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FERMI 2.0 UPGRADE STRATEGY

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Abstract

FERMI is undergoing a series of upgrades to keep the facility in a world-leading position. The ultimate goal of the development plan consists in extending the facility spectral range to cover the water window and above, and to reduce the minimum pulse duration below the characteristic lifetime of core hole electrons of light elements. We present here the main elements of this upgrade strategy.

INTRODUCTION

The upgrade involves deep modifications of the linac and of the two FERMI FELs with the ambition of extending the FEL performances and the control of the light produced to include the K-edges of N and O, the L_{23}-edges of elements of the third period, and early elements of the fourth period (Sc to Cr). One of the main requisites of this upgrade is the preservation of the uniqueness of FERMI: the possibility to control the properties of the radiation by seeding the FEL with an external laser system. Through the control of the microbunching formation in the electron beam the seed allows amplification of almost Fourier transform-limited pulses [1–3], to synchronize the FEL pulses with unprecedented precision to an external laser [4] and to control many pulse properties, such as phase and coherence [5,6]. The extended photon energy range will allow resonant experiments (XANES, XMCD, SAXS, CDI,…) exploiting several important edges (life-time in the range of few fs), larger wave-vector (non-linear optics), ultrafast chemistry (conical intersections, lifetime 0.5 – 10 fs) [7]. Presently, the spectral range up to 310 eV is covered by the two FELs: FEL-1 and FEL-2; the first provides photons in the range 20-65 eV, the second in the range 65-310 eV. In view of the upgrade, the photon energy distribution between the two FELs has to be adapted to the upgraded scenario, with FEL-1 still covering the low photon energy range, but extended to reach a photon energy of 100 eV (see C. Spezzani *et al.*, these proceedings), and FEL-2 dedicated to the high energy range, from 100 eV to about 550 eV.

FEL-2 UPGRADE

To extend the FEL-2 spectral range to the oxygen K-edge, two options were considered, either by using EEHG directly, or with a cascade employing both EEHG and HGHG techniques in the “fresh-bunch” injection technique now used on FEL-2. The implementation of the first solution, EEHG, requires a first large dispersion chicane of up to 15 mm for optimized EEHG operation. This makes the scheme prone to a number of effects which may result in a degradation of the FEL spectral purity and of the FEL gain in the final radiator [8, 9]. The large chicane is indeed an amplifier of microbunching instability (MBI). A second issue is the emission of incoherent synchrotron radiation (ISR) and the intra-beam scattering (IBS) along the chicane. These two effects are the source of mixing of the filamented phase space that produces the high harmonic bunching in EEHG after the second chicane, a factor reducing the bunching at the entrance of the amplifier.

All these effects would be mitigated in a scheme where the chicanes have a lower dispersion. This is the reason why we considered the second option, where the EEHG generates a seed that is then used in fresh-bunch to seed a second HGHG stage, similar to what is done in the present FEL-2 configuration. The present double-stage HGHG with fresh-bunch scheme can be upgraded by converting the first stage to an EEHG configuration aimed at reaching harmonics of the order of 30. The second stage would then up-convert the output of the first stage to harmonics of the order 120-130 as required.

This configuration needs a much lower dispersion, of the order of 4-5 mm, which is only a factor two larger than the one used in the FERMI EEHG experiment. We analysed the four different configurations of seeded FELs shown in Fig. 1 and selected the most promising one with the aim of extending the seed coherence to the highest harmonic orders.

The explicit dependence of the pulse peak power on the various parameters and for linear polarization is shown in the plots represented in Fig. 2. Table 1 lists the parameters used in the calculations.

