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Abstract.

Developments such as the low emittance NSLS-II storage ring, followed by the even lower emittance MAX IV ring, indicate that the technology of storage ring light sources has not reached full maturity. Indeed, these new sources are paving the way toward realizing diffraction-limited angstrom-wavelength storage ring light sources in the not-too-distant future. In this paper, we survey ongoing work around the world to develop concepts and designs for so-called "ultimate" storage ring light sources. Several of these designs target horizontal emittances that are two or more orders of magnitude less than present machines, and thus brightness and coherent fraction that is several orders of magnitude better than existing storage ring light sources.

1. Introduction

X-ray brightness, perhaps the most important measure of synchrotron radiation source performance, is given by $B \propto N_\gamma/((\Delta\lambda/\lambda)\Delta t \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'})$, where N_γ is the number of photons in the central radiation cone per pulse; $(\Delta\lambda/\lambda)$ is the radiation bandwidth; Δt is the time-scale of interest; and Σ_x, $\Sigma_{x'}$, etc., are the transverse beam sizes and divergences of the photon beam in the x (horizontal) and y (vertical) planes, assuming for simplicity upright phase ellipses. The radiation distribution is given approximately by the convolution of the electron distribution with the single-electron radiation distribution, which for an undulator of length L is approximately described by an rms size $\sigma_{r'} \approx \sqrt{\lambda/(2L)}$ and rms divergence $\sigma_r \approx \sqrt{2\lambda L}/(2\pi)$ [1]. The minimum possible emittance is $\epsilon_r = \sigma_r \sigma_{r'} = \lambda$.

For upright Gaussian phase space distributions, we can add the electron and intrinsic photon distribution parameters in quadrature to obtain the total emittances $E_q = \Sigma_q \Sigma_{q'} = \sqrt{\sigma_q^2 + \sigma_r^2}\sqrt{\sigma_{q'}^2 + \sigma_{r'}^2}$, where σ_q and $\sigma_{q'}$ are the transverse rms size and divergence of the electron beam for plane q. Since σ_r, $\sigma_{r'}$, and the products $\epsilon_q = \sigma_q \sigma_{q'}$ are fixed, E_q is minimized (and B is maximized) when $\frac{\sigma_q}{\sigma_{q'}} = \frac{\sigma_r}{\sigma_{r'}} \approx \frac{L}{\pi}$, where the quantity on the left is the usual beta function. If $\epsilon_q < \lambda$, then B approaches the maximum possible value and the source is "diffraction-limited" in plane q.

Present-day rings deliver radiation from (typically) 100 eV to 100 keV, or $2pm \leq \lambda \leq 2nm$. Since typically ϵ_x is 3 to 5 nm, we see that typically $\epsilon_x \gg \lambda$. For a diffraction-limited source, we must have ϵ_x and ϵ_y of a few 10's of picometers or less. Such an "ultimate light source" would provide close to the best possible brightness for a given beam current.

## 2. Storage ring emittance and energy spread

It can be shown [2; 3] that the natural emittance is approximately given by

$$\epsilon_0 \approx F(\nu_x, \text{lattice}) \frac{E^2 \theta^3}{J_x} \frac{P_d}{P_d + P_w}, \tag{1}$$

where θ is the bending angle per dipole, ν_x is the horizontal phase advance per cell, J_x is the horizontal damping partition number [4], and P_d (P_w) is the power emitted in dipoles (wigglers). The fractional energy spread σ_δ scales weakly, like $\theta^{\frac{1}{2}}$, but can be adversely impacted by damping wigglers.

For a fixed cell design and length, $F(\nu_x, \text{lattice})/J_x$ will be approximately constant, giving $\epsilon_0 \sim 1/C^3$, where $C \propto 1/\theta$ is the circumference. To reduce ϵ_0, one can adopt the usual double-bend [5] cells used for third-generation sources, but create a large ring with many such cells. This is the approach taken by NSLS-II [6], which for a 3-GeV ring has a large circumference of 792 m, giving $\epsilon_0 = 2$ nm.

