SCHEME FOR GENERATION OF SINGLE 100 GW 300-AS PULSE IN THE X-RAY SASE FEL WITH THE USE OF A FEW CYCLES OPTICAL PULSE FROM TI:SAPPHIRE LASER SYSTEM

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Abstract

Femtosecond optical pulse interacts with the electron beam in the two-period undulator and produces energy modulation within a slice of the electron bunch. Then the electron beam enters the first part of the X-ray undulator and produces SASE radiation with 100 MW-level power. Due to energy modulation the frequency is correlated to the longitudinal position, and 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. After the first undulator the electron beam is guided through a magnetic delay which we use to position the X-ray spike with the largest frequency offset at the "fresh" part of the electron bunch. After the chicane the electron beam and the radiation enter the second undulator which is resonant with the offset frequency where only a single (300 as duration) spike grows rapidly. The final part of the undulator is a tapered section allowing to achieve maximum output power 100-150 GW in 0.15 nm wavelength range.

INTRODUCTION

With the realization of the fourth-generation light sources operating in the X-ray regime [1, 2], new attoscience experiments will become possible. In its initial configuration the XFEL pulse duration is about 100 fs, which is too long to be sufficient for this class of experiments. The generation of subfemtosecond X-ray pulses is critical to exploring the ultrafast science at the XFELs. The advent of attosecond X-ray pulses will open a new field of time-resolved studies with unprecedented resolution. X-ray SASE FEL holds a great promise as a source of radiation for generating high power, single attosecond pulses. Recently a scheme to achieve pulse duration down to attosecond time scale at the wavelengths around 0.1 nm has been proposed [3]. It has been shown that by using X-ray SASE FEL combined with terawatt-level, sub-10-fs Ti:sapphire laser system it will be possible to produce GW-level X-ray pulses that are reaching 300 attoseconds in duration. In this scheme an ultrashort laser pulse is used to modulate the energy of electrons within the femtosecond slice of the electron bunch at laser frequency. Energy-position correlation in the electron pulse results in spectrum-position correlation in the SASE radiation pulse. Selection of ultra-short X-ray pulses is achieved by using the monochromator. Such a scheme for production of single attosecond X-ray pulses would offer the possibility for pump-probe experiments, since it provides a precise, known and tunable interval between the laser and X-ray sources.

In this paper we propose a new method allowing to increase output power of attosecond X-ray pulses by two orders of magnitude. It is based on application of sub-10-fs laser for slice energy modulation of the electron beam, and application "fresh bunch" techniques for selection of single attosecond pulses with 100 GW-level output power. The combination of very high peak power (100 GW) and very short pulse (300 as) will open a vast new range of applications. In particular, we propose visible pump/X-ray probe technique that would allow time resolution down to subfemtosecond capabilities. Proposed technique allows to produce intense ultrashort X-ray pulses directly from the XFEL, and with tight synchronization to the sample excitation laser. Another advantage of the proposed scheme is the possibility to remove the monochromator (and other X-ray optical elements) between the X-ray undulator and a sample and thus to directly use the probe attosecond X-ray pulse.

Operation of 100 GW attosecond SASE FEL is illustrated for the parameters close to those of the European XFEL operating at the wavelength 0.15 nm [1]. Optimization of the attosecond SASE FEL has been performed with the three-dimensional, time dependent code FAST [5] taking into account all physical effects influencing the SASE FEL operation (diffraction effects, energy spread, emittance, slippage effect, etc.).

HIGH POWER ATTOSECOND FACILITY

A basic scheme of the high-power attosecond X-ray source is shown in Fig. 1. An ultrashort laser pulse is used to modulate the energy of electrons within the femtosecond slice of the electron bunch at 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 modulator which consists of a short (a few periods) undulator. Following the energy modulator the beam enters the baseline (gap-tunable) X-ray undulator. In its simplest configuration the X-ray undulator consists of an uniform input undulator and nonuniform (tapered) output undulator separated by a magnetic chicane (delay) as it is shown in Fig. 2.

