# A NEW 5BA LOW EMITTANCE LATTICE FOR SIRIUS

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*Abstract*

Sirius is a third-generation low emittance synchrotron light source under construction at LNLS, the Brazilian Synchrotron Light Laboratory. A new 5BA lattice was designed in replacement for the previous TBA lattice with the aim to reduce the emittance to sub-nm.rad values. The new design has a circumference of 518 m with 20 achromatic straight sections and a natural emittance of 0.28 nm.rad at 3 GeV for the bare lattice (without IDs). The dipoles combine low 0.58 T field magnets for the main beam deflection with a 2 T short superbend magnet sandwiched in the center dipole. This creates a longitudinal dipole gradient that is used both to lower the emittance and to provide hard X-ray dipole sources.

## INTRODUCTION

Sirius is a new synchrotron light source under construction at the LNLS campus in Campinas, state of São Paulo, Brazil. The previous source, known as UVX, still today in operation for users, is based on a 1.37 GeV electron storage ring that was built along the late 1980s and into the 1990s. Over more than 15 years of routine operation, the expansion capabilities of UVX have reached limits that can no longer be overcome. In November 2008 the Brazilian Federal Government approved funding for preliminary studies for a new source with the aim to provide the SR user's community with a brighter light source. Since then the design of Sirius evolved to a TBA lattice in 2011 [1] that was already excellent by today's standards. However, a decision was taken in June 2012, after the first MAC meeting, to push Sirius for tomorrow's brightness standards, to sub-nm emittances, to ensure it will be a first-class source when it is commissioned in the near future. Figure 1 shows an aerial view of the LNLS campus with the location of UVX and Sirius.

The natural next step to further reduce the emittance is by increasing the total number of dipoles in the ring. We tried thus the 5BA lattice. A factor of about 4.5 emittance reduction could be expected from the third power dependence of the theoretical minimum emittance (TME) on the bending angle per dipole, and this would be sufficient to bring the emittance down to sub-nm values. We have however achieved a factor of 10 reduction for the achromatic mode, meaning that the new 5BA solution is now closer to the TME than the previous TBA.

The circumference increased to 518 m, an acceptable 8% increase, and the 20 straight sections are now composed of 10 sections of 7m and 10 sections of 6m.

Up to now only lattices under the achromatic condition were explored. This condition is preferred to preserve and even improve the emittance when strong insertion devices are used. Besides the number of dipoles, we also resort to other known methods to reduce the emittance, as was done in the TBA design. We introduced transverse field gradients into the dipoles to increase the horizontal damping partition number, we used shorter dipoles at the achromat ends where the dispersion function is matched to zero, and we introduced a longitudinal field gradient in the center dipole. This longitudinal field gradient is created by sandwiching a thin high-field superbend of 2 T in the center of the low field main deflection dipole of 0.58 T. In addition to reducing the emittance, these thin superbends will also produce hard X-rays of critical photon energy of 12 keV in just a small fan, keeping the overall dipole radiation power at low level. The option for a relatively low dipole field favors a smaller beam energy spread as well as further emittance reduction with insertion devices.

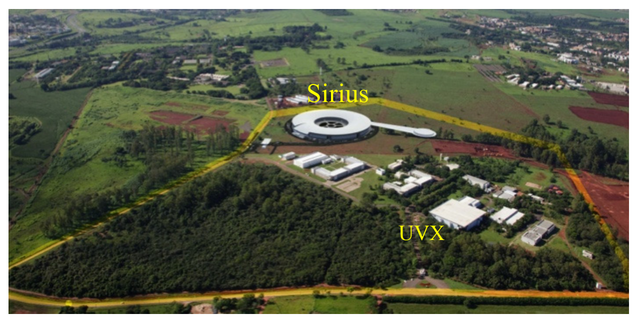


Figure 1: Aerial view of LNLS campus.

Table 1 compares the main parameters of the previous TBA lattice in the Low Emittance Mode and the new 5BA design.

All efforts were made to minimize the impact of the new design on the cost and schedule as well as on the specifications of the subsystems. While the total budget and schedule could be kept almost the same, the specifications for the subsystems required from drastic changes for some, like vacuum, to little for others.

A major modification is caused by the much stronger quadrupoles and sextupoles required in the new lattice. The stronger magnets result in smaller apertures for the vacuum chamber, and this led us to change the main chamber material from stainless steel to copper and the main pumping system from discrete ion pumps to distributed NEG coating. A license agreement has been signed between LNLS and CERN allowing the manufacturing of these chambers at LNLS.

The small beam aperture also requires a low emittance booster to assure an efficient injection process. We have thus redesigned the booster to share the same tunnel as the storage ring. The achieved booster emittance of 3.8

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nm.rad is considerably lower than the 37 nm.rad of the previous booster design.

