

DOUBLE RF SYSTEM DESIGN USING NORMAL CONDUCTING PASSIVE HARMONIC CAVITY FOR SOLEIL II

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Abstract

Double rf systems are critical for achieving the parameters of fourth-generation synchrotron light sources. These systems relax stochastic collective effects but also introduce instabilities, such as Robinson and periodic transient beam loading (PTBL) instabilities, which depend heavily on the cavity parameters. In the framework of the SOLEIL II project, we demonstrate how we can use semianalytical algorithms to predict and analyze these instabilities, in conjunction with multibunch tracking simulations, to optimize rf cavity parameters in high-dimensional parameter spaces, thereby maximizing the Touschek lifetime. Finally, the expected performances of the double rf system, using the optimized normal conducting passive harmonic cavity parameters, are presented.

INTRODUCTION

SOLEIL II [1–3], is a 4th-generation synchrotron light source (4GLS) presently in construction phase. Like most 4GLS, it will rely on a double rf system, composed of main rf cavities (MC) and harmonic rf cavities (HC), to mitigate the intra-beam scattering (IBS) and Touschek effects.

During the design of the accelerator, different HC types were considered: superconducting (SC) passive of the 3rd or 4th harmonic [4, 5], normal conducting (NC) active [6] and passive [7]. Best performances were expected from the SC passive solution, but overall almost similar to what can be expected from an optimized NC HC at a fraction of the cost. The final choice settled on 4th harmonic passive NC cavities, based on a custom design made in the framework of a collaboration with the ESRF [8, 9], which operates on the TM₀₂₀ mode, to achieve low R/Q and large damping of lower and higher order modes (LOM and HOM). These cavities are equipped with a coupling port, which will be used for the rf conditioning before the installation in SOLEIL II, and may be used for powering the cavities in the future if needed.

The present article details the beam dynamics of the double rf system, how the choice of HC parameter was made and the expected performance of the system. The main SOLEIL II parameters relevant to the results shown here are presented in Table 1.

BEAM DYNAMICS IN DOUBLE RF SYSTEMS

The beam dynamics of the double rf system is investigated by using two distinct approaches. The first is multibunch tracking simulation using `mbtrack2` [10, 11], and the second

Table 1: SOLEIL II Storage Ring Parameters

Parameter	Value
Electron beam energy E_0	2.75 GeV
Natural emittance	84 pm
Circumference L	353.97 m
Revolution frequency f_0	846.9 kHz
Rf frequency f_{rf}	352.3 MHz
Harmonic number h	416
Momentum compaction factor α_c	1.057×10^{-4}
Energy loss per turn (w/o IDs) U_0	469 keV
Longitudinal damping time τ_L	11.64 ms
Relative energy spread σ_s	9.06×10^{-4}
Natural bunch length σ_τ	8.9 ps
Main rf voltage V_1	1.7 MV
Main cavity (total) shunt impedance R_{s1}	20 M Ω
Main cavity quality factor Q_{01}	35.7×10^3
Main cavity loaded quality factor Q_{L1}	6×10^3
Harmonic cavity $(R/Q)_2$ (per cavity)	30 Ω
Harmonic cavity quality factor Q_{02}	31×10^3

is a set of semianalytical methods used to predict and analyze instabilities, which is implemented in ALBuMS [7, 12]. ALBuMS solves a system of coupled Haissinski equations [13] and checks whether the resulting equilibrium is stable or not for various instabilities.

Figure 1 shows the predicted instabilities for SOLEIL II storage ring with 2 passive HC. For each pair of beam current I_0 and HC tuning angle ψ_2 in the plot, either the ALBuMS algorithm (left) or `mbtrack2` tracking (right) is used to compute the beam stability at that point. If the corresponding point is unstable, a marker related to the instability is shown. The instability map is superimposed with ξ isolines, the ratio of the harmonic to main cavity “force” [7, Eq. (A4)], showing how far that point is from the “near flat potential conditions”.

