

EXPECTED LIFETIME IMPROVEMENT WITH A SUPERCONDUCTING HARMONIC RF SYSTEM AT THE ESRF

V. Serrière, J. Jacob, ESRF, Grenoble, France

Abstract

Due to the low transverse emittance of the ESRF storage ring light source, Touschek scattering is the dominant factor that limits the beam lifetime. This has mainly an impact for fill patterns with a high intensity per bunch such as standard single bunch and 16-bunch operation, for which the lifetime does not exceed 5 and 10 hours, respectively. In principle, the lifetime can be increased by means of a harmonic RF system that flattens the RF wave and thereby elongates the bunches. For the ESRF it turns out that only superconducting cavities would provide the necessary harmonic voltage within a reasonable space. This paper gives an estimation of the longitudinal beam dynamics and instability mechanisms. In particular, the condition for Robinson stability in the presence of a non-linear RF wave is included in the computations.

1 INTRODUCTION

The minimisation of transverse beam emittance to optimise the brilliance of synchrotron radiation leads to a limitation of beam lifetime through Touschek scattering within bunches. With 6 GeV of beam energy, the lifetime for multibunch operation at the ESRF still remains above 60 hours. However, fill patterns with a high intensity per bunch are much affected by Touschek scattering. The installation of a harmonic RF system is considered for single and 16-bunch fill patterns with a maximum beam intensity of 20 and 90 mA, respectively. The additional voltage provided by a harmonic RF system flattens the total accelerating voltage seen by the beam and improves the lifetime by lengthening the bunches [1]. Taking into account the bunch lengthening and the limitation on the energy acceptance, a maximum improvement of the Touschek lifetime by a factor up to 4 is predicted with a third harmonic RF system operated at an optimum harmonic voltage of 2 MV.

An accurate evaluation of a harmonic RF system should take into account the non-linearity of beam motion and all longitudinal instability mechanisms. A multibunch multiparticle tracking code has therefore been developed, which computes the longitudinal beam motion by taking into account simultaneously the Robinson instabilities, potential well distortion, the microwave instability and longitudinal coupled bunch instabilities (LCBI). The tracking model and examples of computer simulations are presented in section 2. The application to the ESRF is discussed in section 3, allowing to conclude on the interest in the use of a harmonic RF system at the ESRF.

2 TRACKING MODEL AND EXAMPLES OF COMPUTER SIMULATION

2.1 Tracking model

This tracking code is an extension of two existing tracking codes. The first one, BESAC [2], based on a single bunch multiparticle model, was developed for the ESRF to compute the longitudinal beam motion by taking into account the potential well distortion and the microwave instability. The second tracking code [3] was developed in collaboration with the ALS to compute transient beam loading effects with harmonic RF systems: it is based on a multibunch model with one macro-particle per bunch. The new multibunch multiparticle tracking code allows computing the longitudinal beam motion taking into account simultaneously the fundamental impedance of the RF systems, the longitudinal broadband impedance of the storage ring and the Higher Order Modes (HOM) of the RF cavities. The longitudinal motion of each particle within a bunch is tracked turn by turn using the following equations:

$$\begin{aligned} \phi_p^{t,b} &= \phi_p^{t-1,b} + 2\pi T_0 \alpha h \varepsilon_p^{t-1,b} \\ \varepsilon_p^{t,b} &= \left(1 - 2 \frac{T_0}{T_{rad}}\right) \varepsilon_p^{t-1,b} + 2 \sqrt{\frac{T_0}{T_{rad}}} \varepsilon_{int}(R_n) + \\ &\quad \frac{e}{E_b} (V_{RF}(\phi_p^{t,b}) + V_{HC}(\phi_p^{t,b}) + V_{HOM}(\phi_p^{t,b}) + V_{BBR}(\phi_p^{t,b}) - U_0 / e) \end{aligned}$$

where ε and ϕ are the energy deviation and the phase advance relative to the synchronous particle. Indices t, b and p refer to subsequent turns, bunches and particles within bunches, respectively. The accelerating voltage of the main RF system V_{RF} is computed as the sum of the generator voltage and beam voltage:

$$V_{RF}(\phi_p^{t,b}) = V_{gen,m}(\phi_p^{t,b} + \phi_s + \psi + \phi_L) + \left| \tilde{V}_{t,b}^{beam} \right| \cos(\phi_p^{t,b} + \varphi_{t,b}^{beam}).$$

