COHERENT ATOMIC K-SHELL IONIZATION INDUCED BY ULTRASHORT ELECTRON BUNCHES IN ULTRATHIN CARBON AND BERYLLIUM TARGETS

S.V. Trofymenko[1,2], V.S. Skorobohatov[1,2]
[1]National Science Center “Kharkiv Institute of Physics and Technology”,
Kharkiv, Ukraine;
[2]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine
E-mail: Vsevolod.skorobogatov@gmail.com; strofymenko@gmail.com

The work is dedicated to a theoretical investigation of the ionization of atomic K shells by ultrashort relativistic electron bunches. It is shown that in thin light-element targets the ionization cross section can be dramatically affected by the interference of the proper electromagnetic fields of the electrons in the bunch. This can lead to a strong coherent enhancement of the cross section for bunch parameters achievable at modern facilities. It is demonstrated that, for microbunched beams, the ionization cross section can be resonantly amplified over a wide range of microbunching periods.

INTRODUCTION

A fast charged particle moving in a medium excites and ionizes the atoms. The ionization of inner atomic shells, in particular K shells, is of special interest. This is because the subsequent filling of these shells by electrons from outer atomic shells can lead to the emission of characteristic photons in the X-ray range, which are relatively weakly absorbed by the medium. Together with the broad angular distribution and monochromaticity of this emission, this makes it relatively easy to detect these photons and thereby study the K-shell ionization process.

If a group of particles interacts with a medium simultaneously, various interference effects may occur. In this case, the result of the interaction of the group can differ from the simple sum of the results of independent interactions of its individual particles. One of the most fundamental examples of this kind is the King-Perkins-Chudakov effect [1, 2], which is the suppression of the ionization energy loss of a high-energy electron-positron pair due to destructive interference of the electron’s and the positron’s proper electromagnetic fields.

In the present work, we investigate the process of K-shell ionization by ultrashort relativistic electron bunches. It is demonstrated that in targets made of sufficiently light elements (for practical reasons, carbon and beryllium targets are considered), the cross section of this process (per single electron of the bunch) can be coherently amplified by several orders of magnitude compared to the conventional K-shell ionization cross section for relativistic electrons. It is shown that such amplification can occur for bunch parameters achievable at modern X-ray free-electron lasers (XFEL), as well as at sources of sub-femtosecond bunches, such as ARES [3], which has recently begun commissioning at DESY. It is also shown that for a beam with periodic modulation of the longitudinal particle density (representing a model of a microbunched beam formed in the undulator section of an XFEL), a strong resonant amplification of the K-shell ionization cross section can occur within a rather wide range of density modulation periods, whereas in another range the resonant effects can suppress the coherent part of the ionization cross section. The magnitude of the discussed coherent effects depends significantly on the bunch parameters (its length, transverse size and the bunch shape), which could be of interest for the development of new diagnostic techniques for sub-femtosecond bunches, which is a problem of current relevance. Furthermore, detecting characteristic X-rays emitted as a result of K-shell ionization may reveal a purer manifestation of the discussed effects than measurements of the total bunch energy loss, since the contribution in this case comes from a single inner atomic shell. These aspects make the study of these effects in K-shell ionization particularly relevant.

1. RESULTS OF THEORETICAL INVESTIGATION

Let us consider the conditions under which coherent effects are significant. These effects are expected to be significant when the transverse size of the bunch is comparable to or smaller than the typical transverse size of a particle’s field γ/ω, while the longitudinal size of the bunch is comparable to or smaller than the wavelength $\lambda = 2\pi/\omega$ of equivalent photons contributing to K-shell ionization. This motivates the consideration of rather low-Z elements, in particular beryllium and carbon.

