Accelerator Options for the APS Renewal and Beyond

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Outline

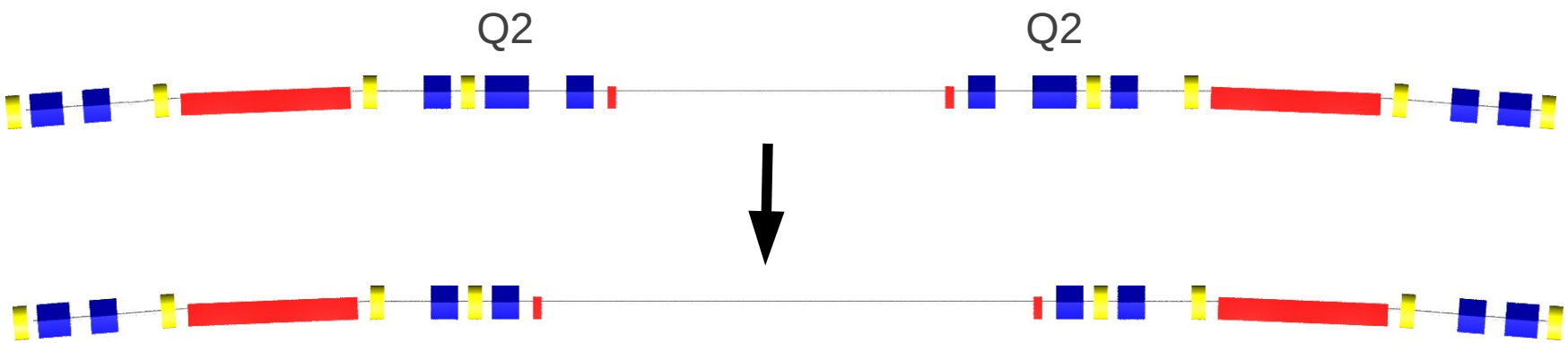
- Components of the APS renewal
  - Long straight sections
  - Short-pulse x-rays
  - Insertion devices
- Not covered today
  - Other lattice options
  - Higher current
  - Beam stability
- Beyond the renewal
  - Options for next-generation spontaneous hard x-ray sources

Lattice changes

- Primary lattice change will be long straights
- Other options
  - Stronger dipole magnets
  - Split dipole magnets for additional IDs
  - Alternating high/low beta functions
- Concerns with any lattice change
  - Loss of flexibility
    - E.g., ability to provide RHB
  - Increased emittance
    - Lattice is optimized for low emittance so this is almost inevitable
  - Decreased injection efficiency and lifetime
  - Decreased single bunch current limit
    - Can result from, e.g., increased beta functions at ID transitions
  - Ability to accurately predict the above

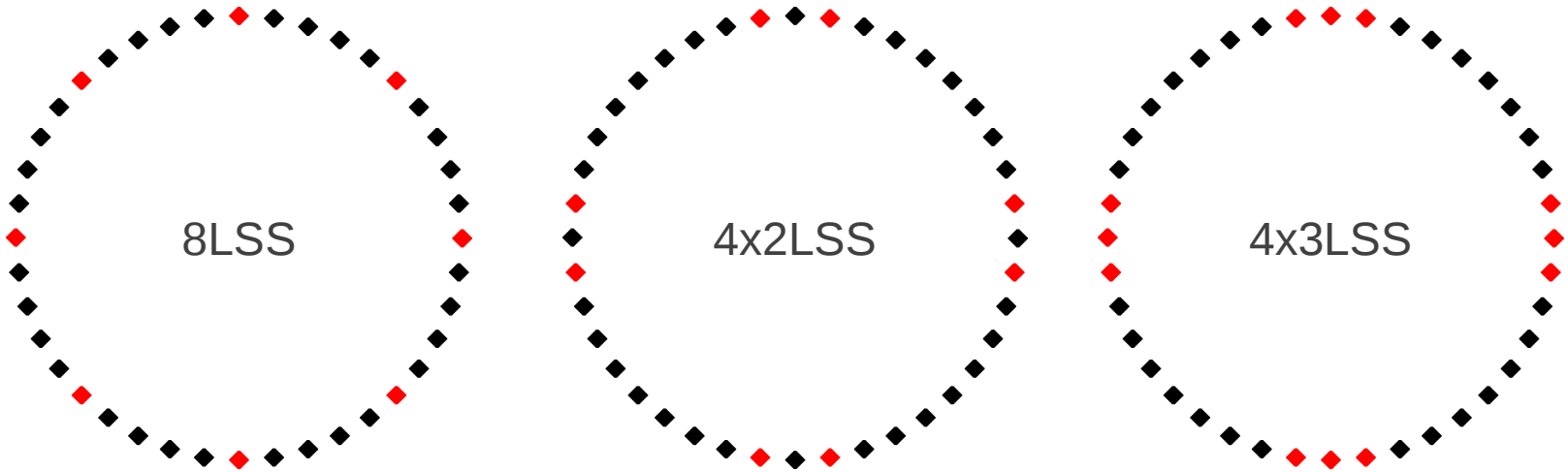
LSS scheme

- LSS can be implemented at APS with a simple scheme
  - Remove the Q2 magnets on either side of SS
  - Remove the adjacent correctors
  - Remove the adjacent BPMs
  - Slide other components away from the ID



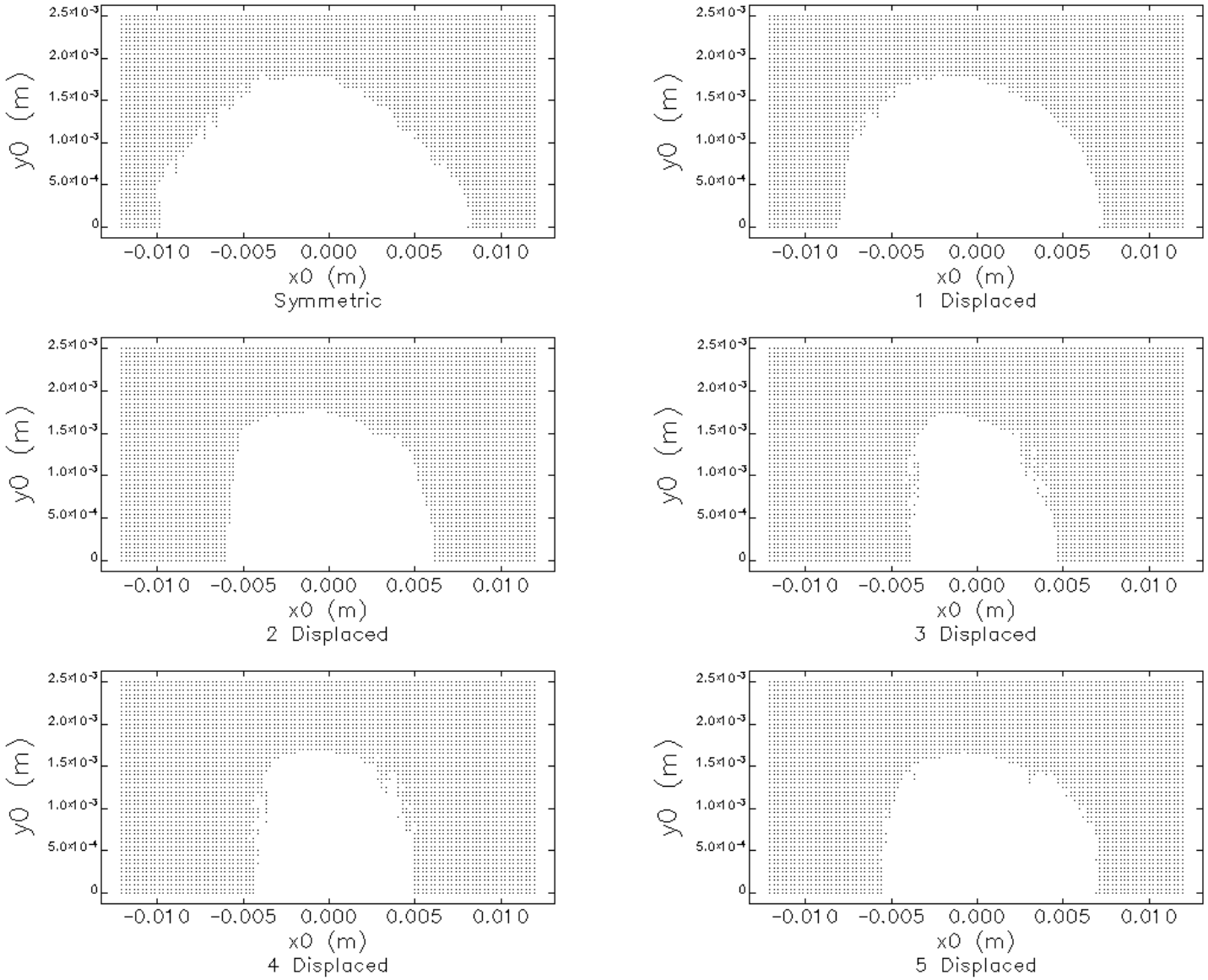
- Increases space available for ID from 4.8 to 7.7m
- Most cost-effective option for LSS

Options for symmetric LSS placement



- Symmetry is important for lifetime and injection efficiency
- Can implement gradually by making use of independent power supplies
- E.g., if we want to modify Sector 10, we can turn off Q1 magnets in Sector 30 to make it look quasi-symmetric

