ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEXG1

TOWARDS A TRUE DIFFRACTION LIMITED LIGHT SOURCE

L. Hoummi*, N. Carmignani, L.R. Carver, S.M. Liuzzo, T. Perron, S. White,
ESRF, Grenoble, France

Abstract

Multi-bend achromat (MBA) lattices have initiated a fourth generation for storage-ring light sources with orders of magnitude increase in brightness and transverse coherence. A few MBA rings have been built, and many others are in design or construction worldwide, including upgrades of APS and ALS in the US. The Hybrid MBA (HMBA), developed for the successful ESRF–EBS MBA upgrade [1] has proven to be very effective in addressing the nonlinear dynamics challenges associated with pushing the emittance toward the diffraction limit.

DIFFRACTION-LIMITED STORAGE RING LIGHT SOURCE

Fourth generation storage ring (SR) light sources are flourishing worldwide. New storage ring light sources, or so-called green-field SR, as well as upgrade projects of existing facilities aim at increasing the photon beam quality in the hard X-ray range, by providing a much brilliant photon beam, increasing the photon density and reducing the time resolution of user experiments [2]. As for any other photon sources, a SR light source can be considered diffraction limited if the photon size and divergence at a given wavelength do not depend on the electron beam characteristics.

For the particular case of an undulator of length L, period N and odd harmonic n, the maximum brilliance of a Gaussian photon beam of wavelength λ can be expressed as:

$$B = \frac{N F_n(\lambda)}{(2\pi)^2 (\Sigma_x \Sigma'_x)(\Sigma_y \Sigma'_y)} \tag{1}$$

where $F_n(\lambda)$ is the spectral flux, $\Sigma_{x,y} = \sqrt{\sigma_r^2 + \sigma_{x,y}^2}$ and $\Sigma'_{x,y} = \sqrt{\sigma_r'^2 + \sigma_{x,y}'^2}$ are the total photon beam sizes and divergences, σ_r, σ'_r the size and divergence of a photon beam emitted by a single electron and $\sigma_{x,y}, \sigma'_{x,y}$ of the electron beam. Therefore, the electron beam conditions for a diffraction limited storage ring light source are:

$$\sigma_{x,y} \ll \sigma_r \tag{2}$$
$$\sigma'_{x,y} \ll \sigma'_r \tag{3}$$

It is customary to reinforce these conditions using the smallest achievable photon size and divergence, reached for a purely Gaussian beam, using for instance the following convention for the photon beam sizes: $\sigma_r = \sqrt{\frac{\lambda L}{8\pi^2}}$ and $\sigma'_r = \sqrt{\frac{\lambda}{2L}}$ [3]. In a dispersion-free area, the previous condition can be translated into electron beam emittance and Twiss function β_x, considering $\sigma = \sqrt{\epsilon\beta}$ and $\sigma' = \sqrt{\frac{\epsilon}{\beta}}$, into:

$$\epsilon_{x,y} \ll \frac{\lambda}{4\pi} \tag{4}$$

This condition translates into $\epsilon_{x,y} \ll 99$ pm rad for a (1 keV, 3 GeV) photon and electron beams, and $\epsilon_{x,y} \ll 9.9$ pm rad for (10 keV, 6 GeV). Therefore, the required electron emittances for a hard X-ray photon beam are, with the present technology and the foreseen storage ring upgrades and construction projects, unreachable. To have overlapping electron and photon beam phase space, the condition on the β−function, $\beta_{x,y} \leq \frac{L}{\pi}$ provides an optimum of the brilliance regardless of the photon beam energy: it is the matching condition [4]. Its expression is often discussed depending on the Gaussian photon beam conventions used, and the technical limitations on the vertical β-functions especially for in-vacuum undulators [5].

