

FERMI PLANS FOR A 2 nm SEEDED FEL

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Abstract

Most Free Electron Lasers (FEL) use the mechanism of self-amplified spontaneous emission (SASE) from a relativistic electron beam to generate intense femtosecond pulses in the X-ray spectral range. Such SASE FELs are characterized by a broad bandwidth and relatively poor longitudinal coherence, and offer a rather limited control over the spectro-temporal properties. The limitations of a SASE FEL can be overcome by using an external laser to trigger the amplification process. Echo-enabled harmonic generation (EEHG), alone or in combination with the high-gain harmonic generation scheme (HG HG), is currently the most promising candidate for extending the operation of externally-seeded FELs into the soft X-ray region. Here, we discuss the plan at FERMI to upgrade the second FEL line in order to reach ~ 2 nm at the fundamental emission wavelength. In a first step, coherent radiation at ~ 10 nm will be generated with an EEHG layout and used as a seed in an HG HG stage on a fresh part of the electron beam. The experience with EEHG at the FEL-1 line will be an important step towards the final realization of the FERMI FEL as a reliable source of highly coherent radiation at ~ 2 nm and below.

FERMI 2.0

FERMI is the FEL user facility operated by Elettra - Sincrotrone Trieste, which delivers highly coherent pulses ranging from 100 nm down to 4 nm [1]. The wide spectral range is covered by two FEL lines, FEL - 1 [2] and FEL - 2 [3]. Thanks to the use of an external laser used to initialize the FEL process, FERMI FEL pulses are characterized by a high degree of coherence and stability. These characteristics have made FERMI very appreciated by the scientific community and have also been used for pioneering experiments of coherent control in the EUV and soft-X-ray spectral range.

Motivated by the successful scientific programme of the facility and by the growing interest of the FERMI scientific community in shorter wavelengths, an upgrade programme, named FERMI 2.0, has been initiated [4]. The plan consists of two phases; the upgrade of FEL - 1 and the final upgrade of the facility, including part of the linac and the FEL - 2 line. With the recently completed upgrade of FEL - 1 [5], the capabilities of the long-wavelength FEL (FEL - 1) have been extended with the implementation of the new seeding scheme based on Echo Enabled Harmonic

Generation [6]. The ultimate goal of extending the FERMI tuning range toward 2 nm or shorter wavelength is part of the second upgrade phase. This requires a substantial upgrade of the FERMI linac together with a newly designed FEL - 2 line.

FEL-2 REQUIREMENTS

Extending the tuning range of FEL - 2 toward shorter wavelength is not the only goal of the new FEL. The successful continuation of the FERMI scientific program at the existing beamlines [7-11] depends on the possibility to maintain important properties of the FEL pulses currently available at FERMI also in the future FEL - 2.

In addition to the standard parameters characterizing FEL pulses and listed in Table 1, discussion with the FERMI scientists revealed that the new configuration should support the following aspects:

- high stability and reproducibility
- the possibility to operate in two-colors configurations with large wavelength separations
- the possibility to simultaneously generate two pulses.

Table 1: FEL Parameters Required for FEL - 2 Upgrade

Parameter	Value	Units
Photon energy	Up to 900	eV
Pulse length	<10	fs
Polarization	Variable	
Energy per pulse	>10	μ J
Bandwidth	100	meV

FEL-2 LAYOUT

Given these requirements for the new FEL a complete redesign of the FEL line is necessary. Thanks to the extended tuning range of the recently upgraded FEL - 1 [5] the long wavelength tuning range for FEL - 2 can be limited to 10 nm or shorter. This allows a reduction of the undulator period to about 2.9 cm in order to reach a fundamental wavelength of 2 nm, with even shorter wavelengths being made available with the electron parameters planned for FERMI 2.0 (Table 2).

