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Date: 2022-05-20T17:07:58+00:00

Abstract

A dilation X-ray detector (DIXD) based on time dilation and microchannel plate (MCP) gated technology has been reported. The DIXD passes a driving pulse along the transmission photocathode (PC) to obtain a dilated electron signal and finally achieves a high time resolution of 12 ps. Furthermore, the waveform of the PC driving pulse can be obtained using the DIXD, and a DIXD oscillographic function can be obtained. An experiment is presented to demonstrate the DIXD oscilloscope. The waveform of the PC driving pulse from points t1 to t12 is achieved by the DIXD. The waveform agrees well with that measured by a high-speed oscilloscope with a difference of less than 6%. The maximum theoretical bandwidth of the DIXD oscilloscope is theoretically studied. The bandwidth is limited by the potential difference between the PC and mesh. When the potential difference is 3.4 kV, the theoretical limiting bandwidth is 1000 GHz. The bandwidth increases with an increase in the potential difference.

Full Text

Development of an Ultrafast Detector and Demonstration of Its Oscillographic Application

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A dilation X-ray detector (DIXD) based on time dilation and microchannel plate (MCP) gated technology has been developed. The DIXD propagates a driving pulse along a transmission photocathode (PC) to obtain a temporally dilated electron signal, achieving a high time resolution of 12 ps. Furthermore, the waveform of the PC driving pulse can be obtained using the DIXD, thereby enabling an oscillographic function. An experiment is presented to demonstrate the DIXD oscilloscope capability. The waveform of the PC driving pulse from points t_1 to t_{12} is captured by the DIXD and agrees well with that measured by a high-speed oscilloscope, with a difference of less than 6%. The maximum theoretical bandwidth of the DIXD oscilloscope is studied theoretically and found to be limited by the potential difference between the PC and mesh. When the potential difference is 3.4 kV, the theoretical limiting bandwidth is 1000 GHz, and the bandwidth increases with increasing potential difference.

Keywords: Inertial confinement fusion, Ultrafast diagnosis, Dilation X-ray detector, X-ray framing camera, Microchannel plate

I. INTRODUCTION

Deuterium and tritium can be used in nuclear fusion to release large amounts of energy. Inertial confinement fusion (ICF) and magnetic confinement fusion (MCF) represent effective methods for achieving nuclear fusion [?]. In ICF and MCF experiments, plasma diagnostics technology is essential for obtaining data to analyze the fusion process. Two-dimensional ultrafast X-ray cameras based on gated microchannel plates (MCPs) are widely used in ICF experiments to image the implosion shape and measure peak X-ray emission [?]. Such cameras have been successfully deployed at ICF facilities including SG-III, NIF, and OMEGA for several decades [?]. They achieve time resolutions of 35–100 ps by conveying ultrashort electrical pulses onto MCP microstrip transmission lines to gate photoelectrons [?]. However, current ICF requirements continue to advance; for example, the self-emission process with a 100 ps duration demands higher time resolution than existing cameras can provide. Faster cameras must be developed to diagnose such ultrafast processes [?].

Recently, a camera named the dilation X-ray imager (DIXI) was developed, achieving time resolution better than 10 ps through time-dilation technology [?]. Prosser first introduced electron beam velocity dispersion in 1976 to improve electronic detector bandwidth [?]. This technology was applied to the DIXI in 2010 by Hilsabeck et al. [?]. The DIXI dilates the electron signal converted from the incoming X-ray signal, then samples the temporally magnified electron signal using a time-resolved MCP imager to achieve high time resolution. The electron signal time-dilation unit consists of a transmission photocathode (PC), grounded anode mesh, and electron drift tube. A negative high DC voltage plus a dilating pulse are applied to the PC to create a time-dependent electric field between the PC and mesh, resulting in electron energy dispersion. Photoelectrons generated earlier acquire larger energies than those generated later and drift faster in the region from the mesh to the MCP, thereby magnifying the time duration of the electron signal up to 50 times. Subsequently, the temporally magnified electron signal is sampled by a 200 ps time-resolved MCP imager [?], greatly improving the DIXI time resolution.

