STABILIZATION OF THE PULSED REGIMES ON A STORAGE RING FREE ELECTRON LASER: THE CASES OF SUPER-ACO AND ELETTRA

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Abstract

In a Storage Ring Free Electron Laser (SRFEL) a relativistic electron beam interacts with the periodic magnetic field of an undulator, thus emitting synchrotron radiation. The light is stored in an optical cavity and amplified during successive turns of the particles in the ring. The laser intensity may appear as a "continuous wave (cw)" or show a stable pulsed behavior depending on the value of the temporal detuning, i.e. the difference between the electron beam revolution period and the round trip of the photons in the cavity. It was recently shown, that the loss of stability in a SRFEL occurs through an Hopf bifurcation [1, 2]. This observation opens up the perspective of introducing a derivative self-controlled feedback to suppress locally the bifurcation and enlarge the region of stable signal. A feedback of this type has been implemented on Super-ACO and shown to produce a significant and reproducible extension of the stable "cw" region. First the detuning curves of the Super-ACO and ELETTRA FEL, which points out the dynamics of the laser, will be presented. Then, the principle of the feedback system and the results obtained on the Super-ACO and ELETTRA FEL are exposed. To end, new experiments performed on ELETTRA will be discussed.

DETUNING CURVE

The amplification process of a Free Electron Laser (FEL) results from the interaction between a relativistic electron beam and an electromagnetic wave in a magnetic periodic structure called undulator. The electromagnetic wave generated by the electrons passing through an undulator, i.e. the synchrotron radiation emission, is stored in an optical cavity. When the electron beam and the optical wave interact, the radiation can be amplified to the detriment of the electrons kinetic energy, allowing the laser effect to occur [3]. At the nanosecond time scale the laser is pulsed at the pass frequency of the electron bunches in the undulator. At the milli-second time scale, the laser dynamics depends on the detuning frequency between the repetition rate of the optical wave in the optical cavity and of the electron bunch in the undulator [4]. This detuning can be experimentally modified by changing the radio frequency (RF), thus the electron revolution period, or by changing the length of the optical cavity. Figure 1 illustrates the detuning curves of the Super-ACO and ELETTRA FEL, i. e. the laser intensity versus detuning. In the Super-ACO FEL, five distinctive zones can be pointed out in the detuning curve. In zones 1, 3 and 5, the laser is continuous at the milli-second time scale, whereas of zones 2 and 4, where the laser is pulsed at around 300 Hz. In zone 3, the laser has the highest power, the best stability and the smallest spectral and temporal width. As it is of paramount importance to keep the laser in zone 3 for users applications, it has been developed at Super-ACO and UVSOR [5, 6], a longitudinal feedback, which brings back the laser at perfect tuning for compensating the pulse jitter. The ELETTRA FEL dynamics presents a somehow more complex situation [7]. In zones 1, 3 and 5, the laser is almost 'cw' and is quite noisy, because of the presence of 50 Hz perturbation on the elec-

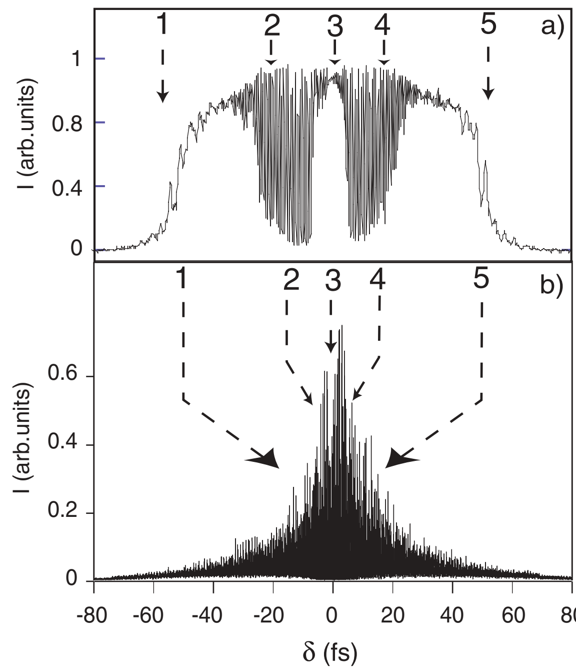

Figure 1: Detuning curve, i. e. laser intensity versus detuning obtained in the a) Super-ACO FEL, b) ELETTRA FEL. The experimental detuning curve is obtained by applying a slow ramp on the RF frequency and detecting the laser intensity by a photomultiplier or a photodiode.

