ATTOSECOND X-RAY SOURCE FOR LIGHT-TRIGGERED TIME-RESOLVED EXPERIMENTS ASSOCIATED WITH THE X-RAY SASE FEL

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Abstract

We describe a technique for the production of attosecond X-ray pulses which is based on the use of X-ray SASE FEL combined with a femtosecond laser system. A few-cycle optical pulse from a Ti:sapphire laser interacts with the electron beam in a two-period undulator resonant to 800 nm wavelength and produces energy modulation within a slice of the electron bunch. Following the energy modulator the electron beam enters the X-ray undulator and produces SASE radiation. Due to energy modulation the frequency is correlated to the longitudinal position within the few-cycle-driven slice of SASE radiation pulse. The largest frequency offset corresponds to a single-spike pulse in the time domain which is confined to one half-oscillation period near the central peak electron energy. The selection of single-spike pulses is achieved by using a crystal monochromator after the X-ray undulator. Our studies show that the proposed technique is capable to produce 300-attoseconds long single pulses with GW-level output power in the 0.1 m wavelength range, and is applicable to the European X-Ray Laser Project XFEL and the Linac Coherent Light Source at SLAC.

INTRODUCTION

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 an XFEL. In its initial configuration the XFEL pulse duration is about 100 femtoseconds [1, 2]. Even though this is a few hundreds times shorter than in third generation light sources, it can probably be further reduced to about 10 femtoseconds [3, 4, 5]. A novel way to generate sub-10-fs x-ray pulses – the slotted spoiler method has been proposed recently [6]. This method is based on spoiling the beam phase density in a part of the electron bunch so that this part will not lase, while preserving lasing in a short length of the bunch. The FEL performance of the spoiled beam approach was computed using the time-dependent GENESIS simulation. It has been shown that it is possible to produce X-ray pulses with duration of 3-4 fs FWHM for nominal LCLS bunch compression parameters [6, 7].

Recently an approach for the generation of attosecond pulses combining fs quantum laser and harmonic cascade (HC) FEL scheme was proposed in [8]. The HC FEL scheme has the potential to produce coherent light down to wavelengths of a few nm in an undulator sequence [9]. The analysis presented in [8] shows that this technique has potential to produce 100 as long radiation pulses with MW-level of output power down to 1 nm wavelength.

The shortest possible X-ray pulse duration generated by XFEL is limited by the intrinsic bandwidth of the SASE process. In the case of the European XFEL and the LCLS, the FWHM bandwidth near saturation (at 0.1 nm) is about 0.1%, indicating a 300-as coherence time determined by the bandwidth product. Recently a scheme to achieve pulse durations down to 400-600 attoseconds at a wavelength of 0.1 nm has been proposed [10]. It uses a statistical property of SASE FEL high harmonic radiation. The selection of a single 10-GW level attosecond pulses is achieved by using a special trigger in data acquisition system. A promising scheme for attophysics experiments using this approach has been studied and could be implemented in the XFEL design [1].

In this paper we describe a new method to allow reducing the pulse length of the X-ray SASE FEL to the shortest conceptual limit of about 300 as [11]. It is based on the application of a sub-10-fs laser for slice energy modulation of the electron beam, and application of a crystal monochromator for the selection of single attosecond pulses with GW-level output power. Optimization of the attosecond SASE FEL has been performed with the three-dimensional, time dependent code FAST [12] taking into account all physical effects influencing the SASE FEL operation (diffraction effects, energy spread, emittance, slippage effect, etc.).

