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APS Long-Term Upgrade Options

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Introduction and Motivation

- APS is a mature, highly-optimized light source
  - Emittance pushed down to 3.1 nm
  - Close to the practical minimum with existing hardware
  - Difficult to make changes without increasing emittance
- Meanwhile,
  - Large, on-going investment in beamlines and facilities
  - New sources are on the horizon
    - *LCLS in early stages of commissioning*
    - *NSLS II approaching construction*
- An upgrade will eventually be required to
  - Keep APS scientifically relevant
  - Capitalize on our investments
- Long-term upgrade options include
  - In-tunnel replacement of the storage ring
  - Energy recovery linac injector.

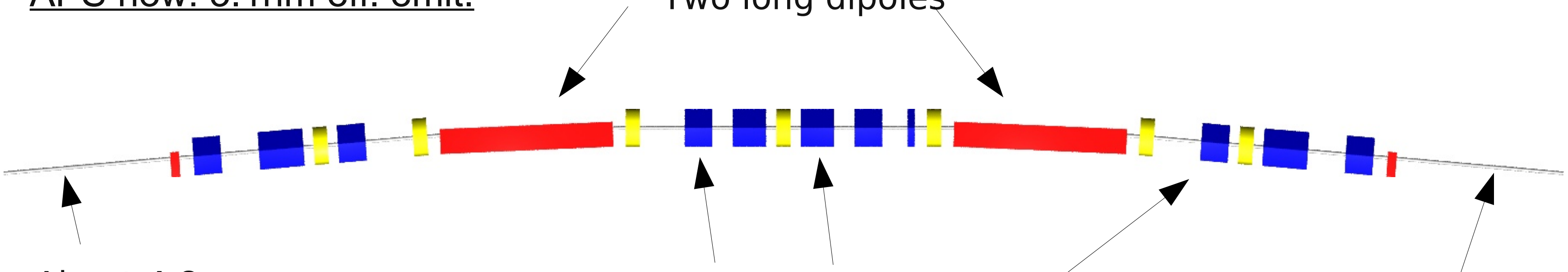
Goals for Replacement Ring

- Tailored to experimental requirements
  - More than just lower emittance!
- Use “crab” cavities to support experiments requiring
  - Short pulse x-rays
  - Coherent imaging with large beam size
- Long straight sections essential
  - Innovative IDs (e.g., fast polarization switching)
  - More beamlines
  - Crab cavities
- Straight sections optimized for
  - Small beam size or
  - Small beam divergence
- Higher brightness.

Mostly from E. Gluskin

Layout for "APS 1nm" Replacement Ring Design[1]

APS now: 3.1nm eff. emit.



Two long dipoles

About 4.8m space
for undulators

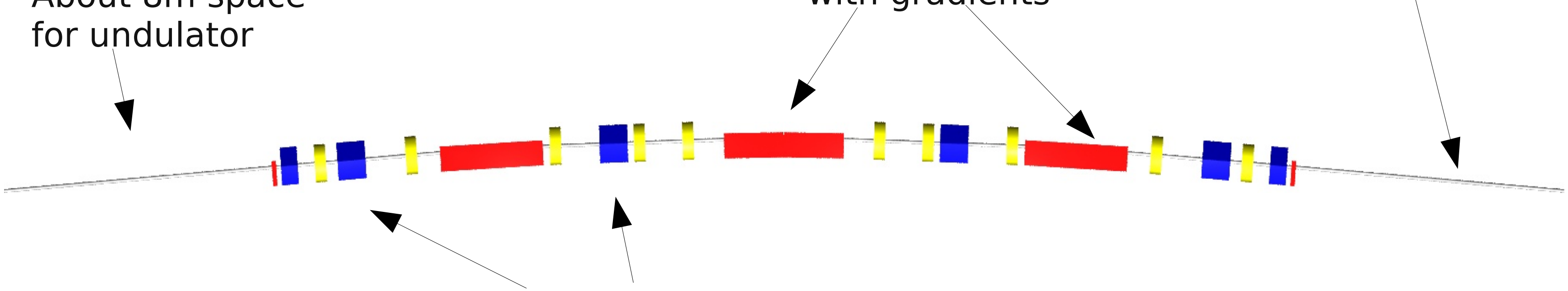
Many long quadrupoles

"APS 1nm": 1nm eff. emit.

ID straight section
unmoved

Shorter dipoles
with gradients

About 8m space
for undulator



Fewer, shorter quadrupoles

Diagrams courtesy L. Emery.

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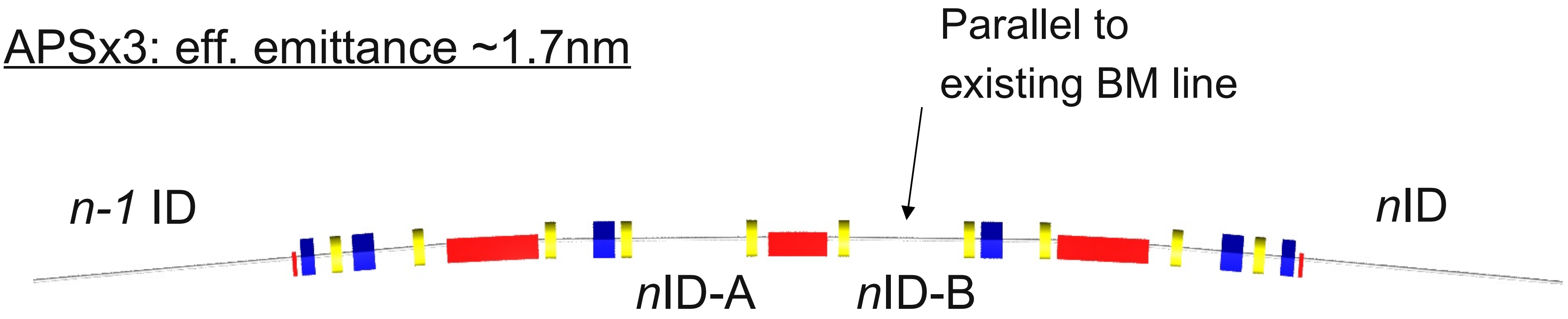
[1] A. Xiao *et al.*, PAC07, 3447-3449.