Thanks to newly designed RF structures, the electron beam energy will be extended to 2.0 GeV. The new accelerating cavities, characterized by reduced transverse and longitudinal wake fields, will also ensure better control of the electron beam phase space. This, in combination with a double compression scheme, will allow reaching the peak

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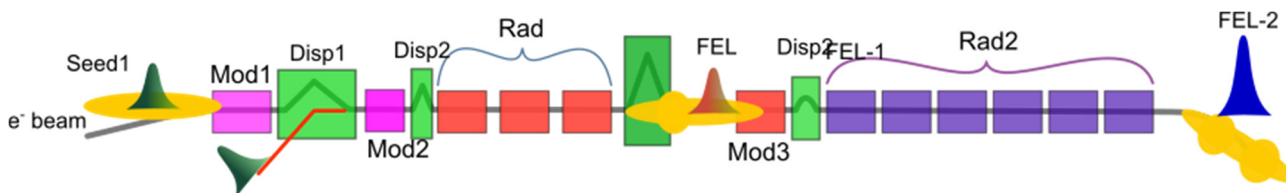


Figure 1: Layout of the new FEL - 2 line for FERMI 2.0.

Table 2: Electron Beam Parameters for FERMI 2.0

Parameter	Value	Units
Beam energy	Up to 2.0	GeV
Bunch charge	500	pC
Normalized emittance	1	mm mrad
Energy spread	<200	keV
Peak current	1	kA

current of 1 kA required for supporting the FEL amplification at the shortest wavelength.

The best FEL configuration to meet all the requirements for the new FEL - 2 has been identified as a two stage configuration with EEHG in the first stage (see Fig. 1).

With EEHG in the first stage, it is possible to produce radiation down to 8 nm with sufficient power to seed the second stage with only three radiators. The first stage should be very similar to the recently upgraded FEL - 1. The ongoing experience with EEHG on FEL - 1 will be fundamental for informing the optimal final design of the first stage of FEL - 2. The current design includes two modulators for the interaction of the beam with the two UV seed lasers. Two chicanes provide the dispersion required by the EEHG FEL (R_{56} of a few mm in the first chicane and few 100s of μm in the second one). The first stage amplifier is realized by three 55 mm period APPLE-II undulators. After the first stage a magnetic chicane delays the electron beam with respect to the FEL radiation produced in the first stage to seed a fresh part of the electron beam in the second stage HGHG FEL. The seed interacts with fresh electrons in the modulator. The downstream dispersive section converts the energy modulation into a density modulation and the FEL modulation is amplified to saturation in the final radiator. The radiator is based on short period variable polarization undulators. In the present design, the radiator is based on six 29 mm period undulator modules, each two meters long, of the APPLE-X type.

FEL Simulations

FEL simulations with the code GENESIS [12] have performed with both nominal (Fig. 2) and start to end parameters (Fig. 3). The simulations show that hundreds of MW can be generated from the first stage while a GW level FEL pulse is produced at the final FEL wavelength. Start-to-end simulations show that FEL pulses from both the stages are characterized by well-defined single line spectra, with a modest growth of sidebands mainly from the second stage. Dedicated studies have shown that these sidebands can be present at the final FEL wavelength when there are residual

modulations of the electron beam due to the microbunching instability developed in the linac.

Given the large number of dispersive elements required by the proposed configuration, it is then crucial to study their impact on the growth of the microbunching instability. In addition to numerical and theoretical studies, this problem will be addressed by dedicated experiments on the existing EEHG setup at FEL - 1.

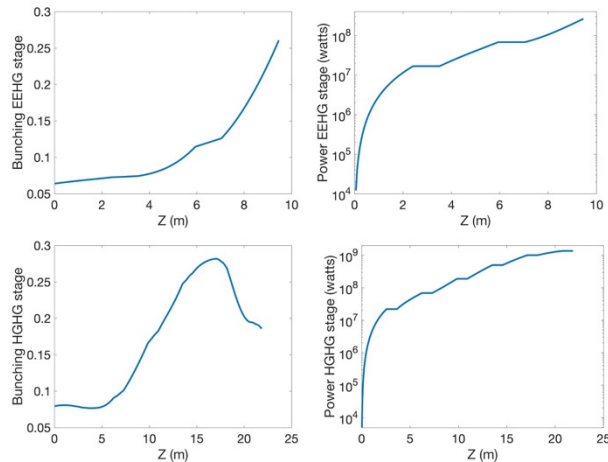


Figure 2: Simulated bunching and power evolution in the first stage (upper panels) and at the final FEL wavelength (bottom panels).

