Possibilities for a Very Large Storage Ring Light Source

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Outline

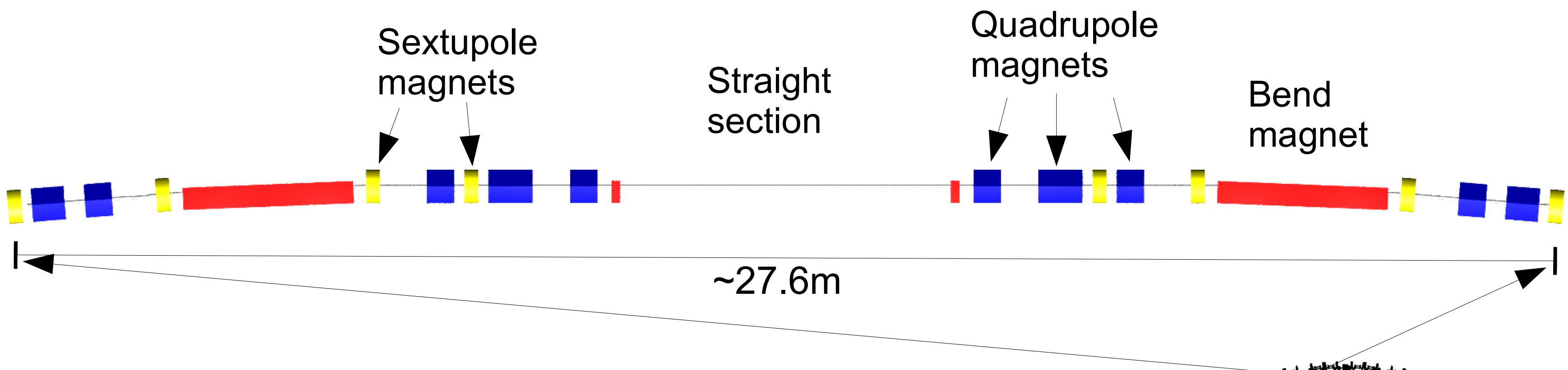
- Motivation for this work
- Emittance in electron rings
- Present and near-future rings
- Possible Tevatron-sized light source
- What’s stopping us?

Strengths of Rings as Light Sources

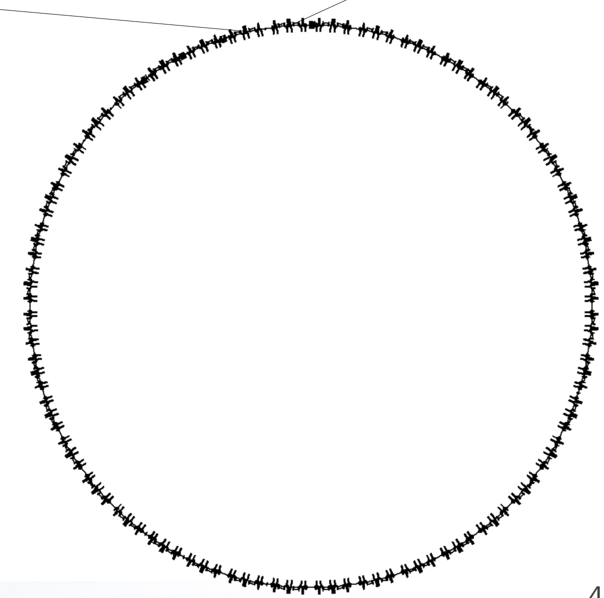
- Storage rings light sources are extremely successful scientific facilities
  - Many thousands of users per year from dozens of scientific disciplines
- There is a good reason for this
  - Wide, easily-tunable spectrum from IR to x-rays
  - High average flux and brightness
  - Excellent stability
 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

