Scheme for Time-Resolved Experiments Based on the Use of Statistical Properties of the Third Harmonic of the SASE FEL Radiation

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A closer inspection of the statistical properties of the third-harmonic radiation from the SASE FEL reveals that it is possible to select single, temporary coherent radiation spikes by using a simple intensity trigger. A carefully designed optical system for splitting, delaying, filtering, and recombining the radiation would then allow time-resolved measurements with resolution down to the coherence time of the FEL, i. e. a few femtoseconds in the case of the TTF FEL.

The field of synchrotron radiation research has grown rapidly over the last 30 years due to push of the electron (positron) storage ring technology. Three successive generations of synchrotron radiation facilities have provided an increase in brilliance by more than ten orders of magnitude. However, the storage ring technology itself approaches its theoretical limits of performance with respect to average and peak brilliance, as well as to minimal pulse duration. Recently a new era of synchrotron radiation research has begun with first user experiments on the free electron laser (FEL) based on self-amplified spontaneous emission (SASE). The results have been obtained at the Tesla Test Facility (TTF) at DESY using radiation pulses of 80-120 nm wavelength with 30-100 fs pulse duration and peak power at GW level [1]. Compared to present day synchrotron radiation sources its peak brilliance is more than a 100 million times higher, the radiation has full transverse coherence and pulse duration is reduced from the 100 picoseconds down to the sub-100 femtosecond time domain. Furthermore a soft X-ray SASE FEL project with wavelengths down to 6 nm was started at DESY. Commissioning of this facility starts in year 2003.

The discussion in the scientific community over the last two years has produced many ideas for novel applications of the soft X-ray SASE FEL at the TESLA Test FAcility. Brilliance, coherence, and timing down to the femtosecond regime are the three properties which have the highest potential for new science to be explored with soft X-ray FEL. It is obvious that studies of time dependent phenomena can be tackled for the first time which relate the structural aspects with the transition states of those electrons which are responsible for the formation process of intra-molecular bonds, clusters, nanoparticles, liquids, solids and hot dense plasmas. This can possibly show us directly how matter is formed out of atoms.

In this paper we describe a new scheme for time resolved experiments. SASE FELs are capable to produce powerful radiation not only at fundamental frequency, but also at higher harmonics. When a beam is strongly bunched in the sinusoidal ponderomotive potential (formed by the undulator field and the radiation field of the fundamental frequency), the electron beam density spectrum develops reach harmonic contents. Coherent radiation at the odd harmonics can be generated in a planar undulator and significant power levels for the third harmonic can be reached before the FEL saturates [2]. It is expected that the power of the transversely coherent third-harmonic radiation can approach 1% of the fundamental power level at the TTF FEL [3,4].

Using the results of numerical simulations, we illustrate statistical properties of the third-harmonic of SASE FEL radiation. Analysis of data obtained shows that the statistical properties of the third-harmonic radiation from the SASE FEL, operating in

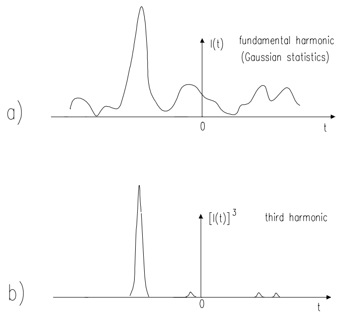

Figure 1. *Illustration of the results of a nonlinear transformation (a) sample function of fundamental harmonic instantaneous intensity for SASE FEL; (b) the nonlinear transform of Fig. (a) representing the third harmonic instantaneous intensity*