Importance of symmetry: dynamic apeture



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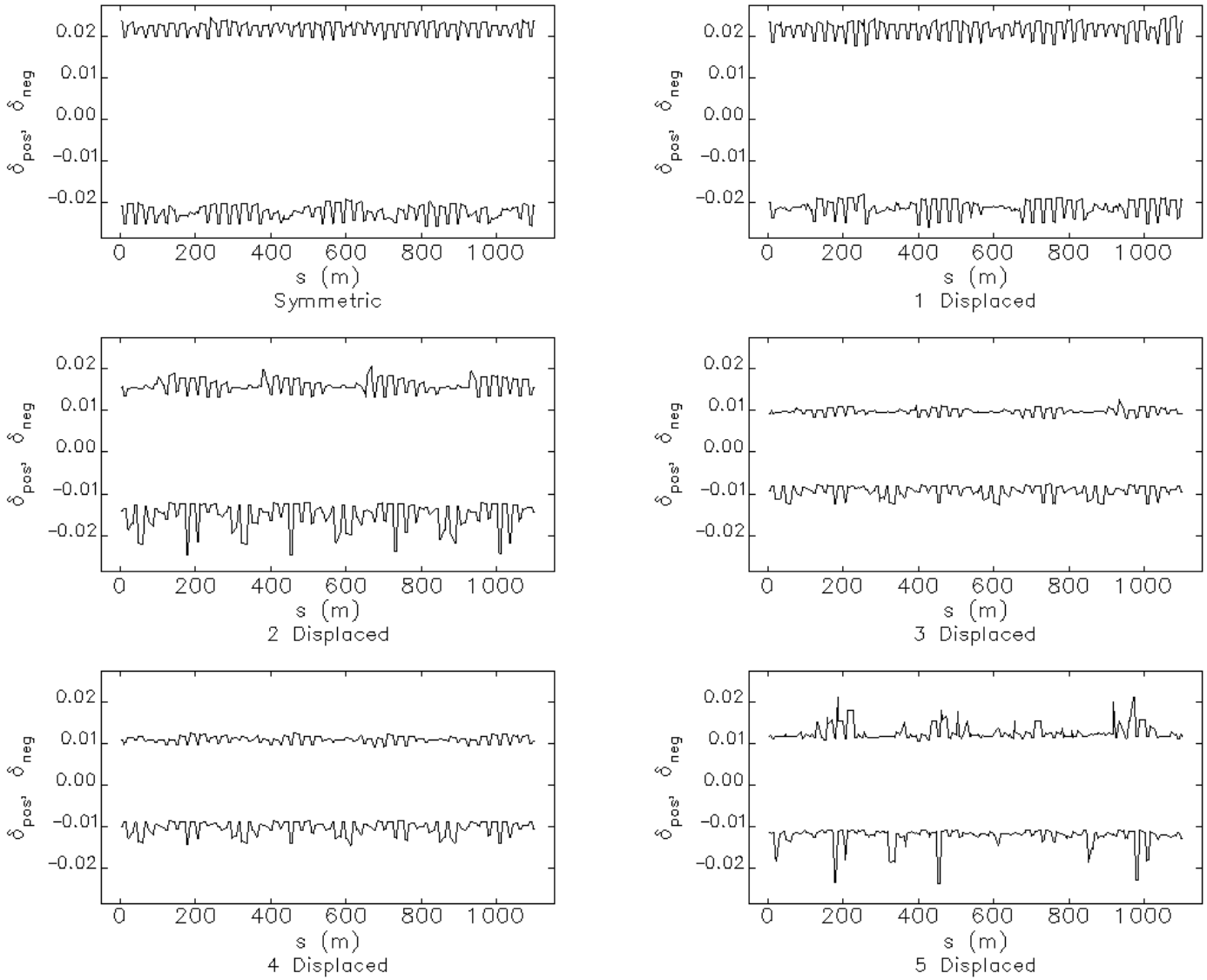
Importance of symmetry: momentum aperture



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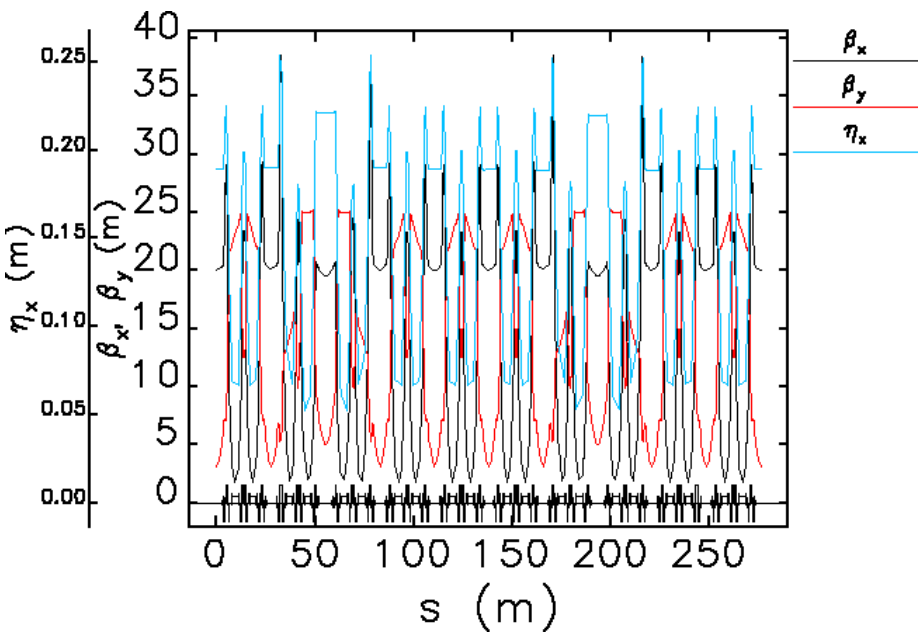
Status of lattice development

- Have developed numerous configurations
  - Fully tested in simulation: 2xLSS, 4xLSS, 8xLSS
  - Test pending, but should work: 10xLSS, 4x2LSS, 4x3LSS
  - Not workable so far: 20xLSS
- An 8xLSS mock-up was tested[1]
  - Same injection efficiency as regular lattice
  - 30% better lifetime
  - Breaking reflection symmetry of sextupole strengths was key
- 40xLSS is attractive since no beamlines have to move
  - Would be too costly if implemented literally
  - Another option[2]
    - Can mock up all non-LSS sectors (turn off Q1s)
    - Might allow arbitrary placement of real LSS sectors
  - Work on this idea is on-going
  - May have issues with single-bunch limit
    - Can be mocked up in machine studies

[1]M. Borland *et al*., PAC09, TH6PFP062
[2]R. Gerig, private communication.

Parameters of NxLSS lattices

Quantity	Now	2xLSS	4xLSS	8xLSS
Short straights:				
Effective emittance (nm)	3.14	3.23	3.20	3.36
ID betax (m)	19.49	19.90	20.10	20.20
ID betay (m)	2.90	3.05	3.10	3.06
Long straights:				
Effective emittance (nm)	3.14	3.48	3.45	3.60
ID betax (m)	19.49	19.20	20.00	19.60
ID betay (m)	2.90	5.08	5.00	5.03
Max. betax (m)	28.85	37.00	37.00	37.30
Max. betay (m)	27.80	25.90	25.60	25.70



Lattice functions for a portion of the 8xLSS lattice

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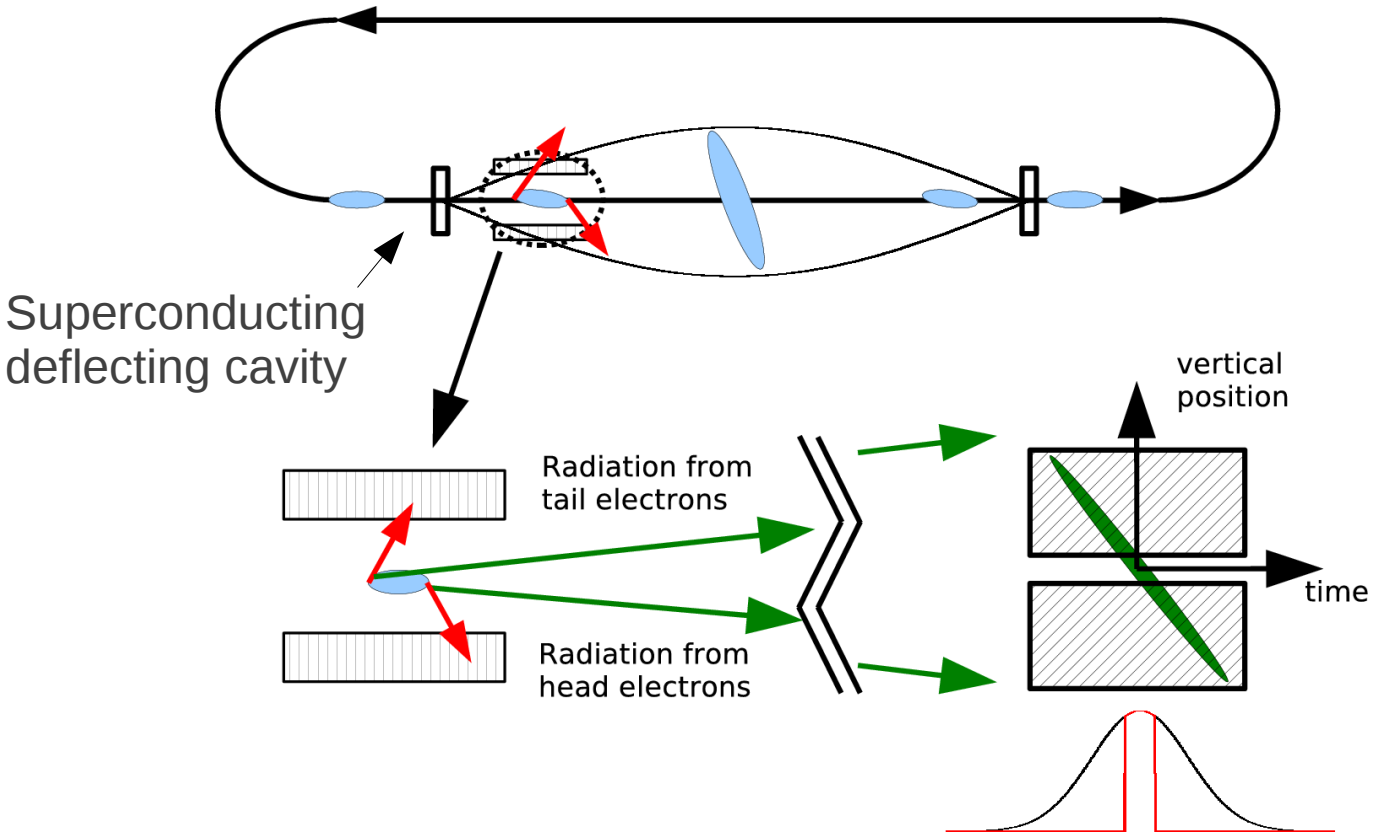
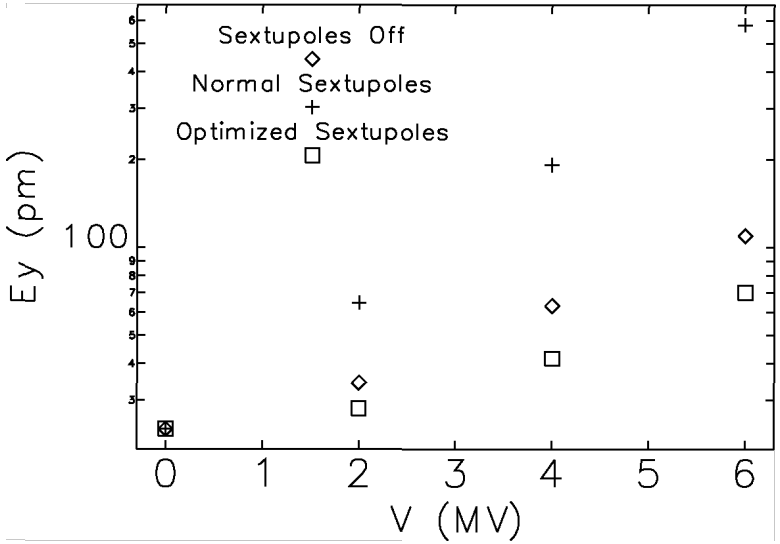
Short-pulse x-rays using Zholents' scheme[1,2]

