PERSPECTIVES AND CHALLENGES FOR DIFFRACTION-LIMITED STORAGE RING LIGHT SOURCES*

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Abstract

This paper provides an overview of the scientific motivation for developing diffraction limited storage ring (DLSR) light sources, reviews the main R&D challenges associated with DLSR implementation and summarizes the worldwide effort presently in progress to build a new generation of very low emittance rings.

INTRODUCTION

Synchrotron radiation from storage rings is the dominant source of high brightness photons from the infrared to hard X-rays, serving a multitude of scientific applications. Recently X-ray free electron lasers (FELs) have emerged, offering orders-of-magnitude higher peak brightness in ultra-short pulses. FELs offer nearly complete transverse coherence and energy bandwidth that will approach the transform-limit with seeding. Both ring- and FEL-based sources will play a vital role as they offer complementary beam properties, with rings providing low peak brightness with high average brightness and pulse repetition rate, which does not over-excite or damage samples as FELs do [1]. Another complementary capability for some storage ring sources is the production of high repetition rate (MHz), picosecond pulses for probing materials dynamics on the >10 ps timescale.

There are scientific applications and experimental methods that would greatly benefit from ring-based sources having much higher average brightness and transverse coherence. These include nanometer imaging applications; X-ray correlation spectroscopy and spectroscopic nanoprobes; and diffraction microscopy, holography and ptychography [2]. These applications will benefit from X-ray sources with average spectral brightness exceeding ~10^{22} photons/s/mm^2/mrad^2/0.1% BW and significantly higher coherent photon flux than presently available. This can best be provided only by reducing the electron beam emittance well below the present-day standard of nanometer-radians, towards the diffraction limit for X-ray beams.

WHAT IS A DLSR?

Diffraction-Limited Photon Emittance

While diffraction is typically associated with the divergence of a photon beam as it passes through a limiting aperture, it can be shown by solving the electric field wave equation that diffraction also occurs for a transverse spatially restricted photon beam, such as a Gaussian laser beam [3]. The transverse size and divergence of the electric field are related by a Fourier transform and the observed radiation intensity pattern, proportional to the square of electric field strength, satisfies the following:

$$\sigma_r(\lambda)\,\sigma'_r(\lambda) = \frac{\lambda}{4\pi} = \varepsilon_r(\lambda) \qquad (1)$$

where $\sigma_r(\lambda)$ and $\sigma'_r(\lambda)$ are the rms size and divergence, respectively, and $\varepsilon_r(\lambda)$ is the diffraction-limited emittance for a Gaussian photon beam having wavelength λ.

Extensive calculations of the radiation emitted by an undulator having N periods and length L have been carried out by several authors [3,4]. They reveal transverse beam size and divergence profiles that are only approximately Gaussian, so that the transform-limited value for the radiation emittance in (1) does not hold exactly. The rms size and divergence associated with the Gaussian fits to the calculated patterns are [4]

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

and thus

$$\sigma_r(\lambda)\,\sigma'_r(\lambda) \approx \frac{\lambda}{2\pi} = \varepsilon_r(\lambda)\;. \qquad (3)$$

It should be noted that the factor of 1.9 for $\sigma_r(\lambda)$ in (2) is missing in [3]. This is not a serious issue – in fact, several other values can be derived depending on calculation and fitting assumptions. For the remainder of this paper, $\lambda/4\pi$ will be used since that value is commonly used by the synchrotron radiation community.

Diffraction-Limited Electron Emittance

A hypothetical filament of electrons having essentially no transverse size or divergence ("single electron" dimensions) passing through an undulator would emit radiation having the dimensions and emittance given in (2) and (3). A real electron beam has transverse size and divergence, which must be convolved with the single-electron photon parameters to determine the photon beam properties. Assuming Gaussian profiles, total horizontal or vertical emittance $\Sigma_{x,y}$ is given by