The voltage induced by the beam in the harmonic RF system and in the HOM is computed by adding the time pulse response of the center of mass bunch motion:

$$V = -q_b * \sum_{nt=0}^t \sum_{nb=1}^{M_b} W[\phi_p^{nt,b} + \langle \phi \rangle^{t,b} - \langle \phi \rangle^{nt,nb} - (nt + \frac{nb}{M_b})T_0].$$

The voltage induced by the beam in the longitudinal broadband impedance of the storage ring is computed by summing the voltage induced by each particle of a bunch:

$$V_{BBR}(\phi_p^{t,b}) = -q_b * W[\phi_n].$$

$W[\phi]$ is the Wakefield of the corresponding impedance.

2.2 Examples of computer simulation

In this section we present results computed with the tracking code and the ESRF parameters. The harmonic cavities used in the simulations are a scaling of the two-cell superconducting (SC) third harmonic modules Super-3HC ($R/Q = 90 \Omega$ and $Q_0 = 2 \cdot 10^8$) [4] to the resonant frequency: $f_{res, hc} = 3 f_{rf} = 1056.6 \text{ MHz}$.

Figure 1 shows the phase motion of an AC Robinson instability computed with a single bunch of 20 mA, a harmonic voltage set to 1.6 MV and two passive harmonic modules. For the same conditions but four harmonic modules, the beam motion is stable as shown in figure 2 and the bunch is lengthened by a factor 2.

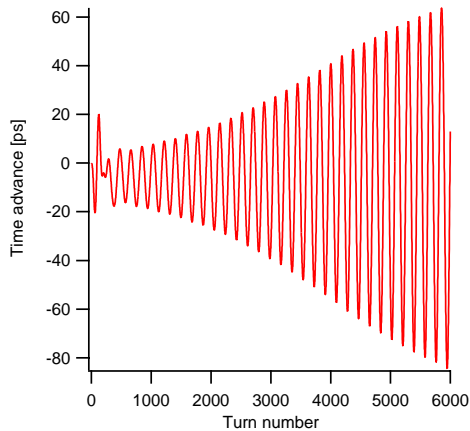


Fig. 1: AC Robinson instability

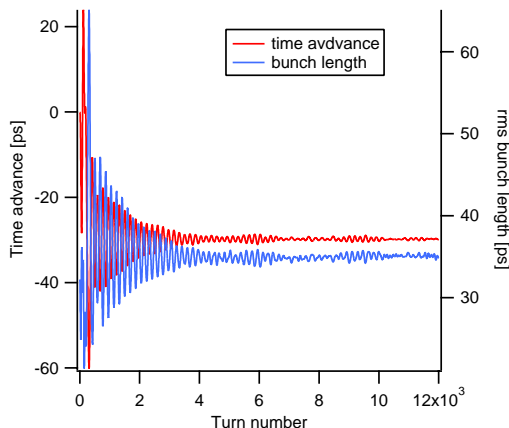


Fig. 2: AC Robinson stable operation

Figure 3 depicts a typical HOM driven LCBI obtained without harmonic RF system at 90 mA. Four bunches are sufficient to simulate the LCBI for any symmetric fill pattern. The new tracking code clearly takes into account non-linear effects, which lead to a saturation of beam motion. Such saturation is also generally observed at the ESRF, thereby validating the tracking model. A plot of the bunch length and the energy spread also shows the expected bunch shape modulation at $2 * f_s$.

Harmonic cavities at MAX II provide not only bunch lengthening. They also strongly reduce the amplitude of LCBI by means of Landau damping. A reduction of the resulting relative energy spread from about $5 \cdot 10^{-3}$ to 1.1

10^{-3} has been reported when tuning the passive harmonic cavities [5]. We have applied the new tracking code assuming an arbitrary HOM leading to a LCBI threshold at 8 mA. Without harmonic cavity, an energy spread of $6 \cdot 10^{-3}$ is computed for 250 mA. The simulation predicts a reduction down to $0.74 \cdot 10^{-3}$ i.e. close to the natural energy spread when a properly tuned harmonic cavity is included. The simulation thus explains the observation.

