The Effects of Space Charge on Electron Pulse Broadening in Streak Cameras

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Abstract

Streak cameras are used to record the time history of laser pulses and experimental signals at LLE. However, space charge effects can distort images recorded on the phosphor screen of streak cameras, making it difficult to impossible to accurately interpret the image. Space charge effects are caused by the interactions between the photoelectrons while in transit in the streak tube. These interactions cause the electrons to repel, making the entire pulse broaden. For this project, a computer program was written to simulate the movement of electrons through the streak camera. This program enables one to accurately predict the amount of space charge broadening that would occur with given initial conditions for a particular design. This predictive capability will lead to improvements in streak cameras in the future, allowing streak cameras to record pulses with sub-picosecond temporal resolution.

Introduction

Streak cameras are essential for the work done at the Laboratory for Laser Energetics (LLE) at the University of Rochester. Streak cameras measure the time history of pulses by converting the temporal dimension into a spatial dimension. In a standard streak camera at LLE, a laser pulse is first converted into electrons at the photocathode via the photoelectric effect.

These electrons then go through a short accelerating region, in which they spend < 100 picoseconds. For the next 2 to 3 nanoseconds, the electrons pass through an electron lens, which focuses them. The electrons then enter a drift region that includes a pair of deflection plates, which have a time-varying electric field applied between them. This time-varying electric field deflects the electrons sideways; electrons later in the pulse are deflected more than electrons earlier in the pulse. As a result, the electrons develop a streak pattern. Finally, after a two to three nanoseconds flight time in the drift region, the electrons hit a phosphor screen, which converts the electron energy back into photons. The phosphor screen is connected to a charge-coupled device (CCD), which is used to electronically record the streak pattern. Since the photoelectric effect linearly converts photons into electrons, the number of electrons incident on any spot on the image recorded on the phosphor screen is proportional to the intensity of the laser pulse at that time (see Figure 1).

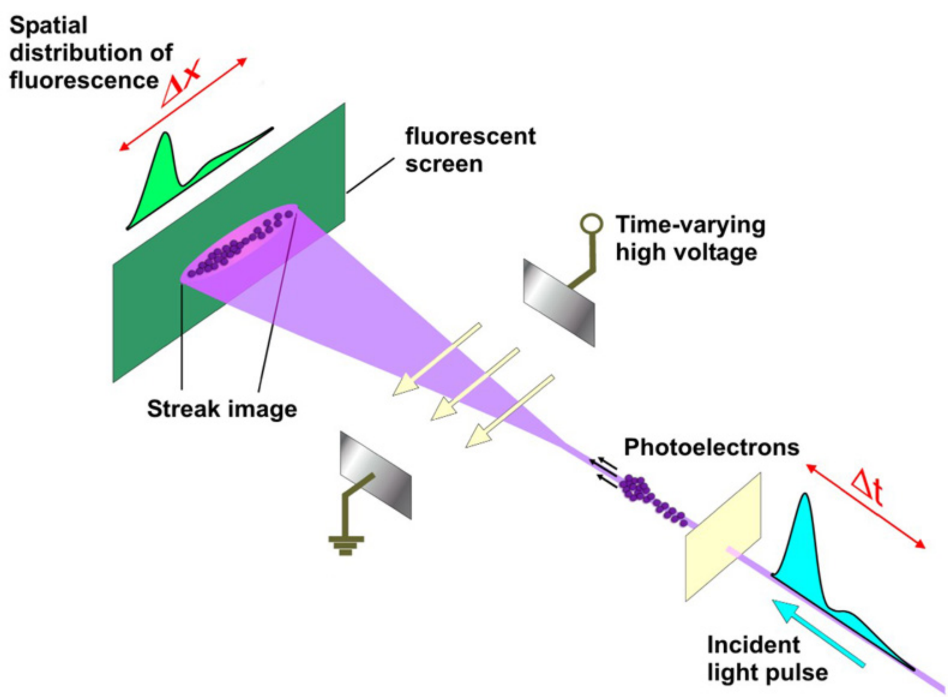

Figure 1- Diagram of a simple streak camera. More electrons on the phosphor screen corresponds to a greater intensity in the laser pulse.

