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# START-TO-END SIMULATIONS OF SASE FEL AT THE TESLA TEST FACILITY

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VUV SASE FEL at the TESLA Test Facility (Phase 1) was successfully running and reached saturation in the wavelength range 80–120 nm. We present a posteriori start-to-end simulations of this machine. The codes Astra and `elegant` are used to track particle distribution from the cathode to the undulator entrance. An independent simulation of the beam dynamics in the bunch compressor is performed with the code CSRtrack. SASE FEL process is simulated with the code FAST. The simulation results are in good agreement with the measured properties of SASE FEL radiation. It is shown that the beam dynamics after the bunch compressor is mainly defined by space charge fields. FEL radiation is produced by the head of the electron bunch having a peak current of about 3 kA and a duration of 100 fs.

Рентгеновский лазер на свободных электронах (ЛСЭ) (фаза 1) на тестовом ускорителе TESLA успешно достиг режима насыщения в диапазоне длин волн 80–120 нм. В данной работе представлены результаты численного моделирования работы установки. Алгоритмы Astra, `elegant`, CSRtrack использовались для расчета динамики электронного пучка в ускорителе и компрессоре сгустка. Расчет работы ЛСЭ проводился с помощью алгоритма FAST. Результаты моделирования находятся в хорошем согласии с экспериментальными результатами. Показано, что динамика пучка после компрессии существенно определяется полем пространственного заряда. Проведенный анализ дает основание для заключения о том, что излучение ЛСЭ генерируется головной частью сгустка с пиковым током 3 кА и длительностью 100 фс.

## INTRODUCTION

SASE FEL at the TESLA Test Facility (TTF), Phase 1, reached saturation in the wavelength range 80–120 nm and produced GW level radiation pulses with a duration of 30–100 fs [1]. Previous analysis of the experiment used a simplified model of the electron bunch (the lasing part of the bunch was approximated by gaussian) [1]. Although that model allowed us to describe main properties of the radiation, some important features were not understood well. In this paper we perform comprehensive studies of the beam dynamics (including, for instance, space charge effects after compression), as well as SASE FEL simulations. We compare simulation results with a set of experimental data taken at similar tuning of TTF FEL in a femtosecond mode of operation and published earlier in [1,2]. Not all of these characteristics were measured at the same time, so that the electron beam parameters may be slightly different for different measurements. For start-to-end simulations we took settings for one of typical accelerator tunings (settings for magnetic elements and RF system from logbook), and found very good agreement with experimental results.

## 1. BEAM DYNAMICS SIMULATIONS

The description of the TTF accelerator, operating under standard lasing conditions, can be found in [1]. The details of beam dynamics simulations are presented in [3]. Start-to-end simulations of the beam dynamics were performed in the following way. The initial part of the machine, from the cathode to the bunch compressor entrance, was simulated with Astra [4]. Then the beam was tracked through the bunch compressor with the code `elegant` taking into account a simplified model of coherent synchrotron radiation (CSR) wake [5]. The bunch compression at TTF was strongly nonlinear, resulting in banana-like shape of the longitudinal phase space. In time domain we obtained a short, high-current leading peak, and a long, low-current tail. In order to check that we did not miss any important CSR-related effect, we performed independent simulations of the bunch compressor with a newly developed code CSRtrack [6]. The main results were in agreement with the results of `elegant`. From the bunch compressor exit to the undulator entrance we used Astra again, because the space charge effects are very important for a short, high-current leading peak. A part of the longitudinal phase space at the undulator entrance as well as the slice parameters in the head of the bunch that were used in SASE FEL simulations are presented in Fig. 1. One can notice a strong energy chirp $\Delta\gamma$ induced by the longitudinal space charge field on the way from the bunch

