Preliminary Expected Performance Characteristics of an APS Multi-Bend Achromat Lattice

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Outline

- Goal of MBA upgrade
- Multi-bend achromat storage rings on the horizon
- Possible APS upgrade to a 4^{th}-generation source
  - Preliminary parameters
  - Preliminary performance
- Summary

Goals

- Basic goal:

Dramatically enhance the performance of the APS as a hard x-ray source

- Measures of performance
  - Average brightness
  - Average flux
  - Brightness per pulse
  - Flux per pulse
- Opportunity exists with new lattice designs to provide
  - Much higher brightness
  - Higher flux
  - Significantly improved timing characteristics

4^{th}-Generation Storage Rings on the Horizon

- World-wide activity to develop ultra-bright storage ring x-ray sources based on MBA lattices
  - MAX-IV and SIRIUS under construction
  - MBA upgrade proposals for ESRF, SPring-8, ALS
  - New MBA rings proposed by SLAC, IHEP (China)
- Broad consensus that much lower emittance is possible
  - Advances in simulation fidelity and sophistication
  - Newly applied evolutionary optimization methods
  - Success of top-up allows short beam lifetime
  - Advances in beam diagnostics and machine correction
  - Demonstration of few-picometer vertical emittances
  - Demonstration of sub-micron and sub-microradian beam stability
- APS facility is well positioned to take advantage of these developments

Preliminary APS MBA Parameters

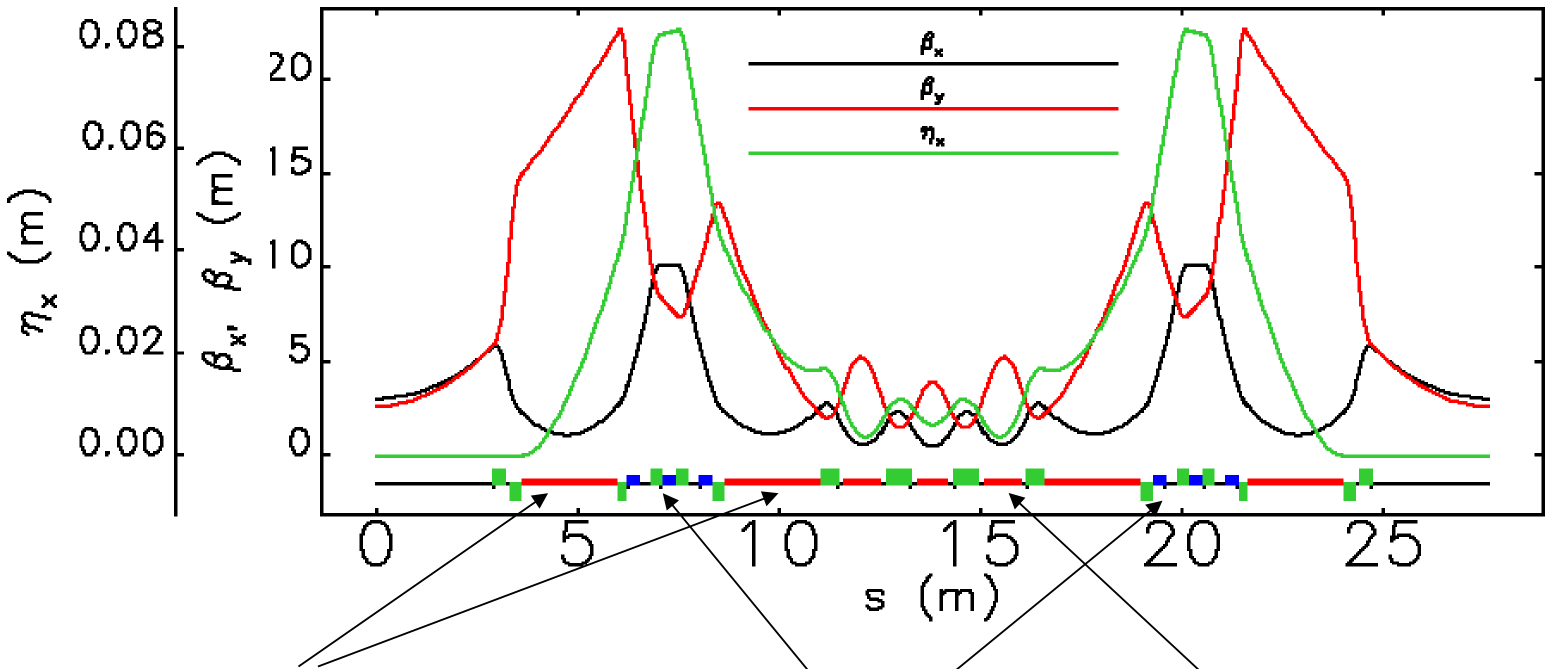
- Based on an LDRD-funded study, we've developed a set of preliminary parameters for a possible APS MBA lattice

