A Method for Measuring the FEL Radiation Power Along an Undulator

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Abstract

A highly desirable measurement in Free Electron Laser experiments is the dependency of the radiation power along the undulator. Most designs of undulators prohibit detection of the radiation power within the undulator or extracting the electron beam at arbitrary positions. Transport of both, the radiation field and the electron beam, through the entire undulator, and thus an ongoing FEL interaction, is unavoidable. If there are many correction magnets distributed along the beam pipe, one can think of exciting a large orbit distortion downstream from any of these correctors. For a gain length comparable to or larger than the beta function this excitation of a coherent betatron oscillation might degrade the FEL amplification to a level, for which the radiation power does not further grow over the remaining length of the undulator. This paper presents the efficiency of this method for the parameters of the VUV Free Electron Laser at the TESLA Test Facility.

1. Introduction

The ability of beam diagnostics within the undulator is limited due to the small undulator gap and the vacuum chamber design. In particular no information can be obtained about the radiation power growth along the undulator except for the radiation power at the end of the device. Theoretically the FEL amplification can be stopped by extracting the beam transversely from the undulator but for most Free Electron Lasers, such as the VUV FEL at the TESLA Test Facility [1], the design of the undulator and vacuum chamber denies this. The beam has to be transported to the end of the undulator through the beam pipe. Over the transport distance the already modulated electron beam radiates at the resonant wavelength although a further amplification is reduced if the beam is separated from the radiation field. This radiation is added up to the formerly undisturbed FEL radiation.

The main principle of extracting the information about the radiation power growth is to separate the electron beam from the radiation field and to keep the further interaction to a minimum level. The separation is initialized by exciting a coherent oscillation. For this purpose steering magnets are used. Typically several of them are distributed along the undulator for a VUV or X-ray Laser [1, 2, 3, 4].

For a high gain FEL [5, 6] the radiation power grows exponentially along the distance of the undulator. The question whether the output power of an FEL with excited betatron oscillation can be used to measure the power growth is investigated by means of simulation with the code Genesis 1.3 [7]. The simulation are based on the Free Electron Laser at the TESLA Test Facility, whose parameters are listed in Tab. 1.

2. Transverse Motion of the Electron Beam

The goal for a high efficient Free Electron Laser performance is the synchronization between the

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Electron Beam	
Energy	230 – 390 GeV
Bunch Length (rms)	250 μm
Normalized Emittance	2 π mm·mrad
Undulator	
Period	2.73 cm
Undulator Parameter (rms)	0.898
Length	15 m
FEL	
Radiation Wavelength	120 – 40 nm
FEL Parameter ρ	$(4.6 - 2.8) \cdot 10^{-3}$
Gain Length	0.9 – 1.6 m

Table 1. Design Parameters of the VUV FEL (Phase I) at the TESLA Test Facility

electron beam and the radiation field. Any coherent transverse motion of the electron beam would disturb this synchronization and degrade the FEL amplification [8, 9]. Beside the missing overlap between the radiation field and the electron bunch the transverse motion affects the longitudinal velocity and thus the electrons change their ponderomotive phase relatively to the radiation field. These two sources of degradation – often referred to as beam wander and phase shake [10] – have different impact depending on the focusing properties of the undulator and the resonant wavelength.

The transverse beam offset depends linearly on the average transverse velocity while the longitudinal motion, expressed by the ponderomotive phase θ, is influenced by a square dependency according to

$$\frac{d\theta}{dz} = k_U - k\frac{1+K^2}{2\gamma^2} - k\frac{v_x^2 + v_y^2}{2c^2} \quad , \qquad (1)$$

where z is the position within the undulator, k_U is the undulator wave number, k the radiation wave number, K is the dimensionless rms undulator parameter, γ the electron energy normalized to the electron rest mass and $v_{x,y}$ are the transverse velocities in the x- and y-direction, respectively.

