THE USE OF PHASE SHIFTERS FOR THE OPTIMIZATION OF FREE ELECTRON LASERS' PERFORMANCE

G. De Ninno, University of Nova Gorica, Slovenia and Sincrotrone Trieste SCpA, Trieste, Italy
E. Allaria, Sincrotrone Trieste SCpA, Trieste, Italy

Abstract

In single-pass Free Electron Lasers (FELs), for the amplification process to be effective, it is necessary to compensate the phase advance of photons with respect to electrons in the break region between undulator sections. In this work we present different methods for which the use of phase shifters can be useful for a further improvement of the FEL performance. As a specific example, we focus on the first stage of the FERMI@Elettra project.

INTRODUCTION

The FERMI@Elettra project is based on two seeded FELs and aims to cover the spectral range between 80 nm and 3 nm [1].

Based on the layout of the first FERMI FEL [2], named FEL-1, we investigate possible methods that use the phase shifters to improve the FEL performance. We show that a proper use of phase shifters may lead to an increase of the FEL output power, and also to an increase of the FEL harmonic content.

Our studies are based on numerical simulations using the FEL numerical codes Genesis and Ginger.

NEED OF PHASE SHIFTERS

High gain FELs normally require long radiators in order to allow the radiation to grow up to saturation. Usually, the required radiator length is of the order of several tens of meters. Such a long radiator are normally made of a chain of short undulators (few meters), separated by break sections where diagnostic, electron beam optics and vacuum equipments are placed.

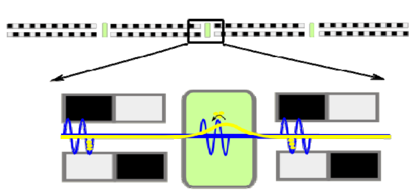

Figure 1: Sketch of a typical undulator chain for high gain FELs. Phase shifters (green box) allow controlling the slippage between electrons and the FEL radiation in the breaks.

Generally, and especially in the case of variable gap undulators, break sections contain phase shifters that are used in order to control the phase advance of the FEL radiation with respect to electrons when propagating through the free space of the break section (See Fig.1).

These devices are needed because, when passing through the dispersive sections, due to the different speed between electrons and light, electrons lag behind photons. The shift inside a single break reads:

$$\delta l \approx L_B \cdot \frac{1}{2\gamma^2}, \quad (1)$$

where L_B is the length of the break sections and gamma is the electron-beam relativistic factor.

The FEL resonance condition imposes that the FEL wavelength λ is given by:

$$\lambda \approx \frac{1}{2\gamma^2} L_w \cdot \left(1+k^2\right), \quad (2)$$

where L_w is the undulator period and k is the undulator parameter. From equations (1) and (2) it is easy to see that it is possible to properly choose the length of the break section in order that the phase advance in the break section is a multiple of the resonant FEL wavelength λ

$$L_B = N \cdot L_w \left(1+k^2\right) \quad (3)$$

However this is only possible given a fixed value for the undulator parameter *k*. In the case one considers undulator with a variable *k*, it is necessary to have in the break a phase shifter in order to be able to put in resonance the different undulators.

LAYOUT

As a case study, we consider the FERMI FEL-1 layout. The FERMI FEL-1 is based on a high gain harmonic generation (HGHG) scheme that starting from a seed laser in the UV (~200mm) aims at producing FEL radiation in the range between 80 and 20 nm.

Table 1: Electron Beam Parameters of the Studied FEL.

Electron beam parameter	Value	Units
Energy	1.2	GeV
Current	750	A
Emittance	1.2	mm mrad
Energy spread	150	keV

Table 2: Seed and Layout Parameters of the Studied FEL.

Parameter	Value	Units
Seed wavelength	200	nm
FEL wavelength	20	nm
Undulator period	55	mm
Undulator length	2.42	m
Number of undulators	6	-
Dispersive section	10-30	μm

The interaction between the seed laser and the electron beam that occurs in the modulator produces an energy modulation of electrons with the periodicity of the seed wavelength. As a consequence of this energy modulation, when passing thought the dispersive section (R56) the electron beam becomes density-modulated (bunched) at the period of the seed wavelength and also at its harmonics. A schematic view of the layout is reported in Fig.2.

