THE SUPER-ACO STORAGE RING FREE ELECTRON LASER OPERATING WITH AN HARMONIC RF CAVITY

M. Billardon, ESPCI, Paris, France, M.-E. Couprie, L. Nahon, D. Nutarelli, LURE - CEA/SPAM, Orsay, France, B. Visentin, CEA/LNS, Saclay, France, A. Delboulbé, G. Flynn, R. Roux, LURE, Orsay, France

Abstract

The Super-ACO Storage Ring Free Electron Laser (SRFEL) so far operates in the Ultra-Violet with a 100 MHz cavity at 800 MeV. With a recently installed 500 MHz harmonic cavity, properly tuned with respect to the main cavity, the bunch is shortened by a factor 2 (150 kV) to 3.5 (280 kV), but can be rather instable (sawtooth instability at 200 - 800 Hz, phase oscillations in longitudinal space and vertical excitation that can be partially damped with a high chromaticity). The SRFEL operation stabilizes both the longitudinal and vertical instabilities. A reasonably "stable" SRFEL is achieved with 90 - 175 kV, with a twice bigger tunability and higher output power.

INTRODUCTION

The Super-ACO FEL source has been the first storage ring FEL to provide coherent radiation for users in the UV, since 1993 [1,2]. Extensive studies on FEL dynamics have been carried out, allowing to improve the stability of the source for users [3].

The interaction between an electron bunch and a light pulse, which governs the FEL amplification process, requires temporal synchronisation between the electrons stored in the ring and the photons propagating in the optical cavity, called detuning. Apart for the micro-temporal structure, reproducing that of the electrons circulating in the ring at a high repetition rate, different temporal behaviours appear versus detuning: around perfect tuning and for large desynchronisation, the laser is "cw", whereas for intermediate detuning the laser is pulsed at a millisecond range (cf. Table 1). In the central tuning range, where the FEL exhibits the smallest temporal and spectral widths, the FEL can present a temporal jitter, a spectral drift, and intensity fluctuations, limiting the stability of the source for users. The jitter however, is routinely reduced for user applications by using a longitudinal feedback on the laser micropulse position [4]. The FEL operation, and influence on the beam is then analyzed in the second section. Finally, the first results concerning the improvements of the FEL performances are presented, such as an enhancement of the tunability, an increase of the laser power and short FEL micropulses.

Table 1: laser and electron beam characteristics operating with the 100 MHz cavity alone.

Laser	rise-time (μs)	FEL natural frequency (Hz)
	20 - 100	300 - 400
e-beam	damping-time (ms)	sync. freq. (kHz)
	10	14

Whereas the Super-ACO FEL first user applications were successfully carried out exploiting its coherence and high stability, the limited gain (less than 2 %) prevented further improvements of the FEL source. As a modification of the undulator, shared with synchrotron radiation users, was impossible; the solution was to shorten the bunch length with an harmonic RF cavity [5]. The enhancement of the gain is described in the first section.

1 ENHANCEMENT OF THE GAIN

For the Super-ACO FEL, the small signal gain is deduced from the J. M. J. Madey theorem [6]. The gain depends on the electron beam features and on the FEL insertion device (optical klystron in the Super-ACO case). But for the operation with the 500 MHz cavity, the main issue is the dependance of the gain with the electronic density and the energy spread that could not be modified [7]. So, the operation with the 500 MHz cavity leads to a reduction of the bunch length, therefore the gain is increased. In order to evaluate the latter, measurements of the bunch length were performed using a double sweep streak camera [8], and the energy spread was deduced from the optical klystron spectrum measurements [9], versus the current stored in the ring.

As the 500 MHz RF harmonic cavity properly tuned reduces the bunch length by a factor 1.7 to 3.5 depending on the RF voltage and on the stored current, we expect a gain enhancement of the same factor with respect to the 100 MHz RF cavity alone.

