Exploration of a Tevatron-Sized Ultimate Light Source

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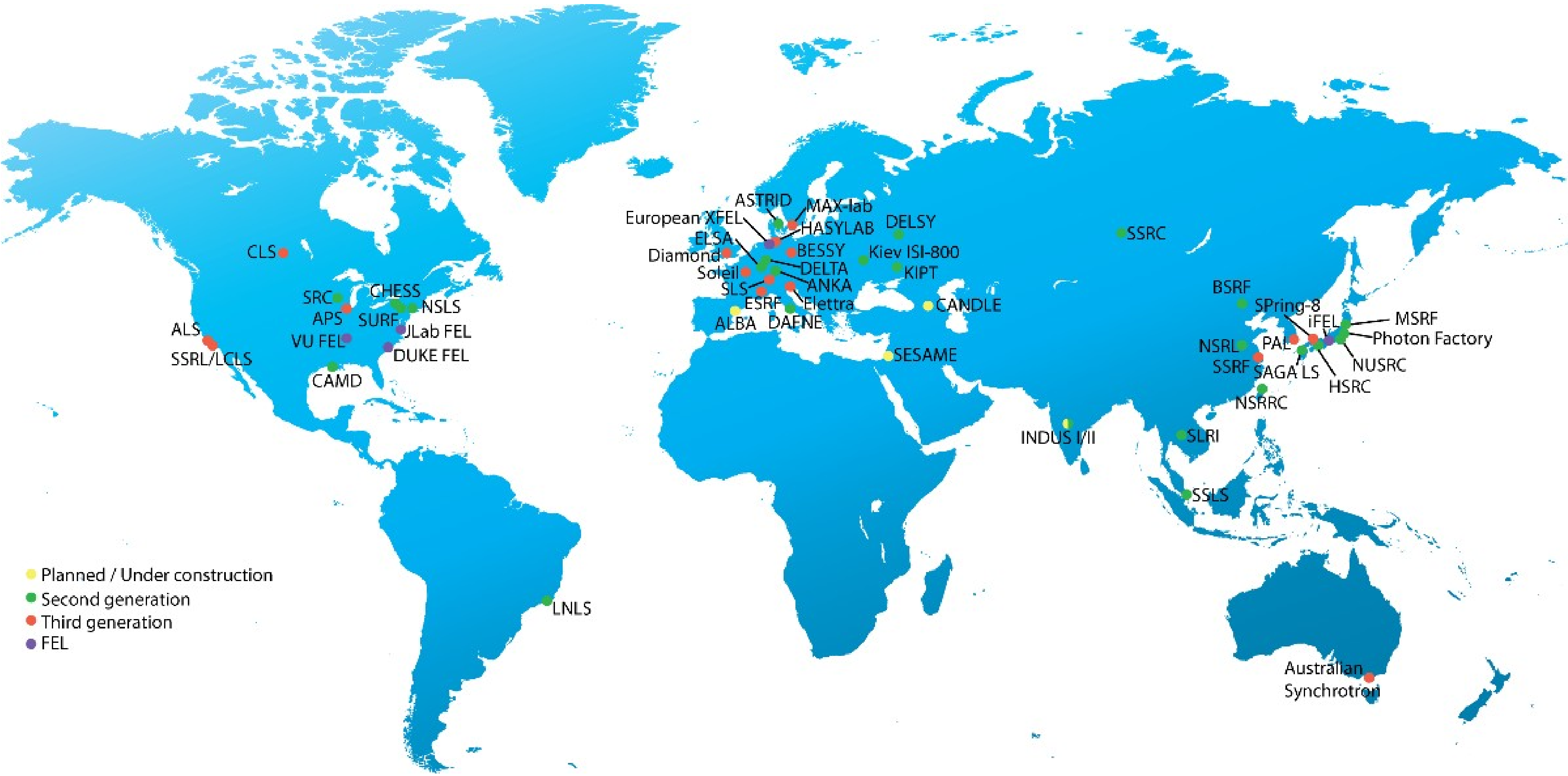
Synchrotron Light Sources Worldwide



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Outline

- Motivation for this work
- Basic concepts and terminology
- Present and near-future rings
- Scaling of ring performance
- "USR7": 7 GeV Ultimate Storage Ring light source
  - Multi-objective genetic optimization
  - Operations concept
- Possible Tevatron-sized USR
  - Design concept
  - Potential
  - Challenges
  - Comparison to alternatives

Motivation

- X-ray brightness is one of the primary requirements of x-ray users
- Brightness of x-rays from storage ring scales like R^3
- Tevatron has been shut down and will be decommissioned
  - Tunnel has a radius of 1 km compared to 175 m for APS
  - A Tevatron-sized light source would be orders of magnitude brighter than existing light source rings
- Chicago would make an ideal location for an international light source
  - Air connections
  - Educational institutions
  - Two national labs with accelerator, x-ray, and computational expertise
- Given these facts, exploration of a Tevatron-sized light source seems reasonable

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Basic Electron Beam Properties

- Electron beam properties strongly affect the properties of the radiation
  - Single-electron radiation phase space is convolved with the electron beam phase space
- Important measures of beam quality
  - Low energy spread (0.02~0.1%)
  - Brief time duration (20 fs ~ 50 ps)
  - Small transverse size and divergence, e.g., 10~100 μm by 1~10 μrad
- The quality of a beam is expressed by the brightness

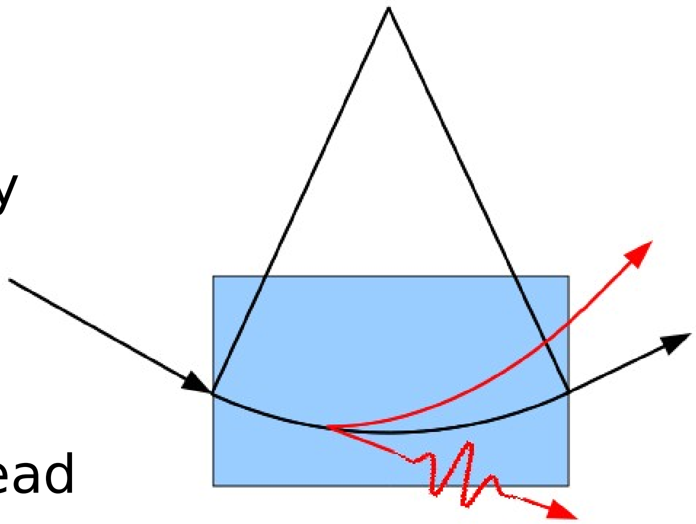
$$B \propto \frac{N_e}{\sigma_E \sigma_t \sigma_x \sigma'_x \sigma_y \sigma'_y}$$ (simplified form)

- Commonly combine transverse quantities into "emittances"

$$\epsilon_x = \sigma_x \sigma_{x'}$$ Geometric emittance (simplified)

Quantum Excitation of Electron Beams

- Radiation emission has a random component
  - Different electrons emit differently
  - Quantum-mechanical effect
- Bending will diminish beam brightness
  - Directly by increasing energy spread
  - Indirectly by increasing bend-plane emittance
- Hence, when electron beam brightness requirements are very demanding, may prefer system with very minimal bending
  - Effect can be reduced by controlling the dispersion (more later)



$$\langle \mathcal{N}_p \rangle \sim \gamma\alpha$$

per radian

See, e.g., M. Sands, SLAC-121 (1972).

Radiation Damping

- Geometric emittance is the product of size and divergence

$$\epsilon_x = \sigma_x \sigma_{x'}$$

- Divergence decreases when beam is accelerated

$$x' = \frac{p_x}{p_z} \longrightarrow \frac{p_x}{p_z + \Delta p_z}$$

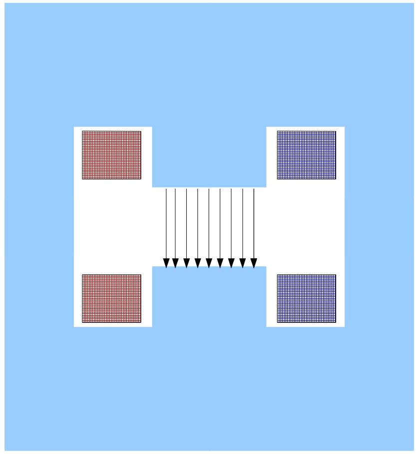
- Results in damping of emittance in rings as beam is reaccelerated to restore energy lost to SR
- In storage rings, an equilibrium is reached between QE and damping

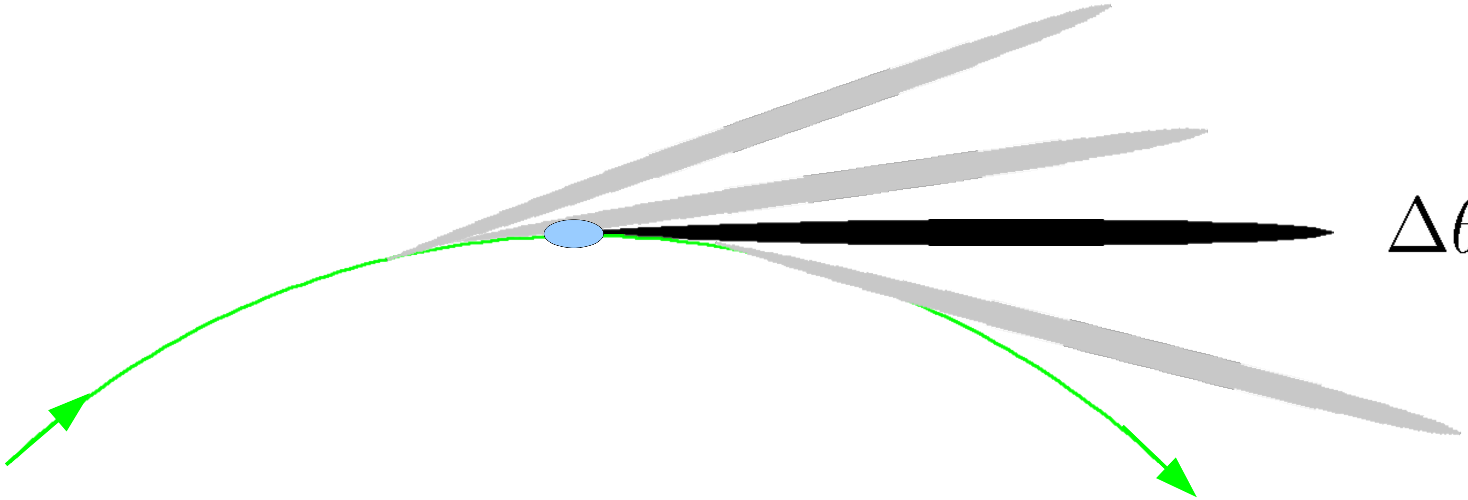
$$\epsilon_0 \sim \frac{E^2}{N_d^3} \qquad \left(\frac{\sigma_E}{E}\right)_0 \sim \frac{E}{\sqrt{\rho}}$$

See, e.g., M. Sands, op. cit., and
J. Murphy, Light Source Data Book.

Radiation Producing Devices: Bending Magnets

- Synchrotron radiation originally observed for beam circulating in a single dipole magnet
- Modern rings have many bends to force the beam into a closed path
  - The radiation they produce may or may not be used
- Bend magnet radiation is like a "moving searchlight"

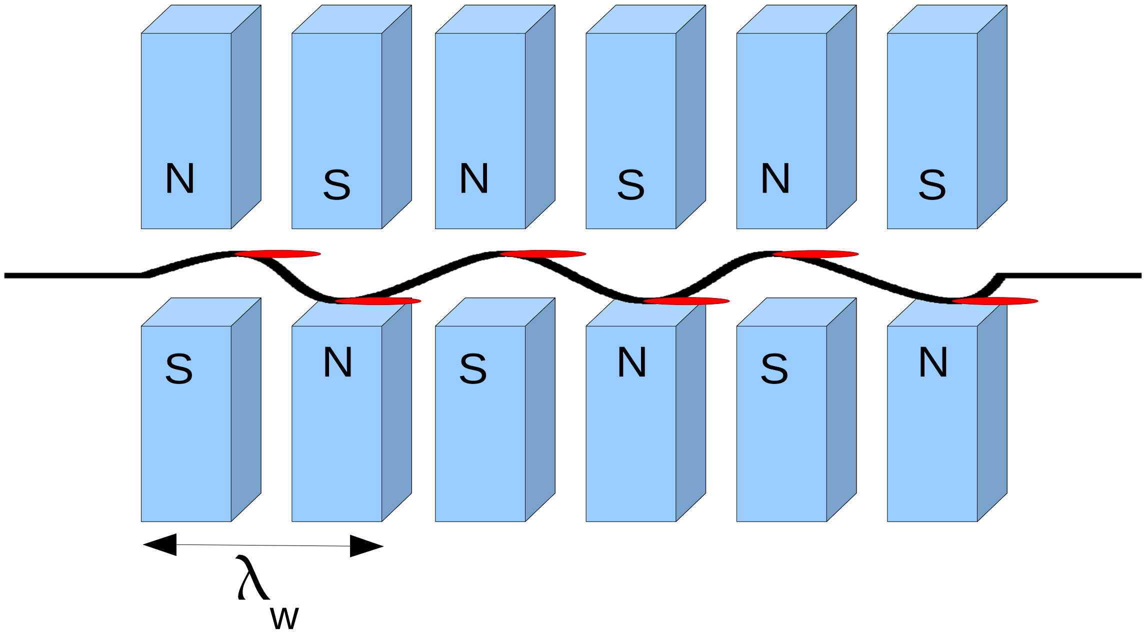




$$\Delta\theta \sim \frac{1}{\gamma}$$

Radiation Producing Devices: Wigglers

- A wiggler is a series of N_w strong bends of alternating sign
- The beam "wiggles" in a sinusoidal trajectory



- Trajectory angle and amplitude characterized by K parameter

$$K = \frac{\theta_{\max}}{1/\gamma} \qquad x_{\max} = \frac{K\lambda_w}{2\pi\gamma}$$

See, e.g., K. J. Kim, AIP Conf. Proc. 184 (1989).

