# THE EUROPEAN UV/VUV STORAGE RING FEL PROJECT AT ELETTRA*

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## *Abstract*

An overview of the European storage ring FEL project is presented, including details of initial lasing and future plans.

## 1 INTRODUCTION

Free-electron lasers (FELs) are sources of tuneable, spatially coherent, monochromatic radiation with high peak and average power. Of the various types of possible implementations the storage ring FEL [1,2] has a long history, the ACO FEL being the second FEL in the world to operate in 1983, in the visible region of the spectrum. Since then 7 further projects have been successful in further developing the source characteristics and in pushing the lower wavelength limit into the UV and most recently into the VUV (194 nm). Storage ring FELs have also reached a stage of maturity in that user programmes are active at two centres, SuperACO and Duke University.

Storage ring FELs, while not being candidates for achieving the very shortest wavelengths, because of the difficulties of obtaining mirrors with sufficiently high reflectivity, or electron beams with sufficiently low emittance and high peak current, nevertheless have several particular characteristics that make them suitable for carrying out a range of experiments:

- continuous MHz repetition frequency
- synchronization with synchrotron radiation from the same storage ring, on a 1:1 pulse basis, allowing the possibility of pump-probe experiments
- relatively small wavelength spread

In addition, if the storage ring in which it is installed is a synchrotron radiation user facility:

- the additional cost of the FEL is relatively small
- the source is automatically integrated in an environment that is likely to lead its best utilisation as an experimental facility.

In this case the storage ring FEL can rightly be thought of as a relatively inexpensive additional feature, or a more sophisticated insertion device. The price to pay however is a limit to the amount of available commissioning time compared to a dedicated FEL experiment.

The European storage ring FEL project at ELETTRA [3] began officially in May 1998 with partial EC funding. It is as a collaboration between six laboratories interested in the development of storage ring free-electron lasers, five of which operate synchrotron radiation facilities.

The goals of the project are orientated towards a future FEL user facility in the UV/VUV, providing tuneable output between 350 nm and at least 190 nm. Other than pursuing development of the FEL itself, other important issues to be addressed therefore are the compatibility with operation of other synchrotron radiation beamlines, and the carrying out of pilot user experiments.

The main distinguishing features of the project are –

- the integration of the FEL on a low emittance “third-generation” synchrotron radiation facility
- the use of a helical undulator (optical klystron) to reduce power loading on the mirrors
- the use of sophisticated mirror chambers that allow in-situ switching between different mirrors

In this first report since first lasing in February 2000, we describe the layout and main parameters of the project, the main hardware items, pre-commissioning studies, first and subsequent lasing, as well as future plans.

## 2 LAYOUT, PARAMETERS, HARDWARE

### *2.1 Layout*

Figure 1 shows the layout of the free-electron laser in ELETTRA. The optical cavity length of 32.4 m, synchronized to the 4-bunch mode of operation, is a

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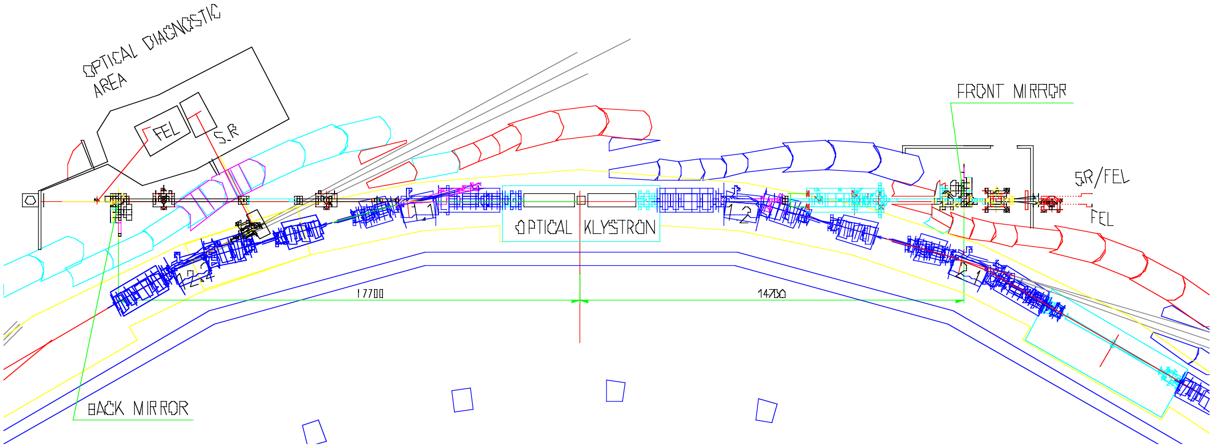

