LASER-ELECTRON BEAM DYNAMICS OF THE EUROPEAN FREE ELECTRON LASER AT ELETTRA

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Abstract

This paper gives an overview of both the experimental and theoretical studies which have been recently performed in order to characterise the laser-electron beam dynamics of the European Storage Ring Free Electron Laser at ELETTRA.

1 INTRODUCTION

After the first lasing in February 2000 [1], the initial phase of development of the European Free Electron Laser (FEL) at ELETTRA [2] has been successfully accomplished[1]. The laser has been operated at wavelengths down to 190 nm and an increased output power has been obtained [3]. Further improvements of the source are, however, necessary in order to allow the FEL to become a reliable user facility [2]. In particular, the laser dynamics on the macro-temporal (ms) time-scale needs to be stabilised. The stability improvement requires a better understanding of the laser-electron beam interaction, which, for the case of ELETTRA, presents some specific issues compared to other storage ring (SR) FELs. In this context, a campaign of experiments has been undertaken. At the same time, numerical simulations have been carried out, making use of a phenomenological theoretical model which includes the relevant features of the laser-electron beam interaction. This paper gives an overview of state-of-art of the obtained results.

2 FEL DYNAMICS

A SRFEL is a complex, strongly-coupled dynamical system. The coupling between the electromagnetic field stored in the optical cavity and the electron beam originates from the fact that, unlike a LINAC based FEL, where the beam is renewed after each interaction, electrons are re-circulated. As a consequence, at every light-beam energy exchange, the system keeps memory of previous interactions. Under given conditions of proper longitudinal and transverse overlap between the photon pulses stored in the cavity and the electron bunch(es) circulating in the ring, an energy exchange can occur, via the Lorentz interaction, between photons and electrons. The amplification of the optical pulse is possible at the expense of the particles kinetic energy. This leads to an exponential laser amplification which results in a heating of the energy beam distribution. Because of the increase of the beam energy spread, the gain of the light amplification process is reduced until it reaches the level of the optical cavity losses (laser saturation). The amount of energy spread induced by the FEL interaction fixes the maximum average lasing power according to the Renieri limit [4].

During their motion, the electrons interact with the ring environment. This interaction manifests itself as a “wake” electromagnetic field that acts on the electrons and may perturb their stability. The instability of microwave type [5] is one of the mostly likely observed. It limits the accelerator performance at high currents and leads to an increase of energy spread with consequent anomalous bunch lengthening [6], [7]. Both theoretical and experimental results show that the microwave instability and the laser growth are competitive phenomena [8]: when the laser is able to develop, the instability is completely counteracted even though ready to grow up again if, for some reason (for example due to an external perturbation), the laser is switched off.

When there is more than one bunch in the ring and the impedance is large enough that successive bunches can still feel the wake-field created by the previous ones, all bunches may simultaneously execute a growing coherent oscillation (coupled-bunch instability [9]). When it is noticeable (as in the case of ELETTRA), this kind of instability may prevent the laser onset. In principle, the coupled-bunch instability may be compensated by appropriate tuning of the radio-frequency (RF) temperatures (which control the higher-order mode frequencies). In reality, the relatively low energy at which the FEL is operated makes the compensation more difficult, the instability thresholds being much lower. Apart from instabilities which are “intrinsic” to the interaction of the electron bunch(es) with the ring environment, external perturbations (e.g. line-induced modulations, mechanical vibrations . . .) may disturb the electrons dynamics and, as a consequence, the laser stability. This is, for example, the case of a 50 Hz instability [2], [10], whose origin has not been for the moment fully clarified, and which constitutes one of the major limitations to the performances of the ELETTRA FEL (see next Section).

The laser induced energy spread is not the only mechanism leading a SRFEL to saturation. In fact, the FEL dynamics strongly depends on the longitudinal overlap between the electron bunch(es) and the laser pulse at each pass inside the optical cavity: a small detuning leads to a cumulative delay between electrons and light pulses and, as a consequence, to a reduction of the optical gain [12]. The FEL dynamics in the presence of a finite detuning may be investi-

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gated by means of a phenomenological pass-to-pass model [13], [12],[14]. Such a model, on which numerical simulations are based (see the next Section), couples the evolution of the laser intensity to those of the optical gain and of the induced electron-beam energy spread. The gain evolution takes into account the effect of the optical klystron (i.e. the modulation rate of the spontaneous emission) and has the same temporal profile (assumed to be gaussian) of the electron bunch. The effect of the interaction between the electron bunch(es) and the ring environment is, to a first approximation, neglected. This assumption is justified for the case of machines (such as ELETTRA [6]) which are characterised by a small impedance.

