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ECHO-ENABLED HARMONIC GENERATION LASING OF THE FERMI FEL IN THE SOFT X-RAY SPECTRAL REGION

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Abstract

The layout of the FERMI FEL-2 undulator line, normally operated in the two-stage high-gain harmonic generation (HGHG) configuration, was temporarily modified to allow running the FEL in the echo-enabled harmonic generation (EEHG) mode. The EEHG setup produced stable, intense, and nearly fully coherent pulses at wavelengths as short as 5.9 nm (~211 eV). Comparing the performance to the two-stage HGHG showed that EEHG gives significantly better spectra in terms of the central wavelength stability and bandwidth, especially at high harmonics, where electron-beam imperfections start to play a significant role. Observation of stable, narrow-band, coherent emission down to 2.6 nm (~474 eV) indicates the possibility to extend the lasing region to even shorter wavelengths.

INTRODUCTION

The FERMI free-electron laser (FEL) in Trieste, Italy is an externally seeded FEL facility consisting of two undulator lines that provide users with laser-like pulses in the entire extreme-ultraviolet (EUV) spectral region. The FEL-1 line is based on a single high-gain harmonic generation (HGHG) stage [1], where an ultraviolet (~264 nm) seed laser is used to trigger the amplification process at a high harmonic h of the seed, producing nearly fully coherent pulses in the range from 100 nm to 20 nm [2]. To reach shorter wavelengths, the FEL-2 line employs a two-stage HGHG cascade based on the fresh-bunch (FB) approach [3], generating output in the range from 20 nm to 4 nm [4]. The high degree of (longitudinal) coherence at FERMI allows performing experiments previously not possible in the EUV, such as, e.g., four wave-mixing [5], and coherent control [6].

Experience has shown, however, that at the shortest wavelengths available at the FEL-2 line, the sensitivity to the shape of the electron-beam (e-beam) phase space becomes critical and may severely affect the FEL radiation in terms of longitudinal coherence, pulse energy, and shot-to-shot stability. In addition, the two-stage HGHG cascade employed at FEL-2 cannot cover the whole harmonic range, as the final harmonic number is a product between the harmonic numbers of the individual stages. Last, but not least, the two-stage setup uses a relatively large portion of the e-beam to accommodate the double seeding process, which makes the implementation of double-pulse operation somewhat difficult.

Recent experiments [7-11] have suggested that the drawbacks of the two-stage HGHG could be overcome by using a seeding technique called echo-enabled harmonic generation (EEHG), where the e-beam phase space is shaped with two seed lasers to enable FEL emission at high harmonics [12]. The method is intrinsically much less sensitive to the initial e-beam imperfections, making it a strong candidate for producing highly stable, nearly fully coherent, and intense FEL pulses, down to soft x-ray wavelengths.

Here, we demonstrate the first EEHG lasing at wavelengths as short as 5.9 nm at the (modified) FEL-2 line at FERMI [13]. We show that EEHG gives significantly better spectra in terms of the central wavelength stability and bandwidth, as compared to the two-stage HGHG cascade. The observation of stable, narrow-band emission down to 2.6 nm indicates the possibility to extend the lasing region to shorter wavelengths.

EXPERIMENT

The implementation of the EEHG seeding scheme at FERMI required modifying the FEL-2 line. The technical details are given in Ref. [14]. In summary, a second seed laser line required by EEHG and delivering up to 50 µJ per pulse at 264 nm was setup; the second stage modulator of FEL-2 was replaced by a new one, allowing resonant interaction at 264 nm; the dispersion of the magnetic chicane normally used for the FB approach was increased to be suitable as the first (strong) chicane for EEHG; new e-beam and laser diagnostics were installed to allow overlapping the e-beam and the second seed laser.

In EEHG, the output wavenumber k_E is given by $k_E = nk_1 + mk_2$, where n and m are non-zero integers and $k_{1,2} = 2\pi/\lambda_{1,2}$ are the wavenumbers of the two seed lasers operating at wavelengths λ_1 and λ_2 [12]. In our experiment, the two seed lasers had the same wavelength, $\lambda_1 = \lambda_2$, so $k_E = (n+m)k_1$, or $\lambda_E = \lambda_1/h$, where $h = n+m$ is the harmonic number and λ_E is the EEHG output wavelength. Most of the measurements were performed in the $n = -1$ configuration to maximize the signal [12], but we have also observed output at $n = -2, -3$, and $n = -4$. The latter option was employed at high harmonics due to the limitations of our setup (limited first dispersion and limited second seed power).

