# Challenges in the Design of Diffraction-Limited Storage Rings

Robert Hettel, SLAC

# DLSR Workshops

- ICFA Future Light Source Workshops (especially over last few years)
- ICFA Low Emittance Rings Workshops (LowERing)
- XDL 2011 Workshops for ERLs and DLSRs, Cornell, June 2011
- Beijing USR Workshop, Huairou, October 2012
- DLSR Workshop, SPring-8, December 2012
- DOE BESAC Subcommittee on Future Light Sources, July 2013
- Low Emittance Ring Workshop, Oxford, July 2013
- SLAC DLSR Workshop, SLAC, December 2013
- Workshop on Advances in Low Emittance Rings Technology (ALERT 2014), Valencia, May 2014
- Low Emittance Rings Workshop (LER2014), Frascati, September 2014
- DLSR Workshop, Argonne, November 2014

**many other workshops on low emittance rings, including those in the past for ILC damping rings**

# Acknowledgments

**Many appreciated contributions from:**

- D. Robin and C. Steier, ALS
- M. Borland, L. Emery, APS
- R. Bartolini, Diamond
- P. Raimondi, ESRF
- M. Eriksson, S. Leemann, MAX-IV
- L. Liu, Sirius
- A. Streun, SLS
- L. Nadolski, Soleil
- H. Ohkuma, K. Soutome, H. Tanaka, SPring-8
- Y. Cai, T. Rabedeau, SLAC and SPEAR3 Beam Physics Groups
- SLAC  Directors, I. Lindau, C. Pellegrini, J. Stohr, H. Winick

**and participants in FLS, LowERing and DLSR workshops over the past few years**

# Reference

**Journal of Synchrotron Radiation**, in publication

- 8 articles on accelerator physics and technology
- 2 articles on MBA rings in construction (MAX-IV and SIrius)
- 10 articles on scientific applications
- 4 articles on X-ray beam line technology (optics, instrumentation, detectors, etc.)

# Outline

- Introduction
- Diffraction limited emittance, brightness and coherence
- Properties of 4th generation storage ring (4GSR) and diffraction limited storage ring (DLSR) light sources
- Scientific motivation for 4GSRs
- 4GSR challenges and solutions
- Future DLSRs?

# PEP-X

**C = 2.2 km**

**2010 (baseline):**

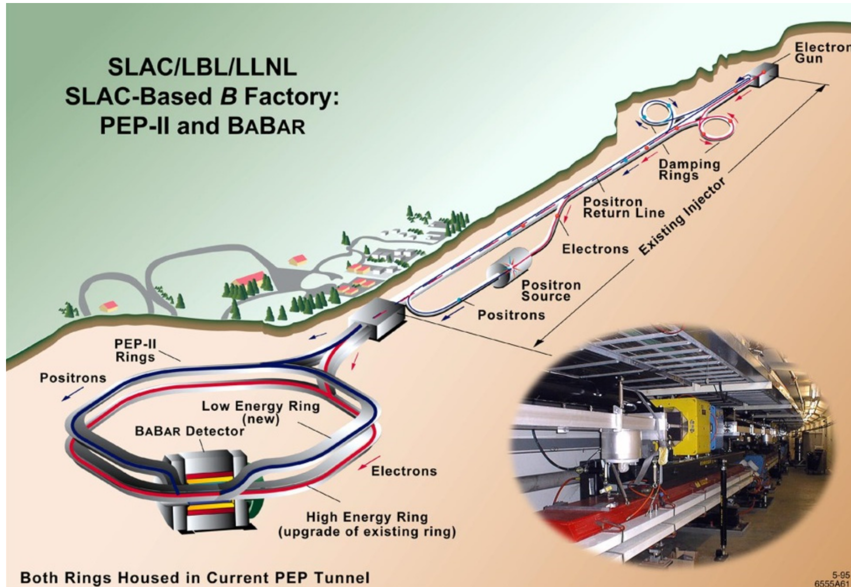
hybrid TME/DBA
4.5 GeV, 1.5 A
164/8 pm-rad

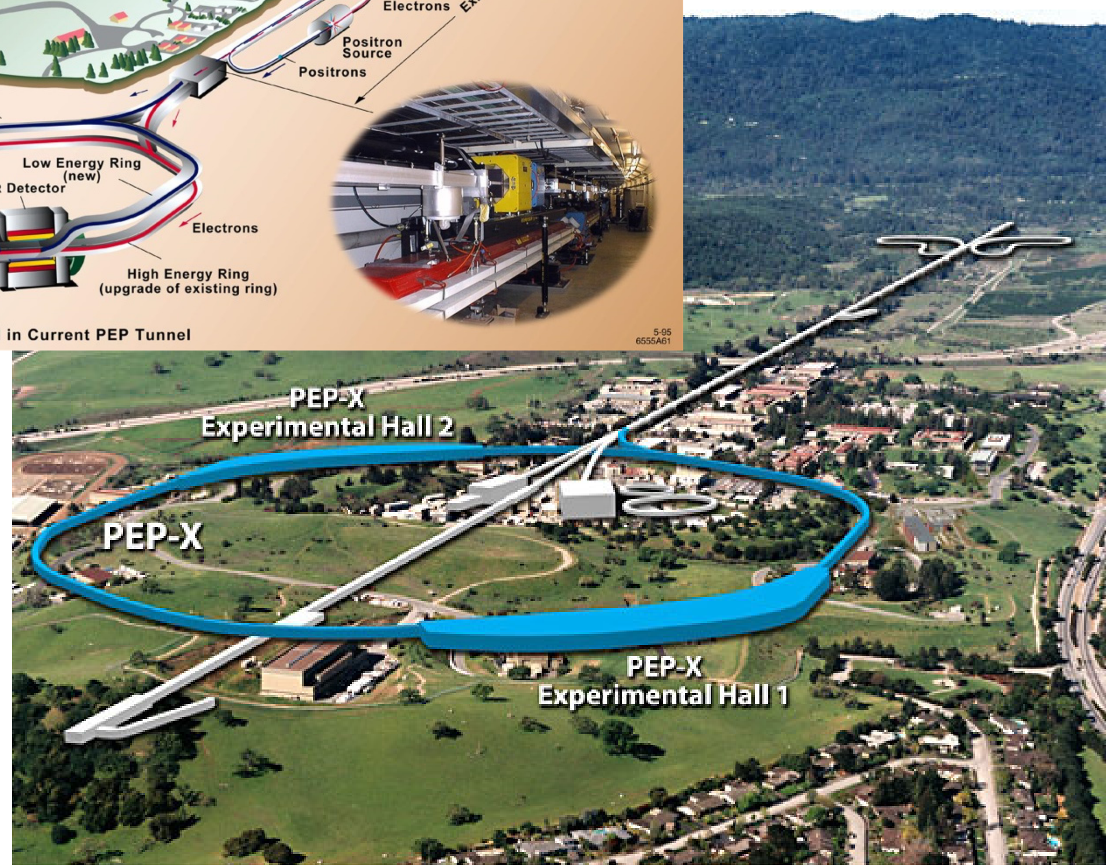
**2012:**

7BA hexagon
4.5 GeV, 0.2 A
11/11 pm-rad

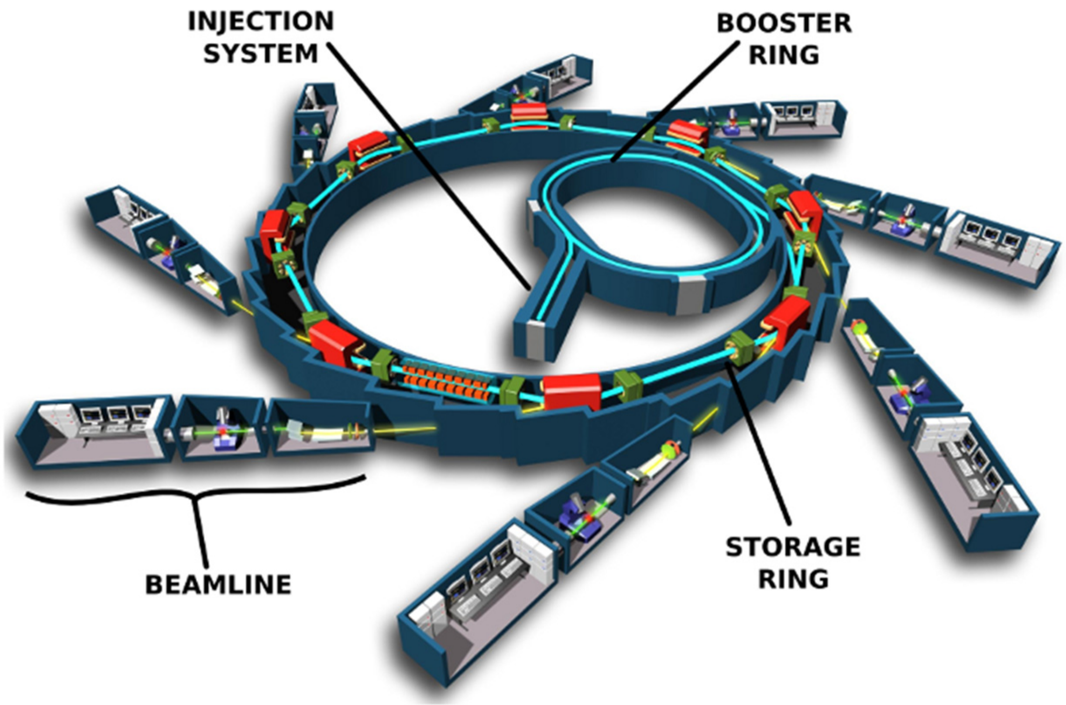
**2013:**

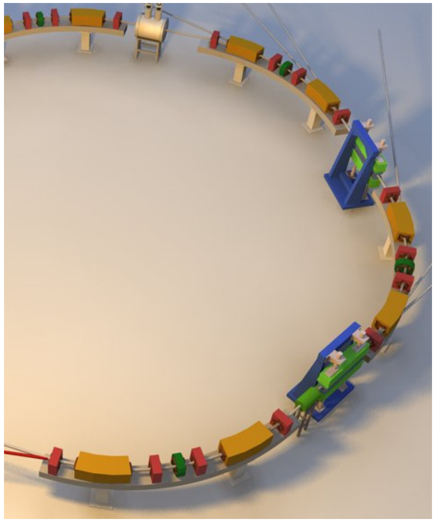
7BA circle
6 GeV, 0.2 A
5/5 pm-rad



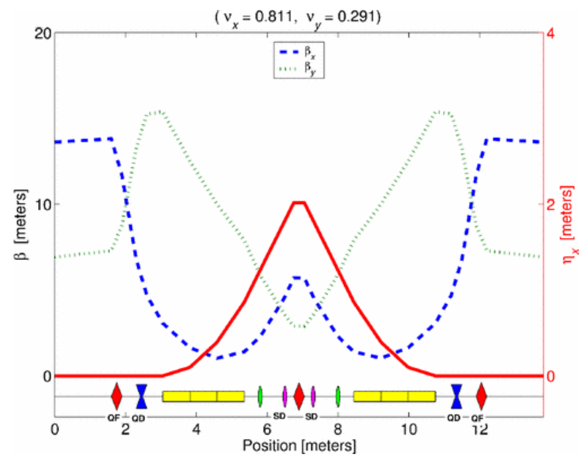



# Storage ring light source



Astrid II




nominal DBA lattice

## Light source metrics:

– spectral brightness, flux and photon spectrum

– coherent flux

– bunch length

– etc…..

