SMALL SIGNAL GAIN OF THE SUPER ACO STORAGE RING FEL

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Abstract

The gain per pass of a Storage Ring Free Electron Laser is a crucial quantity to be known for a correct operation of the laser. The relatively low gain exhibited by second generation machines, as in the Super ACO case, calls for the minimization of the losses of the optical cavity for obtaining the laser oscillation. However, the gain needs to be evaluated accurately also on FELs installed on third generation machines, like ELETTRA, in order to control the ultimate performances of the laser, in terms of temporal and spatial dynamics and power. This work intends, through the characterization of the Super ACO FEL performances, to check the reliability of the gain evaluations based on pure experimental measurements.

1 INTRODUCTION

Free Electron Lasers are the most promising coherent sources delivering high brightness, high power of coherent light on a very broad spectrum extending from millimeter waves to XUV. Moreover, oscillator FELs operating with an optical cavity, either on Linac drivers or on Storage Rings (SRFEL), operate already as useful sources for application experiments [1]. Like in conventional lasers, most of the performances of FELs rely on the gain parameter, which summarises the interaction process (microbunching of the electrons in the undulator, process of amplification of the coherent light) and participates to the laser saturation. In FELs the gain has several formulations, following the various laser device configurations. One can then distinguish the "small signal small gain" regime (typical in most of the optical cavity-based FELs), the intermediate "small signal large gain" one and the high gain regime shown by the SASE sources. The "Small signal small gain" regime is ruled by the so-called "Madey Theorem", stating that the gain is proportional to the first derivative of the spontaneous emission spectrum given by the undulator [2]. The direct experimental measurement of the gain per pass (i.e the ratio between the optical energy emitted collected after the undulator and the optical energy at the entrance, in the same bandwidth) is not straigthforward. The experiment performed by the ACO team [3] in the amplifier configuration, with a seeding laser passing through the undulator and without optical cavity revealed uncertainties on the results, given mainly by the control of the entrance energy involved in the process, the synchronism between the electron bunch and the external laser, and finally the optical mode adjustment. On the opposite, gain can be evaluated in terms of the beam experimental parameters or by a fine characterization of the laser performances. In this work some experimental methods for evaluating the small signal gain of the Super ACO storage ring FEL are illustrated.

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2 SRFEL SMALL SIGNAL GAIN

SRFELs operate with the same electron bunch circulating in the ring and interacting successively with the spontaneous emission stored in an optical cavity, provided that the cavity length be a submultiple of ring circumference, in order to keep the longitudinal super-position of the two beams all along the interaction region in the undulator. Since the first operation of the ACO SRFEL in the visible (1983) [4], there has been the necessity to optimise the gain in order to extend the FEL emission spectrum towards the UV region, in parallel with a strong effort on limiting the optical cavity losses. Starting from the "Madey theorem", a formulation of the maximum gain per pass G_0 has been obtained as a function of the electron beam and undulator parameters. In the case where the undulator is replaced by two undulator sections separated by a "dispersive" section, one obtains an Optical Klystron (OK)[5], device which aims to increase G_0 by enhancing the microbunching in short straight sections. For an OK G_0 is:

$$G_0 \propto K^2 (N\lambda_0)^2 F_f \frac{(N+N_d)}{\gamma^3} \frac{\Im T_{el}}{e\sigma_x \sigma_y c\sigma_\tau} \qquad (1)$$

where c is the light speed and e the electron charge. The beam parameters are : $\Im$ the stored electron beam per bunch, T_{el} the revolution period of the electrons in the ring, γ is the Lorentz factor and $\sigma_{x,y,\tau}$ respectively the transverse and longitudinal dimensions. The Optical Klystron is characterized by the undulator period λ_0, the number of periods N(i.e. the interaction length), by the deflection parameter K and by the interference term of the two undulators N_d. Finally F_f represents the filling factor between the electron bunch and the stored light pulse.

2.1 Maximum Detuning

In the SRFEL saturation process, a main feature which has to be taken into account is the synchronism between the electron beam and the light beam stored in the optical cavity. For a perfect synchronism, the strongest energy exchange between electrons and photons "heats" the electron

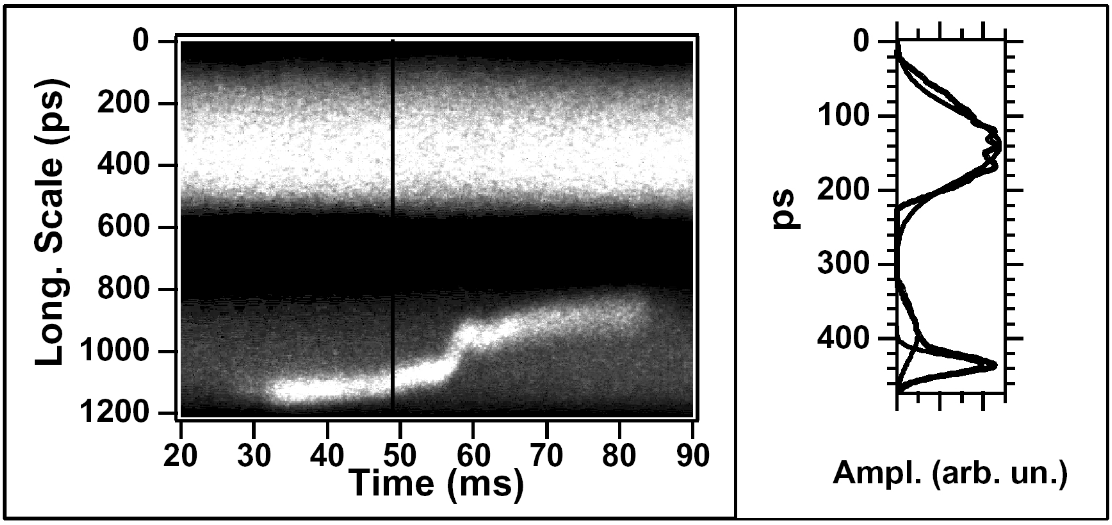

Figure 1: Left: double sweep streak camera Image Upper trace : Temporal Behaviour of the longitudinal bunch profile; Lower trace : Variation of the laser Pulse position by applying a ramping detuning on the RF cavity. Right : longitudinal profile analysis and fitting of σ_τ,σ_L and τ_0.

