Q-SWITCH TECHNIQUES IMPLEMENTED AT THE ELETTRA STORAGE-RING FREE-ELECTRON LASER

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Abstract

In a Storage-Ring Free-Electron Laser (SRFEL) giant pulses can be produced by the interaction between the light stored in the optical cavity and an electron beam with low energy-spread (cold beam). This interplay produces the heating of the beam. After the generation of a single giant pulse the overlap between electrons and radiation is periodically prevented for a time necessary to dump the energy spread and recover the cold-beam condition. Two different methods are now implemented at Elettra for giant pulse generation. In the first, by modifying the radio-frequency of the ring, a change of the revolution time of electrons is induced. This avoids the temporal overlap between the electron beam and the optical field in the mirror cavity. The second method relies on a mechanical gating (chopper) which intercepts the light produced during previous interactions, inducing a periodic depletion of the optical cavity. The giant-pulses repetition rate is determined by the periodicity of the radio-frequency changes and the rotating velocity of the chopper, respectively. In this paper we compare the different techniques mentioned above for the case of the Elettra SRFEL.

INTRODUCTION

The customary layout of a Free-Electron Laser (FEL) in oscillator configuration takes advantage of an optical klystron. This magnetic structure is made up of two undulators and a dispersive section in between (see Figure 1). In the small gain case [1], which is indeed the oscillator case, the strong magnetic field of the dispersive section induces a delay between the radiation emitted in the first and in the second undulator. In comparison to the light the electrons spend longer time to pass through a magnetic chicane and, once in the the second undulator, their emission will have a different phase with respect to the light emitted formerly. This delay produces a constructive interference of radiation, changing the optical klystron spectrum in a more spiky structure and enhances the FEL process because its gain is proportional to the derivative of this interference structure. The other main component of an oscillator FEL is the optical cavity, composed by two mirrors on axis with the two undulators and the dispersive section, as depicted in Figure 1.

In the normal operational mode of a storage-ring FEL in oscillator configuration, the light emitted has a temporal structure depending on the ring filling and each pulse has a quite low power. When the electron beam interacts with the light stored in the optical cavity, emitting coherently, its energy spread grows up. This effect, called beam "heating", limits the maximum power achievable, because the gain is proportional to the electron density. Between the generation of two consecutive giant pulses it is necessary to wait few synchrotron damping times, this allows to restore the cold beam condition. In this period of time, in fact, if the light-electron interaction is prevented, the beam energy spread decreases to the initial value.

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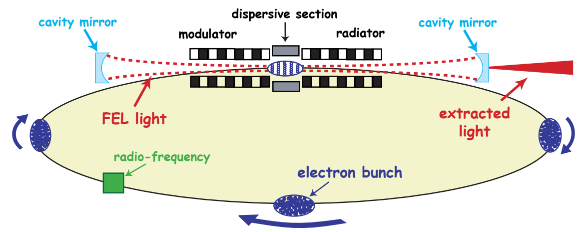

Figure 1: Layout of the Elettra storage-ring FEL in oscillator configuration.

Several methods have been studied and applied in oscillator FELs [2, 3, 4, 5] to create "giant pulses". There are basically three techniques that have been implemented:

- the gain modulation [6];
- the modulation of RF frequency [4, 5];
- the mechanical gating (chopper).

The first method is presently employed at Duke, where a dedicated magnet steers the electron beam orbit in the transverse direction. When the electron beam orbit is off-axis with respect to the optical cavity, the lasing is stopped and the electron beam can cool down. Once the electron beam orbit returns on-axis, a new giant pulse starts. The RF frequency modulation has been used in Super-ACO and is currently implemented at Elettra and UVSOR. This technique may excite synchrotron oscillations of the electron beam, or enhance them if already present. The induced oscillations can reduce the net gain at the laser start. While the first two techniques can be considered equivalent for generating giant pulses (as demonstrated for Duke in [7]), the mechanical gating is still under investigation.

