Title

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Lattices for Low-Emittance Light Sources

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Third generation light sources have been highly productive, enabling diverse experiments in physics, chemistry, biology as well as technology applications, since the first ones went into operation around 1992. More recently, with MAX-IV and ESRF-EBS being the first two examples, fourth generation rings have come online with even lower beam emittances. Both generations are based on lepton storage rings, in most cases using electron beams. The fundamental properties of these facilities are high beam currents (≥ 100 mA), small emittances (≤ 10 nm for third and ≤ 250 pm for fourth generation rings), moderate beam energy spreads ($\leq 10^{-3}$) and the use of insertion devices-mostly undulators-in long (≈ 5 m) straight sections to produce high brightness (Sec.?.?) photon beams. For third generation rings, there were two main lattice types that were optimized to meet these requirements: the double bend achromat (DBA [1]), first used in the NSLS at BNL, and the triple bend achromat (TBA [2]), first developed for the ALS at LBNL. Later on, facilities evolved further by detuning the achromat lattices to allow dispersion leakage into the straight sections [3]. Newer light sources also use multi bend achromats [4], which is the enabling technology for fourth generation rings, and in some cases damping wigglers to reduce the emittance further.

Lattice choices Traditionally the straights were designed with zero dispersion, which minimizes synchrobetatron coupling, avoids beam size increase due to energy spread and results in the largest possible reduction of the equilibrium emittance due to radiation emitted in insertion devices. All early 3rd generation light sources employed achromat lattices. Over time, however, nearly all of the early 3rd generation rings moved away from the achromatic condition resulting in lower equilibrium emittances. In most cases the dispersion in the straights is small enough that insertion devices continue to reduce the overall equilibrium emittance and the effective emittance is smaller than in the achromatic case. For multi-bend achromat lattices with their much smaller equilibrium emittance, dispersion leakage is usually not advantageous, so most 4th generation rings use achromat lattices, in some cases with higher order achromats.

The wavelength λ of radiation emitted by an undulator is given by

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2}\right), \tag{1}$$

where λ_u is the undulator period, γ is the relativistic Lorentz factor, $K \approx \lambda_U Be/(2\pi m_0 c)$ (the "undulator parameter"), B is the magnetic field, and $n = 1, 3, 5, \ldots$ denotes the harmonic. The term $\lambda_u/(2\gamma^2)$ shows that one can arrive at the same wavelength using larger beam energies and longer periods, or lower beam energies and shorter periods. Many parameters enter in the evaluation of the optimum beam energy, including cost, natural emittance, intrabeam scattering, beam instabilities, heat load on optics, magnetic material properties, and the desired photon wavelength range. In general, even with advanced undulator technology, low energy rings (~2 GeV) are unchallenged at low photon energies (below 20 eV) and provide excellent performance up to 4 keV, intermediate energy rings (~3 GeV) from a few 100 eV to above 10 keV, and, if higher photon energies are needed, higher electron energies are necessary (~4.5 - 7 GeV) enabling high brightness beams to many tens of keV photon energy.

Brightness and coherence

The spectral photon brightness, $B(\lambda)$ (Sec.?.?.?), of light emitted at wavelength λ from an insertion device in a synchrotron light source is given by

$$B(\lambda) = \frac{F(\lambda)}{(2\pi)^2\,\sigma_{\mathrm{Tx}}\sigma_{\mathrm{Ty}}\sigma_{\mathrm{Tx'}}\sigma_{\mathrm{Ty'}}} \tag{2}$$

where $F(\lambda)$ is the photon flux and σ_{Tx}, σ_{Ty}, $\sigma_{\mathrm{Tx'}}$, and $\sigma_{\mathrm{Ty'}}$ are the wavelength dependent convolutions of the respective electron and photon beam sizes and divergences. For a given flux, maximum brightness is achieved when the electron beam emittance is reduced toward and beyond the intrinsic diffraction-limited emittance $\lambda/(4\pi)$ of the photons and when the electron beam beta function is close to the equivalent beta function of the diffraction ellipse.

