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Nuclear Instruments and Methods in Physics Research A 483 (2002) 62–69

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Generation of high power femtosecond pulses by a sideband-seeded X-ray FEL

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Abstract

New proposal of a fs X-ray facility, which is described in this paper, is based on the use of X-ray SASE FEL combined with a fs quantum laser. An ultrashort laser pulse is used for modulation of the energy and density of the electrons within a slice of the electron bunch at a frequency $\omega_{\rm opt}$. The density modulation exiting the modulator (energy-modulation undulator and dispersion section) is about 10%. Following the modulator the beam enters an X-ray SASE FEL undulator, and is bunched at a frequency ω_0. This leads to an amplitude modulation of the beam density at the sidebands $\omega_0 \pm \omega_{\rm opt}$. The sideband density modulation takes place at the part of the electron pulse defined by the duration of the seed laser pulse that is much shorter than the electron pulse. Following the SASE FEL undulator the beam and SASE radiation enter undulator section (radiator) which is resonant at the frequency $\omega_0 - \omega_{\rm opt}$. Because the beam has a large component of bunching at the sideband, coherent emission is copiously produced within fs slice of the electron bunch. Separation of the sideband frequency from the central frequency by a monochromator is used to distinguish the fs pulses from the sub-ps intense SASE pulses.

PACS: 41.60.Cr; 52.75.M; 42.62.Cf

Keywords: Free electron laser; UV-radiation

1. Introduction

Femtosecond (fs) X-ray pulses are considered to be perspective tool for probing matter. Recent efforts at applying 300 fs X-rays pulses to probe structural dynamics have used a synchrotron source combined with a femtosecond optical quantum laser [1]. Femtosecond synchrotron radiation pulses were generated directly from an electron storage ring (ALS). An ultrashort laser pulse was used to modulate the energy of electrons within a 100-fs slice of the stored 30-ps electron bunch. The energy-modulated electrons were spatially separated from the long bunch and used to generate 300-fs X-ray pulses at the bending magnet beamline. On the basis of the parameters of an ALS small-gap undulator and laser pulses of 25 fs and 100 μJ at a repetition rate of 20 kHz, one

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PII: S0168-9002(02)00287-5

can expect in the future an average brilliance of 10^{11} photons s^{-1} $mrad^{-2}$ mm^{-2} per 0.1% BW at the photon energy of 2 keV [1].

Another proposal of femtosecond synchrotron radiation soft X-ray facility is based on the use of a linac as a driver [2]. Proposed technique includes the generation of energy chirped short electron bunches that would subsequently spontaneously radiate frequency chirped soft X-ray pulses in an undulator. These pulses are then spectrally dispersed using grazing incident grating. The spectrum is propagated through an exit slit (spectral window) which filters the fs pulses. Expected average brilliance is about 10^{14} photons s^{-1} $mrad^{-2}$ mm^{-2} per 0.1% BW in the photon energy range 50–200 eV. The average number of photons at the monochromator exit (at the monochromator efficiency 10%) can exceed 10^5 photons within 30 fs pulse. The pulse duration can be tuned by changing the resolution of the monochromator (by means of changing the spectral window) from 30 to 160 fs.

The possibility of producing femtosecond pulses by chirping and compressing (in grazing incidence grating compressor) the output X-ray SASE FEL radiation is analyzed in Ref. [3]. Proposed technique includes the generation of energy chirped short electron bunches that would subsequently coherently radiate frequency chirped X-ray pulses in an undulator. Another idea for production of femtosecond high power X-ray pulses is based on a technique of "manipulating" the energy spread along the electron bunch [4]. The latter approach allows to achieve an average brilliance of 10^{22} photons s^{-1} $mrad^{-2}$ mm^{-2} per 0.1% BW. The average number photons can exceed 10^{12} within 30 fs (FWHM) pulse duration.

