Attosecond x-ray pulses produced by ultra short transverse slicing via laser electron beam interaction

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Abstract. We propose a method of generation of $\sim 115$ attosecond x-ray pulses in a free electron laser (FEL) by means of producing ultra-fast angular modulation of the electron trajectories prior to entering the FEL. For this modulation, we employ a few-cycle laser pulse in a higher-order Gaussian mode and with carrier-envelope phase stabilization.

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1. Introduction

Breakthrough progress in the generation of solitary vacuum ultraviolet pulses of attosecond duration has been made in the wake of technology development that allows generation of few-cycle laser pulses with carrier-envelope phase stabilization [1]–[5]. Following this lead, few-cycle laser pulses with carrier-envelope phase stabilization were adopted in proposals for generation of attosecond x-ray pulses using free electron lasers (FELs) by means of high gain harmonic generation [6] and self amplified spontaneous emission (SASE) [7]–[10]. In all these proposals the ultra-short laser pulse is used to produce energy modulation of electrons in an ultra-short electron beam slice with amplitude that significantly exceeds the uncorrelated electron beam energy spread. The FEL is tuned in such a way that either electrons in the region with the highest amplitude of energy modulation [6]–[8] or electrons in the region with the highest gradient in energy modulation along the electron slice [9, 10] produce the x-ray signal that dominates the output from the entire electron beam. As a result one gets a few hundred attosecond x-ray pulse whose arrival time is ultimately linked to the timing of the laser pulse, a necessary requirement for pump-probe experiments with attosecond pulses.

In this paper, we keep with the tradition of using a few-cycle laser pulse with carrier-envelope phase stabilization for generation of the attosecond x-ray pulses in an FEL, but this time, instead of energy modulation we use modulation of the electron angles. We show that angular modulation can also be effective for the creation of specific conditions when a solitary attosecond x-ray pulse can be generated in the FEL. Moreover, the angular modulation can be combined with energy modulation for a shortening and improved selection of the attosecond pulse.

2. Electron interaction with the laser field

The energy gain/loss obtained by an electron in its interaction with a laser field $E_x$ polarized in the horizontal plane and co-propagating in a planar wiggler magnet together with the electron in the z-direction can be found by solving the equation [11]:

$$\frac{d\gamma}{dt} = \frac{e}{mc} E_x \cdot \beta_x,$$

where $\gamma$ is the relativistic factor, $\beta_x = v_x / c$, where $v_x$ is the horizontal velocity of the electron and $c$ is the speed of light, $e$, $m$ are the electron charge and mass, $E_x$ is the laser field and we consider the Hermite–Gaussian TEM$_{10}$ mode [12]:

$$E_x = \frac{E_0}{1 + (z/z_0)^2} \frac{2\sqrt{2}x}{w_0} \sin(k(z - ct) + \psi) \exp\left(-\frac{(z/c - t + s/c)^2}{4\sigma_t^2}\right) \exp\left(-\frac{x^2 + y^2}{w_0^2(1 + (z/z_0)^2)}\right),$$

where $E_0$ is the field amplitude, $k = 2\pi / \lambda$ is the wave vector, $\lambda$ is the carrier wavelength, $z_0 = kw_0^2 / 2$ is the Rayleigh length, $w_0$ is the waist size which is assumed to be in the center of the wiggler, $\psi = \psi_0 - 2\tan^{-1}(z/z_0) + k(x^2 + y^2) / 2R$, $\psi_0 = ks$ is the phase of the wave at the beginning of the interaction with the electron at the entrance of the wiggler, $s$ is the electron coordinate within the electron bunch, $R = (z^2 + z_0^2) / z$, and $\sigma_t$ is the rms width of the laser pulse intensity. For brevity and in order to simplify the analysis we consider an electron beam with horizontal and vertical size $\sigma_{x,y} \ll w_0$ and ignore the second exponent in (2) and a term with $x$, $y$ in $\psi$. 

