FERMI UPGRADE PLANS

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Abstract

FERMI has reached its nominal performance on both FEL lines, FEL-1 (12 eV to 62 eV) and FEL-2 (62 eV to 310 eV). After a brief overview of the activities with users, we will describe plans for LINAC, FEL and beamline upgrades for 2016-2018 and beyond. This includes EEHG schemes for FEL-2.

INTRODUCTION

FERMI is the seeded Free Electron Laser (FEL), operating in the VUV to soft X-rays range, located at the Elettra laboratory in Trieste, Italy [1]. FERMI is the only FEL user facility designed to operate in the seeded HGHG mode [2] and has successfully demonstrated operation from 100 nm down to 4 nm [3, 4].

The VUV to EUV FEL line, FEL-1, started operation with external users, i.e. selected by the FERMI Review Panel, in December 2012. Since then a period of actual commissioning of the source with users has been conducted, in a strong interaction between machine and laser team and the users. This resulted in proposing and implementing innovative solutions and schemes for pump-probe experiments. A portion of the seed laser is delivered as optical laser pulse to the experimental stations for pump-probe experiments with extremely low jitter to the FEL pulse, less than 7 fs rms [5]. Several schemes to produce two colour, FEL-pump and FEL-probe, pulses have been implemented [6-9]; the most recent FEL scheme makes use of two seed laser beams of different wavelengths and of a split radiator section to generate two extreme ultraviolet pulses from distinct portions of the same electron bunch [10].

A parameter under observation during user's beamtimes is of course the actual availability of the FEL compared to the scheduled time. The uptime has been always around 85% of the scheduled time and, thanks to some improvements on the machine systems, has lately attained 90%.

FEL-2 is the second FEL line of FERMI. It uses a double stage cascade scheme and the fresh bunch technique. First lasing was observed in 2012 [4] and the performance was gradually improved [11], in parallel to FEL-1 operation, until it reached nominal performances in 2014 [1]. The FEL emission of FEL-2 is characterized by excellent spectral line shapes and the transverse profile of the FEL pulses is close to the TEM_{00} Gaussian mode. At wavelengths below 5 nm the FEL tuning turned out to be critical, with large shot-to-shot energy fluctuations and with the necessity of a seed energy in excess of 40 μJ.

Based on the experience of the operation for users on FEL-1 and of the commissioning of FEL-2, and with the aim of increasing the uptime of the facility beyond the 90% mark, a number of upgrade actions have been activated in 2015 and are being planned for 2016-2018. These upgrades shall further improve the performance of FEL-1 in the various multicolour schemes and should allow on FEL-2 similar tuning possibilities as on FEL-1, along with improved stability and flexibility of operation.

OPERATION FOR USERS

FERMI has been in operation for 6528 hours during 2015; 3520 hours thereof, that is 54% of the total operation time, were dedicated to users with a clear increase compared to the 43% reached in 2014. The remaining time has been divided between machine commissioning (1312 hours equal to 20% of the total operation time; was 40% in 2014) and machine and beamlines tuning (1696 hours, equal to 26% of the total operation time; was 17% in 2014). The average FEL uptime for users in 2015 was equal to 88.0% of the scheduled FEL time, confirming the effectiveness of the constant effort in increasing the reliability of the machine. In fact, in 2014 the uptime was equal to 86.1% and in 2013 to 84.7%. In the last run of 2015, that lasted three months under continuous operation, a value of 91% was registered.

A total of 27 Users' beamtimes, 20 peer-reviewed and 7 in-house, were allocated on the three beamlines operated in 2015, namely Diffraction and Projection Imaging (DiProI, 12 experiments), Low Density Matter (LDM, 7 experiments) and Elastic Inelastic Scattering TIMEX

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(EIS-TIMEX, 6 experiments). In-house beamtimes in 2015 also included commissioning of the EIS-TIMER experimental station, which started in July [12] and continued in November, when the first evidence of a transient-grating signal was observed from a BaF_2 sample. Also the commissioning of the TeraFERMI beamline, that collects the THz radiation (ultrashort pulses in the 0.1-15 THz range) naturally emitted by the electron beam already spent by the FEL undulators, has started in December 2015 and the first THz photons have been observed. The sixth beamline at FERMI is MagneDyn, dedicated to the exploration of the ultimate limits of magneto-dynamic processes in conventional and advanced magnetic materials. This beamline is still under construction, with the commissioning expected to begin at the end of 2016.

