Progress Towards Ultimate Storage Ring Light Sources

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Outline

- Optimization of brightness and emittance
- Challenges of low emittance
  - Nonlinear dynamics
  - Collective effects
- Early ideas for diffraction-limited or “ultimate” light sources
- Trends in light source design
- Progress in next-generation designs
- Conclusion

X-ray Brightness

- The quality of a beam is expressed by the brightness

$$B \propto \frac{N_\gamma}{(\Delta\lambda/\lambda)\Delta t \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$ (simplified form)

- Approximate description of <u>single-electron</u> undulator radiation distribution[1]

$$\sigma_{r'} \approx \sqrt{\frac{\lambda}{2L}} \qquad \sigma_r \approx \frac{1}{2\pi}\sqrt{2\lambda L}.$$

$$\epsilon_r = \sigma_r \sigma_{r'} \approx \frac{\lambda}{2\pi} \qquad \beta_r = \frac{\sigma_r}{\sigma_{r'}} \approx \frac{L}{\pi}$$

- "Diffraction-limited" condition for electron beam

$$\beta_q = \frac{\sigma_q}{\sigma_{q'}} = \beta_r \qquad \epsilon_q = \sigma_q \sigma_{q'} \lesssim \epsilon_r$$

[1]P. Elleaume, in *Wigglers, Undulators, and Their Applications*, 2003.

Example

- 8 keV is sometimes taken as defining the lower boundary of "hard x-rays"

$$\lambda = 1.5\mathring{A} \rightarrow \epsilon_r = 24\mathrm{pm}$$

- For typical 3rd-generation rings

$$\epsilon_x : [1,5]\mathrm{nm} \qquad \epsilon_y : [4,40]\mathrm{pm}$$

so we are several orders of magnitude away from DL performance in horizontal

- For an undulator filling a typical 5-m-long straight

$$\beta_r = 1.6\mathrm{m}$$

which is feasible, but not commonly delivered.

Emittance in Electron Rings

- Equilibrium emittance is given by[1,2]

$$\epsilon_0 = C_q \frac{F(\nu_x, \text{lattice})\gamma^2}{N_d^3} \frac{P_d}{P_d + P_w}$$

- Naively, then, we want
  - Low energy
  - Many weak dipoles
  - Judicious choice of lattice type and tune
  - Strong damping wigglers

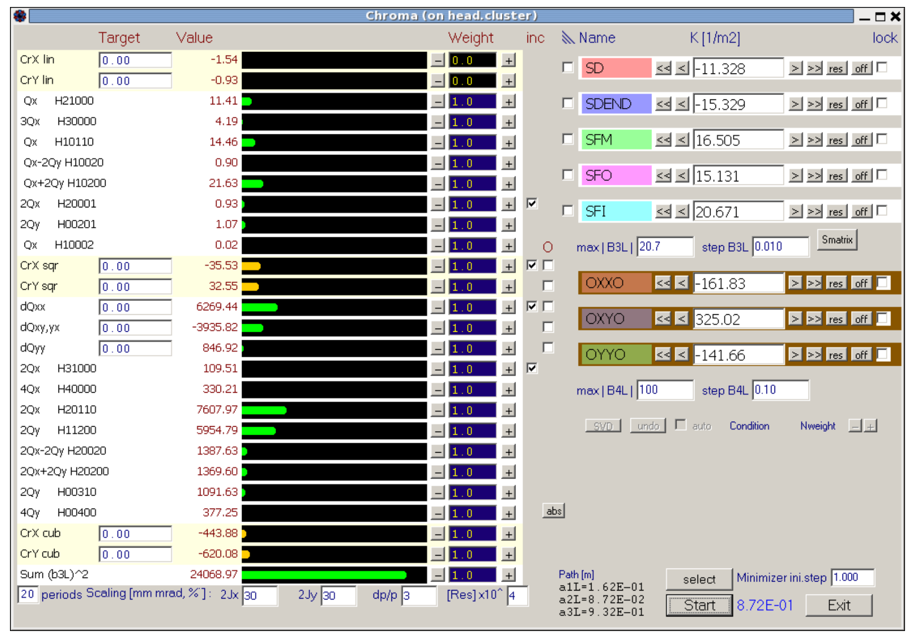
[1] H. Wiedemann, Particle Accelerator Physics, Vol. 1 (1993)
[2] J. Murphy, NSLS Light Source Data Book (1989).

Challenges of Low Emittance

- If we increase N_d to reduce emittance
  - Stronger sextupoles like N_d
  - Dynamic aperture decreases like $1/N_d$
  - Second order chromaticities increase like N_d
- If we optimize tune to reduce emittance
  - Dispersion smaller
  - Chromaticity larger
  - Means stronger sextupoles…
- The essential challenge: stronger sextupoles lead to difficult non-linear dynamics
  - Greater difficulty injecting
  - Reduced lifetime

Optimization of Nonlinear Dynamics

- These issues present even for early 3rd generation sources
  - Led to introduction of “geometric sextupoles”
  - Emphasis on reducing amplitude-dependent tune shifts[1]
- Resonance driving term (RDT) minimization[2]
  - Supports tuning larger numbers of sextupole and octupole families
  - Many successful applications
  - Must check and iterate with tracking

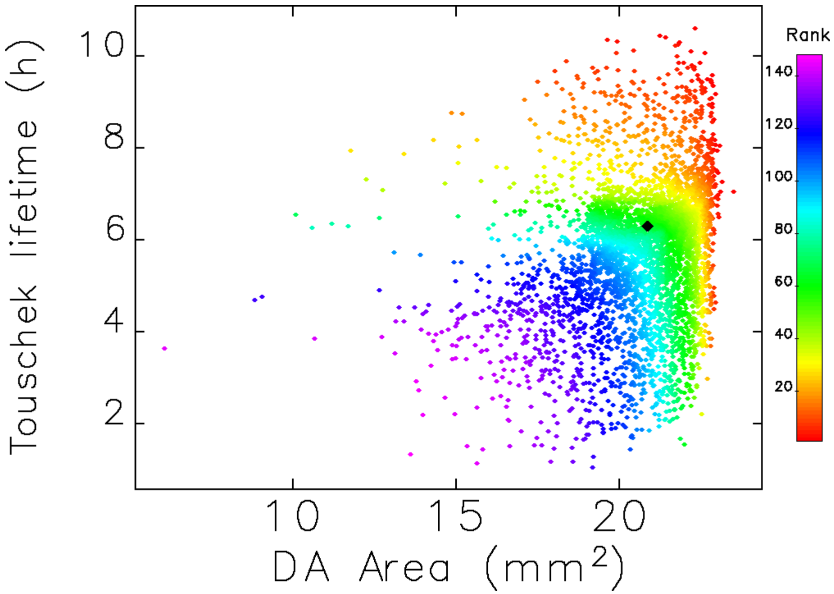


1: E. Crosbie, PAC 1987, 443-445.
2: J. Bengtsson, SLS 9/97 (1997).
3: A. Streun, OPA Lattice Design Code.

The program OPA[3] is one of several used for RDT minimization.

Direct Optimization of Nonlinear Dynamics[1-6]

- Optimize quantities determined by tracking, e.g., dynamic acceptance, momentum acceptance, Touschek lifetime, diffusion rates
  - Made possible by increases in computing power
  - Often used with multi-objective optimizer
- Tune linear lattice as well as sextupoles, octupoles

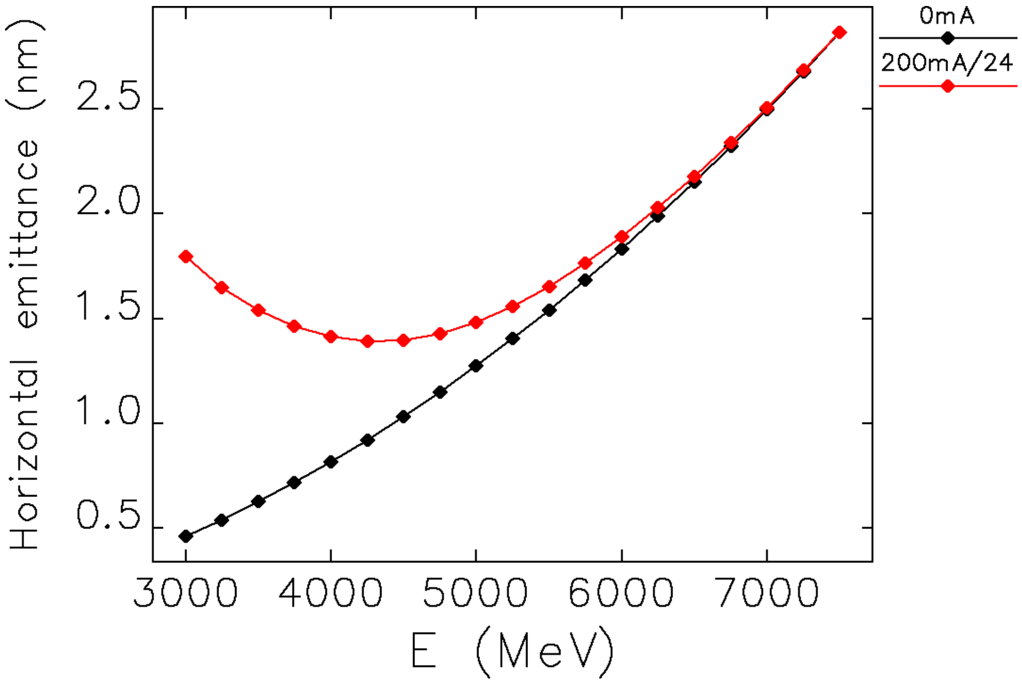


Example of direct optimization of APS dynamic acceptance and Touschek lifetime

1: H. Shang, PAC 2005, 4230-4232.
2: M. Borland, PAC 2009, 3850-3852; APS LS 319 (2010).
3: C. Steier *et al*., IPAC2010, 4746-4749.
4: C. Sun *et al*., PAC 2011, 793-795.
5: L. Yang, PRSTAB 14, 054001 (2011).
6: W. Gao, PRSTAB 14, 094001 (2011).

