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STATUS AND PERSPECTIVES OF THE FERMI FEL FACILITY (2019)

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Abstract

FERMI is the 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 wavelength stability, low temporal jitter and longitudinal coherence in the range 100-4 nm. During 2018 a dedicated experiment has shown the potential of an Echo Enabled Harmonic Generation (EEHG) scheme to cover most of this spectral range with a single stage cascade [1]. Such a scheme, combined with an increment of the beam energy and of the accelerator performances, could extend the FERMI operating range up to the oxygen K-edge. With this future perspective, we 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, consisting in the conversion of FEL-1 first, and FEL-2 in a second moment, into EEHG seeded FELs.

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 seeded FELs, FEL-1 [2] and FEL-2 [3], both based on the High Gain Harmonic Generation seeded mode (HGHG) [4-6] to operate in the range 100-4 nm, producing radiation characterized by wavelength stability, low temporal jitter and longitudinal coherence [7-10].

The FELs are in operation with users since 2010. During the commissioning phase "with users", concluded in December 2018, seven calls for experiments (see Fig.1) contributed to establish and consolidate the various modes of operation. In January 2019 the facility entered into standard operation mode, with two calls for experiments every year and more than 4k hours per year of user operation regularly scheduled.

Strategic development goals for FERMI are the reduction of the pulse duration, which is typically in the range 30-100 fs depending on the duration of the seed and on the harmonic order [11], and the extension of the photon energy range of operation; there is indeed significant interest and there are important science opportunities in extending the photon energy range to include the K-edges of nitrogen (410 eV) and oxygen (543 eV) [12-14].

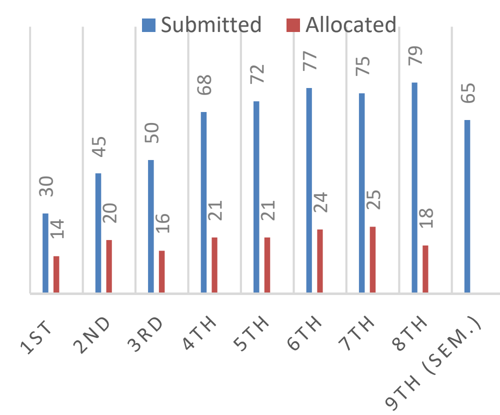

Figure 1: User proposal statistics at FERMI

As to the reduction of the pulse duration, an upgrade of the laser system to start with a shorter seed is under development. This, combined with nonlinear dynamics in the FEL amplifier [15] has shown the potential to reduce to sub 10-fs the FEL pulse duration. As to the extension of the photon energy range, 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. This fact limits the harmonic multiplication factor of FERMI FEL-1 to 13-15. Substantially higher orders can be reached with FEL-2 with the double stage HGHG cascade, where the harmonic conversion is performed with the fresh bunch injection technique [6]. This scheme was implemented for the first time on FERMI FEL-2 [3] and was used to demonstrate the seeded FEL coherent emission in the soft-X rays, up to harmonic orders of 65, and higher [7].

An alternative method to increase the order of the harmonic conversion in a single stage is the Echo Enabled Harmonic Generation (EEHG) scheme proposed in [16-17]. During 2018 a dedicated experiment has shown the potential of EEHG to cover at FERMI most of this spectral

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range with a single stage cascade [1]. The experiment consisted in a modification of the FEL-2 layout to accommodate the installation of dedicated systems necessary for the EEHG. Main changes included a new undulator 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 was increased to reach a maximum of 2 mm dispersion required for the EEHG experiment.

The experiment demonstrated high-gain and high-quality lasing using the EEHG scheme down to wavelengths as short as 5.9 nm with narrow and clean spectra with low shot-to-shot central wavelength jitter [1]. Coherent emission was observed at harmonics up to 101 indicating the potential to extend the lasing region to the oxygen K-edge either by using EEHG directly, or with a cascade employing both EEHG and HGHG techniques.

Regardless of the selected approach, a prerequisite for the extension of the spectral range to the oxygen K-edge is the upgrade of the linac/final amplifier performances, in terms of beam energy, undulator parameters and phase space quality. The first will ensure sufficient gain at 2 nm, the second will preserve as much as possible the longitudinal coherence and wavelength stability that are distinguishing features of FERMI.

