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TRANSIENT BEAM LOADING STUDIES IN VIEW OF THE ELETTRA 2.0 UPGRADE PROJECT

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Abstract

An upgrade project is ongoing at Elettra Sincrotrone Trieste for a 4th-generation storage ring light source called Elettra 2.0. The new machine poses new challenges in terms of performance of the accelerator and sub-systems. One concern, currently under investigation, is about the effects of the passive superconducting third harmonic cavity on the stored beam due to the presence of a dark gap in the beam filling pattern. A simulator based on an analytical frequency-domain model was developed to evaluate the variation of the synchronous phase and synchrotron frequency along the bunch train, as well as the distortion of the bunch profile. Experiments have been carried out in the present Elettra storage ring to characterize the harmonic cavity and to measure the effect of transient beam loading by using the longitudinal multi-bunch feedback system. An ongoing benchmarking of the model and experimental results is reported.

INTRODUCTION

Elettra 2.0 [1] will be an ultra-low emittance light source providing high brilliance and coherence, with the option to produce very short pulses for time resolved experiments using deflecting crab cavities. The new machine features the same diameter as Elettra using the existing building and will operate mainly at 2.4 GeV. While the majority of the systems and plants will be replaced, some of them will be reused as for example the RF cavities and some insertion devices. A partial upgrade program is foreseen also for the beamlines, allowing experiments to better exploit the unique characteristics of the enhanced synchrotron radiation. The shutdown for dismantling the existing machine and mounting the new storage ring is planned to start in July 2025, followed by machine commissioning and eventually return to users experiments in January 2027.

A passive superconducting third harmonic cavity (3HC) [2] is in operation at Elettra since 2002 to lengthen the electron bunches, thus producing the twofold advantage of increasing the Touschek lifetime and help curing multi-bunch instabilities due to Landau damping. After renovating the cryogenic plant and the cryostat during the shutdown for the Elettra upgrade, 3HC will be put back into operation.

The effects of 3HC on the Elettra longitudinal dynamics have already been studied in 2005; in particular, the change of bunch characteristics along the bunch train have been evaluated and measured [3]. This effect is called transient beam loading and is produced by RF cavities in the presence of a dark gap in the filling pattern. Generally speaking, the beam loading is the voltage induced by the beam in a cavity at the frequency of the bunches; in the fraction of one machine turn where the buckets are not filled, the voltage in the cavity freely oscillates at its own resonant frequency. This transient generates a periodic modulation of the cavity voltage, with period equal to the revolution time, resulting in different total voltage seen by the bunches depending on their position in the bunch train. As a result, the bunch characteristics, such as synchronous phase, synchrotron frequency, charge profile and lifetime change along the bunch train. This effect can be generally tolerated by finding proper conditions (gap duration and 3HC detuning) able to provide the nominal bunch lengthening while minimizing the disruptive effects.

For Elettra 2.0 additional aspects must be considered, such as for example a new longitudinal bunch-by-bunch feedback kicker working at the fourth harmonic of the RF, instead of the third presently used, whose efficiency could be affected by the ununiform bunch synchronous phase. Moreover, the performance of the crab cavities, due to the particular filling pattern, namely one every two filled buckets and a single bunch in the dark gap, could be affected by the 3HC impact on the beam. In order to study the transient beam loading in such particular conditions, a simulator based on an analytical model has been developed.

FREQUENCY-DOMAIN SIMULATOR

Comprehensive accelerator simulators based on tracking of particles such as *elegant* [4] or *mbtrack2* [5] can be used to study the transient beam loading, as well as simple tracking codes based on analytic time-domain models [6, 7]. More recently, analytical methods to get the equilibrium longitudinal bunch density distribution through self-consistent equations have been adopted [8, 9]. At Elettra a simple simulator has been developed in Matlab based on an analytical frequency-domain model of the beam and the harmonic cavity, which gets to a stable consistent solution by means of a fast converging iterative process.

