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SIRIUS COMMISSIONING RESULTS AND OPERATION STATUS

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Abstract

Sirius is a 4th generation 3 GeV synchrotron light source that has just finalized the first commissioning phase at the Brazilian Center for Research in Energy and Materials (CNPEM) campus in Campinas, Brazil. This paper describes the main Accelerator Physics issues faced during the storage ring commissioning, methods that were used to work them out and the current operation status of the machine.

INTRODUCTION

The Sirius 3 GeV synchrotron light source in Campinas, Brazil, is based on a 4th generation storage ring which uses a five-bend achromat lattice (5BA) to reach an emittance of 250 pm rad. The project design started back in 2012, after a turning point where a previous TBA design was presented at the first MAC meeting. The following 7 years were dedicated to R&D activities on the various subsystem prototypes and production of accelerator components, including the new building with high stability floor. All activities favoured development either in-house or in collaboration with the local industry. As a result, about 85 % of Sirius budget have been spent in Brazil. One exception is the 150 MeV Linac, that was produced by SINAP, in Shanghai, China, and was the first accelerator to be commissioned, early in 2018. A few months later, in May, the accelerators tunnel was ready to start booster installation, albeit with no temperature stabilization system. In the first quarter of 2019 the booster commissioning started in parallel with storage ring installation activities, with a policy of time-sharing and priority for the storage ring installation. In November 2019, the storage ring was ready to start commissioning and the first stored beam was obtained with on-axis injection on December 14th. Two days later, the first X-ray tomography experimental result was obtained at the superbend beamline MOGNO. The capability of storing a beam with on-axis injection was very useful for the initial characterization, correction of the machine optics and commissioning of the subsystems. In February 2020, the first beam accumulation using the non-linear kicker (NLK) was achieved. Unfortunately, soon after that the activities on campus were interrupted due to the Covid-19 pandemic. However, a reduced staff proceeded with the on-site activities related to accelerators commissioning and beamline installations. By the end of 2020, five undulators had been installed in the storage ring and operation for users for beamline commissioning were routinely scheduled with an initial current of 40 mA in decay mode, with two injections per day. The Sirius building was designed to provide high stiffness from floor to magnets to ensure high beam stability in face of vibrations. However, a new building of course lacks long-term settlement and we have noticed the effects of large girders misalignment during this first commissioning phase. A stored beam has been achieved despite these problems, but it became clear that a fine alignment campaign for all accelerator girders was needed. In special, the orbit correction system was pushed to the limit and the beam was prevented from passing through the center of magnets as designed. The alignment campaign was performed in January this year, requiring a second commissioning of the whole system in February. Presently, May 2021, the storage ring is operating in decay mode with an initial current of 70 mA with uniform filling and lifetime of 30 h with 1% coupling. The current is presently limited by the RF system, that is being operated with a temporary Petra 7-cell cavity without higher order modes (HOM) dampers [1]. To reach 70 mA in a stable way, we have performed temperature tuning. The final RF system will be comprised of 2 main superconducting cavities and a third harmonic cavity (3HC) for a stored current of 350 mA in top-up mode.

LATTICE DESIGN AND OPTICS

Sirius lattice design and optics have been described elsewhere [2]. Here we summarize the main aspects for the sake of completeness. The magnet lattice is based on a modified 5BA cell with three different types of dipoles. Two of them, B1 and B2, are low field electromagnetic dipoles (0.58 T) with field gradients which are connected to the same power supply, and one central permanent magnet superbend, BC, where the peak field reaches 3.2 T in the center. The twenty 5BA cells are connected by 20 straight sections that are matched to the arcs by using quadrupole triplets and doublets to form 15 low and 5 high beta straight sections respectively. The 15 low beta sections provide better matching between the electron and the photon beam phase spaces, optimizing the conditions for higher brightness from undulators. The low beta sections also allow for installation of new types of undulators with small horizontal as well as vertical gaps. The superbends provide 20 dipole sources with critical photon energy of 19 keV and very small beam sizes ($9.6{\times}3.6\,\mu m^2$) due to the naturally small optical functions at the arc center. Figure 1 shows a schematic view of Sirius 5BA cell and Table 1 shows Sirius main parameters. Figure 2 shows Sirius optical functions.

