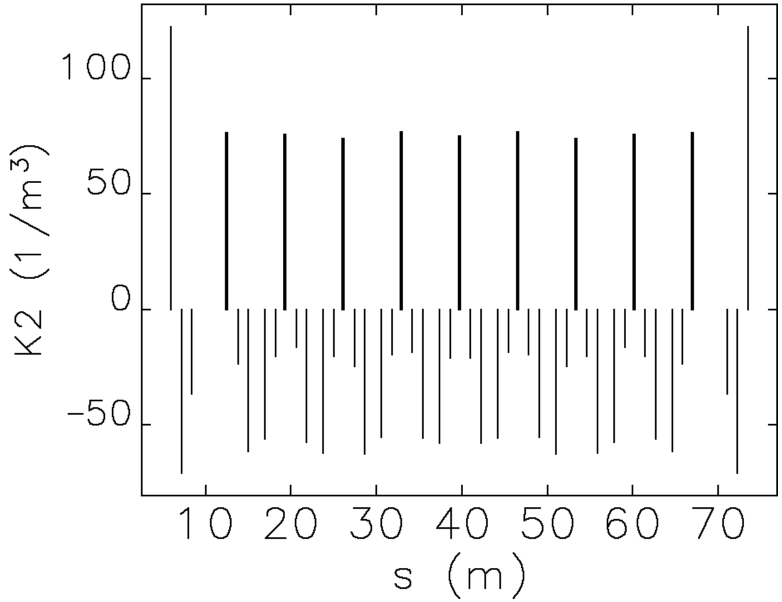


[1]M. Borland, H. Shang, **geneticOptimizer**.
[2]M. Borland *et al.*, Proc. PAC09, to be published
[3]M. Borland *et al.*, Proc. ICAP09, to be published.

Magnet Strengths

- Nothing remarkable here: only slightly stronger than APS quadrupoles

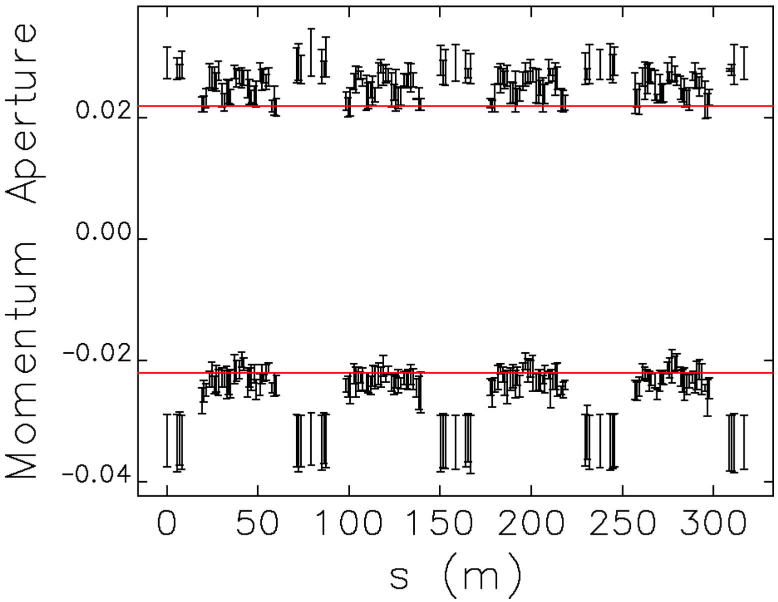




- About 4x stronger than APS sextupoles
- Preliminary design shows this is feasible with 20mm bore radius[1]

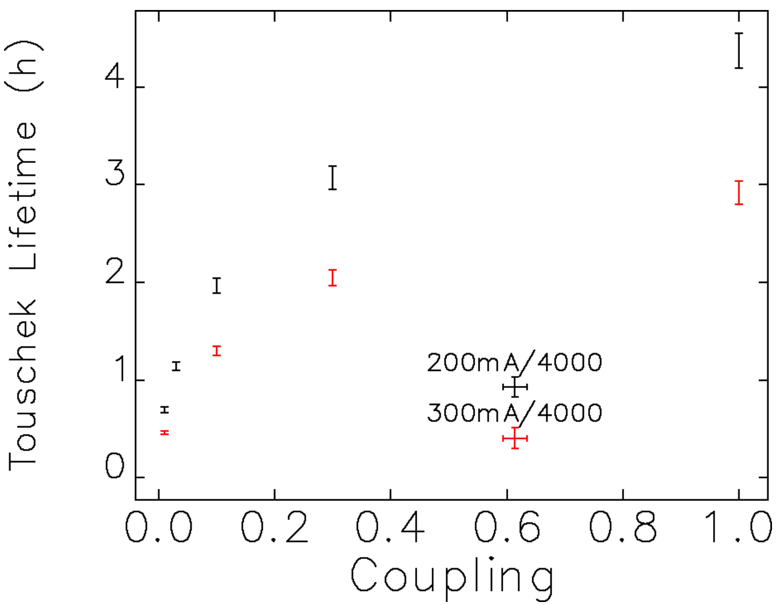
[1]A. Xiao *et al*, Proc. PAC07, THPAN096.