Nevertheless, measurements with the double sweep streak camera show the presence of several types of electron bunch instabilities which probably reduce the laser gain (explanations in the following section). On short time scales (200 μs), very different aspects of the bunch are periodically observed : partially coherent phase oscillations (fig. 1a), quadrupolar and hexapolar coherent synchrotron oscillations and stable beam. These instabilities are stronger for higher 500 MHz voltage, and the bunch distribution is further split in to several parts as in figure 1a while normal coherent synchrotron oscillations are rather observed at low voltage. In addition, for a given voltage, periodic bunch aspect (instabilities, lower amplitude instabilities, stable beam) are also observed. In addition, at longer time scales (50 ms), the electron beam shows sawthooth type instabilities at low frequency (fig. 1b). The analyse of the figure 1b shows that the electron bunch length quickly increases with an exponential growth rate of approximately 1 ms, reaches a maximum and then decreases with an exponential time decay of 4 ms. Moreover, the average bunch position adopts a similar behaviour. Besides, as in short time scale instabilities, the amplitude of sawtooth instabilities increases for higher 500 MHz cavity voltage and their frequency can spread over 50 up to 400 Hz. Comparing bunch longitudinal behaviours on the two different time scales, it seems that the bunch, strongly perturbated, performs either coherent or partially coherent synchrotron oscillations modulated at a low frequency describing a sawtooth form. These e-beam instabilities lead to a variation of the longitudinal position and bunch length (figure 2), this can affect the laser gain and behaviour, as described in the next sections.

In addition, vertical excitations are observed above 10 mA, and can be damped with a high chromaticity.

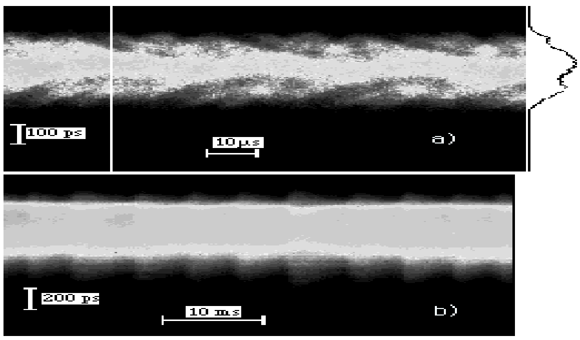

Figure 1. The e-beam temporal profile evolution acquired with a double sweep streak camera.
a)Partially coherent phase oscillations. The acquisition corresponds to a 500 MHz voltage of 175 kV.
b) Slow sawtooth instability at about 200 Hz. The acquisition corresponds to a 500 MHz voltage of 180 kV.

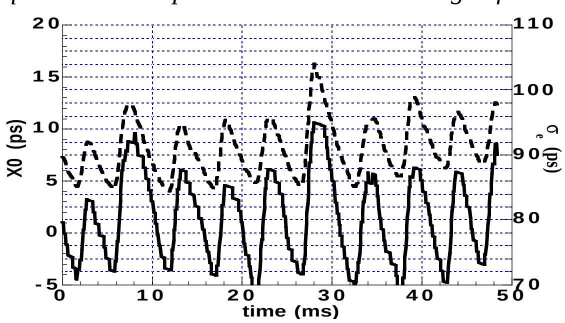

Fig 2. Temporal evolution of the centre of the bunch (full line) and of the bunch length (dashed curve) obtained from a double sweep streak camera image. In both profiles the sawtooh instability is visible (at about 300 Hz). The profiles correspond to a 500 MHz voltage of 180 kV.

2 FEL AND E-BEAM STABILITY COUPLING

Let's first analyse how these instabilities can affect the laser start-up and its equilibrium.

2.1 Influence of the e-beam longitudinal instabilities on the laser

Rapid bunch movements such as coherent phase oscillations (at the synchrotron frequency and its harmonics) can lead to a gain reduction and somehow prevent the FEL start-up.

Since the variation of the shape and position of the electron bunch is rapid compared to the laser risetime (see table 1), the laser roughly sees a gain averaged over several periods of the synchrotron oscillations, leading to a reduction with respect to the initial value. The situation is probably more complex with the type of instabilities observed with the 500 MHz cavity, but, in first approximation, one can still consider that the laser gain can be evaluated considering the RMS values of the bunch distribution (evaluated here with the moment's method).

In addition to the effect on the gain, the long time scale instabilities can also affect the laser stability. Figure 3 shows the correlation between a perturbation on the e-beam and the laser time and intensity fluctuation. The laser generally establishes at perfect synchronism with damped oscillations of relaxation [10]. A sudden change of the bunch longitudinal profile drives the laser to an oscillating regime, or even the laser stops (between 32 and 40 ms in fig. 3), and the laser starts again in its oscillating regime when a shorter bunch length is restaured (after 42 ms).