Quantity	Symbol	Range	Units
Beam energy	E	6	GeV
Natural emittance	ϵ_0	60 - 80	pm
Rms energy spread	σ_δ	0.09 - 0.12	%
Emittance ratio	$\kappa = \epsilon_y/\epsilon_x$	0.1 - 1.0	
Emittance increase due to IBS	-	< 25	%
Horizontal emittance	ϵ_x	30 - 91	pm
Vertical emittance	ϵ_y	40 - 5	pm

- Note that horizontal emittance is very similar to our present vertical emittance of 35 pm

Hybrid 7 Bend Achromat APS Lattice Concept

Emittance of 80 pm or less at 6 GeV



Long dipoles with 5-segment longitudinal gradient, reduces emittance while boosting dispersion bump amplitude

Three families of sextupoles separated by π or 3π phase advance to cancel nonlinear kicks

Transverse gradient dipoles to eliminate quads and change damping partition

Original lattice concept from ESRF.
L. Farvacque *et al.*, Proc. IPAC13, 79 (2013).

Preliminary APS MBA Fill Patterns

- Total beam current would be 200 mA
- Fill patterns with 48 to 432 bunches would be possible
- Various timing patterns should be possible with up to 4 mA/bunch

Quantity	Symbol	Range	Units
Total current	I	200	mA
Number of bunches	N_b	48-432	
Bunch rate	f_b	13-117	MHz
Rms bunch duration	σ_t	67-12	ps

Preliminary APS MBA ID Source Parameters

- Beam sizes and divergences would be small in both planes

Quantity	Symbol	MBA Range	Present-day	Units
Horizontal beta function	β_x	1-4	19.5	m
Horizontal dispersion function	η_x	< 3	170	mm
Horizontal beam size	σ_x	5 - 19	275	μm
Horizontal beam divergence	$\sigma_{x'}$	3 - 10	11	μrad
Horizontal size-divergence product	$\sigma_x \sigma_{x'}$	30 - 91	3100	pm
Vertical beta function	β_y	1-4	2.9	m
Vertical dispersion function	η_y	0	0	mm
Vertical beam size	σ_y	2 - 13	10	μm
Vertical beam divergence	$\sigma_{y'}$	1 - 6	3.5	μrad
Vertical size-divergence product	$\sigma_y \sigma_{y'}$	5 - 40	35	pm

Preliminary APS MBA ID Parameters

- ID gaps would be much smaller than in the present machine
  - More than compensates for decrease of beam energy
- Also, MBA would permit
  - Vertically polarized undulators (small horizontal gap)
  - Helical devices at a few locations

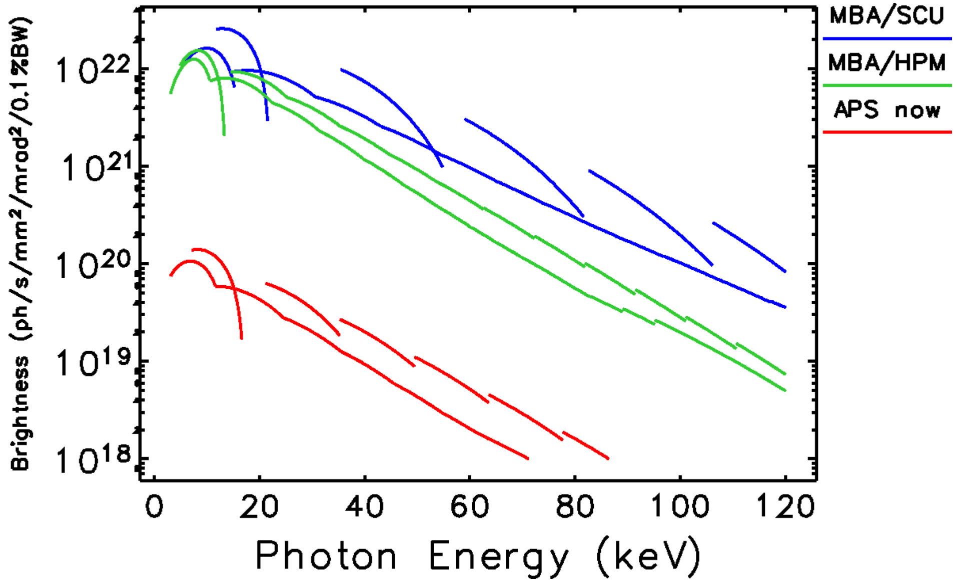
Quantity	Symbol	Range	Units
Maximum length	L_u	4.8	m
Vertical chamber inside gap	g_v	≥ 6	mm
Horizontal chamber inside gap	g_h	≥ 6	mm
Vertical magnet gap	m_v	≥ 8.5	mm
Horizontal magnet gap	m_h	≥ 8.5	mm

