Shot Noise Startup of the 6 nm SASE FEL at the TESLA Test Facility ⋆

P. Pierini, [a] W.M. Fawley [b,1]

[a] *INFN Sezione di Milano, Laboratorio LASA, Via F.Cervi, 201, I-20090 Segrate (MI), Italy*

[b] *Lawrence Berlekey Laboratory, 1, Cyclotron Rd., Berkeley, CA, USA*

We present here the results of an extensive simulation activity for the TESLA SASE FEL. We have used the program GINGER to determine the FEL saturation length and its fluctuations from shot to shot. The spectral properties of the output power and the correlation functions are investigated and compared with available theoretical models.

1 Introduction

A strong effort to design a VUV Self Amplified Spontaneous Emission (SASE) Free Electron Laser (FEL) is currently taking place in DESY[1]. One of the merits of the SASE scheme is that it does not require any input signal from a master oscillator, since the spontaneous radiation emitted by a sufficiently intense electron beam entering in the undulator drives the high gain collective instability[2,3]. For a complete study of the shot noise startup and in order to evaluate the correct saturation length and its fluctuations, the time dependence of the initial shot noise of the electron phases and slippage effects have to be taken into account both in the theory and in the numerical modeling.

The 1D analysis[4] of the SASE FEL shows that depending on the relative length of the electron pulse with respect to the "cooperation length", defined as $\ell_c = \lambda/(4\pi\rho)$, where ρ is the dimensionless FEL parameter[2], the system can operate in very different dynamical regimes. In the long bunch case, when the beam is much longer than the cooperation length, the time structure of the output radiation

⋆ Th3-64. Presented at the 17$^{\mathrm{th}}$ International Free Electron Laser Conference, August 21-25, 1995, New York, NY, USA

[1] Work Supported at LBL by the Director, Office of Energy Research, blah blah, und so weiter

beam is dominated by the onset of superradiant spiking, seeded by the shot noise nonuniformities, whereas in the short bunch case the output pulse consists of a single clean superradiant pulse, which will exhibit strong fluctuations from shot to shot.

The beam and ondulator parameters for the TESLA FEL have been extensively studied in the framework of the steady state theory, where slippage effects are neglected, and an optimization has been performed both with the help of analytical and numerical tools. In this approximation the SASE device is modeled as an amplifier seeded with the spontaneous radiation emitted in the first gain length of the undulator. The results of this study are presented in Ref.[5].

In this paper we present an investigation of the time structure and spectral characteristics of the emitted pulses from the TESLA FEL, giving an estimate of the emitted bandwidth and of the relevance of shot to shot fluctuations.

In Table 1 we summarize the TESLA FEL parameters.

Table 1
Main parameters of the TESLA FEL[1,5].

Total bunch Charge	1 nC
Peak Current	2.5 kA
Beam energy	1 GeV
rms normalized emittance	2π mm mrad
rms energy spread	0.1%
rms beam length	50 μm (166 fs)
FEL parameter ρ	1.67×10^{-3}
1D Gain length ℓ_{gain}	1.3 m
1D Cooperation length ℓ_{coop}	0.3 μm (1.02 fs)

2 TESLA FEL modeling

For the analysis of the shot noise startup at the TESLA FEL we have employed the LLNL 2D time dependent simulation code GINGER[6], which takes into account the 3D electron motion of the electrons interacting with an axisymmetric radiation field. The electron and radiation pulses are allowed to travel the wiggler with different velocities. GINGER can also treat any time dependent beam parameter variation over the electron/radiation pulses, like arbitrary beam current or energy distributions, and the initial shot noise over the electron phases. SASE startup is modeled adding random fluctuations to the particles longitudinal and transverse coordinates[7].

The simulations described here have been performed with a 6D gaussian distribution in the electron phase space. A series of runs has been performed with different shot noise initial configurations, to assess the influence of shot to shot fluctuations over the relevant quantities of the FEL. All the beam parameters have been set to the nominal values obtained from a parameter optimization that has been performed with steady state analytical and numerical techniques. For a discussion of the TESLA FEL parameter list, refer to Refs. [1],[5].