Electrostatic repulsion between the electrons (termed the space charge effect) affects all electron beams. Although a 100 fs space charge broadening of a nanosecond duration pulse may not be measureable, it would be a significant distortion on a picosecond duration pulse. When the electrons inside a streak camera repel each other, the electron pulse broadens in all three spatial dimensions, and the information carried by these electrons can be distorted, since the electrons will not end up at their projected positions on the phosphor screen. Since space charge is a nonlinear effect, information about the original pulse cannot generally be recovered. Other considerations such as initial electron energy spread can also cause distortions of the image recorded on the phosphor screen, but the main problem addressed here is the electron pulse broadening due to space charge.

Past Work

In the past, models were created to simulate the movement of electrons through the drift region of a streak camera. One of these models is a one-dimensional fluid model.[1] This model ignores the movement of electrons in the radial direction, assuming that magnetic coils in the streak camera will constrain the motion to the axial direction. However, no such magnetic coils are used in LLE streak cameras, and so the one-dimensional fluid model is not a good model for LLE streak cameras. This model predicts that the temporal broadening Δt due to space charge in the drift region scales as

$$\Delta t \propto \frac{L^2 N}{V^{3/2} r^2} \quad (1)$$

where L is the length of the region, N is the number of electrons in the pulse, V is the initial potential, and r is the radius of the pulse. However, this seems to fit only for short periods of time, since only then could one safely assume a constant radius. Other models that allow the electrons to move radially are more reliable.

Another model used in the past was the mean-field model, which included movement in the radial direction.[2] This model is expected to give better agreement for an actual streak camera, but it assumes non-relativistic electrons, rather than the relativistic electrons common to streak cameras at LLE. So, although a better model than the one-dimensional fluid model, the mean-field model does not perfectly represent what happens in an actual streak camera. Also, this mean-field model was only useful for the drift region of a streak camera; external fields were not taken into account.

Methods

In order to improve a streak camera's resilience to the damaging effects of space charge, a program was written to simulate the movement of electrons through the drift region of a streak camera. It is in this region that electrons have the most time to interact with each other, hence broadening the electron pulse significantly. The electromagnetic interaction between electrons is given by the Lorentz force equation

$$F = q(E + v \times B) \qquad (2)$$

where F is the force felt by an electron, q is the charge of the electron, E is the electric field, v is the instantaneous velocity of the electron, and B is the magnetic field. The electrons are assumed to propagate primarily in the z direction; therefore, the magnetic field can be modeled by concentric circles around the z-axis. This magnetic field will have a negligible effect on the motion of the electrons given the small beam currents in a streak tube and was neglected.

The electric field surrounding a charge can be modeled with the equation

$$E = kq\left[\frac{e_{r'}}{r'^2} + \frac{r'}{c}\frac{d}{dt}\left(\frac{e_{r'}}{r'^2}\right) + \frac{1}{c^2}\frac{d^2}{dt^2}e_{r'}\right] \qquad (3)$$

where k is Coulomb's constant, q is the charge of the electron, $\boldsymbol{e_{r'}}$ is the unit vector in the direction of r', r' is the displacement between two electrons at the retarded time t_R and c is the speed of light.[3] The retarded time is defined by $t_R=t-r'/c$. The third term, which is the radiation term, has been deemed negligible; the direction of the electrons will not change significantly, making the second time derivative of the unit vector nearly zero. The first term is a slightly modified version of Coulomb's law, and the second term is a correction due to the velocity of the electrons.

Since information can only be carried between electrons at the speed of light, there is a non-zero time taken for one electron to know of another's presence. As a result, the electric field is not calculated at the current distance, but at the distance at the retarded time, as indicated by r'. This causes a sharper leading edge in an electron pulse, and a sparser trailing edge. This effect is most pronounced when the electrons are moving near the speed of light; electrons in a streak tube are accelerated to between 0.2c and 0.3c.

In order to advance the electrons in the computer program, the leap-frog method of integration was used, with a second order degree of accuracy in the time step.

Results

The computer program was run many times, with varying numbers of electrons, beam dimensions, initial electron energy spreads, and distances traveled. First, it was run with no external fields applied, simulating the drift region. When the beam spread of the simulated electron pulse was plotted against time (see Figure 2), it was easy to see that space charge effects significantly broaden electron pulses in the drift region. The particular simulation whose results are shown in Figure 2 was run with 100 electrons, an initial beam energy of 2500 eV, and initial beam dimensions of 100 x 50 x 5 microns. The beam spread shown resulted in a temporal spread of about 3-4 picoseconds.

