UPGRADED OPTICS FOR SIRIUS WITH IMPROVED MATCHING OF ELECTRON AND PHOTON BEAM EMITTANCES

L. Liu[*], F. H. de Sá, N. Milas, A. H. C. Mukai, X. R. Resende, LNLS, Campinas, Brazil

Abstract

A new optics has been designed for Sirius with improved betatron function matching in the 6 meter-long low beta straight sections for insertion devices. Both horizontal and vertical betatron functions are set to 1.5 m in the center of the section, improving the matching of the electron and undulator photon beams. In addition, the horizontal beam stay clear has also been reduced allowing for small horizontal gap devices as well as the conventional small vertical gap ones. The new design optics has been optimized to the same previous performance regarding dynamic aperture and momentum acceptance.

INTRODUCTION

To take advantage of the unprecedented X-ray brightness from insertion device photon sources offered by the 4th generation storage rings, it is important to match the electron and photon beam phase space orientations. It is well known that the effective photon beam distribution in phase space is the convolution between the diffraction-limited radiation emittance and the transverse electron beam emittances [1]. When the electron beam emittance becomes comparable to the diffraction-limited photon emittance, the effective photon beam brightness is greatly affected by the mutual orientations of both beams in phase-space. Matching the orientations will maximize the photon beam brightness. To improve the matching conditions in Sirius, we have reduced the horizontal betatron function at the center of the low β_x straight sections (SSB) from 4 in the previous mode [2] to 1.5 m in the new mode.

This modification also results in a reduction of the horizontal beam-stay-clear (BSC) at the SSB sections, which opens the possibility for small horizontal gap insertion devices in addition to the conventional small vertical gap ones.

DESIGN OPTICS

The Sirius lattice has alternating high and low horizontal betatron function straight sections for insertion devices. A high β_x is desired at the injection straight section and at long or canted undulator sections; and a low β_x optimizes the brightness from short undulator sources. At the high β_x sections (SSA) a quadrupole doublet is used to match the optical functions whereas at the low β_x sections (SSB) a quadrupole triplet is used.

* liu@lnls.br

The extra quadrupole at SSB reduces the straight section length from 7 to 6 meters.

We have recently upgraded the Sirius design optics to further improve the beam brightness from undulator sources installed in the center of the low beta sectors by reducing the horizontal betatron function from 4 to 1.5 m. This corresponds to the optimum matching for undulators of approximately 4.5 m in length, according to the relation $\beta_{opt} \approx L/\pi$. For Sirius, 2-m long undulators are planned for SSB sections. Although not perfectly matched for this case, an increase of 10 to 25% in brightness, depending on the photon energy, is expected.

The new optics can be implemented preserving the bare lattice emittance of 0.27 nm.rad and without requiring changes to magnets or power supplies. The reduction in horizontal beta leads to an increase in the horizontal tune by two integers while the vertical tune is reduced by one. The dynamic aperture and momentum acceptance for this new operation point in tune space have been optimized to the same values of the previous mode. As a result a similar beam lifetime of approximately 10 hours is achieved for 500 mA with third harmonic cavity, uniform filling, 1% emittance ratio and both chromaticities set to +1.5 to reduce resistive wall growth rates. The optimization process uses the tracking-based multi-objective genetic algorithm MOGA [3] to refine the initial solutions. The new optics has thus been adopted as the official design mode for Sirius.

Further modifications in the lattice have been implemented in connection with the detailed design of the magnets. In particular, the quadrupole lengths have been reduced, the slow orbit correctors and skew quadrupoles have been combined with the sextupoles, the different types of dipoles have been segmented into a rectangular unit block, and the horizontal and vertical fast orbit correctors have been combined to minimize the length of special vacuum chambers. The BPMs adjacent to the insertion straight sections have been moved closer to quadrupoles to optimize the beam-based alignment process and the BPM downstream the central dipole has been removed to avoid synchrotron radiation power. The reduction in quadrupole length and the option for combined sextupoles and orbit correctors opened up significant space in the lattice: the magnets share in the total circumference is reduced from 45% to 39%.

The new lattice configuration is shown in Figure 1 and the main parameters in Table 1. Figure 2 shows the lattice function modifications for the previous and the new design optics.
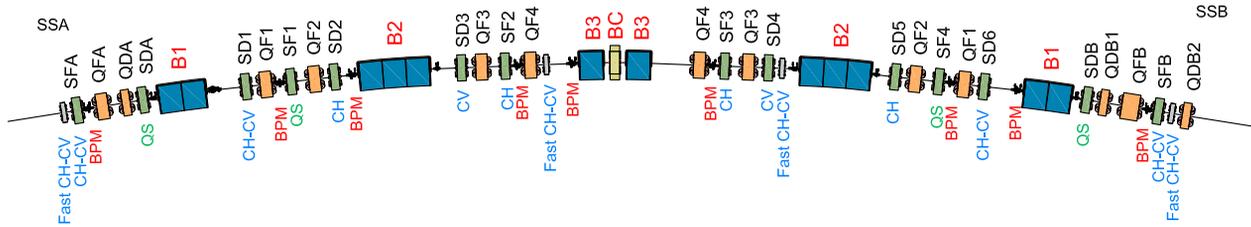
Figure 1: One arc of the Sirius storage ring new lattice with shorter quadrupoles, combined sextupoles and segmented dipoles. The center bending magnet BC is a high field (2 T) dipole radiation source. A quadrupole doublet is used in the high β_x straight sections SSA and a quadrupole triplet in the low β_x sections SSB.