Several instabilities are predicted in Fig. 1. A longitudinal coupled bunch instability (CBI) driven by a HOM of the MC is shown in purple. The fast mode coupling instability (FMCI) [14], corresponding to the coupling between the dipole ($m = 1$) and quadrupole ($m = 2$) azimuthal modes, is shown in red. Both the periodic transient beam loading (PTBL) instability [15, 16] and pure CBI of coupled-bunch mode number $l = 1$ are shown in green. Overall, the agreement between the predicted instability using the semi-analytical algorithm and what is observed in tracking is excellent.

For the SOLEIL II operation, both the CBI and the FMCI shown in Fig. 1 should not be an issue. The FMCI can be

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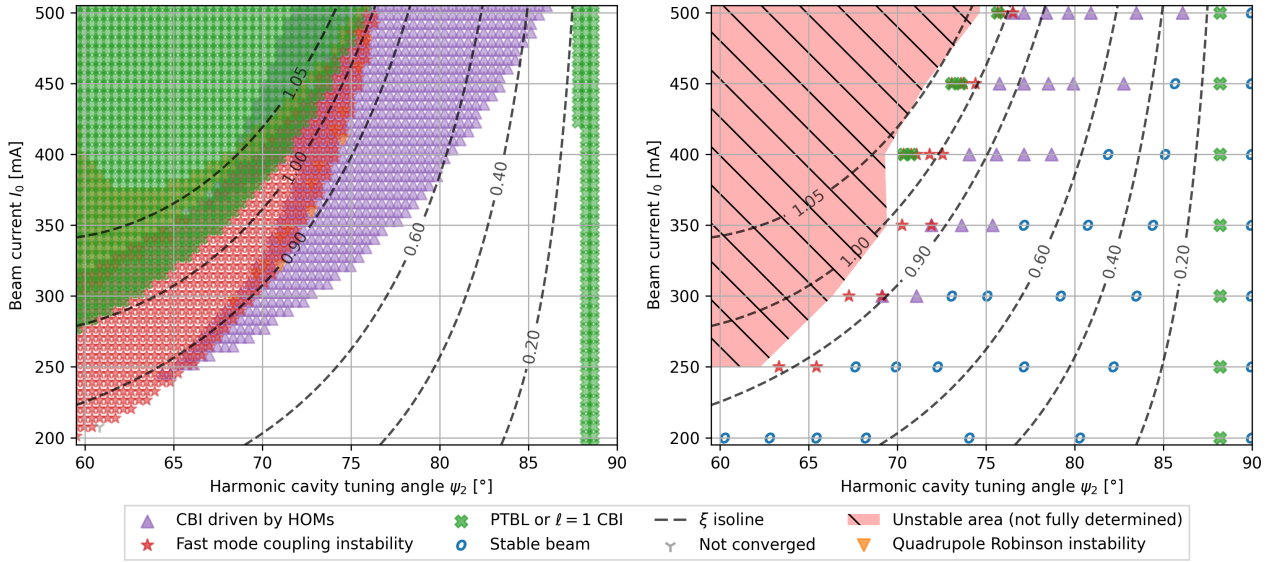


Figure 1: Instabilities predicted for the SOLEIL II storage ring, with ALBuMS (left) and with mbtrack2 (right). A HOM is included with $f_{\text{HOM}} = 1.7$ GHz, $Q_{\text{HOM}} = 670$ and $R_{s_{\text{HOM}}} = 8.8$ k Ω . Using 2 HC, i.e. $(R/Q)_2 = 60$ Ω . Figure from [7].

dealt with by using a direct rf feedback [6, 17] lowering the MC effective impedance seen by the beam. The CBI should be damped by the longitudinal bunch by bunch feedback [18].

