SUPER-ACO FEL DYNAMICS FOR DIFFERENT EXPERIMENTAL CONDITIONS

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Abstract

In a Storage Ring Free Electron Laser, the interaction between the relativistic electron bunch and the optical wave stored in the optical cavity leads to a complex dynamics especially relying on the machine optics and on the interaction of the electron bunch with the storage ring vacuum chamber. In the particular case of the Super-ACO FEL, the dynamics is further complicated because of the harmonic cavity installed in order to increase the gain of the amplification process. The laser behaviour on the millisecond time scale depends on the difference between the repetition rate of the electron bunch in the insertion device and of the optical wave in the optical cavity : the so-called detuning. This paper aims to study the laser dynamics by changing both the setting of the rf harmonic cavity and the laser-electron bunch detuning.

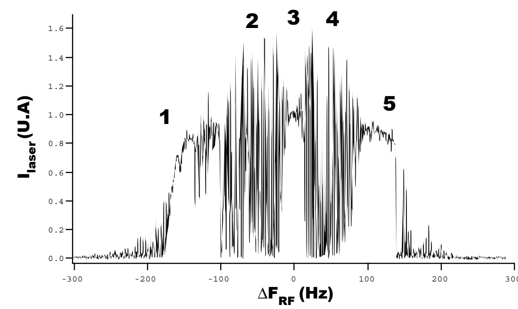

Figure 1: Detuning curve [2], i.e. laser intensity versus the detuning, taken at 58 mA with a passive harmonic cavity. At the central zone (zone 3), corresponding to a quasi-zero detuning, and for largest detuning (zone 1 and 5), the laser is " cw ". At the zone 2 and 4 the laser is pulsed at about 300 Hz. A detuning of 1 Hz corresponds to an emission displaced by 1.2 fs ahead with respect to the emission at the previous pass.

1 DETUNING CURVE

The amplication process of a Free Electron Laser (FEL) results from the interaction beetwen a relativistic electron beam and an electromagnetic wave. 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 [1].

The FEL reproduces the pulsed temporal structure of the electron beam, from which it is generated. In the Super ACO case, two electron bunches are stored in the ring, spaced out at 120 ns. At the nanosecond time scale the laser is pulsed at the pass frequency of the electron bunches in the undulator, 8.33 MHz. At the macrotemporal time scale (millisecond time scale), the laser dynamics (Cf. Figure 1) depends on the synchronisation condition between the repetition rate of the optical wave in the optical cavity and of the electron bunch in the undulator. This detuning frequency can be experimentally obtained by changing the radio frequency (rf), thus the electron revolution period.

Simulations of the detuning curves can be performed with pass to pass numerical codes [3] and semi analytical models [4], which give a qualitative agreement.

2 THE HARMONIC CAVITY

2.1 Bunch length reduction

On Super ACO, the main rf cavity at 100 MHz compensates the energy lost by the electrons at each turn in the storage ring. In 1996, a rf cavity at 500 MHz harmonic of the main rf cavity, was installed to reduce the bunch longitudinal dimension [5]. The Super ACO FEL can operate when the harmonic cavity is either passive or active. When it is active, the reduction factor of the bunch length depends on the potential of the longitudinal electric field of the harmonic cavity (Cf. Figure 2). This reduction allows an increase of the small signal gain of the laser.

2.2 Asymmetric bunch longitudinal distribution

In presence of an active harmonic cavity, the longitudinal distribution is more asymmetric [5]. The radiation from the electrons situated on the head of the electron bunch interacts with the vacuum chamber and modify the tail of the electron bunch. Consequently, the slope of the tail of the bunch longitudinal distribution is more important. The principal consequence of this asymmetry is a reduction of the pulsed zone 2.

