Perspectives and Challenges for Diffraction Limited Storage Ring Light Sources

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Outline

- What is a diffraction-limited storage ring (DLSR)?
- Scientific motivation for DLSRs – brightness and coherence
- Design challenges and solutions
- Future DLSRs – USRs?

Acknowledgments

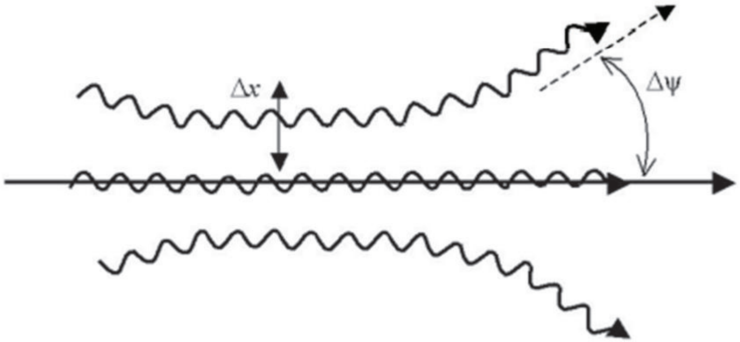
Many appreciated contributions from:

M. Borland, APS
Y. Cai, SLAC
Z. M. Eriksson, MAX-IV
T. Rabedeau, SLAC
C. Steier, ALS

and light sources that provided parameter and design information:

ALS
APS
BAPS (IHEP)
Diamond LS
ESRF
MAX-IV
NSLS-II
Sirius
SLAC
SLS
Soleil
SPring-8

Diffraction



K-J Kim in *Characteristics of Undulator Radiation*, AIP 1989

Coherent beam of wavelength λ focused to spot size Δx will diffract with angle $\Delta\psi = \sim\lambda/\Delta x$

Time-harmonic electric field of form $E(\boldsymbol{x};z)e^{-i\omega t}$ satisfies wave equation

$$\left[\frac{\partial^2}{\partial z^2}+\left(\frac{\partial}{\partial \boldsymbol{x}}\right)^2+k^2\right]E(\boldsymbol{x};z)=0,\quad k=\frac{\omega}{c}=\frac{2\pi}{\lambda}\qquad \boldsymbol{x}=(x,y)$$

In transversely coherent beam, spatial distribution ***$E_k(x,z)$*** **for wavenumber k is related to angular distribution** ***$\mathcal{E}_k(\psi,z)$*** **by Fourier transform** (for 1-D in x):

$$\mathcal{E}_k(\psi,z)=\frac{1}{\sqrt{2\pi}}\int E_k(x,z)e^{-ik\psi x}\,dx \qquad E_k(x,z)=\frac{1}{\sqrt{2\pi}}\int \mathcal{E}_k(\psi,z)e^{ik\psi x}\,d\psi$$

$$\psi \ll 1$$

Diffraction-limited emittance

For fully coherent Gaussian **laser beam** spatial distribution at waist (z = 0):

$$E_k(x,0) = E_k(0,0)\exp(\frac{-x^2}{2\sigma_{Ex}{}^2}) \qquad \mathcal{E}_k(\psi,0) = \mathcal{E}_k(0,0)\exp(\frac{-\psi^2}{2\sigma_{\mathcal{E}\psi}{}^2})$$

$$\sigma_{\mathcal{E}\psi} = \frac{1}{k\sigma_{Ex}} = \frac{\lambda}{2\pi\sigma_{Ex}} \Rightarrow \sigma_{Ex}\sigma_{\mathcal{E}\psi} = \frac{\lambda}{2\pi}$$

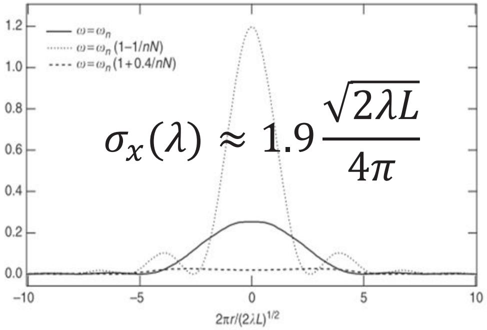
Photon intensity profile ∝ E^2 and $\mathcal{E}^2$:

$$\Rightarrow \sigma_{Ix}(\lambda)\sigma_{I\psi}(\lambda) = \frac{\lambda}{4\pi} = \varepsilon_r(\lambda)$$

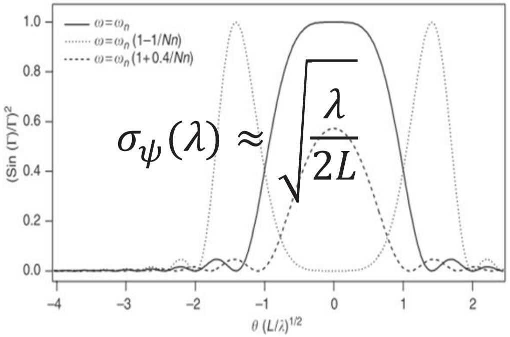
Diffraction limited emittance for coherent Gaussian photon distribution

Fitting Gaussian profiles to spatial and angular profiles for **undulator radiation** at λ:

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



$$\sigma_x(\lambda) \approx 1.9\frac{\sqrt{2\lambda L}}{4\pi}$$



$$\sigma_\psi(\lambda) \approx \sqrt{\frac{\lambda}{2L}}$$

$$\Rightarrow \sigma_x(\lambda)\sigma_\psi(\lambda) \approx \frac{\lambda}{2\pi} = \varepsilon_r(\lambda)$$

Diffraction limited emittance for undulator radiation from single electron filament

X-ray emittance from electron source

Transverse emittance $\Sigma_{x,y}(\lambda)$ of X-ray beam from undulator (length L) is convolution of photon emittance ε_r from e- filament and e- emittance $\varepsilon_{x,y}(e-)$ (Gaussian beams):

$$\boxed{\Sigma_{x,y}(\lambda) = \varepsilon_r(\lambda) \oplus \varepsilon_{x,y}(e-) = \sqrt{\sigma_r{}^2(\lambda) + \sigma_{x,y}{}^2(e-)}\sqrt{\sigma'_r{}^2(\lambda) + \sigma'_{x,y}{}^2(e-)}}$$

Here

$$\sigma_r(\lambda) \approx \frac{\sqrt{2\lambda L}}{2\pi} \qquad \sigma'_r(\lambda) = \sigma_\psi(\lambda) \approx \sqrt{\lambda/2L}$$

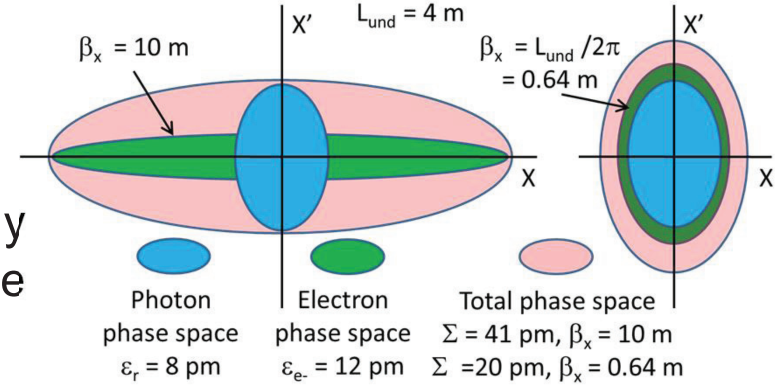
$$\sigma_{x,y}(e-) = \sqrt{\varepsilon_{x,y}\beta_{x,y}} \qquad \sigma'_{x,y}(e-) = \sqrt{\varepsilon_{x,y}/\beta_{x,y}}$$

Transverse emittance $\Sigma_{x,y}$ minimized when $\varepsilon_{x,y}$ is minimized and photon and e- phase space orientations are matched:

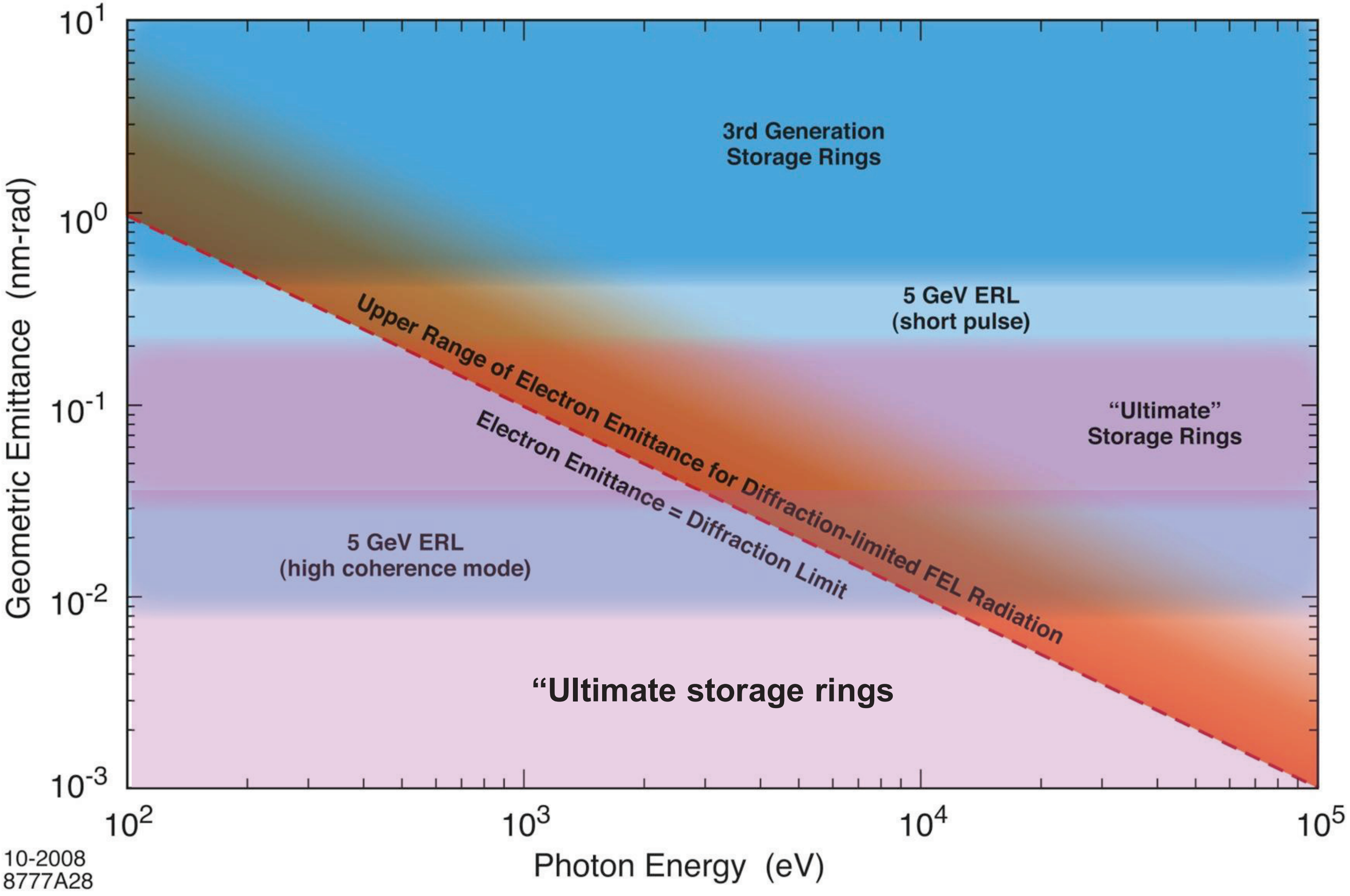
$$\frac{\sigma_r(\lambda)}{\sigma'_r(\lambda)} = \frac{\sigma_{x,y}(e-)}{\sigma'_{x,y}(e-)} \Rightarrow \boxed{\beta_{x,y} = \frac{L}{\pi}}$$

