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FERMI FEL-1 UPGRADE TO EEHG

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Abstract

In order to extend the FERMI FEL spectral range over the whole water window, we are developing an upgrade strategy that is based on the implementation of the Echo Enabled Harmonic Generation scheme.

The strategy is structured as follows: during a first phase, the single cascade FEL-1 branch will be adapted to operate either in EEHG or in HGHG. This upgrade can be achieved with relatively low cost and impact on FERMI operations and will extend the spectral range, and improve spectral quality and flexibility of FEL-1. Furthermore, it will provide a versatile test bench opening the possibility to explore in detail the EEHG scheme potentialities in the operation of the facility. This will contribute to identify and address the possible issues related to the second and more critical phase of the upgrade project: the upgrade of FEL-2. These two phases will proceed in parallel to an upgrade of the LINAC where we will increase the maximum energy of operation. Solutions aiming at a peak beam energy of 1.8 and 2.0 GeV are under study.

In this contribution, we will focus on the upgrade of the FEL-1 branch that has already started and is foreseen to provide light to users with the new configuration by spring 2023.

INTRODUCTION

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

The main limitation of the HGHG technique is related to the reduction of the ratio between bunching at a given harmonic and energy spread as the harmonic order increases. On FEL-1, efficient bunching for harmonic amplification can be created up to approximately harmonic 15 in single cascade. This is the limiting factor for achieving shorter wavelengths on this FEL line.

EEHG has been successfully tested at FERMI in 2018 [2]: implementing a temporary modification of the FEL-2 layout, we have demonstrated high gain lasing in EEHG mode up to harmonic 45 in a single cascade.

The need to increase the photon energy of FEL-2 by a factor of 2 with respect to the current limit requires a significant change in the FEL-2 layout and a change in the undulator parameters. This may affect the FEL-2 capability to be operated in a wavelength range extended from 20 nm to 2 nm. As a result, the FEL-2 upgrade is planned in parallel with an upgrade of FEL-1, such that the 20 – 10 nm can be also covered by FEL-1.

The upgrade of FEL-1 is realized with relatively modest impact on the original layout. It has been scheduled early in time with respect to the one of FEL-2 also to contribute to form our experience in running an EEHG seeded FEL for users and to provide additional studies of EEHG at very high harmonics, which will help in steering the design of FEL-2 in the technical definition of the final FEL upgrade.

Echo-enabled harmonic generation (EEHG) was first proposed by G. Stupakov [3] as a means to overcome the limitations of the standard HGHG scheme, posed by incoherent energy spread, in reaching extremely high harmonic numbers (e.g., n>100) for generation of soft X-ray radiation when starting from the radiation from an external, ultraviolet seed laser.

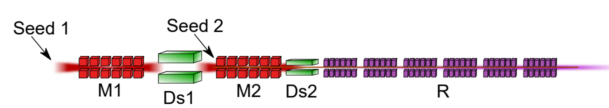

Figure 1: A sketch of the EEHG configuration.

Unlike the standard HGHG scheme that for high harmonic number n has the coherent bunching fraction b_n decaying exponentially as n^2, EEHG when properly tuned leads b_n decaying only as $n^{1/3}$ in the absence of other effects such as incoherent intrabeam scattering. Figure 1 illustrates schematically the EEHG approach. At the beginning, a seed laser (seed-1) at wavelength λ_1 together with a short modulator induces a moderate, coherent energy modulation on the input electron beam. The dispersive section that follows is sufficiently strong such that $R_{56}\frac{\sigma_\gamma}{\gamma} \gg \lambda_1$, thus shearing the longitudinal phase space and, at a given phase, leading to multiple, alternating bands of large and small density as a function of the energy. The first part of the EEHG configuration is devoted to the generation of this energy modulated beam distribution. The

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second part is the same as an HGHG configured FEL, i.e. the electron beam passes into a second modulator section where it interacts with a second seed laser (whose wavelength λ_2 may or may not be equal to λ_1) producing new energy modulation on top of the sheared bands produced in the first section. A second chromatic dispersion is then tuned in strength to rotate these ripples by approximately $\pi/2$ in their longitudinal phase. The resultant phase space is rich in harmonic content and, for appropriate choices of seed laser and dispersion section strength, can be tuned to produce an echo effect whose maximum bunching appears at a net harmonic n >> 1 relative to the initial seed wavelength (see Figure 3 of Ref. [3]). EEHG exhibits a lower sensitivity to electron-beam energy modulations induced by self-fields during the acceleration and compression. The first dispersion required for EEHG leads to strong damping of beam modulations leading to FEL spectral sidebands [4-6]. EEHG is therefore particularly promising in reaching high order harmonics of the seed, not only for the possibility of inducing electron-beam density modulation with a lower energy spread with respect to that required in HGHG, but also for the possibility of getting a cleaner spectrum, with less sidebands and closer to the Fourier limit.

