FERMI STATUS REPORT

M. Svandrlik[#], E. Allaria, F. Bencivenga, C. Callegari, F. Capotondi, D. Castronovo,
P. Cinquegrana, M. Coreno, R. Cucini, I. Cudin, M.B. Danailov, G. D'Auria, R. De Monte,
G. De Ninno, P. Delgiusto, A. Demidovich, S. Di Mitri, B. Diviacco, A. Fabris, R. Fabris,
W. M. Fawley, M. Ferianis, E. Ferrari, P. Finetti, L. Fröhlich, P. Furlan Radivo, G. Gaio,
D. Gauthier, F. Gelmetti, L. Giannessi, M. Kiskinova, S. Krecic, M. Lonza, N. Mahne,
C. Masciovecchio, M. Milloch, F. Parmigiani, G. Penco, L. Pivetta, O. Plekan, M. Predonzani,
E. Principi, L. Raimondi, P. Rebernik Ribic, F. Rossi, L. Rumiz, C. Scafuri, C. Serpico, P. Sigalotti,
C. Spezzani, C. Svetina, M. Trovò, A. Vascotto, M. Veronese, R. Visintini, D. Zangrando,
M. Zangrando, Elettra, Trieste, Italy

Abstract

FERMI, the seeded FEL located at the Elettra laboratory in Trieste, Italy, is now in regular operation for users with its first FEL line, FEL-1, which covers the wavelength range between 100 and 20 nm. We will give an overview of the typical operating modes of the facility for users and we will report on the status of beamlines and experimental stations. Three beamlines are now opened for users, three more are in construction. Meanwhile, the second FEL line of FERMI, FEL-2, a HGHG double stage cascade covering the wavelength range 20 to 4 nm is still under commissioning; we will report on the latest results in particular at the shortest wavelength, 4 nm in the fundamental.

INTRODUCTION

The facility covers the photon energy range between 12 and 310 eV thanks to two seeded FEL lines. The low energy FEL line, FEL-1 reaching up to 62 eV, is made by a single stage HGHG scheme, with a modulator undulator and a radiator with six undulator elements [1]. The high energy FEL line, FEL-2 which generates photons down to 4 nm wavelength in the fundamental and 1.3 nm in the third harmonic, is made by a double stage HGHG cascade, in which the first stage is presently made by a modulator undulator and two radiator modules, and the second stage by a modulator undulator and six radiator modules; the “fresh bunch injection” mode is used [2].

FEL-1 started operation for users in December 2012 and since then welcomed scientists from Italy and from all over the world to perform experiments on the three experimental stations so far available, namely the Diffraction Projection Imaging (DiProI) station, the Elastic Inelastic Scattering TIMEX (EIS-TIMEX) station and the Low Density Matter (LDM) station.

FEL-2 produced the first coherent photons at 14.4 nm in October 2012; that was the first experimental demonstration of a high gain seeded free electron laser configured as a two stages cascade operating in the "fresh bunch injection” mode [3]. Since then FEL-2 commissioning runs were performed in-between user operation runs on FEL-1. They allowed to gradually extend the wavelength reach of FEL-2, as can be seen for instance in Fig. 1 that shows the spectrum at 10 nm, until the nominal performance at 4 nm was attained last June.

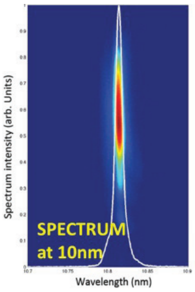

Figure 1: FEL-2 spectrum at 10 nm.

USERS OPERATION REPORT

Three calls for proposal of experiment on FERMI have been opened between 2012 and 2013. A total number of 125 proposals were received and 50 have been ranked by the FERMI Review Panel (FRP) for beamtime. In the 3rd call, 50 proposals have been submitted and 16 have been short listed in the FRP meeting of January 2014 for beamtime, that is, with an oversubscription rate of 3.13. Table 1 shows the standard parameters offered for experiments on FEL-1.

