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 available for users, down to the shortest wavelength of 4 nm. We report on the completion of the commissioning of the high energy FEL line, FEL-2, on the most recent progress obtained on FEL-1 and on the operational experience for users, in particular those requiring specific FEL configurations, such as two-colour experiments. We will also give a perspective on the improvements and upgrades which have been triggered based on our experience, aiming to maintain as well as to constantly improve the performance of the facility for our user community.

INTRODUCTION

The distinguishing features that make the FERMI FEL facility [1-3] attractive for the scientific community are the wavelength tunability, the spectral stability, the high degree of longitudinal and transverse coherence with pulses close to the Fourier limit. The capability of providing pulses with different polarizations in various controllable configurations [4,5] and the availablility of a synchronized user laser (IR &UV) with very low time jitter with respect to the FEL pulses [6], are other important and unique characteristics of FERMI.

FERMI FEL-1, the VUV to EUV line covering photon energies between 12 eV and 62 eV [2], has been operating for external users since December 2012. FEL-2, covering the EUV to soft X-rays photon energy range (62 eV to 310 eV) [3], reached in September 2014 the nominal energy per pulse of 10 μJ at the short-wavelength end of the spectral range (4 nm) [7] and is now also available for user experiments. In optimized conditions the spectral quality and operating characteristics of FEL-1 and FEL-2 are similar, with the latter more critical in terms of tuneup and stability requirements. An upgrade program has been started to guarantee for FEL-2 the same robustness, reliability and flexibility of FEL-1.

Three beamlines, each one with its own experimental station, are open for users: Diffraction and Projection Imaging (DiProI) [8], Elastic and Inelastic Scattering TIMEX (EIS-TIMEX) [9], Low Density Matter (LDM) [10]. Three more will be available for users in 2016.

FEL-2 COMMISSIONING RESULTS

In order to efficiently seed the electron beam at low 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 radiator with two sections; the photon pulse generated in the 1st stage seeds the 2nd one, consisting of a second modulator and a radiator with six sections. The magnetic chicane after the 1st stage delays the electron beam with respect to the photon pulse, so that the latter overlaps with fresh electrons.

First lasing of FEL-2 was successfully demonstrated in October 2012 at 14.4 nm and 10.8 nm [3]. The performance of FEL-2 was extended to progressively shorter wavelengths and optimized during the following commissioning periods. In September 2014 specified operating conditions were attained at the lower end of the nominal wavelength interval of FEL-2, namely 4.0 nm [7]. These performances were confirmed in March 2015. These results were achieved after an accurate machine optimization, by setting the peak bunch current to 700 A and the beam energy at 1.5 GeV, by keeping the emittance around 1.5 mm mrad for a properly matched beam at the undulator entrance and by an accurate control of the beam transport along the undulators. The main parameters of FEL-2 are listed in Table 1.

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The spectral quality of FEL-2 at 5.4 nm and at 4 nm is shown in Fig. 1. The FEL spectral line shapes show very high quality and the transverse profile is very close to the TEM_{00} Gaussian mode.

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%(~30%, 4 nm)

At 5.4 nm the harmonic conversion is 12x4, the 1st stage being seeded at 261 nm and the 2nd stage seeded at 21.7 nm and tuned at its 4th harmonic. At 4.0 nm the conversion factor is 13x5.

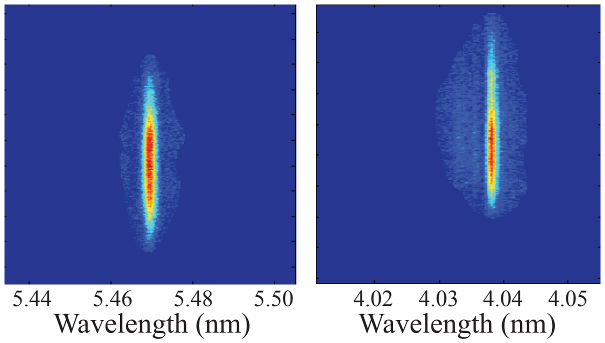

Figure 1: FEL-2 spectrum at 5.4 nm and at 4.0 nm.

In March 2015 in the same configuration at 4 nm an energy stability (rms) of about 30% (see Fig. 2) was achieved. At 4 nm the FEL tuning is more critical and the average line-width is larger than at 5.4 nm. In addition it is not straightforward to achieve simultaneously top energy figures and minimum shot to shot fluctuations together with good spectral linewidth performances. Based on the experience on FEL-2 at short wavelength, a series of upgrades has been initiated as described later.