The purpose of the Q-switch technique is twofold: to concentrate the average power of storage-ring FEL in a series of giant-pulses and to have a regular temporal dynamics of the light. This allows to use the light emitted for experiments, for example synchronizing an external trigger which drives the giant pulse repetition rate [8]. Besides, it is well known that the FEL light at the fundamental wavelength, which is reflected by the mirrors of the optical cavity, produces higher harmonics [9]. These harmonics survive just for a single pass in the optical cavity, because the mirrors do not reflect light with their wavelength. In normal operation mode the power of higher harmonics, which depends on the fundamental power, is too low to be detected. Giant pulse production is therefore a suitable way to enhance the fundamental power and accordingly the higher harmonic power. One example of harmonic generation in cavity is reported in Figure 2.

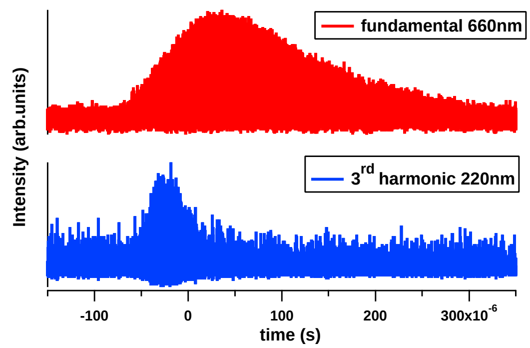

Figure 2: The fundamental (660 nm) and the third harmonic (220 nm) giant pulses. The harmonic signal is about a factor 25 above spontaneous emission.

The giant-pulse risetime provides also an estimation of the initial FEL gain. Between each pulse the electron beam is restored and when the giant pulse starts the only negative effect is due to the optical cavity losses. This allows to calculate the net gain of the FEL process, if the mirror reflectivity is known.

TWO DIFFERENT EXPERIMENTAL TECHNIQUES

In this section, we concentrate on the two techniques used at Elettra for the giant pulse generation, i.e., the RF frequency modulation and the Q-switch with the chopper.

RF frequency modulation

In a storage-ring FEL, in order to obtain the synchronization between the electron beam and the light stored in the optical cavity, the mirrors are placed at inter-bunch distance. Stepper or piezo-electric motors provide the fine tuning of the mirror position along the undulator axis. If the RF frequency of the storage ring changes the revolution time of electrons changes as well, causing the loss of synchronization with the optical filed in the cavity. Without temporal overlap the electrons do not interact with the radiation stored in the optical cavity and then the energy spread of the beam can decrease. The RF frequency modulation is based on a periodic detuning between the electron beam and the radiation stored into the optical cavity. When the system is detuned the lasing process is stopped. An external signal source induces the detuning and modifies the slope and the amplitude of the RF frequency jump. The detuned condition is maintained for few synchrotron damping times to allow the electron beam to cool down and the gain of the amplification process to recover its initial (i.e. laser-off) maximum value. Once this situation is reached, the system is led back to the perfect tuning condition which is maintained for a long enough time (order of dozens of milliseconds) to induce the onset of the laser giant pulse. Then the system is detuned again and the process repeated.

The main advantage of this technique is the fast transition time. The RF modulation is driven by a signal generator, therefore one can choose the slope of the signal to reach the maximum power. The unfavorable aspect is the beam perturbation caused by the RF modulation. The damping is regulated by the synchrotron frequency. Figure 3 shows a streak camera image of the synchrotron radiation and the FEL signal.

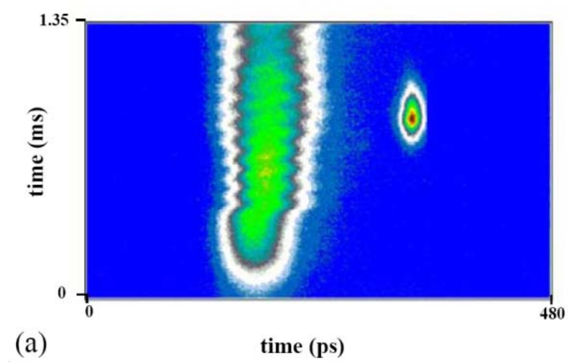

Figure 3: Streak-camera image of the electron beam (left trace) and of the FEL pulse (right trace) in Q-switch operation mode.

Along the vertical axis of the picture, the evolution in time of the distribution profile is reported and one can also see the excitation of synchrotron oscillation starting before the laser. The analysis in Figure 4 also shows the electron beam heating that begins before the giant pulse start.

