LONGITUDINAL SINGLE-BUNCH INSTABILITIES FOR DIFFERENT OPERATION ENERGIES AT ELETTRA

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Abstract

The ELETTRA storage ring is currently operated over a wide electron-energy range (0.75-1.5 GeV and 2-2.4 GeV). This paper reports on measurements performed in order to characterize the longitudinal beam stability when the machine is operated in the low-energy range in single-bunch filling mode.

INTRODUCTION

Instabilities of different nature may affect electron beams circulating in a Storage Ring (SR) [1], [2] and cause severe limitation in the performances of devices dedicated to exploitation of Synchrotron Radiation or to Free Electron Laser (FEL) operation. The origin of such instabilities can be traced back either to the electromagnetic wake field which is generated by the interaction between the electron beam and its environment (e.g vacuum pipe, low-gap chambers, discontinuities, etc.) and re-acts on the electrons perturbing their motion, or to external perturbations (e.g. line-induced modulations, mechanical vibrations, etc.).
The presence of the instability may manifest in different ways. For example, the so-called saw-tooth regime is currently observed on many SR [3]; in this case the beam evolution is characterized by a periodic fast blow-up of the energy spread and bunch length followed by a damping. In other cases, the effect of the instability is less dramatic and simply manifests in a smooth increase of the beam energy spread and bunch length with current [1].
Longitudinal instabilities can be basically grouped in two classes: the fast ones, which are characterized by coherent (or pseudo-coherent) oscillations at frequencies close to the synchrotron frequency (and its harmonics) and the slow ones, whose typical frequencies range from 50 to few hundred Hz. Since coherent synchrotron oscillations represent the "natural" beam response to kick-like external perturbations, slow-frequency instabilities often induce high-frequency ones.
The ELETTRA SR is currently operated over a wide electron-energy range. The high-energy multi-bunch operation mode (2-2.4 GeV), which is characterized by a better beam stability (the synchrotron damping being more effective), is the standard one for experiments requiring high fluxes. An increasing interest is being manifested in the operation mode where the machine is run in few-bunch filling mode at relatively low energies (0.75-1.5 GeV). In fact, this low-energy domain is well suited both for FEL operation [4], [5] and for experiments exploiting the time structure of synchrotron radiation.

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IMPEDANCE AND SINGLE-BUNCH MEASUREMENTS

During the first year of commissioning (1993-94) it was possible to store in the ELETTRA storage ring more than 60 mA in single bunch and more than 700 mA in multibunch. According to calculations performed in the same period, the longitudinal broad band impedance was < 0.5 (measured < 0.5) Ω and the transverse one < 200 (measured 130) kΩ/m giving a tune shift with current of about 0.12 ± 0.02 kHz/mA [6].
Since then, many new installations took place, the most serious from the impedance point of view being the replacement of straight section vacuum chamber with low gap ones. With each new installation a broad band transverse impedance increase of about 0.1 kHz/mA/installation has been measured. An even greater increase [7] has been measured when Aluminum chambers with NEG (Ti, Va, Zr) sputtered material was used [8]. Although since 1994 the transverse impedance increased by about a factor 12, this did not affect the multi-bunch operating mode. However, a great reduction of the maximum stored current and of the beam stability has been observed when the machine is operated in single-bunch mode. The theoretical transverse mode coupling threshold is now at about 14 mA/bunch [7] whereas in 1994 was above 40 mA. No clear change of the longitudinal effective impedance, that was $Z \simeq 0.2\Omega$, has been measured until 2000. Recent measurements [7] of bunch length versus single bunch current have been performed using a double sweep streak camera: Figure 1 shows the bunch length increse detected at the end of 2002 together with the reduction of the maximum current stored in a single bunch indicating an impedance of 0.32Ω, i.e. a change of 50%.

The biggest contributors to the longitudinal impedance are the main rf-cavities and, although since 2000 there was installed a longitudinal kicker as a part of a longitudinal multi-bunch feedback (spring 2002) and a third harmonic super-conducting cavity (autumn 2002), this change cannot be attributed solely to the increase of the cut-off frequency being now above 3.5 GHz.

