MODELING OF ULTRAFAST STREAK CAMERAS*

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Abstract

We present progress on modeling of x-ray streak cameras with application to measurement of ultrafast phenomena. Our approach is based on treating the streak camera as a photocathode gun and applying modeling tools for beam optics and electromagnetic fields. We use these models to compare with experimental results from a streak camera developed at the Advanced Light Source. We also shows how this model can be used to explore several ideas for achieving sub-100 fsec resolution.

INTRODUCTION

Streak cameras are one of the tools for study of ultrafast phenomena. Streak cameras have recently achieved a temporal resolution of 280 fs for UV light [1], but significantly worse for x-ray illumination, due to the chromatic nature of the x-ray induced secondary emission from the photocathode. For example [2], a temporal resolution of sub-100fs is desired for the study of electron dynamics using x-rays, in ultrafast magnetization research.

The principle of an x-ray streak camera (XSC) is to convert the time structure of a photon pulse into an electron pulse and apply a time dependent transverse deflection. This results in a transverse image size proportional to the photon pulse length. The main challenge of the XSC is to preserve the time structure of the electron pulse and properly focus the electron beam at the image plane.

We have built an end-to-end model of an XSC to optimize its resolution by treating the camera with similar analytic and simulation techniques as those applied to photocathode guns. We have developed the model using the MAFIA [3] code and compared it with an existing x-ray streak camera developed at the Advanced Light Source (ALS)[4].

In this paper, we describe the model and show several simulation results. Due to the lack of space, we concentrate our results on the performance of the deflectors.

END-TO-END MODEL OF ULTRAFAST STREAK CAMERA

A schematic diagram of the XSC developed at the ALS is shown in the top of Fig. 1. It includes a transmission photocathode, an anode to provide an acceleration field, a pair of meander stripline as a deflection structure, a solenoid to focus the electron to the image plane, an MCP to amplify imaged electrons and a CCD camera to recode the images. Only the components within the dashed line are included in the model. The overall model geometry in MAFIA is plotted with mesh line and shown in the bottom of Fig. 1. Note that the mesh is finer along the beam path.

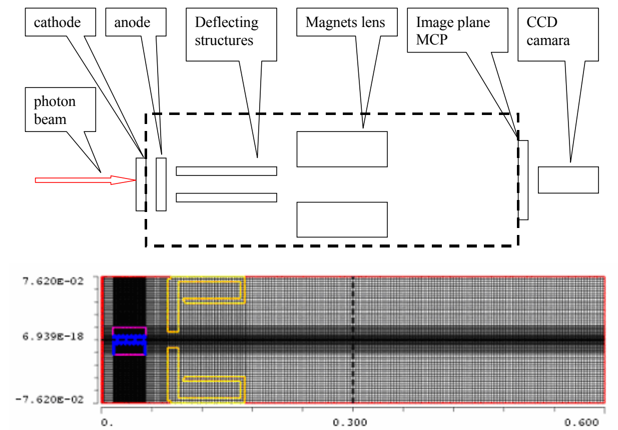

Figure 1: schematic of streak camera and Top view of the MAFIA model.

The electrons are emitted from the cathode during illumination. The initial distribution of the electrons are given by the probability density function of x, y, theta, phi. The initial electron velocity can be given by the probability density function of beta (=v/c). The time structure can be specified by the probability density function of time of ejection. Those probability density functions can be user-defined. In our case, the distribution function of x, y, phi and time are uniform functions. The

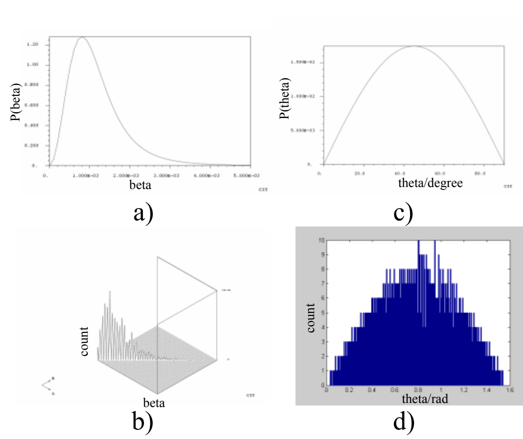

Figure 2: initialize bunch distribution a) beta distribution b) sampled beta distributionc) theta distribution d) sampled theta distribution.

