EFFECTS OF UNDULATOR STEERING ON FERMI@ELETTRA FEL

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Abstract

The extension of Free Electron Laser (FEL) operations to VUV and X-ray range places stringent requirements on the straightness of the electron beam trajectory along the undulator chain. The misalignment of magnetic active elements such as quadrupoles and undulators has a great impact on the beam trajectory. The FERMI FEL project foresees the adoption of the Beam Based Alignment (BBA) technique with open undulators to steer the electron beam on a straight path along the whole undulator chain. Quadrupole magnets will be centered on desired trajectory and steerer will be used to maintain that trajectory when quadrupole strengths are changed for different quadrupole polarization. Steering elements at the undulator edges counteract the steering action of strong focusing of the apple type devices restoring the correct trajectory between the undulators. This article analyzes the effect of this trajectory distortion on the FERMI FEL performance.

INTRODUCTION

The FERMI FEL project foresees the adoption of the Beam Based Alignment (BBA) technique [1, 2] to steer the electron beam on a straight path along the whole undulator chain. Initially, the BBA will be carried on with open undulators by means of steering magnets (correctors) and 1 μm resolution Beam Position Monitors (BPMs) inserted in the inter-module drift space; the algorithm to steer the beam will take into account the Earth magnetic field. Once the straight path is determined on the basis of the beam launching error, of the quadrupole misalignment and of all the errors generating the initial trajectory distortion, quadrupole magnets will be centered on it through remote micro-movers (in both transverse planes) so that no additional trajectory steering will occur when the quadrupoles will change their focal length for different undulator polarizations.

Once the undulators are closed to the nominal gap, they will contribute to the trajectory distortion in two ways. First, an error of the first field integral will be compensated by correction coils mounted at the undulator edges. Second, the focusing of the undulator traversed off axis induces an angular kick error. The relative displacement of the electron beam and of the undulators has two sources: first, the static alignment of the undulators with respect to the machine reference axis has a finite accuracy. Second and more important, the straight path determined by the BBA algorithm is not necessary on the same line of the machine reference axis. Simulations actually show that it is far from the linac axis by several 100’s micron and that it is dependent on the beam launching error and on the accuracy of the initial machine alignment.

The trajectory distortion induced by the closure of the devices can be observed and measured by successively closing each undulator and looking at the beam centroid position immediately downstream of it. In this way it is possible to calculate the device misalignment with respect to the electron beam path (averaged over the module length). If needed, this offset can therefore be compensated by means of undulator micro-movers. The vertical movers are already part of the Fermi undulator design, since they will have a tunable gap. As for the horizontal plane, we foresee to use the correction coils associated with the undulators: as mentioned before, they are devoted to the compensation of the dipole field component of the device. Then, assuming this additional trajectory correction, the beam path (in both transverse planes) inside the device will be different from a rectilinear path but the beam position and divergence at the device edges will be the same as for the unperturbed case.

TANAKA CRITERION

The Tanaka’s criterion characterizes the FEL process degradation in terms of radiation efficiency and bunching smearing. In general, the trajectory distortion induced by the undulators is proportional to their offset relative to the beam straight path. If the electrons travel on a segmented trajectory in the undulator chain, they accumulate a phase slippage with respect to the radiation by reducing the bunching efficiency of the FEL process. At the same time, the transverse coupling with the radiation in the undulator is corrupted. Finally, the perturbation can be interpreted as a lengthening of the FEL gain length, a reduction of the bunching coefficient and as a reduction of the FEL power [3].

If θ is the kick angle error perturbing the electron beam trajectory in the undulator chain, then the FEL power will be reduced according to:

$$P \sim P_0 e^{-\vartheta^2 \frac{\Delta z}{\lambda}} \qquad (1)$$

where Δz is the longitudinal distance over with the correction is applied, typically equal to two undulator modules. With growth in the exponential regime, the power reduction is equivalent to a lengthening of the gain length:

$$L_g^{'} = L_g \frac{1}{1-\left(\vartheta/\vartheta_c\right)^2}, \quad \vartheta_c = \sqrt{\frac{\lambda}{L_g}} \qquad (2)$$

In a similar way, the bunching smearing generated by the phase slippage of electrons and photons is described by:

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$$|B(z)| \sim |B(z_0)| \frac{\Delta z}{2L_g^{"}} \qquad (3)$$

The new gain length is given by:

$$L_g^{"} = L_g \frac{1}{1-\pi\left(\vartheta/\vartheta_c\right)^2} \qquad (4)$$

One can notice that the efficient gain length given in (4) is a stronger constraint than that in (2). Moreover, the relative decrement of the bunching coefficient in (3) has a linear dependence on $\frac{\Delta z}{L_g}$, while the power is exponentially decreasing with the same coefficient $\vartheta^2 \frac{\Delta z}{\lambda} \sim \frac{\Delta z}{L_g}$. This means that the stronger constraint between these two comes from the power reduction that is the physical effect one is interested into, at the end.

