THE SECOND STAGE OF FERMI@ELETTRA: A SEEDED FEL IN THE SOFT X-RAY SPECTRAL RANGE

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Abstract

The second stage of the FERMI FEL, named FEL-2, is based on the principle of high-gain harmonic generation and relies on a double-seeded cascade. Recent developments stimulated a revision of the original setup, which was designed to cover the spectral range between 40 and 10 nm. The numerical simulations we present here show that the nominal (expected) electron-beam performance allows extension of the FEL spectral range down to 4 nm. A significant amount of third harmonic power can be also expected. We also show that the proposed setup is flexible enough for exploiting future developments of new seed sources, *e.g.*, high harmonic generation in gases.

INTRODUCTION

Driven in part by strong user interest [1] in performing experiments at wavelengths below 10 nm, the design of the second stage of FERMI@Elettra (*i.e.,* FEL-2) has been changed in the past year to employ both a shorter period final "radiator" undulator (35 mm as compared with 50 mm) and a higher electron beam energy (~1.5 GeV as compared with the original energy of 1.2 GeV [2]). These changes allow reaching output fundamental wavelengths as short as 4.2 nm (300 eV) and third harmonic photon energies above 0.8 keV, thus enabling L-edge studies of magnetic materials such as Fe, Ni, Cr, etc. [1].

The nominal output pulse duration has also been decreased to ~30-100 fs as being best suited to a majority of the users. Other output requirements, *e.g.*, variable polarization, good temporal and transverse coherence, a wide tuning range in wavelength, remain unchanged. FEL-2 remains based upon a 2-stage harmonic cascade configuration (see Fig. 1). The new design is also compatible with a change to HHG-seeding at some point in the future if HHG power levels for $\lambda <= 50$ nm become sufficiently strong.

THE LAYOUT

To maintain the overall tuning range (*i.e.*, 4-20 nm), it will be necessary to vary the electron beam energy over a factor of ~2 (see Fig. 2). Variable polarization and a "fast" tuning range of >= 10% will be provided by a variable gap Apple-2 undulator. In order to efficiently produce FEL radiation at high harmonics with respect to the seed wavelength, FEL-2 will use the “fresh bunch” technique; we note that this approach has not yet been demonstrated experimentally. Nevertheless, according to the present status of the technology development, we believe that the double cascade HGHG approach is a more reliable choice when compared to other methods such as the use of HHG [3] as a seed or the very recent echo-enabled harmonic generation scheme [4].

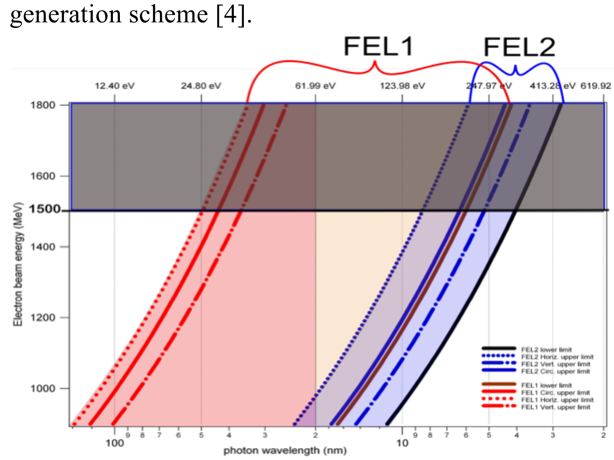

Figure 2: Tuning ranges for both FERMI FELs for different electron beam energies. While FEL-1 has a large wavelength tunability at fixed energy (due to the 55-mm undulator period), FEL-2 tunability at fixed energy is limited by the 35-mm final radiator period to about +/- 10% in the case of vertical polarization.

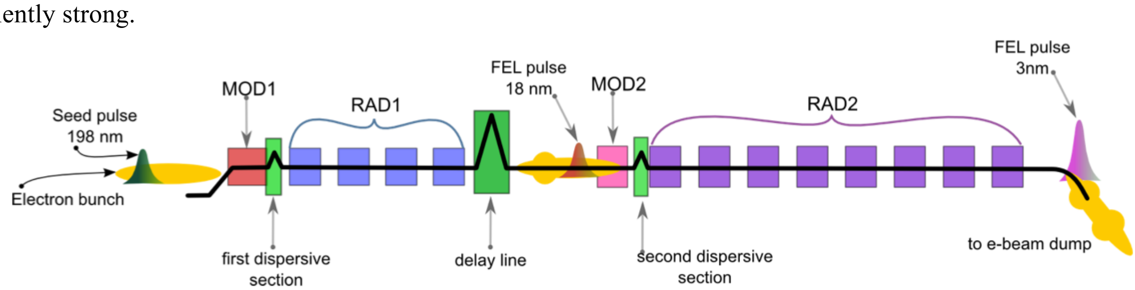

Figure 1: As was true for the design presented in the FERMI Conceptual Design Report [2], the new FERMI FEL-2 is based on a double high-gain, harmonic generation cascade. Relative to the original design, a longer radiator with shorter undulator period has been chosen for the final stage.

