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# Shot noise startup of the 6 nm SASE FEL at the TESLA test facility<sup>☆</sup>

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## Abstract

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 the power 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

Currently, DESY [1] and collaborators are designing a VUV Free Electron Laser (FEL) operating in Self Amplified Spontaneous Emission (SASE) mode. 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]. A proper study of the shot noise startup, the correct saturation length and its fluctuations requires that the time dependence of the initial shot noise of the electron phases and slippage effects must be taken into account, both in the theory and in the numerical modeling.

The 1D analysis [4] of a SASE-mode FEL shows that depending on the relative length of the electron pulse with respect to the ‘‘cooperation length’’, defined as  $l_{\text{coop}} = \lambda / (4\pi\rho)$  where  $\rho$  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 beam is dominated by the onset of superradiant spiking, seeded by the shot noise nonuniformities. In the short bunch case by contrast, the output pulse consists of a single, clean superradiant pulse, which will exhibit strong shot-to-shot fluctuations.

Previously (see Refs. [1,5]), the beam and undulator parameters for the TESLA FEL have been extensively studied and optimized (see Table 1) in the framework of the steady state, monochromatic theory and simulation,

where slippage effects are neglected. 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.

In this paper we investigate the time structure and spectral characteristics of the emitted pulses from the TESLA FEL, seeking an estimate of the emitted bandwidth and the amplitude of shot-to-shot fluctuations in output power and saturation length.

## 2. TESLA FEL modeling

Our analysis of the shot noise startup of the TESLA FEL employs the 2D, time-dependent simulation code GINGER [6], which models the interaction of the 3D motion of the beam electrons with an axisymmetric, polychromatic radiation field. The electron and radiation pulse are allowed to travel the wiggler with different velocities. In addition to a time-dependent radiation field, GINGER can also include time-dependent electron beam parameters such as arbitrary current or energy distribu-

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	$2\pi$ mm mrad
rms energy spread	0.1%
rms beam length	50 $\mu\text{m}$ (166 fs)
Undulator wavelength $\lambda_w$	27.3 mm
Undulator strength $a_w$	0.896
FEL parameter $\rho$	$1.67 \times 10^{-4}$
1D gain length $l_{\text{gain}}$	1.3 m
1D cooperation length $l_{\text{coop}}$	0.3 $\mu\text{m}$ (1.02 fs)

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tions. SASE startup from shot noise is modeled by adding random fluctuations to the macroparticle 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 random number seeds to assess the influence of shot-to-shot fluctuations over the relevant quantities of the FEL. The beam parameters were set to the nominal values listed in Table 1.

2.1. Spectrum, bandwidth and superradiant spiking

From the analytical theory of a SASE-mode FEL [3,4], 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:

$$\frac{\Delta\omega}{\omega} \Big|_{\text{HWHM}} = 6\sqrt{\frac{\ln 2}{3}} \rho \sqrt{\frac{I_{\text{gain}}}{z}}, \tag{1}$$

$$\tau_{1/2} = \frac{2}{3} \frac{I_{\text{comp}}}{c} \sqrt{\frac{z}{3 \ln 2}} \sqrt{\frac{z}{I_{\text{gain}}}}, \tag{2}$$

where  $\tau_{1/2}$  is the time required by the electric field autocorrelation function to decay to 0.5 and  $I_{\text{gain}} = \lambda_w / (4\pi\rho)$  is the gain length. These relations neglect 2D effects such as diffraction and emittance, and also presume a cold beam with no energy spread. Thus, Eq. (1) represents an upper limit for the FEL bandwidth, since inclusion of energy spread and 2D effects will decrease  $\rho$  and narrow the gain bandwidth.

In Fig. 1 we compare the bandwidth and the autocorrelation time computed from a series of 15 GINGER simulation with expressions (1) and (2). The error bars on the simulation points denote the magnitude of the rms fluctuations around the average value computed from the runs. As was found in previous GINGER simulations of a 4 nm FEL operating in SASE mode [7],  $\tau_{1/2}$  grows with the  $\sqrt{z}$  dependence predicted in Eq. (2) with an absolute magnitude ~30% greater due to 2D effects. Likewise, we

see that the system experiences a systematic bandwidth narrowing with respect to the 1D theory, due to diffraction. For the parameters used in this simulation the initial Rayleigh range ( $z_r = \pi\sigma^2/\lambda$ ) of the radiation beam is 1.87 m, whereas the 1D gain length is 1.3 m. From the GINGER simulations, the predicted TESLA FEL bandwidth (HWHM) for the power spectrum is approximately 0.1%, which is ~60% that of the “natural” FEL bandwidth given approximately by  $\rho$ , again due to diffraction effects.