To correct chromaticities and optimize the nonlinear dynamics in Sirius, a total of 280 sextupoles grouped into 21 families are used. Octupoles are not used in Sirius. The optimization was performed using MOGA algorithms already considering operation with chromaticities set to 2.5 in both transverse planes.

Full-energy injection into Sirius is performed off-axis in the horizontal plane, in one high beta straight section,

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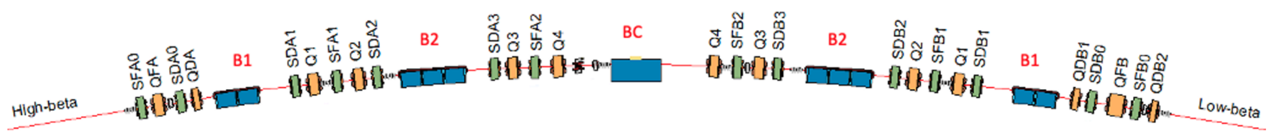

Figure 1: Schematic view of Sirius 5BA magnet lattice. B1 and B2 are low field electromagnets and BC is a permanent magnet superbend reaching 3.2 T at the center.

Table 1: Sirius Main Parameters

Parameter	Value	Unit
e⁻ beam energy	3.0	GeV
Circumference	518.4	m
Lattice	20×5BA	
Hor. Emittance (bare)	250	pm rad
Betatron tunes (H/V)	49.11/14.17	
Natural chrom. (H/V)	−119.0/−81.2	
Nominal chrom. (H/V)	2.5/2.5	
Energy spread	0.085	%
Energy loss / turn (bends)	473	keV
Damping times (H/V/L)	16.9/22.0/12.9	ms
Nominal current (top-up)	350	mA

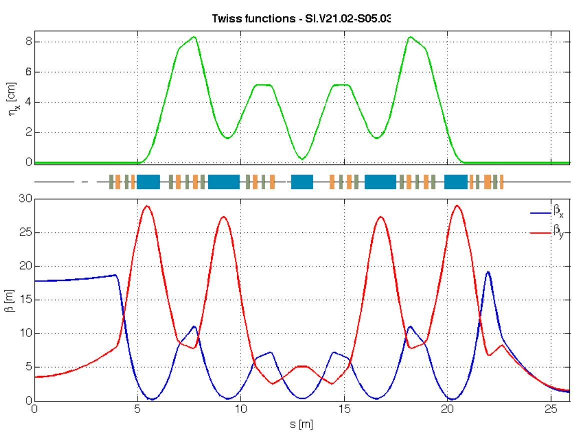

Figure 2: Sirius optical functions with a high-beta section on the left and a low-beta section on the right.

by means of a pulsed nonlinear kicker (NLK). A dipolar kicker (DipK) is also available for on-axis injection that was used during initial commissioning. The Sirius injector is described in [3] and consists of a 150 MeV Linac and a low emittance full-energy booster installed in the same tunnel as the storage ring, on the inner wall of the tunnel. The booster lattice has a very high symmetry and comprises 50-fold symmetric FODO cells with no dispersion free straight sections. The high symmetry results in an almost round accelerator with a geometry that fits well inside the 20-fold symmetric storage ring without narrowing the passage between the rings. The almost 500 m in circumference results in a 3.5 nm rad booster emittance at 3 GeV, that produces a small beam for injection into the storage ring, helping to achieve a high injection efficiency.

STORAGE RING COMMISSIONING

First Turn and First Orbit Measurement

As soon as the injector parameters were adjusted to deliver a 3 GeV beam at the end of the booster to storage ring transfer line (TS), commissioning work on the storage ring started by looking for the first turn using on-axis injection with the DipK and RF off. At first, the beam was not completing one turn only with adjustments in the strength of DipK and injected beam parameters (position and angle), and we had to used trajectory correction with the model matrix. It is worth noting, however, that this approach worked only when the correction matrix was used piece-wise, so that the real trajectory remained almost in phase with the related part of the correction matrix in use. The difference between the model and real machine tunes implies in a shift in phase-advance between the measured and model first-turn trajectories that become evident as the trajectory propagates, as Fig. 3 illustrates. In a short sector, the trajectory oscillation phase shift can be kept small enough so that trajectory correction stays effective. With the first turn completed, the tunes could be roughly adjusted and the model trajectory matrix was then extended to a few turns. Using the extended beam trajectory matrix was very effective to thread the beam through a few turns. After that, by averaging about 5 turns, a coarse orbit could be measured and corrected. By essentially iterating these steps, thousands of turns could be obtained, and an orbit could be measured.

