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Electron pulse broadening due to space charge effects in a photoelectron gun for electron diffraction and streak camera systems

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The electron pulse broadening and energy spread, caused by space charge effects, in a photoelectron gun are studied analytically using a fluid model. The model is applicable in both the photocathode-to-mesh region and the postanode electron drift region. It is found that space charge effects in the photocathode-to-mesh region are generally unimportant even for subpicosecond pulses. However, because of the long drift distance, electron pulse broadening due to space charge effects in the drift region is usually significant and could be much larger than the initial electron pulse duration for a subpicosecond electron pulse. Space charge effects can also lead to a considerable electron energy spread in the drift region. Temporal broadening is calculated for an initial electron pulse as short as 50 fs with different electron densities, final electron energies, and drift distances. The results can be used to design electron guns producing subpicosecond pulses for streak cameras as well as for time resolved electron diffraction. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1419209]

I. INTRODUCTION

Picosecond and subpicosecond electron guns have wide applications in streak cameras[1–15] and in time resolved electron diffraction.[16–34] In recent years, the generation of electron pulses with pulse widths of a few hundred femtoseconds or less has also become of much interest because of the ultrafast temporal resolution requirement for investigating various reactions.[9,10] Electron pulses of 50 fs, 2.6 MeV energy with $(2-4.6)\times 10^8$ electrons per pulse have been reported in Ref. 35. In this fully relativistic electron beam case, the 50 fs electron pulses were produced by pulse compression using a magnetic prism. However, for applications in streak cameras and electron diffraction, the electron energy is in the nonrelativistic regime, which makes magnetic electron pulse compression, as applied to the relativistic case, unfeasible. Also, the electron pulse needs to be produced from a photocathode. A method of temporal dispersion compression to produce 50 fs electron pulses was suggested for the nonrelativistic case, but has not been experimentally implemented.[9,10] The main mechanisms of electron pulse broadening in streak cameras and time resolved electron diffraction systems are photoelectron energy spread and space charge effects.

For several types of photocathodes, including metals, the electrons are produced from the surface of the photocathode with almost the same duration as that of the activating laser pulse. It has been shown that increasing the electric field in the vicinity of the photocathode improves the temporal resolution of a streak camera by reducing the effect of the photoelectron energy spread on electron pulse broadening in the photocathode-to-mesh region. However, for femtosecond photoelectron pulses, maintaining the electron pulse duration in the femtosecond range as the electron pulse propagates through the drift region is difficult. Data have shown that electron pulse broadening is often larger in the electron drift region than in the photocathode-to-mesh region.[5] Several factors can cause electron pulse broadening in the drift region.[9,10,26,27] These include energy spread of the electron distribution near the surface of the photocathode, trajectory differences due to focusing elements in the drift region, and space charge effects. We show that space charge is the most dominant cause for pulse broadening. A femtosecond electron pulse with about 10^3–10^4 electrons, 10–50 keV energy, $\sim$1 eV energy spread, $\sim 10^{-3}$ rad beam divergence, and a beam diameter of several hundred micrometers is suitable for streak camera and electron diffraction applications. In this case, the electron density is large enough to cause significant space charge effects.

Electron pulse broadening due to the initial energy spread of the photoelectrons and trajectory differences in the focusing lenses was analyzed in Refs. 4, 5, and 14. Space charge effects on the electron energy spread have been estimated on the basis of a time-independent model in which the axial variations of variables are neglected.[36] The space-charge-limited current density has also been studied as a function of electron flow duration using a generalization of the Langmuir–Child equation derived from the fluid equation in the time-independent case.[37] In Refs. 3 and 38, the space charge effects were investigated using a numerical so-

