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STUDY OF COLLECTIVE BEAM INSTABILITIES FOR SIRIUS

F. H. Sá*, L. Liu, H. O. C. Duarte, X. R. Resende, N. Milas
Brazilian Synchrotron Light Laboratory (LNLS), Campinas, Brazil

Abstract

In this paper we present the on going work of construction of the Sirius impedance budget and instability threshold estimates for several machine operation scenarios.

MAIN PARAMETERS

Sirius is a 3 GeV synchrotron light source that is being built by the Brazilian Synchrotron Light Laboratory (LNLS) in Campinas, Brazil. It is based on a low emittance (0.28 nm.rad) 5BA lattice, with large horizontal and vertical tunes (46.17 and 14.14, respectively), which requires small aperture for the magnets and vacuum chambers, arising potentially dangerous impedance issues. The circumference of the machine will be 518.40 m (revolution frequency of 578 kHz) and the RF frequency will be 500 MHz, implying an harmonic number of 864.

The operation scenarios considered for Sirius from commissioning to maximum current and full insertion devices (IDs) usage are presented in Table 1 and are fully discussed in reference [1].

Table 1: Operation Scenarios for Sirius

	Phase 0	Phase 1	Phase 2
I_T [mA]	100	100	500
I_B [μA]	116	116	579
3HC	no	no	yes
σ_s^{rms} [mm]	3.2	3.3	12.7
τ (H/V/L) [ms]	16/21/12.5	12/15/8.5	10/12/7
IDs	-	6 IVUs 4 EPUs 1 SCW	12 IVUs 8 EPUs 1 SCW

IMPEDANCE BUDGET

The Sirius impedance budget is still being constructed and relies on analytical calculation and numeric simulation of the components of the storage ring. In this section the modeling of some subsystems will be presented.

Vacuum Chamber Impedance

The standard dipole and straight section vacuum chambers will be round, made of copper and coated with NEG (see Table 2). We model them as cylindrical tubes using the formulas presented in reference [2]. Curvature and radiation exit effects are neglected and the effect of NEG coating is considered.

Besides the standard chamber, Sirius will have special chambers for the fast corrector magnets that will operate at a rate of 10 kHz. These chambers will be made of thin foil of stainless steel (SS316L), brazed to the copper chamber and also coated with NEG.

Table 2: Main Parameters used to Estimate the Vacuum Chamber wall Impedance

NEG thickness	1	μm
NEG conductivity	4.0	MS m^{-1}
Chamber inner radius	12	mm
Conventional chamber		
Chamber thickness	1	mm
Copper conductivity	59	MS m^{-1}
Copper relaxation time	27	fs
Length	480	m
Fast Corrector chamber		
number of correctors	80	
Chamber thickness	0.3	mm
SS316L conductivity	1.3	MS m^{-1}
Length	0.1	m

Undulators

We considered three types of undulator for Sirius, as seen in Table 1. In this initial budget, the impedance of the Superconducting Wiggler (SWC) was not taken into account, because this device is shorter, just one will be installed and the larger gap makes its impedance negligible compared to the others.

Table 3 shows the main parameters used in the undulator impedance modeling. There are two types of IVU with different gaps because they will be installed in sections with different betatron functions.

For the undulators it is possible to separate the impedance in two main contributions: the geometric impedance from the tapered transitions and the chamber wall impedance from the low gap sections. The first one is difficult to calculate, because it depends on the detailed design of the component and is not available yet. For this reason it will be included in the budget as a contribution to the broad band model.

The second contribution, the wall impedance, was estimated using the mulitlayer formulas for the round chamber and applying the Yokoya factors [3] to correct the results for the flat chamber. This approach is well justified for the EPUs, where the vaccum chamber will be made of copper with an elliptical cross-section with large eccentricity.

