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FIRST LASING OF A FREE ELECTRON LASER IN THE SOFT X-RAY SPECTRAL RANGE WITH ECHO ENABLED HARMONIC GENERATION

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Abstract

We report on the successful operation of a Free Electron Laser (FEL) in the Echo Enabled Harmonic Generation (EEHG) scheme at the FERMI facility at Sincrotrone Trieste. The experiment required a modification of the FEL-2 undulator line which, in normal operation, uses two stages of high-gain harmonic generation separated by a delay line. In addition to a new seed laser, the dispersion in the delay-line was increased, the second stage modulator changed and a new manipulator installed in the delay-line chicane hosting additional diagnostic components. With this modified setup we have demonstrated the first evidence of strong exponential gain in a free electron laser operated in EEHG mode at wavelengths as short as 5 nm.

INTRODUCTION

With two FEL lines the FERMI user facility [1] is providing powerful radiation in the spectral range from 100 nm to 4 nm characterized by high degree of longitudinal and transverse coherence. Both FEL lines rely on the use of an external seed laser to initialize the coherent emission process. FEL-1 [2], optimized for the long wavelength spectral range (100 nm – 20 nm), is based on a single stage, high gain harmonic generation (HGHG) scheme [3], while FEL-2 [4] operates at a shorter spectral range (20 nm – 4 nm) thanks to a double stage HGHG process employing a fresh bunch scheme(HGHG-FB) [5].

In the recent years, scientists have started exploiting the capability of FERMI of producing fully coherent pulses performing experiments not possible with other sources. Due to FERMI's strong coherence, techniques such as four wave mixing [6], coherent control [7], are now available for scientific users in the EUV- soft x-ray spectral range.

Because longitudinal coherence has become an important distinguishing parameter for FERMI with respect to other FEL sources, studies for possible future upgrades have been driven by the goal of extending its capabilities for coherence control toward even shorter wavelengths [8]. As a first step toward this direction an experiment has been organized at FERMI in 2018 to experimentally validate the benefits predicted by theory for the recently proposed seeding scheme EEHG [9].

We report here on the successful operation of the EEHG FEL at FERMI [10]. We first present the experimental setup pointing out the modifications done to some

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of the existing FEL-2 hardware necessary for EEHG implementation. Then we give results showing the clear evidence of strong exponential gain initiated by coherent, narrow-band EEHG bunching in the XUV spectral range.

EXPERIMENTAL SETUP

The FEL-2 line at FERMI was temporarily modified to allow EEHG seeding. This process required the installation of a new modulator for the second stage of FEL-2, a new seed laser line delivering up to 50 μJ pulses at 264 nm, an increased dispersion in the magnetic chicane and several new diagnostics. Figure 1 shows the layout of the FEL-2 undulator line for the standard operational mode (HGHG-FB) and for the EEHG.

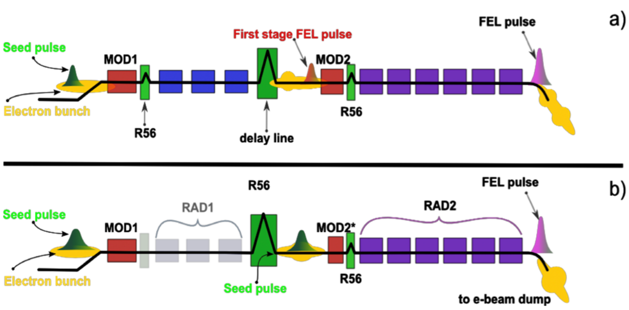

Figure 1: a) Nominal layout of FEL-2 for HGHG-FB. b) Modified layout used for the EEHG experiment.

These modifications took into account the temporary scope of the experiment (i.e., a six month period). The standard operating mode of FEL-2 in HGHG-FB was restored within few weeks following the end of the EEHG experiment.

New Second Modulator

In order to allow the resonant interaction of the electron beam with an UV seed laser, the second modulator (MOD2) had to be replaced by one with a longer period (MOD2*). The modification of an existing Elettra undulator provided a system with the required characteristics, as summarized in Table 1.