Table 1: Sirius Main Parameters

	Previous	New lattice
Energy [GeV]	3.0	3.0
Circumference [m]	518.4	518.4
Magnet share [%]	45	39
Emittance [nm.rad]	0.2-0.28	0.19-0.27
Horizontal tune	46.19	48.14
Vertical tune	14.14	13.12
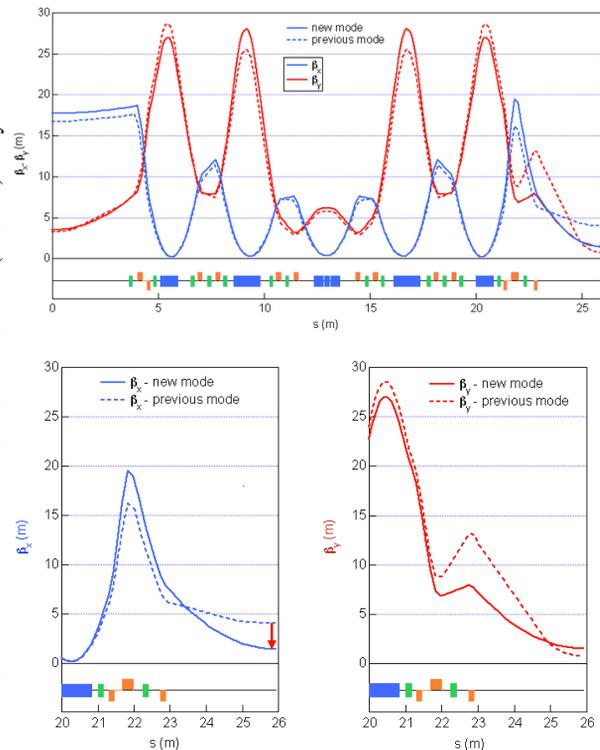
Figure 2: Lattice functions for one Sirius superperiod (top) and for the low horizontal beta straight section (bottom). The solid lines show the betatron functions for the new design optics and the dashed lines for the previous optics. Blue lines indicate horizontal and red line vertical betatron functions.

BRIGHTNESS IMPROVEMENT

To estimate the improvement in brightness for the new optics as compared to the previous one, we have assumed a 2 meter long undulator in the center of the straight section SSB. The electron beam distribution in phase space is convoluted with the photon beam distribution (fundamental peak only) along the undulator. The total density, given by the integration along the undulator, is shown in Figure 3 for 1 keV and 10 keV photons and both optics. As expected the gain in brightness is higher for lower energy photons, where the electron beam emittance is closer to the diffraction limited photon emittance and matching has a more important effect.
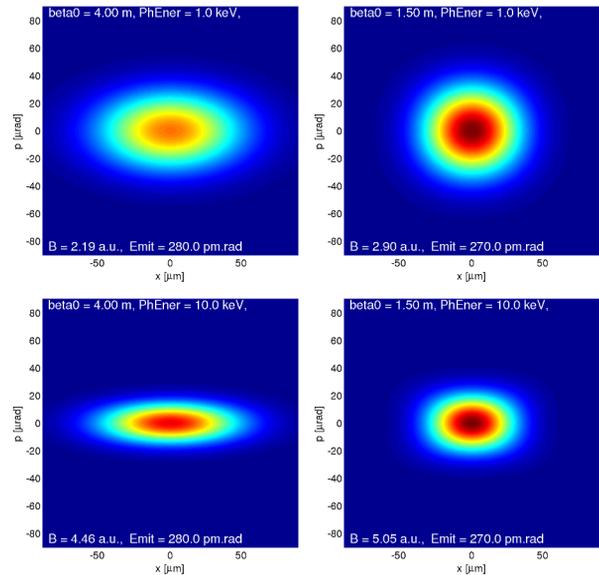
Figure 3: Phase space density representing the sum of the convolutions of the electron and photon beams along a 2 meter long undulator located at the center of SSB. Top row: 1 keV photons. Bottom row: 10 keV photons. Left: previous optics with β_x=4 m. Right: new optics with β_x=1.5m. The increase in brightness is 25% for 1 keV photons and 13% for 10 keV photons.