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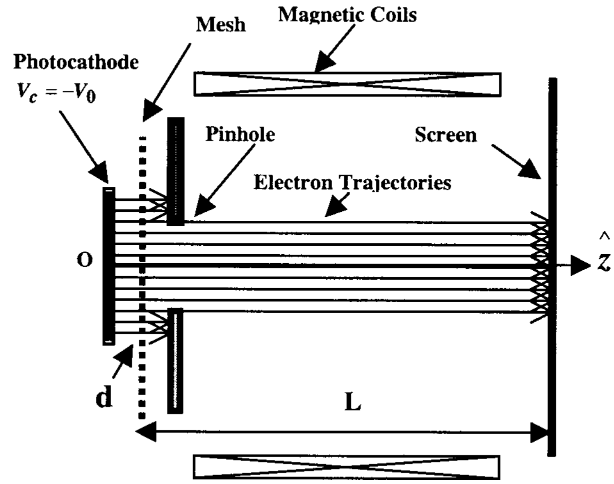

FIG. 1. The photoelectron gun configuration. The magnetic lens maintains beam collimation.

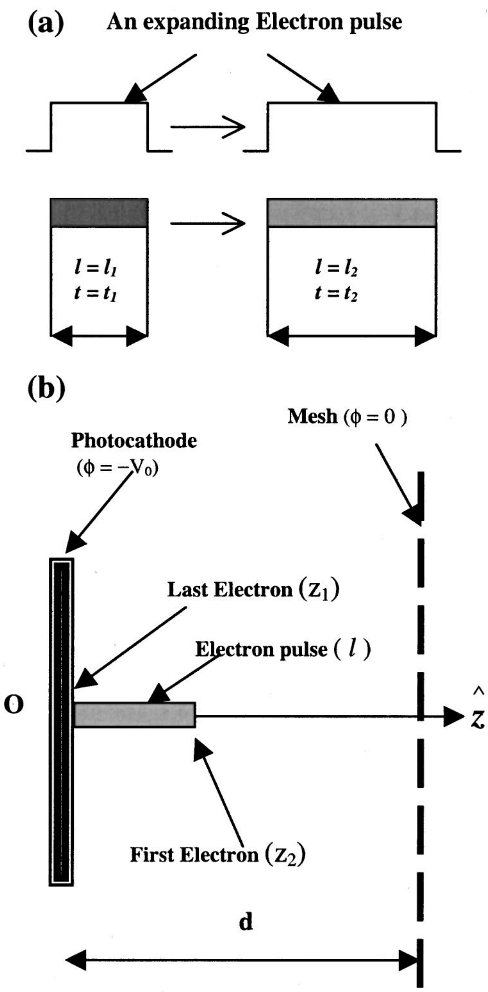

FIG. 2. (a) The time-dependent model describing the expanding electron pulse due to space charge effects. The electron density n within the electron pulse is spatially uniform but temporally nonuniform. The spatial length $l = l_1$ of the electron pulse at time $t = t_1$ is shorter than $l = l_2$ at $t = t_2$, where $t_2 > t_1$. (b) The positions of electrons contained in the electron pulse at $t = 0$.

lution of the equations of motion for electrons. However, detailed analytical results based on a fully time-dependent model of the space charge effects on the electron pulse broadening and electron energy spread are not available.

In this paper, we develop a time-dependent fluid model of electron pulse broadening and electron energy spread due to space charge effects in a photoelectron gun. The analytical results we describe clarify the limitations imposed on the duration of ultrafast electron pulses by space charge effects, and can be used for developing femtosecond photoelectron guns. The paper is organized as follows: In Sec. II, the basic formulation of the fluid model describing the space charge effects in a photoelectron gun is given. In Sec. III, the space charge effects on the electron pulse broadening and electron energy spread are analyzed, and conclusions are stated in Sec. IV.

