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ECHO-ENABLED HARMONIC GENERATION AT FERMI FEL-1: COMMISSIONING AND INITIAL USER EXPERIENCE

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on behalf of the FERMI FEL-1 Upgrade Collaboration

Abstract

The FERMI free-electron laser (FEL) facility has recently achieved a significant milestone with the successful implementation of the echo-enabled harmonic generation (EEHG) scheme in the FEL-1 amplifier line. This advancement is part of a broader upgrade strategy aiming at expanding the covered spectral range of the facility to the entire water window and beyond. Through this upgrade, the maximum photon energy of FEL-1 has been doubled and the spectral quality has been enhanced. The updated FERMI FEL-1 is the first user facility operating in the spectral range 20–10 nm utilizing the EEHG scheme. It will serve also as the ideal test bench for conducting new machine studies in the perspective of future developments. In this contribution, we present the results obtained during the commissioning phase and the first user experiments.

INTRODUCTION

The FERMI Free Electron Laser (FEL) facility has been in operation since 2010 and provides ultrashort coherent pulses in the VUV- XUV range (100 – 4 nm) [1,2] to the user community. It works in the High Gain Harmonic Generation (HGHG) scheme, making use of a tunable external UV laser to create the electron bunching needed at high harmonic order. FERMI offers two FEL amplifier lines operating in single (FEL-1) and double (FEL-2) cascade mode. This layout covers the above-mentioned wavelength range with nearly transform-limited XUV pulses and GW peak power at a repetition rate of 50 Hz.

FERMI is undergoing a series of upgrades to keep the facility in a world-leading position. The ultimate goal of the development plan consists in extending the spectral range to cover the water window and above, and to reduce the minimum pulse duration below the characteristic lifetime of core-hole electrons of light elements. The main limitation of the HGHG scheme is related to the reduction of the ratio between bunching at a given harmonic and energy spread as the harmonic order increases. Our strategy to overcome these limitations focuses on the introduction of the *Echo Enabled Harmonic Generation* (EEHG) scheme in the FEL amplifier layout [3]. Compared to HGHG, the EEHG scheme can produce bunching values significantly exceeding the electron bunch shot-noise at very large harmonic order [4, 5], thus allowing the photon energy range of a single-stage FEL amplifier from UV to be extended to the soft X-ray. Moreover, with respect to HGHG, EEHG is less affected by electron bunch phase space imperfections and variation [6]. On the user side, this translates into the opportunity to conduct experiments utilizing an extremely coherent and spectrally stable FEL light source.

The upgrade to EEHG of the FEL-1 line at FERMI has been recently concluded and commissioning has started. In this contribution we present, together with some details about the new layout, the main results obtained during the commissioning and the very first user's experience.

LAYOUT MODIFICATION

FEL-1 has been designed as a single-stage seeded FEL operating in HGHG mode. The original layout is sketched in Fig. 1 a. An external UV laser (Seed) is used together with an undulator (referred as modulator M) resonating at the same wavelength to create a phase space modulation of the electron bunch. By means of a dispersive magnet (Ds) the energy modulation is converted into a spatial modulation, efficiently creating bunching up to harmonics ~ 15. Then, the micro-bunched electron beam is injected into the radiator chain (R) in order to amplify one selected harmonic until saturation of the HGHG process.

The implementation of the EEHG scheme on the FEL-1 line was achieved applying the following modifications to the amplifier layout (Fig. 1 b): the radiator chain and the dispersive magnet (now Ds2) have been repositioned downstream. In the free space created, we have installed a large magnetic chicane (Ds1), capable of reaching a maximum R56 of 10 mm. The chicane is followed by a second modulator (M2). For R56>1mm, the corresponding offset of the electron beam in the middle of the chicane is large enough to permit the insertion of a UV mirror that is used to steer a second UV laser (Seed2) onto the electron bunch when it is travelling through M2. The same manipulator hosting the UV mirror can be used to insert other diagnostic tools that are used for both the electron and laser beams.

