ESTIMATION OF UNDULATOR REQUIREMENTS FOR COHERENT HARMONIC GENERATION ON FERMI@ELETTRA

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Abstract

The FERMI project is devoted to the realization of a FEL user facility based on the principle of coherent harmonic generation (CHG). The advantages of such a method (with respect, e.g., to self amplified spontaneous emission) is that the output properties of the light are strongly determined by the interaction of the seed laser with the electron beam within the modulator undulator. In CHG FELs therefore, in addition to the requirements for the radiator where FEL radiation is produced, it is important to understand and satisfy the requirements for the modulator. In this work, we present a study focused on the first stage (FEL1) of the FERMI@Elettra setup. The study aims at providing an estimation of the undulator requirements in terms of magnetic field accuracy for both the modulator and the radiator.

The work is based on numerical simulations of the FEL1 using the numerical code GINGERH [1]. The required undulator tolerances have been obtained by means of a large number of simulation runs, taking into account different sets of undulator parameters.

INTRODUCTION

An important role in the CHG scheme [2] for FELs is played by the first undulator (modulator), which is the responsible for the production of the bunching necessary for the coherent emission in the forthcoming radiators. Within the modulator, the resonant electrons interact with the strong external field of the seed laser and an energy modulation on the electron bunch is produced. This coherent energy modulation is then transformed into bunching within the dispersive section. Finally, the bunched electrons enter the radiator and start emitting coherently initiating the FEL process. Similar to simpler FELs schemes, like e.g. self-amplified spontaneous emission (SASE) [3] or direct seeding [4], CHG require high quality undulators for the radiator. Moreover, FELs relying on CHG are expected to be quite sensitive also to the stability of the magnetic field on the modulator.

In the following, we will present the results of our studies, which aim at giving an estimation of the required accuracy for some of the undulator parameters, both for the modulator and the radiator. Continuing the work that has been initiated for FEL1 and FEL2 radiators [5], we performed a series of simulation runs of the FERMI FEL1 nominal setup where the AW parameter has been considered to have random fluctuations along undulators. Undulator errors have been generated by using the code XWIGERR [1], that allow to have also information about the main effects (i.e. electron beam trajectory and phase perturbation) that the considered errors on the magnetic field have on the electron beam when the latter passes through the undulator. Moreover, the use of XWIGERR allows one to generate undulator errors that take into account the fact that some preliminary corrections are possible. Indeed, during operations it is possible to partially compensate the trajectory errors induced by the undulator by centering the beam trajectory at the beginning and at the end of the undulator using beam correctors. Moreover, a shimming can be performed to the undulator in order to compensate configurations with too large phase or orbit errors.

A large number of simulations have been done in order to be able to distinguish the effect of different undulator properties on the FEL performance.

REQUIRED TOLLERANCES FOR THE MODULATOR

In the case of the modulator, instead of performing the complete FEL simulation (modulator, dispersive section and radiator), we only simulate the modulator and the dispersive section. As parameters of merit for evaluate the effect of undulator errors, we calculated the amount of bunching produced at the desired harmonic at the exit of the dispersive section. Tolerances have been estimated from the decrease of the bunching in cases with perturbed undulator with respect to the ideal case with a perfect undulator. We considered 10 % as a limit for the allowed decrease of the bunching due to undulator error.

FEL1 at 40nm

Between possible configurations at which the modulator should work, we here focus our attention to the one necessary for the production of a 40nm FEL output from the radiator, the sixth harmonic of the 240nm of the seeding. This configuration, which is necessary for reaching the nominal shortest wavelength of FEL1, is also the most critical due to both the high harmonic conversion and the short wavelength of the seed.

Simulations have been done using the setup that maximizes the output power at the exit of the radiator in the case of the ideal undulator. Fig.1 reports the results of more than 10000 GINGERH simulation runs of the modulator characterized by different AW errors. AW errors have been generated with XWIGERR considering

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different values for the rms fluctuation and different evolution of the undulator strength along the modulator.

The calculated bunching at 40nm at the exit of the dispersive section is plotted as a function of the rms AW error (Fig.1a), and as a function of the phase, position and tilt errors (Fig.1b,c,d respectively).

Considering 10% as a limit for the allowed bunching reduction, we obtain quite stringent values for the allowed RMS errors (AW<0.2%, phase<60mrad, tilt<50μrad; position <12μm).

