STUDIES OF DELTA-TYPE UNDULATORS FOR SIRIUS

L. N. P. Vilela*, L. Liu, X. R. Resende, F. H. de Sá, Brazilian Synchrotron Light Laboratory (LNLS), Campinas, Brazil

Abstract

In this work we present the studies of the effects of Delta-type undulators in the storage ring beam dynamics of Sirius. The undulators were included in the ring model as kick maps and their effects on tune shift, dynamic aperture and beam lifetime were evaluated.

INTRODUCTION

Sirius is the new 4th generation synchrotron light source that is being built by the Brazilian Synchrotron Light Laboratory (LNLS) [1, 2]. The storage ring 5BA lattice design comprises a 5-fold symmetric configuration with 5 high beta and 15 low beta sectors [3]. The low beta sectors have a small beam-stay-clear in both horizontal and vertical planes, which opened up the possibility to install insertion devices (IDs) with small horizontal as well as vertical gaps, allowing a whole new class of IDs to be considered.

The Delta undulator is a compact adjustable-phase device [4] that provides full polarization control and was first developed at Cornell University for operation with Energy Recovery Linac [5, 6]. Due to the capability of producing radiation with an adjustable and arbitrary polarization state, this type of undulator is already being used in FEL sources [7, 8], but its limited aperture in both planes has prevented the possibility of its use in storage rings so far.

In this work, the effects of a Delta-type undulator on the storage ring beam dynamics were evaluated to validate the applicability of these devices for X-ray generation for Sirius beamlines.

INSERTION DEVICE MODELING

The Sirius version of the Delta undulator consists of four arrays of NdFeB permanent magnet blocks ($B_r = 1.37T$) placed around the beam axis as shown schematically in Fig. 1. It is an adjustable phase undulator, as both the radiation polarization and the amplitude of the on-axis magnetic field are controlled with the longitudinal displacement of the magnetic arrays. The block's shape is similar to that of [7] to provide mechanical stability.

The kick map formalism was applied to include the Delta undulator models in the storage ring lattice. The Radia software [9] was used to calculate the 3D magnetic field of the undulator and generate the kick maps from the numerical integration of the equations of motion with the Runge–Kutta method. Table 1 shows the parameters of two of the undulators studied, which are being considered for installation in the first operation phase of Sirius, and the maximum K value obtained with the Radia model.

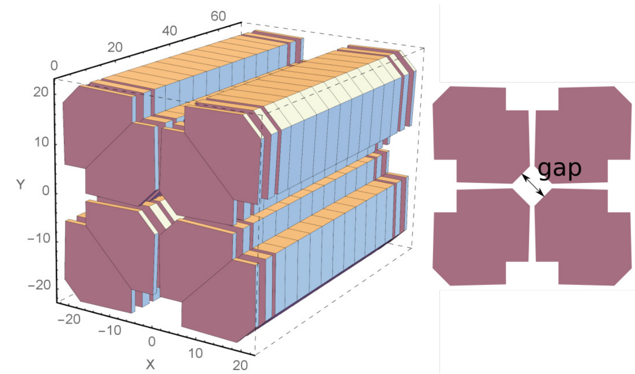


Figure 1: Magnetic blocks arrangement of the Sirius Delta-type undulator.

Table 1: Models Parameters

ID	Gap [mm]	Period [mm]	Length [m]	Maximum K
Delta-21	6.92	21.0	2.4	2.06
Delta-52	13.85	52.5	3.6	6.14

In order to speed up the calculations and allow the study of a larger number of magnetic field configurations, the shape of the permanent magnet blocks was approximated to rectangles, which made the kick maps calculations about 10 times faster, due to the simplified form of the analytical expressions for this case. The value of the magnetization of the blocks was adjusted in each case studied so that the on-axis field amplitude remained unchanged. In addition, the magnetization of each block was considered constant.

