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DLSR design and plans: an international overview

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It has been known for decades that the emittance of multi-GeV storage rings can be reduced to very small values using multi-bend achromat (MBA) lattices. However, a practical design of a ring having emittance approaching the diffraction limit for multi-keV photons, *i.e.* a diffraction-limited storage ring (DLSR), with a circumference of order 1 km or less was not possible before the development of small-aperture vacuum systems and other accelerator technology, together with an evolution in the understanding and accurate simulation of non-linear beam dynamics, had taken place. The 3-GeV MAX IV project in Sweden has initiated a new era of MBA storage ring light source design, *i.e.* a fourth generation, with the Sirius project in Brazil now following suit, each having an order of magnitude smaller horizontal emittance than third-generation machines. The ESRF, APS and SPring-8 are all exploring 6-GeV MBA lattice conversions in the imminent future while China is considering a similar-energy green-field machine. Other lower-energy facilities, including the ALS, SLS, Soleil, Diamond and others, are studying the possibility of such conversions. 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 very high coherence for >10-keV X-rays. A review of fourth-generation ring design concepts and plans in the world is presented.

Keywords: storage rings; light sources; accelerator technology.

1. Introduction

Third-generation storage ring light sources brought unprecedented X-ray brightness and flux from insertion device photon sources to the synchrotron radiation scientific community. While brightness is not necessarily the figure of merit for many X-ray experiments,[1] it 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. As discussed elsewhere in this issue, the scientific case is growing for X-ray applications requiring at least an order of magnitude higher brightness, *i.e.* exceeding $\sim 10^{22}$ photons s^{-1} mm^{-2} $mrad^{-2}$ (0.1% bandwidth)$^{-1}$, and significantly higher coherent photon flux than presently available.

A new generation of storage ring light source designs is emerging that uses 'multi-bend achromat' (MBA) lattices (Einfeld *et al.*, 2014) to push beyond the brightness and coherence reached by third-generation storage rings. The first implementations of these 'fourth-generation' ring light sources have an order of magnitude smaller electron emittance than their predecessors and use accelerator technology that permits even further emittance reduction towards the sub-100-pm-rad diffraction-limited emittances for multi-keV X-ray beams. Sometimes referred to as 'ultimate storage rings' (USRs) (Ropert *et al.*, 2000) when emittances are sufficiently small, such fourth-generation rings are more aptly described as 'diffraction-limited storage rings' (DLSRs). Moreover, the small horizontal emittance produces very small horizontal beam size, enabling the generation of round, or almost round, photon beams that are more optimally matched to X-ray optics and detectors in many cases (Fig. 1).

In the following sections we present a short review of key photon source parameters and an overview of the efforts worldwide to reach higher performance in storage ring light sources.

2. Brightness, coherence and emittance

Photon beam spectral brightness $B_{avg}(\lambda)$ is defined as photon density in six-dimensional phase space,

[1] 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, SSRL/SLAC, private communication).

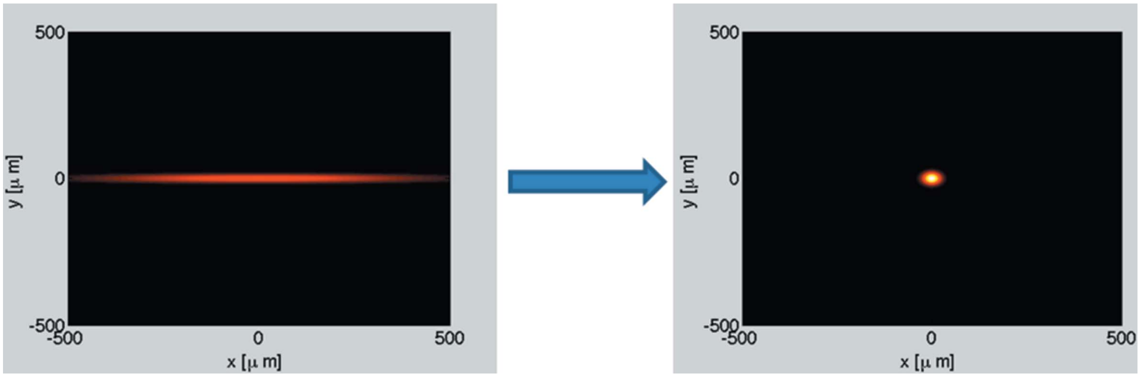

Figure 1
The reduction of horizontal emittance for DLSRs will transform photon-beam cross section from flat to almost round. (Courtesy of C. Steier, ALS.)

$$B_{\rm avg}(\lambda) = \frac{N_{\rm ph}(\lambda)/{\rm s}/\%{\rm BW}}{(2\pi)^2 \cdot (\varepsilon_r(\lambda) \oplus \varepsilon_x({\rm e}-)) \cdot \big(\varepsilon_r(\lambda) \oplus \varepsilon_y({\rm e}^-)\big)}, \qquad (1)$$

where $N_{\rm ph}(\lambda)/{\rm s}/\%{\rm BW}$ = $F_{\rm ph}(\lambda)$ is the spectral photon flux for wavelength λ, and $\oplus$ indicates convolution between the diffraction-limited radiation emittance $\varepsilon_r(\lambda)$ and the transverse electron emittances $\varepsilon_x({\rm e}^-)$ and $\varepsilon_y({\rm e}^-)$. In each case emittance is given by the product of r.m.s. beam size and divergence [*i.e.* $\varepsilon_r(\lambda) = \sigma_r(\lambda)\sigma_r'(\lambda)$, a function of λ, and $\varepsilon_{x,y}({\rm e}^-) = \sigma_{x,y}({\rm e}^-)\sigma_{x,y}'({\rm e}^-)$]. The diffraction-limited photon emittance is given by

$$\varepsilon_r(\lambda) \simeq \lambda/4\pi \qquad \text{or} \qquad \lambda/2\pi, \qquad (2)$$

where the first value applies for a purely Gaussian beam (Kim, 1989) [*e.g.* ε_r(1 Å) = 8 pm-rad], and the second value is more appropriate for the actual non-Gaussian photon beam emitted from an undulator (Onuki & Elleaume, 2003) [*e.g.* ε_r(1 Å) = 16 pm-rad]. Transverse electron emittances are given by

$$\varepsilon_x({\rm e}^-) = \frac{1}{1+\kappa}\,\varepsilon_0({\rm e}^-), \qquad \varepsilon_y({\rm e}^-) = \frac{\kappa}{1+\kappa}\,\varepsilon_0({\rm e}^-), \qquad (3)$$

where $\varepsilon_0({\rm e}^-)$ is the ring's natural emittance and the emittance ratio κ ranges between 0 and 1.

Closely related to spectral brightness is the fraction $f_{\rm coh}(\lambda)$ of photons that are transversely coherent, given by the product of the coherent fractions $f_{{\rm coh}\_x}(\lambda)$ and $f_{{\rm coh}\_y}(\lambda)$ for each transverse plane,

$$\begin{aligned} f_{\rm coh}(\lambda) &= f_{{\rm coh}\_x}(\lambda) f_{{\rm coh}\_y}(\lambda) \\ &= \frac{\varepsilon_r(\lambda)}{\varepsilon_r(\lambda) \oplus \varepsilon_x({\rm e}^-)} \frac{\varepsilon_r(\lambda)}{\varepsilon_r(\lambda) \oplus \varepsilon_y({\rm e}^-)}, \end{aligned} \qquad (4)$$

with coherent flux $F_{\rm coh}(\lambda)$ given by the product of $f_{\rm coh}(\lambda)$ and $F_{\rm ph}(\lambda)$.