The beam can be modelled by the "complex beam current" $\bar{I}$, an array of complex values each representing one of the bunches, where the module of each value is the bunch current and the phase is the bunch synchronous phase. It can be expressed as $\bar{I}(i) = I_b(i)\ \bar{F}(i)$ where I_b is the bunch current, $\bar{F}$ is the complex form factor and i is the bunch index. $\bar{F}$ is given by the following equations where φ is the longitudinal coordinate (phase at RF frequency) and $\mathcal{F}$ is the Fourier Transform of the bunch charge density Ψ, which is evaluated at the third harmonic of the RF:

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$$\bar{F}(i) = \frac{\mathcal{F}(\Psi_i)(3\omega_{RF})}{\mathcal{F}(\Psi_i)(0)} = \frac{\int_{-\pi}^{\pi} \Psi_i\,(\varphi)\, e^{-j3\varphi} \mathrm{d}\varphi}{\int_{-\pi}^{\pi} \Psi_i\,(\varphi)\, \mathrm{d}\varphi}$$

The Fourier Transform of the 3HC voltage induced by the beam can be calculated with the product of the Fourier Transform of the complex current by the harmonic cavity transfer function: $V_{3HC}(\omega) = \mathcal{F}(\bar{I})(\omega)\, H_{3HC}(\omega)$. Module and phase of $H_{3HC}(\omega)$ can be calculated with the following expressions where R_s, Q and ω_{3HC} are respectively the shunt impedance, the quality factor and the frequency of the harmonic cavity:

$$|H_{3HC}| = \frac{R_s}{Q} \frac{\omega_{3HC}}{\omega_{3HC} - \omega} \sin \mathrm{atan}\left(\frac{2Q(\omega_{3HC} - \omega)}{\omega_{3HC}}\right)$$

$$arg(H_{3HC}) = \mathrm{atan}\left(\frac{2Q(\omega_{3HC} - \omega)}{\omega_{3HC}}\right)$$

which are obtained from the well-known equations of the beam induced voltage [10].

After calculating the 3HC voltage seen by each bunch using the Inverse Fourier Transform of $V_{3HC}(\omega)$, we can compute the total voltage seen by the beam and then the potential:

$$V_{tot}(\varphi) = V_{RF} \sin(\varphi + \varphi_s) + V_{3HC} \sin(3\varphi + \varphi_{3HC})$$

$$U(\varphi) = -\frac{c\,\alpha}{EC\omega_{RF}} \int_0^{\varphi} (eV_{tot}(\varphi') - U_0)\mathrm{d}\varphi'$$

with V_{RF} the peak RF voltage, φ_s the synchronous phase, α the momentum compaction factor, c the light speed, E the beam energy, C the machine circumference, e the electron charge and $U_0$the energy loss per turn.

$U(\varphi)$ is eventually used to determine the charge distribution

$$\Psi(\varphi) = \frac{e^{-\frac{U(\varphi)}{\alpha^2\sigma_e^2}}}{\int_{-\pi}^{\pi} e^{-\frac{U(\varphi)}{\alpha^2\sigma_e^2}} d\varphi}$$

where σ_e is the energy spread. By means of Ψ the new values of the bunch form factor are calculated and a new iteration can be started.

The equilibrium bunch charge distribution is obtained by iterating this process until a consistent stable solution is found, i.e. the difference between two consecutive iterations is negligible. In order to assure convergence of the iterations, only a fraction of the difference form factor is applied at each step; the complete convergence is normally obtained in 50 to 100 iterations, meaning in a few seconds. Finally, from the equilibrium bunch charge distribution we can calculate all the characteristics of each bunch (stable phase, bunch length, Touschek lifetime, etc.), while the synchrotron frequency is determined analytically from the longitudinal gradient of the total voltage seen by each bunch.

Recently also the beam loading due to the main RF accelerating cavities has been included in the simulator; to this regard an RF cavity is considered as an additional passive cavity using the same model employed for 3HC with different parameters.

SIMULATION RESULTS

Being a new development, in order to validate it, the simulator has been compared with the present Elettra machine and with *mbtrack2*. Figure 1 shows the transient beam loading measured in Elettra by means of the longitudinal multi-bunch feedback system compared with the simulations. In order to have a good matching it was essential to include in the simulator the main RF cavities, which contribute significantly to the transient beam loading.