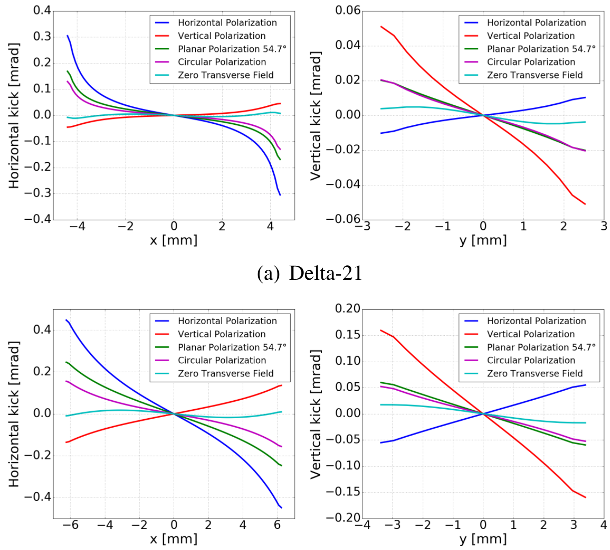
The effects caused by the Delta-type undulator were studied for several phases: horizontal polarization, vertical polarization, planar polarization with angle $\theta = 54.7°$, circular polarization and the phase with zero transverse magnetic field (non-zero longitudinal field on-axis). Figure 2 shows the horizontal and vertical on-axis kicks for the cases studied. The total on-axis kick is approximately linear for the Delta-52 device in both planes, so the residual effects after adjusting the strength of the quadrupoles located in the ID straight section are small. In the case of Delta-21, the amplitude of the kick is smaller, but the effects introduced in the horizontal plane are less linear and, consequently, more difficult to correct, thus being more harmful to the non linear optics.

EFFECTS ON SIRIUS BEAM DYNAMICS

The beam dynamics calculations were performed with the MatLab Accelerator Toolbox (AT) [10] and a library developed at LNLS by the accelerator physics group called

* luana.vilela@lnls.br

ISBN 978-3-95450-182-3



(a) Delta-21

(b) Delta-52

Figure 2: Total on-axis kick for the Delta-21 (top) and Delta-52 (bottom) IDs.

trackcpp [11], which is a C++ library of beam dynamics calculations and tracking routines closely based on, and tested against, Tracy [12] and AT passmethods.

A comparison of the linear effects introduced in the dynamics by the Delta-type undulator and a more conventional undulator type, the APPLE-II device, is presented in Tables 2 and 3. Both undulators have the same gap, period, length and K value defined in Table 1 for the Delta-52 ID. To perform the comparison the APPLE-II blocks magnetization was artificially increased for each phase to match Delta's field amplitudes. In the horizontal polarization phase, the horizontal focusing strength and tune-shift introduced by the APPLE-II are smaller. For the other cases, the effects caused by the Delta undulator are lower than the ones introduced by APPLE-II, mainly due to the smaller roll-off of the horizontal magnetic field provided by Delta's geometry. Similar results were found for the Delta-21 device.

Table 2: Inverse of Focal Distance [mm^{-1}]

Polarization	**Delta**		**APPLE-II**	
	$1/f_x$	$1/f_y$	$1/f_x$	$1/f_y$
Horizontal	-43.7	16.6	0.0	-28.3
Vertical	16.4	-43.6	42.5	-67.6
Circular	-14.2	-14.1	21.3	-48.9

To estimate the Delta undulators effects in the non linear optics of Sirius storage ring, the impact of this IDs in the dynamic aperture and momentum acceptance was calculated. The calculation was performed including the kick maps of the undulators in all 14 low beta sectors available for IDs, with a random distribution of the analyzed phases. Then, for each ID, a local symmetrization of the optics was applied,