Strictly speaking, a DLSR for wavelength λ is one whose horizontal electron emittance is less than the diffraction-limited $\varepsilon_r(\lambda)$, small enough so that the convolved electron–photon emittance yields a coherent fraction close to 1. By this definition all light-source rings are DLSRs for very long wavelengths. However, it is inferred that λ should be representative of the nominal spectrum of interest for a DLSR, *i.e.* ∼100–10 Å for soft X-ray sources, ∼10–1 Å for mid-energy sources, and ∼1–0.1 Å for high-energy sources. It should be noted that many present-day storage ring light sources already operate with vertical emittances near the diffraction limit for angstrom or shorter X-ray wavelengths by reducing the emittance ratio κ to very small values ($<10^{-3}$ in some cases); many of the stability and optics challenges for these vertically small and coherent X-ray beams have therefore already been addressed. On the other hand, diffraction-limited horizontal emittance extends the challenges for optical components and stability into a second dimension.

The horizontal coherent fraction as a function of horizontal electron emittance for various photon wavelengths is depicted in Fig. 2. As can be seen in the figure, (i) there is a diminishing return in the increase of $f_{\rm coh}(\lambda)$ as electron emittance approaches $\varepsilon_r(\lambda)$, a fact for consideration in optimizing ring design; and (ii) the coherent fraction is enhanced for wavelengths within about a decade of $\lambda_{\rm diff} = 2\pi\varepsilon({\rm e}^-)$, the diffraction-limited wavelength corresponding to electron emittance $\varepsilon({\rm e}^-)$, by matching the transverse size-divergence phase space orientations of the electron and photon beam. This phase space matching minimizes the convolved electron–photon emittance and is achieved when $\sigma_r(\lambda)/\sigma_r'(\lambda) = \sigma({\rm e}^-)/\sigma'({\rm e}^-)$. For an undulator having length $L_{\rm und}$, matching is achieved when the lattice betatron function β_x (or β_y for the vertical plane) at the center of the undulator straight section is $\beta_x = L_{\rm und}/\pi$ [assuming $\varepsilon_{\rm r}(\lambda) \simeq \lambda/2\pi$].

Although increasing photon flux $F_{\rm ph}(\lambda)$ is a path to higher brightness and coherent flux, a goal that can be realised by increasing stored beam current and/or by enhancing undulator performance, these gains are accompanied by a potentially deleterious increase in radiated beam power and thermal loading on accelerator and beamline optical components which can diminish the return in light source performance. Perhaps an increase of a factor of two can be gained by increasing flux, but much higher gains, including increased coherent fraction, can be realised by reducing electron emittance.

The dependence of electron emittance on storage ring parameters is discussed in detail elsewhere in this issue (Borland *et al.*, 2014). In brief, electron emittance can be reduced by:

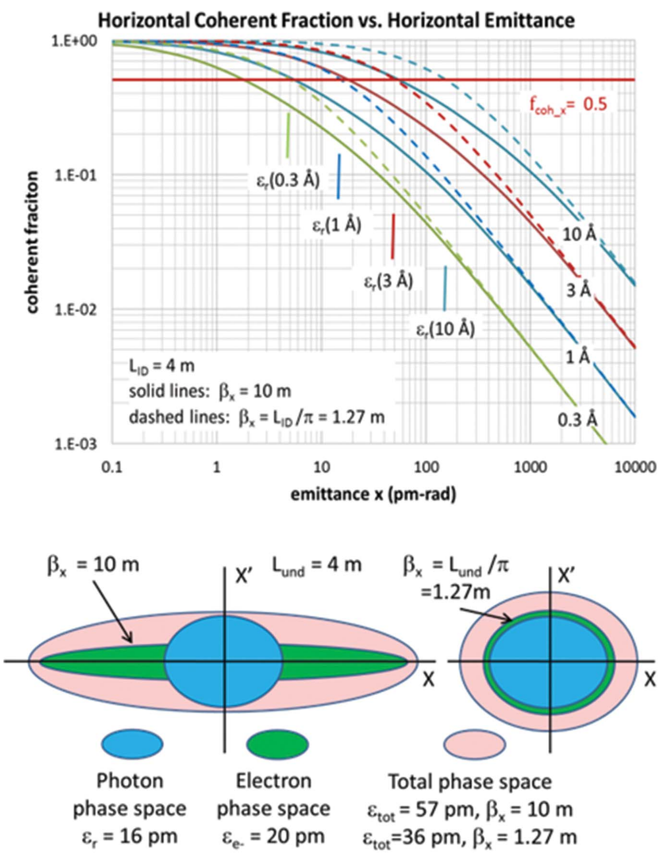

Figure 2
Horizontal coherent fraction *versus* emittance [from equations (2) and (4), with $\varepsilon_r(\lambda) \simeq \lambda/2\pi$] for various X-ray wavelengths (top) and electron–photon phase space matching that minimizes convolved emittance (bottom). Dashed curves indicate coherence gain for a 4 m undulator when β_x is reduced from 10 m to 1.27 m (= $L_{\rm und}/\pi$).

(i) Increasing the horizontal damping partition J_x using gradient dipoles, Robinson wigglers or steering off-axis in quadrupoles. Emittance scales approximately as $1/J_x$.

(ii) Using damping wigglers that add electron energy loss per turn $U_{\rm W}$ to the loss per turn U_0 from dipoles. The factor of emittance reduction is given by $\varepsilon_{\rm W}/\varepsilon_0 \simeq 1/(1 + U_{\rm W}/U_0)$ for $U_{\rm W}$ comparable with or larger than U_0, where $\varepsilon_{\rm W}$ is the damped emittance.

(iii) Tailoring optics parameters in dipoles to minimize quantum excitation of emittance.

(iv) Decreasing the bending angle $\theta_{\rm d}$ for each dipole, thereby increasing the number of dipoles in the ring, and/or by reducing ring energy E. Emittance scales approximately as $E^2\theta_{\rm d}^3$, or $E^2/N_{\rm d}^3$ where $N_{\rm d}$ is the number of dipoles, subject to modification due to intrabeam scattering (IBS) for non-zero electron current and other effects. For a given cell type with fixed magnet dimensions, $\varepsilon_0 \propto \sim E^2/C^3$, where C is the ring circumference.[2]

While the first three methods are already exploited in many present-day storage rings to provide moderate emittance reduction (up to a factor of $\sim$2 *via* J_x and a much smaller value resulting from the damping provided by the insertion devices used as photon sources), it is the fourth method, perhaps in combination with high field damping wigglers, that promises to provide one or more orders of magnitude reduction from the nm-rad-scale emittances of third-generation light sources.

