LIFETIME IMPROVEMENTS WITH A HARMONIC RF SYSTEM FOR THE ESRF EBS

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Abstract

A third-harmonic RF system to increase the Touschek lifetime is under study for the European Synchrotron Radiation Facility (ESRF) Extremely Brilliant Source (EBS) storage ring, in particular for modes with high current per bunch. Multi-particle simulations have been done to study the bunch lengthening and shape in presence of inductive impedance and a third-harmonic RF system.

INTRODUCTION

The ESRF EBS is a 6 GeV synchrotron light source, based on a hybrid multi-bend achromat lattice [1], which will be operating in Grenoble in 2020. The horizontal emittance will be reduced to 132 pm rad, i.e. approximately by a factor 30, compared to the present ESRF storage ring. The vertical emittance will be 5 pm rad.

The RF system will provide 6 MV accelerating voltage to recover the energy loss per turn $U_0 = 2.61$ MeV. The insertion devices will increase the energy loss per turn by approximately 0.5 MeV when they are all fully closed [2].

The electron beam lifetime will be dominated by Touschek effect, due to the low emittances, and it is expected to be less than 2 h in few bunch modes. In Table 1, the lifetimes for multi-bunch (MB), 16 bunch (16B) and 4 bunch (4B) modes are shown, with the total current (I) and the bunch current (I_b).

Table 1: Electron Beam Lifetime for the Three Modes

Mode	I (mA)	I_b (mA)	LT (h)	% of use
MB	200	0.23	17	70 %
16B	92	5.75	1.7	25 %
4B	40	10	1.2	5 %

A third-harmonic RF system to increase the bunch length and the Touschek lifetime of the electron beam is under study.

HARMONIC VOLTAGE AND PHASE

The total voltage of the RF system is the sum of the main RF voltage and the harmonic voltage.

$$V(z) = V_M(z) + V_H(z) \tag{1}$$

where $V_M(z)$ is the voltage of the main RF system, $V_H(z)$ is the harmonic voltage and z is the longitudinal coordinate.

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The optimum phase and voltage of a harmonic RF system are obtained with the following conditions [3]:

$$V(z_s) = U_0 \tag{2}$$
$$V'(z_s) = 0 \tag{3}$$
$$V''(z_s) = 0 \tag{4}$$

where z_s is the synchronous beam position. The potential $U(z)$ in this case is a quartic function around z_s.

$$U(z) = -\frac{1}{C}\int_{z_s}^{z} (eV(z) - U_0)\,\mathrm{d}z \tag{5}$$

where C is the ring circumference and e is the elementary charge.

The voltage of a passive harmonic cavity can be changed by adjusting the difference between its resonance frequency f_{res} and the harmonic of the RF frequency f_{RFh}. The phase between the harmonic cavity and the beam is defined by the detuning angle ψ.

$$\tan\psi = 2Q\,\frac{f_{res} - f_{RFh}}{f_{RFh}} \tag{6}$$

Where Q is the cavity quality factor. With a passive harmonic cavity, the conditions of Eqs. (3) and (4) cannot be satisfied together, because there is only one degree of freedom that can be controlled. In the case of a high Q superconductive cavity, the detuning angle is very close to 90°, so the harmonic cavity is almost in phase with the beam.

From the potential $U(z)$ we can compute the bunch distribution $\lambda(z)$ [4] [5]:

$$\lambda(z) = K\exp\left[-\frac{U(z)}{\alpha\sigma_\delta^2}\right] \tag{7}$$

where α is the momentum compaction factor, σ_δ is the equilibrium energy spread and K is the normalisation factor to have $\int \lambda(z)\,\mathrm{d}z = 1$.

We consider three possible cases to define the phase and voltage of a third-harmonic RF system in our simulation.

In *case 1* the conditions of Eqs. (2), (3) and (4) are satisfied. In *case 2* only conditions of Eqs. (2) and (3) are satisfied and the zero-crossing phase of the harmonic voltage is exactly at the synchronous phase of the main RF system. In *case 3* the zero-crossing phase of the harmonic voltage is obtained with a multi-particle tracking simulation: the phase is moved to the center of mass of the bunch at each turn, starting with the values of *case 2*. Iteration is performed until equilibrium is reached.