– photons/pulse

– repetition rate

# Spectral brightness and coherence

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## Spectral brightness: photon density in 6D phase space

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

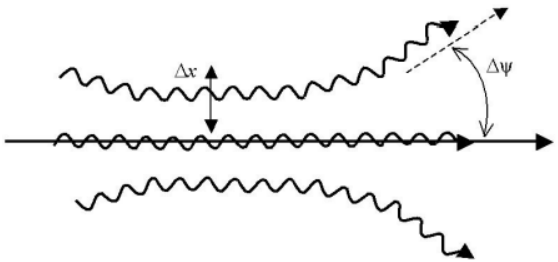
## Coherent fraction:

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

## Coherent flux:

$$F_{coh}(\lambda) = f_{coh}(\lambda) \cdot F(\lambda) = B_{avg}(\lambda) \cdot \left(\frac{\lambda}{2}\right)^2$$

# Diffraction-limited emittance $\varepsilon_r(\lambda)$




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

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

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):

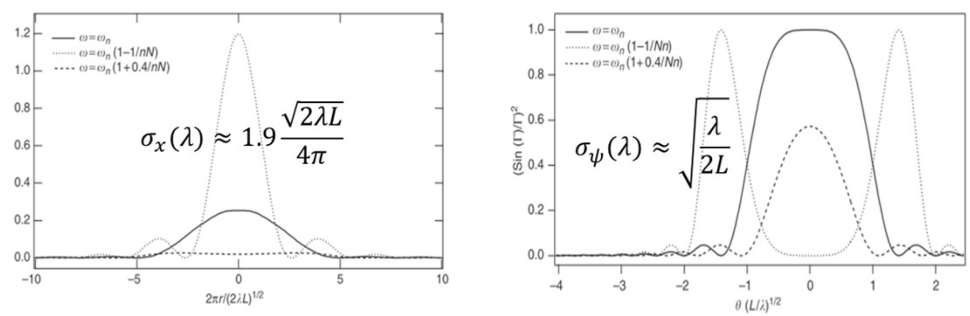
$$\mathcal{E}_k(\psi, z) = \frac{1}{\sqrt{2\pi}} \int E_k(x,z) e^{-ik\psi x}\, dx \qquad \psi \ll 1 \qquad E_k(x,z) = \frac{1}{\sqrt{2\pi}} \int \mathcal{E}_k(\psi, z) e^{ik\psi x}\, d\psi$$

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

Diffraction limited emittance for coherent Gaussian photon distribution

Gaussian fit to actual undulator radiation from electron filament:

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




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

# X-ray emittance from electron source

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

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

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

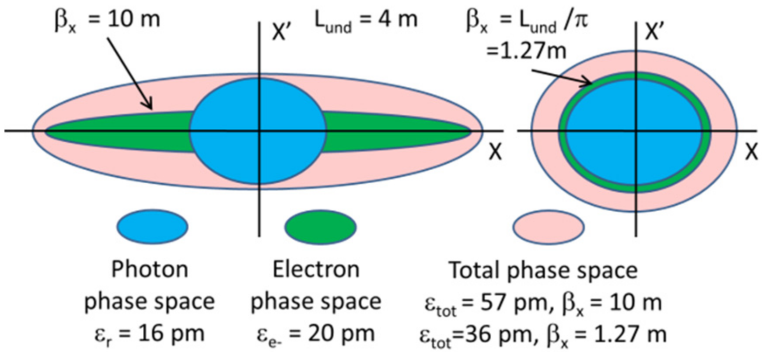
$$\sigma_{x,y}(e-) = \sqrt{\varepsilon_{x,y}\beta_{x,y} + (\eta_{x,y}\delta)^2} \qquad \sigma'_{x,y}(e-) = \sqrt{\frac{\varepsilon_{x,y}}{\beta_{x,y}} + (\eta'_{x,y}\delta)^2}$$

($\eta$, $\eta'$ =0 for achromat)

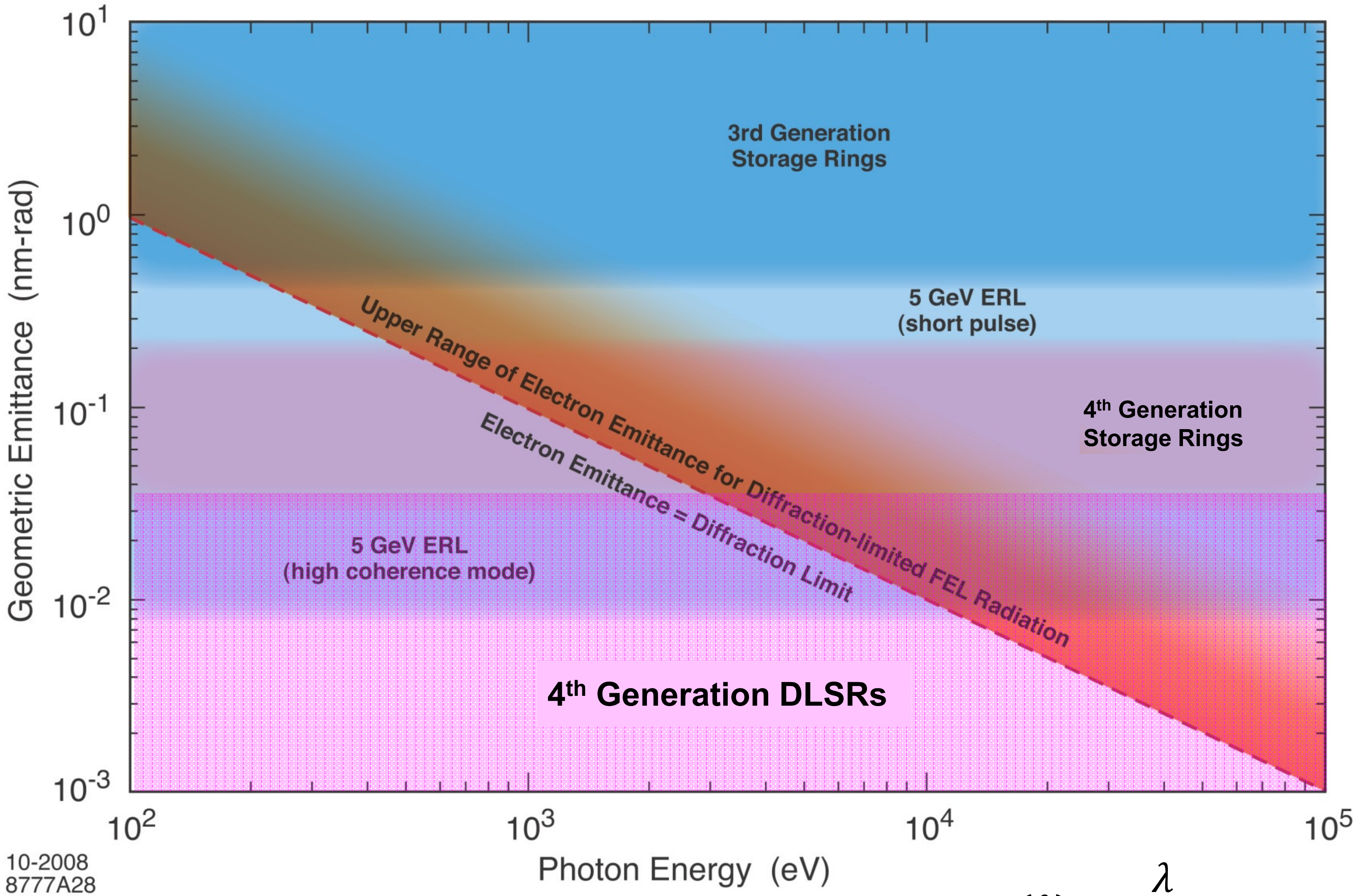
Total emittance minimized when $\varepsilon_{x,y}$ is minimized and photon and e- phase space orientations are matched:

