# Demonstration of Gain Saturation and Controlled Variation of Pulse Length at the TESLA Test Facility FEL

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**Abstract**

We report on experimental evidence that the free-electron laser at the TESLA Test Facility has reached the maximum power gain of $10^7$ while operating in the Self-Amplified Spontaneous Emission mode. Following request of first scientific users, the TTF FEL has been tuned in the wavelength range between 80 and 120 nm (vacuum ultraviolet, VUV), and saturation has been achieved in this entire wavelength range. At saturation the FEL emits short pulses with GW peak power and a high degree of transverse coherence. Also, the paper reports on the demonstration of controlled pulse length variation between 30 fs and 100 fs and on detailed intensity fluctuation studies in this operation mode.

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## 1. Introduction

For most FELs presently in operation [1], the electron beam quality and the undulator length result in a gain in radiation power of up to a few 100% per undulator passage, making it necessary to use an optical cavity and a synchronized multi-bunch electron beam to build up high brightness upon several round-trips of the radiation in the cavity.

If one aims at very short wavelengths, where good mirrors are unavailable, high-gain FEL amplification [2,3] up to laser saturation is required within a single passage of the electron beam. This requires extreme parameters of the electron beam and a long undulator. In this mode, the radiation power P(z) is expected to grow exponentially with the distance z along the undulator.

In order to become independent of the availability of a seed laser providing the input power at the desired wavelength, the spontaneous undulator radiation from the first part of the undulator can be used as an input signal to the amplification process. Since a decade, FELs based on this Self-Amplified-Spontaneous Emission (SASE) principle [4] are considered the most promising candidates for extremely brilliant, coherent light sources with wavelengths down to the Angström regime [5-7].

The TESLA Test Facility (TTF) was set up at DESY in 1993 to provide a testbed for the TESLA linear collider project, especially the superconducting niobium cavities for particle acceleration. In 1994, work began on the test accelerator to extend it into a 300-metre SASE FEL user facility for wavelengths down to 6 nm, comprising all the basic elements that will be needed in a future TESLA X-ray laser.

In a first phase (called TTF1 FEL) [8], now brought to laser saturation, the TTF was equipped with a 15m undulator, a bunch compressor (reducing the bunch length, thus increasing the bunch peak current) and a radiofrequency photocathode electron gun.

## 2. SASE results from TTF1 FEL

### *2.1 Demonstration of FEL Saturation*

FEL action at the shortest wavelength achieved so far has been demonstrated at TTF1 FEL at DESY, Germany [9]. Details of the TTF1 FEL technical layout can be found in Refs. [10,11]. SASE FEL gain was observed up to saturation level in the range from 80 nm to 120 nm, and studied in great detail at wavelengths slightly below 100 nm. Figure 1 presents the measured average energy in the radiation pulse as a function of the active undulator length, defined as the distance over which the electron beam and the photon beam overlap [12]. The active length of the undulator can be varied over a large range by generating suitable orbit displacements of the electron beam, making use of the steering dipole magnets mounted inside the undulator. The radiation energy has been measured within a 10 mm aperture located 12 m behind the undulator by two kinds of detectors: a gold wire mesh scattering light into a microchannel-plate detector [13] and a thermopile [14]. Both agree within 50% in the measured pulse energy. Saturation sets in at the predicted pulse energy level of 30 to 100 μJ, depending on the accelerator tuning.

Figure 1 clearly exhibits the exponential growth of SASE power with the undulator length, yielding a power gain length of $L_g$=67±5 cm. The almost constant level of radiation energy observed for an active undulator length of less than 5 m does not imply that there is no FEL gain in this part of the undulator. In contrast, this is due to the fact that in the first few meters of the undulator, the FEL radiation stays below the energy of spontaneous radiation accumulated over the entire undulator. In fact, extrapolation of the exponential gain curve down to the beginning of the undulator results in a pulse energy of 0.3 pJ, in good agreement with the equivalent input power of the shot noise from spontaneous radiation, estimated for a random electron distribution [3]. The measured power growth is in agreement with the theoretical expectation indicated by the solid line in Fig. 1.

In the context of world-wide efforts towards proof-of-principle experiments on the SASE principle[16,17], the TTF1 FEL result plays a particular role as it demonstrates the SASE FEL principle for the first time in a wavelength regime where it is clearly superior to classical lasers and to optical cavity FELs.