Preliminary APS MBA Dipole Source Parameters

- Emphasis is high brightness for ID beamlines
- Goal would be to retain all dipole beamlines with comparable performance to present day

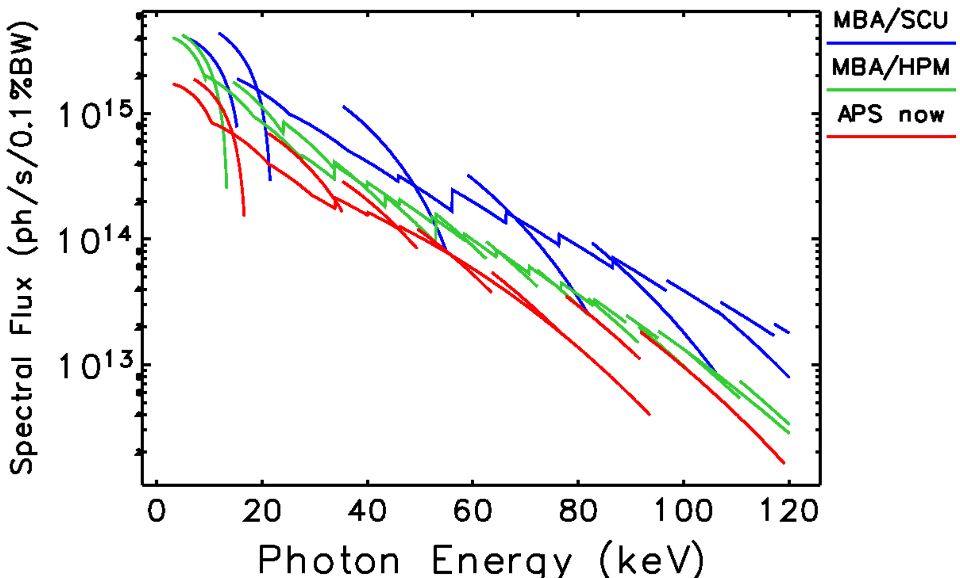
Quantity	Symbol	Range	Units
Critical energy	e_c	15-20	keV
Radiation fan width	θ_B	>1	mrad

Examples of Preliminary Expected Performance



Brightness increases of 100x or more compared to the brightest devices in APS today

