Properties of the radiation from VUV-FEL at DESY (femtosecond mode of operation)

E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov
Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

Abstract

Present bunch compression scheme at the VUV FEL is essentially nonlinear and naturally results in a formation of a short high-current leading peak (spike) in the density distribution that produces FEL radiation. The main feature of the considered mode of operation is the production of short, down to 20 fs radiation pulses with GW-level peak power and contrast of 80%.

INTRODUCTION

The project of the VUV FEL at DESY is realized in two phases. Phase I (1999-2002) served for a proof-of-principle of SASE FEL operation and for system tests of the hardware. Phase II of the VUV FEL has been built as an extension of Phase I to shorter wavelengths (down to 6 nm) and will be used as the first VUV FEL user facility starting in spring, 2005. VUV FEL Phase I demonstrated unique femtosecond mode of operation which was not considered at an early design stage of the project [1, 2]. Thorough analysis has shown that due to nonlinear compression and small local energy spread the short high-current (3 kA) leading peak (spike) in the bunch density distribution was produced by beam formation system. Despite strong collective effects (of which the most critical was the longitudinal space charge after compression) this spike was bright enough to drive FEL process up to the saturation for the wavelengths around 100 nm [3]. In addition to the possibility for production of high-power femtosecond pulses this mode of FEL operation demonstrated high stability with respect to drifts of machine parameters. Successful operation of the VUV FEL Phase I in the femtosecond regime encouraged us to extend such a mode of operation for shorter wavelengths. Relevant theoretical study has been performed in [5]. It has been found that the beam formation system of the linac can be tuned for production of bunches with a high-peak-current spike capable for effective driving of the FEL process such that the VUV FEL can safely saturate even at the shortest design wavelength of 6 nm with a GW level of the peak power in short pulses of 15-50 fs duration.

Optimum parameters determined in [5] have been chosen for the commissioning of the VUV FEL. First experimental results obtained at the VUV FEL operating at the radiation wavelength around 30 nm did show perfect agreement with predictions [6]. Commissioning of the VUV FEL proceeded in parallel with first user experiments. Our contacts with user community did show that planning of future user experiments at the VUV FEL requires more detailed knowledge of the expected statistical properties of the source, and present paper covers this gap.

RADIATION PROPERTIES

Operation of the bunch formation system has been studied in details in [5]. We considered two possible options of operation with a nominal charge of 0.5 nC, and with higher charge, 1 nC (see Fig. 1). Both options can be realized experimentally and provide different modes of the VUV FEL operation in terms of output characteristics of the radiation. Complete set of the electron beam properties at the undulator entrance can be found in [5].

Some output characteristics of VUV FEL (energy in the radiation pulse, angular divergence, etc) have been described in our previous paper [5]. Here we present more detailed features of the radiation related to ultra-short pulse duration. To extract more detailed information about photon beam properties, we performed 500 statistically independent runs with FEL code FAST [7]. Figure 2 shows mean energy in the radiation pulse and rms fluctuations as functions of position along the undulator. One can see that for both charges (0.5 and 1 nC) saturation is expected in the middle of the undulator for the wavelength of 30 nm.

Expected level of the output energy at saturation is approximately the same, of about 100 μJ, while the saturation length is shorter for the case of 0.5 nC. More pronounced

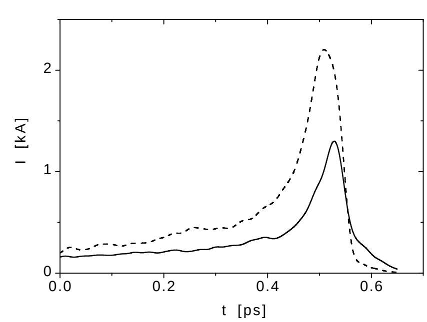

Figure 1: Current along the electron bunch. Solid and dashed line correspond to bunch charge 0.5 and 1 nC, respectively. Bunch head is on the right side