Intrabeam scattering (IBS)

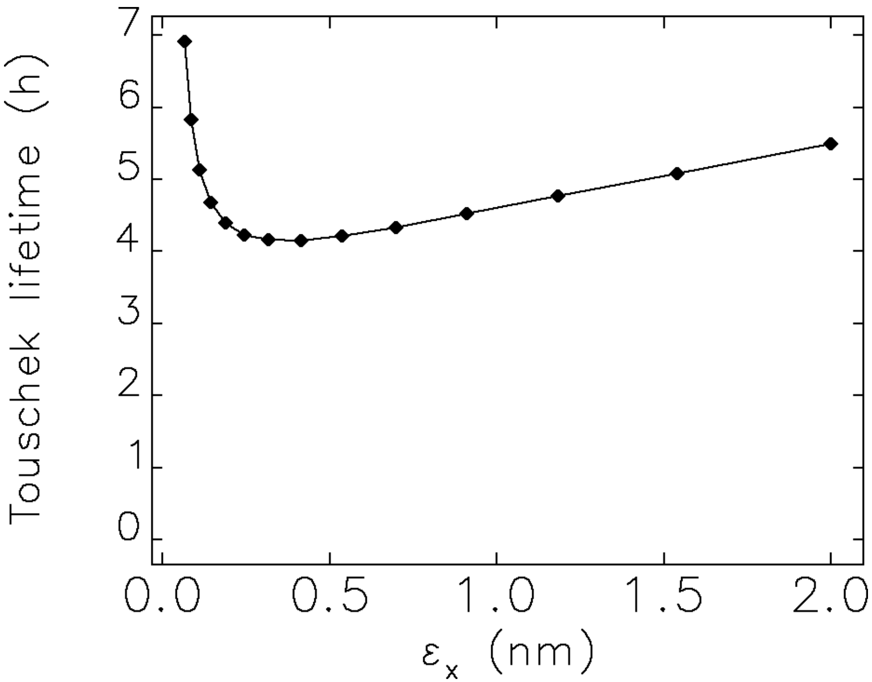
- Multiple electron-electron scattering in a bunch
  - Leads to increased emittance and energy spread
- Fights the beneficial E^2 scaling of emittance
- Motivates having many low-intensity bunches



APS emittance at 200 mA as a function of energy with and without IBS

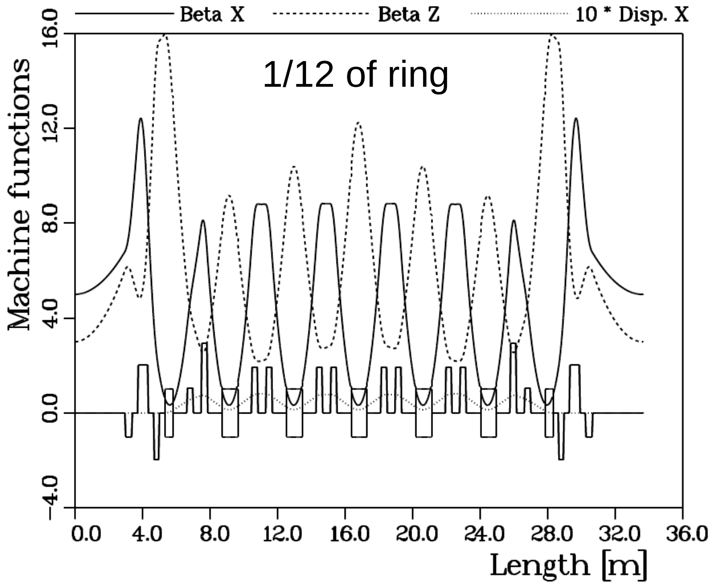
Touschek scattering

- Hard electron-electron scattering leading to large longitudinal momentum kicks
  - Particle loss if outside local momentum acceptance
- Normally thought of as worse for low emittance
  - However, if beam is very "cold", Touschek lifetime increases!



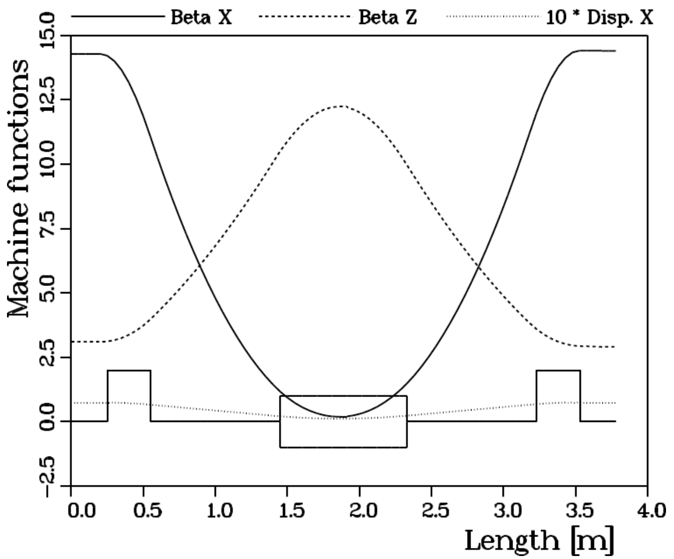
Touschek lifetime for NSLS II assuming emittance can be arbitrarily reduced
(lattice courtesy W. Guo)

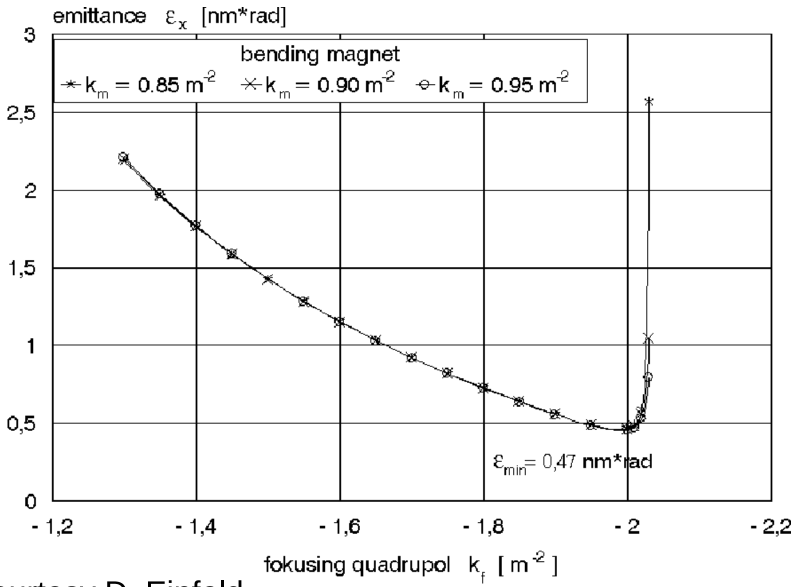
Diffraction-Limited Light Source[1]



In 1995, Einfeld *et al*. described a diffraction-limited light source based on a multi-bend achromat (MBA)

- 7 bends per achromat
- TME-like cells in the center
- Defocusing in dipoles to save space
- 0.5 nm emittance at 3 GeV
- Small beta values at IDs
- Only 400m circumference

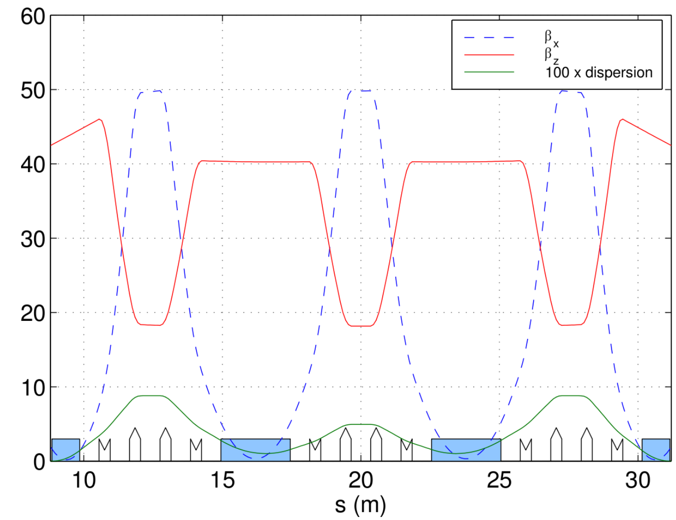


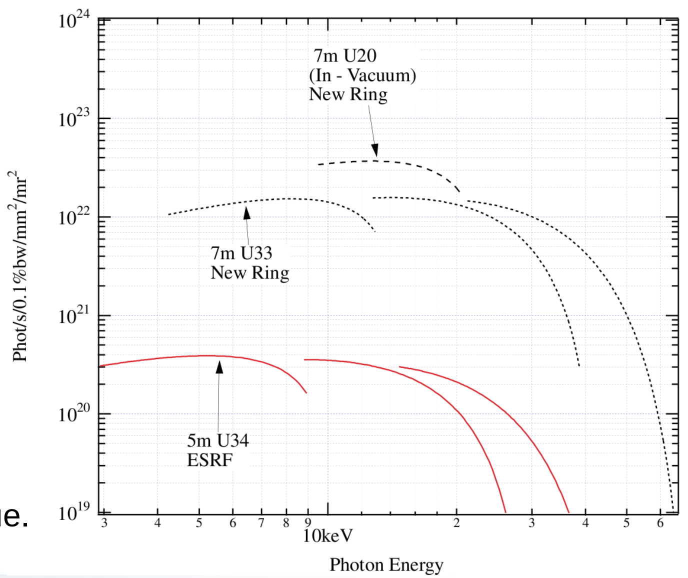


1: D. Einfeld *et al.*, PAC 1995, 177-179. Figures used courtesy D. Einfeld.