The Tanaka's treatment of such a perturbation concerns a single kick angle provided by one undulator module and all the consequences are extended by generality to the whole SASE FEL process. This means that the Tanaka's critical angle can be taken, in a more realistic picture, as the rms kick angle error calculated over all the kicks along the undulator chain.

GENESIS SIMULATIONS

The formulas (1) – (4) were evaluated for the FERMI FEL1+ configuration at two different wavelengths: the 40 nm case foresees a nominal gain length of 1.2 m (θ_c=183 μm); the 20 nm case foresees a nominal gain length of 1.5 m (θ_c=115 μm). The distance Δz already defined in (1) was set to 5 m (the length of about two radiator modules). A strong constraint was set on the efficient gain length, on the power reduction and on the bunching smearing: the first one must not to lengthen more than 10%, the second and the third one must not to reduce more than 10%. As a result, the kick angle error was calculated satisfying all these conditions; the results are listed in Table 1.

As expected, the minimum kick angle error is given by the constraint on the power reduction. From a conservative point of view, we can say that a ratio $(\vartheta/\vartheta_c) < 1/5$ ensures a power reduction <10% for whatever FEL configuration and further smaller perturbations in terms of all the other parameters. More in general the ratio ϑ/ϑ_c expressed through the power reduction is given by:

$$\frac{\vartheta}{\vartheta_c} \cong \sqrt{\frac{L_g}{\Delta z}|\ln x|} \qquad (5)$$

where x=P/P$_0$ that is the relative power reduction specified a priori. The FEL wavelength dependence is implicit in the definition of the gain length. Since all the single pass linac based FELs presently existing have their characteristic parameters in the same or very close orders of magnitude, it comes out that, according to the Tanaka's criterion, a reduction of 50% of the FEL power is provided by a ratio ϑ/ϑ_c in the range 1/1.5 – 1/2.5.

Simulations of the kick angle error provided by a single radiator in several FERMI FEL configurations were performed including the realistic focusing properties of the device. The vertical polarization was considered since it is the shows the most perturbing effect on the beam trajectory. A beam launching error was set and the beam propagated through the undulator. The kick angle error induced by the undulator was then compared with the critical angle for that specific FEL configuration. The results are listed in [4], where a threshold $(\vartheta/\vartheta_c) = 1/5$ was defined according to the prescriptions discussed above.

Time independent simulations were carried on for the FEL1+ at 60 nm case because it is the most critical configuration [4]. The BBA algorithm [1] was repeatedly applied to Fermi to construct a statistic and to find the average launching conditions of the beam straight path with respect to the linac axis. Finally, a GENESIS particle tracking simulation was performed assuming x_0=200 μm and x_0'=12.5 μrad (see Figure 1, solid line).

Table 1. Simulations of the particle tracking through one FERMI FEL radiator with realistic focusing and misalignment of the device provided the ratio of the single kick angle to the critical angle for several FERMI FEL configurations.

FEL configuration	**θ_c [μrad]**	**θ/θ_c**
Fel1 100nm	300	1/6
Fel1 40 nm	189	1/19
Fel1+ 60nm	256	1/4.5
Fel1+ 20nm	130	1/15
Fel2 40nm	211	1/5
Fel2 10nm	77	1/19

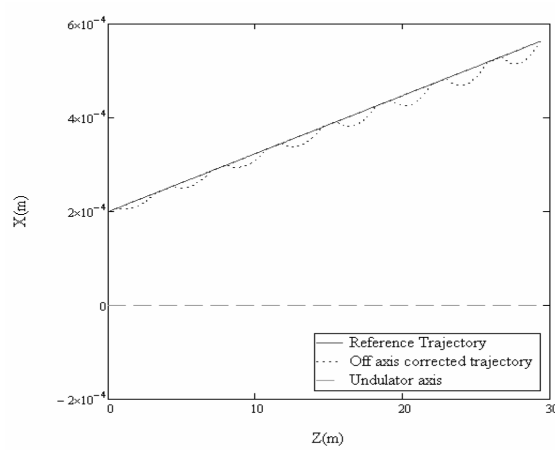

Figure 1. Electron beam straight path constructed through the BBA algorithm (solid line) with pessimistic launching condition. The realistic beam trajectory (dotted line) is affected by distortion inside the undulators.

Quadrupole magnets located between the radiators were moved onto this reference trajectory with the accuracy of a few microns, such as they were moved by micro-movers. The residual trajectory oscillation inside the undulators is shown by the dotted line in Figure 2. To compensate for the trajectory distortion induced by the radiators, the correction coils were used to perform small trajectory bumps with angular kicks in the range 15 – 50 μrad along the undulator chain.