Coherence is a measure of the degree to which the radiation can exhibit interference patterns. The fraction f_{coh} of photon flux at wavelength λ that is transversely coherent is related to the ratio of the intrinsic photon emittance to the total emittance of the photon beam:

$$f_{coh} = \frac{F_{\mathrm{coh,T}}(\lambda)}{F(\lambda)} = \frac{\lambda/(4\pi)}{\sigma_{\mathrm{Tx}}\sigma_{\mathrm{Tx'}}}\,\frac{\lambda/(4\pi)}{\sigma_{\mathrm{Ty}}\sigma_{\mathrm{Ty'}}} \tag{3}$$

Flux, brightness, coherent flux, and coherent fraction are not the only figures of merit for a synchrotron light source, for example beam stability is often of high importance, but they are always important considerations. Which of the four quantities is most important depends upon each particular experiment.

Equilibrium emittance

The horizontal emittance ϵ_x results from the combined effect of an excitation of horizontal betatron oscillations (Sec.?.?.?), S_x, and its damping, τ_x:

$$\epsilon_x = S_x\tau_x, \quad \epsilon_x = C_q\frac{\gamma^2}{J_x}\frac{I_5}{I_2},$$
$$\frac{1}{\tau_x} = \frac{J_x C_\gamma E^3}{4\pi T_0}\oint\frac{1}{\rho^2}ds = \frac{J_x C_\gamma E^3}{4\pi T_0}I_2,$$
$$I_5 = \oint\frac{\gamma_x\eta_x^2 + 2\alpha_x\eta_x\eta_x' + \beta_x{\eta_x'}^2}{|\rho^3|}ds$$

where ρ is the bending radius, E the beam energy, $\beta_x, \alpha_x, \gamma_x$ the horizontal twiss-functions, η_x is the horizontal dispersion, and $\eta_x' = \frac{d\eta_x}{ds}$. J_x is the horizontal damping partition number. The integrals along s are nonzero only in bending magnets and insertion devices, while they are zero in drift spaces and negligible in quadrupoles and sextupoles. In most machines the contributions of the insertion devices to

S_x and τ_x are negligible and the essential contribution comes from the bending magnets. It is clear from Eq. 4 that a small emittance requires the use of a lattice with small values of η_x and β_x in the bending magnet. The first lattices to achieve this, as well as to provide the space for insertion devices were the double and triple bend achromat lattices [1,2]. The principle is shown in Fig.1.

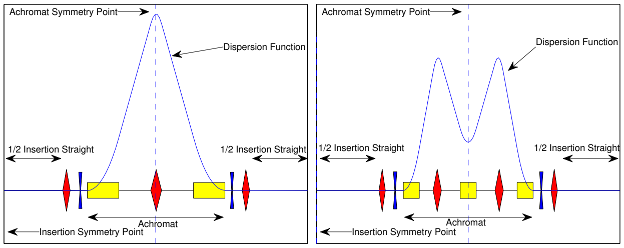

Figure 1: Principle of double and triple bend achromat lattices.

The minimum emittance of a DBA lattice is given by

$$\epsilon_{\mathrm{DBA,min}} = \frac{1}{4\sqrt{15}} \frac{C_q \gamma^2 \theta_b^3}{J_x} \tag{4}$$

where θ_b is the bending angle per magnet. Lattices of facilities in operation are detuned significantly from these minimum values, to make optimization of nonlinear effects easier (see below). Instead of striving for minimum emittance in an achromatic condition, further optimization was achieved by allowing dispersion to leak into the straight sections, thereby lowering the dispersion in the arcs.

How small one can get the natural emittance is related to the bending angle of individual magnets. Therefore newer rings with smaller emittances generally are larger for a given beam energy, resulting in more unit cells. Alternatively, one can segment the bending into more magnets per unit cell and refocus both β_x and η between each pair of successive bending magnets. The resulting lattice is called a multiple bent achromat (MBA). For MBAs, the arcs usually resemble the so called theoretical minimum emittance structure [5]. The emittance from such a lattice scales asymptotically as

$$\epsilon_x \propto \frac{E^2}{N^3}, \tag{5}$$

where N is the number of bending magnets. Fig. 2 shows the lattice structure for a seven bend achromat lattice (Max-IV). Because quadrupoles and sextupoles need to be stronger, to achieve the optimum emittance, the more dipoles are used in a unit cell, there are technology and beam dynamics challenges that put practical limits on the number of bend magnets.