Note: many authors cite

$$\beta_{x,y} = \frac{L}{2\pi}$$



Diffraction-limited emittance



Spectral brightness and coherent fraction

Spectral brightness: photon density in 6D phase space

$$B_{avg}(\lambda) \propto \frac{N_{ph}(\lambda)}{(\varepsilon_x(e-) \oplus \varepsilon_r(\lambda))(\varepsilon_y(e-) \oplus \varepsilon_r(\lambda))(s \cdot \% BW)}$$

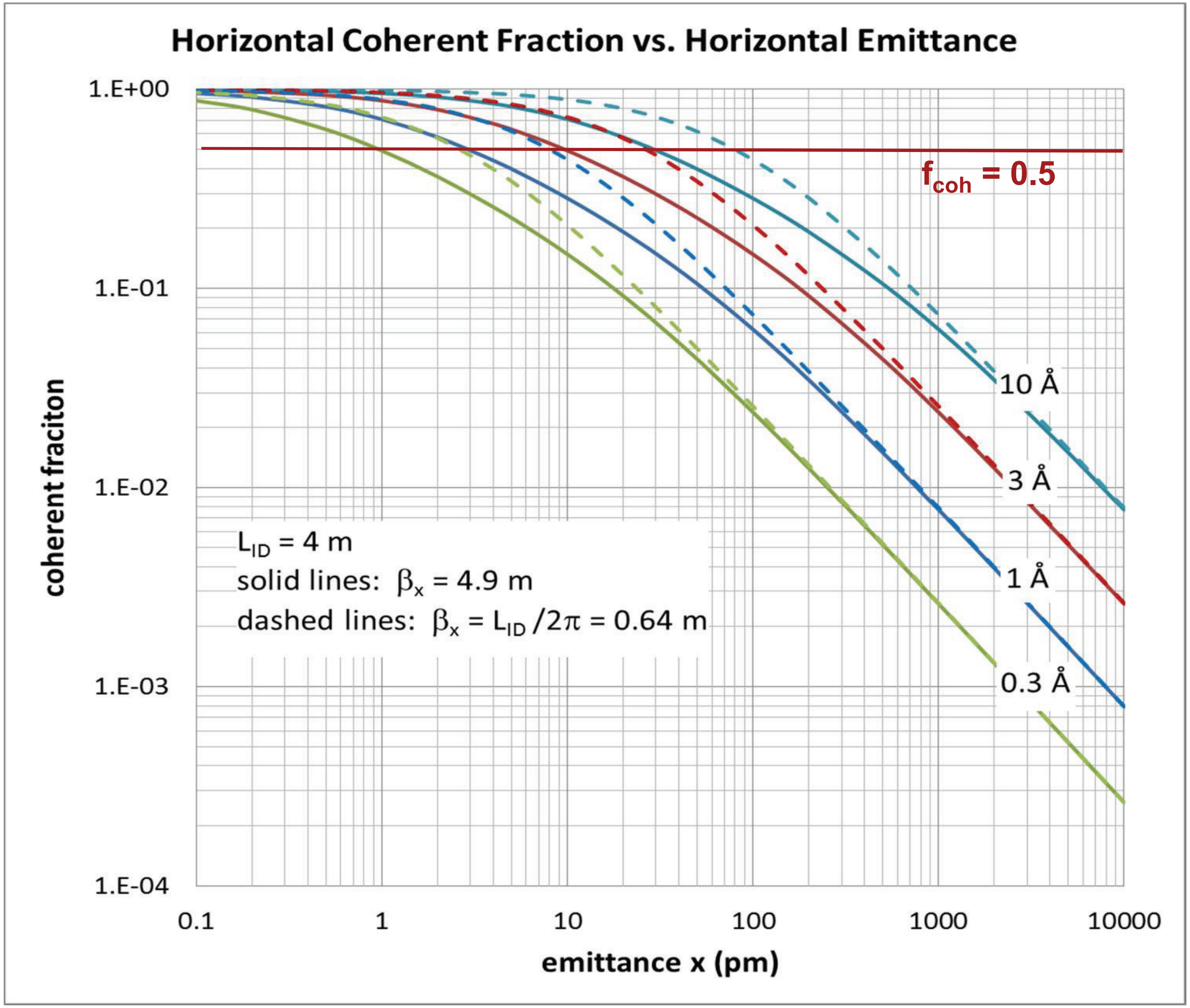
$$B_{pk}(\lambda) \propto \frac{N_{ph}(\lambda)}{(\varepsilon_x(e-) \oplus \varepsilon_r(\lambda))(\varepsilon_y(e-) \oplus \varepsilon_r(\lambda))(\sigma_t \cdot \% BW)}$$

σ_t = bunch length

Coherent fraction:

$$f_{coh}(\lambda) = \frac{\lambda / 4\pi}{(\varepsilon_x(e-) \oplus \varepsilon_r(\lambda))} \cdot \frac{\lambda / 4\pi}{(\varepsilon_y(e-) \oplus \varepsilon_r(\lambda))}$$

Coherent fraction



Coherent flux is important too: a low coherent fraction and high flux can yield the same coherent flux as a high coherent fraction and low flux

Optimize trade-off between low of emittance vs. stored current

What is a DLSR?

from M. Borland, GRC 8/13

“Pure” meaning: A ring is diffraction-limited for wavelength λ when the e- emittance is so small that it might as well be zero:

$$\varepsilon_{x,y}(e-) \ll \varepsilon_r(\lambda) = \frac{\lambda}{2\pi} \; (or \; \frac{\lambda}{4\pi} \; or \; \dots.)$$

More common meaning: the electron emittance is about the same as the photon emittance

Note: many rings operate now with ε_y<< 1Å/4π = ~8 pm-rad by reducing vertical coupling to a very small number

The path to low emittance rings

Emittance scaling with energy and circumference:

$$\varepsilon_0 = F(\nu, cell)\,\frac{E^2}{(N_s N_d)^3} \propto \frac{E^2}{C^3}$$ for fixed cell type

$$\varepsilon_x = \frac{1}{1+\kappa}\varepsilon_0 \qquad \varepsilon_y = \frac{\kappa}{1+\kappa}\varepsilon_0$$

N_s = # sectors in ring, N_d = # dipoles/sector

Emittance reduction with damping wigglers:

$$\frac{\varepsilon_w}{\varepsilon_o} = \frac{1+f}{1+\dfrac{L_w}{4\pi\,\rho_o}\left(\dfrac{\rho_o}{\rho_w}\right)^2} \approx \frac{1}{1+\dfrac{U_w}{U_o}}$$

U_0 = energy loss/turn in dipoles

U_W = energy loss/turn in wigglers

Emittance reduction with damping partition:

$$\epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\oint H(s)/\rho(s)^3\,ds}{\oint 1/\rho(s)^2\,ds}$$