Radiation Producing Devices: Undulators

- If K≤3 radiation from successive periods interferes constructively
- Average forward electron velocity is

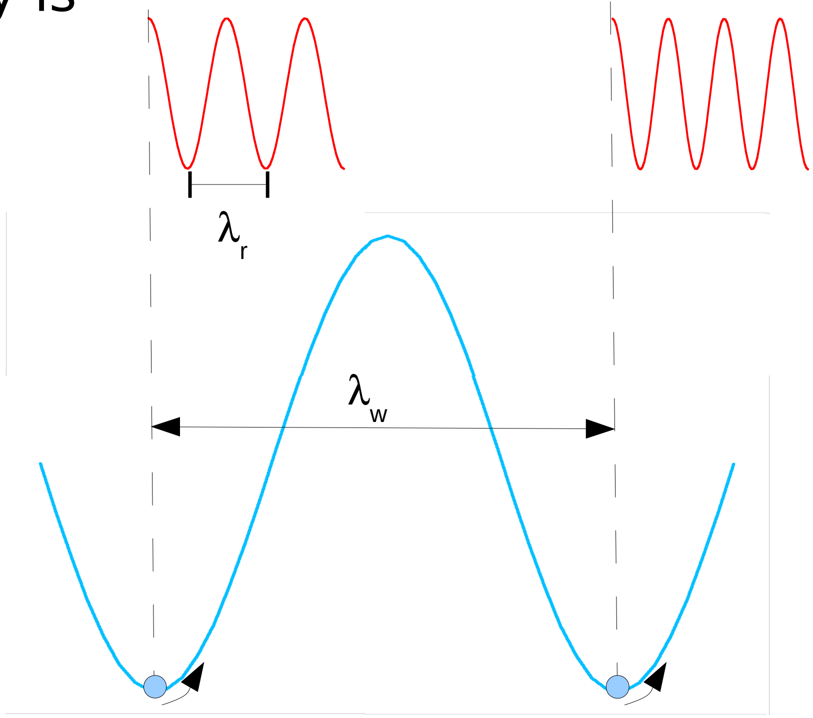
$$\bar{v}_z = c\left(1 - \frac{1+\frac{1}{2}K^2}{2\gamma^2}\right)$$

- Radiation has v=c, so after each period it slips ahead by

$$\Delta l = \frac{\lambda_w\left(1+\frac{1}{2}K^2\right)}{2\gamma^2}$$

- Coherent addition between poles for certain radiation wavelengths

$$\lambda_r n = \Delta l, \qquad n = 1, 2, 3, \ldots$$

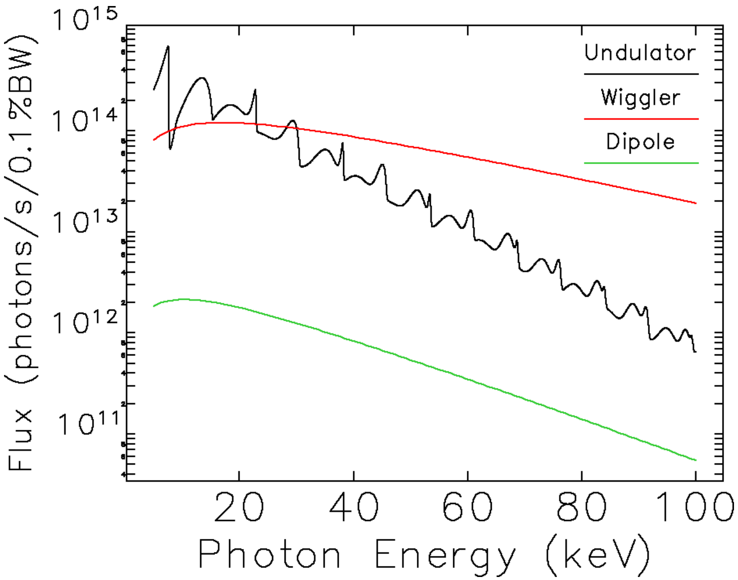


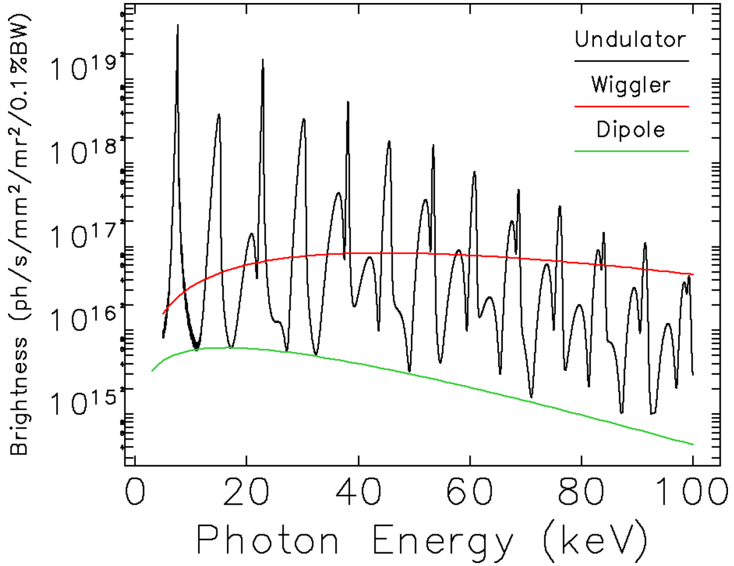
- Undulator radiation peaked at *odd* harmonics

$$\lambda_{r,n} = \frac{\lambda_w\left(1+\frac{1}{2}K^2\right)}{2n\gamma^2} \qquad \Delta\theta \sim \frac{1}{\gamma\sqrt{N}} \quad \text{for} \quad \frac{\Delta\lambda}{\lambda} \sim \frac{1}{N}$$

Diagram after B. McNeil, “How an FEL works”, FEL2010.

Comparison of Radiation Spectra





- With realistic electron beam, undulator shows even harmonics as well as odd harmonics
- Undulators preferred for high-brightness applications
- Wigglers provide high energy and flux

Undulator: K=1.3, 3.3cm period, 2.4m length
Wiggler: B=1.0T, 8.5 cm period, 2.4m length
Dipole: B=0.6T

Flux computed through 5x5 mm^2 pinhole at 30 m for 100 mA APS beam.

Computed with SPECTRA (T. Tanaka, H. Kitamura).

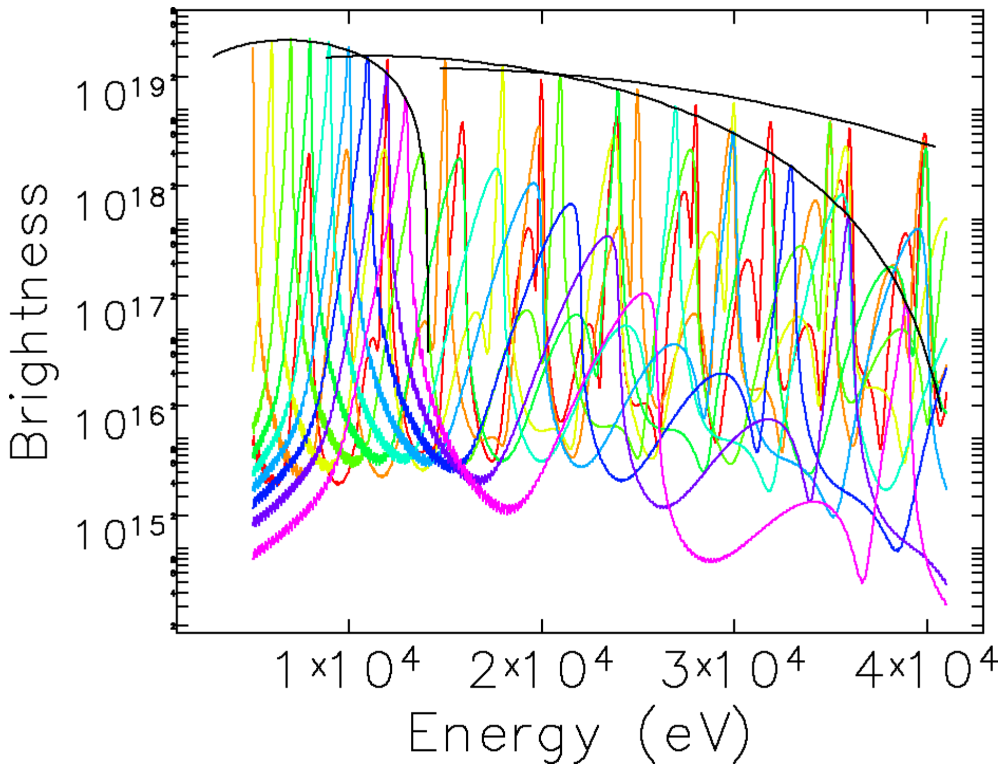
Tuning Curve for Undulator

- Undulators have adjustable gaps that allow changing the field

$$K = 93.4 B(\mathrm{T}) \lambda_w(\mathrm{m})$$

- Hence, users can move the location of the maximum brightness to correspond to experimental needs
- Maximum brightness occurs for first harmonic when K=1.3

The envelope of many brightness spectra as the gap is varied creates a “brightness tuning curve”



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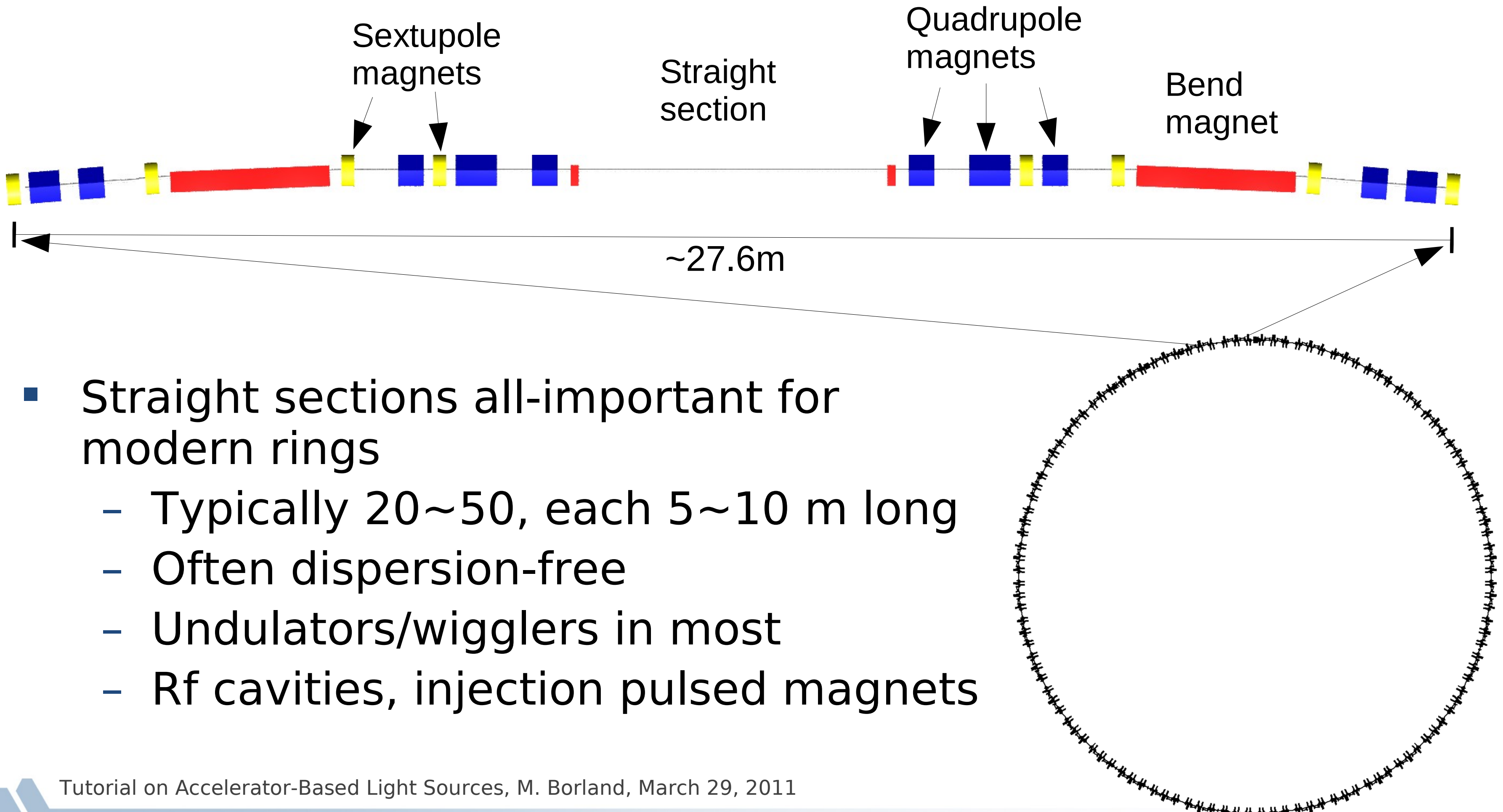
Strengths of Rings as Light Sources

- Storage rings light sources 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