The “Ultimate Storage Ring”

- In 2000, Ropert *et al.* described[1] an Ultimate Storage Ring Light Source
- 7 GeV, 2 km circumference, four-bend achromatic cells
  - 0.3 nm emittance
- 7-m-long undulators
- 500 mA
- ~100x increase in brightness
- Suffered from comparison with ERL concepts[2]
  - Emittance significantly larger
  - High power loads
- Many misinterpreted these problems as fundamental

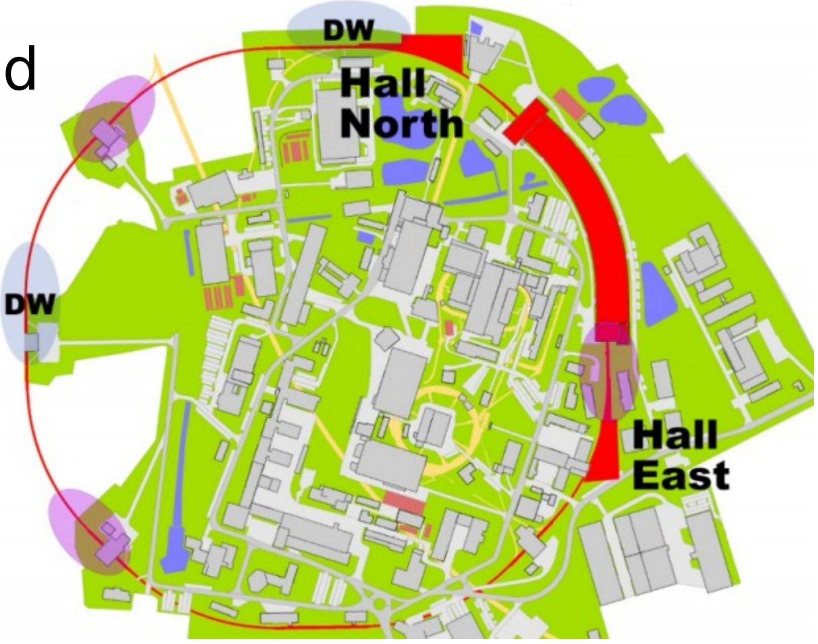


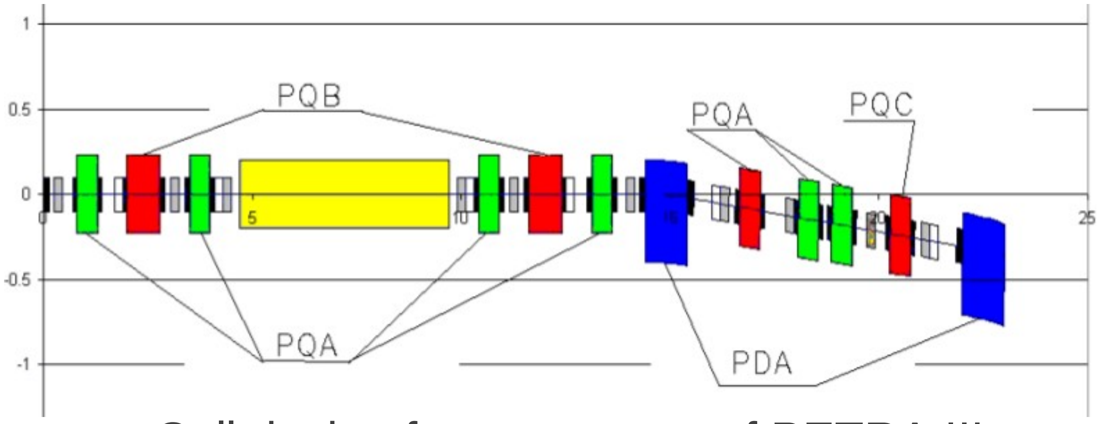


1: A. Ropert *et al.*, EPAC 2000, 83-87; Figs. courtesy L. Farvacque.
2: I. V. Bazarov *et al.*, PAC 2001, 230-232.

PETRA III Facility[1]

- In 2004, PETRA III was proposed
- Conversion of 2.3-km high-energy physics ring
- Replaced one arc with DBA cells for IDs
  - Beta functions approaching the ideal values L/π
- 80 m of wigglers reduce emittance 4.5-fold to 1 nm
- Now in operation at 6 GeV, 100 mA



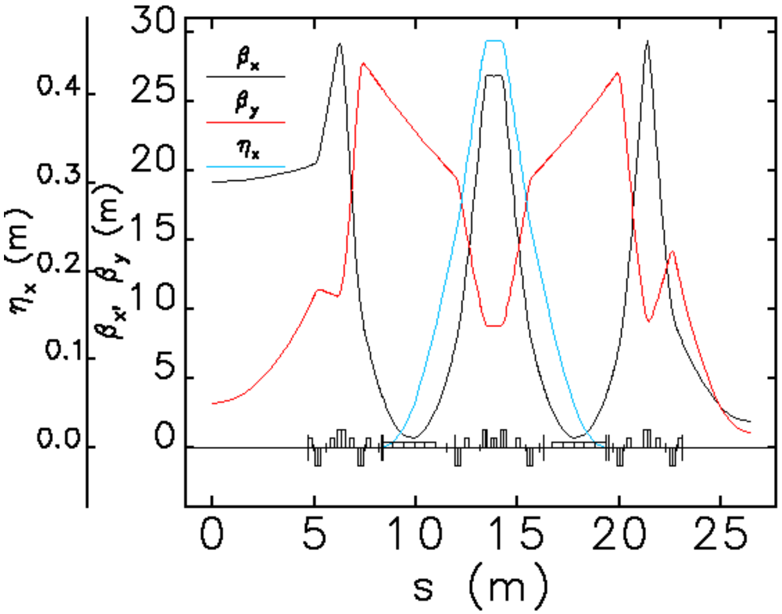


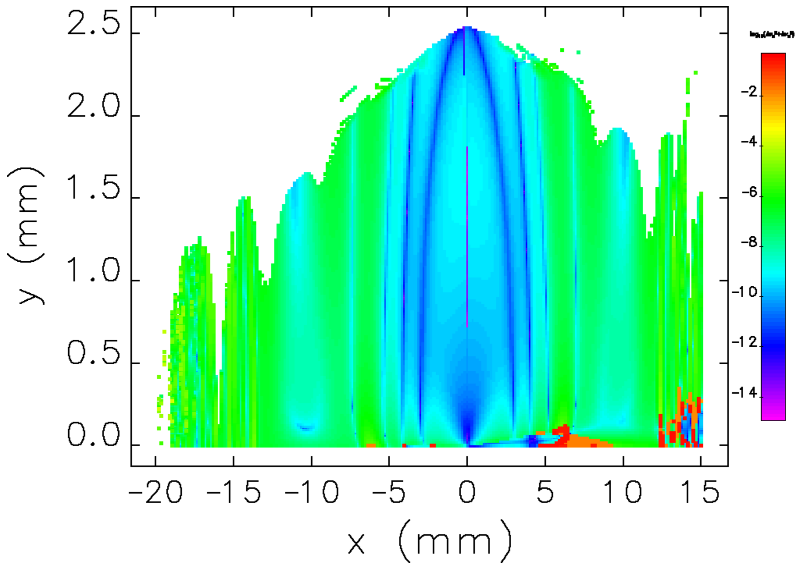
Cell design for new octant of PETRA III.

1: K. Balewski *et al.*, PETRA-III TDR (2004). Figures courtesy K. Balewski.

NSLS Upgrade: NSLS II[1]

- Shares features with PETRA III
  - Large ring (792 m) for its energy (3 GeV)
  - Damping wigglers planned
    - Will reduce emittance up to 4-fold
    - 0.5 nm emittance with 8 DWs
- Beta functions in short straights within factor of two of ideal values
- Challenging nonlinear dynamics tuned with 10 sextupole families
- Commissioning in 2014

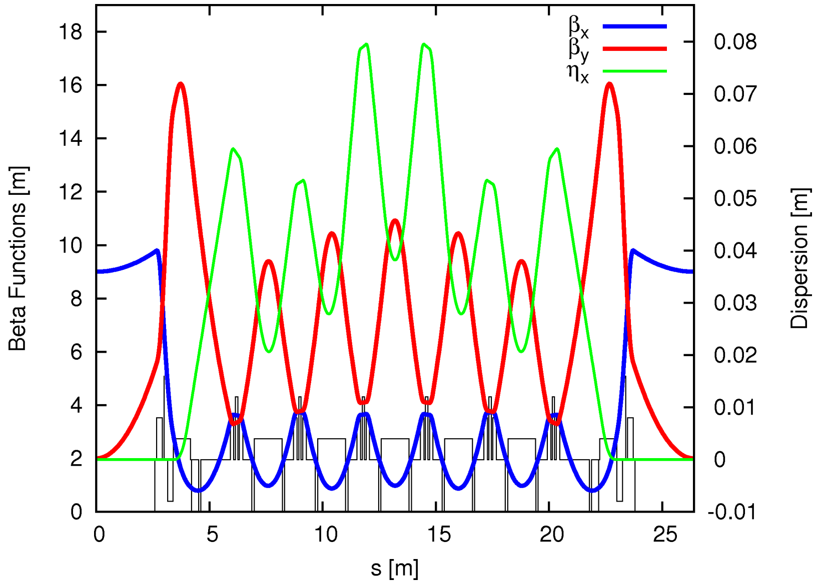


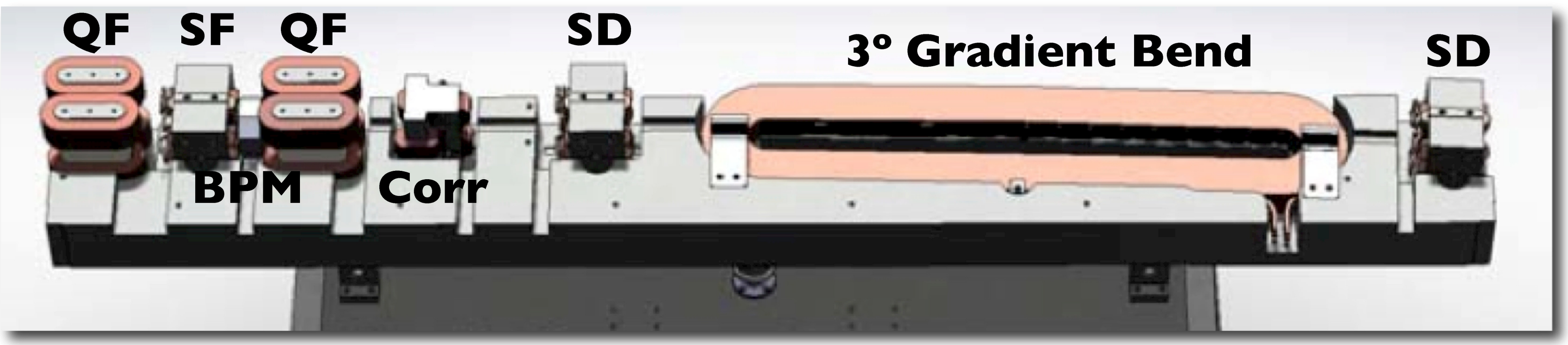


1: J. Ablett et al., NSLS-II CDR (2006).
NSLS-II lattice file courtesy W. Guo.