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For electron motion inside the wiggler one obtains:

\[
\beta_x = -\frac{K}{\gamma}\sin(k_wz),
\]

\[
\beta_z = \sqrt{1 - \frac{1}{\gamma^2} - \beta_x^2} \approx 1 - \frac{1}{2\gamma^2} \left(1 + \frac{K^2}{2}\right) + \frac{K^2}{4\gamma^2} \cos(2k_wz),
\]

where \(k_w = 2\pi/\lambda_w\), \(\lambda_w\) is the wiggler period, \(K = eB_0/k_wmc\), \(B_0\) is the peak magnetic field, and \(\beta_z\) is the normalized velocity along the wiggler. From (3) one obtains:

\[
x(z) = x_0 + \frac{K}{k_w\gamma} \cos(k_wz),
\]

\[
z(t) = c \int_0^t \beta_z(t') \, dt' \approx ct - \frac{1}{2\gamma^2} \left(1 + \frac{K^2}{2}\right) ct + \frac{K^2}{8k_w\gamma^2} \sin(2k_wz),
\]

where \(x_0\) is the electron coordinate at the entrance of the wiggler.

Then, using (1) and (3) we write:

\[
\frac{dy}{dt} = \frac{eE_0K}{mc\gamma(1 + (z/z_0)^2)} \frac{2\sqrt{2}}{w_0} e^{-(z/c - t + s/c)^2/4\sigma_t^2} \left(x_0 + \frac{K}{k_w\gamma} \cos(k_wz)\right) \times \sin(k_wz) \sin(k(z - ct) + \psi).
\]

It is further convenient to define the resonance electron energy, also called an FEL resonance energy, \(\gamma_r^2 = \frac{k}{k_w}(1 + \frac{K^2}{2})\). Then, assuming a small energy spread \(\Delta\gamma/\gamma_r\) one obtains (with the help of equation (4)):

\[
k(z - ct) = -k_wct \frac{\gamma_r^2}{\gamma^2} - \frac{\xi}{2} \sin(2k_wz),
\]

with \(\xi = K^2/(2 + K^2)\). Using a generation function for Bessel functions [13] we find:

\[
2\sin(k_wz) \sin(k(z - c) + \psi) = \cos[k_wct(1 - (\gamma_r/\gamma)^2) - \xi/2 \sin(2k_wz) + \psi] - \cos[k_wct(1 + (\gamma_r/\gamma)^2) - \xi/2 \sin(2k_wz) + \psi] \\
\approx (J_0(\xi/2) - J_1(\xi/2))(\cos[k_wct(1 - (\gamma_r/\gamma)^2) + \psi],
\]

where \(J_0\) and \(J_1\) are the first- and the second-order Bessel functions of the first kind. We note that in the second step in equation (7) we retain only a slowly varying term with \(1 - (\gamma_r/\gamma)^2 \ll 1\). Finally, by averaging over one wiggler period and using dimensionless variables [14]: \(\hat{z} = ct/L_w, v = N2\Delta\gamma/\gamma_r\) and \(q = L_w/z_0\), where \(L_w\) is the length of the wiggler with \(N\) periods, \(\hat{\sigma}_r = \sigma_r/t_0\) and \(t_0 = 2\pi N/kc\), one obtains:

\[
\left\langle \frac{dy}{d\hat{z}} \right\rangle = \frac{eE_0KL_w}{2mc^2\gamma} \left\{ JJ \right\} \frac{2\sqrt{2}x_0 \cos(2\pi v\hat{z} - 2\tan^{-1}(q\hat{z}) + ks)}{w_0} \times \exp \left(\frac{(\hat{z}/2\hat{\sigma}_r - s/2c\hat{\sigma}_r)^2}{1 + (q\hat{z})^2}\right),
\]

\[
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\]
where the definition \( JJ = J_0(\xi/2) - J_1(\xi/2) \) is used following [15]. By introducing the laser pulse energy \( A_L \) and defining the laser peak power \( P_L = A_L/\sqrt{2\pi}\sigma_r = (E_0^2/8\pi)(\pi w_0^2)c \), equation (8) can be written as:

\[
\left\langle \frac{dy}{dz} \right\rangle = \frac{2K}{\gamma} \sqrt{\frac{P_L}{P_0}} (JJ) k x_0 q \frac{\cos(2\pi v z - 2\tan^{-1}(q z) + k s)}{1 + (q z)^2} \exp \left( - \left( \frac{z}{2\hat{\sigma}_r} - \frac{s}{2c\sigma_r} \right)^2 \right),
\]

(9)

where \( P_0 = I_A m c^2/e \) and \( I_A \) is Alfvén current.