FOURTH GENERATION OF STORAGE RING LIGHT SOURCES

Inaugurated with the upgrade project and commissioning of the MAX IV 3 GeV light source in 2016 [6], a fourth generation of storage ring light sources is emerging, increasing the hard X-ray brilliance for a higher photon beam quality and closer to fully diffraction-limited light sources. The natural horizontal emittance link with the storage ring lattices is defined as:

$$\epsilon_h = C_q \gamma^2 \frac{I_5}{(I_2 - I_4)} \propto \frac{E^2}{(N_{cells} N_{bends})^3} \tag{5}$$

with C_q the Compton constant, γ the Lorentz factor, I_i the radiation integrals, defining the emittance as the equilibrium between the radiation damping (I_4) and the quantum excitation (I_5). I_2 integrates the weak focusing effects of the bending forces along the ring. This emittance expression is commonly linked to the machine energy E, its number of cells N_{cells} and bending magnets per cell N_{bends}. The latter encourages the multiplication of bending magnets in the SR, leading to the extensive use of Multi-Bend Achromats (MBAs).

Figure 1 extrapolates the current trends by comparing the normalised natural emittance with the SR circumference. The third generation (blue line) started with the implementation of Chasman-Green lattices or Double- and Triple-Bend Achromats (DBA and TBA) [7, 8]. Later, their modified versions released the dispersion constraint of the achromat to approach the theoretical minimum emittance conditions. In 1993, the Quadrupole Bend Achromat introduced the MBA principle along with the use of combined-function magnets [9]. Now, stronger reduction of the natural horizontal emittance is obtained with the extensive use of Multi-Bend

* lina.hoummi@esrf.fr

14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEXG1

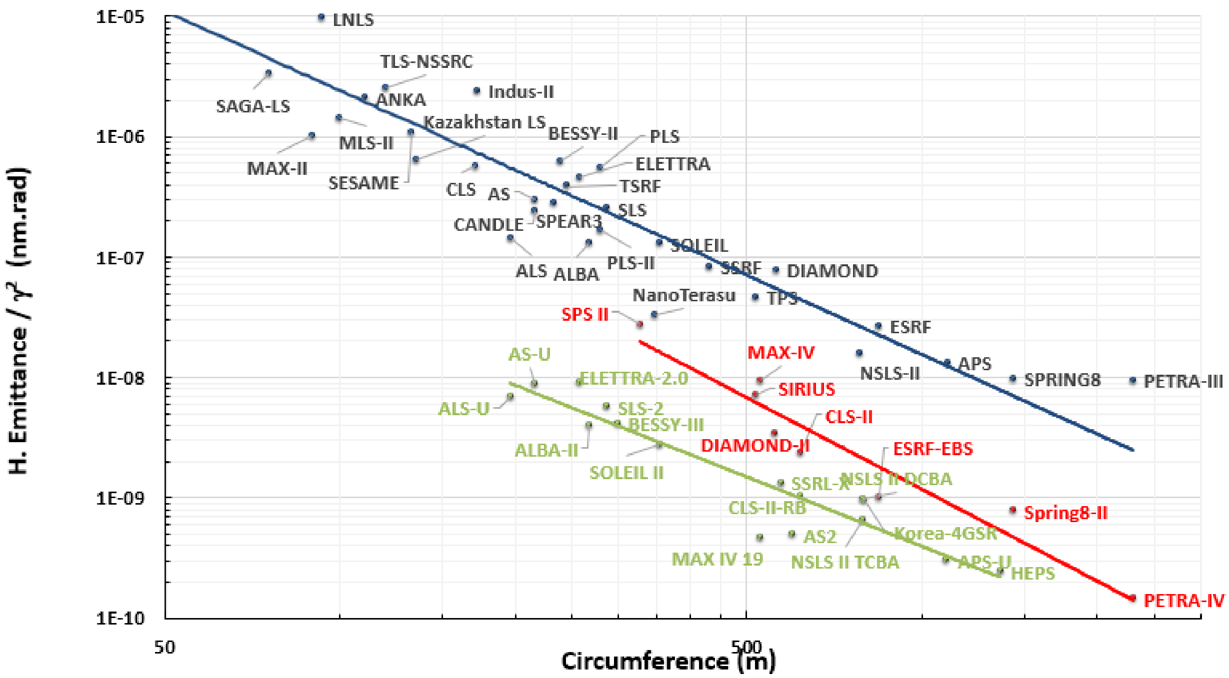

Figure 1: Normalised natural horizontal emittance as a function of circumference for third- and fourth-generation storage rings, or so-called Bartolini plot.