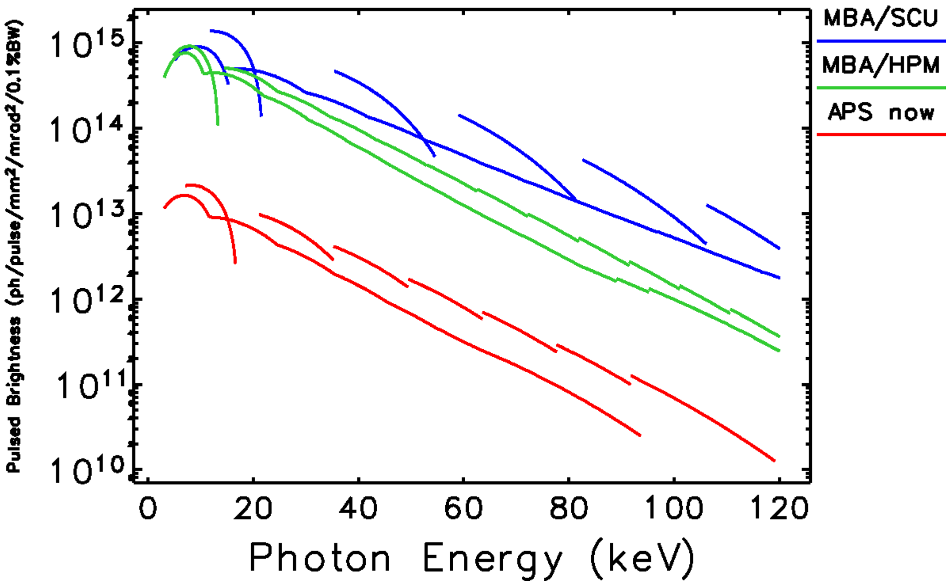
Biggest increases for hard x-rays



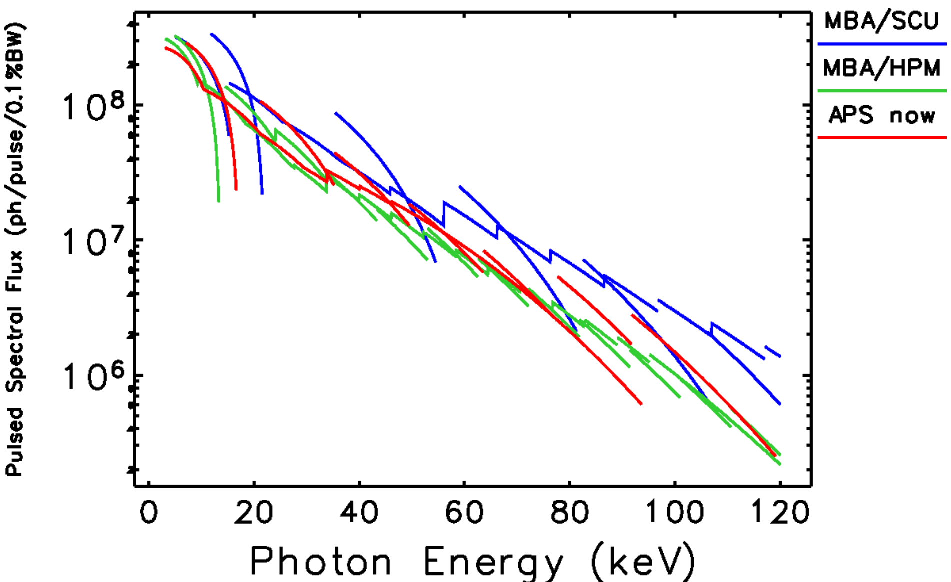
Flux increases of about a factor of two or more

APS now: existing 4.8-m U27 and U33 at 100 mA
MBA curves based on latest 80-pm lattice, 200 mA
MBA/HPM: 8.5-mm-gap,4.8-m-long HPMs.
MBA/SCU: 8.5-mm-gap, 3.7-m-long NbTi SCUs.

Examples of Preliminary Expected Timing Performance



Brightness per pulse increases by 100x or more, with larger gains for harder x-rays



Flux per pulse comparable to or better than present-day APS

APS now: existing 4.8-m U27 and U33 at 100 mA
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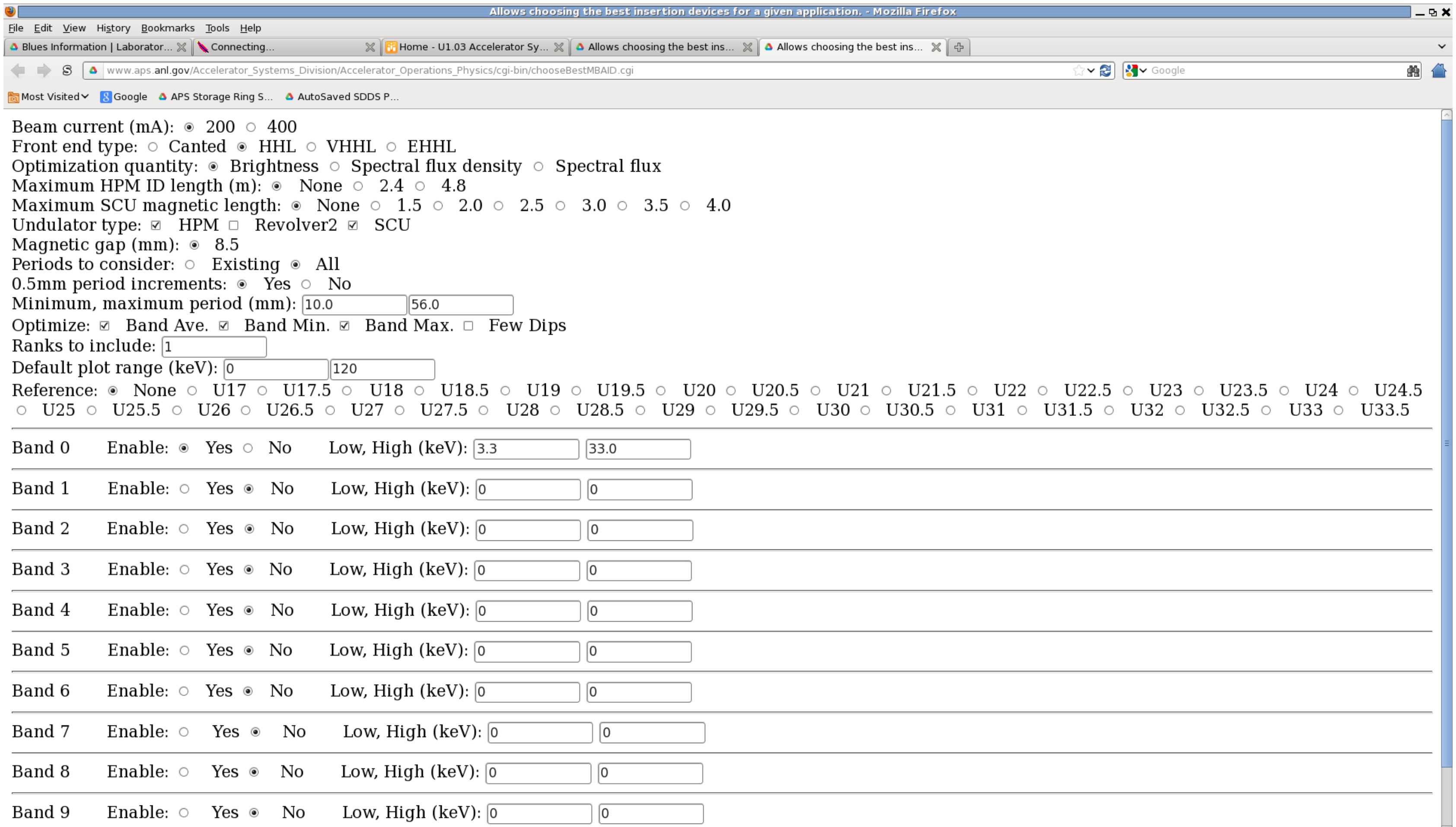
Web App for Brightness/Flux Optimization