OPTIMIZATION PROCESS

Because a computation with ALBuMS only takes a few tens of milliseconds, compared to hours for multibunch tracking simulations, ALBuMS can be used during rf system and cavity design to do large multi-dimensional parameter scans. To find the optimal HC parameters for SOLEIL II, ALBuMS was coupled to an optimization algorithm, with an objective function designed to maximize the Touschek lifetime ratio R [19]. Figure 2 shows the maximum R achievable with a stable beam in the $((R/Q)_2, Q_{0_2})$ parameter space for a given beam current of $I_0 = 500$ mA.

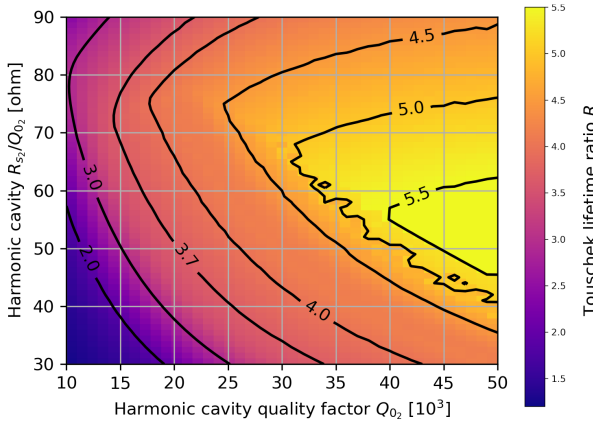


Figure 2: Maximum Touschek lifetime ratio R achievable with a stable beam. $(R/Q)_2$ is varied for different values of Q_{0_2} for a beam current of $I_0 = 500$ mA. Figure from [7].

As shown by Fig. 2, for a constant total HC shunt impedance R_{s_2} , it is better to have a lower $(R/Q)_2$ and higher

Q_{0_2} to get a larger Touschek lifetime. In this case, at 500 mA, this corresponds to optimizing the HC to avoid the PTBL instability while maintaining the total HC shunt impedance R_{s_2} to be able to obtain the required HC voltage. Interestingly, the parameters found to maximize the Touschek lifetime ratio R are very different from the ones computed using the usual flat potential condition method [7].

For SOLEIL II, the HC needs to be used from 200 mA up to 500 mA to cover operations in 32 bunch mode and uniform filling mode. Using ALBuMS, we were able to specify optimal $(R/Q)_2$ and Q_{0_2} values for cavity design. The choice was made to use 2 or 3 HC of $(R/Q)_2 = 30$ Ω each with $Q_{0_2} = 31 \times 10^3$, to be able to vary the total $(R/Q)_2$ from 60 Ω to 90 Ω . It is close to the optimal solution shown in Fig. 2 while remaining compatible with engineering constraints ($V_2 < 250$ kV, $P_2 < 35$ kW per cavity).

EXPECTED PERFORMANCE

The overall expected performance of the double rf system, taking into account a larger set of effects in tracking, is presented in Table 2. These results correspond to the largest Touschek lifetime ratio obtained while scanning the HC tuning angle ψ_2 . In addition to the effects considered in the previous sections, the tracking model now includes the SOLEIL II impedance model [20], HOMs from the main cavities and IBS [21]. The MC model includes a proportional-integral loop to converge toward the voltage and phase setpoints and a direct rf feedback, which helps against the FMCI.

For uniform filling cases at 500 mA, the results from Table 2 align closely with the ones from ALBuMS, like the left part of Fig. 1 for the 2 HC case. A large Touschek lifetime ratio, close to 6, can be expected in ideal conditions with 2 HCs (low noise on the beam filling pattern, no gap). Part of the bunch lengthening comes from the broad band impedance, which is not accounted for in Fig. 1 and 2. When there is

Table 2: Best performances achieved at equilibrium without instabilities while scanning the HC tuning angle ψ_2 . Tracking with mbtrack2 includes direct rf feedback, PI feedback, impedance model, HOMs and IBS. The transverse emittance ratio is set at 30% using white noise excitation.