It is worth noting that, once the manipulator is extracted, we can switch off Ds1, open M2 and the machine can be operated in HGHG as before the upgrade. We will show in the next paragraph that moving downstream the dispersive section and radiator chain with respect to the modulator did not have any impact on the performance of FEL-1 when operated in the HGHG mode.

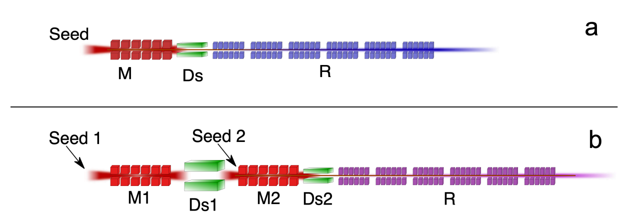

Figure 1: a) Original layout of FEL-1, b) modified layout for FEL-1 operation in EEHG mode.

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COMMISSIONING RESULTS

The modifications to FEL-1 were designed to preserve the operability and the established performance in HGHG mode. For this reason, the first phase of the commissioning was scheduled as soon as it was possible to test the FEL with the radiator and dispersive section in the final position. Figure 2 presents a sequence of real-time acquisitions of the FEL pulse energy during the optimization process of the machine tuned at 38.6 nm (i.e., at harmonic 7 of the seed laser tuned at 270 nm). The pulse energy is well above the mJ level, exceeding the specification usually considered for users. Tests have been performed also at 20 nm, indicating once more that FEL-1 performs as before the upgrade.

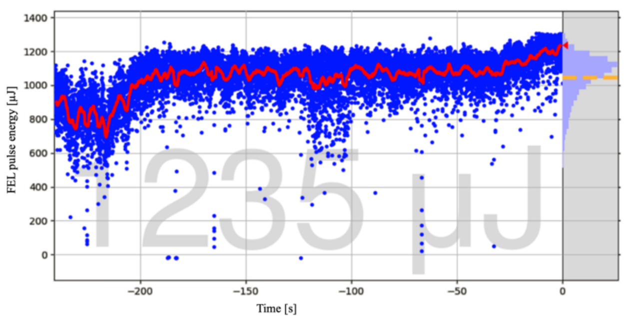

Figure 2: FEL pulse energy: real-time sequence of single-shot records during machine tuning at 38.6 nm in HGHG after the layout was modified to create the space for the installation of the EEHG section (magnetic chicane and second modulator).

After obtaining this important result, we completed the installation, adding to the layout the magnetic chicane, the Seed2 transport and the injection breadboard, the manipulator with the UV mirror and diagnostics located in the middle of the chicane. This part of the installation was conducted during a two-month shutdown period in summer 2023, after which FERMI operation restarted for users on the FEL-2 branch of the facility. During this period, the new hardware was integrated into the control system and tested off-line prior to the main commissioning phase scheduled for November 2023.

The commissioning was divided into two weeks separated by a two-weeks gap to accommodate the need to fix potential hardware issues. The first days of commissioning were dedicated to checking once more the performance in HGHG, seeding the electron bunch in both modulators: in the first one using Seed1 only, then in the second one using first Seed1 and then Seed2. By performing a detailed characterization of the HGHG emission and fitting the results with time-dependent simulations [7], we were able to derive the value of important parameters such as the slice bunch current and energy spread together with the energy modulation amplitude produced by the seeding lasers. An accurate knowledge of these parameters is fundamental to finding the best working point for the FEL and to speed up the optimization time. Once obtained, these parameters were used to calculate the bunching amplitude for EEHG and to set the machine hardware (undulators, lasers and dispersive magnets) to the desired target [8].

Thanks to this strategy, after a few days of commissioning we were able to obtain stable lasing from FEL-1 in EEHG and to study the sensitivity to operating parameters of the EEHG harmonic up-conversion technique [9].

