DEPENDENCE OF FEL INTENSITY ON THE AVAILABLE NUMBER OF UNDULATORS FOR FERMI FEL-1*

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Abstract

FERMI@Elettra [1] is a free electron laser user facility based in Trieste Italy. The first FEL line (FEL-1), based on the high gain harmonic generation scheme, covers the spectral range from about 80nm down to 20nm with high quality FEL pulses and started producing FEL light for user operations in 2011. FERMI FEL-1 radiator is composed by six undulators 2.4 meter long with the available space for additional two undulators. In this work we investigate the impact of additional undulators on the FEL performance in the case of FERMI FEL-1. We finally extend the work studying the dependence of the FEL power as a function of the length of the radiator for FELs based on the high gain harmonic generation scheme showing that for typical parameters there is a linear dependence.

INTRODUCTION

The use of harmonic generation to produce FEL pulses at short wavelength starting from an external seed laser at long wavelength has been applied to high gain single pass FELs to generate VUV coherent emission [2]. In the last decade HGHG has been demonstrated and studied in few FEL test facilities [3] and all experiments have shown the capability of HGHG to produce FEL pulses with a well-controlled and narrow bandwidth. Due to the quality of available electron beam parameters and the length of undulators some of these experiments does not necessary implies a strong exponential growth of the power along the undulator that in some cases is just few meter long. In those cases, the FEL power only has coherent emission in the radiator without exponential gain and the process is generally called coherent harmonic generation (CHG) while HGHG should be associated to cases with an exponential growth of the power in the radiator that generally is much longer.

In this work we focus on the impact of the length for the final radiator in the case of a HGHG FEL using the parameters of FERMI as a case study.

As it will be shown the results for HGHG are different from what occurs for a simple FEL amplifier that starts from a week signal. In FEL amplifiers the input signal can be provided by an external source or by the spontaneous emission as in self-amplified spontaneous emission (SASE) [4] and the output power drastically depends on the length of the radiator. Indeed, the power that a FEL amplifier can produce increases exponentially with the length of the available radiator till saturation is reached.

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HGHG AT FERMI

An HGHG or a coherent harmonic generation (CHG) FEL can be divided into three parts, the modulator, the bunching section and the radiator.

In the modulator the electron beam is in resonance with the electromagnetic wave of the external seed laser. Due to the interaction with the seed laser the electron beam become energy modulated with a periodicity equal to the seed wavelength.

The energy modulation is then converted into density modulation when the electron beam is passing through the dispersive section where high-energy electrons perform a path shorter than low energy electrons. Density modulation is created at the seed laser wavelength and its harmonics

The final radiator is set so that the electron beam is at resonance with the desired harmonic of the seed laser. As a consequence of the bunching, electrons will immediately emit coherently and this emission is generally several orders of magnitude larger than the spontaneous emission. In HGHG the further interaction of the electron beam with the produced coherent radiation lead to an increase of the bunching and a rapid increase of the produced FEL radiation.

In a simple view the first part, where only coherent emission is generated, power increases quadratically with the undulator length while an exponential growth of the power along the undulator characterize the second part. In this final part the bunching increase is associated with the self induced effect that characterized high gain FELs

FERMI Parameterts

FERMI uses electron beams accelerated by a normal conducting linear accelerator with electron beam energy in the range between 0.9 and 1.5GeV. Electron bunches with a charge of few hundreds of pC are generated in a high brightness RF photocathode gun. The accelerator has two bunch compressors and has been designed to preserve the high quality and brightness of the beam up to the entrance of the undulator. The design value for the normalized emittance of the electron beam at the undulator entrance is of the order of 1 mm mrad and the energy spread of the order of 100keV. A more detailed description of the accelerator design and configuration is reported in [1].

FEL studies at FERMI started in 2011 demonstrating the capability to generate high quality FEL pulses in the 30 nm spectral range starting from an UV seed laser at about 260nm [5]. Due to incomplete installation of all accelerator components, the electron beam used in the first period of FERMI has not been the final one. In particular the electron beam peak current used during first

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periods of operation has been in the range between 350A and 500A compared to about 800A that is the design value.

In this study we focus on the 500A peak current electron beam and study its impact on the output power of the radiator length. Other electron beam parameters are reported in Table I.

Table 1: Electron Beam Parameters

Parameter	Value	Units
Energy	1.2	GeV
Energy spread	100	keV
Normalized transverse emittance	1.0	mm mrad
Peak current	500	A
Average beta	10	m

The undulator parameters used for these studies are the ones of the first FEL at FERMI (FEL-1) [1] and the scheme is sketched in Figure 1. The FEL-1 radiator (RAD) is composed of six 2.4 meter long undulators with a period of 55 mm. FERMI has the possibility to extend the length of the present radiator by adding two additional undulators (Free). In order to study the effects of undulator length also beyond the present capability of FERMI we have considered a radiator up to 10 undulators long.

