PROGRESS TOWARDS ULTIMATE STORAGE RING LIGHT SOURCES *

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Abstract

Developments such as the low emittance NSLS-II storage ring, followed by the even lower emittance MAX IV ring, demonstrate 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. Our discussion begins with a review of recent trends and developments in storage ring design. We then survey on-going work around the world to develop concepts and designs for so-called "ultimate" storage ring light sources.

INTRODUCTION

X-ray brightness is one of the most important measures of synchrotron radiation source performance. Assuming upgright phase ellipses, the brightness B is

$$B \propto \frac{N_\gamma}{(\Delta\lambda/\lambda)\Delta t \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}, \tag{1}$$

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. The radiation distribution can be approximated as a convolution of the electron distribution with the single-electron radiation distribution. For an undulator of length L, the latter is approximately described by a radiation source at the center of the undulator with rms size and divergence given by [1]

$$\sigma_{r'} \approx \sqrt{\tfrac{\lambda}{2L}} \qquad \sigma_r \approx \tfrac{1}{2\pi}\sqrt{2\lambda L}. \tag{2}$$

The product $\sigma_r \sigma_{r'} = \lambda\!\!\!^{-} = \lambda/(2\pi)$ sets the minimum possible emittance, which is achieved in the limit of zero electron beam emittance.

Continuing with our simplifying assumptions, the convolution of the electron beam phase space and the single-electron radiation distribution is

$$E_q = \Sigma_q \Sigma_{q'} = \sqrt{\sigma_q^2 + \sigma_r^2}\sqrt{\sigma_{q'}^2 + \sigma_{r'}^2}, \tag{3}$$

where σ_q and $\sigma_{q'}$ are the transverse rms size and divergence of the electron beam for plane q. A similar equation holds for the vertical plane. To maximize the brightness, we must minimize the total emittances E_x and E_y. Given that σ_r, $\sigma_{r'}$, and the products $\epsilon_q = \sigma_q \sigma_{q'}$ are fixed, the minimum value for E_q is obtained when we have

$$\frac{\sigma_q}{\sigma_{q'}} = \frac{\sigma_r}{\sigma_{r'}} \approx \frac{L}{\pi}, \tag{4}$$

where the quantity on the left is the usual beta function. When Eq. (4) is satisfied, we maximize the brightness for a given electron beam emittance ϵ_q. If, in addition, $\epsilon_q < \lambda\!\!\!^{-}$, then the brightness is not much diluted by the electron beam transverse phase space, and the source is referred to as "diffraction-limited" in plane q. If $\epsilon_q \ll \lambda\!\!\!^{-}$, one will still obtain diffraction-limited performance even if Eq. (4) is not satisfied.

Today's sources deliver radiation from 100 eV to 100 keV, corresponding to $\lambda\!\!\!^{-}$ from 2 nm to 2 pm, which is generally small compared to typical horizontal emittances of 3-5 nm. However, typical vertical emittance is a few 10's of pm, so today's sources are diffraction-limited in the vertical plane for a few keV and below. To make a fully diffraction-limited source, we must reduce both emittances to a few 10's of picometers or less. Such a source would qualify as an "ultimate light source," as it would provide the best possible brightness for a given beam current.

The electron beam fractional energy spread σ_δ also impacts the brightness, given that $\lambda \propto 1/(h\gamma^2)$, where h is the radiation harmonic, λ_u is the undulator period, and γ is the relativistic factor for the electron beam. The contribution of the electron energy spread to the bandwidth is $(\sigma_{\Delta\lambda})_e = 2\sigma_\delta\lambda$. For an N_u-period undulator, the intrinsic line width is [2] $(\sigma_{\Delta\lambda})_i \approx \frac{0.4\lambda}{hN_u}$. These two contributions add in quadrature, so we need $hN_u\sigma_\delta \leq 0.1$ to avoid diluting the brightness. However, typically, $N_u \sim 100$ and $\sigma_\delta \sim 10^{-3}$, meaning that this requirement is usually satisfied only for $h = 1$.

EMITTANCE AND ENERGY SPREAD

The equilibrium energy spread and emittance result from the balance between quantum excitation (QE) and radiation damping (RD) [3]. QE results the from random nature of photon emission in magnetic fields and their dispersive properties on particle trajectories. RD occurs because the energy loss per turn increases with increasing energy and because the momentum carried away by emitted photons is very nearly co-linear with the momentum of the electron, whereas the momentum restored by the rf cavities is in the forward direction only.

