ORBIT CORRECTION BY DISPERSION MINIMIZATION IN AN UNDULATOR WITH SUPERIMPOSED F0D0 LATTICE

P. Castro, DESY, 22603 Hamburg, Germany

Abstract

A procedure to align the beam in the FEL undulator of the TTF superconducting linear accelerator at DESY is presented. In order to achieve a high density electron beam, quadrupoles made of permanent magnets are integrated into the undulator. Due to quadrupole misalignments (of less than 50 μm), the spatial overlap of the photons being emitted and the electron bunch will be perturbed, limiting the interaction between each other and reducing the photon power amplification (or gain) of the FEL.

The procedure described in this paper consists of measuring the change of the orbit along the undulator and also at monitors upstream of the undulator for an electron beam energy change of about 20%. The orbit position and angle at the entrance of the undulator are kept constant in order to measure the dispersion created by quadrupole misalignments and field errors in the undulator. The dispersion measured, which is independent of BPM offset errors, is corrected using horizontal and vertical corrector magnets (coils). Simulation results are presented, showing that a corrected orbit rms of 12 μm (averaged over 10^4 random seeds) can be achieved assuming an orbit measurement resolution of about 1 μm rms.

1 INTRODUCTION

The Free Electron Laser (FEL) of the TESLA Test Facility (TTF) [1] is based on the principle of Self-Amplified Spontaneous Emission (SASE) [2, 3]. This process requires a very high particle density of the electron bunch which is achieved with small transverse beam emittances provided by the TTF superconducting linac and small β functions in the undulator. The undulator of the TTF-FEL (with a 14 m length for phase I) contains a superimposed F0D0 lattice made of permanent quadrupole magnets. Quadrupole misalignments deflect the electron beam, limiting its interaction with the photons being emitted and reducing the photon power amplification (or gain) of the FEL. Simulation studies [4] indicate that the rms deviation of the electron beam from a straight line has to be around 10 μm at least over the length of one undulator module (4.5 m). This is beyond the absolute precision of the Beam Position Monitors (BPM). The procedure described in this paper consists of measuring and minimizing the beam dispersion at the BPMs of the undulator.

2 DISPERSION MINIMIZATION

Quadrupole misalignments and undulator field errors deflect the beam trajectory and introduce beam dispersion. The method proposed in this paper is based on the minimization of measured beam dispersion using corrector magnets located in the undulator and upstream. We use the Micado algorithm [5] to find a set of corrector strengths $\{c_j\}$ which minimize the beam dispersion $\{d_i\}$ observed at the BPMs

$$\psi^2 = \sum_{i=1}^{N_{\rm mon}} \left(d_i + \sum_{j=1}^{N_{\rm corr}} a_{ij} c_j \right)^2 \qquad (1)$$

where $N_{\rm mon}$ and $N_{\rm corr}$ are the number of monitors and correctors. The corrector matrix coefficient a_{ij} is the calculated beam dispersion at BPM i introduced by corrector j. In linear transfer lines, the correction matrix is triangular, i.e., $a_{ij} = 0$ for a corrector j located downstream BPM i.

The Micado algorithm uses the method of "best correctors" to search for a set of correctors strengths that minimizes ψ (if $N_{\rm corr} < N_{\rm mon}$) or make it zero (otherwise). Eventually, a reduced set is obtained by either specifying the maximum number of correctors to be used or giving a maximum value for ψ.

3 THE TTF-FEL UNDULATOR

In the TTF-FEL phase I, an undulator of 14 m long [6] will be installed at the end of the accelerator section of the TTF. The TTF will provide a beam energy of 390 MeV with first tests and a proof-of-principle experiment at 300 MeV. The undulator is subdivided into modules of about 4.5 m length. The undulator creates a sinusoidal field of 0.5 T peak value with a period of $\lambda_u = 27.3$ mm. The focusing structure of the FEL is provided with ten quadrupoles per module with alternating focusing gradients (F0D0 cell). The quadrupoles are $5\lambda_u$ long with a gradient of $g = 12.5$ Tm^{-1} [7]. The length of the F0D0 cell is $35\lambda_u$ (955.5 mm).

For the correction of the electron orbit a BPM and a corrector magnet per quadrupole will be integrated into the vacuum chamber of the undulator. The undulator gap of 12 mm constrains dramatically the geometry and design of BPMs and correctors. The BPM block consists of two pairs of electrodes (or waveguides) and has a length of about 10 cm. Correctors are made of four wires 30 cm long which can be powered independently to provide a horizontal or/and a vertical dipole field.