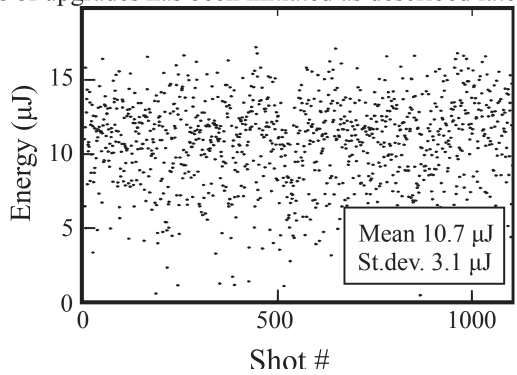

Figure 2: FEL-2 pulse energy.

FEL-1 RECENT EXPERIENCE AND SPECIAL USER MODES

The recent developments on FEL-1 were focused on the characterization and control of the source properties, in particular in terms of polarization [4,5] and pulse/coherence, showing the possibility to tailor the spectro-temporal content of the light pulses [11]. Concerning the latter, we also implemented a SPIDER [12-14] setup for the reconstruction, both in the temporal and spectral domains, of the envelope and phase of pulses generated by the FEL. The method is based on seeding the FEL with two identical replicas of a seed pulse to generate two FEL pulses, shifted in frequency relative one another, by an appropriate electron phase space energy-time quadratic curvature. SPIDER phase interferometry was then used to reconstruct the pulse properties (duration of about 71-73 fs, with deviation of 1.1-1.2 from the Fourier limit) [15]. Some of these studies were also carried out on the first stage of FEL-2, which has identical parameters to those of FEL-1 except for a reduced number of radiators.

Special user modes have been developed to offer to the scientific community extended operating conditions of the FEL with respect to the nominal design parameters, either in terms of wavelengths below the nominal spectral range [16], or in terms of pulse tailoring, with two FEL pulses produced by the same electron beam [17, 18, 19] for pump and probe experiments. Special optimization of the electron beam and of the FEL parameters allowed generation of coherent radiation from FEL-1 at 12 nm, well below its nominal spectral range, to perform user experiments with 10 μJ energy per pulse. After the pioneering two colour FEL-pump/FEL-probe experiment in 2012 [17], a new FEL configuration allowing two colour operations with a wide spectral separation between the two FEL pulses has been proposed and successfully used in experiments [20]. In this configuration, two seed laser pulses with slightly different wavelengths and a controllable delay interact with the same electron bunch. The final radiator is divided into two sections tuned at two different harmonics of the two seed lasers (Fig. 3a). Coherent emission is produced by each of the two bunched portions of the beam in only one of the two

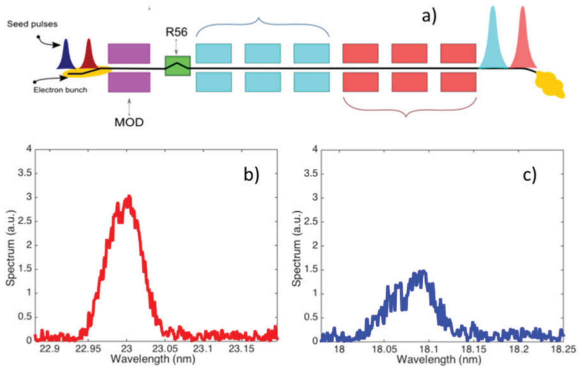

Figure 3: Layout used for two colour FEL operation (a) and measured spectra for the two FEL pulses (b, c).

radiator segments, generating two temporally and spectrally separated pulses (Fig. 3b and 3c).

Notwithstanding the high gain harmonic generation configuration of FERMI, it is also worth mentioning that lasing in SASE Optical Klystron mode was demonstrated [21]. This configuration is considered as an interesting back-up solution when the seed laser is, for any reason, unavailable.

OPERATION FOR USERS

FERMI operates for about 6500 hours a year; the rest of the time is dedicated to maintenance and upgrade activities [22]. In 2014 60% of the operation time was dedicated to users activities, one quarter of which was devoted to tuning and setting up the FEL and the beamlines. In the remaining 45% of total operation time the facility ran routinely for user experiments, with 86% average FEL uptime availability (with respect to the ideal 100% of the scheduled beamtime), thus improving from the 84.3% value in 2013. Besides 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. In 2015 it will reach 55% of the total operation time; the number of allocated experiments will increase from 16 to 19 in 2015.