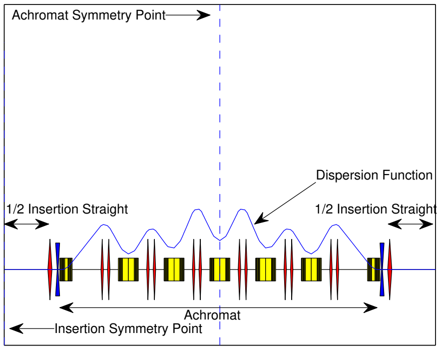

Figure 2: Example of a multi-bend achromat lattice, in this case a seven bend achromat.

Chromaticity correction and nonlinear optimization The low emittance design of light sources inherently relies on strongly focusing quadrupoles. These quadrupoles generate large chromatic aberrations that need to be corrected with sextupoles. The sextupoles in turn generate geometrical and nonlinear chromatic aberrations, exciting nonlinear resonances that can make the motion of the electrons unstable. This inherent feature has been the major design challenge and continues to be a dominant topic for lattice upgrades as well as new rings. Many techniques have been developed to accurately predict the dynamic aperture (Sec.?.?.?) as well as the dynamic momentum aperture and to allow their optimization, thereby maximizing injection efficiency and Touschek lifetime. The techniques include design optimization tools, as well as measurement methods useful to optimize existing accelerators based on beam based measurements.

In terms of lattice designs, the trend has been to include more quadrupole families (multi bend achromats often have more than 10 quadrupole families per cell) to allow full control of the linear lattice, and more sextupole families (state-of-the-art is 5-10 families) to allow control of detuning with amplitude terms as well as resonance driving terms, or a comprehensive optimization of the dynamic (momentum) aperture. Many rings have each magnet powered by an individual power supply to allow flexibility and improved correction of insertion device effects. In some cases octupole magnets are used to manipulate detuning with amplitude terms directly. An alternative is the use of more relaxed lattices combined with damping wigglers to reduce the equilibrium emittance.

Beyond correction of the chromaticity, while maintaining maximum dynamic and dynamic momentum aperture, lattice designers must also verify: (1) sensitivity of the dynamic (momentum) aperture to magnet imperfections or other lattice symmetry distortions; (2) sensitivity to insertion devices as well as optimum compensation schemes; (3) beam lifetime, in particular the influence of Touschek scattering (Sec.?.?.?); (4) emittance growth due to intrabeam scattering (Sec.?.?.?), which is a significant effect in the newest light sources.

Systematic lattice optimization techniques Historically, lattice design depended strongly on the experience of the person developing the design often choosing from a menu of known lattice choices. Many choices in this approach are subjective and usually the optimization of the nonlinear dynamics properties is carried out separately from the linear lattice design.

One alternative technique to find the globally optimal lattices in terms of emittance or brightness is GLASS [6]. It uses a global grid scan of the few parameters of a simplified standard cell. It then analyzes the properties of all lattices that were stable. This allows to search for potential lattices with certain properties. The most common technique used recently involves multi-objective, genetic algorithms. Those algorithms by themselves are already fairly old, but applications to accelerators are still fairly new. The first major one involved the optimization of a high brightness DC photoinjector. More recently they have been used for detailed linear lattice design and for multi-parameter optimization of the nonlinear dynamics of complex or low-periodicity lattices. They also allow for the simultaneous optimization of linear and nonlinear lattice properties [7]. An alternative technique is to look at resonance driving terms and to minimize all lower order ones by symmetry and tuning of sextupoles [8].

These new techniques are now used for many purposes, including the optimization of special insertions (e.g. low beta straights, convergent beta straights, fs-slicing facilities, crab cavity insertions), development of lower emittance upgrades for existing facilities, optimization of linear and nonlinear lattices for new facilities, and the evaluation of candidate designs for diffaction limited storage rings.

Evolution of 3rd generation light source lattices 3rd generation light sources have seen a steady evolution in the 20 years since their initial operation. This does not just include new and more advanced facilities, but also continuous improvements of existing ones. Lattice developments have evolved into two main directions. One of them is to allow for reduction of the natural emittance. The other is to incorporate complex local lattice insertions or breaks of the global lattice symmetry, to enable radiation sources with improved characteristics, while minimizing the negative effects on the global nonlinear beam dynamics. Some examples of those developments are described below.

Advances to enable lower equilibrium emittances started with the move to distributed dispersion lattices. Later on, the addition of more sextupole families and most recently the inclusion of octupoles helped to control the nonlinear dynamics and enabled lattices closer to the minimum emittance.

