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COLLECTIVE EFFECTS STUDIES FOR THE SOLEIL UPGRADE

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Abstract

The SOLEIL upgrade project aims to replace the actual SOLEIL storage ring by a 4th generation light source. The project has just finished its conceptual design report (CDR) phase [1]. Compared to the SOLEIL storage ring, the upgraded storage ring design includes many new features of 4th generation light sources that will impact collective effects, such as reduced beam pipe apertures, a smaller momentum compaction factor and the presence of harmonic cavities (HC). To mitigate them, we rely on several damping mechanisms provided by the synchrotron radiation, the transverse feedback system, and the HC (Landau damping and bunch lengthening). This article presents a first estimate of the collective effects impact of the upgraded design.

INTRODUCTION

This paper is a summary of the collective effects studies done in the framework of the SOLEIL upgrade conceptual design report (CDR) [1]. General information about the SOLEIL upgrade project is available in [2] and the lattice and its main parameters are presented in [3].

This article follows the different steps of this study. First we estimated the impact of the collective effects by summing up the different machine element contributions in an impedance model. Then it was used to establish the current thresholds corresponding to the various single and multi-bunch instabilities.

IMPEDANCE MODEL

For every element of the storage ring, the geometric impedance is computed from 3D drawings made by the SOLEIL design office using CST [4]. The resistive-wall (RW) impedance for the beam pipes and NEG has been computed using IW2D [5]. The components included in the model and their respective numbers are described in Table 1.

The spectrum for the longitudinal impedance is shown in Fig. 1 for the real part. The longitudinal effective impedance $\Im(Z/n)_{eff}$ computed from the model is about 0.14 Ω for the natural bunch length of 9.2 ps (so without the HC), part of which the NEG coating is the major contributor. In comparison, the longitudinal effective impedance of the SOLEIL storage ring was estimated to be about 0.2 Ω from the model [6] and 0.45 Ω was measured [7].

The reduced longitudinal effective impedance and power loss as compared to the present ring are due to two factors:

- The increase of the characteristic frequencies of the impedance from 1.8 GHz to 12.5 GHz (cutoff frequency, in the rectangular waveguide approximation) thanks to the reduced beam pipe dimensions.
- The reduction of the frequency range of the bunch spectrum in high current modes thanks to the harmonic cavity (HC).

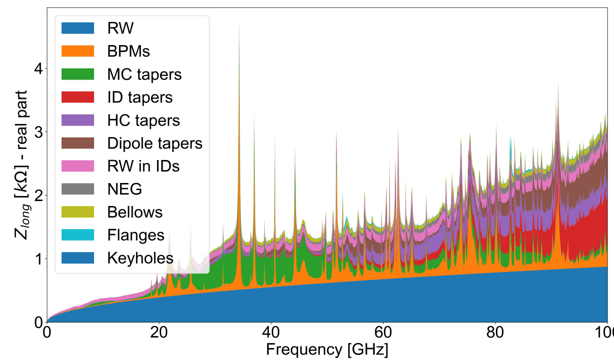

Figure 1: Real part of the longitudinal impedance.

For the transverse planes, the sum of the transverse impedance weighted by the betatron functions at the impedance location is shown for the vertical dimension in Fig. 2. The transverse effective impedances are $\sum \beta_y (Z_y^{Dip})_{eff}$ = 1019 + 2458 i kΩ and $\sum \beta_x (Z_x^{Dip})_{eff}$ = 638 + 1448 i kΩ, compared to $\sum \beta_y (Z_y^{Dip})_{eff}$ = 328 + 1369 i kΩ and $\sum \beta_x (Z_x^{Dip})_{eff}$ = 94 + 695 i kΩ in the SOLEIL model [6].

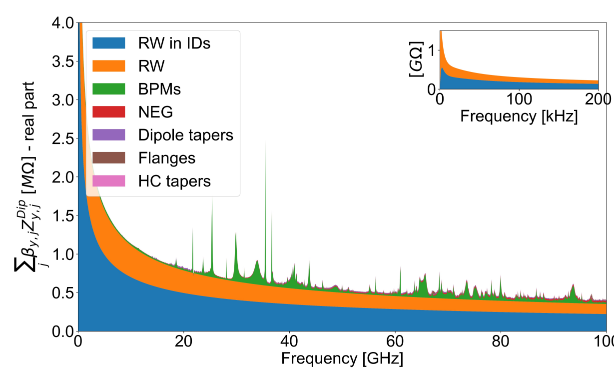

Figure 2: Real part of the vertical dipolar impedance weighted by the vertical betatron function at the impedance location.