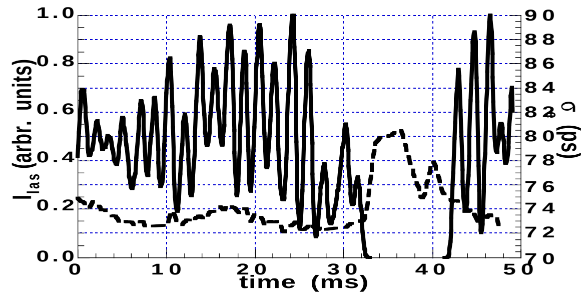

Figure 3. Temporal evolution of the laser intensity (full line) and of the bunch length (dashed curve). The profiles are obtained from a double sweep streak camera image for a 500 MHz voltage of 185 kV. The stability of the laser is clearly affected by the bunch length variations.

2.2 The laser action on the e-beam instabilities

When the laser succeeds to oscillate in spite of the longitudinal instabilities, it modifies the longitudinal bunch distribution because of the heating process (energy exchange between the optical wave and electron bunch, resulting in the laser saturation). As previously observed, the laser establishment systematically damps the quadrupolar modes of synchrotron oscillations, as shown in fig. 4. The FEL induced stabilization also occurs in the millisecond time scale as shown in fig. 5, where the sawtooth profile is suppressed.

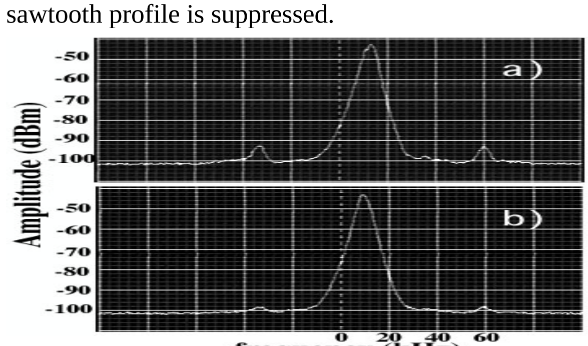

Figure 4: Quadrupolar coherent synchrotron oscillations (50 kHz) in a) FEL off. In b), FEL on, coherent modes are damped.

In addition, in the temporal space, analysis of a double sweep streak camera image (figure 5) shows that sawtooth instability is damped by the FEL with respect to the case FEL off.

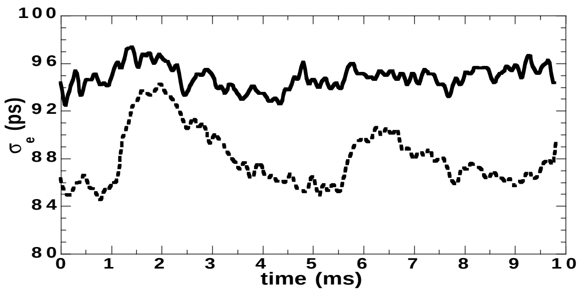

figure 5 : analysis of double sweep streak camera image : bunch length (σ_e) versus time acquisition, 500 MHz cavity voltage = 90 kV, I = 47 mA, FEL off, presence of the sawtooth instability (dashed line), FEL on (plain line), the bunch length, enhanced by the laser heating, stays stable.

In addition, the FEL also stabilizes the beam vertical excitations. Consequently, the FEL dynamics in interaction with the electron beam is very complicated.

3 NEW FEL PERFORMANCES

The FEL benefits from a higher gain (factor 2) for a 150 kV voltage of the 500 MHz cavity. Considering a given set of mirrors (for a given transmission and spectral bandwidth), the FEL spectral tunability is increased by a more than a factor 2 and a higher transmitted power (see figure 6) was obtained, the laser output power depending on the gain over losses ratio.

In addition, the temporal behaviour is roughly equivalent to the well known one with the 100 MHz cavity (detuning curve for example, though the widths of the different zones are modified, according to the more disymetrical and narrow profile of the electron bunch distribution). However the laser stability can be very easily affected by the different types of instabilities. The FEL was nevertheless operated with a high stability for users, by applying carefully the FEL longitudinal feedback monitoring in its central tuning region.