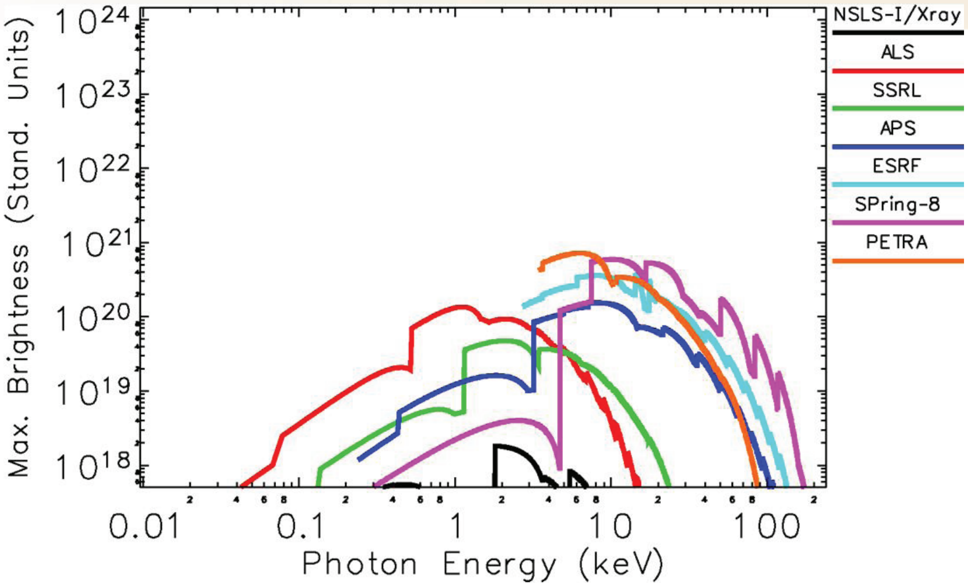
Damping partition →

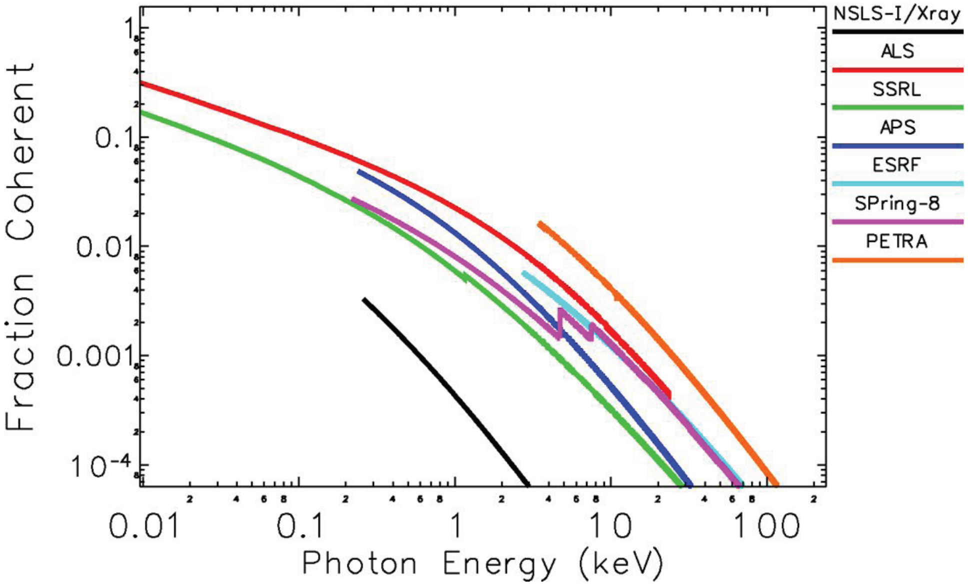
Gradient dipoles

Robinson wigglers

Amplitude bumps in quads

Brightness and coherence of present rings



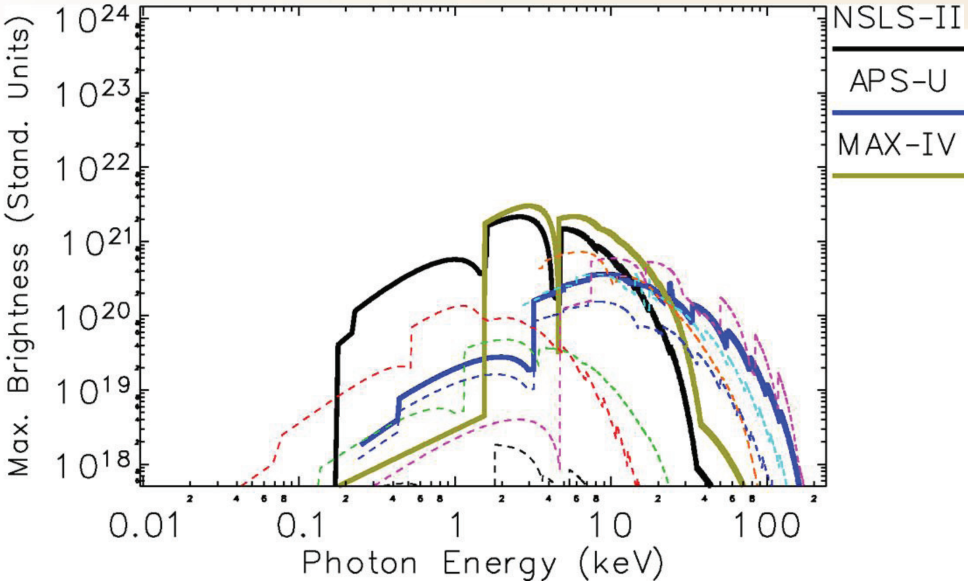


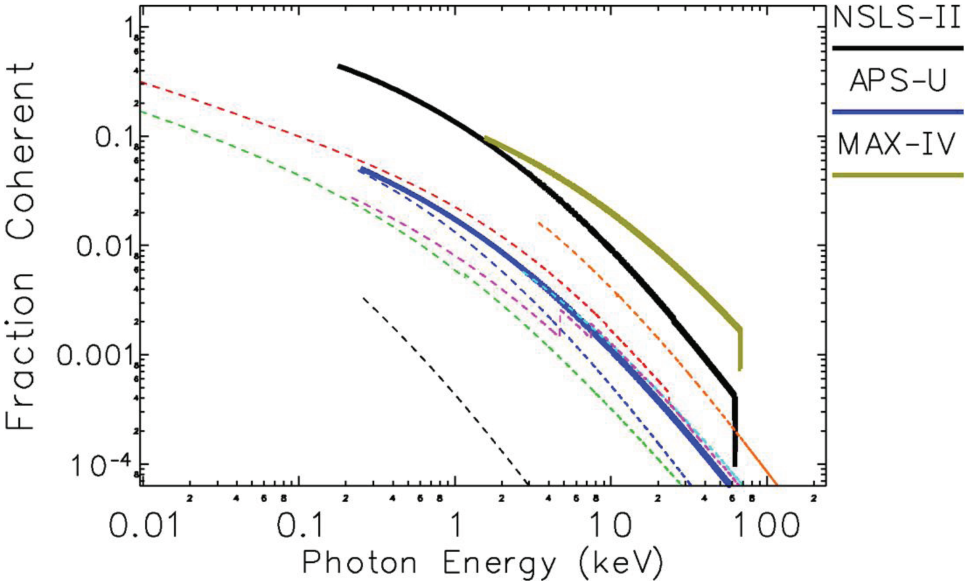
Best-available brightness and coherent fraction for selected presently-operating rings, with operating parameters and insertion devices.

Parameters provided by facility contacts.

Compiled by M. Borland for BESAC Sub-Committee meeting, July 2013.

Brightness and coherence of near-future rings



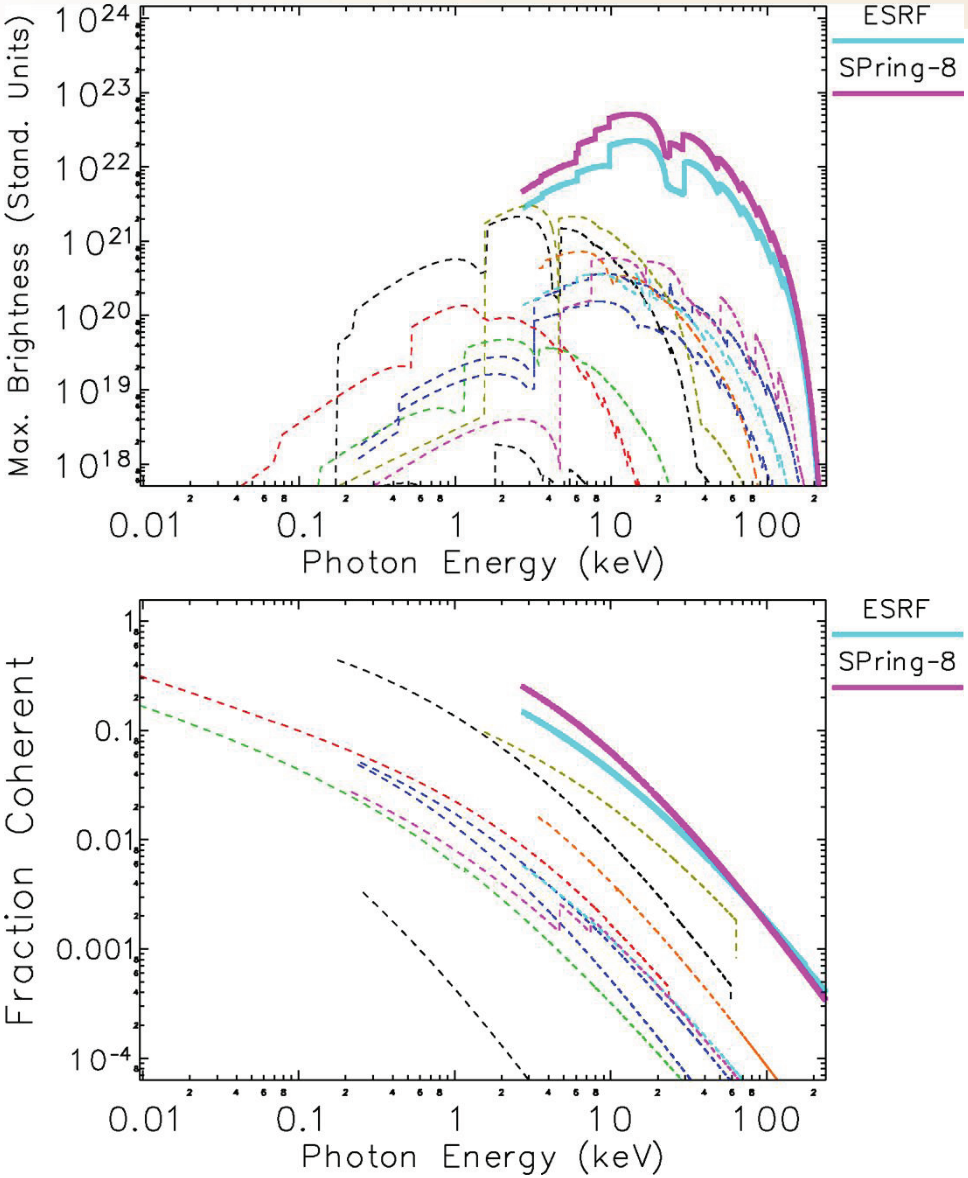


Selected rings/upgrades now under construction, with anticipated parameters and insertion devices

Parameters provided by facility contacts.

Compiled by M. Borland for BESAC Sub-Committee meeting, July 2013.

Brightness and coherence of planned rings



Selected upgrades now being planned (except APS-II), with anticipated parameters and ESRF-specified insertion devices.

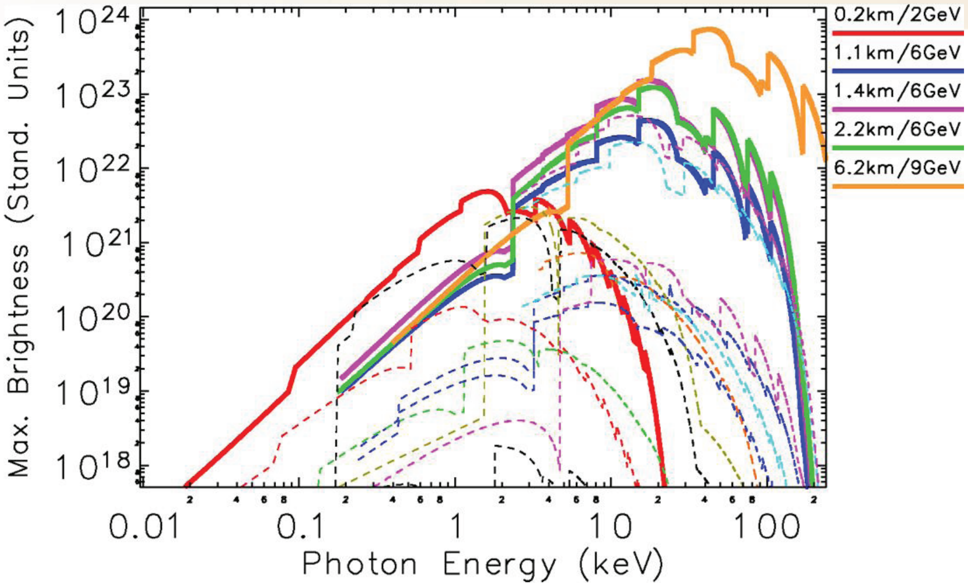
Parameters provided by facility contacts.

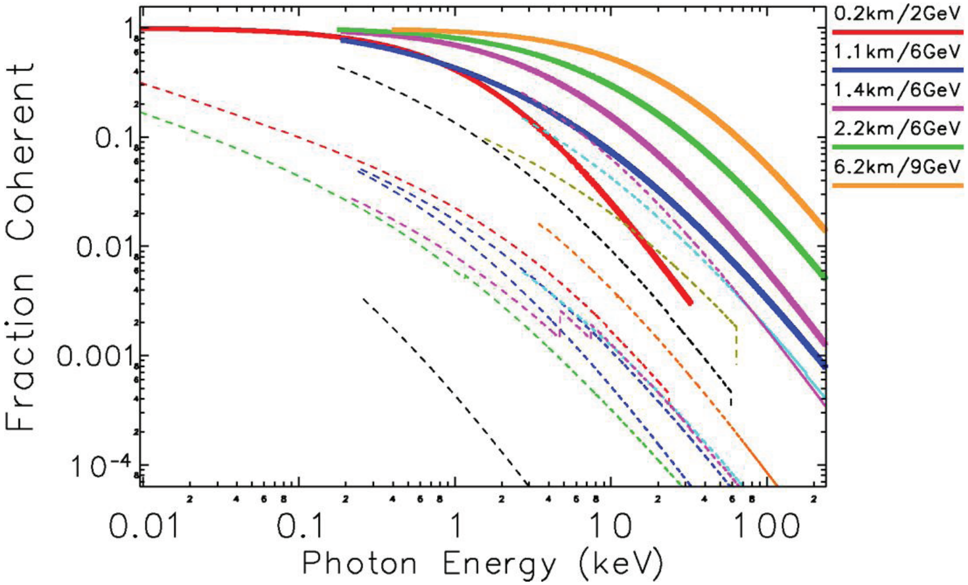
Compiled by M. Borland for BESAC Sub-Committee meeting, July 2013.