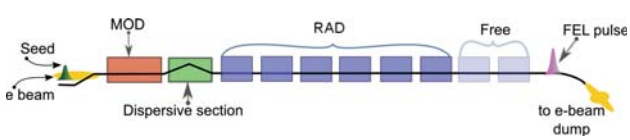

Figure 1: Layout of the undulator system of FERMI FEL-1 and used for this work.

The studied setup uses a seed laser at 260 nm with a seed power that for this work can be varied in the range between 20 MW and 1GW. The seed power level is used as an optimization parameter to maximize the FEL output power for the various cases. Seed laser interacts with the electron beam in the modulator (MOD) that in FERMI is a 3-meter long undulator with an undulator period of 100 mm. The energy modulation produced in the modulator is converted into density modulation by the "dispersive section" that has a R56 that can also be varied to maximize the output power from few microns to more than 100 microns.

FEL DEPENDENCE ON RADIATOR LENGTH

Due to the different processes that originate the coherent emission of the FEL the effects of the available length for the radiator is different for FELs operating in the HGHG regime with respect to the case of a simple FEL amplifier or a SASE FELs.

In an amplifier FEL the start-up power is defined by the seed laser power or by the electron beam shot noise. By contrast, the start-up in an HGHG can be easily controlled by adjusting the seed power or optimizing the bunching in the dispersive section.

In the case of a HGHG the amount of bunching and coherent emission that initiate the process can be optimized in order to allow the beam to reach the maximum bunching before the end of the radiator. Since this optimization can be done independently the length of the radiator the effect of the undulator length on the FEL output power is less critical than in a simple FEL amplifier. In the case of an amplifier indeed, the radiator has to be long enough to allow the FEL to reach the saturation while starting with the available input power. Being in the exponential regime in case of a shorter undulator the FEL power would be significantly reduced.

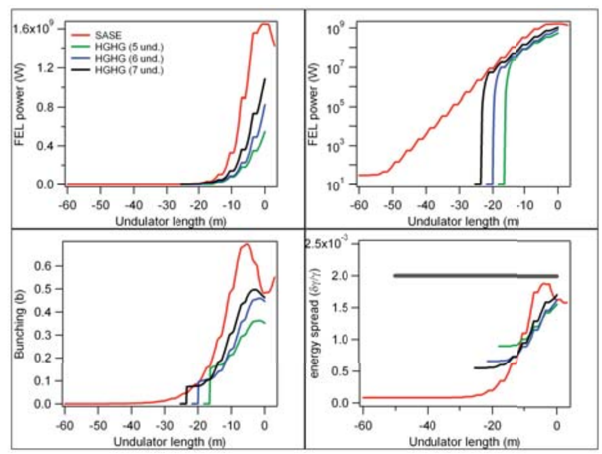

Figure 2: FEL evolution as a function of radiator length for simple amplifier (SASE, red) and HGHG with 5, 6 and 7 undulators (green, blue, green respectively). FEL power is reported in linear (a) and logarithmic (b) scales. The bunching (c) shows a local maximum in all cases in the last undulator. The value of the maximum bunching is different for various cases due to different seeding that has been used to optimize the system and that produce different energy spread (d) into the beam entering the radiator.

Figure 2 reports the results of GINGER [6] simulations of the FEL process in different conditions. A case of FEL amplifier (red) is shown together with three HGHG cases with different radiator length. All cases use the same electron beam and HGHG cases have been optimized in terms of seeding power and strength of the dispersive section to maximize the FEL output power. HGHG results show how for each length of the radiator it is possible to optimize the seeding in order to reach the maximum bunching within the length of the available undulator (Figure 2-c). Since shorter undulator requires stronger seed and hence a larger energy spread the absolute values for the maximum bunching and output

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power depend on the length of the undulator. However such dependence is less critical than in the simple amplifier regime.

Power vs Undulator Length

Results of HGHG numerical simulations in terms of maximum power as a function of the number of used undulators is reported in Figure 3-a. Results indicate an almost linear increase of power with the length of the radiator. The FEL saturation power [7] is reached by HGHG with about 8 undulators and longer radiators allow slightly exceeding the saturation power.