2.1 Spectrum, bandwidth and superradiant spiking

From the analytical theory of the SASE FEL[4,3], it is possible to evaluate the evolution of the half-width of the power spectrum and the decay time of the field autocorrelation function along the wiggler:

$$\left.\frac{\Delta\omega}{\omega}\right|_{\mathrm{HWHM}} = 6\sqrt{\frac{\ln 2}{\sqrt{3}}}\frac{\rho}{z/\ell_{gain}} \qquad (1)$$

$$\tau_{1/2} = \frac{2}{3}\frac{\ell_{coop}}{c}\sqrt{3\ln 2}\sqrt{\frac{z}{\ell_{gain}}} \qquad (2)$$

where $\tau_{1/2}$ is the time required by the electric field autocorrelation function to decay to 0.5 and $\ell_{gain} = \lambda_{\mathrm{w}}/(4\pi\rho)$ is the gain length. To derive these relations diffraction effects have been neglected and a cold beam, with no energy spread and emittance, has been assumed. In particular, eq. (1) represents an upper limit for the FEL bandwidth, since most narrowing effects has been neglected.

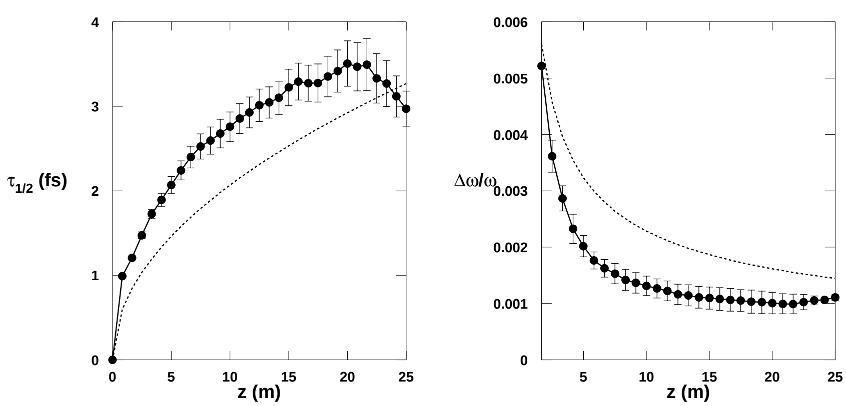

Fig. 1. Half width of the autocorrelation function (left) and power spectrum halfwidth (right) computed from a series of 2D GINGER runs (solid line and dots with error bars) and the predictions of the 1D analysis (dashed line).

In Fig. 1 we compare the bandwidth and the autocorrelation time computed from a series of 10 GINGER simulation with expressions 1-2. The error bars on the simulation points denote the magnitude of the rms fluctuations around the average value computed from the runs. We can see that the system experiences a systematic bandwidth narrowing with respect to the 1D estimation, due to diffraction. For the parameters used in this simulation the initial Rayleigh range ($z_{\rm r} = \pi\sigma^2/\lambda$) of the radiation beam is 1.87 m, whereas the 1D gain length is 1.3 m.

From the GINGER simulations the TESLA FEL bandwidth (half width at half maximum) for the power spectrum has been estimated to approximately 0.1%, showing a narrowing with respect to the "natural" FEL bandwidth given approximately by ρ, due to diffraction effects.

The temporal structure of the emitted pulse shows the presence of superradiant spikes seeded from the shot noise on the electron beam, as it can be seen from figure 2. As for the TESLA FEL parameters the beam length is much larger than the cooperation length, the temporal structure is dominated by sharp superradiant spikes, reaching more than 10 GW peak power. This spiking behavior is clearly seen also in the spectrum of the emitted radiation in Figure 2. Here the wavelength is resolved in bins of width 2.73$\times 10^{-4}$ nm. Different shot noise realizations generally lead to different spike positions and relative power.

