Development of a Pump-Probe Facility with Sub-Picosecond Time Resolution Combining a High-Power Ultraviolet Regenerative FEL Amplifier and a Soft X-ray SASE FEL

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Abstract

This paper presents the conceptual design of a high power radiation source with laser-like characteristics in the ultraviolet spectral range at the TESLA Test Facility (TTF). The concept is based on the generation of radiation in a regenerative FEL amplifier (RAFEL). The RAFEL described in this paper covers a wavelength range of 200–400 nm and provides 200 fs pulses with 2 mJ of optical energy per pulse. The linac operates at 1 % duty factor and the average output radiation power exceeds 100 W. The RAFEL will be driven by the spent electron beam leaving the soft X-ray FEL, thus providing minimal interference between these two devices. The RAFEL output radiation has the same time structure as the X-ray FEL and the UV pulses are naturally synchronized with the soft X-ray pulses from the TTF FEL. Therefore, it should be possible to achieve synchronization close to the duration of the radiation pulses (200 fs) for pump-probe techniques using either an UV pulse as a pump and soft X-ray pulse as a probe, or vice versa.

1. Introduction

Pump-probe techniques using either the soft X-ray pulse from the TTF FEL [1] as a pump and the visible-UV laser as a probe pulse, or vice versa, promise unprecedented insight into the dynamics of electronic excitations, chemical reactions and phase transitions of matter, from atoms, through organic and inorganic molecules and clusters, to surfaces,

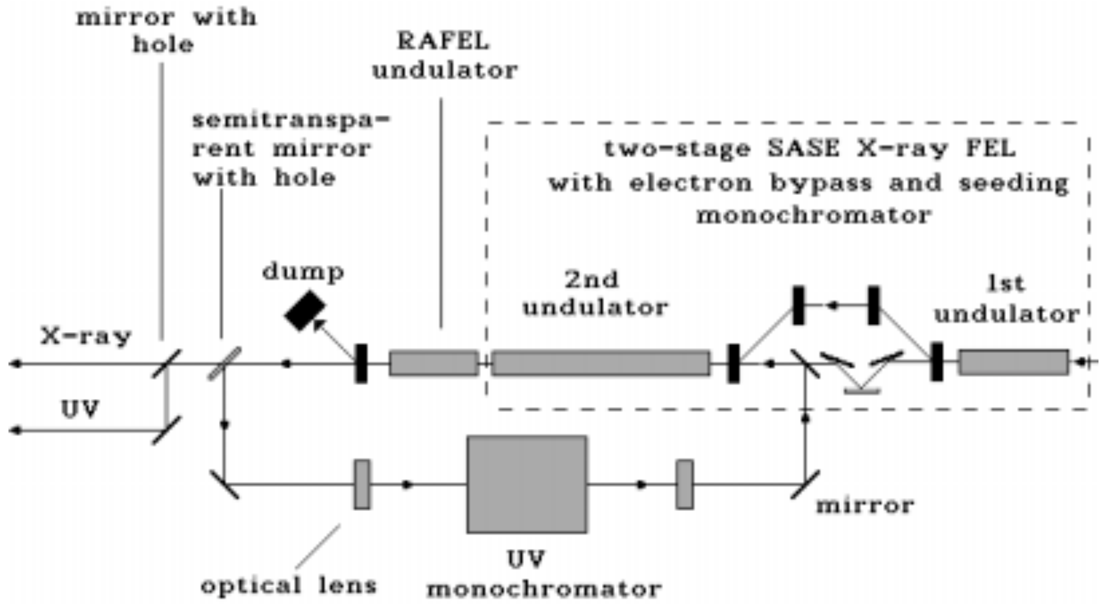

Fig. 1. Schematic layout of the pump-probe facility combining UV regenerative FEL amplifier and soft X-ray FEL at TTF

solids and plasmas. For applications in the visible and near-visible wavelength range a pump-probe facility based on a conventional quantum laser system will be available at the TTF [2]. The laser will provide in the visible spectral region between 750 and 900 nm a train of 150 fs pulses with 100 μJ of optical energy per pulse, at the same repetition rate as the X-ray FEL. The synchronization of the optical laser with the soft X-ray FEL pulses to within 200 fs is the most challenging task of this project. The main problem is the time jitter (± 1 ps) of electron bunches which are synchronous with the soft X-ray FEL pulses.

