HARMONIC RF SYSTEM FOR THE ESRF EBS

N. Carmignani *, J. Jacob, B. Nash, S. White, ESRF, Grenoble, France

Abstract

A harmonic RF system for bunch lengthening to increase the Touschek lifetime of the ESRF Extemely Brilliant Source (EBS) is under study. Multiparticle simulations have been performed to study the bunch lengthening and the bunch shape with impedance effect and with third or fourth harmonic cavities. The effect of a harmonic RF system on the microwave instability is studied, finding an increase in the threshold. The AC Robinson instability threshold with a superconducting harmonic cavity has been studied with multiparticle simulations.

INTRODUCTION

The ESRF EBS is a 6 GeV synchrotron light source, based on a hybrid multi-bend achromat lattice, which will be operating in Grenoble in 2020 [1, 2]. The horizontal emittance of the EBS will be 132 pm rad, approximately a factor 30 smaller than the one of the present ESRF storage ring. The light source will operate at low vertical emittance of 5 pm rad. The RF system will provide up to 6.5 MV accelerating voltage to recover the energy loss per turn $U_0 = 2.52$ MeV. The storage ring will operate in three main modes: the multi-bunch (MB), with a single 8 mA bunch and 868 low current bunches, with a total current of 200 mA; the 16 bunch (16B), with 92 mA of total current; the 4 bunch (4B), with 40 mA of total current. Due to the small emittances, the electron beam lifetime will be dominated by Touschek effect. The lifetime will be smaller than the one of the present machine and it will be less than 2h in few bunch modes. In table 1, the lifetimes (LT), the bunch current (I_b), the energy spread (σ_δ) and the bunch length for the three modes and for the high current single bunch of the multi-bunch mode are shown. The bunch length given is the Touschek effective bunch length (tebl), that is defined in [3].

Table 1: Lifetime and Bunch Length for Different EBS Filling Modes with a Vertical Emittance of 5 pm

Mode	I_b (mA)	tebl (mm)	LT (h)	$\sigma_\delta(10^{-3})$
MB	0.23	4.0	18.6	0.94
SB	8	10.3	1.47	1.21
16B	5.75	9.3	1.75	1.09
4B	10	11.1	1.20	1.32

Harmonic RF System Technological Choices

A study for harmonic cavities was carried out in 2002 for the existing machine [4], which showed that the AC Robinson instability and transient beam loading effects have to be considered for the system design. Three possible technological choices are being considered for the harmonic RF system of the EBS, excluding the passive normal conducting cavities, which are unrealistic [4]. For each choice, we study the options of a third harmonic system (at 1.057 GHz) and a fourth harmonic system (at 1.409 GHz). The harmonic cavities can be:

- **Passive superconducting cavities:** the voltage is induced by the beam itself. This requires a minimum of beam current and is suited for multibunch operation, at 200 mA. For few bunch modes, with low total current, the system is close to the AC Robinson instability. This solution requires a powerful 4 K cryogenic system based on liquid helium cooling of a Nb or Nb coated Cu cavity in a corresponding highly isolated cryostat.
- **Active normal conducting cavities:** the voltage is driven and controlled by a harmonic RF power generator (probably solid state technology). It is well adapted for low current beam modes, like 4B and 16B modes. However, 200 mA is more challenging due to the high beam loading of the system.
- **Active superconducting cavity:** this could be an alternative to the normal conducting active cavity if a harmonic voltage has to be provided for any beam mode.

SIMULATIONS

The results of this paper come from multiparticle simulations done with the Matlab [5] Accelerator Toolbox (AT) [6, 7], using the `atfastring` function. The global impedance model of the EBS machine has been computed doing electromagnetic simulations using either CST particle studio [8] or GDFIDL [9] [10]. The impedance effect in AT is included using the integrator `impedance_tablePass`, developed by S. White. To study the AC Robinson instability of the superconducting cavities, an integrator for AT for an RF cavity with beam loading effect has been developed.