Table 1: FEL-1 Standard Parameters for User Operation

Parameter	**FEL-1**
Electron beam energy	1.0 - 1.4 GeV
Bunch charge	500 pC
Bunch Peak Current	400 – 600 A
Wavelength	100 – 20 nm
Energy per pulse*	30 – 200 μJ
Photons per pulse**	10^{13} at 20 nm
Intensity stability, rms	10%
Relative bandwidth	10^{-4}
Central wavelength stability	10^{-4} rms

**average, depending on wavelength and spectral purity.*
***up to 10^{14} at longer wavelengths.*

[#] michele.svandrlik@elettra.eu

ISBN 978-3-95450-133-5

The bar plot in Fig. 2 shows the natural increase of beamtime dedicated to users and the decrease of machine development (commissioning) time, as it has to be expected for a facility entering into its operational phase.

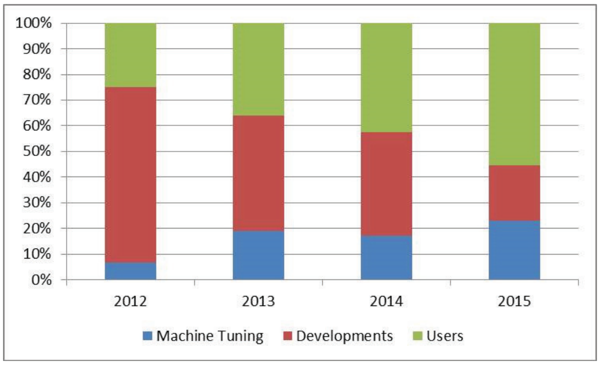

Figure 2: Operation hours distribution 2012-2015.

In 2013 the FERMI operation time attained almost 6500 hours, divided between time for linac, FEL-1 and FEL-2 commissioning and developments (55% of total hours) and time for users operation (45% of total). The latter includes machine tuning and beamline preparation time, beamtime for internal scientific groups and beamtime for external users assigned via the FRP. In total, during 2013 FERMI hosted 15 experiments that were peer reviewed by the FRP, pertaining to both the first and second call for proposals, equally divided between DiProI (5), EIS-TIMEX (5) and LDM (5). During 2014 the time for users operation will increase up to 60% of the total 6640 operation hours, leaving 40% for the developments still ongoing on FEL-2; 16 experiments will be hosted in 2014, namely 7 on DiProI, 2 on EIS-TIMEX and 7 on LDM. In 2015 the development time will be limited to 21% of the 6456 scheduled operation hours, while time for user operation will rapidly increase up to 79% of the total time, of which 55% is the portion of net time for experiments; 12 user experiments have been already allocated during the first semester of 2015.

The goal for the uptime of the FEL during user beamtime has been set at 80% of the scheduled operating hours. Figure 3 shows the actual achieved uptime during user runs, starting from run 14, December 2012, to run 20 that ended in July 2014. With the exception of run 17 in all other runs the uptime exceeded the goal; the recent trend is towards the 90% mark.

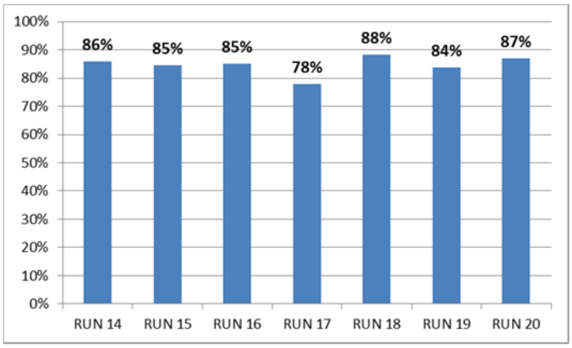

Figure 3: Uptime statistics December 2012 – July 2014.

Various actions have been launched to increase the reliability of some of the most critical systems, like the linac RF plants and the seed laser system, along with the aim to reduce the time needed for the optimization and fine tuning of the FEL parameters. For instance, after the installation of a new seed laser oscillator, with reduced phase noise, the seed laser system uptime is equal to 100%, along with a phase noise and jitter reduction by more than a factor of 3.