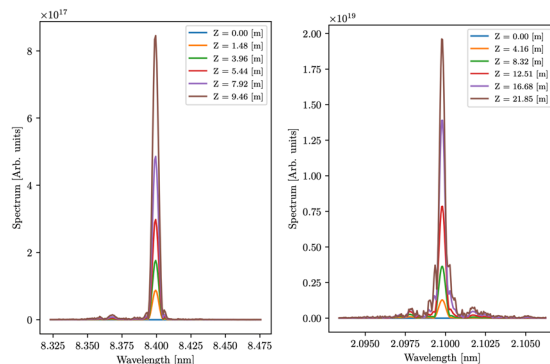


Figure 3: Power spectrum for the first stage radiation at 8.4 nm and the final FEL at 2.1 nm obtained from start to end simulations.

Impact of Big Chicane on e-beam

With the new setup of FEL - 1 it was possible to investigate the influence of the chicane on the electron beam quality, by characterizing the behavior of FEL - 1 in HGHG seeded in the second modulator only. Measurements of the FEL sensitivity to the laser heater intensity were made for different values of the first, large dispersion chicane (Fig. 4). These measurements have shown that up to a

dispersion of 2.0 mm the optimum FEL intensity is obtained for the minimum value of the laser heater intensity, indicating that the beam is not affected by microbunching. For larger values of the first chicane dispersion, data show that FEL optimal intensity requires instead an increase of the laser heater intensity, suggesting that some extra gain of the microbunching has occurred in the chicane.

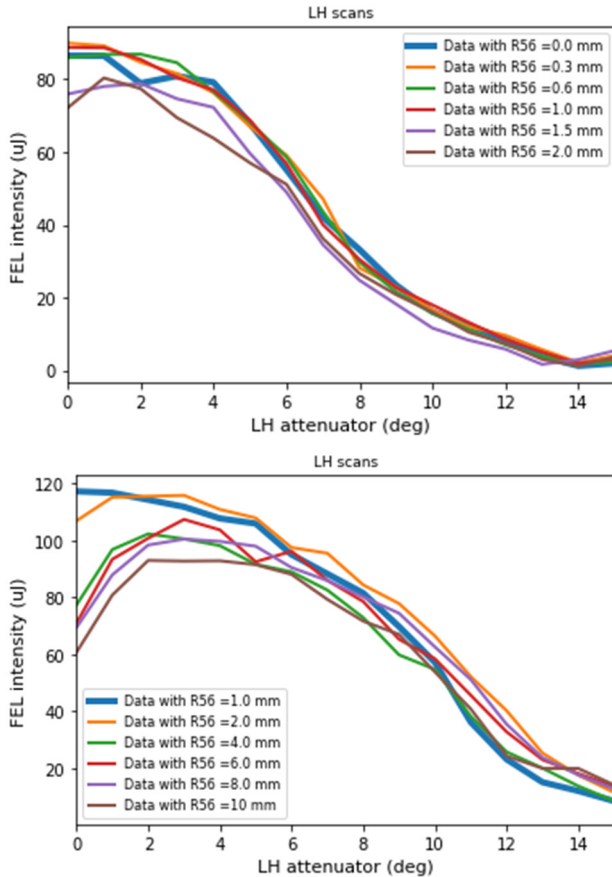


Figure 4: Measurements of the FEL intensity as a function of the laser heater attenuator for different values of the big chicane when working in HGHG using modulator 2.

These studies need to be continued by exploring possible ways to mitigate the effect of the chicane on the microbunching gain, and also in combination with the second bunch compressor along the linac, which has been shown to have a significant effect on the microbunching gain.

CONCLUSION

FERMI has started an upgrade program with the aim of extending the tuning range toward shorter wavelengths, to access important resonances. Based on the user requirements for the new FEL, a new layout for the second FEL has been identified and dedicated studies are in progress. Thanks to the available hardware installed in the recently upgraded FEL-1 experimental studies aiming at identifying the best solution have also started.

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