With an active harmonic RF system, both phase and voltage can be changed and they can be chosen to have zero first and second derivative of the RF signal at the synchronous phase [3]. However, the simulations shown in this paper are done assuming an Elettra/SLS type cryomodule with two superconducting cavities with a total $R/Q = 90\,\Omega$ and $Q = 2 \cdot 10^8$ [11]. The voltage induced in the cavity is defined by the detuning angle of the cavity and it is chosen to have only zero first derivative of the RF signal at the synchronous phase. If the main accelerating voltage is 6 MV, the voltage for the third harmonic cavity is $V_{3HC} = 1.81$ MV and for the fourth harmonic cavity it is $V_{4HC} = 1.36$ MV.

The RF signals of the main and harmonic cavities are shown in Fig. 1, in both cases of third harmonic and fourth harmonic.

* nicola.carmignani@esrf.fr

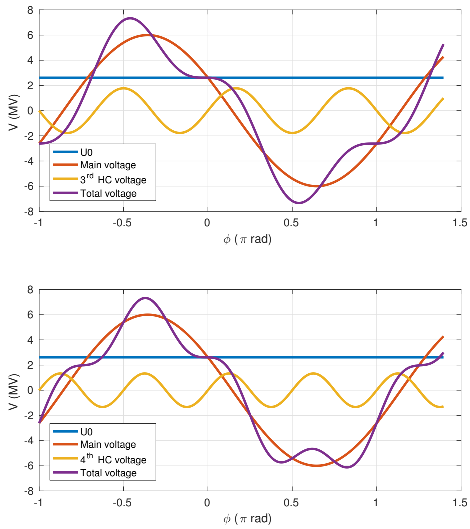

Figure 1: RF signals in case of third and fourth harmonic RF system.

The simulations are done with $3 \cdot 10^5$ particles and $2 \cdot 10^5$ turns. The damping times are several thousands turns.

BUNCH LENGTHENING AND MICROWAVE INSTABILITY

The equilibrium bunch shape in presence of impedance effects is not gaussian and is asymmetric. With a passive harmonic cavity, the equilibrium distribution is also asymmetric, as shown in [3]. The effects of impedance and third harmonic cavity in the bunch shape are shown in fig. 2.

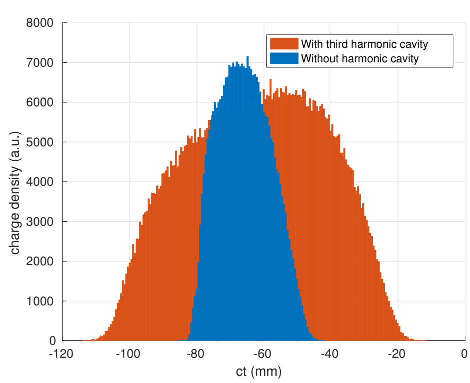

Figure 2: Bunch shapes with bunch current of 6 mA with impedance, with and without third harmonic cavity.

The bunch length versus bunch current is shown in Fig. 3, without harmonic cavities (blue), with a third harmonic cavity (red) and with a fourth harmonic cavity (yellow). The bunch lengthening at zero current are a factor 5.5 for the third harmonic cavity and a factor 4.9 for the fourth harmonic cavity. The lengthening factor reduces at high current: at $I_b = 10$ mA it is 2.4 for the third harmonic cavity and 2.2 for the fourth harmonic cavity.

The bunch lengthening due to the harmonic cavity helps to increase the Touschek lifetime and increases the threshold

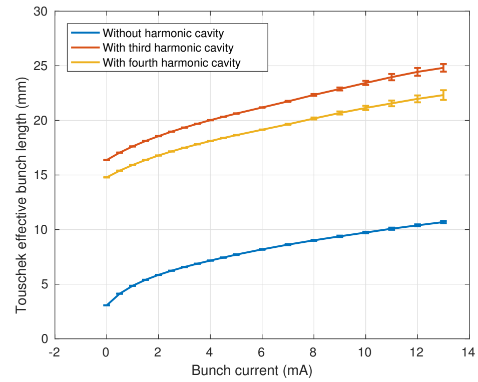

Figure 3: Touschek effective bunch length as a function of bunch current with impedance and harmonic cavities.

of the microwave instability. In Fig. 4 the energy spread of the beam as a function of the bunch current is shown with and without harmonic cavities. The microwave instability threshold without harmonic cavity is at about 4 mA, while with harmonic cavities it increases to about 6 mA. The simulation shows that in the microwave instability regime the energy spread is oscillating. The error bars of the plot are the standard deviations of the energy coordinate in the last 50000 turns.