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beta distribution follows [5] $P(E) \propto \frac{E}{(E+W_f)^4}$, where E is the initial energy of the electron and the Wf is the work function of the cathode material. The theta distribution function follows $P(\theta) \propto Sin(2\theta)$. The probability density function and the sampled distribution of electrons are shown in Fig. 2.

The parallel plate static field is calculated and used as the acceleration field. The mesh of the anode grid is not simulated to keep the size of the simulation reasonable. It was necessary to use a time step of 1fs during the electrons emission and acceleration to accurately model the transit time dispersion.

The geometry of the meander stripline is shown in Fig. 3. The plates are operated with a DC voltage of ±250 V.

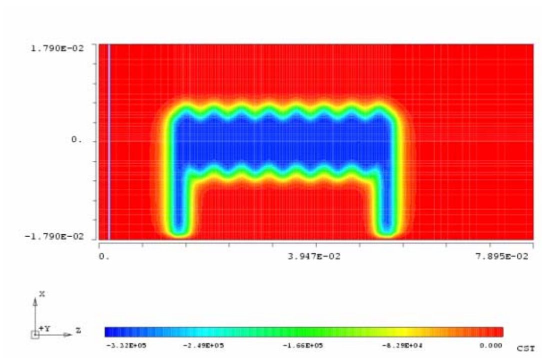


Figure 3: static field used in streak camera model.

An external circuit triggered by a GaAs photoswitch sends an input pulse of 500V/250ps to the stripline input via a 3 m coaxial cable. The pulse propagates along the meander line and forms a slow wave to match the velocity of the electrons.

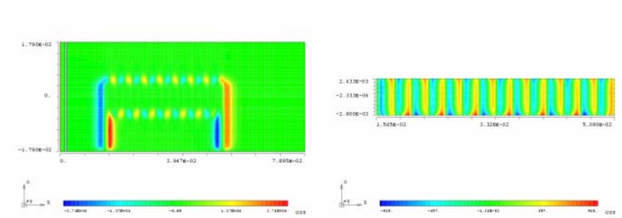
A solenoid magnetic field is calculated and used as the focusing lens field. The model allows the beam parameters to be displayed anywhere along the path of the beam.

MEANDER-LINE DEFLECTORS

The purpose of the meander line is to slow down the electrical deflecting pulse to match the beam velocity by winding the path of the electromagnetic field. In principle, this allows a more efficient deflection of the beam. Ideally, the meander line reproduces the input pulse, allowing the maximum deflection between the head and tail of the electron pulse.

Our modeling has shown that the meander line has several shortcomings as a deflector. First, the meander lines guide the electromagnetic field propagation transversely, while the electrons goes longitudinally. The velocity of the electron is much slower then the pulse, and so the electron slips on the pulse for each leg of the meander line. The overall matching we can see in the experiment is when the integral vertical kick is zero. Although the integral is zero, within the deflector, there is a finite kick, making the electron go off axis not only for the unmatched electron, but also for the "matching" electron.

Secondly, electrons that pass off-axis in the deflection direction experience a significant longitudinal field. Passing through one meander, the electron beam will sample a range of longitudinal fields, and hence will broaden in longitudinal energy spread. The longitudinal field distribution of the meander line 0.2 mm off-axis is shown in figure 4. This energy spread is then imaged by the magnetic lens as a dynamic increase in the swept



a) b)

Figure 4: a) longitudinal field(V/m) of meander line (vertical offset 0.2mm). b) center part of a).

focus size, reducing temporal resolution.

Thirdly, the meander used to slow down the longitudinal velocity of the pulse limits the bandwidth of the meander line, thus limiting the deflection speed. The S parameter of the meander line is simulated by Microwave Studio[3] and shown in Fig. 5. The simulation shows the shorter the leg (xoutmax), the wider the bandwidth. For the meander line used in experiment for 10keV electron, the cutoff frequency is about 5.5GHz.

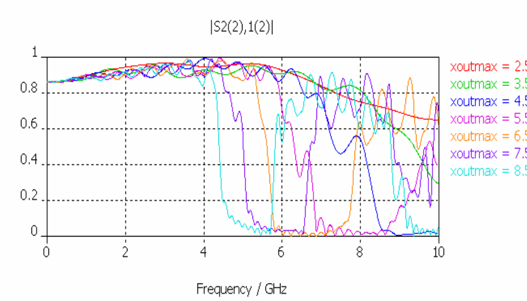


Figure 5 S_{21} of meander line

SIMULATION RESULTS

The beam trajectory of the electrons in the streak camera is shown in Fig. 6. The static image is simulated to get comparable focus lens parameter with experiment.