Notes:

1. ESRF-II: 6 GeV, 200mA, 150 pm
2. SPring-8-II: 6 GeV, 300 mA, 67pm

Brightness and coherence of future rings





Selected diffraction-limited rings now being designed, with identical Nb_3Sn super-conducting insertion devices and some PM devices.

Parameters provided by facility contacts.

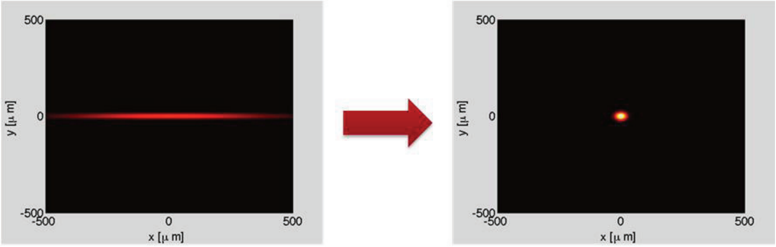
Compiled by M. Borland for BESAC Sub-Committee meeting, July 2013.

Notes:

1. 0.2km/2GeV: ALS-II, 52 pm
2. 1.1km/6GeV: APS-II, 80 pm
3. 1.4km/6GeV: SP8-II, 2nd stage, 34 pm
4. 2.2km/6GeV: PEP-X, 5 pm
5. 6.2km/9GeV: tauUSR, 3 pm
6. Except for 0.2km ring, uniform selection of SCUs and APS HPMs used.

Properties of DLSRs

- Brightness and coherence are as high as possible for given beam current
- Small horizontal and vertical beam sizes and the possibility of “round” beams



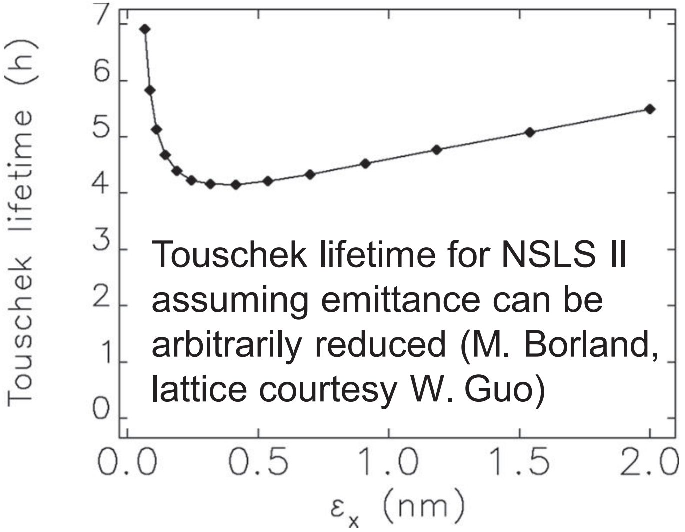
courtesy of C. Steier

- Short bunches

  ~5-10 ps RMS from low momentum compaction factor – bunch lengthening usually needed to combat emittance growth from IBS and improve lifetime

- “Long” lifetime:

  Touschek lifetime increases with small bunch dimensions



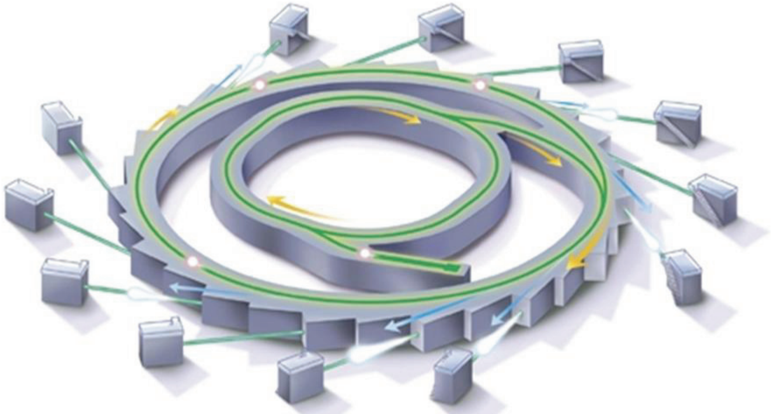
Touschek lifetime for NSLS II assuming emittance can be arbitrarily reduced (M. Borland, lattice courtesy W. Guo)

- Large circumference for multi-GeV rings (km)
- Damping wigglers used in some cases to combat IBS and reduce emittance by ~x2-3
- On-axis “swap-out” injection for aggressive lattices having small dynamic aperture

DLSRs: so what?

BESAC Subcommittee on Future Light Sources:

July 10-12, 2013



A consensus report on future opportunities from scientists at

ALS, LBNL

APS, ANL

NSLS-II, BNL

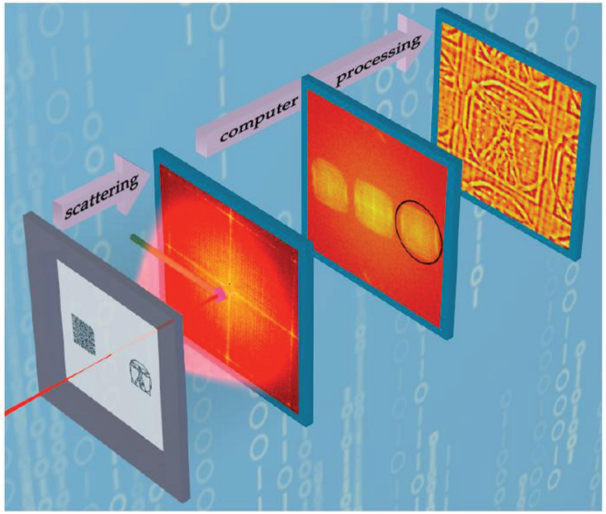
SSRL, SLAC

together with a broad community of scientists

at laboratories and universities.

DLSR capabilities – coherence and brightness

- **Transversely coherent x-rays**
  - **Uniform phase wavefronts:** coherent imaging, holography, speckle, etc.
  - **Focusable to smallest spot size**: nano-focus
  - **High flux** (~10^{14}-10^{15} photons/sec) in small spot: slits may not be required, etc.
  - **Round beams**: H-V symmetric optics, circular zone plates, flexibility in optics
- **Advanced applications**
  - **Coherent diffractive imaging** with wavelength-limited spatial resolution; **ptychography**
  - **Spectroscopic nanoprobes** using powerful x-ray contrast modes: XRF, XAS/XES, ARPES, RIXS
  - **Photon correlation scattering/spectroscopy**
  - Science case continues to be developed



- **Addresses "Grand Challenge Science"**
- **Some issues with coherence:**
  - **Reduced depth of focus** – a problem for some forms of imaging
  - **Speckle** from coherent beams a problem for some applications
  - These problems can be resolved by "spoiling" beam on beamline

Fundamental challenges of low emittance

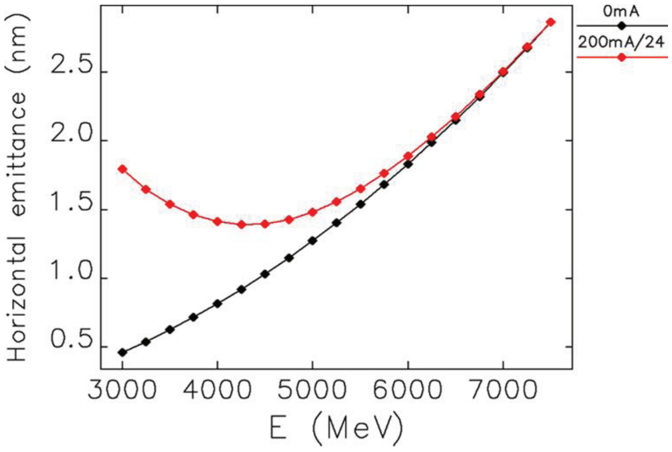
from M. Borland,
GRC 8/13

- **Inescapable fact**
  - To reduce the amplitude of dispersive orbits, must focus more frequently and more strongly
- **Focusing (quadrupole) elements have chromatic aberrations**
  - Sextupole magnets added to correct these
  - Introduces higher order aberrations
  - More sextupoles or octupoles added to correct these...
- **As N_d is increased to reduce emittance[1]**
  - Stronger chromatic correction sextupoles increase like N_d
  - Dynamic aperture decreases like $1/N_d$
  - Second order chromaticities increase like N_d
- **Stronger focusing leads to difficult non-linear dynamics**
  - Poor “momentum aperture” ⇒ reduced lifetime ⇒ frequent injection
  - Poor “dynamic aperture” ⇒ greater difficulty injecting ⇒ on-axis injection?

1: M. Borland, IPAC12, 1013-1017.
2: M. Borland, “Can APS Compete with the Next Generation,” 2002; L. Emery et al., PAC03, 256.

Fundamental challenges – cont.

