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INTRA-BEAM SCATTERING EFFECT IN THE SOLEIL STORAGE RING UPGRADE

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Abstract

As the work on the design of the upgrade of SOLEIL storage ring advances, the study of the impact of Intra-Beam Scattering (IBS) on the equilibrium emittance is also progressing, showing a significant contribution of this effect. Different measures can be taken to mitigate the emittance dilution, like operating the machine with full transverse coupling and using harmonic cavities to increase bunch length. The calculation of the IBS effect needs then to take into account the different beam dynamics and its effect on the particle distribution. In this paper the current state of the ongoing study is presented, reporting on the results obtained for the different options considered, and comparing the results of different codes and their implicit assumptions.

INTRODUCTION

The studies for the design of the SOLEIL storage ring upgrade entered in the phase of preparation of the Conceptual Design Report (CDR), to be published at the end of 2020. The target natural emittance of the new ring is below 100 pm rad while the energy is kept at 2.75 GeV conserving most of the operation modes and filling patterns in use today. The existing enclosure can accommodate a ring with a circumference around 354 m; with a frequency about 352 MHz (like today) the harmonic number is 416 (also unchanged). At nominal intensity (500 mA) with uniform filling the bunch intensity is around 1.2 mA but we are interested, for some operations, in bunch intensities up to 12 mA and during commissioning or machine studies it may also reach 20 mA (bunch charge up to 23.7 nC). From these parameters it is not surprising that simulations show the presence of strong IBS effect which may blow up emittances and deteriorate the performance of the machine. For this reason the impact of IBS on equilibrium parameters of the new ring is evaluated. It is also checked the effectiveness of introducing transversal coupling and employing harmonic cavities to lengthen bunches (diluting the charge density) as countermeasures to cure IBS induced emittance blow-up.

STUDIED LATTICES

The candidates for the new lattice of the storage ring are mainly of 2 types: the Hybrid and the Higher Order Achromat (HOA). This study will focus on the estimation of IBS effect in 2 solutions composed of 20 periodic cells of either one of the 2 types; currently other solutions are being studied to best fit constraints given by the beamlines. Details about these lattices may be found in [1-3].

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Figure 1 shows the optics and layout of a cell of Hybrid type while Fig. 2 shows a cell of HOA type.

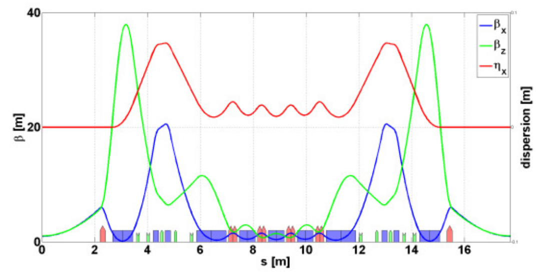

Figure 1: Periodic cell of Hybrid type.

The lattices currently studied have similar Twiss parameters and dispersion compared to the ones treated here, so that results should not be significantly different.

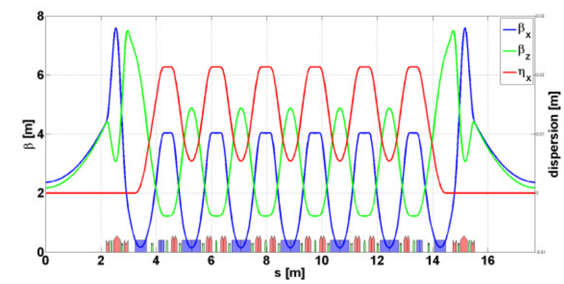

Figure 2: Periodic cell of HOA type.

At a more advanced stage of the design study new simulations of the new candidate lattices will be performed. In Table 1 relevant parameters for the 2 rings analysed are reported.

Table 1: Parameters of Hybrid and HOA Lattices

Lattice	Hybrid	HOA
Circumference	354.8 m	354.2 m
N. of cells	20	20
Nat. emittance	72.2 pm	76.3 pm
Nat. energy spread	$8.63\ 10^{-4}$	$7.75\ 10^{-4}$
Nat. bunch length	12.3 ps	8.3 ps
Damping times (x, z, s)	9.86, 20.89, 23.98 ms	10.39, 16.45, 11.60 ms

CODES EMPLOYED

For our investigation we used different codes to cross-check the results, including ZAP [4], program *ibsEmittance* which is distributed with *elegant* [5], and SIRE [6]. ZAP calculates the equilibrium emittances in the storage ring by iteratively calculating the contributions to the