Worth noting is that it was not necessary to perform single-pass beam based alignment (BBA) due to the tight mechanical tolerances specified (500 µm of offsets) and achieved (250 µm) for the BPMs and a careful characterization of electric offsets created by cables and electronics [4,5].

Stored Beam: Turning the RF On

The next step was to obtain a stored beam by turning the RF on. We soon noticed that only RF phase sweeps would not be enough to store the beam because our energy

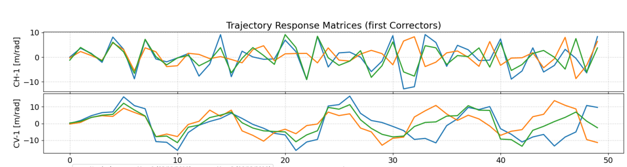

Figure 3: Beam trajectories from model (blue), initial measurement (orange) and measurement after tune correction (green).

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acceptance seemed to be very small (1 %), and RF frequency variation would be needed. But, since the same RF generator is used for the whole system, it was very difficult to vary the RF frequency without the need to re-optimize the injector. To circumvent this problem, we adopted the solution of temporarily using two RF generators: while the first was connected to the injector and the timing system, the second was defining the reference for the low level RF of the storage ring.

To ensure coincidence between the booster and storage ring buckets in subsequent injection pulses, the frequency of the second RF system was varied in discrete steps such that a coincidence clock could be generated by the timing system with a frequency large enough not to compromise the 2 Hz injection signal. Actually, since the precision of the frequency in the generator was 2 decimal places, the coincidence was not exact, which decreased even further the set of possible frequency steps that could be used to those frequencies which guaranteed that the phase slip was small enough along the duration of the experiment.

Once the storage ring RF frequency was found, we reconnected all systems to the same RF generator. The frequency was kept at the optimum value for the storage ring while the injector is operating with an offset of about 1 kHz. The two RF generators operation was not needed this year to recover the machine after alignment.

Beam Based Dipoles Calibration

Lattices with more than one type of dipole are subjected to the possibility of having differences in their excitation curves. These differences generally are masked by the horizontal orbit correction system, that encodes them into the correctors strengths and residual orbit after correction (in the case of an over-determined system, or when orbit response matrix singular values selection is employed). It is possible to access this information using a very simple procedure of calculating model matrices that correlate dipoles deflection errors with the correctors strength or with the orbit residue. Then, by fitting the actual orbit residue and correctors strength signature with these matrices, it is possible to obtain two independent estimates for the dipole errors.

Since early commissioning days there was an indication that the dipole calibration curves were not matching one another. We have thus used the procedure described above to make a fine calibration for dipoles. In this process we found out that the excitation curves of the B1 and B2 were matching each other but they did not match the permanent BC magnet in approximately 2 %. Since both electromagnetic dipoles are connected to the same power supply, this type of error was compensated during operation last year. This result also triggered a re-calibration of the excitation curves of the dipoles, such that in this year commissioning this experiment was repeated and it was verified that they agreed with each other within the accuracy of the method (0.15 %).

Injected Beam Position and Angle Adjustment

The Sirius pulsed thin and thick septa used for injection into the storage ring present a pulse variation with temperature that makes the injected beam conditions not very repetitive between injections. It is particularly important to keep the beam horizontal position and angle repetitive at injection since the NLK field profile is very sensitive to the horizontal position, demanding several iterations to optimise injection efficiency. To help speed up this process, a high level control system [6] tool was developed that uses the first turn beam trajectory and the lattice model to fit the initial beam conditions (position and angle in both planes and energy offset) right after the NLK longitudinal position in the ring. This tool can be used only when there is no stored beam in the ring and depends on the correction of BPM non-linearities for high amplitudes. Figure 4 shows a fitting result during injection.