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



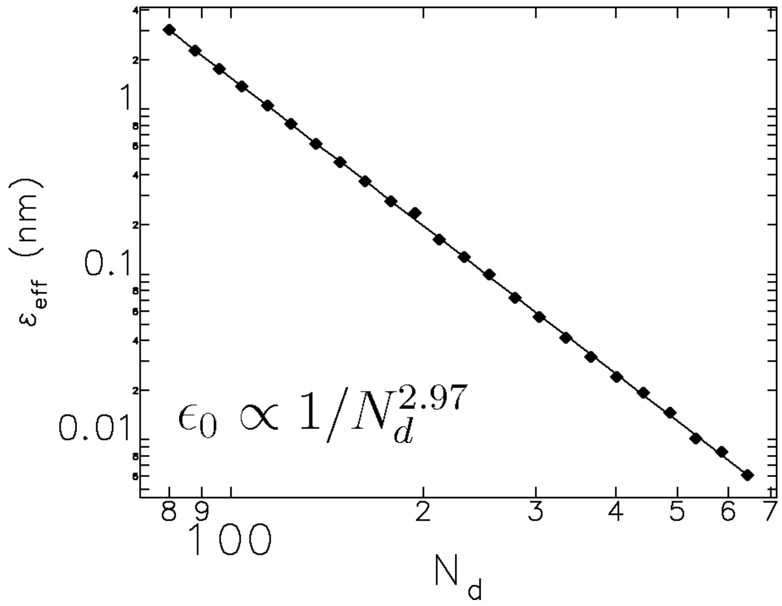
Methods of Decreasing Emittance

- To decrease the natural emittance, we can
  - Reduce the energy
    - Changes spectral reach and limits bunch charge
  - Employ stronger or more frequent focusing
    - More chromaticity
    - Nonlinear dynamics issues
  - Increase damping
    - Damping wigglers need space and increase power consumption
- A useful approximation[1]

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

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

Emittance scaling is as expected.



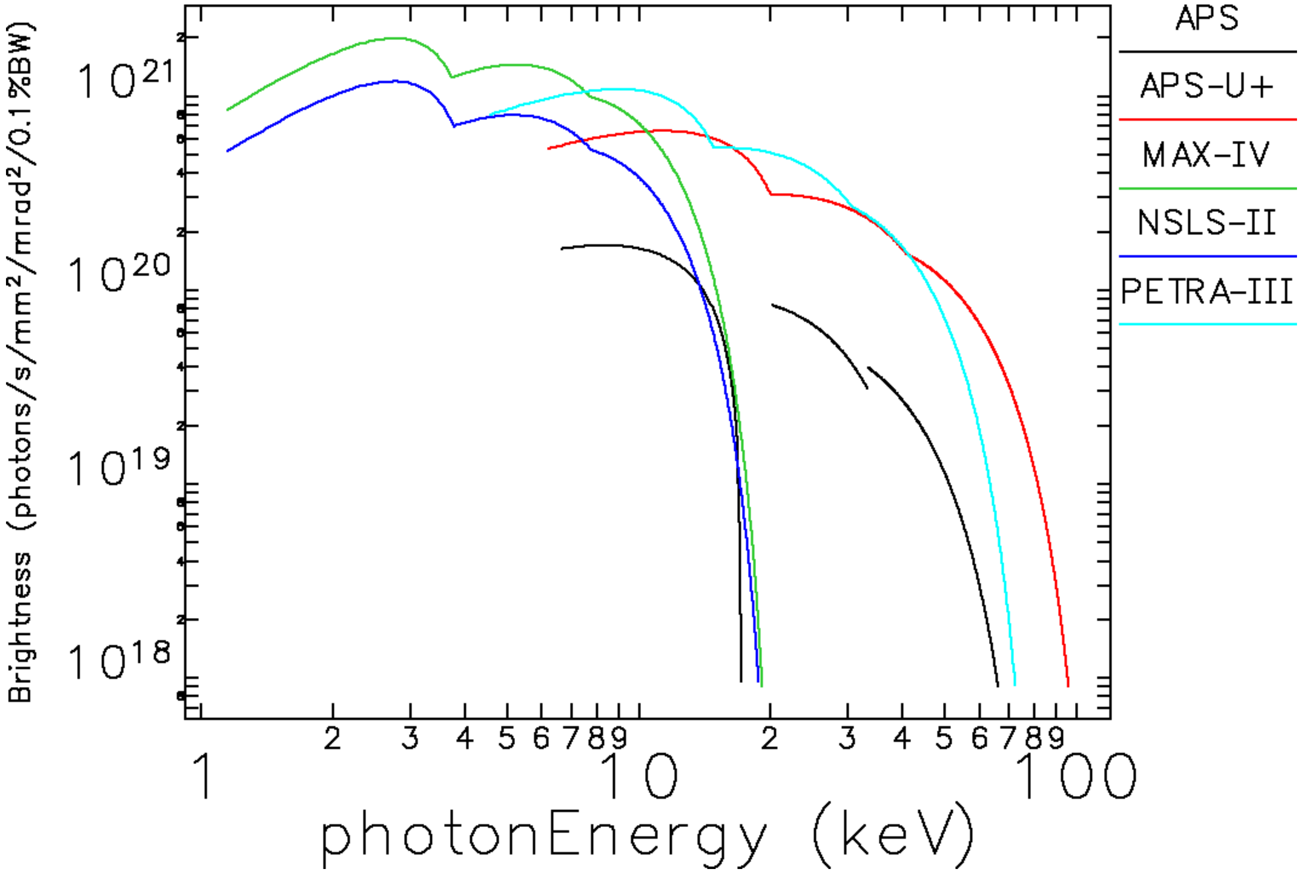
[1]J. Murphy, Light Source Data Book, BNL.