Achromat lattices, increasing the number of bending magnets per cell (red line), defining a new generation of storage ring based light sources. The upgrade projects around the green curve in Fig. 1 exploits the radiation damping effect to further decrease the natural horizontal emittance, including reverse bending magnets or damping wigglers in their lattices [10].

The emergence of the Multi-Bend Achromat lattice and its extensive use in the recent and foreseen upgrades creates a new generation of storage ring light sources (in red). The reduction in horizontal emittance provided by the MBA lattice is paired with low dispersion and strong focusing, which require stronger sextupole magnets for chromaticity correction. To compensate the stronger resonances that arise from the stronger magnets, the linear optics design stage include forms of compensation of the lowest resonant driving terms: building a MBA lattice using unit cells, with careful choice of phase advance to cancel resonance driving terms (RDTs) over the cell, and the Hybrid MBA (HMBA) exploiting a $-I$ transformation between the sextupoles, developed for and in operation at the ESRF-EBS since 2019.

ULTRA-LOW EMITTANCE LATTICES

Strong focusing in MBA lattices requires the adaptation of linear optics to include nonlinear effects and compensate the large RDTs generated by the strong sextupolar correction. Two main schemes are used: the High-Order Achromat lattice (HOA) and the Hybrid Multi-Bend Achromat lattice (HMBA).

High-Order Achromat

High Order Achromat is composed of a series of unit cells, with phase advance fixed to cancel lowest orders geometric resonances over a single period [11]. For a N-BA HOA unit cell, the phase advances verify the condition $(\nu_x, \nu_y) = \left(\frac{a}{N}, \frac{b}{N}\right)$, with $a, b \in \mathbb{N}, a \wedge b = 1$, with typical $\left(\frac{3}{7}, \frac{1}{7}\right)$ phase advances for a 7BA lattice for cancellation of first- and second-order geometric resonances [12]. Each unit cell includes a sextupolar triplet for local chromaticity correction, and its focusing quadrupole can be transversely translated to create a reverse bend and further reducing the natural horizontal emittance. Optimal combination of longitudinal gradient dipole and reverse bending magnets for emittance minimisation are discussed in [13].

Hybrid MBA

HMBA has been developed by P. Raimondi for the upgrade of the ESRF-EBS [1]. Sextupoles are symmetrically placed at the location of two dispersion bumps, with a $-I$ transformation for kick cancellation [14]. The scheme has been widely adapted to different upgrade projects. A Double Minus I (DMI) cell concatenates two HMBA cells, a first with only focusing sextupoles, the other defocusing, for perfectly non-interleaved sextupoles [15]. Some integrate reverse bending magnets, achieving about 40 pm radin the case of APS-U and HEPS [16, 17]. A further development of the hybrid scheme was conducted in [18] for a 72 cells, 6 GeV and 1.6 km storage ring, reducing the number of bending magnets to 6, and including focusing quadrupoles between two consecutive dipoles to further focus the electron beam

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEXG1

thus reduce the emittance creation, while maintaining a large dynamic aperture and a high Touschek lifetime.

The Complex Bend

Against the current trend of MBA lattices, aggressive combined-function magnets are developed to minimise the average of the ratio H-function with the square of the bending radius, of which the Complex Bend (CB). It is a tight and compact arrangement of quadrupolar components along the bending magnet [19, 20], developed at the NSLS-II for their upgrade. A full-scale prototype is being produced [21].

The CB was implemented in a Triple Complex Bend Achromat (TCBA) for an upgrade of their 3 GeV storage ring, achieving 23 pm rad natural emittance. The strong focusing of the CB generates large natural chromaticity, which correction by sextupoles increases RDTs and Amplitude-Dependent tune shift (ADTS). Both are simultaneously corrected using octupoles [22] for increased transverse dynamic aperture towards standard off-axis injection.

MBA With M > 10

Several proposals for MBA lattices furiously increased the number of bending magnets per lattice, to obtain reduced emittances [23, 24]. Among them, a 19BA lattice proposed for a future upgrade of the MAX IV 3 GeV storage ring, keeping its current circumference. Its main technical limitations are the high-gradient combined-function and focusing magnets. Furthermore, its reduced dynamic aperture and beam lifetime requires the implementation of a different injection scheme. These challenges are shared with the majority of fourth generation upgrade project, which conserve their present SR tunnel [25].