II. BASIC FORMULATION

Consider a photoelectron gun consisting of a photocathode with a potential of $V_c = -V_0 < 0$, a grounded mesh, a grounded pinhole for selecting the electrons, and an electron beam drift region with a magnetic lens, as shown in Fig. 1. A laser beam with pulse duration τ_0 is incident perpendicular to the photocathode and photo-emits the electrons. The electron pulse starts from the photocathode surface with an electron energy spread of ΔE_0, and the motion of the electrons is assumed to be one dimensional (along the z direction), which means that all the physical quantities are assumed uniform across the beam cross section. The electron pulse duration is much shorter than the transit time of the electrons across the photocathode-to-mesh region. It is also appropriate to assume that the electron density n within the electron pulse is spatially uniform but temporally nonuniform for very short electron pulses, i.e., n is only a function of time. A schematic illustration of the temporal expansion of the electron pulse and the initial position of the electrons in the pulse are shown in Fig. 2. As shown in Fig. 2(a), the electron pulse is assumed to be of square shape, and the spatial length $l = l_1$ of the electron pulse at the time $t = t_1$ is shorter than $l = l_2$ at $t = t_2$, where $t_2 > t_1$. Therefore, the electron pulse can be considered as a cylinder containing all electrons and temporally expanding in length because of space charge effects along the axial direction. For the sake of simplicity, we further assume that the laser pulse also has a square shape.

The one-dimensional fluid model describing the electron pulse includes the equation of motion

$$mn \frac{dv}{dt} = -enE, \tag{1}$$

the particle conservation equation in a pulse

$$\int_{z_1}^{z_2} n \, dz = nl = N/A = \text{constant}, \tag{2}$$

and the Poisson equation

$$\frac{\partial^2 \phi}{\partial z^2} = \frac{en}{\varepsilon_0} \tag{3}$$

for $z_1 \leqslant z \leqslant z_2$. The electric field is expressed as

$$E=-\frac{\partial\phi}{\partial z}. \tag{4}$$

Here, $-e$, m, and v are the charge, mass, and velocity of the electrons, respectively; $n=n(t)$ represents the electron density in the pulse as described previously; E represents the electric field, which is the sum of the external electric field and the beam self-electric field produced by the collective space charge effects; ϕ is the potential distribution; z_2 and z_1 are the positions of the first and last electrons in the electron pulse, as illustrated in Fig. 2(b); $l=z_2-z_1$ is the spatial length of the electron pulse; N is the number of electrons contained in the electron pulse; A is the cross section of the electron beam; and ε_0 is the vacuum permittivity.

In Eq. (1), the pressure term in the fluid equation and the effects of Coulomb collisions between the electrons due to electron random thermal motion have been ignored because they are too small to affect the electron pulse duration and energy spread. The collective electron space charge effects are included in Eq. (1) since the electric field is related to the electron density n and the external voltage via Eq. (3). The effects of the initial electron energy spread are included in the initial conditions.

Equations (1), (3), and (4) can be combined to give

$$\frac{\partial}{\partial z}\left(\frac{dv}{dt}\right)=\frac{\partial}{\partial z}\left(\frac{d^2z}{dt^2}\right)=\frac{e^2n}{\varepsilon_0 m}, \tag{5}$$

and integrating Eq. (5) from $z=z_1$ to $z=z_2$ yields

$$\frac{d^2l}{dt^2}=\frac{e^2n}{m\varepsilon_0}l, \tag{6}$$

where $l=z_2-z_1$ is the spatial length of the electron pulse. In deriving Eq. (6), one should note that the electron density $n=n(t)$ is independent of z within the pulse contained in $z_1<z<z_2$.

Equation (6) indicates that space charge effects lead to variations of the spatial length l of the electron pulse. In addition, Eq. (6) also describes space charge effects on electron pulse broadening. One can obtain the particle conservation equation, which is written as

$$n_0 l_0=nl=\text{constant} \tag{7}$$

under the condition that the diameter of the electron beam is a constant according to Eq. (2). Here $n_0=n(t=0)$ and $l_0=l(t=0)$ are the initial density and spatial length of the electron pulse, and in this case the first electron is at $z=l_0$ and the last electron is at $z=0$. Thus, Eq. (6) becomes

$$\frac{d^2l}{dt^2}=\frac{e^2n_0l_0}{m\varepsilon_0}=\omega_{\text{pe}}^2 l_0=\text{constant}, \tag{8}$$

where

$$\omega_{\text{pe}}=\left[\frac{e^2n_0}{m\varepsilon_0}\right]^{1/2}$$

is the initial electron plasma frequency of the electron pulse.

