SUPER-ACO ELECTRON BEAM DYNAMICS WITH A REDUCED MOMENTUM COMPACTION FACTOR FOR FREE ELECTRON LASER OPERATION

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Abstract

After the demonstration that the Super-ACO storage ring can be operated with emittance close to its minimum theoretical value, the new optics revealed to be interesting also for the Free Electron Laser (FEL). This optics is characterized by a reduced momentum compaction factor and by a non-zero dispersive function in the FEL section. It should allow to better point out some interesting features of the laser-electron beam interaction and could provide a new reliable working point for the FEL operation. This work intends to report about the detailed experimental study of the Super-ACO FEL in the new operation mode.

1 INTRODUCTION

Free Electron Lasers (FELs) are coherent and tunable light sources. A relativistic electron beam passing through the periodic permanent field of an undulator emits synchrotron radiation with wave-length

$$\lambda = \frac{\lambda_o}{2\gamma^2}\left(1+\frac{K^2}{2}\right), \qquad (1)$$

$K = \frac{e\lambda_o B_o}{2\pi m_e c}$ being the undulator deflection parameter with m_e and e respectively the mass and the charge of the electron, γ the Lorentz factor, c the light velocity, B_o the amplitude of the sinusoidal magnetic field of the undulator and λ_o its spatial period. Under given conditions, the light and the electron beam interaction can lead to the light amplification with spectral and temporal narrowing to the detriment of the electron kinetic energy and it results in the laser effect. The FEL small signal gain is proportional to the inverse of the electronic density. In the oscillator configuration an optical resonator, whose length corresponds to the temporal interval between two successive bunches, is used to store the light pulse. Besides, when the FEL is implemented on a Storage Ring, an optical klystron is used [1]. It consists of two identical undulator separated by a dispersive section, creating a large wiggle of magnetic field allowing the radiation of the two undulators to interfer and the FEL gain to be enhanced.

At saturation, the gain reaches the optical cavity losses and the laser-electron beam interaction leads to an increase of the energy spread σ_γ/γ, the so called "bunch heating". Due to the synchrotron motion, electrons oscillate longitudinally inside the bunch at a frequency which is proportional to the square root of the momentum compaction factor α. This means that α controls the phase space refreshment taking place during the laser onset [2,3].

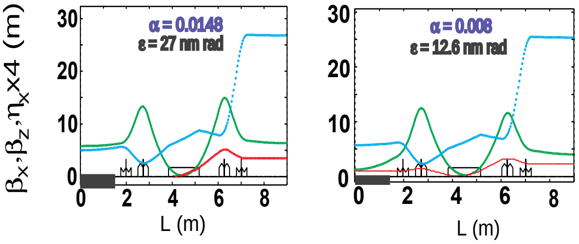

Fig.1 Super-ACO half cell beam optics with nominal and reduced α (red: η_x dispersion function; green: β_x horizontal betatron function; blue : β_y vertical betatron function)

The momentum compaction factor α is defined as the ratio of the relative variation of the longitudinal path and the corresponding relative variation of the energy. Typical operation point of the Super-ACO positron storage ring (see Tab.1) is $\alpha=0.0148$. A new operation regime for Super-ACO has been recently designed and tested [4] in order to achieve the minimum emittance ε. Such different machine set-up offers therefore the interesting possibility to study the temporal evolution of the laser micro-pulse at a different time scale [3,5]. The characteristics of the Super-ACO FEL are reported in Tab.2.

2 SUPER-ACO OPTICS WITH LOW ALPHA

The lattice structure is composed by 8 dipoles and 4 families of quadrupoles with sextupolar corrections. The lattice configuration set-up (fig.1) for $\alpha = 0.0148$ foresees an horizontal dispersion function η_x alternatively zero and non-zero along the straight sections. The FEL optical klystron being located in a free dispersion straight section, the longitudinal and transverse FEL dynamics can be considered in first approximation as decoupled. The Super-ACO optics [4] with a reduced momentum

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compaction factor ($\alpha = 0.008$) presents a non-zero dispersion function in the straight sections (fig.1).

Tab.1. Main Super-ACO storage ring characteristics: beam energy 800 MeV, revolution period 240 ns, 100 MHz RF cavity voltage 170 KV. Horizontal and vertical tunes ν_x and ν_y. Beam transverse dimension (σ_x,σ_y) at the center of the optical klystron.

