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CHALLENGES IN THE DESIGN OF DIFFRACTION-LIMITED STORAGE RINGS*

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Abstract

We review the present developments in the design of ultra-low emittance storage ring light sources - those having emittances approaching the diffraction limit for multi-keV X-ray production - and the associated design challenges. An overview is presented of the design approaches for these 4^{th} generation storage ring (4GSR) light sources now in construction or being studied for near-term implementation, together with concepts for future rings that would operate with emittances at or below the diffraction limit for 1-Å (12-keV).

INTRODUCTION

The world has entered a new, fourth generation of storage ring light source design – rings having electron emittances well below the nanometer-radian-scale emittances of third generation machines. The NSLS-II, now in commissioning, will reach ~0.6 nm-rad emittance with its 792-m-circumference double-bend achromat (DBA or 2BA) lattice operating with damping wigglers. Meanwhile, lower emittance with smaller circumferences has been made possible with the advent of buildable multi-bend achromat (MBA) lattices. The first such undertaking is the 3-GeV, 528-m-circumfernce MAX-IV project [1], which will have 250-pm-rad or less emittance using a 7BA lattice. Such low-emittance MBA lattices having five or more bending magnets per achromat been envisioned for decades [2] but were never constructed due to technical challenges associated with the requisite small dimensions of the lattice magnets.

These challenges have been addressed over the past few years and many have been overcome. In short, it took the development of small aperture vacuum technology using chambers coated with non-evaporable getter (NEG) material for distributed vacuum pumping, development of precision machining and alignment methods needed for the smaller high performance magnets, and an evolution in the understanding and simulation of non-linear beam dynamics before a practical design for a low emittance MBA storage ring light source could be proposed.

Following close behind the MAX-IV project is the Sirius project in Brazil [3], now in construction, that will have similar performance properties. Meanwhile the ESRF [4], the APS [5] and SPring-8 [6] are all exploring 6-GeV MBA lattice conversions in the imminent future while China is considering a similar-energy green-field machine, the Beijing Advanced Photon Source (BAPS) [7]. Other lower energy facilities, including the ALS [8], SLS, Soleil, Diamond and others, are studying the possibility of such conversions. These machines have spectral brightness on the scale of 10^{21} to 10^{22} ph/s/mm^2/mrad^2/0.1%BW, an order of magnitude higher than present day rings, while future larger circumference rings, possibly housed in >2-km tunnels made available by decommissioned high energy physics accelerators, could have sub-10-pm-rad emittances, providing high coherence for >10-keV X-rays and brightness on the scale of 10^{23} [9]. When emittance is sufficiently small, such a 4^{th} generation ring (4GSR) is more aptly named a "diffraction-limited storage ring" (DLSR). Parameters for various 4GSRs are given in Table 1.

Table 1: Parameters for some low-emittance rings. (IC/IS = in construct/study; LGD = longitudinal gradient dipoles; SB = superbend insert; 3PW = 3-pole wiggler; DW = damping wiggler.)

Facility	E(GeV)/ I(A)	C (m)	ε_0 (pm)	Features
NSLS-II	3/0.5	792	600	2BA, DW, IC
MAX-IV	3/0.5	528	250	7BA, 100 MHz RF, IC
Sirius	3/0.5	518	280	Hybrid 5BA, SB, IC
ESRF-U	6/0.2	844	150	Hyb7BA ,LGD,3PW, IS
APS-U	6/0.2	1104	65	ESRF style, swap-out, IS
SPring8-2	6/0.2	1436	100	5BA, IS
ALS-U	1.9/0.5	200	100	9BA, SB, swap-out, IS
BAPS	5/0.2	1500	50-100	IS
SLAC	6/0.2	2.2	10	7BA, 90m DW, IS
TauUSR	9/0.2	6280	3	7BA, DW, IS

ENHANCED SYNCHROTRON LIGHT SOURCE PERFORMANCE

Third generation storage ring light sources brought unprecedented X-ray brightness and flux from insertion device photon sources to the synchrotron radiation scientific community. Brightness is a key parameter for a growing number of applications benefiting from a large transversely coherent spectral flux, including nanometer imaging applications, X-ray correlation spectroscopy and spectroscopic nanoprobes, and diffraction microscopy, holography and ptychography. The scientific case is growing for X-ray applications requiring an order of magnitude or more brightness and significantly higher coherent photon flux than presently available [10]. Nevertheless, it is noted that brightness is not necessarily

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the figure of merit for many X-ray experiments*; 3rd generation machines will be valuable for a long time.