Near-Term Outlook

- From 1990's onward, emittance pushed to few nm
  - ESRF, APS, SPRING8, ...
- New rings pushing to 1 nm and below
- PETRA III[1]
  - Converted high-energy physics ring
  - Now world-leading 6 GeV, 1 nm light source
  - Large circumference with damping wigglers
- 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

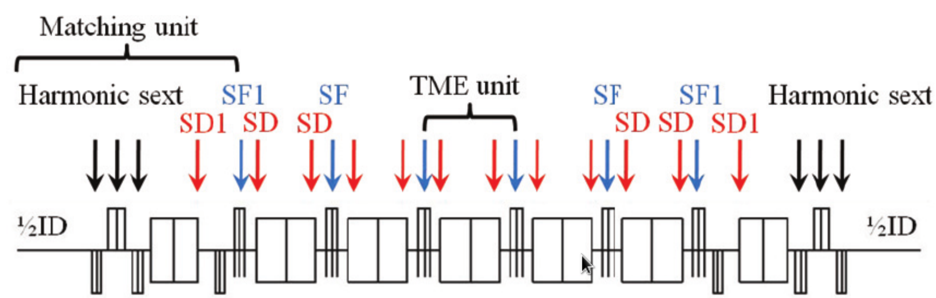


- APS curve assumes existing 4.8m long U27
- Others assume maximum length SCU20 (future 1.25T device[1])
- Used best published electron beam parameters, with 1% coupling
- First three harmonics shown only

[1]R. Dejus, private communication.

Exploratory "TevUSR" Lattice

- All lattice modules are taken from the PEP-X design[1,2,3]
  - N=30 MBA cells in each of six arcs
    - N_d=1260 (N_d=80 for APS)
    - 180 ID straight sections (!)
  - Long straight sections use FODO cell
  - Six matching quads between arc and FODO cells

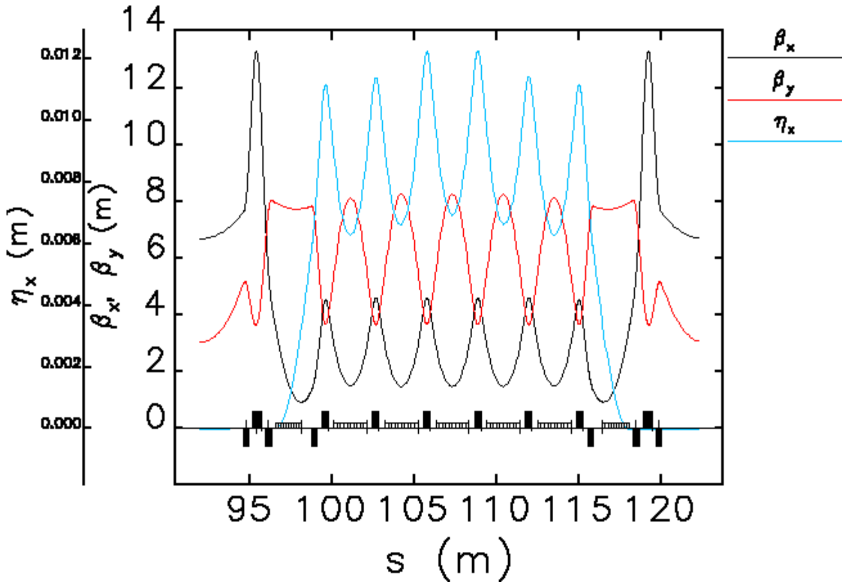


- Differences from PEP-X design
  - Larger bending radius
  - Higher energy for shorter damping time
  - No high-beta insertion needed (on-axis injection)
  - Ignore (weak) vertical undulator focusing at this stage

