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RESULTS OF THE FIRST ALIGNMENT RUN FOR SIRIUS

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Abstract

It is widely known that the position of particle accelerator components is critical for its performance. For the latest generation light sources, whose magnetic lattice is optimized for achieving very low emittance, the tolerable misalignments are in the order of a few dozen micrometers. Due to the perimeter of these machines, the requirements push the limits of large-volume dimensional metrology and associated instruments and techniques. Recently a fine alignment campaign of the Sirius accelerators was conducted following the pre-alignment performed during the installation phase. To conform with the strict relative positioning demands, measurement good practices were followed, and several 3D metrology procedures were developed. Also, to improve positioning resolution, high rigidity translation devices were produced. Finally, the special target holders designed as removable fiducials for the magnets were revisited to assure maximum reliability. Data processing algorithms were implemented to evaluate the alignment results in a robust and agile manner. This paper will present the final positioning errors for Sirius magnets with an expression of the estimated uncertainty.

INTRODUCTION

Particle accelerators are complex machines with many technological challenges. To work properly, its main components need to be correctly placed on the installation volume. For the latest generation Synchrotron Light Sources, such as the Brazilian Synchrotron Sirius, the tolerated relative position between adjacent Storage Ring (SR) magnets on a same support is 0.040 mm, and for adjacent magnets on separate supports this value is 0.080 mm for the horizontal (H) and vertical (V) directions [1].

The requirements for the so-called diffraction-limited SRs have not changed considerably with respect to older machines [2]. The understanding about the effects of misalignments, on the other hand, evolved considerably. Also, from the perspective of the metrology behind the large-volume alignment of components, the knowledge about the conformity assessment, the expression of the results and the reliability of the process have been maturing [2, 3]. Afzali-Far *et al* [4] present a modern view on the survey and alignment process for a synchrotron. From the instrumentation standpoint, laser trackers have long been used as the main tool for alignment [5], and recent technology advancements in multilateration could point to future applications in this field [6].

This paper intends to address the first fine alignment operation for Sirius, and present the results obtained. This work is part of a larger effort that comprises the development of a reference network [7] and the study of structural stability using monitoring systems and verification strategies [8].

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MATERIALS AND METHODS

The reference network needed for the alignment was established in 2020, and since then the radius of the concrete structures that support the accelerator have been monitoring. Figure 1 shows the stabilization trend that validated the use of this network to conduct the fine alignment. Comparing two period of Sirius operation (March 2020 and November 2020), we noticed the radius was already sufficiently stable.

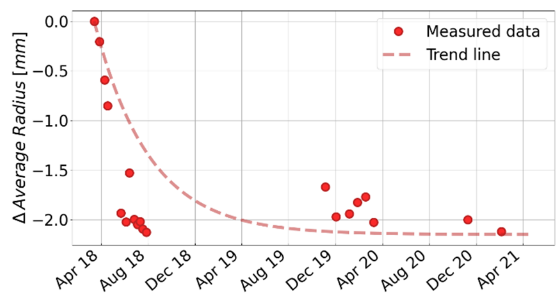

Figure 1: Radiation shielding radius over the years.

For the intra-girder alignment, Coordinate Measuring Machine inspection on the magnets assembly demonstrated we reached an alignment better than ± 0.030 mm for the multipole girders. The alignment strategy counted with reference surfaces better than 0.010 mm flatness and perpendicularity, and the devices used in this "alignment by construction" are shown in Fig. 2.

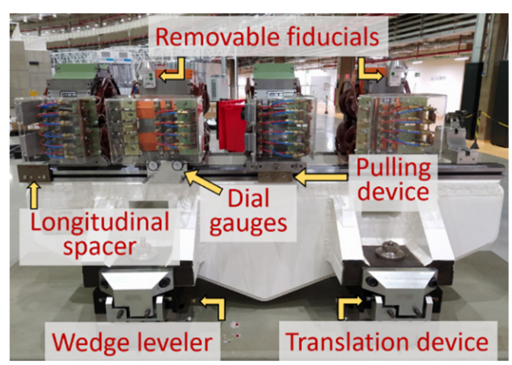

Figure 2: Devices used during alignment operations.

