

START-TO-END TIME-DEPENDENT STUDY OF FEL OUTPUT SENSITIVITY TO ELECTRON-BEAM JITTERS FOR THE FIRST STAGE OF THE FERMI@ELETTRA PROJECT

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Abstract

Sensitivity of the output laser pulse to electron-beam jitters is one of the major issues affecting the expected performance of both SASE and seeded FELs. Focusing on the first stage of the FERMI@Elettra project, in this paper we present results of time-dependent numerical simulations in which the codes GENESIS and GINGER have been used to run a large number of electron-beam distributions generated at the gun by the code GPT and propagated through the linac using the code ELEGANT.

INTRODUCTION

The FERMI@ELETTRA project is dedicated to the development of a FEL facility based on the principle of harmonic up shifting of an initial “seed” signal in a single pass [1]. The first stage of the project will be a single harmonic cascade tuneable in the 40-100 nm range. At present, it is believed that the major application for FEL-1 will involve time-domain experiments such as pump-probe interactions and possibly nonlinear phenomena. Consequently, the requirements for FEL-1 are more related to total photon number per pulse (*i.e.*, $0.4 - 2 \times 10^{14}$) and pulse duration (20-100fs) than they are to spectral bandwidth. Another important parameter associated with FEL-1 time-domain experiments is shot-to-shot repeatability [1]. Time-independent simulations of the FEL process based on the Fermi layout show a strong sensitivity of the output power with respect to many electron-beam parameters [2]. Jitter studies performed using jitter of input parameters as estimated by the linac group of the Fermi project provided fluctuation on the output power that can be greater than 20% for the radiation at 40nm. However, while time-independent simulations can give just an indication of the FEL performance, more accurate investigations should rely on “start-to-end” (S2E) simulations, that begin at the emitting cathode and end at the undulator exit.

In collaboration with the injector and linac groups of the Fermi project, dedicated simulations have been performed considering fluctuations on main machine parameters [3]. To examine the effects of injector and accelerator jitters upon the shot-to-shot, time-resolved properties of the output FEL-1 radiation, 100 individual files of 1M macroparticles were propagated starting from the injector (GPT code) through the linac (Elegant code). Nominal beam parameters are reported in the following table [3,4].

Table1: Nominal electron-beam parameters for the first stage (FEL-1) of the FERMI project

Parameter	Value	Units
Input Seed power	100	MW
Electron Beam Energy	1.2	GeV
Peak current	800	A
Uncorrelated energy spread (“slice” value)	150	KeV
Norm. Transverse Emittance (“slice” value)	1.5	mm-mrad
Electron Bunch Length (flat portion)	0.6	ps

Each file included the effects of random jitter in the individual injector and accelerator cell voltages. The jitter follows Gaussian distributions with variances set by the budget allowances allocated by the gun and linac groups.

GINGER and GENESIS time-dependent simulations for the FEL-1 lattice tuned at 40 nm were performed over a large time window with high resolution. For each jittered file, simulations were done using artificial macroparticles created from the time-dependent envelope quantities previously determined by the *elegant2genesis* code and also using directly the ELEGANT particles.

It is important to note that we here only consider the effect of the jitter on the electron bunches, without taking into account any jitter source on the seed laser.

ANALYSIS OF ELEGANT JITTERED FILES

The 100 jittered files have been produced starting from 100 GPT files that consider the possible jitter sources in the gun. Those files have been propagated through the linac with ELEGANT. Output distributions have been pre-processed in order to evaluate the resulting jitter in bunch arrival times (Fig.1).

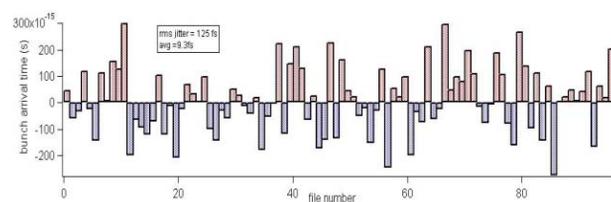


Figure 1: Arrival time jitter of the 100 elegant files with respect to the arrival time of the nominal file.

