DESIGN AND PERFORMANCE OF THE FERMI AT ELETTRA FEL

G. De Ninno, E. Allaria, Sincrotrone Trieste, 34012 Trieste, Italy;

W. Fawley, G. Penn, LBNL, Berkeley, CA 94720-8211 USA.

Abstract

The FERMI at ELETTRA project will be comprised of two FELs, each based on the principle of seeded harmonic generation. The first undulator line, FEL-1, will operate in the 40-100 nm wavelength range relying upon one stage of harmonic up-conversion. The second undulator line, FEL-2, extends the output spectral domain to the 10-40 nm wavelength range and will use two harmonic stages operating as a cascade. We review the FEL studies that have led to the final design and present results of numerical simulations with GENESIS and GINGER codes including predicted output bandwidths and the effects of shot-to-shot fluctuations in multiple input parameters.

INTRODUCTION

The FERMI@ELETTRA project is based on the harmonic up-shifting of an initial radiation "seed" signal in a single-pass FEL amplifier employing multiple undulators. The basic principles which underlie this approach are: energy modulation of the electron beam via the resonant interaction with an external laser seed in a first undulator (modulator); use of a chromatic dispersive section to then develop a strong density modulation with large harmonic overtones; production of coherent radiation by the microbunched beam in a downstream undulator (radiator). The first stage of the project, FEL-1, aims at generating coherent output radiation in the 40-100 nm spectral range. For these wavelengths, users require short (< 100 fs) pulses with adjustable polarization together with high temporal and spatial reproducibility. The project's second stage, FEL-2, will extend the spectral range down to 10 nm. Present users' requirements for FEL-2 point to long (narrow-bandwidth) pulses with high peak brilliance and adjustable polarization. FEL-1 relies upon a single-stage scheme (i.e., modulator-dispersive section-radiator), similar to the one already operational at Brookhaven [1]. As for FEL-2, a two-stage harmonic cascade is necessary for reaching short wavelengths. The selected configuration is based on the so-called "fresh bunch" approach [2], in which the output radiation from the first radiator is used to energy-modulate in a subsequent modulator a part of the electron beam that did not interact in the first stage with the external seed.

In this paper we review the FEL studies that have led to the final design of FEL-1 and FEL-2 and present results of both time-independent and time-dependent numerical simulations with GENESIS and GINGER.

BASIC FEL OUTPUT REQUIREMENTS AND RELATED ISSUES

Table 1 summarizes the basic FEL output requirements for FEL-1 and FEL-2. At all wavelengths, both FEL-1 and FEL-2 are to have continuously tuneable output polarizations ranging from linear-horizontal to circular to linear-vertical. Consequently, the FEL-1 radiator and final radiator in FEL-2 have an APPLE-type configuration. Both FELs will operate at the accelerator repetition rate of 10-50 Hz.

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 (20-100 fs) than they are to spectral bandwidth. A critical parameter affecting the needed electron beam duration is the timing jitter in the beam relative to that of the seed laser. In order that there be reasonably overlap between the seed and the electrons, the duration of the electron beam must be bigger than the duration of the seed pulse plus two times the RMS timing jitter. The expected RMS timing jitter from the accelerator is of order 130 fs [3], and therefore an electron-beam pulse duration of at least 600 fs is needed for 100-fs seed pulses. This timing jitter requirement may be one of the more difficult to satisfy in terms of the injector and accelerator subsystems.

Another important parameter associated with FEL-1 time domain experiments is shot-to-shot repeatability. Ideally, for nonlinear phenomena experiments, shot-to-shot RMS jitter in normalized photon number should be 5% or less. As reported in [3], we do not at present believe that such a low value is obtainable with the expected accelerator and injector parameters. Many FEL-1 experiments will be able to deal (via recording individual shot photon number for later post-processing) with values as high as 25% or greater.

In contrast to FEL-1 users, for whom timing and photon number jitter are critical parameters, most FEL-2 users are (presently) interested in the frequency domain experiments where longitudinal coherence and narrow bandwidth are crucial. The most important output goal for FEL-2 is $\geq 10^{12}$ photons/pulse/meV. Consequently, FEL-2 requirements favor long output pulses (≥ 200 fs) whose spectral properties are as close as possible to the transform limit. Although the total photon jitter is not critical for most experiments in the frequency domain, shot-to-shot central wavelength jitter is of concern. Consequently, in order not to increase the effective timeaveraged, output bandwidth as seen by the user, the wavelength jitter needs to be less than the individual shot bandwidth.

UNDULATOR DESIGN

In the FERMI case, wavelength tuning in the undulators will be done by changing the gap (and thus a_w) and not by changing the electron beam energy.

The FEL-1 undulator layout is shown in Fig. 1.