CHALLENGES

Ultra-low emittance is generally achieved with Multi-Bend Achromat lattices. The strong focusing in such compact schemes requires a stronger nonlinear correction, which effect on the dynamics is now included in the linear optics. Nonetheless, other design and technical challenges are limit the performances, feasibility and operability of future storage ring light sources. A non-exhaustive list is displayed in Fig. 2. This section focuses on the permanent magnets for energy savings, the cross-talk between neighbouring magnets and transparent injection schemes.

High-Gradient Magnets

Strong focusing and high compactness require stronger gradients and smaller magnets, with lower tolerances in magnet field errors [25, 26]. High gradient (HG) can be achieved by reducing the magnetic gap. This yields to small vacuum chamber apertures which subsequently magnifies pumping, coating and larger impedance challenges. Furthermore, the compactness of the MBA lattices offers tight distances between magnets, leading to few space for coils, cables, and correctors. In all, numerous upgrades consider using Permanent Magnets (PMs) for their linear elements [26–31]. Table 1 non-exhaustively lists some advantages and challenges to be considered for the large implementation of PMs in a storage ring [32].

Table 1: Advantages and challenges of the use of permanent magnets in a storage ring. A non-exhaustive list.

Advantages	Challenges
High gradient	Fixed fields
Compactness	Tunability
Reliability, stability	Temperature stability
Less control systems	Field homogeneity
Low operational costs	First turns, commissioning
	Demagnetisation

Among them, the fixed field of the PM elements require the insertion of correctors and increases the complexity of the SR correction scheme. Tunable PMs could provide a solution to this limitation [33]. Nonetheless, the motorisation and the variation of the magnetic position with the poles motion limits the speed of correction of these elements.

The extensive use of PM magnets in storage rings reduces the overall electrical consumption of the SR operation. Table 2 lists the required power of different magnet families before and after EBS. A reduction of 20 % in the electricity costs is achieved thanks to the storage ring upgrade and the use of permanent magnets in longitudinal gradient dipoles.

Table 2: Magnet power and overall energy consumption of the ESRF storage ring, before and after the EBS upgrade [34].

	Before EBS	After EBS
Dipole	270 kW	0 kW
Other magnets	1925 kW	1059 kW
DQs	NA	16 %
High Gradient quad.	NA	29 %
Moderate Gradient quad.	NA	44 %
Sextupoles	NA	10 %
Octupoles	NA	1 %
Correctors and steerers	10 kW	11 kW
Total	2355 kW	1070 kW
Yearly energy consumption	16.9 GW h	7.7 GW h

Despite the ideal performances of the PM elements in terms of electricity, the environmental impact of such magnets amounts to their electric counterparts, from the materials extraction to the limited recycling and reuse possibilities [35].

Cross-Talk

The proximity of high-gradient fields magnets induces parasitic gradient errors on the edges of neighbouring magnets. This phenomenon is most commonly known as cross-talk. During the commissioning of the ESRF-EBS storage ring, large β-beating in optics measurements lead to the discovery of gradient differences between the model and the SR, due to