Now we define the change of electron horizontal momentum due to the interaction with the laser electric and magnetic fields in the wiggler:

\[
\frac{dp_s}{dt} = e(E_s - \beta_s H_s) \approx \frac{e E_s (1 + K^2/2)}{2\gamma^2} = \frac{e E_0 (1 + K^2/2)}{2\gamma^2 (1 + (z/z_0)^2)} \frac{2\sqrt{2}}{w_0} e^{-(z/c - ts/c)^2/4\sigma_t^2} \left( x_0 + \frac{K}{k w y} \cos(k w z) \right) \sin(k (z - ct) + \psi),
\]

(10)

where \( |H_s| = |E_s| \) is the laser magnetic field. Then, by averaging over the wiggler period we obtain:

\[
\left\langle \frac{dp_s}{dt} \right\rangle = \frac{e E_0 K}{\gamma (1 + (z/z_0)^2)} \frac{2\sqrt{2}}{k w_0} e^{-(z/c - ts/c)^2/4\sigma_t^2} \langle \sin(k (z - ct) + \psi) \cos(k w z) \rangle.
\]

(11)

Similar to equation (7) we have:

\[
2 \langle \sin(k (z - ct) + \psi) \cos(k w z) \rangle \approx (J_0(\xi/2) - J_1(\xi/2)) \sin(k w c t (1 - (\gamma_\perp/\gamma)^2) + \psi).
\]

(12)

Finally, defining \( x' \approx p_s/mc\gamma \) and introducing as before the laser peak power \( P_L \) and dimensionless variables \( \hat{z}, q, v, \hat{\sigma}_r \) we rewrite equation (11) in similar form to equation (9):

\[
\left\langle \frac{dx'}{dz} \right\rangle = \frac{2K}{\gamma^2} \sqrt{\frac{P_L}{P_0}} (JJ) q \frac{\sin(2\pi v \hat{z} - 2\tan^{-1}(q \hat{z}) + k s)}{1 + (q \hat{z})^2} \exp \left( - \left( \frac{\hat{z}}{2\hat{\sigma}_r} - \frac{s}{2c\sigma_r} \right)^2 \right).
\]

(13)

Comparing equations (13) and (9) we find that:

\[
\frac{\partial \Delta x'}{\partial s} = \frac{\partial}{\partial x_0} \left( \frac{\Delta y}{\gamma} \right).
\]

(14)

where \( \Delta x' \) and \( \Delta y \) are electron angular kick and energy change accumulated from the beginning of the wiggler. We note that this result is in agreement with the Panofsky–Wentzler theorem [16] and equation (13) can be directly obtained from (9) using this theorem.

Using equation (9) and (13) we obtain:

\[
\frac{\Delta y}{\gamma}(q, v, \hat{\sigma}_r, s) = \frac{2K}{\gamma^2} \sqrt{\frac{P_L}{P_0}} (JJ) k x_0 f(q, v, \hat{\sigma}_r, s) \cos(k s + \varphi),
\]

\[
\Delta x'(q, v, \hat{\sigma}_r, s) = \frac{2K}{\gamma^2} \sqrt{\frac{P_L}{P_0}} (JJ) f(q, v, \hat{\sigma}_r, s) \sin(k s + \varphi),
\]

(15)
where $\varphi$ is an arbitrary phase and

$$f(q, \nu, \hat{\sigma}_r, s) = q \int_{-0.5}^{0.5} \cos(2\pi \nu \hat{z} - 2 \tan^{-1}(q \hat{z})) \exp\left(-\left(\frac{\hat{z}}{2\hat{\sigma}_r} - \frac{s}{2\sigma_r}\right)^2\right) d\hat{z}. \quad (16)$$

We note that it is possible to generalize expression (16) to the case with an arbitrary ratio between $u_0$ and $\sigma_{x,y}$ and find the energy gain and the angular kick experienced by an electron entering the wiggler with arbitrary $x = x_0, y$ coordinates. In order to do that one must add a factor $\exp[-(x_0^2 + y^2)/(u_0^2(1 + (q \hat{z})^2))]$ under the integral in formula (16). In this case the only approximation used is that we ignore a weak dependence on $x, y$ in the argument of the cosine term.

3. Generation of attosecond x-ray pulses

Consider a few-cycle carrier-envelope phase stabilized laser pulse at $\lambda = 800$ nm with a full width at half maximum (FWHM) pulse width $\sqrt{2\pi}\sigma_r = 5$ fs and pulse energy $A_L = 0.4$ mJ. Figure 1 shows plots of $f(s = 0)$ as a function of $\nu$ for various $q$ and for $\hat{\sigma}_r = 0.4$ corresponding to a wiggler with two periods (figure 1(a)) and $\hat{\sigma}_r = 0.8$ corresponding to a wiggler with one period (figure 1(b)).

