Nuclear Instruments and Methods in Physics Research A 375 (1996) 295–298

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

ELSEVIER

Parameter study of the VUV FEL at the TESLA Test Facility

W. Brefeld[a], B. Faatz[a,*], Yu.M. Nikitina[a,1], J. Pflüger[a], P. Pierini[b], J. Roßbach[a], E.L. Saldin[c], E.A. Schneidmiller[c], M.V. Yurkov[d]

[a]*Deutsches Elektronen Synchrotron, DESY, Notkestrasse 85, 22603 Hamburg, Germany*
[b]*INFN Milano-LASA, Via Cervi, 201, 20090 Segrate (MI), Italy*
[c]*Automatic Systems Corporation, Samara, Russia*
[d]*Joint Institute for Nuclear Research, Dubna, Russia*

Abstract

We present a short description of the theoretical and numerical activity for the design of the VUV FEL proposed at DESY. The FEL will be a 6 nm SASE device driven by a 1 GeV beam from the superconducting rf accelerator which is under development by the international TESLA collaboration.

1. Introduction

R & D on future generation linear colliders promises to give in the nearest future high-energy, low-emittance and monochromatic electron beams which could be used for a wide range of applications. One of them, which is under study at DESY, is to use the electron beam of the TESLA Test Facility (TTF) superconducting linear accelerator as a driving beam for a self-amplified spontaneous emission (SASE) FEL operating at a 6.4 nm wavelength [1–3]. The obvious advantage of a SASE FEL compared to a seeded FEL amplifier is the fact that it does not need a master oscillator, unavailable at these short wavelengths [4].

One of the problems in designing a SASE FEL is to determine the characteristics of the generated radiation. In a traditional FEL amplifier scheme, the radiation generated by a narrow bandwidth master oscillator, which can be controlled both in amplitude and frequency, is amplified. Under these initial conditions the field amplitude of the radiation generated in the undulator does not depend on time, but only on the spatial coordinates. This was the main factor which has allowed development of a wide range of reliable theoretical approaches, e.g. steady-state models, for calculation of characteristics of an amplifier [5–13]. Contrary to the traditional FEL amplifier, in a SASE FEL fluctuations of the beam current density play the role of input signal. These fluctuations vary in time and the associated spectrum is "white". To describe such a situation and to address the problem of longitudinal coherence, a time-dependent theory of the FEL amplifier should be used. For the analysis of transverse coherence, the time-dependent model should be extended to a full three-dimensional model.

Nevertheless, the theoretical approach developed for the description of traditional FEL amplifiers can be used to find some characteristics of the SASE FEL. First of all, such an approach allows one to calculate the main characteristics of the radiation modes. This is a consequence of the fact that the "effective" power of the input signal is rather small with respect to the saturation power. As a result, only the mode having the largest growth rate survives. The characteristics of this mode do not depend on the nature of the input signal used, and are determined by the amplifier parameters. Therefore, with the aid of the results obtained with steady-state theory it is possible to calculate the gain and radial field distribution. Calculations of the frequency characteristic of the FEL amplifier allow to estimate the maximal bandwidth of the SASE FEL. Calculation of the amplitude characteristic of the FEL makes it possible to estimate the influence of the fluctuations of the input onto output amplitude. Using estimations of the "effective" power of shot noise we can calculate an approximate saturation length of the device.

Special attention is payed to the undulator of the VUV-FEL. In order to achieve saturation in a single pass, an undulator of a total length of 30 m is required. To keep the beamsize small over the whole undulator length, additional focusing has to be provided. A very suitable arrangement for that is a quadrupole lattice consisting of focusing and defocusing sections (FODO-lattice). The plan is to realize it by the incorporation of alternating field gradients into a

* Corresponding author. Tel. +49 40 8998 2694, fax +49 40 8998 2787, e-mail faatz@vxdesy.desy.de.

[1] Permanent address: Department of Mathematical Physics, Tomsk Polytechnical University, 634004 Tomsk, Russia.

SSDI 0168-9002(95)01189-7

hybrid permanent magnet (PM) structure. Structures, which fulfill these requirements, as well as investigation of the influence of field errors, are described elsewhere [1,14,16].

We have performed an optimization of the FEL amplifier characteristic using different 2D/3D simulation codes. Furthermore, we began to employ existing codes to calculate time-dependent effects [17].