$$\Sigma_{x,y}(\lambda) = \varepsilon_r(\lambda) \oplus \varepsilon_{x,y}(e-) \qquad (4)$$
$$= \sqrt{\sigma_r{}^2(\lambda) + \sigma_{x,y}{}^2(e-)}\sqrt{\sigma'_r{}^2(\lambda) + \sigma'_{x,y}{}^2(e-)}$$

where $\oplus$ denotes convolution, and $\sigma_{x,y}(e\text{-})$ and $\sigma'_{x,y}(e\text{-})$ are electron size and divergence, respectively, given by

$$\sigma_{x,y}(e\text{-}) = \sqrt{\beta_{x,y}\varepsilon_{x,y}(e-)} \qquad \sigma'_{x,y}(e\text{-}) = \sqrt{\varepsilon_{x,y}(e-)/\beta_{x,y}} \qquad (5)$$

at the waist of the electron beam (and assuming zero dispersion). Total emittance is minimized when photon

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[†] Work supported in part by Department of Energy Contract DE-AC02-76SF00515 and Office of Basic Energy Sciences, Division of Chemical Sciences

and electron phase space orientations are matched, i.e.

$$\sigma_{x,y}(e\text{-})/\sigma'_{x,y}(e\text{-}) = \sigma_r(\lambda)/\sigma'_r(\lambda) \Rightarrow \beta_{x,y} = L/2\pi \quad (6)$$

(Fig. 1). This result assumes $\varepsilon_r = \lambda/4\pi$ and imposes a demanding requirement, e.g., $\beta = 0.6$ m for $L = 4$ m, a difficult value to achieve in the horizontal plane when using accumulation-based injection. Relaxing β_x to ~10 m can increase effective emittance by a factor of ~2 for emittances near the diffraction limit. This condition is less difficult if actual $\varepsilon_r = \lambda/2\pi$; then $\beta_x = L/\pi$. An optimization of beta functions that depends on undulator and electron beam properties is required in real designs.

From the above it can be inferred that a diffraction-limited emittance is reached when $\varepsilon_{x,y}(e\text{-}) << \varepsilon_r(\lambda)$. However it is conventional to say a ring is diffraction-limited when $\varepsilon_{x,y}(e\text{-}) = \varepsilon_r(\lambda)$. The diffraction-limited emittance for 1-Å X-rays (~12 keV) is 8 pm-rad, far below the nm-rad horizontal emittances for present-day storage ring light sources. However, vertical emittances at or below this scale are routinely reached in present machines by reducing vertical dispersion and coupling.

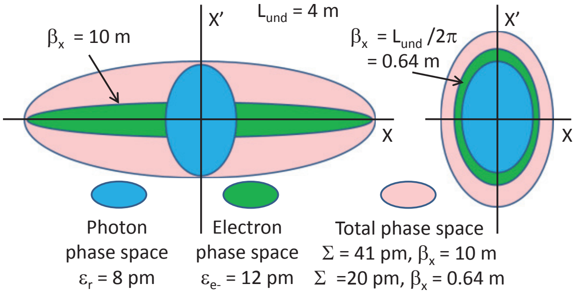

Figure 1: Total emittance (pink) is minimized when electron (green) and photon (blue) phase space ellipse orientations are matched. $\varepsilon_r = \lambda/4\pi$ is assumed.

Brightness and Coherence

The average brightness for a photon beam having wavelength λ is defined as the photon density in 6-dimensional phase space at that wavelength:

$$B(\lambda) = \frac{N_{ph}(\lambda)}{4\pi^2 \Sigma_x(\lambda) \cdot \Sigma_x(\lambda) \cdot (s \cdot \%\, BW)} \quad (7)$$

Closely related to brightness is the fraction f_{coh} of photons that are transversely coherent in each plane:

$$f_{coh-x,y}(\lambda) = \frac{\varepsilon_r(\lambda)}{\Sigma_{x,y}(\lambda)} \quad (8)$$

$$f_{coh-tot}(\lambda) = f_{coh-x}(\lambda) \cdot f_{coh-y}(\lambda)$$

When e_x (e-) = e_r (λ), the horizontal coherence is 50%. If both horizontal and vertical electron emittances are at the diffraction limit, the total coherent fraction is 25%. Horizontal coherent fraction as a function of electron emittance for different wavelengths is shown in Fig. 2.