APSx3 Lattice Design[1]

- Some users felt 1nm emittance not that useful
  - More beamlines are really what they need
- This design has 1 long and 2 short straights per sector
  - Main straight accepts 8m ID
  - Two short straight sections with ~1m available for ID
    - *One is parallel to present BM beamline*
    - *Could provide a three-pole wiggler for beamlines that still want bending-magnet-like source*

APSx3: eff. emittance ~1.7nm



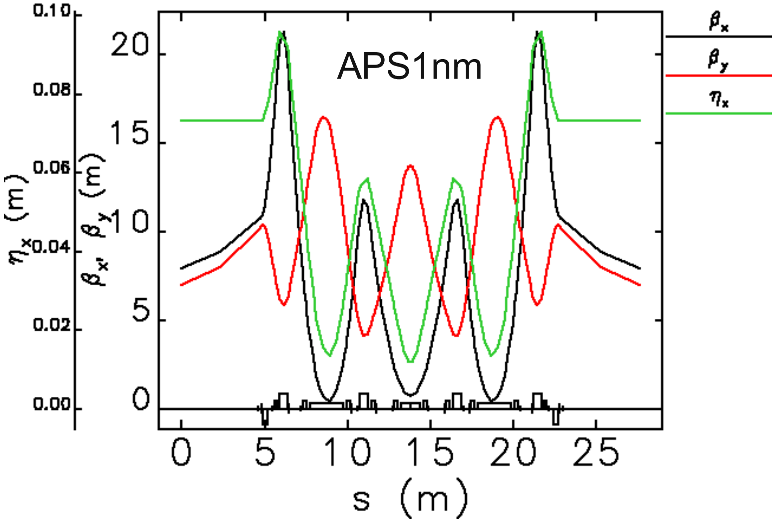
2.1m magnet-to-magnet
in new straight sections.

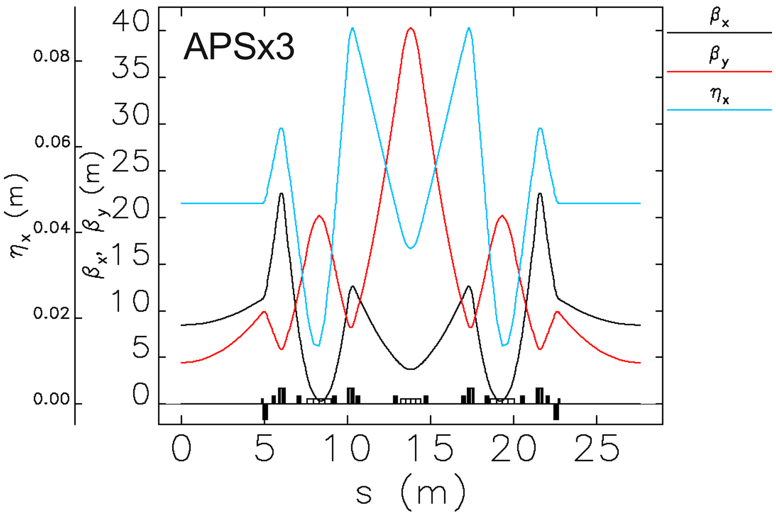
[1] V. Sajaev *et al.*, PAC07, 1139-1141.

Diagram courtesy L. Emery.

Summary of APS 1nm and APSx3 Studies[1,2]

- Quadrupole and sextupole strengths feasible with 20mm bore radius
  - Vacuum chamber workable from impedance standpoint[3]
- Dipole gradient is on the margin of what's possible, needs work
- Dynamic aperture with ~1% beta beating is similar to APS today
  - Do on-axis injection and lattice correction to get to this point
  - Present 65 nm booster emittance low enough for symmetric lattice[4]
- Momentum aperture is about ±3%, giving 4~5 hour lifetime with 8mA bunch
  - Acceptable with top-up





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[1] A. Xiao *et al.*, PAC07, 3447-3449.

[2] V. Sajaev *et al.*, PAC07, 1139-1141.

[3] Y. Chae *et al.*, PAC07, 4330-4332.

[4] N.Sereno and M. Borland, PAC07, 3438-3440.

Discussion

- APS1nm lattice provides about 35-fold increase in brightness assuming 200 mA and 1% coupling
  - More than half of this comes from things other than emittance
    - *Double the beam current*
    - *8m-long instead of 2.4m U33*
- Transverse coherence increases about 3-fold compared to best for present APS design (i.e., minimum coupling and maximum ID length)
- Most APS users were unexcited about these rings
  - Won't revolutionize x-ray science at APS
  - Beamline and detector improvements will give more benefit with less disruption and cost
  - Users very worried about ~1 year shutdown[1] needed to replace ring
- Conclusion:
  In-tunnel ring replacement not a great approach to an upgrade.

[1] J. Noonan, private communication.

Cornell ERL Parameters[1] Scaled to 7 GeV

	APS	ERL		
	now	High flux	High coherence	Ultrashort pulse
Average current (mA)	100	100	25	1
Repetition rate (MHz)	0.3~352	1300	1300	1
Bunch charge (nC)	0.3~60	0.077	0.019	1
Emittance (nm)	3.1 x 0.025	0.022 x 0.022	0.006 x 0.006	0.37 x 0.37
Rms bunch length (ps)	20 ~ 70	2	2	0.1
Rms momentum spread (%)	0.1	0.02	0.02	0.3

- Promise of very high brightness
  - Extremely low emittance, equal in both planes
  - Very low energy spread
- Decent flux: 25 mA to 100 mA current.

[1] G. Hoffstaetter, FLS 2006 Workshop, DESY.

Ultimate APS ERL Upgrade Concept[1]