3. The advent of MBA lattices

Most third-generation light sources built in the last two decades use double-bend achromat (DBA or 2BA), triple-bend achromat (TBA or 3BA) or sometimes quadruple-bend achromat (QBA or 4BA) lattices having circumferences large enough to reach emittances of a few nm-rad. For example, 3-GeV rings having circumferences in the $\sim$200–500-m range provide emittances between $\sim$3 and 10 nm-rad. Higher-energy rings (6–8 GeV) require kilometer-scale circumferences to achieve few nm-rad emittances. To reach sub-nm-rad emittance, the goal for new machines, the 3-GeV NSLS-II circumference was increased to 792 m to increase the number of bending magnets in its DBA lattice (NSLS-II, 2006). With damping wigglers the NSLS-II will operate with 0.6 nm-rad emittance, the first 3-GeV light source to reach this low emittance in normal operation.[3]

While increasing ring circumference is a path to lower emittance, it is a costly approach, both in terms of hardware and the real-estate size required for the facility. Another path that is likely to be more cost effective is to increase the number of bending magnets in each lattice achromat while minimizing achromat length to avoid very large ring circumference. Such MBA lattices having five or more bending magnets per achromat have been envisioned for decades (Einfeld *et al.*, 1996), but the technical challenges associated with the requisite small dimensions of the lattice magnets and vacuum chambers together with beam dynamics issues caused by the high magnet field gradients needed for the strong focusing lattices made it impractical to actually build such lattices in the past. The recent development of MBA lattices and the associated accelerator physics issues are discussed in detail elsewhere in this issue (Einfeld *et al.*, 2014; Borland *et al.*, 2014). In short, it took the development of small-aperture vacuum technology using chambers coated with non-evaporable getter (NEG) material for distributed vacuum pumping, the development of precision machining and alignment methods needed for the smaller high-performance magnets, and an evolution in the understanding and accurate simulation of non-linear beam dynamics before a practical design for the first MBA storage ring light source having very low emittance could be proposed.

MAX-lab in Lund, Sweden, was the first to make such a proposal with its 3-GeV MAX IV project. As discussed in

[2] The number of dipoles $N_{\rm d}$ that can fit in a ring of fixed circumference C as a function of energy E is subject to dipole field strength limitations. When dipoles operate near maximal field, scaling to higher energy requires increased dipole length. Then $N_{\rm d} \simeq C/E$ and $\varepsilon \simeq E^2/N_{\rm d}^3 \simeq E^5/C^3$ (X. Huang and J. Safranek, SSRL/SLAC, private communication).

[3] The 2.3 km PETRA-III ring, normally operating at 6-GeV with 1 nm-rad emittance, operated in a 3-GeV, 5-mA test mode with 158-nm-rad emittance in 2013 to test low-ε accelerator physics issues (A. Kling, DESY, private communication).

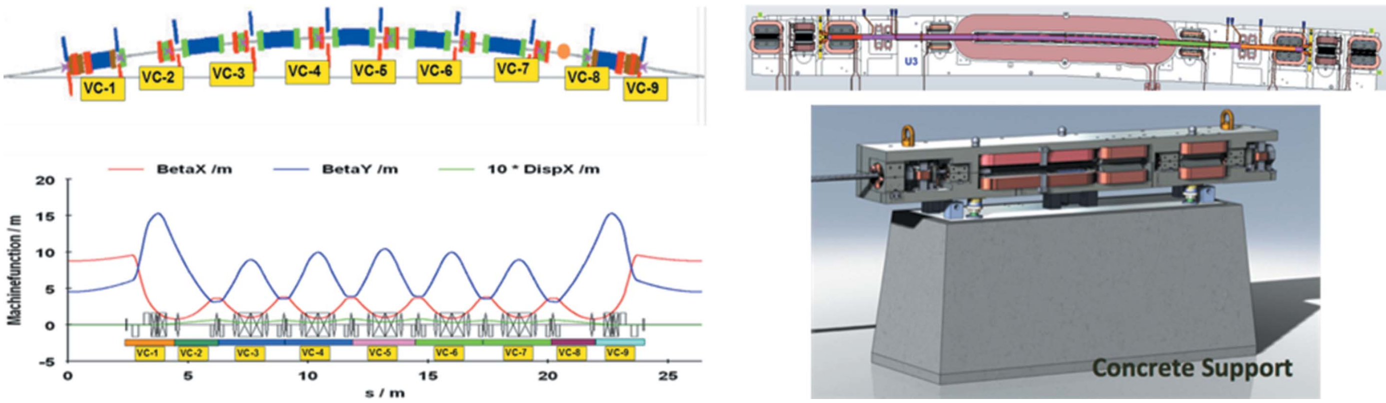

Figure 3
The MAX IV 7BA lattice (left) is realised in part with a machined magnet block with vacuum chamber mounted on a stable concrete support (right). (Courtesy of S. Leemann, MAX-lab.)

detail in this issue (Tavares *et al.*, 2014), the MAX IV design has made a pioneering step in marrying technological developments in small-aperture NEG-coated vacuum chambers with magnets machined within single iron blocks to obtain small dimensions, high alignment precision without individual magnet movers or shims and simple but very stable support for its 7BA lattice (Fig. 3). With a total of 140 gradient dipoles in 20 7BA cells, the 528-m-circumference MAX IV expects to have an emittance of 0.2–0.3 nm-rad when operating with 500 mA stored beam current and damping wigglers. This emittance can be compared with the ~0.6 nm-rad emittance expected by the 792-m 3-GeV NSLS-II with its 60 dipoles in 30 2BA cells, also using damping wigglers. Both rings take advantage of the emittance reduction gained by the increased horizontal damping partition provided by using gradient dipoles. The discrepancy in the simple $\theta_{\rm d}^3$ and C^{-3} emittance scaling mentioned above is attributed to the difference in cell types, ring geometry and other lattice parameter differences.

The technology step taken by MAX-lab has opened the door for other MBA lattice proposals and concepts. The new 3-GeV Sirius light source, now in construction in Campinas, Brazil, will use a 20-cell, 5BA lattice on a 518-m circumference to reach ~0.3 nm-rad with 500-mA (Liu *et al.*, 2014). While Sirius is adopting a vacuum chamber solution similar to that for MAX IV, the lattice and magnet design approaches are largely different. The lattice has stronger focusing than the nominal MAX IV lattice and thus has lower, but still acceptable, dynamic acceptance. Lattice dispersion functions at dipole locations are typically smaller than for the MAX IV lattice to reduce emittance and, in particular, the dispersion is almost zero at the achromat's central dipole locations, allowing a high-field (~2 T) 'super bend' to be inserted there as a hard X-ray source, an implementation that is also proposed for the ALS Upgrade (ALS-U) (Steier *et al.*, 2013). The longitudinal gradient associated with this short magnet helps minimize emittance. Using an idea first proposed for the ESRF MBA lattice (Fig. 4), deemed a 'hybrid MBA', gaps