From (7) it is evident that brightness can be increased either by reducing emittance in the denominator, or by increasing photon flux ($N_{ph}(\lambda)$/s) in the numerator. The latter can be achieved by increasing the stored beam current and through the use of longer or higher-performance undulators. Nevertheless, while X-ray users are interested in high coherent flux, achieving it by increasing coherent fraction is more desirable since this reduces the amount of “unusable” incoherent flux and mitigates issues associated with high heat loads.

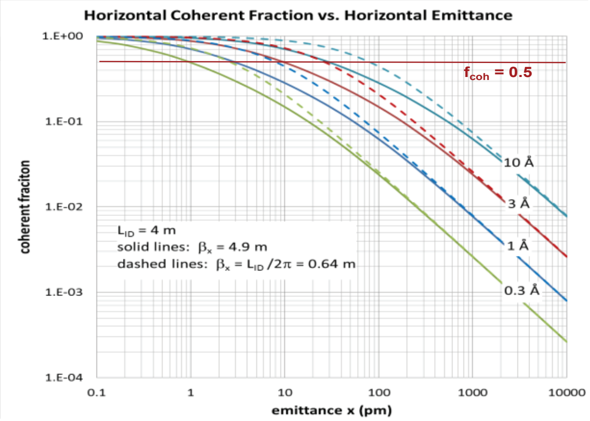

Figure 2: Horizontal coherent fraction versus emittance for various X-ray wavelengths. Dashed curves indicate the gain coherence for 4-m undulators when β_x is reduced from 4.9 m to 0.64 m (= $L/2\pi$).

The brightness and coherent fraction for various existing, imminent and potential future storage ring light sources are shown in Fig. 3. While these parameters will be increased ten-fold in the 0.1 to 10 keV range by sources now in construction, an even greater increase in that spectral range, and an enhancement of 2 or more orders of magnitude in the 10 to 100-keV range should be achieved by converting existing high energy rings (ESRF, SPring-8, APS) to lattices with emittances in the 60-150

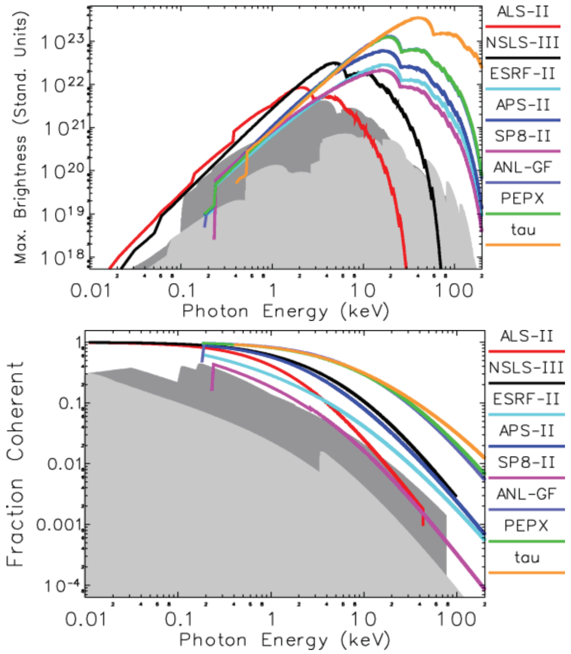

Figure 3: Brightness and coherence for present day storage rings (light gray), rings in construction (MAX-IV, NSLS-II, dark gray) and future rings (colored curves). Ring parameters given in Table 1.

pm-rad range. Large circumference green-field machines having emittances of 1 to 10 pm-rad (e.g. PEP-X [5], TauUSR [6]) would approach maximal brightness and coherent fraction for hard X-rays.