MAX IV Light Source[1]

- MAX IV will be the first MBA-based light source
  - 3 GeV, 528 m circumference
  - 20 7BA cells
    - Relaxed from TME condition to improve nonlinear dynamics
  - ε_0=263 pm with 4 wigglers
  - In construction



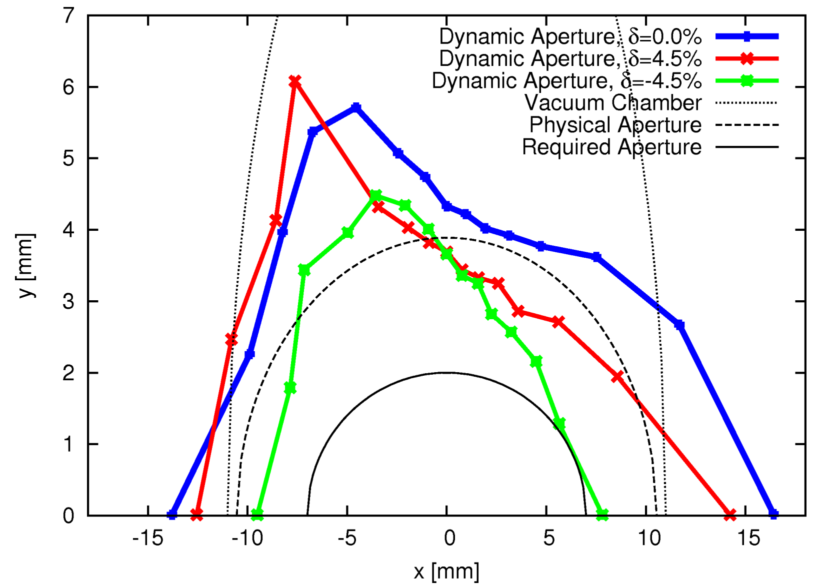


Magnets are built with common yokes to reduce cost while improving relative alignment and stability.

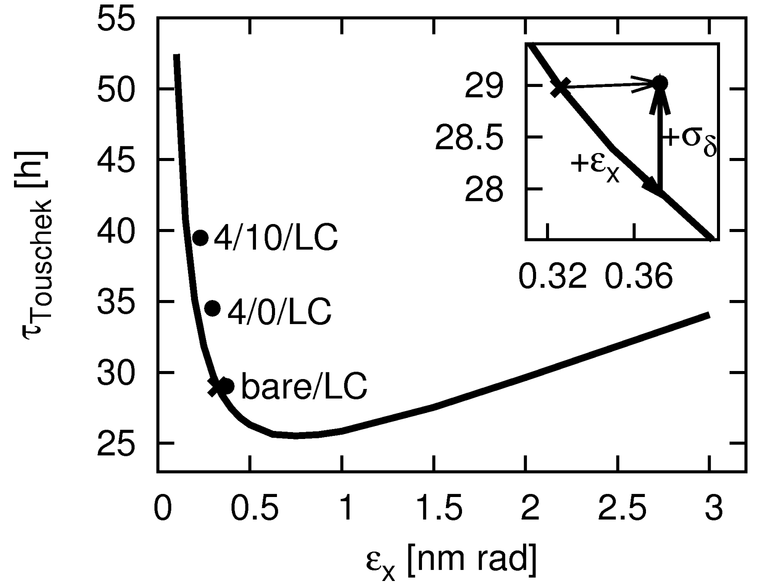
1: S.Leemann *et al.*, PRSTAB **12**, 120701 (2009). Figures courtesy S. Leemann.

MAX IV Light Source

- Nonlinear dynamics tuned using RDT minimization
  - 5 sextupole families
  - 3 octupole families
    - Directly address tuning of amplitude-dependent tune shifts



- Touschek lifetime improves significantly as emittance is lowered
- IBS at 500 mA controlled using bunch-lengthening cavity



Figures courtesy S. Leemann.

Next-Generation Designs: XPS7[1]

- 7 GeV, 1.1 km circumference (APS replacement)
- 40x6BA cells, giving ε_0=78 pm
- Feasibility not shown
  - Poor nonlinear dynamics performance
  - Strong combined function quad/sextupole magnets
- First attempt to challenge ERLs
  - 0.5 µm normalized emittance
  - Too extreme for a 1.1-km circumference
- However, revived some earlier ideas[2,3]
  - Operation with "round beams" to reduce IBS and increase lifetime
  - Use of on-axis injection and "swap-out" mode to deal with small dynamic aperture

1: M. Borland, NIM A 557, 230-235 (2006); ERL2005 workshop.
2: L. Emery *et al*., PAC 2003, 256-258.
3: E. Rowe *et al*., Part. Accel 4, 211 (1973).

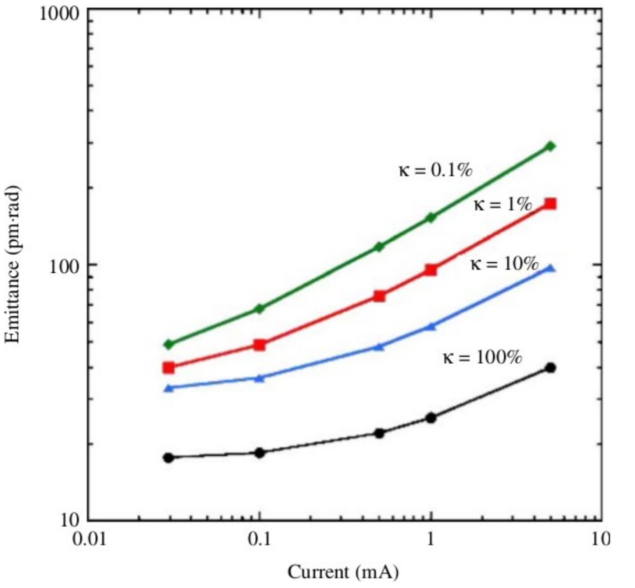
Operation with "Round Beams"

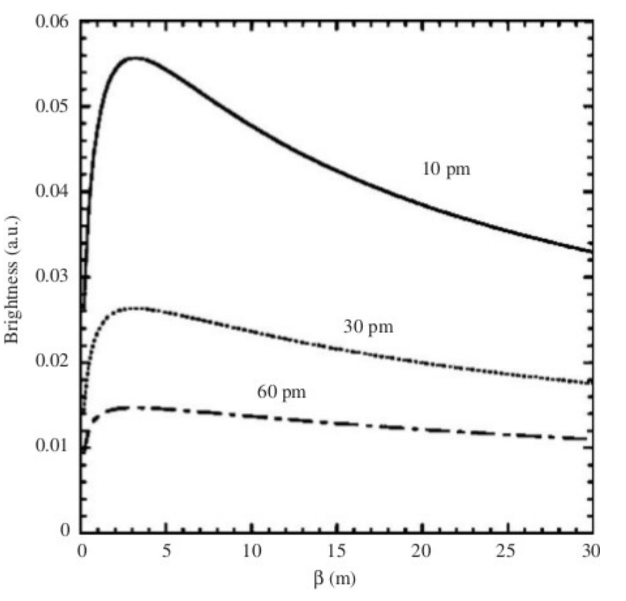
- Present rings have $\kappa=\varepsilon_y/\varepsilon_x \ll 1$
  - Improves brightness
  - Essential for accumulation with small gap chambers
- When we make ε_x very small, $\kappa \ll 1$ is pointless
  - Brightness dominated by single-electron radiation distribution
  - Drives up IBS and Touschek scattering rates
- Better approach[1,2]
  - Run with $\kappa=1$ ("round beams")
  - Inject on-axis
    - Greatly reduces acceptance requirements
    - Drive emittance much lower!
  - Use swap-out mode of operation:
    - Upon injection, old bunch (trains) are ejected and replaced

1: L. Emery *et al*., PAC 2003, 256-258.
2: E. Rowe *et al*., Part. Accel 4, 211 (1973).

Next-Generation Designs: Tsumaki *et al.*

- 6 GeV, 2 km circumference
- 32x10BA cells, giving ε_0=35 pm
- First feasible <100 pm design
  - DA suitable for beam accumulation
  - Several hour Touschek lifetime
  - Workable magnet designs with 20mm bore radius
  - With full coupling and IBS, 21 pm in both planes
- However
  - Large beta functions in straights not ideal for brightness
  - Straight sections only 4m long

