Relation between the Super-ACO Storage ring Free electron laser and the longitudinal characteristics of the positron beam

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Abstract

The Super-ACO storage ring Free Electron Laser FEL has been operated in the visible with two opposite bunches stored at 600 MeV since 1989 in Orsay (France).

The positron beam stability acts on the FEL operation : the laser threshold is modified with synchrotron coherent oscillations ; the FEL temporal structure at the ms range besides being continuous can be pulsed, or chaotic, resulting from a small gain modulation due some ring instabilities ; a proper Q-switched FEL obtained by modifying the RF frequency and thus the laser tuning curve requires the response of the beam to an RF excitation to be studied.

In addition, the FEL establishment changes the stored bunches : it damps the synchrotron coherent modes of oscillation and modifies the longitudinal bunch distribution, creating a competition between a enhancement due to the laser interaction and the phenomena responsible for the synchrotron coherent motion.

Several methods of measurement are used : a spectrum analyser, a dissector (ps detector) for the longitudinal bunch distribution and the phase oscillation, the temporal evolution of the fringes of the optical klystron spectrum for the energy spread.

1. INTRODUCTION

The Super-ACO Free Electron Laser (FEL) operates since 1989 in the visible and recently in the near UV range at 600 MeV, with two stored positron bunches [1]. The constituting elements are listed in table 1. The FEL has been operated between 500 and 650 MeV, with one or two stored bunches during 3 (resp. 0.8) hours at 650 (resp.500) MeV at 630 nm. The achievable tunability at this wavelength is of 780Å at 10 mA/bunch, with a linewidth of 1.2 Å. Several transverse modes TEM_{0n} were observed up to n=5 [2]. The total extracted power at 110 mA is 290 mW. It has also been successfully operated at 350 nm recently in october 1991. One can distinguish two ranges of temporal structures :

- the microtemporal one, resulting from the revolution of the bunches in the storage ring. The laser amplification takes place at the maximum of the electronic density, so that the laser micropulses (around 50 ps) are shorter than the positron bunches, their spacing is identical (120 ns) [3].
- the macro-temporal one, generally seen on storage ring FELs such as on ACO[4], VEPP3[5] and TERAS[6]. It results from a kind of oscillations of relaxation at the ms range. Nevertheless, they were not always seen on the Super-ACO FEL, and a "continuous" structure was recorded. This allowed a gain modulation to be performed, putting in evidence its chaotic behaviour [7].

Finally, The FEL is very sensitive to the coherent synchrotron oscillations, as is going to be developped further.

Table 1
The Super-ACO FEL constituting elements

The storage ring Super-ACO at 600 MeV	
current /bunch (mA)	50
energy spread	$6\ 10^{-4}$
transverse sizes (µm)	300
longitudinal size (ps)	90-300
RF frequency (MHz)	100
RF voltage (kV)	140-200
The optical klystron	
undulator period (cm)	12.9
number	2x10
deflection parameter K	0-5.75
dispersive section length(m)	0.5
The optical cavity	
length (m)	18
dielectric mirrors	Ta_2O_5/SiO_2
Gain at 600 MeV for 630 nm (%)	
for I<8mA/bunch	I(mA)/4
for I>8mA/bunch	2

2. METHODS OF MEASUREMENT

Several methods of measurements are used in order to study the beam stability.

2.1 the spectrum analyser

First, a spectrum analyser (MARCONI) is recording the signal from a pick-up station collecting the signal emitted by the positron beam. It shows the spectrum of harmonics of the revolution frequencies. When it is centered around a given harmonic, it displays in the sidebands the synchrotron frequencies (at around 17 kHz at 600 MeV for the dipolar mode, at roughly twice this frequency for the quadrupolar modes, and three times for the hexapolar mode).

2.2 the dissector

The dissector is a high speed phenomena detector using a stroboscopic method of electro-optical chronography developped by E. I. Zinin [8]. The optical pulsed signal (synchrotron radiation, FEL) is projected onto a photocathode. The emitted electron pass through deflection plates on which is applied a RF deflection voltage strongly synchronised with the luminous signal (from the RF cavity of the storage ring). The electron are then collected after a slit by a system of amplifying dynodes. The signal collected on the anode is proportional to the electronic density passing through the slit at a given moment. With a low frequency sweeping voltage added on the plates, the entire distribution can be scanned, as shown, after analysis, in Fig.

1. Without the sweeping voltage, the temporal response of the signal through the slit allows the synchrotron motion to be followed in the temporal space.