Examples of modifications to provide special photon sources include Superbends [9], a cost effective way to provide hard x-rays with moderate brightness using low beta function locations in low energy rings. Other examples are the fs-slicing facilities, that use horizontal or vertical dispersion manipulation to provide spatial separation of energy modulated bunch slices to generate fs duration x-ray pulses. Intentional symmetry breaks were also introduced to allow for individual straight sections to be lengthened, enabling longer undulators, as well as for straight sections with smaller (or convergent) beta functions, to optimize the photon beam properties for specific beamlines.

Multi-bend achromat lattices - 4th generation rings While storage rings are a “mature” technology, it was realized about 15 years ago that there was significant potential for significantly further enhanced performance. Multi bend achromat rings through a combination of accelerator physics and technology advances reduce the natural emittance by 2 orders of magnitude, allowing to produce high-brightness, transversely coherent x-rays [10]. Some of the enabling design features are small aperture vacuum systems, often employing NEG coated chambers, as well as tightly spaced, high gradient quadrupole and sextupole magnets with excellent alignment tolerances.

To maximize transverse photon coherence, the beam emittance in these rings is extremely small in both transverse planes, around the wavelength-dependent diffraction limit. 3rd generation storage ring sources had achieved diffraction limited emittances for hard x-rays in the vertical plane by minimizing beam coupling, but many of the newest designs reduce the horizontal emittance by a factor of 100 or more from the lowest values achieved on 3rd generation rings to reach that limit in both planes. One way to achieve this, especially for the highest photon energies of interest, is with very large circumferences, but dramatic improvements are also possible with seven or nine bend achromats on rings similar in size to previous 3rd generation rings (compare Tab. 1). The main feature is the use of more bending magnets per cell, smaller physical apertures to allow for higher gradients of magnets, operation with large (or full) coupling to alleviate intra beam scattering effects and possible on axis injection with beam replacement to mitigate small dynamic apertures. Multi-bend achromat rings have brightness and coherent flux one or two orders of magnitude higher than the highest performance 3rd generation ring-based light sources.

One of the draw-backs of multi bend achromats is that they typically provide a smaller fraction of available straight section space than what was possible in double or triple bend achromats. One optional approach is the use of damping wigglers. They allow to use a more relaxed lattice in the arc cells, resulting in larger momentum compaction factors and less lattice related nonlinear dynamics challenges while still achieving extremely small emittances. However, they use up space, require more expensive RF and cooling systems, increase the equilibrium energy spread and use up straight section space. Furthermore, nonlinear dynamics challenges due to wigglers can be significant as well. So to determine the optimum use of damping wigglers requires a careful design trade-off study. Tab. 1 lists lattice parameters of a selection of the newest light sources in operation or under construction, as well as parameters of future facilities under design.

Despite the relative recent introduction of multi-bend achromat lattices, there is already a large variety of design variants that allows to meet specific boundary conditions of different facility designs. This includes the choice of different chromaticty correction schemes, where correction is performed either in a very distributed way, or is concentrated in a few high dispersion regions. The later solution is called

Table 1: Selected advanced storage ring facilities that are in operation, under construction, or under design [11]. Status: (a) in operation; (b) under construction; (c) technical design phase.

Project	Energy [GeV]	Circumf. [km]	Hor. Emit. [pm]	Current [mA]	Lattice Design	Status
PETRA III	6	2.3	1000	100	7/8 FODO + 1/8 DBA + DW	(a)
NSLS-II	3	0.792	750	400	30 x DBA + DW	(a)
MAX IV	3	0.528	240	300	20 x 7BA	(a)
ESRF-EBS	6	0.843	133	200	32 x H7BA	(a)
APS-U	6	1.1	42	200	40 x H7BA	(b)
ALS-U	2	0.196	69	500	12 x 9BA	(b)
PETRA IV	6	2.3	8	100	8 x 8 x H7BA	(c)

a hybrid multi bend achromat [12] and is especially popular for higher energy rings, since it allows to reduce the required sextupole strength, staying within achievable strength limits. The hybrid multi bend achromat also typically employs a specific phase advance between the two sextupole locations in each arc, so that their resonance driving terms cancel.

Another variation is the use of reverse (or anti-) bends [13]. This allows better independent control of beta functions and dispersion, allowing to reduce the natural emittance further. Reverse bends also modify the damping partition number, reducing the horizontal emittance (at the expense of a longer longitudinal damping time). Disadvantages are the higher overall synchrotron radiation loss, requiring more RF voltage as well as complexities in lattice tuning, magnet and vacuum system design.