USR7 Momentum Aperture (5 Ensembles)



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

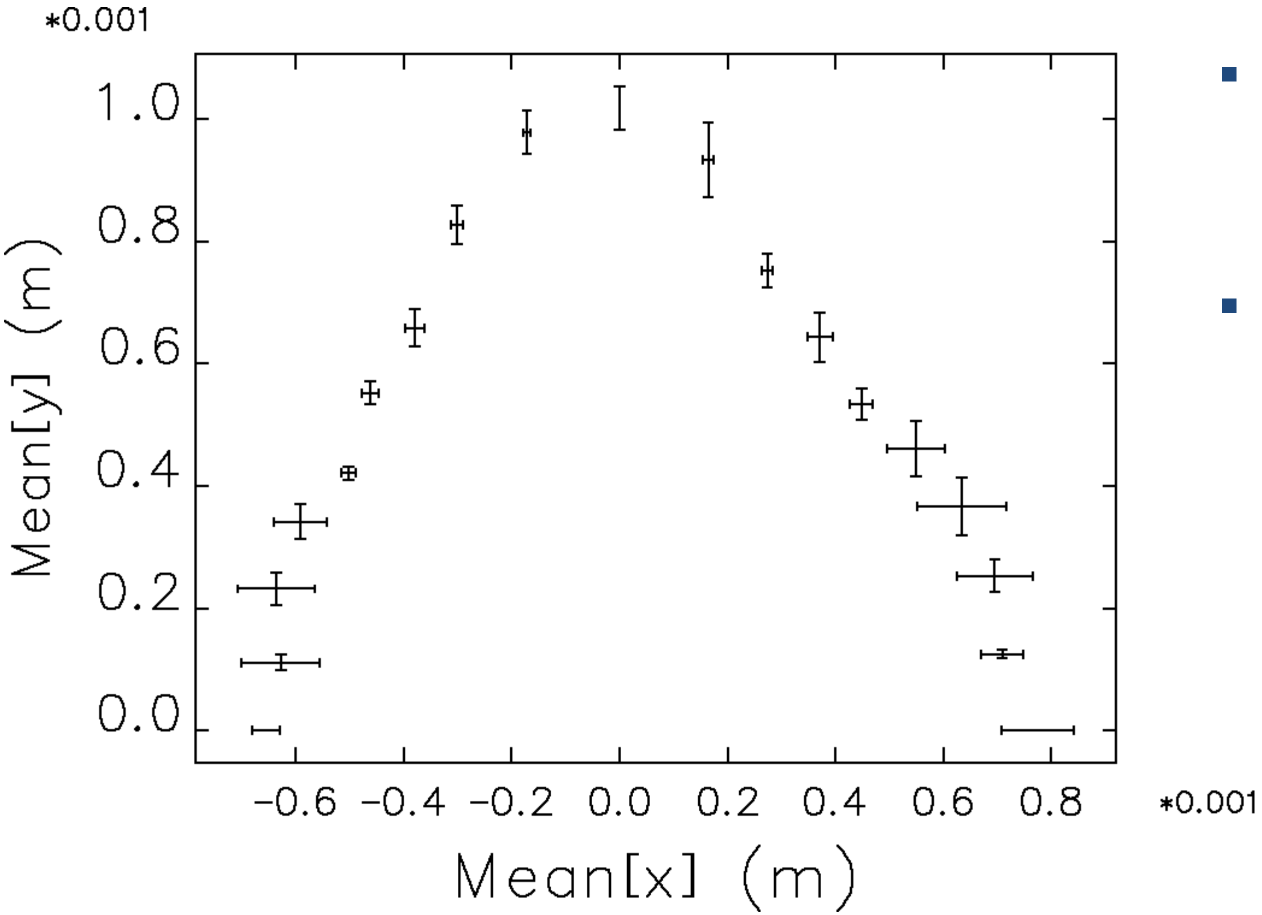
Computed with **elegant** (M. Borland, *et al.*)