2. Numerical simulation codes

The SASE FEL characteristics have been calculated with different 2D/3D steady-state simulation codes.

2.1. NUTMEG and GINGER

The codes NUTMEG and GINGER consider 2D axisymmetric radiation field and take into account the 3D electron motion in an undulator, allowing the use of an external focusing field [8]. Diffraction and guiding, effects of finite beam emittance and undulator errors, are included in the model. NUTMEG is a steady state simulation code. It provides a possibility to calculate higher harmonics of the emitted radiation and simulate multiple undulator schemes. The code GINGER extends the model to include time-dependent effects, and properly takes into account the longitudinal structure of electron beam and radiation field, and the slippage between pulses. GINGER can also model the shot noise startup by means of an incoherent random noise over the initial electron pulse without needing any equivalent input signal to start the SASE process, and can give information on the temporal and spectral characteristics of the emitted radiation.

2.2. TDA3D

The code TDA3D solves the electron and wave equations in the paraxial, single frequency approximation [9]. The wave equation is expanded into azimuthal modes to take into account non-axisymmetric effects in the interaction process. Equations are averaged over an undulator period, with the exception of the error term in the undulator field. An external FODO lattice is taken into account without a smooth approximation.

2.3. FS2R

The program package FS2R has been designed for calculations of an FEL amplifier with an axisymmetric electron beam. It covers all the aspects of the calculations of FEL amplifiers with an axisymmetric electron beam and consists of three codes [13], namely FS2RD (analysis of the eigenvalue problem), FS2RL (analysis of the initial-value problem) and FS2RN (nonlinear simulation code). Codes FS2RD and FS2RL are essentially based on the use of analytical techniques and FS2RN makes use of Green's function methods for the calculation of the radiation field.

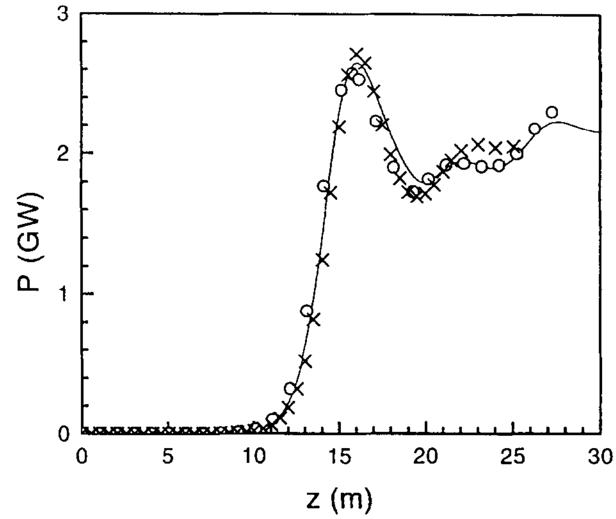

Fig. 1. Dependency of the FEL output power on the undulator length calculated with different simulation codes. Solid curve – FS2RN code, crosses – NUTMEG code and circles – TDA3D code.

In Fig. 1 we show the dependence on the undulator length of the output radiation power of the FEL amplifier. It is seen that the codes give similar results.

3. Calculations of the SASE FEL performance

The region of parameters has been studied analytically [18,19] and with numerical simulation codes [1,19]. Taking into account the technical limitations, we have chosen the parameters of the SASE FEL to be as close as possible to optimal ones (see Table 1) [1]. For the chosen parameters, the influence of the space charge field is negligible. A general analysis of the TTF FEL, presented in Refs. [1,19], includes the study of undulator design, the influence of the imperfections of the undulator magnetic field and the beam quality on the FEL amplifier operation, time-dependent effects, etc. In this section we illustrate with numerical examples some characteristics of the SASE FEL. In the calculations we have simulated the initial conditions for the input signal as a Gaussian laser beam. The value of "effective" power of the input signal due to fluctuations of the beam current density has been chosen in accordance with Refs. [19,20].