Fine Girders Alignment

Sirius is a green-field accelerator that was built on a new piece of land in the same CNPEM campus, next to the first Brazilian light source, UVX. Alignment of the magnets follows two steps: the individual magnets are installed on the girders by definition, using precise reference surfaces on magnets and girders, a tested procedure; and girder with magnets alignment in the tunnel. The girders were pre-aligned in the tunnel in 2018 to allow for vacuum chamber installation. Although alignment surveys showed that the girders have moved above tolerance due to building settlement since pre-alignment, it was decided to proceed with commissioning without a fine alignment campaign, that would be too time consuming. Only a few girders position corrections were performed in 2019 before commissioning. The year of 2020 was dedicated to the beam commissioning under these non-optimum alignment circumstances. Although we have

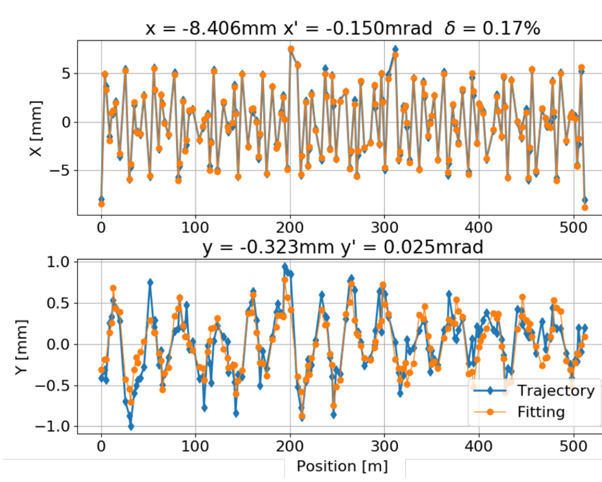

Figure 4: Injected beam position and angle measurement at the NLK position by first-turn trajectory fitting. The injected beam horizontal position is adjusted to −8.4 mm and the NLK strength is adjusted so that the beam horizontal angle after the NLK is approximately zero.

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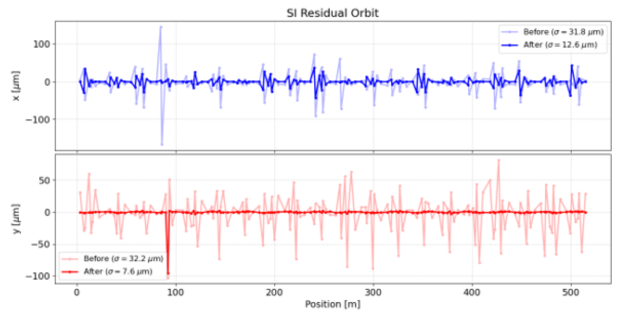

Figure 5: Residual orbit at BPMs before and after girders fine alignment campaign in January 2021.

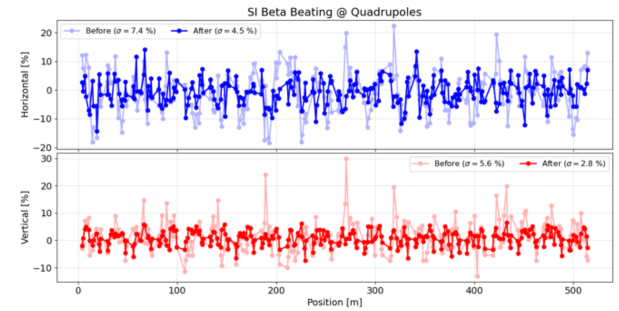

Figure 6: Betabeating after LOCO before and after alignment.

successfully achieved a stored beam that was even used for beamline commissioning, it became clear that a fine alignment of the girders was necessary: large orbit residues could not be corrected due to saturation of corrector strengths, betabeating was larger than expected, etc. A fine girder alignment campaign for all accelerators was performed in January this year (2021) [7–9] and the re-commissioning of the accelerators was performed in February. This time the commissioning was much faster and resulted in a more behaved optics and orbit correction. From March, commissioning of the beamlines restarted. In the next sections we report on the re-commissioning results.

Alignment Effect on Orbit and Optics

Here we compare the orbit correction performance before and after the girder alignment campaign. The propagation distance of the injected beam with correctors off has doubled, from half a turn to more than one turn. The orbit correction system in Sirius has 120 horizontal correctors and 160 BPMs, so horizontal orbit correction is not exact, and from simulations with the specified alignment errors, we expect 17 μm of horizontal orbit rms at BPMs. In the vertical plane, the orbit at BPMs can be completely corrected. The horizontal orbit residue improved by a factor of 3, reaching 12 μm rms. In the vertical, except for one BPM, the orbit residue was completely corrected as shown in Fig. 5.