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEXG1

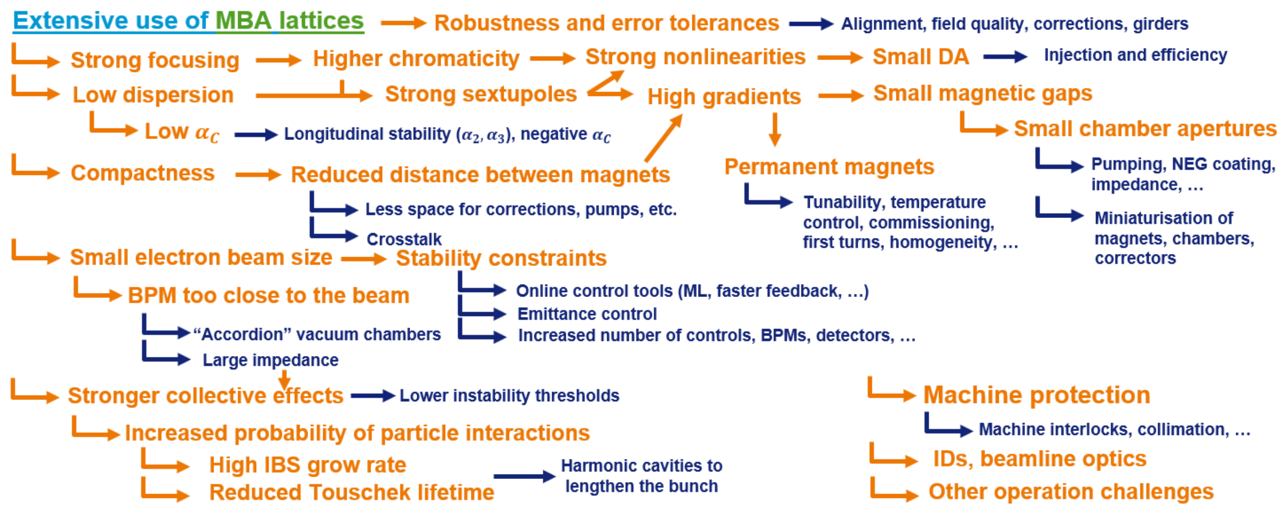

Figure 2: Non-exhaustive list of fourth-generation storage ring challenges.

cross-talk between magnets [36]. Cross-talk modelling and optics correction was conducted in the SR to resume commissioning. Several models of cross-talk and calculations were developed, to address the magnet design specificities of the different upgrades [37–40].

Towards A Transparent Injection

Ultra-low emittance lattices often lack transverse dynamic aperture, due to strong focusing and the strong sextupolar correction required. In these conditions, the standard off-axis injection with a four-kicker bump could be accommodated including a high-β_x straight section [42]. Yet, the reduction of the electron beam sizes is combined with a higher sensitivity to perturbations, tightening the request for beam size stability during operation, especially for frequent top-up injections. To answer this transparency requirement, replacements of the standard off-axis injection and three/four kicker bumps are widely considered to reduce or avoid the inevitable betatron oscillations of the injected beam. The plurality of the transparent injection schemes is combined with the emergence of higher performance kickers, either nonlinear (NLK), short-pulse (SPK), flat-top (FTK). More information can be found in [41] for instance. Swap-out injection is considered for the APS-U, ALS-U and HEPS upgrades [16, 43, 44], either from a full charge booster or an accumulator ring. The innjection scheme will be tested this year, during the APS-U commissioning period. Longitudinal on-axis injection is envisaged for SLS 2.0, using a SPK [45]. The commissioning of their storage ring will be conducted using the aperture sharing scheme, kicking a selection of stored bunches while kicking injected bunches in [46]. Transparent off-axis injection replace the standard three/four kicker bump with a single nonlinear kickers. For instance, the MAX-IV Multiple Injection Kicker (MIK) [47, 48] provides a transparent injection of low betatron oscillations with an injection at x = 10 mm. In view of SOLEIL II, several MIK designs were developed with a magnetic peak field of the kicker at x = −3.5 mm [49].

The selected design minimises the perturbation to the stored beam with two mobile conductors for fine tuning of the flat potential.

LATTICE ADAPTATION OF BUILT FOURTH-GENERATION STORAGE-RING LATTICES

After commissioning and operation of the machines, some improvements of the optics could be used to better match the optics at the IDs.

Mini-β Optics The insertion of additional quadrupoles around an undulator reinforces the beam focusing for enhanced brilliance [5]. Several optics design are assessed for the ESRF-EBS, and four additional quadrupoles have been installed to locally reduce, in a first approach, the vertical β-function from 2.7 m to 1 m. This reduction increases the expected brilliance by 40 % along with a reduction of lifetime and dynamic aperture. Experimental studies will be conducted in 2023.

Off-Energy Operation Further reduction of the equilibrium emittance was achieved by putting the electron beam on a dispersive orbit thanks to a frequency shift of the RF cavities and restoration of the HMBA optics within the power supply limits of the magnets [50]. The off-energy operation was tested on the ESRF-EBS storage ring. Measurements confirmed the restoration of the HMBA optics and dynamic aperture, and lifetime could be optimised using the standard online optimisation [51].

