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Double-mode electrostatic dispersing prism for electron pulse time-domain compression

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ABSTRACT

The generalized theory of double-mode electrostatic dispersing prism for time-domain compressing electron pulse is presented. The fundamental difference between the two modes of o mode and e mode lies in the dispersive dependence of electron's time of flight on its initial kinetic energy at prism entrance: the electrons with higher initial axial energy definitely have longer time of flight for o mode, while not the case for e mode, which results from the electron pulse's U-shaped motion in the prism. The dispersive dependence of time of flight constitutes the mechanism of electron pulse compression for each mode. An example is given to demonstrate the issue of parameter choosing for the prism and to verify its tunable performance of compression.

1. Introduction

Electron-optical methods based on ultrafast manipulation of short electron pulse have become firmly established as the most advanced in the area of time-resolved events recording and investigation [1–4]. Ultrafast electron diffraction (UED) is a typical representative [4], in which the photoelectron pulse from photoemission is considered as a probing tool for subsequent applications. Thus the key to UED is to gain a high-brightness electron pulse with controllable duration at the target plane. Currently there still remains a big technological challenge in improving time-resolved performance of UED. Temporal broadening of electron pulse induced by both space charge effect and its initial energy spread prevents obtaining such electron pulses with sub-100 fs durations, limiting the range of phenomena that can be studied by this technique. The space charge effect refers to the self-broadening due to the Coulomb repulsion between electrons in an electron pulse, which is strengthened when the electron density is getting higher. Due to that, time duration for a pulse of 50 fs containing only 10,000 electrons after 10 cm of travel at 30 keV is limited to several picoseconds [5,6]. So exploring techniques of electron pulse modulation is always in the forefront of UED since its advent.

More has been done theoretically and experimentally to obtain femtosecond or even attosecond electron pulse [7–25]. The techniques available now can be classified into two types. For the first type the electron pulse duration is modulated with spatially nonhomogeneous stationary electromagnetic field provided by specifically devised electron-optical system [8,9,21,22], such as introducing the accelerating element in the traditional photoelectron gun [9]. In contrast to the first type, the electron-pulse-duration modulation is accomplished by non-stationary electromagnetic field for the second one [10–20,23–25], in which electrons in different portion are subject to differential velocity (or energy) modulation. With these methods, progress has indeed been made theoretically on the time-resolved performance of UED. Compared with the former, the latter will be subject to more technical problems, such as the most important issue of synchronization between electron pulse and the non-stationary electromagnetic field. As for the methods using magneto-static electron optics, however, they require electrical currents on the order of an ampere to focus electrons of 30 keV or even above and, consequently, generate a huge amount of heat. In a word, more needs to do for majority of these methods to be implemented into practice. Weber et al. [8] first proposed using an electro-static electron mirror called "reflectron" to compress electron pulse for femtosecond electron diffraction experiments. Kassier et al. [21] performed detailed numerical calculations of its compression performance for a single-stage reflectron. In 2012, Wang and Gedik [22] proposed a practical design for reflectron-based pulse compression using two-stage reflectron and got the impressive temporal compression ratio

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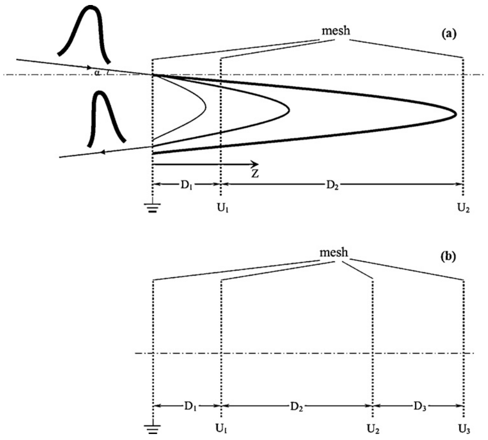

Fig. 1. Schematic diagram of (a) two-stage and (b) three-stage double-mode dispersing prism.

of 60:1 for an electron pulse containing 100,000 electrons. Just as pointed out in literature [22], the two-stage reflectron has superior performance of tunable temporal focal distance. But the generalized theory about two-stage or even multi-stage reflectron is not available, except for some incomplete description in literature by Wang and Gedik [22].

In this contribution, we elaborated the generalized theory of double-mode electrostatic dispersing prism for time-domain electron pulse compression. Based on the energy-related dispersion characteristics of electron's time of flight, the system can operate in two modes, o mode and e mode. The technical details on how to operate in either mode are analyzed. An example is given to demonstrate the issue of parameters choosing for the prism and to verify its tunable performance of compression.