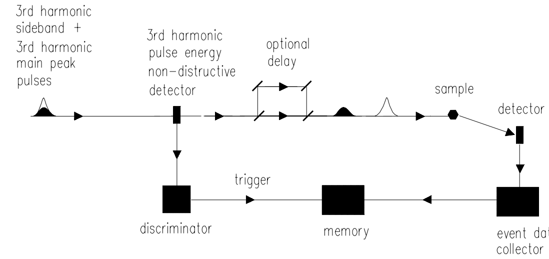

Figure 2. *Experimental setup to obtain single spike pulse duration. Signals from a non-destructive third-harmonic energy pulse detector are used to give trigger. The energy threshold is used to reject events with E smaller than $10\langle E_3\rangle$*

the linear regime, can be used for selection of radiation pulses with a single spike in time domain (of about few femtoseconds in the TTF FEL case). The selection of a single third harmonic radiation spike is based on the specific, instantaneous intensity variation within the radiation pulse. This is illustrated in Fig. 1 for a simple example. Consider the intensity function $I(t)$ of a SASE FEL pulse at the fundamental frequency shown in Fig. 1 (a). In the linear regime of the SASE FEL, the instantaneous intensity of the third harmonic is proportional to $[I(t)]^3$ plotted in Fig. 1 (b). Due to the nonlinear transformation the intensity variation becomes much more pronounced, leading to a distribution which is dominated by a single spike in this case. In practice this will not occur for every pulse, and for those cases where single spike is left, we expect a large intensity fluctuation from pulse to pulse. The main question is how likely we are to observe a single bright spike in the intensity of the third harmonic radiation. Clearly, a necessary condition for this event is that the energy $E_{(3)}$ in the third-harmonic radiation pulse is much larger than the average energy $\langle E_{(3)}\rangle$. The results of numerical simulations confirm these simple physical considerations. The predicted probability for the TTF FEL is about 1 %. This is completely acceptable for practical applications because the superconducting TTF accelerator can deliver up to 72 000 electron bunches per second such that a kHz-level average repetition rate of femtosecond third harmonic pulses can be obtained

In practice single-spike third-harmonic pulses can be identified by measuring their total pulse energy $E_{(3)}$ using a nondestructive technique such as gas ionization. The schematic arrangement of a pump-probe experiment employing these femtosecond pulses is shown in Fig. 2. A multilayer singles out the third harmonic radiation, a gas cell at low pressure measures the pulse energy, then the pulse is split into two parts which are delayed with respect to each other and then recombined on the sample. Only such data are selected for which the pulse energy exceeded a certain threshold, typically of the order of 10 $\langle E_{(3)}\rangle$.

To describe the single-spike selection, we should define the degree of contrast. Because of our lack of knowledge of the detailed microscopic structure of the radiation pulse intensity profile, it is necessary to discuss the properties of single-spike selection in statistical terms. SASE radiation is a stochastic object and at a given time it is impossible to predict the amount of energy which flows to a detector. First we should remember that the initial modulation of the electron beam is defined by the shot noise and has a white spectrum. Second, we obtain that the high-gain FEL amplifier cuts and amplifies only a narrow frequency band of the initial spectrum $\Delta\omega/\omega \ll 1$. In the time domain, the temporal structure of the fundamental harmonic radiation is chaotic with many random spikes, with a typical duration given by the inverse width of the spectrum envelope. Even without performing numerical simulations, we can describe some general properties of the fundamental harmonic of the radiation from the SASE FEL operating in the linear regime. Indeed, in this case we deal with Gaussian statistics. As a result, the probability distribution of the instantaneous radiation intensity I should be the negative exponential probability density distribution: $p(I) = \langle I\rangle^{-1}\exp(-I/\langle I\rangle)$. Here one should realize clearly that the notion of instantaneous intensity refers to a certain moment in time, and that the analysis must be performed over an ensemble of pulses. Also the energy in the radiation pulse E should fluctuate in accordance with the gamma distribution [5]:

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

where $\Gamma(M)$ is the gamma function of argument M, and $1/M = \langle(E-\langle E\rangle)^2\rangle/\langle E\rangle^2$ is the normalized dispersion of the energy distribution. These properties are well known in statistical optics as properties of completely chaotic polarized radiation [6].