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Extending the shortest fundamental wavelengths down to the 3-nm region with the present layout may become possible in the case of a future upgrade of the electron beam energy to 1.8 GeV. Such an upgrade may require some additional acceleration structures for the FERMI linac.

Table 1: Nominal values for the seed laser of FERMI

Parameter	Value	Units
Wavelength	190-280	nm
Pulse length (rms)	40-70	fs
Peak power	100	MW

Table 2: Nominal values for the electron beam parameters excepted from the FERMI linac.

Parameter	Value	Units
Electron Beam Energy	0.9-1.5	GeV
Peak current	750	A
Uncorrelated slice energy spread	150	KeV
Norm. slice transverse emittance	0.8-1	mm-mrad
Electron Bunch Length (flat portion)	~ 0.6	ps

To evaluate expected FEL-2 performance, we performed a series of both time-independent and time-dependent simulations with the GINGER and GENESIS simulation codes, adopting electron beam and input seed parameters as summarized in Tables 1 and 2.

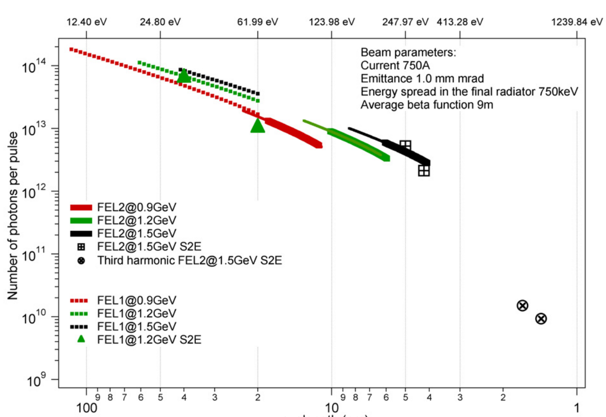

Figure 3: Expected output levels (photons/pulse) for the two FERMI FEL's. Solid lines: estimates using adaptation of M. Xie scaling formula [5] to adjust for increased energy spread in final radiator. Points: results of start-to-end numerical simulation (GPT + ELEGANT + GINGER/GENESIS).

Producing output at wavelengths < 3 nm will most likely require use of the third harmonic. For planar polarizations, the 3rd harmonic emission level for FEL-2 is expected to be ~1% of the fundamental. In the case of pure circular polarization, on-axis emission will be strongly suppressed. Use of cross-polarized and/or slightly elliptically polarized configurations (both easily produced by Apple undulators) to generate reasonable FEL harmonic content is currently under investigation.

The expected emission level for both FERMI FELs in terms of number of photons per pulse on the whole spectral range between 100 and 4 nm is shown in Fig. 3; more than 10^{12} photons per pulse are expected over the whole tuning range.

NUMERICAL SIMULATIONS

A series of time steady FEL simulations have been done in order to calculate the FEL performance of FEL-2 for different electron beam energies and at different wavelengths.

Using the parameters reported in Tables 1 and 2 we have found that with the present layout of a double HGHG cascade seeded from a UV external laser, FERMI FEL-2 can reach saturation and provide more than 1 GW power in the whole spectral range between 20 and 4 nm.

As an example, Fig. 4 presents the FEL power evolution along the final radiator tuned at 4.2 nm in the case of electron beam energy of 1.5 GeV and a planar-polarized undulator. The third harmonic content has also been evaluated by FEL codes and is plotted on the same graph, with typical power levels of ~0.5% of the fundamental.

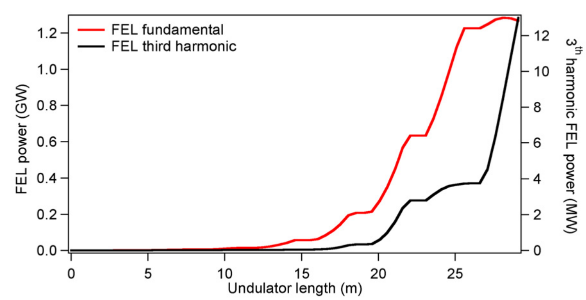

Figure 4: Results of numerical simulation of FEL-2 operating at 4.2nm in horizontal polarization.

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 CSR effects) propagated through the full linac and to the undulator entrance with the transport code ELEGANT. An analysis of one of those files is reported in Fig. 5 showing the beam characteristics at the entrance of the first modulator of the FEL-2 in terms of electron beam energy (Fig.5-a), incoherent RMS energy spread (Fig.5-b), current (Fig.5-c) and transverse emittance (Fig.5-d) for the 1.5-GeV case. Similar results have been obtained also for smaller electron beam energies.