The peak brilliance of the TTF1 FEL photon beam exceeds that of any other source at this wavelength by several orders of magnitude. In particular, in comparison to the performance of state-of-the-art synchrotron radiation storage rings operating at this wavelength, the peak brilliance is larger by 8 orders of magnitude. The peak power is at the 1 GW level, corresponding to $2\times10^{13}$ photons per pulse of 50 fs length (FWHM).

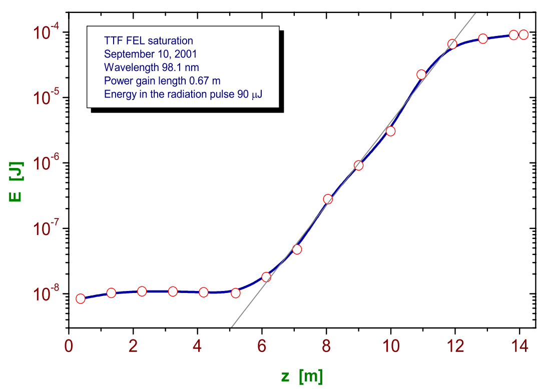


Figure 1: Demonstration of SASE exponential growth and saturation at the TTF1 FEL, DESY, Hamburg [12]. The undulator is approx. 15 m long. The solid line represents a numerical simulation with the code FAST [15].

As a consequence of this extraordinary photon beam quality, first scientific pilot experiments were performed already a few weeks after FEL saturation was demonstrated [18,19]. The operation statistics during one week of user operation is shown in Figure 2. The availability for users was some 65 % during this early week of "routine" operation.

### *2.2 Properties of SASE FEL radiation*

In addition to the energy in each FEL pulse as discussed above, there are three more properties of the FEL radiation relevant to users:

- Transverse coherence
- Longitudinal coherence and/or pulse duration
- Fluctuation behaviour

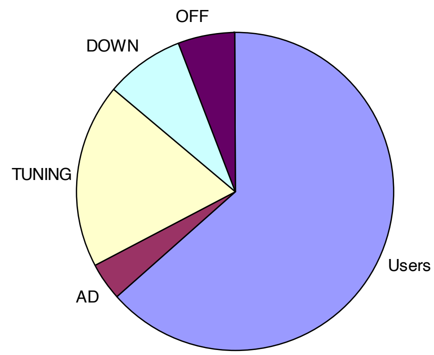


Figure 2: Reliability of TTF1 FEL during one week of operation for scientific users. The statistics was taken only short time after saturation was demonstrated for the first time.

According to FEL theory, one expects a large degree of transverse coherence close to saturation. Figure 3 shows a diffraction pattern of the TTF FEL radiation measured with a gated CCD camera viewing a Ce:YAG screen in a distance of 3 m behind a double slit [20]. The slits are located 12m behind the exit of the undulator. The remarkable high fringe visibility with a modulation depth of up to 70% is a proof of the high degree of transverse coherence. This interpretation has been corroborated by measurement of the opening angle of the radiation [12]. FEL theory expects the transverse coherence to drop significantly when entering the deep saturation regime [21]. This might be the reason for the modulation depth shown in Fig. 3 not being even higher.

Measurements of the spectral distribution are presented in Figure 4 [11]. Single-shot spectra were taken with a monochromator of 0.2 nm resolution equipped with an intensified CCD camera [14]. They show an ensemble of a few peaks which reflect the number M of longitudinal modes in the radiation pulse [22] as it is expected for SASE FEL radiation starting from shot noise.

The pulse duration is a very important parameter but not presently accessible to direct measurement in the time domain. The approximate pulse length $\tau_{rad}$ can however be calculated from the FWHM spectral width $\Delta\omega$ of each peak in the single shot spectrum by $\tau_{rad} \approx 2\pi/\Delta\omega$ . For the spectrum shown in the upper part of Figure 4 this results in $\tau_{rad} \approx 40$ fs. The lower plot in Figure 4 was taken with a bunch compressor setting for longer pulses. Consequently, the number of modes is larger (in average, M=6) and the spectral width $\Delta\omega$ of each spike is smaller, resulting in $\tau_{rad} \approx 100$ fs.

In addition to the fundamental wavelength, we have also observed the $2^{nd}$ harmonics radiation. Figure 5 shows the $2^{nd}$ harmonics spectrum, representing the shortest wavelength generated by a FEL so far. The intensity is a factor 100 to 1000 below that of the fundamental, the uncertainty being determined mainly by the uncertainty of the detector sensitivity at this wavelength.

