TOWARDS DIFFRACTION LIMITED STORAGE RING BASED LIGHT SOURCES

L. Liu[†] and H. Westfahl Jr.
Brazilian Synchrotron Light Laboratory, LNLS, Campinas, Brazil

Abstract

Experimental x-ray techniques that benefit from the great increase in brightness and coherent flux provided by the fourth generation of synchrotron light sources, based on recent advances in accelerator design and technology, are widely expanding nowadays. The basic ingredient to higher brightness is a further reduction of the electron beam emittance in storage rings dedicated to light sources. However, to fully explore the potential of these new sources, it is necessary to optimize other variables as well, such as the proper matching of electrons and photons phase-space and the possibility of using new kinds of insertion devices. Equally important is to try new ways to improve the integration between the light source capabilities and the experiment needs. In this work, recent progress of low emittance rings will be reviewed and the efforts to improve transverse coherent flux and source-to-beamline integration at the Brazilian Sirius project will be described.

INTRODUCTION

Recent progress in the development of low emittance storage ring light sources based on multi-bend achromat (MBA) lattices promise to deliver stable x-ray beams with much higher coherent flux in the tender and hard x-ray energy ranges when compared to present third-generation sources. These new rings, reaching natural emittances on the order of 100 pm.rad, have been named the fourth-generation of storage rings (4GSR). Their development was made possible due to recent breakthroughs in key accelerator technologies [1, 2].

Simultaneously, experiments conducted in current third-generation sources over the last years are requiring ever increasing brightness and transverse coherence from the source, promoting big advances in insertion device technology along with experimental techniques and beamline optical component technology. Thus, the scientific cases for applications requiring brightness and coherence beyond what is available at current third-generation sources is growing very fast. Most synchrotron radiation facilities today exploit coherence in their scientific programs in areas such as coherent diffraction imaging techniques, x-ray photon correlation spectroscopy, nano-focusing, etc.

The quest for higher coherence and brightness is usually associated with the reduction of the electron beam emittance. Fourth-generation storage rings can achieve about 1 to 2 orders of magnitude reduction by employing the multi-bend achromat lattice (MBA), where many dipoles per cell are used to keep the dispersion function low inside the dipoles. Besides the number of dipoles, other dependencies can also be explored, such as the transverse field gradient in the dipoles, longitudinal dipole gradient, damping wigglers, and more recently, anti-bends or reverse bend dipoles are also being used. However, in addition to emittance reduction, the proper matching of the phase space distribution of the electrons to the photons is also important to maximize the intensity of coherent flux arriving at the beamlines. In the case of Sirius, the coherent flux is increased by a factor of ~2 for photon energies up to ~4 keV by tuning the electron beam phase-space distribution in 15 insertion device straight sections. We note that this increase can be achieved quite inexpensively as compared to the same increase through emittance reduction.

In this work, we describe the efforts made at Sirius, the new fourth-generation storage ring under construction at the Brazilian Synchrotron Light Laboratory (LNLS) in Campinas, to improve the effective brightness and transverse coherent flux at the beamlines.

THE PATH TOWARDS DIFFRACTION LIMITED STORAGE RINGS

Synchrotrons started to be used as Light Sources in the early 1960's in a parasitic way, in accelerators designed for particle collision. These are known as the first-generation synchrotron light sources. Over the years, the number of experiments using synchrotron light increased and, in the 1980's, the first synchrotrons dedicated to producing light from bending magnets were built, inaugurating the second-generation sources. Spectroscopy and crystallography experiments soon started to require maximum flux within small phase space volume (brightness) to improve the spectral resolution and match the incident beam to the small crystal sizes. The advent of insertion devices represented a big step towards achieving high brightness and the early third-generation of storage rings, built from the 1990's, where specially designed with long straight sections to accommodate wigglers and undulators. A big number of late third-generation sources started to operate from mid-2000's all over the world, based on double-bend achromat lattices (DBA): Soleil in France, Diamond in UK, PETRA-III in Germany, AS in Australia, SSRF in China, PLS-II in Korea, etc. These light sources reached electron beam emittances of a few nm.rad. Two machines based on DBA cells were recently commissioned: NSLS-II in the US, reaching sub-nm.rad emittance with damping wigglers, and TPS in Taiwan. The third-generation machines promoted many advances in accelerator technology to improve brightness and beam stability, such as the top-up injection scheme, orbit and

† liu@lnls.br

ISBN 978-3-95450-182-3

bunch-by-bunch feedback systems, low impedance vacuum components, high stability mechanical support systems, etc. There has also been an extraordinary development in insertion device technology: in-vacuum and cryogenic undulators, super-conducting devices, elliptically polarizing undulators, revolver undulators, canted undulators. These advances are now being extrapolated to make the fourth-generation machines become reality.