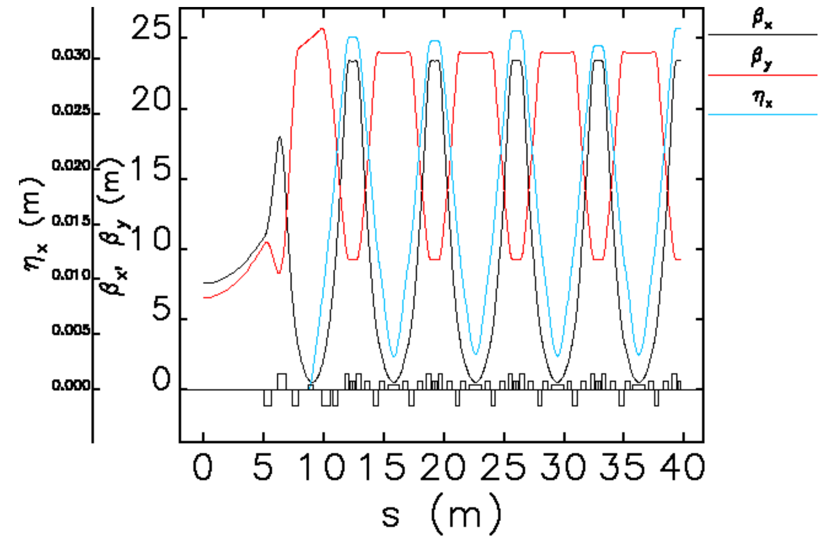


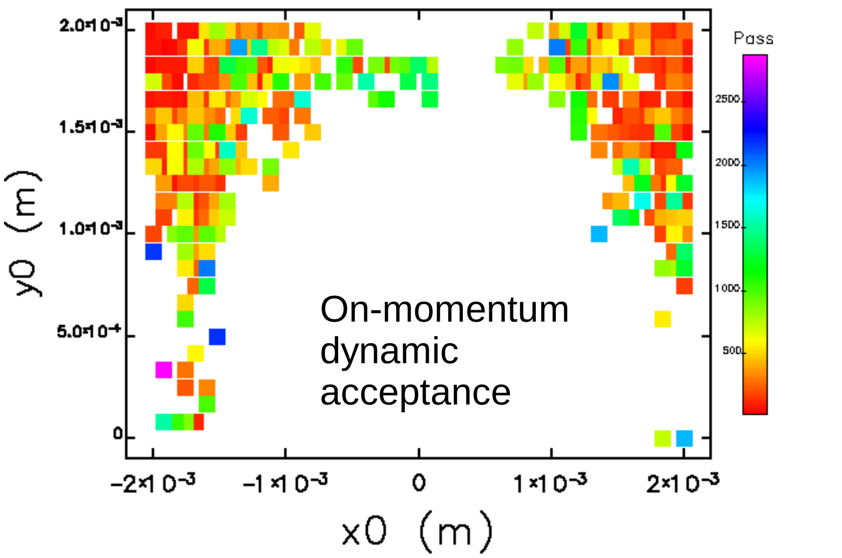


1: K. Tsumaki *et al*., NIM A 565, 394-405 (2006).
Figures courtesy K. Tsumaki.

Next-Generation Designs: USR7[1]

- 7 GeV, 3.1 km circumference
- 40x10BA, giving ε_0=30 pm
  - 10 m straight sections
  - Beta functions in straights better, but still not ideal
- Feasible design
  - DA suitable for on-axis injection
  - Momentum aperture of ±2%
  - Workable magnet designs with 20mm bore radius

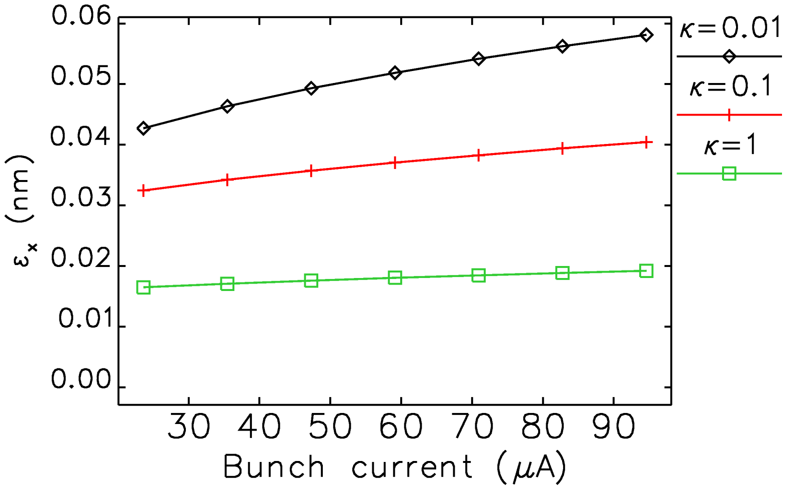


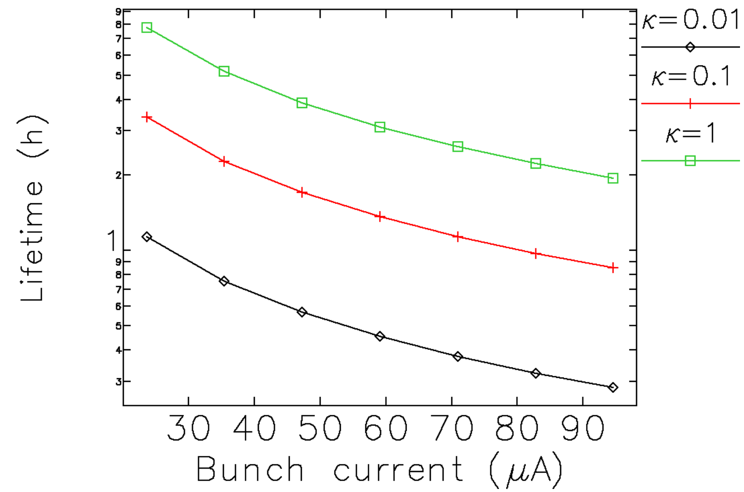


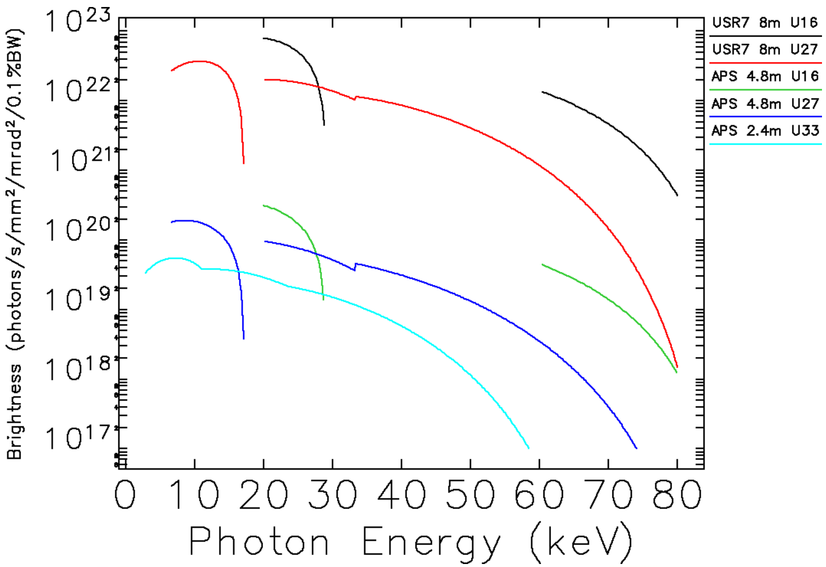
1: M. Borland, AIP Conf. Proc 1234, 911-914 (2010).

Next-Generation Designs: USR7

- IBS and Touschek controlled using full coupling at 200mA with 4200 bunches





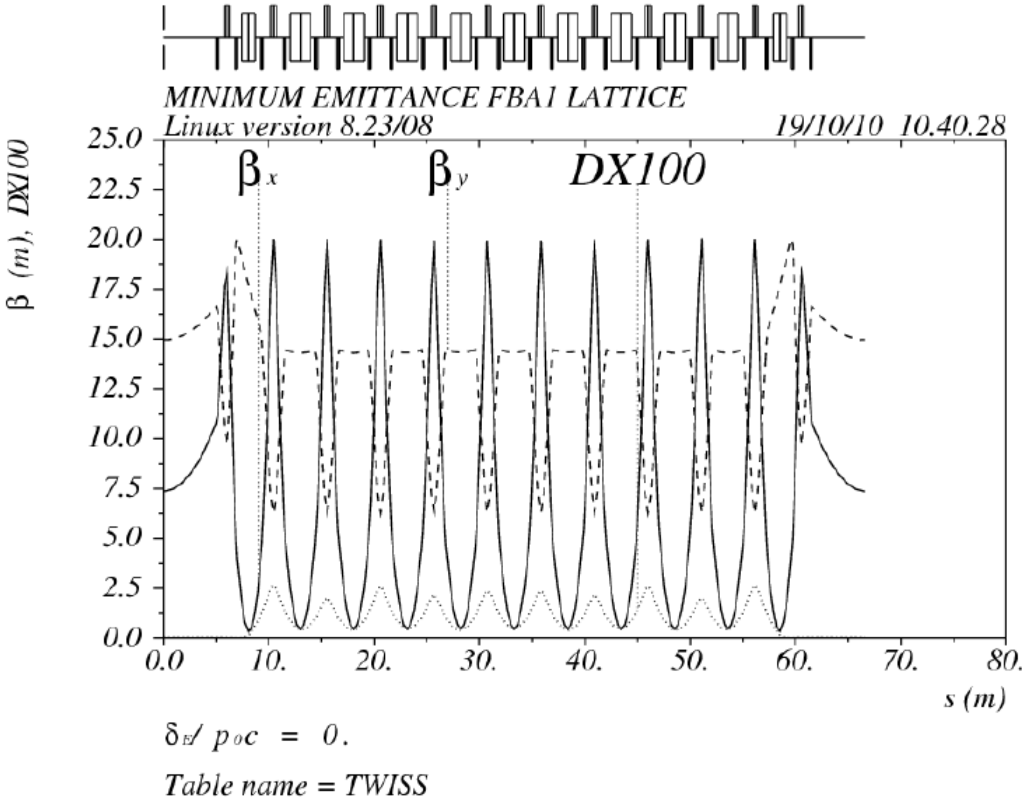


~300-fold increase in brightness compared to APS

Swap-out Example

- For USR7, lifetime is ~4 hours with 200 mA in 4200 bunches
  - 80% of 500 MHz buckets filled
  - 0.5 nC/bunch
- Assume kickers have 10 ns rise and fall times
  - 210 trains of 20 bunches
  - Need 40 ns kicker flattop
- Replace trains when they “droop” by 10%
  - Replace one train every 6 seconds
  - Average injector current is <2 nA
- Take APS injector (c. 1994) for comparison
  - Delivers 6 nA routinely
  - Injector availability is >97% (average of last 12 years)

Indiana University 10pm USR design[1,2]



Parameters	Value
Circumference	2663m
Energy	5GeV(4-7GeV)
Natural chromaticities	-595.339(horizontal) -148.741(vertical)
Qx	202.9
Qy	33.884
dE/E	3.8e-4
Momentum compaction factor	1.223e-5
Natural emittance	9.1pm(before coupling)

Twiss parameters for one superperiod with dispersion function magnified by 100 times.