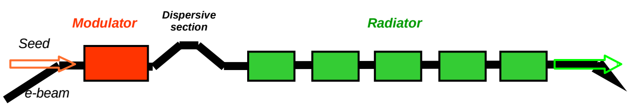

Fig. 1: FEL-1 undulator layout

For the first modulator which must satisfy FEL resonance over a nominal wavelength range of 240 to 360 nm, an undulator wavelength of 16 cm has been adopted. The modulator will be a standard planar undulator about 3-m long. In order to reach saturation over the whole spectral range, the necessary active radiator length for FEL-1 is about 16 m. For many reasons (e.g., magnetic forces, alignment, external focusing and diagnostic needs, possible tapering), this is far too long to construct as one continuous magnetic structure. Consequently, the radiators will be subdivided into six modules, each consisting of an active undulator segment (with a period of 6.5 cm and a length of about 2.3 m) and a break segment (about 1 m long), with the latter containing a number of items such as quadrupoles, a longitudinal phase shifter, beam position monitors, dipole correctors, and diagnostics. In order to produce light with variable polarization, the radiator modules will be APPLE-type. The FERMI design includes external quadrupole focusing to produce an average value of 10 m for the Twiss beta function in each plane.

Following the modulator is a break section (about 1 m long) that contains a magnetic chicane whose chromatic dispersion is used to develop a strong coherent microbunching from the energy modulation impressed upon the electron beam by the FEL interaction in the modulator. The undulator layout for FEL-2 is shown in Fig. 2.

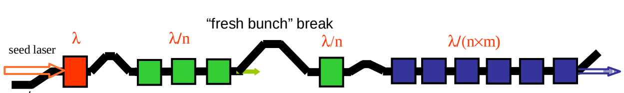

Fig. 2: FEL-2 undulator layout

The selected configuration is based on the so-called "fresh bunch" approach [2], in which the radiation from the first radiator is used to energy-modulate in a subsequent modulator a "fresh" part of the electron beam that did not interact with the external seed. The core design for the first stage of fresh-bunch FEL-2 is extremely similar to that described earlier for FEL-1.

Where the design for FEL-2 fresh bunch layout begins to differ significantly is that the first stage radiator is relatively short (i.e., 2-3 segments) and only brings the radiation to a sufficient level to provide adequate coherent energy modulation in the following undulator. The basic parameters for the second stage modulator are the same as for the first stage radiator (i.e., 6.5-cm period; 2.3-m segment length). In general, the choice has been made to keep the first stage as short as possible, both for cost reasons and to minimize SASE growth which can increase the incoherent energy spread of the "fresh" portion of the e-beam to be used in the second stage modulator and radiator. The second-stage radiator has a shorter period (5 cm) and is subdivided into 2-m long active APPLE-type undulator segments separated by 1-m breaks. These breaks contain a quadrupole singlet for focusing, a phase shifter, dipole correctors, and diagnostics. The length of the final radiator is somewhat arbitrary; in general it has been presumed for the fresh bunch approach one would want sufficient length for power saturation, i.e., 6 segments at 10-nm wavelength. However, one could certainly increase the output power by adding more radiator segments and possibly also taper the undulator strength.

FEL-1 PERFORMANCE

Figure 3 displays the growth of power at 40-, 60-, and 100-nm wavelengths as predicted by the GENESIS and GINGER codes (each operated in time-independent mode). Electron-beam and seed parameters are reported in the figure caption.

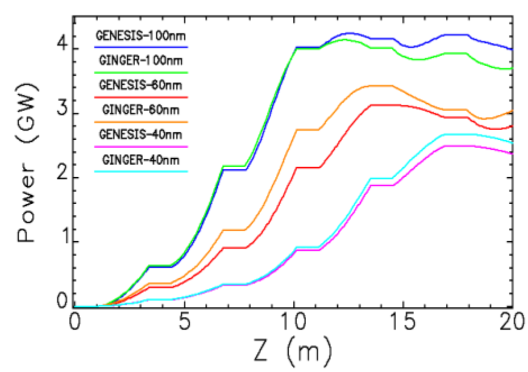

Fig. 3: Power growth as a function of radiator distance for FEL-1 tuned at 100-, 60-, and 40 nm, as predicted by Genesis and Ginger. Electron-beam parameters utilized for the simulation are: energy = 1.2 GeV; current = 800 A; incoherent energy spread (RMS) = 150 keV; normalized emittance = 1.5 mm mrad; input seed power = 100 MW; input seed wavelength = 240-300 nm.

As can be seen in Fig. 3, at the longer wavelengths power saturation is reached well before the end of the sixth section. The simulations show good basic agreement between the GENESIS and GINGER predictions. A factor of about two in output power can be gained by properly tapering the six radiator segments.

