DEVELOPMENT PERSPECTIVES AT FERMI

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Abstract

FERMI is the seeded Free Electron Laser (FEL) user facility at the Elettra laboratory in Trieste, operating in the ultraviolet to 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 FEL 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 multipulse 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

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 [1]. After these upgrades the linac energy attains 1.55 GeV, for compressed and linearized electron beam, and FEL-2 has reached stable operation at 4 nm, harmonic conversion factor 13x5, with OPA-based fully tunable seed. Since June 2016 the repetition rate of the source can be set to either 10 or 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. The latter energy is needed to operate FEL-2 at 4 nm, i.e. photon energy equal to 310 eV, formally the high-energy edge of the facility; however, in November 2016 on the DiProI end-station it was possible to register the first experimental evidence of seeded 3rd harmonic light at λ = 1.6 nm (778 eV, the cobalt L-edge).

In the second semester of 2016 the peer-reviewed user program has started also on FEL-2 and the first user 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 FEL-1 and FEL-2, providing high spectral quality FEL pulses to the users.

The present performance of the facility is well consolidated and there is now a significant feedback by the user community about new science that could be targeted by an upgrade program focussed on the next 3 to 5 years. Hence 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, thus covering beyond the K-edge of carbon (284 eV) also the K-edges of nitrogen (410 eV) and oxygen (543 eV) in the fundamental, 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 on two beamlines at the same time and exotic multipulse configurations. These developments would require a series of upgrades to the source, some of which are described in the following sections, after an assessment of the present FEL performances.

OVERVIEW OF FEL PERFORMANCES

Both FERMI FEL-1 and FEL-2, operating with a common linear accelerator complex, have benefited of the increase of beam energy in the high end of their respective spectral range. The VUV FEL line, FEL-1 [2, 3], can now be operated in the entire spectral range at an energy per pulse greater than 100 µJ, in condition of a single longitudinal mode spectrum (Fig. 1). The figure corresponds to harmonic 12 of the seed tuned at 260 nm.

User experiments at wavelength in the range 16-20 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. The performances of FEL-2 also progressed continuously during these years of commissioning alternated to user experiments requiring the unique spectral properties of this seeded FEL.

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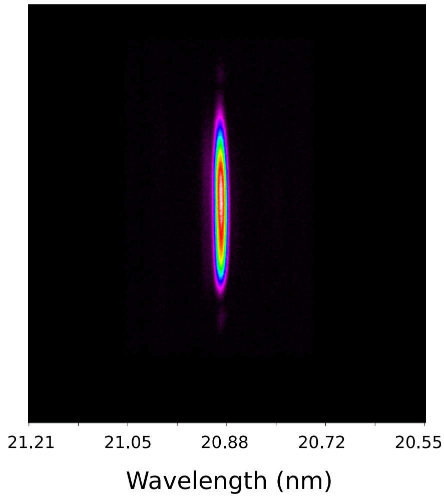

Figure 1: Spectral line of FERMI FEL-1 at harmonic 12.

In Fig. 2 we have summarized the energy per pulse vs. wavelength of operation in the various runs dedicated to commissioning.

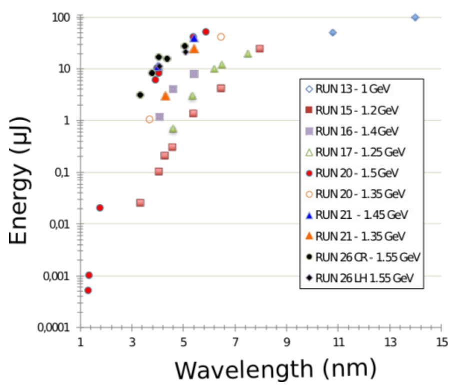

Figure 2: Energy performances of FERMI FEL-2.

While first lasing was achieved in 2012 at 14.4 and 10.8 nm [4] the most recent data corresponding to run 26 in the plot were acquired after the latest upgrades, with the increased beam energy, with the new laser system characterized by a minimum UV seed pulse duration of 70 fs, and with the additional undulator in the first stage. The implementation of this undulator has substantially reduced the seed energy demands, allowing to seed the FEL in the entire spectral range (i.e. down to 4 nm) with a seed pulse energy as low as of 20-25 µJ. This permits to use the OPA laser setup ensuring continuous wavelength tuning in the entire spectral range of FEL-2. The shorter laser pulse allows a shortening of the delivered pulses that are expected to approach 20 fs at 4 nm, according to the expected scaling relations [5]. Notwithstanding 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 features similar to the one of FEL-1 shown in Fig. 1, as can be seen in Fig. 3, showing 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.