Figures 2 and 3 show the behaviour of the bunch length and of the energy spread, as a function of the beam current, when ELETTRA is operated at 0.75, 0.9 and 1.5 GeV. Measurements of energy spread are based on

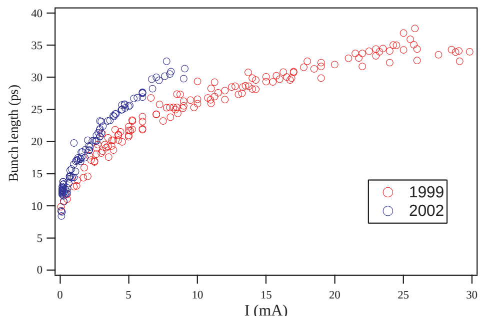

Figure 1: Bunch length as a function of the beam current (single bunch). Measurements performed in 1999 and 2002 at 0.9 GeV. Data have been acquired over the whole current range by means of a double sweep streak camera. The absolute error on each point is about 2 ps.

the analysis of the spectrum of the spontaneous radiation emitted by the FEL optical klystron, as reported in [9].

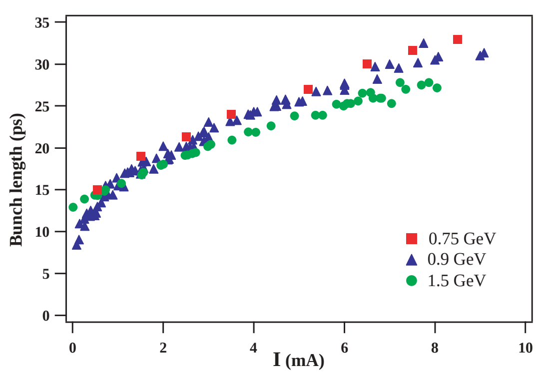

Figure 2: Bunch length as a function of the beam current (single bunch) at 0.75, 0.9 and 1.5 GeV. Data have been acquired by means of a double sweep streak camera. The absolute error on each point is about 2 ps.

It is worth pointing out that while the natural bunch length and energy spread at 1.5 GeV are larger than the corresponding values at 0.9 GeV (in agreement with theory), the trend is reversed already at relatively small values of the beam current (roughly 1 mA). This result confirms that the effect of the microwave instability is reduced when the energy is increased. The curve of the energy spread at 1.5 GeV in Figure 3 shows the transition between the potential well distortion (pwd) regime [10], in which an increase of the bunch length is observed (Figure 2) while the energy spread stays almost constant, and the microwave instability regime [11], characterized both by an ”anomalous” bunch lengthening and by an increase of the energy spread. The current threshold, I_{th}, i.e. the so-called Boussard parameter [12], is given by

$$I_{th} \propto \frac{E\sigma_{\epsilon,0}^3\alpha^2}{Z_n/n} \qquad (1)$$

where E is the nominal electron-beam energy, $\sigma_{\epsilon,0}$ the

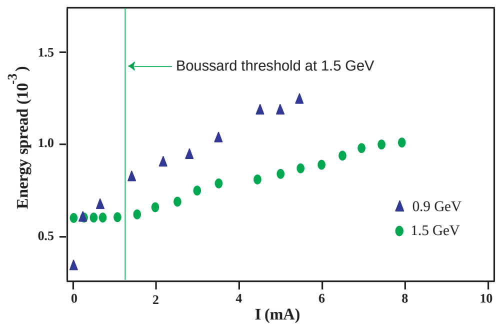

Figure 3: Beam energy spread as a function of the beam current (single bunch) at 0.9 and 1.5 GeV. The natural (i.e. close-to-zero current) values at 0.9 and 1.5 GeV are $0.36{\cdot}10^{-3}$ and $0.6{\cdot}10^{-3}$, respectively.

natural energy spread, α the momentum compaction factor and Z_n the broad band impedence (n being the the harmonic of the revolution frequency). The previous relation shows that a suitable modification of the beam optics could allow to extend the current range in which ELETTRA is operated in pwd regime, possibly improving the the FEL performance.