The temporal structure of the emitted pulse (see Fig. 2) shows the presence of superradiant spikes seeded from the shot noise on the input electron beam. For the TESLA FEL parameters, the beam length is much larger than the cooperation length and the resulting temporal structure is dominated by sharp superradiant spikes, some of which reach more than 10 GW peak power. This spiking behavior also dominates the spectrum of the emitted radiation in Fig. 2, where the wavelength is resolved in bins of width  $2.73 \times 10^{-4}$  nm. As different shot noise realizations generally lead to different spike positions and relative power, Fig. 2 should be considered as output from a representative “sample” shot.

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 previously predicted by Ref. [4] to be

$$v_g = 3 \frac{v_{\parallel}}{2 + v_{\parallel}/c}. \tag{3}$$

Eq. (3) clearly suggests 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 confirmed by Fig. 3, where the normalized radiation intensity,  $\hat{I}(z, t) = I(z, t) / \langle I(z) \rangle$ , from a TESLA GINGER run 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

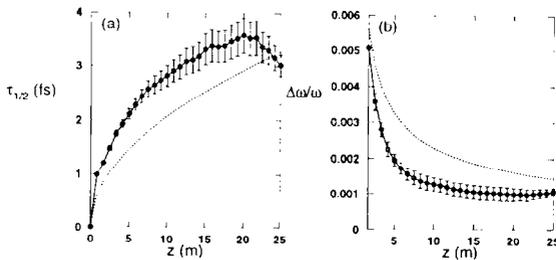


Fig. 1. HWHM of the autocorrelation function (a) and power spectrum halfwidth (b) computed from a series of 2D GINGER runs (solid line and dots with error bars) and the predictions of the 1D analysis (dashed line).

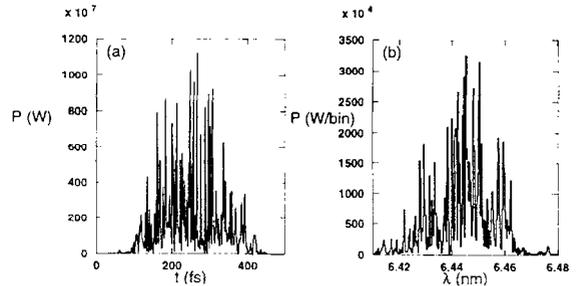


Fig. 2. Predicted temporal structure (a) and spectrum (b) of a typical output radiation pulse of the TESLA SASE FEL.