In this paper we describe the extension of the pump-probe facility into the ultraviolet wavelength range. Our approach is based on the idea to use a narrow band feedback between exit and entrance of a high gain FEL amplifier operating in multibunch mode (so called regenerative FEL amplifier – RAFEL [3]). Such a feedback can be realized in the UV wavelength range using mirrors, lenses, and a grating as a dispersive element. We propose to install an additional undulator after the soft X-ray FEL. A layout of the proposed RAFEL is shown in Fig. 1. This design makes use of the spent electron beam leaving the X-ray undulator. The SASE process in the X-ray FEL induces an additional energy spread in the electron beam. Nevertheless, the electron beam at the exit of the X-ray FEL is still a good "active medium" for an UV FEL amplifier. Because the RAFEL uses the spent electron beam, the proposed laser system operates in a "parasitic" mode not interfering with the main mode of the X-ray FEL operation. Since the X-ray and UV radiation pulses are generated by the same electron bunch, there is no problem of synchronization for pump-probe experiments with an accuracy close to the duration of the radiation pulses (200 fs). The RAFEL proposed here will provide intense, tunable and coherent radiation in the UV region of the spectrum between 200 and 400 nm as direct laser output. The RAFEL output radiation has the same pulse format as the X-ray FEL and produces 200 fs micropulses with 2 mJ of radiation energy per micropulse and transform-limited spectral width.

The RAFEL undulator and outcoupling optical system proposed can be installed in the unoccupied straight vacuum line used to transfer the X-ray beam to the experimental area, behind the dipole magnet separating the electron beam from the X-ray beam. The installation of the feedback is greatly facilitated by the fact that there is free space available for the input optical system. In order to get fully coherent X-ray radiation, a seeding option will be implemented into the X-ray FEL under construction at DESY [4]. The X-ray FEL seeding option consists of an additional 18 m long undulator, an electron bypass and X-ray grazing incidence monochromator (see Fig. 1). The electron bypass is necessary to delay the electron beam by the same amount as the X ray photon beam is delayed by the X-ray monochromator. The magnetic chicane has to deflect the electron beam out of the straight flight pass to make room for the X-ray monochromator and input optical elements of RAFEL.

2. Facility description

The RAFEL parameters are presented in Table 1. The RAFEL operates as follows. The first bunch in a train of up to 7200 bunches amplifies shot noise and produces intense, but wide-band radiation. A fraction of the radiation is back-reflected by a semi-transparent output coupling mirror. The spherical grating which is installed in the straight section of the feedback loop, disperses the light and focuses a narrow band of radiation back on the entrance of the undulator. The bandwidth of the feedback is chosen to produce a photon pulse length about ten times as long as the electron bunch length in order to avoid effects from a ± 1 ps time jitter (see Fig. 2). This requires a resolving power $\lambda/\Delta\lambda \simeq 6000$ at $\lambda = 200$ nm (photon pulse duration at the monochromator exit $l_{\mathrm{ph}} \simeq \lambda^2/(c\Delta\lambda) \simeq 4$ ps).

After the undulator the electron and the radiation beams are separated. The electron beam is guided into the beam dump and the radiation enters the output coupling system. The distance between the feedback outcoupling mirror and the exit of the RAFEL undulator is 20 m, the distance between the mirror and the exit of the X-ray FEL undulator is about 27 m. At a diameter of the hole in the mirror of 3 mm the fraction of the X-ray power directed through the mirror is close to 100%. This mirror is semi-transparent for the UV radiation, and approximately 50% of the UV radiation power is transmitted through it and delivered to the experimental area. Calculations show that an alignment accuracy of about 10 μrad is sufficient for reliable operation of the optical feedback.

