EXPECTED PROPERTIES OF RADIATION FROM VUV-FEL AT DESY (FEMTOSECOND MODE OF OPERATION)

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Abstract

For the next three years the nominal "long pulse" (200 fs) mode of FEL operation at VUV-FEL, based on a linearized bunch compression, is not available due to the lack of a key element – a 3rd harmonic RF cavity. Essentially nonlinear compression leads naturally to a formation of a short high-current leading peak (spike) in the density distribution that produces FEL radiation. Such a mode of operation was successfully tested at VUV-FEL, Phase I. In this paper we present optimized parameters of the beam formation system that allow us to get a current spike which is bright enough to get SASE saturation for the VUV-FEL, Phase 2 at shortest design wavelength down to 6 nm. The main feature of the considered mode of operation is the production of short (15-50 fs FWHM) radiation pulses with GW-level peak power that are attractive for many users. Main parameters of the SASE FEL radiation (temporal and spectral characteristics, intensity distributions, etc.) are presented, too.

INTRODUCTION

The vacuum ultra-violet (VUV) free-electron laser (FEL) at the TESLA Test Facility (TTF), Phase I has demonstrated saturation in the wavelength range 80-120 nm based on the self-amplified spontaneous emission (SASE) principle [1, 2, 3]. It was not simply a proof-of-principle experiment as it was planned at an early stage of the project. TTF FEL at DESY demonstrated an ultimate performance for this class of coherent radiation sources in the VUV wavelength range. It has been realized experimentally a unique mode of operation of SASE FEL producing radiation pulses of ultimately short duration, i.e. about coherence time. Each radiation pulse of about 40 fs duration consisted of one-two wave packets. In other words, TTF FEL produced radiation pulses close to Fourier limit. The degree of transverse coherence was pretty high, too. Peak power (averaged over ensemble) exceeded 1.5 GW. Thus, TTF FEL produced nearly completely coherent (longitudinally and transversely) VUV radiation pulses with ultimate peak power. Number of photons in one mode exceeded the value of 10^{13}. Excellent properties of FEL radiation were used in the pioneering user experiments [4, 5].

The beam dynamics in TTF1 linac was nontrivial [3]. Due to nonlinear compression and small local energy spread the short high-current (3 kA) leading peak (spike) in density distribution was obtained. Despite strong collective effects (of which the most critical was the longitudinal space charge (LSC) after compression) this spike was bright enough to drive FEL process up to the saturation for the wavelengths around 100 nm.

For the next few years the nominal "long pulse" (200 fs) mode of operation of the VUV-FEL at DESY (TTF2), based on a linearized bunch compression, is not available due to the lack of a key element – a 3rd harmonic RF cavity. Essentially nonlinear compression leads naturally to a formation of a short high-current leading peak (spike) in the density distribution that produces FEL radiation. A short current spike regime is the natural solution for producing short SASE pulses (that are requested by many users), provided that collective effects are tolerated.

In this paper we present the results of TTF2 linac optimization (with the codes Astra [7] and `elegant` [8]) for the short spike regime. Choosing appropriate injector settings and using two bunch compressors, one can tolerate collective effects on beam dynamics without 3rd harmonic cavity. SASE FEL process is simulated with the code FAST [9]. It is shown that the FEL can safely saturate even at the shortest design wavelength, 6 nm. SASE FEL output parameters (peak power, pulse duration, spectra, angular distributions etc.) are calculated for 30 nm and 6 nm. With a GW level of the peak power one obtains short pulses in the range 15-50 fs FWHM.

OPTIMIZATION OF TTF2 LINAC

The nominal design of TTF2 [6] (see Fig. 1) assumes the optimized injector and a linearized compression in two bunch compressors, BC2 and BC3, with the help of the 3rd harmonic superconducting RF cavity being developed. For the next few years this cavity will not be available, so that this regime cannot be realized. The main potential advantages of such a regime (as compared to a short spike regime) from the point of view of accelerator physicists

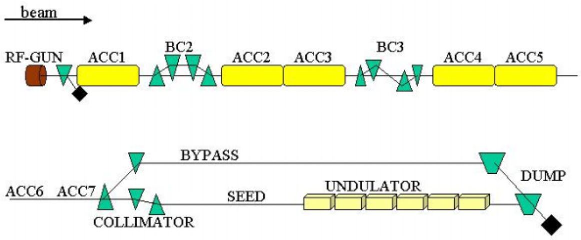

Figure 1: Schematic layout of the TESLA Test Facility, Phase 2.