Explore optimized performance for your application using
www.aps.anl.gov/asd/oag/cgi-bin/chooseBestMBAID.cgi



Conclusions

- We've learned a great deal since the first 3rd-generation sources began operating ~20 years ago
  - What was once considered bold (e.g., APS) is now commonplace
- There is world-wide activity to design 4th-generation storage ring light sources based on MBA lattices
  - Increases of 100x times in brightness and coherent fraction are within reach
  - Serious planning is underway at several existing facilities
- APS is studying how to incorporate an MBA lattice into the APS upgrade

Backup Material

X-ray Brightness

- An important quality of a beam is expressed by the brightness

$$B \propto \frac{N_\gamma}{(\Delta\lambda/\lambda)\Delta t \underbrace{\Sigma_x \Sigma_{x'}}_{\text{Horizontal size*divergence}} \underbrace{\Sigma_y \Sigma_{y'}}_{\text{Vertical size*divergence}}}$$

(simplification)

- Maximizing brightness entails minimizing the denominator, i.e., minimizing the photon beam sizes and divergences
- Ideally, for the electron beam we want “diffraction-limited” emittances and matched beta functions

$$\epsilon_{x,y} \leq \frac{\lambda}{4\pi} \qquad \beta_{x,y} \approx \frac{L_u}{\pi}$$

How Close are We Now to the Diffraction Limit?

- For an undulator filling a typical 5-m-long straight, ideal beta function is

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

which is feasible, though not always easy.

- Emittance is another matter

$$\begin{aligned} \epsilon_q[pm] &\lesssim \frac{100}{E_p[keV]} \\ \epsilon_q[pm] &\lesssim 8\lambda[\mathring{A}] \end{aligned} \Rightarrow \begin{aligned} 1\ \text{keV} &\rightarrow \epsilon_q \lesssim 100\ \text{pm} \\ 10\ \text{keV} &\rightarrow \epsilon_q \lesssim 10\ \text{pm} \end{aligned}$$