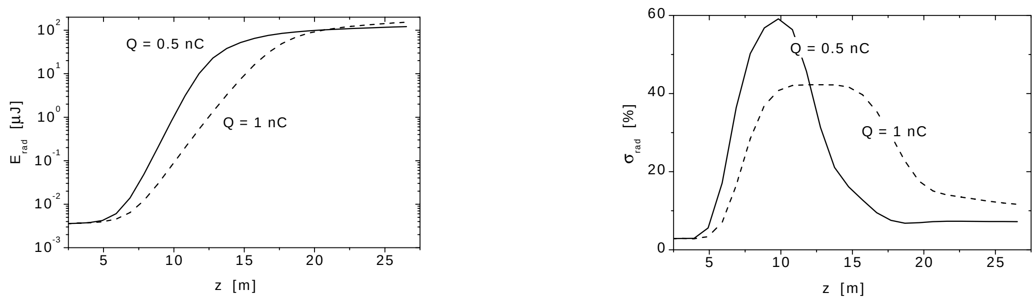

Figure 2: Expected performance of the VUV FEL at the radiation wavelength 30 nm. Left: energy in the radiation pulse versus undulator length. right: fluctuations of the energy in the radiation pulse versus undulator length. Solid and dashed lines refer to bunch charge 0.5 nC and 1 nC, respectively

difference is in the behavior of the fluctuations of the radiation energy. Larger level of fluctuations in the linear regime indicates that the radiation pulse length should be shorter for the case of 0.5 nC. Numerical analysis shows that in the linear regime the VUV FEL driven by 0.5 nC electron bunches reproduces twice shorter, down to 20 fs (FWHM) radiation pulses (see Fig. 3). The reason for this is that 0.5 nC bunch has more narrow lasing part. Group velocity of the radiation in the high gain FEL regime is much less than kinematic slippage which prevents lengthening of the radiation pulse [8]. Figure 4 shows time structure of radiation pulses at saturation. We find that at saturation the 0.5 nC case has no benefit in terms of pulse duration. Radiation pulse lengthening occurs mainly due to two effects. First, there is no suppression of the group velocity in the nonlinear regime. Second, tail of the electron bunch starts to produce visible amount of radiation. Using plots in Fig. 5 one can trace evolution of the radiation pulse envelope from linear regime to the saturation. Figure 6 shows evolution of the FWHM pulse length along the undulator.

For time-resolved experiments it is important to know the degree of contrast of the radiation pulse, i.e. ratio of the

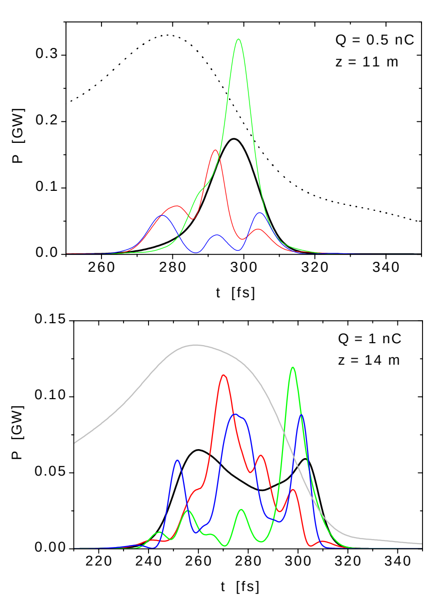

Figure 3: Radiation power along the bunch for the VUV FEL operating in the linear regime. Top: bunch charge 0.5 nC, $z = 11$ m. Bottom: bunch charge 1 nC, $z = 14$ m. Thin curves show single shots. Bold curves show averaged profiles. Grey curves show profile of electron bunch.

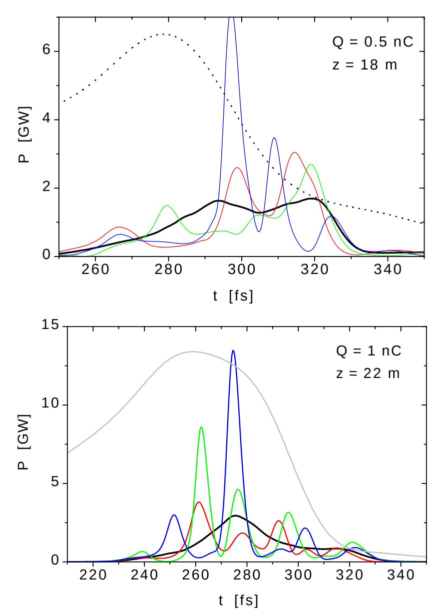

Figure 4: Radiation power along the bunch for the VUV FEL operating in the saturation regime. Top: bunch charge 0.5 nC, $z = 18$ m. Bottom: bunch charge 1 nC, $z = 22$ m. Thin curves show single shots. Bold curves show averaged profiles. Grey curves show profile of electron bunch.

