FEASIBILITY STUDIES FOR SINGLE STAGE ECHO-ENABLED HARMONIC IN FERMI FEL-2*

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Abstract

Recently, the second FEL line of the FERMI FEL has been modified in order to extend its tuning range down to 4 nm. In order to reach such a short wavelength starting from the UV seed laser the FERMI FEL-2 system relies on a double cascade of high gain harmonic generation (HGHG). In this work we study the possibility of using the present FEL-2 layout with minor modifications to generate GW soft x-ray radiation using the recently proposed echo-enabled harmonic generation (EEHG) technique. The final aim is to cover the expected spectral range of FEL-2 with a single stage. The performance of the EEHG in FERMI FEL-2 is estimated by means of FEL simulations with standard FEL codes.

INTRODUCTION

FERMI is a Free Electron Laser user facility [1] under construction at Sincrotrone Trieste that foresees two different FEL lines. Both FELs will use the 1.5 GeV linac, which is currently under commissioning, and is expected to produce first photons at the end of 2010[2].

The first FEL line (FEL-1) has been already defined and the undulators, which are under construction, will cover the spectral range from 100 nm to 20 nm with variable polarization. According to the recent developments of the FERMI scientific case [3], the second FEL line, namely FEL-2, has been recently modified with respect to the original design presented in the FERMI CDR [1]. Such a modification will allow us to meet the new user requirements, by taking advantage of the improved expected performance of the FERMI linac [4].

The new FEL-2 design is still based on a double HGHG cascade[5]. This choice is motivated by the status of the current technology and by the current knowledge of the FEL process. A possible alternative scheme, that may be used to meet user requirements, relies on the use of a HHG seed source for a single HGHG scheme, or for a direct seeding in the spectral range of interest. However, the present status of HHG sources and their performance in terms of tuning and stability still require major R&D efforts before they can be reliably used for a FEL user facility. However, in the design of FEL-2, attention has been taken in order to allow future upgrades to different schemes in case those become more reliable. Different HHG seeded configurations may indeed be implemented on the present layout[5].

Recently, the possibility of generating coherent emission at very high harmonics of the initial seed laser has been proposed [6] and some feasibility studies have been done for a FERMI-like FEL [7]. However, such a technique that relies on the so-called echo effect has not yet been demonstrated in the optical wavelength range and some open points should be addressed before adopting it for a user facility. In this work, we focus our attention on the possibility of implementing the echo-enabled harmonic generation (EEHG) scheme in order to cover the full spectral range of FEL-2, with minor modifications of the proposed FEL-2 layout.

APPLYING EEHG TO FERMI FEL-2

The echo scheme uses two modulators and two dispersion sections. In general, the frequencies of the first, ω_1, and the second, ω_2, modulators can be different. The beam modulation is observed at the wavelength $2\pi/k_E$, where $ck_E = n\omega_1 + m\omega_2$, with n and m integer numbers. The first dispersion section is chosen to be strong enough, so that the energy and the density modulations induced in the first modulator are macroscopically washed out due to the slippage effect. At the same time, this smearing introduces a complicated fine structure into the phase space of the beam. The echo then occurs as a re-coherence effect caused by the mixing of the correlations between the modulation in the second modulator and the structures imprinted onto the phase space by the combined effect of the first modulator and the first dispersion section. The key advantage of the echo scheme is that the amplitude of high harmonics of the echo is a slow decaying function of the integer numbers n and m, which may allow for generation of coherent soft x-ray directly from the UV seed laser in a single stage. When the resonant wavelengths are the same in the two modulators, the optimized bunching factors for various harmonic numbers are found to be [7],

$$\begin{aligned} b_{n,m} &= |J_m((m+n)A_2B_2)| \\ &\quad \times |J_n(A_1((m+n)B_2+nB_1))| \\ &\quad \times \exp\left[-\frac{1}{2}((m+n)B_2+nB_1)^2\right], \quad (1) \end{aligned}$$

where $A_1 = \Delta E_1/\sigma_E$ and $A_2 = \Delta E_2/\sigma_E$ are the dimensionless energy modulation amplitude in the first and second modulator; $B_1 = R_{56}^{(1)}k\sigma_E/E_0$ and $B_2 = R_{56}^{(2)}k\sigma_E/E_0$ are the dimensionless dispersion strength for

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the first and second chicane, respectively.