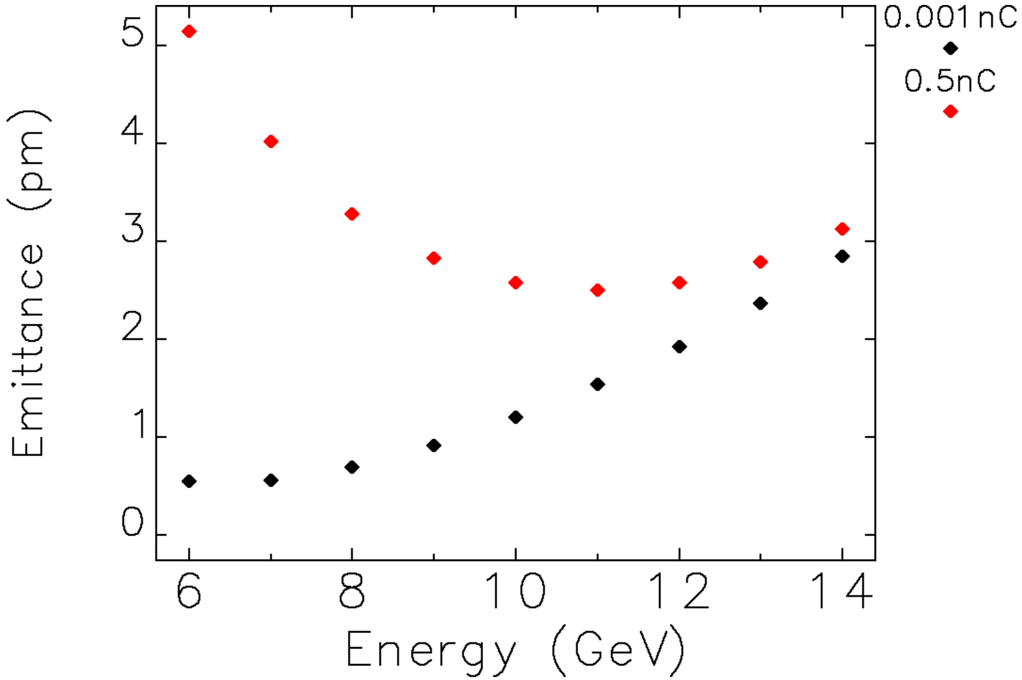
[1]M.-H. Wang *et al.*, Proc IPAC11, THPC074.
[2]Y. Nosochkov *et al.*, Proc. IPAC11, THPC075.
[3]Y. Cai, NIM A 645:168-174 (2011).

10 GeV Lattice w/o Damping Undulators (DUs)

Quantity	Value	Unit
Circumference	**6.28**	**km**
Natural emittance	**3.6**	**pm**
Energy spread	**0.11**	**%**
Maximum ID length	**4.8**	**m**
Beta functions (x, y) at ID	**6.5, 3.0**	**m**
Number of dipoles	7	per sector
Horizontal, vertical tune	344.10, 171.16	
Natural chromaticities	-476, 274	
Energy loss	2.3	MeV/turn

