Design and Performance of the TESLA Test Facility Collimation System

H. Schlarb, DESY, D 22603 Hamburg, Germany

Abstract

To perform a proof of principle experiment of a SASE based Free Electron Laser operating at wavelength between 70-160 nanometer a 15 m long permanent magnet undulator has been installed in the TESLA Test Facility (TTF) linac phase 1. The type of magnets used (NdFeB) is known to be sensitive to radiation damages if exposed to high energy electrons. Already beam losses in the order of 10^{-6} of the nominal TTF beam current (64μA) are critical for the undulator and can cause an irreversible damage of its magnets after a few months of operation. To protect the undulator against radiation a two stage spoiler-absorber collimation system has been implemented to the beamline in front of the undulator. In this paper the design and the performance limits of the collimator system are presented.

1 INTRODUCTION

In summer 99, three permanent magnet undulators, each 4.5 m long, have been installed in the TTF superconduction acceleration linac. Investigations on the radiation threshold of the NdFeB magnets predict 1% reduction of the magnet remanent field at an absorbed dose of about 70 kGy deposited by charged particles with energy above 20 MeV [1]. Since the electron beam is accelerated in the linac to energies between 180 MeV and 300 MeV (nominal 230 MeV) critical dose values can be collected in the permanent magnets during very short time periods (hours) in case of operation with the nominal beam current (64μA). To protect the undulator, an active and a passive protection system have been developed. The active system, based on beam loss detectors with sufficient high sensitivity interrupts the beam operation in case of improper beam transport [2]. However, caused by non-linear space charge forces in the TTF photoinjector a large beam halo is created which can induce losses in the undulator while operating the FEL in optimum conditions [1]. In this case, the linac is not operable with an active protection system alone and the average beam current has to be reduced to a small fraction of the design value. In order to remove the halo electrons with large betatron motion a collimation section, 5.5 m in length, has been installed upstream the undulator.

To increase the SASE gain, the beam is focused in a FODO-cells structure along the undulator with strong permanent magnet quadrupoles superimposed to the alternating dipoles. Because the phase advance along the undulator is larger than 90° (50° per cell at 230 MeV) electrons with large offset or large angle have to be removed. Thus, two collimators in a proper phase advance are required to confine the transverse phase space such that the undulator cannot be hit by electrons of the beam. At an energy of 230 MeV, the transverse phase space acceptance of the collimator and the undulator are shown in Fig. 1. Electrons within the phase space acceptance of the aperture system, i.e. the two collimators, or the vacuum chamber of the undulator, pass through while electrons outside the acceptance hit the aperture. Hence, in linear optics calculation the plot shows that all electrons passing the collimator section also pass the undulator modules. However, towards higher energies the beta function of the undulator increases and its acceptance phase space starts to shrink. The collimator diameters are chosen to allow beam operation also at 500 MeV energy, original planned during TTF phase 1.
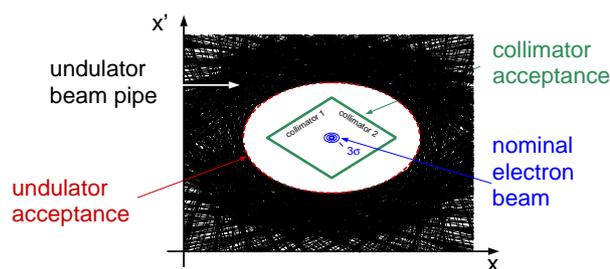

Figure 1: Phase space acceptances of the collimator and undulator at 230 MeV (x-direction).

