

ELECTRON-BEAM STABILIZATION FOR THE EUROPEAN STORAGE-RING FREE-ELECTRON LASER AT ELETTRA*

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Abstract

The temporal structure of the storage-ring free-electron laser at Elettra shows high sensitivity to electron-beam instabilities. In fact, even small beam perturbations may affect the FEL dynamics and periodically switch off the laser. In order to improve the FEL operation and performance, different and complementary feedback systems have been activated. This paper reports on their beneficial effect. Plans for future improvements are also briefly outlined.

INTRODUCTION

Instabilities of different nature may affect electron beams accumulated in a Storage Ring (SR) and degrade the performance of synchrotron light sources by leading to increased beam emittance, energy spread and transverse/longitudinal vibrations of the center of mass of the bunches. The origin of such instabilities can be traced back either to external perturbations (e.g. mains induced modulations, mechanical vibrations, etc.) or to the electromagnetic wake fields, which are generated by the interaction of the electron bunches with the surrounding vacuum chamber and other cavity-like structures. In general, such fields re-act on the bunches and perturb their motion.

Beam instabilities may affect the dynamics of a SR free-electron laser and, if strong enough, even prevent its onset. In this respect, beam perturbations which normally do not affect the performance of normal synchrotron radiation beamlines may instead have a strong effect on the FEL intensity. This is mainly due to the tight requirements on temporal synchronization and transverse overlap between electron bunches and light pulses stored in the optical cavity at each pass inside the interaction region [1].

We have observed that a longitudinal coupled-bunch instability (LCBI) of only few degrees in amplitude can spoil the laser synchronization and prevent it from starting. In order to damp LCBI, a bunch-by-bunch digital feedback system [2] has been activated at Elettra during some FEL shifts.

A different effect is observed when a beam-orbit perturbation of only few microns in the FEL straight section imposes a temporal structure to the laser intensity, changing the natural behavior of the system. The use of a local orbit stabilization feedback (LOF) [3], recently installed in cor-

respondence of the Elettra FEL section, has significantly reduced this low-frequency noise.

A further feedback system, complementary to the previous ones, has been developed in order to prevent the onset of a “naturally” pulsed FEL regime when the light-electron beam detuning is increased (e.g. by an external perturbation) above a given threshold.

In the following we summarize the results obtained so far using these different systems and we present a plan to develop a new feedback acting on the longitudinal bunch motion in the low frequency regime.

OPERATIVE FEEDBACKS

Without the use of any feedback system, the Elettra FEL is generally characterized by a macrotemporal structure showing a disturbed behavior and a high sensitivity to different kinds of electron beam instabilities. Figure 1 shows a measured FEL structure acquired with a photodiode together with its Fourier transform. The spectrum shows a strong 50 Hz component and harmonics.

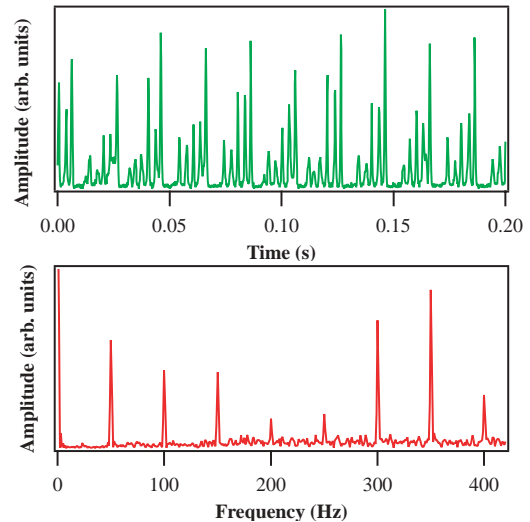


Figure 1: Typical temporal pulsed behavior of the FEL intensity (acquired with a photodiode) and its spectrum.

Since its first operation in February 2000 a lot of effort has been made in order to identify the major photon noise sources and to implement systems for their compensation.

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Longitudinal Multi-Bunch Feedback

When there are many bunches in a storage ring and the electron-beam induced wake fields are strong and persistent enough to act back on successive ones, a coherent oscillation may grow up [4]. This oscillation can affect the bunch motion in the transverse plane and in the longitudinal direction. Both transverse and longitudinal instabilities are undesired for FEL operation, but the longitudinal one is the most dangerous for the laser onset.

During FEL operation, Elettra is run in 4-bunch filling mode at relatively low energies (0.75-1.5 GeV). This configuration is completely different from the one routinely adopted for user operation (96 % multi-bunch continuous filling, 2-2.4 GeV). In the 4-bunch mode, LCBI can be damped by acting on the temperatures of the four radio-frequency cavities, finding a suitable higher-order mode combination [5]. However, the stability intervals are narrow and current dependent, so the operating temperatures have to be continuously adjusted following the natural current decay.

With the goal of improving the longitudinal beam stability and simplifying the operator task of keeping the beam stable, a longitudinal multi-bunch feedback has been recently activated. This feedback system acts on each individual bunch, which is considered an independent oscillator at the synchrotron frequency. A digital processing system is used to calculate the correction signal to be applied to the bunch through a dedicated kicker. Due to a limitation of the system bandwidth, the feedback is not effective in the low-frequency spectrum range.

