IMPLEMENTATION OF SINGLE-STAGE ECHO-ENABLED HARMONIC GENERATION ON THE FERMI@ELETTRA FEL

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Abstract

In this work we study the possibility to implement an Echo-Enabled Harmonic Generation scheme on the FERMI@Elettra FEL. In particular, we present our studies for harmonic generation at 6.6 nm, starting from a seed signal at 210 nm. The harmonic content of the FEL emission at shorter wavelengths is also analyzed. By means of both theoretical calculations and time independent simulations, we estimate the sensitivity of the FEL performance to the fluctuations of the electron beam parameters. The number of photons per pulse and the FEL bandwidth are calculated through time-dependent start-to-end simulations.

INTRODUCTION

FERMI@Elettra [1] is a Free Electron Laser facility that will provide the user community with FEL radiation in the wavelength range from 100 to about 4 nm. In order to satisfy the user requirements FERMI will be a seeded FEL using APPLE2 undulators for generating variable polarization light [2]. While the normal conducting LINAC will provide electron beams with an energy ranging from 0.9 to 1.5 GeV the wide photon energy range will be covered by two different FELs, namely FEL-1 and FEL-2, both of them based on the High Gain Harmonic Generations (HGHG) scheme, see Fig.1.

FEL-1 will cover the range from 100 to 20 nm and will be based on a single-stage HGHG scheme, initiated by a tunable laser in the UV. In order to cover the range between 20 nm and 4 nm, FEL-2 will rely on a cascaded HGHG scheme, in which the second stage is fed by the radiation generated by the first one. During FERMI design, a special care has been taken in order to guarantee the possibility to implement, on both FEL's, alternative schemes, allowing to improve the system performance. In fact, minor modifications of the layout shown in Fig. 1, will allow to perform seeding with short-wavelengths source (HHG), or to implement a single stage for reaching shorter wavelengths using the Echo Enabled Harmonic Generations (EEHG) [3].

In this work, we present the expected performance of the EEHG scheme that may be implemented on the FERMI FEL.

THE LAYOUT

The layout of both FELs, as well as their main components, is shown in Fig.1. More details about the system components may be found in [4].

We here focus on FEL-2. The latter is composed of a first modulator (MOD1), where the electron beam interacts with the seed laser and receives an energy modulation. Electrons pass then through the dispersive section, where the energy modulation is converted into spatial modulation optimized at the desired harmonic of the seed wavelength. At the entrance of the first radiator (RAD1), the bunched electron beam emits coherently at the desired harmonic. The emission is then amplified all along the radiator. At the exit of the first radiator, the e-beam passes through the "delay line", i.e. a magnetic chicane that delays the electrons with respect to the FEL pulse produced by them on RAD1. The delay is optimized so that, in the second modulator (MOD2), the FEL pulse is superposed to a new ("fresh") part of the electron beam, that has not been involved in the previous FEL process. The interaction with the FEL pulse generates an electron-beam density modulation at the FEL wavelength (which is a harmonic of the original seed laser). Similar to what happens in the first stage, the energy modulation is converted into spatial modulation (showing nonzero Fourier components at the seed wavelengths and at its harmonics) when the beam propagates through the second dispersive section.

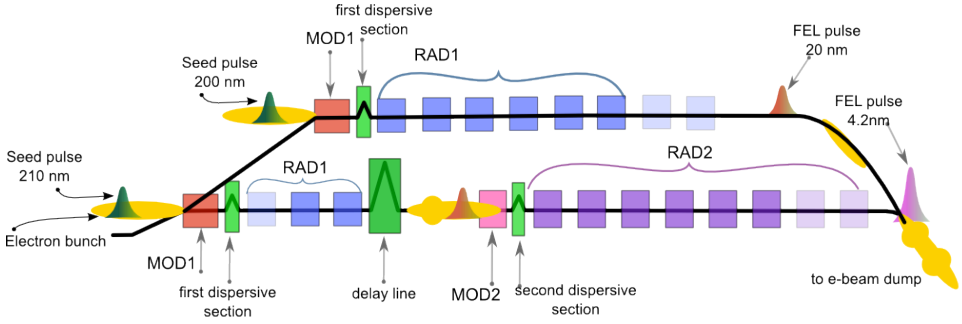

Figure 1: Schematic layout of the two FERMI FELs: FEL-1 and FEL-2. FEL-1 is based on a single HGHG scheme while the nominal configuration of FEL-2 is based on a cascaded HGHG scheme, making use of a "fresh bunch" section.

