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THE FERMI SEEDED FEL FACILITY: OPERATIONAL EXPERIENCE AND FUTURE PERSPECTIVES

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Abstract

FERMI is the seeded FEL user facility in Trieste, Italy, producing photons from the VUV to the soft X-rays with a high degree of coherence and spectral stability. Both FEL lines, FEL-1 and FEL-2, are now available for users, down to the shortest wavelength of 4 nm. We will report on the completion of the commissioning of the high energy FEL line, FEL-2, and on the operational experience for users, in particular those requiring specific FEL configurations, like two-colour experiments. We will also give a perspective on the improvements and upgrades which have been triggered by our experience and are aiming to maintain as well as to constantly improve the performance of the facility for our user community.

INTRODUCTION

FERMI [1] has been operating for external users since December 2012, on the VUV to EUV FEL-1 line, covering photon energies between 12 eV and 62 eV [2]. High degree of longitudinal and transverse coherence, tunability, spectral stability with pulses close to the Fourier limit, very low time jitter synchronization to an optical pump laser are among the distinguishing features that make this facility very attractive for the scientific community. The capability of controlling the radiation polarization is another of the unique characteristics of FERMI; a characterization of the degree of polarization in various configurations has recently been reported in [3].

The EUV to soft X-rays photon energy range is covered by the FEL-2 line (62 eV to 310 eV). As a very important milestone, in September 2014 the energy per pulse reached the nominal expected intensity, 10 μJ at 4 nm, the shortest wavelength. The spectral quality and operability characteristics of FEL-2 are similar to those typical of FEL-1, even if an upgrade program has been started to guarantee the same robustness, reliability and flexibility that the user community experiences on FEL-1.

Three beamlines, each equipped with an experimental station, are now opened for users: Diffraction and Projection Imaging (DiProI), Elastic and Inelastic Scattering TIMEX (EIS-TIMEX), Low Density Matter (LDM). Three more will be available for users in 2016.

FEL-2 COMMISSIONING RESULTS

In order to efficiently seed the electron beam at short wavelengths, FEL-2 is based on a double stage cascaded HGHG scheme. The external laser seeds the 1st stage that consists of a modulator and a two sections radiator; the photon pulse generated in the 1st stage seeds the 2nd stage, made by a second modulator and a six sections radiator. The magnetic chicane after the 1st stage delays the electron beam with respect to the photon pulse, to shift the seed generated in the 1st stage onto fresh electrons.

First lasing of FEL-2 was successfully demonstrated in October 2012 at 14.4 nm [4]. The performance of FEL-2 was then progressively optimized and extended to shorter wavelengths until in September 2014, finally, nominal operating conditions were attained at the lower edge of the wavelength range of FEL-2, namely 4.0 nm [5]. Main parameters for FEL-2 are listed in Table 1.

Table 1: FEL-2 Main Parameters

Parameter	Value
Beam Energy (GeV)	1.0 - 1.5
Peak Current (A)	700 - 800
Repetition Rate (Hz)	10 - 50
Wavelength range (nm)	20 - 4
Polarization	variable
Expected pulse length (fs)	< 100
Energy per pulse (μJ)	up to 100 (~10, 4 nm)
Typical rel. bandwidth % rms	~0.03 (~0.07, 4 nm)
Shot to shot stability % rms	~25% (~ 40%, 4 nm)

This result was achieved after an accurate machine optimization, by setting the peak bunch current to 700 A, the beam energy at 1.5 GeV, keeping the emittance around 1.5 mm mrad for a properly matched beam at the

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undulator entrance and finally by an accurate trajectory control. The FEL spectral line shapes show very high quality and the transverse profile is very close to the TEM00 Gaussian mode. The spectral quality of FEL-2 at 5.4 nm is shown in Fig. 1, which, along with a single shot spectral image on the right, shows the relative line-width distribution over about 500 spectra. The harmonic conversion from 260 nm is 12*x*4, the 1st stage lasing at 21.7 nm and the 2nd stage tuned at its 4th harmonic.

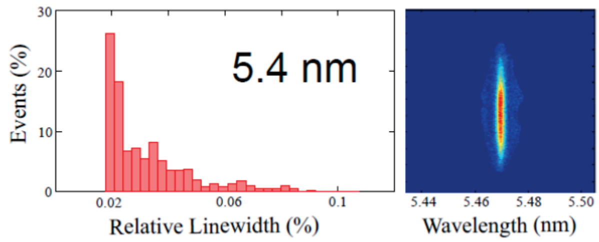

Figure 1: FEL-2 spectrum at 5.4 nm.

At 4 nm the FEL tuning is more critical and the average line-width is three times larger than at 5.4 nm. Based on the observed performance of FEL-2 at 4.0 nm, an upgrade plan has been decided, as described later.