Equation (8) can be used to investigate the space charge effects on the pulse broadening in both the photocathode-to-mesh region and electron drift region.

A. Space charge effects in the photocathode-to-mesh region

Based on the above-described assumptions, we employ the result, Eq. (8), obtained from the cold fluid model to investigate the space charge effects on the electron pulse in the photocathode-to-mesh region, as shown in Fig. 2(b). Solving Eq. (8), one obtains

$$l=\tfrac{1}{2}\omega_{\text{pe}}^2 l_0 t^2+\Delta v_s t+l_0, \tag{9}$$

where Δv_s is the velocity difference between the first and the last electrons in the electron pulse at $t=0$, and

$$\Delta v_s=\Delta v_0+\frac{eV_0\tau_0}{md} \tag{10}$$

with $\Delta v_0=\sqrt{2\Delta E_0/m}$ being the velocity spread of the electrons at the photocathode surface. We note that the initial energies of the electrons at the photocathode surface vary from 0 to ΔE_0. Here, Eq. (10) can be obtained by solving the equation of motion. In deriving Eq. (10), we have assumed that the initial electron pulse duration is equal to that of the laser pulse, and the first electron in the electron pulse has been accelerated by the electric field $E\approx -V_0/d$, as shown in Fig. 2(b). In addition, the electron pulse will reach the mesh at $t=t_d$ with velocity

$$v_d\approx\sqrt{\frac{2eV_0}{m}}. \tag{11}$$

Therefore, the duration of the electron pulse near the mesh can be expressed as

$$\Delta t_p=\frac{l(t\approx t_d)}{v_d}=\frac{\tfrac{1}{2}\omega_{\text{pe}}^2 l_0 t_d^2+\Delta v_s t_d+l_0}{\sqrt{\frac{2eV_0}{m}}}. \tag{12}$$

Substituting

$$t_d\approx\sqrt{\frac{2md^2}{eV_0}} \tag{13}$$

and Eq. (10) into Eq. (12), one obtains

$$\Delta t_p=\frac{\tfrac{1}{2}\omega_{\text{pe}}^2 l_0 t_d^2}{\sqrt{\frac{2eV_0}{m}}}+\frac{\Delta v_0 md}{eV_0}+\tau_0. \tag{14}$$

Here, we have assumed that $\Delta t_p\ll t_d=\sqrt{2md^2/eV_0}$, and that

$$l_0=\frac{eV_0}{2md}\tau_0^2+\Delta v_0\tau_0 \tag{15}$$

is generally much smaller than $\Delta v_s t_d$ and $\omega_{\text{pe}}^2 l_0 t_d^2/2$.

In Eq. (14), the first term is space charge broadening, the second term is broadening due to the initial electron energy spread, and the third term is the initial laser pulse duration τ_0. It should be noticed that the laser and electron pulses are assumed to be of square shapes, and the contribution of each temporal dispersion mechanism is linearly added to the electron pulse duration in Eq. (14).

It can be seen from Eqs. (10) and (14) that electron pulse broadening due to the initial electron energy spread in the photocathode-to-mesh region is then expressed as

$$\Delta t_e = \frac{\Delta v_0 m d}{e V_0}, \tag{16}$$

which is identical to the results obtained in Refs. 2 and 14.

We will focus our attention on the space charge effects. From Eq. (14), electron pulse broadening due to space charge effects in the photocathode-to-mesh region can be expressed as

$$\Delta t_{\mathrm{sp}} = \frac{\frac{1}{2}\omega_{pd}^2 l_d t_d^2}{\sqrt{\frac{2eV_0}{m}}} = \frac{1}{2}\,\omega_{\mathrm{pe}}^2 t_d^2 \Delta t_p\,, \tag{17}$$

where, $\omega_{pd} = [e^2 n_d / m\varepsilon_0]^{1/2}$ and n_d are the electron plasma frequency and electron density near the mesh, respectively, and l_d is the distance between the first and last electrons in the electron pulse near the mesh, i.e., $l_d = l(t = t_d)$. In addition, the electron density can be approximately calculated from