Finally, the bunched electrons emit coherently at the desired harmonic wavelength. Saturation is reached before the end of the final radiator (RAD2).

Table 1: Nominal Parameters of the FERMI Electron Beam

Parameter	Value	Units
Beam energy	0.9-1.5	GeV
Charge	800	pC
Peak current	800	A
Normalized emittance	1.0	mm mrad
Energy spread	150	keV

In order to implement the FEL-2 fresh-bunch scheme, a quite long electron bunch is required, with relatively high peak current (800 pc). The nominal parameters of the FERMI e-beam are reported in Table 1.

The final design of FEL-2 has been optimized so to guarantee the possibility of implementing an EEHG scheme, with minor modifications of the HGHG setup. A preliminary study of such EEHG scheme can be found in [5].

The main components required for implementing the EEHG are two modulators, where the electrons interact with an external laser; a strong dispersive section located between the modulators, having an equivalent R56 of the order of few mm; a second dispersive section with an equivalent R56 of the order of 100 µm, and a final radiator tuned at the desired wavelength.

In the FEL-2 layout that will be used for HGHG, the first modulator is already present, while the magnetic chicane of the delay line may be used to implement the first (strong) dispersive section. The second dispersive section and the final radiator are already included in the HGHG layout. The only missing component is the second modulator, that should replace MOD2 in fig. 1 (that does not allow to fulfil the resonance condition at the seed laser wavelength).

The "Delay Line" Magnetic Chicane

The "delay line" is based on a four dipoles magnetic chicane. The dipole strength, whose maximum magnetic field is 1.06T, and the distance between them allows to produce a dispersion up to about 1 mm at the highest electron beam energy for FERMI (1.5 GeV), and more than 2 mm at 0.9GeV. The most relevant data regarding the chicane are reported in Table 2. Although the allowed R56 is smaller than the one generally required by the EEHG the setup can still be efficiently used for implementing the echo scheme. The mechanical design showing the dipoles and their configurations is reported in Fig. 2.

With the idea of allowing possible injections of seeding sources directly in MOD2 the vacuum chamber of the delay line has been already designed with two input ports in the middle of the chicane, allowing the possibility to seed either in the UV or in the VUV with a HHG source.

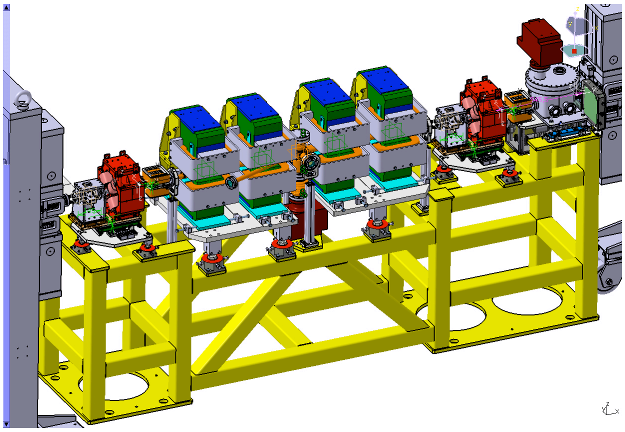

Figure 2: Mechanical design of the electron delay line based on a magnetic chicane with four magnets. In the centre of the chicane two input ports for seeding entrance have been foreseen

Table 2: Design Values of the Delay Line Chicane at Three Electron Beam Energies

Parameter	Value	Value	Value	Units
Electron Beam Energy	0.9	1.2	1.5	GeV
Maximum curvature angle	64	48	38	mrad
Maximum beam offset	23	17	14	mm
Maximum R56	2.4	1.4	0.9	mm

NUMERICAL SIMULATIONS

A series of time steady FEL simulations have been done in order to calculate the FEL performance of FEL-2 using the EEHG scheme. With respect to the actual design of FEL-2 in our simulations only the second modulator has been changed with one with longer period in order to allow setting the resonance condition at 200nm. Simulations have been done with the GINGERH code [6].

The layout employed in our simulations is shown in Figure 3, while the used parameters are the ones reported in Table 2 and Table 3. It is important to point out that the electron beam parameters, best suited for the HGHG cascade, are not the ones optimized for the EEHG.