2. Theory of the double-mode dispersing prism

2.1. Principle of dispersing prism

The double-mode two-stage electrostatic dispersing prism for electron pulse time-domain compression is illustrated in Fig. 1(a). It consists of two neighboring uniform electric field regions of axial distance of D_1 and D_2, formed by three meshes with applied voltages of 0, U_1 and U_2. With foregoing parameters set appropriately, the incident electron pulse with incident angle of α will have a U-shaped turn-around motion in the prism under the action of the field resulted and gets out with compressed duration at the exit. It is interesting that, for the given parameters of the electron-optical system, the electron trajectory will solely depend on its initial kinetic energy, as illustrated in Fig. 1(a). The dispersive characteristics that resulted closely resemble the action of optical prism on electromagnetic wave with a certain frequency range, which is the reason why the item of prism is used to name the system. For more freedom to tune the performance of electron pulse compression, actually more electric field regions can be introduced, as one example of three-stage prism as illustrated in Fig. 1(b).

For simplicity, we assume that the incident electron pulse at the prism entrance comes from the initial one with a uniform ellipsoid profile, as in literature [22]. So the incident electron pulse has an intrinsic correlation of longitudinal velocity v and position along the direction of propagation [14]. In other words, if choosing the time when the electrons at the most front just reach the prism entrance as $t=0$, the times for electrons in the incident pulse to just reach the prism entrance form an intrinsic time distribution $t'(v)$. It is worth mentioning that one must account for this initial distribution when calculating the time of flight for electron pulse duration at the prism exit. An important point to realize here is that space charge effect induced broadening in the prism can be safely ignored since the incident electron pulse has a much reduced space charge effect after a certain distance of propagation outside [4–6].

The pulse duration, the mean energy and the energy spread of the incident electron pulse with incident angle of α at the entrance are assumed to be τ, ε and $\Delta\varepsilon$, respectively. So the maximum initial kinetic energy, the minimum initial kinetic energy and the maximum axial initial kinetic energy are $\varepsilon_{front} = \varepsilon + 0.5\,\Delta\varepsilon$, $\varepsilon_{rear} = \varepsilon - 0.5\,\Delta\varepsilon$ and $\varepsilon_{front}\cos^2\alpha$ respectively. To guarantee the complete reflection of the electron pulse, the following condition must be satisfied

$$-U_2 \geq (\varepsilon + 0.5\,\Delta\varepsilon)\cos^2\alpha, \tag{1}$$

which is irrelevant to the parameter U_1. Taking both the time distribution $t(v)$ in the prism and the intrinsic time distribution $t'(v)$ at prism entrance into consideration, one can get the longest and the shortest electron's time of flight to the prism exit, t_{max} and t_{min}. So the condition of having the electron pulse compressed in the prism can be expressed as

$$0 < t_{max} - t_{\min} < \tau. \tag{2}$$

2.2. Operation modes classification

The electron accelerations in the two field regions are as follows:

$$a_1 = \frac{eU_1}{m_e D_1}, \tag{3}$$

$$a_2 = \frac{e(U_2 - U_1)}{m_e D_2}, \tag{4}$$

where e and m_e are the charge and mass of electron, respectively. Here we have chosen the positive direction to be pointing to the right along the axis. $a_1 \neq 0$ and $a_2 < 0$ are the common settings for this prism system. The axial flying distance $s(v)$ and the time of flight used $t(v)$ of electrons in the prism, with initial axial velocity v, can be given respectively as follows:

$$s(v) = 2\left[\frac{\left[\mathrm{Re}\left(\sqrt{v^2 + 2a_1D_1}\right)\right]^2 - v^2}{2a_1} - \frac{\left[\mathrm{Re}\left(\sqrt{v^2 + 2a_1D_1}\right)\right]^2}{2a_2}\right], \tag{5}$$

$$t(v) = 2\left[\frac{\mathrm{Re}\left(\sqrt{v^2 + 2a_1D_1}\right) - \sqrt{v^2}}{a_1} - \frac{\mathrm{Re}\left(\sqrt{v^2 + 2a_1D_1}\right)}{a_2}\right], \tag{6}$$

where $v = \sqrt{2\varepsilon_i \cos^2\alpha / m_e}$, ε_i is the initial kinetic energy of electrons at prism entrance and Re($\cdots$) stands for the real part of the argument involved. The prefactor 2 signifies the turn-around motion.

For the case with $a_1 > a_2$, it can be divided further into two subcategories, $a_1 > 0$ and $a_2 < a_1 < 0$. Based on Eqs. (5) and (6), the energy-related dispersion characteristics of electron's time of flight are illustrated in Figs. 2 and 3, which show the electron with larger initial axial velocity, even definitely having longer axial flying distance, does not necessarily have longer time of flight as expected for the turn-around motion. The parameter $v_c = \sqrt{-2a_1D_1}$ in Fig. 3 is critical initial axial velocity. The electrons with that initial axial velocity will turn around just at the middle mesh of U_1. The non-monotonic functional change of $t(v)$ shows that the electrons with a certain initial axial velocity will have the minimum flight time,