The equilibrium fractional energy variance and emittance can be expressed respectively as [4]

$$\sigma_\delta^2 = C_q\gamma^2\tfrac{I_3}{2I_2+I_4} \qquad \epsilon_0 = C_q\gamma^2\tfrac{I_5}{I_2-I_4}, \tag{5}$$

where I_i are radiation integrals, given by

$$\begin{array}{lll} I_1 = \int \frac{\eta}{\rho} ds & \text{variation of path-length w/energy} & \\ I_2 = \int \frac{1}{\rho^2} ds & \text{normalized energy loss per turn} & (6) \\ I_3 = \int \frac{1}{|\rho^3|} ds & \text{normalized QE rate for } \sigma_\delta^2 & \end{array}$$

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$$\begin{array}{lll} I_4 = \int \frac{\eta}{\rho^2}(1-2n)ds & \text{damping partition effect} \\ I_5 = \int \frac{\mathcal{H}}{\rho^3}ds & \text{normalized QE rate for } \epsilon_0, \end{array} \qquad (7)$$

where $\mathcal{H} = \beta_x \eta_x'^2 + 2\alpha_x \eta_x \eta_x' + \frac{1+\alpha_x^2}{\beta_x}\eta_x^2$, ρ is the bending radius, and $C_q = 3.84\times10^{-13}m$. β_x, α_x, η_x, and $\eta_x' = d\eta_x/ds$ are the familiar lattice functions. If η_x and η_x' are small inside the dipole magnets, then $\mathcal{H}$ will be small, leading to smaller emittance.

More thorough calculations (e.g., [5] and [6]) show that

$$\epsilon_0 \approx F(\nu_x, \text{lattice})\frac{E^2\theta^3}{J_x}\frac{I_{2,d}}{I_{2,d}+I_{2,w}}, \qquad (8)$$

where θ is the bending angle per dipole, $J_x = 1 - I_4/I_2$, and ν_x is the horizontal phase advance per cell, which measures the strength of the focusing. $I_{2,d}$ and $I_{2,w}$ are respectively the contributions to I_2 (energy loss per turn) from the dipoles and any wigglers or undulators in the ring. (We've ignored the contribution of wigglers and undulators to I_5.)

In order to produce very low emittance, we win quickly if we build a storage ring with a large number of dipoles N_d, since $\theta \propto 1/N_d$. More precisely, we benefit by breaking up the dipoles into small units separated by focusing elements to miminize $\mathcal{H}$. We may also benefit from adding "damping wigglers" to cause the beam to emit more energy without experiencing significant quantum excitation of the emittance. However, as mentioned above, the energy spread also enters into the brightness, so we must be aware that damping wigglers always increase the energy spread.

Equation (8) suggests a figure-of-merit for comparing lattice designs. For a fixed cell design and length, $F(\nu_x, \text{lattice})/Jx$ will be approximately constant. In addition, $\theta \propto 1/C$, where C is the circumference. Hence, $M = \epsilon_0 C^3/E^2$ is approximately constant for machines of various energies and circumferences with similar linear optics. We will use M below to assess the degree to which various designs have optimized emittance, but should keep in mind that other factors, e.g,. the beta functions in the straights and the energy spread, also impact x-ray brightness.

CHALLENGES OF LOW EMITTANCE

So far, we've only discussed the simplest aspect of low emittance, namely, the linear optics. In reality, there are much more difficult problems that must be faced.

Suppose we simply decrease the bending angle per dipole θ to take advantage of the $\epsilon_0 \propto \theta^3$ scaling. The average dispersion will scale like θ and thus the strength m of the chromaticity-correcting sextupoles must scale like $1/\theta$. In the horizontal plane ($y = 0$) the harmonic equation of motion with a quadratic sextupole driving term is

$$x'' + k^2 x = -\frac{1}{2}mx^2. \qquad (9)$$

Substituting $m \to m/\theta$ and $x \to Ax$ gives $A = \theta$. Thus, the dynamic aperture (the stable region for particle motion) will decrease like θ, indicating one difficulty of creating an extremely low-emittance storage ring. With small dynamic aperture, we may have difficulty with injection and even with the gas-scattering lifetime. In addition, the second-order chromaticities $d^2\nu_{x,y}/d\delta^2$ increase like $1/\theta$, leading to greater difficulty in obtaining sufficient momentum aperture, which negatively impacts the Touschek lifetime.

The emittance depends not only on θ, but on the type of lattice and the tune. Most operating light sources use a variant of the Chasman-Green (CG) lattice [7], in which there are two dipole magnets and one undulator straight section per periodic cell. A factor of three improvement over the CG lattice is possible [8] with proper tuning of the dispersion and beta functions in the dipoles, an arrangement known as a theoretical minimum emittance (TME) cell. In general, the best emittance is typically achieved by making the beta function and dispersion small at the center of the dipole. This requires strong focusing between the dipoles, leading to strong sextupoles in order to correct the chromatic effects, which again tends to reduce the dynamic and momentum apertures.