OPERATION FOR USERS

FERMI operates for about 6.500 hours a year; the rest of the time is dedicated to maintenance and upgrade activities [6]. Operation hours were 6640 in 2014, of which 2848 hours for users (43%), 1120 hours (17%) for machine tuning, 2672 hours (40%) for commissioning. During routine operation for users the average FEL availability compared to the scheduled beamtime attained 86.1%, thus improving from the 84.3% mark in 2013. Beside internal beamtimes, 16 peer reviewed experiments were completed. Based on the complexity of the specific experiment, its duration can vary between 3 and 6 days (with an average of about 5 days). As we are approaching the conclusion of commissioning, the time dedicated to user experiments is increasing, up to 55% of the operation time in 2015, with 19 allocated experiments (16 in 2014).

In October 2014 the 4th call for proposals was published and it was opened both on FEL-1 and FEL-2. At the deadline in January 2015 68 proposals were submitted, 30% on FEL-2. The expected number of allocated proposals is between 16 and 20, i.e. an oversubscription factor close to 4 (was 3.1 for the 3rd call). A more efficient operating schedule, based on a weekly turnover between the experimental stations, is considered. The preparation time for a standard experiment is between 1 and 2 days.

The total number of proposals submitted on FERMI to the four calls opened so far from 2012 to 2014 is 193, 76 on DiProI, 55 on EIS-TIMEX and 62 on LDM. About 35% of the proposers are from national institutions, 65% from international ones. The larger foreign community comes from Germany and accounts for 25% of the total.

SPECIAL USER MODES

Special user modes have been developed at FERMI to offer to the scientific community non-standard operation of the FEL, either at wavelengths below the nominal spectral range of FEL-1 [7] or new pump-probe schemes with two FEL pulses produced by the same electron beam [8, 9, 10]. These schemes are possible thanks to the flexible layout of FEL-1 that allows the generation of pairs of FEL pulses with very high degree of coherence.

However, special user modes require careful optimization of all systems involved in the FEL process and close collaboration between scientists and machine experts, in order to define the best strategy to achieve the experiment goal. Therefore the preparation time can be as long as one week; thus only a limited number of experiments of this category can be allocated per year.

Special optimization of the electron beam and the FEL parameters allowed generating coherent radiation from FEL-1 at 12 nm, well below the nominal spectral range, to perform user experiments with 10 µJ energy per pulse.

After the pioneer two colour FEL-pump/FEL-probe experiment successfully done in 2012 [8], a new FEL configuration allowing two colour operations with a wide spectral separation between the two FEL pulses has been proposed and successfully used for experiments on DiProI by M. Sacchi (CNRS-SOLEIL) last November. In this configuration, two seed laser pulses with slightly different wavelength and a controllable delay interact with the same electron bunch. The final radiator is divided in two sections tuned at two different harmonics of the two seed lasers (Fig. 2a). Coherent emission is produced by each of the two bunched portions of the beam in only one of the two radiator segments, generating two temporally and spectrally separated pulses (Fig. 2b and 2c).

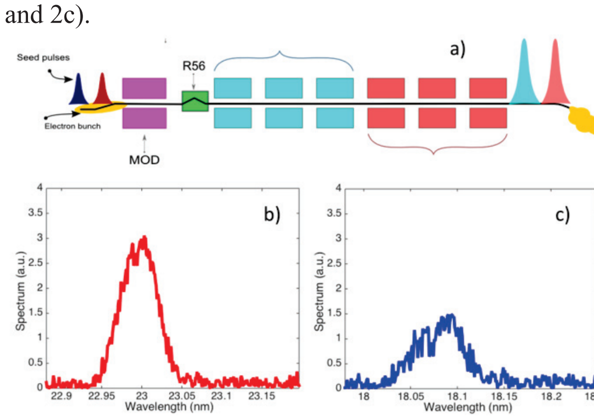

Figure 2: Layout used for two colour FEL operations (a) and measured spectra for the two FEL pulses (b, c).

UPGRADE PROGRAM

LINAC

The nominal beam energy of the FERMI LINAC is 1.5 GeV, which is the working energy for the electron bunches for nominal lasing at 4 nm. Two additional accelerating structures are under construction by Research Instruments GmbH to add operational margin and to improve the beam quality at low energy. The accelerating structures will be 3-meter long, constant gradient, equipped with symmetric input and output couplers and

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will replace the two single feed structures present in the 100 MeV injector part. The two removed sections will be reinstalled in the high energy part of the LINAC, where space and RF power are already available. [11]

The two new structures are presently being brazed, and the first stacks are ready; their delivery is foreseen in June 2015. Afterwards they will be tested under high RF power in the Cavity Test Facility in the LINAC tunnel. Final installation is foreseen in the winter shutdown and commissioning with beam, up to 1.65 GeV, will then start in February 2016. Actions to improve the uptime of the RF plants are as well ongoing, as described in [12].

