SRFEL LINEWIDTH NARROWING IN THE ULTRAVIOLET*

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Abstract

The ELETTRA Storage Ring FEL succeded in operating in the Ultraviolet range, around 350 nm, with an etalon Fabry Perot inserted in the optical cavity. The high vacuum vessel, integrating a totally motorized control system for the principal degrees of freedom of the silica plate, allowed to obtain the laser oscillation, showing a reduction of the spectral linewidth by more than an order of magnitude. Temporal analysis by a double sweep streak camera showed also a broadening of the temporal pulse width. These major results are here exposed and compared with a numerical analysis and the Storage Ring FEL dynamics theory.

INTRODUCTION

In Storage Ring Free Electron Laser (SRFEL) oscillators, the light pulse shows a high degree of coherence, both spatial and longitudinal, thanks to the multiple interaction between electrons and photons and the longitudinal and spatial mode selection done by the optical cavity. The coherence is then mainly ruled by the electron longitudinal dynamics, the inherent one through the synchrotron radiation damping, and by the electron beam stability, as already shown in previous works [1]. However, even for an ideal Fourier Limited laser pulse, the spectral width is mainly determined by the spectral gain width. In an optical Klystron (OK) configuration, the relative bandwidth is $\approx 1/\left[2\pi\left(N+N_d\right)\right]$, where N is the number of periods for one undulator, and N_d is the equivalent periods number for the dispersive section. Because of the long optical cavities (few tens of meters) a high number of longitudinal modes can oscillate, as the longitudinal modes spacing, called the Free Spectral Range (FSR), is $FSR = \frac{\lambda^2}{2L}$ where λ is the laser wavelength and L is the optical cavity length. Typically a SRFEL oscillator, in the OK configuration, shows in the visible and near UV a gain bandwidth of $\approx$ few 10^{-3}, while the natural laser linewidths are in the $10^{-4}-10^{-5}$ range. A way for reducing the spectral linewidth rely on the insertion of a Fabry-Perot Etalon in the cavity, allowing the selection of a limited number of longitudinal modes.This technique, well known in conventional lasers for selecting a single longitudinal mode when the gain bandwidth is very large, was analysed in the FEL supermodes theory framework by Elleaume [2] and Litvinenko [3]. A very important first experiment succeded in 1990 at VEPP3 (Novosibirsk) [4] in the visible, but no further analysis has been made since. Aim of this experiment, performed in the Ultraviolet range on the Storage ring ELETTRA, is manyfold:

- to push the linewidth narrowing towards the shorter wavelengths, together with the progress of the SRFEL oscillators.
- To test the existing analytical and numerical theoretical studies on SRFEL longitudinal dynamics, in presence of an intracavity optical element, and for third generation storage rings.
- the possible exploitation of the new spectral features for spectroscopy in the UV-VUV range, providing a high spectral resolution for FEL users.

In this work, results of the experiment performed on the ELETTRA SRFEL are shown, and a comparison with some numerical results is made.

THEORY AND BASIC PRINCIPLES

In its simplest shape, a Fabry-Perot etalon is a plane-parallel face plate characterised by a thickness d and an optical real index n. Here an absorptionless plate is considered. Other important parameters are the transmission and reflection coefficients, t and r, and the beam incidence angle θ with respect to the axis perpendicular to the etalon surface. It has been analitycally [2, 3] and experimentally [4] shown that the natural linewidth for an SRFEL is proportional to the gain bandwidth by a factor $\sqrt{\alpha}$, where $\alpha = \Delta/2\sigma_b$, with Δ the slippage length for an OK, $\Delta = (N+N_d)\,\lambda_r$, and σ_b the bunch length. A general study with the supermodes theory, including an intracavity Fabry-Perot etalon leads, by assuming a perfect detuning between the laser pulse and the electron bunch and that $\Delta << \sigma_b$, to the following result :

$$\frac{\Delta\lambda}{\lambda} = \frac{\sqrt{2\ln 2}}{\pi}\sqrt{\frac{\lambda_r^2}{4nd\sigma_b}}\sqrt[4]{\frac{g_0}{r}} \qquad (1)$$

In order to study the SRFEL dynamics, especially the microtemporal and spectral behaviour of the laser beam, the Super ACO team had been developed in the past a pass to pass numerical code taking into account the coupled dynamics of the electrons in the storage ring and of the laser pulse in the optical cavity [1]. This numerical approach is here used for studying the etalon effect, by including into the code the characteristic Airy function (classically derived from the development of the multiple interferences in the plate) [5]. This term, implemented in equation (1) of ref. [1] and expressed in relation (2), gives the intensity transmitted

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through the etalon. The spectrum is then derived by Fourier Transform. This numerical code propagates the laser pulse intensity, with a consequent lack of information on the laser field phase. This should not be a strong limitation , as we are not dealing with ultrashort pulses (i.e. femtosecond ones).