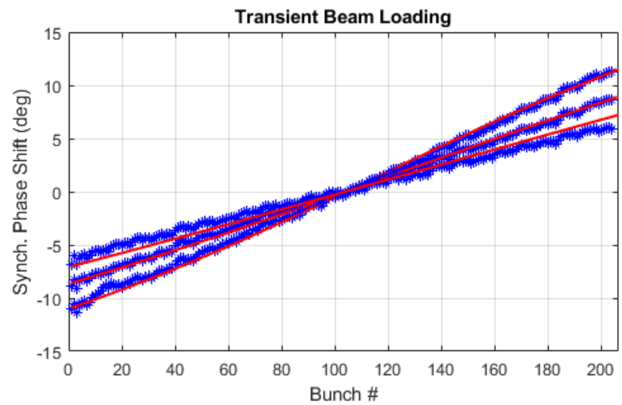

Figure 1: Synchronous phase shift along the bunch train; simulation (red) and experimental (blue) data, with E = 2.0 GeV, I_b = ~200 mA, 50% filling pattern and three different detuning values 45, 60 and 70 kHz.

Simulations with *mbtrack2* have also been carried out using the Elettra 2.0 parameters. The plots in Fig. 2 are the comparison of the results provided by the two simulators at 2.4 GeV, 400 mA, 93% filling and 70 kHz detuning.

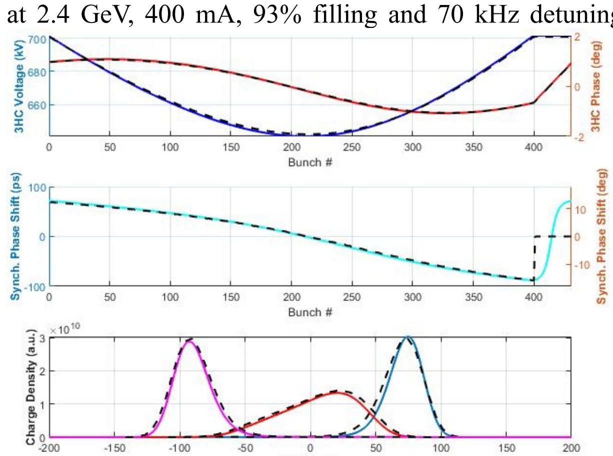

Figure 2: Comparison of results obtained from the Matlab simulator (solid lines) and *mbtrack2* (dashed lines): 3HC voltage/phase and synchronous phase shift along the bunch train, and charge profile of the first/middle/last bunch (blue/red/magenta).

One of the possible scenarios for Elettra 2.0 is the operation with crab cavities used to produce short photon pulses by transversally tilting one single bunch with an RF

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electromagnetic field [11]. This will require a specific hybrid filling pattern with a bunch train filled one every two buckets and a 2 mA single bunch in the middle of the gap. Due to the possibility to include in the simulator any arbitrary filling pattern, we are able to evaluate the impact of transient beam loading on the bunch characteristics, and in particular on the single bunch producing the short photon pulses. An example of results is shown in Fig. 3. The simulations have been done with a gap of 80 ns and a total current of 394 mA; four values of detuning from 80 to 95 kHz have been considered. The nominal bunch length at "zero current" is 6 ps.