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 had been submitted, 30% on FEL-2. The expected number of allocated proposals is 21, i.e. an oversubscription factor 3.3 (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 "special" user modes described in the previous section 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 experimental goals. 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.

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 largest foreign community comes from Germany and accounts for 25% of the total.

UPGRADE PROGRAM

LINAC

The present maximum beam energy of the linac is 1.55 GeV (1.5 GeV with a compressed beam) [23]. Two additional accelerating structures by Research Instruments GmbH will be installed to increase the maximum beam energy to 1.65 GeV and to improve the beam quality at low energy [24]. The accelerating structures are 3-meter long, constant gradient, with symmetric input and output couplers and will replace the two single feed structures present in the 100 MeV injector part. The two existing sections will be reinstalled in the high energy part of the LINAC, where space and RF power are already available. Final installation is foreseen in the winter shutdown and commissioning with the increased beam energy will start in February 2016.

FEL-2

In order to reduce the required seed energy and ensure for FEL-2 similar performances in terms of continuous tunability and operability as FEL-1, a third undulator section will be added to the radiator of the 1st stage of FEL-2. This configuration was already foreseen in the original design and space to accommodate the additional undulator is available. The upgrade will allow extraction of higher energy per pulse from the 1st stage at equivalent seed power or alternatively 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 the OPA seed laser amplifier with a wider range of seed wavelengths. The stringent requirements on the electron beam quality will be relaxed as well.

The new section is a 2.5 m long Elliptically Polarized Undulator (EPU), 55.2 mm period length, 10 mm minimum gap, the same as the other two EPUs of the FEL-2 1st stage. It is under construction by Kyma srl. Delivery is scheduled in 2015, the installation in tunnel in January 2016 and the commissioning with beam in March.

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 new regenerative amplifier main features 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 seed laser pulse. This pulse is delivered with extremely low jitter, less than 7 fms rms [6], to the experimental stations, for pump-probe experiments, and the upgraded system will extend the available range of delays between the FEL pulse and the optical laser pulse.

THREE NEW BEAMLINES

EIS-TIMER

The EIS-TIMER beamline will offer an experimental method based on a Four-Wave-Mixing (FWM) process. In July 2014 a dedicated compact experimental set-up ("*mini-TIMER@DiProI*"), shown in Fig. 4a, was installed

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on DiProI to demonstrate how the coherent FEL pulses delivered by FERMI can generate transient gratings (TGs) in the extreme ultraviolet range and how such TGs, when illuminated by an optical laser pulse, can stimulate an appreciable FWM response [25]. The latter has the form of a well-defined beam (Fig. 4b) that propagates downstream of the sample along the phase matched direction (k_{out} in Fig. 4c). This result is a fundamental milestone for more advanced EUV/soft X-ray FWM applications and a first validation of the EIS-TIMER beamline concept.

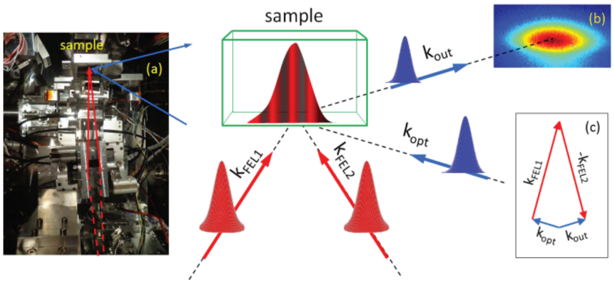

Figure 4: *miniTIMER* set-up (a) and results (b and c).

The first test experiment on EIS-TIMER beamline was performed in July 2015. The beamline will open to the users in 2016.

TeraFERMI

TeraFERMI will collect the THz radiation naturally emitted by the spent electron beam that exits 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 field will then become available. The TeraFERMI source chamber was installed in January 2015. The optical layout and beamline design are completed and the installation started in July 2015. 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, including the weaker radiation at the third harmonic of FEL-2 undulators.

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

The available experimental stations will be increased from three to six in 2016. A short-term upgrade plan is being implemented to further improve the robustness and the reliability of the facility.

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