STREAK CAMERA TEMPORAL RESOLUTION IMPROVEMENT USING A TIME-DEPENDENT FIELD*

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Abstract

Streak camera is an important diagnostic device in the studies of laser plasma interaction, the detailed structure of photo reaction from material science to biochemistry, and in the measurement of the longitudinal distribution of a beam in accelerators. In this paper, we report on a new method which can potentially improve the temporal resolution of a streak camera down to femtoseconds. This method uses a time-dependent acceleration field to defocus the photo electrons longitudinally. This not only reduces the time dispersion distortion caused by initial energy spread but also mitigates the effects from the space-charge forces of photo electrons. An illustration of the method shows significant improvement of the modulation transfer function (MFT) compared with the conventional design.

INTRODUCTION

Streak camera as a diagnostic device to measure temporal information of signal has been widely used in accelerator physics, laser-plasma physics, material science and biochemistry. A number of studies have been reported on improving the temporal resolution of X-ray streak camera below 1 ps [1, 2, 3, 4, 5]. However, it becomes more and more difficulty to build an X-ray streak camera with temporal resolution below 500 fs due to limits of time dispersion from the energy spread of photo electrons, space-charge effects among photo electrons, finite static image size and deflection sweeping speed, and time jitter if multiple shot accumulation operation mode is needed. Among these factors, the energy spread of photo electrons presents an intrinic limit to the temporal resolution of X-ray streak camera [3, 5].

In a streak camera, the temporal information of an incident X-ray laser is converted into longitudinal information of photo electrons following photo-electric effects. Due to the initial energy spread, electrons with different longitudinal positions will mix with each other during the transport to the deflection plate. The mixing of electrons before the deflection plate will destroy the signal imbedded in the photo electrons from the incident laser. The deflection plate will no longer be able to convert the longitudinal temporal information into transverse spatial information. This causes loss of information and defines a temporal resolution that can be achieved. For a given energy spread, the extent of mixing depends on the transport time and the relative positions of individual electrons. To reduce the extent of mixing before the deflection plate, one way is to reduce the transport time by making electron higher energy and by shortening the distance between the cathode and the deflection plate. However, the electron energy is determined by the acceleration voltage. It can not be set as arbitrarily high before field breakdown. A very high electron beam energy also reduces the efficiency of deflection plate. The transport distance to the deflection plate is set by the engineering restriction and should be minimized as much as possible. In this paper, we propose another way to amplify the longitudinal profile of photo electrons so that the relative longitudinal positions of individual electrons become larger. It takes longer time for electrons to mix with each other. If the electron mixing time can be made longer than the transport time to the deflection plates, the photo electrons can be separated transversely using a time-dependent vertical deflection field. The temporal information inside the photo electrons is transformed into transverse spatial information at the image plane and the resolution is improved. To stretch the beam longitudinally, we suggest using a time-dependent field for longitudinal amplification.

LONGITUDINAL AMPLIFICATION IN TIME-DEPENDENT FIELD

The longitudinal relative positions of electrons inside a beam can be amplified by passing through a time-dependent accelerating field. By appropriately choosing field ramping direction or phase of the beam with respect to the field, the electrons arriving earlier see a larger accelerating field than the electrons arriving later. This results in a separation between the early electrons and the late electrons and gives the longitudinal amplification.

The longitudinal equations of motion for an electron inside a time dependent field without space-charge forces are given by:

$$\begin{aligned} \frac{d\Delta t}{dz} &= -\frac{\Delta E}{mc^3\gamma_0^3\beta_0^3} && (1) \\ \frac{d\Delta E}{dz} &= q(E_z(z,\Delta t + t_0) - E_z(z,t_0)) && (2) \end{aligned}$$

where, $\Delta t = t - t_0$ is the time difference between an electron and the assumed reference electron, t_0 is the time of flight of the reference electron, t is the time of flight of the electron, $\Delta E = E - E_0$ is the energy difference between the electron and the reference electron, E_0 is the kinetic energy of the reference particle, m is the electron mass, c is the speed of light in the vacuum, $\gamma_0 = 1/\sqrt{1-\beta_0^2}$, $\beta_0 = v_0/c$, v_0 is the speed of the reference particle, E_z is the external electrical field. Here, the reference electron can be visualized as the centroid of the photo electrons,