Table 1: Comparison of Sirius TBA (in Low Emittance Mode) and Sirius 5BA lattices.

| Parameter | TBA(LE) | 5BA | |
|---|---|---|---|
| Energy | 3.0 | 3.0 | GeV |
| Circumference | 479.7 | 518.25 | m |
| Straight sections, number x length | 4 x 9 m<br>4 x 7 m<br>12 x 5 m | 10 x 7 m<br>10 x 6 m | |
| Betatron tunes, H/V | 24.26/13.16 | 46.19/14.13 | |
| Mom. comp. factor | 7.4e-4 | 1.74e-4 | |
| Nat. chrom., H/V | -48/-47 | -113/-80 | |
| Emittance (w/o IDs) | 1.7 | 0.28 | nm.rad |
| Harmonic number | 800 | 864 | |
| $\sigma$@ superbend, HxV* | 61 x 13 | 11 x 4.0 | μm$^2$ |
| $\sigma$@ short SS, HxV* | 137 x 3.2 | 33 x 1.4 | μm$^2$ |

* rms beam size $\sigma$ considering 1% emittance coupling.

## THE NEW 5BA LATTICE

### *Linear Optics*

The new Sirius lattice is composed of 20 5BA cells with alternating 7m and 6m achromatic straight sections. Matching between the straight sections and the arcs are performed by quadrupole doublets in the 7m straights and triplets in the 6m straights. Although the ring has 10-fold symmetry, the lattice functions can be made 20-fold symmetric since the 6m straight sections are exactly the same as the 7m ones except for an extra quadrupole on each end as shown in Figure 2. This extra quadrupole was included to allow for a mode with low horizontal beta function in the 6m straight sections, the mode AC10, in which the optics will have symmetry 10. The low horizontal beta function optimizes the brilliance of short period undulators and provides a higher coherent flux. The 20-fold symmetric mode, named AC20, with high horizontal beta function in all straight sections, was easier to optimize and we quickly arrived at a sufficiently large dynamic aperture solution. The AC10 mode required a more laborious optimization process but could also be satisfactorily optimized to large dynamic and momentum apertures, even in the presence of realistic, although challenging, multipole, excitation and alignment errors. We have resorted to optimization codes such as MAD, OPA and MOGA [2-4].

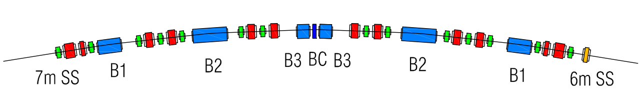


Figure 2: Layout of the 5BA arc showing the 2 T superbend BC sandwiched in the center dipole B3-BC-B3.

Figure 2 and Figure 3 show, respectively, a schematic drawing and the lattice functions for one Sirius 5BA cell, or half-superperiod in the AC10 mode.

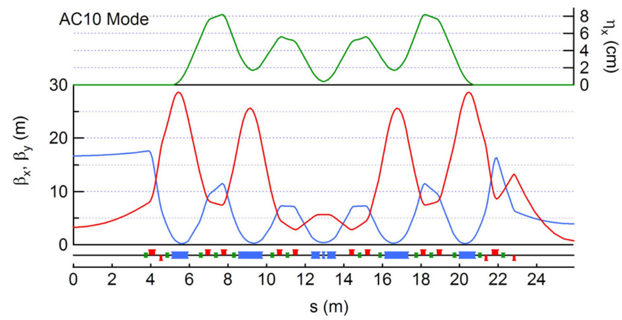


Figure 3: Lattice functions for Sirius half-superperiod in the AC10 mode.

### *Orbit and Coupling Correction*

Beam stability is one of the most important issues in low emittance synchrotron light sources. The usual requirement of stability better than 10% of the beam size at source points implies few tenths of μm stability in the vertical plane for Sirius. To achieve this tolerance many subsystems are being carefully designed, from floor foundations to magnet girders to BPM supports and so on. The orbit feedback will consist of a slow (< few Hz) and a fast system (up to about 100 Hz). The slow feedback will correct the orbit globally in all 200 BPMs in the ring using the 160 horizontal and 120 vertical dedicated correctors. In the new lattice design we have separated the correctors from the sextupoles due to the much higher sextupole strengths. The fast orbit feedback system will use special correctors to correct the orbit at the insertion device locations and superbends.

The skew quadrupoles for coupling correction are installed as additional coils in one pair of weak sextupoles per straight section. Coupling is corrected to a 1% level by minimizing the off-diagonal elements in the orbit response matrix. Full coupling minimization is not needed since the vertical emittance would be lower than the diffraction limit.

Dynamic aperture (DA) simulations have shown that misalignment errors are the dominant source of DA reduction. This is probably due to the fact that the closed orbit displacement at the sextupoles, which introduces an equivalent quadrupole focusing, causes a beta-beating that changes the optimized phase-advance between sextupoles. To minimize these effects the alignment tolerance specifications became tighter for the new lattice and BPMs have been placed close to the strongest sextupoles. The main parameters of the orbit correction system are shown in Table 2.