Low Emittance Optics A more aggressive approach is ongoing at MAX IV, where low-emittance optics have been developed [52]. All quadrupole magnets have been used to change the Twiss functions and dispersion to achieve lower natural emittance and lower β-functions in the middle of the straight section. Consequently, the transverse dynamic

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEXG1

aperture is much reduced, requiring an adaptation of the injection scheme into the storage ring, combining a dipole-kicker (DK) with the standard MIK [53].

ENERGY CRISIS AND CLIMATE CHANGE

The last decade witnessed different shortages of Helium, the Covid19 pandemic and, among others, the Ukrainian-Russian war, along with the spread of climate catastrophes: hurricanes, cyclones, yearly droughts and fires. The increased prices in electricity of various origins - war, gas control, affected the operation of several synchrotron light sources in 2023. Some national synchrotrons were forced to reduce their user delivery time [54, 55].

The prospect of the resolution of those events, disregarding climate change, do not guarantee the return of previous prices level, on the contrary: the International Energy Agency foresees a confirmed increase in the coming years worldwide, with a stronger variation in Europe [56]. This crisis triggered a wave of optimisation to reduce the operational costs of our facilities.

Yet, our direct and indirect environmental impact remains largely untackled. Several studies were conducted on the sustainability of big research infrastructures [34, 57, 58]. These crisis are an opportunity to include sustainability in our projects and management, optimisation of our energy consumption, and sobriety to drastically reduce our impact on climate change.

CONCLUSION AND PERSPECTIVES

The fourth generation era which started with the successful commissioning of the MAX IV 3 GeV storage ring keeps tackling the challenges of the Multi-Bend Achromat lattices in tight storage ring tunnels. Adaptations of the main HOA and HMBA schemes further decreased the natural horizontal emittance, approaching the diffraction limit of 1 keV photon beam. Further reduction of the electron beam sizes at a fixed SR circumference will depend on the technical solutions of the new generation challenges and their operability.

In light of recent and more pressing events, the future of our big research institutes and the doors our accelerators open for science lies in our adaptation capacities to the social, energy and environmental challenges tomorrow's society will request from us, by improving our sustainability, energy consumption optimisation and perhaps implementation of both sobriety and flexibility in our programs.

ACKNOWLEDGEMENTS

The authors would like to express their most sincere acknowledgements to the Accelerator and Source Division colleagues of the ESRF, P. Alexandre, P. Brunelle, A. Gamelin, A. Nadji, R. Nagaoka, M.-A. Tordeux, M. Apollonio, A. Brainbridge, R. Ollier, A. Poyet, P. Tavares, T. Shaftan, for their help, time and the fruitful discussions.

REFERENCES

[1] Raimondi, P., Benabderrahmane, C., Berkvens, P. *et al.*, Commun Phys 6, 82 (2023), doi:10.1038/s42005-023-01195-z.

[2] P. Elleaume, Undulators, Wigglers and their applications, Chapter 2, Taylor and Francis, 2003.

[3] Y. Cai, *et al.*, PRAB2012, doi:10.1103/PhysRevSTAB.15.054002.

[4] H. Wiedemann. Particle Accelerator Physics, 783-784. Springer International, 3 edition, 2007, doi:10.1007/978-3-319-18317-6.

[5] S. White *et al.*, presented at International Particle Accelerator Conference (IPAC'23), Venice, Italy, 2023, paper WEPL029, this conference.

[6] Tavares, P. F., *et al.*, Journal of Synchrotron Radiation, 25, 1291–1316, 2018.

[7] R. Chasman, G.K. Green, E.M. Rowe, IEEE Trans Nucl Sci 22(3), 1975.

[8] A. Jackson, Particle Accelerator. 22, 111, 1987.

[9] D. Einfeld and M. Plesko, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 335(3):402–416, 1993, doi:10.1016/0168-9002(93)91224-B.

[10] A. Streun, Nuclear Instruments and Methods in Physics Research A, 737:148–154, 2014.

[11] S.C. Leemann *et al.*, A novel 7BA lattice for a 196-m circumference diffraction. Physical Review E, 47(3), March 1993.