Finally, the new code also predicts a relaxation of LCBI as observed and computed at SPEAR [6].

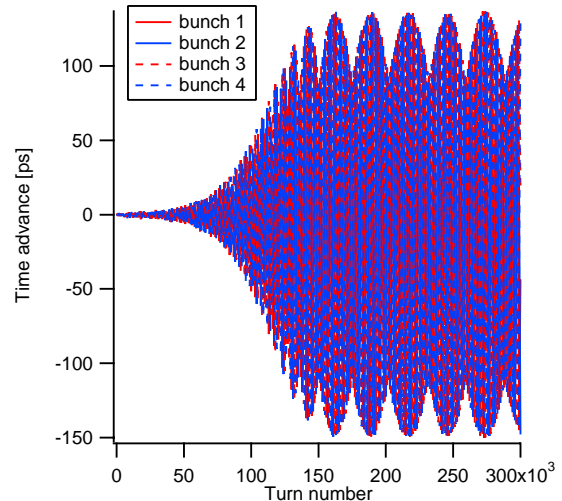


Fig. 3: LCBI, main RF system only

3 APPLICATION TO ESRF

3.1 Robinson Instability

As discussed in section 2, for bunch lengthening in single or 16 bunch fill with passive harmonic cavities, Robinson stability imposes the installation of at least four SC harmonic modules of the Super3HC type. Even with a compact design, a full ESRF straight section would be required. However, the simulations also show that with an active harmonic RF system only one SC module would be sufficient. A maximum generator power below 60 kW would allow to reach the optimum bunch lengthening conditions in 16 bunch mode.

3.2 Microwave Instability

The longitudinal impedance of the storage ring is described by the standard ESRF broad band impedance: $f_{res} = 30 \text{ GHz}$, $R = 42 \text{ k}\Omega$, $Q=1$. Figures 4 and 5 show the computed bunch length and energy spread as a function of the harmonic voltage for various single bunch intensities. With increasing intensity, the microwave instability already generates a turbulent bunch lengthening and an increase of the energy spread with some fluctuation. The error bars show the amplitude of these fluctuations. Figure 4 indicates that the harmonic RF system provides additional bunch lengthening for any current: at 25 mA, a bunch length increase factor up to 2.7 can still be reached.

Surprisingly, the tracking code predicts a slight reduction in energy spread with a harmonic cavity in the microwave instability regime.

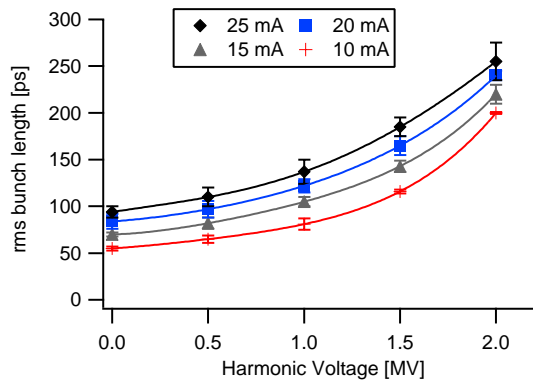


Fig. 4: Microwave Instability- Bunch Lengthening

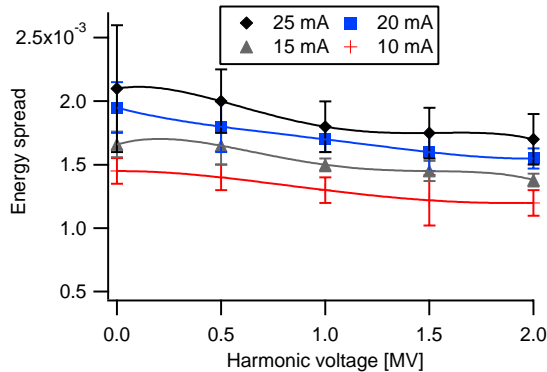


Fig. 5: Microwave Instability - Energy Spread

3.3 Longitudinal Coupled Bunch Instabilities

Figure 6 shows the computed longitudinal coupled bunch motion at 95 mA with the typical HOM of figure 3 and an harmonic voltage of 1.6 MV. The non-linear RF voltage provides Landau damping which increases the instability threshold above the 90 mA of figure 3. At 95 mA in figure 6, the coherent oscillation is still small and the energy spread not yet affected.