Table 1: MOD2* Parameters

Parameter	Value	Units
Length	1.5	m
Magnetic period	113	mm
Maximum k	12	
Peak field	1.2	T

MOD2* was installed in April 2018 and removed in September 2018 at the end of the EEHG experiment.

Large Magnetic Chicane

EEHG relies on the use of a large dispersion (*R56* of a few mm) in the first chicane. The existing delay-line magnetic chicane (Fig.1) was upgraded to produce the larger *R56* necessary to produce bunching at harmonics higher than 40 at 1.5 GeV electron beam energy. Thanks to an increase of the magnet separation together with an upgrade of the power supply that allowed increasing the maximum current from 500A to 750A, the first *R56* could be increased up to more than 2 mm for a 1.3 GeV beam.

Second Seed Laser

EEHG needs two seed lasers interacting with the same (longitudinal) portion of the electron beam in the two modulators. As a first seed laser we used the existing seed laser of FEL-2 which is based on the third harmonic generation of a Ti:Sa laser. The second seed laser was provided by a second Ti:Sa laser that normally is provided to FERMI users for pump and probe experiments [11]. This infrared laser has been converted to the UV on a dedicated optical table installed close to the delay line chicane. A special, in-vacuum mirror installed in a manipulator allowed injecting this second seed laser to the electron beam axis from the center of the delay-line chicane.

For both seed lasers the central wavelength was 264 nm, and the pulse length was in the range 100 – 120 fs (FWHM). In both cases the energy per pulse could be adjusted depending on the requirements in the range 0 – 50 μJ.

A description for the second seed laser injection system and the dedicated diagnostic installed can be found in Ref. [12].

RESULTS

During the period of the experiment the electron beam energy was progressively increased from 0.9 GeV to 1.5 GeV. Due to the limit in the maximum dispersion available from the first chicane, most of the studies were performed at 1.35 GeV [13]. At this energy it is possible to operate the final radiator at wavelengths as short as 7 and 5 nm with sufficient gain and the *R56* of the first chicane can be increased up to the value needed to efficiently operate the EEHG at the harmonics (H=35, 45) required for these wavelengths.

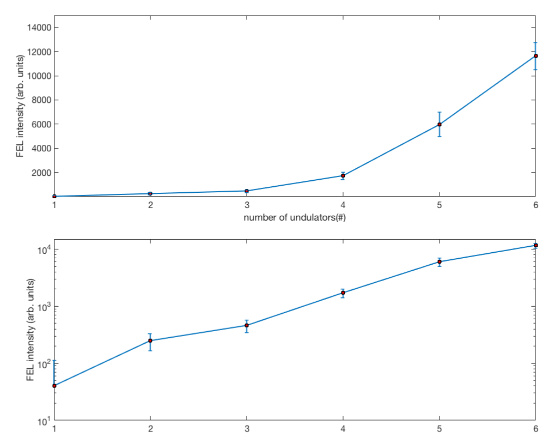

Figure 2: Measured gain curve of EEHG at H35 in linear scale (upper graph) and logarithmic scale (lower graph).

Clear indication of FEL amplification in the final radiator was measured for various harmonics and wavelengths (Fig.2). An optimal amplification of the FEL radiation along the six undulators of the FEL-2 radiator required an accurate alignment of the electron beam trajectory.

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Once the standard EEHG parameters were optimized, the most important parameter for maximizing the FEL intensity was the definition of a straight trajectory for the electron beam in the radiator and the corresponding alignment of this trajectory with pointing of the two seed lasers. Given the significant gain along the radiator and the energy transfer from the electrons to the radiation field tapering of the undulator strength *K* can be important in maximizing the FEL power and preserving the FEL spectral quality. Figure 3 shows how the spectral quality was not degraded during the FEL amplification.