4 CORRECTOR CONFIGURATION

Based on simulation results published in [8], the efficiency of dispersion minimization using Micado algorithm is improved with one horizontal corrector every focusing quadrupole and one vertical corrector every defocusing quadrupole (vertically focusing). The advantages over a configuration with both vertical and horizontal correctors every quadrupole are: the corrected orbit rms is in average 30% smaller; the average corrector strength rms needed is reduced by a factor two; finally, the minimization of dispersion is obtained in only one iteration.

Simulations at 300 MeV including quadrupole position errors with a flat random distribution between -50 and 50 μm result in a corrected orbit rms of 8 μm (average over 10^4 seeds).

5 TOLERANCES ON BPM AND UNDULATOR ERRORS

The BPM resolution and dipole field errors in the undulator have also been included in the simulation. The resolution of the BPMs which will be installed in the undulator is expected to be about 1 μm. The accuracy of beam dispersion measurements depends on the BPM resolution as well as on the ΔE applied. Both magnitudes are varied in the simulation which results are shown in Fig. 1. Undulator field errors are around $\Delta B/B = 4 \cdot 10^{-4}$ rms. Dipole field errors with a Gaussian distribution are included in the simulation. Shimming of undulator field errors has been applied to the set of random dipole errors generated in the simulation. Both integrals

$$\int_o^{n\lambda_u} B(s)\, ds \qquad \text{and} \qquad \int_o^{n\lambda_u} \left(\int_o^s B(z)\, dz \right) ds$$

are evaluated over a certain number n of period lengths of the undulator. Both integrals are compensated by adding dipole fields on both ends of the segment $n\lambda_u$. Both parameters $\Delta B/B$ and n are varied in the simulations. Results of corrected beam orbit rms are shown in Fig. 1.

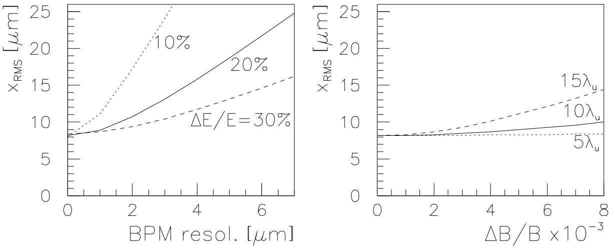

Figure 1: Left: Corrected beam orbit rms (averaged over 10^4 random seeds) versus BPM resolution for $\Delta E/E$ =10%, 20% and 30%. Right: Corrected beam orbit rms versus undulator field error for integral correction every 5, 10 and 15λ_u.

For BPM resolution of 1 μm a $\Delta E/E$ of around 20% is needed. The effect of undulator field errors of $\Delta B/B = 4 \cdot 10^{-4}$ rms on the corrected beam orbit can be tolerated if dipole errors are compensated on intervals of 10λ_u or less. For the error values given above, beam orbit rms of simulating the dispersion minimization are in average about 9 μm.

6 BEAM ERRORS

In the simulation results presented above the beam position and dispersion are zero at the entrance of the undulator. The beam orbit correction in the first module is affected when beam position offset and non zero dispersion are introduced in the simulation. An example of dispersion minimization including a beam position offset of 0.5 mm at the entrance of the undulator is shown in Fig. 2. The corrected orbit in the first module is affected by the initial beam position. A similar effect occurs with non zero dispersion at the entrance of the undulator.

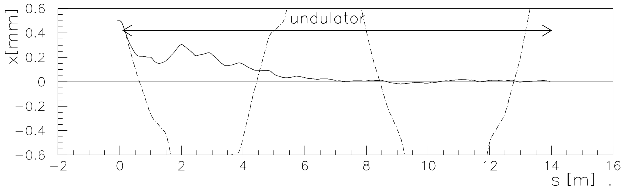

Figure 2: Beam orbit along the undulator before (dashed line) and after (full line) dispersion minimization in presence of a beam position offset of 0.5 mm at the entrance of the undulator.

One solution is to apply the dispersion minimization to the beam line upstream of the undulator. However, the TTF beam line between the last accelerating module and the undulator is very short and there is no physical space to place series of quadrupole-BPM-correctors.

In this paper we have investigated a procedure to fix the beam trajectory (both its position and angle) at the entrance of the undulator during the change of beam energy in order to ”mask” the incoming beam dispersion. Thus, the ”dispersion” observed at the undulator is only the dispersion originated in the undulator which is then minimized and the orbit corrected. A minimum of two BPMs and two correctors are still needed at the beam line upstream of the undulator.

7 THE COMPLETE METHOD

Non-zero beam dispersion at the entrance of the undulator can be ”masked” by fixing the beam position and the angle of its trajectory, which changes (due to beam dispersion) with beam energy. For that two BPMs and two correctors are needed at the beam line between the last accelerating module and the undulator. This beam line has been designed to match the β functions of the accelerating modules to the undulator. It has also to provide the right phase advance between the spoilers and absorbers of the collimation system for the undulator [9]. The layout of quadrupoles, BPMs and correctors of this beam line are shown in Fig. 3.