In Fig. 1, the main RF voltage, the harmonic voltage and their sum are shown for *case 3*. In that case, the voltage of

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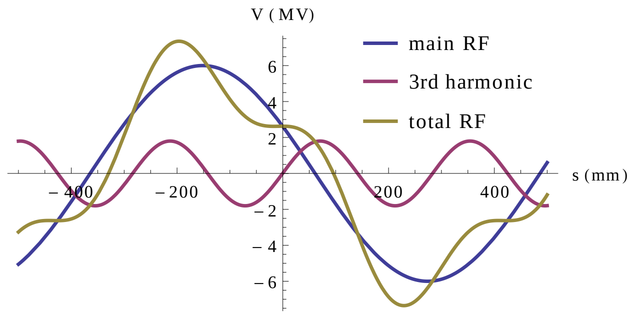

Figure 1: Voltage signal for main and harmonic RF system and total voltage. The synchronous position z_s is 0.

the harmonic system is $V_{HC} = 1.80\,\mathrm{MV}$, for a total voltage of 6 MV and an energy loss per turn of 2.61 MeV.

In Figs. 2 and 3 the potential and the longitudinal bunch distribution are shown for the three cases.

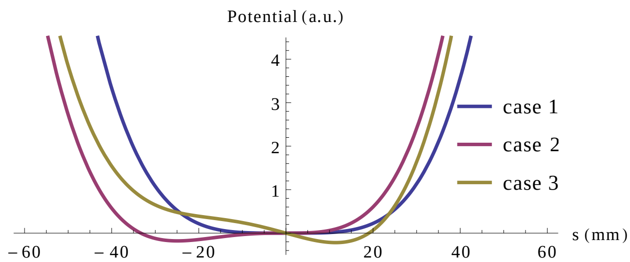

Figure 2: Potential for the three cases.

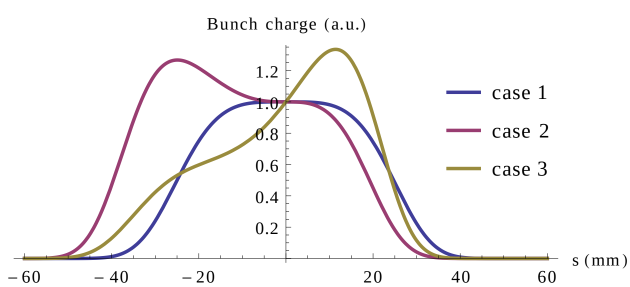

Figure 3: Longitudinal bunch distribution for the three cases.

THE TOUSCHEK EFFECTIVE BUNCH LENGTH

With a passive harmonic RF system, the equilibrium bunch shape is not Gaussian. We want to derive an effective bunch length to compute the Touschek lifetime in case of a non Gaussian bunch.

The Piwinski formula gives [6]:

$$\frac{1}{\tau} \propto \int \lambda^2(z)\,\mathrm{d}z \tag{8}$$

If $\lambda(z)$ is Gaussian,

$$\int \lambda^2(z)\,\mathrm{d}z = \frac{1}{2\sqrt{\pi}\,\sigma_z} \tag{9}$$

where σ_z is the RMS bunch length.

For non-Gaussian $\lambda(z)$, the generalized definition of σ_z is the Touschek effective bunch length (TEBL):

$$\mathrm{TEBL} = \frac{1}{2\sqrt{\pi}\int \lambda^2(z)\,\mathrm{d}z} \tag{10}$$

For most typical cases of $\lambda(z)$, one finds that this quantity is not too different from the RMS bunch length.

SIMULATIONS

The longitudinal bunch distribution in the presence of a harmonic RF system is obtained with multi-particle tracking using the Matlab Accelerator Toolbox [7] [8] and the `atfastring` function [9]. The model includes radiation damping and quantum fluctuations, two cavity elements, at fundamental and third-harmonic frequencies, an inductive impedance element, a linear transformation and a nonlinear kick for chromaticity and tune shift with amplitude.