- **Intra-beam scattering (IBS)**
  - Multiple electron-electron scattering in a bunch
  - Leads to increased emittance and energy spread
  - Fights the beneficial E^2 scaling of emittance
  - **Mitigations:**
    - Many low-intensity bunches
    - Round beam s
    - Bunch lengthening system
    - Damping wigglers



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

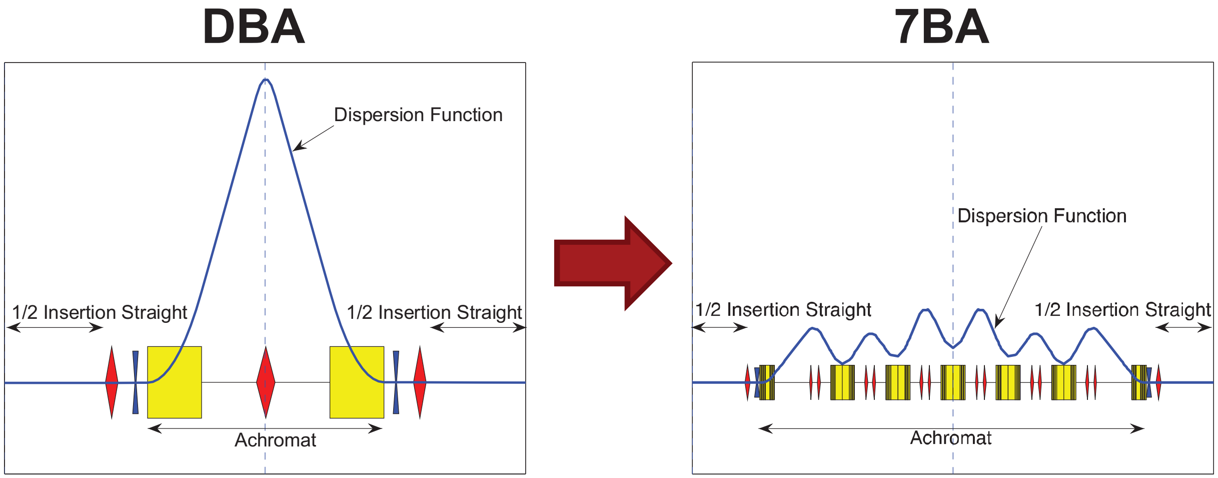
- **Beam instabilities**
  - **Transverse:** resistive wall, ion trapping in multi-bunch mode, single bunch TMCI
    - Beam blow-up ⇒ brilliance reduction
    - transverse beam oscillations ⇒ beam losses
  - **Longitudinal:** primarily from cavity HOMs
  - **Mitigations**: mode-damped cavities, smooth chamber transitions, low-Z chamber material, low charge/bunch, longer bunches, feedback
- **X-ray optics**
  - Advances in optics needed to preserve coherence, handle high power densities
  - Aided by developments for X-ray FELs

DLSRs: why now and not earlier?

Multibend achromat (MBA) lattices

- Lattice design evolution from DBA, TBA to 4BA,…MBA:
- Increased $N_{D,}$ strong focusing, low dispersion, gradient dipoles
- History:

1993: QDA by Einfeld at al. NIMA 335(3)
1994: SLS early design with 7BA, short superbend (Joho and Streun, EPAC'1994)
1995: 7BA by Einfeld et al. (0.5 nm-rad, 3 GeV, 400m), Proc. PAC 95



DLSRs: why now? – accelerator physics

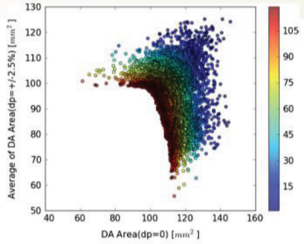


FIG. 1. The last generation of objective functions: DA of on-momentum (horizontal axis) and off-momentum (vertical axis) particles. Points are colored according to their rank.

Symplectic Tracking based methods

DA, MA separated

DA, MA together

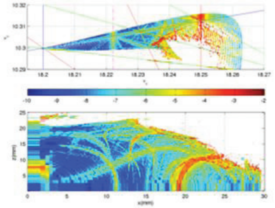
from L. Nadolski, ICFA LowEring, Oxford 7/13

Direct tracking based optimization

GLASS

Analytical based method

Genetic Algorithm
MOGA



Lie Algebra/Differential Algebra

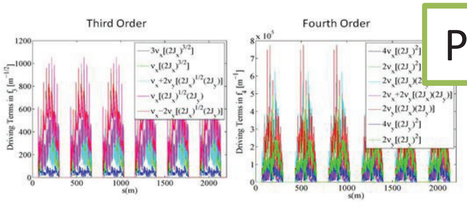
Resonance Driving Terms
RDT minimization

Amplitude Tuneshift
minimization

Frequency Maps
FMA
Diffusion factor

Nonlinear
“LOCO”

Canceling
Sextupole
Resonances



K.L. Brown & R.V. Servranckx
Nucl. Inst. Meth., A258:480–502, 1987
There are still three tune shift terms.

Yunhai Cai
Nucl. Inst. Meth., A645:168–174, 2011.

Phase advances

Resonance identification

Interleaved
sextupoles

Robustness to magnetic, alignment errors

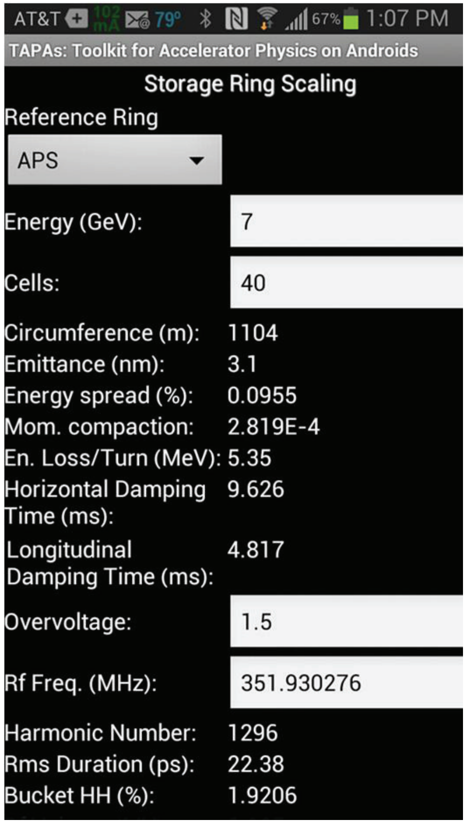
Robustness ID configurations

Tracking codes: PTC MADX TRACY AT LEGO OPA ELEGANT

Ring design app for Android – M. Borland

- A free Android app is available that lets you explore storage ring scaling
  - Also has synchrotron radiation calculations, FELs, top-up/swap-out, etc.
  - Search for “Michael Borland TAPAs” on the Google store

Ring scaling



TAPAs: Toolkit for Accelerator Physics on Androids

Storage Ring Scaling

Reference Ring: APS

Energy (GeV): 7

Cells: 40

Circumference (m): 1104

Emittance (nm): 3.1

Energy spread (%): 0.0955

Mom. compaction: 2.819E-4

En. Loss/Turn (MeV): 5.35

Horizontal Damping Time (ms): 9.626

Longitudinal Damping Time (ms): 4.817

Overvoltage: 1.5

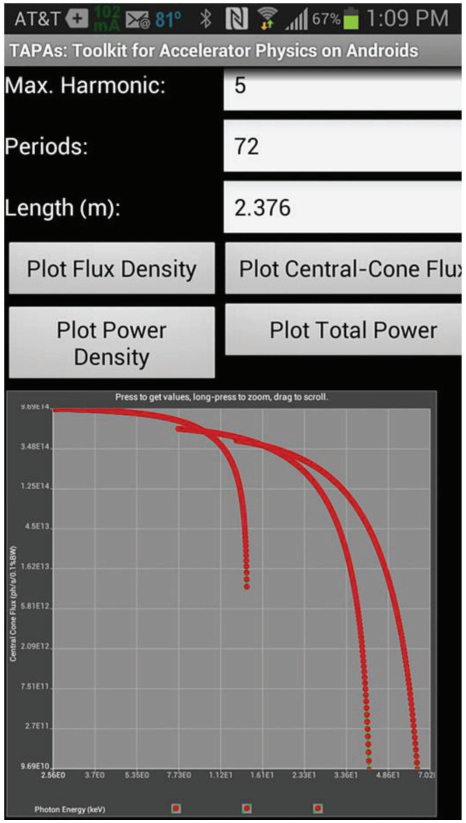
Rf Freq. (MHz): 351.930276

Harmonic Number: 1296

Rms Duration (ps): 22.38

Bucket HH (%): 1.9206

Undulator radiation



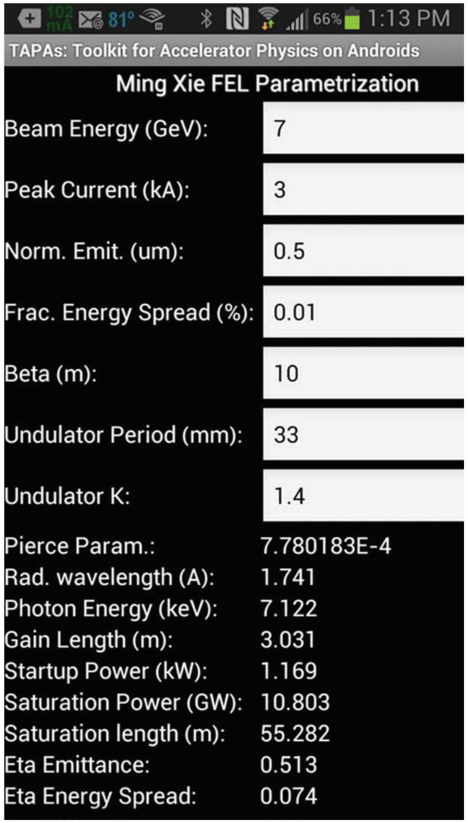
TAPAs: Toolkit for Accelerator Physics on Androids

Max. Harmonic: 5

Periods: 72

Length (m): 2.376

FEL estimation



TAPAs: Toolkit for Accelerator Physics on Androids

Ming Xie FEL Parametrization

Beam Energy (GeV): 7

Peak Current (kA): 3

Norm. Emit. (um): 0.5

Frac. Energy Spread (%): 0.01

Beta (m): 10

Undulator Period (mm): 33

Undulator K: 1.4

Pierce Param.: 7.780183E-4

Rad. wavelength (A): 1.741

Photon Energy (keV): 7.122

Gain Length (m): 3.031

Startup Power (kW): 1.169

Saturation Power (GW): 10.803

Saturation length (m): 55.282

Eta Emittance: 0.513

Eta Energy Spread: 0.074

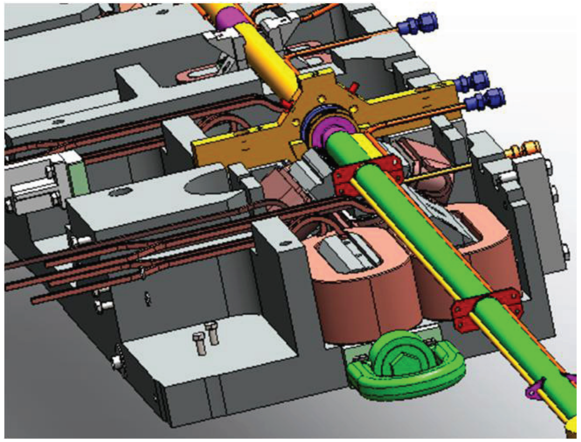
DLSRs: why now? – cont.