[12] J. Bengtsson and A. Streun, Robust Design Strategy for SLS-2, Tech. Rep., pages SLS2–BJ84–001, June 2007.

[13] B. Riemann and A. Streun. Phys. Rev. Accel. Beams, 22: 021601, Feb 2019. doi:10.1103/PhysRevAccelBeams.22.021601.

[14] R. Servranckx and K. Browm, Chromatic corrections for large storage rings, Nuclear Science, IEEE Transactions on, 26:3598 – 3600, 07 1979, doi:10.1109/TNS.1979.4330113.

[15] H.-C. Chao, Proc. 10th International Particle Accelerator Conference (IPAC'19), Melbourne, Australia, 2019, doi:10.18429/JACoW-IPAC2019-TUPGW018.

[16] APS Upgrade Project Final Design Review Report, 2019.

[17] Yi Jiao, *et al.*, Proc. 12th International Particle Accelerator Conference (IPAC'21), Campinas, SP, Brazil, 2021, doi:10.18429/JACoW-IPAC2021-MOPAB053.

[18] P. Raimondi, S. Liuzzo, Towards a diffraction limited light source, PRAB, 2023, doi:10.1103/PhysRevAccelBeams.26.021601

[19] Shaftan, Timur, Smaluk, V., and Wamg, Guimei, Concept of the Complex Bend, United States: N. p., 2018. doi:10.2172/1504393.

[20] Wang, G. and Shaftan, T. and Smaluk, V. and Mezentsev, N. A. and Sharma, S. and Chubar, O. and Hidaka, Y. and Spataro, C., Phys. Rev. Accel. Beams, 2018, doi:10.1103/PhysRevAccelBeams.21.100703.

[21] S. Sharma, *et al.*, IPAC22, talk THIYSP1, unpublished.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEXG1

[22] Plassard, Fabien and Wang, Guimei and Shaftan, Timur and Smaluk, Victor and Li, Yongjun and Hidaka, Yoshiteru,Phys. Rev. Accel. Beams, 2021, doi:10.1103/PhysRevAccelBeams.24.114801.

[23] Penghui Yang, Zhenghe Bai, Tong Zhang, Derong Xu, Lin Wang, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,Volume 943,2019, doi:10.1016/j.nima.2019.162506.

[24] P.Tavares, J. Bengtsson, Å. Andersson, Journal of Electron Spectroscopy and Related Phenomena 224, 2018.

[25] M. Borland, G. Decker, L. Emery, V. Sajaev, Y. Sun, and A. Xiao. Journal of Synchrotron Radiation, 21(5):912–936, Sep 2014, doi:10.1107/S1600577514015203.

[26] M. Johansson, B. Anderberg, and L.-J. Lindgren, Journal of Synchrotron Radiation, 21(5):884–903, Sep 2014. doi:10.1107/S160057751401666X.

[27] G. Le Bec, J. Chavanne, C. Benabderrahmane, L. Farvacque, L. Goirand, S. Liuzzo, P. Raimondi, and F. Villar, Physical Review Accelerators and Beams, 19, 05 2016, doi:10.1103/PhysRevAccelBeams.19.052401.

[28] J. Chavanne and G. Le Bec, Proceedings of IPAC2014, Dresden, Germany, 2014, doi:10.18429/JACoW-IPAC2014-TUZB01.

[29] SOLEIL II, Conceptudal Design Report, 2020.

[30] SLS 2.0 storage ring. Technical design report, 2021.

[31] M. Gehlot, presented at International Particle Accelerator Conference (IPAC'23), Venice, Italy, 2023, paper WEPM100, this conference.

[32] C. Benabderrahmane, Proc. 8th International Particle Accelerator Conference (IPAC'17), Copenhagen, Denmark, 2017, talk THYB1, unpublished.

[33] A.R. Bainbridge, et al., Proc. 13th International Particle Accelerator Conference (IPAC'22), Bangkok, Thailand, 2022, doi:10.18429/JACoW-IPAC2022-THOYSP1.

[34] J.-L. Revol, presented at International Particle Accelerator Conference (IPAC'23), Venice, Italy, 2023, paper THODB3, this conference.

[35] J. Dreikorn, presented at International Particle Accelerator Conference (IPAC'23), Venice, Italy, 2023, paper WEPM133, this conference.