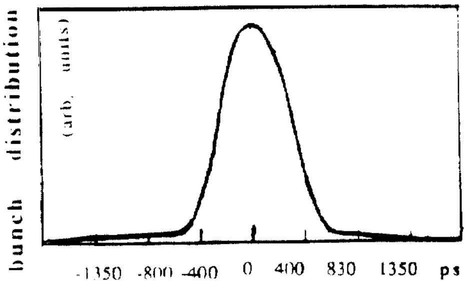

Figure 1 : the electron bunch distribution measured with the dissector

2.3 the optical klystron spectrum

The spectrum of the optical klystron results from the interference of the radiation emitted by the two undulator, leading to a sytem of fringes, which envelopp is given by the radiation from one undulator [9]. The equivalent of the optical contrast for two Young slits is here the modulation rate, depending versus the energy spread σ_γ/γ as :

$$f = f_o \exp\left\{- 8 \pi^2 (N + N_d)^2 (\sigma_\gamma/\gamma)^2\right\}$$

with N the number of periods of one undulator, and N_d the interference order due to the dispersive section. When a monochromator is set-up at half width of a fringe of the optical klystron, it is then possible to record temporally any variation on the energy spread throught the evolution of the fringe signal.

3. ACTION OF THE POSITRON BEAM STABILITY ON THE FEL

The operation of the FEL is conditionned by the stability of the positron bunch. On Super-ACO, the coherent synchrotron modes of oscillations depend on the ring current, and are reproducible from one experiment to another. The dipolar modes of oscillations are counteracted by a longitudinal feedback system, based on a method developped by Pedersen at CERN [10]. For high currents (above 90 mA in two bunches), hexapolar modes of synchrotron oscillations and odd harmonics of the revolution frequency are strong. Below 90 mA, the hexapolar modes are changed into intense quadrupolar modes ; they get damped when the current decreases and around 50 mA, they become intermittent. Below 50 mA, the positron beam is generally stable.

Such a behaviour is obversed for various energies, between 600 MeV and 800 MeV. The adjustment of the RF cavity is very critical (feeder, temperature...). In presence of strong modes of synchrotron oscillations, the optical signal emitted by the positrons passing in the optical klystron is very noisy.

3.1. The laser threshold

It was observed experimentally that the laser can not start when the hexapolar or quadrupolar modes of oscillations are too strong. If the strength of the synchrotron oscillation is reduced, the laser can build up. It can however stop to operate if the synchrotron oscillations become more intense. Theoretically, this can be easily understood taking into account the laser threshold and establishment. Without beam instabilities, below saturation, the intensity grows exponentially as exp(kt) with

k=(gain - losses) / round trip time.

The threshold condition is k>0, that is gain > cavity losses. The laser generally develops in the center of the electronical density distribution (usually gaussian) where the gain is maximum. Let assume now that some instabilities are present, such as coherent synchrotron modes of oscillations. The longitudinal distribution seen by the optical pulses travelling inside the optical cavity is no longer gaussian, the maximum electronical density is modified : its value is reduced and its center can be displaced. Consequently, the synchronism condition between the optical pulses in the optical cavity and the positron bunches is modified, and the gain is reduced. The laser threshold can not be always reached. A detailled derivation of the equations and the threshold condition is given in [11].

3.2 The macro-temporal structure

The macrotemporal structure can be understood with three coupled non linear equations, describing the evolution of the normalized laser intensity I, the positron bunch normalized energy spread σ and the gain g, as :

$$\frac{dI}{dt} = k\, t + I_{spont.}$$

$$\frac{d\sigma^2}{dt} = - \frac{2}{\tau_s}\left(\sigma^2 - \sigma_o^2\right) + \alpha I$$

$$g = g_o \exp\left\{- \beta\left(\sigma^2 - \sigma_o^2\right)\right\}$$

The index o refers to the initial state, τ_s is the synchrotron damping time. The energy spread increases with the laser intensity, which induces consequently a reduction of the gain ; leading to the laser stop if the gain becomes lower than the cavity losses. In addition, the energy spread is damped with the synchrotron damping time (a few ms), so that when the energy spread relaxes sufficiently, the gain increases in order to reach the threshold and the laser can start again. This can explain the pulsed macro-temporal structure on storage rings FELs. With a stable beam, a "continuous" macro-temporal structure can be obtained, as for the Super-ACO case. Then, one can add artificially a small gain modulation in order to simulate some instabilities. This has been performed experimentally and theoretically on the equations given above [7], putting in evidence a deterministic chaotic behaviour (with alternances of 1T, 2T, 3T,4T, T/2 regimes and chaos). Several sources of gain modulation are possible. It might be either the coherent synchrotron modes of oscillations, and experimentally the macro-temporal structure is generally pulsed when the laser operates for a current range where these modes of oscillations are present. It can be also some noise on power supplies, bringing to some pulsed structure on harmonics or subharmonics on the line. In fig. 2 is shown an example of a double modulation of the temporal strcture at 250 Hz (5x50 Hz) and 17 Hz (50 Hz/3).