The monochromator for the RAFEL should be able to select any wavelength between 200 and 400 nm. We adopted the Namioka scheme where tuning of the wavelength is

Table 1
Parameters of the UV pump-probe facility (RAFEL option)

Electron beam	
energy	1000 MeV
charge per bunch	1 nC
rms bunch length	50 μm
rms emittance	2 π mm mrad $/\gamma$
rms energy spread	2.5 MeV
number of bunches	7200/train
bunch spacing	111 ns
repetition rate	10 Hz
Undulator	
type	Planar
period	7 cm
peak magnetic field	1–1.4 T
number of periods	85
Output radiation	
wavelength	200–400 nm
bandwidth	Transform-limited
micropulse duration	200 fs
micropulse energy	2 mJ

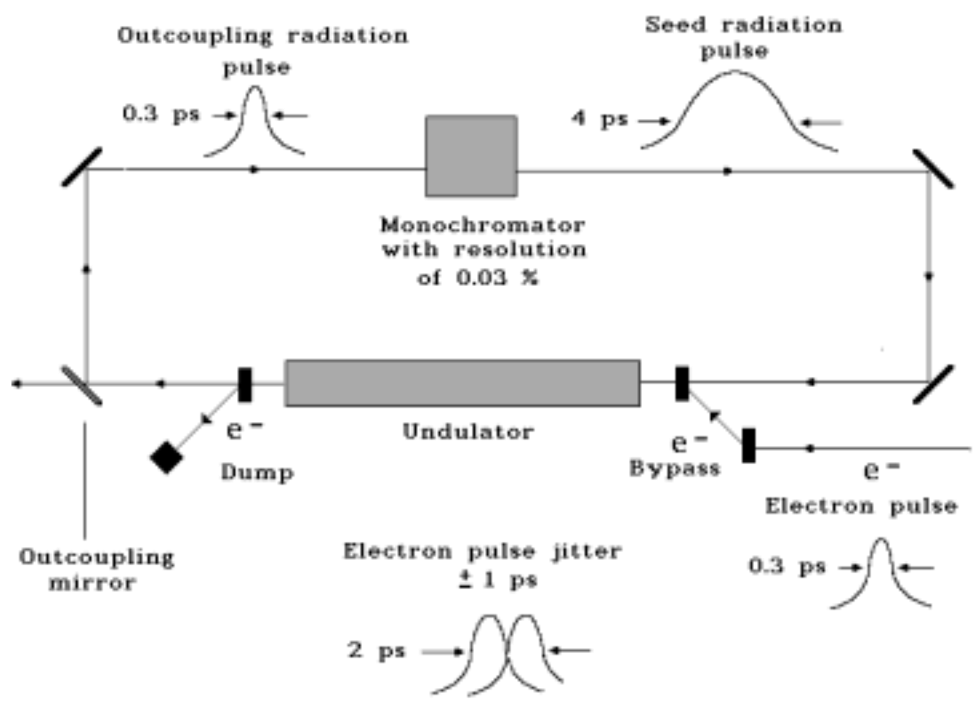

Fig. 2. The use of a monochromator as a pulse stretcher. Drawing illustrates how electron pulse jitter effects on the feedback system can be avoided

performed by means of rotation of the grating, while entrance and exit slits are fixed. Commercially available holographic gratings allow one to focus the image of the entrance slit exactly on the exit slit at small values of coma and astigmatism in the 200–400 nm wavelength band. The feedback transmission factor can be written as $T_{\mathrm{fb}} = K_{\mathrm{coupl}} \times R_{\mathrm{loss}}$, where K_{coupl} is the fraction of output radiation coupled out through the semi-transparent mirror, R_{loss} refers to the losses in the optical elements (mirrors, lenses, grating) of the feedback system. In addition, the grating reduces the peak power of the coherent signal further since it stretches the pulse longitudinally by a factor $\lambda^2/(\sigma_z\Delta\lambda)$ [5].

In the present design the lateral size of the photon beam focus, w, is completely determined by the fixed geometry of the feedback optical system (i.e. the focal distances of the mirrors and the aperture of the X ray undulator vacuum chamber). In our numerical example for 400 nm wavelength the size of the photon beam focus is about $w \simeq 800$ μm, which is about 15 times larger than the rms electron beam size, σ. Such a mismatch, however, is not dramatic and will result in a reduction of the gain by a factor of about 3 only (see section 3 for more details). Taking into account all the effects mentioned above, the overall loss factor for the feedback system is about 2×10^{-2}. When the power gain in the undulator, G, exceeds the relative losses of power in the optical feedback system, the output radiation power begins to grow, i.e. lasing takes place.