Despite the increased technical complexity, EEHG has some considerable advantages with respect to HGHG. With EEHG it is possible with a single harmonic cascade to reach relatively high harmonics, because the bunching amplitude decrease with harmonic number is considerably slower than for HGHG. In Fig. 3 we report the comparison of the two different schemes in terms of pulse energy as a function of the emission wavelength. The red line corresponds to the standard performance that we obtain with FEL-1 in HGHG while blue circles show the best performance registered so far during FERMI operations [10]. Green circles correspond to EEHG results obtained during the commissioning where the slower efficiency decay at high harmonic order is evident. At 8.5 nm, where the HGHG signal is barely detectable, EEHG still provides 10 µJ fully coherent pulses.

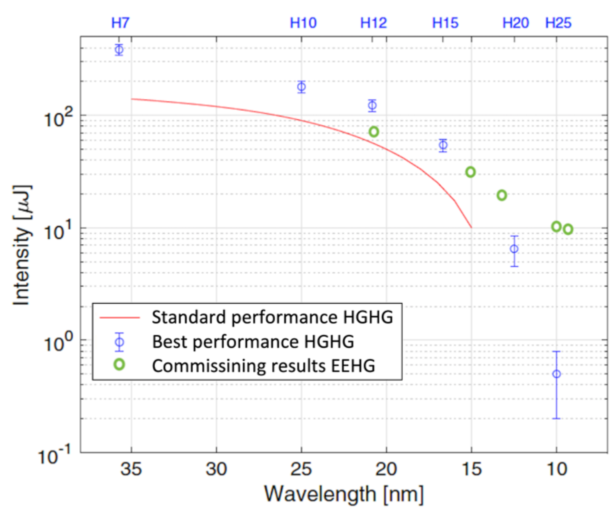

Figure 3: Pulse energy as a function of the emission wavelength (i.e. of the harmonic order) for the two different schemes. Red line: standard HGHG performance, blue circles: best performance achieved so far in HGHG on FEL-1, green circles: commissioning results in EEHG.

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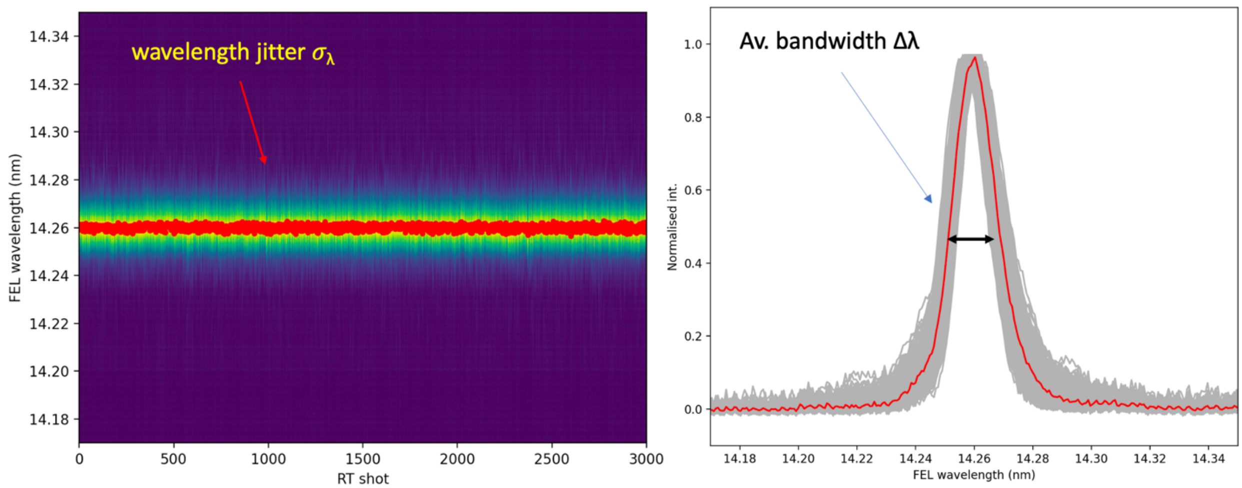

Figure 4: Left: sequence of 3000 single-shot spectra. Red dots indicate the position of the central wavelength of each pulse. Right: normalized single-shot spectra (grey) and their average (red line).