In this paper we propose sideband seeded X-ray SASE FEL capable to produce femtosecond pulses. Integration of proposed femtosecond facility into the soft X-ray SASE FEL being under construction at the TESLA Test Facility (TTF) at DESY [5] is discussed, too. It is shown that it should be possible to achieve an average brilliance of 10^{22} photons s^{-1} $mrad^{-2}$ mm^{-2} per 0.1% BW in the photon energy range 25–100 eV. The femtosecond SASE FEL will provide soft X-ray pulses with 30 fs (FWHM) duration. The number of photons will exceed 10^{11} per pulse. This creates perfect conditions for experiments. It is important to notice that the proposed femtosecond option of SASE FEL at the TTF is an additional to a fully functioning SASE FEL improving the output radiation beam properties considerably and thus extending the range of possible applications.

Pump probe techniques which are commonly used with optical lasers, are highly desirable in order to make full use of the femtosecond soft X-ray pulses.[1] Since in this case precise timing is needed with a jitter of less than 30 fs, we suggest to combine the femtosecond soft X-ray pulses with optical pulses generated in the seed laser system. It should be emphasized that in proposed scheme femtosecond X-ray pulse is naturally synchronized with his femtosecond optical pulse and cancel jitter.

2. Operation of a sideband-seeded SASE FEL

Operation of sideband seeded X-ray SASE FEL is illustrated with Figs. 1 and 2. An ultrashort laser pulse is used to modulate the density of electrons within a femtosecond slice of the electron bunch at a frequency ω_{opt}. We begin the FEL operation by positioning the interaction region on the electron bunch. The seed laser pulse will be timed to overlap with central area of the electron bunch. This ultrashort laser pulse serves as a seed for modulator which consists of an uniform (energy-modulation) undulator and a dispersion section. The interaction of seed pulse with the electron beam produces an energy modulation at ω_{opt}. This energy modulation is converted into a spatial bunching in the dispersion section. Density modulation at the modulator exit is about 10%. The energy modulation, introduced by the modulator, is smaller than the initial energy spread. Following the modulator the beam and seed radiation enter

[1] "Development of a pump-probe facility with sub-picosecond time resolution combining a high-power optical laser and a soft X-ray free electron laser": Joint DESY (Germany), Forschungszentrum Juelich (Germany), Max-Born-Institute Berlin (Germany), Dublin City University (Ireland), MAX-Lab/Lund Laser Center (Sweden) and CNRS/LURE, Orsay (France) Proposal. Available at DESY by request only.

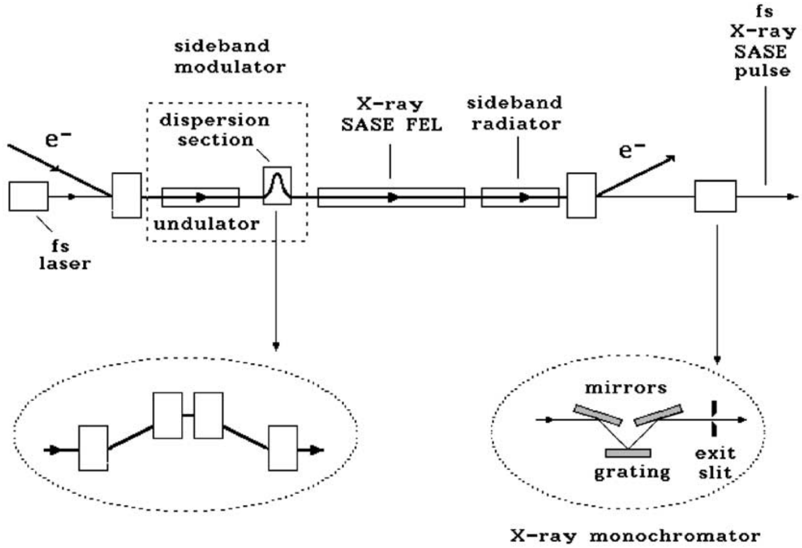

Fig. 1. Basic scheme of a sideband seeded SASE FEL.