The undulator is one of the central components of the RAFEL. The values of the peak field and the period length are given in Table 1. The required field strength can be achieved using a hybrid configuration. At a gap of 12 mm, a peak field up to 1.5 T is feasible for the undulator period of $\lambda_{\mathrm{u}} = 7$ cm. This is more than needed for the RAFEL undulator. To minimize the length of the matching section between the VUV/X-ray undulator and RAFEL undulator, we decided to use the same value of the beta function of 3 meters. It is shown in section 3 that the maximum value of the gain well exceeds the relative losses of peak power in the optical feedback system when the undulator is at least 6 m long. The wavelength can be tuned continuously by changing the undulator magnetic field and adjusting the monochromator wavelength by simple rotation of the grating. Using the present design it should be possible to cover the range from 200 nm down to 400 nm.

3. Operation of the RAFEL

The main physical effects defining the operation of the FEL amplifier are the diffraction effects and the space charge effects. The longitudinal velocity spread was calculated using actual energy distribution in the electron beam after leaving the VUV/X-ray undulator (see Fig. 3). It is seen that the distribution function of the electrons can be fitted well by a Gaussian distribution with the rms deviation $\sigma_{\mathrm{E}} \simeq 2.5$ MeV. The energy spread does not influence too much the gain at chosen parameters (the power gain length is increased by 20% only with respect to the case of a “cold” electron beam). Calculations of the total power gain must take into account the details of focusing of the external radiation on the electron beam at the undulator entrance. A quantitative description may be performed in the following way. We assume that the seed radiation has a Gaussian radial intensity distribution which is characterized by the position of the focus, z_0, and the size of the waist in the focus, w. In the high-gain linear (steady-state) regime the radiation power grows exponentially with the undulator length:

$$G = P_{\mathrm{out}}/P_{\mathrm{in}} = A \exp[z/L_{\mathrm{g}}] \ ,$$

where P_{out} and P_{in} is the output and input power, respectively. The input coupling factor A depends on the focusing of the seed radiation and is a function of z_0 and w. It should

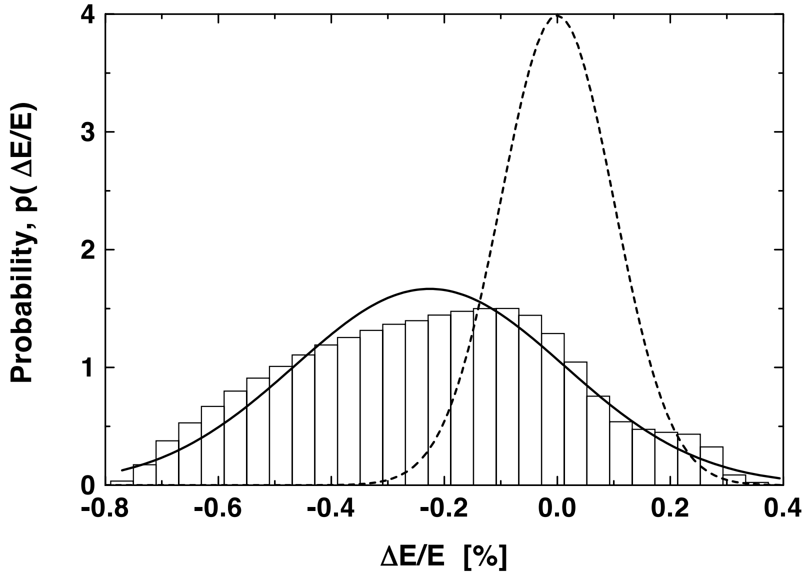

Fig. 3. Histogram of energy distribution of the particles after leaving the VUV/X-ray FEL driven by 1 GeV electron beam. The solid line represents a Gaussian distribution with the rms deviation $\sigma_{\mathrm{E}} = 2.5$ MeV. The dashed line is the energy distribution at the entrance of the VUV/X-ray undulator ($\sigma_{\mathrm{E}} = 1$ MeV)