3.1. Influence of the emittance

Fig. 2 shows the influence of the emittance on the operation of the FEL. In the figure we plot the saturated power and saturation length at the peak FEL gain, using the parameters listed in Table 1. We can see from the figure

Table 1
General parameters of SASE FEL at DESY

Electron beam	
Energy	1000 MeV
Peak current	2500 A
Normalized rms emittance (Gaussian)	2π mm mrad
rms energy spread (Gaussian)	0.1%
rms bunch length	50 μm
Bunch separation	111 ns
Number of bunches per train	7200
Repetition rate	10 Hz
External β-function	3 m
rms transverse beam size in the undulator	57 μm
Undulator	
Type	planar
Period	2.73 cm
Peak magnetic field	0.4972 T
Magnetic gap	1.2 cm
Effective undulator length	25 m
Radiation	
Wavelength	6.42 nm
Bandwidth	0.5%
rms spot size at the undulator exit	130 μm
rms angular divergence	15 μrad
Peak power	5.5 GW
Average power	130 W
No. of photons per electron bunch	7×10^{13}
Peak flux of photons	2×10^{26} photons/s
Average flux of photons	6×10^{18} photons/s
Peak brilliance	7×10^{29} photons/s/mm^2/mrad^2/0.1%
Average brilliance	2×10^{22} photons/s/mm^2/mrad^2/0.1%

that, in order to reach saturation within the currently envisaged undulator length of 25 to 30 m, the beam emittance at the undulator should not exceed 3–4π mm mrad. For bigger values of the emittance the FEL operation is not destroyed, but would require much longer saturation lengths. The decrease of the FEL output power with the emittance increase is mainly caused by diffraction effects. The corresponding increase of the longitudinal velocity spread gives a small contribution to the efficiency decrease.

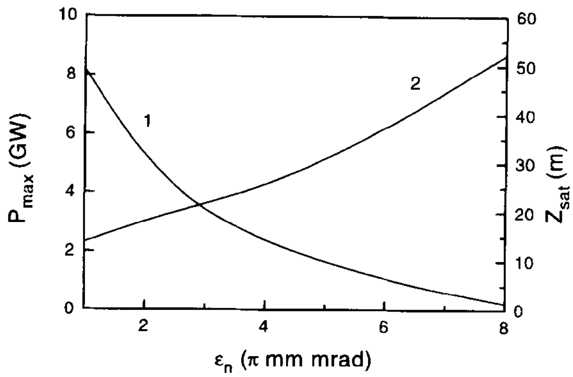

Fig. 2. Dependence of the maximal output power (1) and the saturation length (2) on the value of the normalized emittance. Here $\sigma_E/\varepsilon = 0.1\%$. All remaining parameters used for the simulations are listed in Table 1.

3.2. *Influence of the energy spread*

In Fig. 3 we illustrate the influence of the uncorrelated energy spread of the particles in the beam on the FEL amplifier operation. An analysis of these plots indicates that the safety margin for the energy spread is only a factor of 1.5. An increase of the energy spread by a factor of 3 almost destroyed the FEL amplifier operation, even if an arbitrary long undulator is assumed.

4. Discussion

In conclusion we should like to make some remarks on the problem of transverse and longitudinal coherence of the output radiation of the SASE FEL. Strictly speaking, the steady-state approximation cannot provide quantitative

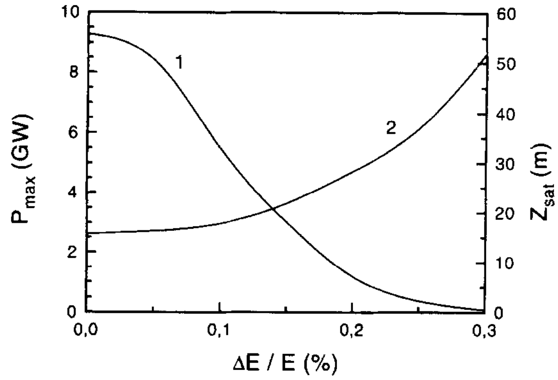

Fig. 3. Dependence of the maximal output power (1) and the saturation length (2) on the value of the energy spread. Here $\varepsilon_n = 2\pi$ mm mrad. All remaining parameters used for the simulations are listed in Table 1.

description of this phenomenon. Nevertheless, it is possible to use simple physical considerations, that have been confirmed by a one-dimensional time-dependent model [20]. The longitudinal coherence length is of the order of the cooperation length: $l_c \approx \lambda l_g / \lambda_w$, where l_g is the gain length. So, if the length of the electron beam σ_z is significantly greater than the cooperation length, there will be temporal dependence of the frequency and amplitude of the output radiation within each pulse. The number of spikes in each pulse is of the order of σ_z / l_c. Also, the spectrum of the output radiation contains many spikes within the bandwidth of the FEL amplifier calculated with steady-state theory [21].