The time for optimization and fine tuning strongly depends on the FEL parameters requested by the users. For the standard operating conditions of FEL-1, listed in Table 1, the operability and reliability of the machine is very good and the uptime is close to 90%. However, a more complex set of FEL parameters can be requested by a given experiment. This is the case of the novel two colour FEL scheme, which is possible with a seeded FEL as FERMI [4], [5]. In this configuration, two FEL pulses, pump and probe, are generated by seeding the electron bunch with two laser pulses. Wavelength and intensity ratio between the two pulses, as well as the time delay between them can be controlled; the feature is that the two pump and probe pulses are practically jitter free. Figure 4 shows a typical spectrum of the two pulses. This configuration, of great interest for the FERMI users' community, may demand for longer machine preparation and optimization times, as it was the case in run 17 (see Fig. 3).

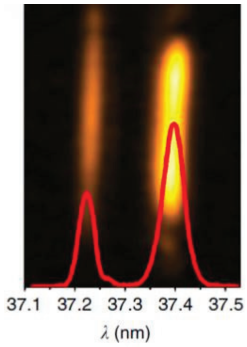

Figure 4: Typical double pulse spectrum.

Another way to perform time resolved experiments at FERMI is provided by transporting a portion of the IR seed laser pulse from the seed laser room down 150 m to the experimental stations. As shown in Fig. 5, low timing jitter is an intrinsic characteristic of the system, since the FEL is generated by the same seed pulse.

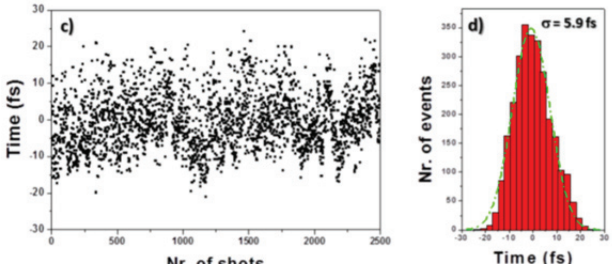

Figure 5: Typical jitter measurement at EIS-TIMEX.

Low jitter and high pointing stability along the transport line and in the distribution tables to the experimental stations are then ensured by advanced optical and mechanical design, along with sophisticated feedback loops. Figure 5 shows the measurement of the pump-probe time superposition at EIS-TIMEX, with an excellent jitter value of less than 7 fs rms [6].

FEL-2 ACHIEVES NOMINAL INTENSITY AT 4 NM

FEL-2 is based on a double stage cascaded HGHG scheme; the external seed laser, the third harmonic of a Titanium:Sapphire laser, seeds the first stage, made up of a modulator and a two segments radiator; the photon pulse generated in the first stage seeds the second stage, made up of a modulator and a six segments radiator. A delay line, made by a magnetic chicane after the first stage, allows to delay the electron beam with respect to the photon pulse. At the end of 2013, after three commissioning periods, FEL-2 was characterized at several harmonic transitions, in both stages, and at different electron beam energies, between 1.0 and 1.4 GeV. After first lasing at 14.4 nm in October 2012, later studies were carried out at 10.8 nm, where the energy per pulse achieved up to 100 μJ. Lasing was also observed at 6.5, 5.0 and 4.08 nm, even if at lower intensities. All studies were carried out with 500 pC electron bunch charge. Finally, in May 2014 it was possible to study the FEL-2 behaviour at the nominal electron beam parameters required for FEL-2 at 4 nm, as reported in what follows.

The run number 20 of FERMI started in May 2014. The first 7 weeks of the run are devoted to commission FEL-2 at its shortest wavelength, that is 4 nm (310 eV), with the electron beam parameters set to the nominal foreseen conditions, 1.5 GeV electron beam energy, 800 A peak current (800 pC extracted from the gun) and well controlled emittance and energy spread.

After few weeks of characterization and optimization, in particular of the beam trajectory across FEL-2, on the 6th of June we could produce FEL pulses at 4 nm with the expected average intensity of 10 μJ and some super-shots at 20 μJ. The first stage was tuned at the 13th harmonic of the seed laser, 20 nm, and the second stage at the 5th harmonic of the first stage (harmonic transition 13x5). Electron beam and FEL parameters are summarized in Table 2, while Fig. 6 shows the FEL-2 spot at 4 nm.