The second advantage of the EEHG method worth noting is the astonishing spectral stability that can be achieved once the operating parameters are optimized. In HGHG, the electron beam phase space curvature produces a wavelength shift that is proportional to the quadratic energy chirp [11]. Therefore, the time jitter between the seed laser and the electron bunch is translated into wavelength jitter. With EEHG, under appropriate condition, this effect is almost cancelled [12] and the emitted spectrum is particularly stable and reproducible at every shot. Figure 4 well demonstrates this unique feature of the EEHG technique. The left panel shows the spectra of 3000 consecutive pulses; red dots indicate the central wavelength of each shot. The recorded standard deviation is 5% of the average linewidth. The right panel displays in grey the normalized spectra together with their average (red line). The calculated average fractional linewidth is 10^{-3} FWHM. While the typical value of the spectral bandwidth is similar with both schemes, the spectral stability can be several times (approximately from 2 to 5) better in the case of EEHG.

USER'S OPERATION

At the end of the commissioning period, we performed a test for "user readiness" providing light to the LDM beamline [13]. The scope of the test was twofold: to check whether it was possible to operate the machine continuously during one shift (8 hours) for users, satisfying the beamline request which included a large wavelength scan. The fundamental scientific question addressed during the beamtime was the excitation of a resonant Auger process with one and two photons for a simple molecule (the well-known S_{2p} shell of CS_2). The purpose of this work goes beyond commenting on the scientific results obtained during the test. We want to focus here on the more technical aspects of the operability of the EEHG configuration.

During the experiment, the FEL wavelength was changed every 5 minutes, spanning over a range of 0.5 nm in steps of 0.02 nm around the central wavelength (15.31 nm) corresponding to a photon energy equal to half of the target resonance, and the Auger photoelectron spectrum of CS_2 was recorded at LDM for every step. Thereafter, the harmonic order was doubled moving from harmonic 17 to 34 and homologous photoelectron spectra recorded as the FEL wavelength was tuned across the target resonance (Fig. 5).

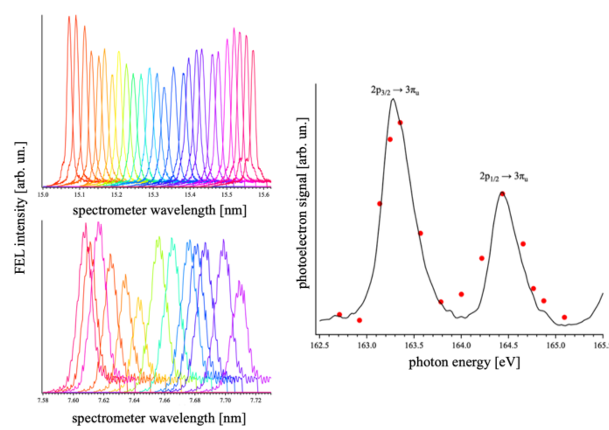

Figure 5: left: samples of FEL spectra recorded during the wavelength scans in the range from 15.07 to 15.57 nm (top) from 7.51 to 7.525 nm (bottom). The total electron yield from CS2 recorded during the latter scan is shown in the right panel (red markers), reproducing the well-known spectrum recorded with synchrotron radiation (black curve, adapted from Ref. [14]).

CONCLUSIONS

The implementation of the EEHG scheme at the FERMI FEL-1 line was successfully concluded. The new layout was commissioned after installation, showing no impact on the usual performance in HGHG mode. The maximum photon energy achievable on FEL-1 is doubled thanks to this upgrade. Excellent spectral quality and superior spectral stability have been recorded when operating in EEHG. The new setup was employed to provide FEL light to users for a scientific application responding promptly to the user's wavelength change requests.

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THE FERMI FEL-1 UPGRADE COLLABORATION

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