Contemporary Storage Ring Light Sources

- Most rings are highly periodic and symmetric
  - APS cell is a typical Chasman-Green configuration
  - Often such cells tuned as double-bend achromat (DBA)



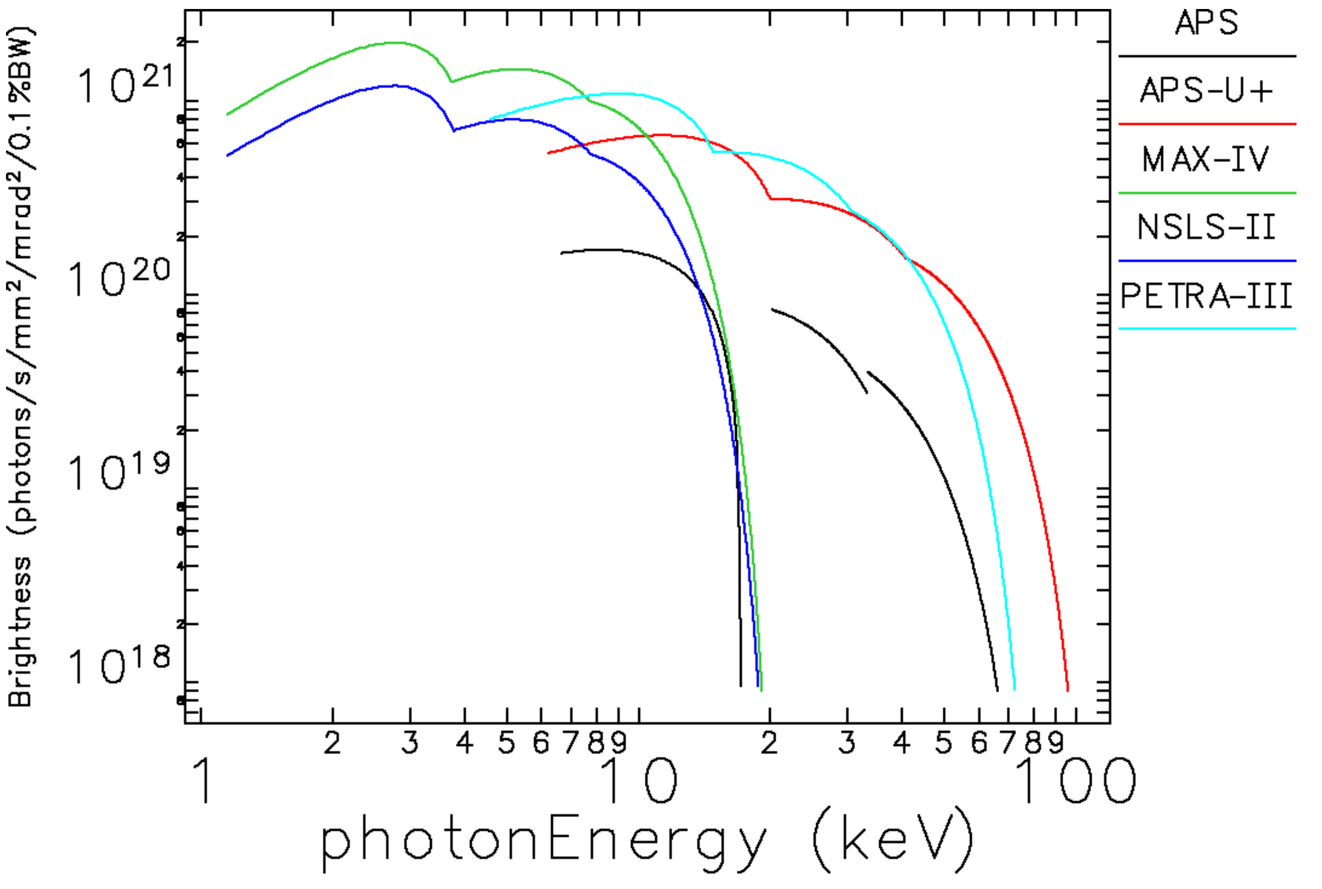
- Straight sections all-important for modern rings
  - Typically 20~50, each 5~10 m long
  - Often dispersion-free
  - Undulators/wigglers in most
  - Rf cavities, injection pulsed magnets

Near-Term Outlook

- From 1990's onward, emittance pushed to few nm
  - ESRF, APS, SPRING8, ...
- New rings pushing to 1 nm and below
  - Motivations: high brightness, nano-focusing, coherence
- PETRA III[1]
  - Converted high-energy physics ring
  - Now world-leading 6 GeV, 1 nm light source
  - Large circumference with damping wigglers
  - Undergoing expansion soon
- NSLS-II[2]
  - 3 GeV, 0.5 nm ring, construction well underway
  - "Large" circumference DBA with damping wigglers
- MAX IV[3]
  - Planned 3 GeV, 0.24 nm ring, beginning construction
  - "Small" circumference 7BA with damping wigglers

[1]K. Baleski *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 4.8m long U27
- Others 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.

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Emittance of Electron Storage Rings[1]

- Quantum excitation causes emittance growth in any bending system

$$\left(\frac{d}{dt}\langle\epsilon\rangle\right)_q \approx \frac{\langle \dot{N}_{ph}\langle u_\gamma^2\rangle \mathcal{H}(s)\rangle_s}{2E_0^2} \propto E_0^5$$

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

- Fortunately, in electron rings there is also damping

$$\left(\frac{d}{dt}\langle\epsilon\rangle\right)_d \approx -\frac{\langle P_\gamma\rangle}{E_0}\epsilon \propto E_0^3$$

- 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.

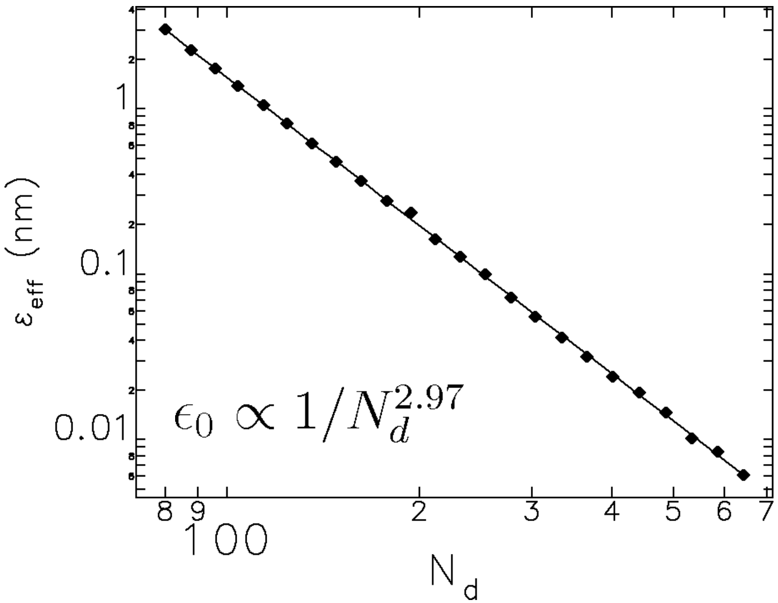
Methods of Decreasing Emittance

- 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.

MBA Concept

- The APS lattice used for this study is a double-bend design
  - We increased N_d by increasing the number of cells
  - Circumference increases with N_d
- Another approach is to make Multi-Bend Achromats[1]
  - Allows more dipoles in the same circumference
  - Smaller number of comparable-length straights
- MAX-IV ring[2] now under construction will be the first MBA ring

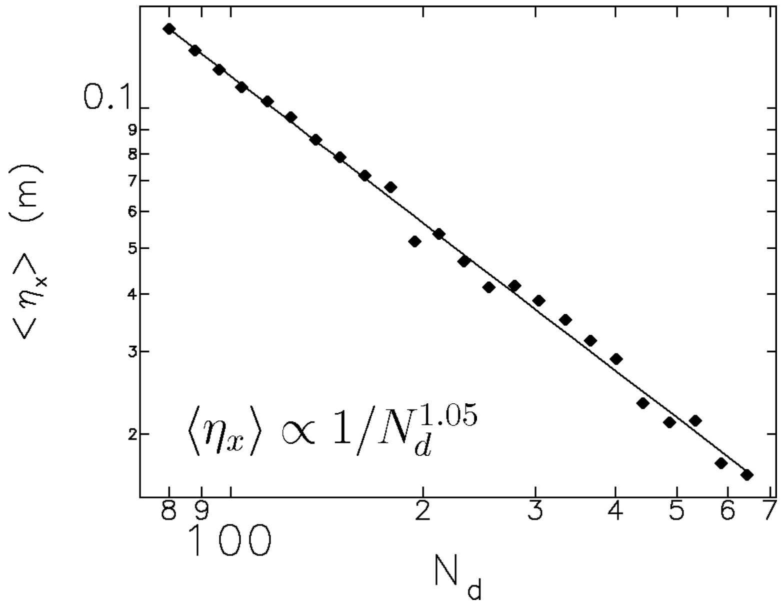
[1]D. Einfeld et al., Proc. PAC 95, 177-179 (1996).
[2]S.C. Leeman *et al*., PRSTAB **12**, 120701 (2009).

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

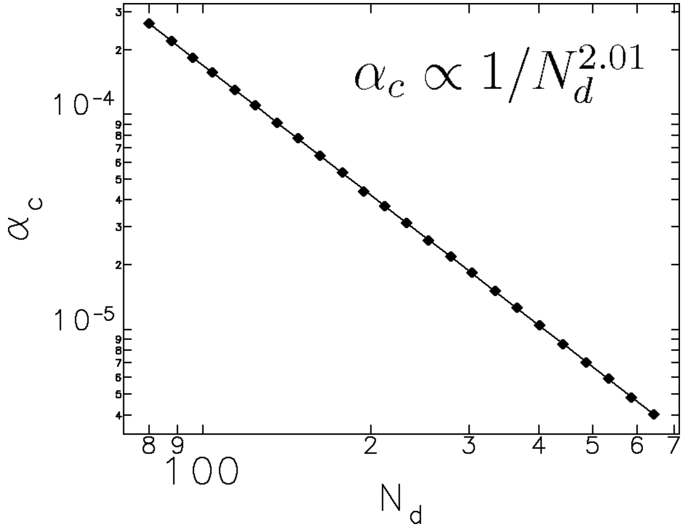
More data from the scaling simulation. Again no surprise.

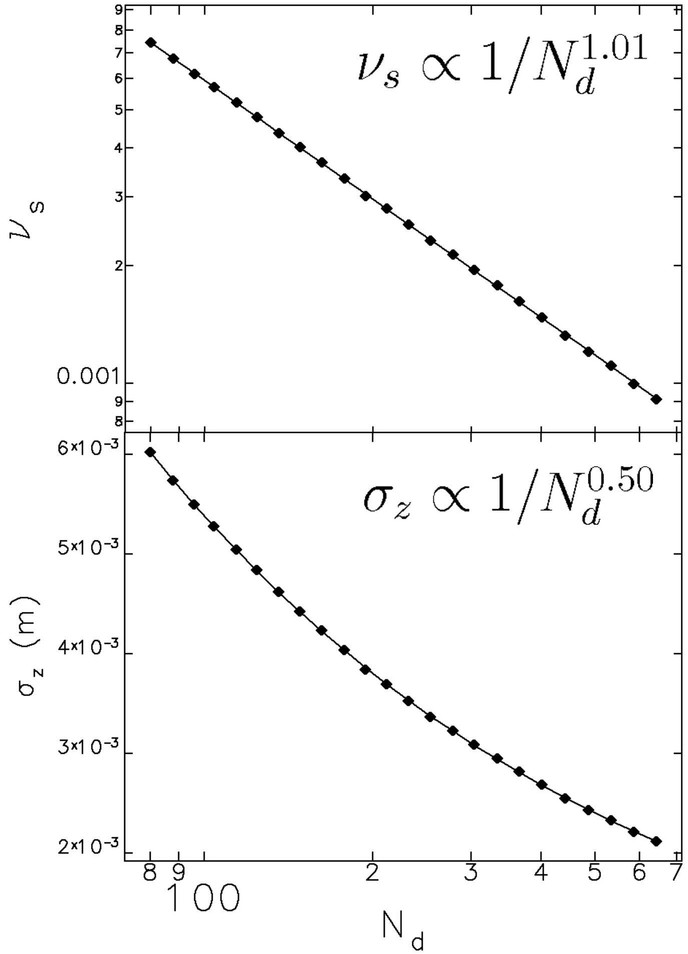
Sextupole strengths are inversely proportional to average dispersion.