Compact magnet and vacuum technology

- NEG-coated vacuum chambers enable small apertures to enable high magnet gradients

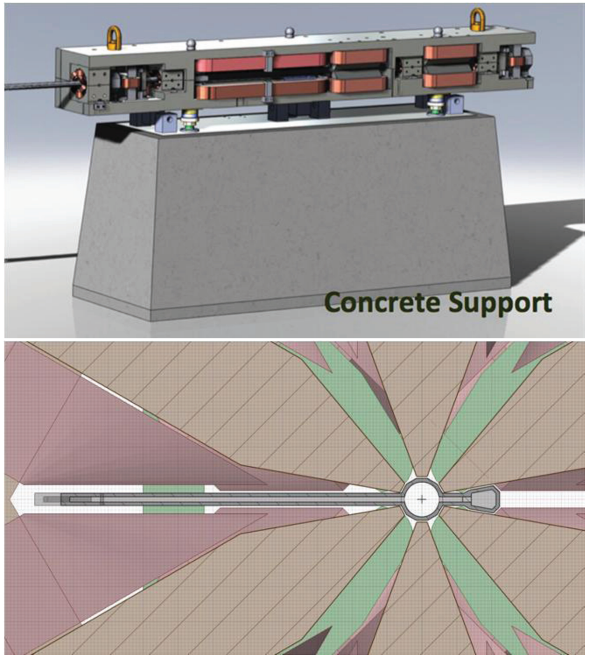
  Pioneered at CERN, used extensively at Soleil, and adopted for MAX-IV and Sirius MBA lattices

- Precision magnet pole machining for small aperture magnets, combined function magnets, tolerance for magnet crosstalk (developed extensively at MAX-Lab)



MAX-IV

Courtesy S. Leemans



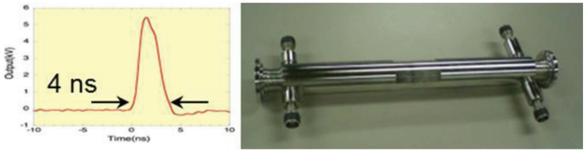
SPring-8 concept

K. Soutome

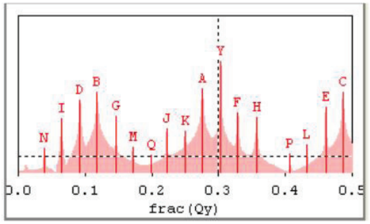
DLSRs: why now? – cont.

Other advances in accelerator and light source technology

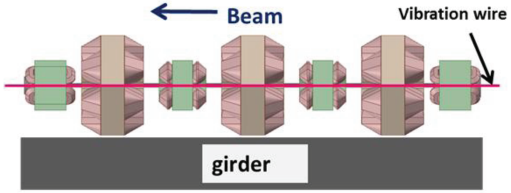
- Fast kickers for swap-out injection
- Sub-micron e- BPMs and orbit feedback
- Accelerator and beam line component mechanical stabilizing systems
- Micron resolution single pass BPMs (non-linear lattice tuning)
- “In-situ” magnet measurement and alignment methods (e.g. NSLS-II)
- Mode-damped RF cavities (fundamental and harmonic)
- Highly stable solid state RF power sources
- High performance X-ray optics to preserve coherence (e.g. for FELs)
- High performance IDs (superconducting, Delta, etc.)



Fast kickers – KEK ATF

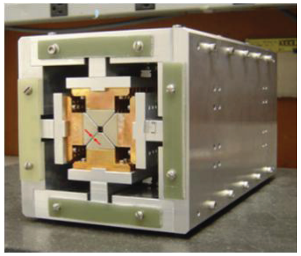


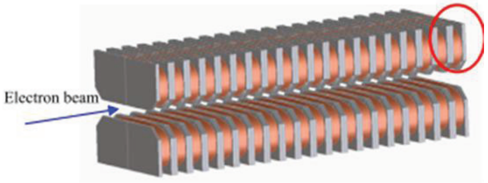
Higher order resonances detected by turn-turn BPMs (A. Franchi)



SPring-8 concept based on NSLS-II vibrating wire method - K. Soutome

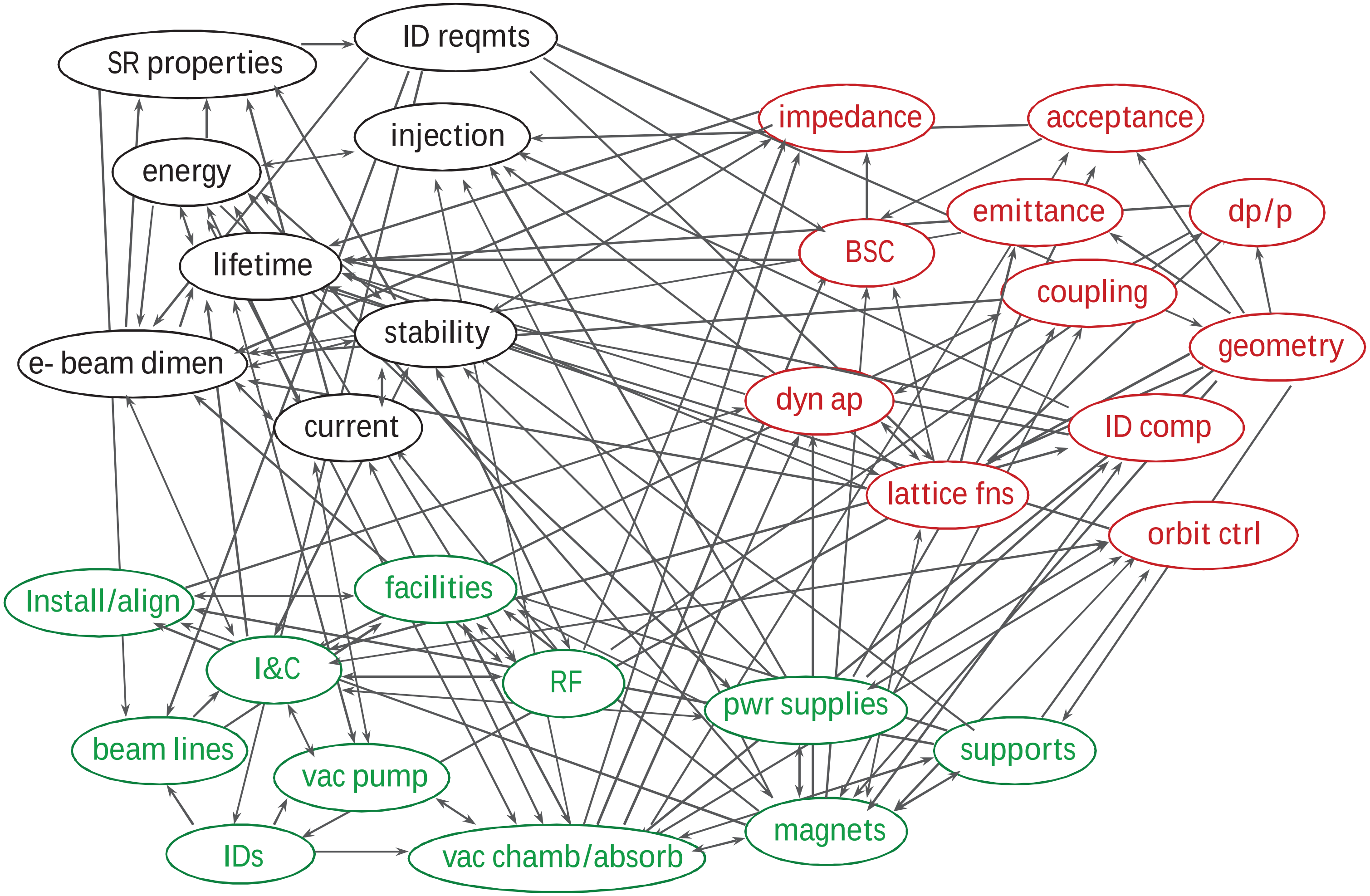
Delta undulator prototype - A. Temnykh





SC undulator development at LBNL (S. Prestemon et al.), APS (E. Gluskin et al.) and elsewhere

DLSR design optimization



R. Hettel
SPEAR 3 Design
Jan. 17 2003

Draft
rev 1

DLSR design – some comments on optimization

Brightness/coherence vs. flux

- User community is divided – some need flux, not brightness
- Possible to get same coherent flux with high current/low coherent fraction as with high coherent fraction/lower current (e.g. PEP-X v1 @ 1.5 A)
- High flux, high emittance is generally less expensive
- Diminishing return on coherent fraction and flux as emittance is reduced

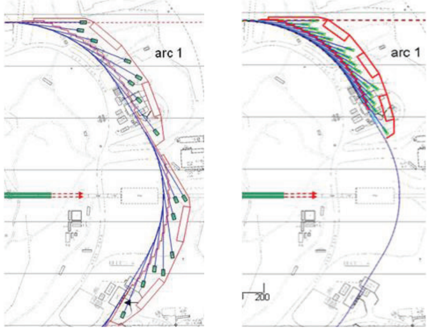
Electron energy

- High energy rings (6+ GeV) are large and costly ($\varepsilon \sim E^2/C^3$, RF voltage ~ E^4/C)
- Hard X-ray brightness can be reached with lower E, lower ε using high harmonics from high performance IDs (especially superconducting)

Lattice geometry

- ID straight section length is always an issue (5 m vs 12 m, etc)
- Spacing between ID straights is an issue with large rings: spacing between beam lines can lead to extremely large and costly experimental halls. Consolidating beam lines with hybrid lattice may be necessary

16 beam lines in PEP-X with 7BA (left) and DBA/TME hybrid (right)



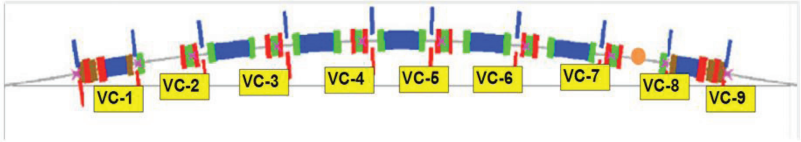
Cost-performance optimization needed for every light source design

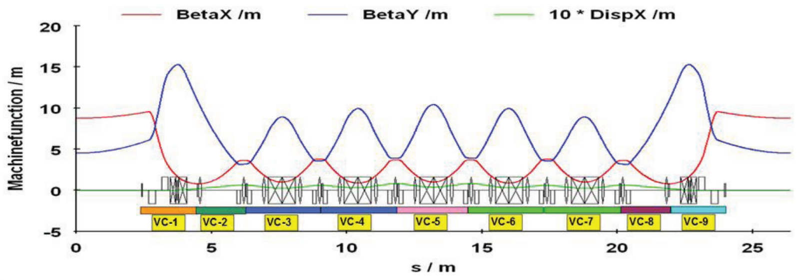
Science case should drive the optimization (is 10 or 1 pm worth it? – maybe!)