FEL-1 UPGRADE

We analyze the steps required for the upgrade of FEL-1 and we show simulation results of this FEL beamline in the new setup.

Although simulations indicate that the first chicane *R*56 value for FEL-1 EEHG operation must be of the order of ~ 3 to 5 mm at 1.8GeV, this device was designed to reach a maximum dispersion of *R*56 ~ 12 mm as it will allow detailed studies of EEHG, important for the future upgrade of FEL-2. In order to get such a large dispersion, the chicane requires few meters of space. Moreover, to operate in the EEHG scheme it is necessary to add a second modulator and a second dispersive section after this. The second UV seed laser will be injected in the middle of the first chicane.

All these implementations can be obtained only with a reconfiguration of the FEL-1 layout: the first two radiators will be displaced to the end of the radiator chain (after the present position of radiator 6) as shown in Figure 2, leaving 6.2 m of space available for the full chicane system, including beam control and diagnostic systems (BPMs, screens, correctors, quadrupoles, …).

In order to convert FEL-1 to EEHG the following modifications and components are required:

- The first two radiators of the FEL amplifier are shifted to the end of the undulator chain
- A first large chicane (*R*56 up to 12 mm) is installed between the first and second modulators.
- In the middle of this first chicane a diagnostic/seed-injection chamber is installed
- A second modulator is installed after this first chicane.
- A second tunable UV seed laser is required.
- A second chicane (R56 up to 200 µm) follows the second modulator.
- New diagnostics and reorganization of the existing one (beam position monitors, multi-screens, bunch arrival monitor), is needed to adapt to the new layout.

In the framework of the upgrade plan of FERMI (Main Beam Dump, Linac, …) the EEHG implementation on FEL-1 is expected to be completed by the end of 2022. After commissioning, the new scheme will provide light to users starting from spring/summer 2023. The FEL-1 upgrade is scheduled to have minimum impact on the scientific program of FERMI and will occur during the ordinary shutdown (SD) periods. The status and plans for the FEL-1 upgrade project are the following:

1. In 2021 we completed the technical design of all parts, purchased the main elements, started the reorganization of the diagnostics.
2. 2022: we are purchasing the remaining components, seed-2 installation in seed laser rooms (spring SD), preparation of the undulator hall, move of the first two radiators at the end of the undulator chain, installation of the new vacuum chambers, second modulator and dispersive section, completion of the diagnostics system, installation of the optical transport for seed-2 (summer SD).
3. Winter SD 2022/2023: installation of the first dispersive section, of the injection/diagnostic station and of the in-tunnel optical table for seed-2.
4. 2023: EEHG commissioning will be conducted during the first part of the year. We plan to deliver light to users in the 10-20 nm range by the end of the first semester.

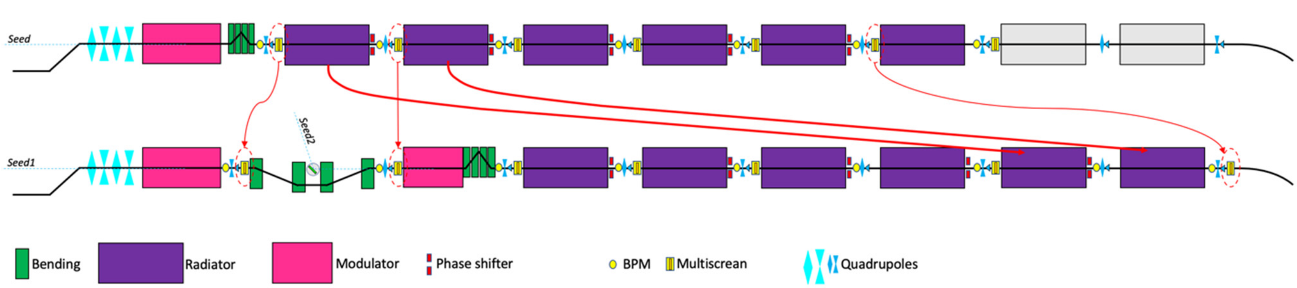

Figure 2: Schematic layout of the changes from the current FEL-1 layout (top) to the one for EEHG (bottom).

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The new configuration will also allow operation of the FEL in the usual HGHG mode and in all the advanced schemes (two color, two pulses, coherent control, …) [7 - 11]. In particular, the new design is optimized to work in HGHG for wavelength longer than 20 nm, and in EEHG in the 10 – 20 nm range.