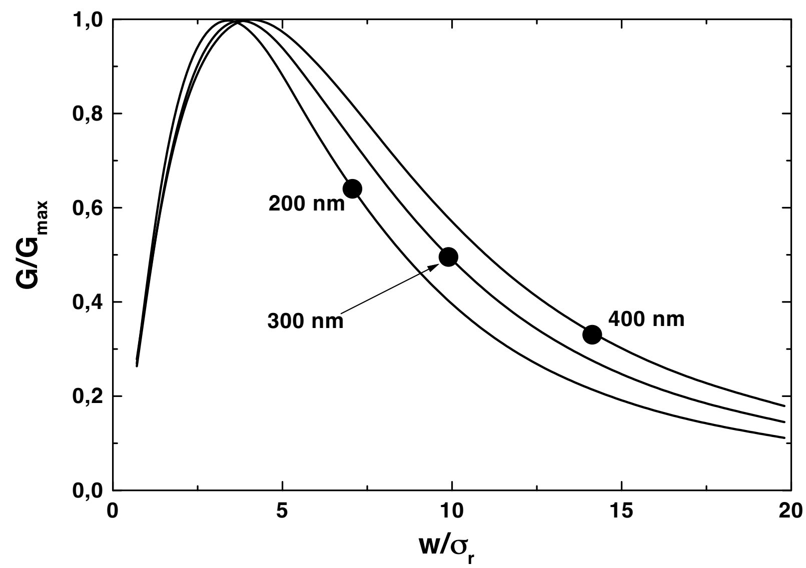

Fig. 4. Power gain in the linear regime versus spot size of the seeding radiation beam (the rms transverse size of the electron beam is $\sigma_{\mathrm{r}} = 55\ \mu$m)

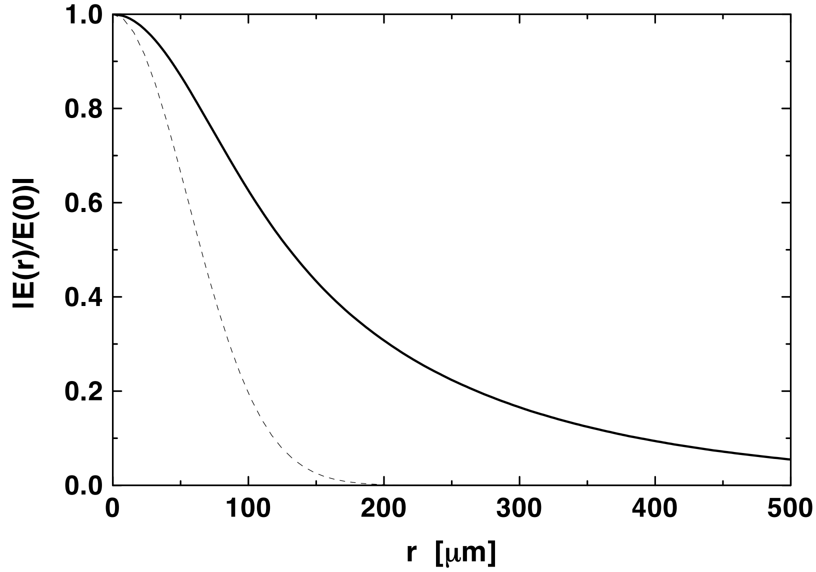

Fig. 5. Transverse distribution of the radiation field amplitude for the FEL amplifier operating at a wavelength of 200 nm. The dashed line is the transverse profile of the electron beam current density, $\exp[-r^2/(2\sigma_{\mathrm{r}}^2)]$ with $\sigma_{\mathrm{r}} = 55\ \mu$m

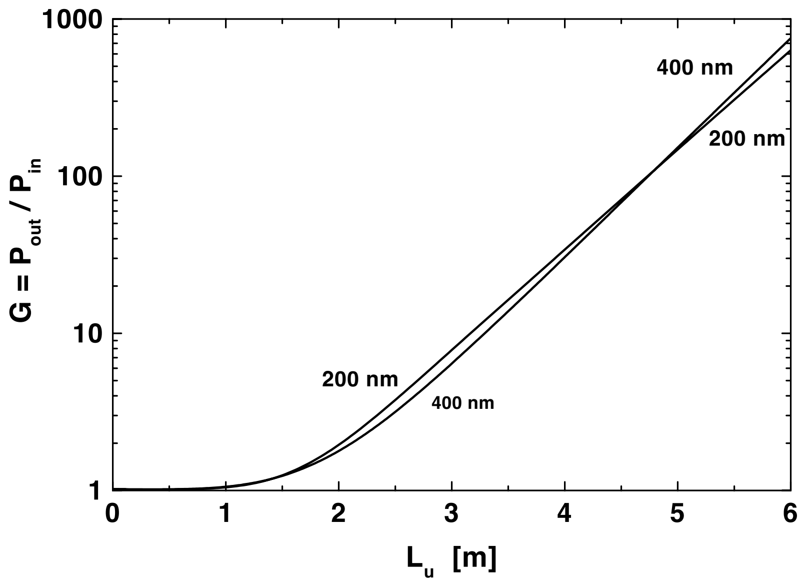

Fig. 6. Power gain, $G = P_{\mathrm{out}}/P_{\mathrm{in}}$ versus undulator length for the FEL amplifier operating at 200 and 400 nm wavelength (radiation beam size at the undulator entrance w is equal to 400 and 800 μm, respectively