Photon beam average spectral brightness B_{avg} (λ) is defined as photon density in six-dimensional phase space:

$$B_{avg}(\lambda) = \frac{N_{ph}(\lambda)}{4\pi^2 \Sigma_x(\lambda)\cdot\Sigma_x(\lambda)\cdot(s\cdot\%\,BW)} \quad (1)$$

where $N_{ph}(\lambda)$/s/%BW = $\mathcal{F}(\lambda)$ is the spectral flux for wavelength λ, and $\Sigma_{x,y}(\lambda)$ is the convolution between the diffraction-limited radiation emittance $\varepsilon_r(\lambda)$ and the transverse electron emittances ε_x(e-) or ε_y(e-). In each case emittance is given by the product of rms beam size and divergence (i.e. $\varepsilon_r(\lambda) = \sigma_r(\lambda)\cdot\sigma'_r(\lambda)$, a function of λ, and $\varepsilon_{x,y}(e\text{-}) = \sigma_{x,y}(e\text{-})\cdot\sigma'_{x,y}(e\text{-})$). For Gaussian electron and photon beam profiles:

$$\Sigma_{x,y} = \sqrt{\sigma_r^2(\lambda) + \sigma_{x,y}^2(e-)}\cdot\sqrt{\sigma_r'^2(\lambda) + \sigma_{x,y}'^2(e-)} \quad (2)$$

$$\sigma_{x,y}(e\text{-}) = \sqrt{\beta_{x,y}\varepsilon_{x,y}(e-)} \qquad \sigma'_{x,y}(e\text{-}) = \sqrt{\varepsilon_{x,y}(e-)/\beta_{x,y}} \quad (3)$$

at the waist of the electron beam (assuming zero dispersion), and

$$\sigma_r(\lambda) = 1.9\frac{\sqrt{2\lambda L}}{4\pi} \qquad \sigma'_r(\lambda) = \sqrt{\frac{\lambda}{2L}} \quad (4)$$

for the actual non-Gaussian photon beam emitted by an undulator of length L [11]. Equation 4 implies that the diffraction limited emittance for wavelength λ is

$$\varepsilon_r(\lambda) \approx \frac{\lambda}{2\pi}. \quad (5)$$

We note that natural electron emittance ε_0(e-) scales as

$$\varepsilon_0(e\text{-}) = F(\nu, \text{cell})\frac{E^2}{N_d^3} \propto \frac{E^2}{C^3} \quad (6)$$

where F(ν,cell) is a function of the betatron tune and cell type, E is the electron beam energy, N_d is the number of cell dipoles in the lattice, and C is ring circumference. The C^{-3} scaling is valid when the cell type is fixed, and the scaling is modified due to intrabeam scattering (IBS) for non-zero beam current and other effects.

Total emittance in (2) is minimized when photon and electron phase space orientations are matched:

$$\frac{\sigma_{x,y}(e\text{-})}{\sigma'_{x,y}(e\text{-})} = \frac{\sigma_r(\lambda)}{\sigma'_r(\lambda)} \Rightarrow \beta_{x,y} = \frac{L}{\pi}. \quad (7)$$

Closely related to brightness is the fraction f_{coh} of X-rays that are transversely coherent (Fig. 1):

$$f_{coh} = f_{coh\_x}\cdot f_{coh\_y} = \frac{\varepsilon_r(\lambda)}{\Sigma_x}\cdot\frac{\varepsilon_r(\lambda)}{\Sigma_y} \quad (8)$$

with coherent flux $\mathcal{F}_{coh}(\lambda)$ given by $f_{coh}(\lambda)\cdot\mathcal{F}(\lambda)$.