The increase of the effective transverse impedance in both horizontal and vertical planes is the consequence of the reduced beam pipe apertures. The transverse impedance is

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Table 1: Impedance Model Considered for Simulations

Element	Number	Remarks
BPM	200	
Keyhole profile chamber	12	
Bellow	125	"comb" type [8, 9]
Flange	250	"impedance free" type [8, 10]
Taper for main RF cavity (per pair)	1	$L = 250$ mm $\iff$ 10.2°
Taper for harmonic RF cavity (per pair)	1	$L = 100$ mm $\iff$ 8.5°
Taper for dipoles (per pair)	116	$L = 43$ mm $\iff$ 8°
Taper for in vacuum IDs (per pair)	9	$L = 100$ mm $\iff$ 2° (vertical plane only)
Resistive wall	over 336 m	elliptic shape beam pipe, 12 mm x 10 mm, copper
Resistive wall in IDs	over 18 m	elliptic shape beam pipe, 3 mm x 80 mm, copper
NEG coating	over 336 m	$\rho_{NEG} \approx 2.5{\times}10^{-5}\,\Omega$ m and $h_{NEG} \approx 1$ µm

dominated by the resistive-wall contribution which increases as $1/(r^3\sqrt{\sigma})$, where r and σ denote respectively the beam pipe radius and the wall electric conductivity, meaning a factor of 12 in the vertical direction compared to SOLEIL (a factor 15 in going from r = 12.5 mm to 5 mm and a factor 0.77 in switching to copper beam pipe instead of aluminum).

Thankfully, there are other effects which decrease the impact of the transverse impedance such as:

- Reduced mean betatron functions from $\beta_x = 8.0$ m and $\beta_y = 9.5$ m to $\beta_x = 3.5$ m and $\beta_y = 4.4$ m in the upgraded ring.
- An increase of chromatic frequency shift f_ξ from 2 GHz to 9.3 GHz per unit of chromaticity because of the reduced momentum compaction factor α_c. For a nominal chromaticity of $\xi_x = \xi_y = 1.6$ the chromatic frequency shift is 14.9 GHz compared to the 2.8 GHz and 4.6 GHz shifts for $\xi_x = 1.4$ and $\xi_y = 2.3$ of SOLEIL.

SINGLE BUNCH INSTABILITIES

In this section, we estimate the single bunch instability threshold which could prevent us from reaching the design performance in the different operation modes. In particular, for a total current of 500 mA in uniform filling, the current per bunch is 1.2 mA. For the ¾ filling pattern with 450 mA, it is 1.45 mA. For the 8 bunch and single bunch modes, the current per bunch is respectively 13.75 mA and 20 mA.

Micro Wave Instability

The micro wave instability (MWI) is responsible for the emergence of density modulations within an electron bunch which results in the increase of the bunch energy spread. The MWI threshold given by the modified Boussard criterion for $\Im[Z/n]_{eff} \approx 0.14\,\Omega$ (so without HC) gives $I_{th} \approx 0.8$ mA.

This value is, in fact, quite pessimistic as the effective longitudinal impedance only takes into consideration the imaginary part of the longitudinal impedance to estimate the MWI threshold. In the upgrade case, the imaginary part of the longitudinal impedance is significantly increased by the NEG coating, whereas it has no impact on the real part of the impedance which is responsible for the MWI threshold.

The MWI threshold has also been estimated using the `mbtrack` tracking code [11], using the longitudinal impedance model and 10^6 macro-particles:

- $I_{th} \approx 2.5$ mA $\pm$ 1 mA without the HC.
- $I_{th} \approx 6.5$ mA $\pm$ 1 mA with the HC.

Coherent Synchrotron Radiation

The coherent synchrotron radiation (CSR) instability corresponds to the same physical phenomenon as the MWI but at higher frequencies. The CSR is partially shielded by the beam pipes up to a characteristic frequency $f_{sh} \approx 430$ GHz for the upgrade, where it is $f_{sh} \approx 80$ GHz for SOLEIL [12].

The CSR instability threshold, considering the steady state parallel plate model [13] and a single dipole type, gives using an analytic formula [14]:

- Between $I_{th} \approx 1.6$ mA and $I_{th} \approx 1.9$ mA without the HC depending on the dipole type.
- Between $I_{th} \approx 9$ mA and $I_{th} \approx 11.4$ mA with the HC depending on the dipole type.
- $I_{th} \approx 6.5$ mA for SOLEIL, for a measured threshold of 8 mA.

The CSR instability threshold also has been estimated using a Vlasov-Fokker-Planck solver [15] considering the same steady state parallel plate model but taking into account the different kind of magnets used in the upgrade. The results agree with the analytic formula:

- $I_{th} \approx 2.5$ mA without the HC.
- $I_{th} \approx 12.5$ mA with the HC.