The key idea to far exceed the 1 nm.rad barrier is the implementation of the MBA lattice. MAX-IV in Sweden was the first machine to explore this kind of lattice and its successful commissioning [3] late in 2015 marks the beginning of the new fourth-generation of storage ring synchrotron light sources. MAX-IV will soon be followed by Sirius [4], in Brazil, with commissioning expected for 2018. Both are green-field projects. The great improvement in brightness promised by the new approach triggered upgrade programmes and studies in most of the existing third-generation machines. Some examples are given in [5-11]. More green-field projects are also being planned [12,13]. The area of storage-ring based synchrotron light sources is experiencing a very exciting period with new developments worldwide in several fronts: tools to design, model and optimize accelerators; new accelerator technologies to cope with very tight lattices, higher demands and requirements on tolerances and stability, smaller apertures for beam injection; new beamline optics and experimental techniques, etc.

Although the idea of MBA lattices to reduce the emittance was already proposed in the early 1990's [14] their practical implementation had to wait for the advances in accelerator technology as well as simulation capability that came only recently. In the MBA cell, many weak bendings are used to keep the dispersion low inside the dipoles and thus reduce the radiation effects on emittance excitation. This condition, in turn, requires strong field gradients from quadrupoles and sextupoles to keep the optical functions focused and to compensate for chromatic aberration effects. The strengths required have a big impact on the design of the magnets: the bore radius must shrink and consequently the aperture available for the vacuum chambers is also reduced. The small vacuum chamber apertures are a challenge to the vacuum system not only because the vacuum conductance is reduced but also because of the high radiation powers involved. Resistive wall impedance also becomes an issue and require R&D on vacuum components. The strong nonlinear dynamics limits the aperture region where the beam is stable making it difficult to inject the beam in the conventional off-axis scheme and novel injection schemes are being proposed using on-axis injection where a new beam replaces the stored beam at each injection pulse [15]. This scheme is known as swap-out injection and requires development of ultra-fast pulsed magnets. Stability requirements for such small beam sizes is also a challenge not only for beam instrumentation and feedback systems but also for mechanical support systems, requiring integrated design optimization of floor, girders, magnets and beamline components. The compactness of the resulting lattices is also very challenging and has led to the development of combined function magnets, use of permanent magnet materials for dipoles, special vacuum components, etc. Finally, fourth-generation machines represent a major engineering challenge that is pushing forward the present state-of-the-art accelerator technology.

The pursuit for emittance reduction is, however, not limited to increasing the number of dipoles. New ingredients seldom used in third-generation machines are now being used: transverse field gradient in the dipoles to help both, increase the horizontal damping partition number and improve betatron function matching; longitudinal gradient bending magnets to compensate the variation of the optical functions along the bend trajectory in a way that lower energy photons are radiated where emittance excitation is higher and vice-versa; use of anti-bends, or reverse bends, to disentangle the dispersion and the horizontal betatron functions, adding extra flexibility to tailor the optical functions, recently proposed by A. Streun [16].

In parallel, continuous improvement of design and accelerator modelling tools together with modern computational resources have contributed a lot to the performance optimization of these highly nonlinear machines. Yet unconventional magnets such as octupoles are increasingly being used to optimize the nonlinear dynamics of these machines [17]. Other strategies are being used either separately or in combination such as the creation of dispersion bumps in the cell to reduce the chromatic sextupole strengths [5] and the setting of special phase advances between sextupoles to cancel higher order resonance terms.

