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AMPLIFIED EMISSION OF A SOFT-X RAY FREE-ELECTRON LASER BASED ON ECHO-ENABLED HARMONIC GENERATION

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Abstract

We report the first evidence of substantial gain in a soft-X ray Free Electron Laser (FEL) based on Echo-Enabled Harmonic Generation (EEHG). The experiment was focused on harmonics 36 (~7.3nm) and 45 (5.8 nm) and clearly demonstrated the expected EEHG capability of generating powerful and coherent FEL pulses, with strongly reduced sensitivity to electron-beam fluctuations. The experiment was carried out at FERMI, the seeded FEL user facility at Elettra-Sincrotrone Trieste.

INTRODUCTION

Echo Enabled Harmonic Generation (EEHG) [1] has been proposed as a suitable method to extend seeded FEL operation with a single stage down to the soft-X-ray spectral range. Past experiments have shown that the EEHG scheme can sustain coherent bunching up to harmonics as high as 75 [2]. Up to now, experiments have been limited to infrared seed lasers and short radiator undulators. Hence the demonstration of the FEL amplification of EEHG bunching at short wavelength has not been demonstrated yet.

At FERMI [3], a detailed characterization of the EEHG process at short wavelengths has recently been reported [4] using a modified FEL-2 layout [5].

LAYOUT

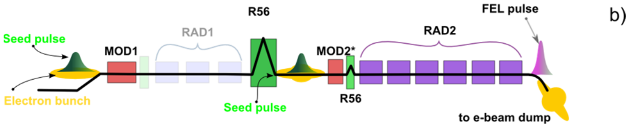

Figure 1: Modified layout of the FERMI FEL used for the EEHG experiment.

The EEHG experiment is performed on the modified FEL-2 line (Fig.1). Operations of the FEL at 7.3 nm are based on electron beam parameters as reported in Table 1.

Table 1: E-beam Parameters Used for EEHG at 7.3 nm

Parameter	Value	Units
Energy	1.35	GeV
Peak current	700	A
Normalized emittance	1	mm mrad
Beam size (rms)	100	μm
Energy spread	150	keV

Both seed laser pulses are obtained from the third harmonic of a Ti:Saphire laser and are optimized to maximize the FEL signal at harmonic 36 (7.3 nm). The main laser parameters are reported in Table 2.

Table 2: Seed Laser Parameters Used for EEHG at 7.3 nm

Parameter	Value	Units
λ seed1,2	264	nm
$\Delta\lambda$ seed1	0.9	nm
$\Delta\lambda$ seed2	1.1	nm
Pulse length seed1 (FWHM)	110	fs
Pulse length seed2 (FWHM)	90	fs
Energy seed1,2	0-30	μJ
Spot size seed1	350	μm
Spot size seed2	200	μm

The first dispersive section is set to the maximum available for this electron beam energy ($R56_1$=2.1 mm) and the second dispersive section is used as an optimization parameter. Depending on the laser parameters, it is possible to optimize the FEL at different values of the EEHG n parameter [6]. Few scans of the second dispersive section in case of different parameters optimized for n=-1, -2 and -3 are reported in Figure 2.

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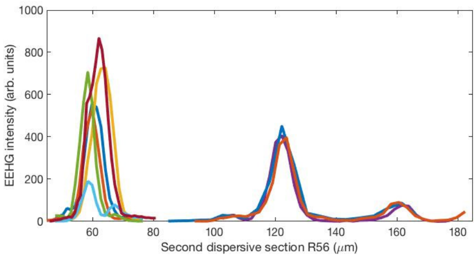

Figure 2: FEL intensity at harmonic 36 (7.3 nm) for different configurations optimized for *n* = -1 (R56~60 μm), *n* = -2 (R56 ~100-130 μm) and *n* =-3 (R56 ~150-180 μm).

FEL OPTIMIZATION

After the first EEHG signal is detected with the preliminary set of the parameters (R56, seed laser power, laser heater, resonances, …), all parameters are optimized in order to maximize the FEL emission and improve the spectral and mode quality.

Optimization starts from the theoretically predicted best working point for the desired configuration [7,8]. First superposition between each laser and the beam and the mutual superposition of the two lasers is maximized. Seed laser timing is also optimized in order to allow interaction with the electrons at the core of the beam and avoid interaction with the head and the tail of the beam [9].

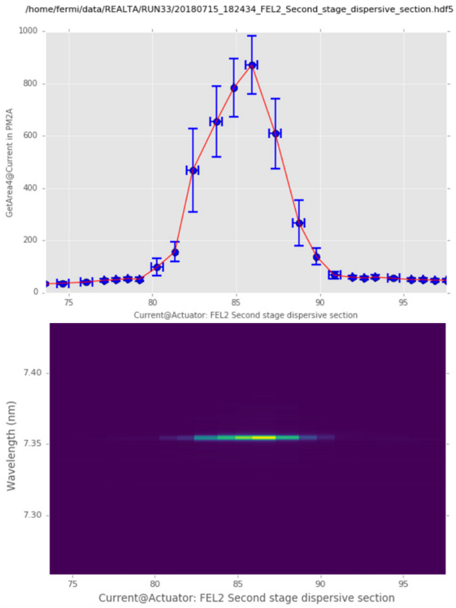

Figure 3: FEL optimization with an R56 scan (current) around the *n* = -1 condition.

Since typically more than one maximum exists in the parameter space, the optimization procedure is iterated few times with slightly different starting points for all the parameters. Figures 3 to 6 show 1D FEL optimizations of the R56, the seed lasers intensity, and the laser heater intensity.