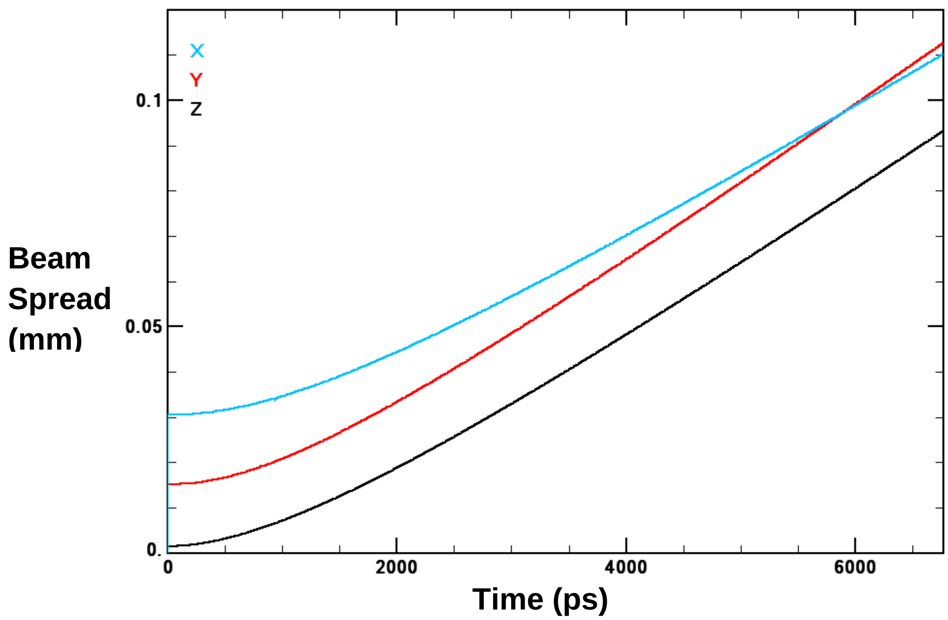

Figure 2-Beam spread plotted against time. As time goes on, the beam spread increases significantly in both the radial and axial directions due to space charge effects.

When the axial velocity was plotted against the axial position, it was evident that the leading electrons gained velocity, while the trailing electrons lost velocity, as shown in Figure 3. This occurs because the electrons in the front will be propelled even farther towards the front by space charge effects, while the electrons in the back will be repelled backwards.