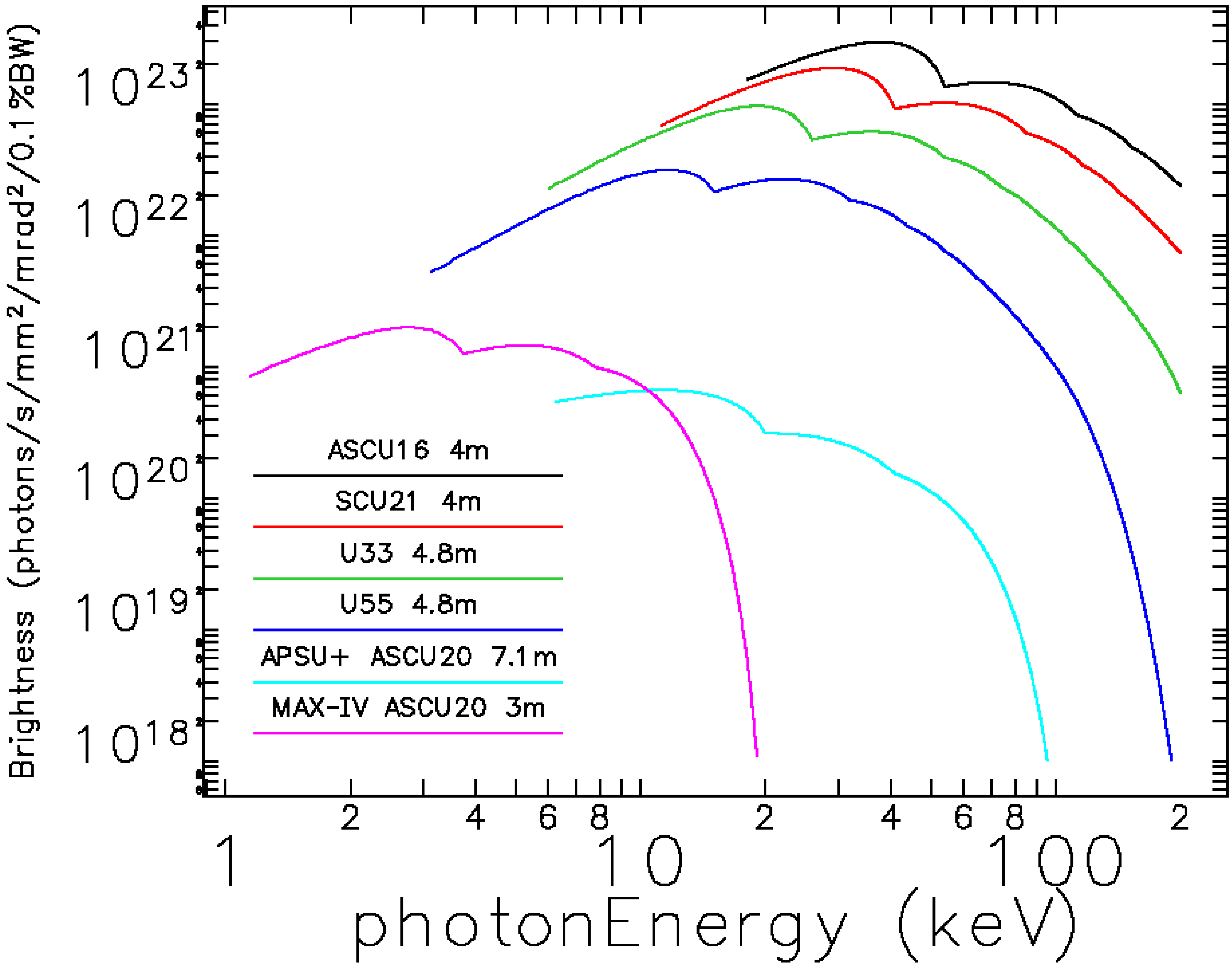


Scan of Energy with 1 Set of DUs

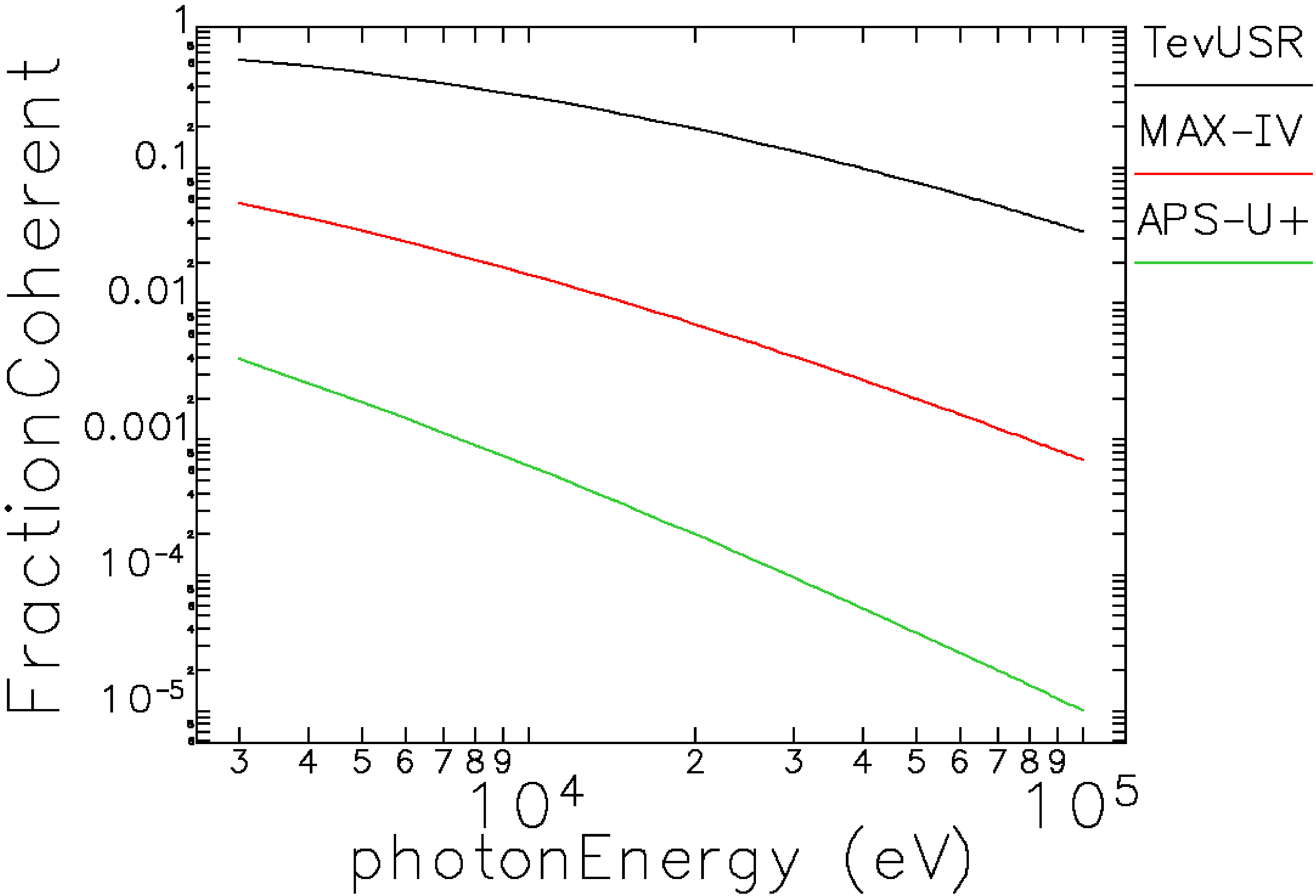


- In this case, one long straight is filled with damping undulators
  - 17mm period, 1T SCUs
  - 14 devices, each 6.7m long
- Computation includes collective effects (IBS, PWD)
  - 0.5 nC in 8300 bunches equates to 200 mA
  - Beam is fully coupled (same emittance in both planes)
  - 10 GeV is close to the minimum

Brightness Comparison



Coherent Fraction



What's Stopping Us?

- Ring is large, expensive
  - Much smaller than LHC or LEP
  - Potentially many more users
- Very small dynamic and momentum acceptance
  - Small DA makes beam accumulation impossible
  - Small MA makes lifetime poor
    - Forces operation with full coupling
    - Makes accumulation *even more* impossible
- All ring-based light sources use beam accumulation
  - Each stored bunch/train is built up from several shots
  - Incoming beam has large emittance and residual oscillation
    - Requires DA of ~10 mm
- Top-up assumes beam accumulation, won't help us
- Fortunately, a solution is in hand

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
- Allows operation with full coupling
  - Provide round beams (e.g., 3pm x 3pm)
  - Increase Touschek lifetime
  - Reduce intrabeam scattering (preserves emittance)
- Several possible injectors
  - Linac/Booster+Accumulator ring
  - Low-emittance booster
  - Full-energy linac

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

Additional Injector Considerations (TeVUSR)

- For 200 mA and 0.5 nC/bunch, need ~8300 bunches