Both experiments and numerical simulations performed for the case of the Super-ACO [12] and UVSOR [15] FELs (second generation machines) show that the laser dynamics on a macro-temporal (ms) scale depends on the laser-electron beam detuning amount: the laser may be “cw” (for weak or strong detuning) or show a stable pulsed behaviour (for an intermediate detuning amount). As will be illustrated in the following, the case of third generation SR-FELs, such as ELETTRA, seems to be more complex. In fact, due to a higher gain with respect to SRFELs of previous generations, the laser dynamics is found in this case to be more noisy and the border between stable and pulsed behaviour less sharp.

3 THE ELETTRA FEL

The main characteristics of the ELETTRA FEL operated at 0.9 GeV are reported in Table 1.

Table 1: Main characteristics of the ELETTRA FEL operated at 0.9 GeV. The laser gain has been theoretically estimated at a wavelength of 250 nm and for different values of the beam current.

natural bunch length (rms)	9.2 ps
Natural energy spread (rms)	$6 \cdot 10^{-4}$
Laser temporal width (rms)	5 ps
Laser spectral width	$4 \cdot 10^{-4}$
Time-bandwidth product/Fourier limit	7.2 - 8.5
Laser gain (%)	10 to 30

Thanks to the combination of high-quality electron beam (i.e. high gain) and flexible undulator parameters, the ELETTRA FEL can be presently operated in the large energy range 0.9 - 1.3 GeV (attempts to reach 1.5 GeV are foreseen in the near future). High energy operation is a crucial issue for providing higher power output and better compatibility with other SR users. Moreover, beam stability is generally easier to achieve at high energy [2]. Concerning the output laser power, a significant difference has been found between experiments and what is predicted by the Renieri limit [3]. Recent theoretical studies [11] show that the origin of this phenomenon, which has been also observed on the Super-ACO FEL, can be traced to the combined effect of potential well distortion and the microwave instability.

As already mentioned, one of the major limitations to the ELETTRA FEL performance comes at the moment from a 50 Hz perturbation acting on the electron bunch. The resulting effect on the laser dynamics is shown in Figure 1. Close to the perfect synchronism, the laser intensity is generally pulsed at the same period of the modulation. This does not allow a stable, “cw” operation and prevents the system from attaining the Fourier limit (see Table 1). In fact, every time that the laser intensity is switched off by the perturbation, the narrowing of the temporal width is stopped (the same happens to the spectral width) and the amplification process restarts from the spontaneous emission.

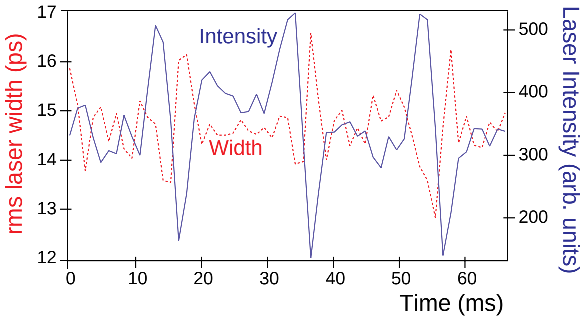

Figure 1: Effect of the 50 Hz perturbation on the intensity and on the temporal width of the ELETTRA FEL. The curves result from the analysis performed on a double sweep streak camera image aquired in the presence of quite large amount of detuning (i.e. large value of the laser temporal width).

In order to counteract the inauspicious effect of this instability, the installation of a feedback system, which will provide a local compensation in correspondence of the FEL section, is foreseen in the near future.

A campaign of experimental and theoretical studies has been undertaken in order to characterise the behaviour of the laser intensity as a function of the laser-electron beam detuning amount. Figure 2 shows a detuning curve obtained at 0.9 GeV by means of an RF modulation. In spite of the spoiling effect of the 50 Hz instability (hampering an accurate resolution of the different regimes), the five “standard” zones can be recognised [12]: three of them where the laser is almost “cw” (close-to-zero and large detuning) and the other two where the laser shows a stable pulsed dynamics (intermediate detuning amount). The inset of Figure 2 shows the result of a simulation (performed by means of the model mentioned above) reproducing the behaviour of the laser intensity as a function of time at perfect synchronism. Measurements and simulations agree on the fact that the width of the central “cw” zone, which is the most