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

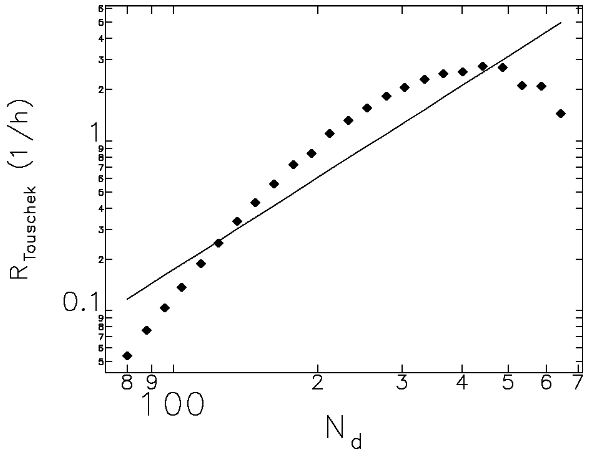
$$\frac{1}{\tau} \sim \frac{N_b N_d^{5.5}}{E^{8.1}}$$

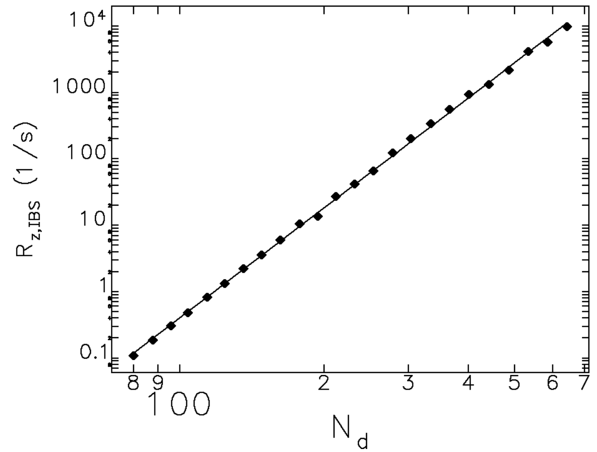
- TMCI

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

- 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.*)

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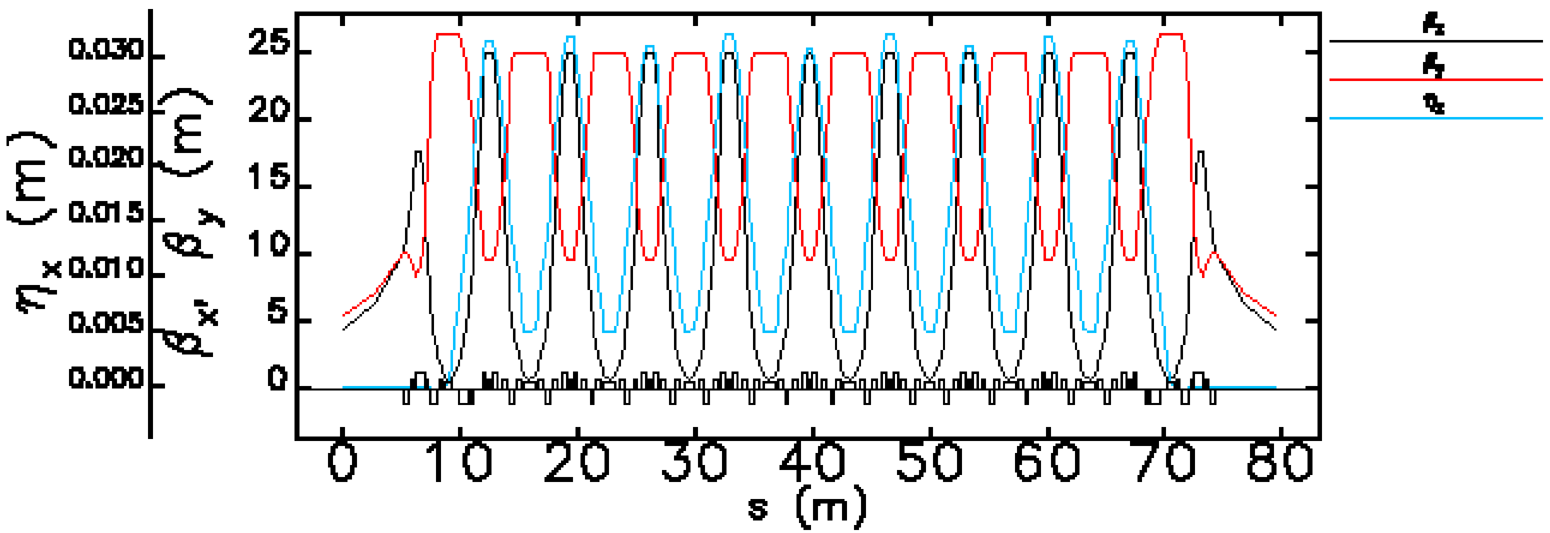
USR7: A 7 GeV, 40 Sector Ultimate Ring[1,2]

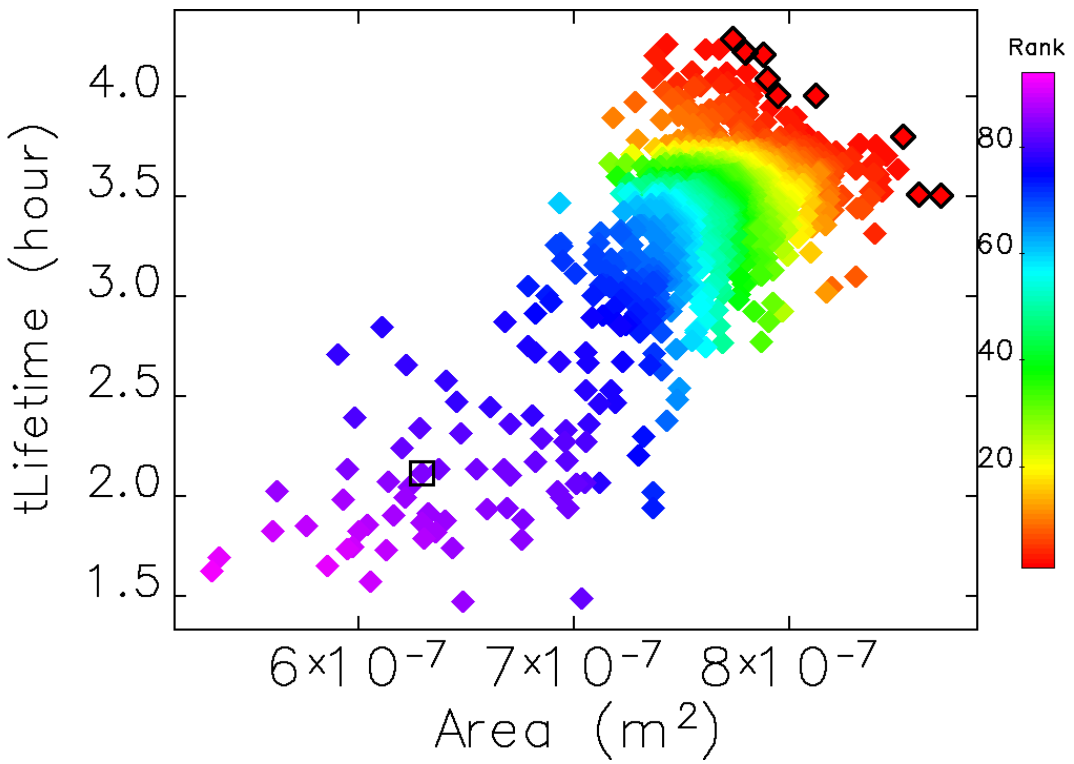
Quantity	Value	Unit
Circumference	3.16	km
Natural emittance	0.028	nm
Energy spread	0.079	%
Maximum ID length	8	m
Number of dipoles	10	per sector
Horizontal/vertical tune	183.18/36.18	
Natural chromaticities	-535/-175	
Energy loss	3.7	MeV/turn
Beta functions (x/y) at ID	4.4/5.5	m



[1]M. Borland, LSU Grand Challenge Workshop, 2008.
[2]M. Borland, Proc. SRI09, AIP Conf. Proc 1234 (2010).

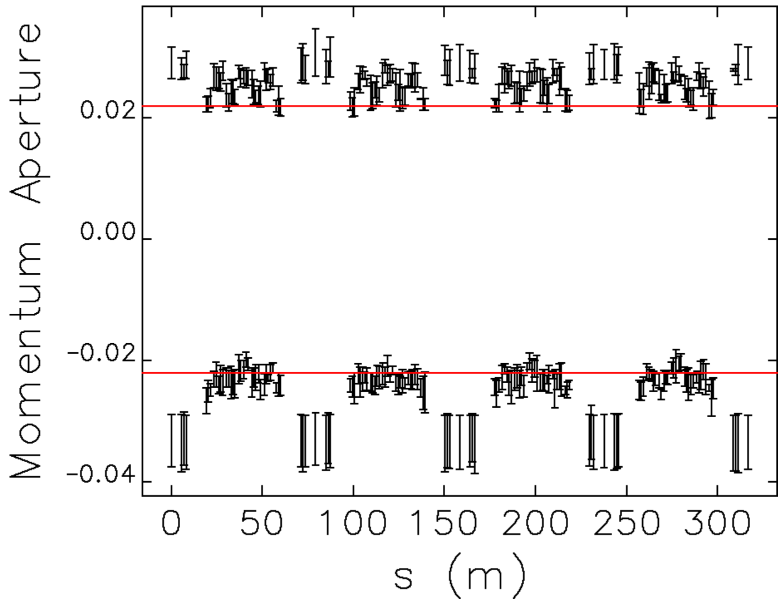
Sextupole Optimization

- 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 on one core
- Typically use 100~300 cores



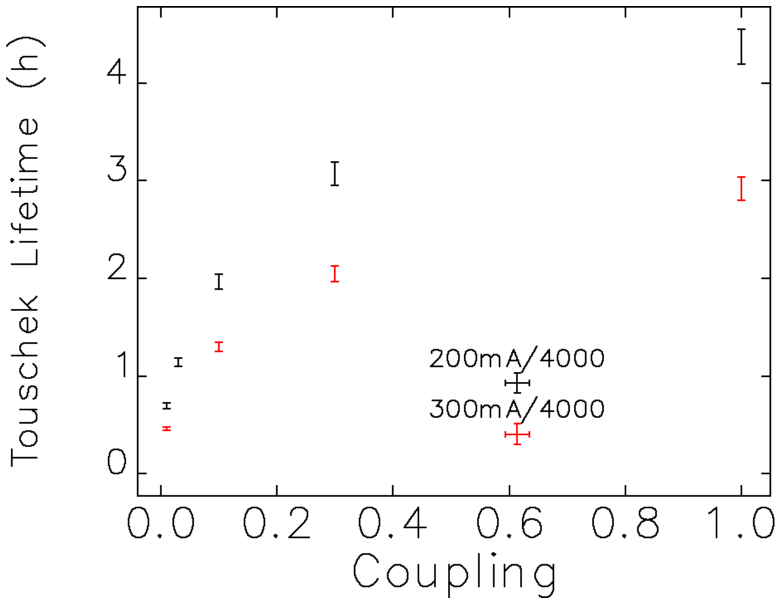
[1]M. Borland, H. Shang, **geneticOptimizer**.
[2]M. Borland *et al.*, Proc. PAC09, 3850-3852 (2009).
[3]M. Borland *et al.*, Proc. ICAP09, 255-258 (2009).

USR7 Momentum Aperture (5 Ensembles)



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

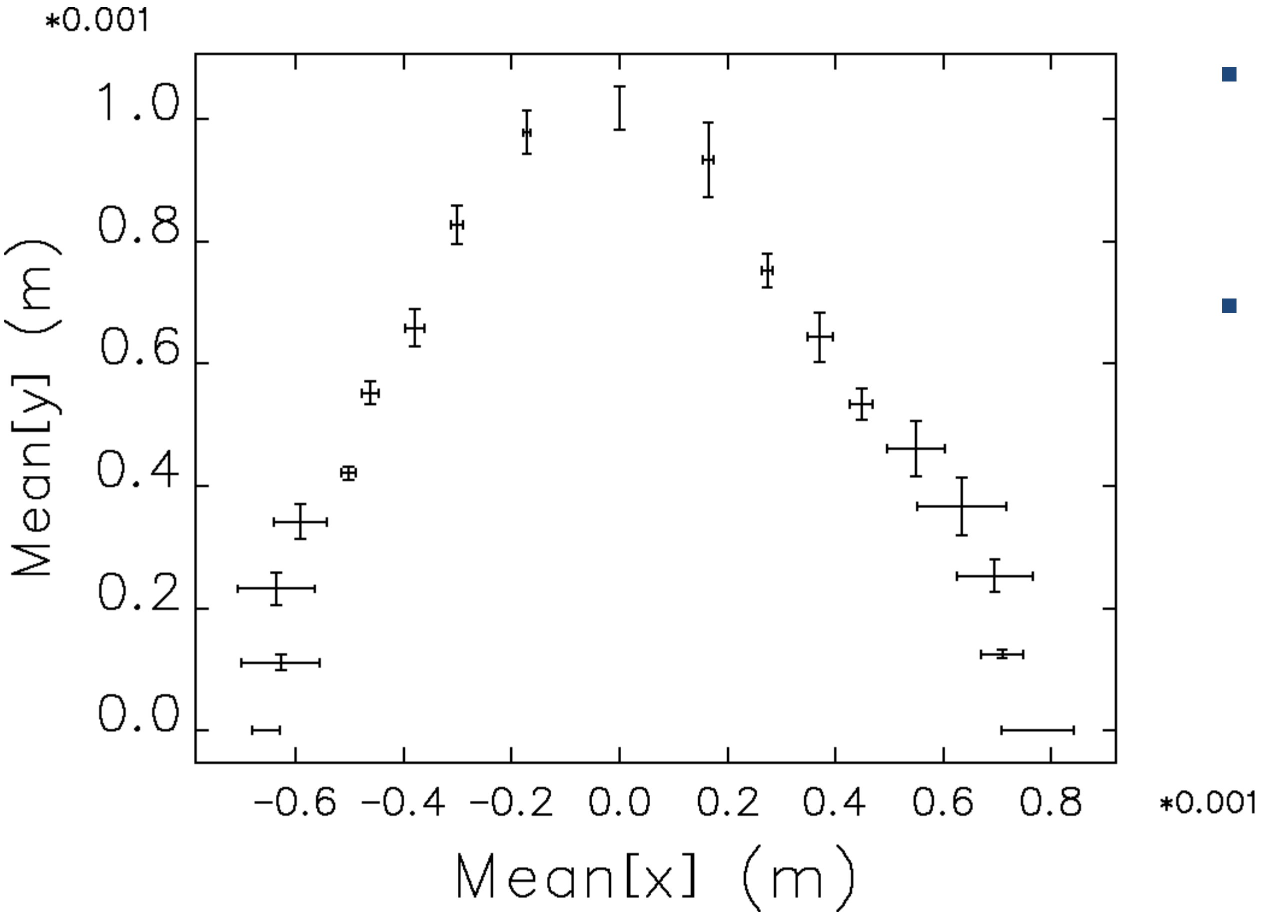
Computed with **elegant** (M. Borland, *et al.*)



