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Contents

The TESLA Test Facility FEL: Specifications, Status and Time Schedule

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Abstract

The TESLA Test Facility (TTF) FEL is a user facility under construction at DESY in Hamburg. The radiation wavelength will reach 6 nm at a power level of several GW, not including the planned higher harmonic radiation generated in a 1 to 1.5 meter long radiator. Specific to the FEL are the low emittance photo injector gun, the bunch compressors, and the undulator with integrated FODO lattice.

Introduction

The TTF-FEL project will be built in two stages [1]. The first stage, which is already under construction, has as main purpose to test the different (FEL specific) components, such as low-emittance injector, bunch compressors and undulator. In addition, it will be the first proof of principle of Self Amplified Spontaneous Emission (SASE) in this wavelength range. For phase two of the project, both accelerator and undulator will be extended to go down in wavelength to 6 nm. In this configuration the machine will be employed as user facility. The peak brilliance of the radiation delivered to the user is shown in Fig. 1. Note its increase compared to existing synchrotron sources by several orders of magnitude.

Major research efforts for the FEL

A large number of subjects is under investigation in order to improve and characterize the performance of the TTF FEL. They can be sub divided in to several areas.

- Make/preserve low emittance. For the FEL process, the beam emittance and energy spread have to be as small as possible along the entire beam

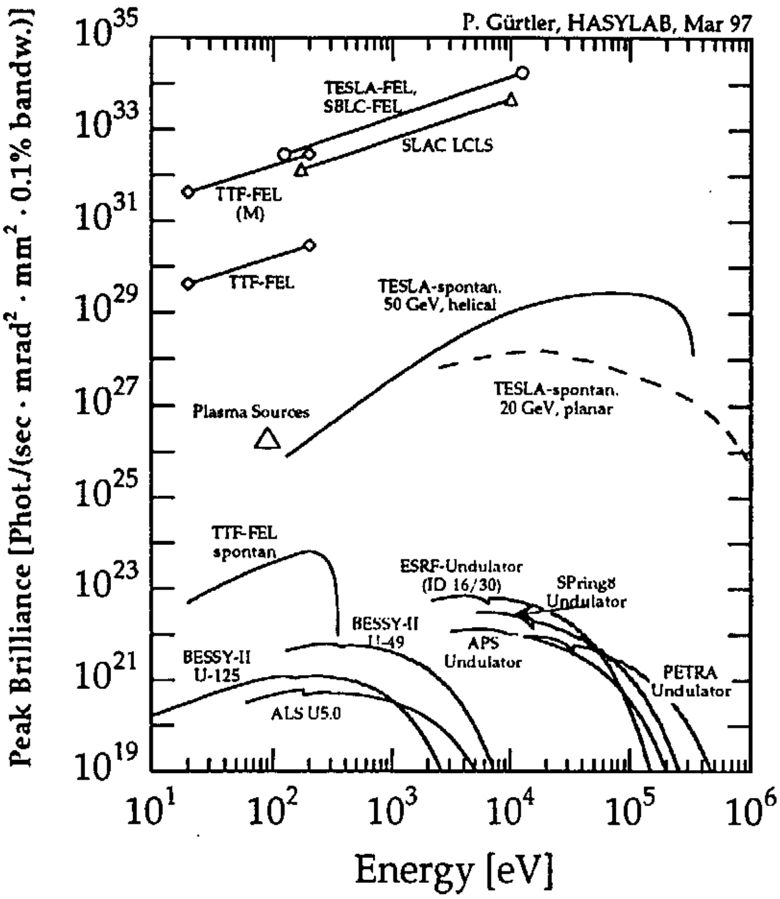

Figure 1: *Peak brilliance of different FELs and synchrotron sources.*

line Because the influence of the electron gun and the several bunch compressors in the entire system are the main source of emittance growth, they have been studied in detail [2, 3].

- Coherence/monochromaticity properties of the SASE FEL radiation. For certain types of experiments, the spectral characteristics of the FEL output radiation, e.g. the bandwidth and/or spikes, needs to be improved. Studies have shown that this can be done by using a two stage undulator. The first undulator is used to generate radiation at low power, which is then monochromatized. The electron beam is debunched and amplifies the small bandwidth radiation in the second undulator. The spectral peak brilliance increases approximately by two orders of magnitude (see

Table 1: *Parameters of the TTF VUV-FEL*

	Phase I	Phase II
Electron beam		
Energy	390 MeV	1 GeV
Peak current	500 A	2500 A
Normalized rms emittance	2π mm mrad	2π mm mrad
rms energy spread	0.17 %	0.1 %
External β-function	1 m	3 m
rms electron beam size	57 μm	55 μm
Undulator		
Type	Planar	Planar
Period	27.3 mm	27.3 mm
Peak magnetic field	0.497 T	0.497 T
Magnetic gap	12 mm	12 mm
Undulator section length	4.5 m	4.5 m
Total undulator length	15 m	30 m
Drift section length	327.6 mm	327.6 mm
FODO-lattice		
Period	955.5 mm	955.5 mm
Quadrupole length	136.5 mm	136.5 mm
Quadrupole strength	18.3 T/m	18.3 T/m
Radiation		
Period	42 nm	6 nm
Saturation length	13.5 m	21 m

in Fig. 1 TTF-FEL (M)) [4].

- Electron beam diagnostics. A specific problem for a single pass, high-gain FEL, is the tight tolerance on the electron beam alignment. Several methods have been proposed to measure and correct the beam trajectory. One of them is beam based alignment, in which several beam position monitors along the undulator are used to measure the dispersion of the electron beam trajectory which is then corrected, resulting in a straight trajectory [5, 6]. Another method uses the undulator radiation emitted by the electron beam under a small angle. A pinhole camera placed off-axis measures the radial dependence of theis radiation and determines the complete trajectory, from which corrector settings are calculated [7].
- Photon beam diagnostics. Although some aspects, such as the energy loss spectrum of the electron beam, give information about the interaction process that has taken place, most information is obtained from measurements of the photon beam properties. In order to determine what kind of

amplification process has taken place, one has to measure both power and spectral properties of the radiation field. For users it is important to know what the properties of the radiation is that they use for their experiments, such as spectrum, peak power and its fluctuations, etc.