Large natural chromaticities are induced by large number of dipoles and small beta functions.

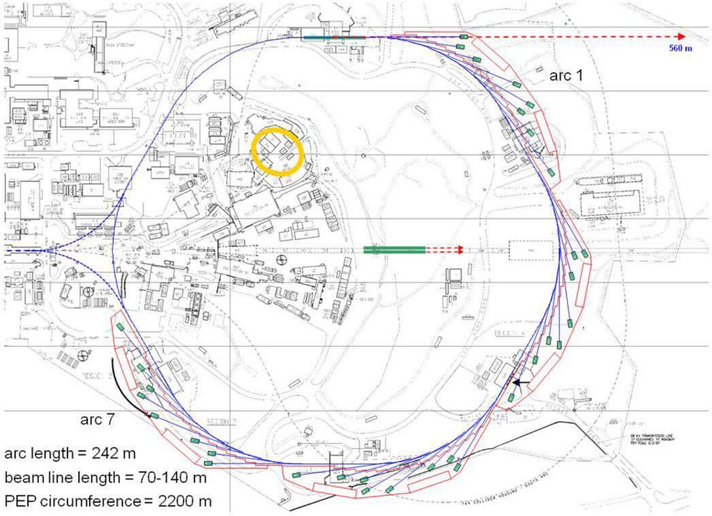
Dynamic acceptance suitable for on-axis injection.
Momentum acceptance >±1.5%

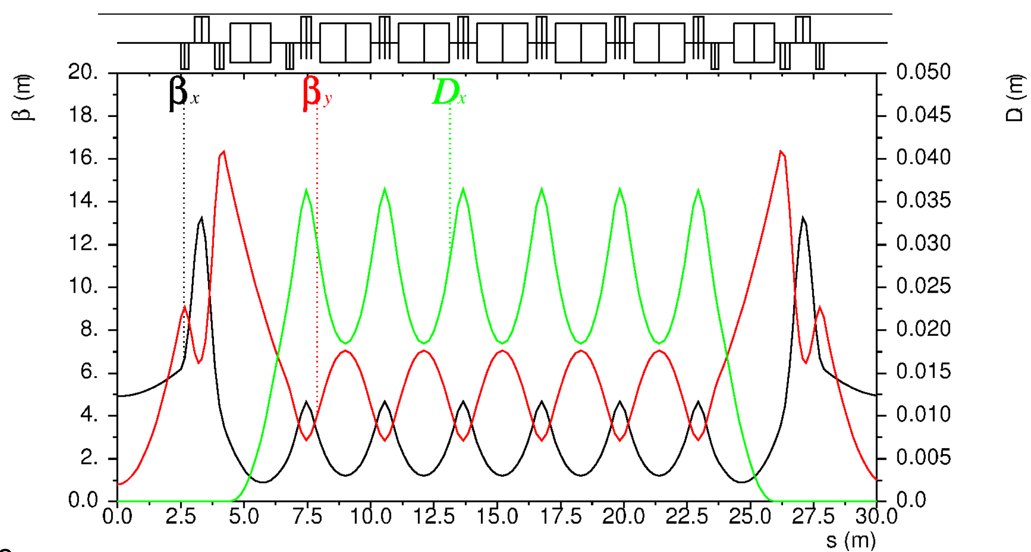
1: Y.Jing, IU thesis, August 2011.
2: Y. Jing *et al.*, PAC 2011, 781-783.

Content courtesy Y. Jing.

Next-Generation Designs: PEP-X[1]

- Would use PEP-II tunnel
  - 4.5 GeV, 2.2 km circumference
  - 48x7BA, giving ε_0=22 pm
    - 90m damping wigglers
  - 5 m straight sections
  - With full coupling and IBS, 11 pm emittances
- Patterned on MAX IV
  - More aggressive tuning for low emittance
- Long straights use up 30% of circumference



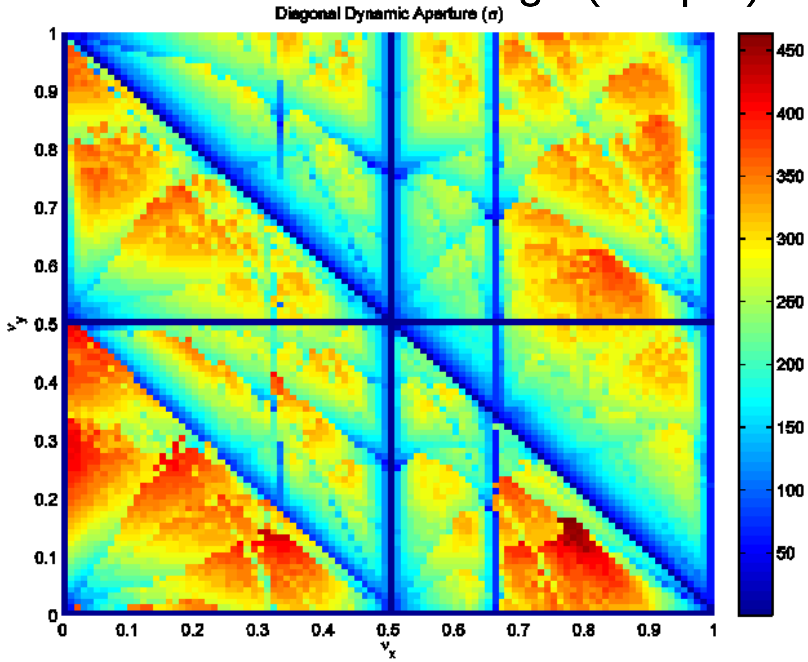


1: Y. Nosochkov *et al*, IPAC 2011, 3068-3070.
Figures courtesy Y. Cai.

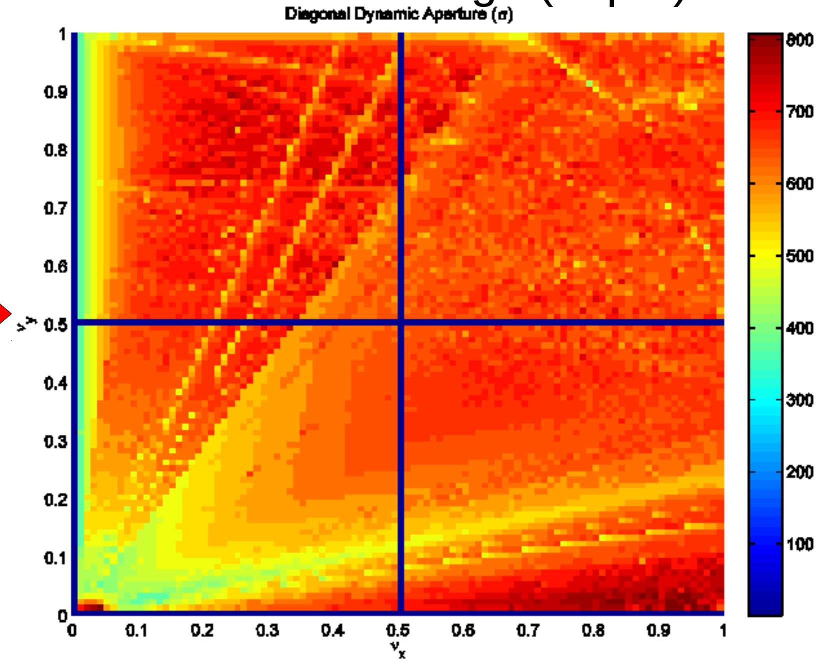
PEPX nonlinear compensation scheme[1,2]

- Automatic cancellation of most 2nd-order RDTs driven by chromatic sextupoles
- Use of geometric sextupoles to cancel remaining RDTs
- Relies on assembling cells into units that have +I transform in both planes

PEPX Baseline design (160pm)



PEPX USR design (22pm)

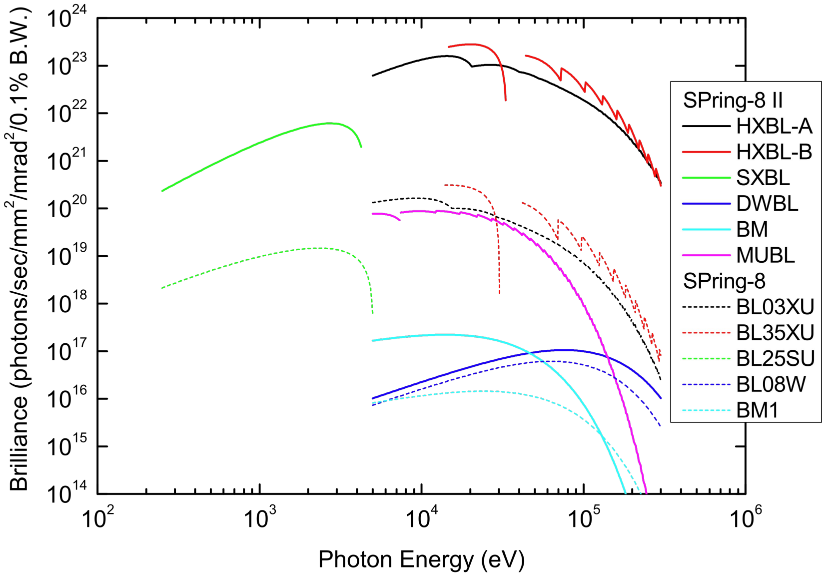


1:Y. Cai, NIM A 645, 168-174, 2011.
2:Y. Cai *et al.*, SLAC-PUB-14785 (2012).

Figures courtesy Y. Cai.
See also, Y.Cai, FLS2012.