A campaign of simulations was carried out to predict the behavior of the new layout of FEL-1 in the EEHG and HGHG configuration. We present here one example of numerical calculation of the performance expected from the new layout at 10 nm in EEHG. The calculation was performed using GENESIS 1.3 simulation code [12].

During the EEHG test preformed on FEL2, it was necessary to increase the energy spread of the electron beam to a value of 200-280 keV by means of the laser heater in order to have the most efficient EEHG lasing. Our explanation of this observation is that an increased energy spread is needed to suppress the microbunching instabilities that are amplified by the large *R*56 of the first chicane. Evidence collected with an OTR screen placed downstream of the undulators seems to confirm this hypothesis. For this reason, in the simulation we used for the energy spread a value of 220 keV.

Table 1: Electron Beam, Seed Lasers and FEL Parameters used for the Numerical Calculation

Beam parameter	**Value (unit)**
Energy	1660 (MeV)
Energy spread	220 (keV)
Current	700 (A)
Emittance	1 (mm mrad)
Seed parameters	**Value (unit)**
Seed1 wavelength	260 nm
Seed2 wavelength	260 nm
Seed1 power	11 MW
Seed2 power	23 MW
Seed1 time duration	120 fs
Seed2 time duration	90 fs
FEL parameters	**Value (unit)**
$R56_1$	4.5 mm
$R56_2$	176.6 µm
Harmonic Number	26
Polarization	circular

Table 1 contains the list of parameters used in the simulations and Figure 3 reports the evolution of the power and spectral profiles of the radiation during the growth along the undulator. The spectrum is quasi-gaussian with a narrow bandwidth and a small sideband content (below 1%). The time bandwidth product at the end of the radiator is 1.40 the Fourier limit.

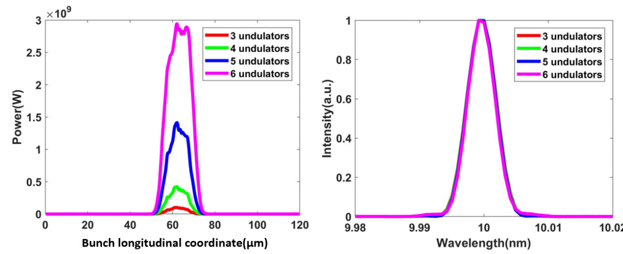

Figure 3: Left: power profile after 3,4,5 and 6 undulators. Right: spectrum shape after 3,4,5 and 6 undulators.

In summary, the simulations are definitely encouraging and show that in EEHG mode the pulse energy can exceed 100µJ at 10 nm.

REFERENCES

[1] E. Allaria *et al.*, "Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet", *Nat. Photon.*, Vol. 6, p. 699–704, 2012.

[2] P. Rebernik Ribič *et al.*, "Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser", *Nat. Photon.*, Vol. 13, p. 555–561, 2019.

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

[4] B. Garcia *et al.*, "Echo-Enabled Harmonic Generation Results with Energy Chirp", in *Proc. 38th Int. Free Electron Laser Conf. (FEL2017)*, Santa Fe, NM, United States, Aug. 2017, pp. 64-67. doi:10.18429/JACoW-FEL2017-MOP017

[5] P. Rebernik Ribič *et al.*, "Echo-Enabled Harmonic Generation Studies for the FERMI Free-Electron Laser", *Photonics* Vol. 4, no. 19, 2017.

[6] E. Hemsing *et al.*, "Sensitivity of Echo Enabled Harmonic Generation to Sinusoidal Electron Beam Energy Structure", *Phys. Rev. Accel. Beams*, Vol. 20, p. 060702, 2017.

[7] E. Allaria *et al.*, "Two-colour pump–probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser", *Nat. Commun.,* Vol. 4, p. 2476, 2013.

[8] E. Ferrari *et al.*, "Widely tunable two-colour seeded free-electron laser source for resonant-pump resonant-probe magnetic scattering", *Nat. Commun.*, Vol. 7, p. 10343, 2016.

[9] P. K. Maroju *et al.*, "Attosecond Pulse Shaping Using a Seeded Free-Electron Laser", *Nature*, Vol. 578, p. 386, 2020.

[10] A. Wituschek *et al.*, "Tracking Attosecond Electronic Coherences Using Phase-Manipulated Extreme Ultraviolet Pulses", *Nat. Commun.*, Vol. 11, p. 883, 2020.

[11] K. C. Prince *et al.*, "Coherent Control with a Short-Wavelength Free-Electron Laser", *Nat. Photon.,* Vol. 10, p.176, 2016.

[12] S. Reiche, "GENESIS 1.3: A Fully 3D Time-Dependent FEL Simulation Code", *Nucl. Instr. and Meth. in Phys. Res. A*, Vol. 429, I. 1-3, p. 243, 1999.