NON-LINEAR LONGITUDINAL BEAM DYNAMICS WITH HARMONIC RF SYSTEMS FOR BUNCH LENGTHENING

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Abstract

Harmonic cavities have been installed on various storage ring light sources to increase the Touschek lifetime by a factor of *2* to *4* by lengthening bunches. Several side effects have been observed, which limit the gain in lifetime. In the worst case, the beam stability can be altered, but harmonic cavities can also provide Landau damping of coherent motion. A multibunch multiparticle tracking code has been developed to evaluate the performance of harmonic RF systems under consideration of all longitudinal beam dynamics issues. Bunches with high intensities are already elongated by the interaction with the ring impedance. The computations indicate that a harmonic RF system provide significant additional lengthening. The application to the ESRF shows that an active superconducting harmonic system would constitute the only appropriate solution. Such a system would be useful in single bunch and sixteen-bunch operation to improve the beam lifetime by a factor of *2* and *3*, respectively.

1 INTRODUCTION

Touschek scattering is the dominant factor that limits the beam lifetime in many low transverse emittance storage rings. Harmonic RF systems have been used in several low-medium energy synchrotron light storage rings to improve the beam lifetime by lengthening bunches. Side effects such as transient beam loading or Robinson instabilities can significantly limit the gain in lifetime [1]. On the other hand, the additional Landau damping that is provided by a harmonic RF system gives a reduction of the amplitude of longitudinal coupled bunch instabilities (LCBI), as for instance at MAX-II [2]. As described in [1], transient effects have been studied with a multibunch single particle model. However, for an accurate evaluation of Landau damping as well as a prediction of LCBI thresholds and Robinson AC instability, non-linear intrabunch effects needed to be included in the computation. In order to evaluate the performance of a harmonic RF system at the ESRF, a multibunch multiparticle tracking code has been developed, which computes the longitudinal dynamic with a harmonic RF system by taking into account all longitudinal instability mechanisms. This code has been used to predict the thresholds of Robinson instabilities and LCBI in the case of the ESRF and the main results were presented at EPAC02 [3]. To further understand the influence of a harmonic RF system on longitudinal instabilities, the beam response to a harmonic excitation was computed and results are presented in section 2. For single and few bunch operation, the effect of the longitudinal impedance must be taken into account for the evaluation of the possible gain in lifetime. A study of the bunch elongation in both potential well and microwave instability regimes is presented in section 3. The conclusion for the implementation of a harmonic RF system at the ESRF is given in section 4.

2 NON-LINEARITY OF THE RF WAVEFORM

2.1 Beam spectrum

To understand further the influence of the non-linear accelerating voltage on the longitudinal beam dynamics, a harmonic excitation $f(\omega) = a_f \times \cos(\omega t)$ was injected into the multibunch multiparticle tracking code. The bunch spectrum was then computed by taking the discrete inverse Fourier transform of the time-dependent beam intensity. For the example of the ESRF with its *352.2 MHZ* RF system, $\omega_{RF} = 2.21295\ GHz$, the beam was excited at the synchrotron frequency f_{s0} obtained at zero current with a main accelerating voltage of *8 MV*. As expected, the beam spectrum shows lines at the angular resonant frequency of the main RF system and the lower and upper sidebands at $\omega_{s0} = \pm 2\pi f_{s0}$. As shown in [4], in the case of optimum bunch lengthening, the average synchrotron frequency amounts to $\langle f_{s,opt} \rangle = 0.2 \times f_{s0}$. Computing the time response of the beam to an excitation at $\langle f_{s,opt} \rangle$ yields the beam spectrum in figure 1.

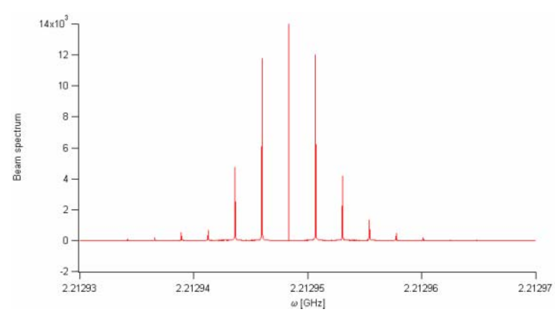

Figure 1: Beam spectrum for $V_h = V_{h,opt}$ around the main RF frequency.

The signal is at its maximum at the main angular RF frequency and exhibits several sideband at $m \times \langle f_{s,opt} \rangle$ with $m=1,2,3,...$ on either side of ω_{RF}. Simulations carried out with an excitation slightly below and above $\langle f_{s,opt} \rangle$ have confirmed that the maximum amplitude of the response is obtained by exciting the beam at exactly $\langle f_{s,opt} \rangle$. The occurrence of sidebands at multiples *m* of the excitation frequency is the signature of the non-linear total accelerating voltage seen by the bunches. The simulations have also shown that the number of sidebands increases with growing amplitude a_f of the excitation. While more and more new sidebands appear, the amplitudes of the lower order sidebands do not increase linearly with a_f but show some saturation effect. This splitting of the excitation power over several sidebands already indicates that Landau damping will limit the amplitude of unstable coherent motion such as the AC Robinson instability or HOM driven LCBI.