Consider an electron beam with parameters similar to the electron beam in the LCLS project [17], i.e. $\gamma \approx 2.8 \times 10^4$, normalized emittance $\varepsilon_x = 10^{-6}$ m, rms energy spread of 1 MeV interacting with the above defined laser pulse in a wiggler with $N = 1$. For this energy we find that the FEL resonance can be obtained in the wiggler with period length of 1 m and $K \approx 50$. Assuming that the laser light is focused with Rayleigh length corresponding to $q = 4$ and using $\nu \approx -1$ corresponding to the peak of $f$ in figure 1(b) we calculate $\Delta x'(s)$ using equation (15) with $\varphi = \pi/2$ and plot it in figure 2. The modulation shown in figure 2 has the periodicity of the laser wavelength and a peak amplitude $\Delta x_0' = 5.2 \times 10^{-7}$ which is larger than the intrinsic angular spread in the electron beam $\sigma_r' = \sqrt{\varepsilon_x/(\beta_{r,0}\gamma)} = 4.2 \times 10^{-7}$ calculated for horizontal beta-function in the wiggler $\beta_{r,0} = 200$ m and $\beta_{r,0}' = 0$. We note that even with this large beta-function the horizontal beam size is $\sigma_x = \sqrt{\varepsilon_x \beta_{x,0}/\gamma} \approx 80 \mu$m and is still much smaller than the waist of the laser beam $u_0 \approx 250$ microns. In part, this is a result of our choice of a relatively long wiggler period and Rayleigh length $z_0 = 1/4$ m. The envelope curves in figure 2 show the fit by the function $\Delta x' = \pm \Delta x_0' \exp(-(t/2\sigma_z^2))$. 

Figure 1. Function $f(q, \nu, \hat{\sigma}_r, S = 0)$ from equation (16) for $N = 2$ (a) and for $N = 1$ (b) and for $q = 4, 6$ and 8 (curves 1, 2 and 3).
In what follows we show how to obtain attosecond x-ray pulses in the x-ray FEL based on SASE [18, 19]. Typically a SASE FEL employs a long undulator where electrons are guided using natural undulator focusing and external focusing. Passing the entire length of the device they complete one or more betatron oscillations. If the above discussed angular modulation of the electron beam is applied prior to entering the device, then ‘modulated’ electrons will propagate through it with orbit oscillations relative to the central axis. We found that slippage caused by orbit oscillations can influence the FEL gain. For example, because of the slippage, electrons acquire additional phase shift \( \Delta \phi \approx k_x (\Delta x')^2 L_G / 2 \) with respect to the radiation wave passing one gain length \( L_G \) in the undulator. Here \( k_x = 2\pi / \lambda_x \) and \( \lambda_x \) is the x-ray wavelength and \( (\Delta x')^2 = (\Delta x'_0)^2 \beta_x / \bar{\beta}_x \), where \( \bar{\beta}_x \) is the average beta-function in the FEL undulator. We estimate that for a large \( \Delta x'_0 > \sigma'_x \) this phase shift can be comparable with the curvature of the radiation wave front caused by the wave guiding due to the FEL gain. For a quick estimate of the increased gain length one can use the expression:

\[
\frac{\Delta L_G}{L_G} \approx \frac{\Delta \phi / 4}{1 - \Delta \phi / 4}.
\]  

Using \( \beta_{x,0} = 200 \) m and \( \bar{\beta}_x = 20 \) m, we estimate that these orbit oscillations will destroy the FEL gain when \( \Delta x'_0 \geq 3\sigma'_x \). Orbit oscillations also reduce the overlap between the electron distribution and the radiation and this also affects the FEL gain, but seemingly with a much lesser impact.

Now we can send the electron beam through the wiggler with the angle \(-\Delta x'_0\) and achieve a condition when ‘unmodulated’ electrons propagate the FEL undulator with orbit oscillations and the electrons located at and near to the peak of the angular modulation without such oscillations. In this situation, the entire electron bunch will not lase except a small part located at and near to the peak of the angular modulation. Because these electrons occupy just a fraction of the laser wave cycle the radiation they produce will be of a subfemtosecond, i.e. attosecond duration. Selective lasing of electrons due to angular modulation was previously considered in [20]. In that case the rf deflector was used and that limited the ability to obtain short x-ray pulses to a few tens of femtoseconds.
4. Simulations

