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STATUS AND PERSPECTIVES OF THE FERMI FEL FACILITY

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Abstract

FERMI is a seeded Free Electron Laser (FEL) user facility at the Elettra laboratory in Trieste, operating in the VUV to EUV and soft X-rays spectral range; the radiation produced by the seeded FEL is characterized by a number of desirable properties, such as wavelength stability, low temporal jitter and longitudinal coherence. In this paper, after an overview of the FELs performances, we will present the development plans under consideration for the next 3 to 5 years. These include an upgrade of the linac and of the existing FEL lines, the possibility to perform multi-pulse experiments in different configurations and an Echo Enabled Harmonic Generation (EEHG) experiment on FEL-2, the FEL line extending to 4 nm (310 eV).

INTRODUCTION

FERMI is located at the Elettra laboratory in Trieste. The FEL facility covers the VUV to soft X-ray photon energy range with two FELs, FEL-1 and FEL-2, both based on the High Gain Harmonic Generation seeded mode (HGHG) [1,2]. The HGHG scheme consists in preparing the electron beam phase space in a modulator where the interaction with an external laser induces a controlled and periodic modulation in the electron beam longitudinal energy distribution. The beam propagates through a dispersive section which converts the energy modulation into a density modulation. The density modulated beam is then injected in an amplifier where the amplification process is initially enhanced by the presence of the modulation. This HGHG scheme is implemented in FERMI FEL-1, to generate fully coherent radiation pulses in the VUV spectral range [3]. The seed signal, continuously tuneable typically in the range of 230-260 nm, is obtained from a sequence of nonlinear harmonic generation and mixing conversion processes from an optical parametric amplifier. The radiation resulting from conversion in the FEL up to the 13-15th harmonics is routinely delivered to user experiments [4]. The amplitude of the energy modulation necessary to initiate the HGHG process grows with the order of the harmonic conversion and the induced energy dispersion has a detrimental effect on the high gain amplification in the final radiator. During the past few years of operations, we have demonstrated the ability to operate the FEL at even higher harmonic orders with reduced performances, e.g., up to the 20th harmonic, but substantially higher orders can be reached with a double stage HGHG cascade, where the harmonic conversion is repeated twice. The double conversion is done with the fresh bunch injection technique [5] on FERMI FEL-2. The FEL is composed by a first stage, analogous to FEL-1, followed by a delay line, a magnetic chicane slowing down the electron beam with respect to the light pulse generated in the first stage. The light pulse from the first stage is shifted to a longitudinal portion of the beam unperturbed by the seed in the first stage. The light from the first stage functions as a short wavelength seed for the second stage. This scheme was implemented for the first time on FERMI FEL-2 [6] and was used to demonstrate the seeded FEL coherent emission in the soft-X rays, up to harmonic orders of 65, and more [7].

A first upgrade program of FERMI was completed beginning of 2016, with the installation of two new linac structures, an additional undulator segment for the radiator of the first stage of FEL-2, and a second regenerative amplifier for the seed laser system of FEL-2 [8]. After these upgrades the maximum attainable energy is 1.55 GeV for a “compressed” and “linearized” electron beam. The higher beam energy improved the performances of both the FELs, particularly for FEL-2 in the high end of the photon energy spectral range. FEL-2 has reached stable operation, with harmonic conversion factor 13 in the first stage and 5 in the second stage, at the shortest wavelength of the operating range of 4 nm. Since June 2016 the repetition rate of the source can be selected between 10 and 50 Hz. Two operation modes are foreseen: low and medium energy (electron beam energy up to 1350 MeV), at 50 Hz rep rate; high energy (1550 MeV) at 10 Hz rep rate. Harmonics of FEL-2 were measured down to 1.33 nm, as the third harmonic of the FEL tuned with the fundamental at 4 nm (this corresponds to harmonic 195 of the seed, see Fig. 2 below). In November 2016, it was possible to use at the DIPROI end-station, the 3rd harmonic of the FEL at the Cobalt L-edge, λ = 1.6 nm (778 eV).

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In the second semester of 2016 the peer reviewed user program started analysing experiments on FEL-2 and the first experiment at the carbon K-edge at about 4 nm was successfully carried out. In general, stable and reliable operating conditions have been established on both the FELs, providing high spectral quality FEL pulses to the users.