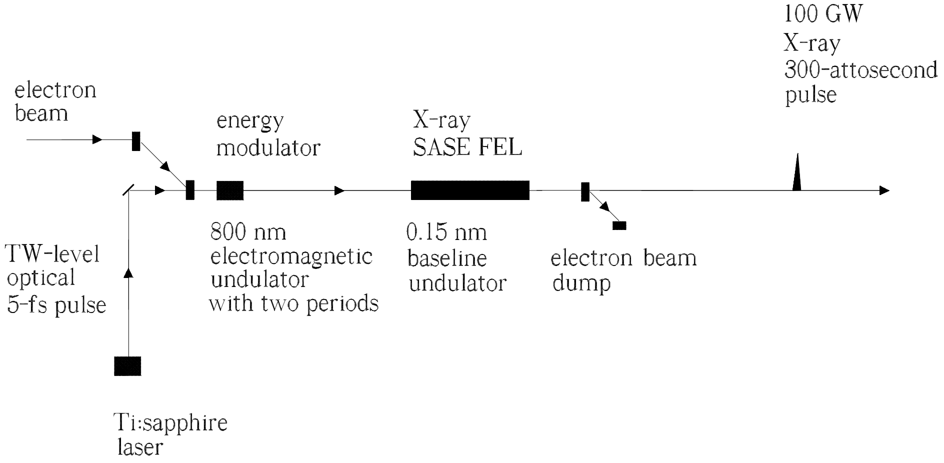

Figure 1: Schematic diagram of high power attosecond X-ray source.

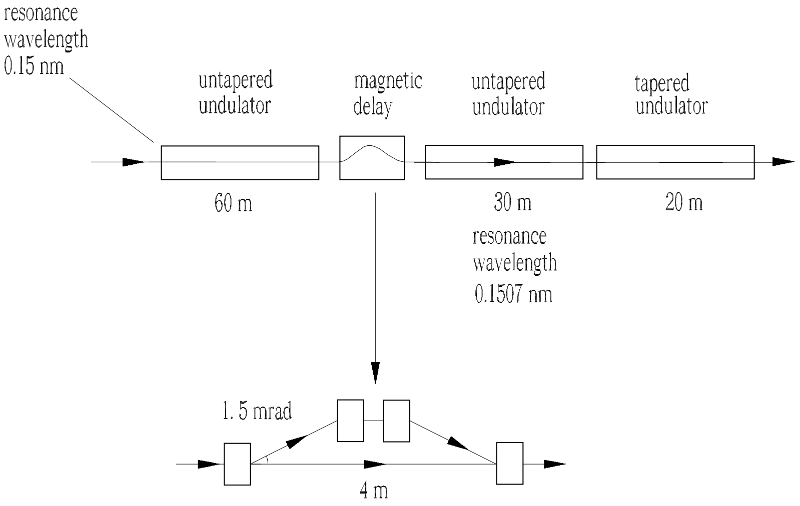

Figure 2: Design of undulator system for high power attosecond X-ray source.

The process of amplification of radiation in the input undulator develops in the same way as in conventional X-ray SASE FEL: fluctuations of the electron beam current serve as the input signal. When an electron beam traverses an undulator, it emits radiation at the resonance wavelength $\lambda = \lambda_{\mathrm{w}}(1 + K^2/2)/(2\gamma^2)$. Here λ_{w} is the undulator period, $mc^2\gamma$ is the electron beam energy, and K is the undulator parameter. In the proposed scheme the laser-driven sinusoidal energy chirp produces a correlated frequency chirp of the resonant radiation $\delta\omega/\omega \simeq 2\delta\gamma/\gamma$.

Our concept of attosecond X-ray facility is based on the use of a few cycle optical pulse from Ti:sapphire laser system. This optical pulse is used for modulation of the energy of the electrons within a slice of the electron bunch at a wavelength of 800 nm. Due to extreme temporal confinement, moderate optical pulse energies of the order of a few mJ can result in electron energy modulation amplitude higher than 30-40 MeV. In few-cycle laser fields high intensities can be "switched on" nonadiabatically within a few optical periods. As a result, a central peak electron energy modulation is larger than other peaks (see Fig. 3). This relative energy difference is used for selection of SASE radiation pulses with a single spike in time domain. Single-spike selection can effectively be achieved when electron bunch passes through a magnetic delay and output undulator operating at a shifted frequency.