For illustration of the above described technique we present calculations made for a hypothetical x-ray FEL using the above defined electron beam parameters and electron peak current 3.4 kA. We consider obtaining attosecond x-ray pulses at 1.5 Å wavelength in the undulator with 3 cm period and 24 cm long break sections used for the quadrupoles at every 2.4 m providing electron beam focusing with $\beta_x = 20 \text{ m}$. Most of the results were obtained with $\beta_{x0} = 100 \text{ m}$ and laser pulse energy of 2.5 mJ. Other laser beam parameters were kept as defined above unless specifically noted. First, we prepare initial particles in a slice of the electron beam using uniform density distribution along the slice and Gaussian distributions in transverse coordinates, angles and energy. Then we apply angular and energy modulations using formulae (15) (with account for transverse coordinates) and off-set all electron angles by approximately $3\sigma_x'$. Figure 3 shows the angular distribution in the slice of the electron beam after these manipulations (left plot). The externally provided angle is adjusted such as only a group of electrons near and at the peak of the angular modulation enters the undulator with close to nominal trajectory. The center plot in figure 3 shows energy distribution in the same slice and the right plot in figure 3 shows the presence of the coordinate—energy correlation apparent in the electron beam after the interaction with the laser according (15).

The following results were obtained via simulations using the computer code GENESIS [21]. Figure 4 shows the x-ray output power per unit solid angle $dP_{x\text{-ray}}/d\Omega$ on the undulator axis close to the end of the 90 m long undulator. Four peaks seen here (one large and three small) belong to the electron beam slices from four locations in the left plot in figure 3 that are closest to a zero orbit angle. The peak closest to a zero orbit dominates the neighboring peaks. We found that FWHM of this peak is approximately 230 attoseconds. This plot and other similar plots that will be shown later are limited to a very short section of the electron bunch. We found that the electrons sitting outside this section produce only spontaneous emission with $dP_{x\text{-ray}}/d\Omega \approx 10^{17} \text{ W rad}^{-2}$. This is because they were displaced by approximately $3\sigma_x'$ in the wiggler and propagate the undulator with relatively large orbit oscillations. Here, we prefer to characterize the FEL output using $dP_{x\text{-ray}}/d\Omega$ rather than total power $P_{x\text{-ray}}$ for the following reason. The x-ray signal in figure 4 is due to coherent FEL radiation that has a tiny divergence angle of the order of $1 \mu\text{rad}$ while divergence of spontaneous emission is of the order of $250 \mu\text{rad}$ (see, for example, [17]). Due to a relatively large divergence most of the spontaneous radiation will intersect walls of the vacuum pipe and masks and will
Figure 4. X-ray output for a case of angular modulation with 0.8 \( \mu \)m laser. Zoomed version of the strongest peak is shown on the right. FWHM of this peak is approximately 230 attoseconds.

not be transmitted into the experimental hall. The intensity of spontaneous radiation can be further limited at the entrance of the experimental hall with adjustable aperture [17]. Therefore, considering only on-axis radiation and assuming 100 fs FWHM electron bunch we estimate the signal to background ratio for attosecond pulse expressed by the ratio of the total area under the central peak in figure 4 to the integral of the background over the bunch length to be approximately equal to 10. We also note that on-axis spontaneous radiation mostly contains high harmonics of the undulator radiation fundamental frequency and can be filtered out using a monochromator if one needed a better contrast for the attosecond pulse.

The amplitude of the signal in figure 4 depends on various factors and one of them is slippage experienced by the electrons in the process of build-up (gain) of the signal until saturation. In the case of figure 4 this slippage is larger than the width of the electron beam slice and, therefore, the gain stops earlier than it would with a larger width of the electron slice. This is largely due to the short wavelength of the laser. To test this hypothesis, we repeated the simulations using an electron beam modulated by the laser with 2 \( \mu \)m carrier wavelength. Accordingly, we increased \( K \) to 79.4, scaled the laser pulse width to 12.5 fs, and also used 2.5 mJ for the laser pulse energy so as to obtain approximately the same peak amplitude of angular modulation as before using \( q = 4 \) and \( \nu \approx -1 \). The result of this simulation is shown in figure 5. In fact, here one can see that the amplitude of the signal has grown almost fifteen times and the pulse width has shrunk to approximately 180 attoseconds. The contrast of the attosecond pulse in this case is approximately equal to 130.