Time schedule of the Project

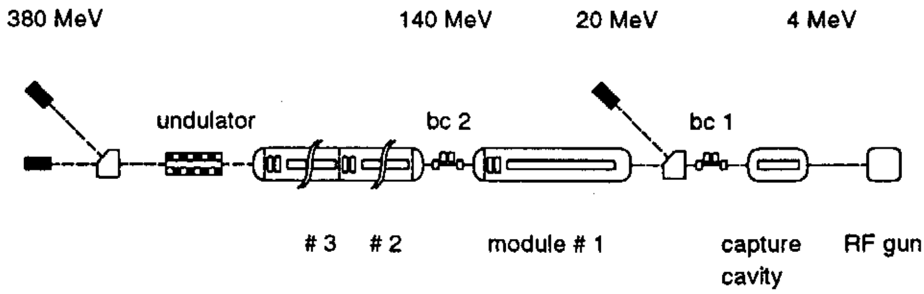

Figure 2: *Layout of phase I of the TESLA Test Facility FEL at DESY*

Phase I of the project, used for the proof of principle of the SASE process and for testing of the different components and procedures, will take the next two to three years. The year 1997 is planned for testing the first accelerator module with a thermionic gun and first magnetic measurements of a prototype of the undulator. The next year is planned for the entire accelerator with a high charge photocathode gun. At the end of that year and the beginning of 1999, the FEL gun will be installed, as well as the undulator. In this configuration, given in Fig. 2, the first FEL tests will be performed. For the final user facility, the accelerator will be extended with five additional accelerator modules, one additional bunch compressor and the undulator length will be doubled.

References

[1] *A VUV Free Electron Laser at the TESLA Test Facility: Conceptual Design Report*, DESY TESLA-FEL 95-03, Hamburg, 1995.

[2] B. Dwersteg, K. Flöttmann, J. Sekutowicz, Ch. Stolzenberg, *RF Gun for the TESLA VUV Free Electron Laser*, Presented at the FEL96 Conference, August 26-31 in Rome, Italy.

[3] M. Dohlus, T. Limberg, *Emittance growth due to Wakefields on Curved Bunch Trajectories*, Presented at the FEL96 Conference, August 26-31 in Rome, Italy.

[4] J. Feldhaus, E.L. Saldin, J. Schneider, E.A. Schneidmiller, M.V. Yurkov, *Possible Application of X-ray Optical Elements for Reducing the Spectral Bandwisth of an X-ray SASE FEL*, to appear in *Optics comm.*, August first 1997.

[5] P. Castro, *TTF Beam Based Alignment by Dispersion Correction using Micado algorithm*, DESY TESLA-FEL 97-04, Hamburg, 1995.

[6] K. Flöttmann, B. Faatz, E. Czuchry and J. Roßbach, *Beam Based alignment Procedure for an Undulator with Superimposed FODO Lattice*, DESY TESLA-FEL 97-05, Hamburg, 1995.

[7] J.S.T. Ng, *A Beam Trajectory Monitor using Spontaneous Undulator Radiation*, DESY TESLA-FEL 96-16, Hamburg, 1995.

[8] J. Feldhaus, Private communications.

Studies for a Beam Trajectory Monitor for TTF-FEL at DESY

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Abstract. A beam trajectory monitor for the FEL at the TESLA test facility at DESY has been proposed for the reconstruction of the electron beam trajectory by observing the spontaneous undulator radiation along the beam using the pinhole camera principle. Simulations for this concept have been performed and results are presented here.

INTRODUCTION

For the successful running of a SASE (self amplified spontaneous emission) FEL one of the keypoints is to guarantee a good overlap of the electron and photon beam along the undulator. Photons usually travel on a straight line but the electrons don't because of imperfections of the magnetic components – undulator dipoles as well as focusing quadrupoles. Therefore the requirement for good overlap can only be fulfilled if the electron beam trajectory is corrected to bring it close to the straight line defined by the photon beam. Simulations have shown that in the case of the TTF-FEL at DESY [1] a gain of approximately 100 % can be achieved if the deviation (rms) of the electron beam from a straight trajectory is below 10 μm [2]. To achieve this tight constraint the current approach for the TTF-FEL is to equip the undulator modules with beam position monitors and correctors [1,3]. As the absolute position of these components is not known beam based alignment correction algorithms have been proposed [4]. They use only the relative position information within each monitor. The idea behind is that a dispersion free trajectory is in first order a straight line. But the electron trajectory itself is not measured directly with this method. Therefore a new type of monitor has been proposed, a beam trajectory monitor (BTM), that can be used to reconstruct the beam trajectory [5,6]. With this information the necessary corrections to bring the electron beam on a straight trajectory can be defined.

The basic idea of this BTM concept is to observe the spontaneous undulator radiation from the electron beam with a pinhole-type camera along the undulator. That means only a single detector setup is needed for each undulator module. As sensitive detector behind the pinhole a silicon pixel detector with two columns of 12 pixels each is foreseen. The boundary between the two columns serves as an absolute reference for the straight electron beam trajectory. By combining one camera in the horizontal and one in the vertical direction the position of the electron beam can be reconstructed (for details of the concept see [5,6]). Simulations for certain keypoints of the concept as the radiation signal or systematic effects on position reconstruction have been performed. Results are presented here.