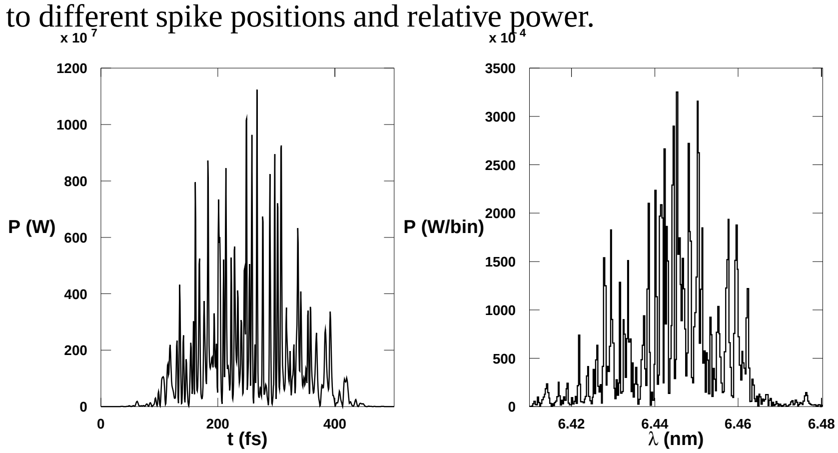

Fig. 2. Temporal structure (left) and spectrum (right) of the output radiation pulse of the TESLA SASE FEL.

The behavior of these superradiant spikes follows accurately the predictions of the 1D SASE theory. In particular, the spikes show an overall width which is related to the cooperation length and travel at the group velocity given by the following expression[4]:

$$v_{\rm g} = 3\frac{v_{||}}{2 + v_{||}/c}, \tag{3}$$

From this expression is clearly seen that the spike velocity is smaller than the light velocity in free space and that the spikes move forward with respect to the electron bunch at approximately one third of the nominal slippage rate of the radiation. This behavior is clearly illustrated by Figure 3, where the normalized radiation intensity, $\hat{I}(z,t) = I(z,t)/\langle I(z)\rangle$, is plotted as a function of the distance along the wiggler (horizontal axis) and of a time measured on a frame moving at the light velocity (vertical axis). In this case, to show the dynamics of a few superradiant spikes, we have modeled a very thin longitudinal slice of the electron beam, only 7 μm long, imposing periodic boundary conditions at its edges. It is clearly seen from the figure that the spikes move slower than the light velocity during the exponential growth of the power up to saturation (and hence accumulate a time delay on the coordinate $\tau \propto t - z/c$). At this point non linear effects take place and the spikes start propagating at c (and they are seen propagating along the wiggler at a fixed value of $\tau \propto t - z/c$).