In the case of the FERMI FEL1, a bunching of about 10% is expected also at the 10th harmonic.

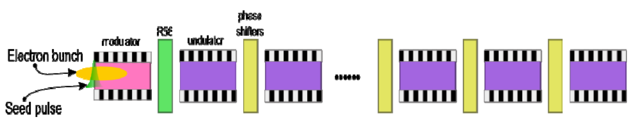

Figure 2: Sketch of the FEL1 layout.

As a consequence of this strong bunching, the electron beam start emitting coherently when entering in the final radiator, which is tuned to the desired harmonic of the initial seed laser. Due to the relatively strong bunching that is produced in the dispersive section, a radiator with only two undulator sections is sufficient to get more than 200 MW at 20 nm (See Fig. 3).

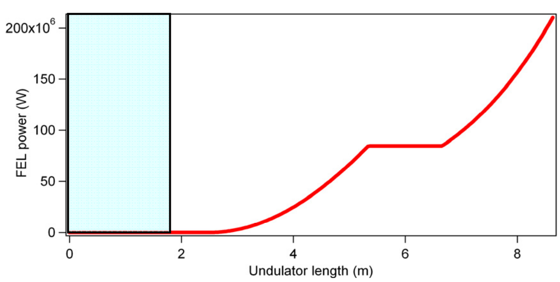

Figure 3: FEL power at 20nm with a short radiator. The shaded region is the dispersive section responsible of the conversion of energy modulation (created in the modulator) into bunching at the desired harmonic.

The use of longer radiators allows further interaction of the electrons with the emitted radiation. This increases the bunching and gives rise to the exponential growth of the FEL power till saturation.

OUTPUT POWER MAXIMIZATION USING PHASE SHIFTERS

Due to the transfer of energy from the electron beam to the FEL electro-magnetic field, electrons loose part of their energy (see Fig.4). As a consequence of this change in the electron beam energy, electrons may go out of the resonance condition given by Eq.2. This affects the FEL gain in the final part of the radiator, limiting the maximum output power (see blak curve in Fig. 5).

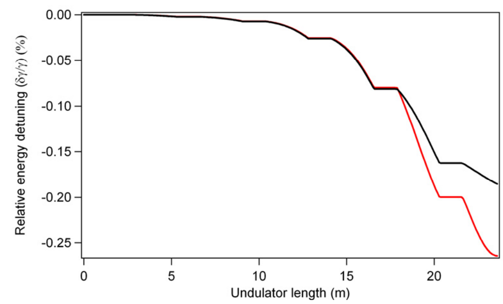

Figure 4: Electron beam energy evolution along the undulator. Energy is transferred from electrons to FEL radiation. After 15 meters, the electron-beam energy has changed of about 0.1% and starts to be out of resonance. The FEL performance may be improved by properly tuning the phase shifters between radiator sections (red curve)..

A possible way to maintain the resonance condition and improve the FEL performance is provided by the tapering, that is a suitable change in the undulator gap (*k* value) along the undulator axis in order to maintain the resonance condition. However, it has been recently pointed out that another possibility is offered by the use of phase shifters [3]. Indeed it is possible to compensate the phase delay accumulated by electrons in a radiator section due to the fact that they are slightly out of resonance, by properly setting the phase shifter.

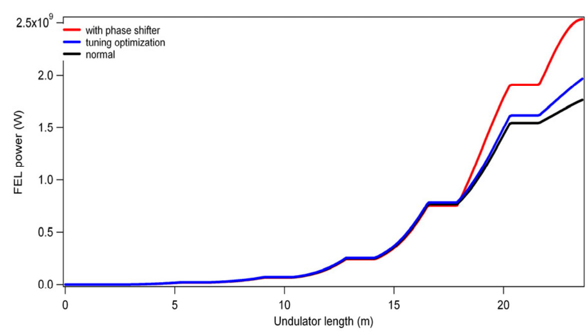

Figure 5: FEL power along the undulator for a standard radiator (black) and for a radiator with a proper set of the phase shifters (blue and red lines), in order to compensate the detuning.