- 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

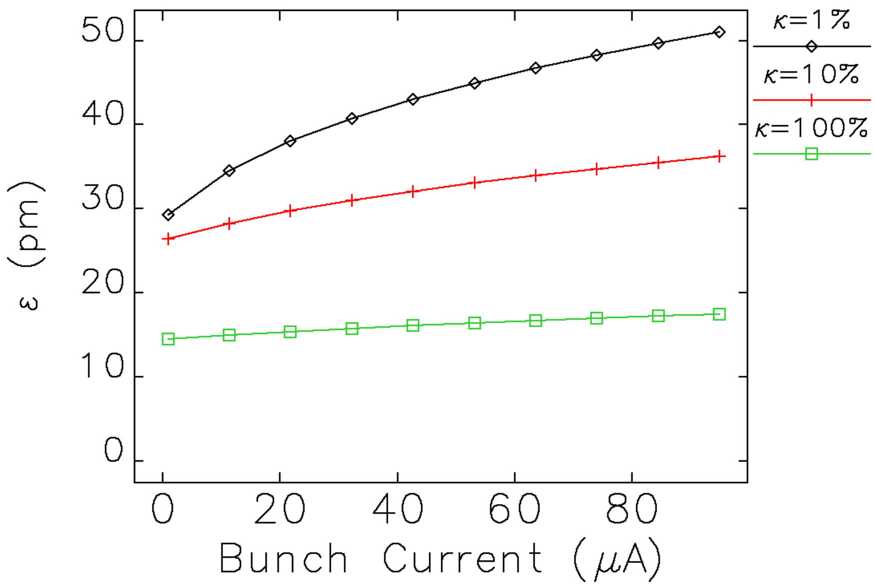
Computed with **elegant** (M. Borland, *et al.*)

Injection Issues

- All present-day 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 horizontal 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 propose to 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]

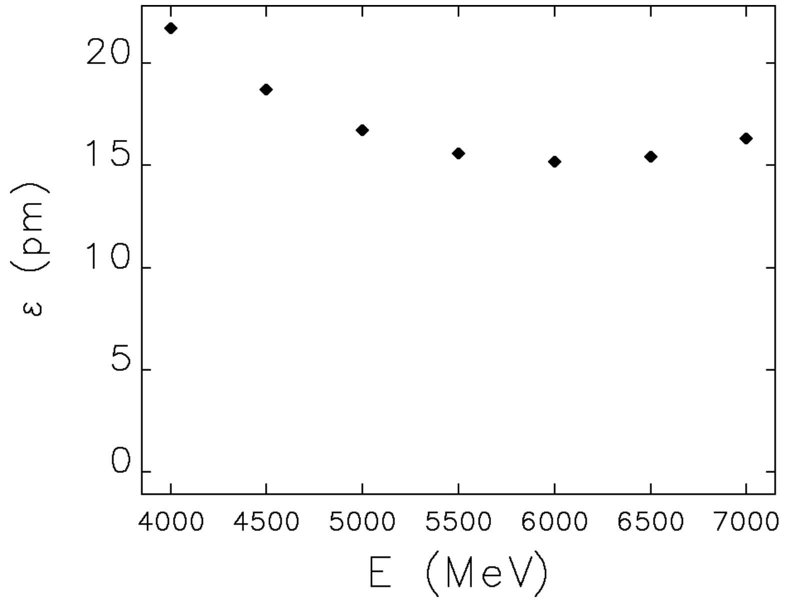
[1] M. Borland, "Can APS Compete with the Next Generation?", APS Strategic Retreat, May 2002.
[2] M. Borland, L. Emery,"Possible Long-term Improvements to the APS," Proc. PAC 2003, 256-258 (2003)
[3] M. Borland, Proc. SRI09, AIP Conf. Proc. 1234, 2010.

Intra-Beam Scattering



- IBS is modest for full coupling

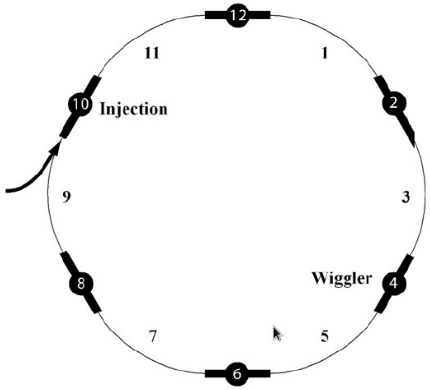
- Even with full coupling, little advantage to reducing the beam energy (assuming 50 μA/bunch)



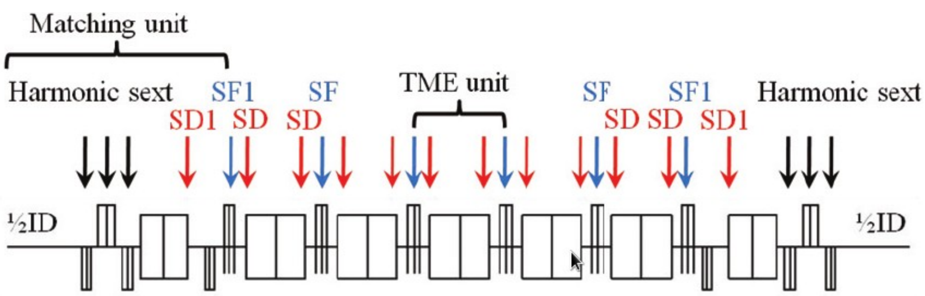
Computed with **ibsEmittance** (A. Xiao, L. Emery, M. Borland)

PEP-X USR Design

- PEP-X group at SLAC has developed a robust 7BA lattice for a proposed light source in the PEP tunnel[1,2]



Courtesy Y. Nosochkov



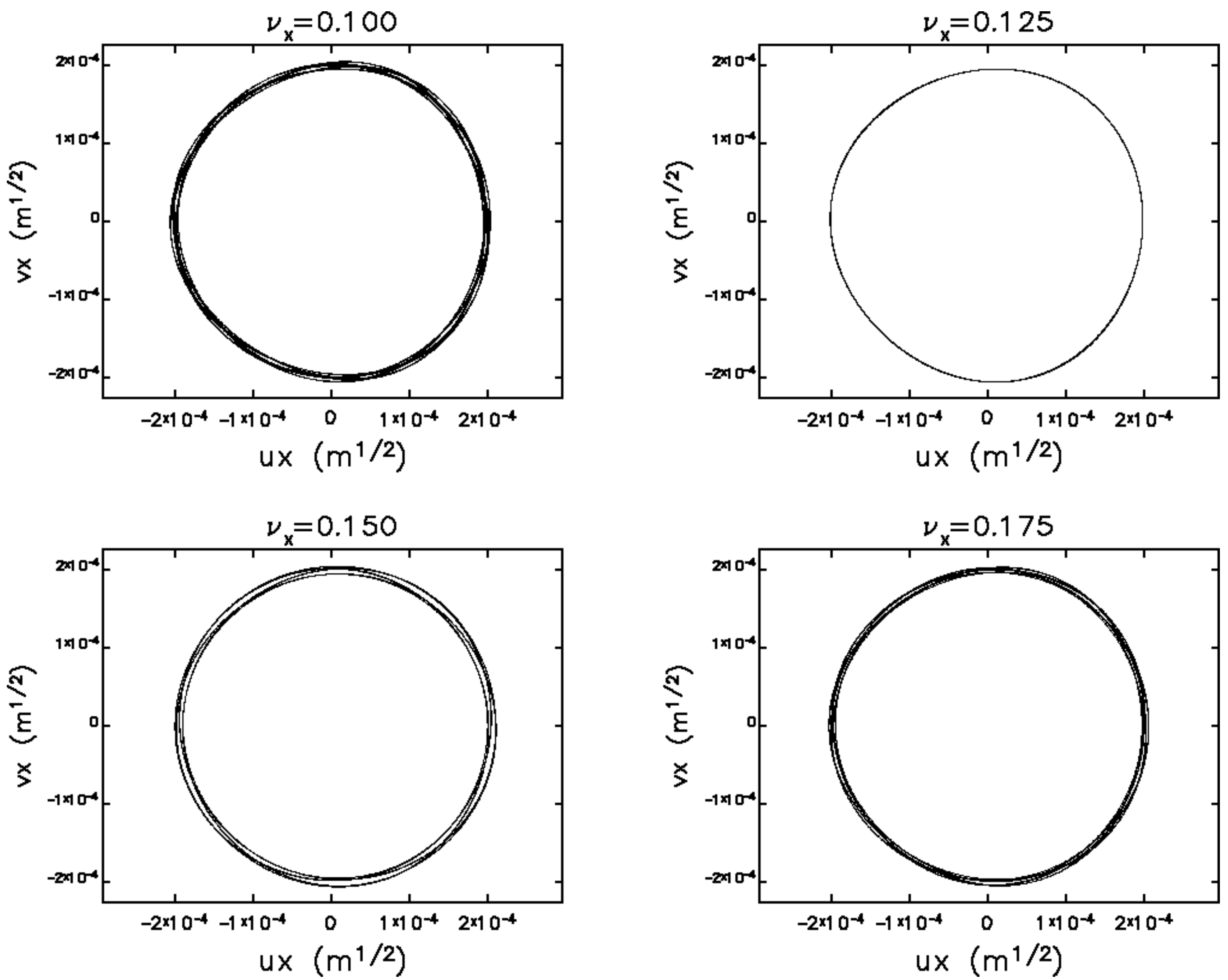
Courtesy M.-H. Wang

- Choose cell phase advance to make +I transform for each arc of N cells:
  - $\nu_x = 2 + m/N$ and $\nu_y = 1 + n/N$
  - This results in cancellation of many 2nd-order geometric and chromatic aberrations[3,4]
  - For PEP-X, N=8 and m=n=1

[1]M.-H. Wang *et al*., Proc IPAC11, THPC074.
[2]Y. Nosochkov *et al*., Proc. IPAC11, THPC075.
[3]K. Brown, SLAC Rep. 75, June 1982.
[4]Y. Cai, NIM A 645:168-174 (2011).

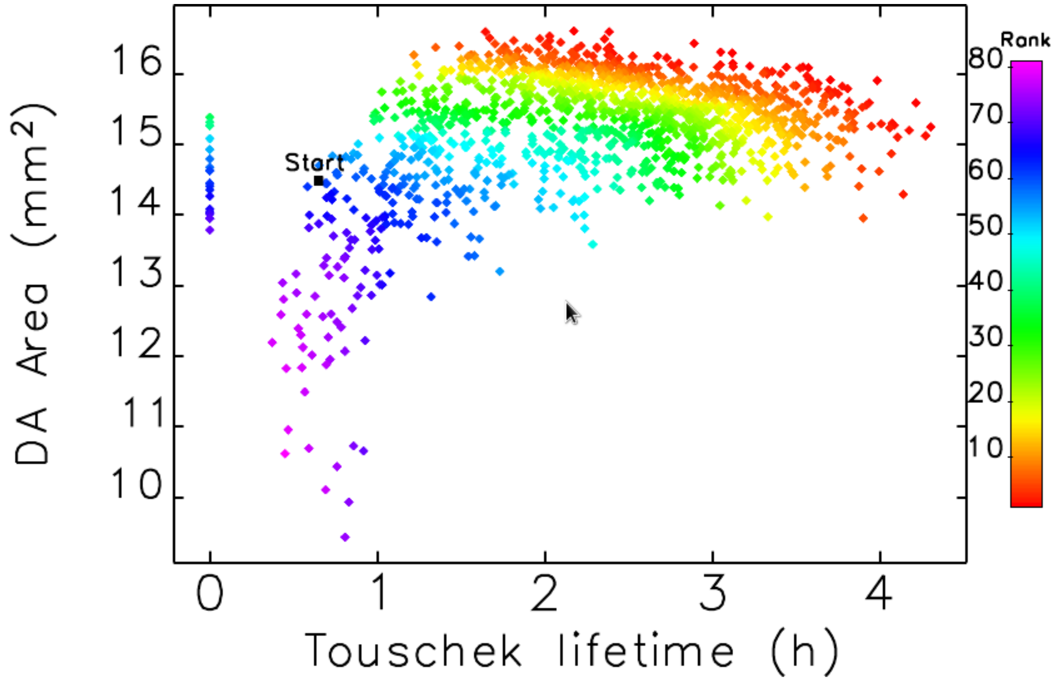
Illustration of Effect of Right Phase Advance

Distortion of phase-space ellipse in PEP-X arc with 8 cells



PEP-X USR Design

- Sextupoles have been optimized using MOGA algorithm[1], providing a dramatic increase in lifetime[2]



Courtesy M.-H. Wang

- Just what MOGA does to make this improvement is yet to be understood.

[1]M. Borland *et al.*, APS LS-319, August 2010.
[2]M.H. Wang *et al.*, Proc IPAC11, THPC074.