The present performance of the facility is quite mature. There is now a significant feedback from the user community about new science that could be targeted by an upgrade program focused on the next 3 to 5 years [9]. Developments are under consideration for the FEL source, addressing the possibility to produce short FEL pulses, between 15 fs and 1 fs, the extension of the wavelength reach of FEL-2 at least down to 2 nm (620 eV), thus covering, beyond the K-edge of carbon (284 eV), also the K-edges of nitrogen (410 eV) and oxygen (543 eV) at the fundamental harmonic, and the possibility to perform the quite popular two colour experiments also on FEL-2, by replacing the HGHG two-stage configuration with an EEHG one. Two-bunch operation is also being considered to allow experiments to use simultaneously the two FEL-s and other exotic multi-pulse configurations.

OVERVIEW OF FEL PERFORMANCES

Both FERMI FEL-1 and FEL-2, operating with a common linear accelerator complex, have benefited from the increase of beam energy in the high end of their respective spectral range. The VUV FEL line, FEL-1, can now be operated in the entire range at an energy per pulse larger than 100 uJ, under the condition of a single longitudinal mode spectrum, as shown in Fig. 1. The figure corresponds to harmonic 12 of the seed tuned at 260 nm.

User experiments at wavelengths in the range of 16 to 20 nm, formerly requiring the more complicated setup of FEL-2, can be now allocated on FEL-1 which may deliver similar spectral performances as the one shown in Fig. 1, at harmonic orders as high as 14 or 15 of the seed. It is worth mentioning that the seeded scheme of FEL-1 allows a wide flexibility of configurations which may be adopted to satisfy experimental demands, such as the generation of multiple pulses/multiple colours [10-14], the control of the phase and phase locking of these pulses [15,16], or the generation of modes with orbital angular momentum [17].

The performance of FEL-2 also progressed during these years of commissioning alternated to user experiments, requiring the unique spectral properties of this seeded FEL. In Fig. 2 we have summarized the energy per pulse vs. wavelength of operation in the various runs dedicated to commissioning of FEL-2. While first lasing was achieved in 2012 at 14.4 and 10.8 nm [6] the most recent data corresponding to run 26 (in Fig. 2) were acquired after the latest upgrades, with the increased beam energy, with the new laser system characterized by a minimum pulse duration in the UV of 70 fs, and with the additional undulator in the first stage amplifier.

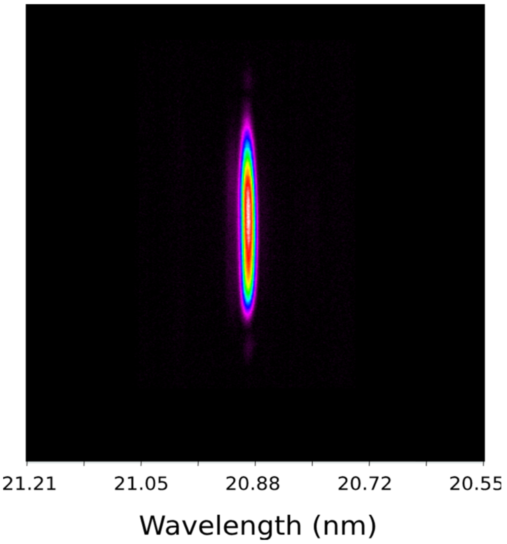

Figure 1: Spectral Line of FERMI FEL-1 at Harmonic 12.

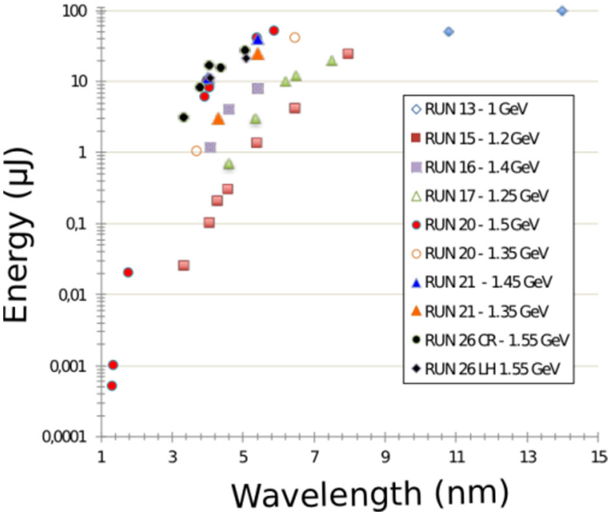

Figure 2: Energy Performances of FERMI FEL-2.