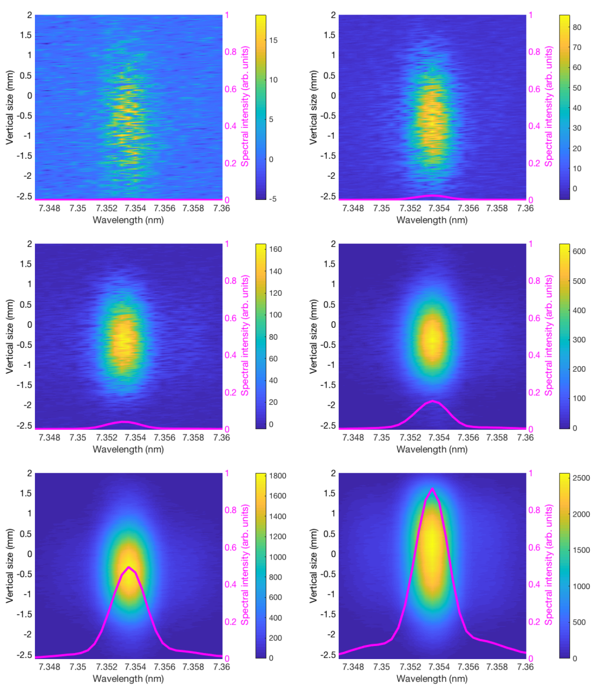

Figure 3: Evolution of the FEL spectrum along the amplification occurring in the radiator.

The sensitivity of EEHG to the induced energy spread controlled with the laser heater was also studied with details given in a separate contribution [14].

Initial operation at 0.9 GeV was quite important for fast commissioning of the new systems. As a result the first EEHG signal at 14 nm (H = 18) was easily obtained and optimized (Fig. 4).

Studies at 0.9 GeV were also important for direct comparison of the two seeding schemes EEHG and HGHG-FB. At this 14-nm wavelength it is indeed possible to operate the FEL in HGHG-FB mode within the modified setup. These comparative studies have shown the reduced sensitivity of EEHG to electron beam phase space distortions as compared to HGHG-FB [15].

For all the harmonics studied during the EEHG experiment it has been possible to optimize the FEL to a condition characterized by very narrow and clean spectra. Two such examples of these narrow spectra are reported in Figure 4.

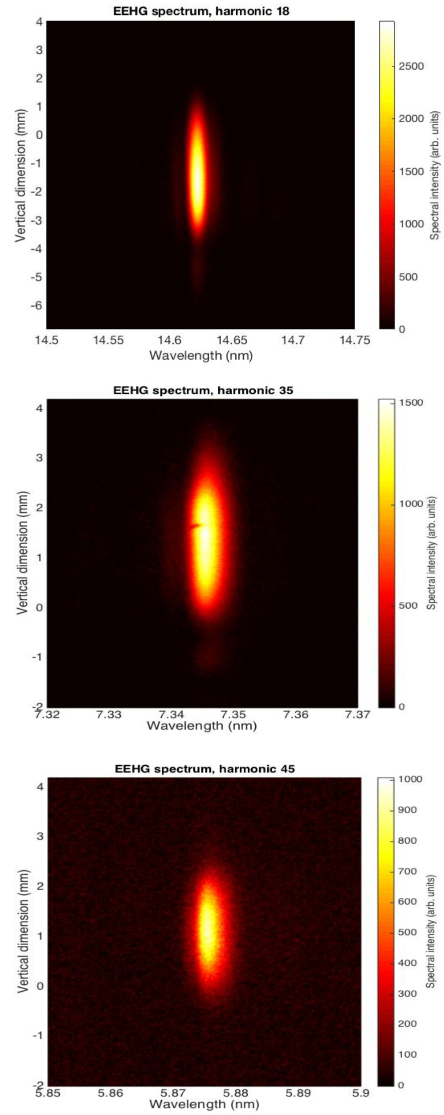

Figure 4: 2D images of the FEL spectrum as measured by PRESTO [16] for the EEHG operated at harmonic 18 a), 35 b), and 45 c).

CONCLUSIONS

We have successfully operated FERMI's FEL-2 in EEHG mode down to 5-nm wavelengths showing large exponential gain and high quality spectra. These results confirm the benefits for the EEHG scheme predicted by theory with respect to other seeding techniques.

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