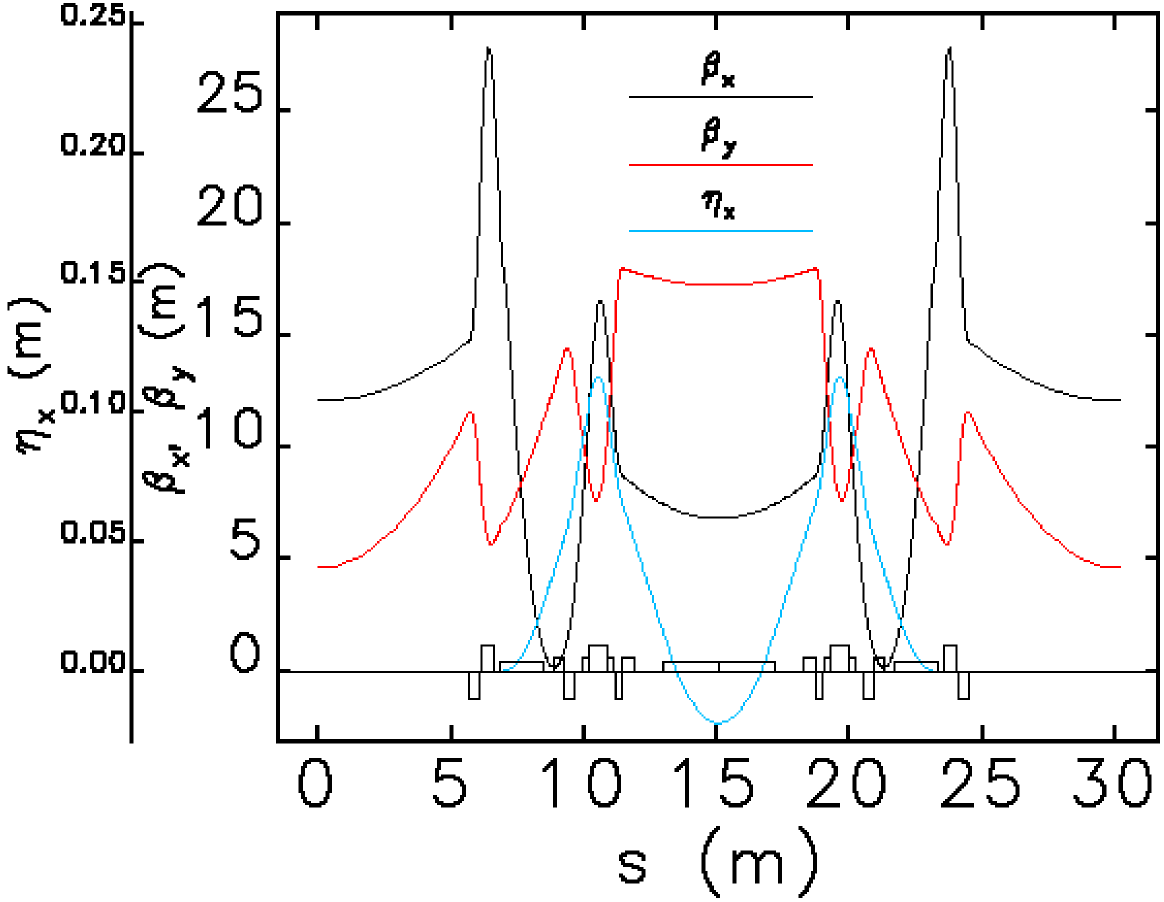
- Single-pass 7 GeV linac points away from APS to permit straight-ahead hard x-ray short-pulse facility
- Beam goes first into new, emittance-preserving turn-around/user arc
  - Second-stage upgrade would add many new beamlines
- ERL can benefit from very long undulators[2]
  - Higher flux and brightness
  - Would use somewhat different geometry than shown here
- Ability to store beam unchanged
- Existing injector complex unchanged
- Developed optics and modeled from 10 MeV to 7 GeV and back with elegant[3].

[1] M. Borland *et al.*, NIM A 582 (2007) 54-56.

[2] S. Gruner *et al.*, erl.chess.cornell.edu/papers/WhitePaper_v41.pdf, 11/30/2000.

[3] M. Borland *et al.*; M. Borland, APS LS-287, Sept. 2000.

Turn-Around Arc Cell[1]



- 10m straights
- 48 cells
- Isochronous to avoid bunch shape changes
- x tune is 1.25 per cell
  - CSR effects cancel every 4 cells[2,3]
- I_5 minimized subject to other constraints to control emittance growth
- Four sextupole families
- As complex as a 3rd generation storage ring.

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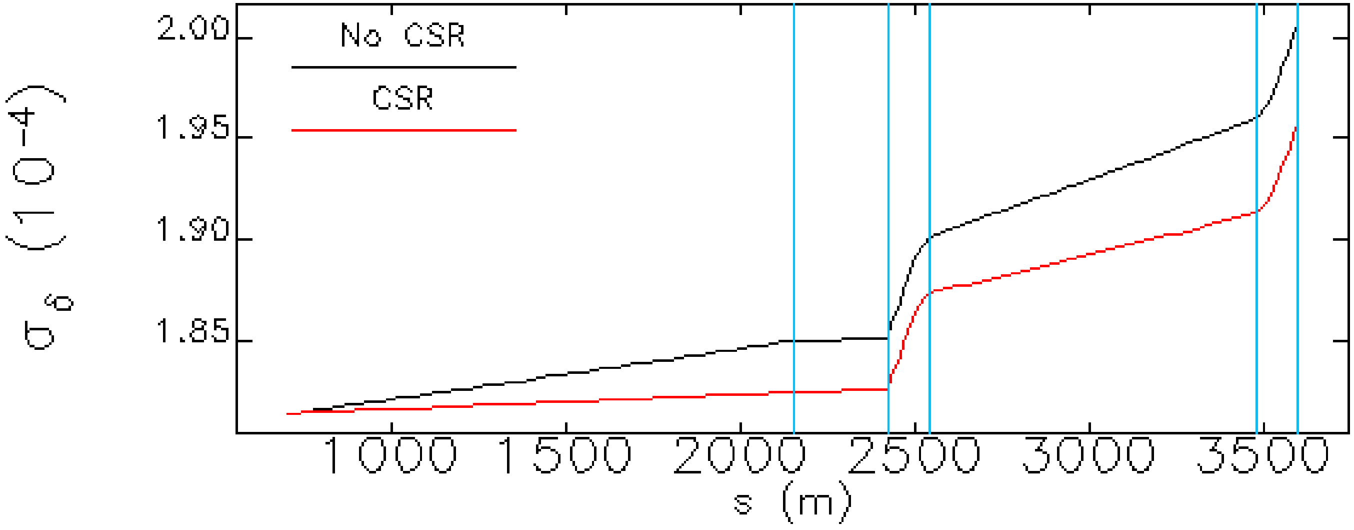
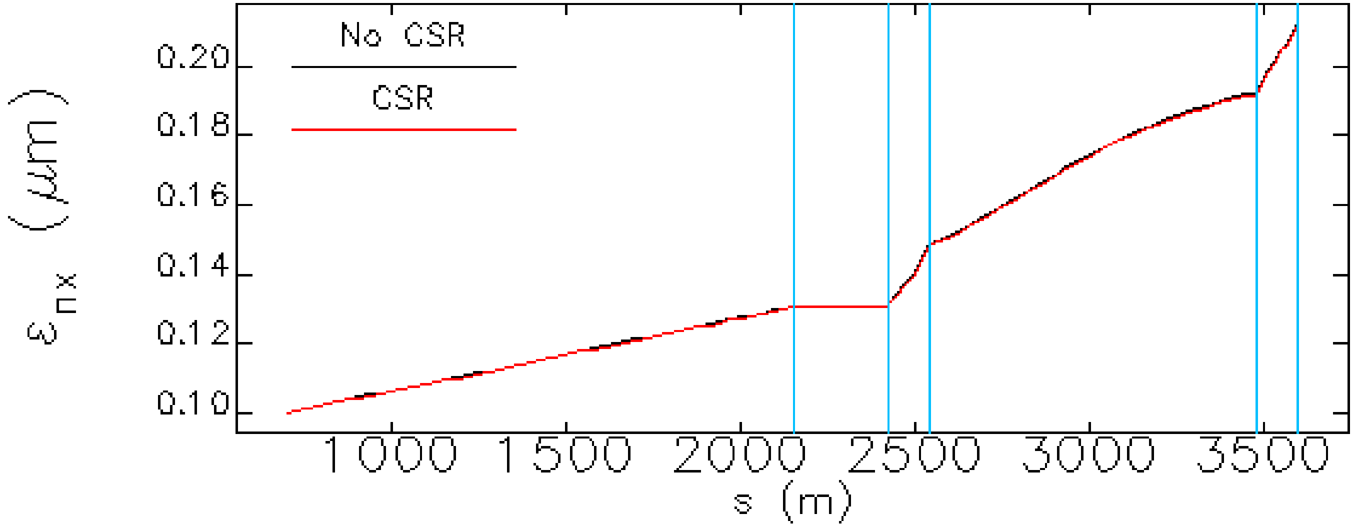
[1] M. Borland *et al.*, AccApp'07, 196-203.
[2] J. Wu *et al.*, 2001 PAC, 2866-2868.
[3] G. Bassi *et al.*, NIM A 557 (2005), 189-204.