GENERATION OF ATTOSECOND PULSES FROM XFEL

A basic scheme of the attosecond X-ray source is shown in Fig. 1. An ultra short laser pulse is used to modulate the energy of electrons within the femtosecond slice of the electron bunch at the seed laser frequency. The seed laser pulse will be timed to overlap with the central area of the electron bunch. It serves as a seed for a modulator which consists of a short (a few periods) undulator. Following the energy modulator the beam enters the X-ray undulator. The process of amplification of radiation in this undulator develops in the same way as in a conventional X-ray SASE FEL: fluctuations of the electron beam current serve as the input signal. The proposed scheme for the generation of attosecond pulses is based on frequency-chirping

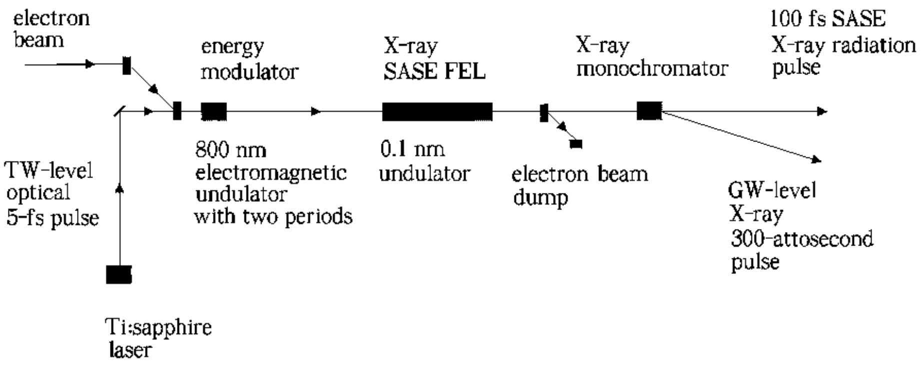

Figure 1: Schematic diagram of attosecond X-ray source.

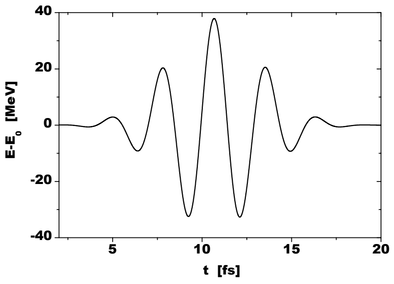

Figure 2: Energy modulation of electron bunch at the exit of the modulator.

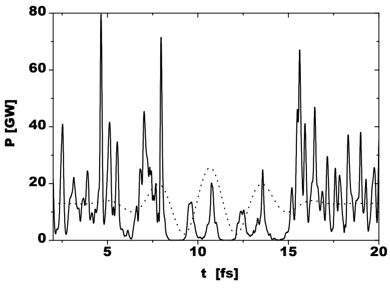

Figure 3: Temporal structure of the central part of the radiation pulse (single shot). Undulator length is 120 m. Dotted line shows energy modulation of the electron bunch (see Fig. 2).

the SASE radiation pulse. When an electron beam traverses an undulator, it emits radiation at the resonance wavelength $\lambda = \lambda_{\rm w}(1 + K^2/2)/(2\gamma^2)$. Here $\lambda_{\rm w}$ is the undulator period, $mc^2\gamma$ is the electron beam energy, and K is the undulator parameter. The laser-driven sinusoidal energy chirp produces a correlated frequency chirp of the resonant radiation $\delta\omega/\omega \simeq 2\delta\gamma/\gamma$. After the undulator, the radiation is passed through a crystal monochromator which reflects a narrow bandwidth. Since the radiation frequency is correlated to the longitudinal position within the beam, a short temporal radiation pulse is transmitted through the monochromator.

In the following we illustrate the operation of an attosecond SASE FEL for the parameters close to those of the European XFEL operating at the wavelength 0.1 nm [1]. The parameters of the electron beam are: energy 15 GeV, charge 1 nC, rms pulse length 25 μm, rms normalized emittance 1.4 mm-mrad, rms energy spread 1 MeV. Undulator period is 3.4 cm.

In the present scheme an electron beam with slice modulation of the energy passes through the undulator and produces SASE radiation. Since only a small fraction of the bunch is modulated (10 fs versus 200 fs of FWHM electron pulse duration, see Fig.2), the total energy in the radiation pulse remains approximately the same as in the case of nonmodulated electron beam, and saturation is achieved at an undulator length of about 120 m. Figure 3 shows a view of the central part of the radiation pulse. The dotted lines in this figure show the initial energy modulation of the electron beam. The temporal structure of the radiation pulse has a clear signature of the slice energy modulation. The FEL process is strongly suppressed in the regions of the electron bunch with large energy chirp, and only regions of the electron bunch with nearly zero energy chirp produce radiation.