The implementation of this undulator has substantially reduced the seed energy demands, allowing us to seed the FEL in its entire spectral range (i.e. down to 4 nm) with a seed pulse energy as low as 20-25 µJ. This permits the use of the continuously tuneable OPA laser setup in the whole spectral range of FEL-2. The shorter seed pulse allows a temporal reduction of the delivered pulses down to an expected threshold of 20 fs at 4 nm, according to the expected scaling relations [18]. Notwithstanding, with the reduction in pulse duration we observed a modest increase in the energy per pulse in run 26, both in circular and in linear polarization. The spectrum in the soft-X ray at 4 nm from FEL-2 has similar features to the one of FEL-1 shown in Fig. 1. In Fig. 3, the spectral line of FERMI FEL-2 at harmonic 65, corresponding to a conversion of the seed to harmonic 13 in the first stage and to harmonic 5 in the second.

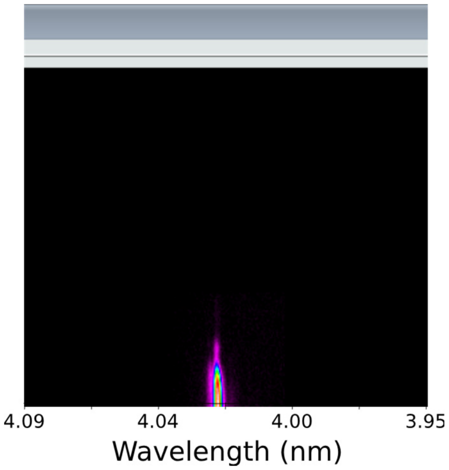

Figure 3: Spectral Line of FERMI FEL-2 at Harmonic 65.

LINAC UPGRADE

The high energy part of the linac is presently equipped with seven Backward Traveling Wave (BTW) structures with small beam apertures and nose cone geometries for high gradient operation. However, we find that these structures suffer from increased breakdown activity when operated at 25-26 MV/m and 50 Hz repetition rate.

In order to improve reliability and operability of the FERMI linac at higher energy and full repetition rate, a plan for the replacement of the seven BTW structures is under evaluation. A new accelerating module for operation up to 30 MV/m (at 50 Hz) and low wakefield contribution has thus been designed [19-21]. The module is comprised by two newly designed 3.2 meters long accelerating structures to replace each single 6.1 m long BTW structure. The new structures are designed to guarantee a reliable operation at 30 MV/m, leading to a final energy of the linac of nearly 1.8 GeV. In order to qualify the RF design and to collect statistics on the breakdown rate at full gradient, a first short (0.5 m) prototype of the structure (Fig. 4) will be fabricated in collaboration with the Paul Scherrer Institut (PSI) according to the PSI recipe.

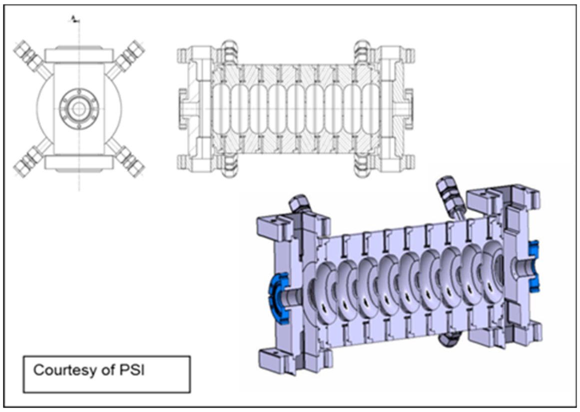

Figure 4: First Prototype.

The prototype will be a tuning free, fully brazed structure equipped with electric-coupled RF couplers [19] to lower electric and magnetic surface fields in the coupler region. The PSI prototype will be delivered at the beginning of 2018 and high power tests at Elettra will begin in the first half of 2018.

EEHG EXPERIMENT

The recent experimental demonstration of coherent emission with EEHG at harmonics as high as the 75th [22] is an encouraging result for the future development of externally seeded FELs in the soft x-ray spectral range using only a single stage of harmonic conversion.