Table 3: Tune Shift

Polarization	**Delta**		**APPLE-II**	
	1000 ×			
	$\Delta\nu_x$	$\Delta\nu_y$	$\Delta\nu_x$	$\Delta\nu_y$
Horizontal	8.0	-3.0	0.0	5.2
Vertical	-3.0	8.2	-7.5	12.8
Circular	2.6	2.6	-3.8	9.2

modifying only the strength of the flanking quadrupoles. Particles tracking was carried out for a set of 20 machines with realistic random alignment, excitation, and multipole errors, with orbit, tune and coupling correction. The results are shown in Fig. 3. For the Delta-21 case, there was a reduction of the dynamic aperture area from 37 mm^2 to 32 mm^2 and the dynamic aperture in the negative horizontal side at the injection straight section was reduced from 9.4 mm to 9.2 mm, however this value still excess the target of 8 mm and is sufficient for the off-axis injection process. For the Delta-52 case, no significant changes were observed in the dynamic aperture of the lattice. The momentum acceptance was not altered with the insertion of the devices indicating that there was no reduction in the beam lifetime.

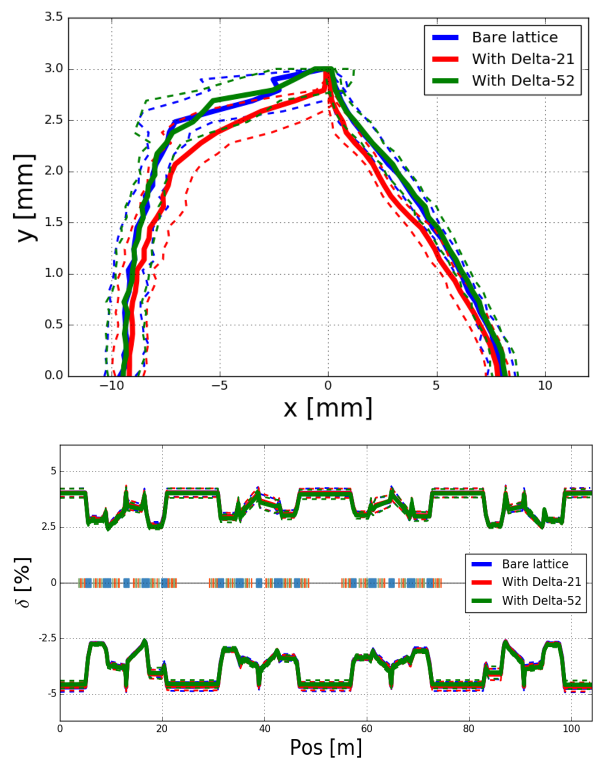


Figure 3: Dynamic aperture and momentum acceptance for the storage ring bare lattice (blue), lattice with 14 Delta-21 (red) and lattice with 14 Delta-52 (green). The dashed curves indicate one standard deviation from the average (solid curve) over 20 random machines.

PROTOTYPE

A prototype of the Delta-type device was constructed by the LNLS Magnet Group to verify the undulator's magnetic field properties. Figure 4 shows the built prototype, which is a 3 periods version of the undulator, with gap of 6.92 mm and period of 20 mm. The total length of the structure is 120 mm and the positioning of each magnetic array must be adjusted manually. The NdFeB (48AH) permanent magnet blocks were ordered from "Dailymag Magnetic Technology Limited" with remanent magnetization specification from 1.37 to 1.43 T and intrinsic coercive force ≥ 2785 kA/m.

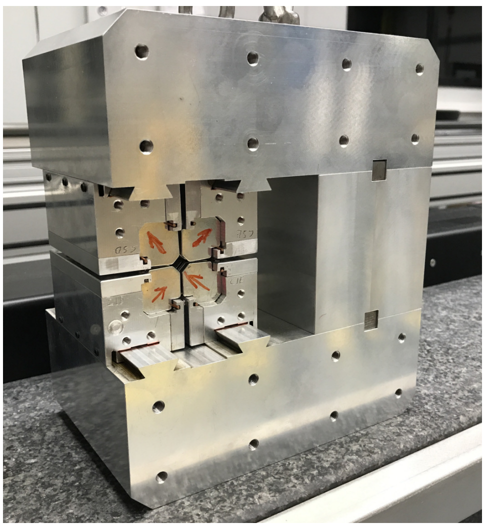


Figure 4: Prototype of the Sirius Delta-type undulator.