After five calls the number of the submitted proposals by users requiring beamtime for experiments at FERMI is still steadily increasing. In the last call for experiments, at the beginning of February, 72 proposals were submitted, 21 of them are experiments using FEL-2. The estimated oversubscription rate is about 3.4.

UPGRADE RESULTS 2016

The first upgrade program started between 2014 and 2015, focused mainly on the LINAC and on FEL-2. The results collected in a dedicated commissioning period scheduled at the beginning of 2016 are discussed in the following sections.

LINAC

FERMI is driven by a 200 meter long S-band LINAC. In the injector region, two 3-meter long forward traveling wave accelerating structures, coming from the old Elettra injector, were installed. In order to improve the electron beam quality, it was decided to replace the first two existing structures with two dual-feed accelerating structures [13]. The structures were manufactured by Research Instruments GmbH and delivered to Elettra in July 2015.

Figure 1: The new accelerating structures in the injector.

After the high power testing in the FERMI cavity test facility, in January 2016 the structures were installed, on schedule, in the injector region, as shown in Fig. 1. The old structures were consequently moved into the high energy region of the LINAC to further increase the final energy by approximately 90 MeV.

In February 2016 normalized emittances of 0.7 and 0.9 mm mrad in the horizontal and vertical plane, respectively, were measured in the 100 MeV diagnostic section. These values at 700 pC are 10-15% smaller than the previous ones. Peak LINAC energies as high as 1629 MeV were measured. The maximum operating energy, with compressed and linearized electron beam phase space, at 700 A of nominal current, is about 1550 MeV (see Fig. 2).

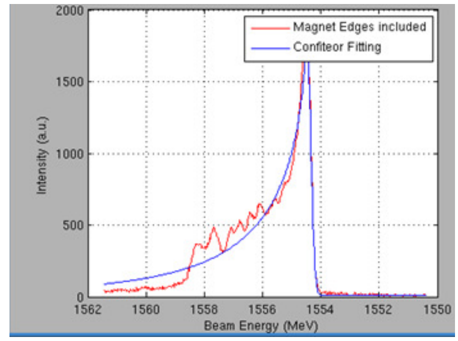

Figure 2: Maximum LINAC operating energy.

FEL-2

In 2014 the design parameters of FEL-2 were demonstrated down to the lower end of the wavelength range, 4 nm. However, it appeared evident that upgrades were needed to improve the stability and flexibility of FEL-2, and to achieve a frequency tunability similar to the one available on FEL-1 (OPA operation). The first of these upgrades addressed the LINAC energy, as described in the previous section. The second upgrade, specific to FEL-2, consists in the installation of a second regenerative amplifier. It produces a shorter seed pulse (infrared pulse duration less than 40 fs, 60-70 fs in the UV) that allows for better filling of the longitudinal phase space in fresh bunch mode. The laser also permits a wavelength tunability in the UV (+/-2%) allowing a limited FEL wavelength tuning with the third harmonic generation setup. As well a second OPA laser system was installed, so that double pulse seeding is possible on FEL-1 with two fully tunable sources. Another important upgrade of FEL-2 consists in the installation of a third Elliptically Polarized Undulator (EPU) in the radiator of the first HGHG stage of FEL-2, completing the design layout of this FEL line, shown in Fig. 3.

Figure 3: FEL-2 with the new installed EPU.

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The additional EPU reduces the seed energy required for operation in the shorter wavelength range, providing the possibility to operate with OPA laser system in a longer wavelength range. The EPU was built by Kyma srl with the same parameters of the two already existing ones: 55.2 mm period length, 42 periods, 10 mm gap.

In March 2016, after the upgrades, FEL-2 reached unprecedented shot to shot stability, below 6% rms at 4.2 nm, as shown in Fig. 4, and average intensity greater than 15 μJ/pulse. The energy requirement from the seed laser could be reduced to less than 20 μJ. The new undulator configuration also offers the flexibility to operate efficiently with different harmonic conversion factors, as 16x4 which is almost equivalent to 13x5 used in the past.