In the simulation, we need to find the "matching" energy for the meander line. A dummy cathode is set at the exit of the anode; a bunch of electrons are ejected with different energy at different times. We then make all the particles arrive at the middle of the first meander line leg while the pulse crosses zero at that location. We then find the electron with zero vertical momentum when it is leaving the meander plane, and use this as the "matching" energy.

An electron bunch with 1fs length is used to measure the impulse response of the system (without space charge). The image and relative histogram of the number of electron distribution in the direction of deflection is shown in figure 7 a) and b). In order to calculate the temporal resolution of the streak camera, two-electron bunches with a separation of 5ps have been simulated. The image and relative histogram of the number of electron distribution in the direction of deflection is shown in figure 7 c) and d). The temporal resolution assessed as the FWHM from figure 7.d is 937fs for 10keV matching electron energy.

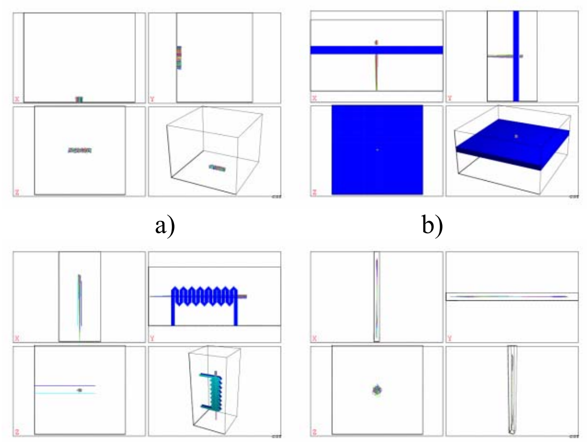


Figure 6: Electron trajectory from simulation a) electron ejection from cathode b) electron accelerated by static field c) electron deflected by the meander line field d) electron focused by solenoid field.

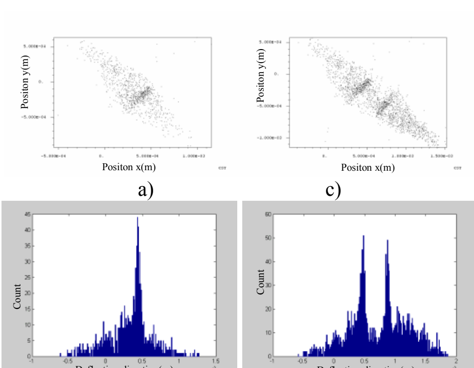


Figure 7: Image of single femto second electron bunch (a) and its histogram (b) Image of two femto second bunch separated (c) 5ps and its histogram (d).

ISSUES FOR SUB-100 FEMTO-SECOND STREAK CAMERA

Development of a < 100 fsec streak camera is important for many experiments. The model built above helps us to understand the physics of beam dynamics in current ultra-fast streak cameras. The temporal resolution of the streak camera comes mainly from the following sources: the transit time dispersion, the deflection dispersion, the sweep speed and the time jitter. The transit time dispersion comes from the initial energy spread and the acceleration gradient. and can in principle be compensated by a magnetic chicane. The sweep speed resolution is limited by the rate of change of voltage on the deflecting structure. This is limited by the voltage step applied from the photoconductive switch used for triggering, and can be increased by more than a factor of 10 if required. The high frequency cutoff of the meander line as shown here also limits the rate of change of deflection voltage. Jitter can be eliminated by use of a better photoconductive switch, temporal fiducialization of each sweep (ie. imprinting on the sweep an additional signal indicating time zero), or use of a resonant phase-locked deflecting cavity.

CONCLUSION

An end-to-end model of an ultrafast streak camera has been built in MAFIA. This study indicates that the meander striplines commonly used in streak cameras give severe restrictions for sub-psec operation. Use of a conventional strip line in which velocity matching is obtained by use of an appropriate dielectric constant is being examined, The large velocity mismatch means however that a large dielectric constant has to be used, an this in turn will mean that dielectric dispersion is an issue.

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