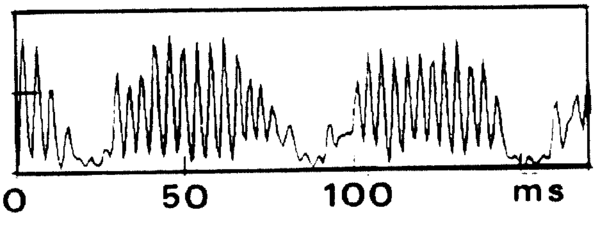

Figure 2 : example of the Super-FEL macro-temporal structure : double modulation due to line instabilities

3.3 The Q-switched FEL

In order to take advantage of the pulsed macro-temporal structure of the FEL, It is desirable to artificially kill the gain, for the laser to be Q-switched. Several methods can be employed, as mechanical change of the position of a mirror with a piezo-electric device, a rapid kick of the transvers position of the positron beam or a frequency modulation modifying the synchronism between the positron and the optical pulses. This last method is nevertheless not so simple to operate, because an RF jump can induce some coherent motion on the stored beam, as it is shown in Fig.3 recorded with the help of the optical klystron spectrum. Only under specific conditions, the positron beam can remain stable.

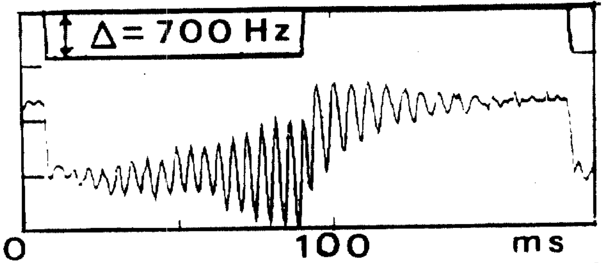

Figure 3 : Response of the positron beam of Super-ACO to an RF frequency jump : some coherent modes of oscillations are induced

4. ACTION OF THE FEL ON THE STORED BEAM

4.1 on the coherent synchrotron oscillations

The establishment of the laser systematically damps the synchrotron modes of oscillations. An example is given in Fig. 4, recorded on the spectrum analyser : the synchrotron sidebands disappear with the lasing. Consequently, the laser can build up when the quadrupolar modes of oscillations are fluctuating : it starts during a short period of time when they are rather low, and then, the lasing suppresses those oscillations. The laser stabilizes the positron bunches and acts as a feedback system on them.

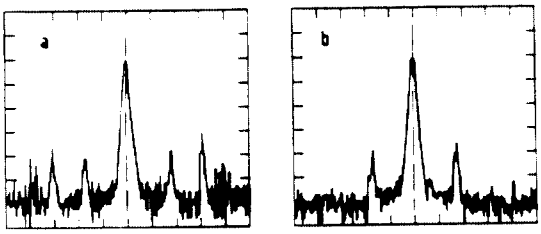

Figure 4 : Suppression of the synchrotron sidebands on the spectrum analyser due to the establishment of the laser (in (a) without laser and in (b) with laser).

4.2 on the longitudinal bunch distribution

The FEL interaction is known to lead to the "bunch heating" phenomenon, that is an increase of the energy spread and consequently the longitudinal bunch length, for tha assumption of gaussian distributions. In the case of a storage ring FEL, it becomes more complicated because there is a competition between the phenomenan responsible for the coherent motion and the bunch lengthening due to the laser. Consequently, several situations can be observed, as even a bunch shortening or a no modification of the length. This can be understood with the previous results, because the laser interaction can suppress the coherent modes of oscillations, and then change the dominant cause of bunch lengthening. The laser really transforms the longitudinal distribution of the bunches.

5. CONCLUSION

In order to understand the dynamics of a storage ring FEL, one has to take into account a global scheme including the "heating" due to the FEL, the bunch lengthening and the mutual influence between the laser and the positron beam. There is a complicated link between the dynamics of the beam in the storage ring, and the loops acting on the beam itself such as the longitudinal feedback, the FEL...

6. REFERENCES

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