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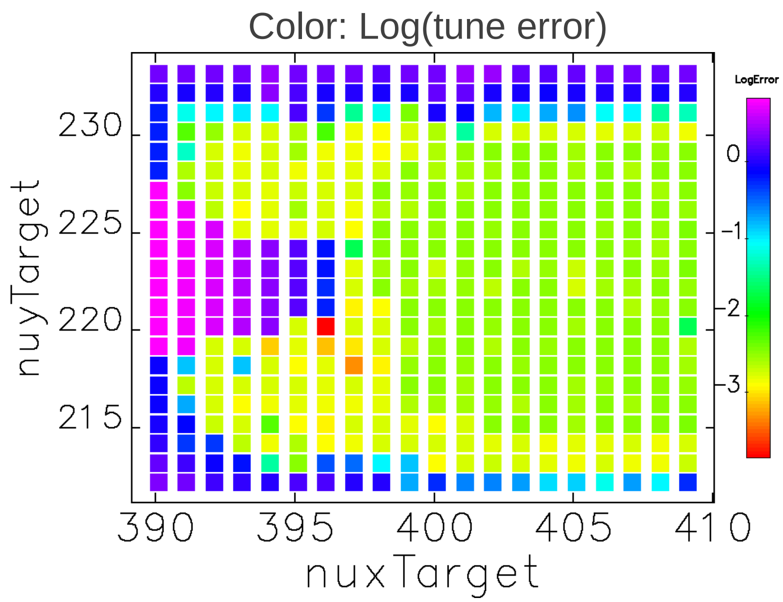
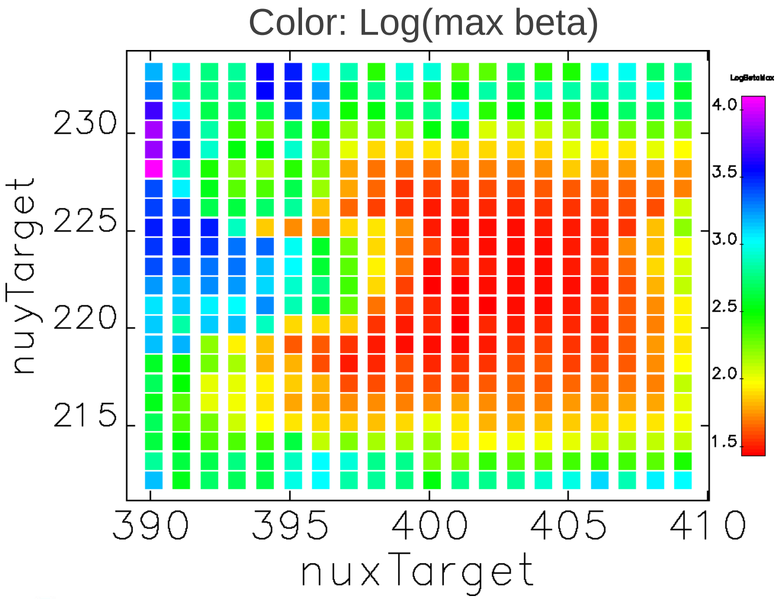
Exploratory “TeVUSR” Lattice

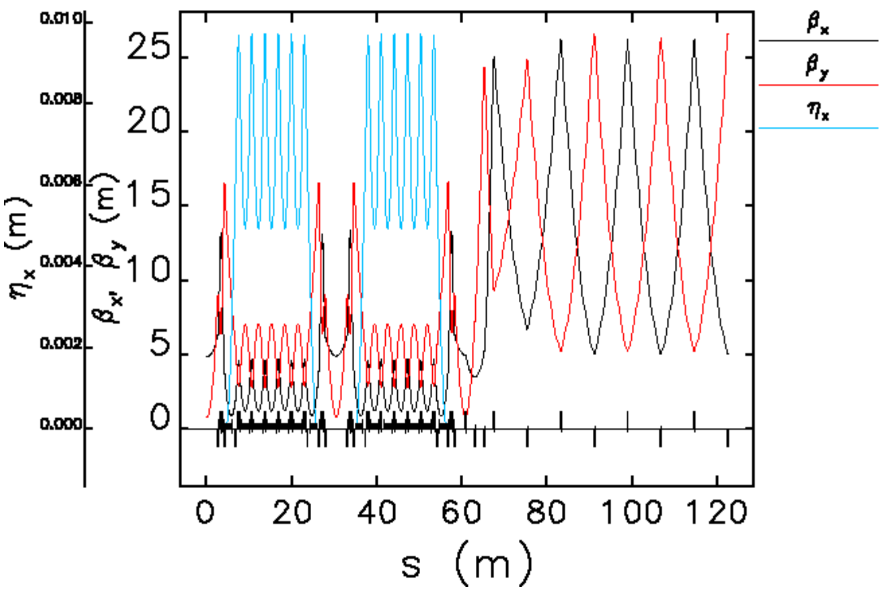
- All lattice modules are taken from the PEP-X design
  - N=30 MBA cells in each of six arcs
  - Use Y. Cai suggestion of m=n=5
  - Straight sections use FODO cell
  - Six matching quads between arc and FODO cells
- Differences from PEP-X design
  - Larger bending radius
  - Higher energy
    - Improves damping times, reduces IBS etc.
  - No high-beta insertion for injection
    - Will use on-axis injection, so not needed
  - No special optics for straights with damping undulators
    - For simplicity, turn off the (weak) vertical undulator focusing at this stage

Integer Tune Scan with Matching/FODO Quads





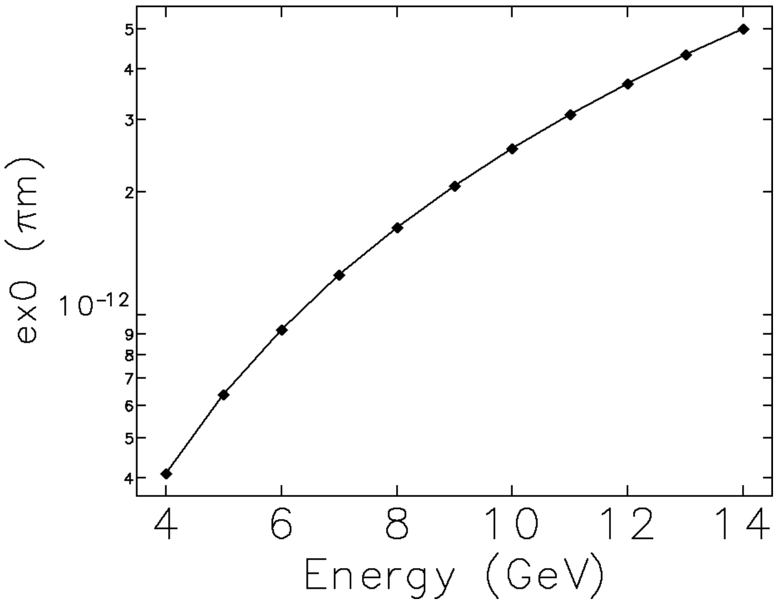
- Fairly wide region within which tune can be varied with matching and FODO quads only
- Start with ν_x=403.1, ν_y=222.2



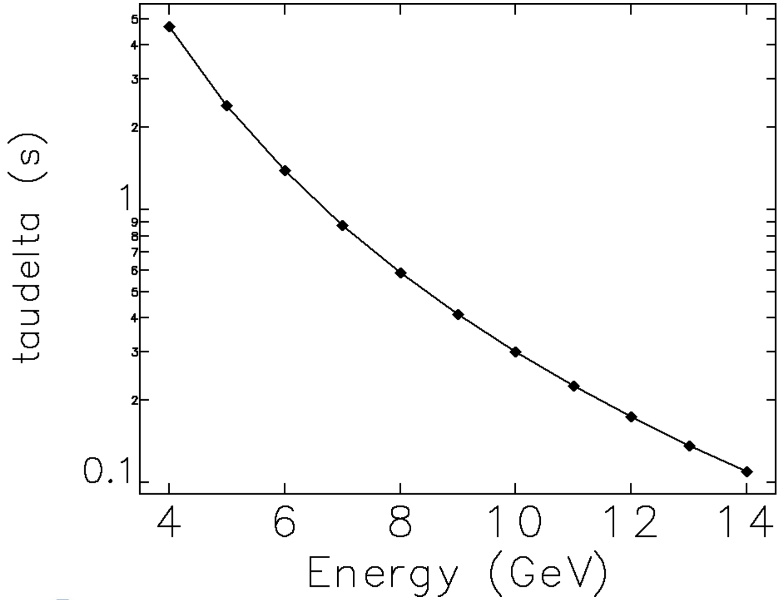
Lattice w/o Damping Undulators (DUs)

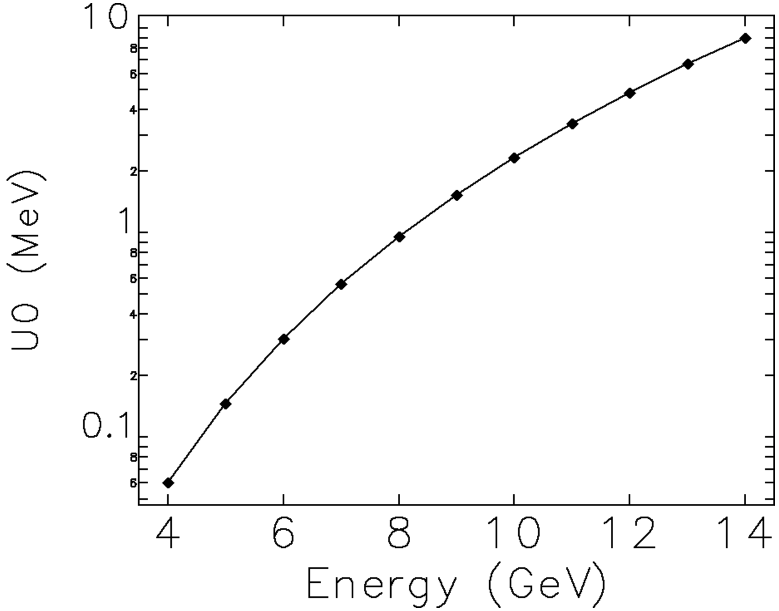
Betatron Tunes		
Horizontal	403.098	
Vertical	222.198	
Natural Chromaticities		
Horizontal	-580.114	
Vertical	-468.581	
Lattice functions		
Maximum β_x	26.341	m
Maximum β_y	29.000	m
Maximum η_x	0.009	m
Average β_x	5.199	m
Average β_y	7.112	m
Average η_x	0.006	m
Radiation-integral-related quantities at 11 GeV		
Natural emittance	3.092	pm
Energy spread	0.089	%
Horizontal damping time	55.241	ms
Vertical damping time	133.097	ms
Longitudinal damping time	225.349	ms
Energy loss per turn	3.425	MeV
Straight Sections		
Effective emittance	0.003	nm
β_x	4.922	m
η_x	-0.000	m
β_y	0.778	m
Miscellaneous parameters		
Momentum compaction	4.468×10^{-6}	
Damping partition J_x	2.409	
Damping partition J_y	1.000	
Damping partition J_δ	0.591	

Energy Scan with no DUs

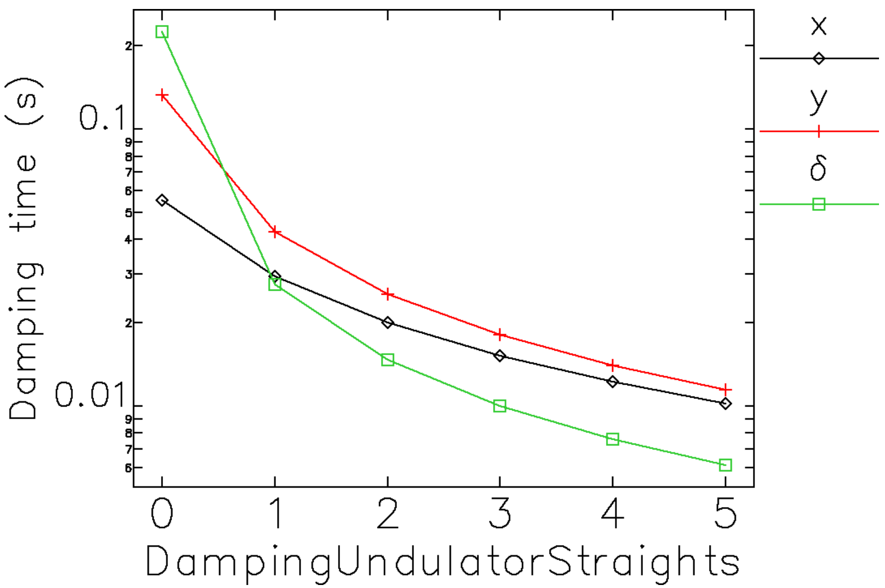


- Longitudinal damping time is very long
- <100ms is "desirable"
  - Means we need damping wigglers plus relatively high energy
- For 11 GeV electron beam, APS U33 can reach below 8 keV x-ray energy