Reducing Emittance

The natural electron emittance ε_0 is given by [7]

$$\varepsilon_0(e-) = F(\nu,\ cell)\frac{E^2}{(N_d N_s)^3} \propto \frac{E^2}{C^3} \tag{9}$$

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 dipoles in a given sector, N_s is the number of sectors (and straights) in the ring, and C is ring circumference. The C^{-3} scaling is valid only when the cell type is fixed. Stated simplistically, ring emittance for a given electron energy is reduced by increasing the total number of dipoles in the ring and by increasing focusing between dipoles to maintain low dispersion. Horizontal and vertical emittances are set by the coupling factor κ:

$$\varepsilon_x(e\text{-}) = \frac{1}{1+\kappa}\varepsilon_0(e-) \qquad \varepsilon_y(e\text{-}) = \frac{\kappa}{1+\kappa}\varepsilon_0(e-) \tag{10}$$

Present-day rings have $\kappa < 0.1$. As ε_0 is reduced towards the diffraction limit, it is reasonable to set $\kappa = \sim 1$, enabling operation with a quasi-round beam that is beneficial to users. This increases Touschek lifetime and combats emittance growth caused by intra-beam scattering (IBS) in the very small electron bunch volumes.

Emittance can also be reduced by introducing more damping to combat radiation- and IBS-induced emittance growth. This can be accomplished using high-field damping wigglers (DW) and is effective if the energy loss per turn U_W in the wigglers is greater than the energy loss per turn U_0 in the dipole magnets, in which case

$$\frac{\varepsilon_W}{\varepsilon_0} \approx \frac{1}{1+U_W/U_0} \tag{11}$$

The dipole field strength for large rings can be low (~0.5 T), making damping wigglers a practical way to reduce emittance by a factor of 2-3.

A third way to reduce horizontal emittance is to increase the horizontal damping partition J_x by a factor of two or so by passing the beam through magnets having a combination of positive dipole and defocusing gradient fields, e.g., gradient dipoles, Robinson wiggler [8], or by orbit offset in quadrupoles [9]. This method increases horizontal damping at the expense of longitudinal damping, reducing emittance while increasing the energy spread. Once gradient dipoles are used in the lattice, the other two methods do not add a significant benefit.

DLSR Properties

Given the discussion above, the properties of DLSRs can be summarized as follows:

- Brightness and coherence are as high as possible for a given beam current.
- 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 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.
- Large circumference for multi-GeV rings allows reaching the diffraction limit for hard X-rays.
- Damping wigglers can be used to combat IBS, reduce emittance and increase lifetime.

As noted below the strong focusing lattices needed to reach a minimum emittance have small dynamic aperture (DA), potentially inadequate for normal beam accumulation using off-axis injection. In this case, an additional property for some designs is the need for on-axis "swap-out" injection [10] where stored electron bunches are completely replaced with new incoming bunches. Such lattice designs also tend to have a low momentum compaction factor, resulting 5-10 ps rms natural bunch lengths in some cases for rings having ~500-MHz RF systems, a factor of ~3 lower than present-day sources. In these cases, bunch lengthening RF cavities are needed to increase lifetime and reduce IBS.

CHALLENGES AND SOLUTIONS

The science case for high coherence storage rings has gained sufficient momentum to motivate existing facilities (e.g., ESRF, SPring-8, and APS) to develop plans to replace their lattices with ultra-low emittance designs. These lattices will increase brightness and coherent fraction by orders of magnitude, reaching diffraction limited horizontal emittances for few-keV X-rays. To reach the diffraction limit and maximal brightness for hard X-rays (<10 pm-rad), new machines with large circumference (~1.5 km for ~5-GeV electrons) will be required. The challenges and technological solutions related to these designs are discussed below.

Fundamental Challenges

The main path to reducing emittance in a storage ring is to increase the number of dipoles while limiting dispersive orbit amplitudes using many strong quadrupoles. These quadrupoles introduce chromatic aberrations that must be corrected with strong sextupoles, which in turn introduce higher order aberrations that must be corrected in order to achieve adequate dynamic and momentum aperture (MA). Without sufficient MA and DA, beam lifetime will be reduced, increasing beam loss, and off-axis injection becomes difficult, if not impossible.