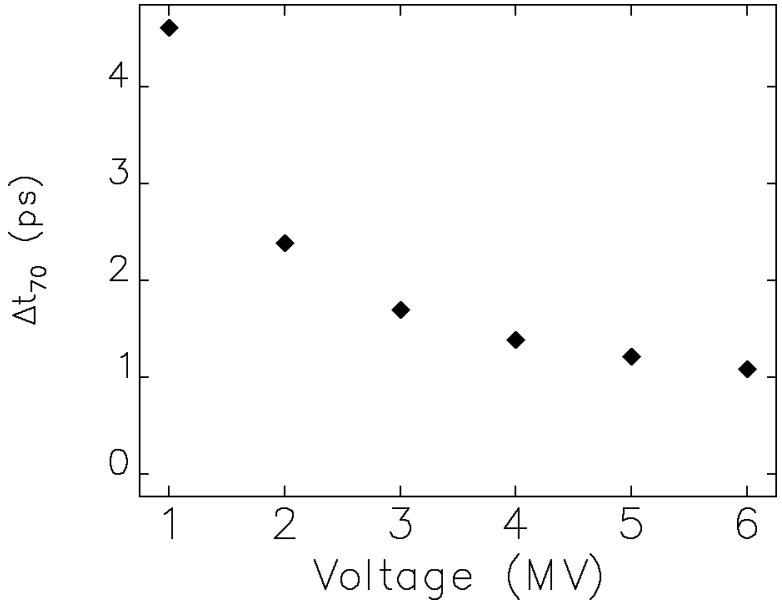


$$\sigma_t \approx \frac{E}{h\omega_a V}\sqrt{\frac{\epsilon_y}{\beta_y} + \frac{\lambda}{2L}}$$

[1]A. Zholents *et al.*NIM A 425, 385 (1999).
[2]M. Borland, Phys. Rev. ST Accel Beams 8, 074001 (2006).

Effects of crab cavities





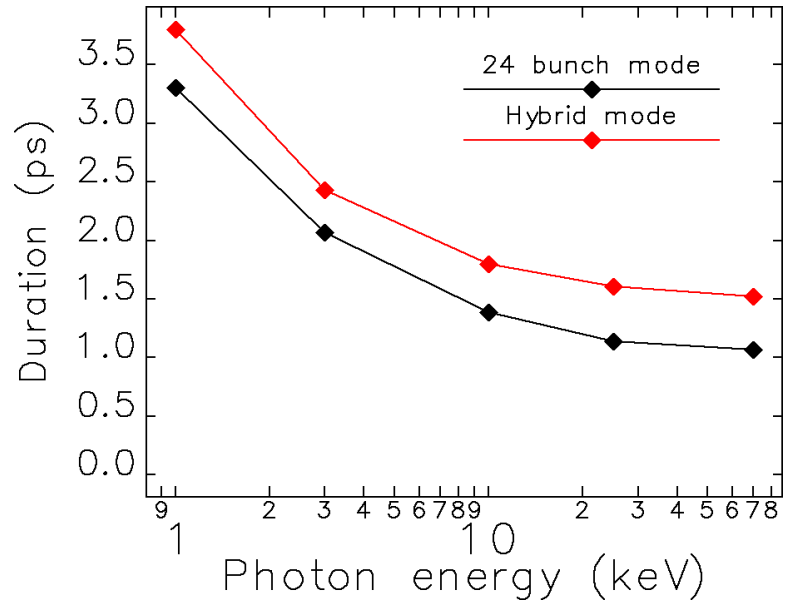
- Existence of sextupoles between crab cavities results in significant vertical emittance growth[1]
- Optimization of these sextupoles can control the growth[2]
- Has implications for dynamic and momentum aperture

- Achievable pulse duration shows diminishing returns vs voltage due to emittance increase

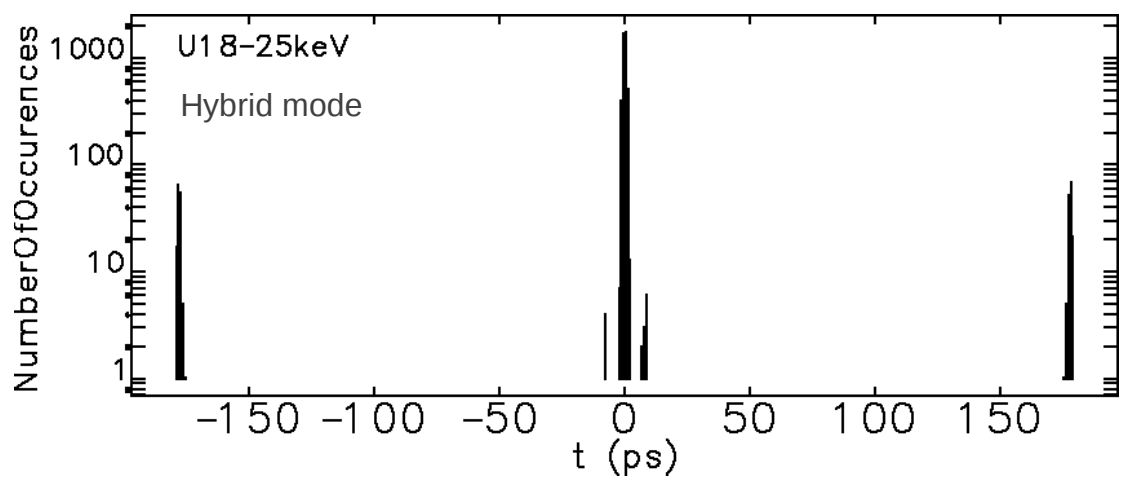
[1]M. Borland, Phys. Rev. ST Accel Beams 8, 074001 (2006).
[2]M. Borland and V. Sajaev, PAC05, RPAE072.

Predicted performance (4MV)

- Curves show duration for 1% transmission through slits
- Pulse duration worse for low photon energies due to large opening angle
- Hybrid mode worse because of increased emittance degradation due to longer bunch



- Time structure is complicated by two effects
  - Off-axis 2nd harmonic radiation
  - Reversal of rf voltage



[1]M.Borland *et al.*, OAG-TN-2008-026.

SPX status and R&D

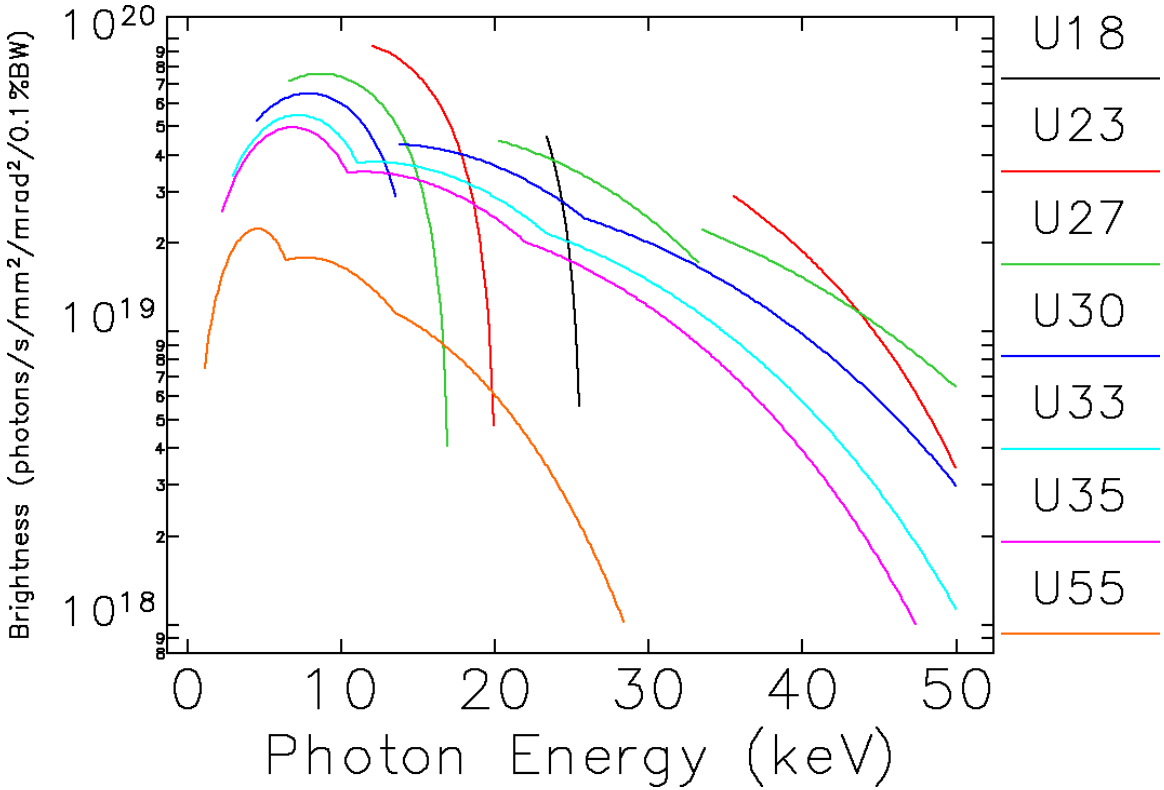
- Cavity prototyping effort
  - Exploring single- and multi-cell cavity concepts
  - Several prototypes built in collaboration with JLab
- HOM/LOM management
  - Must extract unwanted cavity modes to ensure beam stability
  - Lower-order modes are particularly difficult to extract
  - One approach is on-cell dampers which are very compact