SINGLE-BUNCH INSTABILITIES

As a general remark, it is important to point out that while the behaviour of the bunch length as a function of the beam current has been found well reproducible, the same does not hold when the stability is regarded on a temporal scale of the order of few synchrotron period (tens of μs) or larger. Although a slight misalignment of the machine may have its influence, this lack of reproducibility seems mainly due to the presence of non-systematic effects, such as a 50 Hz perturbation (and its harmonics), whose origin has not been for the moment fully clarified. This slow instability may manifest in different ways, e.g. as a ”kick” (Figure 4) or as a continuous modulation (Figure 5) , and it can be at the origin of fast synchrotron-like instabilities.

In most cases, the center of mass of the electron bunch has been found subject to synchrotron oscillations (Figure 4b), the amplitude of which is found to be both energy and current independent. A recurrent mechanism which is at the origin of these oscillations is shown in figure 4a: the study of the beam evolution on a long (several ms) temporal scale shows the occurrence of a kick that excites the beam every 20 ms; the synchrotron oscillations represent the ”natural” beam response to the perturbation. Figure 5c shows that, once excited, the synchrotron oscillations relax with a characteristic time (less than 10 ms) much shorter than the synchrotron damping time, which is around 86 ms for the case shown in Figure 4.

As it has been previously mentioned, the 50 Hz perturbation (or its harmonics) may also manifest itself as a continuous modulation. In this case, as it is shown in Figure 5, the beam centroid tends to follow the dynamics of the

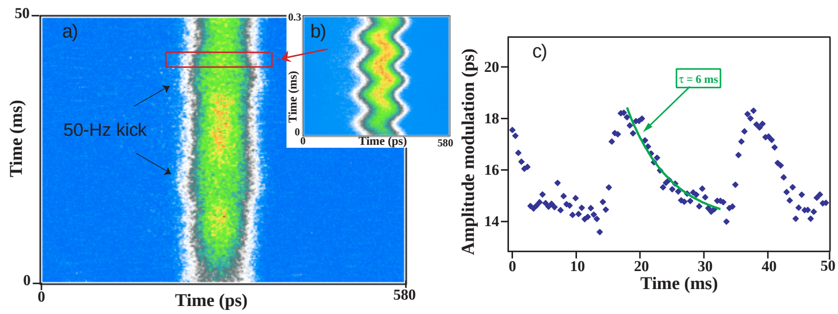

Figure 4: Figure a): streak camera image of the electron beam at 0.9 GeV (0.5 mA). Along the vertical axis one can follow the evolution in time of the temporal beam distribution while a horizontal cut provides the beam distribution profile. Figure b): zoom along the vertical axis of figure a) allowing to visualize the beam dynamics on a temporal scale of the order of few synchrotron periods. Figure c): Evolution of the amplitude of the synchroton oscillations (observed in figure b)) as obtained by the analysis of Figure a).

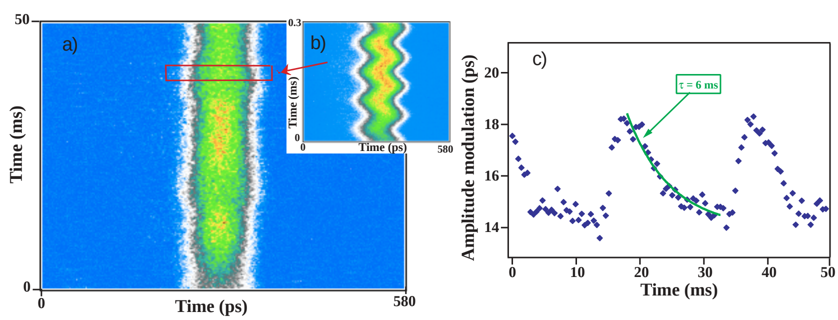

Figure 5: Figure a): streak camera image of the electron beam at 0.9 GeV (6 mA). Figure b): Evolution of the position of the beam center of mass of as obtained by the analysis of Figure a).

instability.

CONCLUSIONS AND PERSPECTIVES

Continuous measurements carried out at ELETTRA allow to characterize the evolution of the electron beam quality when the SR is operated in the single-bunch, low-energy configuration. The study of the single-bunch configuration is to be considered as propedeutic to the few-bunch operation mode which is, in turn, suitable for a number of application exploiting the time structure of the synchrotron radiation. The study points out the existence of non-trivial phenomena, such as the coupling between a slow (50 Hz) perturbation and fast synchrotron-like instabilities. The origin of this non-systematic perturbation will be the topic of a future dedicated analysis.

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