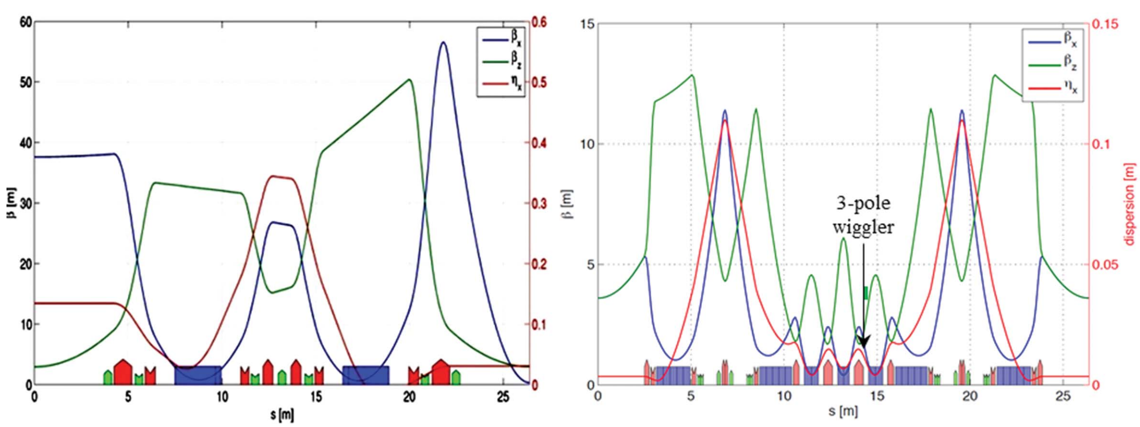

Figure 4
The ESRF is studying the replacement of its DBA lattice (left) with a hybrid 7BA lattice (a version from late 2013 shown at right). Gaps between the first and second dipoles and the sixth and seventh dipoles in the 7BA lattice allow the dispersion (red) to grow at sextupole sites, reducing the required sextupole gradient for chromatic correction. The first two and last two dipoles have a longitudinal gradient that tailors the optics to minimize emittance, while the central three dipoles are combined dipole–quadrupole magnets. A 14 cm, 3-pole wiggler located just downstream of the central dipole serves as a hard X-ray source. Another feature is the 4.6 mrad horizontal angle built in between adjacent achromats that enables ready installation of canted undulators, an angle made up by horizontally displacing the defocusing quadrupoles flanking the insertion straight when no canting is used. Note the vertical scale on the right is magnified by a factor of four. (Courtesy of P. Raimondi, ESRF.)

Table 1
Parameters and features for some low-emittance storage ring light sources.

DW = damping wiggler. LGD = longitudinal gradient dipole.

Facility	E (GeV)/I (A)	C (m)	ε_0 (pm-rad)	Features
NSLS-II	3/0.5	792	600	2BA, DW, operation in commissioning
MAX IV	3/0.5	528	250	7BA, 100 MHz RF, in construction
Sirius	3/0.5	518	280	Hybrid 5BA, superbend insert, in construction
ESRF	6/0.2	844	150	Hybrid 7BA, LGD, 3-pole wiggler insert, exploratory
APS-U	6/0.2	1104	60	ESRF style, swap-out inject, exploratory
SPring-8-II	6/0.1	1436	100	5BA, exploratory
ALS-U	1.9/0.5	200	100	9BA, superbend insert, swap-out, exploratory
SLS-II	2.4/0.5	288	250	Pre-conceptual design
BAPS	5/0.2	1500	50–100	Pre-conceptual design
PEP-X	6/0.2	2.2	10	7BA, 90 m DW, pre-conceptual design
TauUSR	9/0.2	6280	3	7BA, DW, pre-conceptual design

between the first and second dipoles and between the fourth and fifth dipoles in the Sirius lattice have higher dispersion in which sextupoles can be located (Farvacque *et al.*, 2013). The sextupole strengths needed for strong chromatic correction in these dispersion bump sections are reduced to a level that can be reached using conventional magnet technology. Unlike MAX IV with its machined magnet blocks, Sirius will use individual magnets, relying largely on machining precision of magnets and supports to achieve alignment tolerances.

While MAX IV, Sirius and a concept for a kilometer-scale 5–6 GeV Beijing Advanced Photon Source (Gang & Yi, 2013) are new green-field MBA machines, another wave of fourth-generation ring light source concepts is coming from existing facilities desiring to replace their present 2BA or 3BA lattices to reach lower emittance. These include the European Synchrotron Radiation Facility (ESRF) Upgrade in Grenoble (Farvacque *et al.*, 2013) (see Fig. 4), the Advanced Photon Source Upgrade (APS-U) near Chicago (Borland *et al.*, 2013), and SPring-8-II in Hyogo Prefecture, Japan (Shimosaki *et al.*, 2013). Other facilities studying the possibility of future lattice replacement include the ALS-U in Berkeley, USA (Steier *et al.*, 2013), the Swiss Light Source in Villigen, Synchrotron Soleil in Gif-sur-Yvette, France, the Diamond Light Source in Oxfordshire, UK, and SSRL at SLAC in California, USA. Common to all of these replacement proposals are the constraints on emittance reduction imposed by having to maintain an existing circumference and beamline geometry together with keeping approximately the existing operating energy in order to serve an established user community. The most aggressive designs would use on-axis injection (see §4.2) to enable operation with the very strong focusing and resulting reduced dynamic aperture needed to reach diffraction-limited emittances for low-keV photons. In the future, larger-circumference rings such as the 2.2-km PEP-X at SLAC (Bane *et al.*, 2011) or even the 6.28-km TauUSR at Fermilab (Borland, 2012) could have diffraction-limited emittances in the pm-rad regime, providing high transverse coherence for >10-keV X-rays.

A summary of low-emittance light sources in construction or under study is given in Table 1. Brightness and coherent fraction for some of these machines are shown in Fig. 5.

4. Design challenges and solutions

Reducing emittance to very low values requires frequent and strong electron beam focusing to reduce the amplitude of dispersive orbits. 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

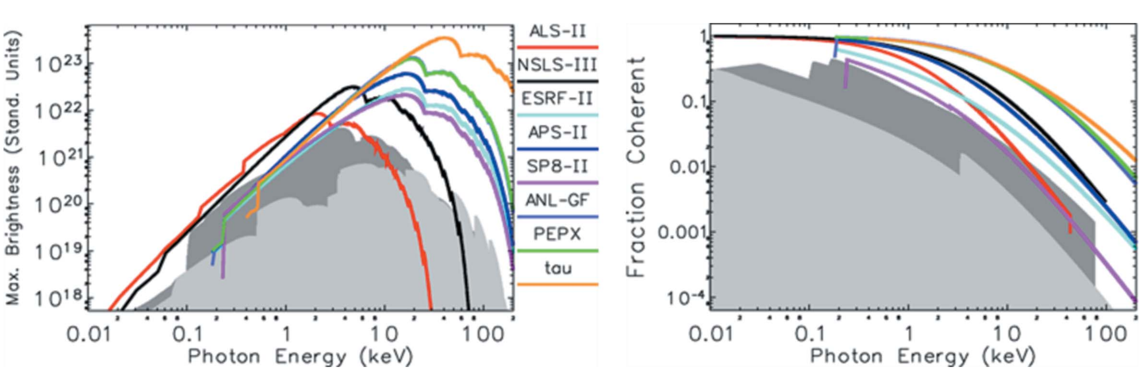

Figure 5
Brightness and coherent fraction for present-day storage rings (light gray), rings in construction (MAX IV, NSLS-II, dark gray) and future rings (colored curves). Curves for the APS-U (APS-II), ESRF upgrade (ESRF-II) and SPring8-II are subject to change as their actual designs progress. (Courtesy of M. Borland, APS/ANL.)

less than for third-generation light sources, which can limit the ability to inject and store beam and reduce maximal bunch charge and beam lifetime. The dynamic aperture for aggressive fourth-generation lattices may only be of the order of a millimeter, a factor of ten smaller than for most third-generation machines.