Courtesy P. Kneisel, JLab

- Cryomodule
  - Cryomodule design is challenging due to large number of waveguide penetrations (perhaps 10 cells/cryostat)
  - Must also carefully shield cavity from stray magnetic fields
- Rf control
  - Tolerances on rf fields are tight: ~0.1% amplitude and ~0.05° phase
  - R&D is needed to develop a suitable low-level rf system

Insertion devices

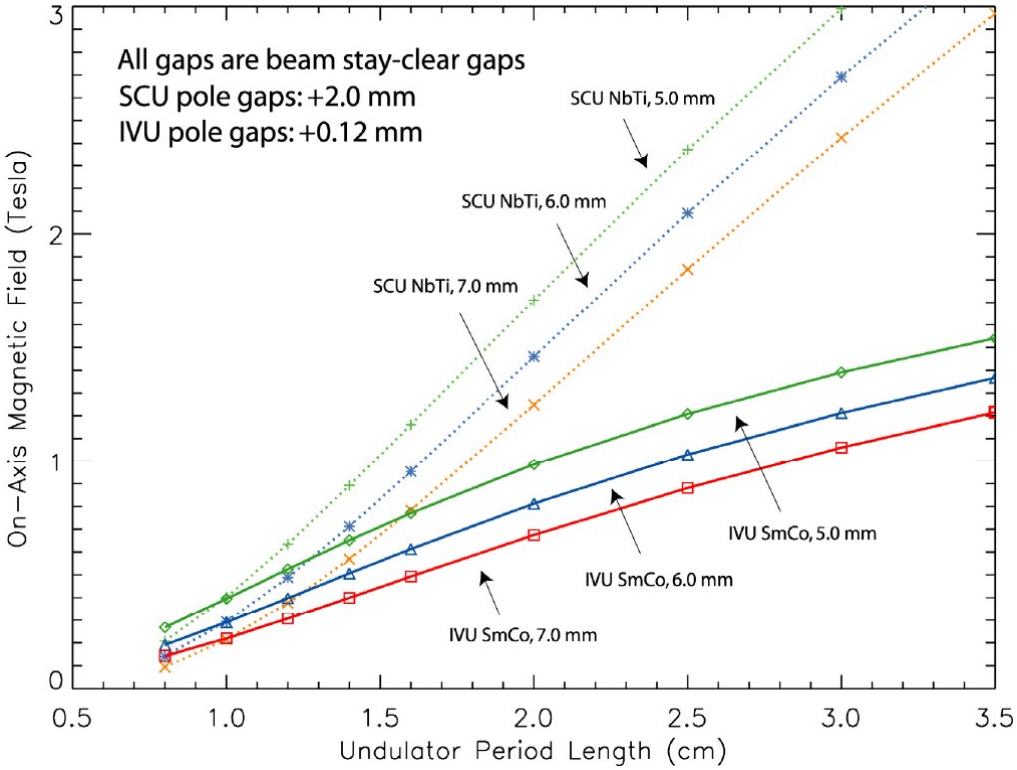
- Presently 45 IDs installed, mostly planar



- Using short-period devices gives higher brightness for shorter wavelengths
  - Tuning range is reduced
  - Anticipate that most general-purpose U33 devices will be replaced

In-vacuum devices for APS?

- Beam impedance of IVUs is large[1]
  - For fixed impedance, IVU gives no improvement
  - We could benefit from IVUs *if* we restricted gaps during hybrid mode
- Superconducting undulator seems a better approach



For the same beam stay clear and period > 10mm, SCU is superior[2].

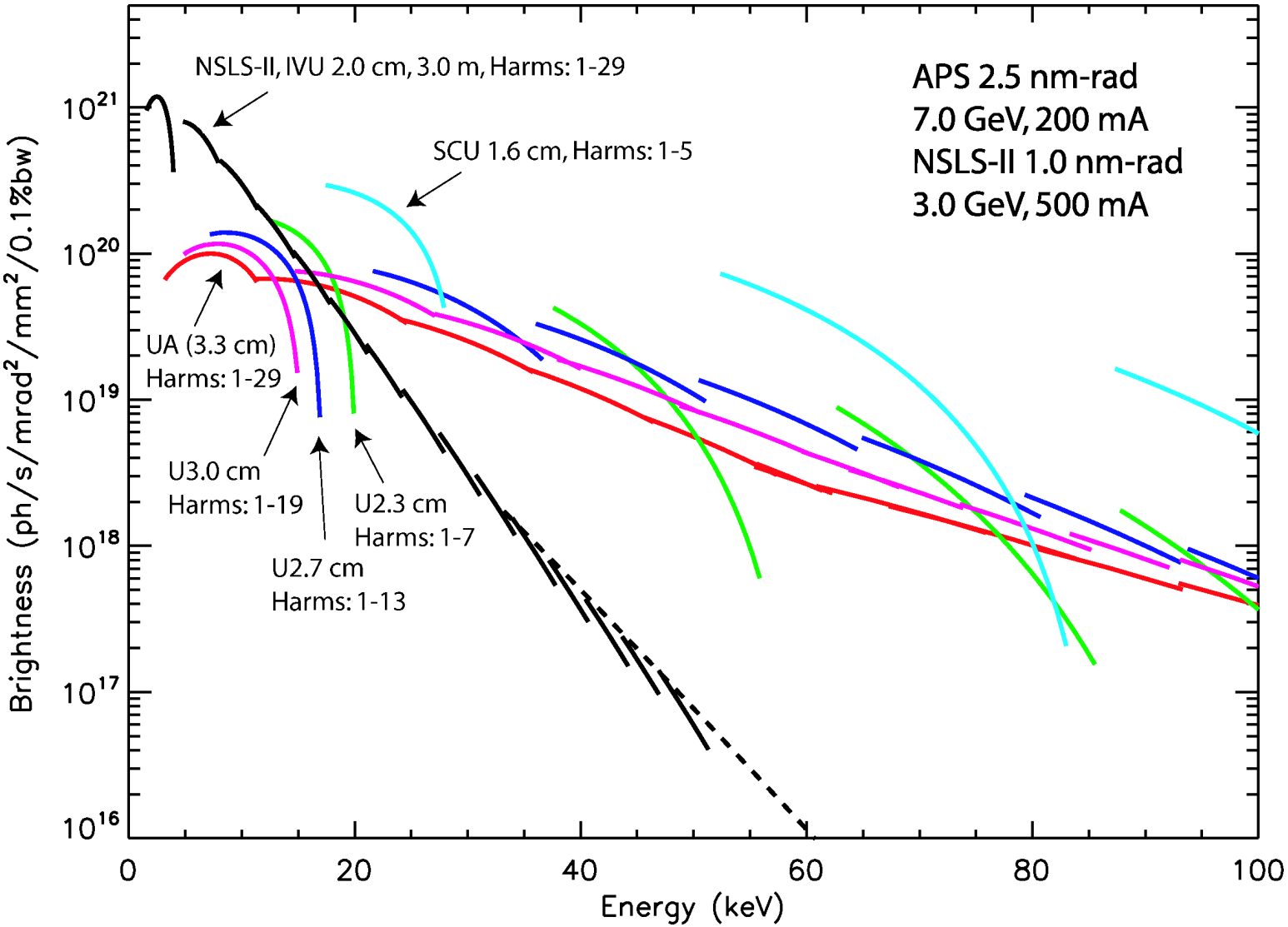
For fixed performance, SCU has 2mm aperture advantage.

N.B.[1]: Impedance ~ $1/g^{2.5}$

[1]Y. Chae, AOP-TN-2009-011.
[2]R. Dejus et al., MD-TN-2009-004.
[3]A. Bernhard *et al.*, EPAC08, WEPC100.

