

## STATUS OF THE FERMI@ELETTRA PROJECT\*

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### Abstract

The FERMI@Elettra seeded Free Electron Laser (FEL) has provided the first photons to the experimental stations during 2011. The first FEL line in operation is FEL-1, covering the wavelength range between 80 nm and 20 nm. The facility will be opened to users by the end of 2012. In the meantime the installation of the second FEL line, FEL-2 covering the shorter wavelengths down to 4 nm, is progressing and the first tests have started. A description of the status of the project is presented here.

### INTRODUCTION

FERMI@Elettra (Fermi) is the fourth generation light source under commissioning at the Elettra laboratory in Trieste. The FEL will produce photons in the ultraviolet and soft X-ray range, between 15 eV and 310 eV. The scientific case, based on three experimental programs, namely *Diffraction and Projection Imaging* (DiProI), *Elastic and Inelastic Scattering* (EIS), *Low Density Matter* (LDM), calls for high peak brightness, fully coherent, narrow and stable bandwidth photon pulses, wavelength tunability and variable polarization [1].

Two FEL lines will cover the foreseen wavelength range. FEL-1, based on a High Gain Harmonic Generation (HG) single stage source seeded by an external UV laser (~260 nm), covers the range from 80 to 20 nm. To get down to 4 nm still starting from an external seed laser in the UV range, a double stage HG cascade is adopted for FEL-2. A delay line allows improvement of the FEL performance by using the *fresh part* of the electron bunch in the second stage of the cascade.

The maximum electron beam energies required for FEL-1 and FEL-2 are 1.2 and 1.5 GeV respectively. The accelerator is a normal conducting linac, working at 3 GHz RF frequency and currently 10 Hz repetition rate (50 Hz in 2013). The high brightness electron beam is generated by a photocathode RF gun. Two stages of magnetic compression are used to get extremely short electron bunches (less than 1 ps) with high peak current. A 4<sup>th</sup> harmonic system provides the longitudinal phase space linearization needed to optimize the compression

process. At high compression factors micro-bunching instabilities are predicted; to eliminate them, a laser heater is used to increase in a controlled way the incoherent energy spread of the electron beam.

Each stage of the two FEL lines is made up by the modulator, where the electron beam is seeded by the external laser, by a dispersive bunching section, and by the radiator, where the interaction between the electron beam and the produced coherent radiation produces the exponential growth of the FEL radiation. Both for FEL-1 and FEL-2 the final radiator is made up by six APPLE-II undulators, with magnetic periods of 55 and 35 mm respectively, that provide full control of the polarization of the FEL radiation. The variable gap allows the wavelength of the emitted radiation to be changed.

### FACILITY PERFORMANCE

After the first evidence of Coherent Harmonic Generation (CHG) was observed at the end of 2010, during 2011 the facility performance was gradually optimized until exponential growth of the FEL radiation was achieved in July [2]. Further optimization studies [3], [4] and commissioning activities have been carried out during the following months; table 1 summarizes the current Fermi performance parameters.

Table 1: current FEL-1 Parameters

Parameter	FEL-1
Electron bunch energy	1.2 GeV
Bunch charge	500 pC
Bunch Peak current	≤ 350 A
Wavelength	80 – 20 nm
Energy per pulse	20 to 50 μJ
Photons per pulse	10 <sup>13</sup> @ 32 nm
Repetition Rate	10 Hz

### Photon Intensity and Spectrum Quality

After optimizing the FEL for on axis operation, on the TEM<sub>00</sub> mode, exponential growth of the FEL radiation with increasing radiator length was observed in a quite

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straightforward way. The maximum achieved photon intensity exceeded 100  $\mu\text{J}$  for isolated pulses, the average being between 20 and 50  $\mu\text{J}$ .

The spectrum of the Fermi FEL radiation shows very narrow bandwidths, with excellent bandwidth and central wavelength stabilities. The photon energy fluctuations are typically better than  $10^{-4}$  rms and the spectral bandwidth stability is below 3% rms. Figure 1 shows a 3D sequence of 500 consecutive spectra acquired for the FEL operated at 52 nm, the 5<sup>th</sup> harmonic of the seed laser. For the reported case, the analysis of the data gives a central wavelength of 52.2 nm, which is in agreement with the measured seed laser wavelength of 261 nm. The measured wavelength fluctuations (*Fig.1, black line*) are 0.006 nm (0.03 %) rms. The measured average bandwidth (*purple lines*) is 0.03 nm that is close to the Fourier limited for the expected FEL pulse length (<100fs). The fluctuation of the measured FEL intensity (*red line*) is about 15% rms.