The above described technique for generation of attosecond x-ray pulses is different from other techniques discussed so far in the literature in the sense that it explores angular modulation of electrons by an ultrashort laser pulse with a carrier-envelope phase stabilization, rather than the energy modulation explored by other techniques. It does not, however, exclude use of energy modulation and one can actually combine the two approaches. Here, we demonstrate what happens if we add energy modulation to the angular modulation from the previous case, and follow the technique described in [9, 22]. We assume that energy modulation will be done by a laser pulse in TEM\(_{00}\) mode with 2 \( \mu \)m carrier wavelength, 12.5 fs FWHM pulse duration, and \( \sim 0.15 \) mJ pulse energy. Interacting with the electrons in the one period wiggler magnet this laser pulse will produce a peak amplitude of energy modulation \( \sim 4 \) MeV. We note that it can be the same wiggler magnet as for angular modulation because of the same carrier wavelength of the laser pulse and because the wiggler detuning \( \nu = -1 \) from the FEL resonance optimized for.
the laser in TEM$_{10}$ mode is still acceptable for a laser in TEM$_{00}$. It is important that both laser pulses, i.e. the laser pulse for angular modulation and the laser pulse for energy modulation, come from a single laser source and have well controlled carrier-envelope phases. In this case a sine-like energy modulation can be added right on top of a cosine-like angular modulation. It has been demonstrated that the laser wave phase inside the ultra-short laser pulses can be controlled with high precision, less than three degrees [4]. Following [9, 22], we used energy modulation in order to bunch electrons at 2 µm spacing and increase peak current as shown in figure 6. Here, again, the electron beam slice from the central location has a higher peak current than side slices as a result of the ultra-short laser pulse. The x-ray signal produced by this electron beam is shown in figure 7. One can see that the peak power grew by an approximate factor of 1.5 compared to figure 5 and FWHM and pulse duration shrank to approximately 115 attoseconds. This is a result of the increased peak current. One additional improvement is a reduction of the amplitudes of the two side peaks (compare figures 5 and 7). The contrast of the attosecond pulse in this case is approximately equal to 130. Figure 8 shows efficiency of microbunching at 1.5 Å in the vicinity of the electron beam slice responsible for an x-ray output in the peak in figure 7. The FWHM of the peak of the microbunching is almost twice as wide as the peak of the x-ray pulse. Similar to what is found in [6], we explain this pulse narrowing by a frequency chirp in the x-ray signal. Because of that the radiation from the head and the tail of the electron beam slice shown in figure 8 destructively interfere, producing narrowing of the output signal. Figure 9 shows that the peak radiation power in this latest example, integrated over the area of 1 mm × 1 mm, reaches 100 GW.

Figure 5. X-ray output for a case of angular modulation with 2 µm laser. FWHM of the strongest peak shown in the right plot is approximately 180 attoseconds.

Figure 6. Longitudinal phase space (left plot) and peak current enhancement (right plot) after the energy modulation with 2 µm laser and bunching.
5. Summary and discussion

We employ a few-cycle laser pulse in Hermite–Gaussian TEM$_{10}$ mode with carrier-envelope phase stabilization to produce angular modulation of electrons while the laser pulse and electrons co-propagate a one period wiggler magnet. With orbit adjustment in the wiggler magnet this modulation allows production of attosecond x-ray pulse in the FEL that follows the wiggler magnet due to suppression of the lasing in the entire electron bunch except for a small part at and near to the peak of angular modulation. The efficiency of the selection of the attosecond pulse depends on the properties of the laser pulse and on the beta-function in the wiggler magnet. In contrast, the efficiency of the selection of the attosecond pulses in the methods of generation of attosecond pulses based on energy modulation of electrons solely depends on the properties of the laser pulse. The added complexity of this new technique is that obtaining the attosecond x-ray pulses will likely require beam based tuning. However, there are no more stringent requirements on pulse-to-pulse orbit stability than already adapted in current
Figure 9. The peak x-ray power calculated for the case of combined angular and energy modulation over an area of 1 mm × 1 mm.

FEL projects [17], and as soon as a desirable result can be achieved, it should stay reproducible. Finally, we showed that angular modulation and energy modulation are not exclusive techniques and can work together producing the shortest possible pulses down to 115 attoseconds and peak power of 100 GW with a remarkable contrast of the signal over the two side peaks and a background due to spontaneous emission approaching 130. This pulse ultimately synchronized to the modulating laser pulse, a feature that may be useful for pump-probe experiments with attosecond x-ray pulses.

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