SIGNAL: PHOTONS FROM THE SPONTANEOUS UNDULATOR RADIATION

As a first step the signal, that means in this case the spontaneous undulator radiation, has to be estimated according to the active area and the energy sensitivity of the BTM. The angular range that is covered by a detector of a single camera lies between 0.33 mrad and 1.36 mrad in the direction off axis (that gives information about the longitudinal position) and ±0.5 mrad on axis in the direction that measures the deviation from the nominal beam axis (see fig. 1 in [6]). To keep diffraction effects as small as possible an energy filter is used. It is transparent for energies above 150 eV whereas the first harmonic of the undulator radiation is at about 20 eV varying slightly for different angles. Although the spectrum of the undulator radiation is well known in the range of the first harmonic, that means the low energy part of the spectrum emitted close to the undulator axis, detailed knowledge of the high energy spectrum far from the axis – that is exactly what is necessary here – is not available. Therefore the amount of signal has to be estimated from simulations. Two approaches have been used:

1. The photon flux has been derived with the help of the widely used Bessel function approximation. It is based on the solution of the general radiation equation in the far field approximation. To derive the flux the contributions from the harmonics has to be added up:

$$\frac{d^3 I}{d\Omega\left(\frac{d\omega}{\omega}\right) dI_B} = 4.55 \cdot 10^{16} \gamma^2 N_U^2 \sum_{n=1}^{\infty} F_n(\theta, \phi) \left(\frac{\sin N_U \pi \frac{\omega-\omega_n}{\omega}}{N_U \pi \frac{\omega-\omega_n}{\omega}}\right)^2 \qquad (1)$$

   with I: photon flux, Ω: unit solid angle, ω: frequency of the undulator radiation, I_B: the electron beam current, $\gamma = E/m$ where E and m are the energy and mass of the electron, N_U: the number of undulator periods, F_n: compositions of the Bessel functions [5,7].
   For the numerical calculations, the package URGENT [7] has been used.

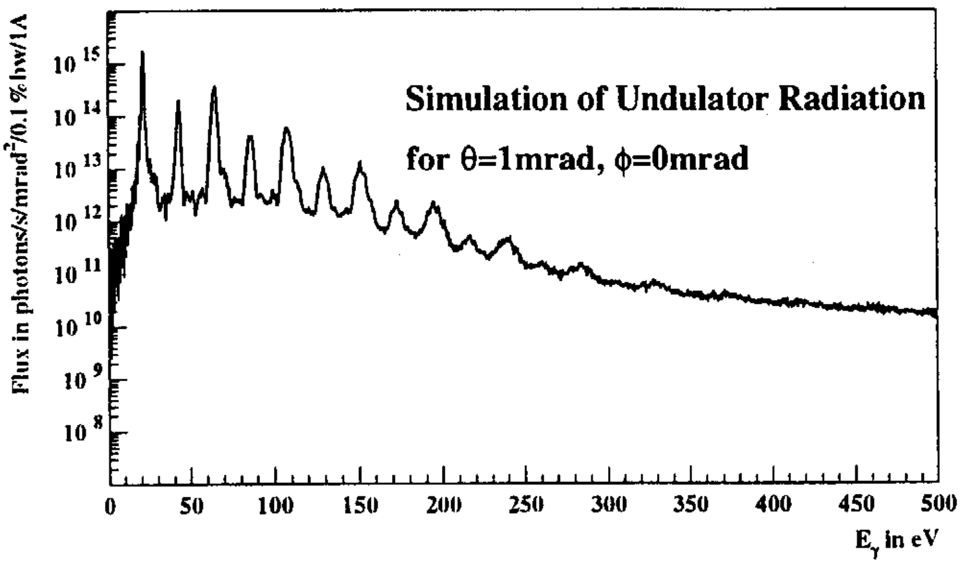

FIGURE 1. Spectrum of the undulator radiation at the angle $\theta = 1\,\text{mrad}$ and $\Phi = 0\,\text{mrad}$ using the simulation program UR [8]. The angle corresponds to an intermediate longitudinal position where the electron beam is on axis. TTF-FEL phase I parameters have been used.

2. The other possibility is to calculate the trajectory for each electron and derive the electromagnetic field from the interaction of the electrons and the magnetic field in the undulator at discrete points along the trajectory. The photon spectrum is the result of a discrete Fourier transformation of this electromagnetic field and a summation for all electrons. The simulation is based on the program UR [8]. One example spectrum at a specific angular position is given in fig. 1.

The spectra of the two approaches have been compared. The peaks of the harmonics agree well but in-between the harmonics the Bessel function approximation is set to zero whereas for the discrete Fourier transformation approach there is also intensity between the harmonics. Also in the high energy region (for energies larger than 300 eV) the level for the second approach is higher than for the first one. Taking these effects into account the discrepancy of the integrated flux that is relevant for the measurement for the two approaches lies in the range of only 10 %. For estimates of the total signal for the different detector pixels see [5]. The amount of signal seems to be high enough for the proposed measurement.

SYSTEMATIC EFFECTS ON THE POSITION AND TRAJECTORY RECONSTRUCTION

Going the next step from the signal to the position measurement, the center of gravity of the undulator radiation emitted from all electrons in a certain longitudinal range can be detected in one pixel row on the detector. No information on the shape of the radiation distribution is measured. Therefore it is very important that the center of gravity of the undulator radiation can be directly related to the center of gravity of the electron beam. Two major effects that might destroy this direct relation have been studied:

1. As the electron beam has a finite width ($\sigma_x \approx 50\,\mu$m [1]) one has to make sure that the angular distribution of the undulator radiation is flat over the full width of the beam and the corresponding angular range. From the simulation of the undulator radiation it has been derived that the distribution is sufficiently flat because of the very small pinhole acceptance, so that the offset between the center of gravity of the undulator radiation and the center of gravity of the electron beam is negligible.

   The variation of the angle with the longitudinal range and the associated variation in the spectral density of the undulator radiation is not critical for the measurement of the center of gravity. It only influences the weighting of different longitudinal areas for one active pixel row.