These issues surfaced even for the early third-generation light sources, leading to addition of "geometric" sextupoles to correct the aberrations introduced by the chromatic sextupoles. Early work [9] used two families of sextupoles to reduce the amplitude-dependent tune shifts. Subsequently, a more general method [10] 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 [11, 12, 13, 14, 15]. However, RDT minimization is the most popular approach.

Touschek scattering—hard electron-electron scattering events that impart signficant longitudinal momentum changes—is a significant issue for low-emittance rings. The problem is two-fold: first, low-emittance rings tend to have reduced momentum acceptance, leading to a higher rate of loss for Touschek scattered particles. Second, low-emittance rings have greater particle density, leading to a higher rate of scattering events. At some point, as the emittance shrinks, the beam becomes sufficiently cold that there is insufficient energy in the transverse motion to produce large disturbances to the longitudinal momentum from a scattering event. When this point is passed, the lifetime depends only weakly on emittance and eventually begins to increase, a phenomenon that is expected to manifest itself in NSLS-II [16] and next-generation designs.

Intrabeam scattering [17]—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 worses with higher beam density (i.e., low emittance) and lower energy. Hence, it acts to counter the beneficial $\epsilon \propto E^2$ dependence we highlighted above, often to a significant degree in near-future (e.g., MAX IV [18]) and next-generation designs.

For longitudinal dynamics, we find the momentum compaction $\alpha_c \propto \theta^2$, while the energy loss per turn scales like θ. Hence, to maintain constant rf bucket height, the rf voltage is required to scale like θ, assuming a fixed rf frequency. Under this assumption, the synchrotron tune scales like θ, while the bunch length scales like $\sqrt{\theta}$, both of which imply reduced thresholds for collective instabilities. Use of bunch-lengthening cavities (as in NSLS-II) or low-frequency rf (as in MAX IV) may be helpful. Indeed, there is some recent indication that natural bunch-lengthening due to potential well distortion alone can help reverse expected trends in intrabeam scattering and instability thresholds [19].

It is hoped that this brief survey will give the reader an appreciation of the complexities of low-emittance light source design and optimization.

TRENDS IN LIGHT SOURCE DESIGN

In 2000, Ropert *et al.* described [20] a large, 500-mA, 7-GeV "ultimate storage ring light source" using four-bend achromatic cells, achieving $\epsilon_0 = 0.3$ nm, much smaller than the 3-5 nm operational values of that time. However, proposed sources based on energy-recovery-linacs (ERLs) promised much smaller emittances in both planes [21]. This, combined with the relatively static values for operational emittances, gave rise to the widespread impression that storage ring light sources lacked a practical path toward significantly higher brightness.

A few years later, work began to convert the PETRA high energy physics ring to a 6-GeV, 1-nm light source, known as PETRA III [22]. The concept used most of the existing components but added 80 m of damping wigglers and a special arc of double-bend cells for accommodating insertion devices. Because of the large circumference (2.3 km) and moderate beam energy, the dipoles are very weak. Hence, the damping wigglers have a dramatic effect, reducing the equilibrium emittance by a factor of 4.5. PETRA III has been in operation for several years with 1-nm horizontal emittance and ~ 10-pm vertical emittance.

The NSLS-II x-ray source, now under construction, shares two important features with PETRA III: first, it has a large circumference (792 m) for the beam energy (3 GeV), resulting in a bare lattice emittance of 2 nm. Second, because of the resulting weak dipoles, damping wigglers are very effective, giving $\epsilon_0 = 0.5$ nm with eight damping wigglers. The NSLS-II lattice is a double-bend achromat with alternating long and short straight sections (30 in total). The beta functions in the 6.6-m-long short straights ($\beta_x = 2.0$ m and $\beta_y = 1.1$ m) are close to the ideal L_u/π values for maximum brightness. (PETRA III takes a very similar approach.) Nonlinear dynamics optimization used both RDT minimization and direct methods.

A very different concept, the use of a multi-bend achromatic (MBA) cell, appears to have been proposed first by Einfeld *et al.* [23]. This scheme capitalizes in part on the $\epsilon_0 \propto \theta^3$ scaling described above, which neither PETRA III nor NSLS-II have done. Einfeld *et al.* used a TME-like cell, with matching cells to provide zero dispersion in the straight sections. They also proposed using defocusing gradients in the dipoles, which provides increased J_x while obviating the need for separate defocusing quadrupoles. The result was a 3-GeV storage ring design with 12 7-bend achromats, giving $\epsilon_0 = 0.5$ nm with a remarkably compact 400-m circumference.