The effect of MBA lattices on emittance reduction can be clearly seen in Figure 1, where the normalized emittance ε/γ^2 is displayed as a function of ring circumference for various machines, where γ is the relativistic electron energy. We note that the possibility of reducing the emittance while limiting the ring circumference is a very significant feature since the size of the machine has a major impact on the total cost of the facility.

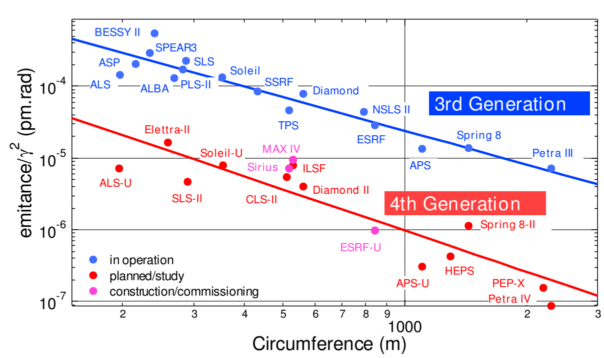

Figure 1: Normalized emittance as a function of ring circumference for various storage ring light sources. The trend lines clearly show the effect of MBA lattices on emittance reduction for the new 4th generation machines.

For a given ultra-low emittance ring, it is also necessary to match properly the electrons and photons phase-space to maximize the coherent flux. For typical undulator lengths the matching condition requires that both, x and y betatron functions, are simultaneously focused to small values close to 1m at the centre of the undulator straight sections. This is a demanding requirement, especially for the horizontal plane.

Finally, the possibility of installing new kinds of insertion devices is also important, such as Delta or helical undulators, as well as the implementation of new ways to improve the integration between the light source capabilities and the experiment needs, such as direct control of source position from the beamline.

In the following sections, we describe some of the efforts to improve transverse coherent flux and source-to-beamline integration at the Brazilian Sirius project.

SIRIUS, THE BRAZILIAN LIGHT SOURCE PROJECT

Sirius is a 4th generation storage ring that is under construction at LNLS in Campinas, Brazil. It will be the second 4th generation machine to start operation worldwide. The 518m circumference electron storage ring is based on a 5BA lattice with a (bare machine) horizontal emittance of 250 pm.rad for a 3 GeV beam. The lattice is designed such that a further reduction to 150 pm.rad can be achieved with the extra damping provided by the envisaged insertion devices. The project is now preparing to start installation by the end of this year and to start beam commissioning in the next year. Figure 2 shows an aerial view of Sirius building construction early March this year and Table 1 lists Sirius main parameters.

Figure 2: Aerial view of Sirius building construction on March 2017.

Table 1: Sirius Main Parameters

Parameter	Value	Unit
Beam energy	3.0	GeV
Circumference	518.4	m
Lattice	20 x 5BA	
Natural emittance*	0.25 → 0.15	nm.rad
Nominal current	350	mA
Straight sections	5 x 7m; 15 x 6m	
Energy spread	0.085	%

* bare machine → with IDs

Sirius Lattice Design and Optics

The Sirius magnet lattice is based on a modified 5BA cell, reaching a horizontal emittance of 250 pm.rad with 20 cells in a 518m circumference and 3 GeV ring. To optimize the emittance, a modest transverse field gradient (7.8T/m) is added to the weak dipoles (0.58T) and a longitudinal gradient bend is used in the centre dipole BC, where a sharp peak field reaches a maximum of 3.2T, creating a collimated hard X-ray dipole source with critical photon energy ε_c=19 keV and low contribution to the total energy loss per turn. Unlike the other dipoles, this central one will be made with permanent magnet material. The side electromagnetic dipoles B1 and B2 have the same curvature but different lengths that were also used as parameters for emittance minimization. Although the lengths are different, they are made with the same unit blocks. A schematic picture of Sirius 5BA cell with the magnetic elements is shown in Figure 3.

The dispersion function is matched to zero at the insertion straight sections, favouring further emittance reduction with the insertion of IDs. In fact, a gradual reduction from 250 to 150 pm.rad is expected from the bare to the fully occupied machine.

