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Characteristics of an ultrafast x-ray streak camera

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ABSTRACT

The detection and temporal dispersion of the x-rays using x-ray streak cameras has been limited to a resolution of 2 ps, primarily due to the transit time dispersion of the electrons between the photocathode and the acceleration grid. The transit time spread of the electrons traveling from the photocathode to the acceleration grid is inversely proportional to the accelerating field^{1,2}. By increasing the field by a factor of 7, we have minimized the effects of transit time dispersion in the photocathode/accelerating grid region and produce an x-ray streak camera with sub-picosecond temporal resolution (≈ 900 fs). The streak camera has been calibrated using a Michelson interferometer and 100 fs, 400 nm laser light. Time resolved x-ray data is shown from an aluminum target heated at 10^{18} W/cm² with a 100 fs, 400 nm laser.

Keywords: X-ray streak camera, ultrafast x-ray detector

1. INTRODUCTION

Ultrashort pulse lasers have provided new opportunities to produce energetic (>100 eV), temporally short (< 10 ps) x-rays from ultra-short pulse laser produced plasmas.³⁻⁵ The short burst of x-rays have various applications and are currently being studied at several laboratories. With sufficient temporal resolution, x-ray streak cameras present an attractive approach to studying the time history of x-rays. X-ray streak cameras provide high photon sensitivity, simplicity of operation, and ease of data deconvolution.

In most standard commercial x-ray streak cameras, the temporal resolution is dominated by the transit time dispersion between the photocathode and the accelerating grid. This is a result of the time required to accelerate the x-ray generated photoelectrons. By increasing the accelerating field by a factor of seven, we have minimized the transit time dispersion between the photocathode and the accelerating grid and produce an x-ray streak camera with sub-picosecond (900 fs) temporal resolution. A calibration of the streak camera was performed using a Michelson interferometer and 100 fs, 400 nm laser light.

2. BASIC THEORY OF OPERATION

When x-rays are incident on a streak camera, they travel through a collimating slit and liberate photoelectrons from the photocathode. The photoelectrons are extracted from the photocathode by large extraction field, accelerating them to a high percentage (in our case $\sim 27\%$) of their final energy. Once extracted, they undergo further acceleration while traveling through electrostatic focusing electrodes. The focusing electrodes image the collimating slit at the phosphor. An anode with an aperture is positioned at the focal length of the electrostatic lens, i.e., the crossover point of the electrostatic lens, allowing the electrons to accelerate through the aperture into a 'drift' region. Inside the drift region the electrons experience a lateral

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acceleration induced by a time varying electric field. The field is applied perpendicular to the electrons' direction of propagation. The electrons strike the phosphor and the signal is intensified and viewed with a detector.

In a streak camera with this layout, there are several sources of temporal dispersion. Photoelectrons are created in a two step process: photo-excitation of primary electrons followed by collisional production of secondary electrons. The secondary electrons are produced with an energy distribution determined by the characteristics of the photocathode material⁶ in addition to an angular spread limited by the width of the collimating slit. When the electrons are extracted by the grid accelerating field, the higher energy electrons increase their distance from the lower energy electrons, increasing the spatial extent of the electron bunch and erroneously producing a longer signal. The angular spread also leads to a longer signal due to the slightly longer path length of electrons moving at non-normal angles to the photocathode. Finally, the Coulomb repulsion of the electrons can lead to further spatial spread of the electron bunch. The initial energy and angular spread in the secondary electron distribution continues to affect the spatial length of the electron bunch as it propagates through the focusing region. The affects in this region are significantly reduced because the electrons have undergone radial bunching (from the electrostatic focusing lens) and the energy spread is a small percentage of the total energy in this region. Using the Gaussian approximation method, the temporal resolution is given by

$$\Delta t_{\text{res}} = [(\Delta t_{\text{phys}})^2 + (\Delta t_{\text{tech}})^2]^{1/2}, \quad (1)$$