α	0.0148	0.008
ε_x,ε_y(nmrad)	18,18	6.3,6.3
β_x,β_y(m) betatron functions	5.4,5.4	1.2,5.8
η_x(m)	0	0.26
ν_x,ν_y tunes	4.720,1.698	5.781,1.768
σ_x,σ_y(μm)	389,387	165,191
f_s(kHz)	14.3	10.5
σ_τ(ps) (theor.)	85	62
$\sigma\gamma/\gamma$ (theor.)	5.4 10^{-4}	5.4 10^{-4}

3 BEAM CHARACTERISTICS MEASUREMENTS AND GAIN OF THE LASER

The low-α regime of the Super-ACO storage ring implies a modification of the usual longitudinal and transverse dynamics of the FEL (cf.Tab.1). Indeed, the synchrotron motion characterized by the frequency f_s, responsible of the electron refreshment taking place with the FEL heating, is modified and it can result in a different FEL dynamics [5]. Moreover, because of the non zero value of the dispersion function η_x in the straight section where the optical klystron is located, the horizontal rms dimension σ_x is sensibly affected by the energy spread heating.

In SuperACO the rms longitudinal bunch length σ_τ is measured versus the stored current by means of a double sweep streak camera. The measurement of the rms transverse size (σ_x,σ_y) of the positron bunch is performed by measuring by means of a CCD camera the synchrotron light pulse emerging from a dispersive portion of the positron orbit in a bending dipole. By the knowledge of the emittance and of the lattice optics in that orbit portion, the rms energy spread value σ_γ/γ can also be inferred by the horizontal beam profile acquired by the CCD camera [6,7].

Fig.2 shows the measured bunch length σ_τ versus the current I stored for the nominal and low α regimes. At quasi zero current the experimental values of σ_τ and σ_γ/γ corresponds to the theoretical ones (see Tab.1). The bunch length evolution versus I shows a growth which is dominated by microwave instability and potential well distorsion [8,9]. Nevertheless, the bunch lengthening is smaller in the low α case at low current. The energy spread shows a similar growth versus current in both cases.

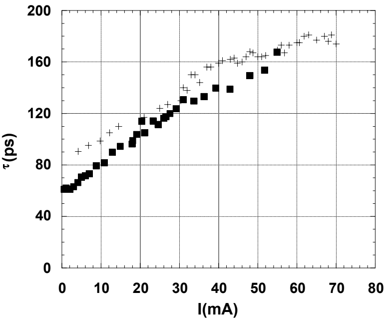

Fig.2 For nominal (+) and low α conditions, behaviour versus current of the bunch length (σ_τ).

This optics can be used for FEL operation. The small signal gain evaluation, in the optical klystron case, can be performed using the following relationship [10,11]:

$$G \propto \frac{I F_f(\sigma_x,\sigma_y)}{\sigma_x \sigma_y \sigma_\tau \sigma_\gamma / \gamma} \quad (2)$$

where F_f represents the transverse filling factor between the electron bunch and the laser pulse. The main Super-ACO FEL characteristics are reported in Tab.2. Fig.3 shows the gain versus I for the two different optics.

Tab.2. Main Super-ACO FEL characteristics

Optical cavity length	18 m
S-ACO circumference	72 m
Number of stored bunches	2
Undulator deflection parameter K	4.96
Undulator spatial period λ_o	12.9 cm
Number of undulator periods	10
Fundamental wavelength	350 nm

The gain clearly increases with the current in both cases, because of increase of the electronic density at higher current, even though anomalous bunch lenghtening is present. The gain is larger for the new optics. This result is confirmed by the laser threshold for the new optics, which is 8.8 mA, whereas the laser is switched off at 27 mA for nominal optics (with mirror losses of 1.25% in both cases).

4 FEL OPERATION

A stable laser can also be obtained in the low alpha case, even though the dispersive function in the FEL straight section introduces longitudinal to transverse coupling.