Figure 1: Layout of the Free-Electron Laser in the ELETTRA storage ring.

convenient choice since it leads to the location of the mirror chambers immediately outside the shielding wall. The possibility to install the FEL in straight 1 of the ring was also very convenient since it allows FEL radiation from the upstream end of the cavity to be directed into an existing diagnostic area, thus allowing the possibility of measuring simultaneously the electron and FEL radiation time structures. The downstream mirror chamber is followed by a standard switching mirror used on several beamlines, thereby permitting a double use of the undulator source: during FEL operation the radiation is sent to a special FEL diagnostic area, while during normal operation the undulator radiation will be able to be sent to a synchrotron radiation beamline, presently under construction. This arrangement, and the choice of beamline, also allows a convenient third option, namely the possibility for the beamline to carry out experiments with the FEL radiation.

## *2.2 Parameters*

Table 1 lists the principle parameters. Further details of the choice of parameters can be found in [3].

Table 1: Main Parameters of the ELETTRA FEL

| **Electron Beam** | |
|---|---|
| Energy | 1 GeV |
| No. of bunches | 4 |
| Total current | up to 100 mA |
| Natural rms emittance | 1.7 nm rad |
| Natural rms energy spread | 0.04 % |
| Natural rms bunch length | 6.3 ps |
| **Optical Cavity** | |
| Length | 32.4 m |
| Distances from mirrors to ID centre | 17.7 m, 14.7 m |
| Mirror radius | 17.5 m |
| Rayleigh length | 4.59 |
| Stability parameter | 0.72 |
| **Optical Klystron** | |
| Undulator type | permanent magnet APPLE-2 |
| Period length | 100 mm |
| No. of periods | 2 x 19 |
| Minimum gap | 19 mm |
| K max. (circular polarization) | 5.9 |
| Max. wavelength (circular polarization, 1 GeV) | 450 nm |
| Phase modulator type | electromagnetic |
| $N_d$ max. (1 GeV, 350 nm) | 85 |

## *2.3 Undulator/Optical Klystron*

The two permanent magnet undulator sections are based on the APPLE-2 design, and were designed and built at Sincrotrone Trieste. The maximum wavelength available in the circular polarization mode at 1 GeV, at the minimum gap of 19 mm, is 450 nm. There is some flexibility therefore to allow an increase in storage ring energy in the future, for greater compatibility with the operation of other SR beamlines; for example up to 290 nm could be obtained at 1.25 GeV.

The undulator field quality was optimised by block sorting and by vertical block displacements, to minimise both phase errors and field integrals [4]. The final rms phase errors are < 3°, and the field integrals < 2 Gm and < 3 $Gm^2$, at any gap and phase. Adjustment of the phase of the radiation emitted in the two undulators is carried out by a 3-pole electromagnet. For FEL operation this also allows an optical klystron mode in order to enhance FEL gain, with maximum phase delay ($N_d$) equivalent to 85 wavelengths (at 350 nm, 1 GeV).

## *2.4 Mirror Chambers*

To make the most of the limited beam time available for FEL commissioning, as well as to provide a wider wavelength range in the operational phase, novel UHV mirror chambers have been designed and constructed at Daresbury Laboratory containing 3 remotely interchangeable mirrors [5]. A transfer arm and load-lock arrangement also permits mirrors to be withdrawn and replaced without breaking the vacuum of the main chamber.

A major concern was to avoid as much as possible thermal distortion of the mirrors due to the synchrotron radiation and laser power. The mirrors are fitted into OFHC copper holders with loose surface clips to hold them in place. A thermal interface of indium/gallium eutectic between mirror and holder can be used to improve thermal conductivity. The base of the mirror holders and the mating surface of the support plate, which is water cooled, are polished to improve heat conduction.

Each of the two identical units contains 8 motion systems: X, Y, and Z position is adjusted using external stepping motors; mirror change is effected using an in-vacuum motor; pitch and yaw movement is carried out by in-vacuum combined motor (coarse)+ piezo (fine) units. The mirror chambers were delivered to Trieste on January 17th, one month was then needed for re-assembly, installation, alignment and bake-out.