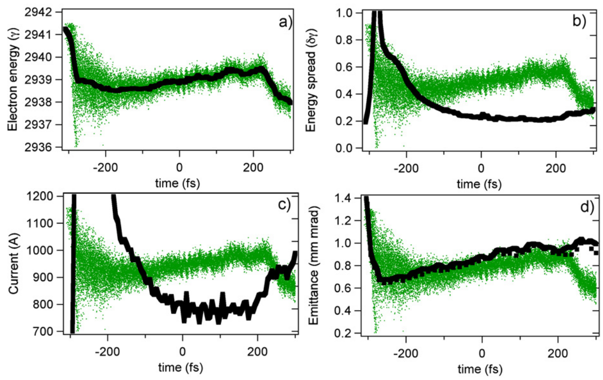

Figure 5: Characteristics of the 1.5 GeV electron beam at the entrance of the FEL. Green dots represent macroparticles plotted in the longitudinal phase space (energy-time). Black lines indicate the average electron beam energy (a), energy spread (b), current (c) and normalized *x* and *y* emittance (d).

The analysis of the start-to-end files shows a reasonably large (~400 fs) portion of the electron beam has the required characteristics needed for performing the seeding. This is enough to accommodate the two FEL pulses necessary for the fresh bunch technique. However, with close inspection of the longitudinal phase space, it is possible to see a small energy and current modulation with a time scale of the order of tens of fs. We believe these are the result of the microbunching instabilities developed along the linac. Although this modulation is relatively small, it may have a detrimental effect on the bandwidth of the produced FEL pulses, especially at the shortest wavelengths [6].

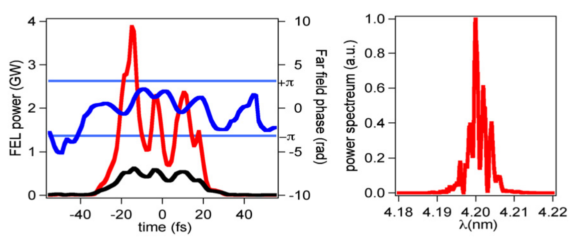

Figure 6: (a) FEL 4.2-nm fundamental power at the undulator exit (red) and on-axis the far field intensity (black) predicted by GINGER S2E simulations. The blue line plots the on-axis far field eikonal phase. (b) Far field power spectrum of the FEL radiation as predicted by S2E simulations.

These start–to-end files have been used as input for time-dependent simulations of the two FEL stages in the double cascade HGHG configuration. These simulations are useful for providing a more accurate prediction of the expected FEL performances, especially with regard to temporal and spectral properties.

Results of S2E FEL simulation for the 4.2-nm case with a 1.5-GeV electron beam are reported in Fig. 6. It is clear both from the temporal and the spectral properties that there are effects from the high frequency energy and density modulations. From the analysis of the temporal data we can estimate that the FEL-2 4.2 nm output pulses will be about 40 fs long (FWHM) and contain~1.8×10^{12} photons per pulse.

From the spectral distribution we can estimate a FWHM bandwidth of about 0.003 nm, about a factor of ~5 above the Fourier limit. The predicted spectral brightness is about 1.1×10^{12} (5.6×10^{11}) photons per pulse in 0.1% (0.003 %) bandwidth.

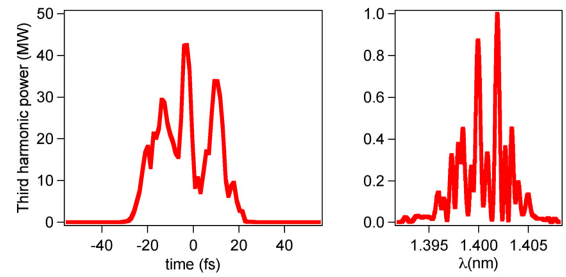

Figure 7: Predicted third harmonic emission at λ=1.4 nm: (a) output power (b) far field power spectrum.

A similar analysis can be done on the harmonic content of the FEL pulses in the case of planar undulator; these results are displayed in Fig. 7.

The pulse of the harmonic emission at 1.4 nm is expected to have about the same length of the fundamental with about 8×10^{9} photons per pulse. The third harmonic shows much more eikonal phase modulation caused by the temporal modulations of the electron beam energy and current at FEL-2 entrance. The number of output photons per pulse is reduced to 2×10^{9} within a 0.1% normalized bandwidth and 5×10^{8} in a 0.03% bandwidth.