Next-Generation Designs: SPring-8 II

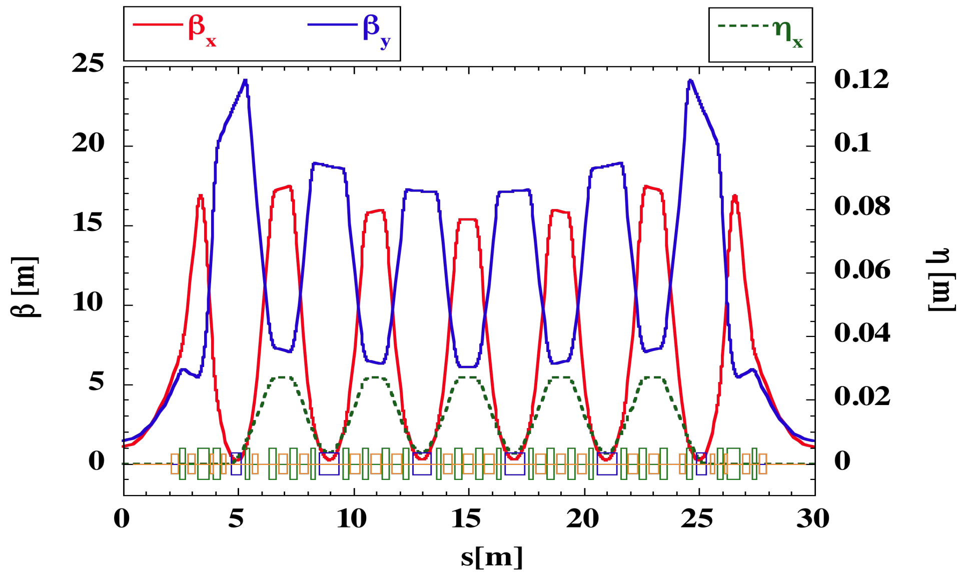
- In early 2012, Ishikawa *et al.*, published a preliminary upgrade report for SPring-8[1]
  - Replace existing 1.4-km ring in 2019 (1-year shutdown)
  - Use existing tunnel and x-ray hutches
  - ~1000x brightness



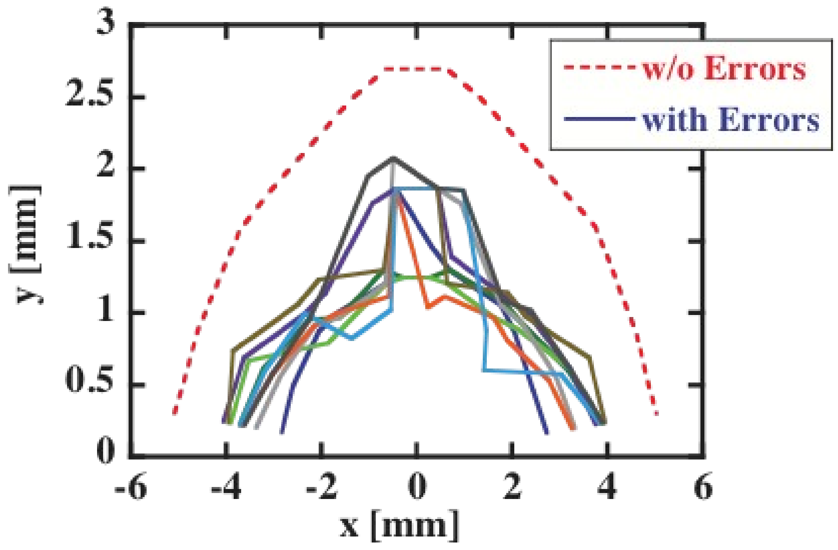
	SPring-8 (present)	SPring-8 II (planned)
Electron energy	8 GeV	6 GeV
Current	100 mA	300 mA
Emittance	3.4 nm	67→10 pm
Coupling	0.2%	~2%
Bunch length	13 ps	>20 ps
# beamlines	62 max.	62+ max

1:T. Ishikawa *et al.*, Jan. 2012. (Google "Spring-8 upgrade plan".)
Graphics and content courtesy T. Watanabe.

SPring-8 II Preliminary 6-BA Lattice



67 pm emittance without damping wigglers or undulator damping



DA with errors suitable for on-axis injection.

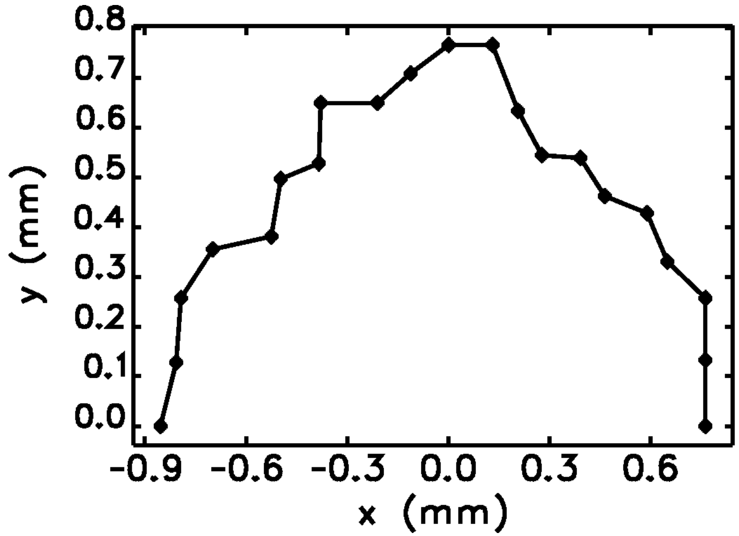
New injection scheme planned with on- and off-axis modes

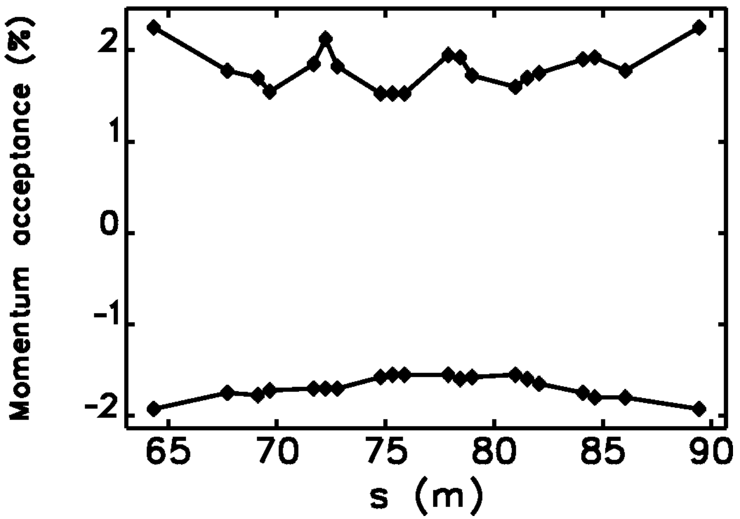
Graphics and content courtesy T. Watanabe.

τUSR: A Tevatron-Sized USR[1]

$\tau \equiv 2\pi = 6.28...$

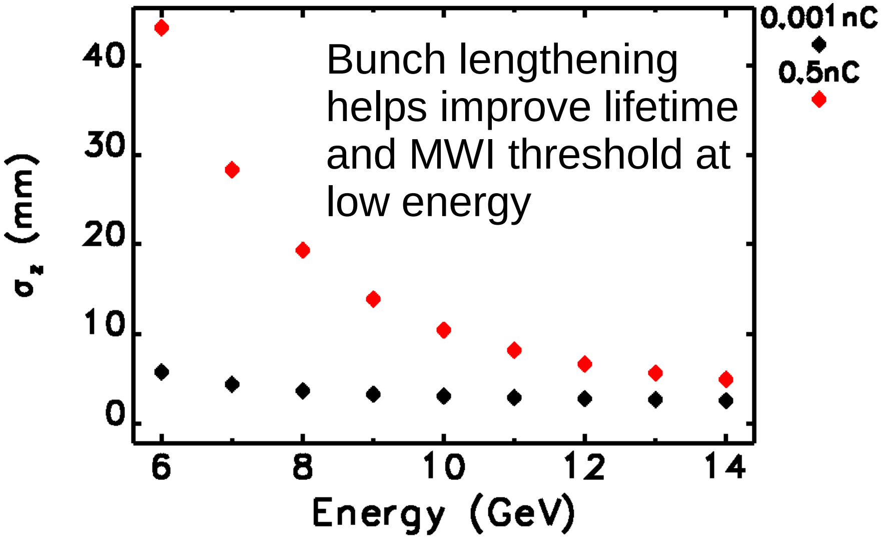
- What to do with Tevatron tunnel now?
- Exploratory light source design
  - Roughly match 6-straight, 6-arc geometry
  - Use PEP-X optics modules
    - 6 arcs with 30 cells of 7BA giving N_d=1260
    - Relax cell tunes, giving ϵ_0=2.9 pm at 9 GeV
  - Preliminary MOGA gives
    - Adequate DA for on-axis injection, 4.5 h gas-scattering lifetime
    - Adequate LMA for 4 h Touschek lifetime for 0.5nC/bunch