CSR Effects Are Modest for 19 pC/bunch



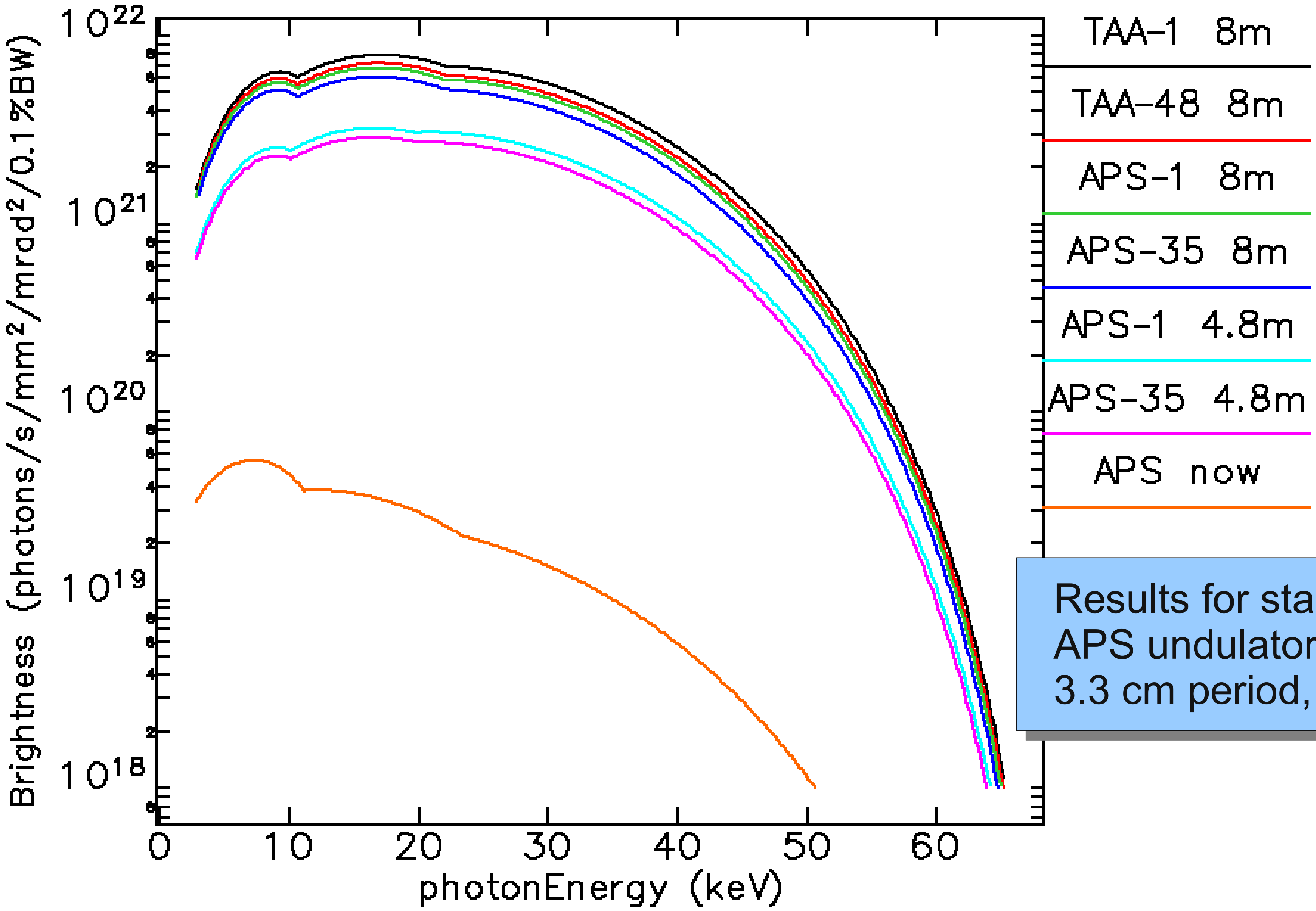
- CSR *decreases* energy spread
- Linac energy spread is rf-curvature-dominated
- CSR flattens out this curvature



- No significant impact on emittance from CSR
- Little different for 77pC

[1] M. Borland *et al.*, NIM A 582 (2007) 54-56.

Brightness Comparison for High Coherence Mode



Results for standard APS undulator A, 3.3 cm period, K<2.8

[1] M. Borland *et al.*, NIM A 582 (2007) 54-56.
Computed with sddsbrightness (H. Shang, R. Dejus).