The MAX IV project, now under construction, uses a very similar approach, deliberately relaxing the optics away from the TME condition in order to improve robustness. The lattice uses 20 cells with five full-length and two half-length dipoles per cell to achieve $\epsilon_0 = 0.33$ nm at 3 GeV with a compact 528-m circumference. This value increases to 0.45 nm because of intra-beam scattering. The addition of four damping wigglers and ten in-vacuum insertion devices is expected to reduce the emittance to 0.25 nm. MAX IV also uses innovative construction techniques that allow closely spaced magnets and hence a compact system while alleviating alignment issues that can significantly impact real-world performance. Nonlinear dynamics optimization used RDT minimization.

To end this section, we mention another trend in high-brightness sources, namely, the provision of very low vertical emittance (see, e.g., [24]). Reducing the vertical emittance to a few pm is clearly easier than dramatically reducing the horizontal emittance, and is thus an attractive way to improve the computed brightness of an existing ring. However, in most applications, the benefit of very low vertical emittance is negligible, whereas the same calculated brightness would be much more useful if delivered by reduction of the horizontal emittance. The reason is that the quality of beamline optics is often not sufficient to transmit a very small vertical emittance without dilution. While this may change as component quality increases, we are near—perhaps beyond—the limit of what can be gained by improving vertical emittance.

NEXT-GENERATION RING DESIGNS

It is clear that the once-popular notion that storage ring light sources have reached the end of their development is not entirely tenable. However, one issue raised by proponents of ERLs has not been addressed by any of the ring projects described above. In particular, in a linac-based light source, the horizontal and vertical emittances are approximately equal and potentially as small as the *vertical* emittance provided by present-day storage rings [21]. In this section, we review the history of efforts to create a storage ring design that addresses this challenge. Table 1 summarizes the parameters of the designs.

In 2005, Borland [25] described a 7-GeV ring based on a six-bend achromatic cell with $\epsilon_0 = 78$ pm, intended as a "drop-in" replacement for the APS. The design required very strong combined-function quadrupole-sextupole magnets and did not demonstrate workable nonlinear dynamics. However, several interesting concepts were promoted [26]. First, it was proposed that the dynamic aperture need not be larger than required for on-axis injection in "swap-out" mode, wherein electron bunches are periodically replaced

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	Date	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[22]	2004	6	FODO/2-BA	2.3	1000	338	0.1	In operation
DIFL[23]	1995	3	7-BA×12	0.4	500	3.6	0.08	
NSLS II[16]	2006	3	2-BA×30	0.792	500	28	0.099	Eight wigglers
MAX IV[18]	2006	3	7-BA×20	0.528	263	4.3	0.096	Four wigglers
USRLS[20]	2000	7	4-BA×50	2.0	300	49	?	No nonlinear optimization
XPS7[25]	2005	7	6-BA×40	1.1	78	2.1	0.176	Poor nonlinear dynamics
Tsumaki 2006[28]	2006	6	10-BA×32	2.0	35	7.8	0.089	Accumulation possible
USR7[29]	2009	7	10-BA×40	3.16	30	19	0.079	On-axis injection
PEP-X ultimate[31]	2011	4.5	7-BA×48	2.2	24	12	0.13	
IU ring[34]	2011	5	10-BA×40	2.66	9.1	6.9	0.038	
τUSR[35]	2011	9	7-BA×180	6.21	2.9	8.6	0.096	~size of Tevatron
SPring-8 II[36]	2012	6	6-BA×48	1.4	67	5.1	0.096	replaces SPring-8

rather than topped-up. Second, the idea of operating with fully coupled beams was invoked in order to reduce the effects of intrabeam scattering and lengthen the Touschek lifetime. (This concept was used by the first dedicated synchrotron radiation source, TANTALUS [27].) This provided $\epsilon \approx 40$ pm in both planes, with brightness comparable to contemporaneous ERL proposals.