2. As the undulator radiation for a single electron has to be calculated with respect to the electron direction, divergence or convergence effects of the beam have to be taken into account. For extreme conditions just at the focusing and defocusing elements the shift between the reconstruction of the center of gravity of the undulator radiation compared to the one for the electrons has been estimated to be less than $\pm 1\,\mu$m. As in reality the measurement averages over a certain longitudinal range the effect will be even smaller.

By combining the measured points of all pixel rows the electron beam trajectory can be reconstructed. A simulated trajectory before and after correction is shown in fig. 2. Realistic errors for the magnetic field along the undulator have been assumed [4]. The positions determined with four BTM setups along the whole undulator are overlayed for the trajectory before correction.

CORRECTION PROCEDURE

Having measured the electron beam trajectory without any corrections (see fig. 2) one can start now to apply a correction algorithm to bring the electron beam as close as possible to a straight line. A simple algorithm has been used as a first step. The parameters for quadrupoles and correctors have

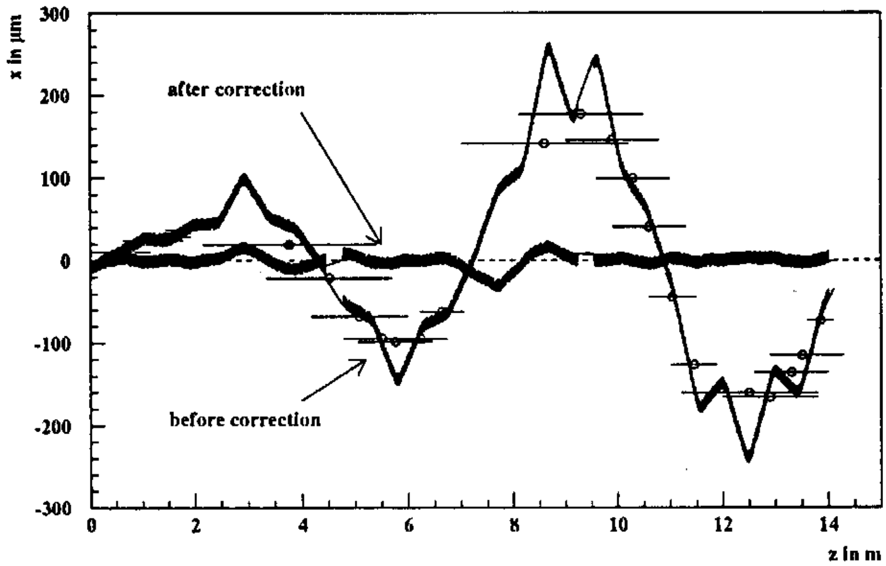

FIGURE 2. Simulation of an electron beam trajectory together with the measured points before correction and the trajectory after the correction algorithm. The rms values of the trajectory are 115 μm before and 9 μm after the correction procedure.

been taken from [3,4]. One corrector after the other is adjusted by looking at the measured point that follows the corrector. The best corrector setting is found when the measured point is closest to the nominal beam axis. It is an iterative procedure but usually reaches the requirement of the rms smaller

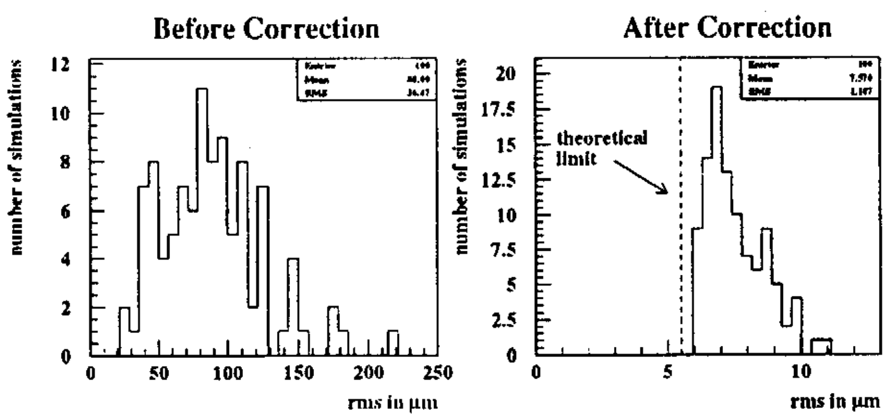

FIGURE 3. Rms values for the electron beam trajectory in the x-plane before and after correction for 100 different error configurations.

than 10 μm already after the second iteration. In fig. 2 an example for a track before and after correction is given. The x coordinate where one can see the wiggling in the undulator is shown. The theoretical limit of the rms because of this wiggling is 5.5 μm. The simulation has been repeated for 100 error configurations. The rms values before and after correction are shown in fig. 3. The rms mean values are 88.0 μm before and 7.6 μm after three iterations of the correction procedure. 98 out of the 100 rms values lie below the requested limit of 10 μm after the correction procedure.

More sophisticated correction algorithms should improve the procedure but already with this simple concept the result is satisfactory.

A big advantage compared to the beam based alignment correction algorithms is that with this BTM the trajectory of the electron beam is actually seen and that the straight line that one wants to have the electrons on is defined by the detector itself.

SUMMARY

Simulations for a new BTM concept proposed for the TTF-FEL at DESY have been presented concentrating on the signal, systematic effects on the position reconstruction and a first simple correction algorithm. The results look promising. A prototype of this BTM is under construction and is supposed to be tested in TTF-FEL phase I.

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REFERENCES

1. TTF-FEL Conceptual Design Report, TESLA-FEL 95-03, DESY, June 1995; J. Roßbach *et al.*, Nucl. Instrum. and Methods **A375** (1996) 269.
2. B. Faatz *et al.*, TESLA-FEL 96-13, presented at the FEL'96 conference August 26-13,1996 in Rome, Italy.
3. B. Faatz, The SASE-FEL at the TESLA Test Facility at DESY, these proceedings.
4. B. Faatz, Beam based alignment for the TTF-FEL, these proceedings.
5. J. S. T. Ng, TESLA-FEL 96-16, DESY (1996).
6. J. S. T. Ng, these proceedings.
7. R. P. Walker and B. Diviacco, Rev. Sci. Instrum. **63 (1)** (1992) 392.
8. R. J. Dejus, Nucl. Instrum. and Methods **A347** (1994) 56.