For the IVUs, the magnetic poles will be made of permanent magnet (NdFeB) array, with different polarization

* fernando.sa@lnls.br

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Table 3: Main Parameters used on the Undulator model

Elliptically Polarizing Undulators		
Length	2.7	m
Chamber thickness	1	mm
Chamber eccentricity	> 0.4	
Chamber minor axis	10	mm
In-Vacuum Undulators		
Full gap	4.5 and 7.8	mm
Copper sheet thickness	75	μm
μ_r of NdFeB	100	
σ of NdFeB	0.625	MS m^{-1}
Length	2	m

directions, and a thin sheet of copper will be placed to shield the beam and reduce heating and other impedance issues. These ferromagnetic materials restrict the applicability of the multilayer formulas, because they were derived under the assumption of linear materials with longitudinal symmetry. However, considering that the fields generated by the magnets themselves were already taken into account on the beam dynamics and that the strength of the electromagnetic fields generated by the beam in the materials is small, it is possible to model this magnets as linear materials with some unknown relative magnetic permeability $\mu_r(\omega)$. This parameter was varied, showing a weak dependence on the impedance, which led to the assumption presented in Table 3, as a worst case estimate.

Injection Kickers

The Sirius injection kickers will have the window frame architecture and will be placed outside vacuum. Its ceramic vacuum chamber will be coated with Ti. Figure 1 shows a simplified scheme of the magnet.

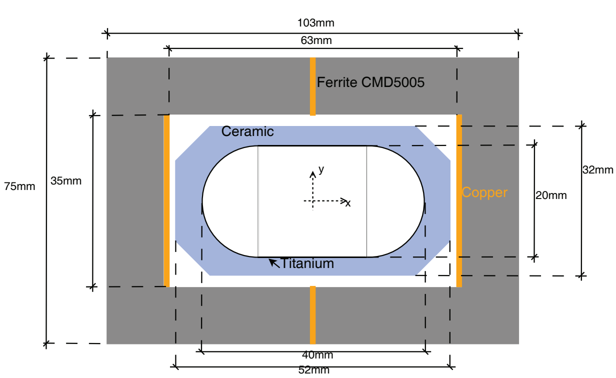

Figure 1: Transverse cross section of the Sirius injection ferrite kickers.

The modeling of their impedance considers two main contributions: the coupled flux, driven by the coupling of the beam with the external circuits, via the endplates of the window frame, and the uncoupled flux, generated by the interaction of the electromagnetic fields of the beam with the lossy materials that compose the magnet.

Regarding the coupled flux, based in references [4, 5], a simplified model of the external circuit was considered. In this model, the generator impedance is $Z_g^{-1} = \left(1/R + i\omega C_p\right)$ which represents a RC circuit in parallel. Together with the inductance of the window frame, this impedance generates a beam impedance with peak centered at ~50 MHz. If needed, this model can be improved with results from measurements with magnets, once the prototypes are produced.

The contribution from the uncoupled flux involves a study of the effect of the coating and the ceramic chamber to the impedance. To evaluate this effect we modeled the kicker as a round chamber with several layers: Ti coating, ceramic, vacuum, ferrite and copper. Even though all the information about the geometry was lost with this approximation, it was possible to determine approximately the frequency in which the coating begin to damp the impedances, the shape of the impedance around this frequency and confirm that it is low enough to damp all the resonances introduced by the ceramic.

Differently from the high frequency behavior, the low frequency impedance may depend very strongly on the geometry and properties of the magnet beyond the coating. In this range, the Tsutsui model for the uncoupled flux [6, 7] applies and was used to fit the low frequency value for the beam impedance of the magnet.

Numerical Calculations

All Sirius components with complex geometries will be calculated with numerical codes, such as GdfidL and ECHO [8]. For some elements, the design will be guided by impedance optimization, together with other specific performance parameters.

So far we have designed some of these components, such as the BPM buttons [9], the flanges, dipole chambers with radiation exit and radiation masks. Most of the work is being done in the longitudinal plane, due to heating effects and longitudinal coupled bunch instabilities, since we do not plan to have a bunch-by-bunch longitudinal feedback system for Sirius. At this design stage, transverse impedance is being be optimized mainly for the tapered transitions for RF cavities and IDs.

Broad Band Impedance

Considering that there are several components of the storage ring for which the impedance was not calculated yet, the budget must be complemented with a broad band model to provide more realist current thresholds results. This model generally is given in terms of the slope of the imaginary part of the longitudinal impedance at low frequencies, $Z_\parallel/n$ with $n = \omega/\omega_0$. Its values vary from 0.2 Ω to 0.4 Ω amongst the 3rd generation light sources in operation.