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emittance increase by IBS, quantum excitation and radiation damping using the user input parameters. The program stops when it finds emittances for which the sum of the 3 contributions cancels. IBS calculation assumes a Gaussian distribution of the beam and follows the Bjorken-Mtwinga formalism. Program *ibsEmittance* also is based on the same formalism but with an extension to include vertical dispersion. Program SIRE is a tracking code which takes the initial coordinates of the macro-particles as inputs and propagates them through the ring assuming linear dynamics. The change in the emittance is produced by the contributions of the 3 effects above. IBS calculation is based on the Piwinski formalism. The macro-particles are divided in cells and made to collide to simulate Coulomb scattering. No assumptions are made on the distribution of the (macro) particles. To compare the results of SIRE with the other codes we run simulations starting with a Gaussian distribution of the macro-particles with the natural parameters of the beam. In Fig. 3 it is shown the evolution of the horizontal emittance in a ring with HOA lattice during a period of 40 ms.

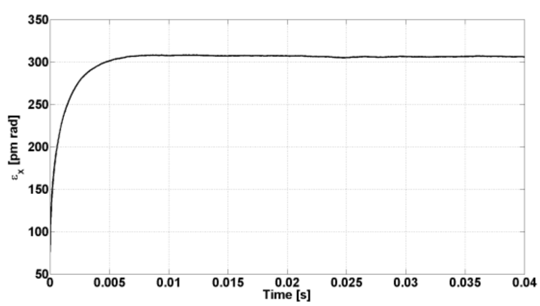

Figure 3: Evolution of the horizontal emittance in a simulation performed with SIRE.

As can be seen the emittance starts to grow because of IBS and in less than 10 ms reaches its equilibrium value. The same behaviour is reproduced in the vertical and longitudinal planes. The plot corresponds to a simulation with 20 mA bunch current which is the maximum current we used, in order to see a big emittance blow up. As can be noted from the plot there are small fluctuations around the equilibrium. Since the scattering between the macro-particles is simulated using a Monte Carlo algorithm statistical fluctuations are expected. To overcome this problem we average the results over the last few milliseconds of the simulation. To reduce these fluctuations we also employ 200000 macro-particles for each simulation.

The results of the 3 codes employed are compared for all the cases studied. In Fig. 4 a comparison for both Hybrid and HOA lattices is shown. A scan of the equilibrium emittances when varying the bunch current in the range of interest is performed, for a value of transverse coupling of 1% in order to have a strong IBS effect on the horizontal plane, making more evident the discrepancies between the different estimations. Only results for the horizontal emittance are shown but the other planes display identical behaviour. We can first note that there is not a big difference between the 2 lattices in terms of IBS effect. Codes ZAP and ibsEmittance show very close results as expected, being based on the same formalism, but overall the results of all 3 codes are reasonably consistent.

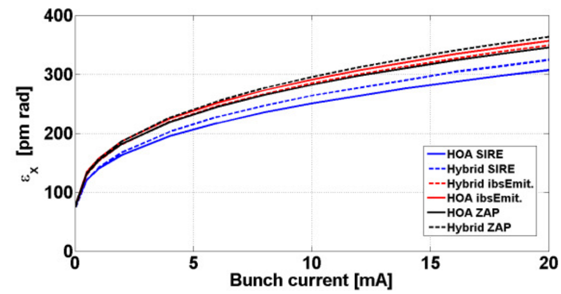

Figure 4: Comparison between the codes used.

From the plot it is also evident that the relative discrepancies between the estimations increase with bunch intensity, showing a maximum 16% at 20 mA (range between 307 and 357 pm rad). At the nominal intensity (1.2 mA) the range is between 145 and 163 pm rad. Bunch lengths also experience similar increase but such increase does not create problems for the users.

IBS MITIGATION

From Fig. 4 we can conclude that IBS effect can become very strong in the new storage ring and can dilute the emittance far from the target parameters. Fortunately there are strategies that can be taken to lower its impact, as for example increase the transverse coupling using some designated skew quadrupoles. In fact a vertical emittance at a level of few pm rad is not strictly required by many users, so that it may be convenient to allow some increase in the vertical plane if this can produce a substantial decrease in the horizontal one. To check this possibility we run simulations with different values of transverse coupling. Figure 5 shows the results obtained with SIRE.