FEL-2

As reported previously, FEL-2 reached in September 2014 the nominal energy of 10 µJ at 4 nm. However, to reduce the required seed energy and ensure on FEL-2 similar performances in terms of continuous tunability and operability as on FEL-1, a third undulator section will be added to the radiator of the 1st stage of FEL-2. It will allow to extract higher energy per pulse from the 1st stage at equivalent seed power or, viceversa, to reduce the required seed power to reach an equivalent seed pulse energy for the 2nd stage. The latter will therefore open the possibility of using a tunable seed laser based on an optical parametric amplifier [13] on a wider range of seed wavelengths. The stringent requirements on the electron beam quality will be relaxed as well, in favour of long term stability.

This upgrade was indeed foreseen in the original design; there is thus space for an additional 2.5 m long Elliptically Polarized Undulator (EPU), 55.2 mm period length, 10 mm gap, equal to the other two EPUs of the FEL-2 1st stage. It is under construction by Kyma srl, with delivery scheduled within 2015, installation in the tunnel in January and commissioning with beam in March 2016.

SEED LASER

The addition of a second regenerative amplifier to the seed laser system, sharing the same femtosecond oscillator with the existing amplifier, will improve the quality of the laser pulse for seeding FEL-2, leading to an improvement of the FEL quality and flexibility. The main features of the new regenerative amplifier are a shorter pulse duration in fixed wavelength (800 nm) mode, i.e. less than 50 fs FWHM, and a central wavelength tunability within ±2%. It will also improve the energy and pulse duration parameters of the optical laser pulse that is delivered with extremely low jitter, less than 7 fs rms [14], to the experimental stations for pump-probe experiments, removing also any limitation on the optical laser to FEL pulse delay time.

THREE NEW BEAMLINES

EIS-TIMER

The EIS-TIMER beamline will offer experimental methods based on Four-Wave-Mixing (FWM) processes. In July 2014 a dedicated compact experimental set-up ("*mini-TIMER@DiProI*"), shown in Fig. 3a, was installed on DiProI to demonstrate how the coherent FEL pulses delivered by FERMI can generate transient gratings (TGs) in the EUV range and how such TGs, when illuminated by an optical laser pulse, can stimulate an appreciable FWM response [15]. The latter has the form of a well-defined beam (Fig. 3b) that propagates downstream the sample along the phase matched direction (k_{out} in Fig. 3c).

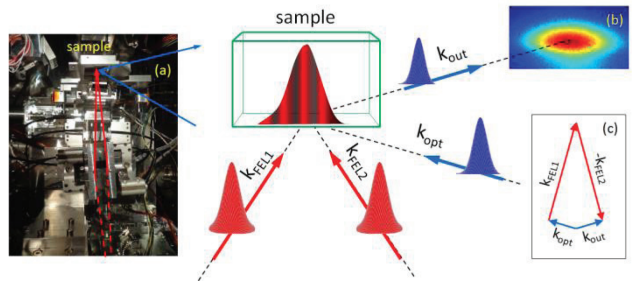

Figure 3: *miniTIMER* set-up (a) and results (b and c).

This result is a fundamental milestone for more advanced EUV/soft X-ray FWM applications and the first validation of the EIS-TIMER beamline concept.

The EIS-TIMER beamline installation is under completion in the FERMI experimental hall. The first test experiment is planned in July 2015; further test experiments will be scheduled in the following months and the beamline will open to the users in 2016.

TeraFERMI

TeraFERMI will collect the THz radiation naturally emitted by the electron beam already spent by the FEL undulators and will guide it into a dedicated THz laboratory in the FERMI experimental hall. Ultrashort (100's fs) pulses in the 0.1-15 THz range with 1-10 MV/cm electric fields and 0.3-3 Tesla magnetic fields will then become available. The TeraFERMI source chamber has been installed in January 2015. The installation of the beamline will start next summer.

The first photons are expected for autumn 2015.

MagneDyn

MagneDyn is the beamline for time resolved magnetic dynamics studies and, differently from other beamlines, it will receive photons only from the FEL-2 source, since the main scientific interest is in the soft X-ray energies, even from the third harmonic radiation. MagneDyn construction is ongoing and it will see its first photons in the second semester of 2016.

CONCLUSION

The two FEL lines of FERMI, covering the spectral range between VUV to soft X-rays, are now both open for users. Thanks to the excellent FEL spectral stability and quality, the high degree of coherence and the flexibility of the source, the number of users is steadily increasing.

The offer in terms of experimental stations will be increased from three to six in 2016. A short-term upgrade plan has been activated to further improve the robustness and the reliability of the facility.

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