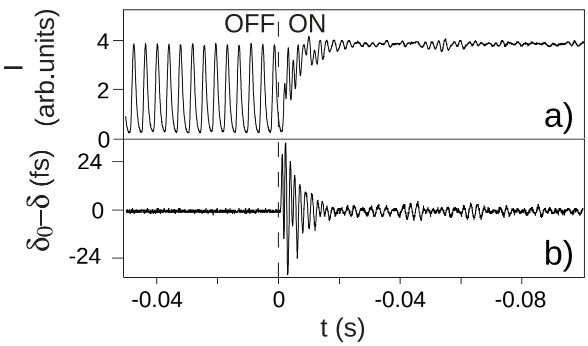

Figure 2: a) Laser intensity, b) control parameter versus time. For negative times (respectively positive times), the feedback was switched off (respectively on) in the Super-ACO FEL case.

tron beam [8]. To extend the zone of detuning for which the laser will be 'cw', a derivative feedback has been developed in both the Storage rings FEL : Super-ACO and ELETTRA.

DYNAMICAL STABILIZATION: DERIVATIVE FEEDBACK

In the conventional laser community, feedbacks have been developed to control the dynamics of the laser, following the proposed OGY methods [9]. The goal of such a feedback was first to control the chaotic dynamics in favor of periodic regime [10]. It has been extended to the control of the pulsed regimes, in favor of steady states one [11], which stabilized the unstable state coexisting with the pulsed regimes thanks to a derivative feedback. It has been demonstrated that such a feedback can be implemented on FELs [1, 2]. The feedback consists in detecting the laser intensity I, which is derived and amplified by an analogical electronic system, and acts on a control parameter to perturb the laser gain. If the gain β of the amplification of the derivative of the intensity is properly adjusted, the laser is stabilized into a steady state regime. For the following experiments, the control parameter, which has been chosen, is the frequency of the RF cavity, implanted on Storage ring to compensate the electron loss energy per turn passing through magnetic devices. The detuning $\delta(t)$ becomes a dynamical variable depending on time t as :

$$\delta(t) = \delta_0 + \beta \frac{dI}{dt} \qquad (1)$$

The laser is preliminary set on a pulsed regime at a detuning δ_0, as shown in figure 2 for the negative time. At $t = 0$, the feedback was switched on, with a preliminary adjustment of the feedback gain. The pulsed laser is stabilized on a steady state regime. The fluctuations of the laser intensity (standard deviation normalized to the mean value), are 4 $\%$ (mean of the data during an experiment) with a standard deviation of 1 $\%$ in the Super-ACO FEL case. After the stabilization of the pulsed behavior, the feedback reacts to the laser intensity fluctuations, and maintains the continuous dynamics of the FEL. The figure 3 presents the stabilization in the ELETTRA FEL case. The fluctuations of the laser intensity are 35 $\%$ with a standard deviation of 7 $\%$ in ELETTRA FEL case. The fluctuations are higher is the case of the ELETTRA FEL than in the Super-ACO FEL one. In figure 3, the stabilized state exhibits some perturbations at a frequency of 50 Hz and its harmonics. As a consequence, a proportional loop has been added to the derivative one with a separate control of the electronic gain in order to try to damp these perturbations.

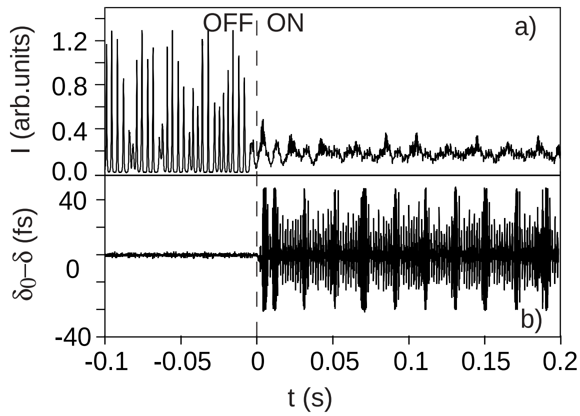

Figure 3: a) Laser intensity, b) control parameter versus time. For negative times (respectively positive times), the feedback was switched off (respectively on) in the ELETTRA FEL case.