The plots in Fig. 4 show the spectrum of the radiation pulse. A signature of the slice energy modulation is reflected by the tails of the spectrum. Each of three clearly visible bumps in the averaged spectrum corresponds to a local extremum of the energy offset shown in Fig. 2. The bump marked as M_1 corresponds to the central peak energy offset. The bump M_2 corresponds to the neighboring two positive energy offsets. The bump M_3 comes from the areas of the electron bunch with negative energy offset. The single-shot spectrum (shown as grey line) exhibits an oscillatory behavior near bumps M_2 and M_3. That is due to an

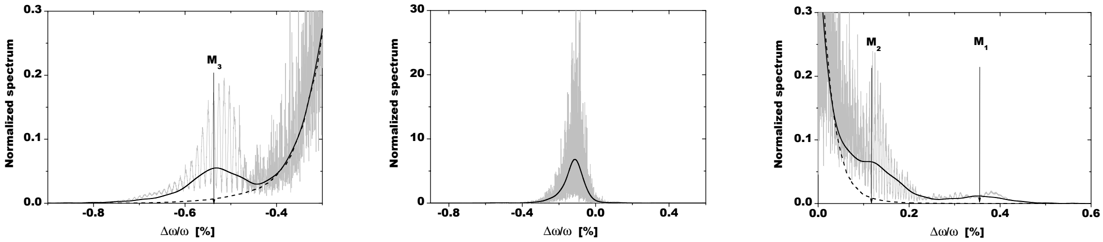

Figure 4: Spectrum of the radiation pulse produced by modulated electron bunch. Undulator length is 120 m. Middle: complete spectrum. Left and right plots show enlarged tails of complete spectrum. Solid line is averaged spectrum. Dashed line is averaged spectrum of non-modulated electron beam. Mark M_1 shows tuning of monochromator for single pulse selection. Marks M_2 and M_3 show tuning of the monochromator for selection of two pulse sequence (see Fig. 5).

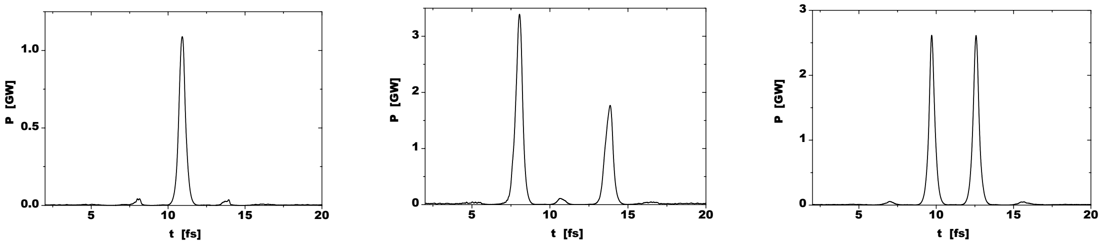

Figure 5: Averaged temporal structure of the radiation pulse behind monochromator tuned to single spike (left plot) and two pulse sequence selection (middle and right plots).

interference of two radiation wave packets with close frequencies coming from different parts of the electron bunch. Other maxima can be hardly distinguished, since they are located within the bandwidth of the main spectrum.

Figure 4 gives a clear idea about separation of the attosecond radiation pulses. Positioning of the monochromator to different maxima of the spectrum allows us to select single pulse, or a two pulse sequence of attosecond duration. The calculation involves the following steps. The FEL simulation code produces 3-D arrays for the radiation field in the near zone. This field is recalculated into the far field zone, and is subjected to the Fourier transform. The latter result is convoluted with the reflectivity function of Ge(111) monochromator, and is subjected to inverse Fourier transform giving temporal structure of the radiation pulse behind the monochromator.