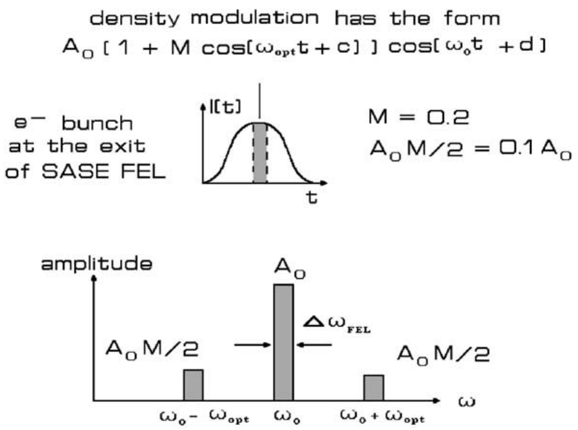

Fig. 2. Description of the sideband generation for the case of the density modulation as initial conditions.

SASE undulator which is resonant with X-ray radiation at frequency ω_0. The process of amplification of the radiation in the X-ray undulator develops in the same way as in the conventional SASE FEL: fluctuations of the electron beam current density serve as the input signal. The seeding optical radiation does not interact with the electron beam in the X-ray undulator and is diffracted out of the electron beam. By the time the beam is bunched in the SASE FEL undulator at frequency ω_0, the X-ray radiation power has reached saturation. This leads to amplitude modulation of density at the sidebands ($\omega_0 \pm \omega_{\mathrm{opt}}$). The sideband density modulation takes place only at that part of the electron bunch defined by the length of the seed laser pulse that is much shorter than the electron bunch. Following the SASE FEL undulator the beam and X-ray radiation enter undulator section (radiator) which is resonant with the $\omega_0 - \omega_{\mathrm{opt}}$ radiation. Because the beam has a relatively large component of bunching at the long wavelength sideband, coherent emission at $\omega_0 - \omega_{\mathrm{opt}}$ is copiously produced within femtosecond slice of electron bunch. After leaving the radiator the electron beam is deflected onto a beam dump, while the photon beam enters the monochromator, which selects fs soft X-ray pulse.

During the passage through a long main SASE undulator the electron density modulation at optical wavelength can be suppressed by energy spread in the electron beam. For effective operation of the fs FEL energy spread suppression factor should be close to unity. This leads to following condition:

$$\langle (\Delta\mathscr{E})^2 \rangle L_{(2)}^2 \omega_{\mathrm{opt}}^2 / (2c^2 \gamma_l^4 \mathscr{E}_0^2) \ll 1,$$

where $\sqrt{\langle(\Delta\mathscr{E})\rangle}$ is the standard energy deviation, $\gamma_l = \gamma/(1+K_{(2)}^2/2)^{1/2}$ is the longitudinal relativistic factor, $K_{(2)}$ and $L_{(2)}$ is the undulator parameter and undulator length, respectively, the subscript (2) refers to the main undulator. The chosen parameters for the SASE FEL and the seed laser system satisfy this condition, and to make preservation of the beam density modulation in the case of the TTF SASE FEL parameters is possible.

In what follows we use the following assumptions: $\omega_0 \gg \omega_{\rm opt} \gg \Delta\omega_{\rm SASE}$. We also assume that $\Delta\omega_{\rm SASE} \gg 1/\tau_{\rm opt} \gg 1/\tau_{\rm e}$. Here $\tau_{\rm opt}$ and $\tau_{\rm e}$ is the seed optical pulse and electron pulse duration, respectively. Such assumptions do not reduce significantly the practical applicability of the result obtained. Let us consider the first condition. It is obvious that the parameter $\omega_{\rm opt}/\omega_0$ is much less than unity for X-ray SASE FEL. We also assume that the SASE bandwidth is much less than the separation of the sidebands from the main peak. This requirement is of a critical importance to the overall performance of the fs SASE FEL. In this case, monochromator can be used to distinguish the fs pulses from the intense SASE pulses. The present study assumes wavelength of seed light to be very long compared to the SASE radiation wavelength. Under this limitation we neglect the gradient of density and energy within the SASE radiation wavelength at the entrance of main undulator. Due to this reason it is also convenient to describe effect of the energy and density modulation not by energy-phase distribution function, but by periodical bunch profile and periodically correlated energy spread. The physical interpretation of approximation $\Delta\omega_{\rm SASE}/\omega_{\rm opt} \ll 1$ is that the slippage of the radiation with respect to the electrons per gain length (in the SASE FEL) is much longer than the seed laser wavelength. Let us consider the second condition. It is obvious that the fs FEL has advantage over conventional SASE FEL only when electron bunch is much longer than the seed laser pulse. The physical interpretation of condition $\Delta\omega_{\rm SASE} \gg 1/\tau_{\rm opt}$ is that the optical pulse is much longer than the slippage of the radiation with respect to the electrons at one gain length.