MBA Lattices are becoming a reality – new rings

MAX–IV (Sweden) is taking the first pioneering step with 7BA, under construction

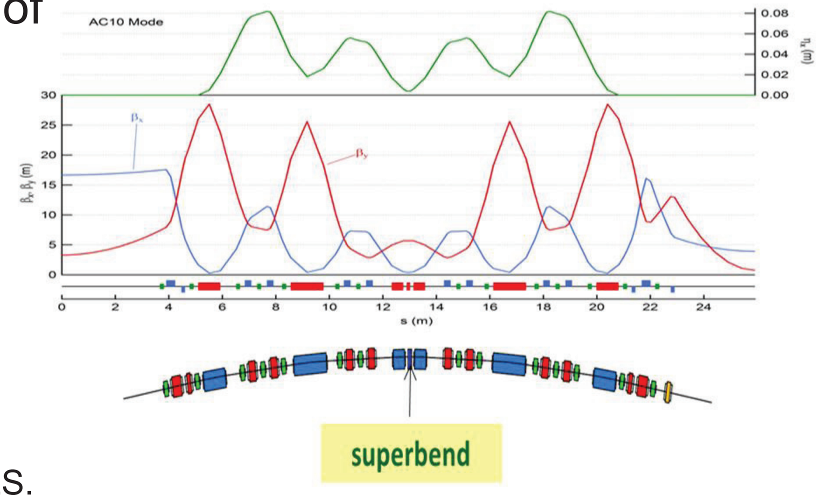
3 GeV, 528 m, 0.25 nm





Sirius (Brazil) just started construction of 5BA with superbend

3 GeV, 518 m, 0.28 nm



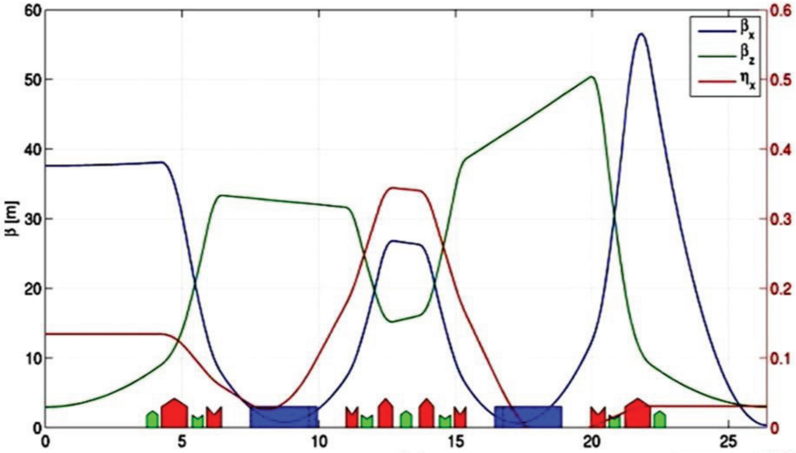
L. Liu, LNLS.

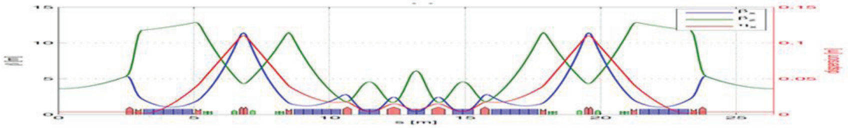
Existing rings are planning conversion to MBA

ESRF (France)

6 GeV, 844 m, 4 nm → 0.15 nm

- Dispersion bumps for efficient sextupoles
- Longitudinally varying field in D1, D2, D6, D7 to further reduce emittance
- Combined dipole-quadrupoles D3-4-5
- High-gradient focusing quadrupoles
- Permanent magnet dipoles





SPring-8 (Japan)

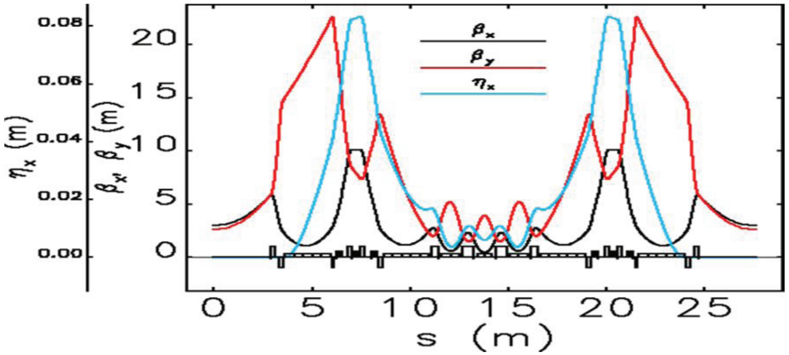
8 → 6 GeV, 1436 m, 2.8 nm → ~40-80 pm

SPring-8 MBA lattice under development

APS (US - premliminary)

7 → 6 GeV, 1104 m, 3.1 nm → ~60-80 pm

- Dispersion bumps like ESRF
- On-axis injection
- Superconducting undulators

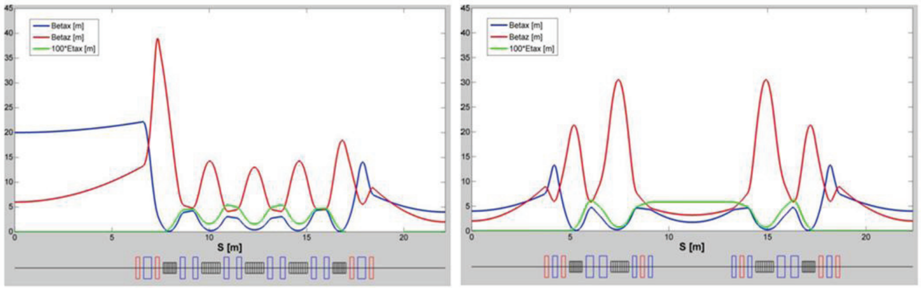


Other rings would like to convert lattices in future

Soleil (France)

2.75 GeV, 354 m, 3.9 nm → 0.5 nm

- 4BA or 5BA

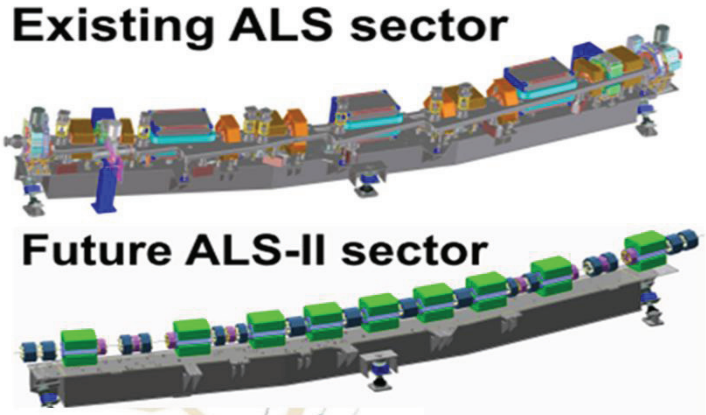


Lattice and envelop functions for the SDL-SDM (left) and SDM-SDC-SDM cells (right), altogether representing 1/8th of the ring

ALS (US - LBNL)

1.9 GeV, 200 m, 2 nm → 52x52 pm

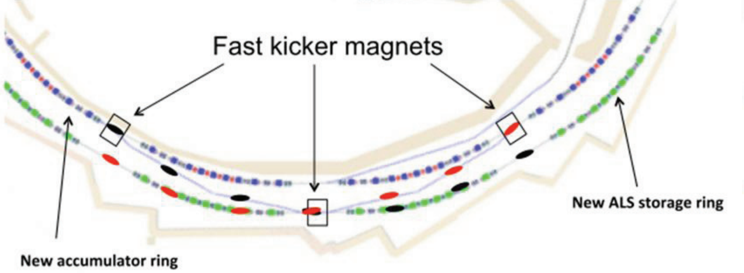
- 9BA
- Swap-out injection from accumulator ring
- 3-T PM superbend insertions



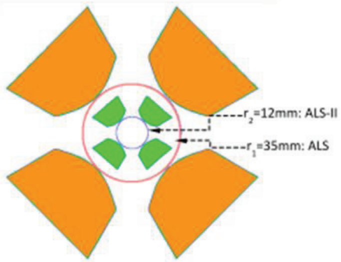
Other rings:

- SLS (Switzerland - PSI)

  2.4 GeV, 5 nm → 0.25 nm
- NSLS-II (US): ?
- …..



ALS-II swap-out/accumulator



ALS-II 24-mm ID chamber

Future green-field DLSRs?

BAPS (China - Beijing)

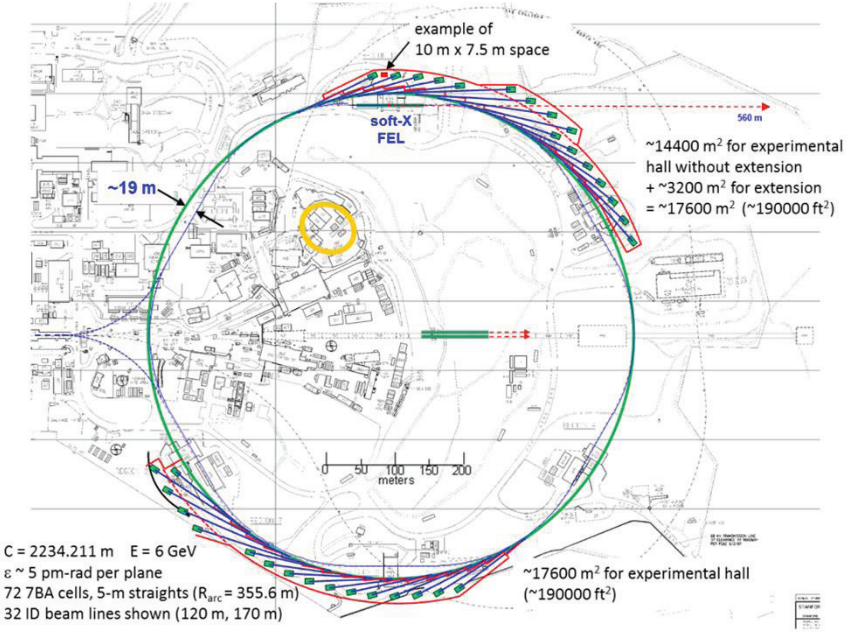
5 GeV, 1-1.5 km, <100pm

- Preliminary proposal

PEP-X (US - SLAC)

6 GeV, 2.2 km, 5 x 5 pm

- 7BA
- Not for a long time given LCLS-II at SLAC



TauUSR (US - Fermilab)

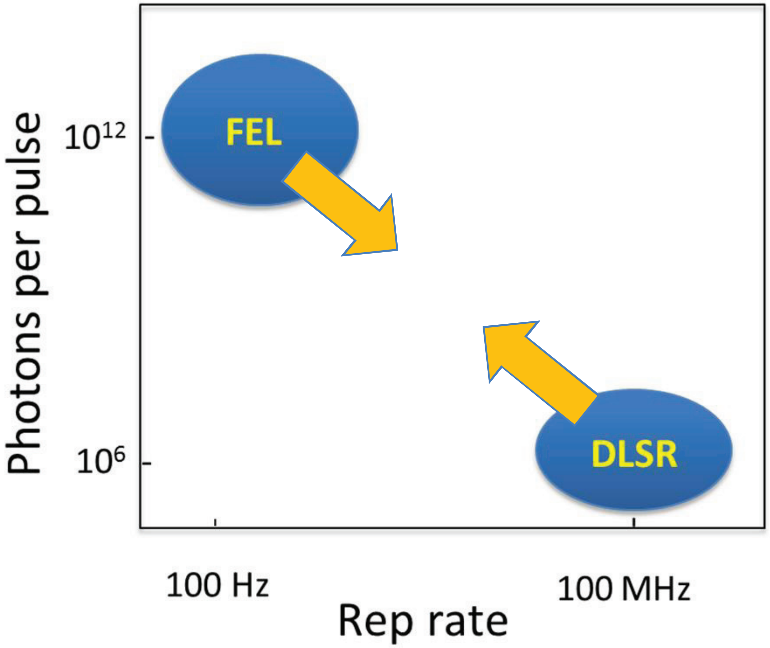
9 GeV, 2π km, 1.5 x 1.5 pm

- 7BA
- A πpe dream?