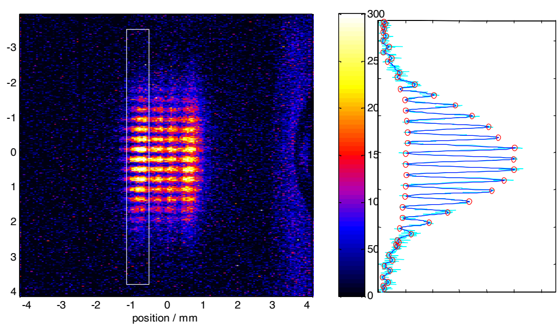


Figure 3, left: Diffraction pattern of a double-slit arrangement illustrating the transverse coherence of the radiation at TTF1 FEL [20]. Each slit is 2 mm wide × 200 µm high, the distance between the slits being 1 mm. Due to the size of the slits it is guaranteed that almost the entire FEL radiation takes part in the interference, thus indicating that the degree of transverse coherence is very high. Right: Intensity modulation within the white rectangle selected in the left.

### *2.3 Fluctuations of FEL pulse energy*

Since SASE FEL radiation results from amplification of spontaneous undulator radiation, the pulse energy is subject to the same statistics. Thus, the spectra shown in Figure 4 will change from pulse to pulse, but they will always stay within the bandwidth of FEL amplification, and the average number of modes will remain unchanged for fixed bunch compressor setting. In addition to fluctuations of the single pulse spectra, there are also fluctuations of the pulse-to-pulse intensity. In the regime of exponential growth, the radiation pulse energy is expected to fluctuate according to a gamma distribution p(E) [22]:

$$p(E) = \frac{M^M}{\Gamma(M)} \left( \frac{E}{\langle E \rangle} \right)^{M-1} \frac{1}{\langle E \rangle} \exp\left( -M \frac{E}{\langle E \rangle} \right) \qquad (1)$$

where <E> is the mean energy, $\Gamma(M)$ is the gamma function with argument M, and $M^{-1} = <(E - <E>)^2>/<E>^2$ is the normalized variance of E.

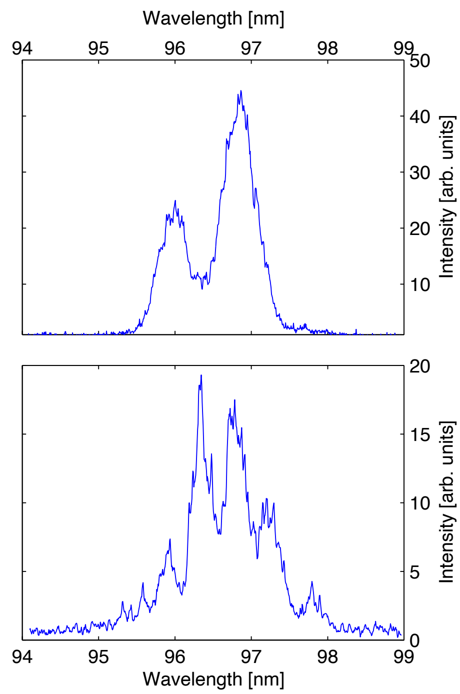


Figure 4: Spectra from short (top) and long (bottom) FEL pulses. It is seen that the number of longitudinal optical modes depends on electron bunch length which can be varied by tuning the bunch compressor settings. For short pulses (duration $\tau_{rad} \approx 40$ fs) there are, in average, 2.6 modes, while in the long bunch pulse setting ($\tau_{rad} \approx 100$ fs, bottom) there are 6 modes in average.

M corresponds to the number of optical modes, which gives an intimate relationship between the number of modes (spikes) derived from single pulse spectra and the fluctuation (and distribution function) of pulse energy. Figure 6 illustrates the pulse--to-pulse fluctuation of SASE pulse energy for different settings of the electron bunch length at TTF1 FEL at DESY [11]. The settings correspond to those used for Figure 4. For this radiation fluctuation analysis, all pulses with charge deviation more than 10 % from the mean bunch charge and all pulses with the electron position at the undulator entrance deviating by more than 50 µm from the mean value were rejected.

If one extracts the mode numbers 6 and 2.6, respectively, from the number of spikes in Figure 4, then there in no more free parameter in the determination of the probability distribution of pulse energies. As seen from Figure 6, the agreement between measurements and the expected distribution calculated from Eq. (1) (solid curves in the histograms) is very good.