The complete procedure has the following steps:

1. Measure beam position in all BPMs.
2. Reduce beam energy (by e.g. 20%).
3. Reduce magnetic fields (same 20%) between BPM 1 and 2 (see Fig. 3).

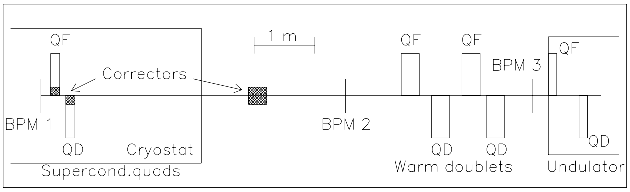

Figure 3: Layout of quadrupoles, BPMs and correctors between the cryostat of the last accelerating module and the undulator.

4. Measure beam position at BPM 1 and 2 to get Δx_1 and Δx_2. Since quadrupole and corrector fields are decreased by the same percent as the energy change, the transfer matrix (m_{ij}) between BPM 1 and 2 remains unchanged. Then, the change of the angle of the beam trajectory can be calculated:

$$\Delta x'_2 = \frac{m_{22}\Delta x_2 - \Delta x_1}{m_{12}}$$

Both Δx_2 and $\Delta x'_2$ are independent of BPM offsets.
5. Use the correctors between BPMs 1 and 2 to correct Δx_2 and $\Delta x'_2$.
6. Measure beam position in the undulator to get $\{d^*_j\}$ which is the "dispersion originated in the undulator".
7. Find the corrector strengths $\{c_j\}$ to minimize $\{d^*_j\}$ as described in Section 2.
8. Change back to previous beam energy and quadrupole and corrector fields and apply $\{c_j\}$

The correctors between BPMs 1 and 2 play two roles: mask the incoming beam dispersion and align the beam trajectory to the undulator. Both functions are explained in the following.

On one hand, these correctors fix the beam trajectory at BPM 2 using the procedure described above. Thus, the beam trajectory remains unchanged at BPM 2 during the beam energy change and the incoming beam dispersion is therefore masked. On the other hand, these correctors determine the beam trajectory at the entrance of the undulator. If the beam trajectory is not aligned to the undulator, then the beam is not centered at the quadrupoles and dispersion is generated. The correctors upstream of the undulator will minimize this dispersion by aligning the beam trajectory at the entrance of the undulator. In other words, the measured dispersion $\{d^*_j\}$ is minimized with the correctors strengths in the undulator and the initial beam parameters x and x' (which are determined by correctors upstream of the undulator).

An example of orbit simulation using this procedure is shown in Fig. 4. The initial beam position is 0.5 mm.

8 SIMULATION RESULTS

Simulations of beam orbit correction by the method described above including the errors listed in Table 1 were performed for a beam energy of 300 MeV and a $\Delta E/E = 20\%$. The corrected beam orbit rms along the undulator averaged over 10^4 random seeds is 12 μm.

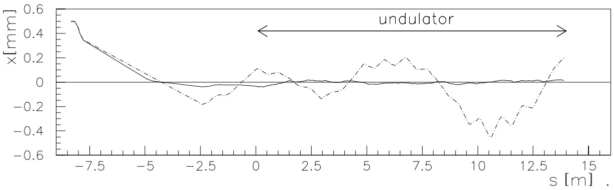

Figure 4: Simulation of orbit before (dashed line) and after (full line) dispersion minimization of a beam trajectory fixed at BPM 2.

Table 1: Errors included in orbit correction simulations

In the undulator:	
Quadrupole offset	$\leq \pm 50$ μm
BPM resolution rms	1 μm
Undulator field error rms	$\Delta B/B = 4 \cdot 10^{-3}$
Field integrals correction	10 λ_u
At the undulator entrance:	
s.c. quad. offset	$\leq \pm 500$ μm
Warm quad. offset	$\leq \pm 200$ μm
Cold BPM resol. rms	10 μm
Warm BPM resol. rms	1 μm
Beam position rms	2 mm
Beam dispersion rms	5 mm

9 CONCLUSIONS

A method to align the beam trajectory in the TTF-FEL undulator is presented. The method is based on dispersion measurements and is completely independent of BPM offsets. Result of simulations including quadrupole misalignments, BPM resolution (both at the undulator and at the beam line upstream) and undulator field errors show that a beam alignment of about 10-15 μm rms can be obtained, which provides a good overlap between electron and photon beams for the FEL. Although the method consists of a single correction iteration, a 2nd or 3rd iteration may be needed due to scaling errors in BPMs and correctors. The effect of beam energy errors will be simulated.

This method will be tested at the TTF linac this year and at the TTF-FEL in 1999. Based on this experience a future application of this method to TESLA will be studied.

10 REFERENCES

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