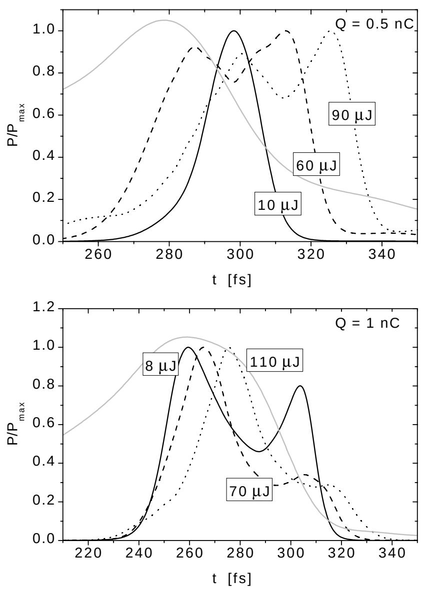

Figure 5: Evolution of the radiation pulse shape versus average energy in the radiation pulse. Grey line shows electron bunch profile. Top: bunch charge is 0.5 nC. Bottom: bunch charge is 1 nC

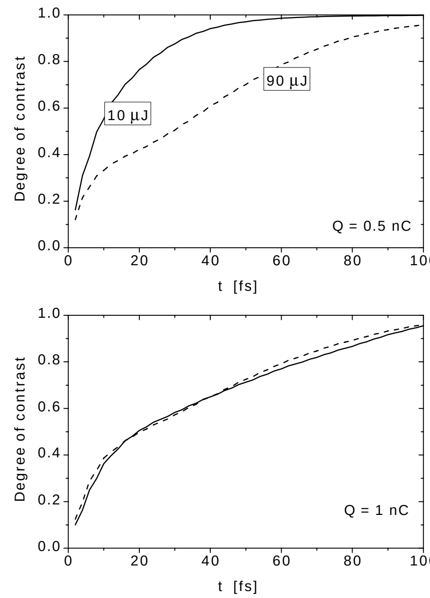

Figure 7: Degree of contrast versus time gate around a spike with maximum intensity. Top: bunch charge is 0.5 nC. Bottom: bunch charge is 1 nC. Solid and dashed line corresponds to the case of the linear regime and saturation, respectively

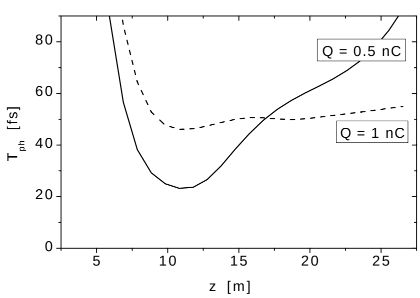

Figure 6: Evolution of the FWHM radiation pulse length along undulator. Solid and dashed line correspond to the charge of 0.5 and 1 nC, respectively

radiation energy within a time window around a spike with maximum peak power to the total energy in the radiation pulse. Relevant function is plotted in Fig. 7.

The radiation from SASE FEL operating in the linear regime possesses properties of completely chaotic polarized light [8, 9]. This means that probability distribution of the energy in the radiation pulse follows gamma-distribution.

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

where $\Gamma(M)$ is the gamma function, $M = 1/\sigma_E^2$, and $\sigma_E^2 = \langle (E - \langle E \rangle)^2 \rangle / \langle E \rangle^2$. The number of mode, M, reaches its minimum value in the end of the linear regime (see Fig. 2). Simulations show that statistics of the radiation change drastically near the saturation point on a scale of one field gain length. Such a fast drop of fluctuations is the feature of ultra-short pulse duration [10]. Nature of this phenomenon can be understood by analyzing structure of the radiation pulse (see Fig. 4). amplification process enters nonlinear stage, radiation power is saturated, and pulses sleep forward. Further growth of the total energy occurs due to the radiation of bunched electron beam. Since maximal bunching of the electron beam is limited to the unity, this additional radiation is well stabilized, leading to the overall stability of the total energy in the radiation pulse.