Table 1: Super ACO FEL beam and undulator parameters

Energy	800 MeV
Bunch revolution time T_{el}	240 ns
Undulator Period λ_0 (mm)	129 mm
Number of periods$N$	10
Interference number N_d	100

bunch, reduces drastically the bunch density and SRFEL saturates, as for all conventional lasers, when gain equals the optical cavity losses P. Under these conditions, the gain per pass is G_0 and the longitudinal (temporal) position of the laser pulse superposes with the beam center-of-mass position. When a temporal detuning is introduced, the laser dynamics changes [6], gain decreases and saturation is achieved at a lower laser intensity. Furthermore, during the saturation, the laser pulse drifts and a new equilibrium position τ_0 is reached. From the laser dynamical features observed by fast temporal detectors [7] and by assuming that the longitudinal gain distribution behaves as the electronic density, say

$$G = G_0 e^{-\frac{\tau^2}{2\sigma_\tau^2}} \qquad (2)$$

an analytical 1D model has been developped [8], in which one of the main result is the evaluation of G_0, which reads

$$G_0 = \frac{P}{1-P}\sqrt{1+\frac{\sigma_L^2}{\sigma_\tau^2}}e^{\frac{\tau^2}{2(\sigma_\tau^2+\sigma_L^2)}} \qquad (3)$$

where σ_L is the laser pulse RS width, σ_τ is the bunch one and τ_0 the laser equilibrium position. An example of this measurement and of the analysis is shown in fig. 1.

2.2 *Laser risetime and Gain-Switched regime*

For perfect synchronism , the saturated Super ACO FEL is ”cw” on a millisecond scale [10] and keeps the condition $G = P$. A different dynamical behaviour of the laser is induced when the synchronism is taken off and then suddenly restored via an adapted modulation of the radiofrequency which drives the electron bunch; in this gain-switched regime, a big amount of radiation energy is stored in the optical cavity and then rapidly delivered . The laser intensity increases then with an exponential behaviour

$$I_L = I_{0L} e^{\frac{t}{\theta}} \qquad (4)$$

where the risetime θ is expressed by [9] $\frac{T_{el}}{G_0 - P}$.

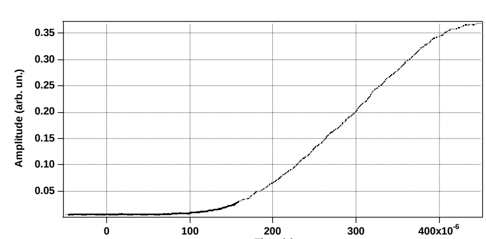

Figure 2: Starting of the laser in the Gain-switch mode. Data are taken with a rapid photomultiplier. The light grey line represents the experimental data, the dark line is the best-fit, giving a risetime of $\theta = 31\mu s$

2.3 Laser threshold

Relation (1) shows the dependency of the gain from the current. Then, for low current intensities, the saturation condition is still valid and at perfect synchronism the laser can last until the threshold level is reached. At threshold one has naturally $G_0 = P$, thus giving another experimental way for evaluating G_0.

3 EXPERIMENTAL RESULTS

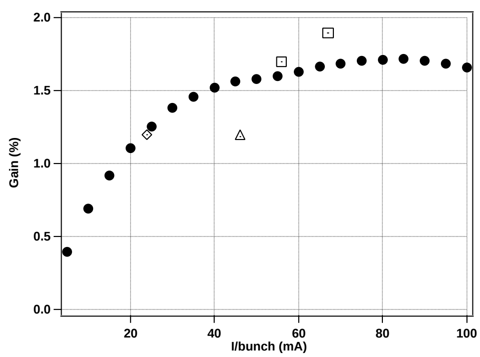

Figure 3: Behaviour of the G_0 versus the total current stored in the ring for a two-bunch mode operation evaluated with different experimental methods. plain rounds: Small signal gain by beam parameters; squares: Maximum Detuning; triangles : Threshold current ; losanges : Gain-Switch.[11]

The different methods have been tested during the normal operation of the Super ACO FEL. Results, shown in table 2, exhibit a quite good agreement with the curve in fig. 3, which has been obtained by computing G_0 vs. the stored current in the ring by using relation (1). In particular, the Maximum Detuning method and the laser threshold measurements seem to be the most reliable for evaluating G_0, but further analysis and comparisons with analytical and numerical models are needed.

Table 2: Evaluated G_0 by different experimental methods

Method	I(mA)	τ_0 (ps)	$\theta(\mu$s)	Gain (%)
Small Signal	20	-	-	1.1
	80	-	-	1.7
Max. Det.	56	155	-	1.7
	67	182	-	1.9
Gain-Switch	46	-	31 μs	1.2
Current Thres.	27	-	-	1.2

4 CONCLUSION

Small signal gain for the Super ACO Storage Ring FEL has been evaluated by using different experimental techniques referring to various laser oservables. Results seem to be consistent with theory. In particular, the Maximum Detuning method and the laser threshold measurements seem to be the most reliable for evaluating G_0, but further analysis and comparisons with analytical and numerical models are needed.

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