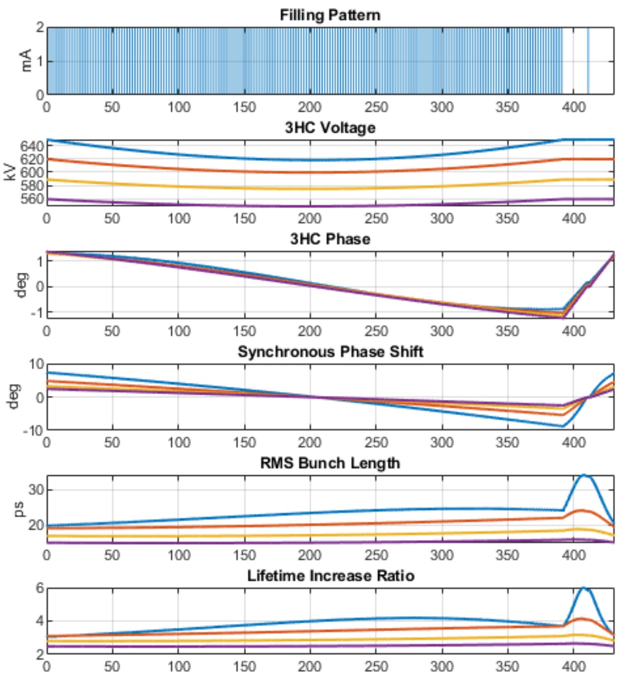

Figure 3: Results for Elettra 2.0 obtained with the Matlab simulator with a hybrid filling pattern: 3HC voltage/phase and bunch characteristics with detuning of 80/85/90/95 kHz (blue/orange/yellow/purple).

Special attention has to be paid to the charge profile distortion of the single bunch, in order not to compromise the quality of the short photon pulses; in fact, from the pictures it is evident that due to the combination of the phase variation of 3HC and the high value of its voltage during the gap, the effect of bunch lengthening could be higher in the middle of the gap than in the bunch train. With high values of harmonic voltage seen by the single bunch the charge profile gets very distorted with the creation of two separated bunches (overstretching), while the rest of the bunches remain almost gaussian. A trade-off between benefits of 3HC in terms of lifetime increase and negative effects for the transient beam loading will have to be found when defining beam and 3HC parameters for this particular operation modality. Exotic filling patterns with two separate bunch trains will also be considered in further simulations to be carried out.

3HC CHARACTERIZATION

A measurements campaign has been carried out in Elettra aiming to measure some machine parameters involved in longitudinal dynamics and the main 3HC characteristics. The most important results are reported below.

3HC Quality Factor

The decay time of the 3HC voltage after a commanded beam dump has been measured by acquiring with an oscilloscope the signal taken from both cavity pickups. The acquired data have been digitally I/Q demodulated in Matlab and the amplitude decay fitted with exponential curves, eventually providing the time constant and thus the Q factor. The experiment has been repeated at different detuning values and beam currents. The measured quality factor is different for the two cells: $Q_1 = 1.33\text{x}10^8$, $Q_2 = 1.45\text{x}10^8$, confirming the results of the laboratory measurements made after fabrication [2].

3HC R_s/Q

R_s/Q is a parameter representing the efficiency of the harmonic cavity, which only depends on its geometric characteristics. It binds the cavity voltage with the beam current and the detuning [3]. The contribution of the harmonic voltage changes the longitudinal gradient of the total voltage and so the synchrotron frequency with respect to its nominal value. By measuring the synchrotron frequency of the central bunch in the bunch train, which is almost unaffected by the phase shift due to beam loading, we can first calculate the 3HC voltage and then R_s/Q. Preliminary measurements have been carried out at different detuning values; the calculated R_s/Q value is 80 Ω, while the nominal value is 88 Ω. This discrepancy will be subject of further analysis.

Momentum Compaction Factor

The momentum compaction factor α can be found with reasonable accuracy from measurements of the photon energy on a beamline at different electron energies. α is determined from the ratio between the f_{RF} relative variation, which changes the electron energy, and the photon energy relative variation. The calculated α value is $1.7\cdot10^{-3}$ while the nominal value is $1.6\cdot10^{-3}$.

CONCLUSIONS

Studies of transient beam loading produced by the harmonic cavity have been carried out at Elettra in view of the Elettra 2.0 upgrade project.

The existing harmonic cavity, which has been operating for 20 years for bunch lengthening, will be reused for the new machine. In order to better know its behaviour and performance, the cavity has been characterized with measurements using the Elettra beam.

The newly developed simulator is a valuable tool to study the transient beam loading. With respect to other well-known tracking codes it only considers the longitudinal dynamics and cannot be used to study instabilities but, thanks to its simplicity and performance, it is easy to use

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and can be efficiently employed to rapidly reproduce in different conditions the effects of the harmonic cavity.

Further studies will be performed for Elettra 2.0 to evaluate the single bunch distortion and its effects on the quality of the produced short photon pulses when operating with the crab cavities.

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