- Intriguing options
  - Variable quasi-periodicity
  - Switchable period length[3], e.g., 15mm and 30mm

SCU keeps APS at the brightness frontier



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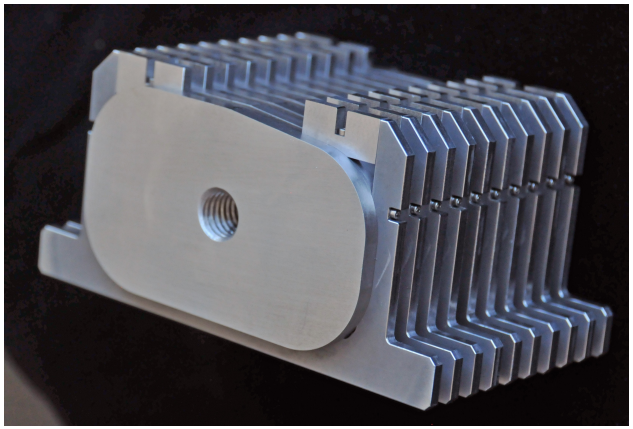
ASD-MD Group SCU R&D program

- APS has an on-going program to develop a SCU
  - Targeting 20~25 keV first harmonic
  - Using 16mm period with NbTi wire
- Several 10- and 42-pole prototype cores created and tested
  - 25 keV level (200 A) easily achieved, ~3 deg rms phase error
  - Need 500A for 20 keV operation, achieved 720 A after training
    - ~7 degree rms phase error
    - Original spec for APS U33 is 8 deg rms error
  - Inadvertent taper partly responsible for phase errors
- Proceeding with plans to install a 42-pole prototype in 2011
  - Test critical issues such as heat load from beam



Ensuring that we "do no harm"

- To make extensive changes, we must have trusted modeling of
  - Single-particle beam dynamics
  - Collective beam dynamics
  - Rf cavities, including beam dynamics effects
  - Insertion devices, including their effect on the beam
- High level of confidence in single-particle dynamics
  - E.g., 8LSS mock-up showed expected behavior
  - Planning further quantitative benchmarking
  - Code testing collaboration with other light sources
    - Preliminary tests show ~25% lifetime improvement for DLS[1]
    - Particularly interested in modeling effects of unusual IDs
- High level of confidence in collective beam dynamics
  - Quantitative predictions of thresholds, bunch lengthening based on calculated impedances[2]
- Prototyping of hardware (e.g., rf cavities, IDs)

[1]R. Bartolini, private communication.
[2]Y. Chae, PAC07, FRPMN104; Y. Chae, ASD/APG/2008-5.

Beyond the Renewal

- The renewal keeps APS up-to-date for the near term
- Spontaneous x-ray sources (SXS) have a future beyond this
  - High repetition rate
  - High average flux and brightness
  - Relatively low peak flux and brightness
  - Excellent reliability and stability
  - Complementary to FELs[1]
- Several options for a next generation SXS at ANL
  - Energy recovery linac
    - Upgrade of the APS ring
    - Stand-alone ERL
  - Storage ring
    - In-tunnel replacement of the APS ring
    - New, “ultimate” storage ring

[1]See, e.g., Next-Generation Photon Sources for Grand Challenges in Science and Energy, www.sc.doe.gov/BES/reports/list.html

Importance of Emittance and Energy Spread

- Average spectral brightness is a primary measure of performance
  - Brightness benefits from high current, high energy, small emittance, and narrow energy spread

$$B \sim \frac{I_{beam}}{E_x E_y \sqrt{4\sigma_\delta^2 + \left(\frac{0.4}{hN_u}\right)^2}}$$

$$E_x = \sqrt{\left(\epsilon_x \beta_x + \frac{\lambda L}{8\pi^2}\right)\left(\frac{\epsilon_x}{\beta_x} + \frac{\lambda}{2L}\right)} \geq \epsilon_x + \frac{\lambda}{4\pi}$$

(Plus similar for y plane)

- Comparison of multi-GeV rings and linacs
  - Linac: Emittance comparable to 1Å/4π in both planes
  - Linac: Greater freedom in matching to ideal beta functions
  - Linac: Small energy spread allows capitalizing on long undulators
  - Ring: Easy to achieve high average current

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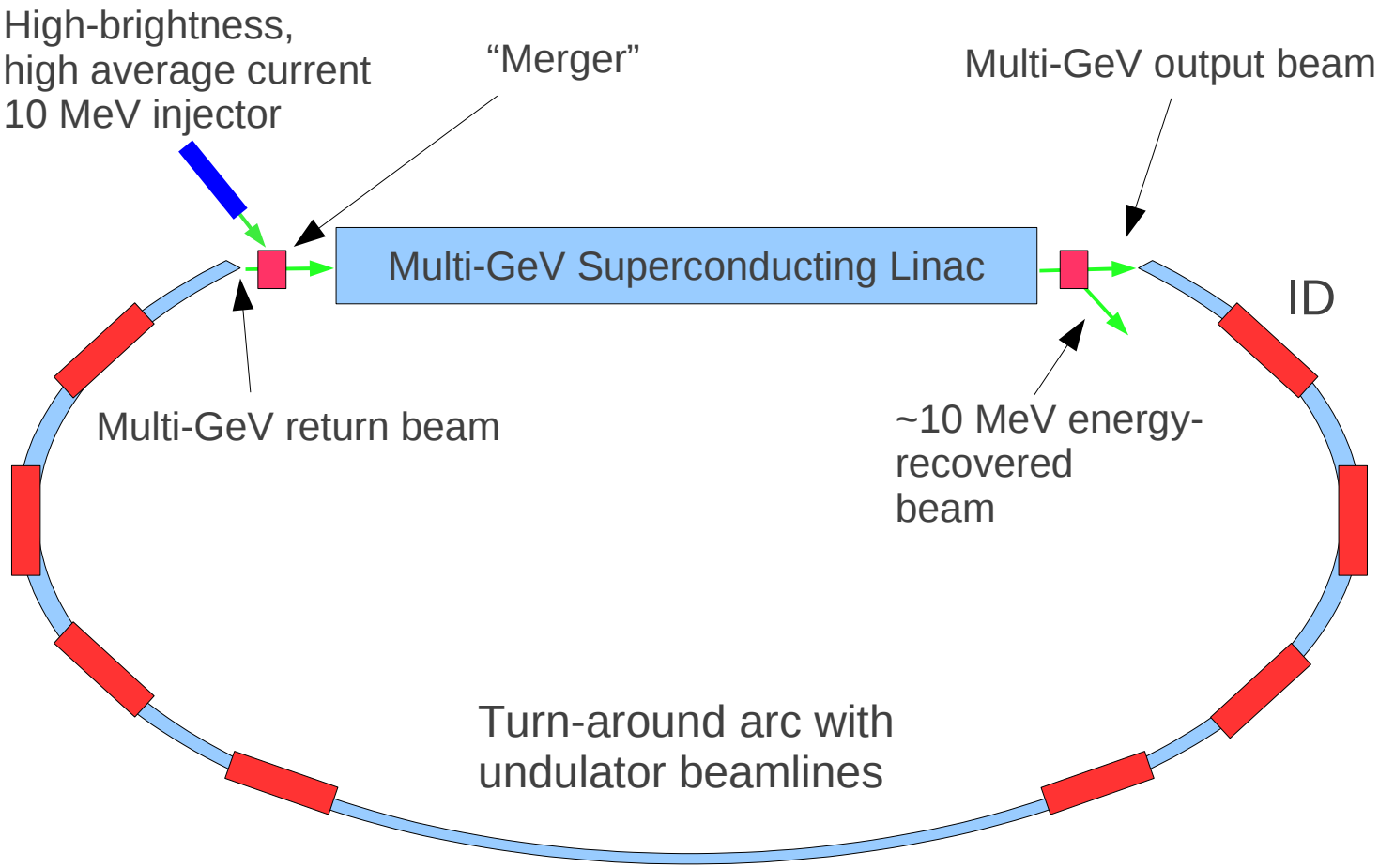
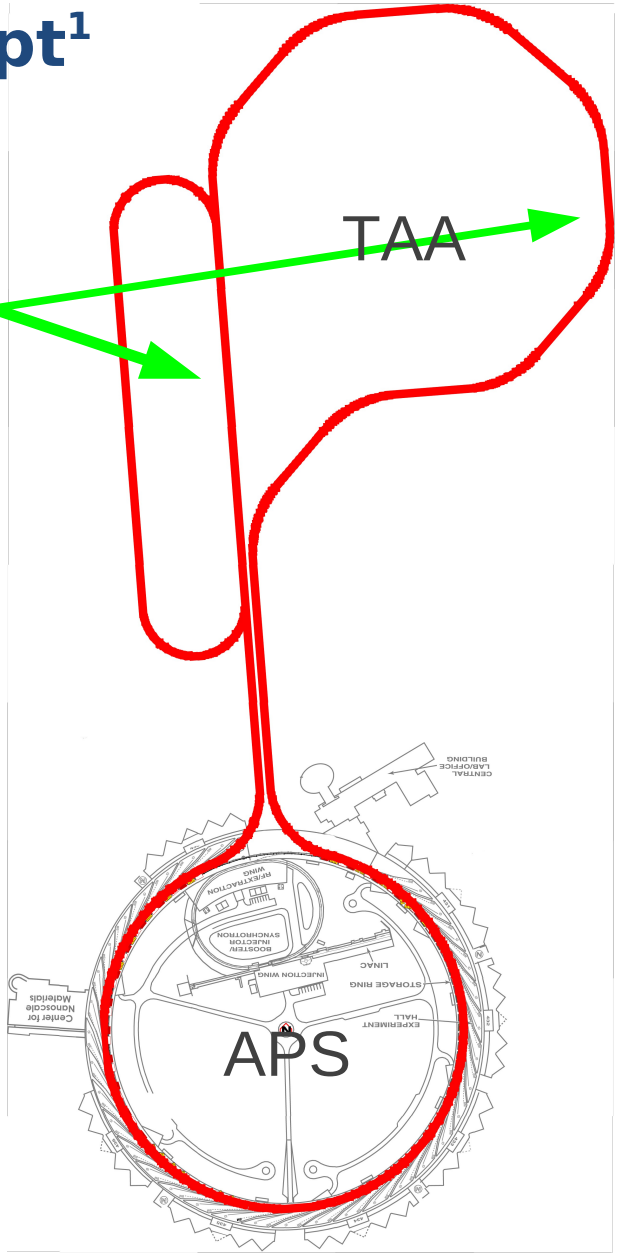
Energy Recovery Linac Concept[1,2,3]



[1]M. Tigner, *Nuovo Cimento* **37**, 1965.
[2]I. Bazarov *et al.*, PAC 2001, 230.
[3]I. Ben-Zvi *et al.*, PAC 2001, 350.