Another trend, often employed in hybrid multibend achromat lattices is the use of longitudinal gradient dipoles [14]. The idea here is to have smaller bending field at places in the lattice with larger dispersion and smaller field at places with larger dispersion. This minimizes the equilibrium emittance, but increases the magnet complexity and usually requires more space. Fig. 3 shows an example of a complex nine bend achromat lattice, which makes use of localized chromaticity correction in high dispersion regions and reverse bending magnets to reduce the equilibrium emittance and improve the momentum aperture (ALS-U).

For modern lattices, the dynamic and momentum aperture as well as trajectory errors that can be achieved with alignment tolerances that are reasonable are usually not sufficient to store beam. Instead of tightening the error specifications to values that are unrealistic, a new approach has been chosen to fully simulate and credit a beam-based correction chain already during the design phase of the lattice. Such commissioning simulations [15, 16] are possible because of the fidelity and speed of todays lattice simulations and are also enabled by the improved performance of beam diagnostics. Crediting these beam-based correction strategies, the alignment specifications for 4th generation rings are actually slightly more relaxed than what was achieved at the newest 3rd generation rings.

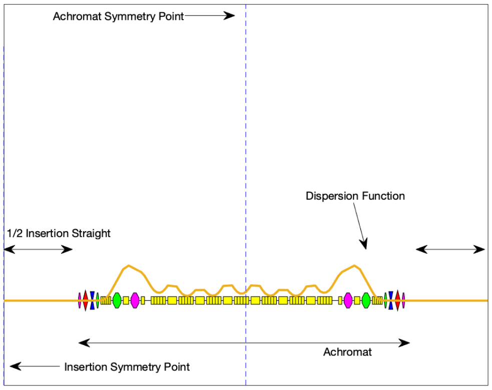

Figure 3: Example of a nine bend achromat lattice with localized chromaticity correction at high dispersion points and use of reverse bends for emittance reduction.

Future directions While multi-bend achromat designs already in operation and under construction already provide dramatically improved coherent flux, further developments are possible. These include the scaling of MBA design to larger rings (>2 km), which might allow to reach the diffraction limit even for hard x-rays. An alternative approach, that might achieve the same goal in rings of more moderate size and cost is to miniaturize magnet technology further. Such an approach creates a set of new challenges, but initial technology studies provide some encouraging results [17]. Another direction that also has been considered before is the combination of such ultra-low emittance rings with FELs. However, all of those design studies are at a very early stage.

REFERENCES

[1] M. Sommer, LAL/RT/83-15 (1983)

[2] A. Jackson, PA 22 (1987) 111

[3] L. Farvacque et al, Proc. EPAC 1994, London, UK

[4] D. Einfel, et al, Proc. PAC 1995, Dallas, TX

[5] S.Y. Lee, L. Teng, PAC 1991, 2679

[6] D. Robin et al, PRST-AB 024002 (2008)

[7] L. Yang et al, NIM A 609 (2009) 50; M. Borland, Proc. ICAP 2009, San Franciso, CA

[8] J. Bengtsson, et al., PRST-AB 18, 074002 (2015)

[9] D. Robin et al, NIM A 538, 1-3 (2005), 65

[10] M. Bai et al, NIM A, 622(3), 518 (2010)

[11] K. Balewski et al, PETRA III TDR, DESY 2004-035; J. Ablett et al, NSLS-II CDR, BNL 2006; M. Eriksson et al, EPAC 2008, Genova, Italy; P. Raimondi, Synchrotron Radiation News, 29:6, 8-15, 2016; M. Borland et al, IPAC 2015, Richmond, VA; C. Steier et al, IPAC 2019, Melbourne, Australia; I. Agapov et al, IPAC 2019, Melbourne, Australia

[12] P. Raimondi, IPAC 2017, 3670, Copenhagen, Denmark

[13] A. Streun, NIM A, 737, 148 (2014)

[14] R. Nagaoka, A. Wrulich, NIM A, 575, 3, 292 (2007)

[15] V. Sajaev, PRAB, 22, 4, 040102, 2019

[16] T. Hellert et al, PRAB, 22, 10, 100702, 2019

[17] G. Wang et al, PRAB 21, 100703 (2018)