EFFECT OF ELECTRON-BEAM FEEDBACKS ON THE ELETTRA STORAGE-RING FREE-ELECTRON LASER*

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Abstract

As is well known, the stability of a storage-ring free-electron laser is strongly related to that of the electron beam. With respect to second-generation sources, such as Super ACO and UVSOR, the free-electron laser at ELETTRA is characterized by a noticeably higher gain and, therefore, shows to be much more sensitive to electron-beam instabilities. In order to counteract the impact of such instabilities, both a longitudinal multibunch and a local orbit feedback have been activated during free-electron laser operation. Aim of this paper is to report on the beneficial effect of these feedback systems on the laser performance.

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 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 other synchrotron beamlines may instead have a strong effect on the FEL intensity. This is mainly due to the tight requirements in terms of temporal synchronization and transverse overlap between electron bunches and light pulses stored in the optical cavity at each pass inside the interaction region [1].

As an example, a longitudinal coupled-bunch instability (LCBI) of only few degrees of amplitude can spoil the laser synchronization and even prevent it from starting. In order to damp LCBIs, a bunch-by-bunch digital feedback system [2] has been activated during some FEL shifts.

A different effect is observed when a beam-orbit low-frequency perturbation (of the order of 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, 4], recently installed in correspondence of the ELETTRA FEL section, has significantly reduced this low-frequency noise. In the following we resume the results obtained so far.

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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 bunches, a coherent oscillation may grow up [5]. This oscillation can affect the bunch motion both in the transverse plane and in the longitudinal direction. Both kinds of 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 it is possible to compensate RF cavity HOM impedance contributions sampled by unstable beam spectrum frequencies with impedances sampled by stable frequencies. Stability even at 0.9 GeV can thus be achieved by fine tuning of the cavity temperatures [6]. Of course the stability intervals are narrow and current dependent, so the operating temperature settings 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 maintaining 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.

Figure 1 shows an example of the measured amplitude of one longitudinal coupled bunch mode with and without the feedback. As can be seen, the instability is completely suppressed when the feedback is active. This system is able to suppress LCBIs without any specific further adjustment of cavity temperatures. The importance of this system is its independence from the filling pattern, namely storing an uneven bunch sequence does not reduce the damp-

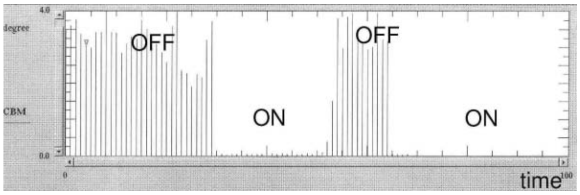

Figure 1: Measured amplitude of one longitudinal coupled bunch mode with and without the longitudinal feedback.

ing efficiency of the system. 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 start without it.
This feature allows us to envisage exotic fillings of the ELETTRA SR, e.g. four symmetric trains of bunches, which would increase the FEL average output power that is proportional to the total 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 and a continuous wave (cw) mode of laser operation is expected only around the perfect condition. For ELETTRA, the pulsed regime is the standard one because the cw region around perfect synchronism is very narrow [7] and never experimentally observed. The natural frequency of the pulsed regime is given by the following relation [8]:

$$f_r = \frac{1}{\pi\sqrt{\tau_0 \tau_s}} \tag{1}$$

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 bunch time spacing, P the optical cavity losses and G the amplification gain at the laser start. Using the ELETTRA parameters, the expression above predicts a frequency of 180-340 Hz depending from the beam current and the mirrors used.

Figure 2 shows the measured macrotemporal structure acquired with a photodiode together with its frequency Fourier transform. The observed behavior is not that of a free oscillator but appears to be regularly perturbed. The spectrum shows a strong 50 Hz component and its harmonics, with the contribution of the 300 and 350 Hz components particularly evident. This disturbed temporal behavior of the laser is probably due to its coupling with the electron beam perturbations. Thanks to the recent implementation of a Local Orbit Feedback (LOF) on the SR section hosting the FEL, the effect of transverse micron-range orbit instability has been measured and compensated up to frequencies of a few hundred Hz. 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 either side to the ID, are used to measure the beam position and direction, while four corrector 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 Suppressor” [3, 4], which remove specific components induced by the mains.