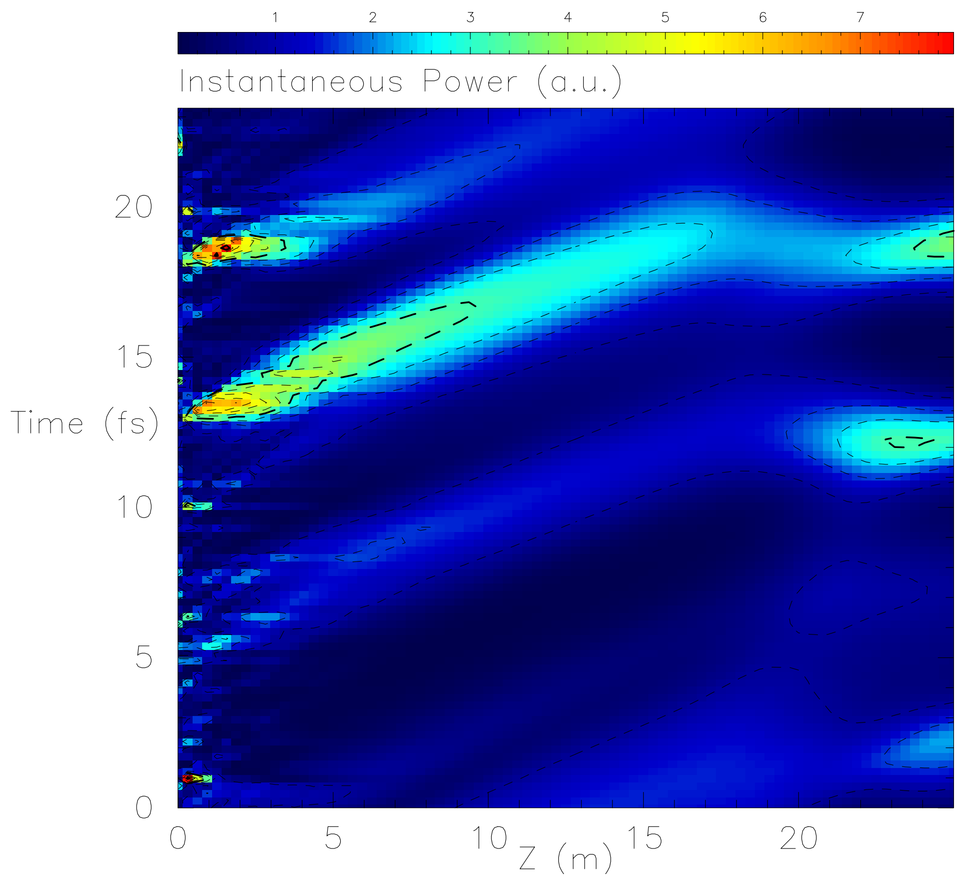

Fig. 3. Plot of the normalized radiation intensity as a function of the wiggler length (horizontal axis) and of the time along a reference frame moving at the ligth velocity, c (vertical axis). For a description of the figure please refer to the text.

2.2 Average emitted power and saturation length fluctuations

As it has been shown by the 1D analysis of the SASE startup[4], in the case where the beam length is much greater than the cooperation length shot to shot fluctuations for output power and saturation length do not play a relevant role. In Figure. 4 we show both the behavior of the average emitted power along the wiggler (left) and its relative fluctuations (right). As expected, the SASE operation is most sensible to shot to shot fluctuations in the exponential regime, where, for the TESLA FEL parameters, these can reach the value of 15-20% of the emitted power.

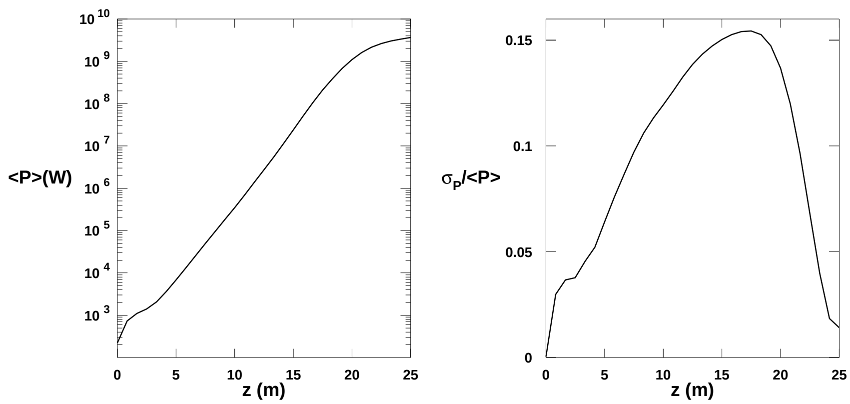

Fig. 4. Evolution of the average emitted power along the wiggler (left) and of the relative power fluctuations along the wiggler (right).

3 Conclusions

In this paper we have studied the operation of the TESLA SASE FEL with the time dependent 2D simulation code GINGER. The main characteristics of the emitted radiation have been analyzed and quantitative estimations for the FEL bandwidth and the influence of fluctuations are presented. The results are generally in good agreement with the available 1D theory, except that a bandwidth narrowing due to diffraction effects is experienced.

References

[1] “A VUV Free Electron Laser at the TESLA Test Facility at DESY: Conceptual Design Report”, DESY PRINT, June 1995, TESLA-FEL 95-03;

[2] R. Bonifacio, C. Pellegrini, L. Narducci, *Opt. Commun.*, **50**, (1984), 373;

[3] K.J. Kim, *Phys. Rev. Lett.*, **57**, (1986), 1871;

[4] R. Bonifacio, L. De Salvo, P. Pierini, N. Piovella and C. Pellegrini, *Phys. Rev. Lett.*, **73**, (1994), 70;

[5] W. Brefeld *et al.*, “Parameter Study of the VUV FEL at the TESLA Test Facility”, these Proceedings.

[6] R.A. Jong, W.M. Fawley, E.T. Scharlemann, “Modeling and Simulation of Laser Systems”, **SPIE 1045**, (1989), 18;

[7] W.M. Fawley, A.M. Sessler, E.T. Scharlemann, in *Proceedings of the 1993 Particle Accelerator Conference*, Washington, D.C., USA, May 17-20, 1993.