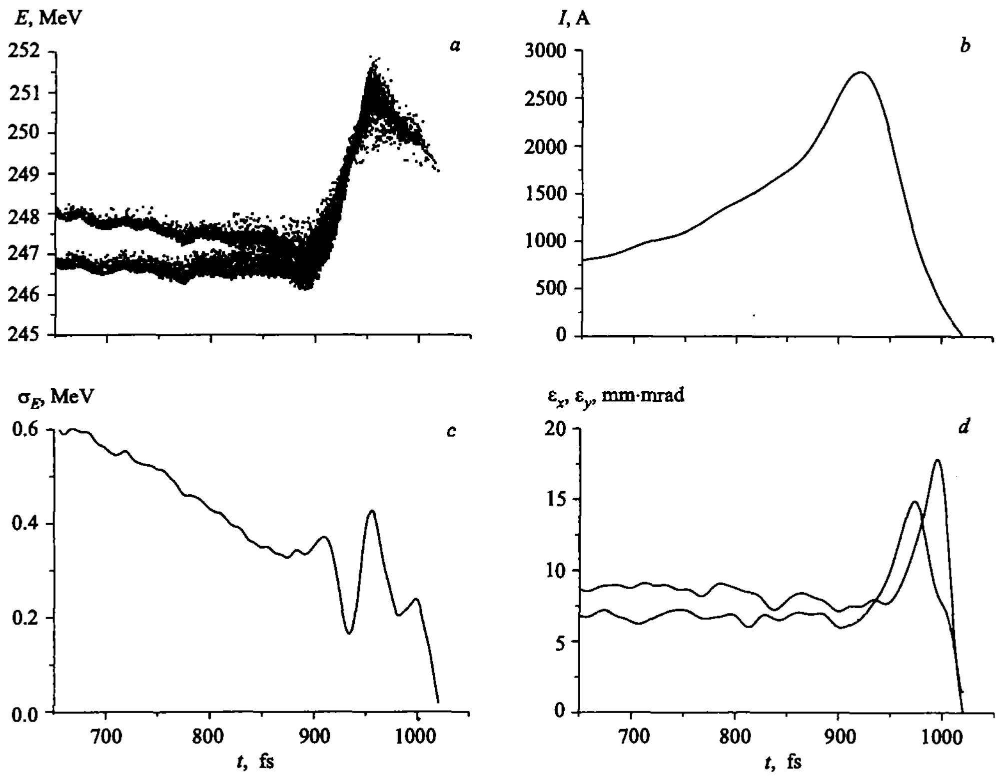


Fig. 1. Longitudinal phase space (*a*), current (*b*), slice energy spread along the bunch at the undulator entrance (*c*) and slice emittance (*d*). Bunch head is at the right side

compressor to the undulator:

$$\frac{d(\Delta\gamma)}{dz} \simeq \frac{I}{I_A} \frac{\ln(\gamma\sigma_z/\sigma_r)}{\gamma^2\sigma_z}.$$

Here $I$ is peak current; $I_A$ is Alfven's current; $\sigma_z$ and $\sigma_r$ are the longitudinal and transverse size of the spike.

## 2. SASE FEL SIMULATIONS

SASE FEL simulations were performed with the three-dimensional time-dependent FEL code FAST [7]. Since SASE FEL radiation is a statistical object (due to the start up from shot noise), we performed 200 statistically independent runs with the code FAST.

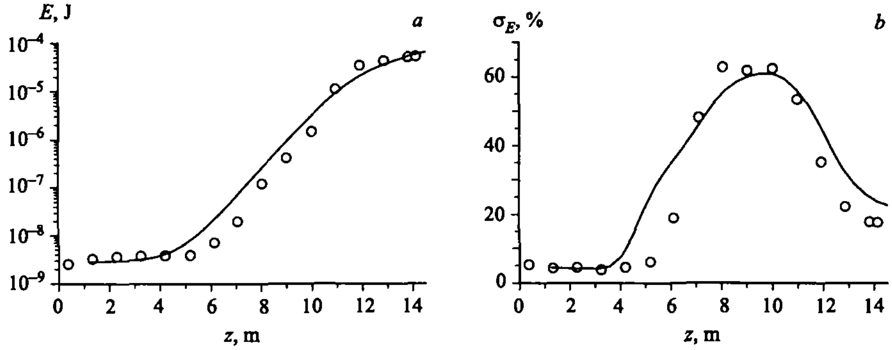


Fig. 2. Energy in the radiation pulse (*a*) and fluctuations of the energy in the radiation pulse (*b*) versus undulator length. Circles are experimental data [1], and curves represent results of simulations with the code FAST