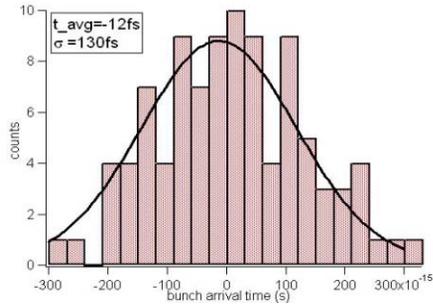


Figure 2: Distribution of the arrival time jitter reported in Fig.1; data can be fitted with a Gaussian distribution, whose sigma is about 130fs.

The analysis shows a distribution with an rms jitter of about 130 fs, which is close to the one predicted by LiTrack simulations [4]. These data can be fit with a Gaussian distribution (Fig.2).

By plotting the electron energy and current profiles of the 100 bunches taking into account of the arrival time (figs.3-6) it is evident that it exists a time window of the order of 400fs where the fluctuations of electron parameters due to the jitter arrival time are small. This is the “useful” part of the bunches to be used for the FEL process. We also report the analysis of the electron beam properties (electron energy, current, emittance, energy spread) on that window.

The electron mean energy, γ , in the useful part of the bunch (from -200fs to 200fs, see fig. 3,4,5) presents a distribution with an rms of 0.09%, in agreement with the values predicted by the linac group.

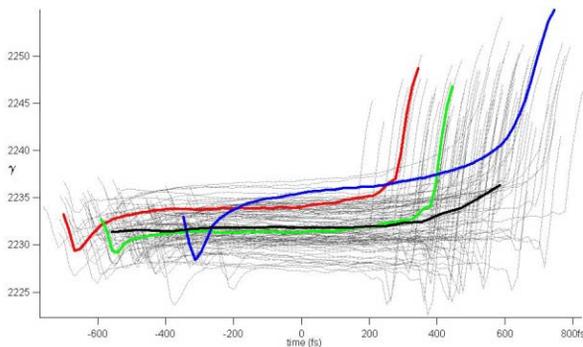


Figure 3: Temporal profile of the electron beam mean energy of the 100 jittered ELEGANT files.

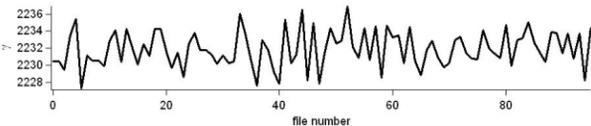


Figure 4: Average of the electron mean energy of the jittered electron bunch calculated in the useful time window (-200fs; 200fs).

The current distribution shows an rms value (6.6%) that is slightly lower than the one predicted by the linac group (8%).

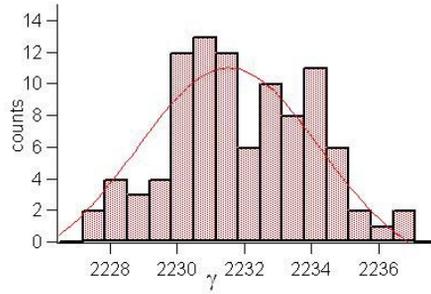


Figure 5: Distribution of the average electron mean energy of the useful part of the jittered bunches; data can be fitted with a Gaussian distribution whose sigma is 0.09%.

Similar analysis have been performed for other electron beam properties, (emittance, energy spread, ..). As for emittance, data show a distribution with an rms value which is close to the one predicted (about 12%). The energy spread, instead, is slightly affected by the temporal jitter of bunches and the rms distribution shows a larger value (almost 20% instead of 10%). Calculated electron-beam average values and corresponding standard deviations are reported in Table 2.

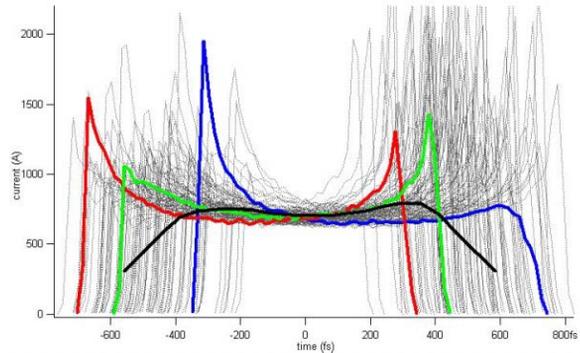


Figure 6: Temporal profile for current of the 100 jittered files.

Table 2: Average values and corresponding standard deviations for the main electron beam parameters extracted from time-dependent simulations.