The international interest in fourth-generation MBA storage ring light sources has prompted a series of design studies and workshops aimed at addressing design challenges. In addition to the facility studies and construction projects mentioned earlier, several workshops devoted to very low emittance ring design have been convened. For example, the International Committee for Future Accelerators (ICFA) has been sponsoring workshops for many years to address design issues related to very low emittance damping rings that would be used for linear lepton colliders (*e.g.* ICFA, 2011). More recent workshops have focused more specifically on fourth-generation ring and DLSR design, informed by the real design efforts for MBA projects underway (Hettel & Qin, 2012; IFCA, 2013; SLAC, 2013). Findings and design solutions from these efforts are summarized as follows.

4.1. Lattice and accelerator physics

MBA lattice design and related accelerator physics issues are discussed in some depth elsewhere in this issue (Borland *et al.*, 2014; Nagaoka & Bane, 2014). To summarize, work over the last two decades on low-emittance damping rings for linear colliders, high-luminosity colliders and high-performance storage ring light sources has led to advances in accelerator physics methods and modeling tools. 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 resonance driving term minimization). The methods have been benchmarked on real machines with beam-based lattice calibration tools [*e.g. LOCO* (Safranek, 1997)] and parameter measurement techniques. Now they can be used to develop MBA lattice designs having high multipole gradients that might otherwise overly restrict dynamic acceptance. Lattice designers work to reduce or cancel non-linear driving terms by adjusting the phase advance between similar magnets in localized sections of the ring; driving terms up to the fourth order are cancelled within a given sextant of the PEP-X design (Cai *et al.*, 2012). These tools also enable finding lattice solutions having closer to optimal straight section betatron functions. Other developments include the hybrid MBA lattice discussed above that uses dispersion bumps in the achromat to reduce the sextupole strength needed for chromaticity correction, longitudinal gradients in some of the dipoles to reduce emittance, study of producing round beams with vertical dispersion instead of 100% emittance coupling and improved understanding of beam collective effects and lifetime that enables practical stable lattice solutions.

Many large-circumference fourth-generation lattices have a low momentum compaction factor that, together with their typical ∼500-MHz RF systems, leads to relatively short bunches (a few picoseconds r.m.s.) that make the rings more susceptible to impedance-driven instabilities. This issue can be mitigated by increasing bunch length using harmonic RF cavities (typically the third harmonic) and/or by using low-frequency RF systems (as MAX IV has done with its 100-MHz system). Longer bunch lengths also serve to reduce RF heating of vacuum chamber components. In contrast, there is an experimental user community that is interested in high-repetition-rate short-bunch operation (of order 1 ps) (Huang *et al.*, 2014), a mode that could entail bunch-shortening RF cavities, or transversely deflecting crab cavities (Zholents *et al.*, 1999), or a higher-frequency RF system to increase longitudinal focusing, or the novel two- or three-frequency RF system that produces a combination of long and short bunches (Wüstefeld *et al.*, 2011), or even injection of short bunches from a linac for one or a few revolutions in the ring. Successful implementation of short-bunch operation in a fourth-generation ring light source will require the advanced modeling developments mentioned above and the likelihood of multi-bunch stabilizing feedback systems.

4.2. Injection

The traditional beam-filling method for a storage ring light source is to use a closed-bump kicker magnet system to inject fresh bunches of electrons off-axis from the already stored beam, accumulating and replenishing the electrons in the ring's RF 'buckets' which are separated by the wavelength of the main RF system frequency. The dynamic aperture of the ring must be large enough to accommodate the resulting oscillation amplitude of the incoming beam, typically several millimeters at the initial injection point, which subsequently damps down as the injected beam merges with the stored bunch. A primary factor in traditional lattice design is to reach a dynamic aperture of order 10 mm to accommodate off-axis injection, although a smaller aperture can be tolerated by increasing β_x in the injection straight section. The dynamic aperture requirement restricts how low the emittance can be made for a given MBA lattice geometry, and the high β_x requirement, which is often repeated in other straight sections to maintain lattice symmetry for the sake of dynamic aperture, compromises the phase space matching between electron and photon beams discussed in §2. MAX IV, Sirius and the ESRF Upgrade, all having relatively large circumferences, have reached 140–300 pm-rad emittances while accommodating off-axis injection with lattices having β_x of order 10–20 m in the injection straight section. Off-axis injection into PEP-X, which has millimeter dynamic aperture, is possible because β_x = 200 m in that one straight section.

Smaller dynamic aperture and smaller β_x, closer to the ideal for electron–photon phase space matching, can be tolerated if the beam is injected on-axis into the ring, eliminating the need to accommodate injected beam oscillations. One method is to use a single injection kicker that completely knocks out one or more already-stored beam bunches, replacing it or them with incoming bunches kicked on-axis with the nominal stored beam orbit. This 'swap-out' injection scheme (Emery *et al.*, 2003) enables lattice focusing and consequent chromatic aberration correction strengths to be increased with a subsequent reduction in emittance from lattice solutions that must accommodate off-axis injection. 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 that can prevent beam accumulation. Because the lattice does not have to accommodate the many-millimeter oscillation amplitudes of the incoming beam, injected beam losses are reduced, the horizontal good-field region of magnets can be reduced, and high-performance insertion devices having small horizontal as well as vertical apertures [*e.g.* helical, Delta-type (Temnykh, 2008) or possibly RF undulators (Yeddulla *et al.*, 2011)] can be accommodated.

Swap-out injection schemes include single-bunch and multi-bunch replacement methods. Single-bunch replacement requires a fast injection kicker having few-nanosecond rise-, flat-top- and fall-times and bunches spaced by several nanoseconds. Bunch train replacement [as is being explored for the APS-U (Xiao *et al.*, 2013) and ALS-U] requires a kicker having fast rise- and fall-times as well as a flat-top of sufficient length and uniformity to kick all bunches in the train approximately equally; bunch trains must be separated from each other by several nanoseconds. These high-performance kickers have been under development by the linear collider community for many years.

While beam for swap-out injection could come from a high-performance on-energy linac (*e.g.* for SPring-8) or linac/booster combination, the full charge per bunch needed for swap-out injection exceeds the capabilities of many injector facilities. For this reason, accumulator rings having the capability of stacking charge with repetitive pulses from an injector in single or multiple bunches have been envisioned as a means to prepare swap-out bunches in advance of injection into the ring. Such an accumulator ring can be located either outside (*e.g.* as presently implemented at the APS) or inside the storage ring tunnel (*e.g.* as considered for the ALS-U), and could be capable of recovering the kicked-out beam from the ring for re-use in a later injection cycle. It has also been suggested that a combined accumulator-booster ring could be configured as a cost-saving solution.

In these swap-out injector scenarios, with the possible exception of a full-energy linac having a very low emittance photocathode gun, the initial injected beam will have significantly higher emittance than the beam stored in the ring, causing a transient fluctuation in average beam brightness that typically decays within a few tens of milliseconds. However, the magnitude of the brightness fluctuation is minimized by reducing storage ring transverse damping times, and/or if the fraction of stored beam being replaced is small.