The electron beam parameters expected from the FERMI linac are summarized in table I. In this paper we will focus on the 4 nm radiation which is the 50th harmonic of a 200-nm seed laser. Applying EEHG at other wavelength can be similarly studied. Assuming $E = 1.5$ GeV, $\epsilon_n = 0.8$ mm mrad and an average Beta function of 8 m in the radiator, the gain length for the 4 nm radiation is calculated and shown in Fig. 1.

Table 1: Nominal values for the electron beam parameters excepted from the FERMI linac

Electron Beam Energy	$0.9 \sim 1.5$ GeV
Peak current	$750 \sim 800$ A
Electron bunch length (flat part)	600 fs
Normalized emittance	$0.8 \sim 1$ mm mrad
Slice energy spread	150 keV

In order to get sufficient bunching factor to suppress the shot noise while limiting the dispersion strength to a moderate value to mitigate the quantum diffusion from incoherent synchrotron radiation, we choose $A_1 = 3$ and $A_2 = 6$. In this case the slice energy spread of the beam at the entrance to the radiator is about 727 keV. From Fig.1 one can see that with this slice energy spread, the gain length only increases by about 15% as compared to the ideal case.

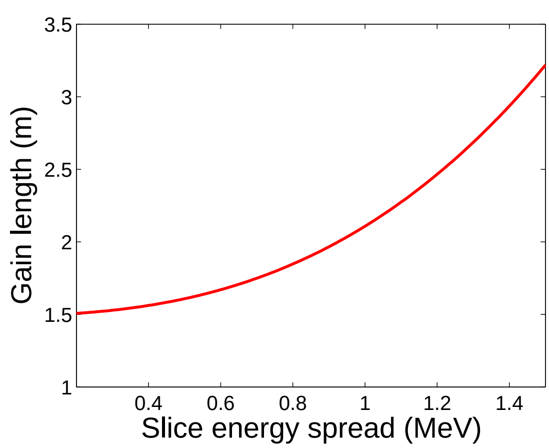

Figure 1: Gain length vs local energy spread at the radiator entrance.

In order to apply EEHG to FERMI FEL-2 with minimal modifications, it is desirable to use the existing chicanes as the two dispersive sections. Since, for the presently adopted (HGHG) configuration, the second dispersion section only requires an equivalent $R_{56}^{(2)}$ of the order of 100 micron, it is straightforward to use the second dispersive section already present in the FERMI layout as the second chicane in EEHG scheme. However, the former is required to be very large compared to standard values used in FELs with an equivalent $R_{56}^{(1)}$ of a few mm. In the FERMI FEL-2 layout a similar value may be obtained from the chicane that is used as the delay line necessary for implementing the fresh bunch in the double HGHG scheme.

To maximize the bunching factor for the 50th harmonic, one should choose $n = -1$ and $m = 51$. In this case the required dispersion strength for the first chicane is about 2.7 mm when $A_1 = 3$ and $A_2 = 6$. However, the delay line chicane may not be able to provide an $R_{56}^{(1)}$ larger than 1.5 mm. Further reducing $R_{56}^{(1)}$ by a factor of 2 involves increasing A_2 by the same amount which makes the slice energy spread at the entrance of the radiator so large that it would significantly degrade the FEL performance. An alternative way to reduce $R_{56}^{(1)}$ without increasing A_2 is to choose $n = -2$ and $m = 52$. In this case the required dispersion strength is reduced by a factor of 2 as compared to the case when $n = -1$ and $m = 51$, at the price that the bunching factor also drops by some amount.

Taking $n = -2$, $m = 52$, $A_1 = 3$ and $A_2 = 6$, the required dispersion strength that maximizes the bunching factor for the 50th harmonic is found to be about $R_{56}^{(1)} = 1.33$ mm which may be provided by the existing delay line chicane. We simulated this case with our 1-D code and the bunching factor for various harmonic numbers is shown in Fig. 2 where we see the bunching factor for the 50th harmonic is about 5.5%, sufficiently large to suppress the shot noise.

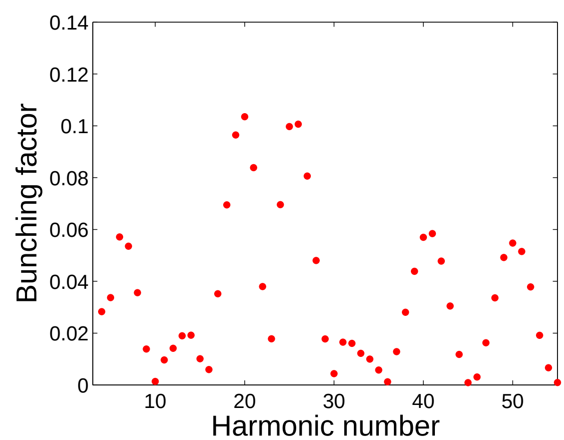

Figure 2: Bunching factor for various harmonic numbers.