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the Δt is related to the relative longitudinal position of an electron inside the beam. In above equations, we neglect the transverse variation of the field. Assuming that Δt is small compared with the time scale of the electric field, the linerized equations of motion are

$$\frac{d\Delta t}{dz} = -\frac{\Delta E}{mc^3\gamma_0^3\beta_0^3} \tag{3}$$

$$\frac{d\Delta E}{dz} = qE_z'\Delta t \tag{4}$$

where the superscript prime denotes derivative with respect to time. For a linear time-dependent electric field, E_z' is a constant. For longitudinal amplification, the qE_z' needs to less than zero. Neglecting energy change of the reference electron, the time difference Δt after a distance L will be:

$$\Delta t_L = \cosh(kL)\Delta t_0 - \frac{k}{qE_z'}\sinh(kL)\Delta E_0 \tag{5}$$

where $k = \sqrt{|qE_z'/(mc^3\gamma_0^3\beta_0^3)|}$.

ILLUSTRATION OF THE METHOD

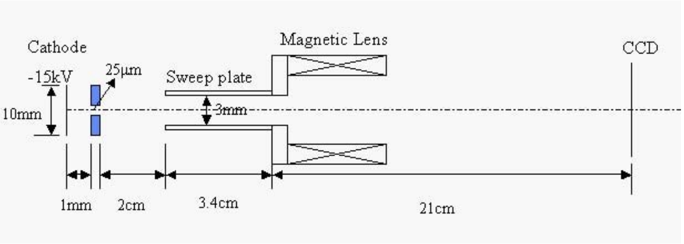

Figure 1: A schematic plot of the streak camera layout at ALS.

As an illustration, we have used a prototype streak camera at Advanced Light Source (ALS) of Lawrence Berkeley National Laboratory to numerically test above concept. A schematic plot of the streak camera layout is given in Fig. 1 [6]. It consists of a photocathode made of gold with assumed 4.6 eV work function for X-ray laser, an acceleration region with 15 kV voltage, a meander sweeping plate for vertical deflection, a solenoid magnetic focusing lens, and a CCD image detector. The field inside the deflection plate is assumed to be an ideal traveling wave with only vertical component E_y:

$$E_y(z,t) = \frac{E_{y0}}{v_0 t_r}((z-z_0) - v_0(t-t_0)) \tag{6}$$

where E_{y0} is the deflection field strength, t_r is the linear rise time, v_0 is the longitudinal propagation speed of the wave, z_0 is the starting location of the deflection plate, and t_0 is the starting time of the sweeping. Here, we assume that the wave propagate inside the meander is well matched to the electron beam velocity. The deflection field is $1.67 \times 10^5 V/m$ with 100 ps rise time. The photo electrons emitted from the gold cathode has a $\cos(\theta)$ angular distribution, where θ is the angle with respect to the normal of the cathode surface. The energy distribution of the photo electrons has a form [7]:

$$N(E) \propto \frac{E}{(E+W_f)^4} \tag{7}$$

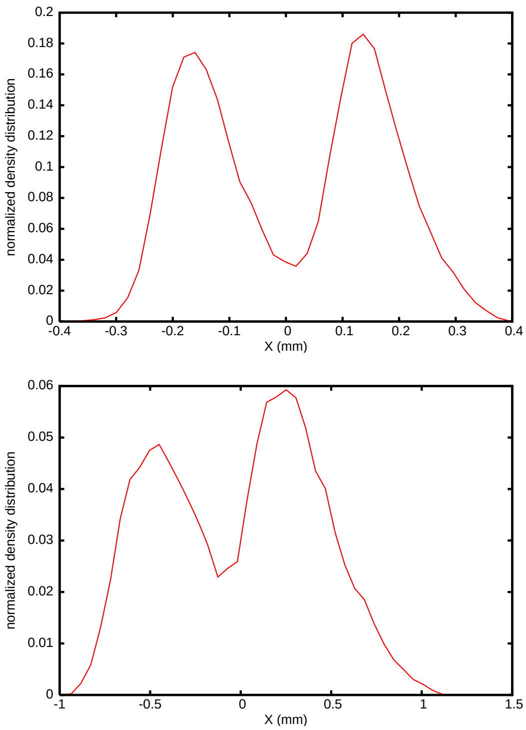

Figure 2: Line density distribution at the image plane with initial 1000 fs separation (top) and 500 fs separation (bottom) through the proposed ALS streak camera.