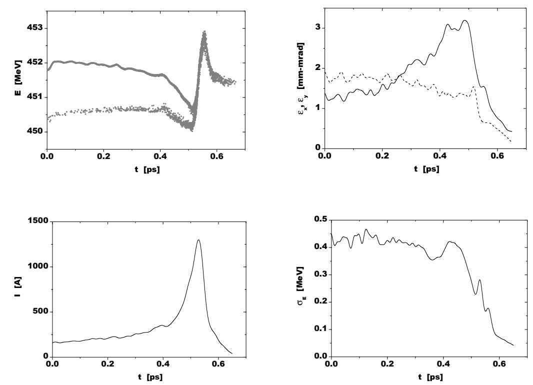

Figure 2: Phase space distribution, current, slice emittance and slice energy spread along the bunch at the undulator entrance. Bunch charge is 0.5 nC. Bunch head is on the right. Only small part of the bunch is shown.

are: longer high-current (lasing) part of the bunch (with rms length σ_z) is less sensitive to coherent synchrotron radiation (CSR) and LSC (for a given current these effects scale as $\sigma_z^{-1/3}$ and σ_z^{-1}, respectively); standard diagnostics (BPMs, screens) is better suited for such a regime since a larger fraction of total charge contributes to the lasing and one can hope that slice parameters do not differ strongly from projected ones. On the other hand, the short spike regime does not require very fine RF phase tuning and is, therefore, less sensitive to RF jitters (typical requirement for phase stability is $\delta\phi \ll 2\pi\sigma_{z0}/\lambda_{RF}$, where σ_{z0} is bunch length before compression and λ_{RF} is the wavelength of the accelerating RF field). From users' point of view, the short spike regime is advantageous for many experiments.

Two regimes of the spike formation were studied experimentally already at TTF1: the nominal one with only one bunch compressor (BC2) [3] and the alternative one with two bunch compressors (BC1 and BC2). The latter regime allowed one to get a longer spike after BC2 due to a mild preliminary compression in BC1. The collective effects could be efficiently tolerated this way. The question arises: can the TTF1 experience be extrapolated to a different layout of TTF2 and much shorter wavelengths? In this paper we give a positive answer: by using the optimized injector and two bunch compressors (BC2 and BC3) one can obtain a short current spike and preserve its quality at the level sufficient for lasing at short wavelengths (down to 6 nm, the shortest design wavelength of TTF2).

The optimization of the beam dynamics in TTF2 linac was done for the 30 nm case (beam energy 450 MeV). The following simulation scheme was used in order to include the most important effects. Simulation of the initial part of the machine (up to the first quadrupole) was performed with Astra. The injector settings and beam parameters can be found in [10]. Then the tracking was done with `elegant` up to the end of the 4th accelerating module, including CSR effects in both bunch compressors. The last part of the machine, up to the undulator entrance, was simulated with Astra using a simplified lattice (excluding dogleg) in order to take into account space charge effects. The low-current long tail of the bunch was cut out in this last part of the simulation.

For the nominal operation point the following main parameters were chosen. A Gaussian laser pulse with the 4 ps rms duration was used to extract 0.5 nC from the gun (the other injector settings and beam parameters at the exit of ACC1 can be found in [10]). Accelerating gradient is about 15 MV/m in the first three accelerating modules (ACC1-3) and 8 MV/m in ACC4. The phase of ACC1 is 8 degrees off-crest, in ACC2-4 beam is accelerated on-crest. The beam energy is about 125 MeV, 380 MeV and 450 MeV after ACC1, ACC3 and ACC4, respectively. The R_{56} are about 18 cm and 10 cm for BC2 and BC3, respectively[1]. For these settings we have a mild compression in BC2, and then a high-current spike (containing about 10 % of the total charge) in BC3. Combination of two phases, ACC1 and ACC2-3, defines a slice (in the initial distribution) of which the spike is made.

Slice parameters in the front part of the bunch at the undulator entrance are shown in Fig. 2. For the slice with a maximal current (1.3 kA) the mean geometric of x- and y-normalized emittances is about 1.5 mm-mrad, and the local energy spread is about 300 keV. One may notice unusual drop of slice emittances (well below the value of emittance in the best slice before compression) in the bunch head. This behavior does not violate Liouville's theorem (stating that phase space density is conserved, not the slice parameters) and is explained by specific correlations between longitudinal and transverse phase spaces in the injector (see [3] for the detailed explanation). Longitudinal phase space in Fig. 2 looks similar to that simulated in [3] for TTF1 case. However, the influence of energy chirp on the FEL saturation length for 30 nm case is a small correction, i.e. it is not that dramatic as it was in TTF1 case. It may become a dominating effect (for 30 nm case) if one does not tune the machine properly, i.e. if the spike becomes too sharp.