We have decided to use a low Q resonator to represent our broad band model, with a resonance frequency at the pipe cutoff, around 9.5 GHz, and a shunt impedance corresponding to $Z_\parallel/n$ equal to 0.2 Ω for phase 1 and 0.4 Ω for phase

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2. For the transverse plane, we applied the transformation rule $R_\perp = R_\parallel / b$, where b is the pipe radius, for the shunt impedance.

The horizontal impedance budget we used for phase 2 is presented in Figure 2, where the horizontal impedances are weighted by the betatron functions at the place of the source.

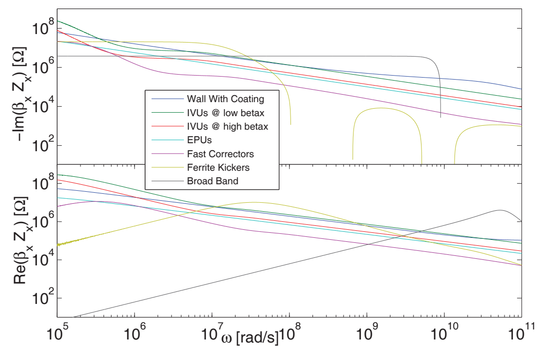

Figure 2: Horizontal impedances weighted by the betatron function.

INSTABILITY THRESHOLDS

The instabilities thresholds estimates for the operation scenarios of Sirius were calculated using codes based on the frequency domain solution of the linearized Vlasov equation for equally spaced and populated Gaussian bunches [10, 11].

Transverse Plane

Figure 3 shows the results of the instabilities estimates in the horizontal plane for the phase 1. This calculation assumes uniform filling and 4 azimuthal and 6 radial modes. The calculations are valid for the coupled bunch mode 817, which is the one with higher resistive wall instability growth rate. We notice that this spectrum is very different from the one of a single bunch. The existence of the coupled bunch instability does not let the modes couple, however a non-linear increase in the growth rate is observed at 1 mA. The spectrum of the coupled bunch 386, which has no effect from the resistive wall, is very similar to the single bunch case, and we observe a coupling of the azimuthal modes 0 and -1.

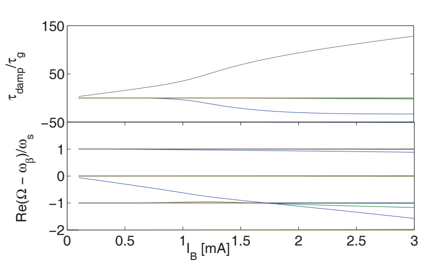

Figure 3: Horizontal TMCI for phase 1.

For the transverse plane, we plan to use feedback systems to damp the resistive wall from the beginning of phase 1. However, it is not clear yet how the feedback will act on this kind of instability, and further studies must be carried out, trying to include the feedback in the codes.

The thresholds for mode coupling instabilities for single bunch are 1.5 mA and 1.0 mA for the horizontal and vertical planes for the phase 1 and 1.5 mA and 2.2 mA for the phase 2. We notice that the transverse mode coupling will not be a problem for these modes, but may affect the single bunch or hybrid filling profile, where the Landau cavity does not lengthen the bunch optimally.

Longitudinal Plane

The calculation assumes uniform filling and 16 azimuthal and 25 radial modes. The results are specifically valid for the coupled bunch mode 0, but as there is no coupled bunch oscilations for the longitudinal plane, they are valid for any mode. The coupling happens at 1.74 mA and the modes which couple have azimuthal numbers 1 and 2.

For phase 2 the third harmonic cavity will elongate the bunches and the threshold for the microwave instability will be much higher than 3 mA. However, foir a single bunch or hybrid filling pattern operation, a pessimistic estimate for the threshold impedance would be half of the value calculated for phase 1, that is 0.8 mA.

CONCLUSIONS

The current impedance model for Sirius presents some important features of the components. However the broad band impedance has a big contribution to the instabilities thresholds and the budget must be continuously updated, mainly with the numerical results. Regarding the instability estimates, it is necessary to further study the effect of the feedback system and the Landau cavity on the beam as well as estimates of other kind of instabilities, such as trapped and fast ions.

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