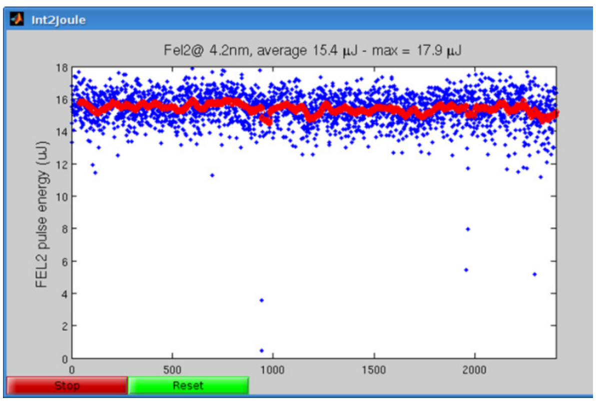

Figure 4: FEL-2 pulse by pulse intensity at 4.2 nm.

Reasonable energy per pulse was measured down to 3.8 nm. Radiation spectra could be measured in single shot even at harmonic 3.1 nm, as shown in Fig. 5.

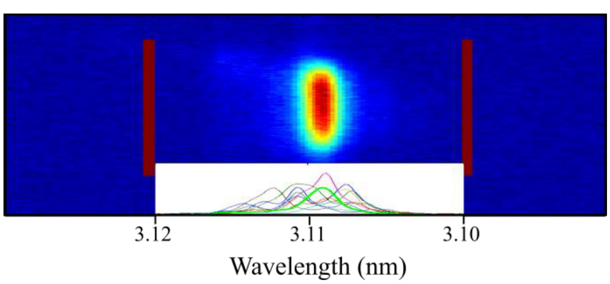

Figure 5: Single shot spectrum at harmonic 17x5=85.

The plots in the inset of Fig. 5 represent spectra from multiple shots during the same sequence. The green line is the projection of the single shot CCD acquisition displayed in the figure. The vertical axis represents the unfocused vertical distribution of the FEL pulse.

PLANS FOR THE NEAR FUTURE

The upgrade plans for 2017-2018 at FERMI foresee exploring the possibility of replacing the aging S-band Backward Traveling Wave structures (BTWs) of the LINAC and to implement the Echo Enabled Harmonic Generation scheme (EEHG) on FEL-2.

S-band High Gradient Structure Development

The high energy part of the LINAC is equipped with seven, 6 m long BTWs, of the old Elettra injector with small iris radius and nose cone geometry that allow for gradients up to 26 MV/m. Nonetheless, such a small iris radius leads to significant longitudinal and transverse wakefield effects that affect the beam dynamics, in particular at high bunch charges. Furthermore, BTWs suffer from increased breakdown phenomena when operated at the maximum gradient and at a 50 Hz repetition rate.

Therefore, a development of high-gradient S-band accelerating structures replacing the existing BTWs is under consideration. The gradient shall be larger than 30 MV/m, the iris radius not smaller than 10 mm and the electromagnetic design tailored for low breakdown rates. A reduced length (0.5 m) prototype will be constructed and tested at FERMI during 2017.

EEHG

The recent experience with FEL-1 operation for users showed several advantages from the seeded scheme adopted at FERMI. In addition to various schemes for two colour FEL operations for FEL-pump – FEL-probe experiments [6-10], schemes for phase control and phase locked double pulse operations have been proposed and demonstrated [14]. This second possibility, which is unique to FERMI, is attracting increasing interest from the scientific community.

Operation of FEL-2 in the present configuration, which is based on a double stage harmonic generation, has demonstrated to allow generation of powerful FEL pulses with tens of μJ down to 4 nm with single spectral mode, small relative bandwidth and good spectral stability. However, due to the complicated scheme, necessary for converting the long wavelength seed from the UV (260 nm) down to the soft x-ray (4 nm), FEL-2 in the present configuration is not suitable for implementing all new operational modes that have been successfully adopted on FEL-1.

These limitations should be overcome by adopting the EEHG scheme proposed in [15]. FERMI and FEL-2 parameters have already been shown to be suitable for an FEL operating with the EEHG scheme at 4 nm [16]. A limited number of modifications would be necessary to allow the implementation of EEHG on FEL-2, the main being a new undulator to be installed in place of the second modulator, to allow tuning the resonance to an optical UV laser. The EEHG scheme will be tested on FEL-2 in the first semester of 2018, in parallel to a FEL-1 user run.

CONCLUSION

FERMI operation for users since 2012 has been very successful and demonstrated the strong interest of the scientific community for using the facility. The results of the first upgrades executed in 2015 are very encouraging. The ambitious upgrade plans for 2016-2018 contemplate new high gradient S-band LINAC structures and EEHG scheme on FEL-2.

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