3. Sideband-seeded option at TTF FEL

Fig. 3 illustrates how the proposed femtosecond facility fits the TTF FEL layout. Tables 1–3 list basic parameters of the electron beam, undulators, seed laser system, monochromator and output radiation. An additional facility to be installed is a sideband modulator and sideband radiator. The sideband modulator is located in front of main undulator. The sideband radiator is located after the main undulator and consists of one or two 4.5 m standard TTF undulator modules tuned to the sideband frequency. In this conceptual design we assume to use a 800 nm Ti:sapphire laser system as a seed laser. The 800 nm pulses will be doubled to 400 nm in a frequency conversion crystal. The installation of the femtosecond seeding system is greatly facilitated by the fact that present design of the SASE FEL at TTF provides required free space for the input optical elements and sideband modulator.

We illustrate operation of a fs option of FEL for parameters of the TTF FEL operating at the wavelength of 20 nm [6]. Parameters of the optical laser are: wavelength 400 nm, energy in the laser pulse 6 μJ, and FWHM pulse duration 25 fs. The laser beam is focused onto the electron beam in a short (five periods) undulator resonant at the optical wavelength of 400 nm. Optimal conditions of focusing correspond to the positioning of the laser beam waist in the center of the undulator. The size of the laser beam waist is twice as large than the electron beam size. Due to the resonant interaction of the electron beam with optical field in the undulator the electron beam is modulated in the energy as it is shown in Fig. 4. Upon leaving the modulator, the electron beam that passes the dispersion section is modulated additionally in the density (see right plot in Fig. 4), and is directed to an X-ray undulator.

Parameter optimization have been performed with three-dimensional, time-dependent code FAST [7] taking into account all physical effects influencing the FEL amplifier operation (diffraction effects, energy spread, emittance, slippage effect, etc.). In Ref. [6] we discussed the modification of code FAST required to carry out the calculations of the sideband generation. The

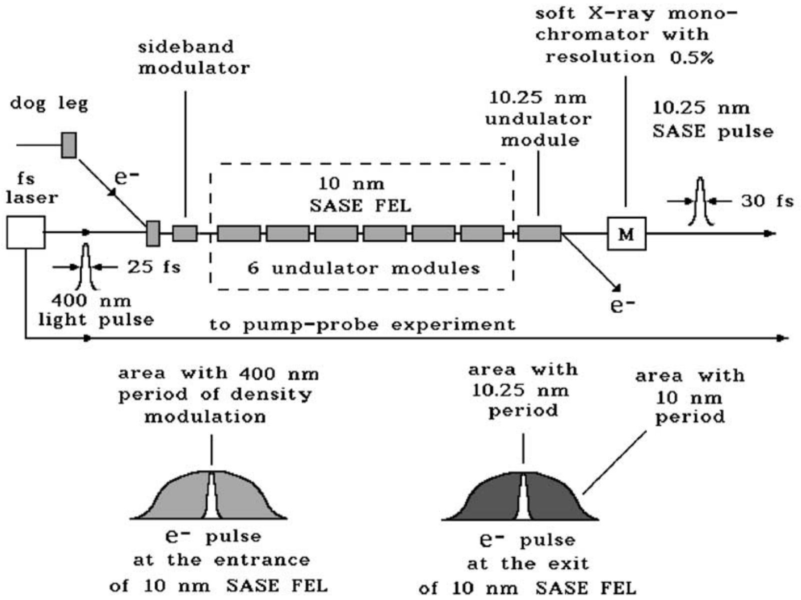

Fig. 3. Schematic layout of the femtosecond pump-probe facility which fits with soft X-ray SASE FEL.