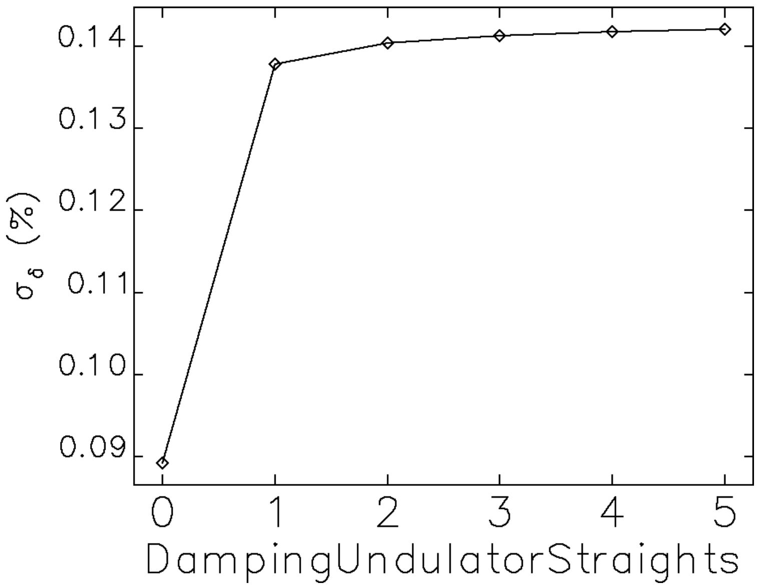


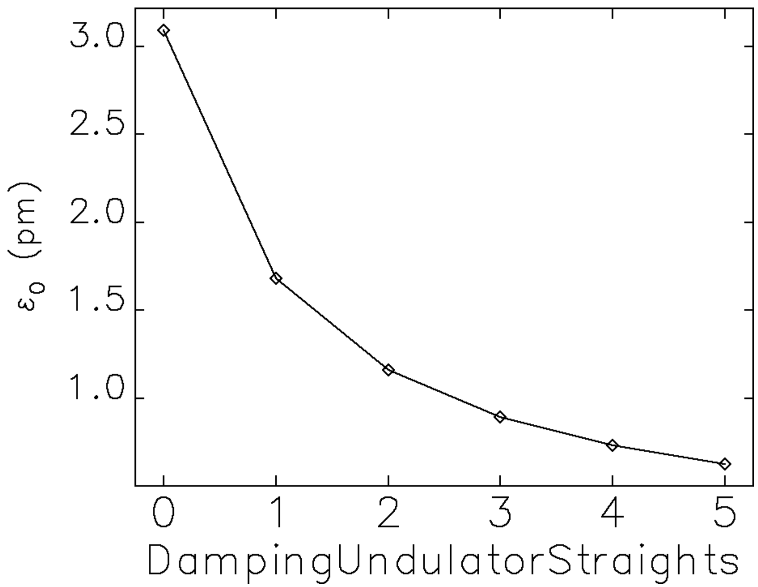


11 GeV with DUs in Several Straights



- DUs assumed to be 1T SCU with 16.7 mm period
- Fourteen 6.7m devices per straight
  - 0.8m per device for warm-to-cold transitions
- Probably 2 straights of DUs is sufficient



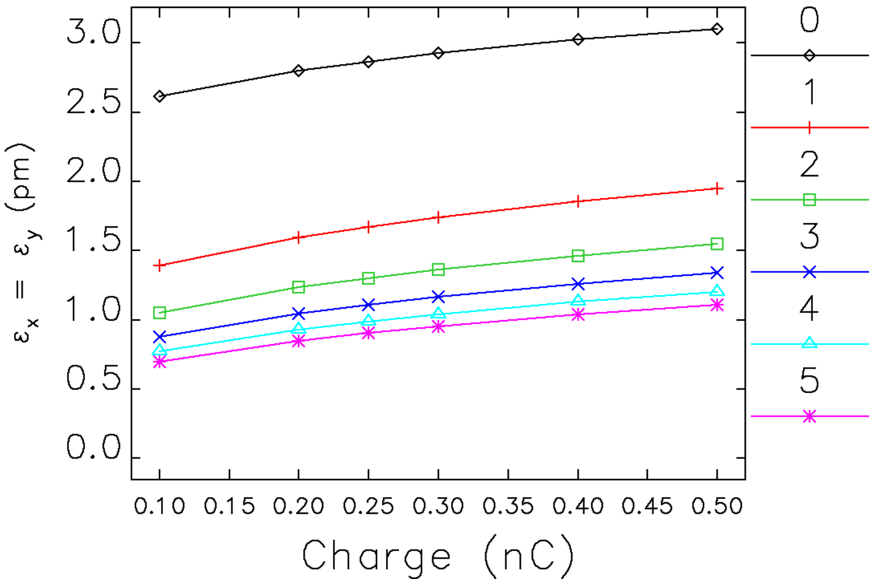


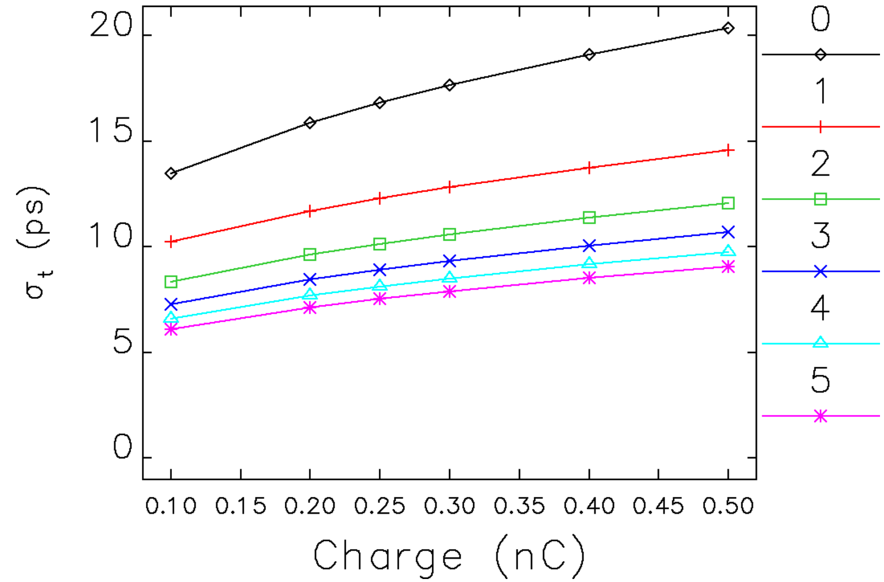
Collective Effects

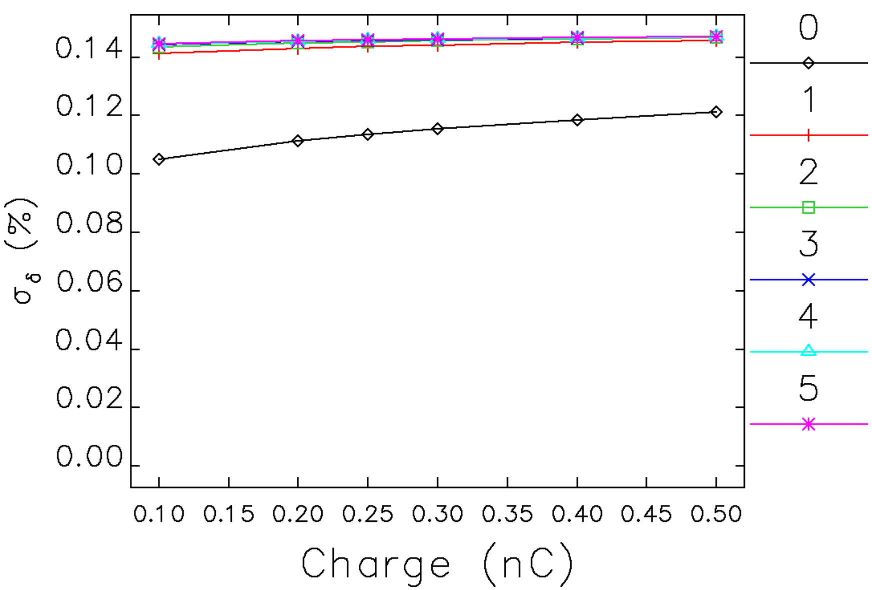
- Took very preliminary look at collective effects
- Solve[1] Haissinki equation assuming |Z/n| = 0.3 Ohm to get bunch length vs current
- Compute[2] equilibrium properties in presence of intrabeam scattering
  - Starting bunch length from Haissinki eqn.
  - Assumed 100% coupling
- Computation[3] of Touschek lifetime, assuming
  - Beam parameters from IBS calculation
  - $\pm$2% constant momentum aperture

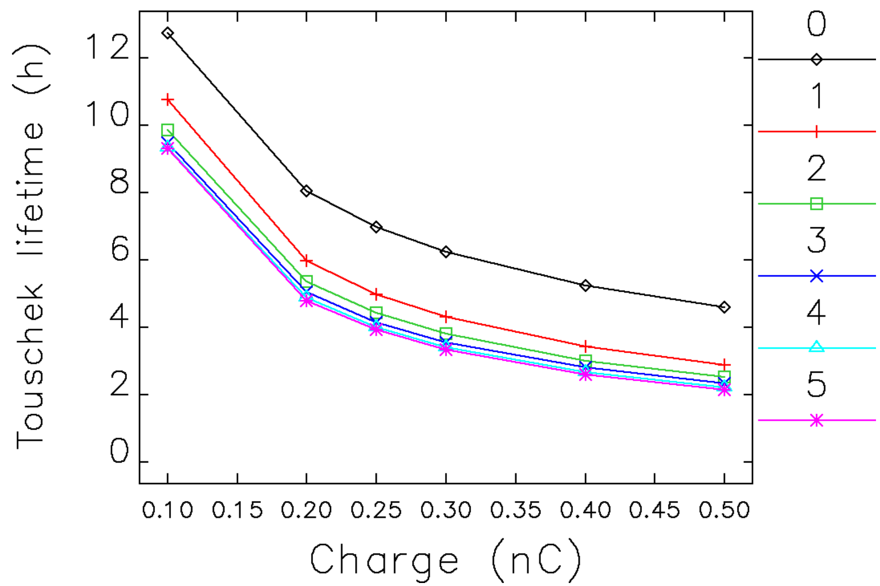
[1]Using **haissinski** (L. Emery, M. Borland).
[2]Using **ibsEmittance** (A. Xiao, L. Emery, M. Borland).
[3]Using **touschekLifetime** (A. Xiao, M. Borland).