Given the above relationships, the path to increased photon spectral brightness, coherence and coherent flux for storage ring light sources has always lain in minimizing natural emittance while maintaining sufficient

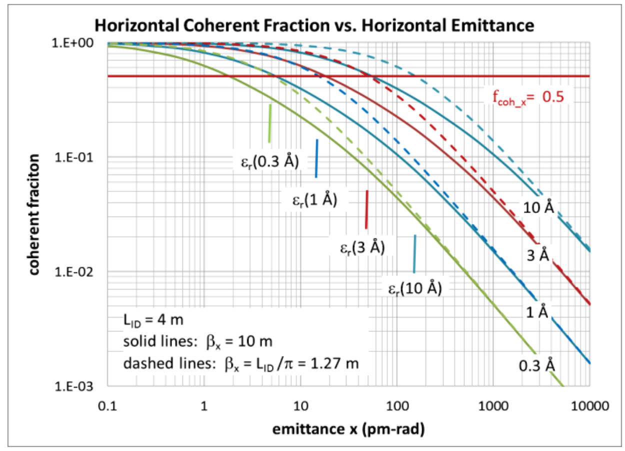

Figure 1: Horizontal coherent fraction vs. emittance (from Eqs. 5 and 8) for various X-ray wavelengths, with enhancement when $\beta = L/\pi$.

beam current for flux-dominated users, tailoring lattice functions for reasonable electron-photon phase space matching, and providing a lattice geometry that provides a sufficient number of optimally sized straight sections to fulfil photon user requirements, all at an affordable cost. Increasing brightness by increasing beam current comes at a cost of higher and possibly deleterious photon powee on X-ray optical components. A much higher gain in brightness and coherent fraction can be realized by reducing electron emittance.

In addition to increasing the number of dipoles in a ring with an MBA lattice (Eq. 6), emittance is also reduced by:

1. Increasing the horizontal damping partition J_x using gradient dipoles, Robinson wigglers, or steering off-axis in quadrupoles ($\varepsilon \propto \sim 1/J_x$). This method increases horizontal damping at the expense of longitudinal damping, reducing emittance while increasing the energy spread.
2. Using damping wigglers that add electron energy loss per turn U_W to the loss per turn U_0 from dipoles. Emittance reduction is given by $\varepsilon_W/\varepsilon_0 \approx 1/(1+U_W/U_0)$ for U_W comparable or larger than U_0, where ε_W is the damped emittance. Damping wigglers combat IBS and increase beam lifetime.
3. Tailoring optics parameters in dipoles to minimize quantum excitation of emittance (i.e. F(ν,cell) in (6)).

While 4GSR light source designers can make use of all these methods to maximize performance parameters, it is the increase in the number of ring dipoles using MBA lattices that is leading to the promise of an order of magnitude or more brightness in new designs.

From the discussion above, the properties of 4GSRs, particularly for X-rays for which these rings are nearly diffraction-limited and operate as DLSRs, can be summarized as follows:

- Brightness and coherence are as high as possible..
- Beam sizes and divergences are small in both transverse dimensions (microns and microradians).
- High coherence and small size allows beams to be focused to very small sizes – "nano-focusing" not

* A more general figure of merit is the number of "usable" photons per unit time in the spatial and energy bandwidth acceptance phase space of the experiment. For example, many protein crystallography experiments benefit from a high focused flux having relatively high divergence, with consequently moderate brightness, because the crystal angular acceptance is quite large. (T. Rabedeau, SLAC)

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achievable with present day sources.