Table 1
Parameters of the electron beam at the TESLA test facility accelerator

Electron beam	
Beam energy, MeV	500–1000
Bunch charge, nC	1
rms bunch length, μm	50
rms energy spread, MeV	1
Normalized emittance, π mm-mrad	2
Number of bunches per train	7200
Bunch spacing, ns	111
Repetition rate, Hz	10

Table 2
Parameters of the sideband modulator

Undulator	
Type	planar
Number of periods	5
Period, cm	7.5
Peak field, T	0.7
External beta-function, m	1.7
Seed laser	
Wavelength, nm	400
Min. pulse duration, fs (FWHM)	25
Energy per pulse, μJ	6
Spectrum width	transform limited
Rep. rate, kHz	10

Table 3
Parameters of the sideband-seeded X-ray SASE FEL

Radiator undulator	
Type	planar
Number of periods	150
Period, cm	2.73
Peak field, T	0.51
External beta-function, m	1.7
Output radiation after monochromator	
Wavelength, nm	10–40
Min. pulse duration, fs (FWHM)	30
Number of photos per pulse	10^{11}
Spectrum width, % (FWHM)	0.5

results of optimized configuration of 20 nm sideband-seeded option of SASE FEL at the TESLA Test Facility are summarized in Table 3. Initial conditions for the seeded sideband have been fixed with general case, i.e. the slice of the electron bunch is modulated in energy and in density at the entrance to the X-ray undulator (see Figs. 3 and 4). Optimal length of the main undulator is given by the condition of maximum spectral purity of the sideband. In the case under study optimal length of the main undulator should be equal to

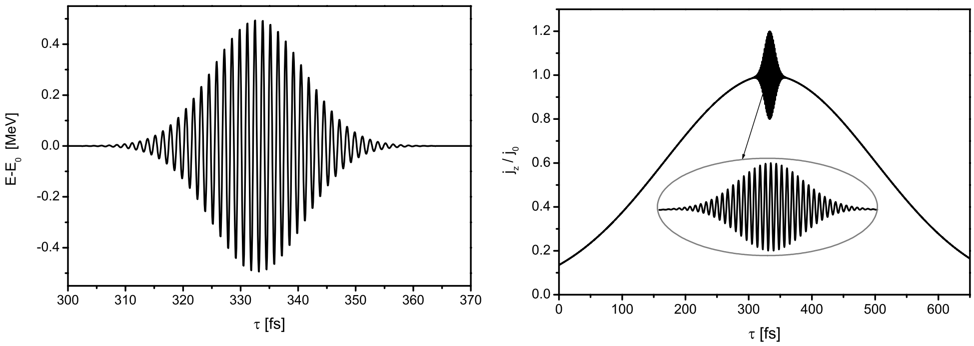

Fig. 4. Energy modulation of the electron beam at the exit of the modulator undulator (plot at left) and density modulation of the electron beam at the exit of the dispersion section (plot at right).