where Δt_{tech} is the technical ideal limit of the temporal resolution, and is defined by the inverse product of the sweep speed and the collimating slit width, i.e., $1/v\delta$, v = the sweep speed, δ = the spatial resolution. The physical limits to the resolution (Δt_{phys}^2), determined by affects mentioned above, is given by,

$$\Delta t_{\text{phys}}^2 = (\Delta t_{\text{Coul}})^2 + (\Delta t_{\text{ang}})^2 + (\Delta t_{\text{pc-m}})^2 + (\Delta t_{\text{f.e}})^2 \quad (2)$$

where, Δt_{Coul} is the temporal resolution due to the Coulomb repulsion of the electrons, Δt_{ang} is the temporal resolution due to angular spread in the electron distribution, $\Delta t_{\text{pc-g}}$ is the temporal resolution due to transit time spread while the electrons are being accelerated from the photocathode to the extraction grid, and $\Delta t_{\text{f.e}}$ is the transit time spread of the electron bunch between the extraction grid and the anode aperture. The Coulomb repulsion for n electrons emitted per space-resolution element d , per resolution time is expressed as⁷,

$$\Delta t_{\text{Coul}} = \frac{8e^2 L^2 n^2}{md^2 v^3} \quad (3)$$

where, e is the electrostatic charge, m is the mass of the electron, v is the electron velocity, and L is the distance over which the Coulomb repulsion is being considered. This reduces to approximately $10^{-21} n^2$, which is negligible except for cases where $n > 10^4$. The temporal resolution due to angular spread can in general be minimized by using a narrow collimating slit. In our case, we use a 100 μm slit over a 30 cm length, making this term also negligible. The remaining two terms are transit time dispersion terms. The transit time dispersion is represented by¹

$$\Delta t \approx \frac{3 \times 10^{-8} \left[\left(E_0 + \Delta kT/2 \right)^{1/2} - \left(E_0 - \Delta kT/2 \right)^{1/2} \right]}{E_{field}} \quad (4)$$

where E_0 is the kinetic energy of the electrons in eV, ΔkT is the FWHM energy spread of the electron energy distribution in eV and E_{field} is the electric field strength of the accelerating field in V/cm. From equation 4, one can see that as E_0 becomes large compared to ΔkT , the transit time dispersion becomes small. Hence, the transit time dispersion is greatest when the electrons are moving slowly, i.e., when the electrons are being extracted and accelerated between the photocathode and the accelerating grid.

Commercially available streak cameras typically use an extraction field of 10 keV/cm and a cesium iodide photocathode.⁸ The cesium iodide (CsI) maximizes sensitivity to low energy (< 5 keV) x-rays and has a 1.6 eV FWHM secondary electron energy distribution.⁹ With these parameters, the temporal resolution is limited to approximately 6 ps. Although improvements to this resolution limit is realized by changing the photocathode material, the greatest improvement comes from increasing the extraction field. We have increased the extraction field by pulse charging the photocathode.

Before pulse charging the photocathode, the photocathode and grid are maintained at the same voltage (~ 10.4 kV), while the focusing potential is at ~ 11.23 kV. The photocathode pulser supplies a 1.8 kV pulse which voltage doubles to 3.6 kV at the photocathode due to the open circuit. The pulse has a 700 ps rise and fall time with a variable temporal duration controlled by a charge line cable. The minimum pulse width is 1.7 ns FWHM. To insure a constant voltage during the photocathode exposure time, the pulse width typically used for the photocathode is 5 ns FWHM. This provides a long period (~ 3.6 ns) of constant voltage on the photocathode. Using this technique, we have successfully applied fields of 270 kV/cm to the photocathode-accelerating grid region. From equation 4, this reduces the transit time dispersion in the photocathode-accelerating grid region from 6 ps to 141 fs.

The sweep structure consist of parallel sweep plates and a pulsing circuitry that allows a 350 ps rise time on the sweep plates.

3. EXPERIMENTAL SETUP

3.1 Streak camera calibration

The calibration was done using 400 nm, 100 fs laser light and a Michelson interferometer.¹⁰ The setup is shown in figure 1. The laser light enters the Michelson interferometer at 800 nm with a 100 fs pulse width. The beam is divided into equal parts by a 50/50, 250 μ m beam splitter.