- High coherence preserves X-ray wavefront phase uniformity, enhancing coherent imaging techniques by providing high coherent flux with minimal need for aperturing slits, etc.
- "Round" beams are possible with the appropriate adjustment of coupling, betatron functions and vertical dispersion, enabling optimal use of H-V symmetric x-ray optics, circular zone plates, etc.

DLSR DESIGN CHALLENGES

In addition to the MBA facility studies and construction projects now underway, several workshops devoted to very low emittance ring challenges and design solutions have been convened [12,13,14]. A near-future issue of the *Journal of Synchrotron Radiation* will be dedicated to the design and use of DLSRs. Findings and design solutions from these efforts are summarized as follows.

Lattice Design and Accelerator Physics

Reducing emittance to very low values requires frequent and strong electron beam focusing to reduce the amplitude of dispersive orbits in MBA lattices. Chromatic aberration from the focusing quadrupoles necessitates strong sextupole correction, which in turn introduce higher order aberrations that must be controlled. The strong-focusing MBA lattices are subject to problematic non-linear beam dynamics that result in reduced dynamic aperture and momentum acceptance, substantially less than for 3rd generation light sources, which can limit the ability to inject off-axis and store beam and reduce maximal bunch charge and beam lifetime. The dynamic aperture for aggressive 4GSR lattices may only be on the order of a millimeter, a tenth that for most 3rd generation machines.

Work over the last two decades on low-emttance damping rings for linear colliders, high-luminosity colliders and high performance storage ring light sources has led to advances in accelerator physics methods, modeling tools and understanding in beam collective effects and lifetime that enable DLSR design. These tools include symplectic tracking methods to accurately determine dynamic and momentum apertures, tracking-based lattice optimization codes and methods (e.g. multi-objective genetic algorithms, frequency map analysis, etc.) and analytical methods (e.g. Lie algebra, amplitude dependent tune shift and high-order resonance driving term minimization [15]. The methods have been benchmarked on real machines with beam-based lattice calibration tools and parameter measurement techniques. Now they can be used to develop aggressive MBA lattice designs with close to optimal straight section betas.

Lattice design developments include the hybrid MBA lattice proposed for the ESRF that uses dispersion bumps in the achromat to reduce the sextupole strength needed for chromaticity correction and longitudinal gradients in some of the dipoles to reduce emittance (Fig. 2), the use of short high-field dipole or 3-pole wiggler insertions in the zero-dispersion centers of the achromats as hard X-ray sources, and the study of producing round beams with vertical dispersion instead of 100% emittance coupling. Beam-based lattice parameter measurement, needed for non-linear lattice correction and optimization to reach maximal performance, will be enabled by turn-by-turn orbit measurements having an order of magnitude higher resolution than presently available [16]. Critical for maximizing performance will be to maintain beam orbit centering in strong sextupoles. Initial ring commissioning would be facilitated with a relaxed optics mode having large dynamic aperture before tuning for lower emittance.

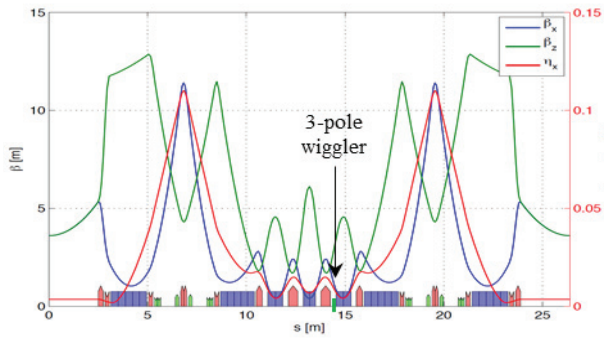

Figure 2: A 2013 version of a 7BA lattice for the ESRF with dispersion bumps and gradient dipoles (1,2,4,7).