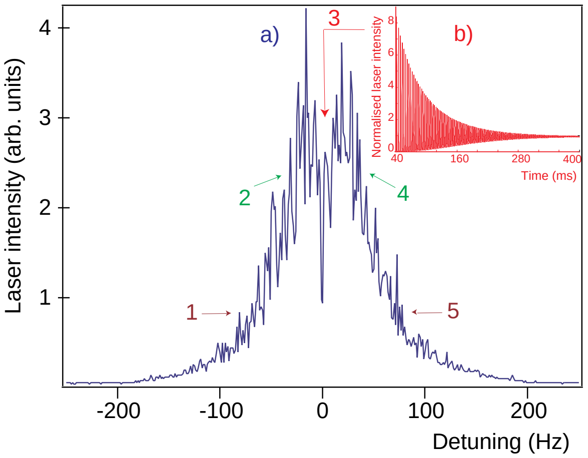

Figure 2: Curve a): Laser intensity as a function of the laser-electron beam detuning amount (shown as variation of the RF with respect to perfect synchronism). The signal has been detected by means of a photodiode and acquired on an oscilloscope in peak detect mode. Zone 3 corresponds to a (close-to-zero detuning) “cw” regime (the output power being reduced with respect to the adjacent pulsed zones), zones 2 and 4 to the “natural” pulsed regime and zones 1 and 5 to the detuned “cw” regime. Curve b): Numerical simulation reproducing the behaviour of the laser intensity as a function of time at the perfect synchronism.

suitable for users applications, is very narrow (about 2 Hz corresponding to a variation of 130 nm of the optical cavity length). As has been shown in [14] for the case of Super-ACO, the width of the central zone is a function of the electron beam energy: higher energies produce larger zones of “cw” laser. Preliminary numerical studies confirm the same trend for the case of ELETTRA: the width of the “cw” zone should become about 10 Hz (650 nm) at 1.3 GeV.

Experiments performed at 0.9 GeV show, however, that the ELETTRA FEL is characterised by a more complex detuned dynamics with respect to Super-ACO and UVSOR. In particular, the amplitude of the “natural” pulsed dynamics is often found to be quite noisy (see Figure 3a) and the frequency range quite large (see Figure 3b). This result has been numerically checked (see Figure 3c) and may be due to the combination of high gain (i.e. short laser rise-time and, as a consequence, high sensitivity to any external perturbation) and relatively low energy (long synchrotron damping time and, as a consequence, greater difficulty in reaching a steady state). Again, increasing the energy (i.e. decreasing the net gain) should improve the situation.

4 CONCLUSIONS AND PROSPECTS

After the successful accomplishment of a first phase of development, further improvements of the European FEL at ELETTRA are now necessary in order to allow the FEL to become a fully reliable user facility. This will require:

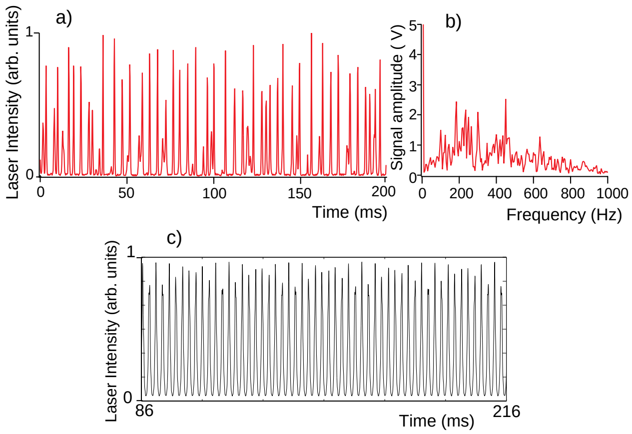

Figure 3: Figure a): Experimental behaviour of the laser intensity as a function of time. The FEL has been operated at 0.9 GeV with a small laser-electron beam detuning. Figure b): Fourier analysis of plot a). Figure c): Numerical simulation performed in the same condtions of Figure a)).

- an improvement of the system stability, which is at the moment strongly limited by a 50 Hz perturbation;
- a deeper analysis, both theoretical and experimental, of the source characteristics.

Concerning the latter point, preliminary studies show that, due to the higher quality of its components with respect to SRFEL of previous generations, the ELETTRA FEL dynamics is quite peculiar. In particular, the conditions of high net gain and low energy (< 1 GeV) do not seem to be the most suitable for the achievement of a stable and reproducible operation. Consequently, one main future aim will be the investigation of FEL operation at energies above 1 GeV. This will also allow to enhance the output power and to improve the compatibility with other SR users.

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