2 BASIC COLLIMATOR LAYOUT

In Figure 2 a scheme of the collimator section is shown. The collimators determining the phase space acceptance are called spoiler, while the collimators dedicated to remove secondary particle produced at the spoilers are called absorbers. The spoilers with diameter of 6 mm are separated by a 2.5 m long drift space. They are made from aluminum to reduce the probability for crack in the material if the beam incidents head on. The copper absorbers are located in the shadow of the spoilers and thus, cannot be hit directly by the beam. The largest clearance between the collimated beam (the part of the beam passing the spoilers) and the undulator vacuum chamber is achieved if the optics has a phase advance of 90° between the spoilers and simultaneously matches the periodic solution of the FODO-cell in the undulator. For that, four quadrupoles Q1 to Q4 are required to properly adapt the collimator phase space acceptance to the acceptance of the undulator. Caused by the energy dependence of the undulator transfer function, the quadrupole strength have to be adapted to the beam energy in a non-linear way, while the optics upstream the collimator is energy independent. The beta-functions in neighbourhood the collimator section are shown in Fig. 3.
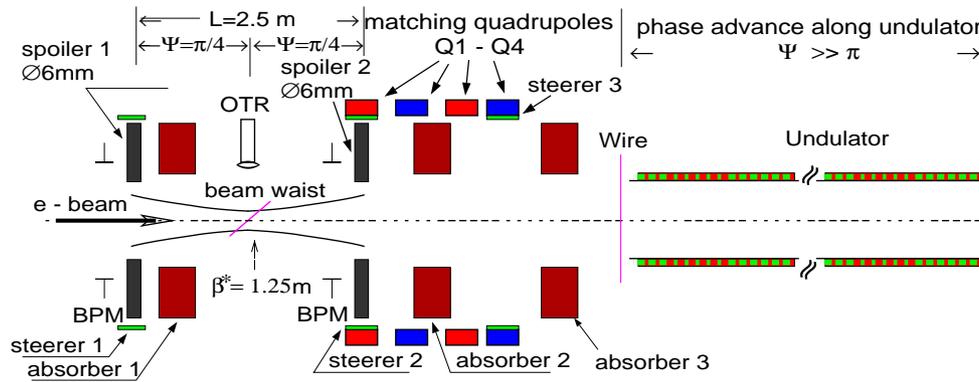
Figure 2: Basic layout of the collimation section.

To guarantee the operability of the collimation section several diagnostic components and correction magnets have been foreseen. Two beam position monitors in front of the spoilers which have been aligned with high precision ($< 200\,\mu$m) to the geometical centers of the spoilers allow the proper positioning of the beam in the collimator drift section. The beam profile can be imaged with a CCD camera by inserting an optical transition radiation screen (OTR) at the beam waist. For a $5\,\mu$m normalized emittance beam, typically measured in the photoinjector, the collimation takes place at 18σ in x and y direction. The relaxed collimation allows an accurate measurement of the beam Twiss-parameter by scanning upstream quadrupole currents (quadrupole scans). Secondary emission photomultipliers usable at high radiation levels control the beam losses at the collimators and interrupt beam operation in case of improper injection. Beam deflections due to quadrupole
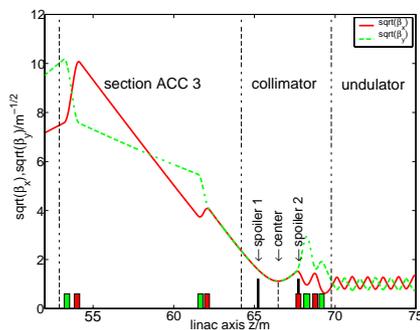

Figure 3: Optics at the collimator section (230 MeV).

displacements can be corrected in both planes by dipole correctors (steerer 2&3). Due to space limitations the correctors are implemented as additional yoke coils at the first and the last matching quadruple.

All collimators are tapered to reduce the contribution of wake fields due to the geometrical changes in the beampipe diameter.

The tolerable beam losses at the collimators are limited by neutron production to about 0.6% of the nominal beam current at 230 MeV. The water cooling system of the spoilers

has been designed for 2% beam losses. All collimators are temperature controlled.

3 PROPERTIES OF THE COLLIMATOR

The properties and limits of the collimation system has been determined by tracking calculation. For simulations, a gaussian distributed particle input ensemble with transmission probability of 50% through the spoilers is chosen (ϵ^N/γ=1.4 μm). The undulator has been modelled by hard-edge magnets including higher order magnetic fields and field errors i.e. geometric aberration of the undulator focusing, octupole field components in the superimposed quadrupoles. Particles are tracked until they hit an aperture. Cylindrical and elliptical tapers of the collimators are taken into account. The obtained loss distribution of the primary particles is used, in a second step, to calculate the initiated electromagnetic showers in the collimator and the undulator section to determine the energy depositions in the various materials as well as in control dosimeter distributed along the beamline.

Studies have been performed concerning the energy bandwidth of the collimation, the sensitivity on quadrupole displacements and gradient errors, displacements of collimator elements, clearance to the absorbers, influence of the spoiler diameter and the reduction of the energy bandwidth due to alignment errors. The most important results are summarized below. Tracking studies of the dark current emitted from the TTF rf gun is presented elsewhere [3].