Another on-axis injection option, *i.e.* longitudinal injection, is being explored (Aiba *et al.*, 2014). Here a fast kicker places an off-energy (∼+4%) injected beam bunch between two RF buckets in the ring, but within the longitudinal acceptance phase space of the leading bucket, enabling its capture in that bucket. Longitudinal injection is made possible by the distortion of phase space into a 'golf club' shape that provides access to the RF bucket by a time-delayed off-energy injected beam bunch (Fig. 6). Whereas swap-out injection requires complete bunch replacement, longitudinal injection enables beam accumulation in a given bucket over many injection cycles, relieving the need for a high-charge injector using an accumulator ring, for example. The drawback of this method is that a very fast kicker is required, one that turns on and off between stored bunches. The spacing between bunches is then constrained to the order of 10-ns or more given practical kicker designs (although the spacing could be reduced with fast kicker development). The technique also requires the ring to have sufficient momentum acceptance, on the scale of 5%, which is a challenge for aggressive lattice designs. The possibility of longitudinal injection is being studied for MAX-IV, which has a 100-MHz RF system and 10-ns bunch spacing.

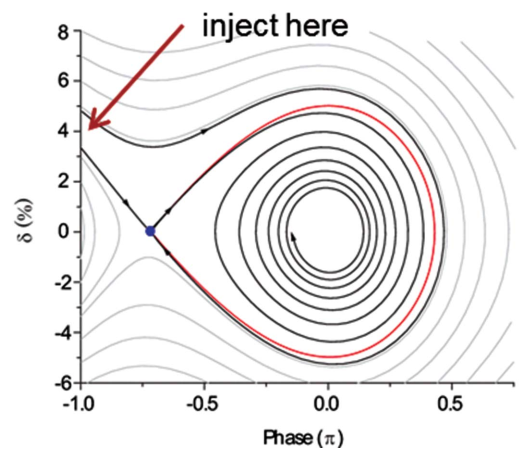

Figure 6
Longitudinal injection for the MAX IV storage ring might be enabled by distortion of the acceptance phase space for an RF bucket caused by RF acceleration and synchrotron radiation losses (Aiba *et al.*, 2014). An electron bunch having ∼4% higher energy than the nominal ring energy is injected approximately 5 ns behind the center of an RF bucket having 5% momentum acceptance where it is subsequently captured after damping of longitudinal oscillations. Bucket spacing is 10 ns for the MAX IV 100-MHz RF system.

4.3. Magnets

As discussed elsewhere in this issue (Johansson *et al.*, 2014), the strong focusing MBA lattices for fourth-generation and diffraction-limited storage rings present challenges for the design of small magnets having very high field quality and tight alignment tolerances. Multipole gradients are typically much higher than those for third-generation machines. For example, quadrupole gradients are approaching 100 T m^{-1} for some of these designs, about a factor of five higher than for third-generation magnets, 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 (Halbach, 1988). The gradients required in some gradient dipole designs are sufficiently large to require the use of offset quadrupoles or half-quadrupoles (Bondarchuk *et al.*, 1998) with horizontal movers to adjust gradients (as is being considered for the ESRF Upgrade, APS-U and ALS-U) in place of more conventional gradient dipole designs.

Other combined function magnet designs, including quadrupole/sextupole and corrector/sextupole/skew quadrupole, provide a way to achieve more compact lattices. Combined function magnets having a single energizing coil system, such as for gradient dipoles, suffer from a lack of independent tunability that ideally should be provided by some other means, such as by using pole-face windings on gradient dipole poles (as for MAX IV) or with small independent 'tweaker' tuning magnets. Additional magnet design innovations proposed for fourth-generation lattices include dipoles having a longitudinal gradient (Guo & Raubenheimer, 2002) that tailor lattice optics to reduce emittance, the aforementioned short high-field permanent magnet 'super bend' splices 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, and the alternative use of small three-pole wigglers (*e.g.* of order 10 cm) adjacent to the central dipoles for this purpose.

MBA magnet support and alignment designs that achieve the requisite nominal 10-µm tolerances on a magnet girder have been following three basic approaches:

(i) Precision machining of individual magnets, followed by individual magnetic measurement and fiducialization, then mounted on girders and aligned using measurements from a stretched or vibrating wire extending through all girder magnets (as done for the NSLS-II).

(ii) Precision machining of magnets having a common yoke consisting of a single block of iron, relying on machining tolerances to achieve alignment tolerances (as done for MAX IV, Fig. 3).

(iii) Precision machining of individual magnets, followed by individual magnetic measurement and fiducialization and mounting on precision-machined girders, relying on machining tolerances to achieve sufficient alignment tolerance [a 'compromise' between methods (i) and (ii), less labor-intensive than (i), being considered for Sirius].

A fourth approach is now being considered that could relax the nominal and costly 10-µm machining tolerances by a significant amount based on the ability to use the electron beam to determine lattice magnetic centers and to make alignment adjustments accordingly (Eriksson, 2013). First-turn beam position measurements during ring commissioning could be used to make the orbit corrections necessary to establish stored beam, followed by high-resolution measurements and alignment of magnetic centers using quadrupole and sextupole field modulation techniques together with beam-based lattice calibration methods to adjust magnet strengths for optimal performance. While these techniques are routinely now used for lattice calibration and correction, reliance on them for the purposes of reducing magnet and girder fabrication and alignment tolerances has yet to be exploited for saving cost.

4.4. Vacuum system

The design of small-aperture vacuum chambers and associated components for fourth-generation storage rings is described elsewhere in this issue (Al-Dmour *et al.*, 2014). In short, as mentioned, the use of discrete vacuum pumps is largely prohibited by chamber conductance limitations. Instead distributed pumping can be provided by coating the chambers with a micrometer or so of NEG material, a technology that was first developed at CERN (Benvenuti, 1998) but that has since been commercialized and in some cases transferred to other laboratories under license from CERN (*e.g.* ESRF and Sirius). NEG coating of vacuum chambers is a mature technology that is frequently used in third-generation light sources for small-vertical-gap insertion devices, and, in the case of Synchrotron Soleil, for a large fraction of the entire ring (Herbeaux *et al.*, 2008). While the MAX IV and Sirius arc vacuum chambers, having ~25-mm diameter, are completely NEG-coated (Fig. 7), other facilities like the ESRF and SPring-8 are exploring hybrid designs that maintain larger aperture antechambers and discrete pumps in some arc chamber locations, using NEG coating only where absolutely necessary.

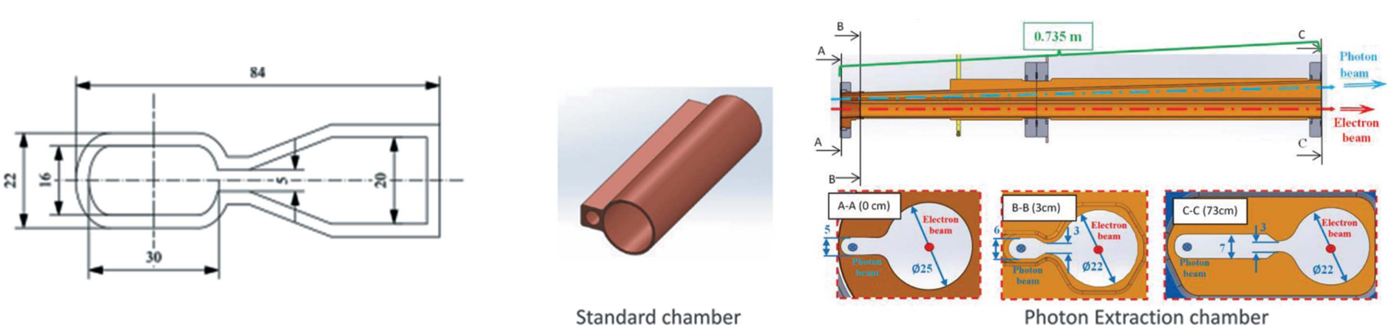

Figure 7
The typical vacuum chamber with antechamber configuration with lumped vacuum pumps used in third-generation rings (left; courtesy of SPring-8) is being replaced in many cases with more compact NEG-coated chambers providing distributed pumping (right; courtesy of MAX IV).