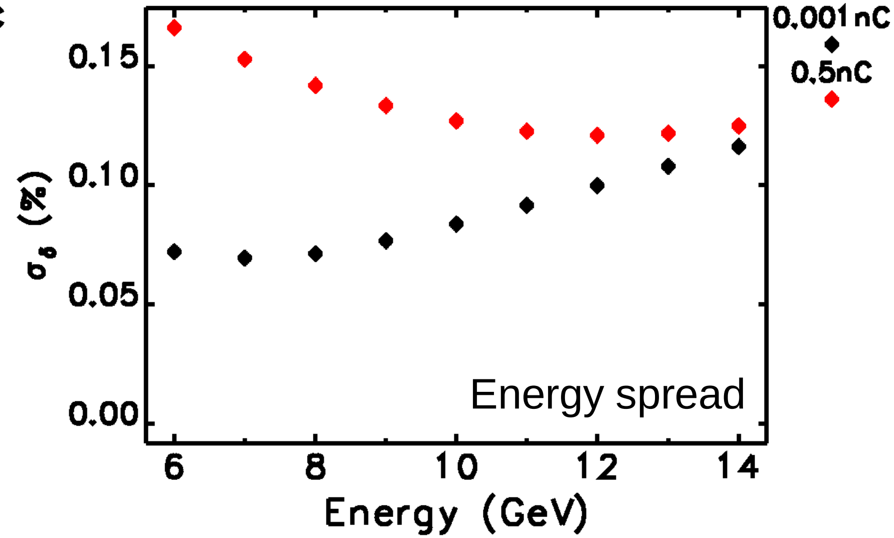


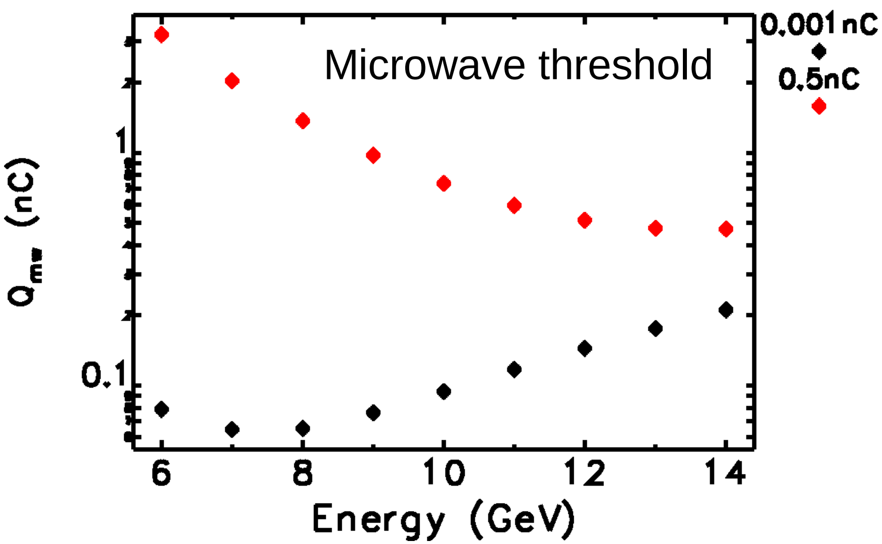


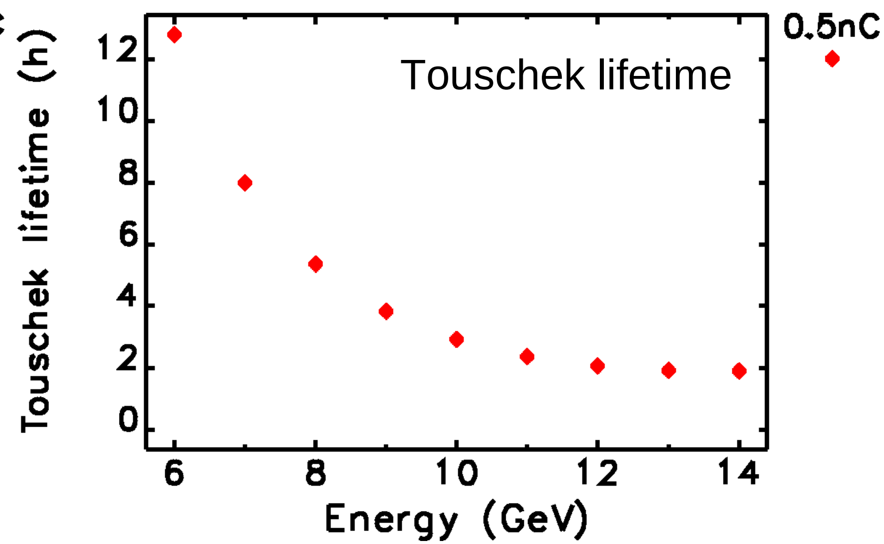
1:M. Borland, ICFA Beam Dynamics Newsletter 57, 2012; these proceedings, TUPPP033.

Collective Effects vs Energy

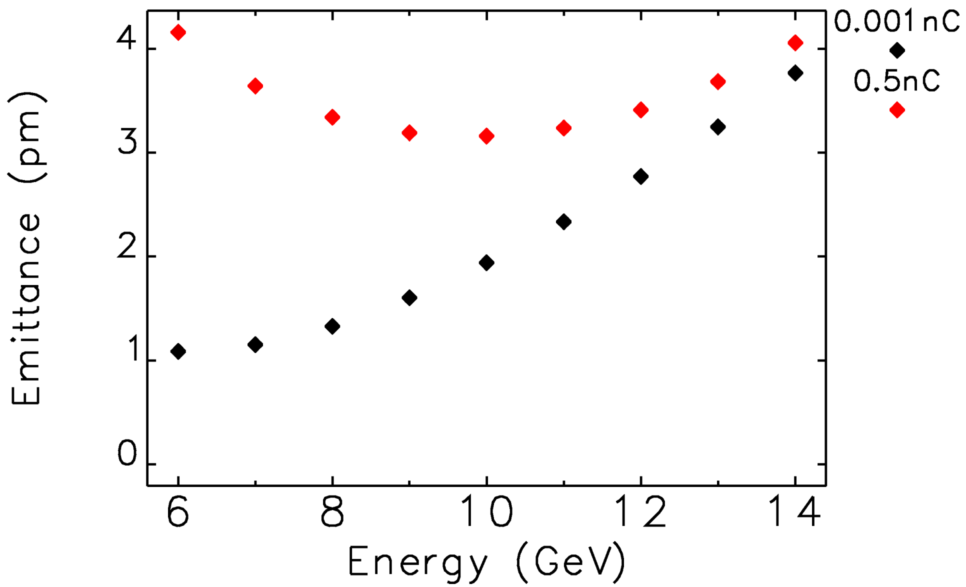




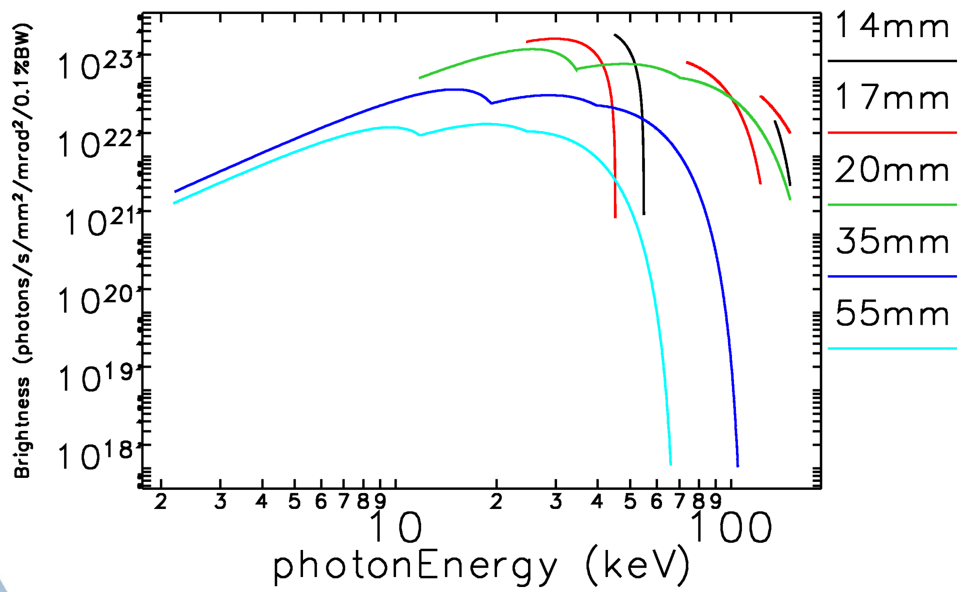




Expected Performance



Emittance with IBS shows broad minimum between 9 and 11 GeV.

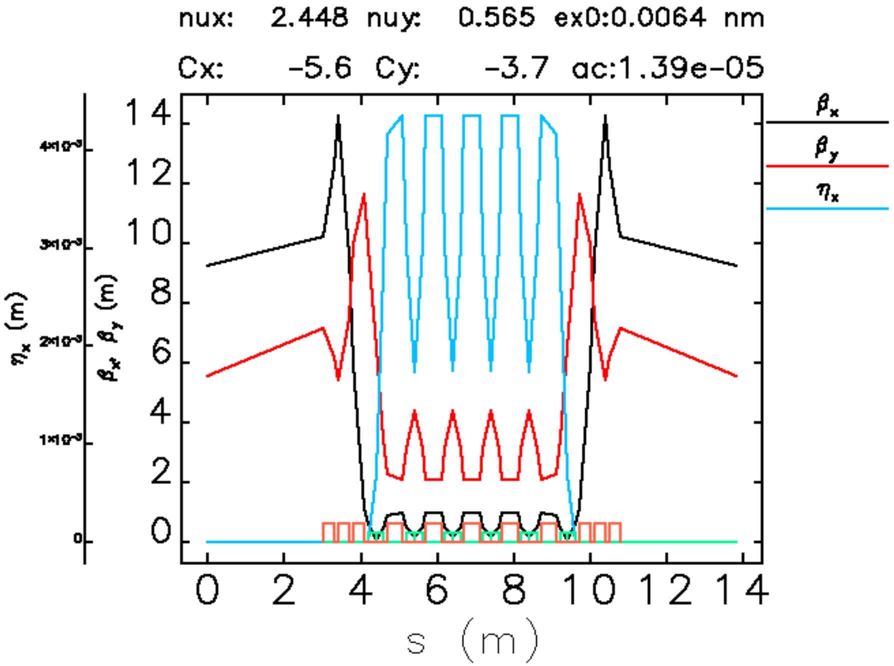


Brightness is spectacular for 10 keV and above

(Calculations assume superconducting undulators.)

Superconducting Ring[1]

- At FLS2012, W. Guo *et al.* described a USR based on superconducting magnets
  - High fields possible
  - Combined function bend/quad/sextupole
  - Implies a very compact source
- Exploratory linear optics design
  - All magnets have gradient
  - 828 m circumference
  - ϵ_0=6.4 pm
- Dynamic aperture is small as of yet
  - Trying lumped chromaticity correction
- Promising idea for bigger rings as well



1:W.Guo *et al*., Superconducting Ultimate Storage Ring Design, FLS2012. Figure courtesy W. Guo.

Conclusion

- Rumors of the death of storage rings were greatly exaggerated
- PETRA III, NSLS II, and MAX IV are demonstrating that significantly higher brightness is possible
- Starting with Einfeld *et al.* in 1995, a series of concepts for diffraction-limited storage rings have been advanced
- MAX IV will provide the first real-world test of the multi-bend achromat concept
- We can expect a 100-1000-fold brightness increase across a wide spectral range

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