Quantity	Mean Value	Std. Dev.
Gamma	2231.9	0.09%
Current (A)	718	6.6%
Incoherent energy spread	0.33	19.5%
Normalized emittance	1.35	12.4%

TIME-DEPENDENT FEL SIMULATIONS OF JITTERED FILES

For the FEL simulation we used the nominal setup of FEL1 [1] that has been optimized in terms of aw and R56 in order to maximize the output power extracted from an

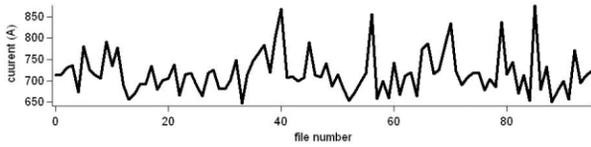


Figure 7: Average of the electron bunch current calculated on the useful part of the jittered files (from -200fs to 200 fs).

ideal bunch, whose parameters are equal to the average values reported in Table 2.

Time-dependent simulations using this optimized setup for the jittered files show a quite high sensitivity to beam jitters (e.g., about 50% of fluctuation in the output power), which is far from what it is predicted by time-independent simulations [2].

A new optimization has been necessary in order to find a setup that minimizes the effect of the beam jitters. In order to reduce the sensitivity of the FEL output power we slightly changed the tuning of the radiator, setting a smaller value of a_w .

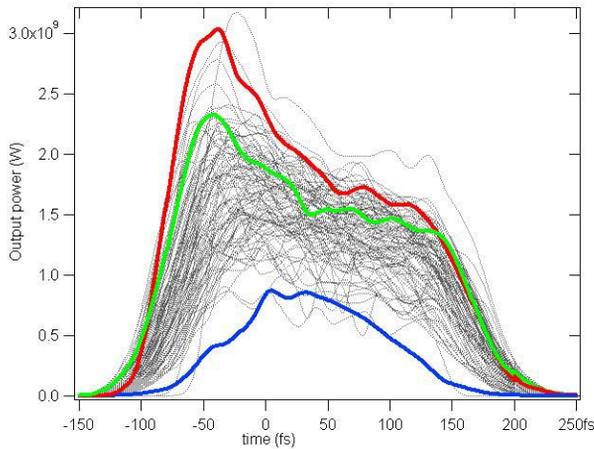


Figure 8: Temporal profiles for the FEL output radiation at 40 nm obtained from GINGER simulations using the jittered ELEGANT files; Red, Green and Blue curve refer to bunches reported with the same colors in figs. 3-6.

The setup utilized for simulations is the following: a seed laser of 100MW with a Gaussian temporal profile (100fs rms), the modulator tuned at 240nm, the dispersive section set with a $R56=19e-6$ and the radiator tuned at 40 nm.

Figure 8 displays the output power profiles obtained from the 100 jitter bunches, while Fig.10 shows the corresponding output spectra. Red, Green and Blue traces

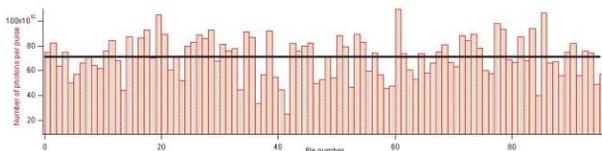


Figure 9: Number of photons per pulse obtained from the FEL simulation at 40 nm. Data show an average number of photons of the order of 70e12 with an rms fluctuation of about 23%.

in Fig.8,10 refers to the electron bunches reported in Red, Green, Blue in Figs. 3-6.

The analysis of the FEL output power has been performed by integrating the pulse profile in order to calculate the number of photons of each FEL pulse. Figure 9 report the number of photons of FEL output pulses for each of the 100 jittered electrons bunches. The statistical analysis of data shows a distribution which is close to a Gaussian centered at 70e12 photons per pulse with a standard deviation of about 23%.

By looking at the output spectra of the FEL pulses, one can see that the jitter of the input electron-beam parameters induces a fluctuation of the central wavelength. However, such a fluctuation is about a factor 3 smaller than the average bandwidth and, as a consequence, is not affecting too much the FEL performance (see Fig.10 and Tab.3). Considering the

$$\text{equation for the undulator resonance } \lambda = L_w \cdot \frac{(1 + a_w)}{2\gamma^2}$$

we can derive that, if the emission wavelength is defined by the resonance wavelength of the radiator, the jitter in wavelength, λ , should be two times that associated to the jitter in electron mean energy, γ . This is not true in a seeded FEL where the emission wavelength is defined by the seeding laser and only partially by the undulator resonance wavelength.