Inductive Impedance

In order to include in our model the bunch lengthening introduced by collective effects, a purely inductive impedance element was added to the tracking code. The ensemble of N macro-particles is distributed over M equidistant slices from which the line density is determined. Particles oscillating at more than 4σ are excluded from the simulation. The energy loss of each particle is then derived from the derivative of the current at its location. The estimation of the current derivative proved to be very sensitive to numerical errors, a smoothing algorithm had therefore to be applied to the line density distribution. It should be noted that resistive impedance, although it should not impact the bunch length, will affect the longitudinal density distribution. This effect is not included in the model. This model makes no assumption on the initial beam distribution or its evolution over time and should provide an accurate estimate of the equilibrium beam distribution to be expected in the presence of harmonic cavities and inductive impedance.

In Fig. 4, the agreement between the tracking with inductive impedance and the bunch length obtained by solving the Haissinski equation is shown. The analytical expression of the bunch length can be found in [10].

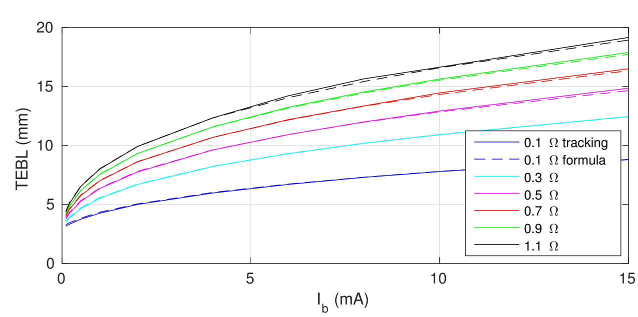

Figure 4: Bunch lengthening due to impedance: tracking and analytical formula. The number of particles N is 200000 and the number of slices M is 200.

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Bunch Length with Harmonic RF System

In Fig. 5, the longitudinal bunch distribution with and without third-harmonic voltage are shown, without impedance effect. The bunch distribution obtained with the formula of Eq. (7) is compared to the tracking result showing a good agreement. The Touschek effective bunch length obtained with the third-harmonic voltage is 16.4 mm instead of 3.1 mm, so the lengthening is a factor 5.3.

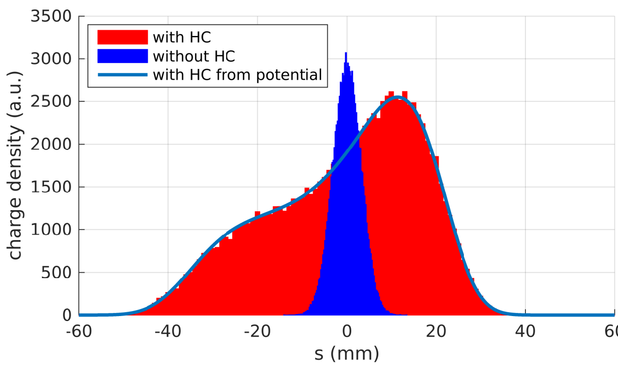

Figure 5: In blue the bunch distribution without harmonic voltage, in red with a third-harmonic voltage. The blue line is derived analytically from the potential.

Impedance and Harmonic RF System

The longitudinal bunch distribution for 10 mA per bunch and an inductive impedance of 0.35 Ω, that is an estimation of the value for the ESRF EBS ring, is shown in Fig. 6, with and without harmonic voltage.

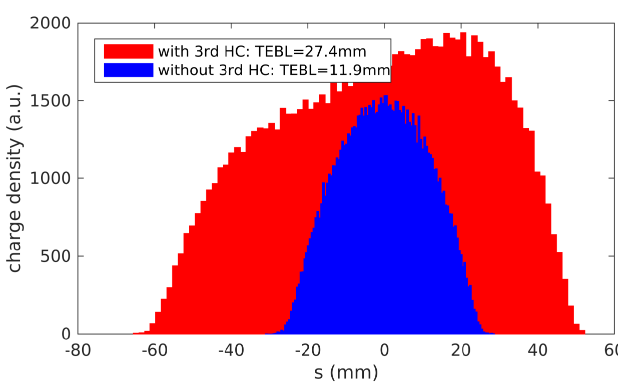

Figure 6: In blue the bunch shape without harmonic RF system, in red with a third-harmonic RF system. The simulation includes an inductive impedance of 0.35 Ω, with 10 mA per bunch.

The bunch lengthening from the harmonic voltage when also the impedance is included is smaller. Results are summarised in Table 2.