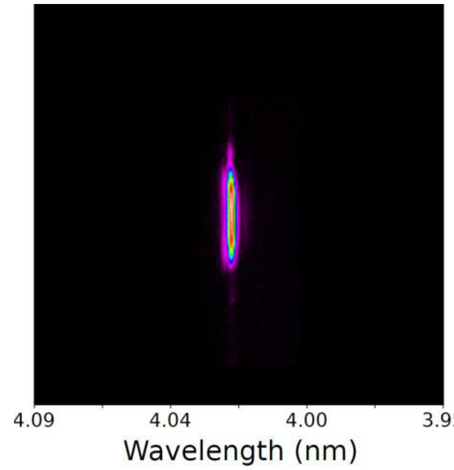

Figure 3: Spectral line of FERMI FEL-2 at harmonic 65.

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. Nevertheless, those structures have been found to 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 [6-8]. The module comprises 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, with a final energy of the linac of nearly 1.8 GeV. In order to validate the RF design and 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.

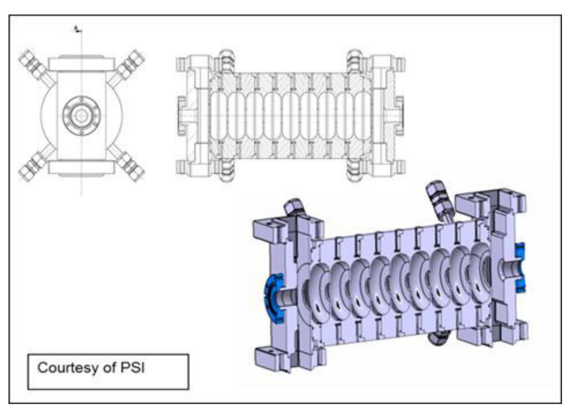

Figure 4: Design of the RF structure short prototype.

The prototype will be a tuning free, fully brazed structure equipped with electric-coupled RF couplers [6] to lower electric and magnetic surface field in the coupler region. The PSI prototype will be delivered at the begin-

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ning of 2018 and tested at high power at Elettra in the first half of 2018.

EEHG EXPERIMENT

The recent experimental demonstration of coherent emission with EEHG at harmonics as high as 75 [9] is an encouraging result for the future development of externally seeded FELs in the soft x-ray spectral range with a single stage.

In order to further investigate the real EEHG capability of 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 strong 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 second seed pulse is obtained from the pulse generated by the second amplifier of the seed laser used for pump-probe experiments.

Figure 5: New modulator magnetic array.

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. At this stage the comparison will be focused on wavelengths in the range 5-7 nm. FEL numerical simulations show that with the proposed setup comparable results are expected using the standard FERMI electron beam [10]. Furthermore, because the fresh bunch portion on the electron beam is no longer needed, EEHG may significantly benefit from an increase of the electron beam brightness, made possible by operating the linac at higher compression.

If numerical and theoretical predictions are confirmed by the experiment, a complete revision of the FEL-2 layout in view of EEHG will be planned, with the possibility to increase the final radiator length that may allow also extending the FEL-2 tuning range towards 3 nm.

TWO-BUNCH OPERATION

The FERMI present layout naturally suggests to investigate the possibility to operate simultaneously FEL-1 and FEL-2 by generating two electron bunches separated by few main RF buckets, i.e. by multiples of 0.33 ns. This implies 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 developed for the SwissFEL switchyard and actually under studies are very promising [11]. However, for ΔT of few ns or sub-ns the state of the art of the magnetic-based technology is too far away to be a reliable and stable solution. It is therefore better to consider RF deflecting cavities that are usually adopted for beam diagnostics but found applications also as fast switching devices in beam distribution systems for multiple beamlines layouts [12, 13].

Apart from the issues related to a redesign of the FERMI layout, the generation and propagation of a two-bunch system in the linac presents a series of criticalities. The most important concerns the wakefields excited in the linac sections by the leading bunch that affect the energy and the trajectory of the trailing bunch. Furthermore, it is 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 system. Moreover the BPM signals of two bunches add like vectors with a response that is practically null for ΔT = 1, 3, 5, 7,… ns. Another issue regards the photo-injector two-pulse laser alignment that becomes critical for large ΔT (~10 ns or more).

In order to test the feasibility of the two-bunch operation at FERMI, we have carried out an experimental study producing two identical bunches with a ΔT from 0.66 ps to 2.33 ns. They were successfully transported through the linac and FEL-1 up to the main beam dump, with an acceptable optics and trajectory control. We have also lased at 16 nm by using the first or the second bunch without relevant differences between the two cases. Finally, fine tuning the leading bunch charge and/or the time-delay has allowed to change the peak current of the trailing bunch and its longitudinal phase space in a controlled way, opening the door to novel machine configurations. More details on this experiment can be found in [14].

CONCLUSION

A first upgrade phase of FERMI has allowed to achieve reliable, intense and stable users' operation on the whole spectral region covered by both FEL-1 and FEL-2.

Further upgrades are presently being considered for FERMI, addressing shorter pulses, shorter wavelengths, EEHG schemes and two-bunch operation. Studies, simulations, tests of prototypes and experiments with beam during the next two years have the goal to produce by the end of 2018 an upgrade proposal for 2019-2022.

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