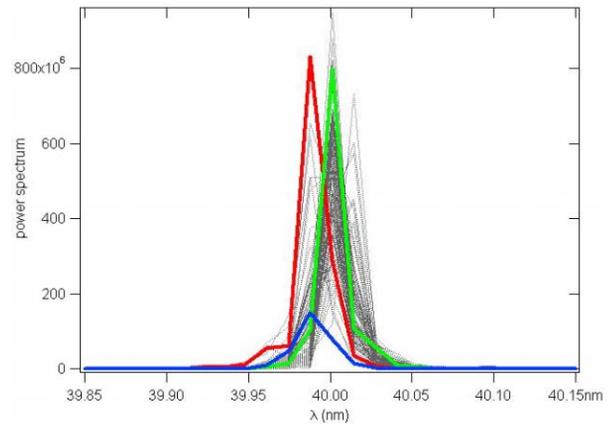


Figure 10: Output power spectra obtained from the FEL simulations of the jittered files.

Our results are in agreement with predictions and the obtained fluctuation for the wavelength is very lower compared to the fluctuation of the mean energy of the input jittered bunches.

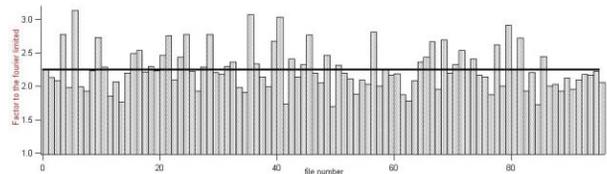


Figure 11: Factor to the Fourier transform limit of the FEL output pulses for the jittered ELEGANT files.

We also characterized the FEL output pulses in terms of how close they are to the Fourier limit. In Fig. 11 we report the distance of each FEL output pulse with respect to the Fourier limit for the 100 simulated jittered files. The average Fourier factor for the simulated data is 2.2 and the standard deviation of the distribution is about 13%.

Table 3: Statistics of the 100 FEL pulses.

Quantity	Mean Value	Std. Dev.
Average pulse width (fs)	73.2	
Average photon number	7.1e+13	23.3%
Average central wavelength (nm)	40.0019	0.013%
Average bandwidth	0.033%	
Fourier factor	2.2	13%

In order to verify the prediction of time independent simulations, which indicate the jitter in the mean electron energy as the most limiting factor for achieving a good output stability, in Fig. 12 we plot the number of photons per pulse vs the average electron-beam energy.

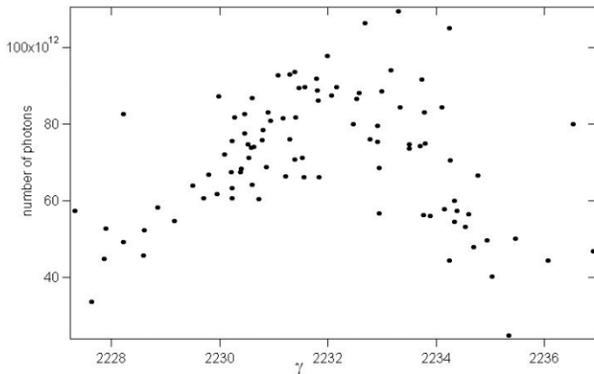


Figure 12: Number of photons per pulse vs the average electron mean energy of the corresponding electron bunch.

The good correlation between the two quantities clearly confirms the high sensitivity of the FEL output to the electron mean energy.

CONCLUSIONS

An extensive campaign of start-to-end simulations for the first stage of the FERMI@Elettra project has been presented. Results show a quite strong sensitivity of FEL characteristics to shot-to-shot jitters of electron-beam parameters.

The effect of the proposed strategies for the reduction of the output power fluctuation by means of sophisticated radiator configuration (tapering) or linear chirping of the electron bunches will be considered in a forthcoming work.

REFERENCES

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- [3] P. Craievich, S. Dimitri, G. Penco, private communication.
- [4] M. Cornacchia *et al.*, Sincrotrone Trieste tech. note, ST/F-TN-06/15.