In order to further investigate the real capabilities of EEHG in producing fully coherent pulses in the few nm wavelength range starting from a UV laser, an experiment is planned at FERMI. The plan relies on the temporary modification of the FEL-2 layout to accommodate the installation of dedicated systems necessary for the EEHG. Main modifications include a new undulator (Fig. 5) to replace the second modulator allowing seeding with a UV laser after the delay line chicane that provides the large dispersion necessary for EEHG. The strength of the delay line chicane will be increased to reach a 2 mm dispersion required for the EEHG experiment. The user's pump and probe laser available at FERMI will be implemented as the second seed laser for the EEHG.

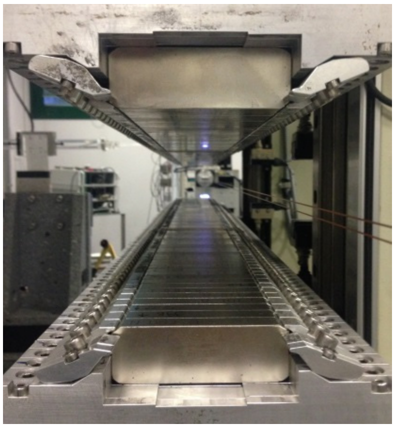

Figure 5: New Modulator Magnetic Array.

The main goal for the experiment is a direct comparison of the FEL performances in terms of FEL pulse quality and stability for the EEHG scheme and the already used two-stage HGHG configuration. The comparison will be focused at wavelengths in the 5-7 nm range. FEL numerical simulations show that with the proposed setup comparable results are expected using the standard FERMI electron beam [23]. Furthermore, EEHG may significantly benefit from an increase of the electron beam brightness that is possible operating the linac at higher compression rates since there is no longer the need for the fresh bunch portion on the e^- beam.

If numerical and theoretical predictions are confirmed by the experiment, a complete revision of the FERMI seeded FELs layout, in view of EEHG possibilities, will be planned, with the option to increase the final radiator length of FEL-2 to extend the tuning range towards 3 nm.

TWO-BUNCH OPERATION

The FERMI present layout naturally suggests investigating the possibility to operate simultaneously FEL-1 and FEL-2 by generating two electron bunches separated by few main RF buckets, i.e. multiple of 0.33 ns. This requires a new design of the transfer line from the linac to the two FEL lines. The method of splitting two bunches strongly depends upon the temporal separation ΔT between them. For ΔT of tens of ns, fast high Q-factor resonant deflecting magnets designed for the SwissFEL switch yard and actually under study are very promising [24]. However, for ΔT of few ns or sub-ns, the state of art of the magnetic-based technology is still far from being a stable and reliable solution. A second option is to consider RF deflecting cavities that are usually adopted for beam diagnostics but may find application also as fast switching devices in beam distribution systems for multiple beam lines layouts [25,26].

Beyond the issues related to a full redesign of the FERMI layout, the generation and propagation of a two-bunch system in the linac presents a series of concerns. The most important involve the wakefields excited in the linac sections by the leading bunch that affect the energy and the trajectory of the trailing bunch. It is also critical to control and steer the beam trajectory by looking at the beam position monitors (BPM) because the latter consider the two bunches as a whole with a phase factor depending on the delay. The BPM signals of two bunches indeed sum up like vectors with a response that is practically null for ΔT=1, 3, 5, 7,… ns. Another issue to be considered is the photo-injector double-pulse laser alignment that becomes critical for large ΔT (~10ns or more).

In order to test the feasibility of the two-bunch operation we have carried out a study producing two virtually identical bunches, with separation ΔT varied between 0.66 ps and 2.33 ns [27]. The two bunches were successfully transported through the linac and the undulator line of FEL-1, up to the main beam dump, with acceptable optics and trajectory control. We have also lased at 16 nm of wavelength using alternately the first or the second bunch, without observing relevant differences between the two cases. A fine tuning of the first bunch charge and/or the time-delay has allowed to change the peak current of the trailer bunch and its longitudinal phase space in a controlled way, opening the door to novel machine configurations.

CONCLUSIONS

A first upgrade phase of FERMI has allowed us to achieve reliable, intense, and stable user operation on the whole spectral regions of FEL-1 and FEL-2. Further upgrades are presently being considered, targeting the generation of shorter pulses, of extending the spectral range to higher photon energies, and of increasing the FEL flexibility for the generation of multiple pulses also in the spectral range of FEL-2, via a single stage EEHG and two-bunch operation. Studies, simulations, tests of prototypes, and experiments with beam during the next year have the goal to produce an upgrade proposal by the end of 2018.

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