Collective Effects for 0-5 DU-filled Straights

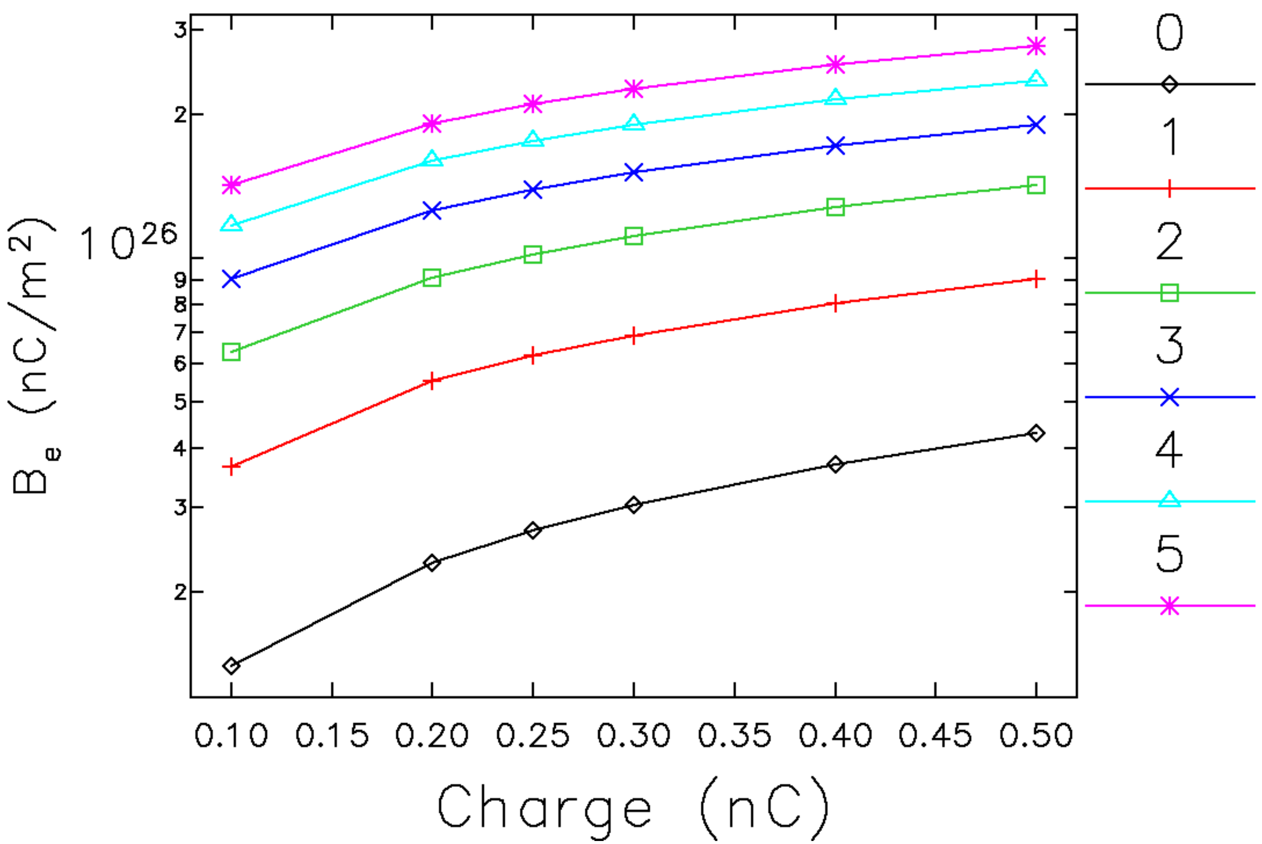








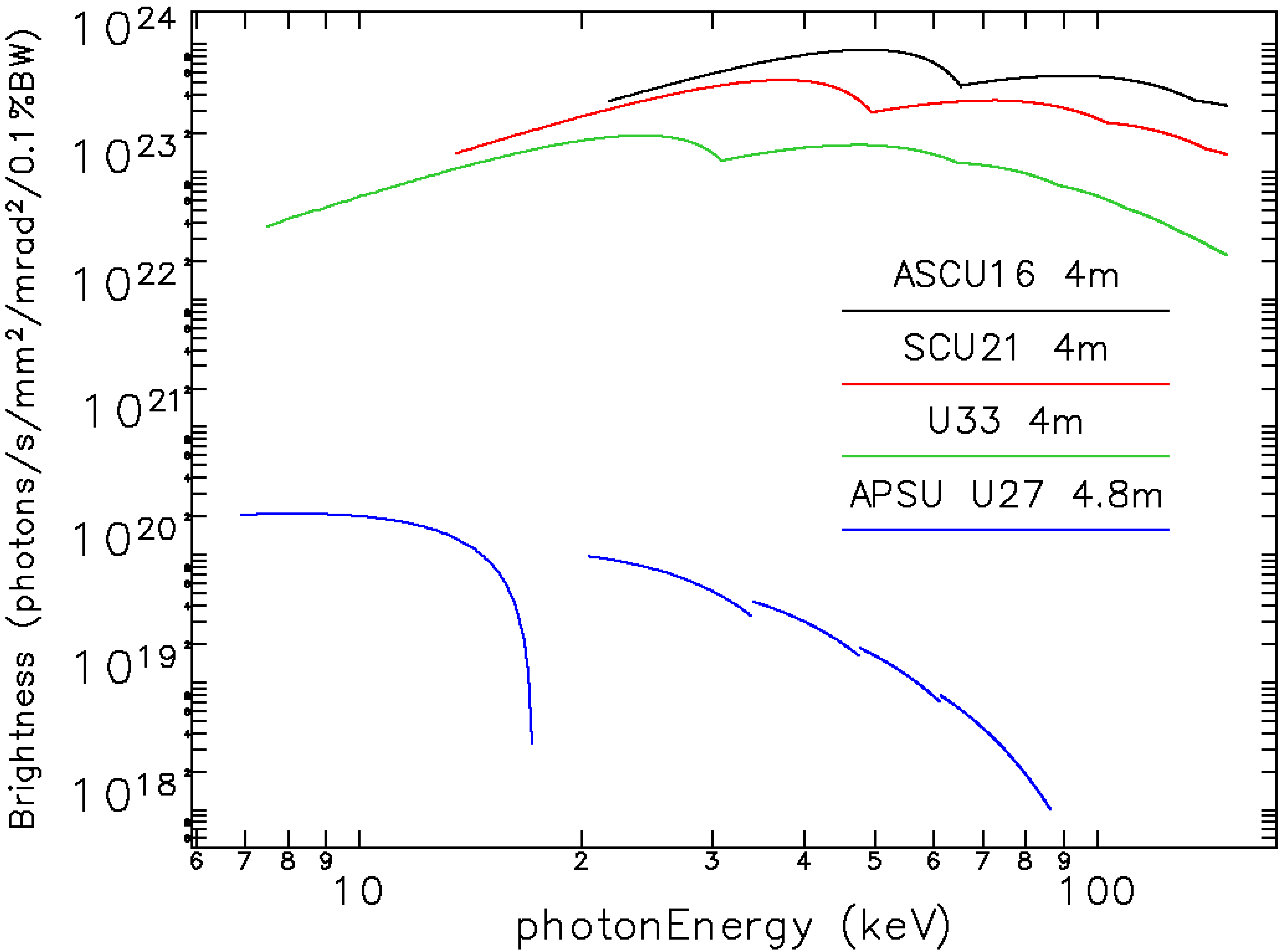
Electron Bunch Brightness



$$B_e = \frac{Q}{\epsilon_x \epsilon_y \sigma_\delta}$$

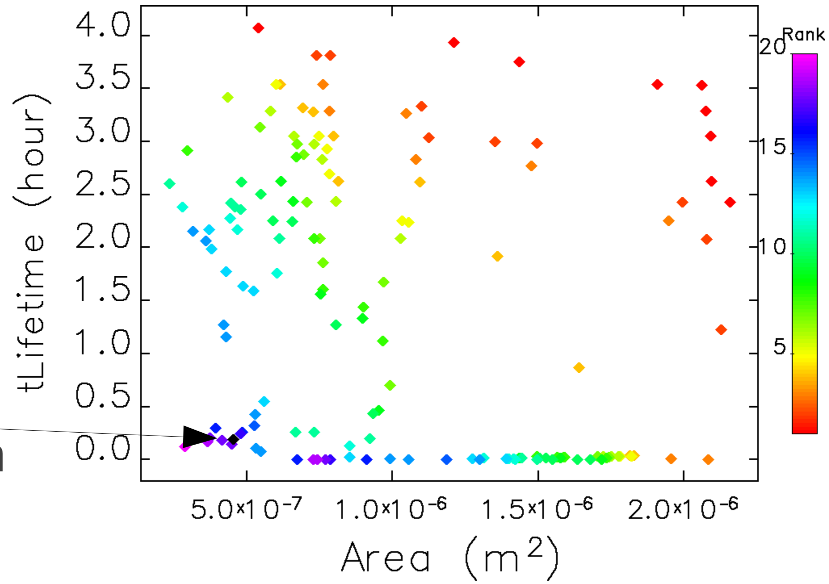
- Diminishing returns evident as more DUs are added
- Similarly as more charge is added
- We'll assume two DU straights

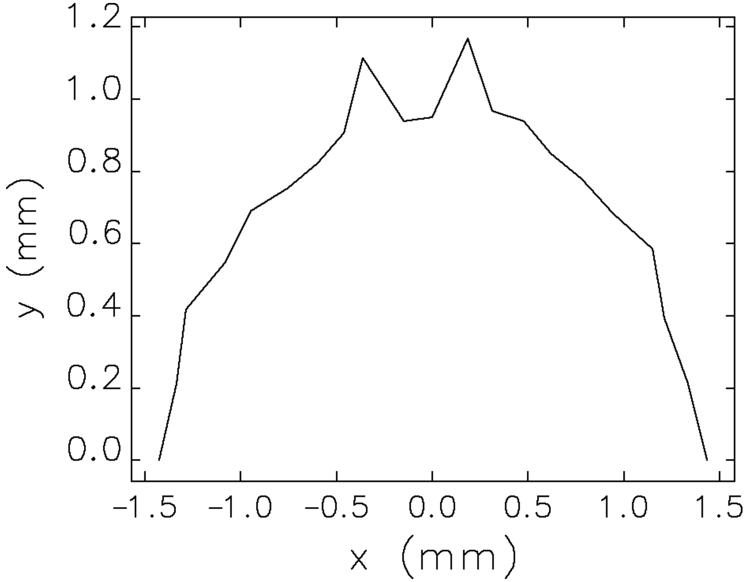
Brightness Performance (2 DU straights)

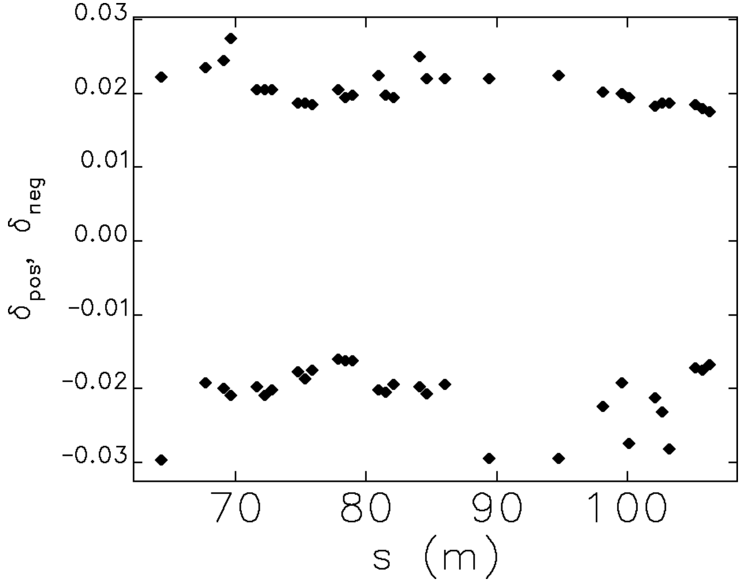


Preliminary MOGA Results (Perfect Machine!)

Starting point
of first optimization







Operational Considerations: Injection

- For 100 mA and 0.25 nC/bunch, need ~8300 bunches
  - 500 MHz rf, fill 80% of 10360 buckets
  - 4.1 µs of 20.7 µs revolution time available for kicker rise/fall
  - If $T_{rise} = T_{fall}$ = 10 ns, need N_T=202 trains of 41 bunches
  - Kicker flat-top is 82 ns long
- Droop between replacements of a given train is

$$D \approx \Delta T_{\rm inj} N_{\rm T} / \tau$$

- Assuming τ=2 h and D=0.1, need ΔT_{inj} = 3.6 s
- Inject 41 bunches of 0.25 nC each time
  - Average power of 31 W

Comparison of “TeVUSR” to Alternatives

- Free-Electron Lasers (FELs)
  - Pro: Unbeatable for peak and average brightness
  - Con:
    - SASE FELs have too much shot-to-shot fluctuation in spectrum and intensity for some experiments
    - High peak power not desirable/workable for all experiments
    - Small number of users per machine compared to USR
    - Difficult to get >25 keV x-rays
  - Seeding and X-ray FEL oscillator address some of these (very narrow bandwidth and reduced fluctuations)
- Energy Recovery Linacs (ERLs)
  - Pro: Probably smaller, cheaper; same flux
  - Con: 10x lower brightness; significant R&D challenges; best performance available to relatively few users

Conclusion

- Storage ring light sources are among the most successful scientific facilities in existence
- Reports that rings had reached the end of the road were premature
  - NSLS-II and MAX-IV under construction
  - MBA lattice design with genetic algorithms
  - 100% coupling and swap-out injection
- Studies continue in Japan, US, Europe
  - Interest in a possible international collaboration on a large ultimate light source
- A Tevatron-sized USR is very intriguing, but much work needed
  - collective instabilities
  - magnet design
  - error studies and nonlinear dynamics optimization
  - cost reduction
  - science case

Acknowledgements

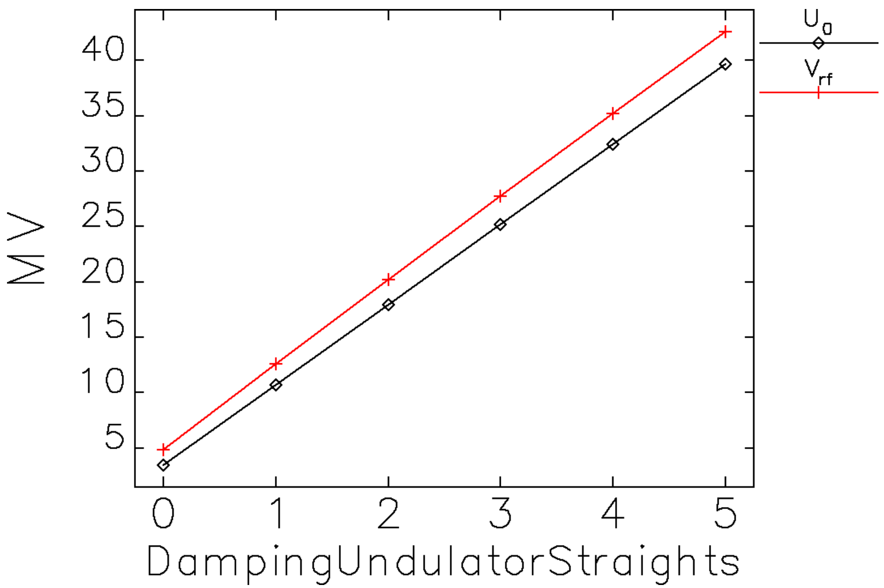
- Thanks to the PEP-X team for providing their lattice and helpful comments and suggestions
  - K. Bane, Y. Cai, R. Hettel, Y. Nosochkov, M.-H. Wang

Issues with DUs

- 1T field is an extrapolation
  - Present APS 16mm SCU achieves ~0.7 T
  - Can reasonably expect to double this in future:
    - Smaller gap
    - Thinner chamber walls
    - Better magnetic material
    - Better superconducting wire
- How to handle 725 kW/straight/100mA ?
  - Will probably need masking within the straights to protect each SCU from upstream SCUs
  - Might be able to cant the devices in order to spread out the power
    - Could then consider varying the device parameters to make useful radiation sources at popular energies (e.g., 12.4 keV)

Rf Voltage and Power Requirements

- Computed required rf voltage assuming 500 MHz and 3% bucket half-height
- With 2 DU straights, need 20MV rf voltage
  - APS 352 MHz cavities, when new, gave 0.75 MV each
  - Assuming same performance for equivalent 500 MHz cavities, would need ~27 cavities
  - Requires ~35m
  - Straights have more than enough room
- At 100 mA, beam power is ~70kW/cavity (not hard)



Running with Round Beams

- There are various ways to make “round beams”, i.e., $\epsilon_x=\epsilon_y$
  - Run on the ν_x-ν_y=N resonance:
    - Pro: $\epsilon_x=\epsilon_y=\epsilon_0/2$
    - Con: hard to control
  - Add a vertically-deflecting damping wiggler
    - Pro: wiggler will provide damping
    - Con: strong, long-period wiggler will impact energy spread; $\epsilon_x=\epsilon_y=\epsilon_0$
  - Add x-y emittance-exchange insertions outside of arcs
    - Pro: simple implementation
    - Con: $\epsilon_x=\epsilon_y=\epsilon_0/\sqrt{2}$
- Of these, the EEX insertion seems preferable
  - Need to explore beam dynamics effects, however
  - Is it actually different from running on ν_x-ν_y=N?