### *Dynamic Aperture*

The Sirius 5BA lattice requires much stronger sextupoles for chromaticity correction than the previous TBA lattice due to the larger natural chromaticities and the lower dispersion function. The nonlinear optimization process becomes more challenging and requires




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adjustments in the phase advance between sextupoles to minimize the resonance driving terms and chromatic tune shifts. We are aiming at minimum required dynamic apertures of 8 mm at the negative horizontal side to allow for injection and accumulation, and 4% momentum acceptance for a reasonable beam lifetime.

We have calculated the effect of optics symmetrization and coupling correction in the simulated lattice model in an attempt to improve the DA. The deleterious effects of alignment errors can be partially compensated in this way and the DA can be restored to almost the same value of the lattice without errors. An initial set of 11 planar insertion devices, including six 2m long in-vacuum undulators (IVU) and 2 high field wigglers, have been added to the lattice model in order to verify their effect on the non-linear dynamics. The IDs are modeled in tracking codes by corresponding kick maps. Their main effect on the DA is a limitation in the vertical plane due to the physical limit represented by the 4.2 mm gap IVU. The impact of undulators in elliptically polarizing mode is yet to be studied.

Figure 4 shows in the top row the effect of optics symmetrization and coupling correction and, in the bottom row, the effects of IDs on the dynamic aperture and momentum acceptance.

Table 2: Main parameters of the orbit correction system.

| | | |
|---|---|---|
| Alignment error* | 30 | μm |
| Roll angle error* | 0.2 | mrad |
| Excitation error* | 0.05 | % |
| Max. rms uncorrected COD (H/V)** | 1.9 / 4.4 | mm |
| Max. rms corrected COD (H/V) | 21 / 29 | μm |

*Gaussian distributions of random errors for all magnets truncated at 1 σ.
** With sextupoles off.

### *Beam Lifetime*

So far all the calculations of beam lifetime were done analytically. Assuming residual gas pressure of 1 nTorr, the elastic scattering lifetime obtained is 68.4 h. The inelastic gas scattering lifetime is 46.9 h for an energy acceptance of ± 4.06%. For the Touschek lifetime calculations we defined three different scenarios. First, the configuration of the bare machine with errors with a momentum acceptance of ± 4.06 %, the second scenario considers the effects of the IDs on beam equilibrium emittance and energy spread, and the last scenario takes into account the inclusion of a 3rd harmonic cavity. For all the scenarios shown we recalculated the lifetime including the IBS blow up. All the calculations consider a total current of 500 mA evenly distributed in all 864 bunches (uniform filling). The Touschek lifetime contributions are summarized in Table 3.

In all the calculations we considered a uniform filling, however when using a passive 3rd harmonic cavity and a non-uniform filling the bunch lengthening created by the cavity will be disturbed by the beam loading. Depending on the gap and filling pattern this effect can reduce the lengthening from a factor of 4-5, for a uniform filling, to a factor as low as 1.6. Further studies on this topic are being carried out.

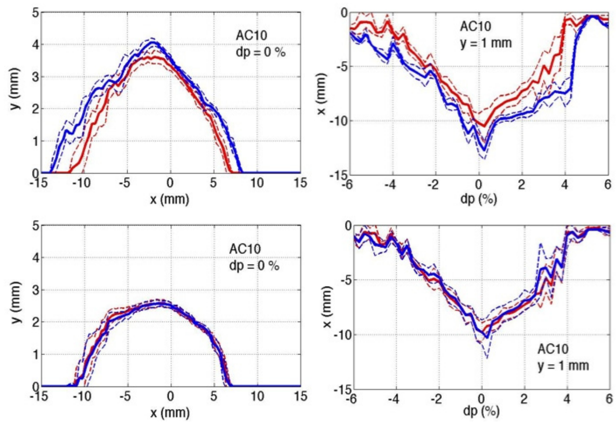


Figure 4: Dynamic aperture and momentum acceptance at the center of the 7m straight section for the AC10 mode for random machines with misalignment, excitation and multipole errors in all cases. Tracking for 3500 turns. Solid curves show the average aperture and dashed curves one standard deviations. Top: (Red) machines without symmetrization and coupling correction and (blue) machines with both corrections. Bottom: (Red) machines with physical aperture including the vertical restriction of the IVUs and (blue) machines with all 11 planar IDs.

Table 3: Calculated Touschek lifetime for Sirius.

| Scenario | Without IBS | With IBS |
|---|---|---|
| Bare lattice* | 3.6 h | 4.7 h |
| With IDs | 4.7 h | 5.3 h |
| IDs and 3rd harm. cavity | 19.7 h | 20.1 h |

*with misalignement, excitation and multipole errors included.

## CONCLUSION

A new lattice with 0.28 nm.rad emittance has been proposed and simulations show that it has large enough dynamic aperture and momentum acceptance to meet the beam injection and lifetime requirements.

## ACKNOWLEDGMENT

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