However, if we break the dipoles into shorter magnets separated by focusing elements, we reduce θ while allowing optimization of F. This "multi-bend achromat" (MBA) concept, first proposed by Einfeld *et al.* [7], is the key to much lower emittance and a more compact ring. This is the approach taken by the MAX IV project [8], a 3-GeV, 528-m circumference ring with $\epsilon_0 = 0.33$ nm. Compared to NSLS-II, the emittance is much smaller in spite of the significantly smaller circumference. Although ϵ_0 is significantly lower than present-day machines, this is not yet an ultimate light source. However, a 7-bend achromatic cell similar to MAX IV, shown in Figure 1, can achieve $\epsilon_0 = 11$ pm at 3 GeV with $C = 1.7$ km. This is smaller than PETRA III [9], the largest present-day light source.
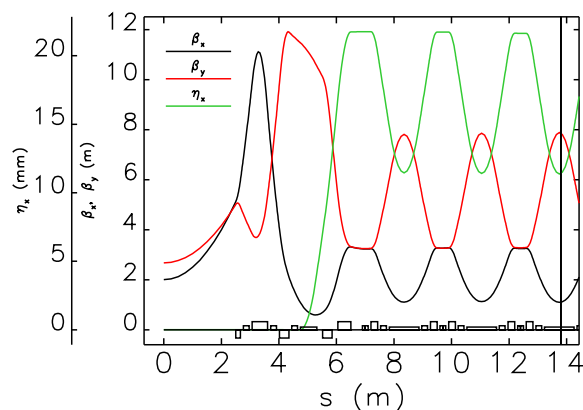
Figure 1. Example of a compact MBA lattice cell for an ultimate storage ring. The vertical line shows the reflection symmetry point of the cell, which has seven dipoles with defocusing gradients. The natural emittance for a 62-cell, 1.7-km circumference ring would be 11 pm at 3 GeV, with an energy spread of 0.05%.

As noted, the emittance can be further reduced by the use of damping wigglers, provided that the power emitted into dipoles is relatively low. Both NSLS-II and MAX IV will use damping wigglers to gain a two-to-four-fold reduction in emittance. Damping wigglers must be used judiciously, since they increase the energy spread, which tends to reduce the brightness of high undulator harmonics.

3. Challenges of low emittance

There are significant challenges in pushing ring performance to ultra-low emittance. In this brief section, we can only touch upon the most important topics, which are covered in more detail elsewhere [10].

One issue is the difficulty of obtaining sufficient dynamic acceptance (DA) for efficient beam injection. The average dispersion scales like θ, implying that the strength of the chromaticity-correcting sextupoles scales like $1/\theta$. This implies that the dynamic aperture will decrease like θ.

Second-order chromaticities increase like $1/\theta$, potentially leading to reduced momentum acceptance (MA) and increased loss rates for Touschek scattered particles. Further, low emittance nominally implies greater particle density and thus a higher scattering rate. However, for very low emittance, the lack of sufficient energy to create large momentum transfer reduces the severity of this issue, as is expected to be evident in MAX IV.

In the early third-generation light sources, "geometric" (non-chromatic) sextupoles were used to correct aberrations from strong chromatic sextupoles [11]. Subsequently, a more general method [12] based on minimization of resonance driving terms (RDTs) was adopted, leading to a gradual increase

in the complexity and sophistication of sextupole schemes. More recently, as computational capabilities have increased, direct methods—i.e., methods based on particle tracking—have emerged [13–17].

Intrabeam scattering (IBS) [18]—multiple electron-electron scattering within a bunch—is another phenomenon that manifests in low-emittance rings, resulting in growth of the emittance and energy spread. The phenomenon worsens with higher beam density (i.e., low emittance) and lower energy. Hence, it acts to counter the beneficial scaling of Eq. (1), often to a significant degree.

Both IBS and Touschek scattering can be mitigated by increasing the bunch volume, e.g., using bunch-lengthening cavities. One can also run with $\epsilon_y = \epsilon_x = \epsilon_0/2$ [19; 20], which does not harm brightness when $\epsilon_0 \lessgtr \lambda$. While this requires the use of on-axis injection, this is not challenging [21]. Since on-axis injection eases the requirement for large DA, we can push the lattice to yet smaller emittance.

For longitudinal dynamics, we find that the synchrotron tune scales like θ, the bunch length scales like $\sqrt{\theta}$, and the synchrotron damping times scale like θ. These all imply reduced collective instability thresholds, again motivating lengthening of the bunch.

4. Next-generation ring designs
Next, we review the history of efforts to create an ultimate storage ring design. Referring to Eq. (1), we note that for a fixed cell design $\epsilon_0 \propto ME^2/C^3$, implying that the quantity $M = \epsilon_0 C^3/E^2$ is a figure of merit for how well optimized the emittance is. This is listed with other design parameters in Table 1.

As noted above, in 1995 Einfeld *et al.* proposed the use of an MBA design for a compact, high-brightness light source. At that time, the impetus for extremely low emittance did not exist since the challenge from ultra-low emittance Energy Recovery Linac (ERL) concepts [22] had yet to surface. This was followed in 2000 by Ropert *et al.* [23], who proposed a large, 7-GeV, 4BA design running 500 mA. Although a 100-fold increase in brightness was predicted, the 300-pm emittance was not competitive with ERL proposals and the high current presented significant difficulty in terms of x-ray power handling.