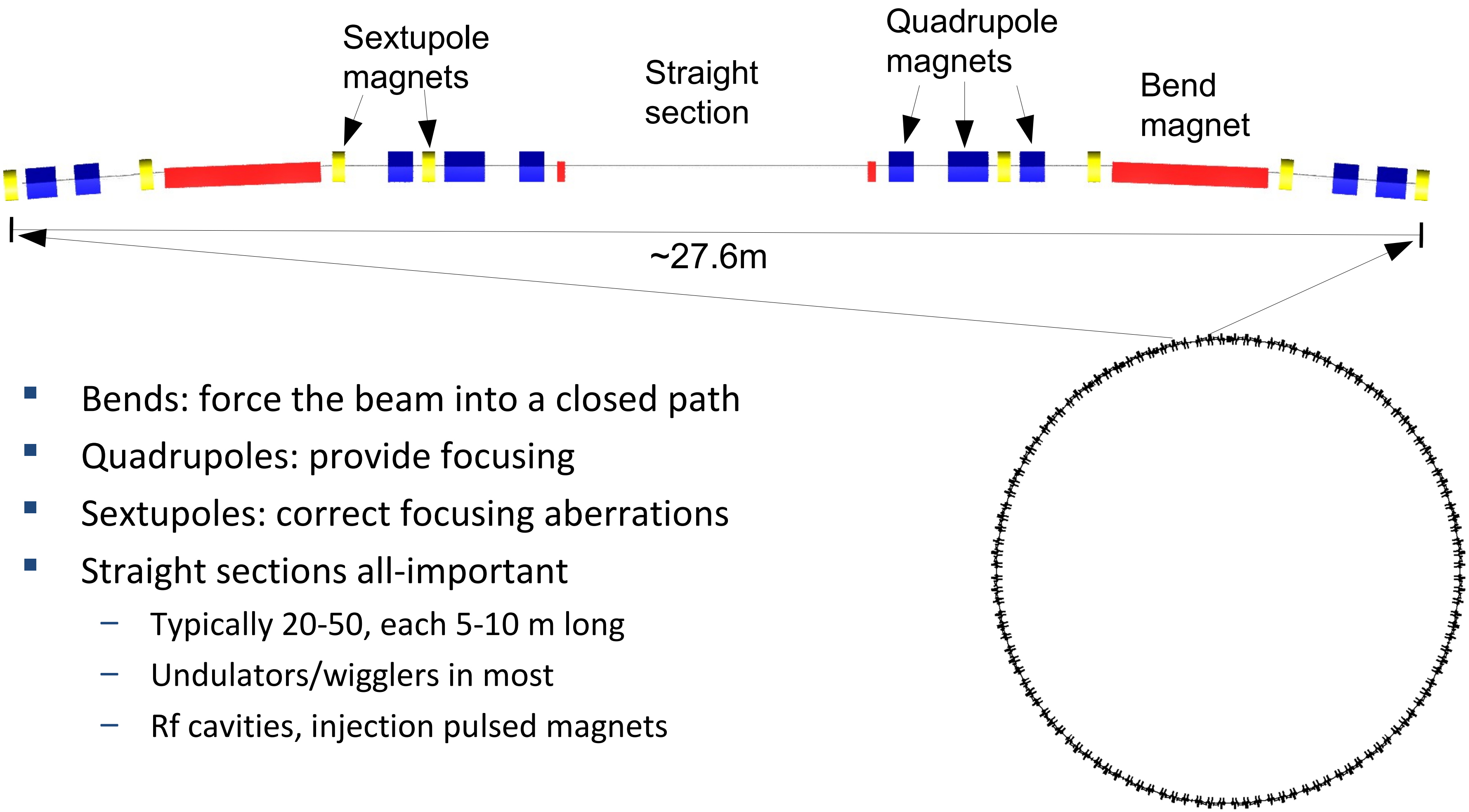
- For typical 3rd-generation rings

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

- <u>Next-generation rings should bring horizontal emittance below ~100 pm</u>

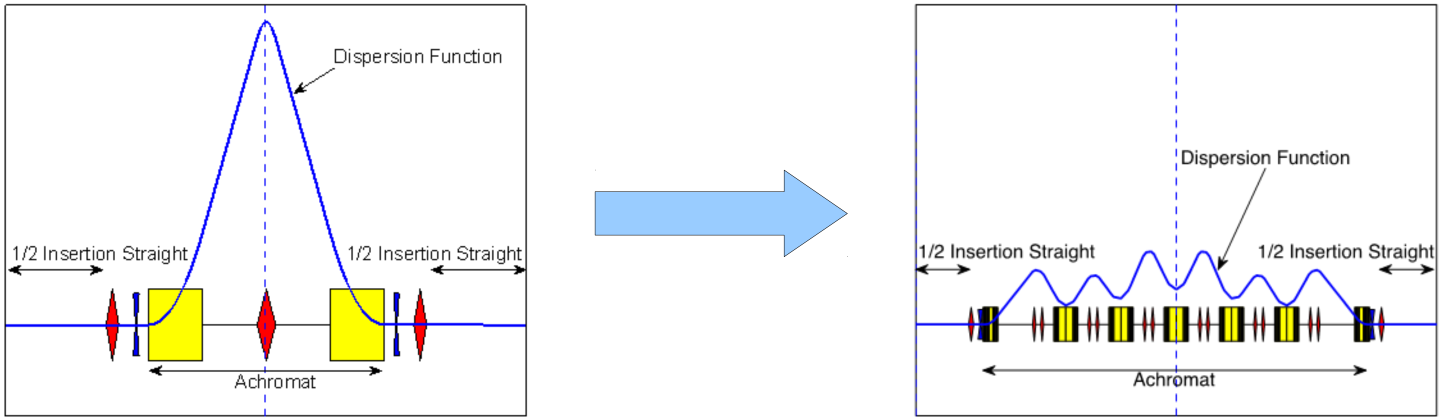
Contemporary Storage Ring Light Sources

- Conventional storage rings (e.g., APS) typically have double-bend configuration



- Bends: force the beam into a closed path
- Quadrupoles: provide focusing
- Sextupoles: correct focusing aberrations
- Straight sections all-important
  - Typically 20-50, each 5-10 m long
  - Undulators/wigglers in most
  - Rf cavities, injection pulsed magnets

From Double- to Multi-Bend Achromats



All figures courtesy C. Steier, LBNL.