### 2.5 Mirrors

Good quality mirrors with high reflectivity and low absorption are essential for the operation of a FEL oscillator. In order to ensure a rapid start-up of the laser an initial wavelength of 350 nm was chosen, in order to profit from the experience available in characterising mirrors for this wavelength at LURE. A number of silica and sapphire substrates were prepared and characterised for radius of curvature, roughness, transmission, absorption and total losses. The best substrates were subsequently coated with oxide multilayers for high reflectivity around 350 nm and a nominal transmission of about 0.1 %.

To proceed to shorter wavelengths other mirror types are also being explored, based on both oxide and also fluoride multilayer coatings. In addition, tests are also being made with silicon substrates, attractive because of its higher thermal conductivity, using holes for coupling out the radiation.

## 3 PRE-LASING COMMISSIONING

### 3.1 Bunch Length

Figure 2 shows the result of several measurements of the bunch length as a function of bunch current, using a streak camera. Measurements after installation of the new aluminium vacuum vessels in August/September 1999 are consistent with previous data, showing no increase therefore in the *effective* longitudinal impedance seen by the short bunches of about 0.15 Ω.

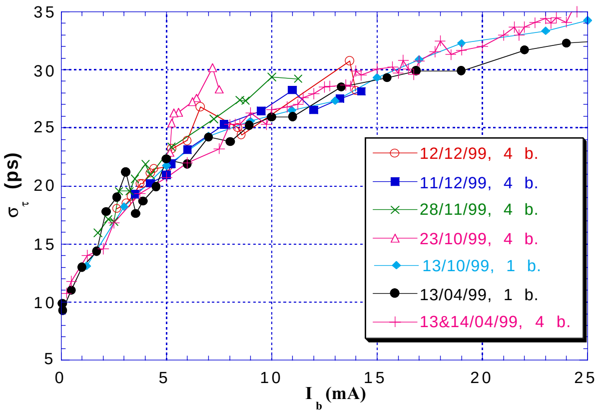

Figure 2: Bunch length as a function of current per bunch, in single and 4-bunch modes.

### 3.2 Undulator Operation

The intrinsic poor field homogeneity of the APPLE design, combined with the relatively high magnetic field and long period length, gives rise to significant focusing effects in the ring, particularly at 1 GeV [6]. At the settings for 350 nm operation with circular polarization (gap = 22.2 mm, phase = 30 mm) each undulator section gives rise to a tune change of about ΔQx = - 0.04, ΔQy = + 0.03. To allow the undulators to be set without losing the beam a temporary procedure had to be developed involving closing them one at a time, with an intermediate tune correction. Experiments have shown that a local tune correction (i.e. using two pairs of quadrupoles on either side of the undulator) gives a significantly better beam lifetime than a global correction (using quadrupoles located in all straight sections). Studies are underway to explore other matching schemes as well as to prepare a program for dynamic tune correction during undulator closure [6].

The undulators also cause a variation in closed orbit, sufficiently small however that all of the present FEL work could be carried out without use of any of the correction coils, which will be implemented in the future.

### 3.3 Spectral Measurements

Various measurements of undulator radiation spectra were made, using a visible/UV monochromator, in order to verify correct functioning of the undulator, to determine the spontaneous emission axis, and also to allow a determination of the electron beam energy spread. Figure 3 shows an example of a spectrum taken with maximum setting of the phase modulator ($N_d$=85), under FEL operating conditions.

The optical klystron spectrum can be written in the following form:

$$I_{OK} = 2\, I_{und} \left[1 + f \cos\left(2\pi (N+N_d)(\Delta\lambda/\lambda)\right)\right]$$

where $I_{und}$ is the spectrum of one undulator and the modulation rate $f$ is given by:

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

Thus, fitting spectra taken with various values of $N_d$ to obtain $f$, and plotting $-\ln(f)$ versus $8\pi^2(N+N_d)^2$ allows one to deduce $f_o$ (the modulation rate for zero energy spread) and $\sigma_\gamma/\gamma$ for any given beam current.

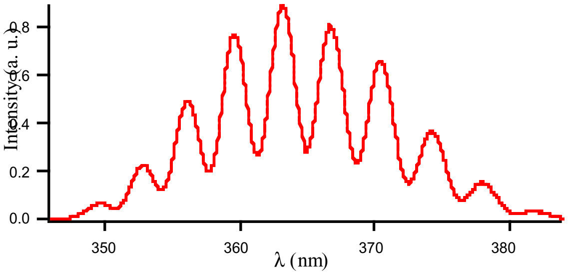

Figure 3: Measured optical klystron spectrum with $N_d$=85 and 2.8 mA/bunch.