In fourth generation storage rings, the strong nonlinear effects make it very important to correct the orbit so that the beam passes through quadrupoles and sextupoles close to their magnetic center. As usual, BPMs have been calibrated by the BBA method in Sirius. The linear optics was characterized with LOCO [10] and the resulting corrections were applied to individual trims coils available in all quadrupoles. Skew quadrupole trim coils available inside sextupoles are used to correct coupling terms in the orbit response matrix. The procedure is described in detail in [11]. BBA and LOCO were applied iteratively until convergence. After alignment, betabeating was reduced by a factor of 2, to 4.5% rms in the horizontal and 2.8% rms in the vertical plane. The residual dispersion function did not improve. Figure 6 shows the residual betabeating in the horizontal and vertical planes.

CURRENT OPERATION STATUS

The Sirius storage ring is currently operating for machine and beamlines commissioning shifts, in addition to installation of new beamlines and maintenance shifts. The beamline commissioning shifts operate with initial current of 70 mA in decay mode with two injections per day.

The beamline dedicated to beam equilibrium parameters measurement is not available yet, but some parameters could be measured by alternative methods, such as beam horizontal emittance, energy spread, coupling and vertical emittance. The horizontal beam emittance was estimated from the undulator radiation spectrum to be close to the nominal value of 250 pm rad, within a range of 50 pm rad. The energy spread was measured by fitting the decoherence pattern in turn-by-turn data after a kick [12] and its value is also close to the nominal within 5×10^{-5}. Beam transverse coupling was estimated by measuring the minimum separation between horizontal and vertical tunes. To set the desired coupling we start by correcting it to a very small value by minimizing coupled terms in the orbit response matrix using skew quadrupoles with LOCO. Then, using only the two vectors of achromatic skew quadrupoles with highest singular values, we set the machine to the desired coupling of 1%. Chromatic skew quads are not used to avoid excitation of vertical dispersion. Estimations with a model that fits the measured vertical dispersion and the coupling of the machine indicates that, considering the operation point of the transverse tunes ($\nu_x = 0.086$, $\nu_y = 0.135$), our verti-cal emittance is approximately 7 pm rad (~3% of emittance ratio)

The beam lifetime is evolving as expected after an obstruction in the scraper was removed last year. Vacuum interventions with neon venting has demonstrated to be very effective in recovering vacuum pressure without the need to active NEG coating [13]. Presently, the average pressure at 70 mA is about 2×10^{-10} mbar and the beam lifetime at 70 mA is about 30 h, limited by Touschek scattering.

Collective Instabilities

As already mentioned, we are operating the Sirius storage ring with a temporary room temperature Petra 7-cell RF cavity without HOM dampers. In this condition, in early

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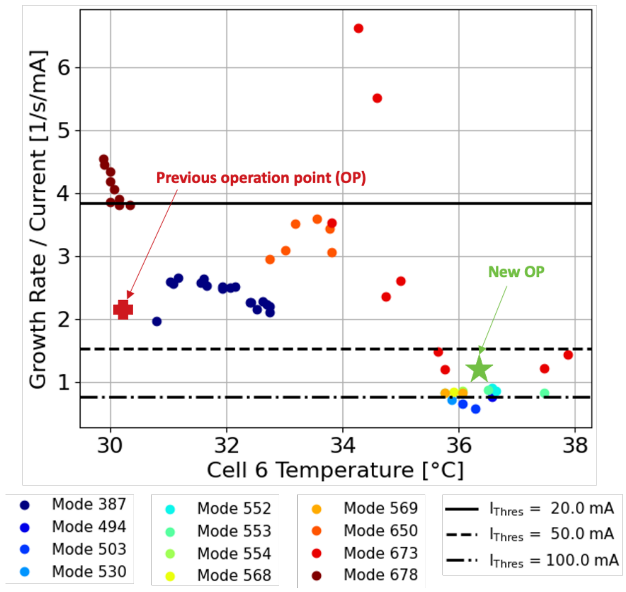

Figure 7: Comparison of Petra 7-cell RF cavity previous and new operation points regarding longitudinal instability mode growth rates per mA.

operation times, we observed longitudinal instabilities in the beam at currents as low as 20 mA. We have even commissioned the available longitudinal bunch-by-bunch (BbB) feedback system, but the instability was very strong. We have thus tried tuning the temperature of the cavity and, indeed, we have found a new temperature setting where the beam is stable at 70 mA without longitudinal feedback. The two operation points are shown in Fig. 7. We are operating at chromaticity values of +2.5 in both planes and resistive wall instabilities have not been observed so far, in accordance with simulations [14].