In order to get an estimate of output power sensitivity to electron beam and laser parameters, an extensive set of GENESIS and GINGER simulations has been performed varying single parameters at a time.

Parameter	FEL-1	FEL-2
Wavelength range [nm]	100 to 40	40 to 10
Output pulse length (rms) [fs]	≤ 100	> 200
Bandwidth (rms) [meV]	17 (at 40 nm)	5 (at 10 nm)
Polarization	Variable	Variable
Repetition rate [Hz]	50	50
Peak power [GW]	1 to >5	0.5 to 1
Harmonic peak power (% of fundamental)	~ 2	~ 0.2 (at 10 nm)
Photons per pulse	10^{14} (at 40 nm)	10^{12} (at 10 nm)
Pulse-to-pulse stability	≤ 30 %	~50 %
Pointing stability [μrad]	< 20	< 20
Virtual waist size [μm]	250 (at 40 nm)	120
Divergence (rms, intensity) [μrad]	50 (at 40 nm)	15 (at 10 nm)

Table1: FEL-1 and FEL-2 expected performance

We present here time-independent calculations in which the input laser seed power and various electron beam quantities were allowed to vary independently around their individual design values (see Table 1) following Gaussian distributions characterized by the following RMS values: mean electron energy: 0.1%; current: 8%; emittance: 10%; energy spread: 10%; input seed power: 5%. Expected output fluctuations are about 22 % (see Fig. 4). The most limiting factor to output stability is represented by the 0.1% input energy fluctuation. Detailed time-dependent start-to-end simulations, including the impact on output stability of seed-bunch time jitter and beam distribution homogeneity, are reported in [3].

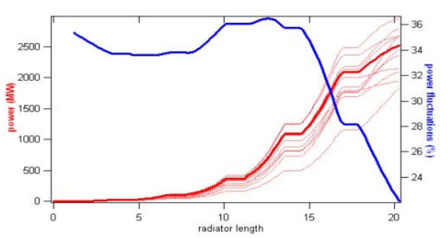

Fig. 4: Power growth for different initial random conditions (red curves, left vertical scale) and associated power fluctuation (blue curve, right vertical scale) vs. radiator distance.

A campaign of time-dependent start-to-end simulations has been performed making use of various electron-beam distributions provided by the FERMI gun and linac groups [4]. Figure 5 shows the GENESIS-predicted output temporal and spectrum profiles at 40-nm wavelength for an optimized (i.e., flat in both energy and current) input electron-beam distribution. The input seed was a 40-fs (RMS) Gaussian at a peak power of 100 MW.

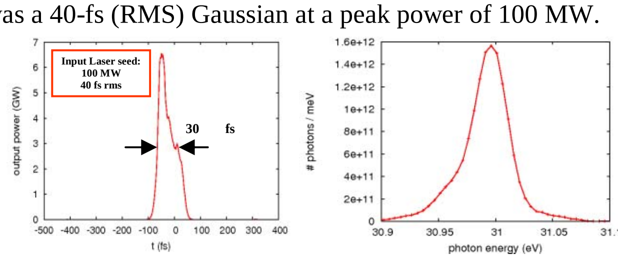

Fig. 5: FEL-1 temporal and spectrum profiles resulting from a GENESIS simulation in time-dependent mode.

The output number of photons per pulse is about $9{\cdot}10^{13}$ with ~80% in single transverse mode. The output pulse length is 30 fs and the spectral bandwidth 17 meV, about a factor of 2.5 above the transform limit

FEL-2 PERFORMANCE

Figure 6 displays the growth of power at 40-, 20-, and 10-nm wavelengths as predicted by the GENESIS and GINGER codes operated in time-independent mode. For a final radiator of six modules (see Fig. 2) deep saturation is reached only at 40 and 20 nm. At 10 nm, the output peak power is 1 GW for 800-A current and 0.35 GW for 500-A beam current (data not shown).

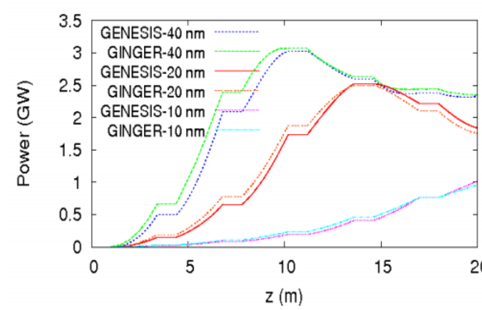

Fig. 6: GENESIS and GINGER time-independent simulations for the FEL-2 radiation power at various wavelengths versus radiator distance in the final radiator for the fresh bunch approach. These runs were done with 800-A beam current and 200-keV initial incoherent energy spread (for the other parameters see caption of Fig. 3).