Injection

The requirement for maintaining sufficient dynamic aperture to accommodate off-axis injection, typically several millimetres, can limit the reduction of lattice emittance. While this problem might be overcome by having a large betatron function in the injection straight section, this solution is usually not practical, except perhaps for very large rings, because of resulting lattice asymmetry. One alternative solution is to inject the beam on-axis into the ring from a linac, booster or accumulator ring, knocking out and replacing already stored beam, a method that requires fast rise- and fall-time kicker magnets. Because the lattice does not have to accommodate many-millimeter oscillation amplitudes of the incoming beam, this "swap-out" injection scheme [17] reduces injected beam losses and the required transverse good-field region of magnets, and thus magnet size, and permits the use of high performance insertion devices having small apertures in both transverse planes. On-axis injection is also more favorable for lattices having near-100% horizontal-vertical emittance ratio for producing round beams; off-axis injection into such lattices is subject to instability issues. Another option – longitudinal injection - is being explored [18]. A fast kicker places the off-energy (~+4-5%) injected beam nearly on-axis between bunches to be captured by the leading rf bucket.

Magnets

The strong focusing MBA lattices for 4GSR and diffraction-limited storage rings present challenges for the design of small magnets having very high field quality and tight alignment tolerances [19]. Gradients are approaching 100 T/m for some quadrupole designs, about a factor of five higher than for 3rd generation magnets,

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while sextupole gradients may be increased by almost a factor of ten to 6000 T/m^2 for some designs.

Small magnet bore radii (of order 12-mm) are required to reach these increased gradients in order to avoid pole saturation. Some very high gradient designs require additional measures, such as using high permeability pole material (e.g. vanadium permendur) or permanent magnet material near the poles to reduce saturation. The gradients required in some gradient dipole designs are sufficiently large to require the use of offset quadrupoles or half-quadrupoles with horizontal movers to adjust gradients (as is being considered for the ESRF, APS and ALS upgrades). Other combined function magnets, including quadrupole/sextupole and corrector/sextupole/skew quadrupole, provide a path to more compact lattices.

Additional magnet design innovations proposed for 4GSR lattices include dipoles having a longitudinal gradient that tailor lattice optics to reduce emittance [4], and the use of short high-field "super bend" splices [3,8] or short 3-pole wigglers (ESRF) that can be inserted in the middle of an MBA achromat in place of the normal dipoles to serve as sources of hard X-rays.

MBA magnet support designs are required to achieve requisite ~10-μm alignment tolerances. Design approaches all require precision magnet machining, typically of individual magnets that are aligned on girders based on precise fiducials or magnetic measurement, but in the case of MAX-IV, dipoles and adjacent quadrupoles were machined from a single blocks of iron and their relative alignment was achieved solely based on machining precision. Under consideration is whether the costly 10-μm machining tolerances can be relaxed, relying on the ability to use beam-based lattice calibration methods to determine and correct magnet alignment.

Vacuum Systems

Small-aperture vacuum chambers and associated components are required for aggressive 4GSR lattices [20]. The use of disrcete vacuum pumps for these chambers is largely prohibited due to conductance limitations. Instead distributed pumping can be provided by coating the chambers with a micron or so of NEG material, a technology that was first developed at CERN but that has since been commercialized and in some cases transferred to other laboratories under license from CERN (e.g. ESRF and Sirius). This mature technology is frequently used in 3rd generation light sources for small vertical gap insertion devices, and, in the case of Synchrotron Soleil, for a large fraction of the entire ring. While the MAX-IV and Sirius arc vacuum chambers, having ~25-mm diameter, are completely NEG-coated , other facilities like the ESRF and APS are exploring hybrid designs that maintain larger aperture antechambers and discrete pumps in some arc chambers, using NEG coating only where absolutely necessary.

Challenges for NEG-coated chambers, including obtaining coating uniformity in "keyhole" chamber shapes (which allow photon beams to escape), minimizing surface roughness and ensuring high plating adhesion for robust and reliable operation have largely been solved but remain matters requiring some development and strict quality assurance for each design.

Common to all chamber designs is the need for low-impedance compact bellows and photon absorbers, maximal smoothness, compact beam position monitor (BPM) assemblies, and highly stable chamber supports, especially at BPM locations. Finally, the extraction of X-ray beams from MBA lattices presents challenges for chamber, photon absorber and magnet designs given the small apertures and close magnet spacing.