The interplay between the laser pulse dynamics and the charged beam dynamics can be also studied, for a fixed value of the stored current, by measuring the intensity of the laser pulse as a function of a frequency detuning of the synchronization of the positron beam with respect to the oscillation frequency of the light pulse bouncing in the optical cavity [12]. Fig.4 shows the FEL induced

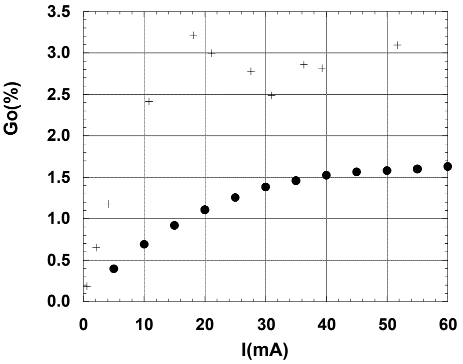

Fig. 3 Gain versus current in the two momentum compaction regimes: α=0.0148; (+) α=0.008.

bunch lengthening. Clearly, it is maximum for a perfectly synchronized FEL and decreases when the laser power is reduced. In fig. 4a), at perfect tuning one observes a relative increase of 14% for the nominal optics, and of 5% for the new optics.

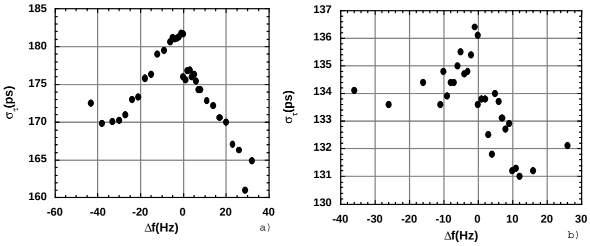

Fig.4 Bunch length versus detuning for a) α=0.0148 and b) α=0.008. The detuning is induced by varying the revolution frequency of the positron bunch.

The increase of energy spread due to the induced FEL heating leads also to the growth of the transverse size via the dispersion function η_x which contributes to the FEL saturation. The different FEL characteristics such as the power, the pulse duration and the bandwidth were also measured.

CONCLUSION

The possibility to operate the Super-ACO storage ring in correspondence of a reduced momentum compaction factor regime (α=0.008), instead of the nominal one (α=0.0148) allows to study as the laser pulse dynamics responds to a modified longitudinal and transverse dynamics of the charged beam.

REFERENCES

[1] NA Vinokurov, AN.Skrinsky, preprint INP77, 59 (1977)

[2] V.N Litvinenko, B. Burnham, J.M.J. Madey, Y. Wu, Nucl.Inst.Meth. A 358, (1995), 334 - 337

[3] G.De Ninno, M.E. Couprie, D. Nutarelli, D. Garzella, E. Renault, M.Billardon, Phys. Rev. E64 (2), 6052 (2001)

[4] A.Nadji, EPAC 2000 Proceedings, Vienna, Austria.

[5] G.De Ninno, D. Nutarelli, D. Garzella, M.E. Couprie, Phys. Rev. E (to be published).

[6] R.J.Bakker, M.E.Couprie, L.Nahon, D.Nutarelli, R.Roux, A.Deboulbe`, D.Garzella, A.Nadji, B.Visentin, M.Billardon, EPAC Proceding (1996), 667-669; M.Hosaka, H.Hama, J.Yamazaki, T .Kinoshita, Nucl.Inst.Meth. A 407 (1998) 234-240.

[7] R.Roux, M.E.Couprie, T.Hara, R.J.Bakker, B.Visentin, M.Billardon, J.Roux, Nucl.Inst.Meth. A 407 (1998) 215-220.

[8] R.Roux, M.E. Couprie, R.J. Baker, D. Garzella, D. Nutarelli, L. Nahon, M Billardon, Phys. Rev. E 58 (1998) 6584-6593.

[9] G.Dattoli, L.Mezi, M.Migliorati, A.Renieri, M.E.Couprie, D.Garzella, D.Nutarelli, C.Thomas, G.DeNinno and R.Walker, Nucl. Inst. and Meth. A471 (2001) 403.

[10] J.M.J. Madey, Nuovo Cimento, 50B, 64 (1979).

[11] P.Elleaume, J.Phys. (Paris) (44), C1-353 (1983).

[12] M. Billardon, D.Garzella, M.E. Couprie, Phys. Rev. Letters 69 (1992) 2368-2371.