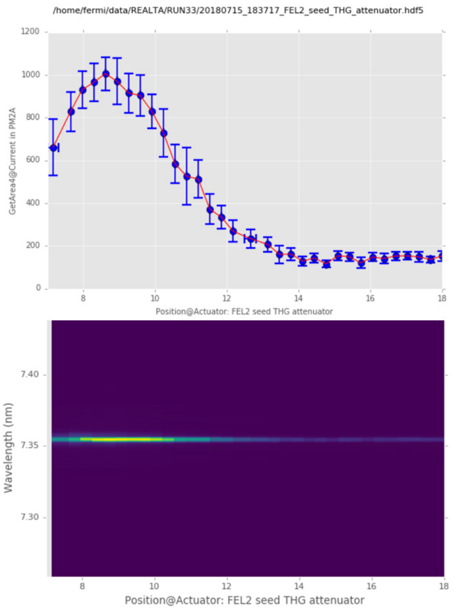

Figure 4: FEL optimization with a scan of the first seed laser intensity (attenuator) with other parameters optimized for *n* = -1.

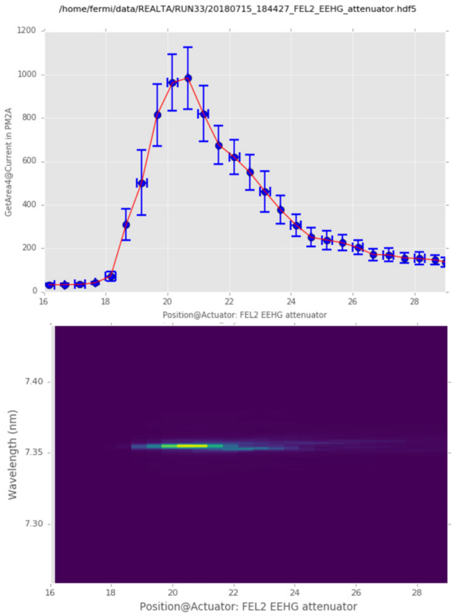

Figure 5: FEL optimization with a scan of the second seed laser intensity (attenuator) with other parameters optimized for *n* = -1.

Scans of first and second seed laser intensity (Fig. 4, and Fig. 5) clearly show the different response of EEHG to the two modulations. Sensitivity to the second seed is much more pronounced and moreover a too intense second seed also affects the spectral properties of the FEL as in the case of HGHG [10]. Variations of the first seed intensity, on the contrary, only affect the FEL intensity (EEHG bunching) but have no significant impact on the spectral quality.

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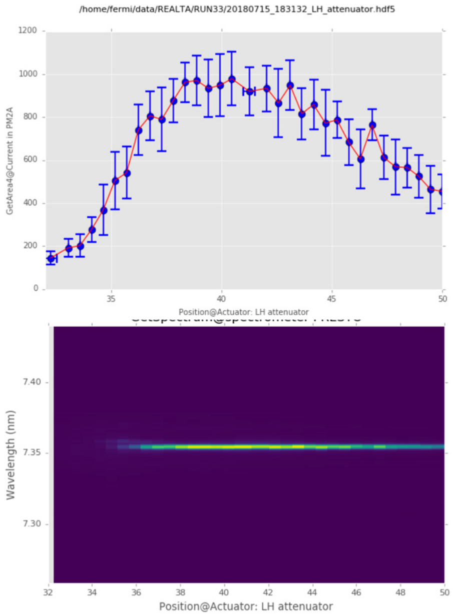

Figure 6: FEL optimization with a scan of the laser heater intensity (attenuator) with other parameters optimized for *n* = -1.

Even tough EEHG has been shown to have a reduced sensitivity to electron beam energy spread [6], optimization of LH is still necessary and particularly important for short wavelength and high harmonics. As reported in Figure 6, a too weak laser heater is not optimal due to the effect of micro-bunching instability that spoils the electron beam brightness. On the other side for a too intense laser heater, both EEHG bunching and FEL gain can be reduced by the larger energy spread. EEHG normally shows the presence of an optimal working point for the laser heater at values slightly larger than what normally required by HGHG. With respect to HGHG the FEL power decrease for higher laser heater intensities is reduced in EEHG.

Finally a very critical work was needed to fully optimize the FEL amplification of the EEHG bunching. The definition of the best electron beam trajectory in the undulator was important to allow the best overlap of the coherent emission produced by the electron within each undulator. Once everything has been optimized also the undulator tapering needs to be adjusted to compensate for the electron energy loss due to FEL the emission

FEL GAIN

After the EEHG parameters have been optimized, FEL emission is measured as a function of the number of undulator set on resonance with the desired harmonic and the FEL gain curve is measured (Fig.7).

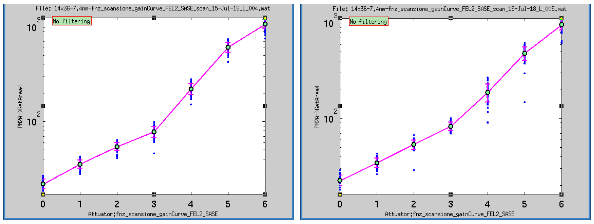

Figure 7: Measured FEL gain for two different trajectories of the electron beam in the undulators.

Typical measured gain length at 7.3 nm is in the range 1.9-2.2 meters showing a good agreement with numerical simulations [4]. FEL output power up to few tens of μJ per pulse are measured for pulses with very narrow bandwidth.

CONCLUSIONS

With the modified FEL-2 setup at FERMI, FEL amplification of EEHG bunching at wavelengths as short as 7 nm has been demonstrated at FERMI.

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