The lattice has two types of straight sections for insertion devices, 7m long high horizontal beta sections and 6m long low horizontal beta sections. The vertical beta is always low in both types of section. A quadrupole doublet is used to match the arcs to the high beta sections whereas a quadrupole triplet is used for the low beta ones. In the low beta sections, we have simultaneously focused both, the x and y beta functions to 1.5m at the center of the straight section to improve the phase-space matching of the electron beam to the photon beam from undulators. In the next section, we show that this matching can increase the coherent flux in low beta sectors by a factor of ~2 with respect to the high beta ones.

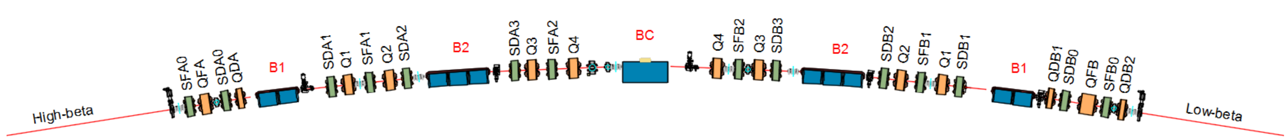

Figure 3: One Sirius modified 5BA cell with electromagnetic low field dipoles B1 and B2, and a permanent magnet dipole BC with a 3.2 Tesla high field peak in the middle. The matching sections consist of quadrupole doublets in the high β_x sections and quadrupole triplets in low β_x sections.

ISBN 978-3-95450-182-3

In addition to improving the electron-photon phase-space matching, the low beta sections also have a reduced horizontal beam-stay-clear, that allows the installation of small horizontal as well as vertical gap insertion devices. With this capability, Sirius will be one of the first storage rings to extensively use Delta type undulators. A modified Delta undulator [18] is being prototyped at LNLS.

With the advantages represented by the low beta sections, we have modified the Sirius optics from a 10-fold symmetric mode with alternating low and high beta sections, to a 5-fold symmetric mode with 15 low and 5 high beta sections. The Sirius lattice functions are shown in Figure 4 and the beam-stay-clear in Figure 5.

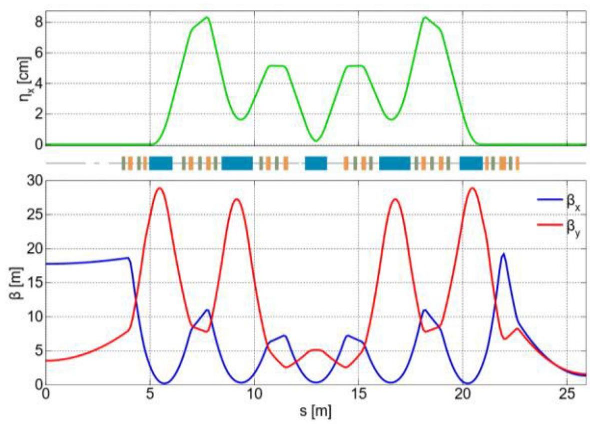

Figure 4: The lattice functions for one Sirius 5BA cell with 1/2 high beta straight to the left and 1/2 low beta straight to the right. One machine period consists of one high beta and three low beta straights.

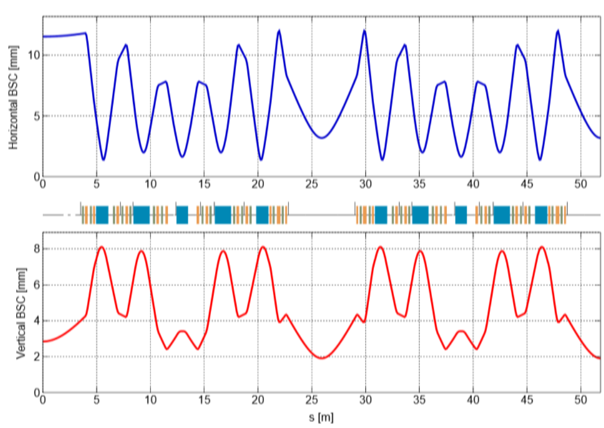

Figure 5: Beam-stay-clear for Sirius. In the low beta sections, the full aperture required for the beam for a 2.4m long undulator at the centre of the straight section is 8.6mm in the horizontal and 4.8mm in the vertical planes.