Present-Day Injector Performance

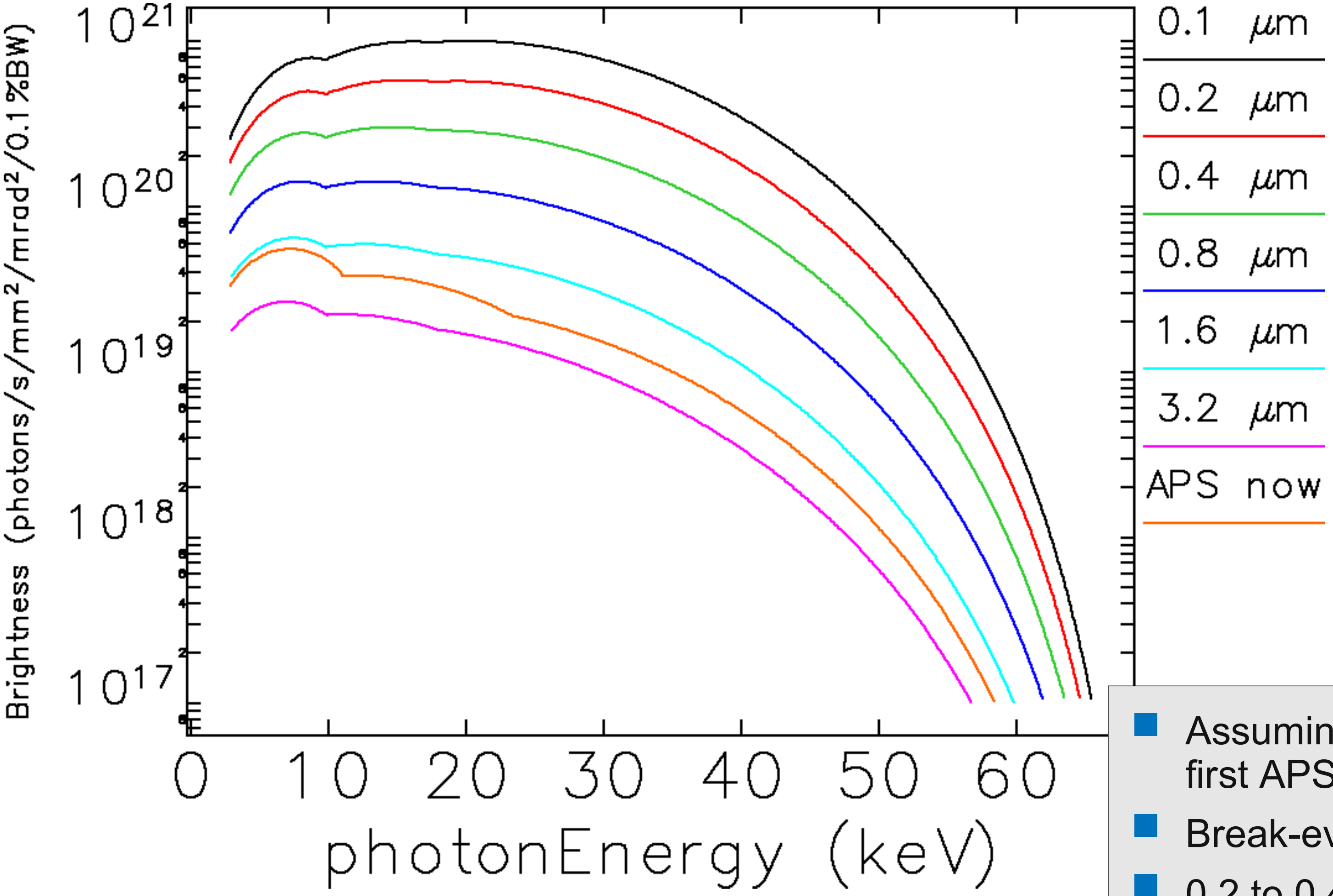
- JLab ERL injector[1] is operating example of the type of system we'll need
  - 120 pC/bunch
  - ~10 μm normalized emittance
  - ~2 ps bunch duration
  - 9 mA average current with ~12 hour cathode lifetime
- Scaling to 20 pC/bunch (linear in charge), we get 1.5 μm
  - We're assuming 0.1 μm
  - We also want 25 to 100 mA with ~24 hour lifetime
- We are about an order of magnitude from where we need to be on several fronts
- Two promising simulation efforts
  - Cornell[2] gets 0.1 μm emittances for ~100 pC without merger
  - JAERI[3] gets 0.1 μm emittances for ~10 pC with merger
  - High-coherence mode (0.1 μm, 19 pC) seems plausible.

[1] C. Hernandez-Garcia et al., Proc. 2004 FEL Conference, 558-561.

[2] I.Bazarov and C. Sinclair, Phys. Rev. ST Accel. Beams 8 (2005) 034202.

[3] R.Hajima and R. Nagai, NIM A 557 (2006) 103-105.

Consequences of "Poor" Injector Emittance[1]



- Assuming 2.4-m devices in first APS beamline
- Break-even at 1.6 µm
- 0.2 to 0.4 µm gives very good result