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

**Note**: many authors cite $\beta_{x,y} = \dfrac{L}{2\pi}$

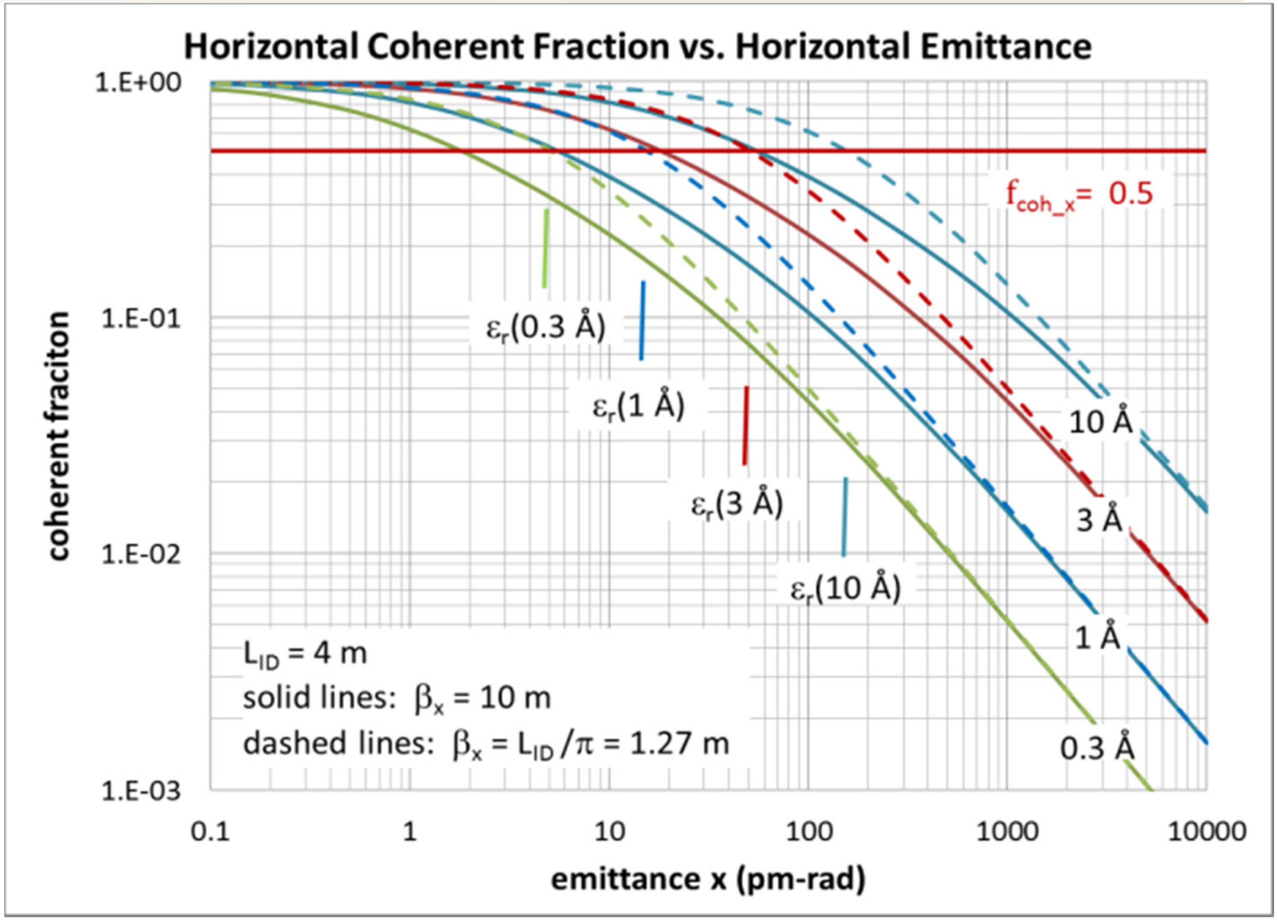


# Diffraction-limited emittance




**Note:** $\varepsilon_r(\lambda) = \dfrac{\lambda}{4\pi}$ assumed

# Coherent fraction

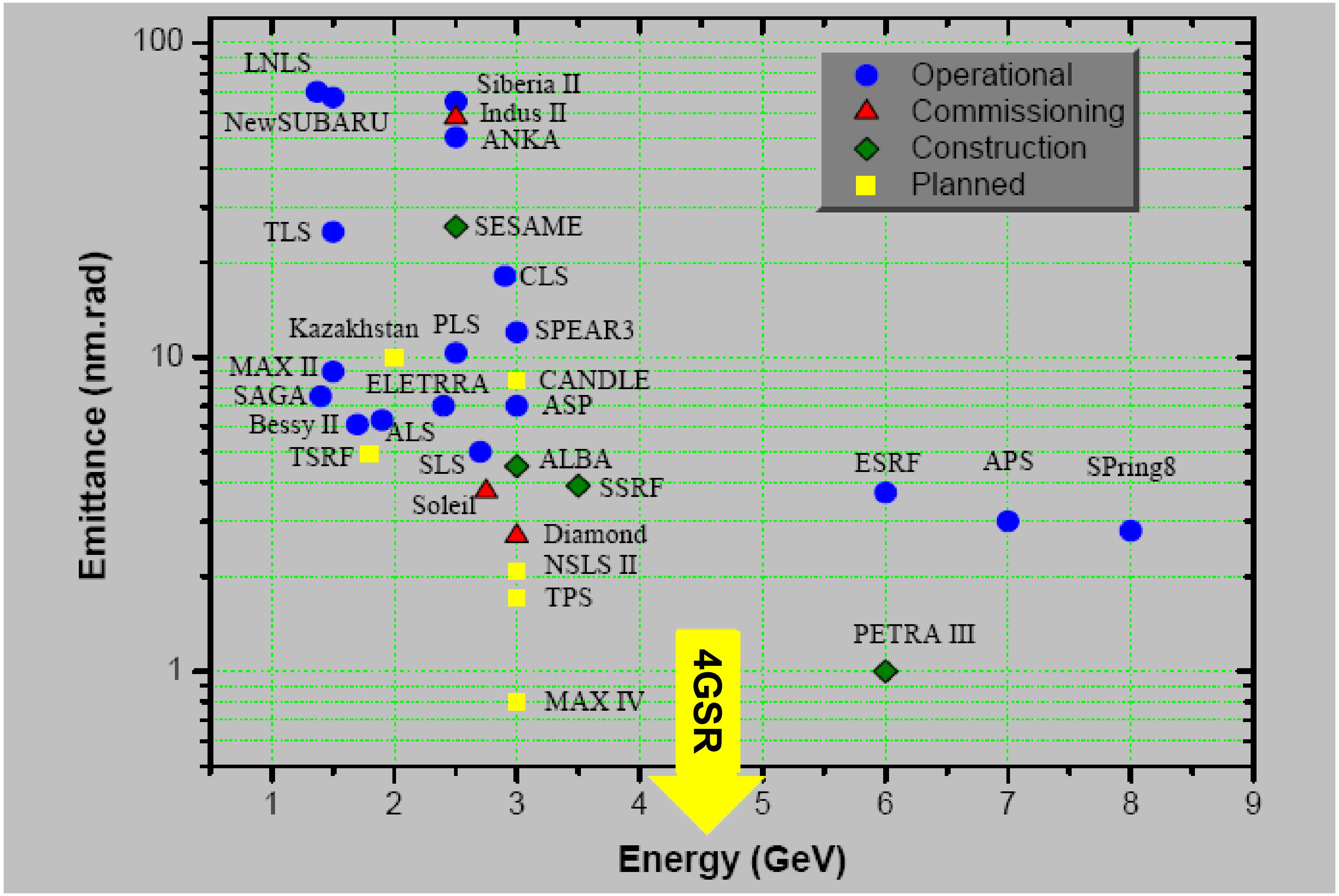



**Coherent flux** is important too: a low coherent fraction and high flux can yield the same coherent flux as a high coherent fraction and low flux

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

- **Many rings operate now with $\varepsilon_y$<< 1Å/4π = ~8 pm-rad by reducing vertical coupling and dispersion to very small numbers**
- **All storage rings are diffraction-limited for λ > $2\pi\varepsilon_{x,y}$(e-)**

# The state of SR light sources




Z. Zhao, SSRF

# Reducing emittance:  higher coherence

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## 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

## Some issues with coherence:

- **Reduced depth of focus** – a problem for some forms of imaging
- **Speckle** from coherent beams a problem for some applications

# Properties of 4GSRs

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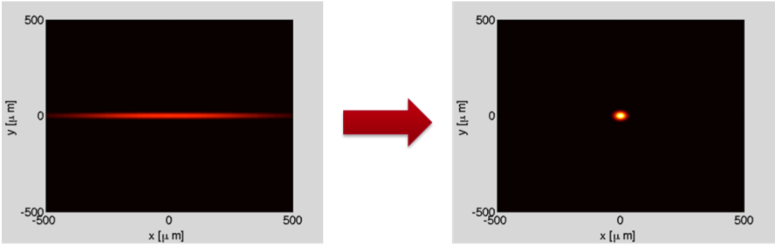
- **Brightness and coherence** are as high as possible for given beam current
- **Small horizontal and vertical beam dimensions** and the possibility of **"round" beams** – good for X-ray optics, minimal need for aperturing



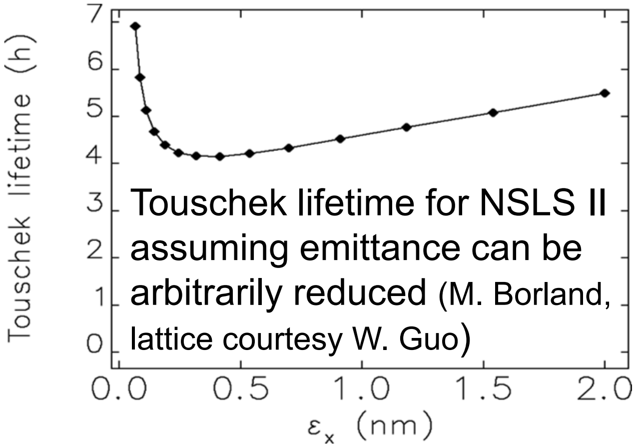

courtesy of C. Steier

- **"Short" bunches**

  ~5-10 ps RMS from low momentum compaction factor – bunch lengthening usually needed to combat emittance growth from IBS and improve lifetime; **synchrotron frequency < 1 kHz for large rings**

- **"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
- **Small dynamic aperture** (~mm) for aggressive lattices

# Fundamental challenge:  science case (in the US)

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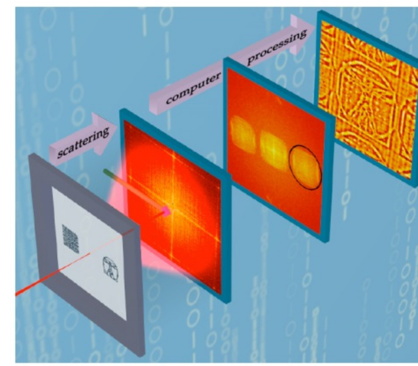
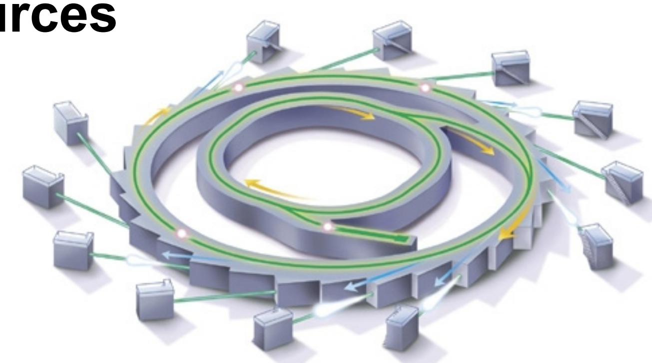
**XDL 2011 Workshops for ERLs and DLSRs (Cornell, June 2011) :**

- Diffraction Microscopy, Holography and Ptychography using Coherent Beams
- Biomolecular Structure from Nnanocrystals and Diffuse Scattering
- Ultra-fast Science with “Tickle and Probe”
- High-pressure Science at the Edge of Feasibility
- Materials Science with Coherent Nanobeams at the Edge of Feasibility
- Frontier Science with X-ray Correlation Spectroscopies using Continuous Sources **(time resolution $\propto$ B$^2$)**




**BESAC Subcommittee on Future Light Sources (July 10-12, 2013)**

A consensus report on future opportunities from scientists at **ALS, APS, NSLS-II, SSRL**, together with a broad community of scientists at laboratories and universities.