To optimize the EEHG output at a specific harmonic h, the first (strong dispersion) $R_{56}^{(1)}$ was fixed (to typically around 2 mm, depending on the e-beam energy) and the strength of the second dispersion section $R_{56}^{(2)}$ was set according to $R_{56}^{(2)} \approx \frac{|n|}{h} R_{56}^{(1)}$ [12]. All of the parameters (second dispersion and both seed laser intensities) were iteratively tuned to maximize emission.

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RESULTS

Figure 1 demonstrates exponential gain (lasing) of the FERMI FEL operated in the EEHG configuration at 7.3 nm, i.e., $h = 36$ of the (second) seed laser. The e-beam energy was set to 1.31 GeV. The dispersion of the first (strong) chicane was fixed at 2.38 mm, while that of the weaker (second) chicane was set to 62 μm to optimize the output in the $n = -1$ tune. The measured gain length of ~1.9 m matches relatively well the one obtained from GENESIS simulations [15] using experimentally determined e-beam and seed laser parameters. To compare the experimental and simulated gain lengths, the measured pulse energies were multiplied by a factor of two. The discrepancy between the measured and simulated values are probably associated with a degradation of the transmission efficiency of the beamline optics and detectors.

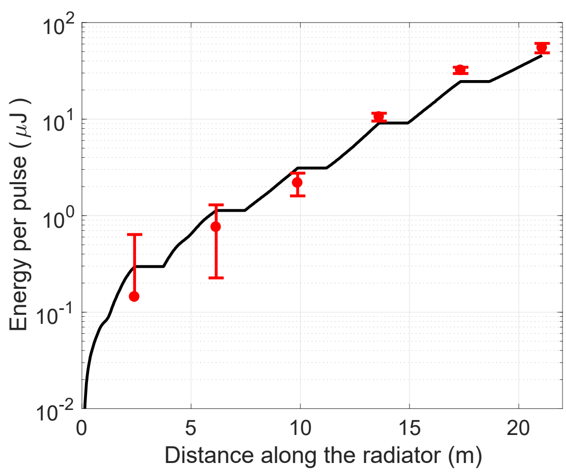

Figure 1: Measured (red circles) and simulated (black line) EEHG gain curve at 7.3 nm. See text for details.

Figure 2 shows a series of single shot spectra demonstrating the high spectral quality and stability of the FERMI FEL operated in the EEHG mode at 5.9 and 7.3 nm. A detailed analysis of 1000 consecutive shots shows a Gaussian-like shape in both cases with a relative central wavelength stability of $\sim 7 \times 10^{-5}$, and 16% and 25% RMS intensity fluctuations at 7.3 nm and 5.9 nm, respectively. We chose the minimum width containing 76% of the pulse energy ($\sigma_{76\%}$) as a measure of the spectral bandwidth. This puts more weight on the tails of the spectrum and accounts for spectral features that can come from e-beam imperfections and laser phase errors. The measured average $\sigma_{76\%}$ at 7.3 nm is 3.0×10^{-3} nm, giving a relative bandwidth of $\sim 4 \times 10^{-4}$. This is approximately 1.5 $\times$ the $\sigma_{76\%}$ of a transform-limited pulse calculated from the EEHG bunching [12]. Such deviations can probably be assigned to a residual linear frequency chirp on the second seed laser and possible spectral broadening due to e-beam instabilities. At 5.9 nm, the measured average $\sigma_{76\%}$ is 2.4×10^{-3} nm, and is around 1.8 $\times$ the value obtained from theory. These increased deviations from the calculated bandwidth, compared to 7.3 nm, are due to significant sideband structures in the spectra shown in the bottom panel of Fig. 2, and are attributed to a higher sensitivity of the output to e-beam instabilities at shorter wavelengths. Additional measurements (not presented here) show a correlation between the position and intensity of the spectral sidebands and e-beam compression, confirming that spectral degradation is related to the e-beam and not laser phase errors.