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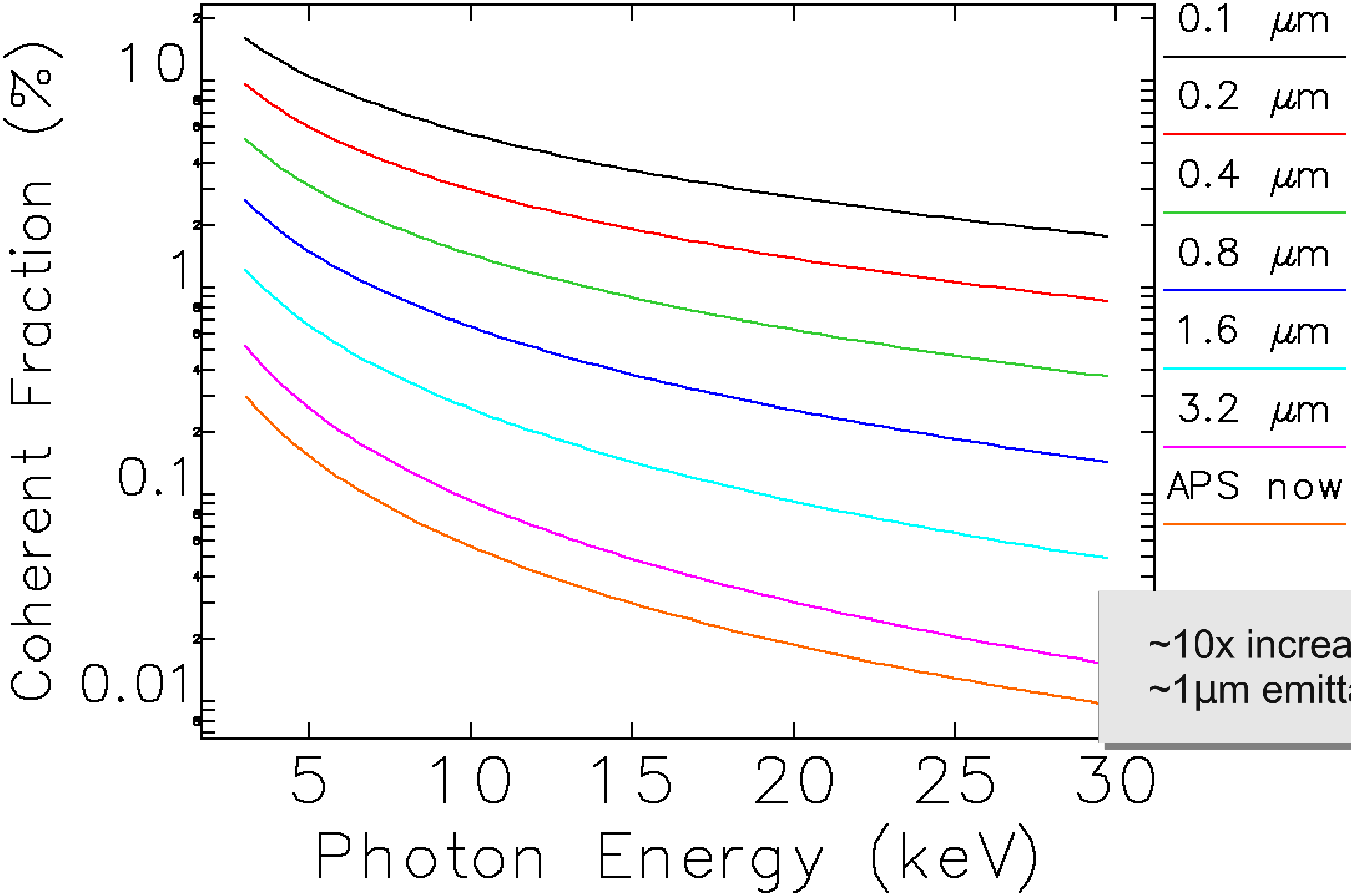
[1] M. Borland *et al.*, AccApp07, 196-203 (2008).

Consequences of “Poor” Injector Emittance[1]



~10x increase for
~1µm emittance

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[1] M. Borland *et al.*, AccApp07, 196-203 (2008).

Cryogenic Power a Concern

- Linac is large and complex[1,2]
  - ~350 linac cavities
  - At 20 MV/m with $Q=10^{10}$, wall losses are ~16 kW total at 2K
  - Experience (e.g., SNS) suggests
    - *Add 50% for static load*
    - *Add 50% for other losses and overhead*
  - This means we'll need ~32 kW cooling power at 2K
  - Cryoplant would require 40~45 MW wall plug power
- Solutions
  - Build a longer linac, since P_{wall}~1/L for fixed total energy
  - Optimize cavities for higher Q, unlike present push for high field
  - Build a multipass linac[3]
    - *Gives up the 7 GeV short-pulse expansion option*
    - *Recent evidence that BBU would be easily manageable[4].*

[1] A. Nassiri, private communication.

[2] M. White, private communication.

[3] M. White and Y. Cho, http://srf2003.desy.de/fap/paper/MoP42.pdf

[4] R. Hajima *et al.*, Proc. 2007 ERL Workshop, to be published.

Other Concerns

- Beam losses must be at 10^{-9} per pass level in APS ring
  - Halo production and loss
  - Touschek scattering[1]
  - Collimation and beam abort system[2]
- Controlling effects of independent undulator gap motion on emittance, energy recovery
- Need for precision lattice correction in single-pass system
- Controlling ion trapping for ultra-low emittance beam
- Need to simplify the optics of the turn-around system
  - May be possible since charge is so low (CSR negligible)
- Need to move rf cavities from four to three straight sections in APS[3]

[1] A. Xiao and M. Borland, PAC07, 3453-3455.

[2] C.Y. Yao *et al.*, "Beam Loss Issues for an ERL Upgrade to the APS," ERL07, WG2.

[3] G. Decker, OAG-TN-2006-058, 9/30/2006.

Can Rings Compete with ERLs?

- ERLs promise spectacular x-ray properties in a true multi-user facility
- What about "Ultimate Storage Rings"[1,2,3] ?
- Three-pronged approach
  - Build a large ring compared to present sources
  - Use multi-bend achromats instead of double-bend[4]
  - Use damping wigglers
- Naively, a multi-kilometer ring could be several orders of magnitude brighter than APS.