- 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

[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)
[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

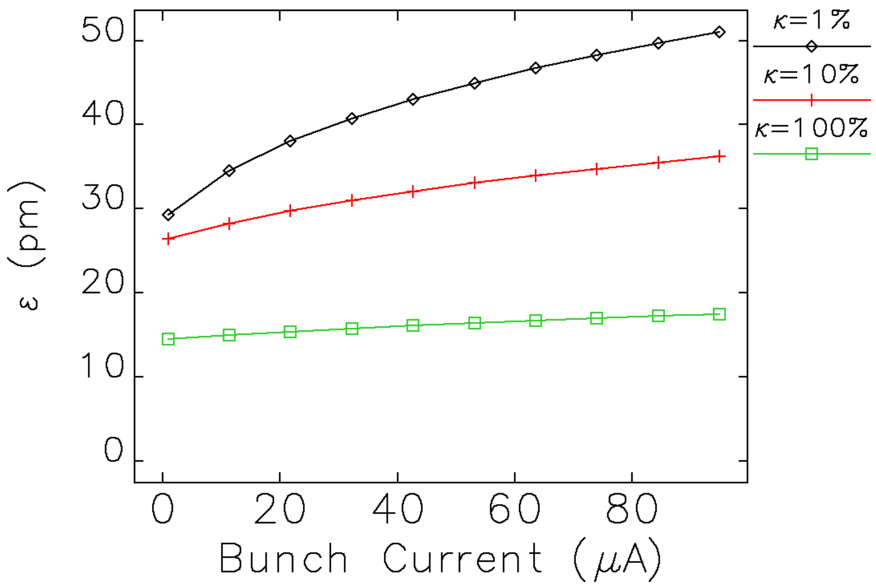
$$D \approx \Delta T_{inj} N_{trains} \frac{1}{\tau}$$

- The required injector current is

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

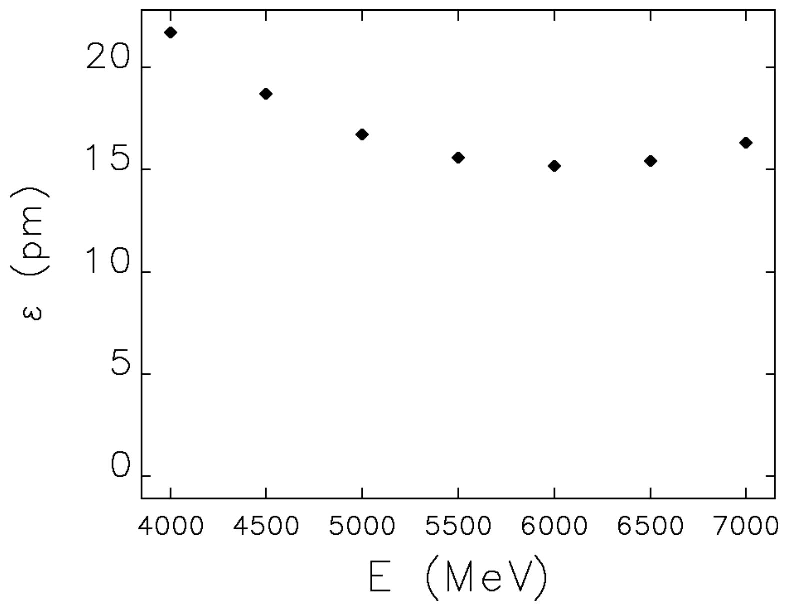
- We probably want D<0.1
- We are considering a very large ring (3.16 km) with up to 300 mA
- For 4000-bunch beam, 20 bunches per train, and 3 hour lifetime
  - Inject a bunch train every 5 s
  - 2.9 nA average current from the injector (APS injector: 4 nA)
  - Each train has 16 nC (APS injector: 3 nC/bunch).