where W_f is work function of the cathode. The transverse spatial distribution is assumed to be uniformly distributed inside a rectangular box with 100 um in horizontal direction and 25 um in vertical direction. In this example, the longitudinal distribution is two 100 fs square wave lase pulses with adjustable temporal separation. Fig. 2 shows the line density distribution at the CCD image plane with initial 1000 fs separation of two pulses (top) and 500 fs separation (bottom) in above prototype streak camera. It can be seen that with 1000 fs initial temporal separation, the two pulses can be well distinguished on the transverse image plane. With the temporal separation down to 500 fs, the two pulses on the image plane is hardly distinguishable. To check the concept of longitudinal amplification, we assume a time-dependent accelerating field inside the acceleration region. The field is linearly ramped from initial 19.25 kV down to 12.62 kV during 26.54 ps time flight of electron inside the gap. Fig. 3 shows the line density distribution with initial 330 fs separation of the two pulses. It is seen that the two pulses can be well separated on the image plane even below 500 fs. As a systematic comparison the two systems (with/without longitudinal magnification),

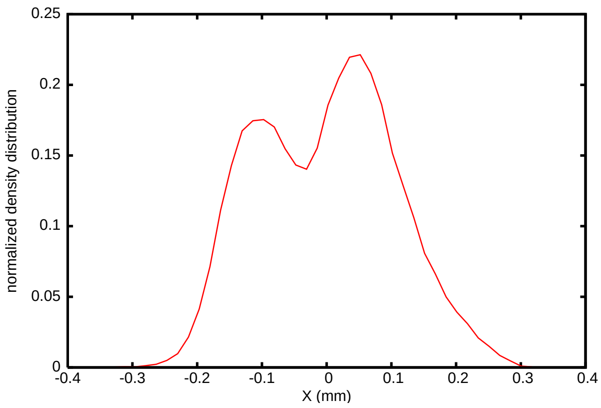

Figure 3: Line density distribution at the image plane with initial 330 fs separation with longitudinal magnification through the streak camera.

we also compute the modulation transfer function through the streak camera. The resulting modulation transfer function as a function of the inverse of the temporal separation is given in Fig. 4. Using longitudinal temporal amplification has significantly improved the temporal resolution of the streak camera.

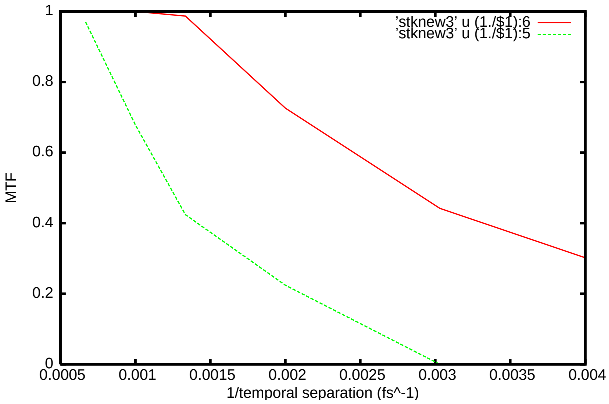

Figure 4: Modulation transfer function as a function of temporal separation frequency with/without longitudinal magnification through the streak camera.

DISCUSSIONS

In section 2 and 3, we presented the theory of longitudinal amplification and showed an example of temporal resolution improvement by ramping down accelerating field in a prototype streak camera. From Eq. 5, the final time difference of an electron passing through a time-dependent field depends on the initial time difference and the initial energy spread. In practice, the second term can be made much smaller than the first term using large ramping slope of the time-dependent field. The large ramping slope of the field can be achieved in a pulsed gap or a rf cavity. Due to the longitudinal amplification, the electron bunch length will increase before the deflection plate. The corresponding transverse beam size will also increase after vertical deflection. This puts stronger requirement for the transverse magnetic focusing system due to nonlinear geometric aberration. This aberration can be avoided by using a focusing element with sufficiently large dynamic aperture. Through the longitudinal amplification, this also mitigrates the space-charge effects since the Coulomb interactions decrease with increasing distance among electrons. This will be especially useful for single shot measurement of high intensity photon signal.

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