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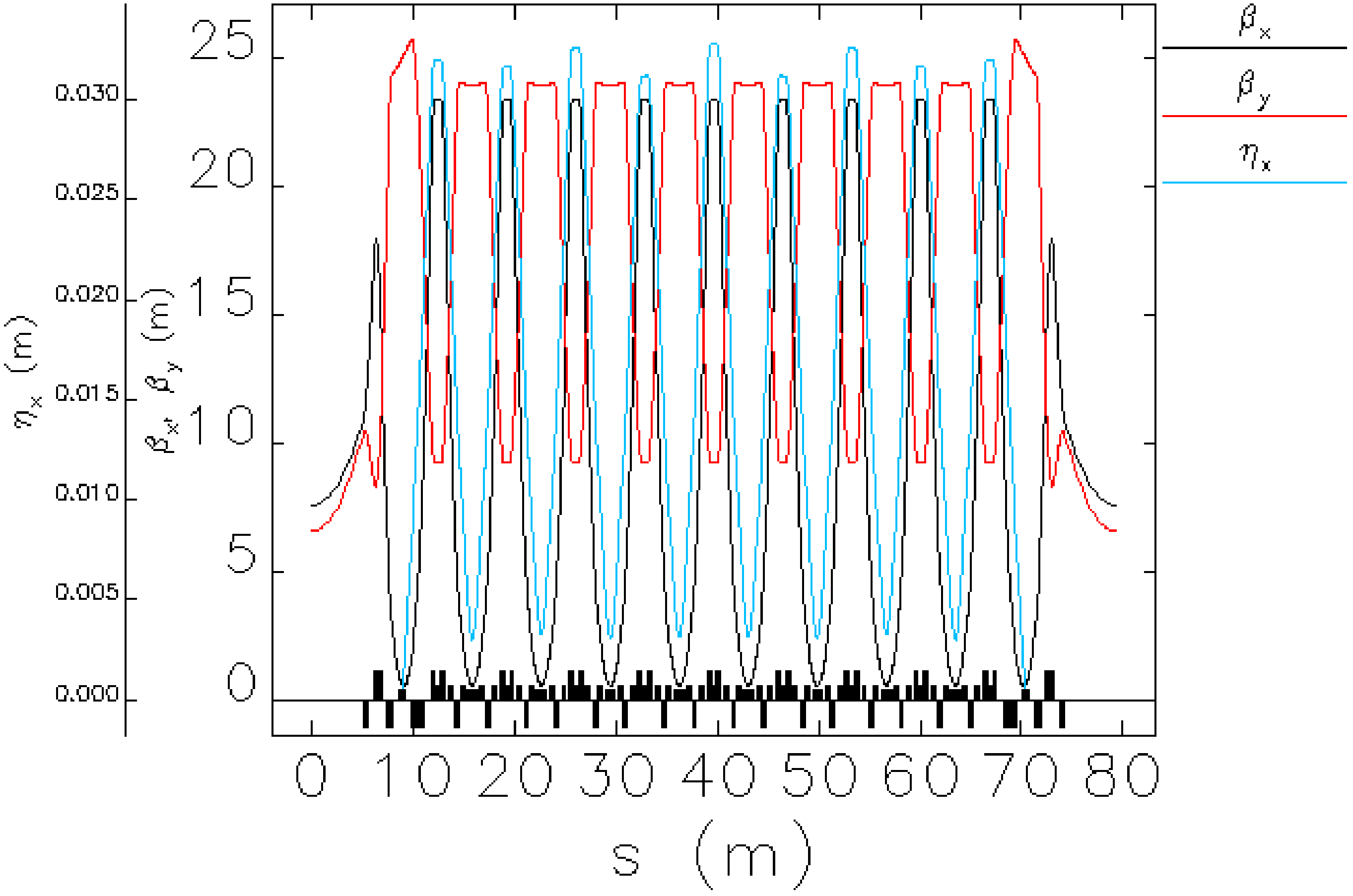
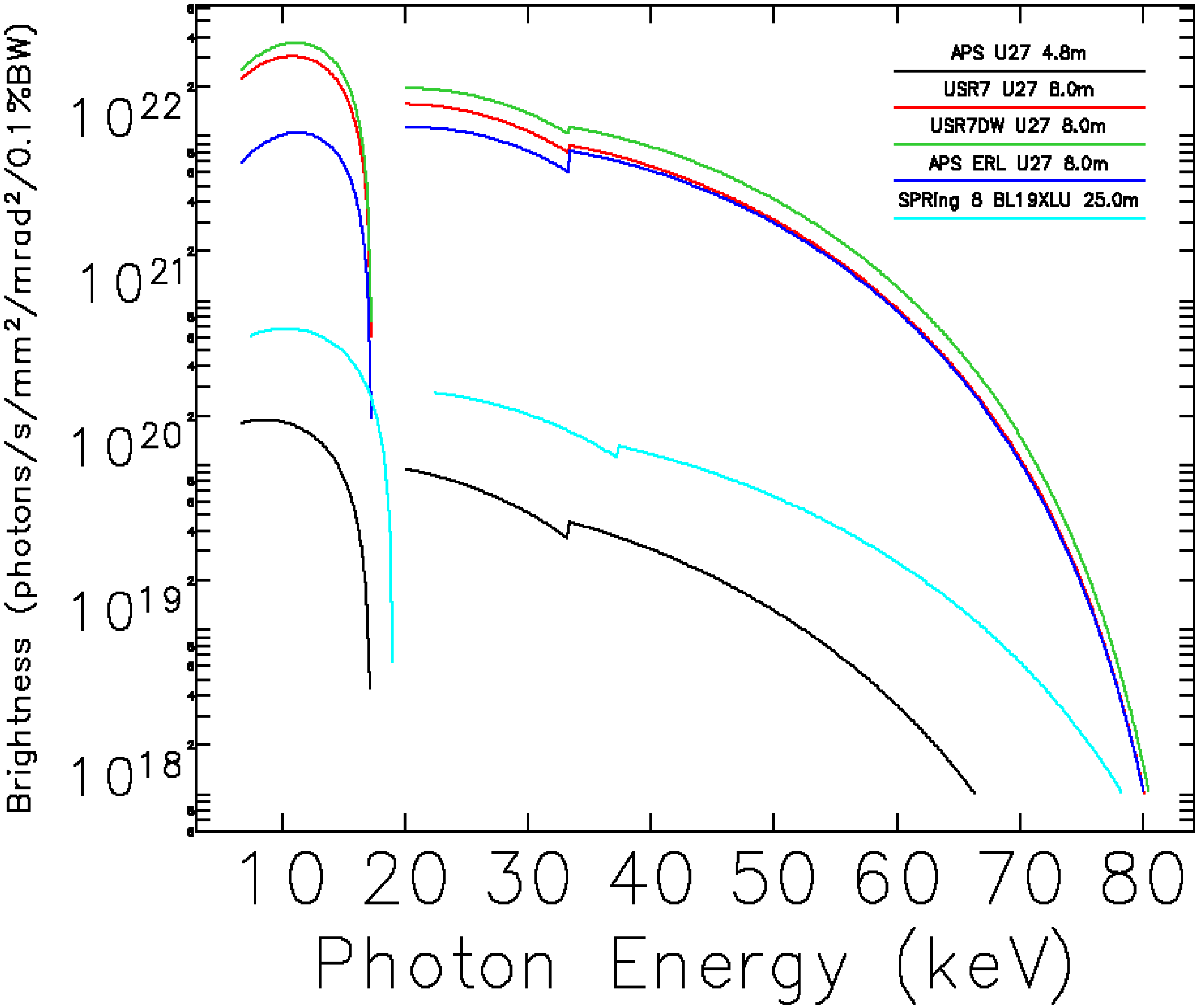
[1] A. Ropert *et al.*, EPAC 2000, 83-87.
[2] M. Borland, NIM A 557 (2006) 230-235.
[3] K. Tsumaki and N. Kumagai, NIM A 565 (2006), 394-405.
[4] D. Einfeld *et al.*, "A Lattice Design to Reach the Theoretical Minimum Emittance for a Storage Ring," EPAC 96, www.jacow.org.

