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COLLECTIVE INSTABILITY STUDIES FOR SIRIUS

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Abstract

In this work we will present the estimates of single and multi-bunch instability thresholds and current-dependent effects, such as tune-shifts and potential-well distortion for the Sirius storage ring. The results were obtained by tracking simulations and semi-analytic methods using the updated and detailed impedance budget of the machine, which includes contributions from all the in-vacuum components and the coherent synchrotron radiation (CSR) impedance.

INTRODUCTION

Sirius is a 3 GeV fourth generation light source being built in Campinas, Brazil, by the Brazilian Synchrotron Light Laboratory (LNLS). The status of the project as well as information about the magnetic lattice can be found elsewhere [1,2].

In a previous work [3] we reported the impedance budget for the storage ring, which was calculated using semi-analytic formulas for the wall impedance [4] and 2D [5,6] and 3D [7] numerical codes for the geometric contribution. We also presented preliminary analysis of the effect of this budget in the stability of the storage ring, using semi-analytic methods based on the mode-coupling theory [8–10].

In this work we have added a simple model for the coherent synchrotron radiation (CSR) impedance to the impedance budget and have used an in-house developed tracking code to estimate the single-bunch instability thresholds and potential–well distortion in the longitudinal plane. The same code, which accounts for chromaticity and longitudinal potential–well distortion, was used in the transverse plane to identify the single-bunch instabilities. We also have attempted to include the effects of intra-beam scattering (IBS) in the simulations with a simple approach.

All results presented here are discussed with more details in reference [11].

MULTI-BUNCH INSTABILITIES

The storage ring will be commissioned with a PETRA 7-Cell cavity. We used the data presented by Bassi *et al.* [12] for the higher order modes of this cavity to estimate the current threshold of coupled-bunch instabilities in all three planes of motion for uniform filling. Figure 1 summarizes the results. Considering the resonant modes can have center frequencies slightly different from the one simulated, there is possibility for instabilities at beam currents as low as 10 mA in the longitudinal and 5 mA in the transverse planes. However, it is most likely that the beam will turn unstable at currents larger than 20 mA. The storage ring will have bunch-by-bunch feedback systems in all three planes with dedicated actuators [13, 14] to help accumulation of larger currents.

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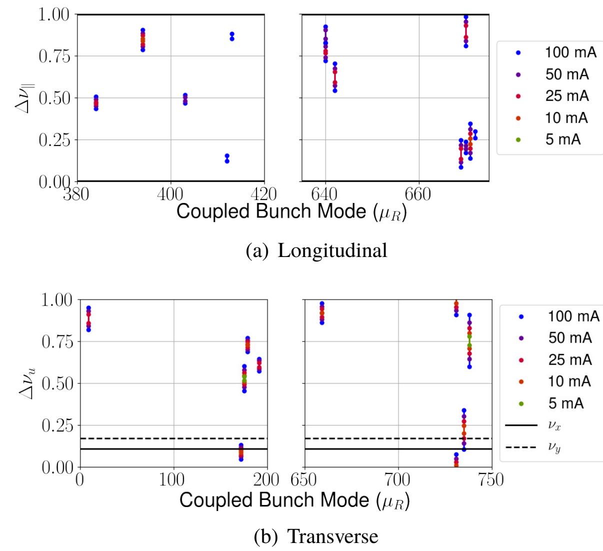

Figure 1: The horizontal axis is the mapping of the cavity impedance peaks in the coupled–bunch modes. Vertical axis indicates the fractional part of one revolution frequency. The vertical intervals defined by the dots are those in which sampling by the tune corresponds to instability at the indicated current. a) Black horizontal lines are $\pm\nu_z$; b) Black solid horizontal line is the fractional part of ν_x and black dashed line is the fractional part of ν_y.

Regarding the coupled–bunch instabilities driven by the resistive-wall impedance in the transverse planes, the results presented in previous works [3] were not investigated any further. However, we additionally estimated the incoherent tune-shift caused by the low frequency part of the detuning impedance to be on the order of $\Delta\nu_{x,y}/I \approx (1.4, -2.2)\mathrm{A}^{-1}$ for uniform filling.

TRACKING SIMULATIONS

The tracking code used to perform the simulations presented here is a standard single-bunch particle-in-cell code, which can perform tracking of the longitudinal plane and one transverse plane simultaneously. Regarding single particle dynamics, damping and excitation effects of synchrotron radiation in the longitudinal and transverse planes are considered. The RF voltage is supplied to the code as an interpolation array as function of the longitudinal coordinate, which allows the simulation of arbitrary potential wells. In the transverse plane, linear chromatic and action dependent tune-shifts are also taken into account.