LAYOUT

FEL-2 will be based on a double HGHG that appears today to be the most reliable configuration for producing coherent radiation while meeting the FERMI user requirements. The sketch, as well as a brief description of the operation of the FEL-2 layout for the double cascade HGHG is shown in Fig. 3a. In Fig. 3b we show the slightly modified layout that we propose here in order to implement in FERMI the EEHG scheme.

The only modification to the layout that is mandatory in order to implement the EEHG scheme on FEL-2 is the substitution of the second modulator. On the present layout its tuning range goes from 60 nm to 20 nm while for the EEHG scheme the resonance at 200 nm is required.

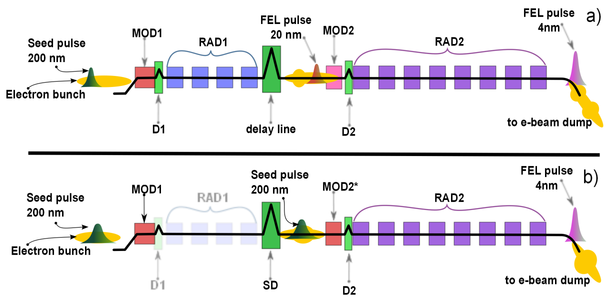

Figure 3: FERMI FEL-2 layout. a) HGHG configuration; the first modulator (MOD1) is resonant at 200 nm, first dispersive section (D1) converts energy modulation into spatial modulation, and the first radiator (RAD1) is resonant at 20 nm. Delay line is used for the fresh bunch techinque. The second modulator (MOD2) is resonant at 20 nm, second dispersive section (D2) convert energy modulation at 20 nm into spatial modulation at 20 nm and its harmonics. The final radiator (RAD2) produced coherent emission at 4 nm. b) For EEHG; MOD1 is tuned at 200 nm, the first dispersive section and the first radiator are not used and the delay line is used as a strong ($R_{56}^{(1)}$ 1.3mm) dispersive section (SD). The second modulator is here changed to one tuned at 200 nm (MOD2*). The second dispersive section optimizes the bunching at the desired harmonic and the final radiator coherently emit at the desired harmonic.

FERMI already has a first modulator, 3.0 meter long, with a 10 cm period tuned at 200 nm. In order to implement the EEHG scheme, the first dispersive section is set to 0 and the gaps of the undulators of the first radiator used in HGHG scheme to produce harmonic emission in the range between 60 and 20 nm are completely open. This allows the energy modulated electrons to be transported with negligible perturbations to the delay line chicane that is here used as the strong dispersive section $R_{56}^{(1)}$.

As a second modulator we here use a 2.4-meter undulator with 10 cm period tuned at 200 nm (MOD2*) instead of the nominal 5.5 cm period undulator (MOD2). The second dispersive section has an $R_{56}^{(2)}$ in the range between 0 and 100 microns. 8 undulators, 2.4 meters long with 3.5 cm period, compose the final radiator.

SIMULATION RESULTS

Simulation parameters

The expected values of the main parameters for the electron beams produced by the FERMI linac are summarized in Table I. The same electron beams can be used for both FEL configurations. However, as the EEHG scheme does not require the fresh bunch techinque, this method may be implemented with shorter electron bunches. It may then come out that better electron beam parameters may be achieved for a specifically EEHG configuration of the FERMI linac. For the purpose of this work we however considered the nominal parameters for the 1.5 GeV that are summarized in Table II together with the parameter for the two seed lasers.

Table 2: Values for the parameters used for FEL simulations

Electron Beam Energy	1.5 GeV
Peak current	800 A
Normalized emittance	0.8 mm mrad
Slice energy spread	150 keV
λ_{seed}^{MOD1}	200 nm
$Power_{seed}^{MOD1}$	20 MW
λ_{seed}^{MOD2}	200 nm
$Power_{seed}^{MOD2}$	150 MW

After having optimized the parameters of the layout for the EEHG scheme using the 1D model, we have done a series of simulations using 3D FEL codes in order to estimate the FEL performance. Time independent simulations, done using FEL codes GINGER and GENESIS, have shown that with the proposed modification to the FEL-2 layout and with the parameters expected for the electron beam, coherent emission at 4 nm (50^{th} harmonic of the seed laser) can be efficiently produced in FERMI with a single stage FEL.