Table 2: FEL-2 Parameters, May – June 2014

Parameter	FEL-2
Electron beam energy	1.5 GeV
Bunch charge	800 pC
Bunch Peak Current	800 A
Wavelength	4 nm
Energy per pulse, average	10 μJ

In summary, a nicely optimized electron beam, with bunches of 800 pC charge and 800 A peak current allowed us to reach peak pulse intensities larger than, 10 μJ at nm. At wavelengths between 5 and 6 nm we could achieve even higher intensities, up to a peak of 80 μJ at 5.9 nm. Third harmonic spectra could be measured both at 5.9 nm and 4 nm.

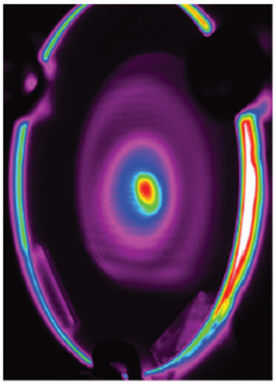

Figure 6: FEL-2 spot at 4 nm.

After the commissioning run, the first user experiment with photons generated by FEL-2 was performed at the EIS-TIMEX endstation [7]. FEL-2 was tuned at 12.4 nm central wavelength to study the Si $L_{2,3}$-edge. The wavelength was tunable by +/-0.5 nm thanks to the OPA installed in the seed laser set-up; both the first and second stage of the cascade. Energy per pulse was around 15 μJ and the spectral bandwidth was $5*10^{-4}$ rms. Machine uptime for this first user experiment on FEL-2 attained 85%, i.e. similar to the value usually obtained on FEL-1.

This is a remarkable improvement compared to the results obtained in 2013; based on these results, FEL-2 will be available for users in the next call for proposals, the fourth of the series, which will be opened on October 1st, 2014. Beamtime will be assigned to the selected proposals in the second semester of 2015.

NEW BEAMLINES AT FERMI

Three more beamlines are presently under construction and will be available for users at the end of 2015. They are EIS-TIMER, a Four-Wave-Mixing instrument, MagneDyn, that will allow to perform time resolved magnetic dynamics studies, and finally TeraFERMI, that will use the spent electron beam in the Main Beam Dump to produce femtosecond, high intensity (MV/cm), broadband (0.1 to 10 THz) TeraHertz pulses.

In the first days of July 2014 a proof of principle experiment of the Four-Wave-Mixing technique was performed by the EIS-TIMER scientific team [8], in collaboration with the DiProI scientific team, by carrying out a transient grating experiment on the DiProI station.

In this successful experiment, a FEL pulse was split in two and recombined at the sample with a finite crossing angle. This allowed the generation of a dynamic XUV grating, which was probed in a pump-probe, four-wave-mixing scheme by an optical pulse coming from the user laser, generated by the seed laser as previously explained. The coherent, non-linear, interaction of the three pulses originated a detectable coherent beam propagating along the phase matching direction, as shown in Fig. 7.

Such kind of non-linear XUV/soft x-ray wave-mixing experiments will be further developed in the EIS-TIMER dedicated beamline, also exploiting the unique capability of FERMI to radiate multi-colour seeded FEL pulses. The multi-colour transient grating approach will enable, for instance, to follow charge flows between constituent elements in molecules with femtosecond resolution, or to study energy transfer processes at the molecular scale.

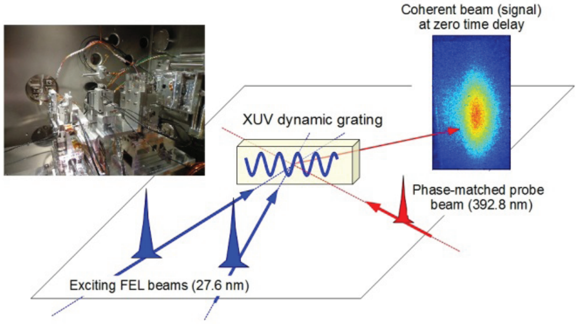

Figure 7: Four-Wave-Mixing experimental set-up and coherent beam signal.