This possibility of using the phase shifter is demonstrated by the results of the numerical simulations reported in Fig.5, where the output power along the final radiator is reported for three different configurations of the undulators and phase shifters.

The black line refers to the case where the radiator is set in order to provide the required resonance condition for the nominal electron beam energy. The blue line is obtained in the case one uses the tuning of the final radiator in order to partially compensate the decrease in electron beam energy. Finally, the red curve refers to the case where the phase shifters have been used to compensate the effect of the decreased energy.

Results clearly show the advantages of using phase shifters. It is also important to point out that the longer is the radiator, the stronger will be the benefit of using phase shifter corrections.

HARMONIC EMISSION MAXIMIZATION USING PHASE SHIFTERS

In addition to the use of phase shifters demonstrated in the previous section, it has been recently proposed to use phase shifters in order to enhance the harmonic content of the FEL emission. [4]. Although such a method requires operating the FEL in deep saturation, some benefit for the harmonic emission may also be found in FELs with shorter radiators, as the case of FERMI we are here considering.

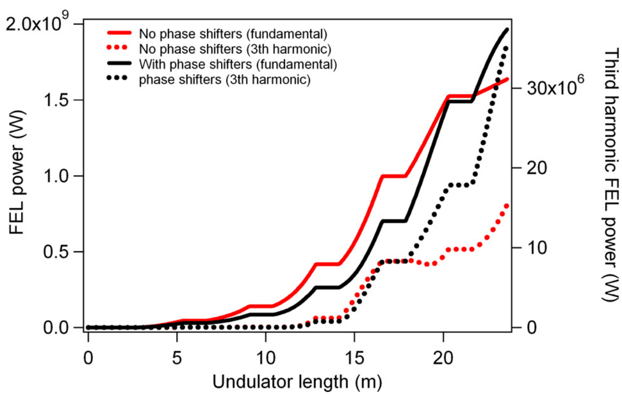

Figure 6: FEL power along the undulator for a standard radiator (black) and for a radiator with a proper set of phase shifts in order to compensate the detuning.

Figure 6 shows that also in the case of the FERMI FEL-1 with a relatively short undulator a factor two of improvement in the emitted third harmonic emission can be obtained.

In order to use phase shifters for improving the third harmonic emission, it is necessary to adjust the phases between consecutives undulator in order to put the harmonic radiation produced by the electrons in phase. It is important to point out that the phase correction has to be done when there is already a small bunching at the harmonic. Indeed the curves for the harmonic emission along the undulator for the standard case and with phase shifter corrections (black dashed line and red dashed line, respectively) are almost identical until 17 meters.

It is also important to emphasize that the optimal setting for the phase shifters that maximize the harmonic emission is different for the setting that maximize the fundamental. Indeed, the power at the fundamental obtained in the case reported in figure 6 is slightly lower than the one obtained in the case presented in figure 5.

CONCLUSIONS

We have shown how phase shifters can be used to improve the FEL performance and to enhance the harmonic emission. Results have been presented for the simple case of the FERMI FEL-1, using a relatively short radiator. More benefits can be expected in the case of FELs with longer radiators, as for the X-fel and LCLS.

The work was supported in part by the Italian Ministry of University and Research under grants FIRB-RBAP045JF2 and FIRB-RBAP06AWK3.

REFERENCES

[1] G. DeNinno, E.Allaria, this conference.
[2] C. Bocchetta et al., FERMI CDR (http://www.elettra.trieste.it/FERMI/index.php?n=Main.CDRdocument).
[3] D. Ratner, A. Chao, Z. Huang, FEL Conference 07, MOPPH023, p. 49 (2007).
[4] N.R. Thompson and B.W.J. McNeil, Phys. Rev. Lett. 100, 203901 (2008).