Even though the second stage modulator of the FEL-2 line was replaced with a longer period one, this still allowed operating FERMI in the two-stage cascade configuration down to a wavelength of ~8 nm. Therefore, it was possible to directly compare the performances of the two schemes employing the same e-beam (at an e-beam energy of 0.9 GeV). To move from the EEHG to the two-stage cascade configuration, the mirror used for insertion of the second seed laser beam was extracted.

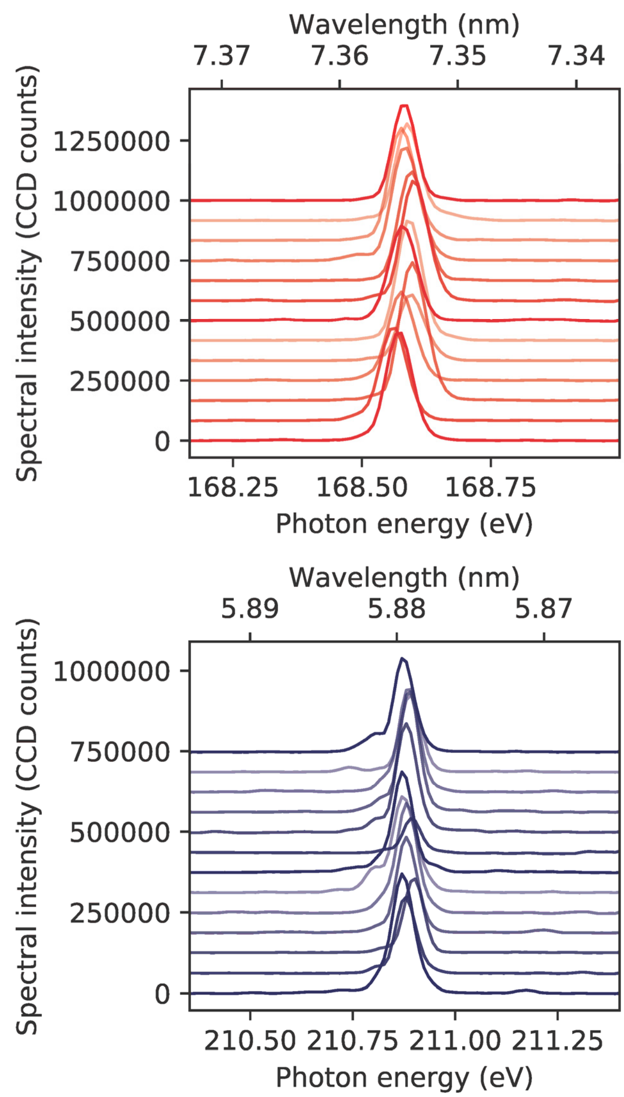

Figure 2: Single-shot spectra randomly chosen in a sequence of 1000 consecutive shots at 7.3 nm (top panel) and 5.9 nm (bottom panel) in the n = −1 configuration.

Figure 3 compares the output of the FERMI FEL operated in the EEHG and the two-stage cascade configurations. While EEHG exhibits clean and narrow, quasi-Gaussian spectra with low fluctuations of the central wavelength, the spectra of the two-stage HGHG cascade are characterized by significant irregularities and relatively high fluctuations of the central wavelength. The expected better performance of EEHG is a consequence of a much lower sensitivity of the scheme to initial e-beam imperfections compared to HGHG [16].