In Fig. 4 we show the typical evolution of the electron phase space during the various steps of EEHG that was obtained from GINGER simulations. The interaction between the seed laser and the electron within the first modulator produced energy modulation at λ_{seed}^{MOD1} (Fig. 4a). The electron phase space after passing through the strong dispersion section (SD) is shown in Fig. 4b where the presence of separated energy bands is clearly seen. The beam is again modulated by the second seed laser in MOD2 at λ_{seed}^{MOD2} and the phase space at the exit of MOD2 is shown in Fig. 4c. Finally after passing through the second dispersion section (D2), the longitudinal phase space evolves to that in Fig.4d, where we clearly see that the energy modulation for each energy band is converted to a density modulation, with significant components also at very high harmonics. It is important to point out that in the reported case the distance in phase between the vertical beamlets in Fig. 4d is about 4π at 4 nm that is the 25^{th} harmonic of the initial 200 nm seed wavelength and not the 50^{th} harmonic. This comes from the fact that, in order to keep the strength of SD compatible with the existing layout and not to induce too large an energy spread in the two modulators, the optimization has been done for $n = -2$ in Eq. 1. Nevertheless the produced bunching is enough to initialize the FEL porcess on the final radiator.

As a result of the density modulation produced in the second dispersive section electrons start emitting coherently on the final radiator at the desired harmonic of the initial seed laser. This coherent emission initializes the FEL

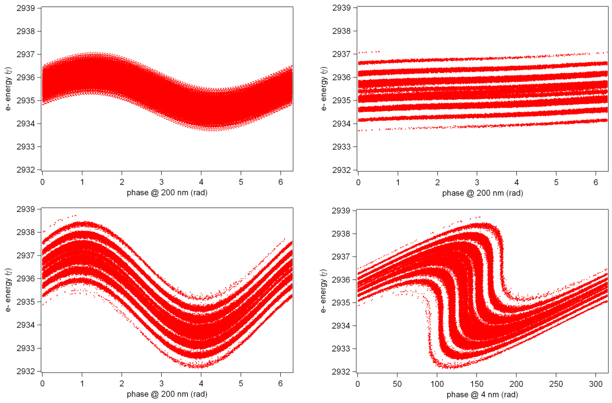

Figure 4: Evolution of the longitudinal phase space of the electrons along different part of the FEL: (top left) at the exit of MOD1; (top right) at the exit of SD; (bottom left) at the exit of MOD2; (bottom right) at the exit of D2.

process that lead eventually to the exponential growth of the power until saturation is reached. For the case under study, GINGER simulations show that the peak power produced after 8 undulator sections exceeds 1 GW as shown in Fig. 5a. The evolution of the bunching (Fig. 5b) along the undulator indicate that with the proposed configuration the FEL operate close to saturation at 4 nm.

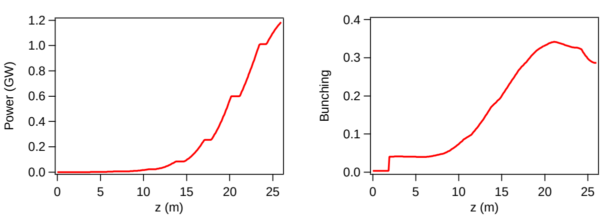

Figure 5: (left) Peak power vs radiator distance for the 4 nm radiation; (right)Bunching factor vs radiator distance for the 4 nm radiation.

It is worth pointing out that we have sacrificed the bunching factor in order to directly use the existing delay line chicane as the first strong chicane in EEHG. If there is enough space to reconfigure the chicane to provide an $R_{56}^{(1)}$ of ∼2.7 mm, then one can increase the bunching factor for the 4 nm radiation to about 9%, with respect to the 4% obtained with the present layout, which should make the FEL achieve saturation within the 8 undulator sections, with a higher saturation power.

Similar FEL performance have been obtained also with time independent FEL simulations using the start file representing the more accurate prediction for the electron beam expected for FERMI.

CONCLUSIONS

In conclusion, we have studied the feasibility of applying the EEHG scheme to FERMI FEL-2 to generate GW radiation in the water window with small modifications to the present FEL layout. Simulation results indicate that it is possible to apply EEHG to FERMI FEL-2. More detailed studies on the stability, tolerance and FEL spectrum, etc. for the EEHG scheme are on going. It is worth pointing out that the parameters used in our simulations are representative rather than being a fully optimized design set. A more careful optimization should lead to further improvements.

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