Further we briefly discuss the results of an analytical consideration of this process. The K-shell ionization cross section was calculated using the method developed in [4, 5] for individual incident particles, adapted to the case of an electron bunch. The K-shell ionization cross section σ_d associated with distant collisions was calculated using the Weizsäcker-Williams method of equivalent photons. For numerical estimations the values of the K-shell photoionization cross section $\sigma_K^{ph}(\omega)$ were obtained from the attenuation lengths $\mu^{-1}(\omega)$ extracted from [6], using the relation $\sigma_K^{ph}(\omega) = p_K\mu(\omega)/n_a$, where p_k is the fraction of the total photoionization cross section associated with K-shell electrons, n_a is the atomic density of the target material. Also, due to rapid decrease of the $\sigma_K^{ph}(\omega)$ with increasing ω at $\omega > \omega_K$ the dominant contribution to the cross section σ_d comes from the frequencies of the order of ω_K. Accordingly, the upper limit of the integration can be set as $\hbar\omega = 1500\ eV$ for beryllium and $\hbar\omega = 3000\ eV$ for carbon. The remaining parameters were taken as achievable at the European XFEL: the bunch electron energy of 17.5 GeV; the bunch transverse FWHM (full width at half maxima) of 30 μm; the bunch length of 24 μm; the bunch charge of 1 nC. In addition, the transverse distribution was assumed to be Gaussian with the corresponding distribution function given by $f_\perp(\rho) = (2\pi d^2)^{-1} e^{-\rho^2/2d^2}$. Three longitudinal distributions were considered: a Gaussian distribution – $f_\parallel(z) = \left(\sqrt{2\pi} l\right)^{-1} e^{-z^2/2l^2}$, homogeneous distribution – $f_\parallel(z) = 1/L$ and periodically modulated distribution – $f_\parallel(z) = [1 - \cos(2\pi z/l)]/sl$, which serves as a simplified model of a microbunched beam realized at free-electron laser.

Applying the mentioned method, the following expression for the spectral density of the number of equivalent photons in the field of the bunch was obtained:

$$\frac{dN_{ph}}{d\omega} = \frac{2\alpha N}{\pi\omega}\left\{\ln\left(\frac{q_0\gamma}{\omega}\right) - \frac{1}{2} + (N-1)F_\parallel(\omega)\psi(\omega, d)\right\} \quad , (1)$$

where N is the bunch particle number, q_0 is the maximal transferred momentum for collision to be considered distant, γ is an electron`s Lorentz factor, $F_\parallel(\omega) = \left|f_\parallel(z)e^{-i\omega z/v}\right|^2$ is a bunch longitudinal form factor, $\psi(\omega, d) = -[1 + e^a(1+a)Ei(-a)]/2$, $a = d^2\omega^2/\gamma^2$ and $Ei(x)$ is the integral exponent function. The quantity σ_d can be calculated using the previous expression:

$$\sigma_d = \frac{1}{N}\int_{\omega_K}^{\infty} \frac{dN_{ph}}{d\omega} \sigma_K^{ph}(\omega) d\omega \,. \qquad (2)$$

Fig. 1 demonstrates the dependence of cross section σ_d on the bunch longitudinal FWHM size l_f with number of particles estimated as $N = (q/e)/(2l_f/L)$.

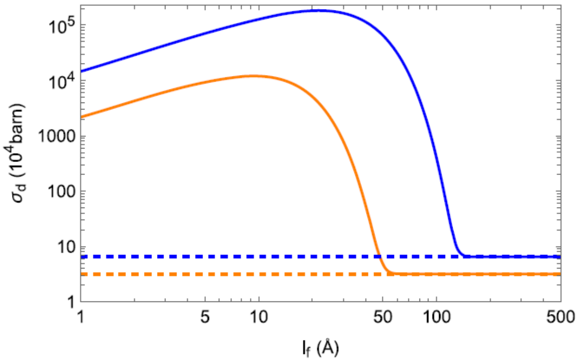

Fig. 1. Dependence of the K-shell ionization cross section due to distant collisions in carbon (orange) and beryllium (blue) targets on the bunch length. Electron energy is $E = 17.5\ GeV$, the bunch transverse size is d_f = 30 µm. Dashed lines show the corresponding single-electron cross sections

The figure demonstrates that the coherent effects can manifest themselves in K-shell ionization for $l_f < 50$ Å for carbon and for $l_f < 150$ Å for beryllium. They can lead to a substantial increase in the value σ_d, up to several orders of magnitude, compared to the single-electron cross section. It is also worth noting the behavior of the σ_d with increasing l_f. At small l_f increase of l_f leads to an increase of σ_d due to the increase of the bunch particle number. After reaching its maximum σ_d rapidly decreases as the coherence condition $l_f < \lambda$ is violated. The cross section for beryllium is more strongly enhanced by the coherent effects due to lower K-shell ionization frequency.

Fig. 2 demonstrates the difference of the dependence of σ_d for a Gaussian and homogeneous distributions. The estimations are made for parameters achievable at ARES: the bunch electron energy of 100 MeV, the bunch transverse FWHM of 0.75 μm; the bunch length of 60 Å; the bunch charge of 0.75 pC.