In this study, a dilation X-ray detector (DIXD) is developed, the waveform of the driving pulse on the PC is measured using the DIXD, and the oscillographic function of the DIXD is presented. Theoretical analysis and experimental verification are performed to demonstrate the performance of the DIXD oscilloscope. This work provides a novel approach for developing new high-speed oscilloscopes. The differences between our DIXD and Hilsabeck's DIXI lie in the electron imaging system and time-resolution measurement method.

In the DIXI, an electron imaging system consisting of four solenoid magnet coils images electrons from the PC onto the MCP. Coils with large excitation currents generate a 370 Gauss axial uniform magnetic field, achieving a spatial resolution of approximately 510 m for the Au PC with three-fold image demagnification [?]. However, large excitation currents generate considerable Joule heating. Fortunately, pulsed excitation current can reduce this heating. Engelhorn et al. successfully used a pulse with ~1–10 ms duration and ~1 kA peak current to excite magnet coils [?]. In the DIXD, a short magnetic lens with a large aperture generates an axisymmetric non-uniform magnetic field, imaging electrons from the PC onto the MCP at a 1:1 image ratio. Such short magnetic lenses are frequently used in streak cameras and electron microscopy to improve optical-electronic imaging quality and focusing capability [?]. The short magnetic lens is excited by a small current to obtain high spatial resolution while reducing Joule heating. However, a short magnetic lens has the disadvantage of non-uniform spatial resolution that worsens with increasing off-axis distances; three or more short magnetic lenses should be used to improve spatial resolution at the PC edge.

Another difference is the time-resolution measurement method. In the DIXI, a Mach–Zehnder interferometer measures time resolution. An ultraviolet (UV) light pulse passes through a Mach–Zehnder interferometer to output a pair of pulses, each containing an arrow-shaped aperture. The arrow aperture in the fixed-length leg is horizontal, while that in the variable-length leg is vertical. The two laser pulse outputs are detected by the DIXI, producing horizontal and vertical arrow images. The arrival time of the laser pulse producing the horizontal arrow image is set at the center of the DIXI gating time interval, and the optical path length of the vertical-arrow UV pulse is adjusted. The vertical arrow image appears and disappears over a ~5 ps temporal adjustment, demonstrating 5 ps time resolution [?]. Six images were used to obtain the DIXI time resolution, but this approach suffers from shot-to-shot timing jitter from the PC driving pulse, MCP ultrashort pulse, or laser, which could affect the 1.66 ps optical path time between adjacent images. This jitter leads to unstable optical path timing and may cause measurement errors. In this study, DIXD time resolution is acquired using a fiber bundle comprising 30 fibers of different lengths, obtaining time resolution from the fiber-gating image in a single shot. Our method avoids measurement errors caused by shot-to-shot timing jitter.

This study extends our previous work [?]. An earlier study described a dilation UV imager with time-resolution measurements; the PC was developed on a fused silica window in a UV camera. The fused silica window blocked X-ray transmission to the PC, preventing X-ray measurements in ICF and limiting use to dilation performance testing with a UV laser in the laboratory. In this study, the DIXD is improved from a UV camera, with a gold PC coated onto a C8H8 film to achieve an X-ray PC. Furthermore, while previous studies investigated camera performance with a focus on improvement, this study focuses on the oscillographic application of the DIXD.

II. DETECTOR DESCRIPTION AND OSCILLOGRAPHIC PRINCIPLE

Figure 1. (a) DIXD diagram. (b) DIXD photograph.