The code supports longitudinal monopole, transverse dipole and detuning wakes which are supplied as interpolation arrays. The wake kicks are calculated by convolution of the wake with the estimated longitudinal particle distribution and/or dipole moments, filtered by a 9-point cubic

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Savitzky-Golay filter [15, 16] to attenuate noise effects. The convolution theorem is employed in this calculation to improve performance [17].

Even though the code allows simultaneous simulations of longitudinal and transverse wakes, the results presented here were obtained by independent runs because the wakes of each plane have different requirements on the simulation parameters. To correctly sample the high frequency content of the wall and the CSR impedances, 10^7 macro-particles and a bin size of 2 µm, which corresponds to approximately 10^4 bins, were needed in simulations of the longitudinal dynamics.

For the transverse plane, a much more relaxed number of macro-particles, 10^5, sufficed to generate reliable results. The distorted longitudinal potential wells as function of the bunch current, obtained by a Haissinski solver, were inserted as input RF voltage for the transverse simulations. Besides, in these cases initial longitudinal distributions in equilibrium with the given potential wells were used to speed up the simulations. This approach is valid for currents below the longitudinal instability threshold. Above it, simultaneous simulation of both planes are mandatory.

The tracking code does not consider Coulomb interaction among the particles. The IBS was artificially introduced in the simulation by increasing the natural emittance and energy spread used to calculate the random excitation due to radiation emission. This approach neglects the interplay between wake induced bunch lengthening and IBS, which may change the stability of the beam, and must be revised in future works.

LONGITUDINAL PLANE

The studies of the longitudinal dynamics of the Sirius storage ring will be presented in this section. First, we will evaluate the effects of the standard impedance budget, without considering the CSR impedance. In the second part we will show the results of the simulations of CSR alone and in the third part we will account for both sources plus IBS.

Machine Impedance

Figure 2 shows the main longitudinal beam parameters obtained from averaging over all the simulated turns. Two different situations were studied, with and without the IBS effects, to account for the best and worst case scenarios regarding the instability threshold. A strong instability rises between 2.8 mA and 3.0 mA for the simulation with the wake effects only, and drastically increases the average energy spread as a function of the current. Only 0.5 mA above the threshold, the energy spread reaches values larger than the one where the effects of IBS are considered.

Even though their time average are comparable, the behavior of the beam above the threshold is completely different in both situations. While the situation with IBS is stable and stationary, the behavior of the beam parameters as function of time (not shown here, see [11]) reveals that a strong saw–tooth instability is happening in the simulation with

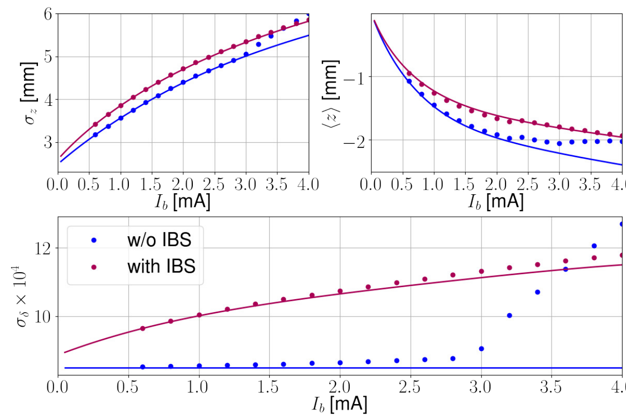

Figure 2: Main parameters of the beam obtained from tracking (dots) as a function of the current for the simulations with and without the effects of IBS. The values shown here are averages over all the 3×10^4 turns of the simulation. The solid lines are the results obtained from the solution of the Haissinski equation.

the machine wakes only, driven by a quadrupole oscillation mode, whose coherent energy grows two orders of magnitude from 2.8 mA to 3.0 mA.

It is worth mentioning that the instability threshold found with tracking agreed well with frequency domain simulations based on mode-coupling theory. However, the use of the non-convergence of a Haissinski solver based on iteration methods to indicate instabilities thresholds, as was done in [3], leads to wrong results, as already pointed out in a recent paper [18].

CSR

The impedance model we used in this work for CSR was the one calculated by Murphy *et al.* [19] for a planar circular trajectory between to infinite superconducting parallel plates. This model was also used by Bane *et al* [20] to show that the threshold for the microwave instability as a function of the plates separation depends only on two dimensionless variables. Since then several experiments revealed good agreement with the theory predictions [21, 22].

Sirius has two different types of dipoles. The low field dipoles, with a bending radius of 17.2 m, are responsible for a total deflection angle of 338° along the ring and have circular chambers of 12 mm inner radius. The high field dipoles have a bending radius of 3.1 m and a chamber of 4 mm. Using the scaling factors defined by Bane *et al.* [20], it is possible to conclude that the threshold for CSR induced microwave instability is 1.0 mA. Our tracking simulations identified the threshold at 1.2 mA and a microbunching behavior above the threshold very similar to the one described by Venturini & Warnock [23].