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 ~4 mA
  - USR7 may be ~360 µA

$$I_{thres} \sim \frac{E}{\langle\beta\rangle N_d^{1.5}}$$

- Microwave instability
  - APS threshold[1] is ~5 mA
  - USR7 may be ~1 µA
  - For 50 µA need significant bunch lengthening (4x)
  - APS runs well above threshold (20 mA or more)

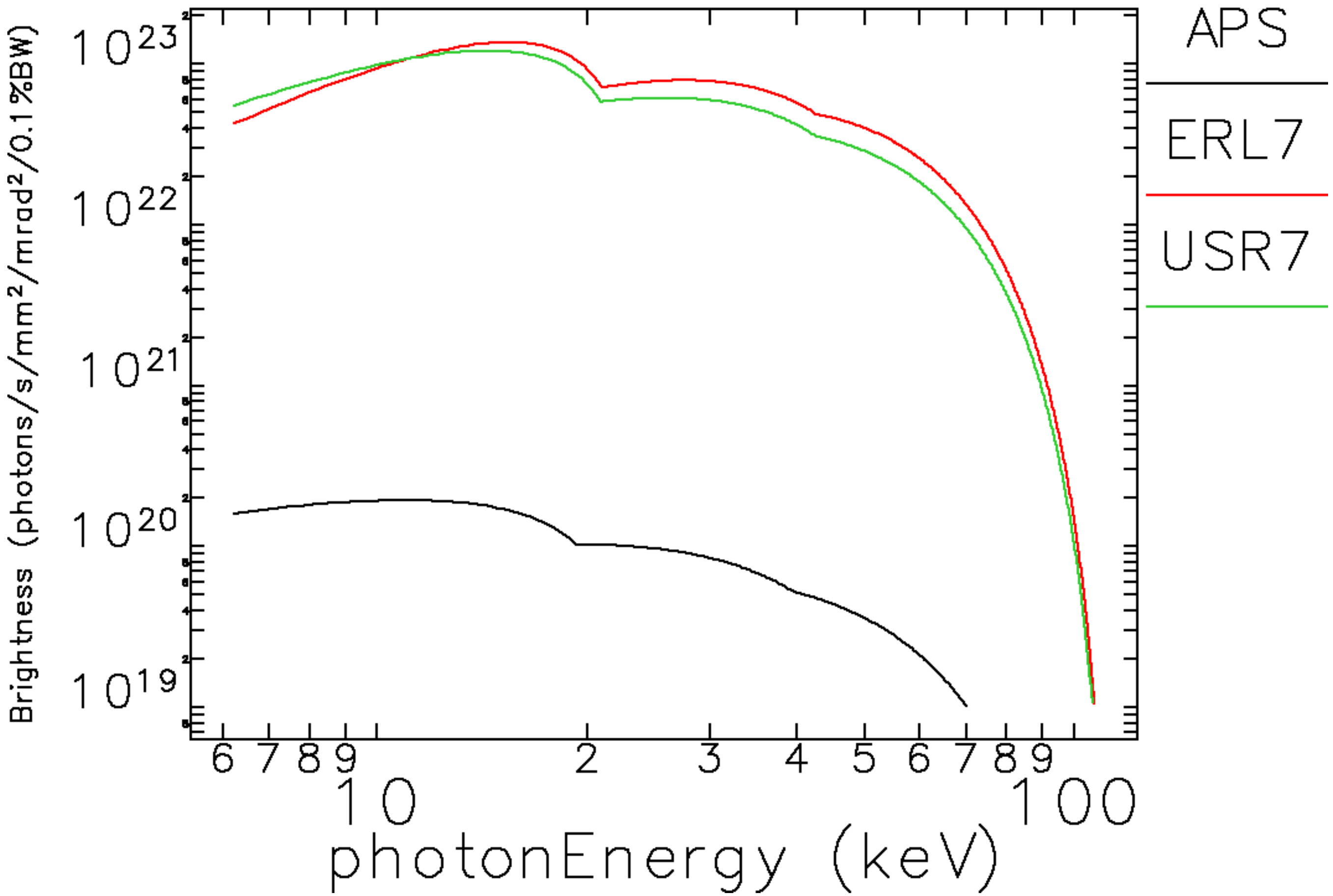
$$I_{thres} \sim \frac{E^{3.3}}{N^{5.5}}$$

[1]K. Harkay *et al.*, Proc. EPAC2002, 1505-1507.