$$\frac{t^4}{\left[1 - 2r^2 \cos\left(\frac{4\pi n d}{\lambda_c}\right) + r^4\right]^2} \tag{2}$$

EXPERIMENTAL SETUP

The experiment has been performed on the SRFEL at ELETTRA, in the framework of the EUFELE collaboration. The main characteristics of the ELETTRA FEL are in [6], while the experiment parameters for the Etalon and the FEL beam are reported in table 1. To achieve our goals, a new high vacuum vessel has been manufactured for the optical cavity at ELETTRA, integrating a totally motorized control system for the principal degrees of freedom of the etalon [5]. The chamber has been installed in spring 2004 in the back side of the optical cavity, close to the upstream mirror, in order to get rid of the irradiation problems for the silica plate. The etalon was a superpolished plate, with a measured roughness well below 2 Å, and a diameter of 40 mm. Absorption and scattering losses were measured not to exceed 100 ppm ($1ppm = 10^{-6}$). Temporal measurements were taken by mean of a double sweep streak Camera (see fig. 1) on the stored synchrotron and laser beams issuing from the upstream semi-transparent mirror, while the spectral diagnostics, composed by a high resolution monochromator (ACTON SP2000 Series, 1200 l/mm diffraction grating) and a Scanning Fabry-Perot (EXFO TL-150), were placed downstream.

Table 1: Main Experimental Parameters

Etalon Parameters	
Material	Fused Silica
Thickness (mm)	3
Optical index n	1.55
Transmission/Reflection $t/r(\%)$	4/96
ELETTRA FEL Parameters	
Beam Energy $E(MeV)$	900
Electron Bunch length $\sigma_b(ps)$	20
Laser Wavelength $\lambda_c(nm)$	355
Gain per pass $g_0(\%)$	8
Optical Cavity Losses $P(\%)$	1

NUMERICAL RESULTS

The code analysed the ELETTRA FEL dynamics both in presence of the Fabry-Perot Etalon, and without it. For both cases, the simulations, performed under the same initial conditions than the experimental ones, showed an analogous macrotemporal behaviour, in which a very intense transient

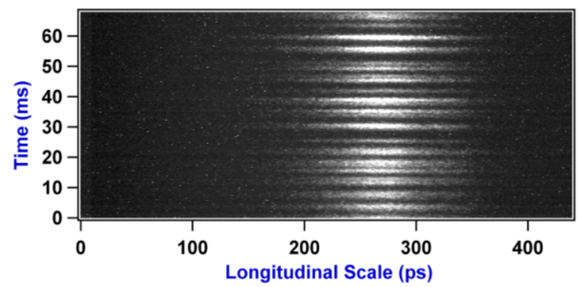

Figure 1: Image from the double sweep streak camera showing the temporal behaviour of the laser micropulse.

pulse occurs in the first 100 μs, followed by a strong damp. Afterwards, between 10 and 100 ms, another oscillatory transient occurs, damping towards the stationary solution (saturation). At the peak of the intense transient pulse, the code shows that the FEL is not spectrally saturated, as the laser line is very wide (0.39 nm, 1.1 10^{-3} relative bandwidth). Under saturation, the laser line is the narrowest and Fourier-Limited ; without the etalon the saturated laser line is 0.049 nm wide, thus having a relative bandwidth of $\approx 1.4\ 10^{-4}$. With the insertion of the etalon, the code lacks in resolution (computation time too high), giving anyway an upper limit for the laser line of 0.01 Å, i.e. with a relative bandwidth smaller or equal to $\approx 3\ 10^{-6}$ (fig. 2).

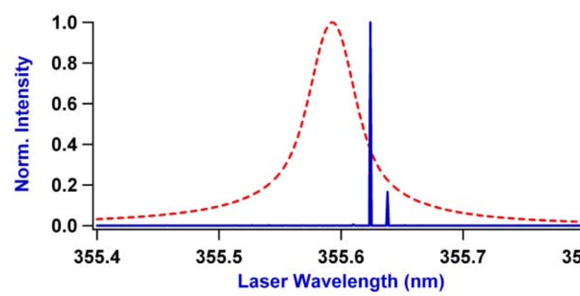

Figure 2: Results obtained on the laser spectrum with the numerical code. The dashed line shows the laser pulse without Fabry-Perot etalon, the plain line the laser pulse with the etalon

EXPERIMENTAL RESULTS

Spectral Analysis

Scanning Fabry-Perot (fig. 3) are high-resolution spectral detectors, allowing to measure lines having a relative Bandwidth as narrow as $\approx 10^{-7}$ in the visible and near Ultraviolet (or $\approx 75\ MHz$ in frequency). With a Free Spectral Range (FSR) of 150 GHz and a mirror finesse of ≈ 100, we had a resolution of 1.5 GHz. After the Etalon insertion, we measured a spectral line of 13.3 $\pm 0.1\ GHz$, corresponding, at 355 nm, to a relative bandwidth of 1.6 10^{-5}. A parallel measurement with the high resolution mochromator (fig. 5)showed a linewidth of 0.09 Å(FWHM), correspond-