LOW-FREQUENCY NOISE REDUCTION: PROPORTIONAL FEEDBACK

Aiming at reducing the low-frequency fluctuations (<200-300 Hz), we have applied an additional proportional feedback loop. The correction is a signal $\alpha Y(t)$ proportional to the signal $I(t)$ after AC-coupling. The dynamical detuning becomes :

$$\delta(t) = \delta_0 + \beta \frac{dI}{dt} + \alpha Y(t) \qquad (2)$$

$$\frac{dY}{dt} = \frac{dI}{dt} - \omega_{AC} Y \qquad (3)$$

with α the gain of the proportional loop, and $\omega_{AC}/2\pi$ the cutoff frequency of the AC coupling (=7 Hz). After an optimization of the feedback gains β and α, the pulsed dynamics of the ELETTRA FEL has been suppressed in favor of a steady state regime. As illustrated in figure 4, the fluctuations of the laser intensity for consecutive laser intensity data were damped with the additional proportional loop from 35 $\%$ to 25 $\%$ with respectively a standard deviation of 7 $\%$ and 4 $\%$. The Fast Fourier Transforms of the laser intensity time series, controlled by an active feedback, has been calculated and compared with or without

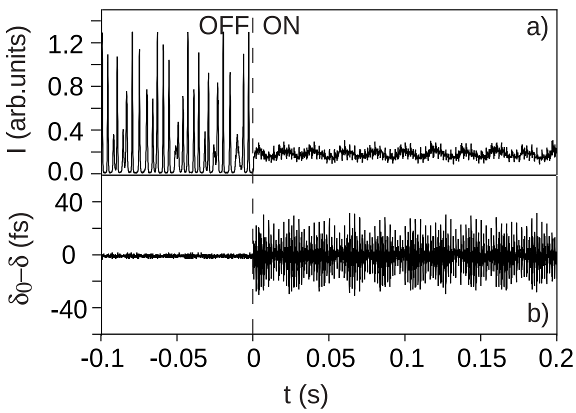

Figure 4: a) Laser intensity, b) control parameter versus time. For negative times (respectively positive times), the feedback was switched off (respectively on with the additive proportional loop) in the ELETTRA FEL case.

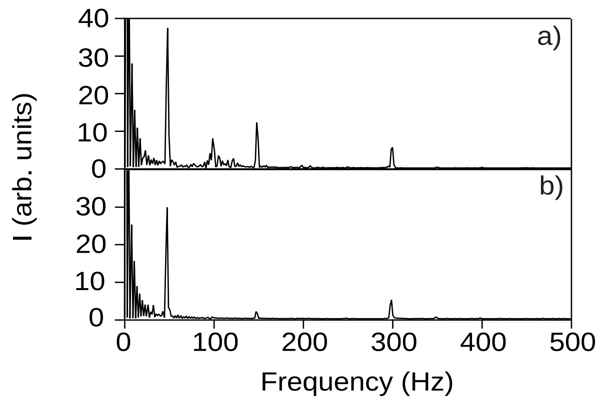

Figure 5: Power spectrum of the intensity signal $I(t)$ for the ELETTRA FEL: (a) with derivative feedback only, and (b) with the derivative and proportional loops activated. (a) and (b) correspond to the signals of Figs. 3 and 4 respectively.

the proportional loop as presented in figure 5. Figure 5a exhibits peaks and line frequency at 50 Hz and its harmonics (100, 150 Hz) in the case of a stabilization with a derivative feedback. When the proportional loop is added, peak frequencies at 100 and 150 Hz are almost suppressed, but only the peak frequency at 50 Hz is damped. As a consequence, the proportional loop has a positive action on the suppression of the harmonics of the 50 Hz perturbation. A feedback system, which has to damp the 50 Hz perturbation on the electron beam, was developed by the machine group of the ELETTRA storage ring. An FEL operation has already be done with such a feedback [12], which improves the 'cw' laser around perfect tuning. In such a condition, the suppression of the pulsed zones with the derivative and proportional loop will be tried in the future.

CONCLUSION

The derivative feedback tested at Super-ACO demonstrate the suppression of the pulsed FEL dynamics on a Storage Ring Free Electron Laser. The necessity of such a stabilization on the ELETTRA FEL is of paramount importance because of the very narrow 'cw' zone around perfect tuning. Such a feedback has been realized on the ELETTRA FEL and demonstrates a suppression of the pulsed behavior with a residual perturbation at 50 Hz and its harmonics. A proportional feedback, which has been added to the derivative one, suppresses almost the perturbations due to the harmonics, but only damps the 50 Hz perturbation. Future experiment has to be investigated with the feedback on the electron beam.

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