If we define the contrast C as the ratio of number of photons in main spike to the total number of photons in the pulse we find that $\langle C\rangle$ asymptotically approaches unity at the ratio $E_{\mathrm{th}}/\langle E_3\rangle$ increases, where E_{th} is the threshold level of the third-harmonic energy pulse discriminator. Clearly, the larger the threshold level of discriminator $E_{\mathrm{th}}/\langle E_3\rangle$, the larger the number of shots per one trigger pulse N_{sh}. Note that the number of degrees of freedom M of the fundamental radiation pulse is a parameter of the functions $\langle C\rangle = F(M, E_{\mathrm{th}}/\langle E_3\rangle)$, $\langle N_{\mathrm{sh}}\rangle = f(M, E_{\mathrm{th}}/\langle E_3\rangle)$ as indeed we might have anticipated.

In Fig. 3 and 4 one can see the basic characteristics of the single-spike pulse selection process. The dependence of the degree of the contrast $\langle C\rangle$ on the value of energy threshold $E_{\mathrm{th}}/\langle E_3\rangle$ is presented in Fig. 3. It is seen that the contrast increases with an increase in the value of energy threshold and it asymptotically approaches to unity. Simulations at different values of M show that the degree of contrast does not differ significantly when the number of modes is within the limits $10 < M < 20$. Figure 4 shows plots

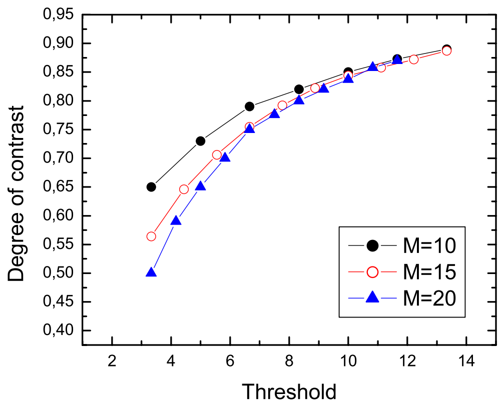

Figure 3. *Degree of contrast* $\langle C\rangle$ *versus energy threshold* $E_{\mathrm{th}}/\langle E_3\rangle$

of the number of shots per one trigger pulse $\langle N_{\mathrm{sh}}\rangle$ on the $E_{\mathrm{th}}/\langle E_3\rangle$ for several values of parameter M. From Fig. 4 it is quite clear that the dependence of $\langle N_{\mathrm{sh}}\rangle$ on the number of modes M is rather strong and can not be ignored.

With the preceding results in hand, it should now be possible to estimate, for example, the pump-probe pulse repetition rate. In the TTF SASE FEL case, the number of modes in the fundamental radiation pulse at wavelength 30 nm is about $M \simeq 10-20$. Suppose that we wish to achieve a degree of contrast of 80%. The discriminator threshold required to achieve this contrast is about $E_{\mathrm{th}}/\langle E_3\rangle \simeq 9$. If the number of modes is close to $M \simeq 15$, plot in Fig. 4 shows that number of shots per one trigger pulse required is about 500 shots. Hence the pump-probe pulse repetition rate is still high (of about 50 single-spike pulses per second). On the other hand, if the contrast of interest is only 70% , the number of shots is about $\langle N_{\mathrm{sh}}\rangle \simeq 100$ and pump-probe pulse repetition rate increases up to a few hundred per second.

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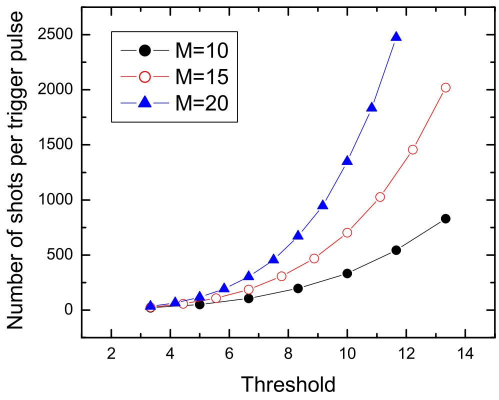

Figure 4. *Number of shots per one trigger pulse* $\langle N_{\rm sh} \rangle$ *versus energy threshold* $E_{\rm th}/\langle E_3 \rangle$

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