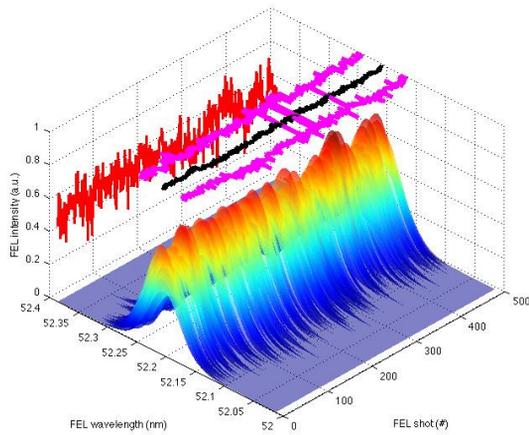


Figure 1: FEL spectra measured at 52.2 nm.

**Tunability and Polarization**

Fine FEL wavelength tuning is achieved by tuning the seed laser wavelength typically by 1 nm, i.e. 0.4 % as shown in Figure 2 that reports the measurement by the LDM-Citius collaboration of the resonant absorption line of the *He 1s-4p* transition around 52 nm.

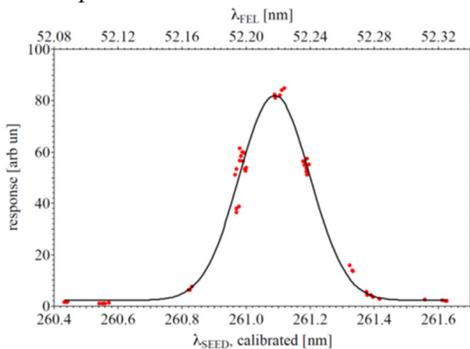


Figure 2: Fine FEL tunability.

In order to tune the FEL over a wider spectral range, for instance from 30 to 60 nm, the seed laser has been equipped with an Optical Parametric Amplifier (OPA).

The seed laser wavelength and the harmonic number can be selected via the control system. FEL optimization requires few minutes for each new wavelength.

Variable polarization of the emitted radiation was tested as well. Test experiments on the beamlines were performed both in circular and linear polarization.

**Transverse Coherence**

Double slit experiments performed at 32.5 nm show a very good degree of transverse coherence, confirmed by the high fringe visibility along the entire FEL pulse.

Thanks to the high degree of transverse coherence, along with a good focussing spot on the sample, the DiProI team successfully performed the first single shot Coherent Diffraction Imaging experiment last March. The collected diffraction pattern encodes the structural information of the sample. From the diffraction pattern one can reconstruct the shape of the scattering object with high spatial resolution by using computational algorithms. The reconstructed image of a nanolithographic sample of the FERMI@Elettra logo is shown in Figure 3.

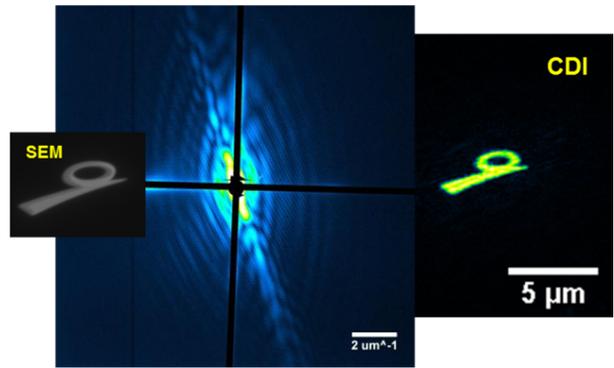


Figure 3: CDI experiment with a Fermi logo as sample.

**RECENT PROGRESS**

All the previously mentioned results have been obtained on FEL-1 with a machine configuration still in progress, the main limitation being the operation at reduced peak current with respect to the nominal value of 800 A. This limitation should soon be overcome by completing the commissioning of the laser heater system and of the X-band linearizing system, which started only recently.

**Laser Heater (LH)**

The LH consists of an undulator located in a magnetic chicane where a Ti:Sa laser induces a sinusoidal energy modulation on the electron beam. At the end of the chicane the modulation is converted to uncorrelated slice energy spread, whose net increase may suppress micro-bunching instability arising during compression.

Aiming for higher compression factors and higher bunch charges to increase the peak current, priority has recently been assigned to the commissioning of the LH. After few shifts of systems checks, evidence of significant beam heating could be observed up to an energy spread of 100 keV at 160 MW of laser power. Figure 4 shows the

longitudinal phase space of the heated beam, vertically dispersed by the high energy RF deflector, measured in the spectrometer at the linac end.