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

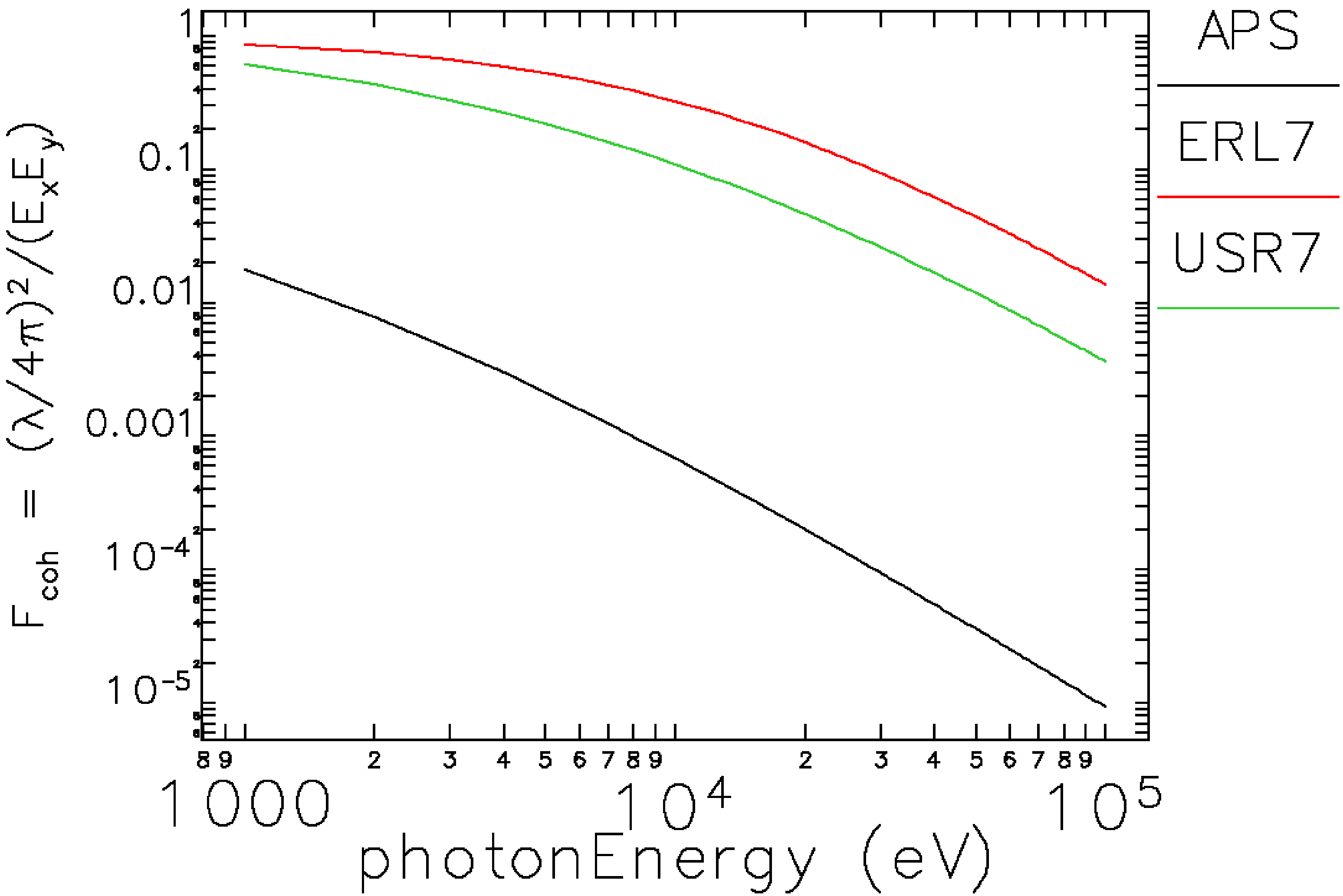


Maximum-length SCU20 (Nb_3Sn wire)