This system has shown to be able to provide a perfect beam LCBI free, also without any specific adjustment of cavity temperatures. Moreover, its damping efficiency does not depend on the storage-ring filling pattern: we have already tested the case with eight bunches arranged in the ring in four pairs of two successive buckets and no LCBI was observed on the beam with the feedback on, whereas strong oscillations appeared without it.

This feature allows us to plan exotic fillings of the Elettra SR, e.g. four symmetric trains of bunches, which would increase the FEL average output power, being the latter proportional to the average beam current.

Local Orbit Feedback

SR-FEL theory predicts a pulsed time structure of the laser intensity on a millisecond temporal scale when the system is not close to synchronization, while a continuous wave (CW) mode of laser operation is expected around the perfect tuning condition. For Elettra, the CW region around the perfect synchronism is very narrow [7] and never experimentally observed. Due to that and to the 50 Hz (and harmonics) instability, the pulsed regime is the standard one for the Elettra SR-FEL. The natural frequency of the pulsed regime is given by the following relation [6]:

$$f_r = \frac{1}{\pi \sqrt{\tau_0 \tau_s}} \quad (1)$$

where τ_s is the synchrotron oscillation damping time and $\tau_0 = T_0/(G - P)$ is the laser rise-time, with T_0 the optical cavity round-trip period, P the optical cavity losses and G the amplification gain at the laser start-up. Using the Elettra parameters, the expression above predicts a frequency of 180-340 Hz depending on the beam current and on the specific mirrors. The observed FEL behavior, see Figure 1, is not that of a free oscillator at its own frequency, but appears to be regularly perturbed at 50 Hz.

With the goal of understanding if and how much the FEL pulsed behavior is sensitive to transverse beam orbit instability, the synchrotron light emitted by the electron beam has been observed making use of a Position Sensitive Detector (PSD). As clearly shown in Figure 2 (continuous lines), a 50 Hz component and its harmonics are present in both planes.

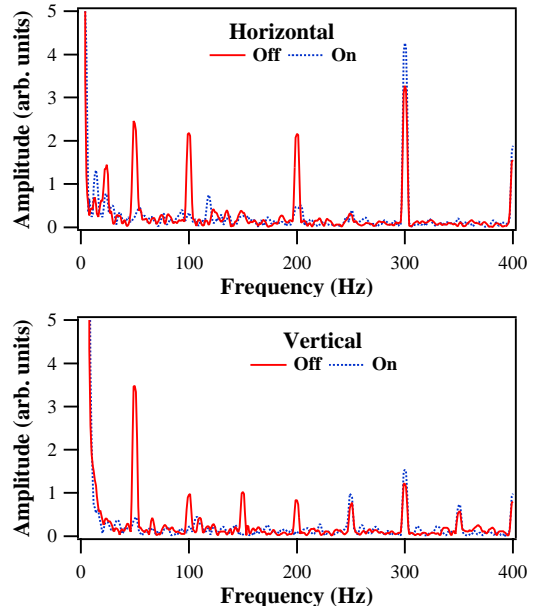


Figure 2: Photon beam transverse position spectra measured in the experimental area by a photon PSD with (dotted line) and without the orbit feedback. In this case, the operational bandwidth is limited up to 200 Hz.

Thanks to the recent implementation of a Local Orbit Feedback (LOF) on the SR section hosting the FEL, the transverse micron-range orbit instability has been measured and compensated up to frequencies of a few hundred Hz, see Figure 2 (dotted lines).

This feedback system detects the electron beam position and angle at the Insertion Device (ID) center and stabilizes it without affecting the rest of the orbit. Two Elettra Beam Position Monitors, located on both sides of the ID, are used to measure the beam position and angle, while four cor-

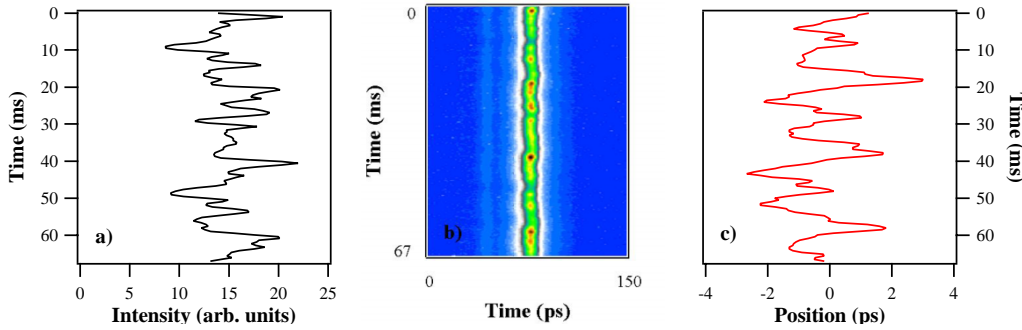


Figure 3: Streak camera image (b) of the FEL light without LOF. Along the vertical axis one can follow the time evolution of the laser on ms scale. Figure a) shows the intensity behavior along the slow time scale as obtained by an analysis of the images, while in Figure c) the phase stability with respect to RF is presented.