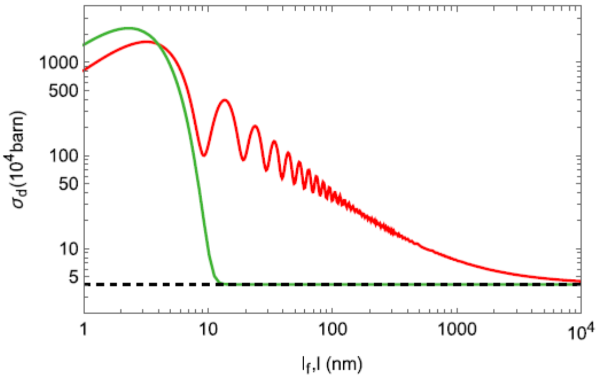

Fig. 2. Dependence of the K-shell ionization cross section due to distant collisions in beryllium on l_f for a Gaussian longitudinal particle distribution (green) and on l for a homogeneous distribution (red). Electron energy is $E = 100\ MeV$, the bunch transverse size is d_f = 0.75 µm. Dashed line shows the corresponding single-electron cross section

The figure demonstrates that coherent effects for a Gaussian bunch profile vanish at much smaller bunch sizes than for a homogeneous profile. In addition, coherent effects cannot be achieved for the ARES bunch with a length of $l_f \approx 60\ nm$ in the case of a Gaussian longitudinal profile, whereas they remain noticeable for a homogeneous bunch profile.

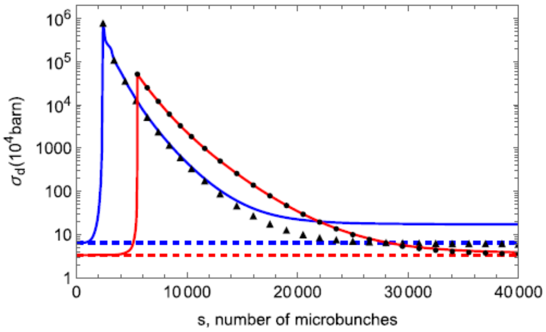

Fig. 3. Dependence of the K-shell ionization cross section due to distant collisions in carbon (orange) and beryllium (blue) targets on the number of microbunches. Electron energy is $E = 17.5\ GeV$, the bunch transverse size is d_f = 30 µm. Solid lines – calculation on the basis of (2), dots and triangles – calculation with the use of analytic formula (3). Dashed lines – single-electron cross sections

Let's now consider a beam with a periodically modulated longitudinal distribution. Fig. 3 demonstrates the dependence of the cross section σ_d on the number of microbunches s for such a beam. In the case of microbunching, owing to the resonant form of the longitudinal form factor, the integral in (2) can be approximately evaluated analytically. As the result, the following expression for coherent part of the cross section σ_d is obtained:

$$\sigma_d^{coh}(s) = \frac{\alpha p_K \mu(\omega_s)(N-1)}{2\pi s n_a} \psi(\omega_s, d)\Theta(\omega_s - \omega_K), \quad (3)$$

where $\omega_s = 2\pi s/L$, L – the beam length, $\Theta(x)$ is the Heaviside step function.

The figure demonstrates that for the number of microbunches for which $\omega_s \approx \omega_K$, which is about $s = 5500$ for carbon (the corresponding microbunching period is $l \approx 2\pi / \omega_K = 4.36\, nm$) and $s = 2200$ for beryllium ($l \approx 11\, nm$) a pronounced resonant enhancement of σ_d occurs. It is also worth noting that interference between the contribution of individual bunches can lead not only to an enhancement, but also suppression of the coherent part of σ_d. This occurs for values of s such that $\omega_s \ll \omega_K$, where the cross section σ_d is reduced compared to the corresponding homogeneous beam with the same length $L = sl$.

A detailed presentation of the results reported here can be found in Ref. [7].

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КОГЕРЕНТНА ІОНІЗАЦІЯ АТОМНИХ К-ОБОЛОНОК, ІНДУКОВАНА УЛЬТРАКОРОТКИМИ ЕЛЕКТРОННИМИ БАНЧАМИ В УЛЬТРАКОРОТКИХ КАРБОНОВИХ ТА БЕРИЛІЄВИХ МІШЕНЯХ

С.В. Трофименко, В.С. Скоробогатов

Теоретично розглянуто іонізацію атомних К-оболонок ультракороткими релятивістськими електронними банчами. Показано, що в тонких мішенях, виготовлених із легких елементів, на поперечний переріз іонізації може суттєво впливати інтерференція власних електромагнітних полів електронів банча. Це може призводити до значного когерентного збільшення поперечного перерізу для параметрів банчів, досяжних на сучасних прискорювачах. Продемонстровано, що для мікробанчованих пучків поперечний переріз іонізації може бути резонансно підсилений в широкому діапазоні періодів мікробанчування.