Transverse Mode-coupling Instability and Head-tail Instability

The transverse mode-coupling instability (TMCI) and the head-tail instability are transverse single bunch instabilities relevant respectively at zero and non-zero chromaticities. Both instabilities are estimated by tracking using

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mbtrack [11], taking into account both longitudinal and transverse impedances and using 10^6 macro-particles. For a nominal chromaticity of $\xi_x = \xi_y = 1.6$, the threshold currents for the head-tail instability are:

- $I_{(th,y)} = 2.5$ mA and $I_{(th,x)} = 10$ mA without the HC.
- $I_{(th,y)} = 5$ mA and $I_{(th,x)} = 16$ mA with the HC.

At SOLEIL, the measured thresholds for a nominal chromaticity of $\xi_x = 1.4$ and $\xi_y = 2.3$ are 8 mA in vertical and 13 mA in horizontal (all IDs open). The transverse bunch-by-bunch feedback then allows reaching 20 mA in single bunch [16], and the same kind of feedback will be used in the upgrade which should also allow reaching 20 mA.

The evolution of the instability threshold versus chromaticity is shown in Fig. 3. Recent studies using the Vlasov formalism [17] have shown that HC can decrease the TMCI threshold current and our simulations seem to confirm this prediction. For non-zero chromaticity, however, the HC increases the head-tail threshold.

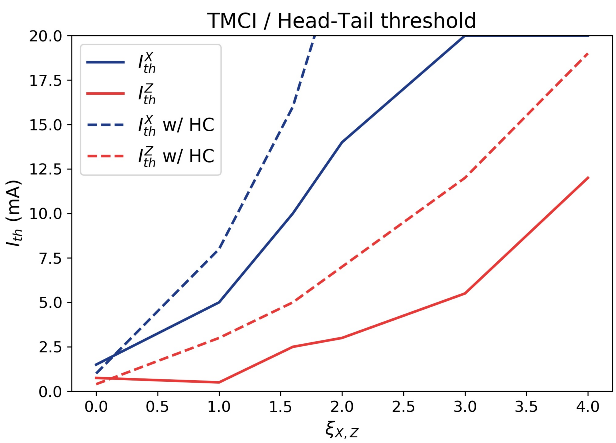

Figure 3: Transverse single bunch instability threshold versus chromaticity, with and without the harmonic cavity.

MULTI-BUNCH INSTABILITIES

Resistive-wall Induced Coupled-bunch Instability

Coupled-bunch transverse instabilities occur when certain frequencies of the beam (coherent modes) are excited by their interaction with impedances having neighboring frequencies. It is the case for the resistive-wall (RW) transverse impedance which presents a large narrow peak at the lowest beam frequency to which the beam strongly responds ($f_{RW} = 0.2 f_0 \approx 170$ kHz).

The RW instability has been estimated both by tracking with mbtrack [11], using 416 bunches with 10^6 macro-particles in each bunch, and by the Vlasov solver rwmbi [18]. The rwmbi code is used to benchmark the mbtrack code in the pure RW case (blue and red dots in Fig. 4), and then results including the full impedance model are obtained using mbtrack (green dots in Fig. 4). At nominal chromaticity, $\xi_x = \xi_y = 1.6$, the multi-bunch current threshold is about 7 mA in vertical and 62 mA in horizontal.

At SOLEIL, the measured vertical threshold is 29 mA at zero chromaticity and the transverse feedback enables reaching 500 mA. We expect that the transverse feedback will also allow us to reach 500 mA in the upgraded ring at nominal chromaticity.

The obtained tracking results indicate that if the HC is used (assuming flat potential conditions), at 500 mA the instability is Landau damped by the synchrotron tune spread generated by the HC as far as the chromaticity is superior to 2 in the vertical plane and superior to 1 in the horizontal plane. So, a slight increase of the vertical chromaticity from the nominal one in order to benefit from Landau damping can also be a cure for this instability.

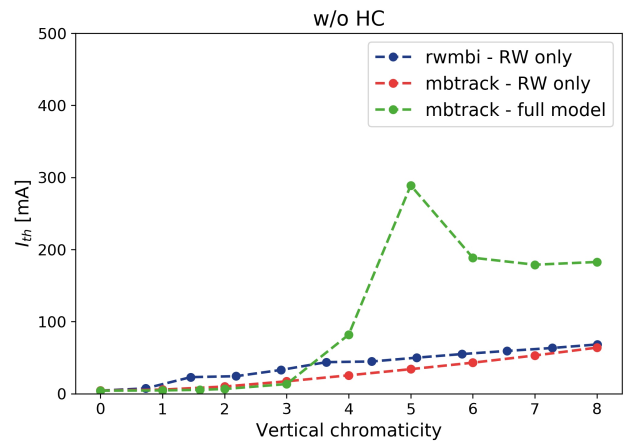

Figure 4: Vertical resistive wall coupled bunch instability threshold versus vertical chromaticity, in the absence of the harmonic cavity.

Ions

Detailed simulations for ion instabilities still need to be undertaken but, under normal vacuum conditions, they are not expected to be a problem. In any case, the transverse feedback should be sufficiently effective against these instabilities.

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