LINAC UPGRADE

The high energy part of the FERMI 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 suffering from increased breakdown rates when operated at 25-26 MV/m and 50 Hz repetition rate. A plan for the replacement of the seven BTW structures is under development. A new accelerating module for operation up to 30 MV/m (at 50 Hz) and low wake-fields contribution has thus been designed [18-20] and the first prototype module is under development in collaboration with the Paul Scherrer Institut (PSI). The modules consist of two newly designed three meters long accelerating structures to replace each single 6.1 m long BTW structure. The new structures are designed to guarantee reliable operation at 30 MV/m, a short (0.5 m) prototype was realized according to the PSI recipe and tested at Elettra during the last few months, showing a fault rate of only $3.9\cdot10^{-8}$ breakdowns per pulse at 35 MV/m.

The installation of the first full-length module replacing the horizontal deflector at the end of the present linac should already ensure a beam energy close to 1.7 GeV (at 10 Hz repetition rate). The replacement of all the BTW structures with new modules will allow a final energy of 1.8 GeV at 50 Hz, with sufficient margin for compression and phase space manipulation.

The reduced transverse/longitudinal wake-fields of the new structures will also allow an improved beam phase space, both transverse and longitudinal, increased stability and higher compression. In the following analysis we assume the parameters in Table 1 for the electron beam generated by the upgraded linac.

Table 1: Linac Parameters

e-beam	
Energy (GeV)	1.8
Peak Current (kA)	1.0
Norm. emitt. (slice – mm-mrad)	1
Relative energy spread (slice)	10^{-4}
β-Twiss parameter (m)	12
undulator	
Period (cm)	2.8
Module length (m)	2.2
Number of modules	8

FEL-2 UPGRADE

We have analysed the performances of the FERMI FELs in both HGHG and EEHG modes of operation using the model developed in [21]. This method implements the Xie scaling relations on an FEL operating with a pre-modulated beam and provides an estimate of the FEL performance, as a function of the undulator parameters (period, UM length …), beam parameters (energy, emittance, energy spread …) and of the scheme used to generate the initial modulation, e.g. EEHG vs HGHG with fresh bunch. The Xie power scaling [22] predicts the output power and the model provides the maximum harmonic order at which saturation should be reached. The power can be converted in pulse energy using the theory in [11] to estimate the expected pulse duration. It can be used to optimize the set of input parameters of a given configuration (seed intensity, amplitude of dispersions ...)

As an example, in Fig. 2 we show the dependence of the FEL peak power in comparable configurations EEHG and HGHG with fresh bunch vs. the harmonic order. The two configurations share the same amplifier and electron beam parameters, as listed in Table 1.

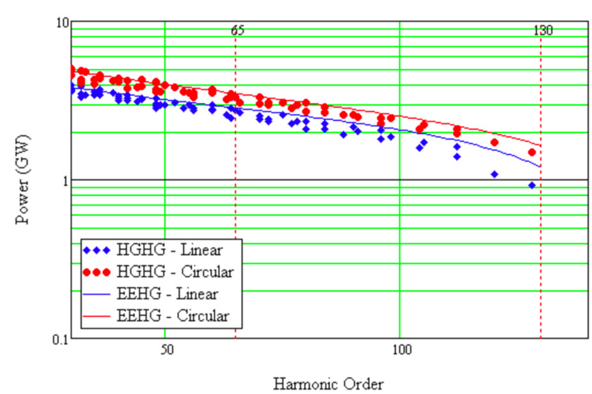

Figure 2: Output peak power for FEL peak power in comparable EEHG (red-blue continuous lines for circular (C) and linear (L) polarizations) and HGHG with fresh bunch configurations vs. the harmonic order; markers: red-blue for C and L polarizations respectively.

The EEHG configuration shows a better behavior at high harmonic orders, but requires a large dispersion in the first chicane. The behavior of the maximum harmonic order reaching saturation vs. the first chicane dispersion in EEHG configuration is shown in Fig. 3. A seed wavelength of 260 nm was assumed; the dispersion required to reach

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saturation at 2.0 nm, corresponding to harmonic 130 is about 15 mm.