**Applications address “Grand Challenge Science”**

# The path to low emittance rings

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## Emittance scaling with energy and circumference:

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

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

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

(Note: $\varepsilon \sim E^5/C^3$ with some magnet dimension constraints – J. Safranek)

## Emittance reduction with damping wigglers:

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

$U_0$ = 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

# 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**
  - Stronger chromatic correction sextupoles: strengths increase like $N_d^3$
  - Dynamic acceptance decreases like $1/N_d^3$
  - Second order chromaticities increase like $N_d^3$
  - Dipole/quadrupole bore $\sim 1/N_d^2$; sextupole bore $\sim 1/N_d^{1.5}$
- **Stronger focusing leads to difficult non-linear dynamics**
  - Poor "momentum aperture" $\Rightarrow$ reduced lifetime $\Rightarrow$ frequent injection
  - Poor "dynamic aperture" $\Rightarrow$ greater difficulty injecting $\Rightarrow$ **on-axis injection?**

# On-axis injection

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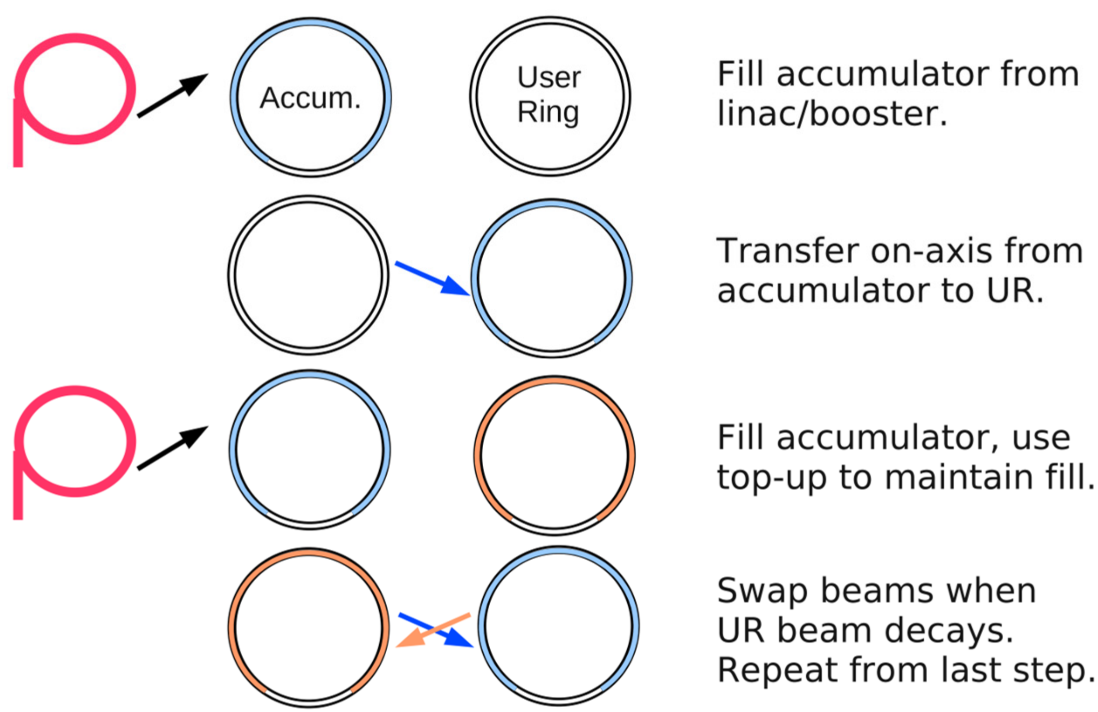
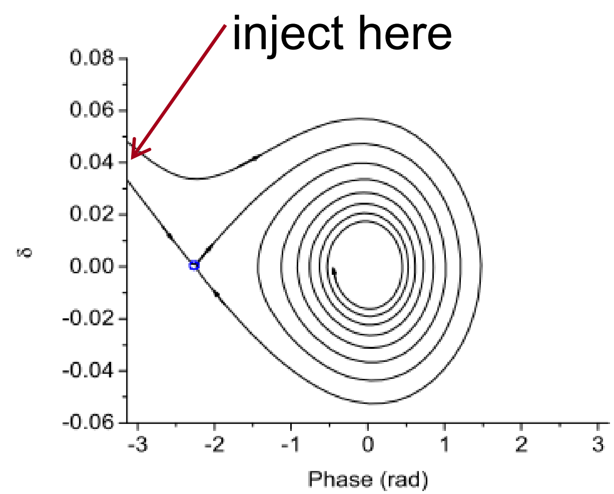
*Swap-Out Concept Using an Accumulator*[1,2]




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

## Bunch Replacement (Swap-Out) Injection

requires fast kicker (width ~ bunch spacing or longer for pulse trains) - M. Borland, L. Emery, Proc. PAC'03



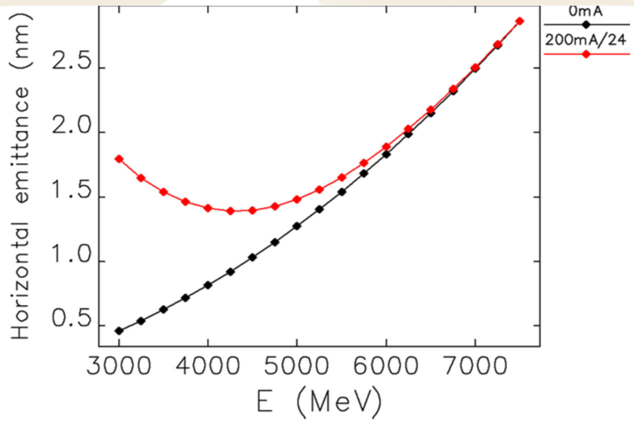

## Longitudinal Injection

requires fast kicker (width < bunch spacing)

M. Aiba, M. Böge, Á. Saá Hernández, F. Marcellini and A. Streun, this conference

# 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 beams
    - 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 and detectors**
  - Advances in optics needed to preserve coherence, handle high power densities
  - Detectors with higher resolution and faster readout rates are needed

# 4GSRs:  why now and not earlier?

## Science case is growing:  NSLS-II, ESRF, SPring-8, APS, …..

## Multibend achromat (MBA) lattices

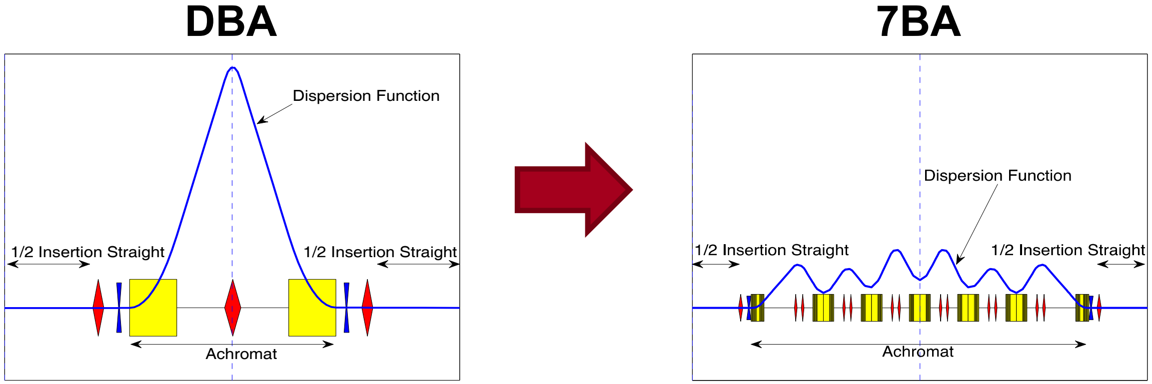
- Lattice design evolution from DBA, TBA to 4BA,…MBA:
- History (partial):

1993:  QDA by D. Einfeld at al. NIMA 335(3)

1994:  SLS early design with 7BA, short superbend, provision for on-axis injection (W. Joho, P. Marchand, L. Rivkin, A. Streun, EPAC'1994)

1995:  7BA  by Einfeld et al. (0.5 nm-rad, 3 GeV, 400m, PAC 95)

2002:  MAX-IV 7BA concept (M. Eriksson, Å. Andersson, S. Biedron, M. Demirkan, G. Leblanc, L. Lindgren, L. Malmgren, H. Tarawneh, E. Wallén, S. Werin, EPAC 2002)



# 4GSRs: why now? – accelerator physics

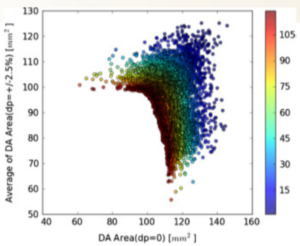



FIG. 1. The last generation of objective functions: DA of on-momentum (horizontal axis) and off-momentum (vertical axis) particles. Points are colored according to their rank.

Symplectic Tracking based methods

DA, MA separated

DA, MA together

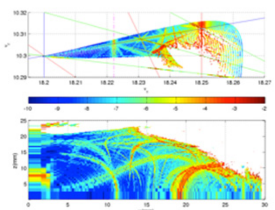
from L. Nadolski, ICFA LowEring, Oxford 7/13

Direct tracking based optimization

GLASS

Analytical based method

Genetic Algorithm
MOGA



Lie Algebra/Differential Algebra

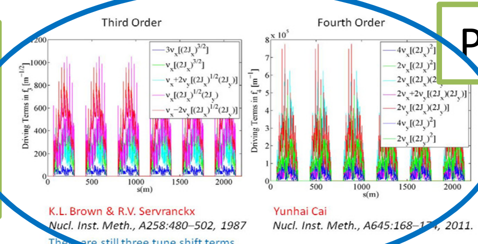
Resonance Driving Terms
RDT minimization

Amplitude Tuneshift
minimization

Frequency Maps
FMA
Diffusion factor

Nonlinear
“LOCO”

Canceling
Sextupole
Resonances




Phase advances

Interleaved
sextupoles

Resonance identification

Robustness to magnetic, alignment errors

Robustness ID configurations

**Tracking codes:** **PTC** **MADX** **TRACY** **AT** **LEGO** **OPA** **ELEGANT**

# 4GSRs:  why now? – cont.

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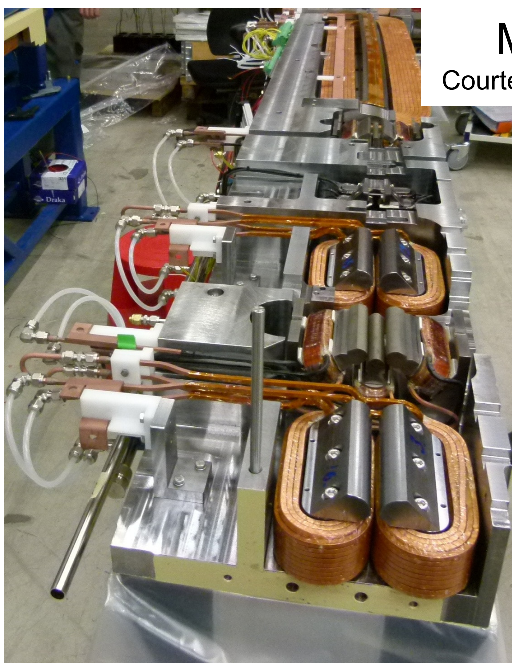
## Compact magnet and vacuum technology