Photon Beam Lines

The small size and high coherence of 4GSR X-ray beams presents an increased challenge for photon beam line design. Added to the usual requirements for high spatial and intensity stability is the need to preserve photon beam coherence in both transverse dimensions through X-ray optical components. Some devices may require cutting-edge technology (e.g. "telescope technology" such as the laser-Doppler stabilization system used for atomic force microscopes). These challenges are similar in many ways to those encountered at X-ray FEL facilities.

Improved mirror polish and figures would reduce degradation of beam emittance and coherence in the beam line. Advances in micro-focusing optics, such as smaller zone plate line widths, would enhance microscope resolution. Development of higher-accuracy optical metrology for manufacturing and wavelength metrology that can be used for characterizing and aligning individual optics would be of great benefit. High power density from the small X-ray beams necessitates development of improved cooling and thermal designs for optical components (e.g. cryogenically cooled mirrors). Developments in minimal optics and lens-less imaging methods would maximize performance in some cases.

The true potential for increased speed and resolution of experiment measurement using the very bright X-rays will only be fully realized with the commensurate development of X-ray detectors, a goal shared with the X-ray FEL community, now in progress [21].

Design Optimization

The scientific community using storage ring light sources is a mixture of those seeking high brightness and coherence and those whose experiments are flux- rather than brightness-limited. Noting that it is possible to get high coherent flux with a high current, low coherent fraction ring of smaller circumference, and that there is a diminishing return in coherent fraction as emittance is reduced (Fig. 1), a cost-benefit optimization for the design of a 4GSR exists, depending on the spectral range and science goals. Other design considerations include single bunch properties (i.e. photons per pulse and pulse length), the number of insertion devices and straight section lengths and the lengths and orientations of photon beam lines.

A key parameter in ring design is the electron energy

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needed to fulfil spectral requirements. Higher energy, larger circumference rings (e.g. 6 GeV or more) will produce higher brightness hard X-rays, but competing coherent flux (within an order of magnitude) up to a few-keV X-ray energy can be achieved with less expensive, lower energy, smaller circumference rings, in some cases using harmonics from high performance undulators. For example, the coherent flux from the 2-GeV, 200-m ALS-U design ($\varepsilon_{x,y}$ = 50 pm-rad at 500 mA) exceeds that for other new, higher energy rings for photon energies up to 3 keV using superconducting undulators. Another factor is that ring energy can be optimized to minimize emittance growth due to IBS for a given beam current; for ~1-km rings, the optimal energy from this standpoint is ~4-5 GeV, while it is 5-6 GeV for 2-km rings. However the gain in hard X-ray emission at higher energy can lead to higher brightness, even if emittance is degraded. These considerations, together with the difficulties of MBA magnet implementation at higher energies, have led the three high-energy synchrotron facilities, the ESRF, the APS and SPring-8, to converge on 6-GeV operating energy for their MBA upgrades, a reduction from the present 7 GeV for the APS-U and 8 GeV for SPring-8-II.

OUTLOOK

While a host of 4GSR light sources having emittances on the scale of 100 pm-rad are now in construction or design, studies for the longer range future envision rings having sub-10-pm emittances – machines whose technology will build on that developed for rings to be built in the next several years and which may require R&D in accelerator technology in order to optimally leverage emittance reducing methods. Future DLSRs might include enhanced capabilities, such as ring-based high repetition rate, low peak power FELs [22] and short bunch operation that offer beam properties complementary to linac-based FELs while serving a larger number of simultaneous users. Methods to reduce longitudinal emittance might be developed, leading to lower energy spread that would benefit high-harmonic performance of insertion devices, short-bunch generation and the possibility of realizing ring-based keV-X-ray FELs. These more "ultimate" machines are likely to be costly and the "billion-dollar question" about their construction will need to be justified by science demand.

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