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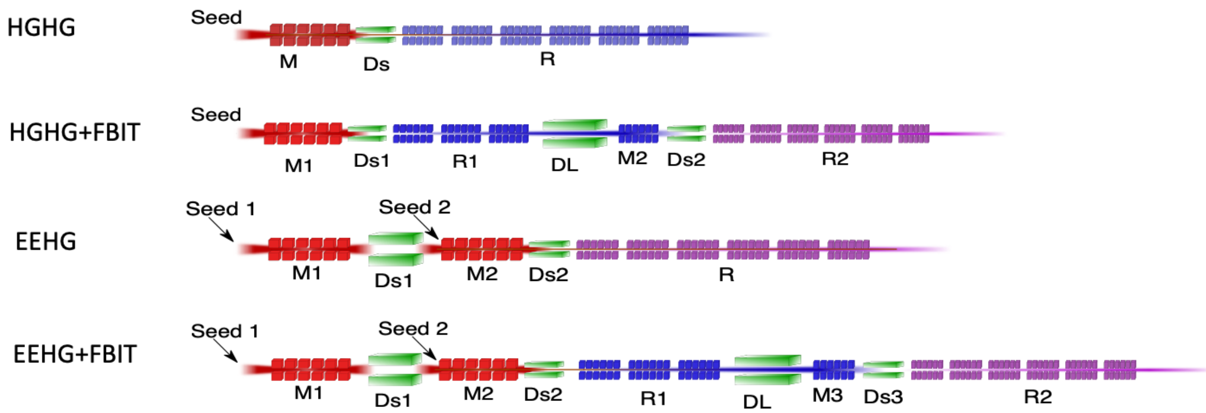

Figure 1: Schematic layout of the four configurations analysed, in order from top to bottom: High-gain harmonic generation (HGHG as in FEL-1), double stage, high-gain harmonic generation with fresh-bunch injection technology. (HGHG+FBIT as in FEL-2), Echo-enabled harmonic generation (EEHG), Double stage, echo-enabled harmonic generation with fresh-bunch injection technology. (EEHG+FBIT).

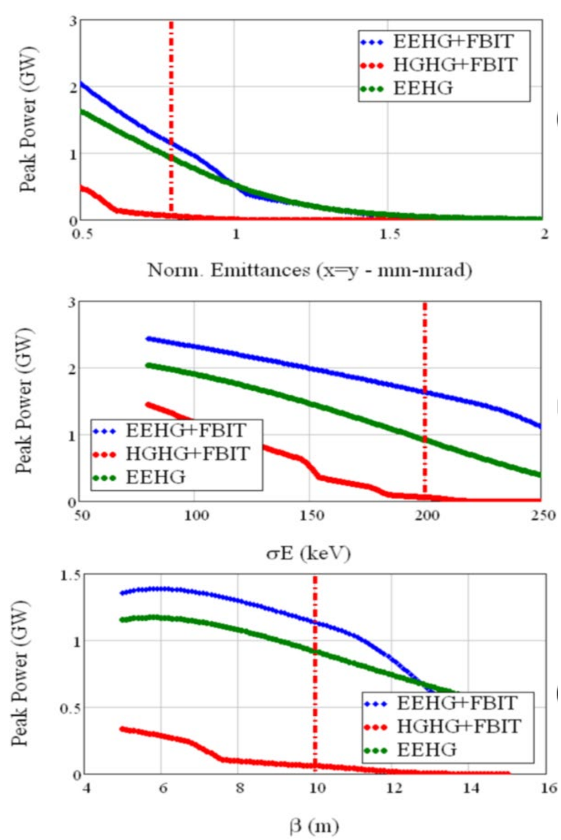

Figure 2: Dependence of the estimated FEL output power on electron beam emittance, energy spread and beta (Twiss) parameter. Assumptions: wavelength of operation 2 nm, linear polarization. Other parameters as listed in Table 1.

Any degradation of the beam parameters with respect to the reference values of Table 1 has an effect on the FEL output power. The figures show a higher sensitivity to the beam quality of the HGHG+FBIT configuration, if compared to the one of the EEHG+FBIT and pure EEHG configurations. Pure HGHG cannot reach this wavelength and is excluded from the comparison.

Table. 1 Reference Beam/seed Parameters

Beam parameter	**Value (unit)**
Energy	1800 (MeV)
Energy spread	200 (keV)
Current	1000 (A)
Emittance	0.8 (mm mrad)
Seed parameters	**Value (unit)**
Seed wavelength range λ_s	240-266 nm
Seed1 time duration	100 fs
FEL parameters	**Value (unit)**
Polarization	linear

HGHG+FBIT shows worse performances in all the conditions because of the large harmonic orders required in both stages to reach harmonics of order 130. The pure EEHG scheme was considered with ten undulators in the final amplifier. Its performance is comparable to EEHG+FBIT, but requires a much larger 1st dispersion (12-15 mm vs. 5 mm in EEHG+FBIT) and is prone to amplification of microbunching instability. In this pure EEHG scheme a lower bunching factor is available at the amplifier, making this configuration sensitive to the gain in the final amplifier. Larger gain requires a longer amplifier and enhances the amplification from "shot-noise", i.e. the SASE background. Another disadvantage associated with the large chicane required by pure EEHG is the effect on a chirped e-beam where current spikes at the head/tail could further enhance SASE emission. Figure 3 indicates the EEHG+FBIT configuration as the more robust solution to reach the 2 nm target wavelength.