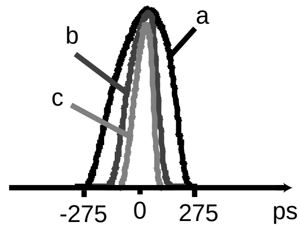

Figure 2 : Longitudinal distribution of the electron bunch with a) a passive harmonic cavity b) an active harmonic cavity at 90 kV (the reduction factor is 1.9), c) the active harmonic cavity at 150 kV (the reduction factor is 2.3). The longitudinal distribution of the electron bunch can be analysed by the moments of the distribution, which allow to deduce the main characteristics of the distribution : x_0 the center of mass, σ_τ the rms value, the skew indicating the asymmetry (equal to zero for a perfect symmetric distribution).

3 LASER CHARACTERISTICS VERSUS THE DETUNING

Figure 3 shows the evolution, versus the detuning, of the center of mass of the laser x_0, with respect to the bunch one. The behaviour of x_0 is similar to an arctangent function. For smaller detuning, the variation is more important, and for larger detuning, the position practically doesn't change anymore. For 1 Hz of detuning, x_0 is around 25 ps. This feature gives a precise measurement of the perfectly synchronised laser operation, whose knowledge is required as a reference for the longitudinal feedback system installed on the Super ACO FEL [6]. The latter obliges the laser to stay in zone 3 for users experiments. The curve on figure 3 shows the asymmetry of the longitudinal bunch distribution. In the case with rf cavity voltage of 90 kV, the laser is switched off at –40 Hz and 60 Hz, and the position variation is more important for positive detuning. The same observation can be made with a rf voltage of 150 kV, but the variation of x_0 is less important because of the smaller bunch length.

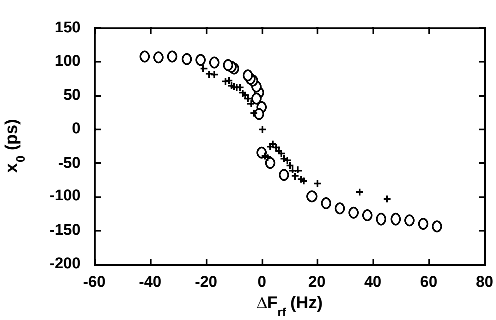

Figure 3 : Laser center of mass versus the detuning taken at 30 mA, with the active harmonic cavity at **o**) 90 kV, +) at 150 kV.

The detuning curves on figure 4 with an active harmonic cavity show clearly the effect of the asymmetric bunch longitudinal distribution on the laser. For a potential of 90 kV of the harmonic cavity, the laser in zone 2 is no longer pulsed as with the passive harmonic cavity case, but it is modulated, i.e. the laser intensity versus time follows a sinusoidal function without being switched off. In this case, the zone 2 is only reduced for a potential of 150 kV of the harmonic cavity.

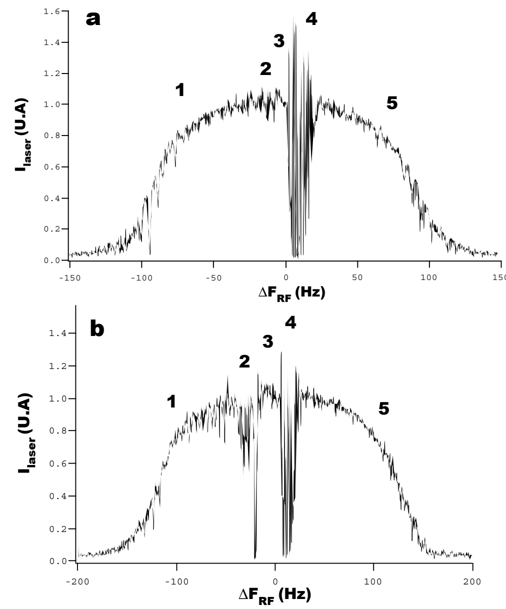

Figure 4 : Detuning curves with the active harmonic cavity a) at 90 kV taken at 32 mA b) at 150 kV taken at 31 mA.

The rms laser pulse width increases with the detuning, and it is smaller for a voltage of 150 kV in the harmonic cavity as shown on figure 5.