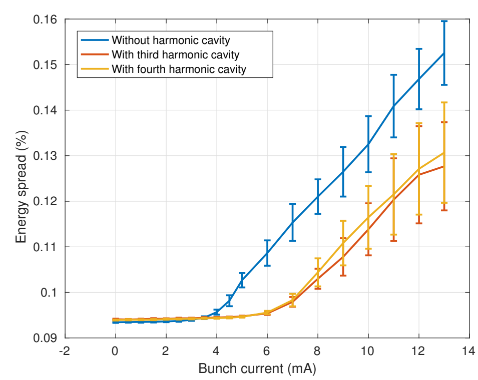

Figure 4: Microwave instability thresholds with and without third harmonic cavity.

The bunch length, the Touschek lifetime and the energy spread for the different bunch currents with a third harmonic cavity are shown in table 2 and with a fourth harmonic cavity in table 3. The vertical emittance in all the cases is assumed to be constant at $\varepsilon_y = 5$ pm.

Table 2: Lifetime, Bunch Length and Energy Spread with a Third Harmonic Cavity for Different EBS Filling Modes

Mode	I_b (mA)	tebl (mm)	LT (h)	$\sigma_\delta (10^{-3})$
MB	0.23	16.7	77.7	0.94
SB	8	22.3	3.18	1.03
16B	5.75	21.1	3.97	0.95
4B	10	23.4	2.53	1.14

ISBN 978-3-95450-182-3

Table 3: Lifetime, Bunch Length and Energy Spread with a Fourth Harmonic Cavity for Different EBS Filling Modes

Mode	I_b (mA)	tebl (mm)	LT (h)	$\sigma_\delta(10^{-3})$
MB	0.23	15.1	70.2	0.94
SB	8	20.2	2.88	1.04
16B	5.75	19.1	3.59	0.96
4B	10	21.1	2.28	1.16

AC ROBINSON INSTABILITY

The damping or the anti-damping from the Robinson effect in presence of only the main RF system can be computed, at first order, using an analytical formula [12]:

$$\alpha_R = \frac{e\pi\alpha I f_{RF}}{f_s E_0 T_0} Re(Z(f_{RF}+f_s) - Z(f_{RF}-f_s)) \quad (1)$$

where e is the electron charge, α is the momentum compaction factor, I is the beam current, f_{RF} is the RF frequency, f_s is the synchrotron frequency, E_0 is the beam energy, T_0 is the revolution time and Z is the cavity impedance. The formula cannot be used in presence of a higher harmonic cavity, because the synchrotron tune changes with the longitudinal amplitude of the particles, so the stability can be studied with a multiparticle simulation including the beam loading effect in the main and harmonic cavities. The damping or anti-damping from the Robinson effect without harmonic cavity has been simulated and compared to eq. 1, showing a good agreement.

In case of low beam current, the passive harmonic cavity has to be tuned close to the resonance frequency to have the desired voltage and it results in being unstable. The longitudinal center of mass of the beam starts to oscillate at the detuning frequency of the cavity, which is of the same order of magnitude as the synchrotron frequency. At higher beam current, the passive harmonic cavity has to be detuned more and the system results in being stable.

Examples of longitudinal center of mass motion with a third harmonic cavity at increasing voltage is shown in Fig. 5. The simulations are done with the total beam current in a single bunch.

In Fig. 6, the thresholds of the Robinson instability are computed as a function of R/Q of the harmonic cavity, for both a third and a fourth harmonic cavity. From the figure we can see that the assumed double cell superconducting cavity with $R/Q = 90\,\Omega$ wouldn't be enough for the 4 bunch mode of the ESRF EBS, where the total beam current is 40 mA. For this mode, either a passive superconducting fourth harmonic double cell cavity or two passive superconducting third harmonic double cell cavities (with total $R/Q = 180\,\Omega$) would be needed.