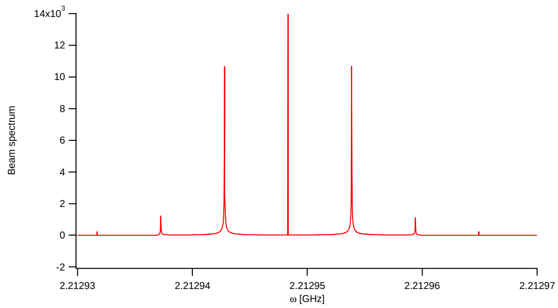

Figure 2: Beam spectrum for $V_h=0.8\times V_{h,opt}$ around the main RF frequency.

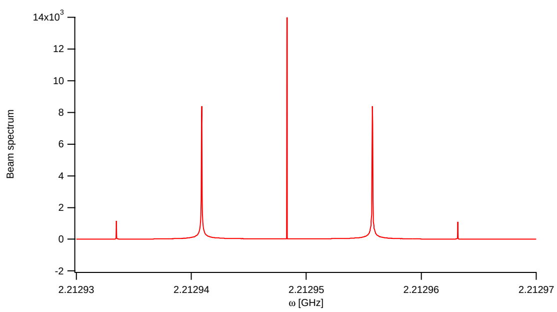

Figure 3: Beam spectrum for $V_h=0.6\times V_{h,opt}$ around the main RF frequency.

Figures *2* and *3* show the beam spectrum obtained for $V_h=0.8\times V_{h,\mathrm{opt}}$ and $V_h=0.6\times V_{h,opt}$, respectively. In each case, the beam was excited at the corresponding average synchrotron frequency. The number of sidebands on either side of ω_{RF} decreases by lowering the harmonic voltage. These computations indicate that the non-linearity of the RF voltage needs to be considered in the prediction of coherent collective effects, and that a linear approximation cannot provide a correct model for the amplitude dependent beam response. In order to evaluate the performance of a harmonic RF system, the intrabunch particle motion as well as the multibunch collective response must be included in the analysis of coherent multibunch oscillations, which can lead to the AC Robinson instability or HOM driven LCBI.

2.2 Landau damping

A thorough analysis of various system configurations has shown that the AC Robinson instability is generally encountered, when a passive harmonic cavity is tuned close to the corresponding beam harmonic in order to provide the required voltage for low beam intensities. It turned out to be a key design element, which imposes a minimum number of passive harmonic cavities, in particular in the case of the ESRF, where harmonic cavities are expected to be operated in single bunch mode. As mentioned in [3], the multibunch multiparticle model constitutes a powerful tool, which allows the prediction of the observed spectacular Landau damping of strong HOM driven LCBI at currents *10* to *100* times the threshold intensity in the case of MAXII. Numerical computations in the case of the ESRF and MAXII allowed the comparison of the LCBI behaviour for both machines. They confirm the experimental observation that for low and medium energy storage rings, harmonic RF systems do not only provide an increase in Touschek lifetime, but that they can also be used to almost suppress the energy blow-up of HOM driven LCBI. For higher energy machines such as the ESRF, only a slight increase in LCBI thresholds is predicted.

3 SINGLE BUNCH EFFECTS

3.1 Potential well regime

The interaction between the beam and the longitudinal broadband impedance of the storage ring produces a local short-range voltage distortion. The wake potential of a given bunch simultaneously acts back on all particles of this particular bunch. At moderate bunch intensities, the voltage induced in the mainly inductive longitudinal impedance locally flattens the voltage waveform and leads to bunch lengthening. In this potential well regime, which is a single bunch effect, the natural energy spread remains unaffected. The longitudinal particle distribution $\Psi(\phi,\Delta E)$ for a given bunch intensity I_0 satisfies the Haissinsky equation [5]

$$\Psi(\phi,\Delta E)=K_1\Psi_0(\phi,\Delta E)\exp\left[-C_1\times h\left|\frac{Z_L\omega_0}{\omega}\right|\left(I(\phi)-I(0)\right)\right],$$

where ϕ and ΔE are the phase advance and the energy deviation relative to the synchronous phase, Z_L is the impedance of the storage ring, K_1 is a constant of normalisation and

$$C_1=-\frac{1}{2}\left(\frac{Q_s}{\alpha h\sigma_E/E}\right)^2.$$

The function $\Psi_0(\phi,\Delta E)$ is the "zero-current" longitudinal particle distribution and $I(\phi)$ is given by