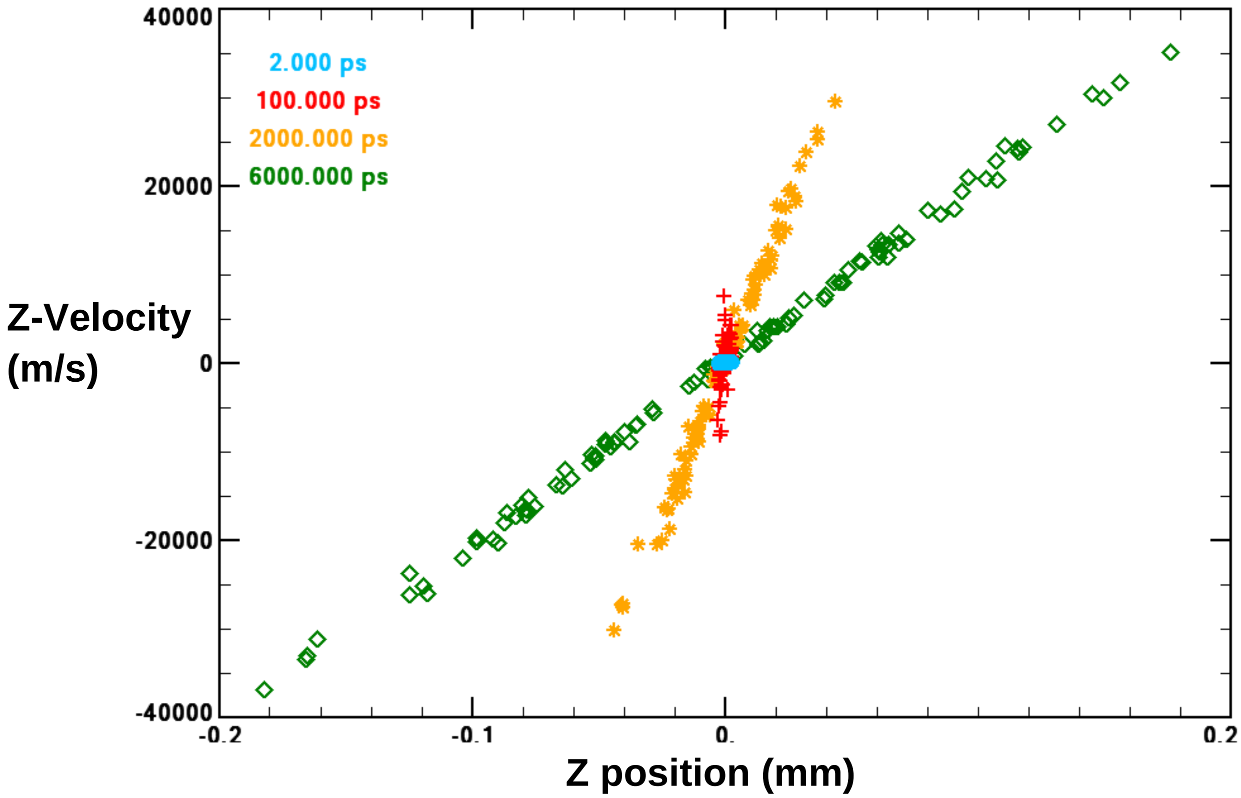

Figure 3-Relative axial velocity plotted against the average axial position for various times. Space charge very quickly generates a linear velocity chirp.

The one-dimensional fluid model predicted that the temporal broadening due to space charge in the drift region scaled as shown in Equation 1. However, analysis of the graphs given by different runs of the computer program shows that temporal broadening scales as

$$\Delta t \propto \frac{L\sqrt{N}}{\sqrt{V}} \qquad (4)$$

where L is the length of the region, N is the number of electrons in the pulse, and V is the initial potential. These scaling laws and other predictive capabilities of the computer program can be used to improve the limiting resolution in streak cameras.

Future Work

Although Figure 2 shows that space charge significantly broadens electron pulses in the drift region, no tests have yet simulated the electron pulse moving through the acceleration region of a streak camera. Simulated electrons could be run through a simple diode in order to confirm or reject the hypothesis that most of the electron pulse broadening due to space charge occurs in the drift region. Also the contribution of relativistic effects to the broadening of electron pulses in streak cameras has not been quantified in detail. The computer program could be run with the non-relativistic Coulomb interaction in place of Eqn. (3) in order to determine the importance of relativity. Similarly, it has only been theorized that the magnetic field and radiation will have negligible effects on electron pulse broadening. Magnetic fields and radiation could be added in to determine their effects on electron movement. More work could also be done to determine how much the beam dimensions of an electron pulse affect temporal broadening.

Instead of using the leap-frog method of integration, the Runge-Kutta method of integration could be used, since it has fourth order accuracy. However, the Runge-Kutta method requires significantly more computational overhead at each time step. The code for the computer program could be optimized further, so that more simulated electrons could be sent through a streak camera at a time, while keeping within a reasonable run-time. Finally, the predictions given by the computer program could be put to practical use through the physical improvement of streak cameras.

Conclusion

The effects of space charge can detrimentally distort the image recorded on the phosphor screen of a streak camera, making it impossible to recover information about the original laser pulse. In order to minimize the damaging effects of space charge, a computer program was written to simulate the movements of electrons through a streak camera. This computer program differs from previous attempts to model the movement of electrons through a streak camera through its inclusion of relativistic effects and its ability to include external fields. The program confirmed that significant broadening occurred in the drift region, and that the effects of space charge generate a linear velocity chirp. Scaling laws were produced that show how temporal broadening changes with the length of the drift region, the number of electrons, and the initial potential. Future work can be done in making the computer program more accurate, and yet more optimal. The predictions of this computer program will eventually be used to develop streak cameras with sub-picosecond resolution.

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