We want to know how the Touschek effective bunch length varies with the harmonic voltage. In Fig. 7, the TEBL is shown as a function of the harmonic voltage, for the current per bunch corresponding to the three filling modes used at the ESRF.

Table 2: Touschek Effective Bunch Lengths (in mm)

	without impedance		with impedance	
mode	no HC	with HC	no HC	with HC
MB	3.1	16.5	4.3	17.5
16B	3.1	16.5	10.1	25.0
4B	3.1	16.5	11.9	27.4

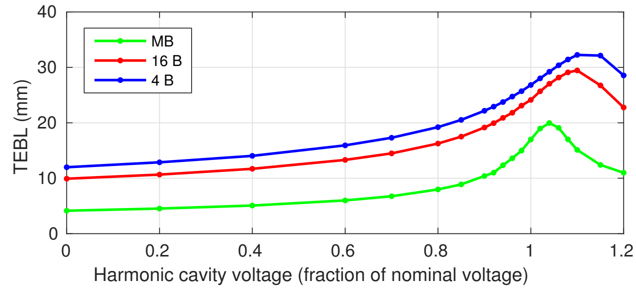

Figure 7: Touschek effective bunch length as a function of harmonic voltage for the three modes used at the ESRF. The voltage is expressed as a fraction of the nominal voltage, computed to satisfy Eqs. (2) and (3).

In Fig. 8, the longitudinal distribution of the bunch is shown for a harmonic voltage higher than the nominal value. The Touschek effective bunch length is longer, but the bunch has a double-peak shape. Whether or not this shape is detrimental for the users or the beam dynamics remains to be investigated.

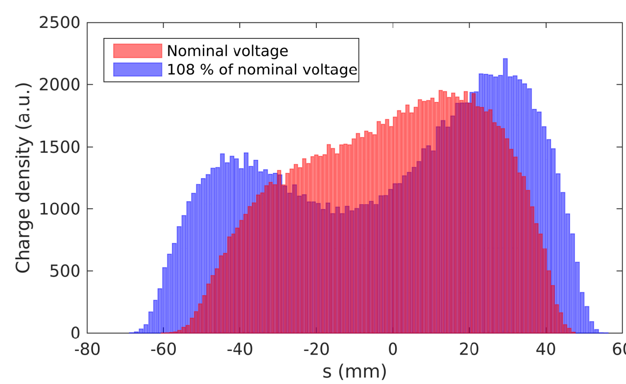

Figure 8: Bunch shapes with impedance and harmonic RF system at nominal voltage (red) and 8 % higher voltage (blue).

CONCLUSION

A passive harmonic cavity would increase the bunch length and the Touschek lifetime for the ESRF EBS electron beam by a factor 4.1 for the multi-bunch mode, 2.5 for the 16 bunch mode and 2.3 for the 4 bunch mode. A larger bunch lengthening could be obtained increasing the harmonic voltage, if we accept a double-peaked bunch.

The Robinson instability thresholds and the transient beam loading effects are currently under investigation.

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

[4] C. Limborg, "Ultimate Brilliance of Storage Ring Based Synchrotron Radiation Facilities of the 3rd Generation. Potential of Storage Ring Based Sources in the Production of Short and Intense X-Ray Pulses.", Section 3.2, Ph.D. thesis, University Joseph Fourier, Grenoble, 1996.

[5] J. Jowett, "Introductory Statistical Mechanics for Electron Storage Rings", SLAC-PUB-4033, Section 7.3, 1986.

[6] A. Piwinski, "The Touschek Effect in Strong Focusing Storage Rings", DESY 98-179, arXiv:physics/9903034.

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

[8] A. Terebilo, "Accelerator modeling with MATLAB accelerator toolbox", in *Proceedings of PAC 2001*, Chicago, USA, pp. 3203–3205.

[9] B. Nash, et al., "New Functionality for Beam Dynamics in Accelerator Toolbox (AT)", in *Proceedings of IPAC'15*, Richmond, VA, USA, 2015, paper MOPWA014, pp. 113–116.

[10] N. Carmignani, "Touschek Lifetime Studies and Optimization of the European Synchrotron Radiation Facility. Present and Upgrade Lattice.", Ph.D. thesis, Università di Pisa, 2014, Springer Theses 2016.

ISBN 978-3-95450-147-2