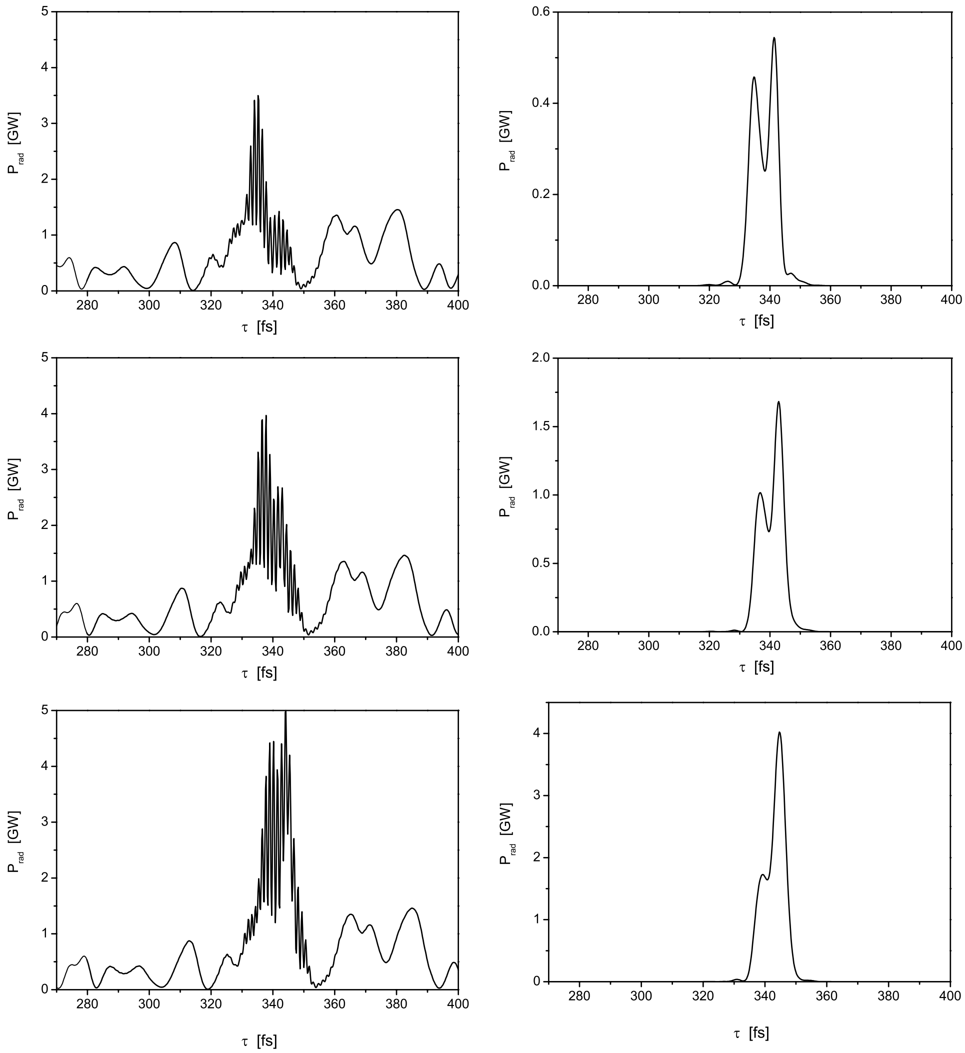

Fig. 5. Evolution of the radiation pulse in the radiator undulator. In the left plots we present total pulse, and in the right plots—spectrally filtered at the sideband. The length of the radiator undulator is equal to 3, 4 and 5 m for upper, middle and lower plots, respectively.