$$I(\phi)=2\pi I_0\int\Psi(\phi,\Delta E)d\Delta E\,.$$

Resolving numerically Haissinski's equation gives the longitudinal particle distribution and thus the bunch length at a given beam intensity. As a result, figure *4* shows the computed evolution of $\Psi(\phi)$ for various bunch intensities with a harmonic RF system at the ESRF tuned for optimum bunch lengthening. The longitudinal distribution is stretched with increasing bunch intensity due to the interaction with the longitudinal inductive impedance. Both the numerical resolution of Haissinski's equation and the results given by the tracking show that in the potential well regime the total bunch length increase is very close to the value obtained by multiplying the elongation from the harmonic voltage and from the potential well effect.

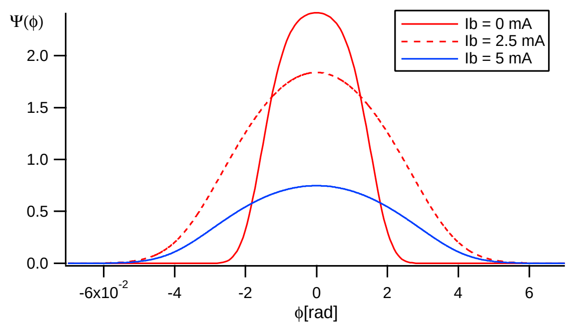

Figure 4: Longitudinal distribution for various bunch intensities in the potential well regime – Prediction with a harmonic RF system at the ESRF tuned for optimum bunch lengthening.

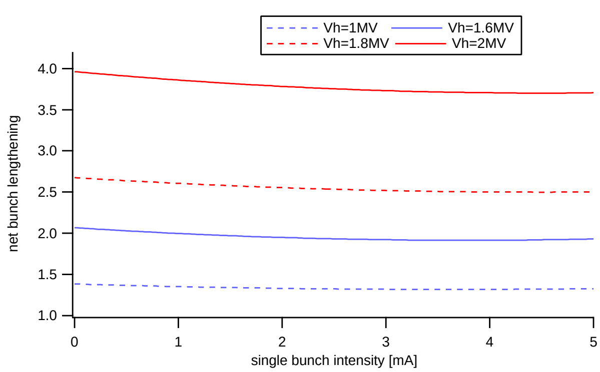

Figure 5: Net bunch lengthening from various harmonic voltages vs bunch intensity in the potential well regime.

In figure 5 the ratio between the total bunch length obtained for various harmonic voltages and the bunch length without harmonic voltage is plotted as a function of the bunch intensity. For any given harmonic voltage, these ratios are almost independent from the bunch intensity. For example $V_h=2.0\ MV$, the ratio decreases only from *4.0* at *0 mA* to *3.7* at *5 mA*.

Below the limit of the potential well regime of about *5 mA* at the ESRF, the effect of the BBR does not limit the possible gain in bunch length and consequently the achievable Touschek lifetime improvement from a harmonic RF system.

3.2 Microwave instability

In the microwave instability regime, both the energy spread and the bunch length increase. In the case of the ESRF, with a microwave instability threshold of *5 mA*, a single bunch of *20 mA* is lengthened by a factor of *6* and its energy spread increases by a factor of 2, with respect to the “zero-current” values. The computations show that a harmonic RF system allows the improvement of the bunch length by a further factor of *3* and to reduce the energy spread to a factor of *1.7*.

4 CONCLUSION ON THE IMPLEMENTATION OF A HARMONIC RF SYSTEM AT THE ESRF

The implementation of a harmonic RF system on the ESRF storage ring is envisaged for operation modes with a high intensity per bunch such as the *20 mA* single bunch and the *90 mA* 16-bunch filling modes. For optimum bunch lengthening, a harmonic voltage of *2 MV* would be required.

As many as 150 normal conducting passive cavities would be needed to obtain good harmonic voltage and phase conditions for a significant bunch lengthening at low intensity: this is not a realistic solution. For an active normal conducting cavity, the maximum field gradient would impose a minimum of 12 cavities: again not a practical solution. It was therefore decided to concentrate on a more modern approach using superconducting technology.

As presented in [3], with a passive superconducting harmonic RF system, the criterion of AC Robinson stability imposes the implementation of four Super3-HC modules. However, only one active superconducting module, powered with up to 100 kW, would suffice to obtain both beam stability and optimum bunch lengthening. Taking into account possible operational difficulties, we could realistically expect that the beam lifetime in 16-bunch operation mode would be increased from the current *10* hours to *30* hours. Concerning the single bunch operation mode dominated by the microwave instability, the lifetime would be doubled from *5* hours to *10* hours.

ACKNOWLEDGEMENTS

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5 REFERENCES

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