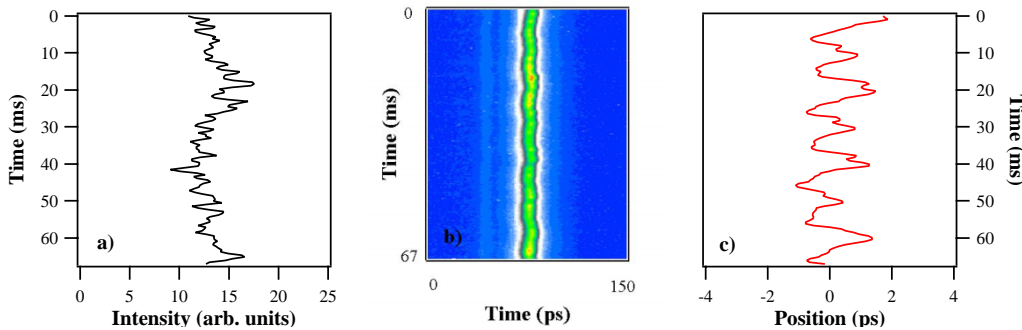


Figure 4: Streak camera image of the FEL light with LOF. Figures a) and c) as the previous figure.

rector magnets apply the closed local bump compensation. The feedback algorithm combines a PID (Proportional, Integral and Derivative) controller, which compensates the slow orbit drifts and lower frequency components of the beam noise spectrum, and a number of so called “Harmonic Suppressors” [3], which remove specific periodic components induced by the mains.

The LOF effect has been studied by means of a streak camera. Collected data (see Figures 3 and 4) show that the orbit stabilization due to the LOF reduces the fluctuations of the FEL intensity (a). Moreover, the FEL phase oscillation with respect to the radio-frequency (c) is halved when the feedback is on. Such oscillations, characterized by a frequency of 100 Hz, are probably induced by a low-frequency longitudinal noise source and, for this reason, they are not completely damped by the two feedback systems.

Derivative Feedback

A further feedback system has been developed as a result of a deeper theoretical understanding of the mechanism leading the system from the continuous to the pulsed behavior when the electron-photon synchronism is increased [8, 9]. When the system is active, the bunch revo-

lution period is modulated making use of a signal proportional to the derivative of the laser intensity.

Preliminary results (see Figure 5) show a damping of the laser oscillations and the achievement of a quasi-continuous regime.

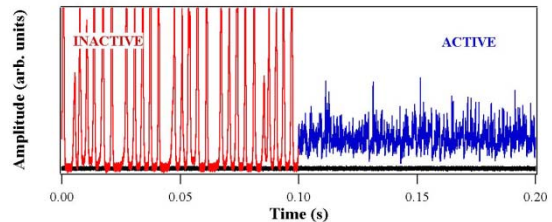


Figure 5: Stabilizing effect of the derivative feedback on the laser intensity.

PLANNED FEEDBACK

The combined action of the previous systems has been recently tested and it has shown to be beneficial for the laser performance. However, such a test has also pointed out that, in order to fully counteract the 50 Hz (+ harmon-

ics) instability affecting the bunch motion (see Figure 6) a further system is needed for the control of longitudinal, low-frequency, perturbations.

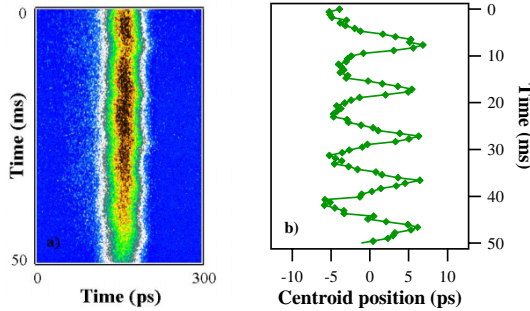


Figure 6: (a): streak camera image of the electron beam (6 mA). A longitudinal instability of the bunch centroid is visible. (b): evolution of the beam center of mass obtained by the image analysis.

We plan to implement a new system to detect the longitudinal low-frequency bunch instability by exploiting the existing LOF Beam Position Monitors. Such devices are equipped with an analog front-end for the demodulation of the RF signal [3] plus a digital receiver. A suitable correction of the Elettra RF will be applied by means of a phase modulation.

CONCLUSION

The performance of a SR-FEL in terms of light stability and extracted power depends on the possibility of simultaneously controlling the electron-beam and laser dynamics. To this purpose, three feedback systems have been recently activated during FEL operation, one acting on longitudinal multibunch instabilities, another on transverse orbit vibrations and a third one directly on the pulsed regime of the FEL intensity. As we have shown, their action significantly improves the beam stability and thus laser performance. Efforts are, however, still required to reach a regular and reproducible CW regime. For that, we plan to design a low-frequency longitudinal feedback which should lead to a further, hopefully decisive improvement of the FEL temporal structure.

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