Q-switch with chopper

In the Elettra storage-ring FEL a mechanical gating has been recently introduced in the optical cavity. This object, called chopper, is a molybdenum disc with a 115 mm radius with a little aperture positioned close to the border (see Figures 5). When the aperture is on-axis with the optical cavity the light stored can pass, otherwise the radiation is intercepted by the disc. The chopper is placed near the back mirror (see Figure 6) and rotates at constant speed, moved by a PHYTRON UHV stepper motor.

The rotating velocity determines the repetition rate of the Q-switch.

Generally speaking, when the electron beam interacts with the laser pulse (stored into the cavity) its longitudi-

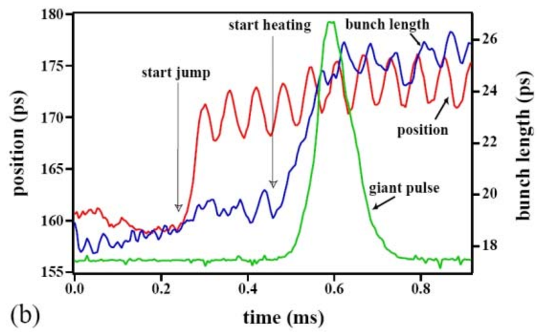

Figure 4: Analysis of the streak camera image in Figure 3. The longitudinal distributions are obtained by means of a horizontal cut of the picture.

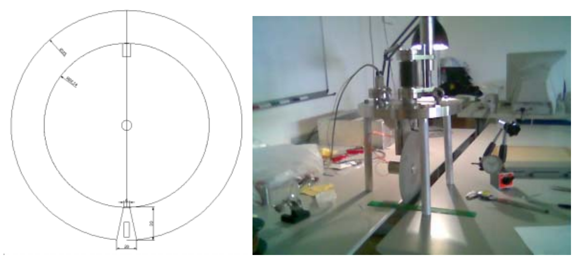

Figure 5: Left: schematic design of the metallic disc. Right: Preliminary studies in air.

nal dimensions grow up and the resulting energy spread reduces the FEL gain. The chopper allows the giant pulse creation because it prevents the electron-light interaction for a suitable time so that the energy spread reduces. This method does not generate beam perturbations and, as a consequence, higher power in the giant pulses is expected.

At the present the chopper technique can achieve only a limited repetition rate if compared to the RF modulation. Nevetheless we expect in the near future to operate the chopper at frequencies of 5 Hz or more. Furthermore, since the chopper Q-switch does not involve the RF frequency,

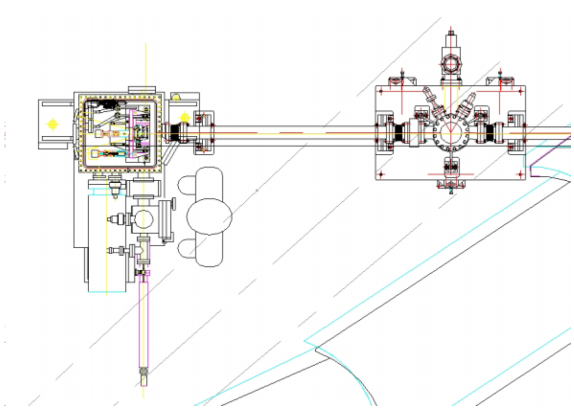

Figure 6: Schematic layout of the chopper chamber (at right), near the mirror chamber (at left).

Figure 7: Pictures of the chopper during the installation.

the latter can be used as a clock for cross-correlation measurement in order to characterize the harmonic signal.

A summary of the peculiarities of both methods is reported in Table 1.

Table 1: Chopper versus RF modulation

chopper advantages	**RF advantages**
no beam perturbation	fast transition time
chopper disadvantages	**RF disadvantages**
longer transition time	beam perturbation

Measurements and results

To compare the RF frequency modulation and the chopper Q-switch techniques, a campaign of measurement has been recently carried out using the Elettra SRFEL. Figure 8 and Figure 9 show preliminary risetime measurements for the RF modulation and the chopper case, respectively. The pictures report a train of giant pulses obtained at the same current and repetition rate. While the RF modulation method displays a quite constant level of the signal, the chopper exhibits an irregular behaviour. The reason is still under investigation.

