# EXTENSION OF THE FERMI FEL1 TO SHORTER WAVELENGTHS

E. Allaria[#] Sincrotrone Trieste, Trieste, Italy

G. De Ninno, University of Nova Gorica, Slovenia and Sincrotrone Trieste, Trieste, Italy

*Abstract*

We propose a modification of the first stage (FEL1) of the FERMI@Elettra project in order to extend the wavelength range from the original limit of 40 nm down to 20 nm. The modified setup takes advantage of a shorter radiator undulator period. We present the numerical studies that have been carried out to compare the expected performance of the new FEL1 with that of the original FERMI setup [1]. Results show that, if expected performances of the FERMI linac are confirmed, the modified configuration represents a good alternative to the second stage of the project (FEL2) in the wavelength range between 40 nm and 20 nm.

## INTRODUCTION

It has been recently shown [2] that single-cascade seeded free-electron lasers (FEL) can produce powerful coherent radiation at seed harmonics higher than the sixth. For example, according to numerical simulations, more than $10^{14}$ photons/pulse can be generated at the twelfth harmonics of a Ti:Sa laser tuned at 240 nm. For that, one needs to use a relatively high seed power and an electron beam with quite low (normalized) energy spread. In fact, the latter parameter is found to set a limit to the minimum reachable wavelength [2].

In this work we demonstrate the possibility of reaching 20 nm in a single cascade using the nominal FEL1 parameters of the FERMI@Elettra project as reported in [1]. The proposed setup, which will be called FEL1$^+$ in the following, relies on the reduction of the undulator period from 65 mm to 55 mm and, possibly, on the extension of the radiator length.

The expected performance has been evaluated by means of three-dimensional start-to-end simulations using the numerical codes Genesis [3] and Ginger [4]. Time dependent simulations have been done using as an input the electron distributions produced by the FERMI start-to-end group [1]. Results show that FEL1$^+$ represents a good alternative to the double-stage FEL2 in the wavelength range between 40 nm and 20 nm.

We also show that the loss of tunability at longer wavelengths due to the shorter undulator period can be recovered by slightly decreasing the electron energy.

## LAYOUT AND INITIAL PARAMETERS

The layout for the FERMI FEL1 is sketched in Fig. 1. With the aim of extending the tuning range towards shorter wavelengths, we considered the possibility to reduce the radiator period from 65 mm to 55 mm and, possibly, to increase the number of radiator modules (e.g., from six to eight).

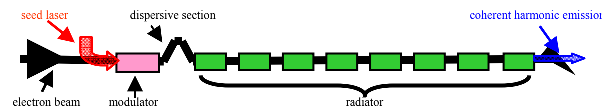


Figure 1: Sketch of the FERMI FEL1 setup [1].

In Table 1 we report the main radiator characteristics, both for the original FEL1 setup and for FEL1$^+$.

Table 1: Radiator parameters for the for the FEL1 and FEL1$^+$ configurations

| Parameter | CDR | FEL1$^+$ |
|---|---|---|
| Radiator period(mm) | 65 | 55 |
| Number of periods | 36 | 42 |
| Modulus length(m) | 2.34 | 2.31 |
| Inter-section length(m) | 1.2 | 1.2 |
| Number of sections | 6-8 | 6-8 |
| Total radiator length(m) | 20.04/27.12 | 19.86/26.88 |

Both setups rely on the same electron-beam optics, which corresponds to an average beta along the radiator of about 9 m [1]. The main electron-beam parameters used as initial conditions for the simulations are reported in Table 2. As for the seed laser, we considered the parameters used for the FERMI conceptual design report [1], that is of the order of 100 MW of peak power and a pulse duration of 100 fs (FWHM).

Table 2: Main electron-beam parameters used for the simulations. For further details, see [1]

| Parameter | Value | Units |
|---|---|---|
| Electron beam energy | 1.14 | GeV |
| Energy spread | 150 | keV |
| Peak current | 750 | A |
| Normalized emittance | 1.5 | mm-mrad |

### *First Comparison Between FEL1 and FEL1$^+$*

A first qualitative comparison of the expected performances from FEL1 and FEL1$^+$ can be done by using Ming-Xie's formulae [5] that allow estimating the gain length, $l_G$, in the two radiators. The gain length can be used to get an indication on how fast the FEL radiation grows during the exponential regime.