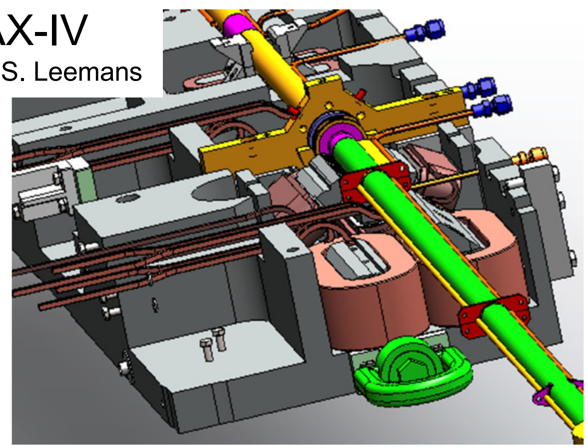
- **NEG-coated vacuum chambers** enable small apertures to enable high magnet gradients

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

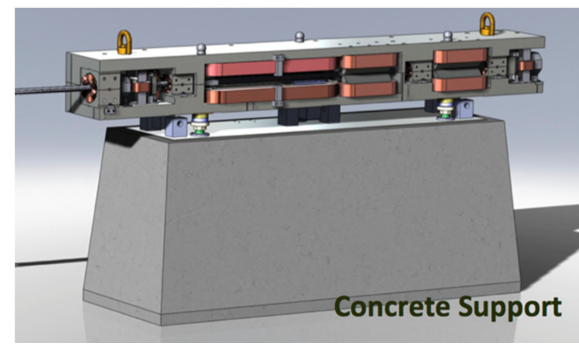
- **Precision magnet pole machining** for small aperture magnets, **combined function magnets**, tolerance for magnet crosstalk (e.g. MAX-Lab)

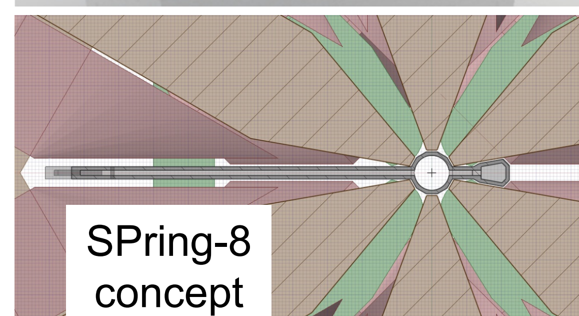


MAX-IV
Courtesy S. Leemans




heater tape for in-situ NEG bake-out Sirius



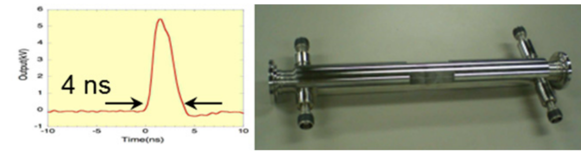
SPring-8 concept
K. Soutome

# 4GSRs:  why now? – cont.

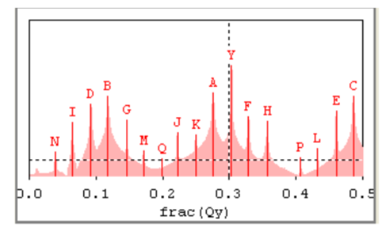
## Other advances in accelerator and light source technology:

- **Fast kickers** for on-axis injection
- **Sub-micron e- BPMs** with micron resolution single pass capability: non-linear lattice tuning
- Accelerator and beam line component **mechanical positioning and stabilizing systems**
- **“In-situ” and beam-based magnet measurement and alignment methods**
- **Mode-damped RF cavities** (fundamental and harmonic)
- Highly stable **solid state RF power sources**
- **High performance IDs** (**superconducting**, Delta, RF, etc.)
- **Advances in X-ray optics and detectors**

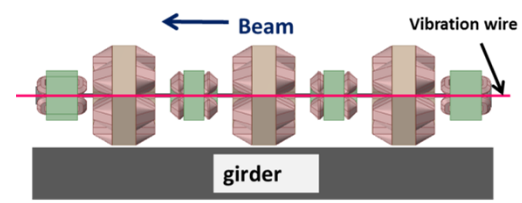
start-to-end beam line system simulations, SC detectors, cryo-cooled mirrors, etc.



Fast kickers (KEK ATF)

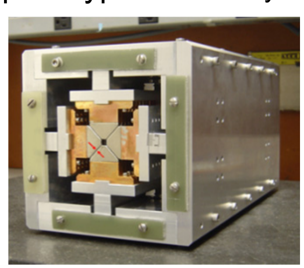


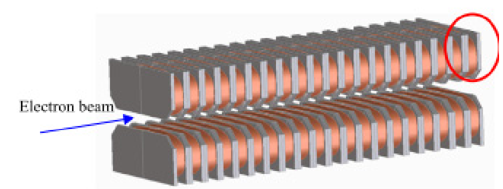
Higher order resonances detected by turn-turn BPMs (A. Franchi)



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

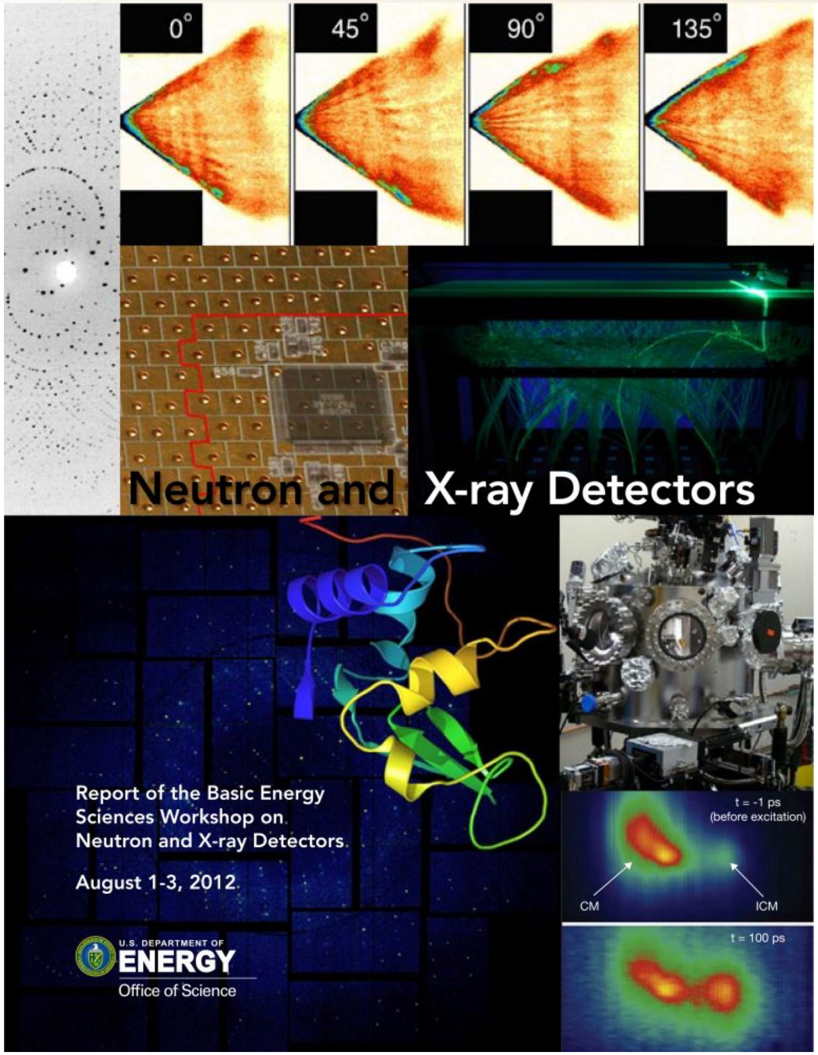
Delta undulator prototype - A. Temnykh

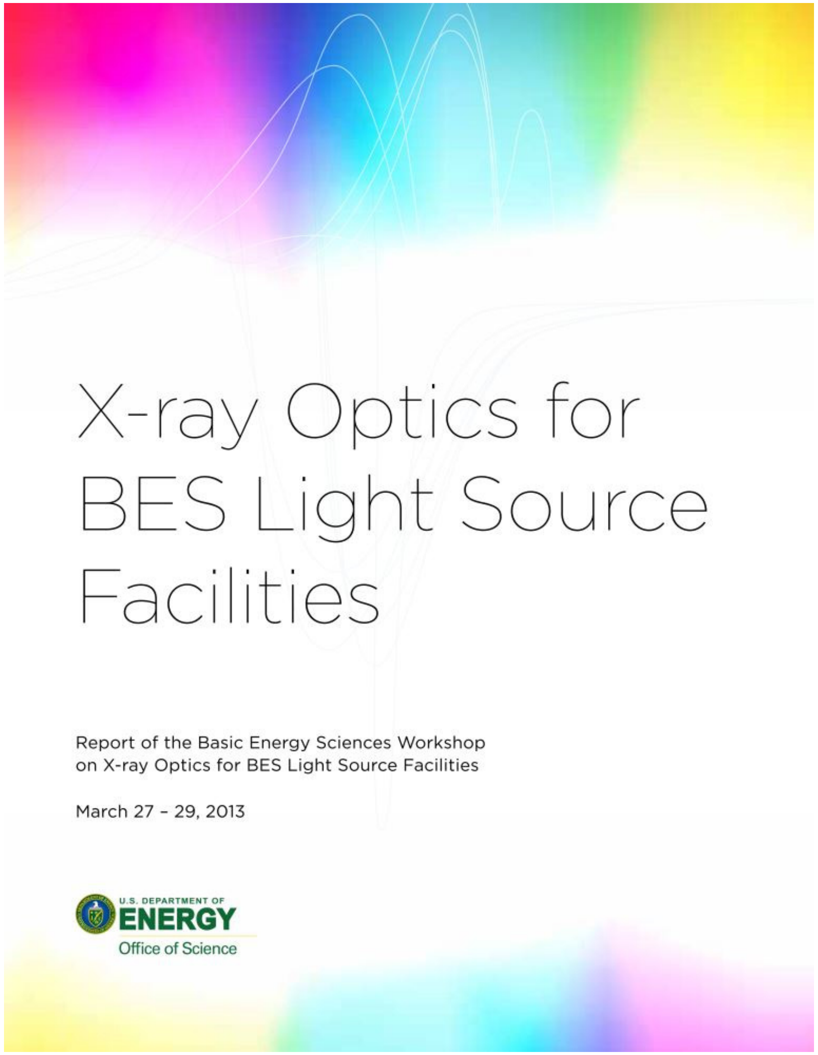




SC undulator development at LBNL (S. Prestemon et al.), APS (E. Gluskin et al.) and elsewhere