Table 2: Sirius Phase-1 ID Parameters

ID	B_0 [T]	λ [mm]	L [m]	K_{max}	g* [mm]
Delta21	1.12	21	2.4	2.2	7.0
Delta52	1.19	52	3.6	5.85	13.85
APU19	1.28	19	2.4	2.3	5.0
APU20	1.07	20	2.4	2.0	6.2

* the gap is diagonal for Delta undulators

The parameters of Sirius Phase-1 IDs are listed in Table 2 and their effect on the equilibrium emittance and energy spread are shown in Figure 6.

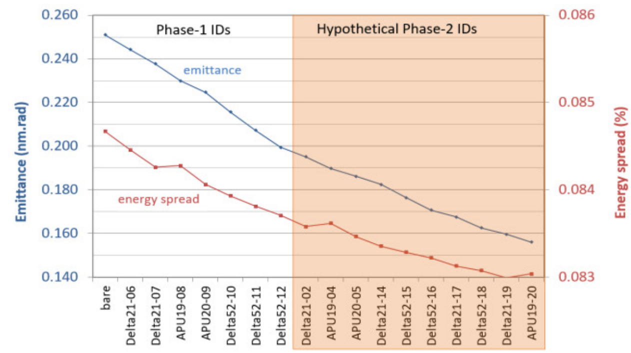

Figure 6: Effect of insertion devices on the Sirius natural emittance and energy spread for Phase-1 IDs and hypothetical Phase-2 IDs.

Low Beta Sections: Phase-space Matching

Extracting the highest possible coherence fraction of the radiation emitted by storage rings is paramount in most experiments performed in third- and fourth-generation synchrotrons. Although a higher coherence and brightness is usually associated with the reduction of the electron beam emittance, this is not the only optimization parameter. The convolution between the phase-space distribution of the photons emitted by a single electron (described by their Wigner Distribution Function – WDF) and the phase-distribution function (PDF) of the electrons in the storage ring results in the effective WDF of the photons delivered to the beamlines. Such convolution is not solely dependent upon the emittance of the electrons and the photons, but also on the betatron function. If a Gaussian beam approximation is assumed for the photons, as for the electrons, it can be shown that the convolved electron–photon emittance is minimized when $\beta_{x(y)} = \sigma_r/\sigma_r'$, where $\sigma_r(\sigma_r')$ is the rms radiation beam size (divergence). For an undulator having length L_u, this is achieved when, at the centre of the undulator straight section, $\beta_{x(y)} = L_u/\pi$.

However, the phase space of the photons emitted by an undulator is not exactly Gaussian, but a more complicated distribution. Figure 7 shows the WDF calculated at the centre of a 3.6 m undulator of 5.2 cm period at 900 eV in a 3 GeV storage ring. Nevertheless, optimizing the convolution between the single electron WDF and the electron beam PDF is still necessary to extract the highest possible brilliance or coherence fraction. To show how this depends on β_x we compare the resulting WDF for Sirius and MAX IV storage rings, which have similar emittances but different β_x functions. The convolution smooths out the effective WDF of the photons in both cases. However, in Sirius β_x =1.5 m and the final WDF still resembles the single electron WDF shape. For the MAX IV storage ring where β_x = 9 m on the other hand, the resulting WDF basically reflects the stretched

Gaussian shape of the electron beam PDF. This results in a final brilliance, (value of the WDF at the centre point of the phase space) that is twice as large for Sirius than for MAX IV, even though their emittances are approximately the same.

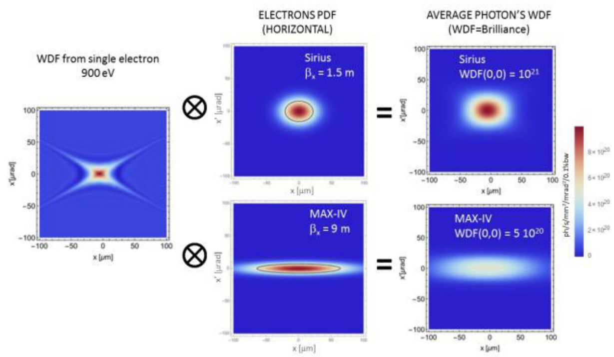

Figure 7: The convolution between the WDF of 900 eV photons and the electron PDF from Sirius and MAX IV calculated with Spectra 10.1 [19].