Figure 4 and Figure 5 report the results of the simulations. From Figure 4 it is possible to appreciate the effect of EEHG on the electron beam phase space

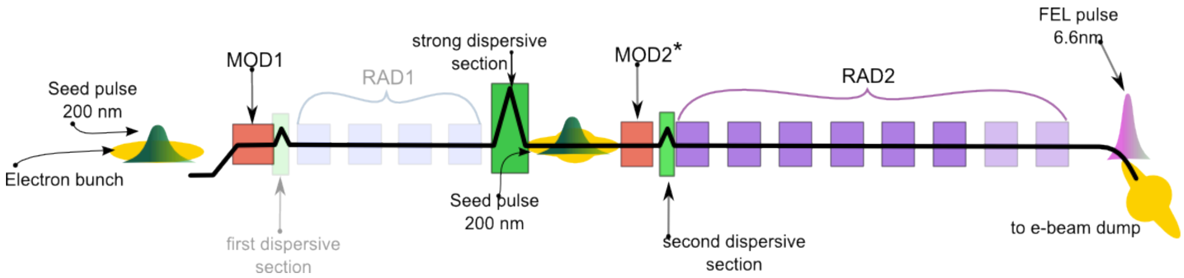

Figure 3: Schematic layout of the modified setup of FEL-2 used for study the EEHG in FERMI. The undulators in RAD1 are not used (open gap), the delay line is used as a strong dispersive section with a R56 of the order of 1 mm. A second seed laser is injected in the middle of the chicane in order to interact with the e-beam in MOD2*. The undulator of MOD2, that in the nominal layout has a period of 55 mm, has been changed with one whose period is 10mm, allowing to set the resonance at 200nm. The last part of the FEL is not changed with respect to the nominal setup.

at the entrance of the last radiator, showing the vertical stripes (Fig. 4a) that are responsible of the fast density modulation of the beam charge (Fig. 4b), whose Fourier components are significant up to the thirty harmonic (Fig. 4c).

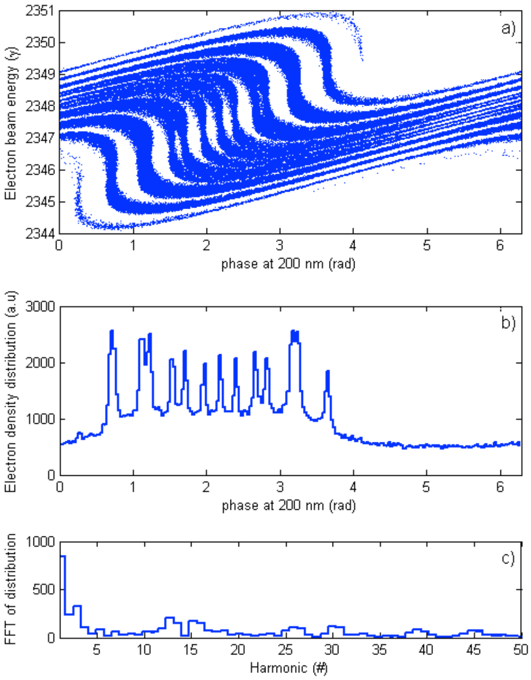

Figure 4: Expected electron phase space at the exit of the last chicane with the optimized seeding for EEHG (a). As a consequence of the vertical stripes in the phase space the beam shows strong density modulation on a fast scale (b) that have also a significant components up to the thirty harmonic (c).

As a consequence of the significant bunching produced by the seeding the thirty harmonic of the seed the FEL emission growth very fast in the final radiator and about 1 GW is reached at 6.6 nm within the six available undulators (Fig.5).

Table 3: Parameters used for the Simulation

Parameter	**Value**	**Units**
Electron beam energy	1.2	GeV
Seed laser wavelength (1,2)	200	nm
Seed laser power (1)	20	MW
Seed laser power (2)	120	MW
R56 (1)	0.88	mm
R56 (2)	60	μm

Also the third harmonic of the FEL is produced and about 2MW are expected.

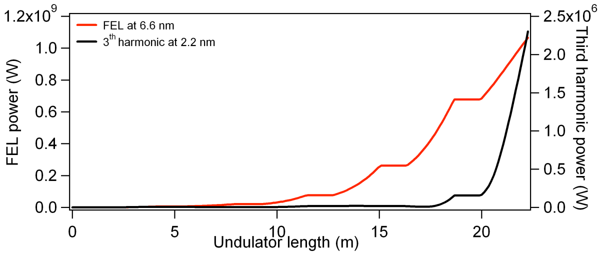

Figure 5: Results of numerical simulation of the FEL emission in the final radiator of FEL-2 operating at 6.6nm in EEHG starting from a 200 nm seed.