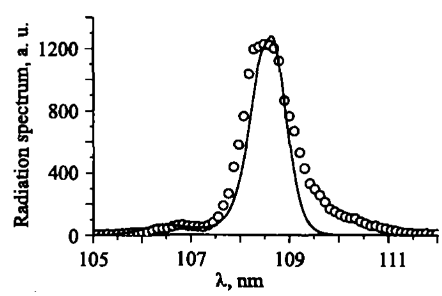


Fig. 3. Average spectrum of TTF FEL operating in the high-gain linear regime. Circles are experimental data [8], and the curve represents results of simulations with the code FAST

In Fig. 2 we present average energy in the radiation pulse and the rms energy fluctuations versus position in the undulator. One can notice reasonable agreement between measurement and simulations.

In Fig. 3 we present measured [8] and simulated averaged spectrum of SASE FEL operating in the linear regime. One can see a little bump on the left — it is due to the energy chirp in the electron bunch.

Single-shot spectra as well as the averaged one are shown in Fig. 4 for the saturation regime [1]. The agreement between simulations and measurements is quite good.

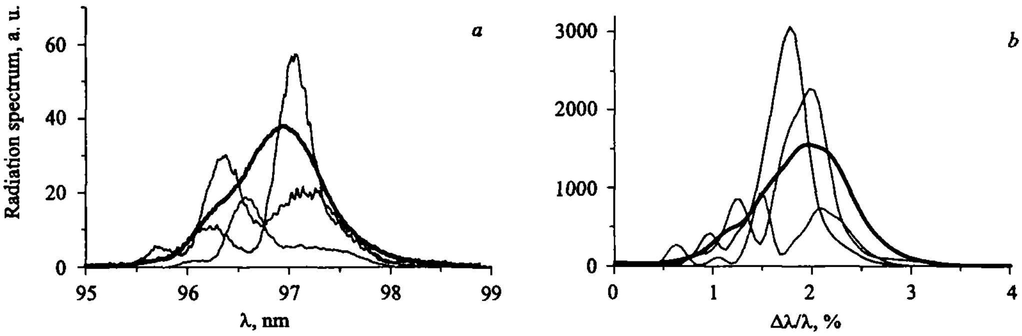


Fig. 4. Single-shot spectra (thin lines) and averaged spectrum (bold lines) of TTF FEL operating in the nonlinear regime: *a*) experimental data [1]; *b*) results of simulations with the code FAST

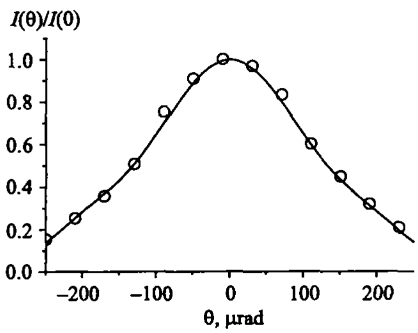


Fig. 5. Angular distribution of the radiation intensity in the far zone. TTF FEL operates in the nonlinear regime. Circles are experimental data [1], and curves represent results of simulations with the code FAST