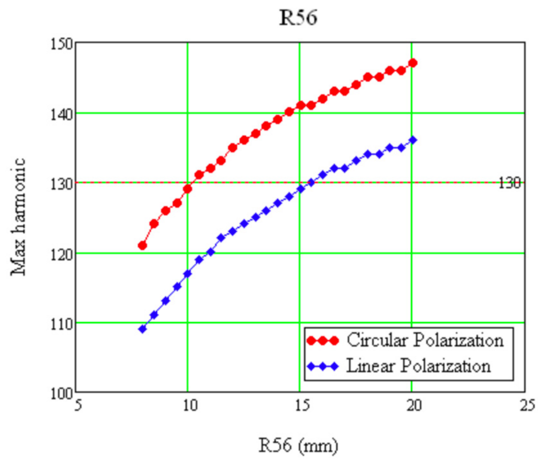

Figure 3: Maximum harmonic order reaching saturation vs. the first chicane dispersion in EEHG configuration.

The model assumes an ideal dispersion and does not include debunching effects due to intrabeam scattering or other effects associated with CSR or non-linear dynamics in the chicane which may degrade the beam emittance or energy spread. Further work is required to determine which configuration is the best suited to reach the 2 nm wavelength or shorter. The final configuration could be HGHG or EEHG, or a hybrid configuration where fresh bunch HGHG at harmonics 4-5 is seeded by a first stage in EEHG operating at a relatively modest harmonic order ∽30-35. In this case the first dispersion could be limited to 3-5 mm and would have a lower impact on the beam quality.

FEL-1 UPGRADE

While we may question the operation of EEHG at harmonic orders higher than 100, we already have convincing experimental evidence that EEHG is a real breakthrough with respect to a single stage HGHG configuration. FERMI FEL-1 may operate in HGHG up to harmonic 15-17, while the EEHG experiment carried out at FERMI [1] has shown convincing FEL performances up to harmonic ∽50. This strongly supports a plan of upgrade of FERMI FEL-1 to an EEHG configuration. The spectral range of FEL-1 would be extended to 100-10 nm and the FEL in the new layout would be an ideal test bed for further EEHG studies. New experimental opportunities would be available for the users, such as the operation at the Fourier limit with longer seed pulses and the possibility of operating multi-pulse multi-colour configurations, presently not available in the range 10-20 nm. A second aspect is connected to the FEL-2 future upgrade, as FEL-1 covering the range 100-10 nm would allow an optimized design of FEL-2 focused on the reduced range 10 - 2 nm.

We are planning the upgrade of FEL-1 preserving the possibility to extend the first dispersive chicane of EEHG up to 15 mm, even if this value exceeds by a factor three the required value, in order to have a test result, aims to explore beam dynamics of a modulated beam in the chicane.

The upgrade of FEL-1 requires an additional laser system for a second, independent seed. The refurbished modulator performed well during the EEHG experiment and will be used as the additional modulator for FEL-1. In Fig. 4 we show the maximum harmonic reaching saturation in the FEL-1 configuration, with a dispersive section of 10 mm.

Highest harmonics reaching saturation are 34 (7.6nm) and 26 (10 nm) in circular and linear polarization respectively.

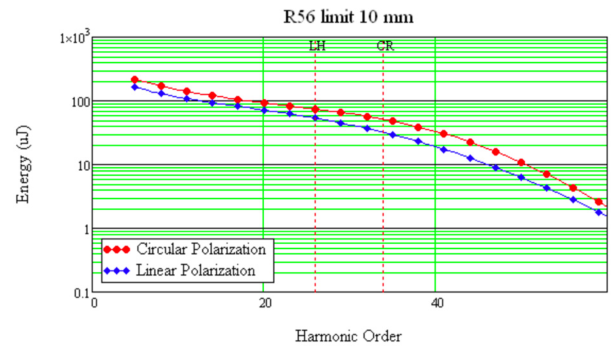

Figure 4: Output pulse energy for FEL-1 in EEHG operation mode (red-blue for circular (C) and linear (L) polarizations) . FEL-1 present configuration: six undulator modules, 2.2 m long, 5 cm of period length.

FEL-1 will operate as a conventional HGHG at low harmonics and in EEHG at intermediate harmonics (h15-h30). These figures support the fact that the present FEL-1 is limited by the configuration (HGHG vs. EEHG) and in EEHG mode can cover the range 100 nm to sub 10 nm wavelengths. Once the linac upgrade will be completed the beam energy will increase to 1.8 GeV and FEL-1 could in principle cover most of the present FEL-2 range.

CONCLUSIONS

A first upgrade phase of FERMI has allowed us to achieve reliable, intense and stable user operation over the whole spectral region 100-4 nm. Further upgrades are presently being considered to extend the spectral range to higher photon energies, and increase the FEL flexibility for the generation of multiple pulses also in the spectral range of FEL-2.

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