In 2005, Borland [24] described a 7-GeV, 6BA ring based with $\epsilon_0 = 78$ pm, intended as a "drop-in" replacement for the APS. Although it began to challenge ERL concepts on emittance, the design did not demonstrate workable nonlinear dynamics and required impractical magnet technology. It did re-emphasize earlier ideas [19; 20] for mitigating issues with small DA and lifetime.

In 2006, Tsumaki and Kumagai [25] described a 6-GeV, 10BA, 2-km ring with an emittance of 21 pm in both planes at 100 mA. They exhibited adequate DA for beam accumulation and sufficient momentum aperture for a several-hour Touschek lifetime. Magnet strengths were consistent with conventional designs with a 20-mm bore radius. Because of its large beta functions ($\beta_x = 25$ m and $\beta_y = 5$ m) and somewhat short (∼4-m-long) straight sections, the design didn't fully exploit the low emittance.

In 2009, Borland [21] described a 10BA, 7-GeV, 200-mA design with a circumference of 3.1 km and emittances of 16 pm in both planes, with practical magnet parameters. The DA and MA were consistent with on-axis injection and a Touschek lifetime of 4 hours. It was asserted that since the dynamic aperture of ±2 mm was more than needed for lifetime or injection, the lattice could be pushed to even lower emittance. The straight sections were able to accommodate 8-m-long insertion devices and had beta functions ∼7 m, giving improved if not optimal exploitation of the emittance.

A group at SLAC has performed extensive studies of PEP-X, a 4.5-GeV ring in the 2.2-km PEP tunnel. In 2011 [26], this team described an $\epsilon_0 = 24$ pm source with a similar structure to MAX IV, but with additional quadrupoles flanking the straight sections to increase flexibility. The design uses combined-function quadrupole-sextupole magnets, which was considered for MAX IV but dropped. A new nonlinear dynamics analysis [27] indicated that particular choices of the phase advance per cell could be used to cancel many of the geometric and chromatic resonance driving terms within a single arc. The result is a robust design [28] with considerable DA (±5 mm) and a lifetime of about 4 hours, assuming operation with full coupling. An initial multi-objective direct optimization of the nonlinear dynamics was successful in increasing both quantities, but it is as yet unclear how the optimizer achieved these improvements.

In 2011, Jing *et al.* published [30] a design study for a 2.7-km, 11BA ring with $\epsilon_0 = 9$ pm and 10

Table 1. Summary of various present and next-generation storage ring light source designs, without intrabeam scattering. $M = \epsilon_0 C^3 / E^2$ is given in units of pm km^3/GeV^2

Name	Energy GeV	Structure	C km	ϵ_0 pm	M	σ_δ %	Comments
ESRF	6	2-BA×32	0.845	4000	67	0.11	In operation
APS	7	2-BA×40	1.1	3100	84	0.096	In operation
PETRA III[9]	6	FODO/2-BA	2.3	1000	338	0.1	In operation
DIFL[7]	3	7-BA×12	0.4	500	3.6	0.08	
NSLS-II[6]	3	2-BA×30	0.792	500	28	0.099	Eight wigglers
MAX IV[8]	3	7-BA×20	0.528	263	4.3	0.096	Four wigglers
USRLS[23]	7	4-BA×50	2.0	300	49	?	No nonlin. optim.
XPS7[24]	7	6-BA×40	1.1	78	2.1	0.176	Poor nonlin. dyn.
Tsumaki 2006[25]	6	10-BA×32	2.0	35	7.8	0.089	Accumulation possible
USR7[21]	7	10-BA×40	3.16	30	19	0.079	On-axis injection
PEP-X ultimate[29]	4.5	7-BA×48	2.2	24	12	0.13	
IU ring[30]	5	10-BA×40	2.66	9.1	6.9	0.038	
τUSR[31]	9	7-BA×180	6.21	2.9	8.6	0.096	~Size of Tevatron
SPring-8 II[32]	6	6-BA×48	1.4	67	5.1	0.096	Replaces SPring-8

m straight sections. As in Einfeld *et al.*, MAX IV, PEP-X, and others, the interior dipoles of the MBA have a defocusing gradient, obviating the need for separate defocusing quadrupoles. The DA is about ±1 mm, adequate for on-axis injection, while the MA was about ±1.5%. With intrabeam scattering and full coupling, the emittance in both planes is 10-20 pm, depending on the assumed peak current, with a minimum at around 7 GeV. A 25BA variant with smaller circumference was also developed.