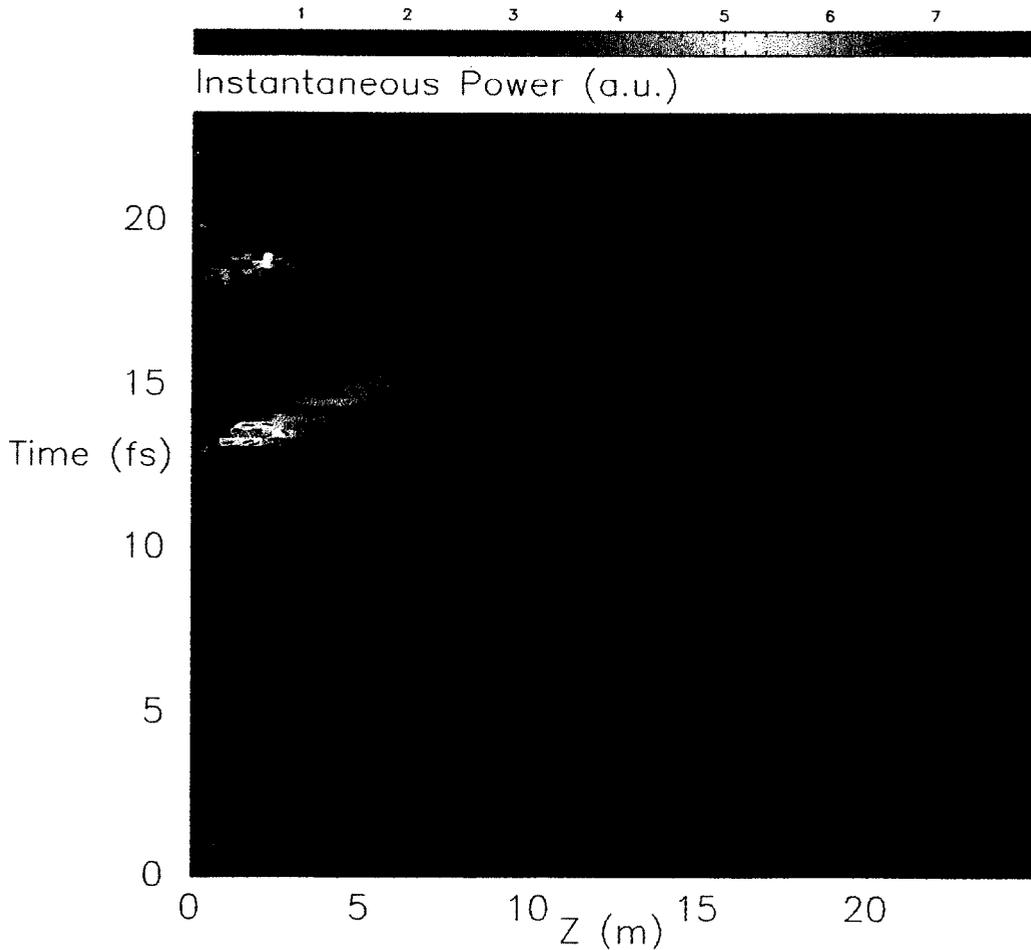


Fig. 3. Plot of the normalized radiation intensity as a function of the wiggler length (horizontal axis) and of the time along a reference frame moving at the light velocity,  $c$  (vertical axis). For a description of the figure, please refer to the text.

superradiant spikes, we have modeled a very thin longitudinal slice of the electron beam only  $7 \mu\text{m}$  long (23 fs), 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  $\tau \propto t - z/c$ ). Near saturation ( $z \approx 20 \text{ m}$ ), nonlinear gain effects become important and the radiation spikes start propagating at  $c$  (i.e. they begin to move horizontally in Fig. 3).

## 2.2. Average emitted power and saturation length fluctuations

Ref. [4]'s 1D analysis of the SASE startup also predicted, in the case where the beam length is much greater than the cooperation length, that shot-to-shot fluctuations for output power and saturation length become quite small. In Fig. 4 we show both the behavior of the average laser power (Fig. 4a) and its relative fluctuations (Fig. 4b) as

functions of distance along the wiggler. As expected, the relative shot-to-shot power fluctuations are greatest in the exponential regime where, for the TESLA, FEL parameters, these can reach a value of 15–20%. Well beyond saturation, the relative fluctuation level drops sharply, indicating that while the necessary saturation length may vary somewhat from shot-to-shot, the saturation power is nearly constant.

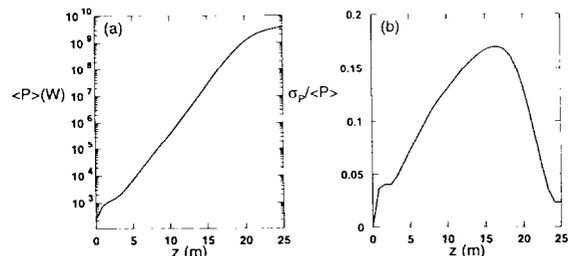


Fig. 4. Evolution of the average emitted power along the wiggler (a) and of the relative power fluctuations along the wiggler (b).

### 3. Conclusions

In this paper we have used the time-dependent, 2D simulation code GINGER to examine the predicted operation of the TESLA SASE-mode FEL. The main characteristics of the emitted radiation, the predicted output FEL bandwidth, the temporal correlation function, and the shot-to-shot power fluctuations are generally in good agreement with the available 1D theory, except that the bandwidth is somewhat narrowed due to diffraction effects. The measured group velocity of the temporal radiation spikes also agrees well with the theory.

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