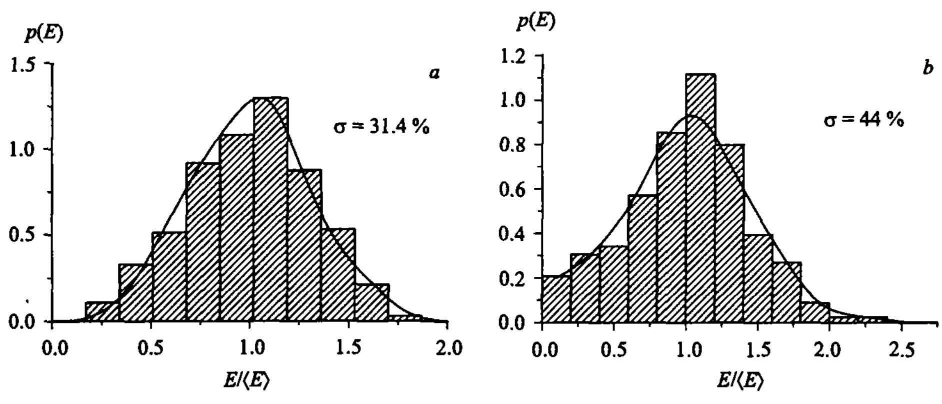


Fig. 6. Probability distributions of the total energy in the radiation pulse (*a*) and after narrow band monochromator (*b*) [2]. TTF FEL operates in the nonlinear regime. Solid lines represent simulations with the code FAST

A comparison between measured [1] and simulated angular distribution of the radiation intensity in the far zone is presented in Fig. 5, and in Fig. 6 we compare probability distributions of the total energy in the radiation pulse and after narrow band monochromator. TTF FEL operates in the nonlinear regime. Note that these are relative characteristics independent of absolute calibration of the radiation detector. Perfect agreement between experimental and simulated results is a strong argument in favor of correct simulations.

## SUMMARY

Detailed analysis of beam dynamics leads us to the conclusion that TTF FEL (Phase 1) was driven by strongly non-gaussian bunch with short leading peak having a current of about 3 kA. Space charge is the main physical effect for the beam dynamics after the bunch compressor: a large value of energy chirp in the leading spike is gained in long drift spaces. Good agreement between experimental and simulation results is an encouraging message that physical models realized in the codes Astra, `elegant`, FAST do not miss important physical effects, at least for the parameter range of TTF FEL, Phase 1. This allows us to determine the parameters of the SASE FEL which are not directly accessible to measurement. First of all this refers to the temporal structure of the radiation pulse (see Fig. 7): the computed FWHM pulse duration is about 40 fs, and averaged peak power is about 1.5 GW.

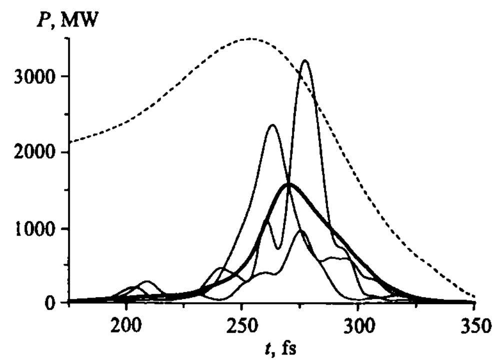


Fig. 7. Radiation power along the bunch for TTF FEL operating in the nonlinear regime. Thin curves represent single shots; bold curve, averaged profile; dashed curve, profile of electron bunch. Simulations are performed with the code FAST


REFERENCES

1. *Ayvazyan V. et al.* // Phys. Rev. Lett. 2002. V. 88. P. 104802; Eur. Phys. J. D. 2002. V. 20. P. 149.
2. *Ayvazyan V. et al.* // Nucl. Instr. Meth. A. 2003. V. 507. P. 368.
3. *Dohlus M. et al.* Start-to-End Simulations of TTF1 FEL // Nucl. Instr. Meth. A (in press).
4. *Flöttmann K.* Astra User Manual. http://www.desy.de/ mpyflo/Astra_dokumentation/
5. *Borland M.* Preprint APS LS-287. 2000.
6. *Dohlus M.* Private communication. 2003.
7. *Saldin E. L., Schneidmiller E. A., Yurkov M. V.* // Nucl. Instr. Meth. A. 1999. V. 429. P. 233.
8. *Andruszkow J. et al.* // Phys. Rev. Lett. 2000. V. 85. P. 3825.