A Beam Trajectory Monitor for the TTF-FEL*

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Abstract. A method to determine the electron beam trajectory inside a long undulator module is described. Three-dimensional information is obtained by imaging the spontaneous radiation off-axis using pinholes and high resolution position sensors. The proposal for such a monitor for the SASE-FEL at the TESLA Test Facility is discussed.

INTRODUCTION

A bright light source with coherent radiation reaching the X-ray range can be created by sending a bright electron beam through a long undulator. This single-pass free electron laser relies on the Self-Amplified Spontaneous Emission (SASE) mechanism which results from the electron bunch interacting with its own radiation from the undulating motion. In order for SASE to take place, the electron and the photon beams trajectories must overlap. Because of the imperfections in the undulator magnets and mis-alignments in the focusing quadrupoles, the average electron beam trajectory tends to deviate from the straight path followed by the photon beam. This deviation must be detected and then corrected using steering coils inside the undulator.

A SASE-FEL operating in the range of 6 nm - 70 nm is under construction at the TESLA Test Facility (TTF) at DESY [1,2]. In the initial stage (TTF-FEL phase-1), the electron beam energy will be in the range of 300 MeV to 500 MeV. Each undulator module is 4.5 m long with a magnetic gap of 12 mm. The beam position inside the undulator will be measured by capacitive pickup-and/or waveguide-type monitors (BPMs), and a beam-based alignment procedure will be used to find the dispersion free trajectory [2]. This approach has the advantage of relying on proven technology, but also the disadvantage of requiring a large number of high precision BPMs (one per 0.5 m) which inevitably translates into cost.

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In this paper, we describe a new method to determine the beam position inside long undulator modules [3]. The off-axis spontaneous radiation is detected through a set of pinholes by high resolution silicon pixel detectors. The imaged space points are used to reconstruct the beam trajectory. The monitor is placed near the end of the undulator module, and only one monitor is needed to detect the beam position inside each module. Because the pixel response can be precisely calibrated, this monitor provides a well-defined optical axis. The ability to determine the beam trajectory complements the beam-based alignment approach which relies on the beam dispersion properties but does not measure the actual beam trajectory. In the following, the beam trajectory monitor (BTM) method is described, followed by discussions on a conceptual design. The status and plans of a prototype being developed for the TTF-FEL are then presented.

METHOD

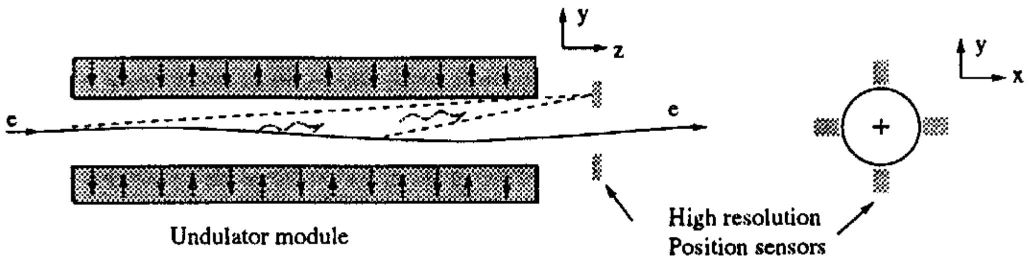
An overview of the beam trajectory monitor is shown in Figure 1. Detailed discussion can be found in [3]. The placement of the position sensors, as well as the sensitive range are shown in Figure 1a. One pair of sensors at orthogonal azimuthal positions is sufficient for beam trajectory reconstruction although two pairs are shown. The two pinhole positions and the pair of measured image points define two lines which are constrained to the same source point (see Figure 1b): $\vec{p} = \vec{v} + a \cdot (\vec{u} - \vec{v})$, where $\vec{u}$ and $\vec{v}$ are the image and pinhole locations, respectively, and a is the slope parameter. Because the two pinholes are at the same distance from the imaging screen, the two slope parameters are identical, and two determinations are available:

$$a_1 = \frac{(h_x - v_x)}{(u_x - w_x) + (h_x - v_x)}, \quad a_2 = \frac{(h_y - v_y)}{(u_y - w_y) + (h_y - v_y)} \tag{1}$$

where $\vec{v}, \vec{u}$ refer to the vertical pinhole and its image, similarly $\vec{h}, \vec{w}$ for the horizontal pinhole. The average can be used. The rest of the equations overconstrain $\vec{p}$. Thus, only one well-measured coordinate in the transverse direction from each pinhole image is required. The x-position of the vertical pinhole image and the y-position of the horizontal pinhole image determine the corresponding components of $\vec{p}$.

The imaging pixels are arranged in two columns with row-wise segmentation, as shown in Figure 1b for the sensor behind the vertical pinhole. In each row, the relative signal in the two pixels is a function of the transverse beam displacement and is measured with high precision. The imaging position accuracy using the charge sharing between the two pixels is expected to be 1 μm, which translates into a 10 μm beam position measurement accuracy at the TTF-FEL for the current design parameters.

a)



b)