To improve the fine alignment operation with respect to the pre-alignment and smoothing campaigns done between 2018 and 2019 [9, 10], the translation devices were revisited, and the material changed from aluminium to steel for increased stiffness and reduction of crosstalk between the adjusted directions. Also, the removable fiducials (target holders for Spherically Mounted Retroreflectors – SMR) were redesigned to have kinematic contact points and machined to better than 0.005 mm so the effect of their variability on the final position estimation of the magnets centerlines would be small. In agreement with the Physics Group, the approach was to try an absolute alignment of

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the magnets to nominal coordinates, besides the existing relative requirements (the radius was redefined after the 1 mm retraction of the concrete since pre-alignment [8]).

Data Preparation and Analysis

Figure 3 shows the data flow for treating and reporting results. The input data is in the form of nominal and measured points, and a list of transformations between Sirius Coordinate System (CS) and nominal magnets CS. An algorithm implementation in Python estimates the measured CS and compares them to the nominal CS, reporting the residuals. By going the opposite way and minimizing the errors, we were able to use the as it is data from each magnet and be deterministic about the positioning, reducing tremendously the number of iterations and improving the final alignment results.

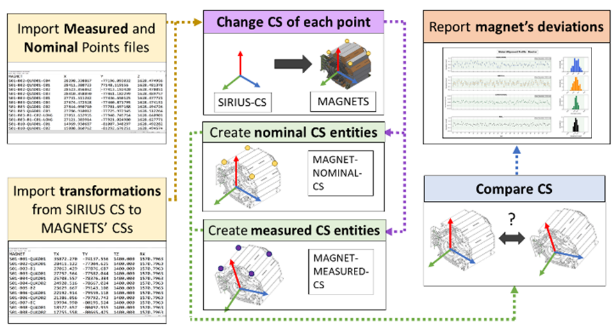

Figure 3: Workflow for data treatment and preparation.

Uncertainty Evaluation

The scheme in Fig. 4 illustrates the uncertainty estimation for the alignment. The idea was to comprehensively consider the influences on the final errors involved. The assessment comprised a mixture of analytical and numerical methods [11, 12]. The following combined standard uncertainties were estimated: 0.02 mm (H), 0.04 mm (V), 0.02 mm (L), and 0.03 mrad (Roll).

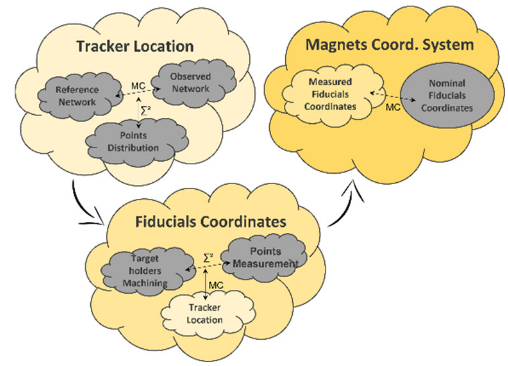

Figure 4: Depiction of the uncertainty components.

RESULTS

The positioning results for the SR can be seen in Fig. 5. Considering both negative and positive errors as equal, the Mean Deviation (MD) [13] can be considered a good metric for the alignment. The alignment residuals are very small for all the degrees of freedom (DOF) analysed. For the BO, Transport Lines and Front ends the errors are also well within tolerance (the MD for the BO was 0.04 mm for the transverse directions). All magnet passed by magnetic characterization (Hall sensor for Dipoles and rotating coil for Quadrupoles and Sextupoles) [14], and Table 1 compile the combined results for an average sector of Sirius SR [15]. If one evaluates a single metric to assess the alignment, as proposed in previous work [16], the so-called Profile Alignment Parameter for Particle Accelerators (PAPPA) for Sirius would result in 0.239 mm for the whole SR, for a coverage probability of approximately 95% (in this case, defined as the diameter of the minimum cylinder that circumscribes the points composed by taking the position errors from the centers of the magnets added to their expanded uncertainties using a coverage factor of 2 [17]). The calculated PAPPA for parts of the SR is very similar to the one for the whole machine, showing a homogeneous alignment result. Also, we can notice how the parameter is currently being dominated by the vertical uncertainty.