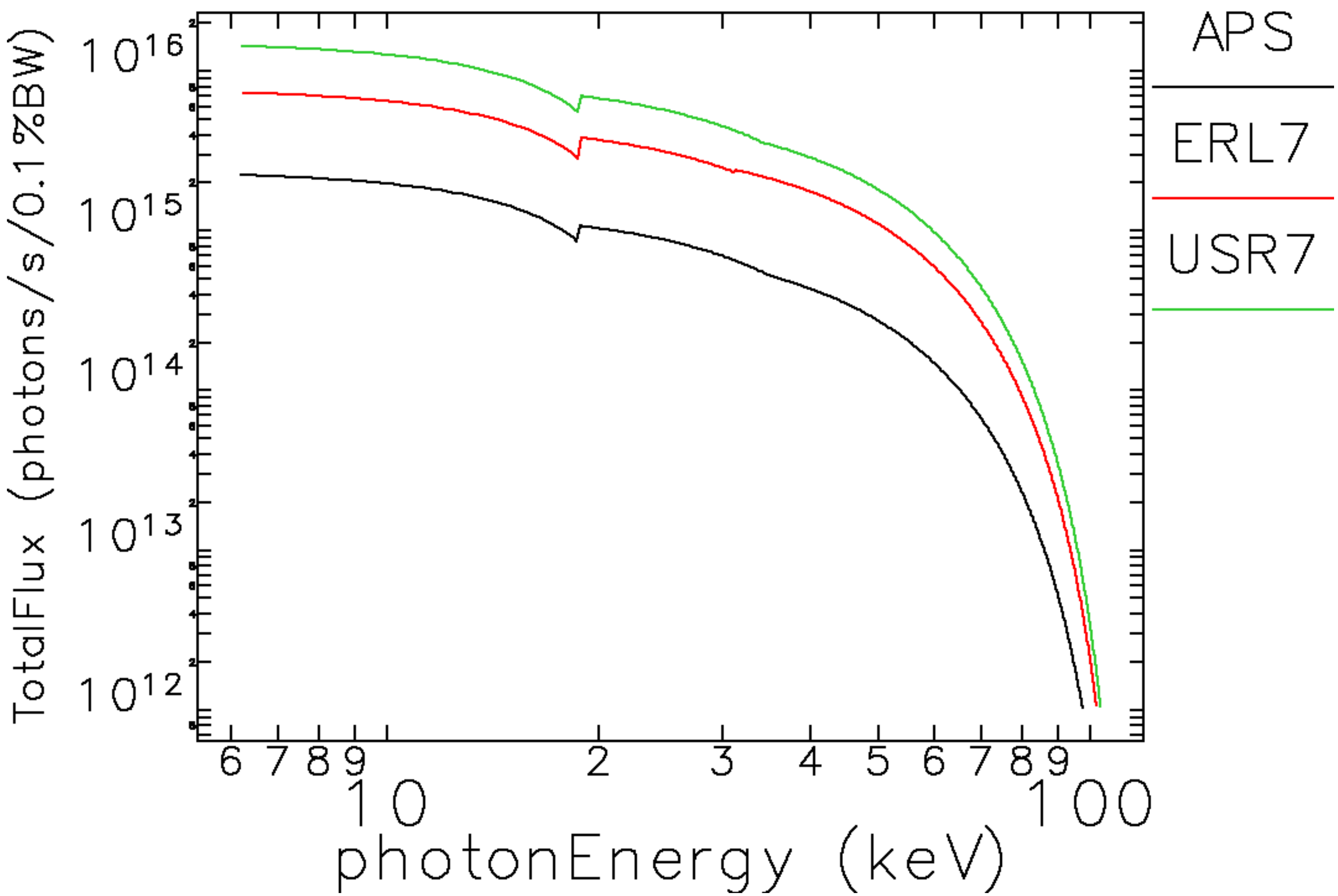
APS: 100mA, 1.3% coupling, 3.8 m device
USR7: 300mA, 100% coupling, 8.0 m device
ERL7: 25mA, “high-coherence” parameters, 48m device

Computed with **sddsbrightness** (H. Shang, R. Dejus, M. Borland)

Transverse Coherence Comparison



Flux Comparison



Maximum-length SCU20 (Nb_3Sn 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