[#]enrico.allaria@elettra.trieste.it

Table 3: Gain length ($l_G$) and undulator parameter (AW) for FEL1 and FEL1$^+$ radiators at various wavelengths

| **Wavelength** | **FEL1** | | **FEL1$^+$** | |
|---|---|---|---|---|
| **(nm)** | $l_G$ | AW | $l_G$ | AW |
| 40 | 1.38 | 2.26 | 1.21 | 2.49 |
| 20 | 1.71 | 1.43 | 1.49 | 1.61 |
| 15 | 1.94 | 1.13 | 1.67 | 1.30 |
| 12 | 2.21 | 0.91 | 1.86 | 1.08 |
| 10 | 2.59 | 0.72 | 2.09 | 0.89 |

Results reported in Table 3 show that the gain length in the FEL1$^+$ radiator is more than 15% shorter than that in the FEL1 radiator. As it will be shown in the following, such a difference is not relevant at 40 nm, where saturation is reached in both cases in few undulator sections. However, it becomes important at shorter wavelengths, when the harmonic bunching is relatively small and more gain lengths are needed to reach saturation.

## COMPARISON AT 40NM

In this Section we compare the performance of FEL1$^+$ and FEL1 at 40 nm.

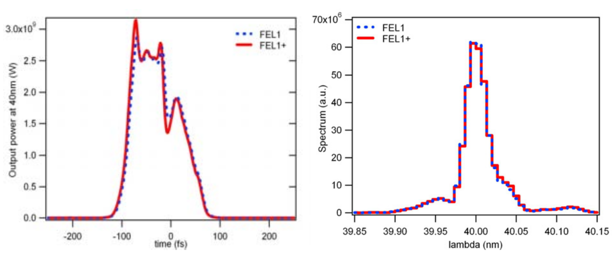


Figure 2: Output temporal (left) and spectrum (right) profiles of FEL1$^+$ (continuous line) and FEL1 (dotted line) at 40 nm. In both cases, six radiator sections have been considered.

The presented results refer to Ginger simulations [4]. Similar results have been obtained by using the Genesis numerical code [3].

Figure 2 shows the output pulse and spectrum profiles obtained from Ginger simulations for FEL1$^+$ and FEL1 at 40 nm using six radiator sections. As anticipated, the two configurations provide similar output light pulses and both the peak power and the spectral bandwidth are the same.

Table 4: Expected performance from FEL1 and FEL1$^+$ at 40 nm using the "M6" electron-beam distribution [1]. The exact used value for the seed power is 70 MW.

| | Peak power (GW) | Pulse duration (fs) (FWHM) | Photons number | Photons in 1E-3 bandwidth |
|---|---|---|---|---|
| FEL1 | 2.7 | 110 | $6.2 \cdot 10^{13}$ | $4.6 \cdot 10^{13}$ |
| FEL1+ | 2.7 | 110 | $6.3 \cdot 10^{13}$ | $4.6 \cdot 10^{13}$ |

### *Sensitivity to Energy Spread*

Numerical results presented in Fig. 2 rely on the use of an external electron bunch, as expected from the linac studies [1]. It is, however, important to evaluate the sensitivity of FEL performance to the input electron beam parameters, and in particular to energy spread that is known to be a crucial parameter in high-gain harmonic generation [2]. For this reason, a time-independent simulation was carried out in order to estimate the sensitivity to electron-beam energy spread values larger than expected.

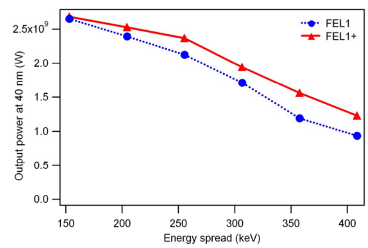


Figure 3: Expected power from FEL1$^+$ (continuous line) and FEL1 (dashed line) at 40 nm as a function of the electron-beam energy spread.

As shown in Fig. 3, due to the slightly shorter gain length, FEL1$^+$ is less sensitive with respect to FEL1 to the increase of the electron beam energy spread.

## COMPARISON AT 20NM

In order to evaluate the performance of FEL1$^+$ at 20 nm it is necessary to compare its performance with that of FEL2 that has been originally designed [1] to operate in this spectral range.

Two FEL1$^+$ configurations (6 and 8 radiator sections) have been simulated, using the medium (M6 [1]) bunch distribution. The FEL2 configuration has been instead simulated using the "long" electron-bunch distribution (L8 [1]), which is necessary in order to implement the fresh bunch technique taking into account the expected jitter. The main difference between L8 and M6 is lower peak current (~500A) of the long bunch with respect to the medium case (~750A). For a more detailed description of the electron beam properties, the interested reader can refer to the CDR [1].

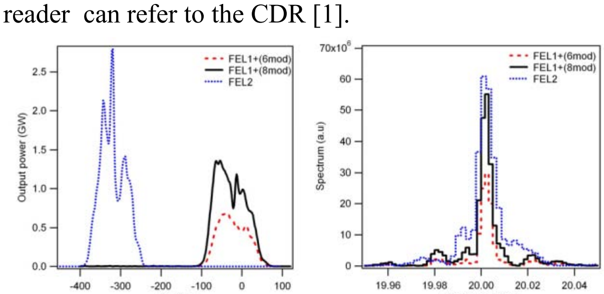


Figure 4: Output temporal (left) and spectrum (right) profiles of FEL-1$^+$ (dashed: 6 radiator sections, continuous: 8 radiator sections) and FEL-2 (dotted line: eight radiator sections) at 20 nm.