$$n_d = \frac{I}{e v_d \pi\ r_b^2} = \frac{Ne/\Delta\tau_p}{e v_d \pi\ r_b^2} = \frac{N}{v_d \pi\ r_b^2 \Delta t_p}, \tag{18}$$

where I is the electron beam current, N is the number of electrons contained in the electron pulse, and r_b represents the radius of the electron beam. Using Eq. (18), one can obtain

$$\Delta t_{\mathrm{sp}} = \frac{e^2 N t_d^2}{2 m \varepsilon_0 v_d \pi\ r_b^2} = \frac{e^{1/2} m^{1/2} d^2 N}{\sqrt{2}\pi\ V_0^{3/2} \varepsilon_0 r_b^2}. \tag{19}$$

It can be seen from Eq. (19) that electron pulse broadening due to space charge effects increases with the photocathode-to-mesh gap distance d, but decreases with the increase of beam radius r_b and voltage V_0 applied between the photocathode and mesh. Large d and small V_0 are not favorable for producing femtosecond electron pulses.

B. Space charge effects in the electron drift region

The above-mentioned analysis of the photocathode-to-mesh region can be generalized to make it applicable in the postanode electron drift region of an electron gun. Consider an electron pulse traveling in the drift region with length L that includes a magnetic field along the z direction, as shown in Fig. 1. The magnetic field is assumed to be strong enough to constrain the motion of the electrons in the radial direction. Following the same treatment, one can also solve the basic equations and obtain the potential distribution in the drift region, which takes the form of

$$\phi = \frac{enz^2}{2\varepsilon_0} + \left[\frac{en}{2\varepsilon_0}\,\frac{2(z_2 - z_1 - d)z_2 - (z_2 - z_1)^2}{L}\right] z + \frac{enz_1^2}{2\varepsilon_0} \quad \text{for } z_1 \leqslant z \leqslant z_2. \tag{20}$$

It is mentioned that in the drift region the boundary conditions of $\phi(z=0)=0$ and $\phi(z=L)=0$ have been employed in deriving Eq. (20). The temporal broadening of the electron pulse due to space charge effects in the drift region can be written as

$$\Delta t_{\mathrm{sp}} = \frac{e^2 N t^2}{2 m \varepsilon_0 v\ \ \pi\ \ r_b^2}, \tag{21}$$

where v is the velocity of the electron pulse at time t in the drift region, N is the number of electrons in the electron pulse, and r_b is the electron beam radius. At the end of the drift region, Δt_{sp} is

$$\Delta t_{\mathrm{sp}} = \frac{e^{1/2} m^{1/2} L^2 N}{4\sqrt{2}\pi V_0^{3/2} \varepsilon_0 r_b^2}. \tag{22}$$

The normalized electron pulse broadening due to space charge is

$$\eta = \frac{\Delta t_{\mathrm{sp}}}{\Delta t_p} = \frac{1}{2}\,\omega_p^2 t^2, \tag{23}$$

where

$$\omega_p = \left[\frac{e^2 n}{m\varepsilon_0}\right]^{1/2}$$

is the electron plasma frequency for electron density n, and Δt_p is the electron pulse duration at time t. The electron energy spread ΔE_{sp} due to space charge effects is expressed as

$$\Delta E_{\mathrm{sp}} = e(\phi_{\max} - \phi_{\min}), \tag{24}$$

where $\phi_{\max}$ and $\phi_{\min}$ are the maximum and minimum potentials within the electron pulse, respectively. It is noticed that $\phi_{\max}$ and $\phi_{\min}$ can be determined using Eq. (20). When the electron pulse reaches the center of the drift region $(z_1 + z_2 = L$ for $0 \leqslant z \leqslant L)$, Eq. (24) becomes