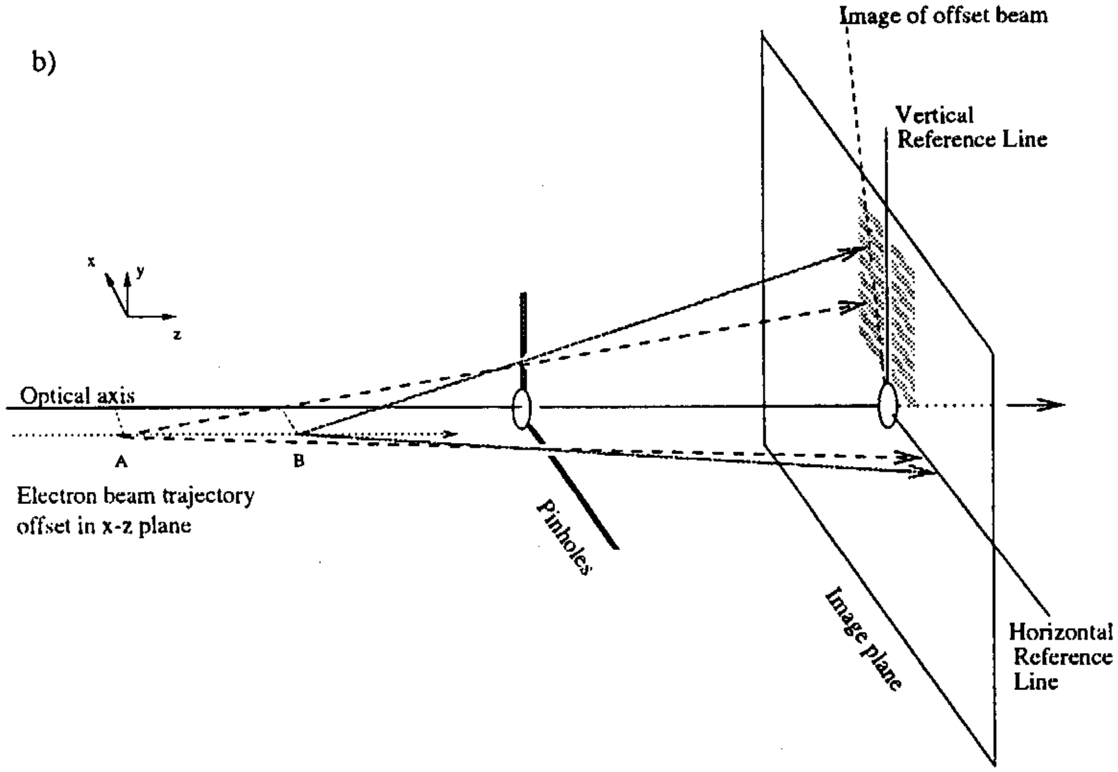


FIGURE 1. An overview of the beam trajectory monitor method. a) The location of the position sensors and the imaging range are shown. b) The method to uniquely determine the source point along the beam trajectory using two pinhole images is illustrated for the simple case of a beam trajectory with an offset. The pixel segmentation and the imaged trajectory for the sensor behind one of the pinholes are also shown.

The row-wise segmentation provides longitudinal resolution along the beam trajectory when it is projected through the pinhole. The longitudinal resolution is determined by the pinhole/pixel angular acceptance, as well as image broadening due to diffraction at the pinhole. For a wavelength of 44 nm, pinhole height of 50 μm, and a distance of 0.5 m between the pinhole and the imaging sensor, the image broadening due to diffraction would be 440 μm in which case the BTM would not be able to resolve the beam trajectory along the beam axis. In order to avoid this effect, a high-pass filter made of a thin layer (0.25 μm) of silver is used. Based on measured optical constants [4], the calculated reduction in the enormous photon flux in the lower harmonics of the spontaneous radiation at TTF-FEL below 150 eV (8 nm) is approximately 10 orders of magnitude.

The results of a trajectory reconstruction simulation are shown in Figure 2. The beam is tracked through the TTF-FEL FODO lattice. The quadrupoles are assumed to have random alignment errors uniformly distributed with a range of $\pm$ 50 μm. (The undulator is not included in this study.) It can be seen that the electron beam deviates from a straight trajectory due to misplaced quadrupole kicks, and the deviation increases as the beam travels towards the end of the undulator. The reconstructed trajectory is also shown. The longitudinal resolution varies from 0.5 m to 2.5 m. A total of four sensors is used to provide two complementing trajectory determinations. For those points with good longitudinal resolution, the transverse beam displacements are well reproduced. When the beam trajectory is averaged over a longer distance, however, the transverse beam position is poorly reconstructed. Despite this apparent shortcoming, an iterative steering correction procedure can be used. For example, the steering dipole strengths can be set one at a time, such that the reconstructed beam displacement near the steerer is minimized. A detailed simulation study using this algorithm, including undulator errors and other effects, shows that the required 10 μm RMS beam displacement can be achieved [5].

CONCEPTUAL DESIGN

The calculation of the undulator photon flux properties and the discussion on the detector requirements are given in [3]. In this section we briefly describe a conceptual design for the BTM. A schematic layout of the BTM is shown in Figure 3.

Silicon pixel detectors are chosen because of the limited available space and the required position accuracy. With a fully-depleted pnCCD with a very thin back-entrance window, a quantum efficiency of more than 50% has been measured for photons in the energy range of 100 eV to 10 keV [6]. The fractional error in the photon signal measurement in each pixel, including electronics noise and fluctuations in the electron-hole pair creation and charge