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 issues requiring some development and strict quality assurance for each new chamber design. The pre-coated chamber cleaning process has proven to be particularly important for successful NEG coating. While the coating is thin, much less than the skin depth of the frequency content of beam bunches having picoseconds length and thus not presenting any appreciable impedance to those bunches, it does add impedance for very high frequencies that could destabilize very short bunches ($\ll$1 ps). NEG material must be activated by heating, which can be done in advance of installation in the accelerator tunnel when special care is taken to preserve vacuum quality during installation, or *in situ* using thin radiation-resistant heater tape wrapped around the chambers. The latter method offers the ability to re-bake the chambers in place to improve NEG pumping, but it requires additional space between magnet pole tips and the vacuum chamber, typically accommodated by a millimeter-scale increase in magnet bore diameter and a consequent reduction of achievable gradients.

Other factors influencing small-aperture vacuum chamber implementation include the choice of material, the design of compact photon absorbers and the reduction of chamber geometric impedance associated with step changes in inner dimensions and transitions between chamber types. MAX IV and Sirius have chosen copper for their arc chambers because of its high electrical and thermal conductivity, thus reducing resistive wall impedance and facilitating simple cooling configurations. The almost round chambers are sufficiently strong to resist deformation under vacuum with millimeter wall thickness. Thin-walled stainless steel, which is being considered for the ESRF Upgrade and will be used for insertion device chambers in several fourth-generation rings, is stronger and offers more inherent radiation shielding than copper, but its lower conductivity increases resistive wall impedance, reducing the threshold for beam instabilities, and requires careful photon-masking and cooling solutions. Aluminium, having conductivity closer to copper and being easy to machine and extrude, has yet to be chosen for fourth-generation chamber designs. Aluminium loses strength when heated above 453 K, necessitating low-temperature bake-out for NEG activation.

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 that define the nominal electron beam orbit for feedback systems. Provision must be made for feedback correctors having kilohertz bandwidth in the vicinity of photon beam sources (*i.e.* insertion device straight sections and near any dipole sources), implying the likely use of stainless steel chambers or high-resistivity chamber splices at those corrector 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.

4.5. Insertion devices

The performance and full brightness potential of present and future light sources will be enhanced with developments now in progress in permanent magnet and superconducting insertion device technology (Ivanyushenkov, 2013). Reducing undulator phase error would enhance performance for very high harmonics. High-temperature superconducting technology, novel magnetic structures for unique applications, devices that minimize unused power on optics and vertically oriented undulators would all contribute to fourth-generation storage ring performance. As noted previously, the round beams and on-axis injection would support the use of high-performance insertion devices having small horizontal as well as vertical gaps, including helical and Delta-type undulators.

4.6. Photon beamline systems

The small size and high coherence of fourth-generation ring X-ray beams presents an increased challenge for photon beamline 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 if the source is to be fully exploited. The photon beams can also present high power densities for beamline components and experimental samples that may need mitigation. These challenges are similar in many ways to those encountered at X-ray FEL facilities.

Improved mirror polish/figures would reduce emittance and coherence degradation. 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 greatly benefit fourth-generation ring light-source performance. These and other developments in X-ray optics are described in the report of a recent workshop sponsored by the US DOE Office of Basic Energy Sciences (BES) (Mills & Padmore, 2013).

The possibility of high power density from the small X-ray beams could necessitate development of improved cooling and thermal designs for optical components (*e.g.* cryogenically cooled mirrors), although in some cases new IDs having short period and low K may actually reduce beam power. Improved thermal designs could reduce masking costs and provide more beamline layout flexibility. Developments in minimal optics and lensless imaging methods would maximize performance in some cases. Because the very low emittance beams are so highly collimated, they pass through beamline photon absorbers with little interception, reducing the need for very high power absorber designs.

Many photon beamlines in larger fourth-generation ring facilities will be quite long (of order 100 m or more) to take full advantage of the nano-focusing potential of the highly coherent beams. As discussed in the next section, maintaining beam stability, especially in long beamlines, requires advanced beam position, shape and wavefront monitors incorporated into feedback systems and continuing improvements in optics support and experimental hall floor stability.

The true potential for increased speed and resolution of experiment measurement using the very bright fourth-generation ring X-rays will only be fully realised with the commensurate development of X-ray detectors. A recent workshop on detectors sponsored by the DOE BES (Carini *et al.*, 2012) concluded that advances are needed for increased efficiency hard X-ray sensors, fast framing detectors, high-speed spectroscopic detectors, very high energy resolution detectors and improved data acquisition and visualization tools. These development goals are shared to an extent with the X-ray FEL facilities and have become a high priority in the strategic plan for the light-source community as a whole.

4.7. Beam instrumentation and stability

As is the case for present-day light sources, a high degree of transverse, longitudinal and intensity stability is required for maximum photon source performance, especially in dimensions critical to experiments having restricted acceptances in some part of six-dimensional phase space. Requirements for monitors detecting photon beam parameters, including size, position, timing, intensity and energy, are qualitatively similar to those for existing facilities. However, the resolution requirements for some of these monitors are increased, especially for the horizontal plane. For example, beam size monitors require micrometer resolution and beam position must be measured with sub-micrometer resolution in a few hundred Hertz bandwidth. 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 (Franchi *et al.*, 2014) having an order of magnitude higher resolution than presently available. Critical for maximizing performance will be to maintain beam orbit centering in strong sextupoles, a goal that would be enabled by locating BPMs close to sextupoles to maintain a centered orbit as determined with a sextupole modulation scheme.

As for present-day light sources, stability requirements are typically a few percent of the photon beam's dimensions. These requirements are already quite stringent in the vertical plane since diffraction-limited emittances are reached routinely in that plane. The very small horizontal beam dimensions in fourth-generation rings will necessitate stabilizing technology, both passive and active, in that plane as well as in the vertical plane. An integrated effort from the accelerator and beamline designers will be needed to maintain stability integrity in all aspects of hardware and control system design. It is likely that high-resolution ($\sim$100 nm or better) mechanical motion/position survey sensors will be needed for critical components in the accelerator (*e.g.* user BPMs) and beamline (*e.g.* optical components, small apertures and collimators, *etc.*). Some of these devices may require cutting-edge technology [*e.g.* 'telescope technology' such as the laser-Doppler stabilization system used for atomic force microscopes and the X-ray nanoprobe at the APS (Shu *et al.*, 1999)].

Maintaining the beam pointing and position stability at user experimental stations located >100 m from the photon source is an engineering challenge. Fast feedback systems, capable of maintaining sub-micrometer transverse beam stability in electron and photon BPMs, will ideally be integrated with other active systems in the accelerator and beamlines designed to monitor and stabilize the motion of BPMs and beamline optical components. BPMs in the beamlines will be needed to improve photon beam stability before and after optical components. Ongoing development of X-ray BPMs that accurately measure the position of low- and high-photon-energy insertion devices is required. Especially problematic and already the subject of R&D are photon BPMs for soft X-ray elliptically polarizing undulators (EPUs), whose transverse intensity distribution changes dramatically with polarization setting.