Table 1: Combined results for the magnets families. The position estimates in each of the DOFs is a sum of the average geometric and magnetic position systematic errors, and the random errors here are the quadratic sum of geometric (position errors distributions and uncertainties) and magnetic surveys (population manufacturing variability and uncertainties).

Magnet	Average Results											
	X	±	σ_X [mm]	Y	±	σ_Y [mm]	Z	±	σ_Z [mm]	Rz	±	σ_{Rz} [mrad]
QDA	+ 0.01	±	0.02	+ 0.01	±	0.04		N/A		– 0.38	±	0.11
QDB1	+ 0.00	±	0.02	+ 0.00	±	0.04		N/A		– 0.29	±	0.11
QDB2	+ 0.00	±	0.02	+ 0.00	±	0.04		N/A		– 0.30	±	0.11
QDP1	+ 0.00	±	0.02	+ 0.01	±	0.05		N/A		– 0.41	±	0.11
QDP2	+ 0.00	±	0.02	+ 0.01	±	0.04		N/A		– 0.39	±	0.11
QFA	+ 0.02	±	0.02	+ 0.01	±	0.05	– 0.00	±	0.03	+ 0.01	±	0.11
Q1	+ 0.01	±	0.02	– 0.00	±	0.04		N/A		+ 0.09	±	0.11
Q2	+ 0.00	±	0.02	+ 0.00	±	0.04	+ 0.00	±	0.03	+ 0.11	±	0.11
Q3	+ 0.01	±	0.02	+ 0.00	±	0.04		N/A		+ 0.01	±	0.12
Q4	+ 0.01	±	0.02	+ 0.00	±	0.04	+ 0.00	±	0.03	+ 0.10	±	0.12
QFB	+ 0.01	±	0.02	– 0.00	±	0.04	+ 0.00	±	0.03	– 0.30	±	0.07
QFP	– 0.01	±	0.02	– 0.00	±	0.04	– 0.00	±	0.03	– 0.20	±	0.11
B1		N/A			N/A		– 0.00	±	0.04	+ 0.01	±	0.05
B2	– 0.00	±	0.03	+ 0.00	±	0.05	– 0.01	±	0.03	+ 0.00	±	0.05
BC	– 0.00	±	0.03	+ 0.00	±	0.05	– 0.00	±	0.03	+ 0.00	±	0.05

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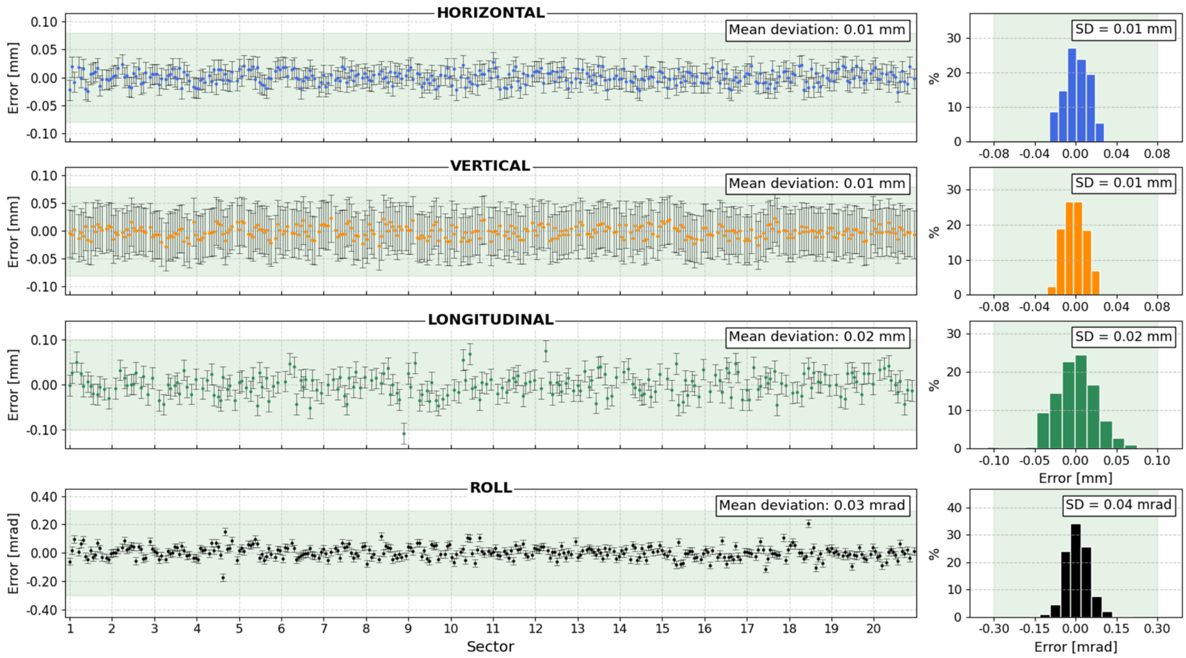