Five spectra were taken for each of 8 beam currents. The residual modulation rate $f_o$ was high, 0.91-0.99, indicating a small effect due to transverse emittance. Figure 4 shows the resulting values of energy spread, plotted as a ratio to the natural value (0.04 %), together with the results of a simultaneous measurement of bunch length, again compared to the natural value (6.28 ps). The trend is clearly the same, but the increase in energy spread is consistently less than that of the bunch length. Further measurements are required to verify this result.

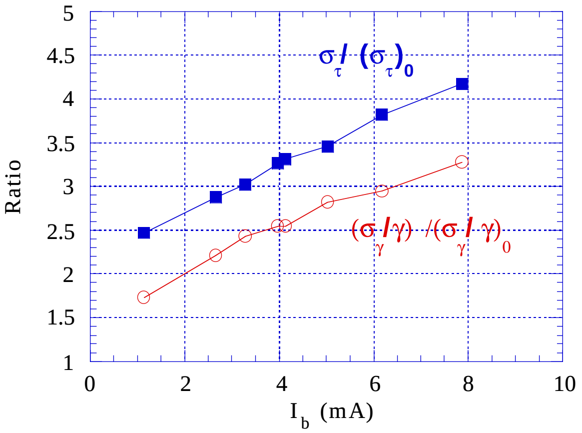

Figure 4. Ratio of bunch length (upper) and energy spread (lower) with respect to nominal zero-current values as a function of current per bunch.

# 4 LASING AT 350 nm

## 4.1 First Lasing

The first FEL shifts began on February 18th-19th. After aligning the front mirror 350 nm radiation was detected at the back mirror, reflected off the front one. During a subsequent shift on February 28th/29th the back mirror was aligned and multiple reflections of the radiation were observed using a photomultiplier; to facilitate this the storage ring was operated in single bunch mode. Further empirical adjustments were then made to the mirror angles to optimise the shape of the image seen through the upstream mirror. In 4-bunch mode the streak camera was then used to adjust the cavity length, by minimising the temporal width of the trapped radiation pulse. At this point with 17 mA total current first lasing was observed.

## 4.2 Lasing Studies

One of the most important parameters which affects FEL operation is the cavity length. To achieve the required measurement precision this is usually carried out by the equivalent method of varying the ring r.f. frequency. In the present case 100 Hz corresponds to a length change of 6.5 µm. Figure 5 shows the variation of measured output power as a function of r.f. frequency detuning. The width, which increases as expected with beam current, is fairly typical for storage ring FELs. So far a maximum extracted power of 20 mW has been recorded, with 30 mA total beam current, in approximate agreement with expectations for the given mirror transmission etc.

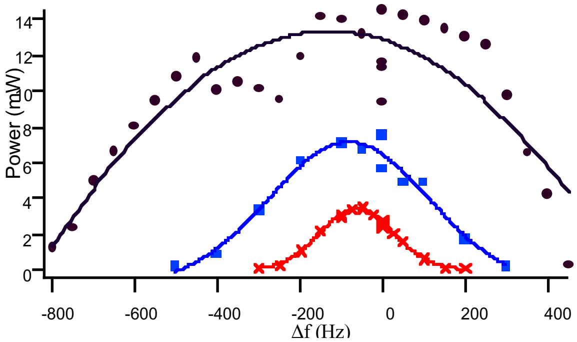

Figure 5: Power output as a function of cavity detuning at different (total) current levels: 19 mA (upper), 10.8 mA (middle), 6.6 mA (lower).

The detuning affects also the spectral linewidth and laser micropulse length as shown in fig. 6. Comparing with fig. 5 it can be seen that minimum spectral and pulse widths are obtained at the detuning corresponding to maximum power. Figure 7 shows the minimum profiles. The spectral width corresponds to 4.2 $10^{-4}$.

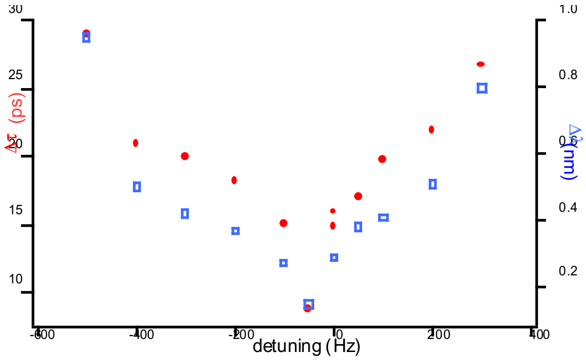

Figure 6: Pulse length (upper, left scale) and spectral width (lower, right scale) as a function of cavity detuning, measured with 10.8 mA.