BEAM STAY CLEAR

The beam-stay-clear is defined here as the free aperture required for the beam as measured from its central orbit. In linear approximation, the BSC is symmetric about the central orbit. Nonlinear elements such as sextupoles can introduce an asymmetry as shown in Figure 4, where the linear and nonlinear BSC for Sirius are presented. The asymmetry in the horizontal plane is a result of the optimization process, in which the negative side of the horizontal dynamic aperture is maximized at the high β_x sections to improve the injection process. For safety, the linear BSC is used to specify aperture requirements for IDs. The vertical acceptance is limited by a 2 meter long insertion device with full gap of 4.5 mm located at the center of SSB straight section, and the horizontal acceptance is limited by the circular cross section vacuum chamber with 12 mm inner radius at the injection section. This corresponds to a 2 meter long insertion device with full horizontal gap of 8 mm at the center of SSB section. The gaps quoted here correspond to free apertures for the electron beam, thus some space have to be added either for tolerance, rf shielding or vacuum chamber to obtain the gap between magnet poles.
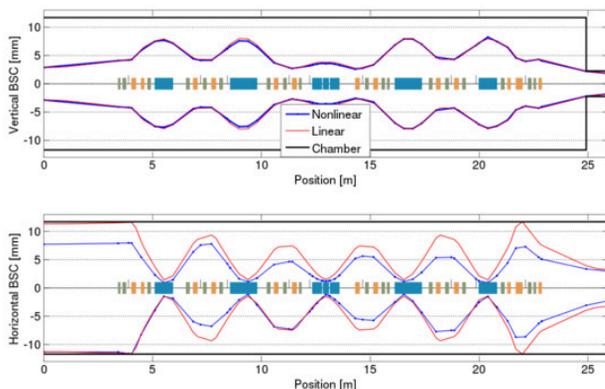
Figure 4: Beam-stay-clear in linear approximation (red curves) and calculated from tracking simulations including nonlinear elements (blue curves) for the vertical (top) and horizontal (bottom) planes. Note the asymmetry in the horizontal plane introduced by the optimization method, in which the negative side of the dynamic aperture is maximized at the high β_x straight sections to improve the injection process.

NONLINEAR OPTICS OPTIMIZATION

The nonlinear optimization for the new optics resulted in a machine performance similar to the previous mode as far as beam dynamics is regarded. A horizontal dynamic aperture at the negative side of the injection straight in excess of the target 8 mm is achieved for all 20 random machines that were simulated with the nominal set of alignment, multipole and excitation errors. Sirius hypothetical Phase-2 IDs described in ref.[2], which would fill up all available straight sections, are also included in the simulations. Figure 5 and Figure 6 show

the statistical results of dynamic aperture and momentum acceptance simulations.
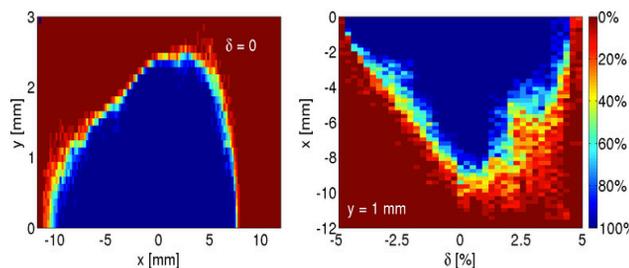
Figure 5: On-momentum (left) off-momentum (right) dynamic apertures at the center of the injection straight section for 20 random machines with Phase-2 IDs and alignment and multipole errors, orbit, tune, coupling and optics corrections. The color scale represents the percentage of simulated machines for which a given point of the grid corresponds to a stable initial condition. Calculation setup: 6D tracking with Trackcpp[*]; 5000 and 3500 turns for, respectively, on and off momentum particles; with vacuum chamber physical aperture (12x12 mm²) and IDs at minimum gap (12x2.25 mm² at SSB sections and 12x4 mm² at SSA sections).
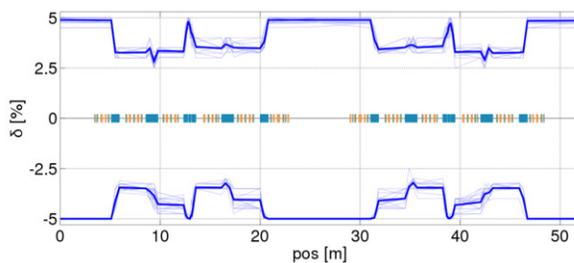
Figure 6: Momentum acceptance for one superperiod of the ring for the same 20 machines and same calculation setup described in Figure 5, except for the number of turns, 2000 in this case.

ACKNOWLEDGEMENT

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[*] Trackcpp is a particle tracking code developed at LNLS and based on Accelerator Toolbox and Tracy passmethods.