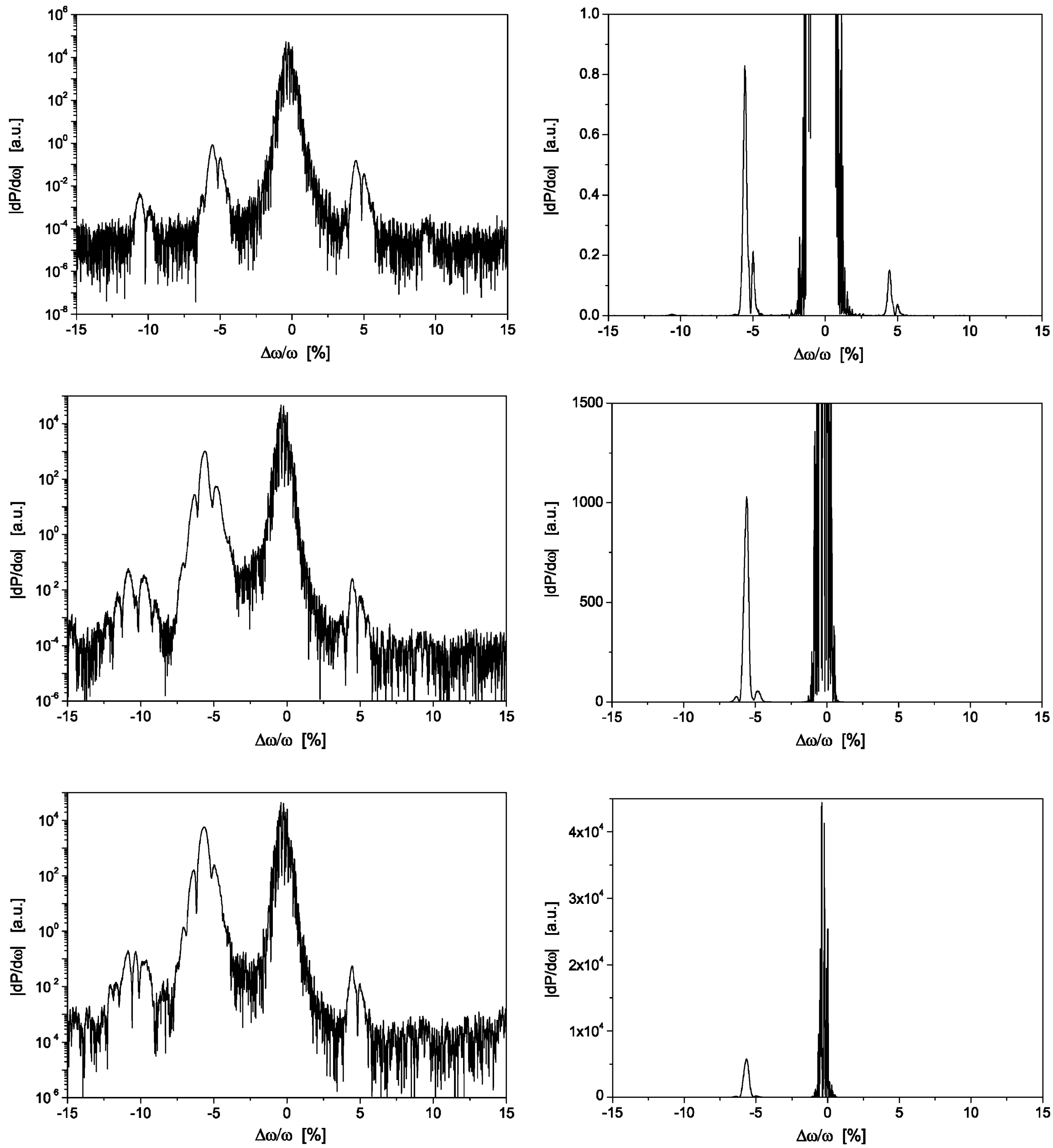

Fig. 6. Evolution of the spectral distribution of the output radiation power in the radiator undulator. In the left plots we present spectrum in logarithmic scale, and in the right plots—in the linear scale. The length of the radiator undulator is equal to 0, 3 and 5 m for upper, middle and lower plots, respectively.

10 m. Figs. 5 and 6 show the evolution of the fs radiation pulse and the spectral distribution of the output radiation power in the sideband radiator. Analysis of the spikes of the complete radiation pulse (plots in the left column of Fig. 5) shows that the radiation, produced in the main undulator, does not interact with the electron beam. Only that slice of the electron bunch, seeded by the sideband,

produces the radiation. Cut structure of the spikes of the central part of the beam is due to the interference of the radiation from the main undulator with frequency ω and from the sideband radiator with frequency $\omega - \omega_{\mathrm{opt}}$. After 5 m long sideband radiator the radiation power in fs pulse rapidly reaches the level of a few GW, and the energy in the fs pulse reaches the value of about 30 μJ. Total undulator length of the sideband seeded SASE FEL is about 15 m. We should notice that calculations of the radiation power have been performed for the case of an ideal monochromator. In the wavelength range of 10–40 nm the monochromator efficiency is about 10 percent only, so the radiation power available for user experiments is roughly one order of magnitude less than that shown in Figs. 5 and 6.

Acknowledgements

We thank J.R. Schneider and D. Trines for their interest in this work.

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