CONCLUSION

A higher harmonic cavity for the ESRF EBS can help to increase the Touschek lifetime, that is the main limitation in

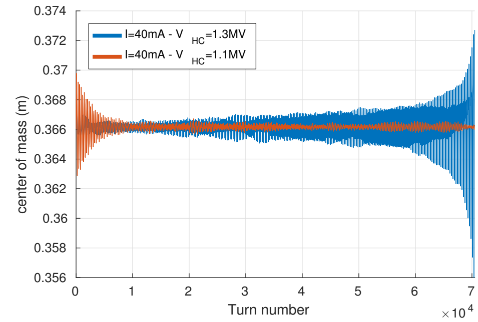

Figure 5: Longitudinal center of mass of the bunch with a third harmonic cavity with voltage below the threshold of AC Robinson instability and above the threshold. The threshold in this example is 1.2 MV for a 40 mA beam current.

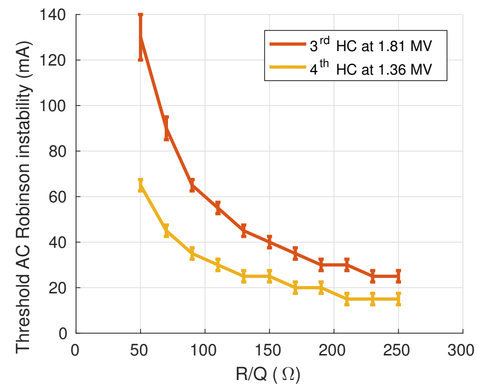

Figure 6: Minimum current for optimum bunch elongation without AC Robinson instability with a passive third or fourth harmonic cavity as a function of R/Q.

the beam lifetime. It would be especially needed in the few bunch modes, where the lifetime will be less than 2 h. The harmonic cavity would also increase the threshold of the microwave instability, resulting in a lower energy spread in the high bunch current modes. The third harmonic frequency would lengthen the bunch about 10% more than the fourth harmonic, resulting in a total Touschek lifetime about 10% larger. Concerning the microwave instability, there is no difference between the third and fourth harmonic cavity.

In case the passive superconducting technology will be chosen, a single third harmonic module cannot be used in 4 bunch mode, because of the AC Robinson instability. Either two third harmonic modules or one fourth harmonic module could be used in all the modes.

In the multi-bunch mode the filling pattern has a gap, where the single bunch is located. For this mode, transient beam loading effect will limit the average bunch elongation. This is currently under study.

The design of an active normal conductive third harmonic cavity as well as the associated beam dynamical issues are also currently under study.

REFERENCES

[1] J. C. Biasci et al., "A low emittance lattice for the ESRF", Synchrotron Radiation News, vol. 27, iss. 6, 2014.

[2] ESRF Upgrade Programme Phase II (2015-2022) Technical Design Report.

[3] N. Carmignani et al., "Lifetime improvements with a harmonic RF system for the ESRF EBS", proc. of IPAC'16, paper TUPOR001.

[4] V. Serrière, "Longitudinal Beam Dynamics in Electron Storage Rings with a Harmonic RF System for Bunch Lengthening", PhD thesis, University Paris XI, France, 2002.

[5] The MathWorks, Inc., MATLAB, Natick, Massachusetts, United States.

[6] A. Terebilo, "Accelerator modeling with MATLAB accelerator toolbox", proc. of PAC'01, paper RPAH314.

[7] B. Nash et al., "New functionality for beam dynamics in Accelerator Toolbox (AT)", proc. of IPAC'15, paper MOPWA014.

[8] CST, `http://www.cst.com`

[9] GDFIDL, `http://www.gdfidl.de`

[10] S. White et al., "Preliminary longitudinal impedance model for the ESRF-EBS", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper WEPIK058.

[11] P. Bosland et al., "Third harmonic superconducting passive cavities for Elettra and SLS", Proc. of the 11th Workshop on RF Superconductivity, Lübeck/Travemünder, Germany, 2010.

[12] A. Hofmann, "Beam Instabilities", CAS 95-06, CERN, Switzerland.

ISBN 978-3-95450-182-3