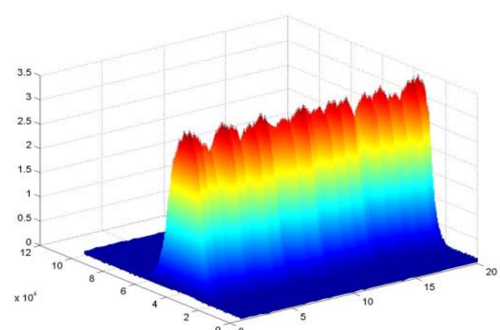

Figure 8: Sequence of 20 giant pulses, acquired by a fast photodiode, generated using the RF modulation. The electron beam current is about 10 mA and the repetition rate is 1.5 Hz

In Figure 10 we compare the two techniques for the 3 Hz case: the giant pulse risetime, calculated as a mean of 20 signals, is displayed as function of the total beam current.

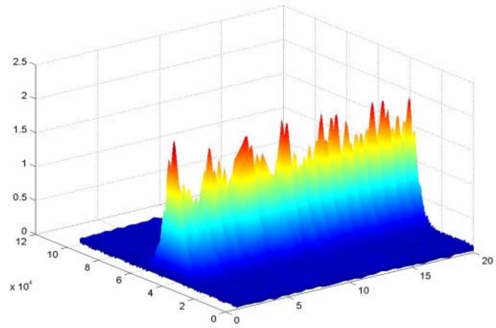

Figure 9: Sequence of 20 giant pulses, acquired by a fast photodiode, generated using the chopper Q-switch. The electron beam current is about 10 mA and the repetition rate is 1.5 Hz

For high currents the chopper and RF modulation seem comparable, while at medium-currents the chopper risetime is quite longer.

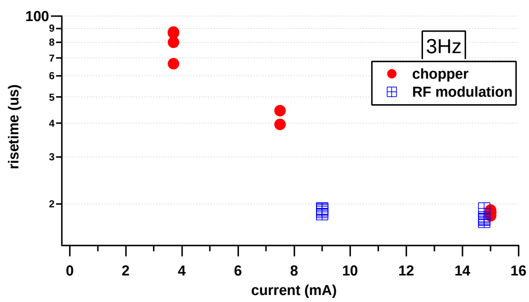

Figure 10: Comparison between chopper and RF modulation techniques, showing the risetime as a function of the total current at the same operational frequency (3Hz).

Figure 11 and Figure 12 report the risetime versus current for the RF modulation and for the chopper technique respectively. These data do not show any strong dependence of the risetime on the repetition rate.

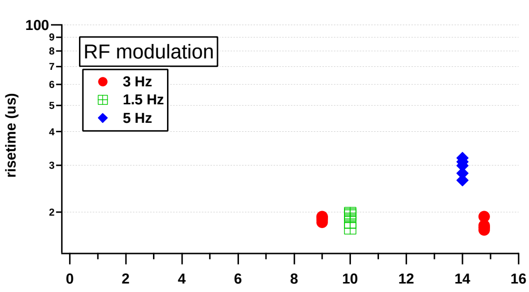

Figure 11: Efficiency of the Q-switch at different repetition rates using RF frequency modulation.

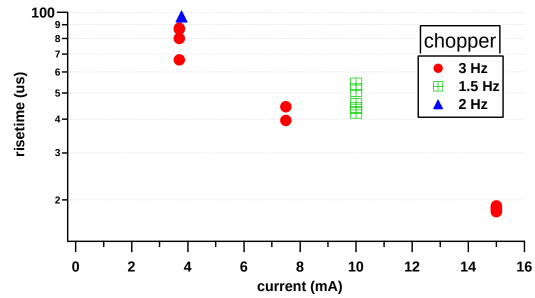

Figure 12: Efficiency of the Q-switch at different repetition rates using chopper.

CONCLUSIONS

The preliminary results presented here show the capability of the chopper method to generate giant pulses. This technique, although promising, needs more development in order to reach, and hopefully improve, the performance of the RF modulation method in terms of reproducibility and higher repetition rate.

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