MACHINE UPGRADE ACTIVITIES AND PLANS

Along with operation of FEL-1 and commissioning of FEL-2, the FERMI construction completion activities and the first upgrades are progressing. Three more beamlines are under construction and will be completed by 2015. Upgrades are now concentrated on the linac, which energy attained 1.56 GeV in September 2013. The new 50 Hz photocathode gun was installed and commissioned during 2013. Two more accelerating structures are in construction and will be installed during the winter shutdown 2015-2016, when also the final upgrade to 50 Hz operation will be completed. This will give operating margin on the nominal energy and is part of an upgrade program which has been launched to get an even more reliable and robust facility for our user's community.

The two new linac structures were designed to minimize phase and amplitude asymmetries in the coupler cells, in order to reduce the induced kick to the beam; they will gain 50 MeV each. They will replace the first two sections in the 100 MeV injector linac [9], that will then be relocated at higher energy where free spots in the layout and RF power plants are already available. This upgrade will increase the maximum linac energy to 1.65 GeV, beneficial both in terms of minimum wavelength achievable and of reliability and uptime. Furthermore, the beam quality at 100 MeV is expected to improve.

There is also a plan to profit of the free spots in the FEL-2 layout to upgrade it; namely there is space available to host a third undulator in the first stage radiator. This would bring advantages in terms of reliability and flexibility of FEL-2 operation. In fact, it would provide a higher energy per pulse from the first stage at an equivalent seed power; alternatively it would allow to reduce the required seed power to reach an equivalent seed pulse energy for the second stage.

Energy per pulse at the level of 10-15 μJ at 20 nm is required from the first stage to seed in best conditions the second stage tuned at 4 nm. During run 20 this was obtained with about 40 μJ of seed energy.

For nominal electron beam parameters, the use of an additional undulator in the first stage would allow to reduce the required seed power level by 30-50% depending on the final FEL wavelength. This would allow to operate with a lower seed power, opening to the possibility of using the OPA amplifier on a wider range of seed wavelengths and to reduce phase distortions associated to non-linear effects due to high seed laser intensity. In general this upgrade relaxes also the requirements on the electron beam, allowing more freedom in the selection of the region in the electron beam longitudinal phase space where the first stage seeding occurs.

To implement this upgrade an undulator of the same type of the two existing ones is needed, i.e., 55 mm period APPLE-II type.

CONCLUSION

FERMI is routinely operating for users with FEL-1. The number of hours dedicated to user experiments has been steadily increasing between 2012 and 2015.

FEL-2 has achieved the nominal energy per pulse at 4 nm. At the end of June 2014 the first user experiment on FEL-2, at 12.4 nm, has been performed. The fourth call for users, which will be published on the 1st of October 2014, will accept proposals both on FEL-1 and on FEL-2, so covering the full energy range foreseen on FERMI that is from 12 eV up to 310 eV.

An upgrade program to widen the experimental opportunities and to further increase the reliability, the robustness and the flexibility of the facility is ongoing, and will particularly be focussed on the linac and on the FEL-2 first stage configuration.

REFERENCES

[1] E. Allaria et al., “Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet”, Nature Photonics Vol 6, No 9 (2012); DOI:10.1038/nphoton.2012.233.

[2] B. Liu et al., “Demonstration of a widely-tunable and fully-coherent high-gain harmonic-generation free-electron laser” PRSTAB 16, 020704 (2013)

[3] W.M.Fawley, L. Giannessi et al., “Two-stage seeded soft-X-ray free-electron laser”, Nature Photonics (2013); DOI:10.1038/nphoton.2013.277.

[4] E. Allaria et al., “Two colour pump probe experiments with a twin-pulse-seed extreme ultraviolet FEL”, Nature Communications, Vol. 4 (2013) doi: 10.1038/ncomms3476.

[5] G. De Ninno et al., “Chirped Seeded Free-Electron Lasers: Self-Standing Light Sources for Two-Color Pump-Probe Experiments”, Phys. Rev. Lett. 110, 064801 (2013).

[6] M.B. Danailov at al., “Towards jitter-free pump-probe measurements at seeded free electron laser facilities”, Optics Express, Vol. 22 Issue 11, pp.12869-12879 (2014).

[7] E.Principi, private communication.

[8] F. Bencivenga, private communication.

[9] G. Penco et al., “Optimization of a high brightness photoinjector for a seeded FEL facility”, JINST, 8 P05015 (2013).

ISBN 978-3-95450-133-5