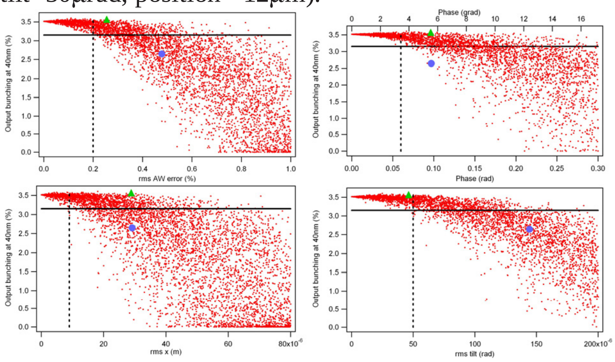

Figure 1: Produced bunching at 40nm at the exit of the dispersive section as a function of the rms AW error (a), rms phase error (b), rms position error (c) and rms tilt error (d). The green triangle and blue square refer to two AW error distributions with similar rms phase error (b). Corresponding evolution of the electron beam's phase, position and tilt along the undulator are reported in Fig.2 (b,c,d).

However, in order to correctly estimate the allowed errors for different quantities it is important to consider the complicated correlations that exist between them. As it is demonstrated by two cases reported in Fig.1 (green triangle and blue square), a similar rms phase error (see Fig.1 and Fig.2) can be originated by two AW random distributions with different rms values and with very different effect on the electron beam trajectories (tilt and position). The corresponding evolution of the phase error, the tilt and the position along the undulator for these two cases are reported in Fig.2.

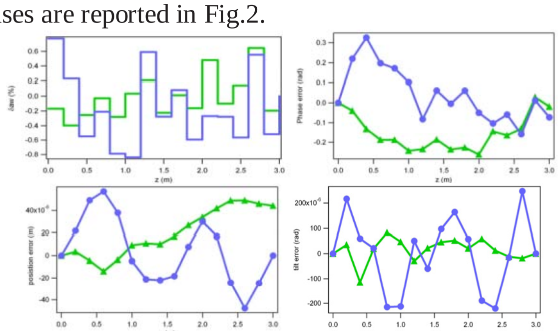

Figure 2: Evolution of AW along the modulator and corresponding position, phase and tilt errors for the electron beam passing through the undulator. Corresponding performance in terms of produced bunching for these two cases are reported in Fig.1 with equivalent colors and symbols.

As a consequence of this complicated correlation between quantities, a right estimation of the allowed errors has to be done in a multidimensional space and cannot be done considering them as independent variables.

Using multidimensional filter

As a consequence of the correlation, the requirements for the maximal error for the parameters are relaxed by about a factor two with respect to the values that one can estimate by considering the parameters separately.

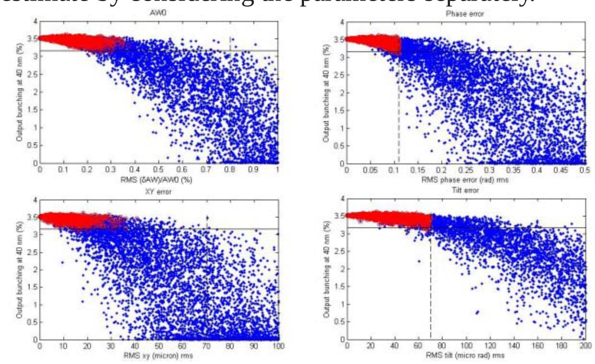

Figure 3: Reported data show how filtering the data in the 4D parameter space allow to relax the requirements for the undulator. In figure red dots refer to data corresponding to undulator error configuration whose errors in terms of AW phase, position and tilt are within the selected limits also reported in figures by vertical dashed lines.

Data in Fig.3 show that considering a set of requirements that has to be met by all the quantities at the same time can relax the requirements. As an example, we show that filtering the data with tilt<70μrad; position<70μm; phase<110mrad; AW<0.8% is sufficient to assure that the produced bunching is never decreased by more than 10% with respect of the bunching produced by the ideal undulator. It is important to note that there exist different combinations of limits that can guarantee the same result.

REQUIRED TOLLERANCES FOR THE RADIATOR

A similar study has been done also for evaluating the requirements for the undulators of the radiator. While the modulator is a single undulator, the FERMI radiator is composed by a sequence of at least six undulators separated by drift sections hosting the necessary electron beam optics and diagnostic. The FERMI undulator layout will allow correcting the electron beam orbit and the relative phase between electrons and radiation by using correctors and phase shifter present in the intra-sections. This has been considered in our simulations by generating partially compensated undulator field errors that almost eliminate the effects in terms of trajectory and phase at the exit of each undulator section. Two examples of considered undulator errors and its effects on the electron beam are reported in Fig. 4, where evolution of AW, phase position and tilt errors along the radiator are reported.