Radiation spectra for VUV FEL operating in the linear regime and saturation are shown in Fig. 8 and 9. One can obtain that spectrum bandwidth for 1 nC case is visibly wider. This is a consequence of larger energy chirp along the lasing part of the electron bunch which appears due to more stronger space charge effects.

Another subject is statistics of SASE FEL radiation filtered through narrow-band monochromator. In the linear stage of SASE FEL operation the value of normalized energy deviation is equal to unity, and energy fluctuates in accordance with negative exponential distribution. This is consequence of the fact that in this case radiation is gaussian random process. However, in the nonlinear mode of operation we obtain significant decrease of fluctuations when the pulse length goes down (see Fig. 10). This effect

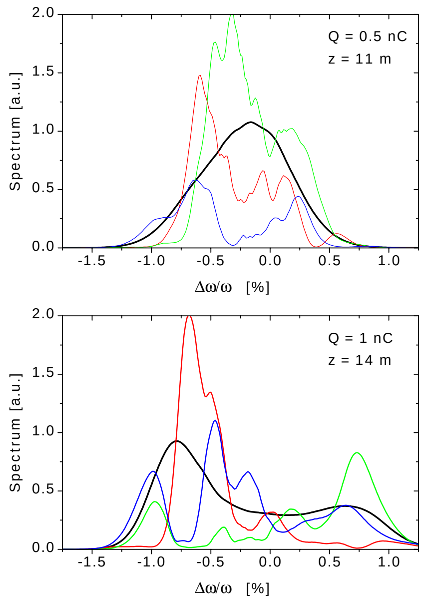

Figure 8: Radiation spectrum of the VUV FEL operating in the linear regime. Top: bunch charge 0.5 nC, $z = 11$ m. Bottom: bunch charge 1 nC, $z = 14$ m. Thin curves show single shots. Bold curves show averaged profiles

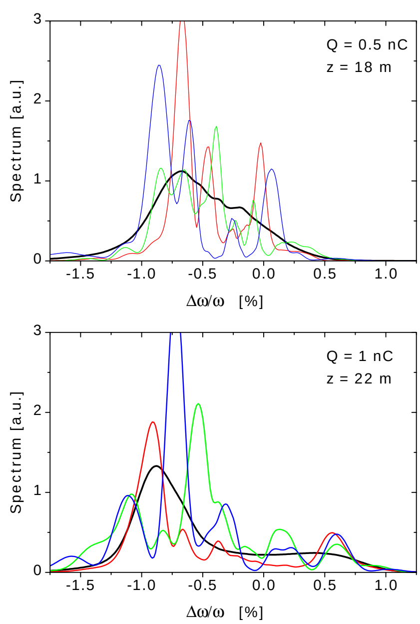

Figure 9: Radiation spectrum of the VUV FEL operating at the saturation. Top: bunch charge 0.5 nC, $z = 18$ m. Bottom: bunch charge 1 nC, $z = 22$ m. Thin curves show single shots. Bold curves show averaged profiles

always takes place for SASE FELs having pulse duration comparable with cooperation length [10].

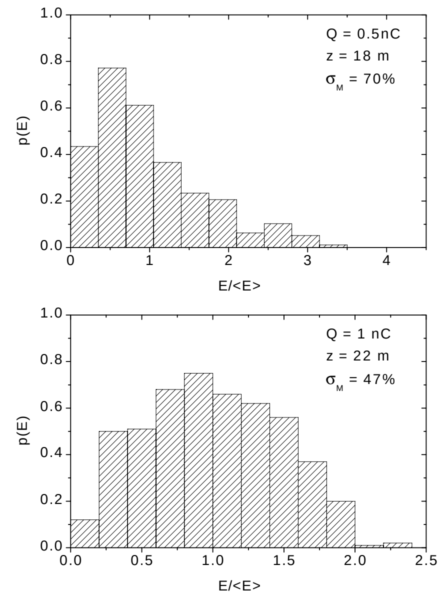

Figure 10: Probability distribution of the energy in the radiation pulse after narrow band monochromator. VUV FEL operates at saturation. Top: bunch charge is 0.5 nC. Bottom: bunch charge is 1 nC

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