An "Ultimate" ERL@APS Concept[1]

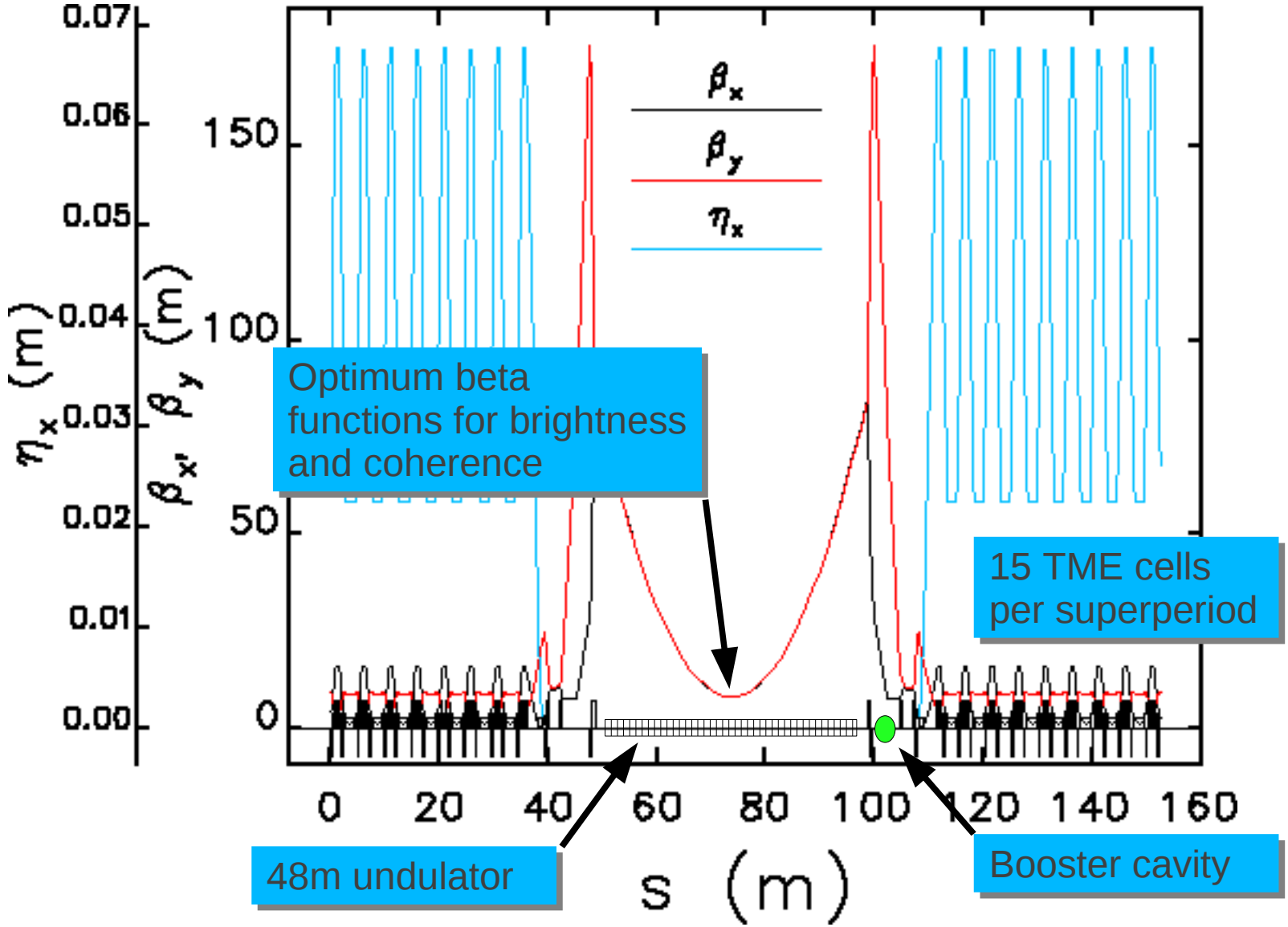
- This design serves to illustrate the promise of an x-ray ERL
- 7 GeV linac
- Large 7 GeV turn-around for new beamlines
  - Accelerate away from APS to put highest-quality beam into TAA
- TAA has nine 50-m straight sections
  - Accommodates 48-m undulators
- Assume "high coherence" beam parameters[2]
  - ~7pm emittance
  - 25 mA
  - 0.02% energy spread
- Performance in TAA identical to green-field ERL



M. Borland *et al.*, Proc. PAC09, MO3PBI01.

[2]G. Hoffstaetter, "Status of the Cornell ERL Project," fls2006.desy.de

TAA Optics



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Challenges for ERL Light Sources

- Beam halo prediction and control
  - Beam halo is a diffuse cloud of particles surrounding the main beam
    - Diagnostics don't see it---until it gets lost somewhere!
    - Major operational issue for JLab ERL[1]
  - Many sources of halo[1,2], but modeling is not where it needs to be
  - Need to understand how to perform effective collimation
    - JLab experience is very negative[1,3]
- Production of ultra-low emittances
  - DC guns give required performance in simulation[4,5]
    - High DC gun voltage still a challenge
    - >700 kV needed, but presently ~400 kV achieved
  - Rf gun might work if there was a suitable cathode material
- Sustaining 25~100 mA for a major user facility
  - Present cathodes in DC guns may only last one shift at 25 mA[3]
  - We need better cathode materials and understanding of limits
  - Can we preserve emittance with a multi-gun injector?

[1]D. Douglas, ERL09, Contribution #72.
[2]C. Yao *et al.*, ERL07, WG2.
[3]G. Neil, private communication.
[4]I. Bazarov et al., Phys. Rev. ST Accel. Beams 8, 034202 (2005).
[5]X. Dong et al., PAC09, MO6RFP044.

Challenges for ERL Light Sources

- Energy spread management
  - Energy spread is added to the high energy beam by many processes
    - Ordinary and coherent synchrotron radiation
    - Wakefields and intrabeam scattering
  - Creates problem near end of deceleration due to ballooning fractional energy spread
  - Short-range wakes are uncomfortably large[1]
    - Possible cures drive up the cost
      - Larger vacuum pipe diameter (larger magnet bores)
      - Don't fully decelerate
- Reducing wall-plug power with advances in RF technology[2]
  - Using present-day technology, need ~28 MW just for linac
  - With several advances, could drop to ~12 MW
- Building 48-m-long variable-gap undulators with required quality to give high brightness

[1]D. M. Billing, ERL09, Contribution #35.
[2]ERL09, WG3 summary talk.

Can Storage Rings Compete with ERLs?

- Major weakness: difficulty of improving emittance

$$\epsilon_o \sim \frac{E^2}{N_d^3}$$

- Possible approach[1,2,3]
  - Build a "large" ring
  - Multi-bend achromats instead of double-bend[4]
  - Use damping wigglers
- A multi-kilometer ring could be several orders of magnitude better than APS
  - Given present constraints, not much can be done in the APS tunnel
- Might compete with an ERL, but should have
  - Much less risk
  - Much less R&D.

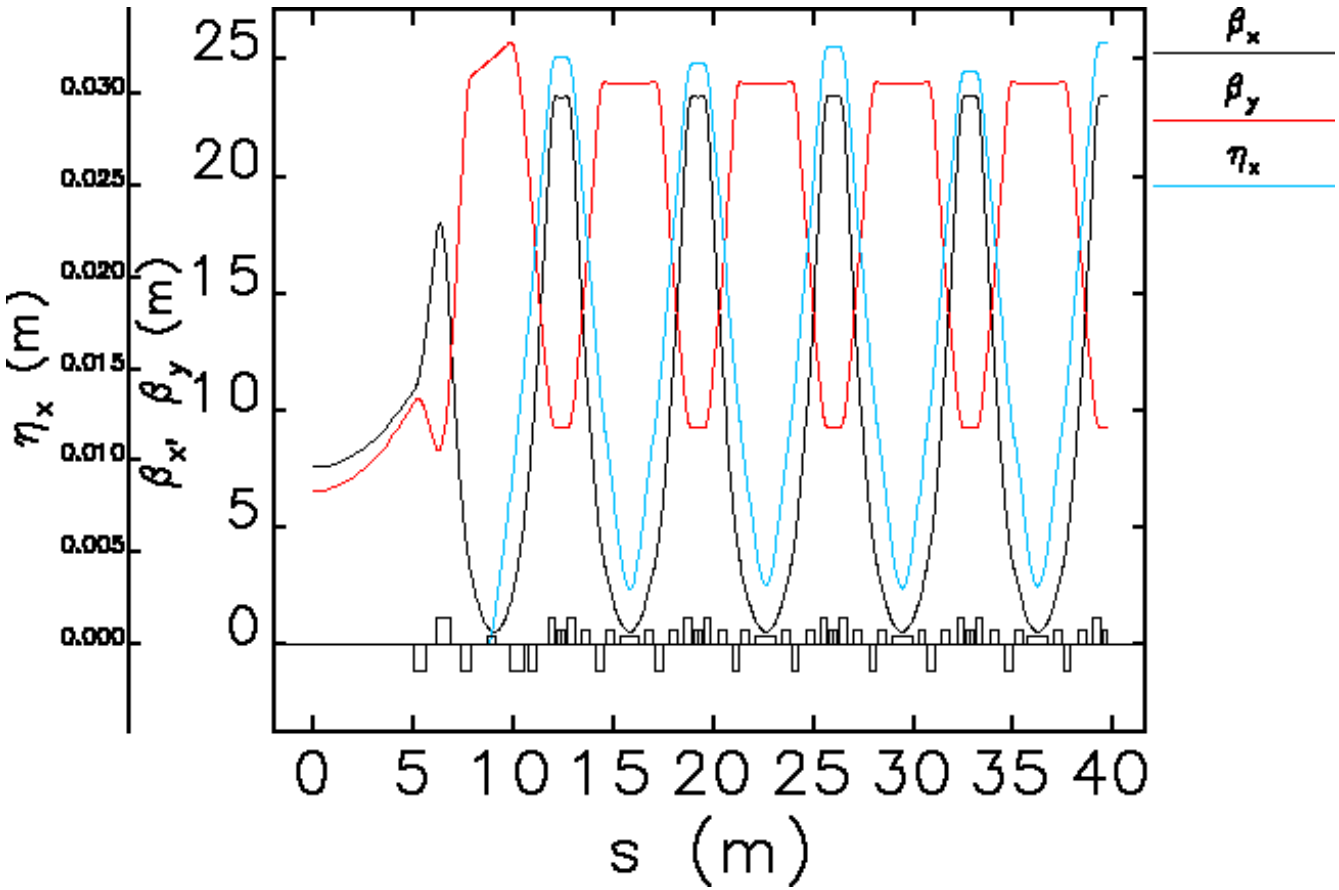
[1]A. Ropert, "Towards the ultimate storage-ring based light source," EPAC 2000, www.jacow.org.
[2]M. Borland, "A super-bright storage ring alternative to an energy recovery linac," NIM A 557 (2006) 230-235.
[3]K. Tsumaki and N. Kumagai, "Very low emittance light source storage ring," NIM A 565 (2006), 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 Ultimate Storage Ring