Operation of proposed attosecond facility is illustrated with Figs. 4-6. The input undulator is a conventional 0.15 nm SASE FEL operating in the high-gain linear regime. This undulator is long enough (60 m) to reach 100 MW-level output power (see Fig. 2). After the input undulator the electron beam is guided through a magnetic delay (chi-

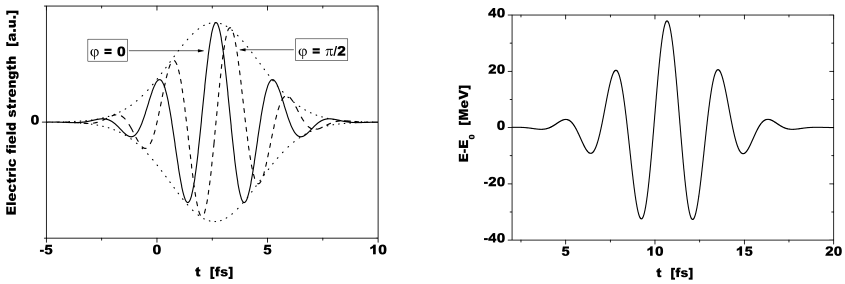

Figure 3: Left plot: electric field strength within femtosecond laser pulse. Right plot: energy modulation of electron bunch at the exit of the modulator.

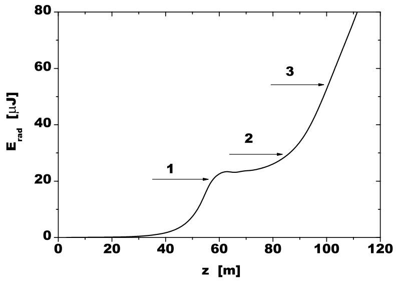

Figure 4: Energy in the radiation pulse versus undulator length. Marks 1, 2, and 3 show the end points of the 1st, 2nd, and 3rd undulator sections, respectively.

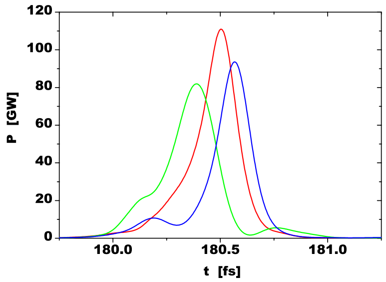

Figure 6: Shot-to-shot fluctuations of the radiation pulse after monochromator with 0.5% linewidth tuned to the frequency of the main maximum. Undulator length is 100 m.

cane). The trajectory of the electron beam in the chicane has the shape of an isosceles triangle with the base equal to L. The angle adjacent to the base, θ, is considered to be small. Parameters in our case are: $L = 4$ m, $\theta = 1.5$ mrad, compaction factor $L\theta^2 = 8\mu$m, extra path length $L\theta^2/2 = 4\mu$m, horizontal offset $L\theta/2 = 3$ mm. In the present design we have only 4 μm extra path length for the electron beam, while the FWHM length of electron bunch is about 50 μm. Calculations of the coherent synchrotron radiation effects show that this should not be a serious limitation in our case.

Passing the chicane the electron beam and seed SASE radiation enter the output undulator operating at an offset frequency. We use a magnetic delay to position the offset frequency radiation at the ”fresh” part of the electron bunch. This seed single spike at an offset frequency starts interacting with the new set of electrons, which have no energy modulation, since they did not participate in the previous interaction with optical laser pulse. This is the essence of the ”fresh bunch” techniques which was introduced in [4].

In the output undulator seed radiation at reference frequency plays no role. However, single spike at an offset frequency is exponentially amplified upon passing through the first (uniform) part of the output undulator. This part is long enough (30 m) to reach saturation. The power level at saturation is about 20 GW. The most promising way to extend output power is the method of tapering the magnetic field of the undulator. Tapering consists in slowly reducing the field strength of the undulator field to preserve the resonance wavelength as the kinetic energy of the electrons changes. The strong radiation field produces a ponderomotive well which is deep enough to trap the particles. The radiation produced by these captured particles increases the depth of the ponderomotive well, and they are effectively decelerated. As a result, much higher power can be achieved than for the case of a uniform undulator. At the total tapered undulator length of 20 m, the single-spike power is enhanced by a factor of five, from 20 GW-level to 100 GW-level. Figure 6 shows temporal characteristics of the radiation pulse at the exit of the undulator after monochromator with 0.5% linewidth. It is seen that the method proposed in this paper allows direct production from XFEL of single 100 GW-level X-ray pulses with FWHM duration of 300 as.