Figure 4 shows the output pulse and spectrum profiles of FEL1$^+$ and FEL2 at 20 nm. The relevant information of the performance at 20 nm is reported in Table 5.

Table 5: Expected performances from FEL1$^+$ and FEL2 at 20 nm

| | Peak power (GW) | Pulse duration (fs) (FWHM) | Photons number | Photons in 1E-3 bandwidth |
|---|---|---|---|---|
| FEL1$^+$(6) | 0.66 | 96 | $6.2 \cdot 10^{12}$ | $4.3 \cdot 10^{12}$ |
| FEL1$^+$(8) | 1.3 | 105 | $1.2 \cdot 10^{13}$ | $8.3 \cdot 10^{13}$ |
| FEL2 | 1.9 | 91 | $1.5 \cdot 10^{13}$ | $9.6 \cdot 10^{13}$ |

### *Sensitivity to Energy Spread*

Figure 5 shows the dependence on energy spread of the output power at 20 nm for both FEL1$^+$ using six or eight radiator sections, and for FEL2. As a consequence of the high harmonic jump (12) which is necessary in the case of FEL1$^+$ for producing 20nm radiation starting from the 240 nm of the seed, this configurations is quite sensitive to a possible increase of the electron beam energy spread. As it can be seen, for FEL1$^+$ an increase of the energy spread from the expected 150keV to only 200keV results in a reduction of about 50% of the produced radiation at 20nm. On the contrary, at this wavelength FEL2, which based on a double cascade, is less sensitive to this parameter and also with energy spread of about 300keV the produced radiation, is reduced of about 10%. In the case of FEL1$^+$, a quite substantial improvement, in terms of produced radiation, is obtained using eight sections instead of six.

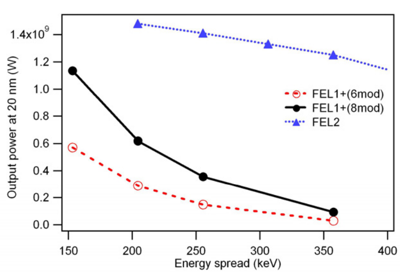


Figure 5: FEL1$^+$ (continuous (8 sections) and dashed (6 section) lines), and FEL2 (dotted line) output power at 20 nm as a function of the electron-beam energy spread.

## RECOVERING LONG WAVELENGTHS

Decreasing the radiator period allows getting higher K parameters at shorter wavelengths, but also limits tunability at longer wavelengths. For the FERMI undulator it has been estimated that the use of a 55 mm undulator period will limit the longer wavelength to about 70 nm. However, if needed, the full tuning range of FEL1 (100-40nm) can be easily recovered by decreasing the electron-beam energy.

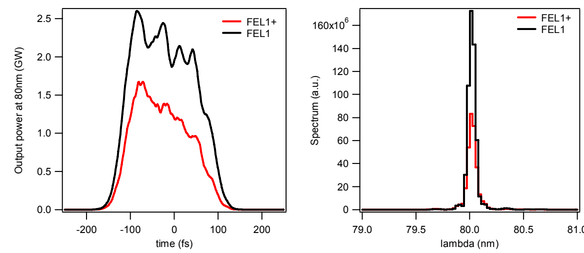


Figure 6: Left: power profile at the exit of FEL1 (black line) and FEL1$^+$ (red line) tuned at 80 nm. Right: Corresponding spectrum profiles. In both cases only three radiator sections have been used.

As an example, we considered the possibility of reaching 80 nm using FEL1$^+$ after rescaling the electron-beam energy to 800 MeV. Obtained results are shown in Fig. 6 and compared with those obtained using FEL1 at 1.2 GeV. In both cases saturation is reached after 3 sections (about 10 m); peak power for FEL1 is about a factor two higher than that obtained using FEL1$^+$. This can be explained by recalling that decreasing the electron energy also saturation power is decreased.

## CONCLUSIONS

The main conclusion we can draw from our study is that FEL1$^+$ is a viable alternative to FEL2 for reaching 20 nm. However, it is worth stressing that such a statement relies on the assumption that the initial electron-beam parameters are those mentioned in the Fermi Conceptual Design Report [1]. A possible degradation of the electron-beam characteristics with respect to the reference values (e.g., increase of incoherent energy spread above 250 KeV and/or loss of homogeneity in longitudinal phase space) may result in a significant degradation of the expected performance.

Decreasing the radiator period allows to extend the spectral range towards shorter wavelengths, but limits the tunability at longer wavelengths. However, longer wavelengths can be easily recovered by decreasing the electron energy.

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