# X-ray optics and detectors



# MBA Lattices are becoming a reality – new rings

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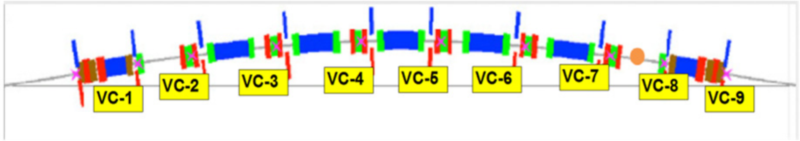
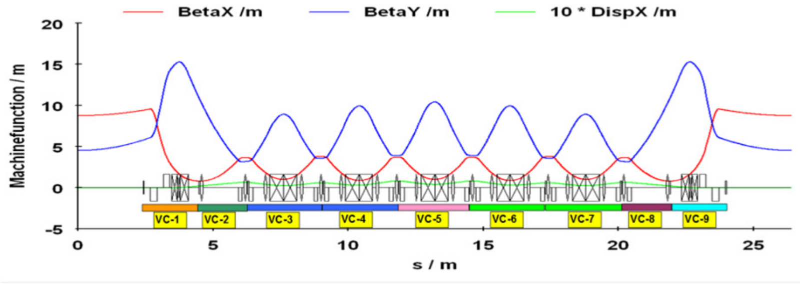
**MAX–IV** (Sweden) is taking the first pioneering step with 7BA, under construction

**3 GeV, 528 m, 0.25 nm**

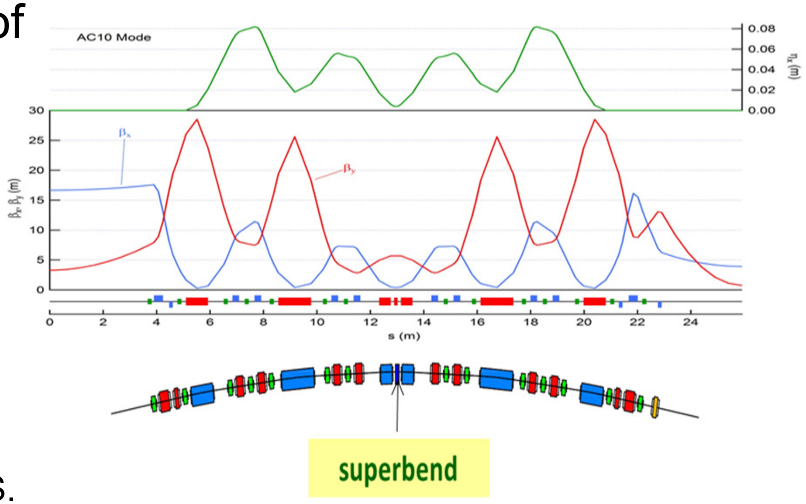



**Sirius** (Brazil) just started construction of 5BA with superbend

**3 GeV, 518 m, 0.28 nm**

L. Liu, LNLS.



# MBA Lattices are becoming a reality – new rings

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

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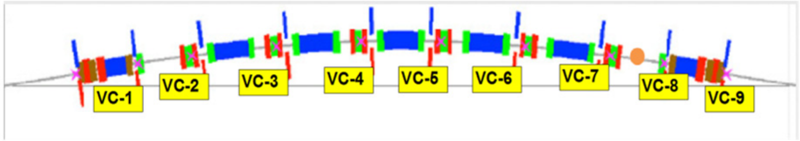


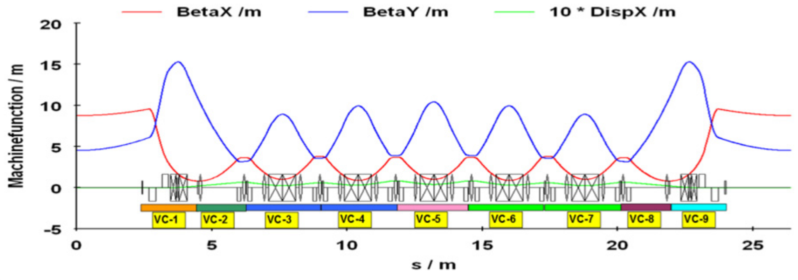


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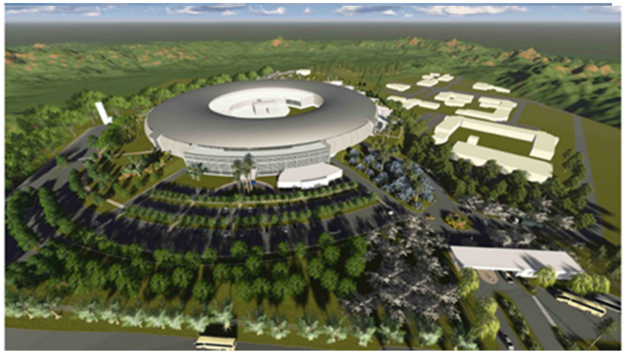

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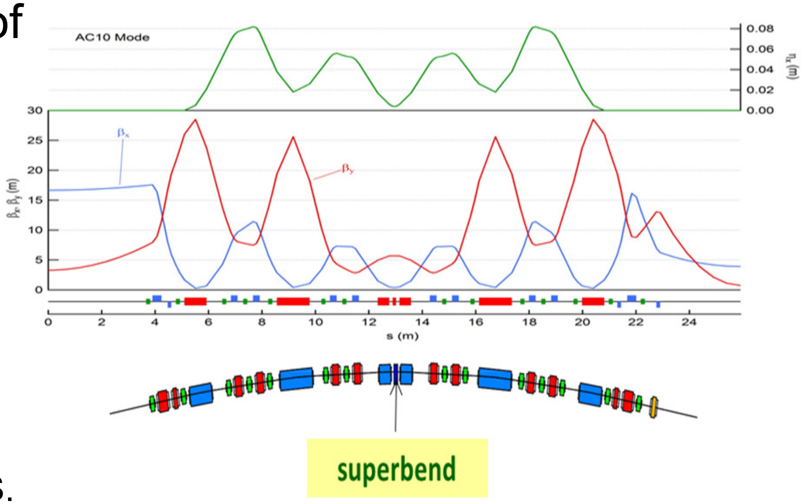


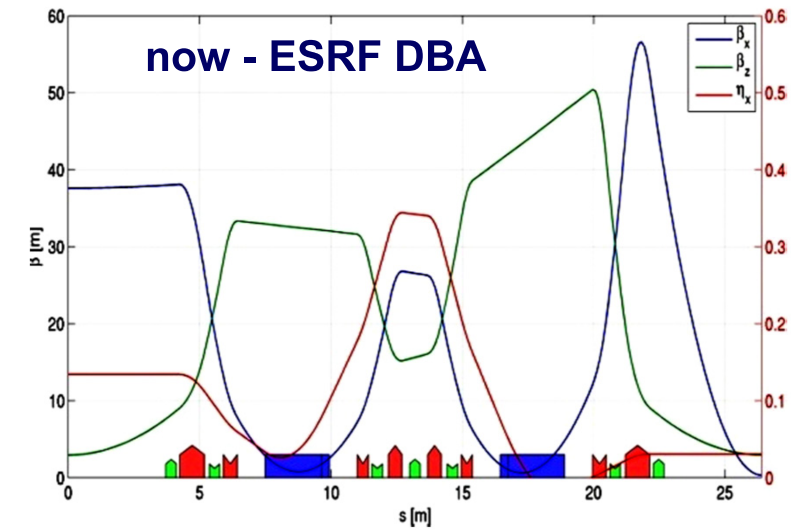
# Existing rings are studying conversion to MBA

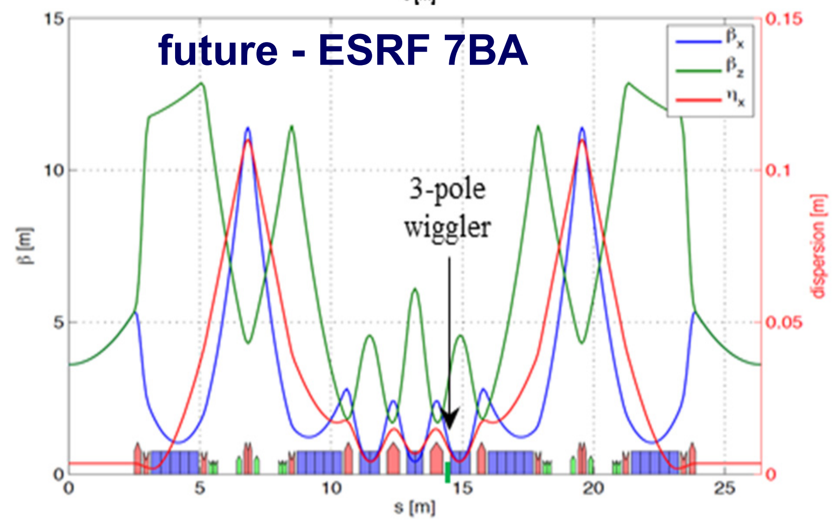
SLAC

**ESRF** (France)

**6 GeV, 844 m, 4 nm → 150 pm**

- **Dispersion bumps** for efficient sextupoles
- **Longitudinal gradient dipoles** (D1, D2, D6, D7) to further reduce emittance
- **Combined dipole-quadrupoles** D3-4-5
- **3-pole wiggler** as hard X-ray source




**APS** (US - preliminary)

**7 → 6 GeV, 1104 m, 3.1 nm → ~65 pm**

- ESRF-style lattice, 3-pole wiggler
- **Swap-out injection**
- **Superconducting undulators**