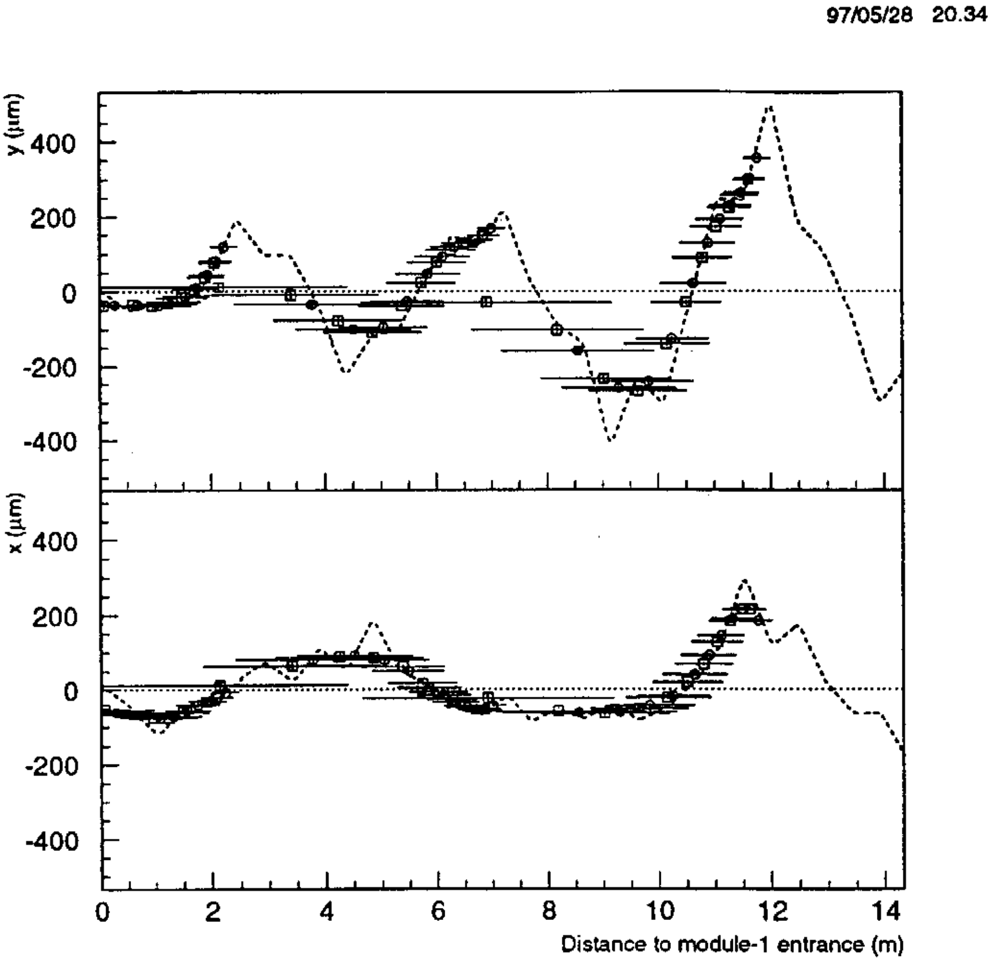


FIGURE 2. Simulation of beam trajectory reconstruction. The TTF-FEL FODO lattice is used, assuming ± 50 μm random quadrupole alignment errors. A typical trajectory is shown as dashed lines in the y-z and x-z planes. The reconstructed trajectory is shown as points (open squares and circles for two pairs of sensors used). The horizontal bars indicate the longitudinal resolution - the range over which the trajectory has been averaged.

collection processes as well as fluctuation in the photon flux, is

$$(\frac{\delta S}{S})^2 = (\frac{ENC}{S})^2 + \frac{1}{N_\gamma}\left[1 + \frac{1}{\alpha}(F + \frac{1}{\epsilon})\right], \qquad (2)$$

where ENC is the noise charge at the preamplifier input, N_γ the number of photons in each pixel, F the Fano factor, ϵ the quantum efficiency, and $\alpha = E_\gamma/w$ where E_γ is the photon energy, w the electron-hole pair creation energy. The position error using the charge sharing method is

$$\delta x = \frac{\sqrt{\pi}}{2}\sigma(\frac{\delta S}{S}) \qquad (3)$$

assuming a Gaussian distributed photon flux with RMS width σ centered between the two pixels. For the TTF-FEL phase-1 prototype BTM design,

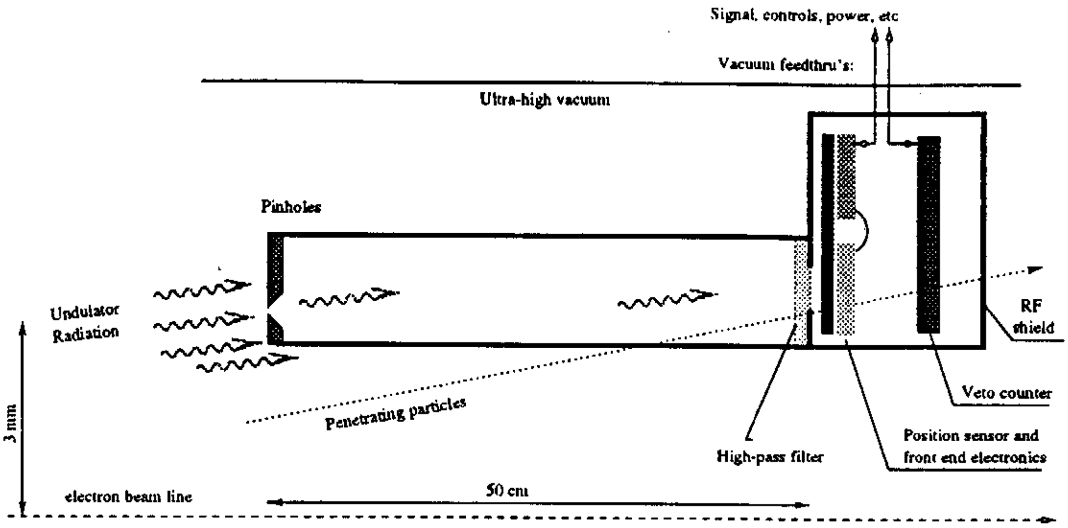


FIGURE 3. A schematic layout of the beam trajectory monitor system showing the detector assembly of pixel detectors, veto counters and front-end electronics, the RF shield, and the pinholes.