Start to End Simulations

Start-to-end simulations have been done using macroparticle distributions first generated at the cathode with the injector code GPT, and then self-consistently (including longitudinal space charge and coherent synchrotron radiation effects) propagated through the LINAC with the ELEGANT code.

Using the same parameters used for time independent simulation (see Table 3), we performed a series of time-dependent simulations in order to estimate the effect due to the variations of electron-beam properties along the beam. The same set of simulations provides an estimate of the number of photons per pulse, as well as of the expected bandwidth.

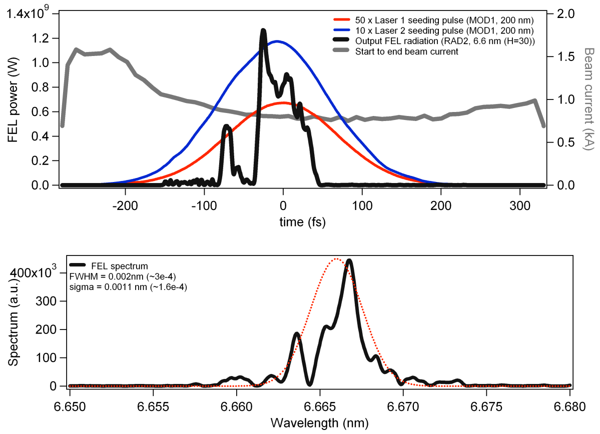

Figure 6: (a) FEL fundamental power at 6.6nm at the undulator exit (black). Used seed pulses are also reported in blue and red as a reference. (b) Far field power spectrum (black line) and spectrum envelope (red curve).

From these start–to-end simulations we can expect that FEL-2 in EEHG at 6.6nm would be able to generate about 60 μJ and 10^{12} photons per pulse with 60fs (FWHM) pulse length and with a relative bandwidth of about $3*10^{-4}$.

SENSITIVITY TO E-BEAM PARAMETERS

Much better performance can be expected from EEHG using an e-beam optimized for such configuration.

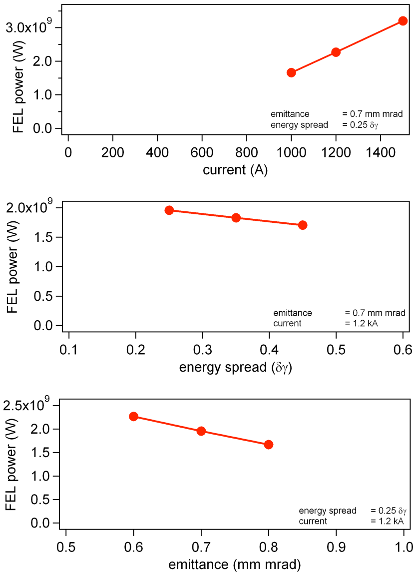

Figure 7: Simulations results for the FEL power at 4nm as a function of various electron beam parameters.

In particular shorter e-beam with higher peak current and possible better emittance provide a significantly better result. Indeed since with the EEHG there is no need to perform the double cascade, a shorter e-beam with less charge could be used.

The possibility of operating with different e-beam is here studied in order to evaluate the sensitivity of EEHG to electron beam parameters. For the presented studies, we focused on the 1.5GeV electron beam and to the generation of FEL emission at 4 nm, the fifty harmonic of the seed laser.

Results reported in Figure 7 show that the FEL output power strongly depends on the beam current, while slightly depends on the beam emittance and energy spread.

According to the indications of our studies, it appears that, if possible or needed, FERMI FEL-2 could be easily optimized to be operated in EEHG configuration.

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REFERENCES

[1] C. Bocchetta *et al.*, "Fermi@Elettra Conceptual Design Report", Sincrotrone Trieste Rpt. ST/F-TN-07/12 (2007).

[2] E. Allaria *et al.*, "The FERMI@Elettra free-electron-laser source for coherent x-ray physics: photon properties, beam transport system and applications" New J. Phys. **12** 075002 (2010).

[3] G. Stupakov, "Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation", Phys. Rev. Lett. **102**, 074801 (2009).

[4] FERMI@Elettra, http://www.elettra.trieste.it/FERMI/.

[5] E. Allaria, G. De Ninno and D.Xiang, "Feasibility Studies for Single Stage Echo-Enabled Harmonic in FERMI FEL-2" FEL Conference 2009, MOPC02 (2009).

[6] W.M. Fawley, LBNL Tech. Rpt. LBNL-49625-Rev. 1 (2004).