SIMULATIONS

The performance of the pure EEHG and EEHG+FBIT schemes at 2.1 nm was evaluated by running time-

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dependent GENESIS 1.3 [10]. The parameter optimization was achieved by analytical estimates and by running preliminary steady state simulations. Figure 3 shows the power (left) and spectrum (right) after 8 radiators, in both pure EEHG and EEHG+FBIT configurations, when an intensity close to saturation is reached in the seeded part of the electron-beam. The electron-beam current, energy, and energy spread profiles at the end of the FERMI linac (just before the first modulator) were calculated using the particle tracking ELEGANT [11] simulations. The results were obtained using smoothed electron-beam profiles, corresponding to initial peak bunching (at the radiator entrance) of around 1.5%. The smoothing procedure was calibrated averaging out modulations on the scale shorter than approximately 5 µm, as could be expected according to the laser heater configuration. These simulations were run with 5 10^6 particles per slice and include effects in the chicane such as intra-beam scattering and wakefields, which significantly affect the output, especially at short wavelengths.

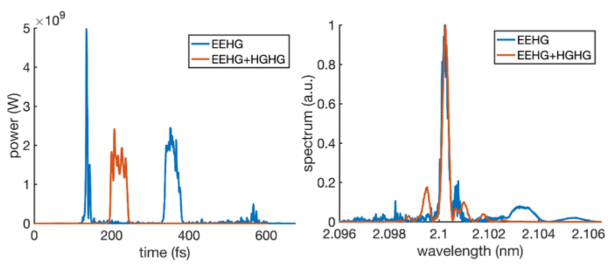

Figure 3: Power (left) and spectrum (right) at 2.1 nm obtained from time-dependent GENESIS 1.3 simulations in EEHG (blue) and EEHG+FBIT (red) configurations.

In Fig. 4 the same simulation was run with Genesis 1.3 ver. 4.4, in one-to-one mode, i.e. one simulated electron per real electron. This second simulation does not include collective effects in the chicane.

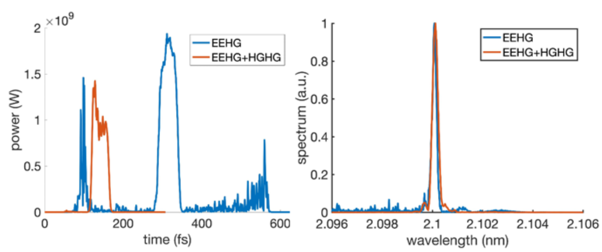

Figure 4: Power temporal profile (left) and spectrum (right) at 2.1 nm obtained from time-dependent GENESIS 1.3 (4.4) in one-to-one mode simulation for the pure EEHG (blue) and EEHG+FBIT (red) configurations.

Pulse energy at the GW level is reached in both the configurations, the small differences in peak power between EEHG and EEHG+FBIT are not significant and may be due to small differences in the tuning of the input parameters. Both simulations in Figs. 3 and 4 point out the higher contamination of SASE background in the pure EEHG configuration with respect to the EEHG+FBIT configuration. This SASE signal depends on the number of macro particles used in the simulation and on the smoothing procedure applied, but even the “smoothed” case of Fig. 3 still shows a residual but visible SASE background after eight undulator modules.

The above results show that using a pure EEHG configuration, the FEL output at such short wavelengths is sensitive to the level of microbunching and starts getting affected by SASE emission. The EEHG+FBIT simulation instead is less affected by the SASE background, and the differences between Figs. 3 and 4 are probably due to the collective effects in the chicane that were not included in Fig. 4. Comparing the pure EEHG and EEHG+HGHG configurations (c.f., Figs. 3 and 4), the latter performs significantly better in terms of the spectral quality because of a lower contribution from SASE background.

We have presented a partial view of the pathway for the upgrade of the FERMI FEL facility over a time span of about nine years. The facility is undergoing technological transformations that will allow the extension of the spectral range to the target of the carbon to oxygen K-edges. The reader is addressed to ref. [7] for a more comprehensive overview.

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