For an excited betatron oscillation the amplitude in the transverse position and velocity are closely related to each other. Therefore a small amplitude degrades the FEL performance mainly by the missing transverse overlap before the phase shake becomes dominant for larger amplitudes. The degradation of the FEL radiation power close before reaching saturation is shown in Fig. 1, for electron beam injected with various offsets into the undulator of the TTF-FEL. In good approximation the dependency is Gaussian. The phase shake plays no significant role for beam wanders comparable to the beam size of about 80 μm [11].

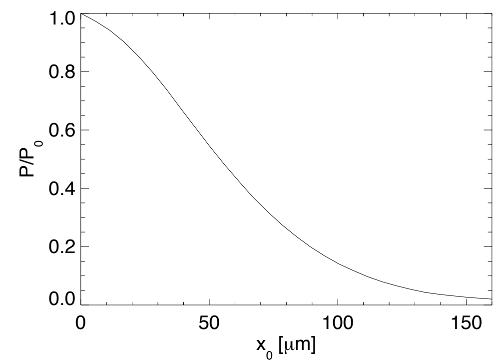

Fig. 1. Reduction of the FEL output power close to saturation of the TESLA Test Facility FEL for various initial beam offsets.

With respect to the electron ponderomotive phase any transverse motion will retard the electrons and the FEL resonance condition is shifted towards longer wavelengths. This change in the resonant wavelength can only compensate the average retardation but not the fluctuation of v_x and v_y in Eq. 1 due to the betatron oscillation. Despite this fact the difference in the resonant wavelength for an electron beam, aligned to the undulator axis, and a beam oscillating coherently with a large betatron amplitude, might be sufficiently large to inhibit the further amplification at the initial resonant wavelength after the excitation of the betatron oscillation.

3. Excitation of Large Betatron Amplitudes

Exciting large betatron amplitudes should be a sufficient method to prevent any further amplification beyond the steering magnet position. The measured output power of the FEL would correspond to the radiation power at the position of excitation. How far the remaining interaction between electrons and radiation field distorts this simple relation is studied by numerical simulations.

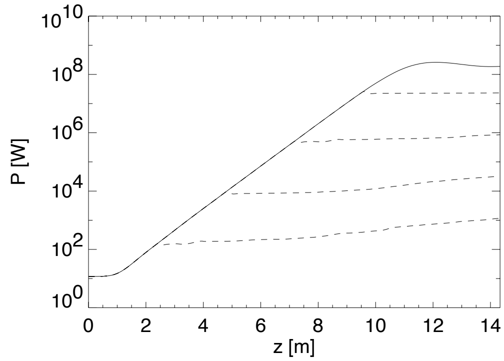

Fig. 2. Evolution of the TTF-FEL radiation power for various positions after a betatron oscillation with an amplitude of 1 mm has been excited.

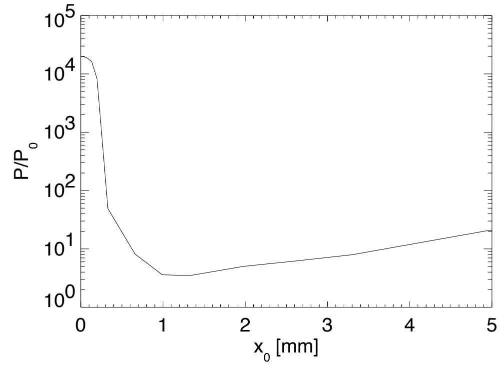

Fig. 3. Output power of the TTF FEL for different exited betatron amplitudes. The radiation power has been normalized to the power at the steering position $z = 5$ m.

In Fig. 2 the radiation power along the undulator is shown for different positions of the exciting steering magnets. An excited betatron amplitude of 1 mm provides the best performances, where the amplification is strongly inhibited and the radiation power is almost conserved to the end of the undulator. If the amplitude is larger than 1 mm the output power of the FEL grows again as it will be discussed below. For an electron beam, steered in an early stage of the amplification, a further growth of the radiation power is unavoidable. The preceding FEL interaction has already modulated the electron beam in the energy as well as in the longitudinal density ('micro bunching'). While the introduced bunching radiates coherently at the resonant wavelength the energy modulation yields an even further growth of the micro bunching.