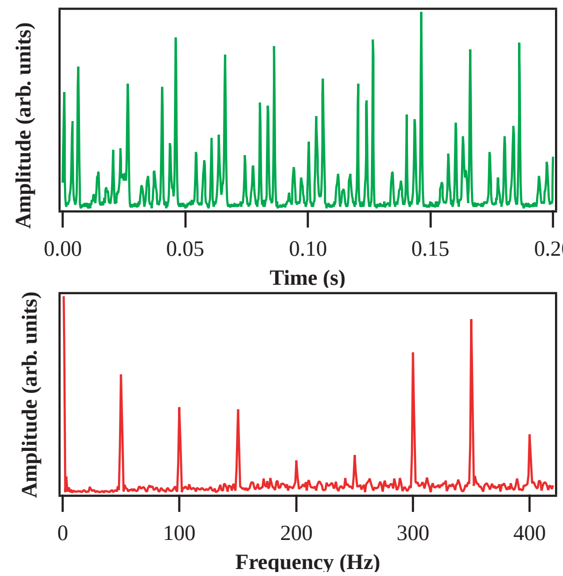

Figure 2: Typical temporal pulsed behavior of the FEL intensity, acquired with a photodiode and its spectrum.

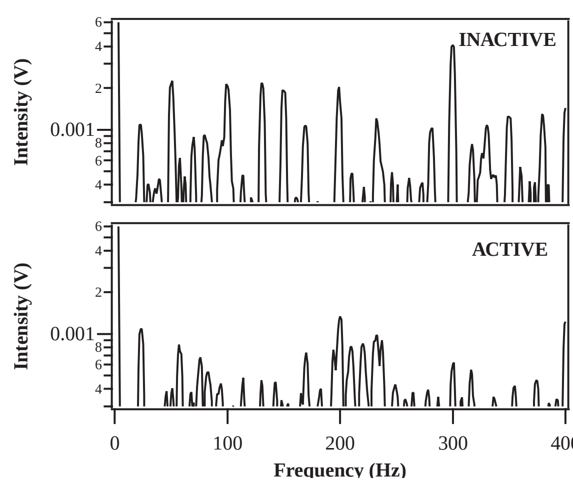

Figure 3: Effect of the LOF on FEL intensity spectrum using the harmonic suppressors centered at 50 Hz and its harmonics up to 300 Hz.

LOF effects on FEL intensity are shown in Figure 3. As can be seen, the main harmonic components disappear showing the efficiency of the harmonic suppressors, while

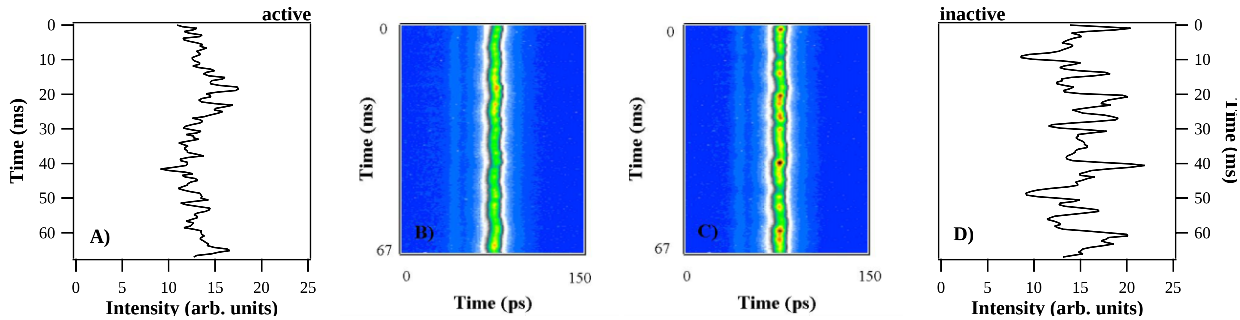

Figure 4: Streak camera images of the FEL light with LOF on (B) and off (C). Along the vertical axis one can follow the evolution in time of the laser on ms scale, while a horizontal cut provides the pulse profile. Figures A) and D) show the intensity behavior along the slow time scale as obtained by an analysis of the images.

a relatively broad band signal comes out around 210 Hz, probably due to the natural frequency of the system (see Eq. 1).

Observations of LOF results have also been performed by using a Streak Camera. Several images have been acquired and, as in Figure 4, they show that fluctuations of the FEL intensity are reduced by the orbit stabilization. Moreover, the FEL phase oscillation with respect to the radiofrequency (visible taking horizontal cuts for different positions along the vertical axis in Figs. 4B and 4C) is halved when the feedback is on. Such oscillations, characterized by a frequency of 100 Hz, are induced by a low-frequency longitudinal noise source and, for this reason, they are not completely damped by the two feedback systems.

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. As a preliminary requirement, the level of longitudinal and transverse electron-beam stability must be high enough to guarantee the laser start-up and growth. With this purpose, two feedback systems have been recently activated during ELETTRA SR-FEL operation, one acting on longitudinal, high-frequency, multibunch instabilities and one on transverse, slow-frequency, orbit vibrations. 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 improvement of the FEL temporal structure.

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