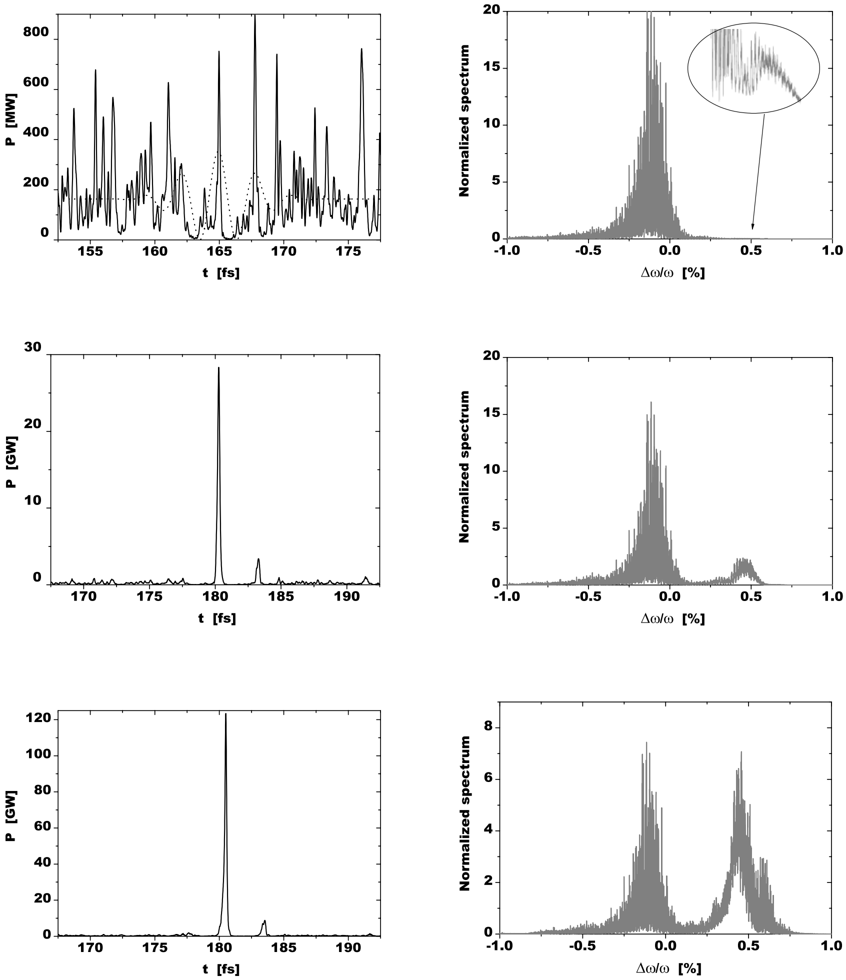

Figure 5: Temporal (left column) and spectral (right column) evolution of the radiation pulse along the undulator. Upper, middle, and lower plots correspond to the undulator lengths of 57, 85, and 100 m. Dashed line shows energy modulation of the electron bunch.

CONCLUSION

Today there are at least two possible attosecond X-ray sources for light-triggered, time-resolved experiments associated with the X-ray SASE FEL: the "attosecond X-ray parasitic" [3] and the "attosecond X-ray dedicated" source mode proposed in this paper. The simplest way to obtain attosecond X-ray pulses from XFEL is to use "parasitic" technique which is proposed in [3]. It also would offer the possibility of providing a beam to a pump-probe experiments with the XFEL that has a precise, known and tunable time interval between the laser and X-ray sources. More power of attosecond pulse could be obtained using the XFEL for dedicated attosecond X-ray pulse production as described in this paper.

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