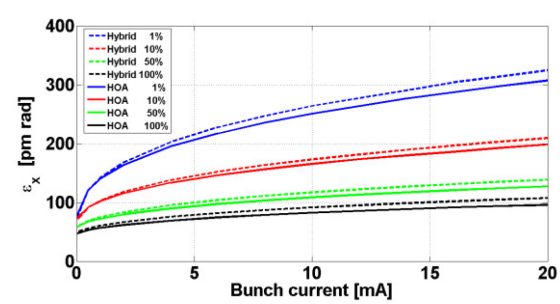

Figure 5: Equilibrium horizontal emittance as a function of the bunch current for different transverse coupling values.

As can be seen, at the bunch current of 20 mA the horizontal emittance can be decreased from around 300 pm rad to around 100 pm rad by varying the transverse coupling from 1% to 100%. For the nominal intensity (i.e. 1.2 mA/bunch or 500 mA with uniform filling) the variation is from 145 to 60 pm rad, which represents a 23% increase from the zero current value. Looking at the

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bunch length, we can see a similar behaviour, showing a reduced bunch lengthening when the coupling is increased. It may be worth noting that the reduction of the emittance blow-up when increasing the coupling is more pronounced in the region of small values of the coupling, for example passing from 1% to 10% and then becomes less and less effective when approaching 100%.

Another technique under study for the mitigation of IBS effect is the addition of a harmonic cavity to produce a bunch lengthening up to a factor 5 the value obtained with just the fundamental cavity. Actually the new RF system studied is more complicated because of the need for compensation of the transient beam loading induced by the different filling patterns used [7]. An accurate study of the IBS effect in such conditions requires substantial modifications to the treatment of the longitudinal dynamics in SIRE in order to include the contribution of 2 or more cavities. Such modifications will be addressed soon, for the moment we simply use the current version of SIRE with a natural bunch length up to 5 times the one calculated with just the fundamental cavity. Figure 6 shows the results of the simulations in the case of 100% transverse coupling for different values of the bunch lengthening (factors 1, 3 and 5).

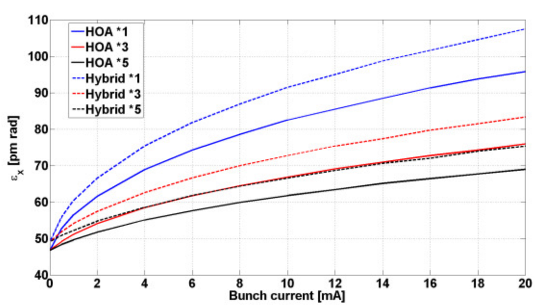

Figure 6: Horizontal emittance (for both lattices) as function of bunch current for different bunch lengthening.

The simulations show a big reduction of the IBS effect in both lattices, with the emittance being reduced respectively to 70 and 75 pm rad for HOA and Hybrid lattices at the maximum bunch intensity. At nominal intensity the emittance is 50 and 53 pm rad for HOA and Hybrid lattices, less than 10% increase from the zero current values. Simulations show a further lengthening of the bunches due to IBS other than to the employment of the harmonic cavity; assuming a factor 5 increase of the bunch length due to the harmonic cavity, IBS will bring it to around 86 and 63 ps respectively for Hybrid and HOA lattices at 20 mA bunch intensity. At nominal intensity their values are 65 and 46 ps.

CONCLUSION

In this paper we have presented the current state of the study of IBS effect in the SOLEIL storage ring upgrade. The ambitious target emittance aimed for requires an accurate evaluation of it in order to avoid unwanted blow-ups that may compromise the performance. To this end we employ different codes to cross-check the results. Our simulations show a potentially very strong contribution of IBS to the equilibrium emittance so that the investigation of the effectiveness of possible countermeasures is necessary. One possible mitigation technique under study is given by the possibility to operate the machine with transverse coupling. Simulations presented here show that a significant reduction of the emittance increase is achievable even for relatively small values of coupling, so that it can be adjusted to the convenience of the users. We also investigate the possibility to use a harmonic cavities to lengthen bunches. Also with this method a considerable reduction of emittance blow-up is seen, especially if combined with coupling. IBS effect can be reduced to less than 10% of emittance increase at nominal bunch intensity corresponding to 500 mA in uniform filling. While we are currently aiming for a factor 5 bunch lengthening with respect to the natural value, simulations show that also for smaller factors this technique is still effective. For our study we adopted the usual computation of IBS effect just increasing the zero current value of the bunch length as input to the codes. A more accurate computation would require a realistic treatment of longitudinal beam dynamics in presence of harmonic cavities and the effects induced by the different filling patterns simulated. This is planned to be the next step of our study. A further step would be the inclusion of collective effects in the computation since they contributes to a large extent to the beam dynamics and are responsible for significant changes of particle distributions in the machine.

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