Fig. 1. The Michelson-calibration setup.

One of the 100 % reflecting mirrors was mounted a micrometer controlled base to provide a variable time spacing between the two laser beams.

A 250 Å gold photocathode coated on 5000 Å of polypropylene was used for the streak camera photocathode. This choice of photocathode was motivated by the absorption characteristics of salt photocathodes at 400 nm.¹¹ The salt photocathodes have extremely low absorption of 400 nm light. Gold has a much higher absorption at this wavelength and, if necessary, can be used in the actual experiment. Shorter wavelength laser harmonic techniques are being considered for future calibration work. The sweep speed used in the calibration was 5.4 ps/mm, while the slit width was 100 μm. Typical calibration results are shown in figure 2.

Fig 2a.

Fig. 2a shows a typical streak of two 400 nm, 100 fs laser pulses temporally separated by 5 ps. Fig 2b shows a typical lineout of the sweep.

Fig 2b.

The lineouts were taken by averaging over a vertical spatial element ($\sim 30 \mu\text{m}$). The values vary from 1.2 ps to 800 fs with an average of ~ 930 fs, all FWHM.

The resolution is believed to be at least 900 fs. The gold photocathode has a significantly broader secondary electron distribution ($\Delta kT \sim 3.95$ eV)¹², producing what can be considered to be an upper bound. The 'ideal' lower bound for the camera is 681 fs. The ideal lower bound is an unlikely achievement in the existing geometry. The reason is the difficulty of maintaining the 100 μm spatial resolution through the camera. Although the physical width of the slit is 100 μm , the measured width at the phosphor is ~ 165 μm . The increase in size is a result of spatial magnification in the electron optics (magnification of 1.2) and other image degrading effects, e.g. spatial spreading of the electron distribution due to a high space charge and transient and fringe fields. The subsequent slit limited resolution is ~ 890 fs.

3.2 X-ray data gathered with the streak camera

An experiment was done to study the time history of the broad band emission from an ultra short pulse laser-produced plasma. The laser used in the experiment produces 10 mJ of energy at 400 nm in 100 fs with a prepulse/peak intensity contrast of 10^6 . The laser is focusable to a minimum 3 μm diameter spot size. The time resolved broad band x-ray emission measurements were done by focusing the laser to a peak intensity of 10^{18} W/cm² on a solid aluminum surface.

A photocathode made from 1500 Å of potassium iodide (KI), coated on 250 Å gold coated on 5000 Å of polypropylene was used to increase the sensitivity to x-rays. The higher energy x-rays are transparent to the gold and polypropylene, while the KI absorbs the x-rays to produce photoelectrons. Although CsI is more sensitive than KI, the KI has a significantly narrower secondary electron distribution ($\Delta kT \sim 0.61$ eV)⁹. The use of a different photocathode material in the experiment is believed to be a minor issue because the KI material has a narrower secondary electron distribution than the gold. The results from this experiment are shown in figure 3.

Fig. 3a.

Fig. 3b.

Fig. 3a shows the folded (photocathode and filter) response and figure 3b shows the time history of the corresponding filtered x-ray emission.

It is note worthy that the shortest temporal history measured is 1.7 ps. This is currently believed to be because the solid target was heated to a high enough temperature to produce H-like (1s state) ions which have a long subsequent recombination time¹³.

4. CONCLUSIONS

We have measured the temporal characteristics of a new ultrafast x-ray streak camera. The high temporal resolution (900 fs) is achieved by overcoming the transit time dispersion between the photocathode and the extraction grid. The field used to overcome the transit time dispersion is 270 kV/cm, and is pulse-charged for approximately 5 ns. The streak camera has been calibrated using 400 nm, 100 fs laser light and a Michelson interferometer. A measurement of the time history of broad band emission from an ultrashort pulse laser produce aluminum plasma was performed using the streak camera. Further improvements to the camera will require minimizing the transit time dispersion between the accelerating grid and the anode, and reducing the effects unwanted fields (fringe fields and transient magnetic fields).

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