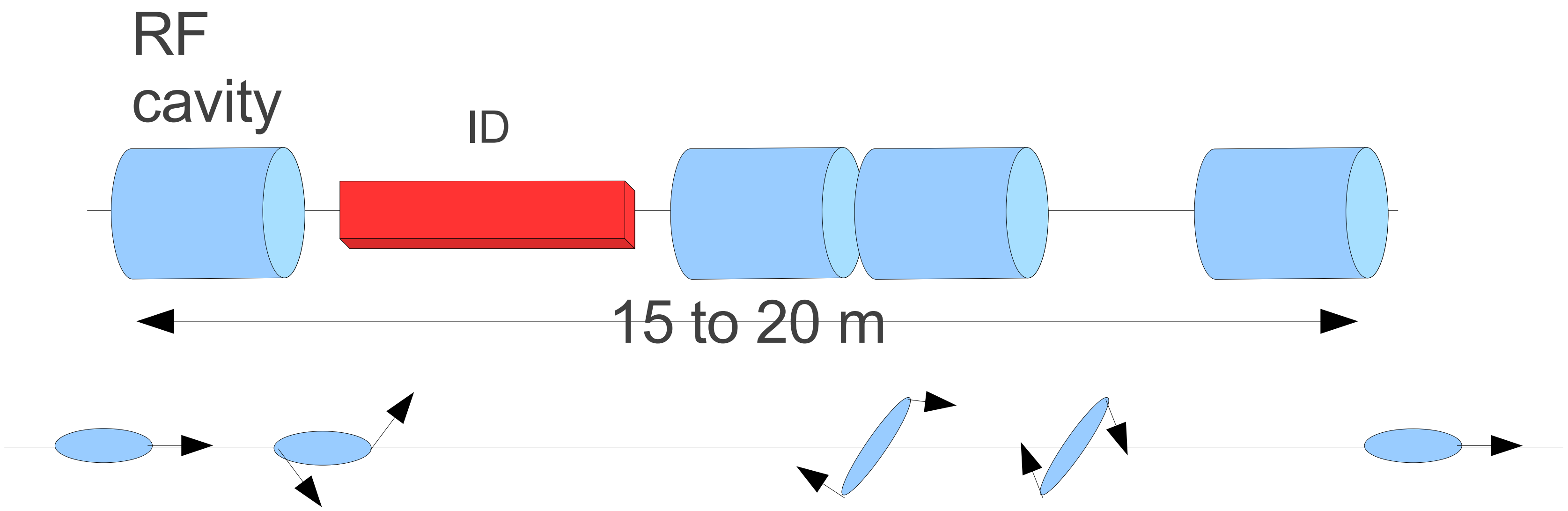
Computed with **sddsfluxcurve** (M. Borland, R. Dejus, H. Shang)

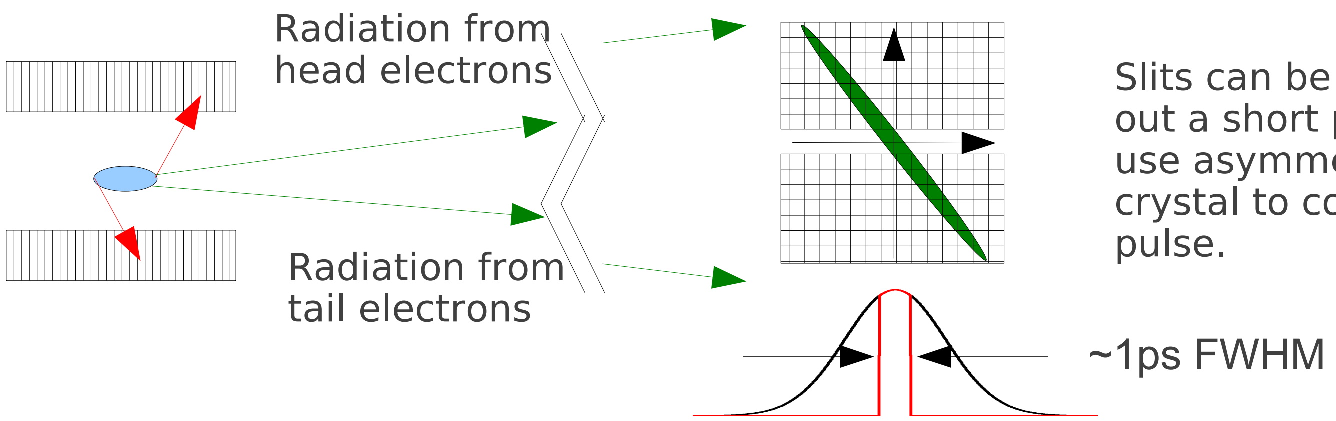
Support for Timing Experiments

- 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





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

Isn't an ERL Better?

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

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 1/8th of ring replaced
  - Resulting 1 nm emittance at 6 GeV is world-leading
- SLAC is considering[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)

[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