The various measurements of detuning curve, threshold lasing current (1.3 mA, total) as well as the increase in the electron bunch length caused by lasing (71 % at 10 mA) all provide estimates of the gain, which are summarised in Figure 8. The results, given the uncertainty in the actual cavity losses, can be seen to be consistent with theoretical predictions.

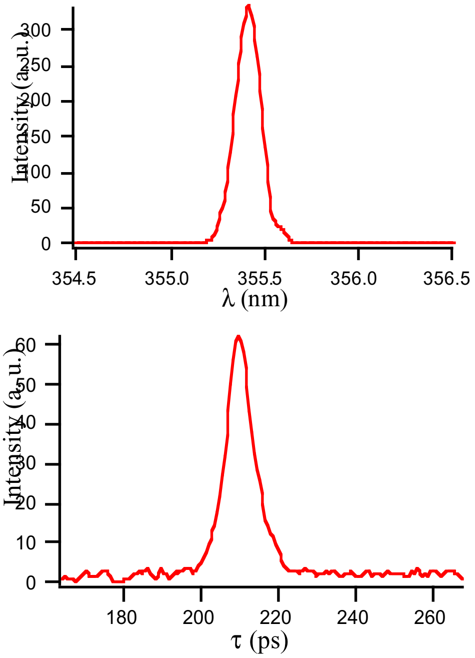

Figure 7: Minimum linewidth (0.15 nm FWHM) and pulse length (8.9 ps FWHM) at 350 nm.

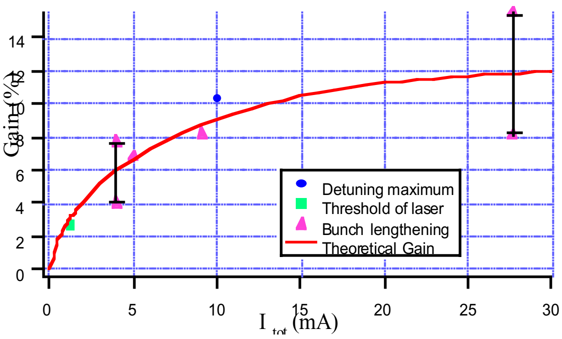

Figure 8: Results of various gain estimations (points) compared to the theoretical value (curve); fixed $N_d$=56.

## 5 LASING AT 220 nm

New multilayer mirrors designed for short wavelength were installed on May 27th. After determining empirically the undulator gap required for the new wavelength, and after the usual alignment process, lasing was first obtained at 220.5 nm with a total current of 10 mA. Changing the undulator gap allowed lasing over the range 217.9-224.1 nm. A typical measured spectrum is shown in fig. 9. The width (FWHM) is 0.05 nm ($\Delta\lambda/\lambda$ = 2.2 $10^{-4}$). A maximum power of 10 mW at 27 mA was obtained, with a detuning curve width of 1.1 kHz FWHM. The lasing threshold was at about 3 mA.

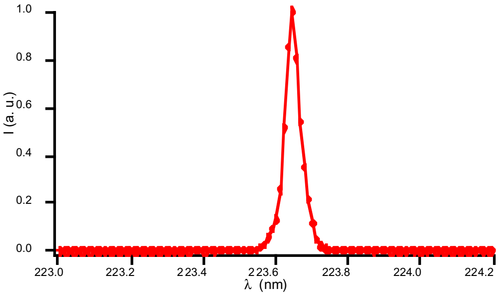

Figure 9: Laser spectrum at 223.6 nm.

## 6 FUTURE PLANS

A relatively short amount of time has been available since first lasing and so many topics have yet to be studied in detail including the macrotemporal structure, wavelength tuning range, effect of phase modulator variation, as well as lasing stability, reproducibility and the effects of mirror degradation etc. Another main aim is also to proceed to shorter wavelength, below 200 nm. In addition, the possibility of creating linear polarization, by having an opposite direction of circular polarization in the two undulators, is of interest for future experiments.

Other than FEL performance issues, mirrors are being prepared to cover the range 280-220 nm for initial single beam experiments, using the new beamline which shares the same undulator source. Consideration will also be given to the possibility of carrying out two beam “pump-probe” experiments next year.

## ACKNOWLEDGEMENTS

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