Figure 5: Alignment results for SR magnets. Specific quadrupoles and dipoles were used as positioning references for each of the girders and DOF, and the plotted data are the results for these magnets.

DISCUSSIONS AND CONCLUSIONS

The alignment of the SR took approximately two weeks. The operation involved 24 people divided in three shifts. Four laser trackers were used in parallel, and verification of the instruments using a calibrated artefact was done to guarantee maximum reliability during the shutdown. Also, to control the process, inspections on the removable fiducials were carried out before, during and after the campaign (to check for damage that could change the SMR center). For the intra-girder alignment, investigations will be carried out to better understand possible assembly errors of the dipole magnet B1 on the girder (H and V). Also, some of the quadrupoles not used as longitudinal references for girder positioning present assembly errors larger than tolerated, and studies will be conducted by the Physics Group to verify the need to future repositioning.

Although still compatible to the current alignment needs, the vertical uncertainty estimations for the final measurement results present a margin for improvement. Besides the aspects already addressed by Geraissate [7], we are investigating the possibility of using a rotary laser alignment system for surveying the height differences between the vertical control points in the reference network. This would take profit from both the high accuracy of the system and the fact that the special slab of Sirius is very flat. This system could, perhaps, be applied to replace optical level campaigns or be used in jointly with it. The wall bracket proposed to replace sturdy tripods will have its design revisited, to improve its long-term stability. As mentioned, there is a stabilization trend in the H and V directions for the Sirius structures. To prepare to future realignment needs, the reference networks will be surveyed soon. Also, to cope with the high amount of data generated by the measurement campaigns, we intend to develop Python-based databases using PostgreSQL solution. For monitoring and verification aspects, Neto [8] discussed several systems and strategies for Sirius. Another possibility for structural deformations would be to perform deformation analyses by the exterior of the radiation shielding, without the need to access the tunnel, what would be possible only during shutdowns. Furthermore, we are validating the use of external radius control points and a closed traverse that can be measured in the perimeter of the radiation shielding. Monitoring these distances will improve our spatial resolution and our understanding of the behaviour of the concrete structure. For the open lines-of-sight for radius observations (since we currently cannot have a long tube connecting the central pillar to the tunnel), we intend to measure environmental quantities along the laser propagation path and compensate for air-refraction influences [18-20].

Finally, in terms of next steps, we intend to further investigate the impact of overlap measurements during positioning of components. This was accomplished during network campaigns, but the localization of tracker stations and the magnet fiducials measurements did not have redundancy. The Sirius SR alignment results, especially the systematic errors for the directions transversal to the beam, are in the limit of the technique. We conclude that the alignment run was successful, and the positioning requirements were met. Moreover, the commissioning results indicate a positive impact on the Sirius performance: the correctors strength in the H direction was reduced from 2.0 A to 1.7 A. The residual orbit improved substantially (from 31.8 μm to 12.6 μm and from 32.2 μm to 7.6 μm in H and V, respectively) [21]. Also, initial estimations indicate the SR is now close to the nominal H emittance of 250 pm.rad [22].

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