Ultimate storage rings?

- The term "ultimate storage ring" was first use in 2000:

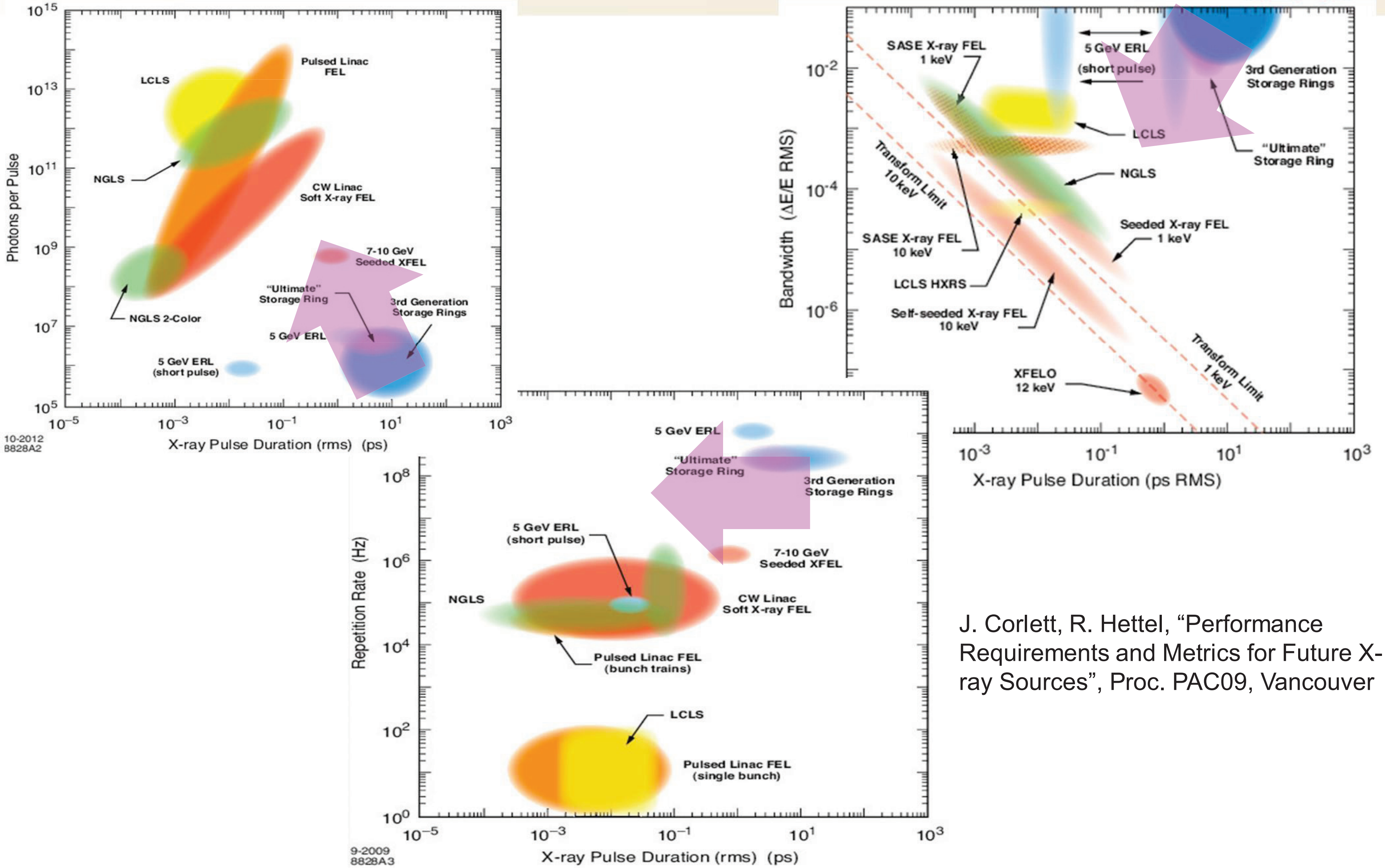
  A. Ropert, J.M. Filhol, P. Elleaume, L. Farvacque, L. Hardy, J. Jacob, U. Weinrich, "**Towards the Ultimate Storage Ring-Based Light Source"**, Proc. EPAC 2000, Vienna.
- "Ultimate" inferred reducing emttance towards the diffraction limit for X-rays
- "Ultimate" may have many meanings, including providing everything for every user
- One way to make storage rings more "ultimate":



FELs becoming more ring-like: higher rep rate, reduced photons/pulse (e.g. NGLS)

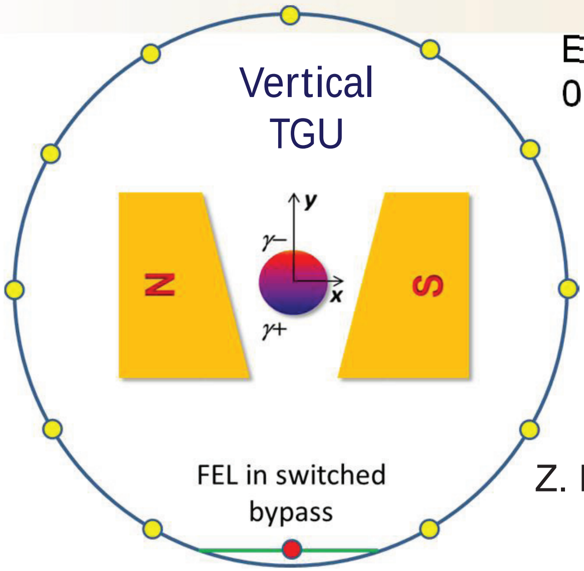
Can rings become more FEL-like: increased ph/pulse, reduced energy spread, short pulses, lasing?

Light source performance: other metrics



J. Corlett, R. Hettel, "Performance Requirements and Metrics for Future X-ray Sources", Proc. PAC09, Vancouver

SASE with transverse gradient undulator



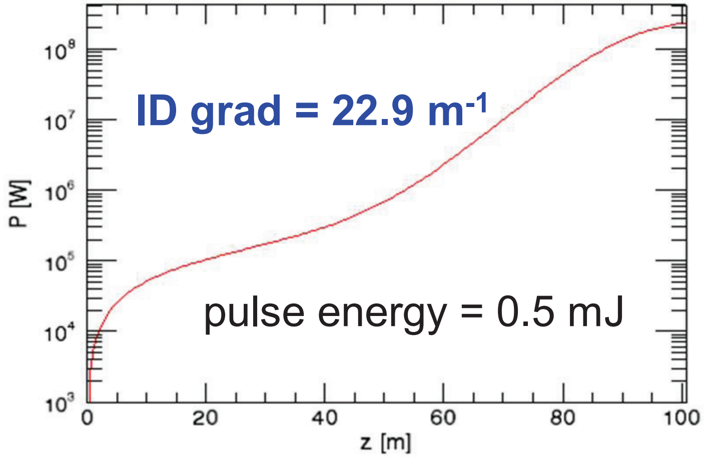
$E = 4.5$ GeV $\varepsilon_{x/y}$=160 / 1.6 pm $\delta E/E = 1.6\text{x}10^{-3}$ rms Q = 0.75 nC η_y = 0.05 m $\beta_{x/y}$ = 16 / 50 m σ_β = 52 mm σ_η = 78 mm λ_u = 3 cm K = 3.7

σ_z= 1ps I_{pk} = 300 A λ_{ph} = 1.5 nm

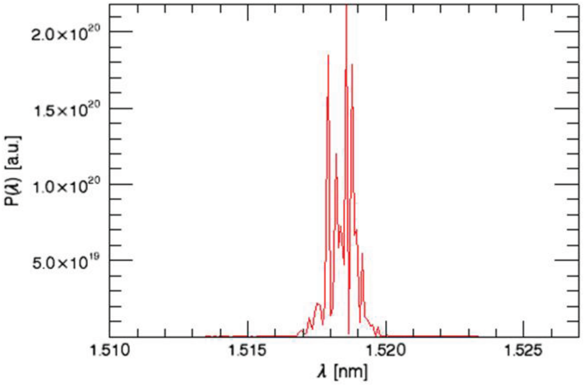
Bunch switched into FEL bypass (10-100 kHz)

Z. Huang, Y. Cai, Y. Ding

IPAC 2013



Reduce longitudinal emittance to reach high peak current – a challenge for future ring designers!

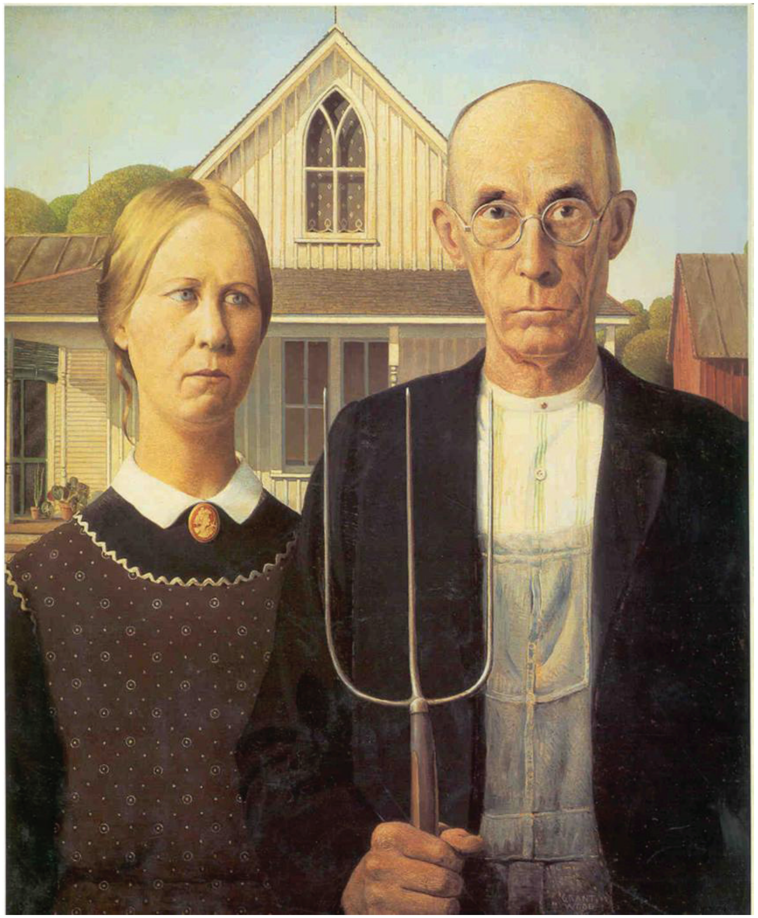


8 CEBAF SC cavities in a cryomodule produce 108 MV for longitudinal focusing

Hard XFEL oscillator? – K-J Kim

A new generation of storage ring light sources

3rd generation



MBA generation

Thank You!