  - 500 MHz rf, fill 80% of 10360 buckets
  - 4.1 µs 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

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

- Assuming τ=2 h and D=0.1, need ΔT_{inj} = 3.6 s
- Inject 41 bunches of 0.5 nC each time
  - Average power of ~60 W
  - APS injector now operates with ~40W average power
  - A photo-injector could easily provide the needed bunch trains

Radiation Issues (TeVUSR)

- We worry about radiation from two sources
  - Extracted beam
  - Losses in the ring
- Beam dump power is “negligible” ~60W for 10 GeV beam
- Touschek losses in the ring are ~6 W total
  - In APS today, have 0.1 W
  - Can presumably design collimation system to intercept these losses

Comparison of “TeVUSR” to Alternatives

- Free-Electron Lasers (FELs)
  - Pro: Unbeatable for peak and average brightness, short pulses
  - 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; similar flux; short pulses
  - Con: 10x lower brightness; significant R&D challenges; excellent 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 optimization with genetic algorithms
  - 100% coupling and swap-out injection
  - SPring-8 seems very serious about an MBA-based USR
- A Tevatron-sized USR promises
  - Diffraction limited radiation to ~50 keV
  - Brightness $\sim 10^{23}$
- Much work needed
  - collective instabilities
  - magnet design
  - error studies and nonlinear dynamics optimization
  - cost reduction
  - science case

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  - K. Bane, Y. Cai, R. Hettel, Y. Nosochkov, M.-H. Wang
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