Although the optimal β function for the convolution cannot be analytically calculated from the Gaussian distribution, one can still infer it numerically by optimizing the horizontal coherence fraction. Figure 8 shows the horizontal coherence fraction as a function of the β_x as calculated from the WDF for two different undulators, one with 2.4m and a 20mm period (blue and yellow dots, from the numerical integration of the WDF, and lines, from the Gaussian approximation) and the other, for a 3.6m and 52mm period (green dots, from numerical integration of the WDF and green line, from the Gaussian approximation). Note that the maxima expected from the analytical approximation closely matches the maxima from the exact numerical calculation. The vertical blue and red dashed lines are placed at the Sirius and MAX IV beta functions, respectively. Note that the Sirius betatron function is nearly optimal for both undulators.

Optimization of other Relevant Parameters

To take full advantage of the increased coherent X-ray flux that will be provided by the new sources, it is important to integrate the light source and beamline teams in the discussions of the best strategies for the beamline experiments. We have been making this exercise for Sirius and a good example of the outcome is an improved solution for the scanning nanoprobe (CARNAÚBA) beamline that will be able to perform simultaneous X-ray fluorescence and ptychography with a diffraction limited focal spot of approximately 50 nm and 10^9 ph/s/nm^2 (at 5 keV) [21]. For the sake of comparison, in reference [22] frozen hydrated cells where scanned with a 100 ms pixel transit time, to deposit a photon density of about 10^4 ph/nm^2 per scanning point, that resulted in a sub-20 nm resolution ptychographic imaging and a sub-100 nm resolution X-ray fluorescence imaging of ions at native concentrations. The gain in coherence flux in Sirius will allow pixel transit times of the order of 10 μs, potentially reaching scanning velocities and accelerations that may be too large for fragile samples or even for optical systems. Therefore, for such experiments we intend to scan the photon beam through the sample instead of (or in addition to) scanning the sample through a fixed beam position, as proposed in reference [23]. In this way, we can potentially have much faster and precise scans with lower mechanical disturbances. For Sirius, this solution can be implemented using 4 fast correctors for each plane, all located in the ID straight section, producing a closed orbit bump through the undulator as shown in Figure 9. Bump amplitudes of ±400μm, that would result in a 20 x 40 pixel scan grid in ptychography would require corrector strengths of ±400μrad, that are within the limits of Sirius correctors. Larger scanning grids could be achieved by combining the fast source scanning with slower mechanical sample scans in a coarser grid.

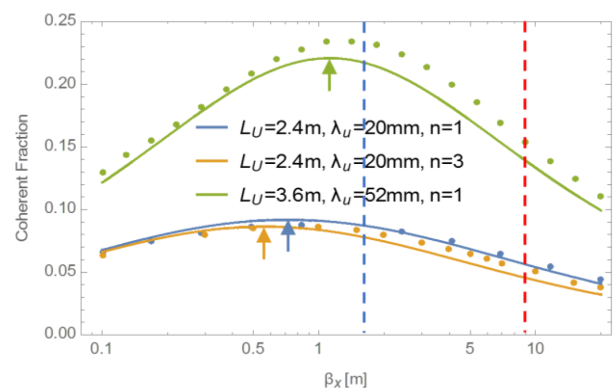

Figure 8: Optimization of the horizontal coherence fraction by tuning the beta function for two different undulators in a 250 pm.rad storage ring. The dots correspond to the numerical integration of the WDF and the full lines correspond to the Gaussian approximation of reference [20] whose optimal values are pointed by the corresponding arrows. The betas for Sirius and MAX IV are represented by the blue and red dashed lines, respectively.

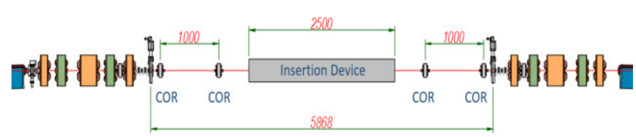

Figure 9: Schematic view of the low beta ID straight section with 4 correctors to scan the beam through the undulator in the Sirius CATERETÊ beamline. The correctors can all be installed in the same straight section producing a closed local beam bump.