HC configuration	Beam filling – current	HC tuning angle	RMS bunch length	Touschek lifetime ratio	RMS energy spread	Limiting instability
2 HC	Uniform – 500 mA	74.9°	55 ps	6.1	0.09 %	PTBL
2 HC + 1 parked	Uniform – 500 mA	73.5°	55 ps	5.9	0.09 %	PTBL
3 HC	Uniform – 500 mA	83°	25 ps	3.0	0.09 %	PTBL
2 HC	32 bunch – 200 mA	57.9°	36 ps	4.3	0.11 %	FMCI
3 HC	32 bunch – 200 mA	71.1°	35 ps	4.1	0.11 %	PTBL

a small gap (up to 8 empty buckets) in the filling pattern or when the bunch-to-bunch charge variation exceeds 5 %, the achievable Touschek lifetime ratio drops closer to 5. With 3 HCs, the total R/Q is too high and triggers the PTBL instability largely before reaching optimal bunch lengthening. With 2 HCs plus one parked, there is a minor performance reduction due to the R/Q of the parked cavity.

For the 32 bunch mode at 200 mA, it was expected from semianalytical computations that the 3 HC case would be more favorable because of the lower beam current than 2 HC case optimized for 500 mA. The opposite is observed in tracking: the 2 HC case is slightly more favorable even if still limited by an FMCI beyond the capabilities of the direct rf feedback. In 32 bunch mode, the difference with semianalytical tools like ALBuMS can be significant because of the high charge per bunch leading to strong single bunch effects impacting the multi-bunch longitudinal dynamics. The 3 HC case, limited by the PTBL instability even far from optimal bunch lengthening, can be explained by the combination of two single bunch effects: the reduced bunch length from HOM capacitive impedance [22] and the strong coherent tune shift from broad band impedance. The first effect reduces bunch length, which is known to lower the PTBL threshold [16] and the second effect can push the azimuthal modes to couple sooner, triggering the PTBL instability [23]. Both effects are proportional to the single bunch charge, so much stronger in 32 bunch mode.

PERSPECTIVES

The results presented in this work open several avenues for future studies. In the short-term, we need to ensure that the expected performances of the double rf system are achieved during SOLEIL II commissioning. And in the long-term, we can aim to gain on both operational flexibility and performance.

The modeling of LLRF feedbacks in tracking simulation must be improved to better match the logic implemented in the SOLEIL II hardware system. In particular, to quantify the risk of self-triggering the dipole-quadrupole instability at high gain [7], and to evaluate the need for alternative mitigation against the FMCI. Experimental validation of the LLRF models will be enabled by the planned installation of the first-of-series of SOLEIL II cavities on the SOLEIL storage ring in 2027/2028.

The coupling port equipping the SOLEIL II HC could allow a transition to active operation. Active operation would, in theory, permit greater flexibility compared to the passive regime, particularly at low beam currents and for exotic filling patterns. However, active harmonic systems require more complex rf feedback loops to stabilize the double rf system. A dedicated study of these instabilities and the associated feedback requirements should be done.

CONCLUSION

The SOLEIL II double rf system has been optimized using a combination of the semianalytical solver ALBuMS for fast multi-dimensional scans and the multibunch tracking code mbtrack2 for detailed verification. This approach drove the choice of a 4th harmonic normal conducting passive cavity based on the TM₀₂₀ mode developed with ESRF ($Q_{02} = 31 \times 10^3$ and $(R/Q)_2 = 30 \Omega$ per cavity), in a configuration where either 2 or 3 cavities can be installed. With this design, tracking predicts a Touschek lifetime ratio close to 6 in uniform filling at 500 mA and above 4 in 32 bunch mode at 200 mA, with the remaining performance limits set by the PTBL instability in uniform filling and by the FMCI in 32 bunch mode. The 32 bunch case also illustrates the importance of single-bunch effects, which can impact the PTBL threshold significantly at high charge per bunch.

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