- MBA-based with 10 dipoles per sector
- 40 sectors
- 8 m insertion devices
- 30 pm natural emittance

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

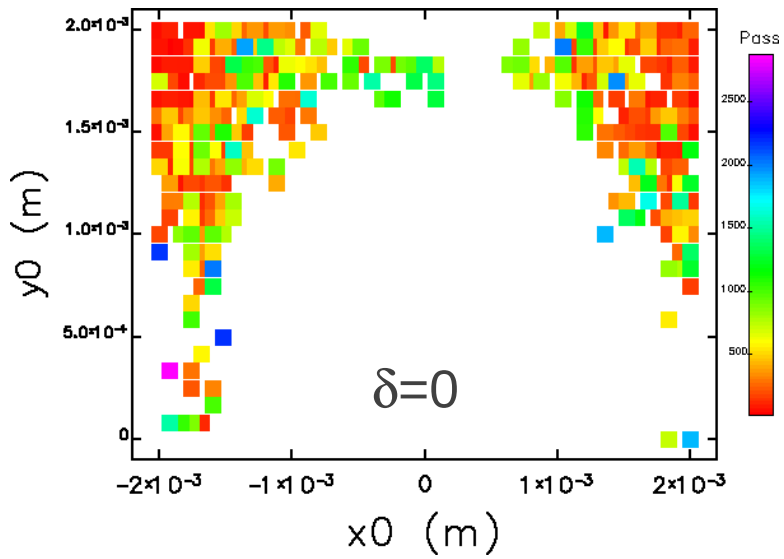
Lattice Functions (half sector)

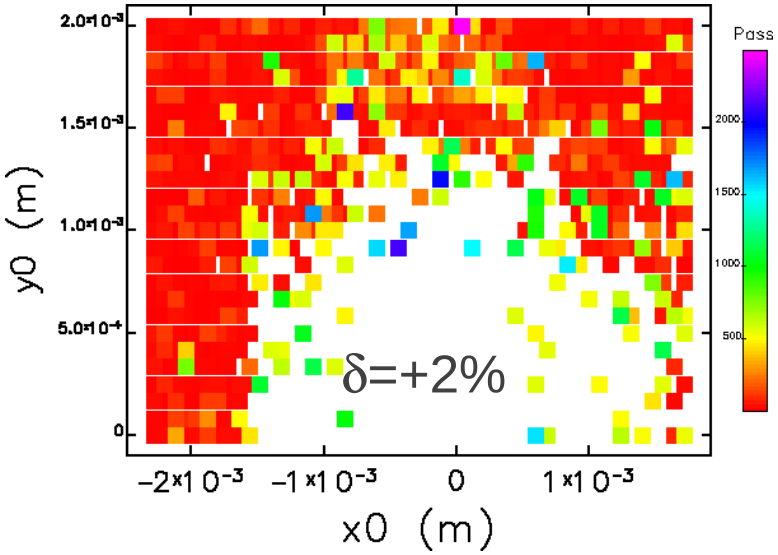


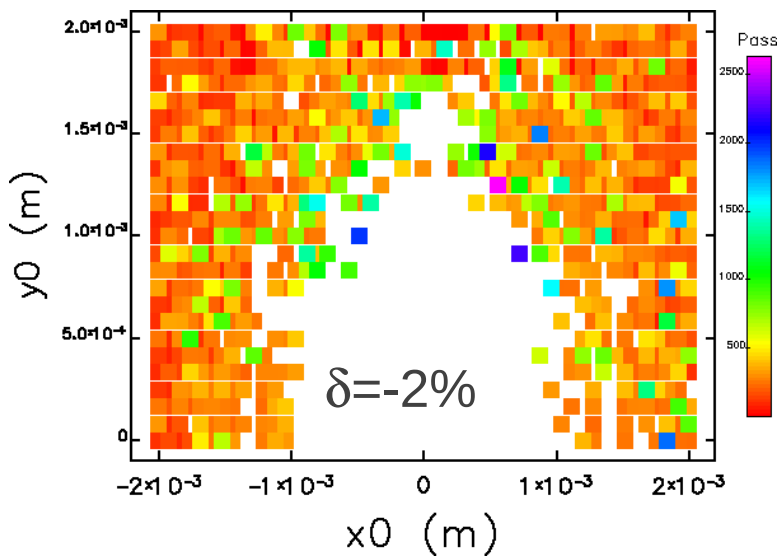
- Uses conventional magnets with workable strengths assuming reasonable 20mm bore radius

Lattice designed with **elegant** (M. Borland, *et al.*)

Dynamic Aperture with Errors



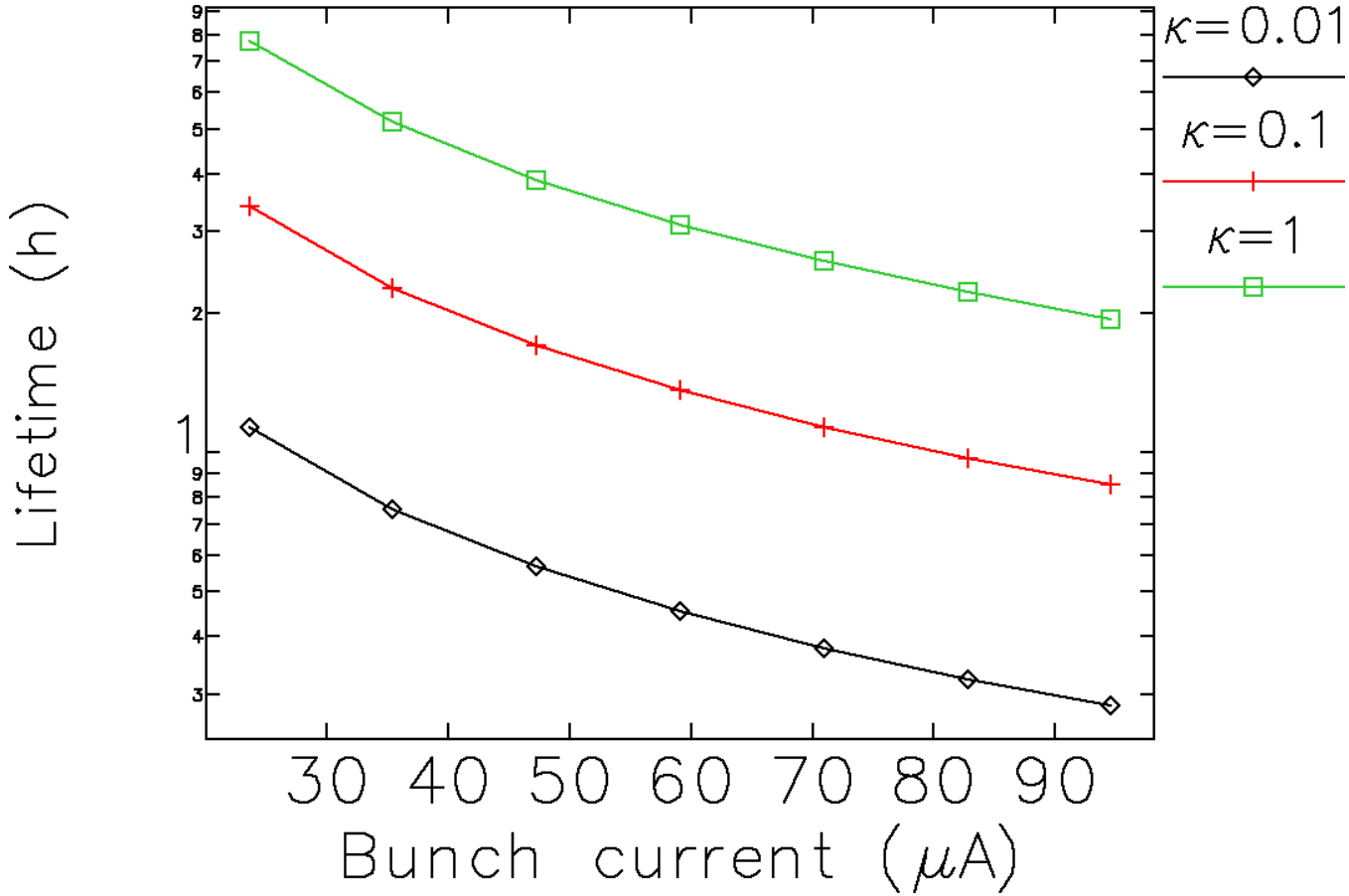




- Nonlinear elements tuned using genetic optimization technique
- 4000-turn tracking with damping and synchrotron oscillations
- Dynamic aperture is small, but very large compared to ~10 μm rms beam size

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

Touschek Lifetime Predictions



- Lifetime is a workable 4 hours for 50 μA/bunch and full coupling ($\epsilon_y = \epsilon_x$)

Computed with **touschekLifetime** (A. Xiao).