Instability Thresholds

The results discussed above suggested all the parameters of the simulation were correctly tuned so as to identify the

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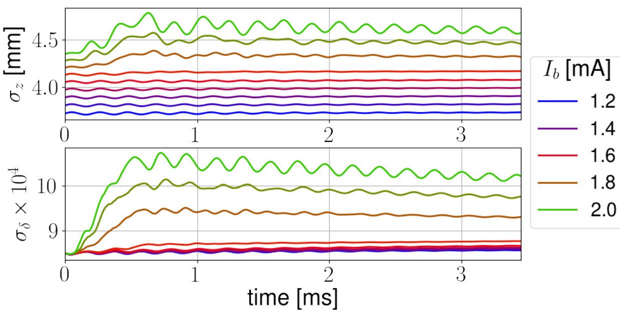


Figure 3: Time evolution of the energy spread and bunch length for different bunch currents in the simulation with CSR and the machine impedance budget.

CSR instability and we proceeded with its inclusion in the storage ring impedance budget. The simulations without the effects of IBS show modulations of the beam density starting from a current of 1.4 mA. Even though the threshold is not affected significantly by the potential–well distortion, the behavior of the beam above the threshold is very different. When only the CSR wake is considered, with a current only 0.1 mA above the threshold, the modulations are strong enough to distort the beam, changing significantly the time evolution of energy spread and bunch length. For the case where both the machine impedance and CSR are considered, the instability remains weak up to 1.7 mA, as shown in Fig. 3. The threshold for the simulations with the effect of IBS included is between 3.4 mA and 3.6 mA, but the instability is weak and does not change the equilibrium parameters up to 4.0 mA.

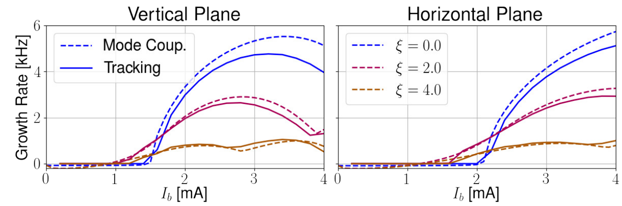
TRANSVERSE PLANES

For the transverse single–bunch instabilities two scenarios were simulated: considering only the transverse wakes; taking into account the effects of IBS and the longitudinal wakes, via the distorted RF potential well.

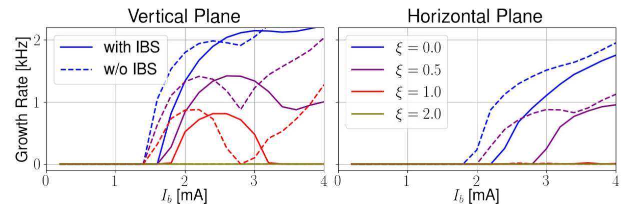
Figure 4(a) shows the growth rate of the single–bunch instability for different values of chromaticity for the first scenario. The solid lines represent the results obtained from tracking and the dashed lines are predictions of mode-coupling theory in frequency domain, considering the first 10 radial modes and azimuth modes from −10 to 10. The good agreement between frequency and time domain simulations shown in the Fig. 4(a) was already expected, considering that the conditions used in tracking perfectly match the assumptions made by the mode–coupling theory.

Figure 4(a) also shows that the chromaticities have a strong effect on the single–bunch instabilities, where positive values reduce growth rates in both planes at the cost of lowering the current threshold. It is expected that this reduced growth rate will improve the effectiveness of the control of this instability with the bunch–by–bunch feedback system, as shown experimentally at ALS [24] and at Diamond [25].

Figure 4(b) shows the effect of the longitudinal impedance on the beam transverse stability at different chromaticities for



(a)



(b)

Figure 4: Transverse single–bunch instabilities for the first phase of operation of the Sirius storage ring, a) without b) with the effects of IBS and potential–well distortion.

two different configurations: with and without the effects of IBS. In the vertical plane, the potential–well distortion alone does not increase the current threshold but helps lowering the growth rates of the instability and increase its sensitivity to chromaticity. In contrast, the additional energy spread introduced by IBS increases the threshold but has not a strong influence on the growth rates. The same qualitative behavior also applies to the horizontal plane.

Finally, Fig. 4(b) shows that both planes are stable when the ring is operated at chromaticity equal to 2.0.

CONCLUSION

The main unknown effect to determine the stability of the beam in Sirius in front of the several impedance sources is the interplay of IBS and potential–well distortion. In this work we tried to address this problem discussing two extreme situations, one optimistic and one pessimistic.

While in the transverse plane the results have not shown a large influence of IBS, where stability was achieved even in the pessimistic scenario, simulation of the longitudinal plane have confirmed the strong influence of IBS on the threshold of microwave instability driven by CSR, requiring further investigations in future works.

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