In 2011, Borland [31; 33] began development of a very large ($C \approx 6.28$ km) design. The impetus for this particular circumference is that it corresponds to that of the Tevatron, which is being decommissioned. The design uses optics modules from the PEP-X group and roughly matches the Tevatron tunnel's geometry, achieving emittances under 4 pm in both planes at 9 GeV with 200 mA in 8300 bunches. The phase advance was relaxed from the PEP-X design to improve the nonlinear dynamics at a slight cost in emittance, giving a preliminary DA of about ±0.7 mm with a ±1.5% MA. The DA is large enough for on-axis injection, but small enough to give a gas scattering lifetime that is shorter than the Touschek lifetime. The total predicted lifetime is about 3 hours. The lifetime as well as instability thresholds are improved by the fact that the bunch lengthens considerably due to potential well distortion. Brightness curves for this design are shown in Figure 2.

In early 2012, Ishikawa *et al.* published [32] a preliminary upgrade plan for SPring-8 that would preserve all of the existing beamlines. The plan uses a 6BA cell with gradient-free dipoles, achieving $\epsilon_0 = 67$ pm. It is anticipated that this can be reduced below 20 pm using damping wigglers and more aggressive tuning. The phase advance between chromatic sextupoles is approximately π, resulting in partial cancellation of nonlinear effects. The dynamic aperture is greater than ±3 mm, which may be adequate for off-axis injection using the beam from the SPring-8 Free Electron Laser linac. However, off-axis injection will also be possible to allow flexibility and further upgrades. Installation of the new ring is proposed for a one-year shutdown in 2019.

From Table 1, we see that for the more robust designs, M is between 3 and 20. MAX IV is near the bottom of this range and will thus serve as a valuable test case for next-generation sources. Indeed, with its rather low value of M, it may be more difficult than some of the presumably speculative designs described above.
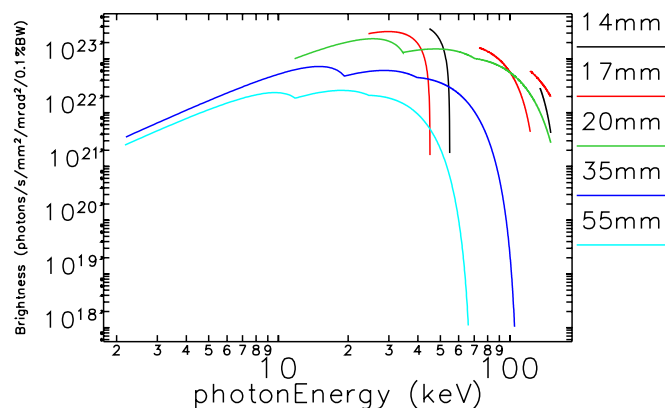
Figure 2. Curves of brightness in ph/s/mm^2/mrad^2/0.1%BW for τUSR [31], a 6.21-km circumference, 9 GeV, 200 mA, ultimate storage ring light source. The legend shows the undulator period, where we have assumed the use of NbTi-based superconducting undulators [34].

5. R&D Needs

Although there is a developing consensus that ultimate storage rings are possible, R&D wil be beneficial [10]. Topics for investigation include: global optimization of x-ray brightness and spectral reach by choice of circumference, number of cells, beam energy, and so on; methods for achieving round beams and their impact on beam dynamics; choice of rf frequency and bunch pattern to control IBS and instabilities; development of advanced undulators to help lower the beam energy without impacting spectral reach; analysis and mitigation of insertion device and damping wiggler effects; cost-effective magnet designs for compact machines with many elements; analysis of instabilities and requirements for vacuum chamber impedance; development of fast kickers geared toward requirements of swap-out injection; exploration of optimal commissioning strategies, including possible relaxed commissioning lattices that might expedite beam-based alignment and optics correction; and development of high-quality x-ray optics to take full advantage of ultra-low emittance.

While some of these issues are or will be explored in MAX IV and other projects, tests at existing facilities can be worthwhile. For example: benchmarking of lattice design codes, particularly the effectiveness of direct optimization methods, is essential; running with very low vertical emittance gives information on beam stability requirements and x-ray optics quality issues; techniques for running with round beams can be tested even in present-day facilities; performing on-axis injection with deliberately low DA will give insight into the practicality of this operations method; predictions for IBS [35] and other collective effects can be tested to validate codes, ideally in regimes not normally used for machine operations.

6. Conclusion

After a summary of the physics and challenges of creating diffraction-limited storage ring light sources, we reviewed the chronology of developments in this field starting from 1995. A significant change has occurred in the last few years, with increasing acceptance of the idea that rings with emittances of 10 to 100 pm are practical. This new attitude results from improved understanding and methods of tuning nonlinear dynamics, but also from improvements in our ability to build and operate storage rings that match design models. Different ideas for machine operation, such as round beams and on-axis injection, are also influencing the degree to which ring designers can optimize for ultra-low emittance.

Acknowledgments

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