3.1 Energy Bandwidth

In case of mono-energetic input distribution (230MeV) and perfectly aligned devices, the clearance of the collimated beam to the undulator vacuum chamber with a radius of 4.75 mm amounts to 1.1 mm (23% tolerance). Chromaticity of the matching quadrupoles reduce the clearance for off-energy particles. If the energy deviation becomes too large particles are lost. The fraction of the collimated beam hitting the undulator chamber as a function of the energy deviation at different beam energies is shown in Fig. 4. The blue area shows the operation condition with

full transmission through the undulator, called the energy bandwidth of the collimation system. The maximum width of 18% is at 250 MeV. For smaller or larger energies the bandwidth reduces, i.e. to 5% at 150 MeV. During proper FEL operation the energy tails of the nominal beam covers a range between -3% and $+1\%$, sufficiently small to guarantee the protection of the undulator. Outside the energy bandwidth, i.e. in the green area, 1% of the collimated beam is lost and the protection of the undulator becomes incomplete. If one assumes that 0.1% of the beam current accounts to a beam halo as simulated by the input ensemble, then typically 10^{-5} electrons of the beam would be lost in the undulator. In this case, the active protection systems would already stop the operation. In the yellow and white area the collimator efficiency is very poor. In particular, toward negative energy deviations ($\triangle E/E < 0$), this regimes are rapidly reached. Dark currents with a different time structure than the regular electron beam are not detected by the active protection system. In presence of low energy tails significant doses can be induced (see [3]). The energy bandwidth is limited due to chromaticity in the vertical plane (by Q2). Therefore, energy depositions induced by off-energy electrons mainly appear close to the vertical focusing quadrupoles in the undulator.
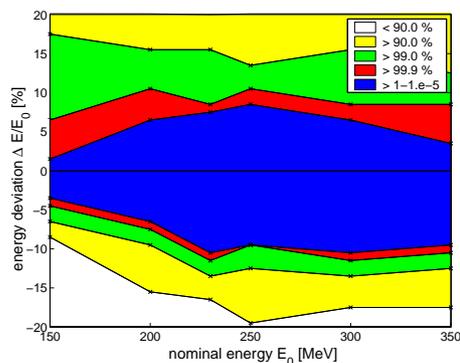

Figure 4: Energy bandwidth of the collimation system.

3.2 Quadrupole Displacements

Dipole kicks due to quadrupole displacements shifts the orbit of the collimated beam with respect to the undulator acceptance. For an input distribution with $\sigma_E/E = 1\%$ and displacements applied to each quadrupole individually 400 μm offsets in horizontal direction and 200 μm in vertical direction are tolerable. If rms-displacements of 200 μm applied to all quadrupoles in both directions simultaneously then in average 10% of the collimated beam is dumped in the undulator. The survey group could align the quadrupole to this value, which is insufficient to protect the undulator. Therefore, the steerers superimposed at the quadrupoles have to be used to correct the orbit through the matching quadrupoles. Proper steerer currents have been found at 230 MeV by beam based alignment using the FEL output as a reference for a proper orbit in the undulator [1].

3.3 Secondary Efficiency

Secondary particles produced at the spoilers which escape the absorber system contribute to the absorbed dose in the undulator and limit the tolerable beam losses in the collimation section. By Monte Carlo simulations using EGS4 [4] the removal efficiency for secondary particles is determined to be 99.83%. Thus, 0.17% of the energy incident on the spoilers is dumped in the undulator. The energy deposition in the dipole magnets and the dosimeters along the undulator at different vertical position ($x \equiv 0$) are shown in Fig. 5. The plotted dose values are normalized to 1 kJ beam energy incident on the spoilers. Most of the secondary particles are low-energy photons and the shower initiated hereby does not penetrate into greater depth. Therefore, the dosimeters located on the vacuum chamber ($y = \pm 7$ mm) overestimate the doses in the undulator magnets. The calculated removal efficiency limits the losses at the spoilers to 1% if 1000 hours beam operation is assumed.
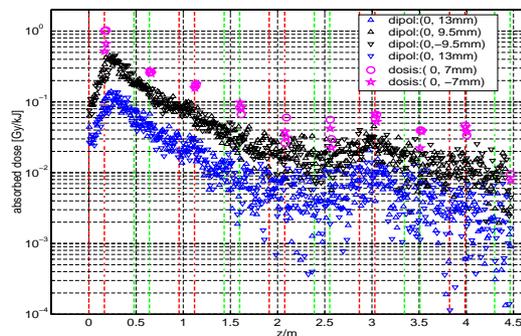

Figure 5: Absorbed dose along the first undulator module.

4 SUMMARY

The basic principle, the layout and the optics of the collimation system is presented. The results of tracking simulations to determine the energy bandwidth and the sensitivity on displaced quadrupoles are discussed. The calculation demonstrate that the collimation system with proper settings to correct for quadrupole offsets protects the undulator against electrons of the regular FEL beam. The production of secondary particles at the spoilers limits the acceptable beam losses in the collimators to 1%, about 3 to 4 orders in magnitude higher than acceptable primary beam losses in the undulator.

5 REFERENCES

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