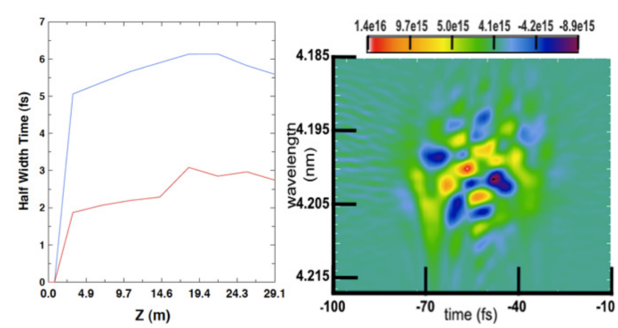

Figure 8: (a) Evolution of the coherence length of the FEL pulse at 4.2 nm along the final radiator. (b) A Wigner transformation of the far field, on-axis, complex FEL electromagnetic field.

Although the output spectral bandwidth is affected by the energy modulation of the electron beam, the output radiation still has relatively good temporal coherence. Figure 8 plot the coherence length (determined by the autocorrelation function) and the Wigner transform (*i.e.*, a measure of the (t, λ) phase space), of the 4.2-nm on-axis, far field amplitude.

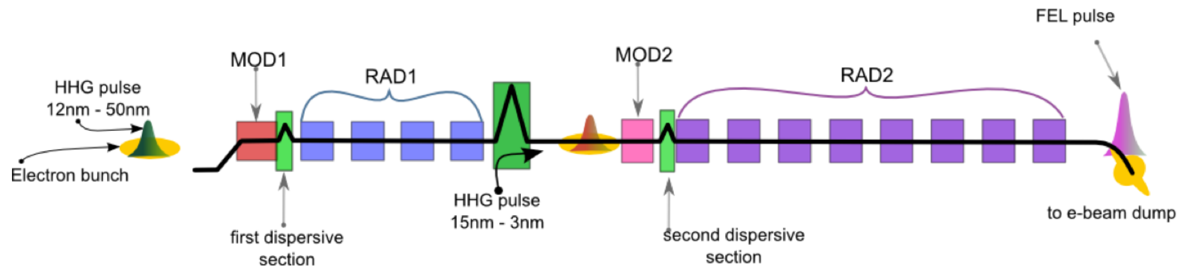

Figure 9: The same layout used for the double cascade scheme may be used without modification for implementing a HHG-seeded FEL, including both HGHG and direct amplifier configurations.

COMPATIBILITY WITH OTHER CONFIGURATIONS

A possible alternative to the two stage harmonic cascade method used here to reach the 4 nm region is to use a a much shorter wavelength seed in order to perform a smaller harmonic jump or implement a direct seeding scheme. Such a possibility exists with regards to HHG sources. Recently, HHG seeds have been experimentally used in FEL amplifiers [7], although with small harmonic upshifts (*i.e.*, >100 nm) from the drive laser. This technique seems very promising as it may allow implementing a seeded FEL at even shorter wavelengths than is possible with frequency-quadrupled TiSa lasers. However, we believe that the *present* development status of HHG sources, particularly with regards to output power levels at wavelengths < 30 nm [3], is not yet sufficiently mature enough to satisfy the stringent requirements of a *near-term* user facility such as FERMI.

Nonetheless, we believe that it is *very* important to be ready in the near future to be able to reconfigure FERMI FEL-2 if a HHG source with the needed requirements becomes readily available. Consequently, serious attention has been paid during the design of the present layout for FEL-2 to permit a future HHG seed capability. Figure 9 displays a possible FEL-2 reconfiguration of the existing layout that would be seeded by an HHG source.

A different alternative for implementing a seeded FEL in the soft x-ray region is based on the echo-enhanced harmonic generation scheme recently proposed by Stupakov [4]. The possibility of implementing such a scheme on the FERMI FEL-2 layout has been studied [8] and, again, relatively small modifications would be needed to do so.

CONCLUSIONS

In conclusion, motivated by user interest in reaching shorter wavelengths than corresponded to the original FERMI FEL-2 design, we have re-examined choices for electron beam pulse format, energy, and undulator wavelength. We then presented the new layout for FEL-2 as well as the expected performance, showing it is possible to extend the FERMI spectral range down to 4 nm or shorter at GW peak power levels, presuming an electron beam energy of 1.5 GeV or greater. The reduced fractional tuning range at fixed electron beam energy will require operating the FERMI linac energy over a factor of two to cover the full wavelength range of 4-20 nm. To reach the L-edges of magnetically active materials, we plan to use third harmonic emission. We also briefly discussed the possibility of reconfiguring FEL-2 to use an HHG seed or Stupakov's harmonic echo scheme, with minor modifications of the standard layout. Further studies about these possibilities are planned in the near future.

ACKNOWLEDGEMENTS

The authors are indebted to the FERMI team for many useful discussions. We also acknowledge the Italian Ministry of University and Research for partially supporting this work under grants FIRB-RBAP045JF2 and FIRB-RBAP06AWK3.

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