- Rings today have N_d=2 or (more rarely) 3
- Emittance scales like[1]

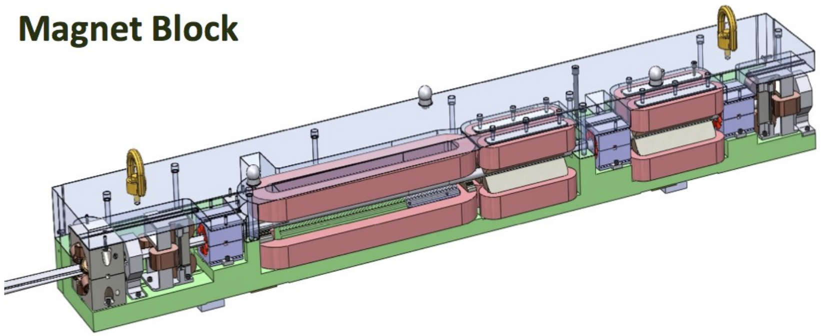
$$\epsilon_0 \sim \frac{E^2}{(N_d N_s)^3}$$

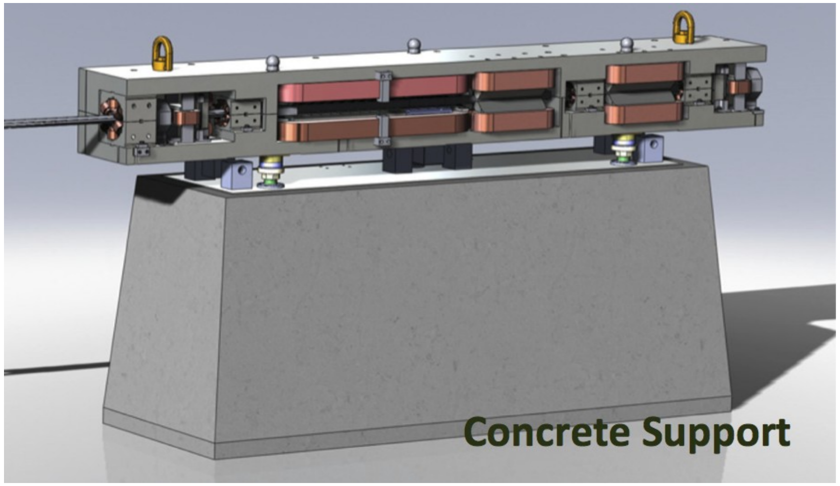
- Several groups proposed N_d>3 lattices in 1990s[2]
  - 7BA should have ~40x lower emittance than today's 2B(A) lattices
  - Promises much higher brightness and coherence over entire spectrum

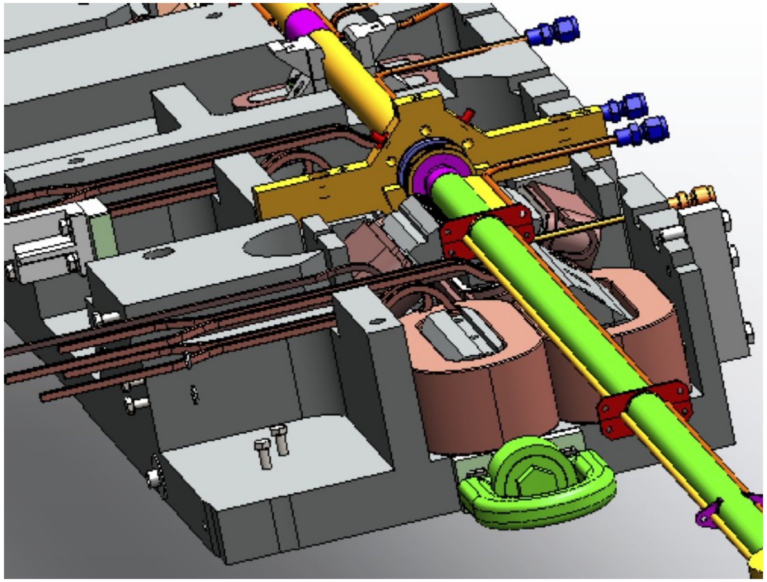
1: J. Murphy, Synchrotron Light Source Data Book, BNL 42333, 1989.
2: Einfeld *et al.*, NIM A 335, 1993; Joho *et al.*, EPAC 94; Einfeld *et al.*, PAC95; Kaltchev *et al.*, PAC95.

MAX-IV (Sweden) 7BA is First in Line

- 3 GeV, 528-m circumference, ε_0=330 pm
- Innovative, cost-effective construction of multiple magnets with a shared iron yoke
- 26-mm magnet bore diameter allows strong fields in magnets
- NEG-pumped round chamber in arcs allows small magnet bores
- Commissioning in early 2015