Orbit Stability

Beam orbit stability is one of the most important aspects of a light source and a big effort was applied during Sirius design phase to ensure a highly stable system. From ground to girders, to supports, to magnets, the whole chain was designed to minimize low frequency vibrations. In addition to this, two orbit feedback systems, SOFB and FOFB, slow and fast, have been designed. Today only SOFB is implemented with 25 Hz actuation rate and approximately 1 Hz bandwidth. The system counts with 160 BPMs and 120 horizontal, 160 vertical correctors and the RF frequency. The FOFB system will operate at 25 kHz actuation rate and the expected bandwidth is 1 kHz. The system will be composed of 80 BPMs, 80 horizontal and 80 vertical correctors, one pair for each beam source point.

Figure 8 shows an overview of the short term orbit stability for Sirius, with the beam position acquisition at one BPM in the straight section of the MANACA beamline. It can be seen that the system stability requirement (10% of beam size) has not been reached yet, especially in the vertical plane. A strong component comes from the 60 Hz mains frequency.

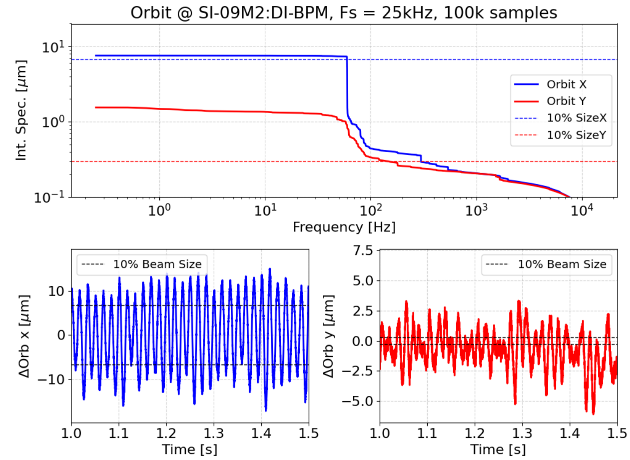

Figure 8: Sirius short term orbit stability.

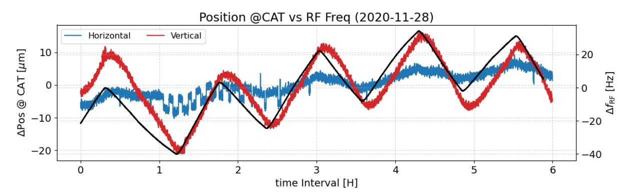

Figure 9: Vertical (red) and horizontal (blue) photon beam position at CATERETE beamline correlates with storage ring RF frequency (black) when SOFB loop is closed.

This problem will be investigated as soon as possible, as the implementation of the FOFB system.

We have also observed a very slow vertical position oscillation of the photon beam at some beamlines with a period of a few hours. This oscillation is correlated to the RF frequency oscillation when the SOFB loop is closed. See Fig. 9. This instability is present on the beamline independently of the state of the SOFB loop and is mostly in the vertical plane, while the RF BPMs of the storage ring measure a horizontal motion only. The source of this variation is being investigated and so far we have found no correlation to magnets, water or air temperatures.

CONCLUSIONS AND PERSPECTIVES

The Sirius first commissioning phase in 2020 has been completed with large girder alignment errors that were corrected in January this year. The recommissioning performed in the sequence is advancing as expected and already allows operation with 70 mA in decay mode for beamlines commissioning. The machine performance is corresponding well to the simulated model including measured magnet field profiles and achieved alignment tolerances. For the near future we plan to continue with machine characterization (*e.g.* lifetime, stability, injection efficiency, impedance measurement) and start preparation for FOFB implementation, top-up operation and new RF cavity installation.

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