ACKNOWLEDGEMENT

The work presented in this paper involves a collective collaboration not only from all LNLS divisions but also from other colleagues from similar laboratories worldwide.

REFERENCES

[1] R. Hettel, "Challenges in the design of diffraction-limited storage rings", in Proc. 5th Int. Particle Accelerator Conf. (IPAC'14), Dresden, Germany, Jun. 2014, paper MOXBA01, pp. 7-11.

[2] R. T. Neuenschwander *et al*., "Engineering challenges of future light sources", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, USA, May 2015, paper TUXC2, pp. 1308-1313.

[3] M. Eriksson *et al*., "Commissioning of the MAX IV light source", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper MOYAA01, pp. 11-15.

[4] A. R. D. Rodrigues *et al*., "Sirius status report", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper WEPOW001, pp. 2811-2814.

[5] P. Raimondi, "The ESRF low emittance upgrade", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper WEXA01, pp. 2023-2027.

[6] C. Sun *et al*., "Optimization of the ALS-U storage ring lattice", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper WEPOW050, pp. 2959-2961.

[7] R. Nagaoka *et al*., "Design considerations of a 7BA-6BA lattice for the future upgrade of Soleil", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper WEPOW003, pp. 2815-2817.

[8] R. Bartolini *et al*., "Concepts for a low emittance-high capacity storage ring for the Diamond light source", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper WEPOW045, pp. 2943-2946.

[9] A. Streun *et al*., "Proposed upgrade of the SLS storage ring", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper WEPOW038, pp. 2922-2925.

[10] S. Henderson, "Status of the APS upgrade Project", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, USA, May 2015, paper TUPJE067, pp. 1791-1793.

[11] H. Tanaka *et al*., "Spring-8 upgrade project", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper WEPOW019, pp. 2867-2870.

[12] G. Xu et al, "Recent physical studies for the HEPS Project", in Proc. 7th Int. Particle Accelerator Conf. (IPAC'16), Busan, Korea, May 2016, paper WEPOW026, pp. 2886-2888.

[13] E. Ahmadi *et al*., "Designing na ultra low emittance lattice for Iranian light source facility storage ring", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper WEPOW016, pp. 2858-2860.

[14] Einfeld, D. & Plesko, M., *Nucl. Instrum. Methods Phys. Res. A*, vol. 335, pp. 402-416, 1993.

[15] A. Xiao, M. Borland and C. Yao, "On-axis injection scheme for ultra-low-emittance light sources", in *Proc. Particle Accelerator Conf. (NA-PAC'2013)*, Pasadena, USA, Oct. 2013, paper WEPSM13, pp. 1076-1078.

[16] A. Streun, "The anti-bend cell for ultralow emittance storage ring lattices", *Nucl. Instr. Meth. Phys. Res. A*, vol. 737, pp. 148-154, 2014.

[17] S. C. Leeman and A. Streun, "Perspectives for future light source lattices incorporating yet uncommon magnets", *Phys. Rev. ST Accel. Beams*, vol. 14, p. 030701, Mar. 2011.

[18] L. N. P. Vilela *et al*, "Studies of Delta-type undulators for Sirius", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper WEPIK053, this conference.

[19] T. Tanaka and H. Kitamura, "SPECTRA – a synchrotron radiation calculation code", *J. Synchrotron Radiation*, vol. 8, p. 1221, 2001.

[20] H. Westfahl Jr *et al*., "The coherent radiation fraction of low-emittance synchrotrons", *J. Synchrotron Radiation,* vol. 24, p. 566-575, 2017.

[21] http://lnls.cnpem.br/linhas-de-luz-sirius/carnauba

[22] J. Deng *et al.* "X-ray ptychographic and fluorescence microscopy of frozen-hydrated cells using continuous scanning" *Sci. Rep.* vol. 7, p. 445, 2017.

[23] M. D. de Jonge, C. G. Ryan, and C. J. Jacobsen "X-ray nanoprobes and diffraction-limited storage rings: opportunities and challenges of fluorescence tomography of biological specimens", *J. Synchrotron Radiation*, vol. 21, p.1031–1047, 2014.