In 2006, Tsumaki and Kumagai [28] described a 6-GeV, 2-km ring based on 10-bend achromatic cells, achieving an emittance of 21 pm in both planes at 100 mA. The nonlinear dynamics tuning was successful, resulting in a dynamic aperture that appears adequate for beam accumulation and sufficient momentum aperture for a Touschek lifetime of several hours. Comparison with [25] invites the conclusion that a circumference of ~1 km is insufficient for a such a source. Magnet strengths were evaluated and found to be consistent with conventional designs with a bore radius of 20 mm. Although a significant advance, the design didn't fully take advantage of the low emittance due to having large beta functions ($\beta_x = 25$ m and $\beta_y = 5$ m) in somewhat short (~4-m-long) straight sections,

In 2009, Borland [29] described a 10-BA, 7-GeV, 200-mA design with a circumference of 3.1 km and emittances of 16 pm in both planes, with practical magnet parameters and straight sections able to accommodate 8-m-long insertion devices. The dynamic and momentum acceptances were consistent with on-axis injection and a Touschek lifetime of 4 hours. Use of damping wigglers was considered, but found to provide a negligible improvement in brightness. 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-section beta functions were ~7 m, giving improved if not optimal exploitation of the emittance.

In 2010, Bane *et al.* published [30] extensive studies of PEP-X, a 4.5-GeV ring in the 2.2-km PEP tunnel at SLAC. Using a concept somewhat similar to PETRA III, this design used two DBA-cell arcs to accommodate insertion devices, four TME-cell arcs, and damping wigglers to achieve $\epsilon_0 = 86$ pm with off-axis injection. To increase brightness to levels competitive with proposed ERLs, a beam current of 1.5 A was assumed, but intrabeam scattering increased the emittance to 164 pm and the predicted Touschek lifetime was under one hour. More recently [31], this team shifted development to a diffraction-limited source similar to MAX IV, but with additional quadrupoles flanking the straight sections to allow more flexible tuning. Adopting a feature that was considered for MAX IV but dropped, this design uses combined-function quadrupole-sextupole magnets. A new nonlinear dynamics analysis [32] 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 [33] with considerable dynamic aperture (±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 [34] a design study for a ring with $\epsilon_0 = 9$ pm, using an 11-bend cell with 10 m straight sections. As in MAX-IV and PEP-X, the TME-like central cells have a defocusing gradient in the dipole and no separate defocusing quadrupoles. The dynamic aperture is about ±1 mm, with a momentum aperture of 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 more compact design with fewer straight sections and 25-bend cells was also explored.

In 2011, following announcement of the decommissioning of the Tevatron, Borland [35, 19] began development of a very large ($C \approx 6.28$ km) design. Using optics modules from the PEP-X design and roughly fitting the geometry of the Tevatron tunnel, this design projects an emittance of under 4 pm in both planes at 9 GeV with a stored current of 200 mA. The cell optics is relaxed from the PEP-X design to reduce the difficulty of nonlinear dynamics tuning. Preliminary tuning provides a dynamic aperture of about ±0.7 mm and a momentum acceptance of ±1.5%. The dynamic aperture is large enough for on-axis injection, but small enough to significantly impact the gas scattering lifetime, which dominates the Touschek lifetime, giving a predicted lifetime of about 3 hours.

Early in 2012, Ishikawa and co-workers published [36] a preliminary plan for an upgrade of SPring-8. At present, the plan incorporates a six-bend achromat with separate quadrupoles and $\epsilon_0 = 67$ pm, with plans to reduce the emittance to below 20 pm using damping wigglers. The phase advance between sextupoles is arrange to be nearly π, resulting in partial cancellation of nonlinear effects. The dynamic aperture is greater than ±3 mm, resulting in consideration of fast kickers with both dipole and quadrupole modes, to allow either off-axis or on-axis injection into a single bucket without disturbing other buckets. The hope is to install the new ring during a one-year shutdown of SPring-8 in 2019.

Looking at the values of M in Table 1, we note that the range of values for the more robust designs is between 3 and 20. MAX IV falls near the bottom of this range and may thus legitimately be considered a prototype for these next-generation sources. In particular, with a relatively low value of M, it has in some sense been pushed harder than several of the "next generation" designs described above.

CONCLUSION

We've reviewed the basic physics and recent history of high-brightness storage-ring-based synchrotron radiation sources, including the challenges inherent in raising the brightness significantly above present levels. Recent years have see a convergence on the idea of using multi-bend achromatic cells, coupled with sophisticated sextupole correction schemes developed using resonant driving term minimization or direct tracking-based optimization. The MAX IV light source, now in construction, is in the same class as these designs, and will provide valuable information on their feasibility. The emphasis of the new generation of sources is provision of diffraction-limited radiation over an extended range of photon energies, which can only be achieved by reducing the emittance to the level of 10's of pm. Several designs indicate that this goal is within the realm of possibility, although it seems clear that a multi-kilometer circumference will be required. It will be important to develop cost-saving strategies for production of large numbers of magnets with the required precision assembly, something which is also addressed in the MAX IV design.

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