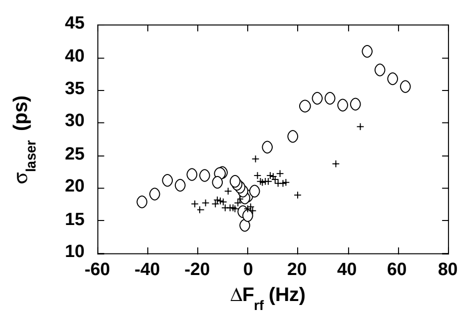

Figure 5 : Laser pulse width versus the detuning taken at 30 mA with the active harmonic cavity **o**) at 90 kV, +) at 150 kV.

4 BEAM CHARACTERISTICS VERSUS THE DETUNING

Figure 6 illustrates the electron beam heating versus the detuning. In the laser-electron beam interaction, an energy exchange takes place, leading to a "heating" of the electron bunch in which the energy spread and the bunch longitudinal distribution are larger at laser saturation [7]. The bunch lengthening induced by the FEL heating decreases with the detuning. In figure 6, the bunch length enhancement due to the FEL saturation is about 20 % in the two rf voltages cases. The electron bunch heating by the laser is much more important when the laser intensity is higher and the pulse width is smaller, thus in the central zone.

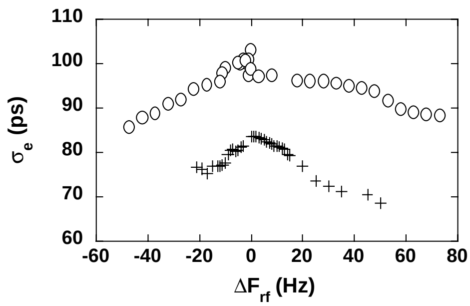

Figure 6 : Behaviour of the bunch length versus the detuning taken at 30 mA with the active harmonic cavity **o**) at 90 kV, +) at 150 kV.

In addition to the FEL induced bunch length, a modification of the shape of the electron beam takes place during the laser interaction [8]. Figure 7 illustrates the change of asymmetry of the electron bunch induced by the FEL [9]. The FEL reduces the asymmetry of the electron bunch longitudinal distribution, which comes back to a more symmetric distribution for perfect tuning whatever is the rf voltage. In consequence, the laser is in competition with the potential well distorsion and the microwave instability [10]. The laser can be considered as an instability itself, which competes with the longitudinal instabilities, changing the behaviour of the electron beam. The effect is less pronouced for larger detuning, and one observes then a more asymmetric shape for 150 kV with respect to 90 kV, because it results from the combined effect of the FEL, the microwave instability and the potential well distortion.

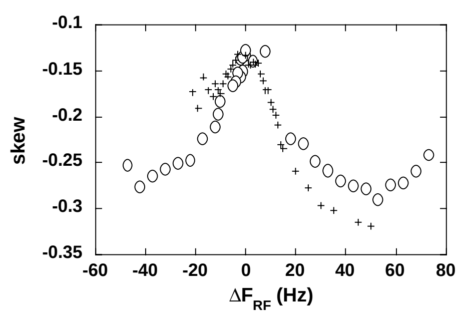

Figure 7 : Skew of the longitudinal distribution of the bunch versus the detuning taken at 30 mA, indicating the asymmetry with the active harmonic cavity **o**) at 90 kV, +) at 150 kV.

The FEL induced heating determines the laser power [7]. It is proportional to the square difference between the energy spread when the laser is established σ_{on} and the energy spread without laser σ_{off}. In order to evaluate σ_{off}, one can consider either its value taking into account the microwave instability, or the energy spread at zero current considering that the microwave instability is damped by the FEL itself. The experimental value of the power is ranging between the two extreme cases.

5 CONCLUSION

Because of the beam interaction with the vacuum chamber and the presence of the harmonic cavity, the bunch longitudinal distribution is asymmetric. The laser dynamics versus the detuning is also asymmetric, allowing a modulated laser in zone 2 instead of a pulsed laser.

In addition, the storage ring FEL heating competes with the microwave instability, leading to a complex coupled laser beam dynamics. The FEL could even be considered as a feedback on the microwave instability.

6 REFERENCES

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