Preliminary Results for a 7 GeV, 3.2-km Ring: USR7



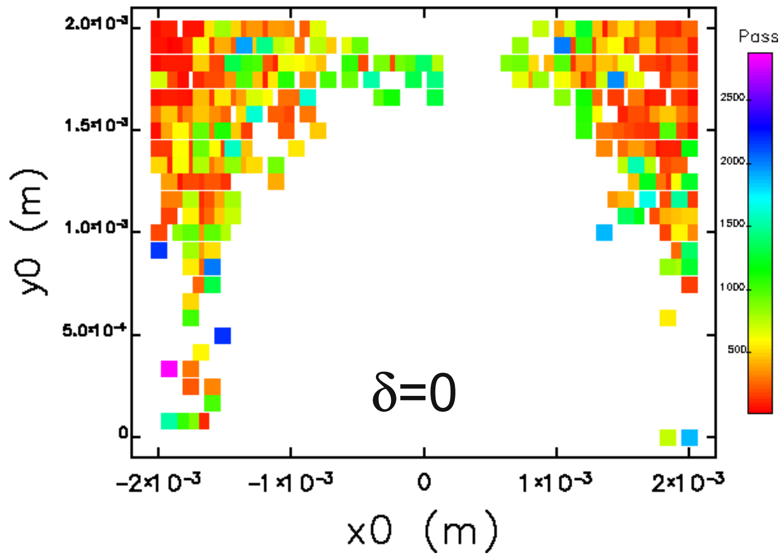
- Uses conventional magnets with workable strengths
- For 200 mA in 4000 bunches, emittance is 16 pm in both planes with full coupling including IBS
- With ten 4-m-long PETRA III damping wigglers, drops to 11 pm

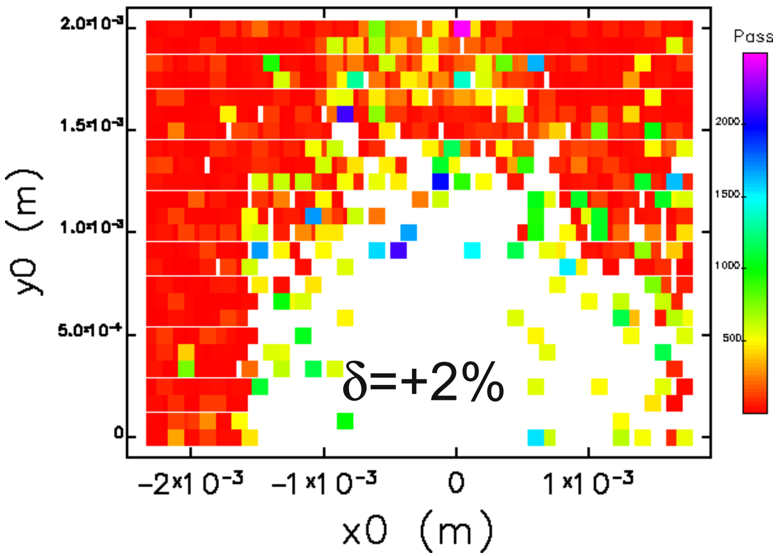
Brightness Predictions

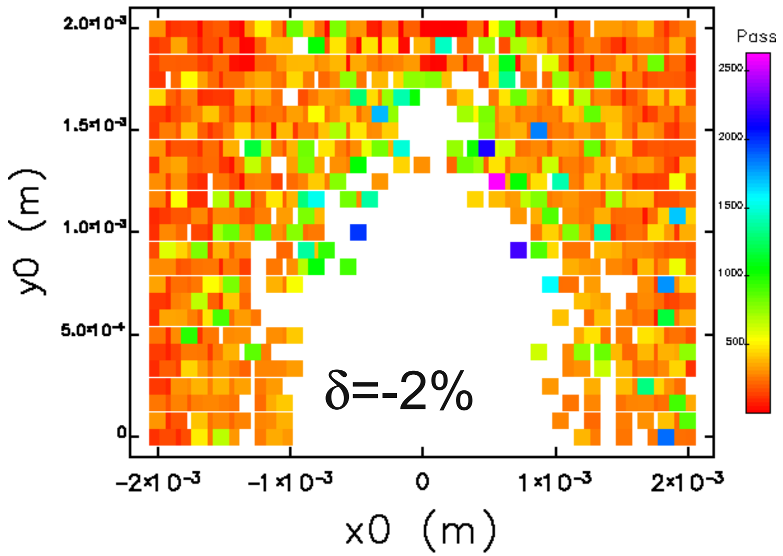


- Better than ERL due to higher current (200 mA vs 25 mA)
- Might improve both with better beta matching, longer IDs

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

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 same-tunnel booster
  - Full-energy linac

[1] M. Borland, “Can APS Compete with the Next Generation?”, APS Strategic Retreat, May 2002.
[2] M. Borland and L. Emery, PAC 2003, 256-258 (2003).

Ultimate Ring Looks Promising

- Two examples of comparable, workable ring designs
  - Tsumaki and Kumagai[1]: 2-km, 32-sector ring
    - *21 pm x 21 pm at 6 GeV*
  - Borland: 3.2-km, 40-sector ring
    - *11 pm x 11 pm at 7 GeV*
- USR7 can perhaps be optimized further, e.g.,
  - More effective damping wigglers
  - Several long straight sections
- Injector requirements not dramatically different from APS today: For 200 mA, 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).

[1] K. Tsumaki and N. Kumagai, NIM A 565 (2006), 394-405.

Conclusion

- APS upgrade options are being investigated in earnest
- Replacement ring designs developed
  - These don't offer enough to justify the expense and disruption
- An ERL upgrade would revolutionize x-ray science at APS
  - Disruption to APS operations greatly reduced
  - Our basic designs that appear to deliver on ERL promise, with some assumptions (e.g., injector performance)
  - We are carefully considering the challenges of an ERL upgrade
    - *A few were noted above*
    - *Much R&D on-going around the world to address these*
- Ultimate Storage Ring designs challenge ERLs
  - Use conventional technology
  - Large and costly
  - Higher brightness, but lower coherent fraction
  - Unconventional operation.

Acknowledgments

- APS participants in upgrade discussions and computations:

  M. Borland, J. Carwardine, Y. Chae, G. Decker, R. Dejus, L. Emery, R. Flood, R. Gerig, E. Gluskin, K. Harkay, M. Jaski, Y. Li, E. Moog, A. Nassiri, V. Sajaev, N. Sereno, H. Shang, R. Soliday, Y. Sun, N. Vinokurov, Y. Wang, M. White, A. Xiao, C. Yao

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