$$\Delta E_{\mathrm{sp}} = \frac{1}{8} m \omega_p^2 l^2 \approx \frac{e^2 N v \Delta t_p}{8\varepsilon_0 \pi r_b^2} \approx \frac{e^2 N \Delta t_p}{8\varepsilon_0 \pi r_b^2} \sqrt{\frac{2eV_0}{m}}, \tag{25}$$

where $l = z_2 - z_1$ is the spatial length of the electron pulse. In addition to space charge effects, the electron pulse duration Δt_p is also dependent on the laser pulse duration, the energy spread of the photoelectrons, and particle trajectory as determined by the specific photoelectron gun design. Equation (25) shows that the electron energy spread due to space charge effects can become severe when the drift length and the electron density of the pulse are large.

III. RESULTS AND DISCUSSIONS

In this section, the numerical evaluation of the formulas derived in Sec. II is described to further explore space charge effects on the electron pulse broadening and electron energy spread in a photoelectron gun. We separate space charge effects into contributions in the photocathode-to-mesh region and in the electron beam drift region. The limitations on the temporal resolution of a photoelectron gun due to space charge effects are described.

The effect of the initial electron energy spread on electron pulse broadening was previously described in Refs. 2, 5 and 14, and the results are consistent with Eq. (16). For

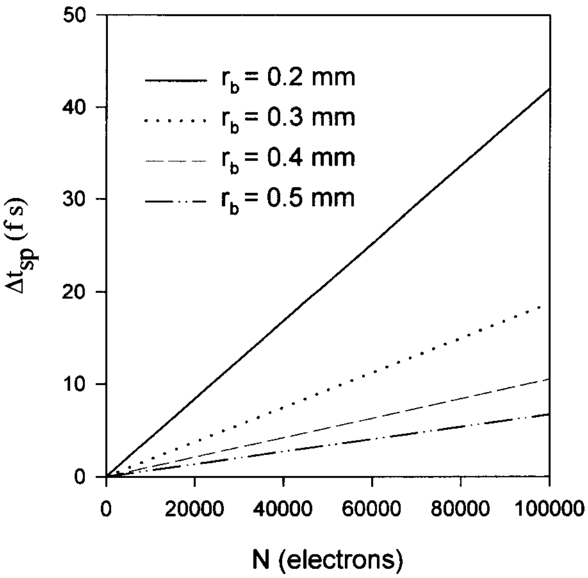

FIG. 3. Temporal broadening in the photocathode-to-mesh region Δt_{sp} vs the number N of electrons contained in the electron pulse for $d=3$ mm and $V_0=30$ kV in the cases of $r_b=0.2$, 0.3, 0.4, and 0.5 mm.

example, the time dispersion Δt_e caused by the initial electron energy spread is $\sim$150 fs for $\Delta E_0=0.2$ eV, $d=3$ mm, and $V_0=30$ kV.

The electron pulse broadening due to space charge Δt_{sp} in the photocathode-to-mesh region is described by Eqs. (17) and (19). Figure 3 shows Δt_{sp} in the photocathode-to-mesh region versus the number N of electrons contained in the electron pulse for $d=3$ mm and $V_0=30$ kV, in the cases of $r_b=0.2$, 0.3, 0.4, and 0.5 mm. One can clearly see from Fig. 3 that Δt_{sp} increases with N and with the electron beam radius r_b. In addition, results of Fig. 3 reveal that the value of Δt_{sp} is generally less than 10 fs when $N \leqslant 20\,000$ and $r_b \geqslant 0.2$ mm. In this case, with the parameters employed in Fig. 3, Δt_{sp} can be ignored for a photoelectron gun designed for more than 100 fs. Figure 4 illustrates the dependence of Δt_{sp}