The small-aperture vacuum chambers for fourth-generation rings will have sufficient impedance to drive resistive-wall multi-bunch beam instability. This and other high-frequency electron bunch motion, driven by accelerator transverse and longitudinal impedances, will be controlled with bunch–bunch feedback systems. Longitudinal instability caused by RF voltage phase and amplitude noise, including that caused by ripple in the high voltage power supply at harmonics of the power line frequency, must be controlled with low-level RF and possibly longitudinal multi-bunch feedback systems. It is expected that the action of a harmonic bunch lengthening cavity may complicate fast RF and longitudinal feedback implementation, and transient beam loading in the harmonic cavity may introduce varying bunch lengthening along the stored beam bunch train unless steps are taken to mitigate this.

4.8. 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. While many of the cutting-edge scientific capabilities discussed in this issue will be best enabled with maximally bright highly coherent diffraction-limited rings, this capability could come at the expense of both flux and facility cost, especially for high-energy hard X-ray machines where the diffraction limit can only be reached with large circumference. Noting that it is possible to obtain high coherent flux with a high-current low-coherent-fraction ring, and that there is a diminishing return in coherent fraction as emittance is reduced (Fig. 2), a cost-benefit optimization for the design of a fourth-generation ring should exist, depending on the spectral range and science applications of interest for the user community. Other considerations include not only flux and coherence but also single-bunch properties (*i.e.* photons per pulse and pulse length) that could influence the design optimization. For example, APS-U designers are striving to accommodate a relatively high single-bunch current ($\sim$4 mA) in order to support a timing mode community that asks for as many photons per pulse as possible. Design optimization includes the choice of RF frequency: lower frequency produces longer bunches that are less susceptible to ring impedances and produce less RF heating in vacuum chamber components but are unlikely to fulfil the requirements for some short-bunch pump–probe applications.

A key parameter in any ring design is the electron energy 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, 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.

A final comment on design optimization concerns the number, length and spacing of straight sections in the lattice, issues for green-field designs since these choices have usually already been made for upgrade designs. Designers must decide whether long straight sections will be used for two IDs in a chicane, as opposed to providing more short straight sections holding single IDs. Very long straight sections (tens of meters) might be used for future possibly unforeseen implementations of advanced beam manipulation and photon generation technologies. The spacing between straight sections, lattice bending radius and thus the angle between adjacent photon beamlines ultimately determines the length of X-ray beamlines and the amount of expensive experimental floor space needed for them. Experimental halls for very large rings can become overly expensive unless ID straights are spaced for efficient beamline clustering. In some cases this could lead to a hybrid lattice design for very large rings where beamline straight sections are consolidated in specific arcs having optimal spacing using one lattice type, while another minimal emittance lattice type is used elsewhere (Hettel *et al.*, 2009).

5. Summary and outlook for the future

A new generation of storage ring light sources having emittances at or near the diffraction limit for X-ray photons is now emerging. With the NSLS-II, MAX IV and Sirius projects, 3-GeV machines having sub-nm-rad horizontal emittances, and as low as 0.2 nm-rad, are now under construction. The ESRF, APS and SPring-8 are all exploring 6-GeV MBA lattice conversions having even lower emittance. China is considering the green-field 5–6-GeV BAPS ring having <100-pm-rad emittance. Other synchrotron facilities worldwide are studying MBA lattice conversions that will bring them into the fourth generation.

Longer range studies 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. The longer-range future for DLSRs might include enhanced capabilities, such as ring-based high-repetition-rate low-peak-power FELs (Ding *et al.*, 2013) (Fig. 8) 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 realising ring-based keV-X-ray FELs. These more ‘ultimate’ machines are likely to be costly and the ‘billion-dollar question’ about whether they should be built will need to be justified by science demand. Meanwhile the construction of more modest cost-effective machines having fourth-generation ring performance is likely to continue.

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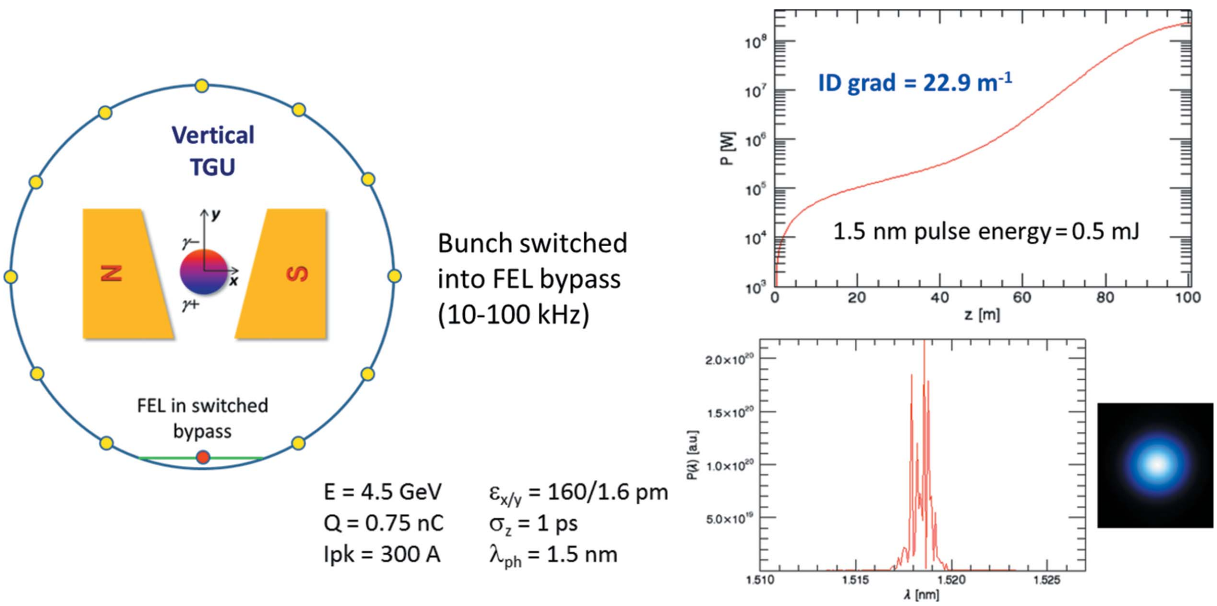

Figure 8
An electron bunch having peak current of order 300 Apk is switched into a transverse gradient undulator (TGU) in a bypass of a 2.2 km ring (left) to produce a 1.5 nm, 0.5 mJ self-amplified spontaneous emission (SASE) FEL pulse (Hettel *et al.*, 2009). The inherent electron energy spread and vertical lattice dispersion in the TGU produce an almost round electron beam with a linear energy distribution in the vertical plane that maintains lasing resonance at a single photon wavelength. Evolution of photon power along the TGU length, radiation spectral content, and single-mode coherent beam profile are shown on the right. The spent electron bunch is returned to the ring where its lasing-induced energy spread is damped before the bunch is ready for lasing again. Other damped bunches are switched into the bypass during this damping period, which is typically a few tens of milliseconds. Producing a high peak current bunch in the ring is challenging, potentially requiring a high-voltage (few hundred MV) high-frequency ($\sim$1.5 GHz or more) RF system.

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