For simplicity the simulation does not foresee undulators randomly placed around the linac axis; in fact, they remain exactly on it (see Figure 1, dashed line). Since the maximum distance of the real electron beam trajectory from the undulator magnetic axis is predicted to be about a few 100’s micron, this constraint was taken into account by adopting the pessimistic launching condition listed above. In the end, the electron beam displacement from the devices axis is in the range 200 – 565 μm.

The evolution of the FEL radiation properties are plotted in Figure 2 and Figure 3. Figure 2 shows that the off axis motion of the electrons with respect to the undulator magnetic axis makes the FEL to saturate at a lower power level. Nevertheless, the FEL resonance condition is mismatched because the off axis motion induces a different K (undulator parameter) distribution along the undulator chain with a resulting tapering effect. This tapering stops the bunching phase at the saturation level (see Figure 2, solid line) so that the power tends to grow even after the saturation point. If the tapering effect is excluded, that is the K values are re-matched for each device, then the total power loss is approximately 20% with respect to the unperturbed case. We want to stress out the excellent agreement between this result and the analytical prediction of the Tanaka’s criterion for FEL1+ at 60 nm for which a factor $\vartheta/\vartheta_c = 1/4.5$ corresponds to a power loss of about 22%.

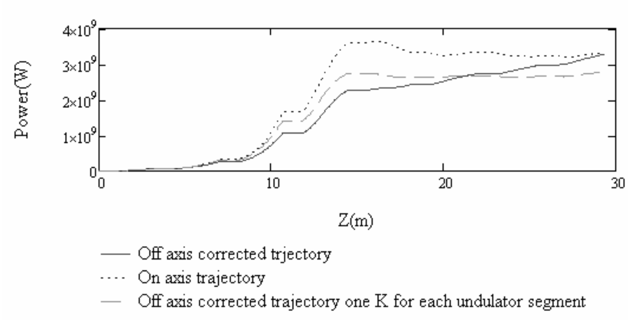

Figure 2. FEL peak power along the FEL1+ radiator chain for 60 nm wavelength. The off axis motion of the electrons with respect to the undulator axis (see Figure 2, dotted line) produces the power behavior represented by the solid line. If the tapering effect is excluded, power loss for the off axis case is approximately 20% with respect to the unperturbed case.

Another series of time independent simulations were carried out by placing all the radiator segments at a fixed distance from the reference electron beam trajectory; they are shown in Figure 3. The tapering effect was compensated by a proper adjustment of the K parameters.

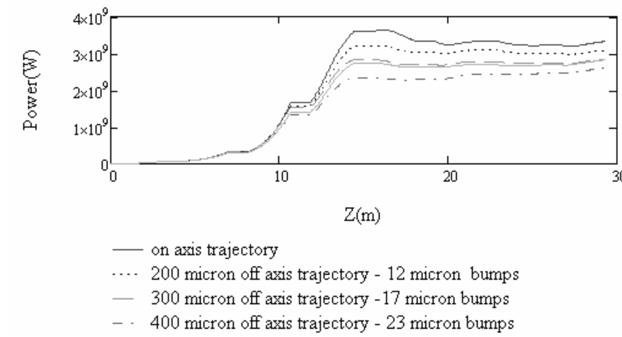

Figure 3. Power evolution along the undulator chain of FEL1+ at 60 nm for a beam reference trajectory parallel to the devices.

CONCLUSIONS

The Tanaka’s criterion applied to the trajectory distortion induced by the undulators traverse off axis in the vertical polarization predicts a power loss of the FEL radiation less than 10% for all the Fermi FEL configurations in the wavelength range 10 – 100 nm, with the exception of about 20% power loss for FEL1+ at 60 nm. Time independent GENESIS FEL simulations confirm for this prediction in absence of tapering and without re-positioning of the undulators. These satisfactory results were achieved on the basis of several constraints on static machine alignment, measurement reliability, accuracy and stability of the systems involved. In particular, a static transverse alignment of the quadrupole magnetic axis of 50 μm rms was assumed. Then, the quadrupoles have to be moved in the transverse planes with an rms accuracy<2 μm and with lateral displacement in the ±1 mm range. The stability of their magnetic axis in the full range of the applied focusing strengths is expected to be <5 μm rms.

The undulator correction coils were used to compensate for the device first and second field integral, the magnetic Earth field and mainly to compensate for the trajectory distortion induced by the undulator focusing when it is traversed off axis. Their maximum kick is specified by 50 μrad. The cavity BPMs are expected to provide a measurement accuracy of 3 μm rms with 1 μm rms resolution. Their electric axis should be determined with an rms accuracy <10 μm. The required static alignment of the undulators in the horizontal plane is 50 μm rms over the whole undulator chain.

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