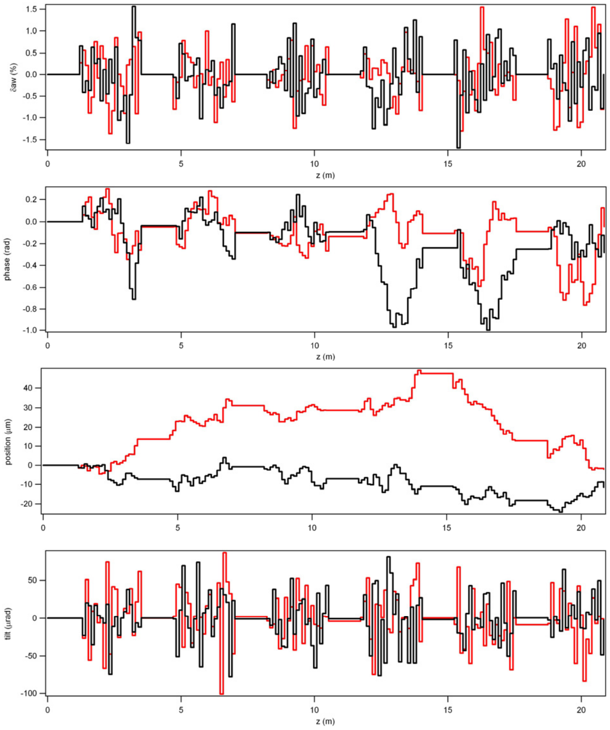

Figure 4: Two examples of the evolution of the undulator error AW along the radiator (a) and their effect on the electron beam in terms of phase (b) position (c) and tilt (d) errors.

Simulations have been done by using the setup that maximizes the output power at 40nm in the ideal case (no undulator errors).

Similarly to the case of the modulator, a large series of GINGERH simulations have been done in order to explore all the possible error configurations. The results are reported in Fig. 5, where the output FEL power is plotted versus the rms value of the AW (Fig. 5a), phase (Fig. 5b), position (Fig. 5c) and tilt (Fig. 5d) errors along the radiator. As for the case of the modulator, Fig. 5 report in red the results of those simulations whose errors are within some limits that have been fixed in order to limit the effect of the undulator error to only a 5% of power reduction with respect to the ideal case.

In particular we show that the effect of undulator errors in the radiator can be limited to only few percent if the electromagnetic field error distribution along the radiator has a rms value lower than 0.5% and its effect on the electron beam are characterized by a rms phase error lower than 0.12rad, a rms position error lower than 50μm and a tilt error lower than 50μm rad. As for the case of the modulator it is important to emphasise that the limits considered here is only one of the possible combinations that can guarantee the desired results.

It is also important to note that for the limits that we used for the results reported in fig. 5, the most stringent errors are those on the rms AW and phase. It is indeed evident that the respect of limits on AW and phase implies that the condition in position and tilt are largely satisfied. In fact, there are no red points with a rms position error larger than 25 μm and a rms tilt error larger than 30μm rad.

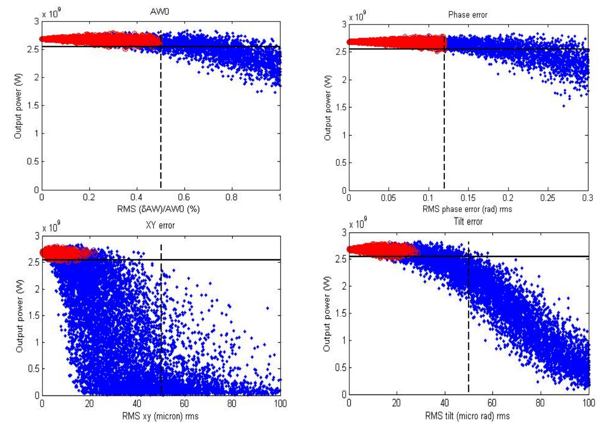

Figure 5: Reported data show how filtering the data in the 4D parameter space allow to relax the requirements for the radiator. Red dots refer to data corresponding to undulator error configuration whose errors in terms of rms AW, phase, position and tilt are within the selected limits (represented by the vertical dashed lines).

CONCLUSIONS

In this work we reported a study about the tolerance requirements for the undulators of the FERMI FEL. The presented results show that for a correct estimation of the tolerance requirements it is necessary to take into account the strong correlation between the different effects of undulator field errors.

By performing the multidimensional filtering of different errors we found that the requirements both for the modulator and the radiator can be met.

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