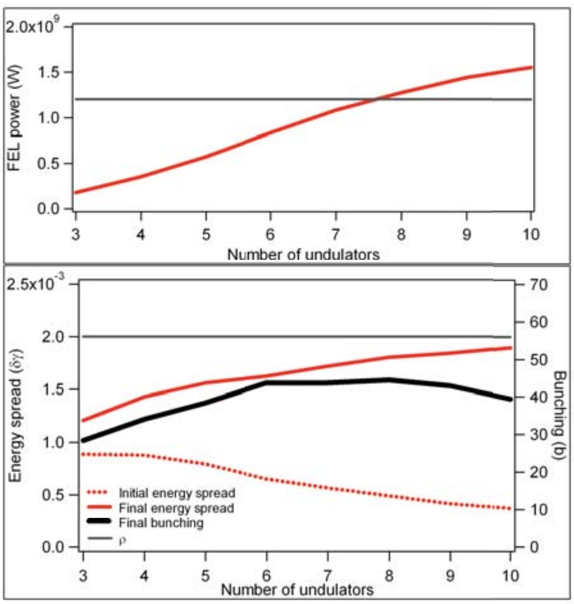

Figure 3: (a) Maximum power achievable from HGHG for the electron beam with 500 A of peak current as a function of the number of undulator used for the final radiator. (b) Final bunching (right axis, black line), and energy spread at the entrance and exit of the radiator (left axis, red dashed and continuous lines respectively) achieved in the conditions that maximize the output power. Data are plotter as a function of the number of undulator that constitutes the radiator.

Figure 3-b reports the energy spread of the beam at the entrance and ant the exit of the radiator (left axis) and the output bunching (right axis) for various length of the final radiator. As it has been anticipated, shorter radiators require a stronger seed that lead to a larger entrance energy spread. As a consequence of the higher initial energy spread the FEL process is less effective and the final power, energy spread and bunching are smaller for shorter undulators.

Generalization of the Results

In this section we report the results of additional simulations where the power as a function of the radiator length are studied for the three different cases characterized by different values of beam peak current. In order to be able to compare results obtained with different electron beams, for each current the HGHG power is normalized to the corresponding saturation power calculated with the M. Xie formula [8]. Similarly the length of the used radiators are normalized to the corresponding gain lengths obtained with Xie formula.

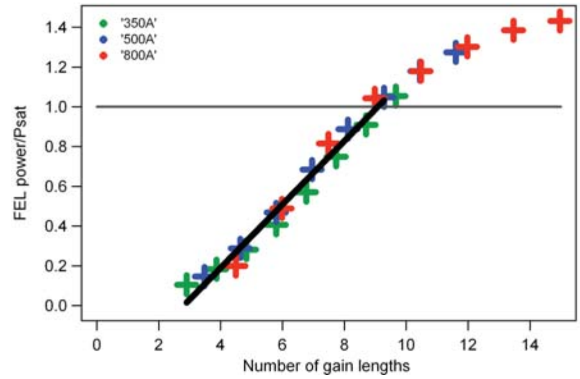

Figure 4: Maximum power normalized to the saturation power for HGHG with three different values for the beam current, 350A, 500A and 800A (green, blue and red respectively). FEL power is reported as a function of the length of the available radiator, length has been normalized to the FEL gain length.

Data reported in Figure 4 show that for HGHG the FEL power that can be produced from a given radiator only increases linearly with the length of the available radiator. In the particular case of FERMI that has been studied here this linear behavior is almost independent on the current of the electron beam.

Using the data corresponding to radiators that are from 3 to 10 gain lengths long, all results can be fitted with an unique linear function that express the power from HGHG (P_{HGHG}) as a function of the available length of the radiator (L_{rad}):

$$\frac{P_{HGHG}}{P_{Sat}} = 0.17 \cdot \left(\frac{L_{rad}}{L_g} - 2.5 \right). \qquad (1)$$

In Eq. 1 L_g and P_{sat} are the gain length and saturation power calculated for the electron beam under consideration.

Eq. 1 could be used to predict the expected power from an FEL in HGHG configuration using a given undulator whose length is larger than 3 gain lengths and shorter than 10 gain lengths.

Additional studies, not reported here, show that the same behavior of normalized power vs normalized undulator length is obtained using different electron beam. Electron beam with larger energy spread and or emittance has been studied with the undulator setup used here and results fit well with the curve presented here.

Reported results summarized by Eq. 1 could be useful in the design of FEL facility based on HGHG. Eq. 1 could be used for a quick estimation of the undulator length in the FEL performance and guide for the decision of the

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length for the radiator length with all the constraints (space, budget, …).

CONCLUSIONS

We report a study that shows the linear dependence of the maximum output power of an HGHG FEL on the length of the radiator. While for a given radiator length the power will still have quadratic or exponential growth along the undulator length, the final power that an HGHG FEL can produce depends only linearly on the length of the radiator. Using the standard FEL normalization a universal linear dependence of power as a function of the length has been found.

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