The ~2-fold stronger quadrupoles and ~10-fold stronger sextupoles required by these rings, necessitates bore radii 2-3 times smaller than today's light sources. Small magnet bores imply small-aperture vacuum chambers in both transverse dimensions, reducing vacuum system conductance, and increasing issues with synchrotron radiation power absorption. Furthermore, the impedance from small aperture chambers exacerbates single- and mutli-bunch beam instabilities.

Challenges for DLSRs have been discussed in several workshops, including [11-13] and others.

DLSR Technology

Multi-bend achromat (MBA) lattices having more than 3 dipoles per sector has been envisioned as a way to increase the number of dipoles while providing many insertion device straight sections beginning with 4BAs in the early 1990s [14], an early 7BA lattice for the Swiss Light Source [15] and a 7BA, 3-GeV lattice reaching 0.5-nm-rad emittance with a 400-m circumference [16] (Fig. 4). Still, the challenges associated with compact magnets and small-bore vacuum chambers were daunting enough at the time to prohibit construction of such a machine.

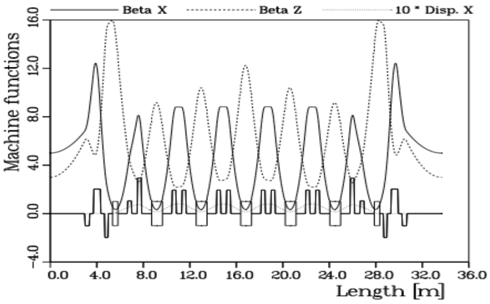

Figure 4: 7BA lattice [16].

Compact magnet and vacuum chamber technology for DLSRs has now been developed, primarily by MAX-Lab in Sweden, enabling construction of MAX-IV, the first 7BA light source [17]. MAX-IV will have a 2.6-cm diameter, primarily round copper vacuum chamber with shallow antechambers where needed to extract the X-ray beams (Fig. 5). To achieve sufficient vacuum pumping the chambers will be NEG-coated, using CERN technology already exploited in nearly 1/3 of the vacuum chambers at Soleil. NEG-coated chambers are now used routinely for small-gap insertion devices (IDs) in many light sources.

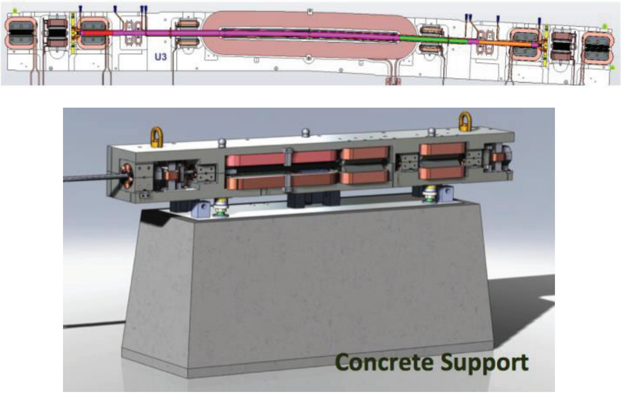

Figure 5: MAX-IV machined magnet block and vacuum chamber (top); a different style magnet block assembly on its concrete support (bottom).

MAX-IV magnets are machined from single blocks of iron, each containing a dipole and adjacent multipoles; the gradient dipole poles are machined directly from the block, while the highly precise multipole poles are machined separately and bolted in place, giving alignment precision on the order of 10 μm. The blocks are mounted on elevated concrete blocks, eliminating both support girders and individual magnet supports (Fig. 5). A magnet measurement system employing rotating coils, Hall probe sensors and precise alignment technology has been developed. The technology has been tested, first by constructing similar combined function magnets for the 700-MeV MAX-III ring in 2008, and then by testing the NEG-coated vacuum chamber system in one area in the 1.5-GeV MAX-II ring. Other DLSR designs use independent magnets having high alignment tolerances.

Accelerator physics methods and modeling tools for storage ring design have advanced appreciably over the last two decades, driven by the design of high-luminosity colliders, low-emittance damping rings, and enhanced light sources. Tools include symplectic tracking methods to accurately determine DA and MA, 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). These methods have been benchmarked on real machines with beam-based lattice calibration tools (e.g. LOCO [18]) and parameter measurement techniques.