By selecting the frequency offset of the monochromator to the position marked as M_1 in Fig. 4, we select single pulses. Their properties are illustrated with Figs. 5 and 6. An analysis of single pulses shows that their pulse duration is about 300 as, the average power has GW-level, and the radiation pulse energy is about a μJ. The larger width of the averaged curve is partially due to shot-to-shot fluctuations of the position of the radiation pulse (a fraction of coherence time). Note that shot-to-shot fluctuations of the radiation energy after monochromator are suppressed significantly due to ultra short duration of the lasing fraction

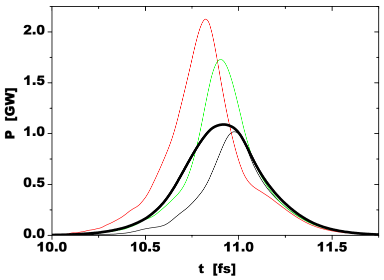

Figure 6: Temporal structure of the radiation pulse behind monochromator tuned to single spike selection (mark M_1 in Fig. 4). Thin curves are single shots, and bold curve is average over many pulses.

of the electron bunch [13]. An advantage of single-pulse selection is the small background from the main radiation pulse due to a large offset from the resonant frequency.

By positioning of the monochromator central frequency to the spectrum bumps M_2 or M_3 one can select a two pulse sequence as illustrated in Fig. 5. Two pulses are separated by two or one oscillation period of optical laser depending on the choice of the monochromator tuning. Note that due to the statistical nature of the SASE process the time

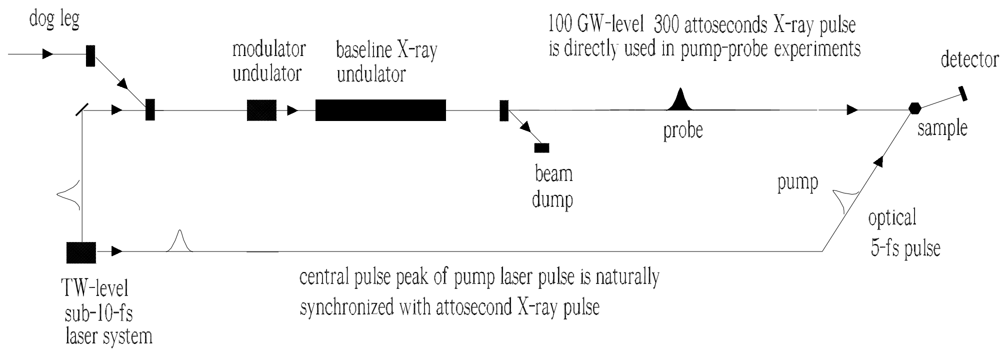

Figure 7: Scheme for femtosecond resolution pump-probe experiments based on the generation of the 100 GW-level attosecond X-ray pulses directly from X-ray SASE FEL.

jitter between two pulses is about 200 as, a fraction of the coherence time. One should not wonder that pulse amplitudes differ visibly for the case of pulse separation by one laser oscillation period. This is a typical nonlinear effect related to the sensitivity of the FEL process to the sign and the value of the energy chirp. Although the energy modulation amplitude is the same in both maxima, the shape of the energy chirp is asymmetric.

CONCLUSION

Attosecond X-ray FEL described here is an ideal tool for organization of pump-probe experiments (see Fig. 7) [11, 14]. Indeed, attosecond X-ray pulse is naturally synchronized with its fs optical pulse, and time jitter is cancelled. Usual optical elements are used for seed laser beam splitting and tunable delay. It should be possible to achieve a timing accuracy close to duration of the half period of the seed laser pulse (1 fs), allowing an unprecedented insight into the dynamics of electronic excitations, chemical reactions, and phase transitions of matter, from atoms, through organic and inorganic molecules, to surface, solids and plasma.

It is important that proposed attosecond scheme is based on the nominal XFEL parameters, and operates in a "parasitic" mode not interfering with the main mode of the XFEL operation. It can be realized with minimum additional efforts. The machine design should foresee the space for installation of modulator undulator and a viewport for input optical system. Many of the components of the required laser system can be achieved with technology which is currently being developed for applications other than the attosecond X-ray source. As a result, a laser system could be developed over the next few years and can meet the XFEL requirements well in advance of XFEL construction schedule.

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