FEL-2 is typically more sensitive to variations in input parameters than is FEL-1. This is largely due to the shorter wavelengths targeted for FEL-2, which leads to similar displacement errors translating into larger longitudinal phase errors, and there is the additional complexity of having two rather than one stage of harmonic conversion. Furthermore, at shorter wavelengths radiation diffraction is less important, which renders the FEL more sensitive to deviations in the electron orbit and to misalignments. However, it is presently believed that most applications for FEL-2 output will be in the spectral domain where reproducibility is less important and there is a premium for obtaining narrow bandwidth. Consequently, most of our work on FEL-2 has concentrated utilizing a relatively long (~1 ps) electron-beam pulse with a moderate (~500 A) current. For the fresh bunch approach, such a long pulse is nearly essential given the practicalities of temporal jitter between the electron beam and input radiation seed. As discussed in [5], flatness of electron-beam phase space and homogeneity of current and energy spread distributions at undulator entrance are essential for obtaining the best output spectral resolution and shot-to-shot stability. An example of output temporal and spectrum profiles at 10 nm based on an optimized input electron-beam is shown in Fig. 7. The obtained number of photons per pulse is about 10^{13} (93% in single transverse mode). The output pulse length is 110 fs (rms) and the bandwidth 5 meV, about a factor of 1.5 above the transform limit. The peak brightness is about 10^{32} photons /mm^2/mrad^2 /sec/ 0.1% bandwidth.

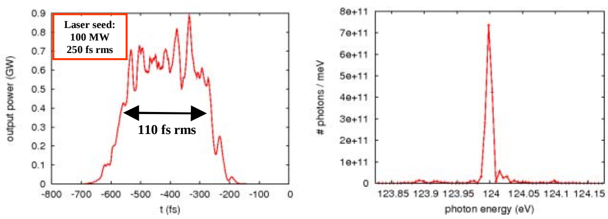

Fig. 7: FEL-2 temporal and spectrum profiles for fresh-bunch scheme resulting from a GENESIS simulation in time-dependent mode.

An alternative scheme we are considering for the FEL-2 is based on the so-called "whole-bunch" approach. Here, the entire electron beam pulse is energy-modulated by the external laser seed and, following the first radiator, there is neither a temporal delay section nor a second modulator. Instead, the electron beam immediately enters a weak dispersive section followed by a second radiator whose FEL resonant wavelength is tuned to an integer harmonic of the first radiator. Due to the relatively small harmonic microbunching at this new wavelength, this second radiator must operate deep in the exponential gain regime. Thus, to keep the exponential gain length and power saturation lengths acceptably small, the energy modulation produced by the first (and only) modulator must be relatively small compared to $\rho_2 \gamma$ where ρ_2 is the FEL parameter for the second radiator (generally ~ 1×10^{-3}). This small energy modulation means that at entrance to the first radiator the e-beam will have a smaller microbunching level relative to that of the fresh bunch scheme.

Consequently, the whole bunch approach can essentially fail (in terms of the needed second radiator undulator length for saturation) if the initial energy spread becomes too large. Moreover, because the microbunching level is small at the beginnings of both the first and second radiator, the relative strength of the shot noise microbunching is much higher and the final SASE strength can be 2 or more orders of magnitude greater in the whole bunch approach than in the fresh bunch approach. The main advantage of such a scheme is that it is less sensitive to shot-to-shot fluctuations of the relative timing between the e-beam and external seed laser. The output temporal profile and spectrum obtained at 10 nm using the whole bunch configuration are shown in fig. 8. The initial electron beam distribution is the same as for the fresh-bunch scheme (see Fig. 7).

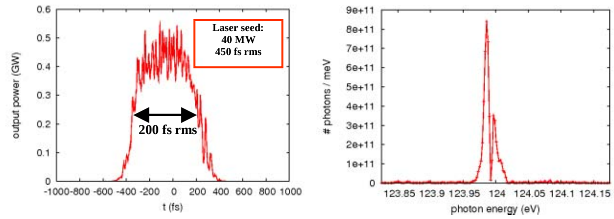

Fig. 8: FEL-2 temporal and spectrum profiles for whole-bunch scheme resulting from a GENESIS simulation in time-dependent mode.

In this case the obtained number of photons per pulse is about 10^{13} (93% in single transverse mode). The output pulse length is 200 fs (rms) and the bandwidth 4 meV. This gives a result which is a factor about 2.5 above the transform limit.

CONCLUSIONS

We have presented the current design configurations for both FELs of the FERMI@Elettra project. Design optimization has been driven by users' requests (see table 1), i.e. short pulse and low shot-to-shot power fluctuations for FEL-1, and high energy resolution for FEL-2. We also give results derived from both time-independent and time-dependent simulations, using reference parameters and electron-bunch distributions as provided by the FERMI start-to-end group.

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