Other relevant advances include: success of top-up injection in accommodating short beam lifetime; advances in electron and photon beam diagnostics, allowing precise characterization and correction of the ring, as well as stabilization of the beam to the sub-micron and sub-microradian level; development of fast high-voltage stripline kickers for the ILC effort, supporting on-axis injection with closely-spaced bunches; advances in electronics, from power supply stability to the speed of digital processors used for orbit feedback; development of highly stable solid state RF power sources; high performance undulator development (including superconducting); and coherence-preserving X-ray optics being developed for FELs.

DLSR Design Optimization

The optimization of parameters for any storage ring is a complex process that can only be briefly addressed here. In the case of DLSRs, the scientific community is likely to be a mixture of users seeking high brightness and coherence and those whose experiments are flux- rather than brightness-limited, leading to tension between reducing emittance and increasing stored current – an optimization that impacts facility cost since it is generally less expensive to increase current than it is to build an ultra-low emittance ring. As mentioned, it is possible to get high coherent flux with a high current, low coherent fraction ring. As seen in Fig. 2 there is a diminishing return in coherent fraction for decreasing emittance that must be weighed in the optimization.

Another consideration 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 brightness (within an order of magnitude) can be achieved with less expensive, lower energy, smaller circumference rings (e.g. 3-4 GeV) using harmonics from high performance 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. There is thus a trade-off between spectrum, emittance, circumference and cost.

A final comment on design optimization concerns the number, length and spacing of straight sections. 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. The spacing between straight sections, lattice bending radius, and thus the angle between adjacent photon beam lines, ultimately determines the length of X-ray beam lines 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 beam line alignment. In some cases this could lead to a hybrid lattice design for very large rings where beam line straight sections are consolidated in specific arcs having optimal spacing using one lattice type, while another minimal emittance lattice type is used elsewhere [19].

Table 1: Parameters for some low-emittance rings. (IC/IP/ID = in construction, planning, development; DW = damping wiggler.)

Facility	E(GeV) / I(A)	C (m)	ε_0 (pm)	Features
NSLS-II	3/0.5	792	600	DBA, DW, IC
MAX-IV	3/0.5	528	250	7BA, 100 MHz RF, IC
Sirius	3/0.5	518	280	5BA, superbend, IC
ESRF	6/0.2	844	150	7BA w/dispersion bumps, long. grad., IP
APS	6/0.2	1104	60	ESRF style, swap-out, IP
SPring-8	6/0.2	1436	280	QBA, ID
ALS	1.9/0.5	200	100	9BA, superbend insert, swap-out, IP
SLS	2.4/0.5	288	250	Pre-conceptual design
BAPS (Beijing)	5/0.2	1500	30-50	Pre-conceptual design
SLAC	6/0.2	2.2	10	7BA, 90m DW, conceptual design
TauUSR	9/0.2	6280	3	7BA, DW, pre-conceptual design

A summary of low emittance rings and future DLSRs being considered for the future is given in Table 1.

SUMMARY AND OUTLOOK

Storage ring light source technology has reached the stage where construction of a new generation of sub-nm-emittance rings is feasible. Machines having horizontal emittances as low as 0.25 nm-rad are now in construction, and several others having sub-100-pm emittances are in planning stages. Longer range plans 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 [12]. The longer range future for DLSRs might include enhanced capabilities, such as ring-based high repetition rate, low peak power FELs [20] and short bunch operation that offer beam properties complementary to linac-based FELs while serving a larger number of simultaneous users. The “MBA generation" is an exciting time for light source designers.

ACKNOWLEDGMENTS

The authors are grateful for the contributions from a large number of colleagues for the information in this paper, including R. Bartolini, Y.Cai, L. Emery, M. Eriksson, W. Guo, Z. Huang, S. Leeman, L. Lin, L. Nadolski, D. Robin, Q. Qing, P. Raimondi, C. Steier, A. Streun, H. Tanaka and many others.

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