Exceeding betatron amplitudes of 1 mm the efficiency of the presented method to measure the radiation power along the undulator is not improved as it can be seen in Fig. 3. A steering position of $z = 5$ m has been used for these simulations. The smallest value of the FEL output power occurs for a 1.2 mm offset. The radiation power grows by a factor of 3.5 over the remaining undulator length after the steering position. For earlier positions the factor is even enlarged. Compared to the suppressed growth of the FEL amplification of 2×10^4 over this distance this slight increase of the measured radiation power is acceptable.

The drop in the radiation power for betatron amplitudes smaller than 0.5 mm exhibits a dependency on the amplitude as $\exp[-ax_0^4]$. This agrees with the model when the phase shake is dominant [12]. The strength of this dependency is even enhanced because the wavelength has not been adjusted to the shift in the resonant condition.

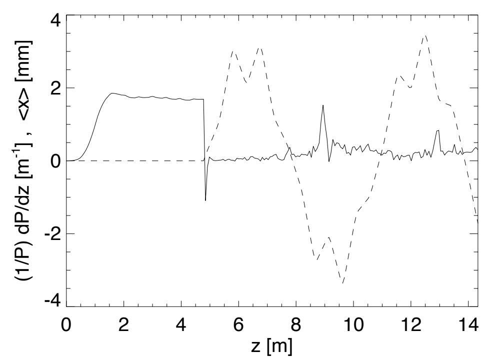

Fig. 4. Betatron oscillation of the electron bunch and exponential increment of the radiation field along the undulator (dashed and solid line, respectively).

For large betatron amplitudes, which upper limit is given by the beam pipe diameter, the power growth has it sources in the energy dependency of the electron trajectory. Modulations in the beam energy change the path length of the trajectories. The bunching is not only enhanced by the longitudinal velocity modulation, as it is mentioned above, but also by run time differences, acting as a bunch compression on the compression scale of the resonant wavelength. The largest compression occurs if the beam has passed a strong deflecting field as it is the case for a large beam offset in a quadrupole field. Fig. 4 shows this enhanced emission by compression for an offset of 3 mm. Two spikes in the growth rate are visible which are clearly correlated with the turning point of the betatron oscillation. For larger amplitudes the growth is not as localized as in Fig. 4 but rather distributed over the remaining length of the undulator.

4. Conclusion

Beside a slight enhancement of the radiation power the simulations show that a kick of 1 mm is sufficient to almost disable the FEL process. This allows to probe the state of amplification at various positions along the undulator, which is an important task to compare the measurements with the theory or simulations.

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References

[1] J. Roßbach *et al.*, Nucl. Inst. & Meth. **A375** (1996) 269

[2] S.V. Milton *et al.*, Nucl. Inst. & Meth. **A407** (1998) 210

[3] R. Tatchyn *et al.*, Nucl. Inst. & Meth. **A375** (1996) 274

[4] Linear Collider Conceptual Design Report, DESY print 97-48, Hamburg, DESY, 1997

[5] A.M. Kondratenko and E.L. Saldin, Par. Acc.**10** (1980) 207

[6] R. Bonifacio, C. Pellegrini and L.M. Narducci, Opt. Comm. **50** (1984) 373

[7] S. Reiche, Proc. of the FEL98-Conference, Wiliamsburg, 1998

[8] B.M. Kincaid, J. Opt. Soc. Am. **B2** (1985) 1294

[9] H.D. Shay and E.T. Scharlemann, Nucl. Inst. & Meth. **A272** (1988) 601

[10] B.L. Bobbs *et al.*, Nucl. Inst. & Meth. **A296** (1990) 574

[11] B. Faatz, J. Pflüger and Y.M. Nikitina, Nucl. Phys. & Meth. **A393** (1997) 380

[12] L.H. Yu *et al.*, Phys. Rev. **A45** (1992) 1163