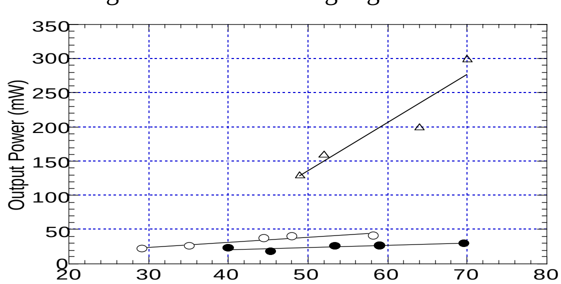

figure 6 : average laser extracted power versus the total current stored in the ring. •, 100 MHz, T = 0.018 %, ❍, 500 MHz, T = 0.018 %, triangle, 500 MHz, T = 0.11 %.

Thus, the FEL narrowing process [7] can proceed so that short FEL pulse duration (25 ps FWHM) and narrow line width (0.24 Å FWHM) were achieved with the FEL longitudinal feedback, allowing to be very close to the Fourier limit. A very stable operation of the FEL is nevertheless much more difficult to achieve at very high voltage of the 500 MHz cavity, where the competition between the instabilities and the laser heating is very strong.

As a consequence of the laser gain enhancement, the FEL can be operated with new sets of mirrors. More transmitting mirrors allowed the FEL transmitted power to be extended up to 300 mW, which is the highest average power ever obtained with a storage ring FEL (see figure 6).

In the future, mirrors with different spectral bandwidth will be installed, in order to obtain the FEL at shorter wavelength, while still maintaining reasonable output power.

4 CONCLUSION

The operation of the Super-ACO FEL with a 500 MHz harmonic cavity allowed the bunch length to be shortened by a factor up to 3.5, though various types of instabilities occur (partially coherent synchrotron oscillations and longitudinal sawtooth instabilities and vertical excitations). Nevertheless, gain is increased in spite of these complex instabilities, the FEL can be operated for users with a high stability using its own feedback system, for intermediate voltages of the 500 MHz cavity. In addition, the FEL stabilizes both the longitudinal and vertical beam instabilities, demonstrating new FEL dynamics under complex beam evolution.

5 REFERENCES

[1] M. E. Couprie, P. Tauc, F. Merola, A. Delboulbé, D. Garzella, T. Hara, M. Billardon *Rev. of Scient. Inst.*, **65** (5)1485-1495 May 1994

[2] "Time dependence of the FEL-induced surface photovoltage on semi-conductor interfaces measured with synchrotron radiation photoemission spectroscopy" M. Marsi, R. Bakker, M. E. Couprie, A. Delboulbé, D. Garzella, T. Hara, G. Indlekofer, L. Nahon, A. Taleb-Ibrahami, M. Billardon 2nd FEL user workshop 1995 New York

[3] “Dynamics of the Super-ACO FEL measured with a double sweep streak camera”, R. Roux et. al, European Particle Accelerator Conference 96 proceedings.

[4] M.-E. Couprie et. al, NIMA 358 (1995) 374-377.

[5] G. Flynn *et. al*., "A New 500 MHz Fifth Harmonic RF System for Super-ACO", This conference.

[6] J.M.J. Madey, H.A.Schwettman and W.M.Fairbank *IEEE Tans. Nucl. Sci.* 1973 **20**, 980-983

[7] “Temporal dynamics of storage ring free electron laser”, M.-E. Couprie, T. Hara, D. Gontier, P. Troussel, D. Garzella, A. Delboulbé, and M. Billardon, Phys. Rev. E V. 53, N° 2 february 1996

[8] “The Super-ACO FEL dynamics measurement with a streak camera”, R. Roux, M.E. Couprie, T. Hara, R. J. Bakker, B. Visentin, M. Billardon, J. Roux, NIMA 393 (1997) 33 - 37.

[9] Phase-Space Distribution in a Storage Ring : Influence of the Beam Current and the Compaction Factor”, R.-J. Bakker et. al, European Particle Accelerator Conference 96 proceedings.

[10] Thèse T. Hara "Etudes du laser à électrons libres de courtes longueurs d'onde et de ses applications" July,12, 1995, Université de Paris-Sud