The magnetic field measurement of the prototype was performed with a "SENIS GmbH" high-resolution low-noise Hall probe. The results for the vertical field component in the horizontal polarization phase configuration are presented in Fig. 5. The measured field amplitude is 5% larger than the value obtained with the model. The reason for this discrepancy is under investigation, one possible explanation is that blocks magnetization must be near the upper limit of the specification.

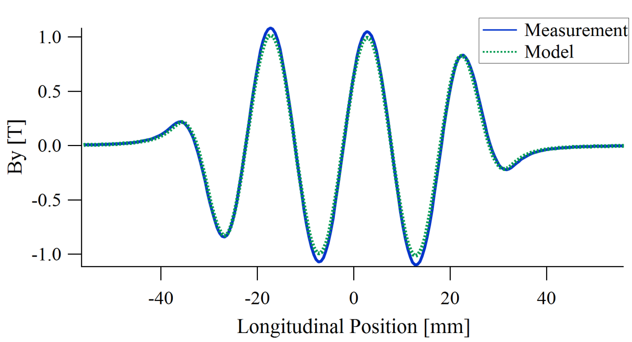


Figure 5: Vertical magnetic field component measured along the beam axis in the horizontal polarization phase. Dashed lines show the model calculation.

CONCLUSION

The results show that the inclusion of Delta-type undulators in the Sirius storage ring lattice did not cause changes in the beam dynamics that would restrict their use. Since the effects introduced are mostly linear, active multipolar compensation is not required. However, further analysis must be carried out, taking into account construction and positioning errors and interaction effects between the magnetic blocks. It was recently decided that 5 Delta-type undulators will be installed in the initial operation phase of Sirius.

ACKNOWLEDGEMENT

The authors would like to thank Natalia Milas and Harry Westfahl for their help with the implementation of the Radia models, James Citadini for providing data from finite elements simulations for comparison, the members of the LNLS Magnet Group for providing the prototype data and the members of the LNLS Mechanical Design Group for conceding the spare time of their computers to our calculations.

REFERENCES

[1] Sirius Official Documentation, `https://wiki-sirius.lnls.br`

[2] L. Liu and H. Westfahl Jr., "Towards diffraction limited storage ring based light sources", presented at *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, paper TUXA1, this conference.

[3] L. Liu, F. H. de Sá, X. R. Resende, "A new optics for Sirius", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 3413–3416.

[4] R. Carr, "Adjustable phase insertion devices as X-ray sources", *Nucl. Instr. Meth. Phys. Res. A*, vol 306, pp. 391–396, 1991.

[5] A. B. Temnykh, "Delta undulator for Cornell energy recovery linac", *Phys. Rev. ST Accel. Beams*, vol 11, no. 12, p. 120702, Dec. 2008.

[6] A. B. Temnykh, "Delta undulator magnet for Cornell energy recovery linac", in *Proc. PAC'09*, Vancouver, Canada, May 2009, pp. 324–326.

[7] H. D. Nuhn *et al.*, "R&D towards a Delta-type undulator for the LCLS", in *Proc. FEL'2013*, New York, USA, Aug 2013, pp. 348–350.

[8] H. D. Nuhn *et al.*, "Commissioning of the Delta polarizing undulator at LCLS", in *Proc. FEL'2015*, Daejeon, Korea, Aug 2015, pp. 757–763.

[9] E. Pascal, O. Chubar and J. Chavanne, "Computing 3D magnetic fields from insertion devices", in *Proc. PAC'97*, Vancouver, Canada, May 1997, pp. 3509–3511.

[10] A. Terebilo, "Accelerator Toolbox for MATLAB", SLAC, Stanford, USA, Rep. SLAC-PUB-8732, May 2001.

[11] LNLS Accelerator Physics Group, Tracking library, available at `https://github.com/lnls-fac/trackcpp`

[12] H. Nishimura, "TRACY, A tool for accelerator design and analysis", in *Proc. EPAC'88*, Rome, Italy, Jun 1988, pp. 803–805.

ISBN 978-3-95450-182-3