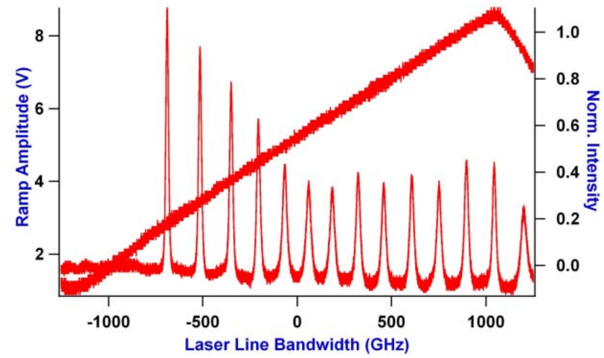

Figure 3: Operation of the Scanning Fabry-Perot. The ramp amplitude is applied on the piezoelectric motors, allowing one of the two plane mirrors to move, thus scanning several Free Spectral Ranges (in this example, the spacing between two peaks is $150\ GHz$, corresponding to a movement of $\approx 650\ \mu m$)

ing to a relative bandwidth of $2.6\ 10^{-5}$. Without plate, the bandwidth has been measured to be in the range $5-8\ 10^{-4}$.

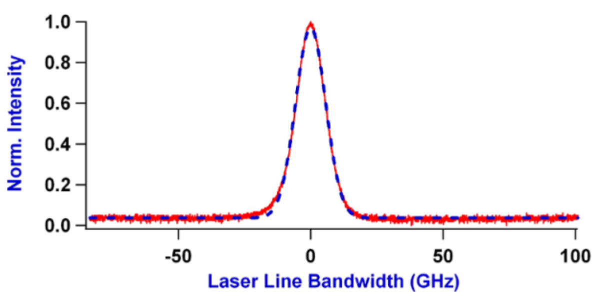

Figure 4: Laser linewidth measured by the scanning FP. The plain line is the experimental result, the dashed line is the gaussian fit.

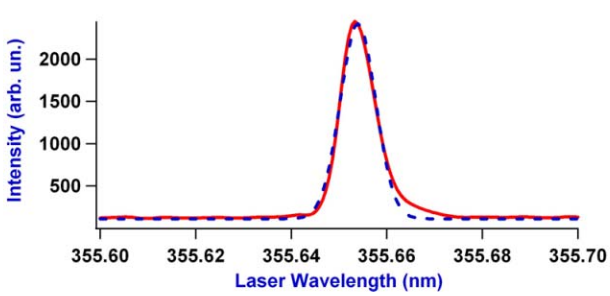

Figure 5: Laser linewidth measured by the high resolution monochromator. The plain line is the experimental result, the dashed line is the gaussian fit.

Temporal Analysis

The analysis performed on the images taken with the Double Sweep Streak Camera before and after the etalon insertion show the induced broadening of the laser pulse duration. As shown in fig. 6, an RMS duration of $7.5\ ps$ is measured for the laser pulses without the etalon, while the laser is clearly broadened with a σ_l of 32 ps after the Fabry-Perot insertion.

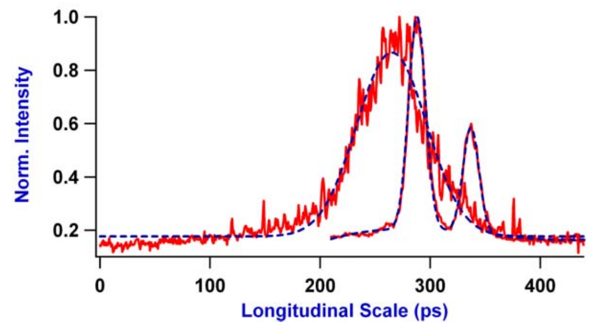

Figure 6: Results from streak camera images. The broader pulse (plain line, experiment; dashed line, gaussian fit) appears as the etalon is inserted. Ghost laser pulses appear as stray reflections, but the fits give the same result)

CONCLUSIONS

The experiment was successful in achieving the line narrowing in the UV at 355 nm, with a narrowing factor of about 40! Further, experiment was reproductible, giving access to useful data to analyse. The experimental results are in a very good agreement with the formula given by [4], as with the latter, in the same initial conditions, one founds a relative bandwidth of $1.5\ 10^{-5}$, accordingly to the Scanning Fabry-Perot results. However, several considerations arose. The temporal laser pulse broadening led to a product duration-linewidth at least 3times the Fourier Limit. Furthermore, the laser linewidth without the inserted etalon was fluctuating, and the code shows how the saturation time is quite long, and the stationary solution is more difficult to achieve. Some further work is then foreseen, both on the numerical codes and on the experiments.

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