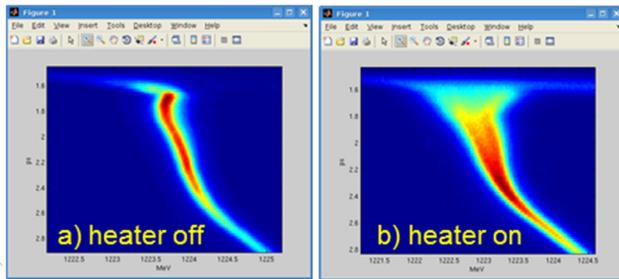


Figure 4: beam heating with the laser heater.

### X-band Linearizing System

The installation and high power RF processing of the linearizing system at the 4<sup>th</sup> harmonic of the RF frequency was completed in mid-February 2012 [5]. The system is based on a XL5 klystron built by SLAC, operating at the European frequency of 11.992 GHz. The required accelerating voltage is about 20 MV/m, which needs 20 MW of RF power at the cavity input. On February 27<sup>th</sup> the RF cavity was activated for the first time, and the linearizing effect shown in Figure 5 could be observed [6].

Correspondingly the compressed bunch profile is flattened as expected. Significant beam energy jitter is however still noticed, inducing accordingly oscillations in the bunch compression factor. This is due to a preliminary set-up of the low level RF control system for the X-band cavity; final system shall be available in summer 2012.

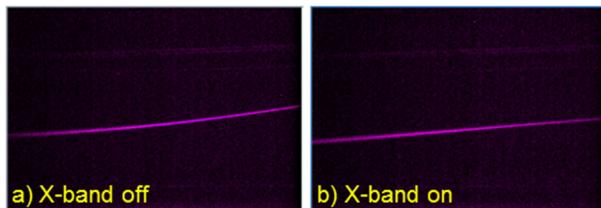


Figure 5: The linearizing effect of the X-band cavity.

### e-beam Transport along the FEL-2 Line

After completing the installation of the FEL-2 transport line in January 2012, its commissioning started at the beginning of February. At the time no undulators were installed yet, in order to avoid the risk of radiation damage to their magnetic structure during *e*-beam transport steering. In few shifts it was possible to get transport rates close to 100 % along the FEL-2 line, with 350 pC of bunch charge. Hence the undulators of FEL-2 were installed during the Easter shutdown in April.

### FUTURE PLANS

There are two main goals for Fermi in 2012, namely the start of the user program on FEL-1 and the first FEL-2 radiation production by the HGHG double cascade.

The first call for external proposals was published end of December 2011 and more than thirty proposals were submitted by the deadline at the end of April. The

selection process will be completed in June. Beamtime for selected proposals will be assigned on FEL-1 in autumn 2012.

As for FEL-2, following the installation of the undulators, in May the first evidence of CHG is expected from the first stage (planar modulator plus two APPLE-II type undulators). In September we expect to complete also the installation of the photon front-end of FEL-2, which merges with the FEL-1 line in front of the spectrometer. During the October run the HGHG double cascade will then be commissioned, including the FEL optimization by using the fresh part of the bunch, at 17 nm, a wavelength compatible with 1.2 GeV electron beam energy. In 2013 the linac energy will increase to 1.5 GeV, by full activation of the SLED doubling cavities, in order to reach 4 nm, i.e. the lower wavelength limit for FEL-2.

The repetition rate of the facility will be upgraded in 2013 from 10 Hz up to 50 Hz upon the installation of the new photocathode gun and the completion of the upgrade program of the linac modulators.

An intense development program of the beamlines is also ongoing, including, among others, the construction of the second EIS beamline, TIMER, and the installation of the user laser for pump and probe experiments. First test experiments with FEL-2 are foreseen in 2013.

### CONCLUSIONS

FEL-1 has already reached fairly intense photon fluxes, producing routinely 20-30  $\mu$ J, which corresponds to a factor 3 to 5 less than the final goal. This limitation is mainly due to the reduced peak current intensity, due to a still evolving machine. As soon as both the X-band cavity and the laser heater now under commissioning reach their nominal performance, we expect to increase the peak current in a stable and reliable way and to attain the nominal photon flux intensity.

Good single shot spectra are obtained, showing single narrow emission and excellent central wavelength stability. A very good degree of transverse coherence has been observed. FEL tunability and variable polarization have been successfully operated.

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