be maximized by an appropriate choice of w and z_0. This problem has been studied in detail in [8] using the solution of the initial-value problem. It has been found that the value of A at $z_0 = 0$ does not differ significantly from its maximal value and the position of the Gaussian beam waist can be placed at the coordinate of the undulator entrance.

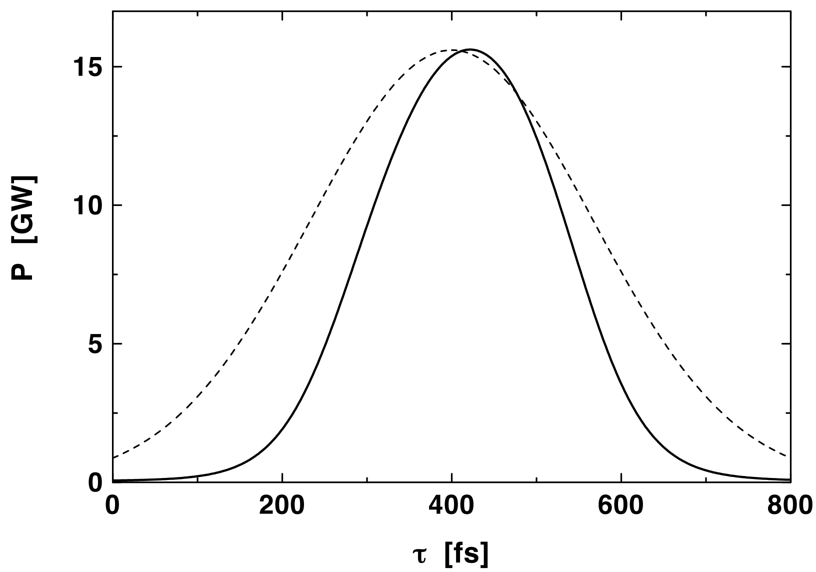

Fig. 7. Temporal structure of the radiation pulse at the exit of the RAFEL undulator. The dotted line represents the longitudinal profile of the electron beam current (the maximum corresponds to 2.5 kA)

However, due to the constraints of the present design we have no possibility to achieve the optimal value. The reason for this is that the focusing mirror can only be placed at a fixed position of 20 meters apart from the RAFEL undulator entrance. Also, there is an aperture limitation of 9 mm due to the diameter of the vacuum chamber in the VUV/X-ray undulator. Fortunately, this does not lead to significant degradation of the gain as it is illustrated in Fig. 4. The reason for this is the strong influence of diffraction effects. In the general case the seeding radiation should be matched with the beam radiation mode, but not with the transverse size of the electron beam. In the case of small diffraction parameter [8], the transverse size is larger than the transverse size of the electron beam as it is illustrated in Fig. 5.

Figure 6 presents the plots for the power gain versus undulator length for the FEL amplifier operating in the linear regime at 200 and 400 nm wavelength. It is seen that the gain only slightly depends on the wavelength for an undulator length of 6 meters. On the one hand, the focusing of radiation becomes less optimal at increasing wavelength (see Fig. 4). On the other hand, the power gain length decreases with the increase of the wavelength. At a relatively short undulator length these two effects compensate each other.

The final optimization of the FEL amplifier parameters has been performed with the nonlinear, three dimensional, time-dependent simulation code FAST [7]. The optimized parameters of the FEL amplifier are presented in Table 1. Figure 7 shows the time structure of the radiation pulse at the exit of the undulator. We obtain that the RAFEL operating at saturation produces 4 mJ pulses of about 200 fs pulse duration.

The analysis of the RAFEL parameters has shown that it will operate reliably even at a value of the energy spread exceeding the project value for the TTF by a factor of two. There is also a safety margin (by a factor of two) with respect to the value of the emittance.

Acknowledgments

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