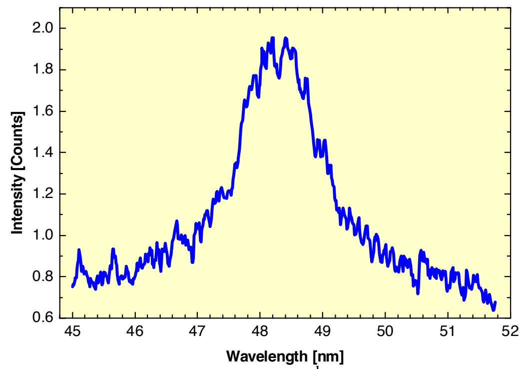


Figure 5: Spectrum of 2$^{nd}$ harmonics radiation from the TTF1 FEL, averaged over 3100 radiation pulses.

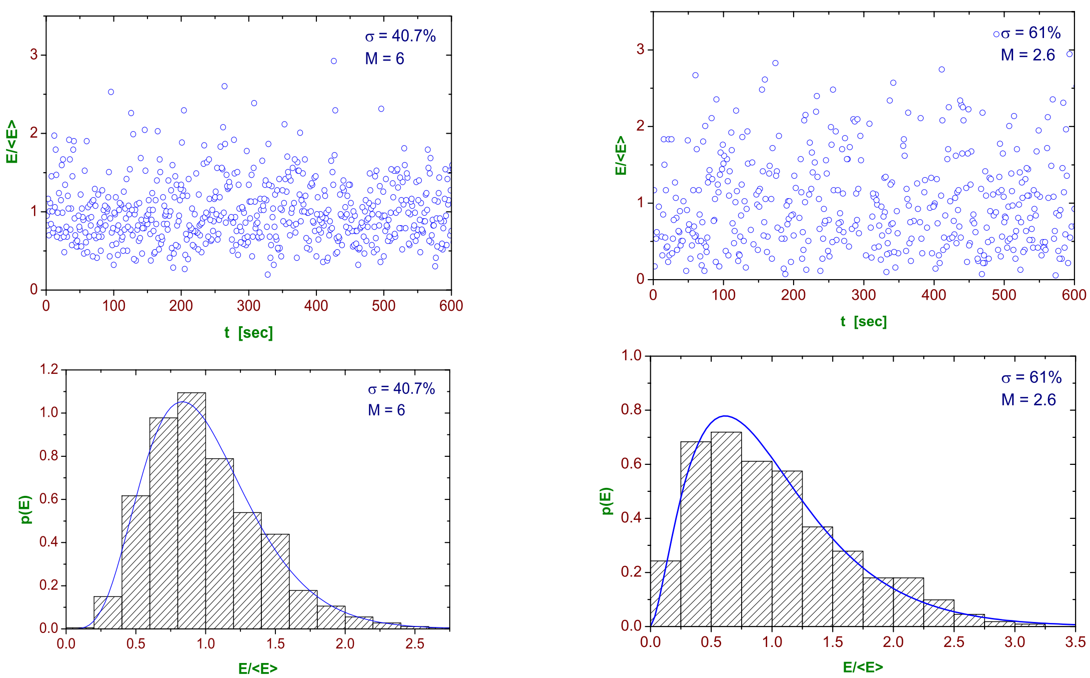


Figure 6: Pulse-to-pulse fluctuation of SASE pulse energy for different settings of electron bunch length at TTF FEL at DESY. Upper row: measured single pulse energy versus time; lower row: histogram of probability distribution extracted from the measurement. The SASE pulses are observed at high gain, but still in the exponential regime, not yet in saturation. The plots on the left hand side illustrate the long pulse case (M=6 modes), while on the right hand side the short pulse mode is shown (M=2.6).

## 3. Outlook

In the next phase of the TTF project, it will be extended into a 300-metre SASE FEL user facility for wavelengths down to 6 nm (TTF2 FEL). Figure 7 shows the linac tunnel (covered with sand for shielding) and the experimental hall for the TTF2 FEL at DESY.

For the TESLA X-ray FEL laboratory proposed as part of the TESLA project, it was originally planned to share the first part of the superconducting electron linac with the linear collider in an alternating rf pulse mode [7], mainly for cost saving reasons. Following a recommendation by the German Wissenschaftrat, this design has now been modified towards a solution where the XFEL has its own linac thus avoiding unwanted coupling between collider and XFEL operation, and to allow for more flexibility in the XFEL beam parameter space. It keeps all the other advantages of a joint project like savings in hardware, personnel and land, potential synergetic effects from various research communities on the same site, and it keeps the option of sharing part of the collider linac in a later stage.

Figure 7: Photography of TTF2 FEL at DESY. The hall in the background is housing TTF1, and in the foreground the experimental hall for scientific users of TTF2 FEL is seen.

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