Figure 7 depicts LCBI thresholds, defined by the beam intensity at which the energy spread starts to increase: a factor 3 inside the error bars. The simulated threshold of 90 mA without harmonic voltage is in agreement with the linear theory. While the linear model predicts a reduction in thresholds due to the lowered synchrotron frequency, the extended tracking code indicates that the Landau damping provided by the harmonic voltage predominates.

4 CONCLUSIONS

A new longitudinal multibunch multiparticle tracking code has been developed, which allows computing simultaneously non-linear single bunch and coherent multibunch effects. For the ESRF, the main motivation in the use of a harmonic RF system is to improve the beam lifetime in single and 16 bunch filling. To remain AC Robinson stable four pairs of passive SC harmonic cavities would be required or 1 pair of active SC harmonic cavities. The computations show that the microwave instability reduces slightly the gain in lifetime from a factor 4 to a factor 3 for single bunch operation. An increased lifetime by a factor up to 3.5 can be reached

with an active system. An interesting result is that the harmonic RF system reduces slightly the energy spread due to the microwave instability. The additional Landau damping provided by the RF system increases slightly the threshold of HOM driven longitudinal coupled bunch instabilities. The computations, confirmed by measurements at MAX II, indicate that Landau damping with a harmonic cavity is much more effective for low energy machines.

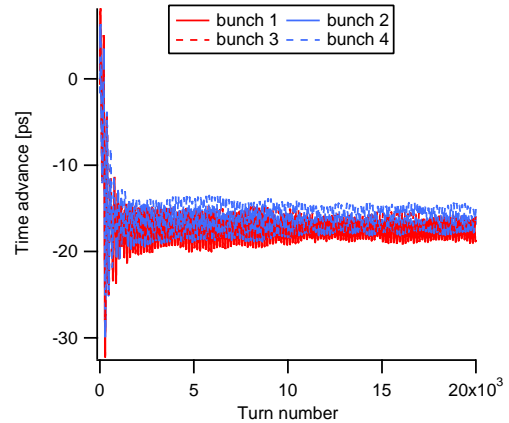


Fig. 6: Landau damping of LCBI with a harmonic voltage

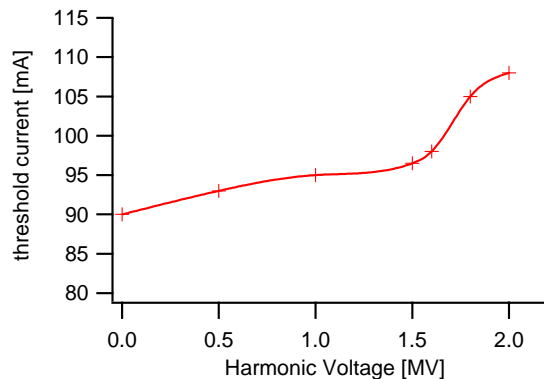


Fig. 7: LCBI threshold current with a harmonic RF system

5 REFERENCES

- [1] A. Hofmann, S. Myers, "Beam dynamics in a double RF system", Proc. of the 11th Int. Conf. on High Energy Acc. *ISR-TH-RF/80-26 (1980)*.
- [2] G. Besnier, "Simulation numérique de la stabilité longitudinale d'un paquet dans l'anneau ESRF", Technical report, University of Rennes, France, 1990.
- [3] J. Byrd, S. De Santis, J. Jacob, V. Serrière, "Transient beam loading effects in harmonic RF systems for light sources", to be published in PRST-AB.
- [4] M. Svandrik et al., "The Super-3HC project: an idle superconducting harmonic cavity for bunch length manipulation", EPAC'2000, Vienna, 2000.
- [5] M. Georgson, A. Anderson, M. Erikson "Landau Cavities at MAX II", Nucl. Inst. and Meth. in Phys. Res. A 416, 1998.
- [6] C. Limborg, J. Sebek, "Longitudinal relaxation oscillations beyond the threshold of HOM induced instabilities", EPAC'98, Stockholm, 1998.