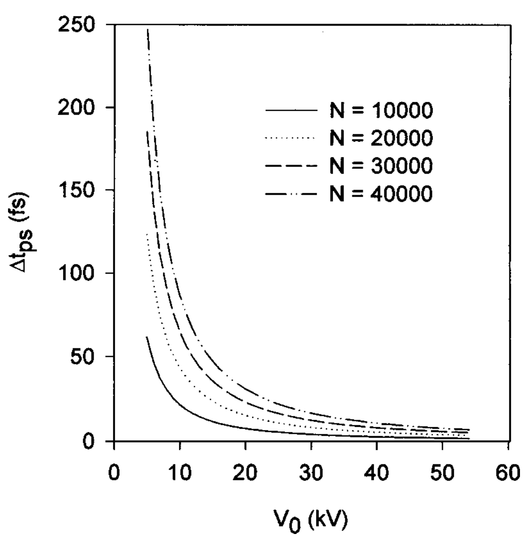

FIG. 4. Temporal broadening in the photocathode-to-mesh region Δt_{sp} as a function of voltage V_0 between the photocathode and mesh for $d=3$ mm and $r_b=0.2$ mm in the cases of $N=10\,000$, 20 000, 30 000, and 40 000.

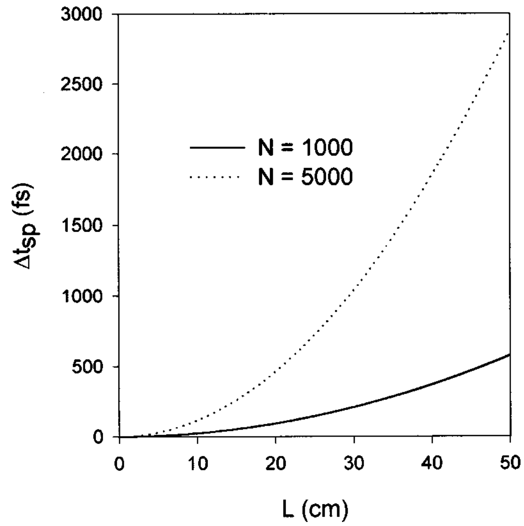

FIG. 5. Temporal broadening Δt_{sp} in the electron beam drift region vs the length L of the drift region for $r_b=0.45$ mm and $V_0=30$ kV in the cases of $N=1000$ and 5000.

on the accelerating voltage V_0 applied between the photocathode and the mesh for $d=3$ mm and $r_b=0.2$ mm for the cases of $N=10\,000$, 20 000, 30 000, and 40 000 in the photocathode-to-mesh region. As can be seen from Fig. 4, the time dispersion Δt_{sp} decreases with increasing V_0 but increases with N. For the parameters used in Fig. 4, the value of Δt_{sp} in the photocathode-to-mesh region becomes important only when $N>20\,000$ and $V_0<10$ kV for a photoelectron pulse of $\sim$100 fs in duration. Figure 4 also indicates that space charge effects are reduced when the electric field within the photocathode-to-mesh region is increased.

The electron pulse broadening Δt_{sp} due to space charge effects in the electron beam drift region is expressed by Eqs. (21) and (22). Figure 5 shows Δt_{sp} versus the length L of the drift region for $r_b=0.45$ mm and $V_0=30$ kV in the cases of $N=1000$ and 5000 electrons in the electron beam drift region. Electron pulse broadening in the drift region, Δt_{sp}, increases linearly with the number of electrons in the pulse, N, and as the square of the drift distance, L. According to Figs. 3 and 4, electron pulse broadening due to space charge effects in the photocathode-to-mesh region can be neglected for $d=3$ mm. However, space charge effects in the drift region broaden the electron pulse by 350 fs for $L \approx 40$ cm and $N=1000$, as indicated in Fig. 5. We can compare our results with those of the experiment reported in Ref. 32 because the parameters employed in Fig. 5 resemble those used in that experiment. In Ref. 32, the initial electron energy spread on the surface of the photocathode is $\Delta E_0=0.5$ eV and the laser pulse duration is $\tau_0=60$ fs; therefore, the time dispersion due to ΔE_0 is $\Delta t_e \approx 238$ fs. By ignoring trajectory differences that affect the electron pulse broadening, the final electron pulse duration is $\Delta t_p=\tau_0+\Delta t_e+\Delta t_{sp} \approx 648$ fs, which includes $\Delta t_{sp} \approx 350$ fs. This is basically in agreement with the experimental result $\Delta t_p \approx 540$ fs of Ref. 10. Limitations of our model include the fact that the laser and electron pulses are assumed to have a temporal square shape and the electron distribution in the electron pulse is treated as spatially uniform.