The situation for the transverse coherence of the output signal is somewhat complicated. In the region of parameters of our SASE FEL, the extension of radiation at the gain length is much less than the transverse size of the electron beam, so there is no total transverse coherence of the shot noise at the entrance of the undulator. We can suppose only that the process of amplification from shot noise begins to develop independently in clusters [19]. Simple qualitative consideration cannot describe this process and three-dimensional numerical simulations should be performed in the same way as it was done in the one-dimensional model (see Ref. [20] and references therein).

Acknowledgements

We thank B.H. Wiik, D. Trines and I. Ivanov for their interest and support in our work. One of the authors (Yu.M.N.) would like to thank the HASYLAB at DESY for their hospitality during here stay in Hamburg and DAAD for the financial support of her work.

References

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

[2] D.A. Edwards, (ed.), TESLA Test Facility Linac: Design Report, DESY Print TESLA 95-01, Hamburg, DESY, 1995.

[3] J. Rossbach, Studies on a Free Electron Laser for the TESLA Test Facility, presented at PAC-95.

[4] A.M. Kondratenko and E.L. Saldin, Part. Accel. 10 (1980) 207;
Ya.S. Dervenev, A.M. Kondratenko and E.L. Saldin, Nucl. Instr. and Meth. 193 (1982) 415;
R. Bonifacio, C. Pellegrini and L. Narducci, Opt. Commun. 50 (1984) 373.

[5] G.T. Moore, Opt. Commun. 52 (1984) 46.

[6] G.T. Moore, Nucl. Instr. and Meth. A 250 (1986) 381.

[7] C.-M. Tang and P. Sprangle, IEEE J. Quantum Electron. QE-21 (1985) 970.

[8] E.T. Scharlemann and W.M. Fawley, in Modelling and Simulation of Optoelectronic Systems, SPIE, vol. 642 (1986) p. 1;
R.A. Jong, W.M. Fawley and E.T. Scharlemann, in Modelling and Simulation of Optoelectronic Systems, SPIE, vol. 1045 (1989) p. 18.

[9] T.-M. Tran and J.S. Wurtele, Comput. Phys. Commun. 54 (1989) 263;
P. Iha and J.S. Wurtele, Nucl. Instr. and Meth. A 331 (1993) 477.

[10] J.C. Goldstein, T.F. Wang, B.E. Newman and B.D. McVey, Proc. 1987 Particle Accelerators Conf., Washington, DC, USA, p. 202.

[11] L.H. Yu, S. Krinsky and R.L. Gluckstern, Nucl. Instr. and Meth. A 304 (1991) 516.

[12] Y.H. Chin, K.-J. Kim and M. Xie, Nucl. Instr. and Meth. A 318 (1991) 481.

[13] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Opt. Commun. 97 (1993) 272;
E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Opt. Commun. 95 (1993) 141;
E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Preprint DESY 94-219, Hamburg, DESY, 1994.

[14] Yu.M. Nikitina and J. Pflüger, these Proceedings (17th Int. Free Electron Laser Conf., New York, NY, 1995) Nucl. Instr. and Meth. A 375 (1996) 325.

[15] J. Pflüger and Y.M. Nikitina, Undulator schemes with the focusing properties for the VUV-FEL at the TTF, to be published.

[16] B. Faatz, J. Pflüger and P. Pierini, Ref. [14], p. 441.

[17] P. Pierini and W.M. Fawley, Ref. [14], p. 332.

[18] W. Brefeld, calculations with fitting formulae in accordance with ref. K.J. Kim and M. Xie, Nucl. Instr. and Meth. A 331 (1993) 359.

[19] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, DESY Print May 1995, TESLA-FEL 95-02, Hamburg, DESY, 1995.

[20] R. Bonifacio et al., Phys. Rev. Lett. 73 (1994) 70; and Nucl. Instr. and Meth. A 341 (1994) 181.

[21] K.J. Kim, Phys. Rev. Lett. 57 (1986) 1871.