Although we did the simulations for 30 nm case (450 MeV), we can do a simple generalization towards higher energies. We assume that machine settings are the same up to the end of BC3. Then we accelerate the beam up to the required energy (say 1 GeV). Since space charge effect cannot be worse for higher energies, we can use the results of Fig. 2, and simply move the energy up. Although this is a pessimistic estimate, in the following section we show that even in this case one can safely reach saturation at 6 nm.

To illustrate the sensitivity of the FEL operation to the non-optimal settings of the accelerator, we simply changed the charge extracted from the cathode, keeping other ma-

[1] In [10] the R_{56} of the BC3 is 4.9 cm. In order to get the same current one should then accelerate beam off-crest in ACC2-3.

chine parameters untouched (see [11]) for more details). One can see from the next section that the FEL saturation at 30 nm should be relatively safely achieved, while a 6 nm case must be carefully optimized.

RADIATION PROPERTIES

Simulations of the FEL have been performed with three-dimensional, time-dependent simulation code FAST [9] using bunch parameters shown in Fig 2 for 0.5 nC case. In addition, a (non-optimized) 1 nC case was simulated in order to show the total sensitivity of the machine to non-optimal conditions [11]. Summary of the calculated FEL properties is shown in Table 1. More detailed information about the radiation properties is presented in graphical form in Figs. 3-5.

Figure 3 shows mean energy in the radiation pulse and rms fluctuations as functions of position along the undulator. One can see that for both charges saturation is reached in the middle of the undulator for the wavelength of 30 nm. For the wavelength of 6 nm the (optimized) 0.5 nC beam has a visible advantage, saturation is reached at the end of the 5th undulator module. The plots in Fig. 3 present numerical experiment of a specific measurement being planned for TTF2 (similar procedure has been used at TTF1). The interaction length is to be changed by means of switching on electromagnetic correctors installed inside the undulator. The value of the orbit kick provided by a corrector is sufficient to stop FEL amplification process downstream the corrector. The radiation energy is measured by means of a radiation detector installed 18.5 m downstream the undulator. When the FEL interaction is suppressed along the whole undulator length, the detector shows the level of spontaneous emission collected from the full undulator length into the detector aperture. Then FEL interaction is to be switched on gradually along the undulator and the energy in the radiation pulse is recorded. Contribution of spontaneous emission depends on the angular acceptance of the detector. In our simulations we used 10 and 5 mm diameter aperture for 30 and 6 nm wavelength, respectively.

The energy in the radiation pulse fluctuates from shot to shot. The plots for standard deviation σ, are presented in Fig. 3. At the initial stage fluctuations are defined mainly by the fluctuations of the undulator radiation in the central cone. When the FEL amplification process takes place, fluctuations of the radiation energy are mainly given by the fundamental statistical fluctuations of the SASE FEL radiation [12]. A sharp drop of the fluctuations in the last part of the undulator is a clear physical confirmation of the saturation process. When the FEL amplifier operates in the high-gain linear regime, the value of parameter $M = 1/\sigma^2$ gives the number of spikes (wave packets) in the radiation pulse. This allows one to estimate the radiation pulse length as $\tau_{\rm rad} \simeq ML_{\rm c}/c$. The cooperation length is about $L_{\rm c} \simeq 2\lambda L_{\rm g}/\lambda_{\rm u}$. The value of the power gain length $L_{\rm g}$ can be measured experimentally from the gain curve (see Fig. 3). Such an experimental technique has been proven to be very useful during operation of TTF FEL, Phase I [1, 2, 3].

Table 1: Expected parameters of the TTF FEL, Phase 2 (femtosecond mode of operation)

	Units	30 nm option	6 nm option
beam energy	MeV	450	1000
bunch charge	nC	0.5-1	
peak current	kA	1.3-2.2	
normalized emittance	μm	1.5-3.5	
bunch spacing	μs	1.6-3.5	
# of bunches in a train	#	up to 1800	
repetition rate	#	up to 10 Hz	
undulator period	cm	2.73	
undulator peak field	T	0.47 T	
averaged beta-function	m	4.5	
undulator length	m	27	
radiation wavelength	nm	30	6
power gain length	m	0.7-0.9	1.1-1.6
saturation length	m	18-22	22-32
radiation pulse energy	μJ	50-150	
radiation pulse duration	fs	15-50	
radiation peak power	GW	2-4	
radiation average power	W	up to 2 W	
spectrum width	%	0.8	0.4-0.6
radiation spot size	μm	180-270	120-180
angular divergence	μrad	70-80	25-35

Properties of the radiation at 30 nm wavelength are expected to be similar to those obtained at TTF1 [1, 2, 3]. Number of modes in the radiation pulse is expected to be $M = 3 \dots 6$ depending on the tuning of the driving beam. As it was demonstrated at TTF FEL Phase I, we predict some suppression (down to 40%) of the fluctuations of the radiation energy after a narrow band monochromator [13]. Radiation properties are expected to be distorted by the energy chirp along the lasing part of the electron bunch. First, this is widening of the radiation spectrum. Second, spatial distortion of the beam radiation mode takes place. This is reflected by the angular distribution of the radiation intensity in the far zone – appearance of the tails at large angles.