**SPring-8** (Japan)

**8 → 6 GeV, 1436 m, 2.8 nm → <100 pm**

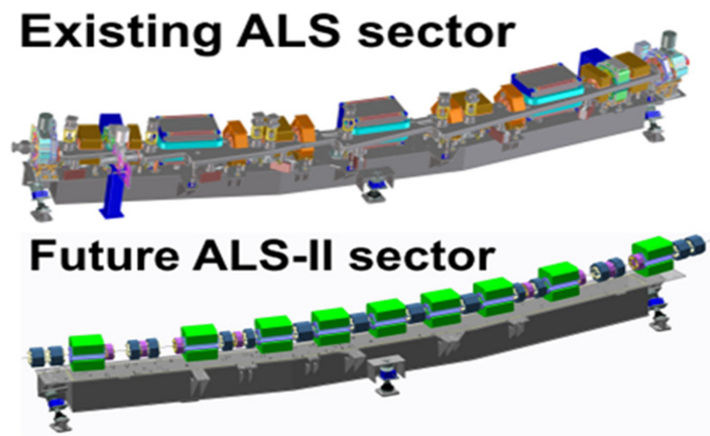
- lattice under development

# Other rings would like to convert lattices in future

**ALS-U** (US - LBNL)

**1.9 GeV, 200 m, 2 nm → 52x52 pm**

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



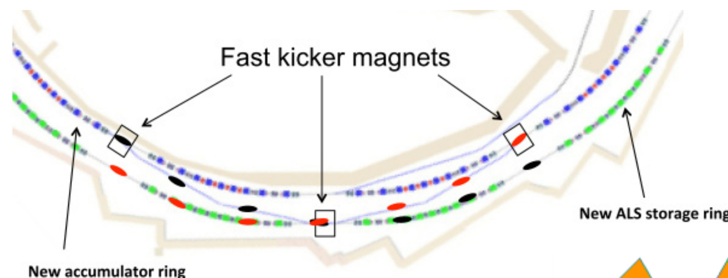

## Other rings:

- **SLS** (Switzerland - PSI)

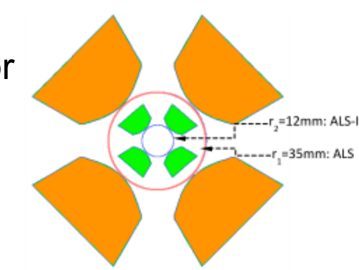
  2.4 GeV, 288 m, 5 nm → 0.25 nm
- **Soleil** (France)

  2.75 GeV, 354 m, 3.9 nm → 0.5 nm

…..




ALS-II swap-out/accumulator




ALS-U 24-mm ID chamber

# Future DLSRs?

**BAPS** (China - Beijing)

**5 GeV, 1-1.5 km, <100pm**

- Preliminary proposal

**PEP-X** (SLAC)

**6 GeV, 2.2 km, 5 x 5 pm**

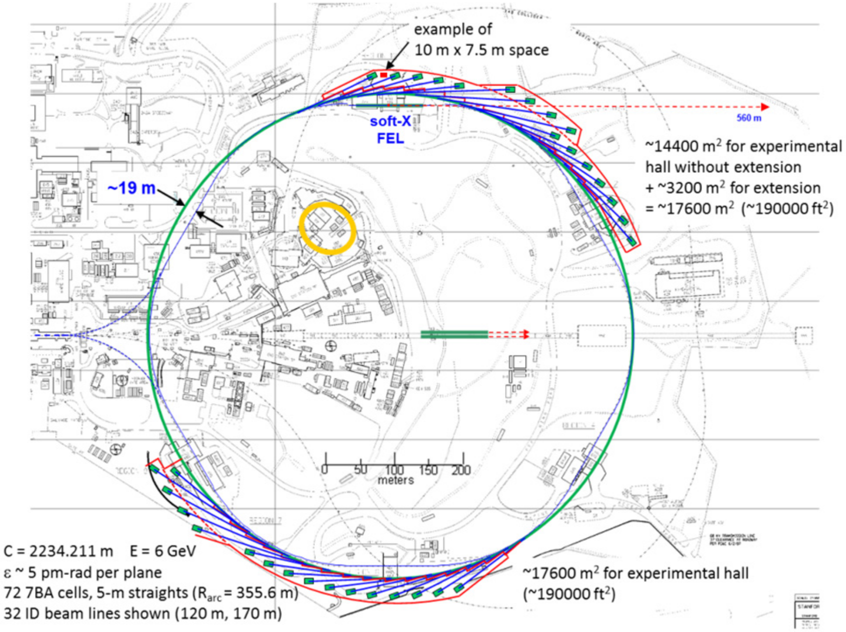
- 7BA
- Not for a long time given LCLS-II at SLAC

**PETRA-IV?** (DESY)

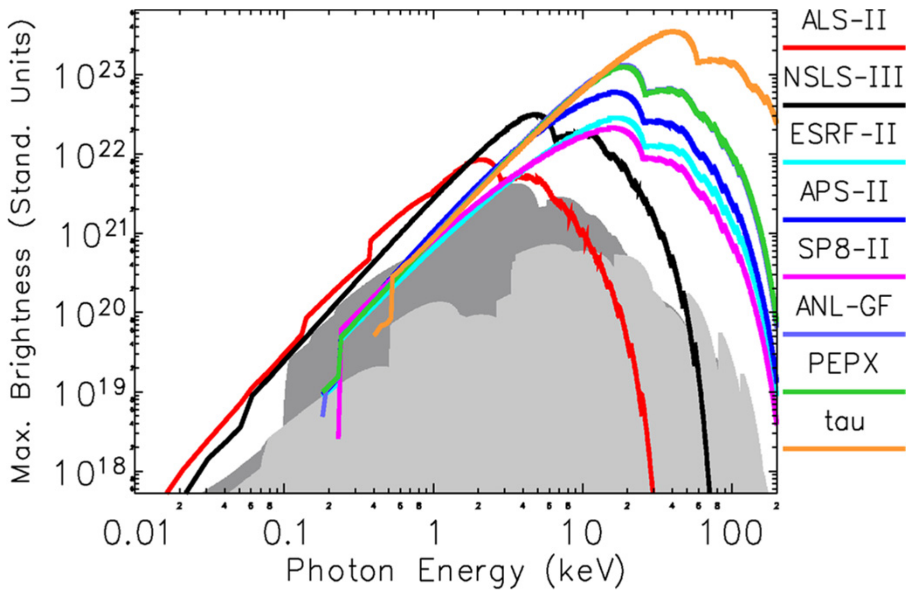
**TauUSR** (Fermilab)

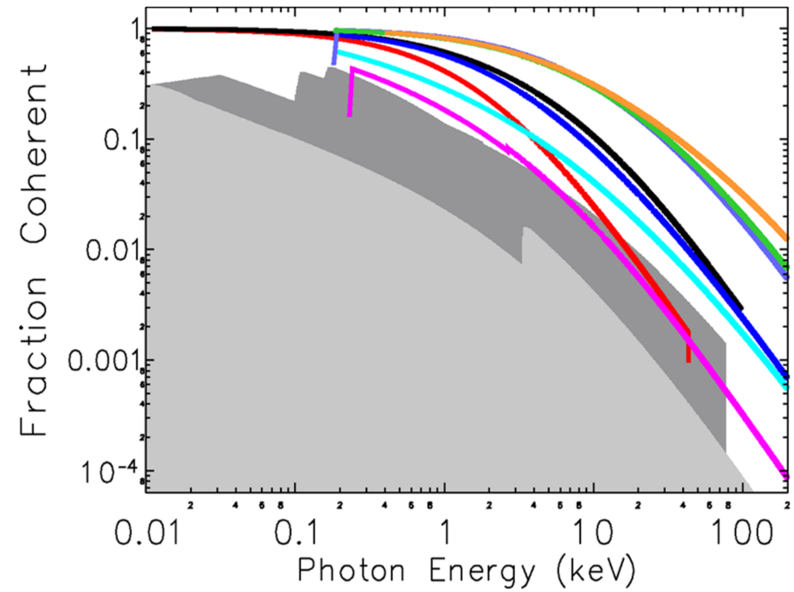
**9 GeV, 2$\pi$ km, 1.5 x 1.5 pm**

- 7BA
- A $\pi$pe dream?



# Brightness and coherence of future rings



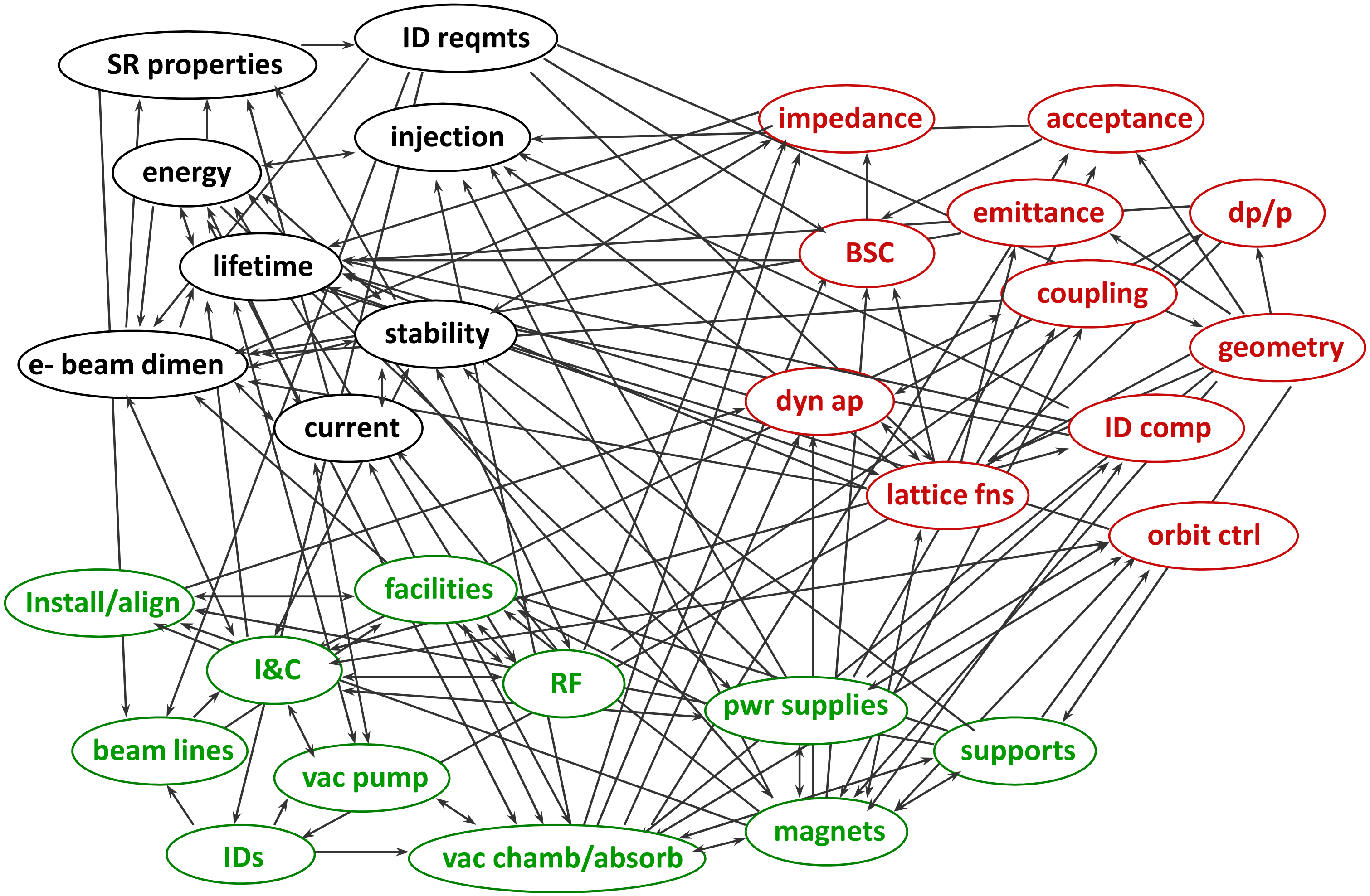

Parameters provided by facility contacts.