[36] G. Le Bec, *et al.*, PRAB 24, 072401, 2021, doi:10.1103/PhysRevAccelBeams.24.072401.

[37] J. Keil *et al.*, presented at International Particle Accelerator Conference (IPAC'23), Venice, Italy, 2023, paper WEPM032, this conference.

[38] M. Abliz, M. Jaski, A. Jain, M. Borland, G. Decker, J. Kerby, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 913, 2019, Pages 48-53,doi:10.1016/j.nima.2018.10.036.

[39] B. Riemann and M. Aiba, Proc. 10th International Particle Accelerator Conference (IPAC'21), Campinas, Brazil, May 2021, doi:10.18429/JACoW-IPAC2021-TUPAB238.

[40] P. Sunwong *et al.*, presented at International Particle Accelerator Conference (IPAC'23), Venice, Italy, 2023, paper WEPM047, this conference.

[41] M. Aiba, Proc. 9th International Particle Accelerator Conference (IPAC'18), Vancouver, Canada, 2018, doi:10.18429/JACoW-IPAC2018-WEXGBE1.

[42] L. Farvacque, *et al.*, Proc. 4th International Particle Accelerator Conference (IPAC'13), Shanghai, China, 2013, paper MOPEA008, pp. 79–81.

[43] C. Steier, Proc. 8th International Particle Accelerator Conference (IPAC'17), Copenhagen, Denmark, 2018, doi:10.18429/JACoW-IPAC2017-WEPAB103.

[44] Z. Duan, Proc. 9th International Particle Accelerator Conference (IPAC'18), Vancouver, Canada, 2018, doi:10.18429/JACoW-IPAC2018-THPMF052.

[45] M. Aiba, M. Böge, F. Marcellini, Á. Saá Hernández, and A. Streun, Phys. Rev. ST Accel. Beams 18, 020701, doi:10.1103/PhysRevSTAB.18.020701.

[46] J. Kallestrup, Proc. 13th International Particle Accelerator Conference (IPAC'22), Bangkok, Thailand, 2022, doi:10.18429/JACoW-IPAC2022-THPOPT018.

[47] J. Da Silva Castro, P. Alexandre, R. Ben El Fekih, and S. Thoraud. 10th Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation, Paris, France, 2018, doi:10.18429/JACoW-MEDSI2018-TUPH12.

[48] P. Alexandre, R. Ben El Fekih, A. Letr´esor, S. Thoraud, J. da Silva Castro, F. Bouvet, J. Breunlin, A. Andersson, and P. Fernandes Tavares. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 986:164739, 2021, doi:10.1016/j.nima.2020.164739.

[49] P. Alexandre, presented at International Particle Accelerator Conference (IPAC'23), Venice, Italy, 2023, paper THPA175, this conference.

[50] L. Hoummi *et al.*, Proc. 13th International Particle Accelerator Conference (IPAC'22), Bangkok, Thailand, 2022, doi:10.18429/JACoW-IPAC2022-MOPOTK006.

[51] L. Hoummi *et al.*, presented at International Particle Accelerator Conference (IPAC'23), Venice, Italy, 2023, paper MOPA143, this conference.

[52] M.Apollonio *et al.*, Proc. 13th International Particle Accelerator Conference (IPAC'22), Bangkok, Thailand, 2022, doi:10.18429/JACoW-IPAC2022-MOPOPT023.

[53] M.Apollonio *et al.*, presented at International Particle Accelerator Conference (IPAC'23), Venice, Italy, 2023, paper MOPM012, this conference.

[54] L. Nadolski, oral presentation, European Synchrotron Light Source workshop, Grenoble, France, 2022.

[55] E. Karantzoulis, oral presentation, European Synchrotron Light Source workshop, Grenoble, France, 2022.

[56] IEA, Indexed quarterly average wholesale prices for selected regions, 2019-2024, IEA, Paris.

[57] M. Seidel, Proc. 13th International Particle Accelerator Conference (IPAC'22), Bangkok, Thailand, 2022, paper FRPLYGD1

[58] Energy for Sustainable Science at Research Infrastructures workshop series, https://indico.esrf.fr/event/2/