$N_\gamma \sim 1000$ and $ENC \sim 300\ e$ would give $\delta x \sim 1\ \mu$m. This condition can be satisfied. In addition, careful attention to the uniformity of the entrance window as well as calibration of the pixel response is required. A pixel detector with an active area of 0.5 mm $\times$ 1.0 mm and a total of 24 channels has been designed with the thin entrance-window technology [7]. Each pixel is directly connected to an on-chip JFET for low noise readout. The pixels are 250 μm long, with widths varying from 25 μm (nearest to the beam) to 100 μm to partially account for the rapid change in the undulator flux angular (θ) distribution and to give an angular acceptance favorable for good longitudinal resolution.

In order to suppress background due to penetrating particles (stray electrons or bremstrahlung X-rays), a veto counter is placed behind the 300 μm thick pixel detector which absorbs completely the VUV signal flux. The veto counter could be either a PIN diode, or another pixel detector.

Each readout electronics channel consists of a charge-sensitive amplifier followed by filter and sample/hold circuits. A remotely controlled switch at the amplifier input is used to vary the signal accumulation time, and the amplifier can be reset by a switch across the feedback capacitor. The photon flux expected in the pixels has a large range. For θ in the range of 0.5 mrad to 2 mrad, the number of expected photons varies by a factor of 4 at $\phi = 0°$ and by a factor of 1000 at $\phi = 90°$. In order to accumulate the required photon signal the integration time is expected to vary from ~ 300 ns to $\sim 200\ \mu$s depending on the radial position of the pixel. To avoid noise pickups, the front-end electronics is placed near the detector in vacuum. Vacuum feed-throughs are needed for connection to the ADC and the control system outside. A buffer/multiplexer is used for serial readout. Precision charge injections into the readout electronics and separately into the detector pixels provide on-line calibration. With this readout system, several measurements of the beam trajectory within one TTF macro-pulse (800 μs long) can be made.

The detectors and the readout electronics are placed inside an RF shield for protection against electromagnetic fields propagating through the beam pipe. For a 5 mm radius beam pipe at the TTF-FEL, the fields above cut-off can be safely shielded with copper approximately 0.5 mm thick. The frequency spectrum of fields excited by a 250 μm long bunch extends up to 190 GHz and then falls off rapidly. Any residual fields leaking through the pinholes (80 μm $\times$100 μm) are shielded by the high pass filter (0.25 μm thick silver).

The pixel response is precisely calibrated to provide a well-defined optical axis. The pinhole is aligned with respect to the pixel detector using laser light. The relative alignment of two nearby BTMs placed along the beam line is obtained in-situ because there is an over-lap in the beam trajectory measured by the two stations. Absolute alignment of each BTM can be made by referencing to a nearby wire-scanner station which is aligned with respect to the undulator magnetic center.

The variation in the illumination pattern, due to structure in the undulator radiation angular distribution in (θ_x, θ_y), could lead to apparent beam motion. However, because of the very small pinhole width the accepted flux angular variation (in θ_x for the vertical pinhole, for example) is very small, after taking into account the E_γ dependences in filter transmission and quantum efficiency, and the resulting position error is negligible [5].

Further simulation studies are underway to investigate other possible systematic errors. The issue of wakefields due to the BTM as well as the mechanical design of the vacuum chamber need to be studied.

STATUS AND PLANS

The conceptual design phase of a BTM for the TTF-FEL is nearly complete. A prototype is being built and tests are planned. The silicon pixel detector has been designed and the production will start soon. Initial tests in the laboratory will include measurements of noise and position accuracy. Measurements at an undulator beam line will check our calculations of the radiation properties. For the TTF-FEL phase-1, it is proposed to place one BTM at the end of the undulator beam line as a first test of the BTM concept. The initial operation will be parasitic but in a realistic environment to study the effects on wakefield and the background condition. Comparison with the BPMs will provide a cross-check of the optical-axis definition. Steering corrections will demonstrate the effect on the SASE-FEL performance.

SUMMARY

A method to measure the electron beam trajectory inside long undulator modules is described. The conceptual design of a beam trajectory monitor for the TTF-FEL is given, and the required performance is shown to be feasible. A prototype is being built, and a staged test program is starting. With some minor variation, the same concept perhaps could be applied also at other planned SASE-FELs using long undulator modules. From the discussions at this Workshop, it can be concluded that a large number of experimental parameters, such as the electron beam trajectory, needs to be precisely measured in order to understand SASE-FEL in the short wavelength regime. The BTM is not only a useful diagnostic device but will also provide information for the understanding of SASE-FEL physics.

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REFERENCES

1. TTF-FEL Conceptual Design Report, TESLA-FEL 95-03, DESY, June 1995; J. Rossbach *et al.*, Nucl. Instrum. and Methods **A375** (1996) 269.
2. B. Faatz, these proceedings.
3. J.S.T. Ng, TESLA-FEL 96-16, DESY, 1996. This report is also available through WWW at `http://www.desy.de/~ng/TTF/btm_report.html`.
4. B.L. Henke *et al.*, Atomic Data and Nucl. Data Tables, **54(2)** (1993) 181.
5. U. Müller, these proceedings.
6. H. Soltau *et al.*, Nucl. Instrum. and Methods **A377** (1996) 340.
7. MPI Halbleitorlabor, Munich, and KETEK GmbH, Oberschleißheim.

Numerical Study of Performance Limitations of X-ray Free Electron Laser Operation due to Quantum Fluctuation of Undulator Radiation

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Abstract

One of the fundamental limitations towards achieving very short wavelength in a self amplified spontaneous emission free electron laser (SASE FEL) is connected with the energy diffusion in the electron beam due to quantum fluctuations of undulator radiation. Parameters of the LCLS and TESLA X-ray FEL projects are very close to this limit and there exists necessity in upgrading FEL simulation codes for optimization of SASE FEL for operation at a shortest possible wavelength. In this report we describe a one-dimensional FEL simulation code taking into account the effects of incoherent undulator radiation. Using similarity techniques we have calculated universal functions describing degradation of the FEL process due to quantum fluctuations of undulator radiation.

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