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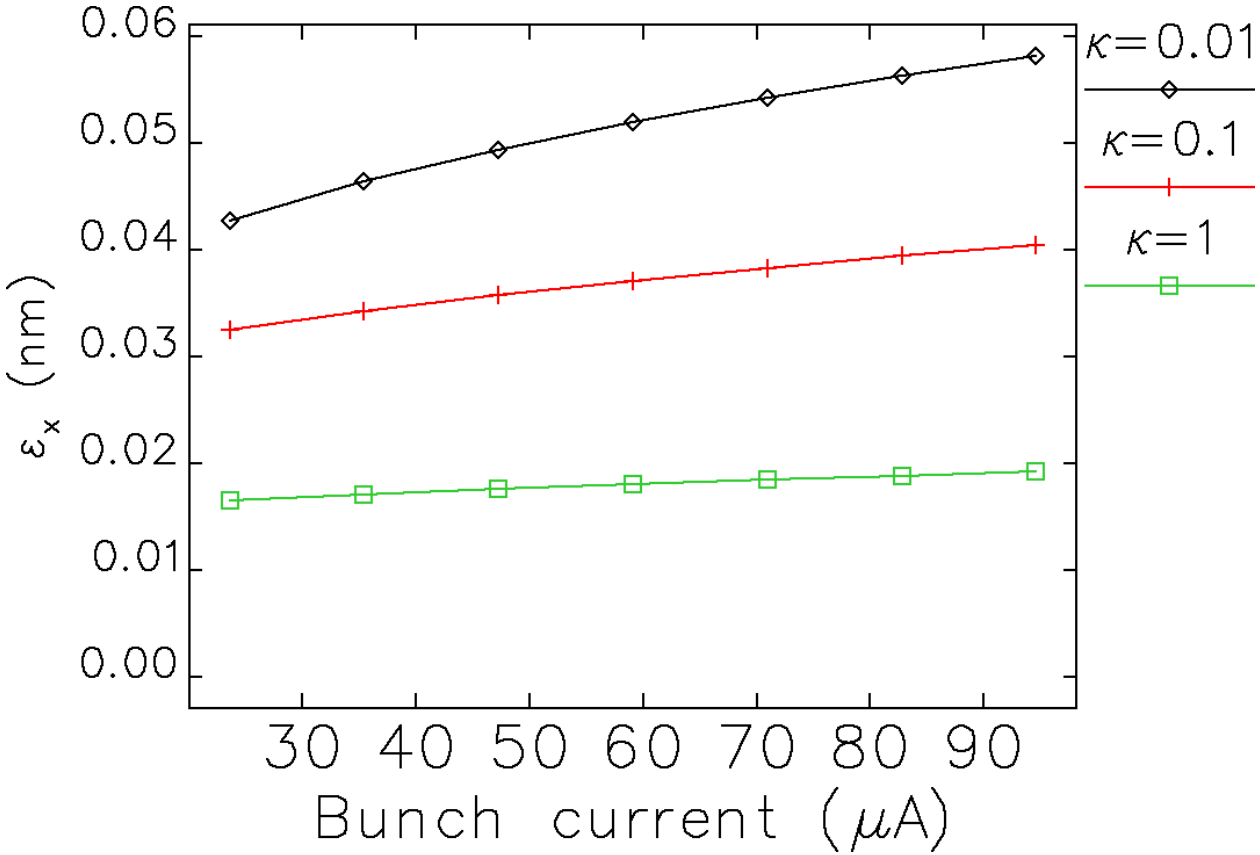
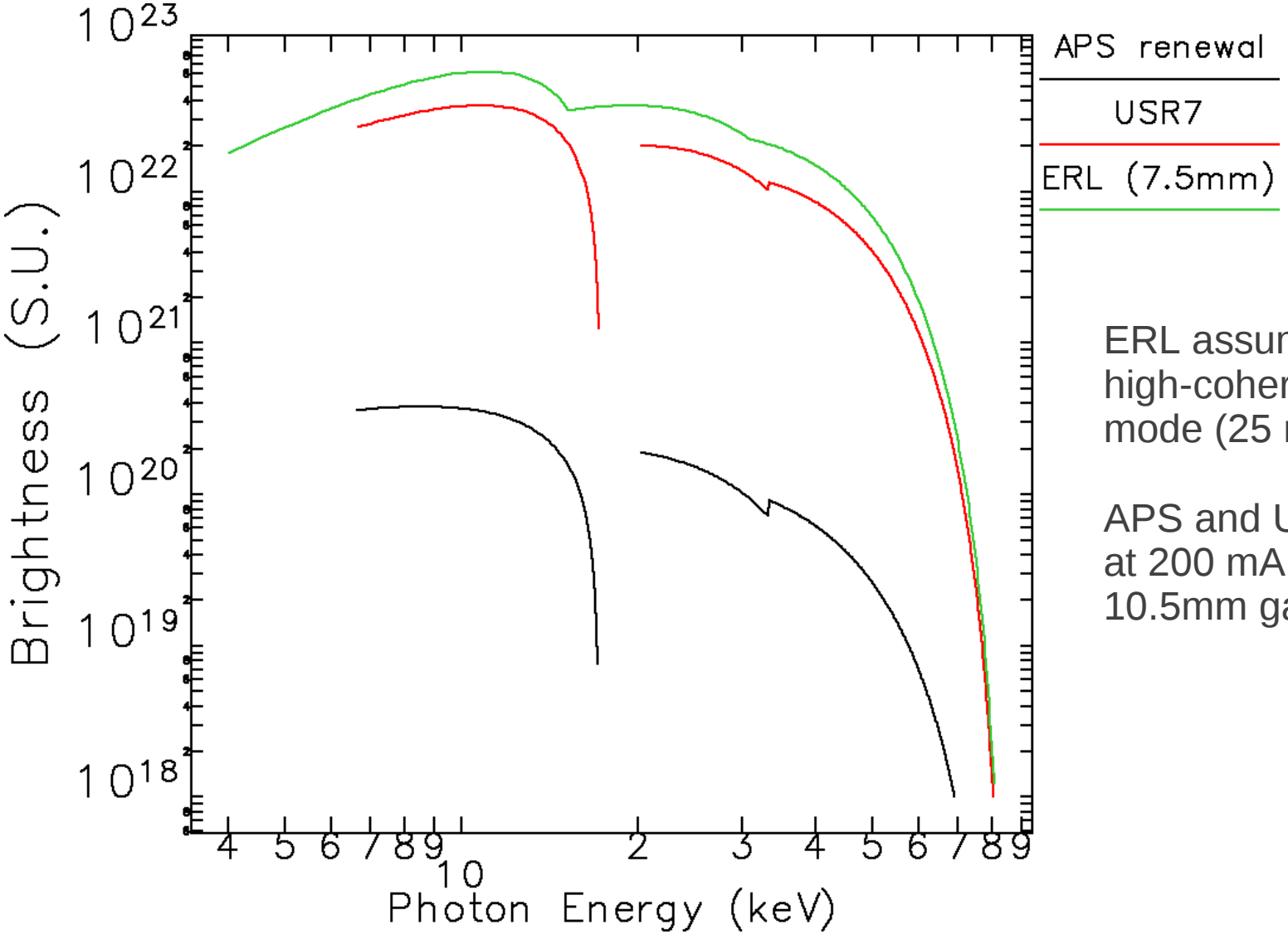
Intrabeam Scattering Impacts Emittance



- IBS effects greatly reduced for full coupling and low current/bunch
- For 200 mA, need 4000 bunches at 50 μA/bunch

Computed with **ibsEmittance** (L. Emery, A. Xiao, M. Borland)

Brightness Predictions for Max. Length U27 Devices



ERL assumes high-coherence mode (25 mA)

APS and USR7 at 200 mA with 10.5mm gap.

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

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Operation with Full Coupling[1,2]

- Present-day rings all use accumulation
  - Charge is added via repeated injections into each bucket
  - Top up replenishes the charge when it decays
  - Requires large dynamic aperture (off-axis injection)
  - Prevents working on coupling resonance
- Need to abandon accumulation in favor of "swap-out"
  - Inject on-axis
  - Kick out depleted bunch or bunch train
  - Simultaneously kick in fresh bunch or bunch train
- Many benefits
  - Can tune for very low emittance
  - Provide round beams
  - Reduce intrabeam scattering and improve lifetime

[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).

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
- For 4000-bunch beam, 20 bunches per train, and 4 hour lifetime
  - Replace a bunch train every 7.2 s
  - 1.5 nA average current from the injector (APS injector: 4 nA)
  - Each train has 11 nC (APS injector: 3 nC/bunch)
- Shorter lifetimes should be acceptable

Outlook for Further Improvement

- 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
  - Need to evaluate beam instabilities
- Add damping wigglers
  - ~30% reduction in emittance from 10 DWs
- Decrease the beam energy
  - Optimum a ~6 GeV gives slight improvement
- Ring DA is ~20x larger than needed
  - Push lattice harder to get lower emittance
  - Adding geometric sextupoles will also help
- An R&D plan is being developed following the BES workshop on next-generation light sources

Conclusion

- A significant upgrade of the APS storage ring is anticipated as part of the renewal
- Several lattice options, including
  - Long straights
  - Stronger/split dipoles
  - Alternating beamsize
- SPX promises to deliver <2 ps FWHM pulses with 1% intensity and 6.5 MHz repetition rates
- Many of the remaining U33 devices will likely be replaced with optimized devices
  - Customized period lengths, SCUs for higher brightness
  - APPLE devices and quasi-periodic devices
- Several ideas for a next-generation spontaneous x-ray source
  - ERL promises 1000-fold brightness increase but needs extensive R&D
    - APS upgrade or new facility
  - USR gives similar performance with less R&D

Acknowledgements

We are grateful to many of our colleagues for collaboration, stimulating discussions, and suggestions. They include:

- ANL: Y.-C. Chae, L. Emery, G. Decker, R. Dejus, P. Den Hartog, X. Dong, R. Gerig, E. Gluskin, K. Harkay, M. Jaski, K.-J. Kim, A. Nassiri, E. Moog, V. Sajaev, N. Sereno, H. Shang, R. Soliday, Y. Wang, M. White, A. Xiao, C.-Y. Yao
- Cornell University: B. Dunham, G. Hoffstaetter, I. Bazarov
- FNAL: Y. Sun
- LBNL: J. Qiang
- TJNAF: D. Douglas, G. Krafft
- TRIUMF: L. Merminga