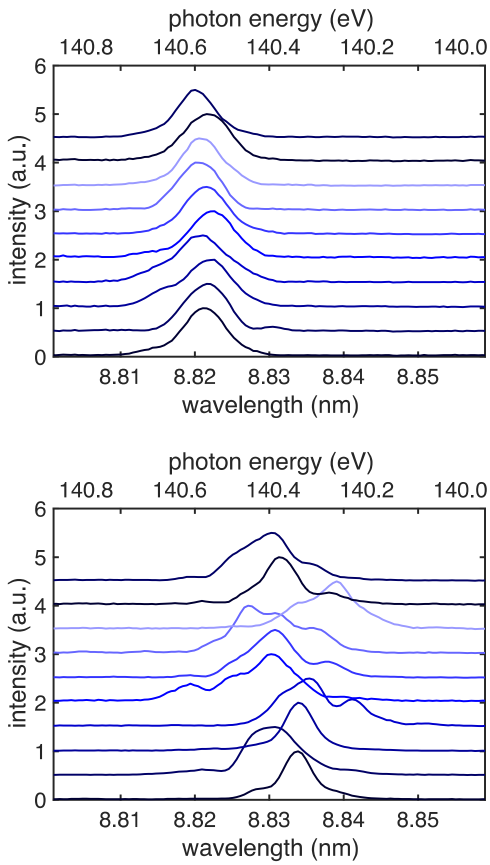

Figure 3: Consecutive single-shot spectra of the FERMI FEL operated in the EEHG (top) and two-stage cascade (bottom) configurations.

In an attempt to reach even shorter wavelengths with EEHG, we increased the e-beam energy up to 1.5 GeV. Due to the limitations of our setup (i.e., limited dispersive strength of the first chicane, limited second seed power), we had to operate EEHG in the $n = -4$ configuration, which resulted in reduced bunching. Furthermore, because of decreased gain at <4 nm, the output was considerably weaker compared to the one at 5.9 and 7.3 nm and was mainly due to coherent emission. Nevertheless, using an in-vacuum CCD to directly detect the soft X-ray photons diffracted by the spectrometer grating allowed us to measure the signal down to wavelengths as short as 2.6 nm, as shown in the bottom panel of Fig. 4.

CONCLUSION

We reported the first EEHG lasing in the soft x-ray spectral region (below 10 nm) at the modified FEL-2 line of the FERMI FEL. The output at 7.3 nm is characterized by clean, quasi single-line spectra and pulse energies on the order of tens of µJ. At 8.8 nm, the EEHG setup clearly outperformed the two-stage cascade configuration in the investigated parameter space in terms of spectral purity and stability. It should be noted, however, that the two-stage cascade still provided higher energies per pulse compared to EEHG. The reason is that the maximum bunching achievable with EEHG was lower compared to the two-stage cascade. EEHG therefore strongly relied on the exponential gain, which required careful alignment of the e-beam trajectory along the whole undulator line, while for HGHG, the conditions could be significantly relaxed.

By optimizing the EEHG parameters we could observe coherent emission down to wavelengths as short as 2.6 nm. These observations establish EEHG as a strong candidate for producing highly stable, nearly fully coherent, and intense FEL pulses in the soft x-ray spectral region. More details on the experiment can be found in Ref. [13] and Ref. [14].

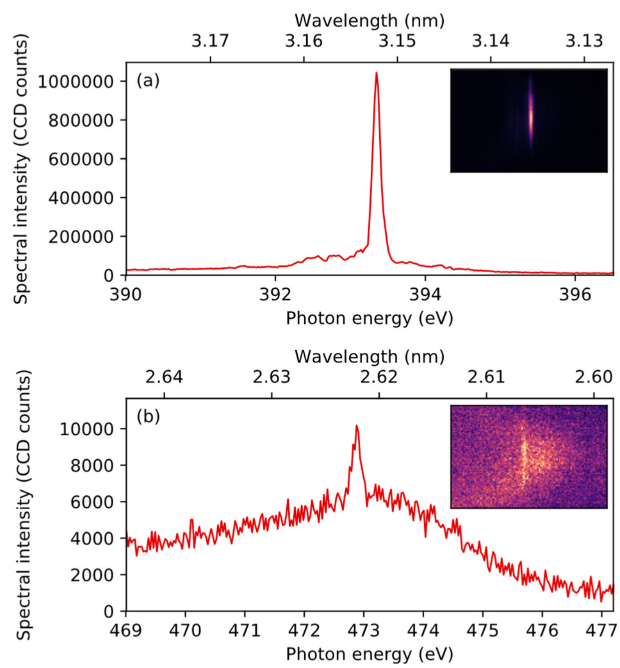

Figure 4: Coherent EEHG emission at 3.1 nm (top) and 2.6 nm (bottom).

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