SUMMARY

Conclusion of our study is optimistic: femtosecond mode of operation will allow overlapping complete operating wavelength range of the TTF FEL. Minimum wavelength will be mainly limited by the available energy of the electron beam. Starting of operation at 30 nm wavelength seems to be a reliable way to get success for the first lasing. The next milestone for the TTF FEL would be the operation at the wavelength around 12 nm (linac energy about 700 MeV) that can be done without installation of additional hardware. With the third harmonic of the radiation

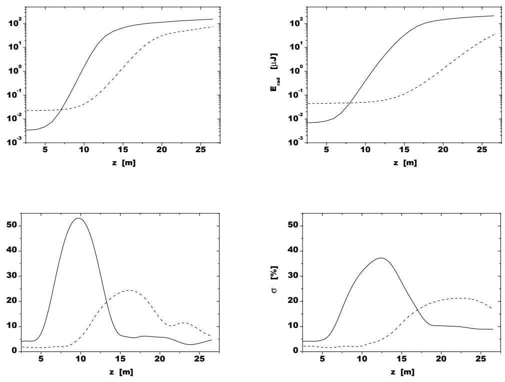

Figure 3: Top: energy in the radiation pulse versus undulator length. Bottom: fluctuations of the energy in the radiation pulse versus undulator length. Left column corresponds to the case of bunch charge 0.5 nC (see Fig. 2). Right column corresponds to the case of bunch charge 1 nC. Solid and dashed lines refer to the radiation wavelength 30 nm and 6 nm, respectively.

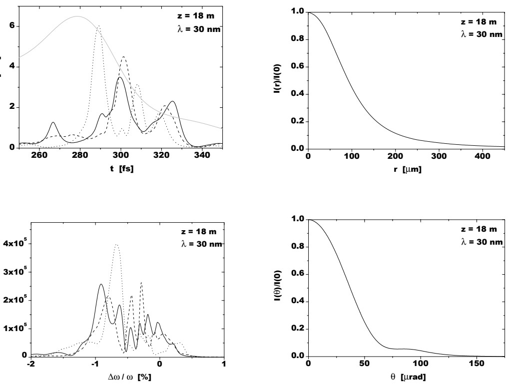

Figure 4: Summary of the radiation properties of TTF FEL operating in the nonlinear regime at the undulator length of 18 m. Bunch charge is 0.5 nC (see Fig. 2). Radiation wavelength is 30 nm. Left column: temporal and spectral structure of the radiation pulse. Three single shots are shown with different line shapes (solid, dashed, and dotted). Grey line shows profile of the bunch current. Right column: averaged distribution of the radiation intensity in the near and far zone.

it would be possible to reach the “water window” with the pulse duration on a 10 fs scale. This will greatly extend possibilities for user experiments. In principle, saturation at 6 nm can be achieved with five undulator segments. Replacement of the last segment with frequency doubler [14] will allow reaching 3 nm wavelength with GW level of output power.

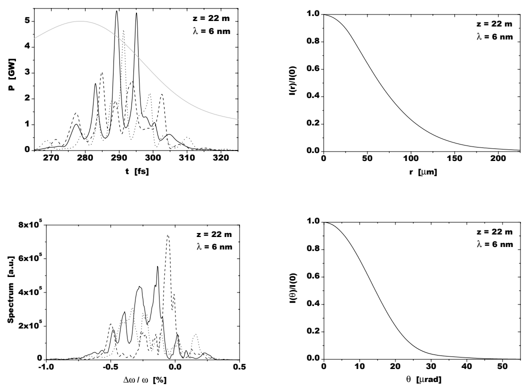

Figure 5: Summary of the radiation properties of TTF FEL operating in the nonlinear regime at the undulator length of 22 m. Bunch charge is 0.5 nC (see Fig. 2). Radiation wavelength is 6 nm. Left column: temporal and spectral structure of the radiation pulse. Three single shots are shown with different line shapes (solid, dashed, and dotted). Grey line shows profile of the bunch current. Right column: averaged distribution of the radiation intensity in the near and far zone.

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