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

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

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.

# 4GSR design optimization



# 4GSR design – comments

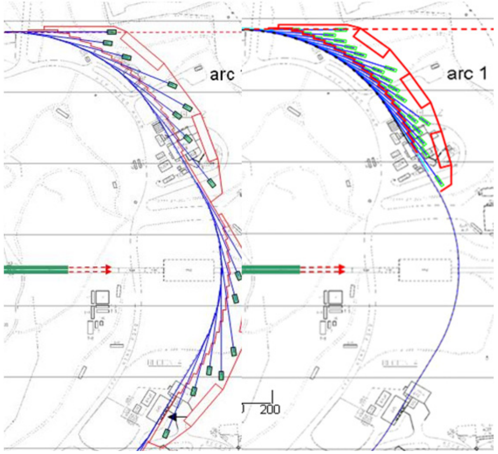
## Brightness/coherence vs. flux

- User community is divided – some need flux, not brightness
- Figure of merit: number of "usable" photons per unit time in the spatial and energy bandwidth acceptance phase space of the experiment (e.g. protein crystal angular acceptance is quite large – moderate brightness is OK). "Brightness isn't everything".
- Diminishing return on coherent fraction and flux as emittance is reduced
- Cost-performance optimization needed for every light source design
- Science case should drive the optimization **(is 10 or 1 pm worth it? – maybe!)**

## Lattice

- ID straight section length is always an issue (canted IDs?)
- Spacing between ID straights is an issue with large rings, leading to large, expensive experimental halls. Consolidating beam lines with hybrid lattice may be more efficient (e.g. PETRA-III)
- A relaxed, larger dynamic aperture mode for aggressive lattices?: "emittance knob"


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

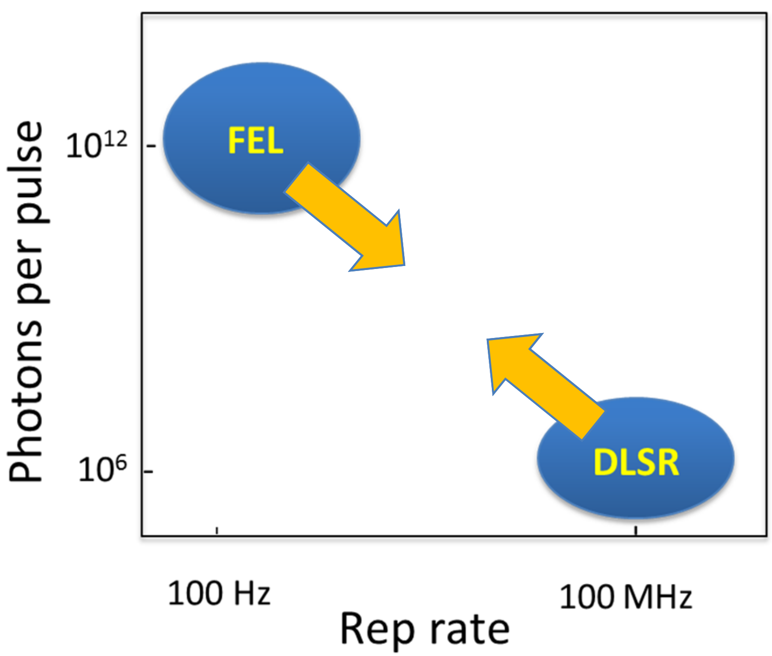


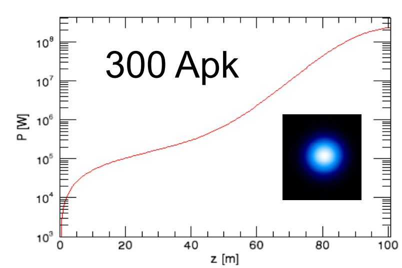
# The future: ultimate storage rings?

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

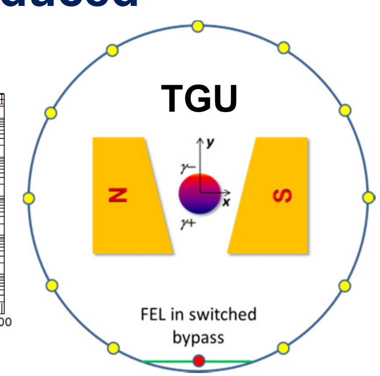
  A. Ropert, J.M. Filhol, P. Elleaume, L. Farvacque, L. Hardy, J. Jacob, U. Weinrich, "Towards the Ultimate Storage Ring-Based Light Source", Proc. EPAC 2000, Vienna.

- “Ultimate” inferred reducing emttance towards the diffraction limit for X-rays
- “Ultimate” has many meanings, e.g. providing everything for every user
- Ways to make storage rings more “ultimate”:
  - **M>>7** MBA lattices for < 1km rings
  - **FELs becoming more ring-like**: higher rep rate, reduced photons/pulse (SC CW RF)
  - **Can rings become more FEL-like?:** increased peak current, **reduced longitudinal emittance**, lasing?

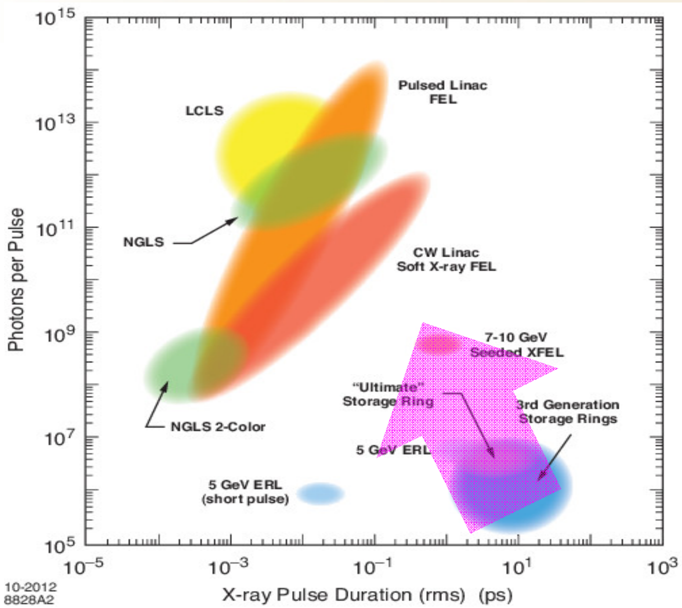


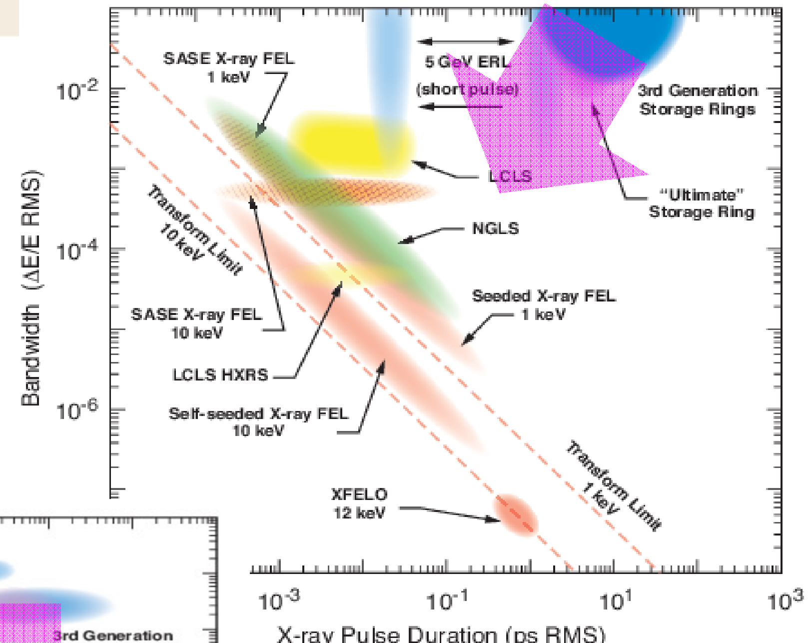




Z. Huang, Y. Cai, Y. Ding IPAC 2013

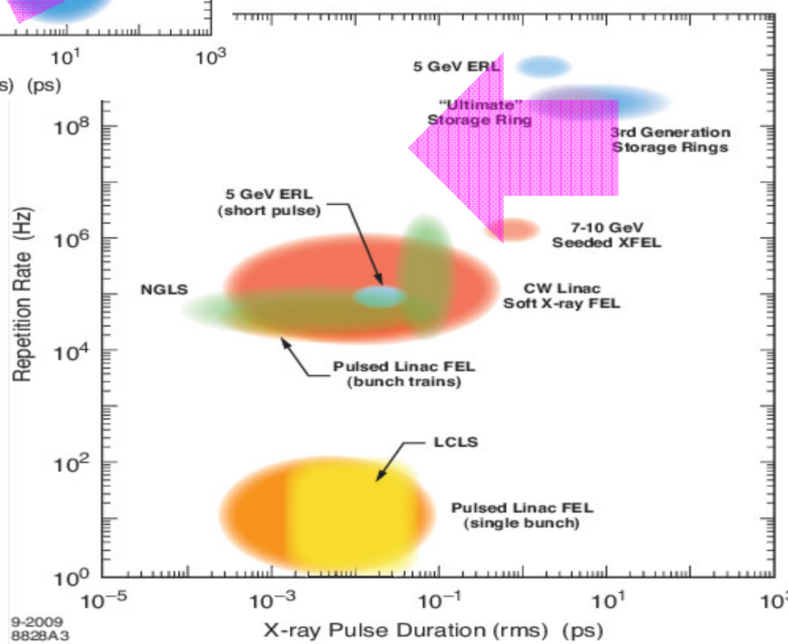


# Light source performance: other metrics




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




**Longitudinal and transverse transform-limited beams?**

**ultimate!**

# Success of a synchrotron radiation light source

- Success is built on the quality and innovation of the science program and those carrying it out, not necessarily on who has the “biggest gun”
- There are vast improvements to be made, even on existing light sources, with better X-ray optics, detectors and experimental techniques
- On the other hand, if we build a better source, they will come!

# Thank You!