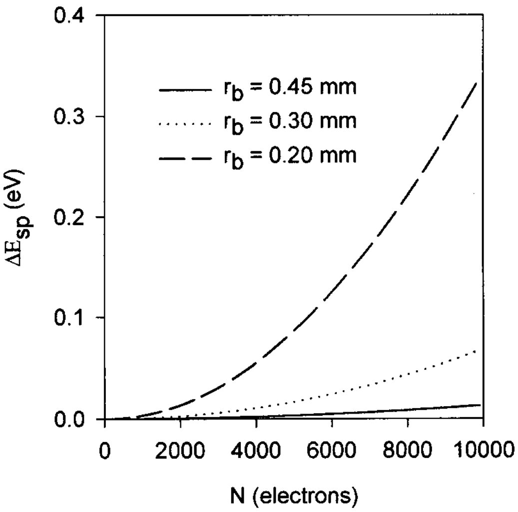

FIG. 6. The energy spread ΔE_{sp} in the electron beam drift region versus the number N of electrons contained in the electron pulse for $L=40$ cm, $V_0=30$ kV, $\tau_0=50$ fs, and $\Delta t_e=150$ fs in the cases of $r_b=0.45$, 0.30, and 0.20 mm.

The energy spread ΔE_{sp} caused by the space charge effects in the drift region is given by Eq. (25). Figure 6 shows ΔE_{sp} versus the number N of electrons contained in the electron pulse for $L=40$ cm, $V_0=30$ kV, $\tau_0=50$ fs, and $\Delta t_e=150$ fs in the cases of $r_b=0.45$, 0.30, and 0.20 mm. It can be seen from Fig. 6 that ΔE_{sp} increases with N but decreases with r_b. In addition, a large drift length L will also lead to significant electron energy spread according to Eq. (25). Figure 6 also indicates that the energy spread ΔE_{sp} caused by space charge effects can be less than 0.4 eV for $r_b \geqslant 0.20$ mm and $N \leqslant 10\,000$. However, ΔE_{sp} becomes larger than 3 eV for $r_b \leqslant 0.10$ mm and $N > 10\,000$ (not shown in Fig. 6). Therefore, space charge effects not only result in electron pulse broadening but also cause additional energy spread in the electron pulse when the electrons travel through the drift region.

IV. CONCLUSIONS

Space charge effects in an ultrafast photoelectron pulse are explored using a fluid model. The model is applicable in both the photocathode-to-mesh region and the postanode electron beam drift region. The electron pulse broadening and the electron energy spread, caused by space charge effects, are investigated analytically. The dependence of electron pulse broadening, due to space charge effects, on the electron energy V_0, the beam radius r_b, the photocathode-to-mesh gap d, the length L of the drift region, and the number N of electrons contained in the electron pulse has been analyzed. Space charge effects in the photocathode-to-mesh region are generally unimportant even for the subpicosecond photoelectron gun. However, the electron pulse broadening due to space charge effects in the drift region can be significant because of the long drift distance of the electron pulse. The electron pulse broadening due to space charge effects in the drift region may be much larger than the initial electron pulse duration for a subpicosecond photoelectron gun. The space charge effects can also lead to a considerable energy spread in the electron pulse in the drift region.

The design of a photoelectron gun with an electron pulse duration of 100 fs or less containing 10^3–10^4 electrons per pulse requires an efficient compression technology to remove space charge effects, and the total length of the electron gun should be kept as short as possible. In general, the electron pulse compression device would make the faster electrons slow down and slower electrons accelerate. Before considering a compression device, one should first estimate space charge effects on the electron pulse broadening and electron energy spread. Therefore, the above-mentioned model can be used to design subpicosecond photoelectron guns for streak cameras and time resolved electron diffraction.

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