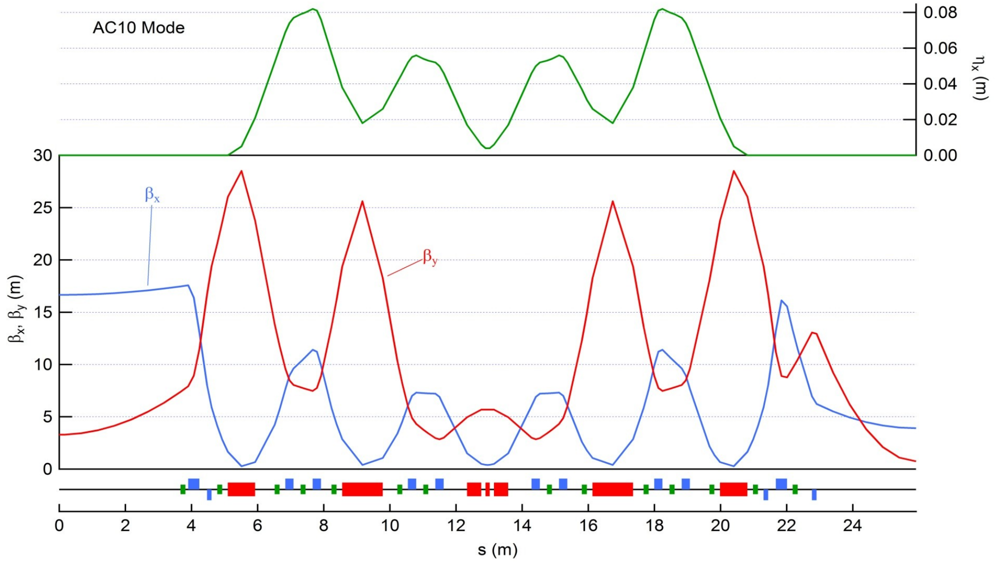




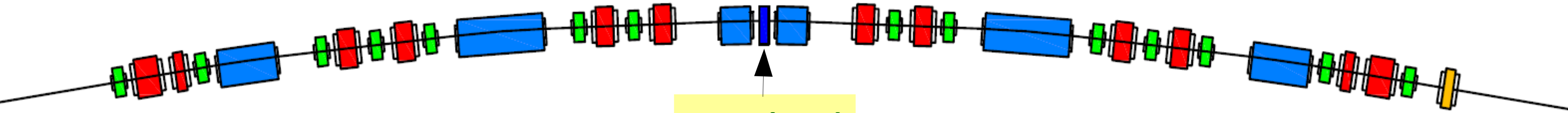
All figures courtesy S. Leemann, MAX-Lab.

5BA SIRIUS Project (Brazil) Underway

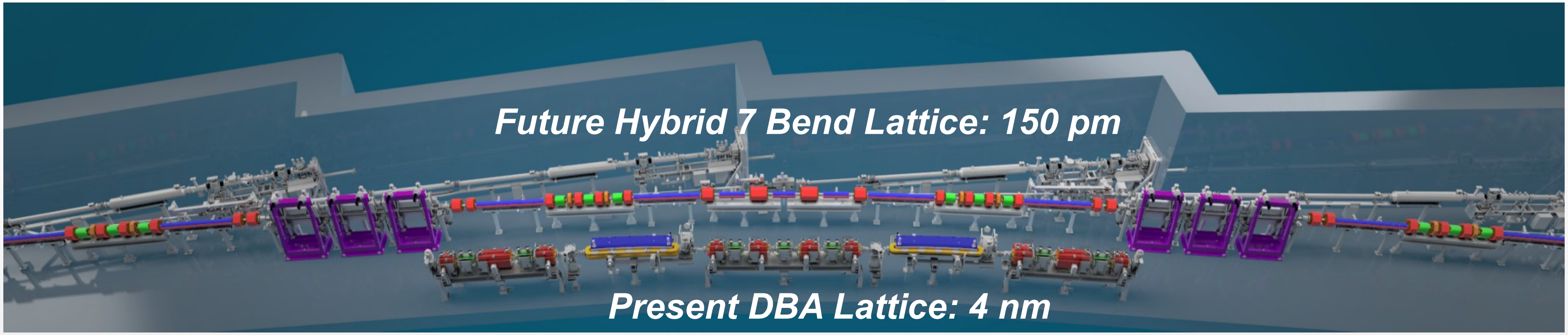
- 3 GeV, 518-m circumference, ε_0=280 pm
- Ten 6-m and ten 7-m straights
- Alternating high/low beta functions
- 2-T superbend for 12-keV critical energy



All figures courtesy L. Liu, LNLS.



ESRF Upgrade Phase II



Thanks to the large expertise gained during ESRF UP phase 1 and the worldwide efforts to develop an Ultimate Storage Ring

ESRF Upgrade Phase II will be an excellent opportunity to:

- Drastically increase the brightness of our Light Source to maintain world-wide excellence for the next 1-2 decades
- Improve and expand the science reach of the SR-based light sources
- Enable new technologies
- Provide important know-how to continue the push for higher performances of the SR-based Light Sources

Courtesy P. Raimondi, ESRF