The DIXD comprises a temporally magnified electron pulse device, a sampling MCP imager, a magnetic lens, and a fast pulse generator, as shown in Figure 1. The temporally magnified electron pulse device increases the time duration of the photoelectron pulse emitted from the PC. The device consists of three transmission photocathodes, an anode mesh, and a drift tube. The photocathodes are prepared by depositing 80 nm Au on a C8H8 film with a 56 mm diameter. Each PC has a microstrip transmission line structure with a width of 8 mm, and a 2.8 mm gap is left between PCs. A nickel mesh with 10 lp/mm spatial frequency and 56 mm diameter is placed 1.8 mm from the PC. The mesh is parallel to the PC and at ground potential. The PC is applied with a driving pulse and biased by a negative DC high voltage, producing a varying electric field to achieve electron energy dispersion. The electrons then enter the drift tube between the mesh and MCP. The 50 cm drift tube produces temporal magnification of the electron pulse because of the higher flight speed of the front electrons. However, the electron pulse becomes spatially dispersed while moving through the drift tube. To obtain sufficient spatial resolution, a magnetic lens images the electron pulse from the PC to the MCP. An annular magnetic lens composed of a soft iron shield and 1200-turn copper coils is placed midway between the PC and MCP, with axial length, inner diameter, and outer diameter of 100 mm, 160 mm, and 256 mm, respectively. A circular slit with 4 mm width in the inner circumference allows magnetic field leakage from the soft iron into the drift tube to image the electron pulse. When the coil current is 0.34 A, the magnetic field clearly images 3 keV electrons onto the MCP with a 1:1 image ratio. Subsequently, the MCP imager with 78 ps time resolution samples the magnified electron pulse. The sampling MCP imager consists of an MCP signal sampling part, phosphor screen, and charge-coupled device (CCD). The

MCP input surface is deposited with three microstrip lines formed by a Cu layer overlying an Au layer. Au and Cu films are also coated on the MCP output surface, which is successively deposited across the entire surface and connected to ground. An ultrashort pulse is transmitted from one side of the MCP microstrip line to the other. When the magnified electron pulse is synchronized with the ultrashort pulse, the electron pulse is sampled and amplified by the MCP. The electric field from the phosphor to the MCP accelerates the amplified electrons, and high-speed electrons impact the P20 phosphor, generating fluorescence that is collected by a CCD. The MCP has a diameter of 56 mm, thickness of 0.5 mm, channel diameter of 12 m, and bias angle of 6°. Each MCP microstrip line has an 8 mm width with a 2.8 mm gap to adjacent lines. The phosphor is applied with a +4 kV DC high voltage and placed 0.5 mm from the MCP.

The fast pulse generator produces both the PC driving pulse and the MCP ultrashort pulse, comprising an avalanche transistor circuit and diode shaper. First, avalanche transistor stacks are formed in a Marx bank circuit to produce six fast step pulses. Three of these excite the photocathodes, and an avalanche diode separately shapes the other three to acquire three MCP ultrashort pulses [**?**]. Each PC driving pulse has a maximum slope of approximately 1.6 V/ps. The MCP ultrashort pulses achieve a width of 220 ps and amplitude of −1.8 kV.

Time resolution depends primarily on the PC driving pulse slope, PC voltage, drift tube, and time resolution of the MCP signal sampling part [**?**]. In the DIXD, the drift tube and MCP signal sampling part have fixed parameters, so the PC voltage and driving pulse slope determine time resolution. These parameters can also be obtained from time-resolution results, meaning the PC driving pulse waveform can be reconstructed from DIXD time resolution measurements, demonstrating that the DIXD can function as an oscilloscope.

The time resolution T of the DIXD is given by [**?**]:

$$T = \sqrt{T_{phys}^2 + T_{tech}^2}$$

where T_{phys} is the physical or limiting time resolution, which depends mainly on transit time dispersion in the PC-to-anode-mesh region [**?**], and T_{tech} is the technical time resolution related to the MCP signal sampling part time resolution T_{MCP} and temporal magnification factor M.

$$T_{phys} \approx 2.63\sqrt{\frac{\delta\varepsilon}{E\phi(t)}}$$

where $\phi(t) = [-V_B - V_P(t)]$. Here $\delta\varepsilon$ (in eV) is the full width at half maximum (FWHM) of the energy distribution of electrons emitted from the PC; the $\delta\varepsilon$ of Au under 266 nm illumination is approximately 0.5 eV [**?**]. E (in kV/mm) is the electric field from the anode mesh to the PC, and $\phi(t)$ is the potential difference between the PC and anode mesh when the photoelectron is produced at time t. L_{pa} is the 1.8 mm length from the PC to the anode mesh. $V_B < 0$ is the PC bias voltage (-3 kV), and $V_P(t)$ is the PC driving pulse voltage at time t.

T_{tech} is approximately:

$$T_{tech} \approx \frac{T_{MCP}}{M}$$

Generally, the sampling MCP imager parameters are fixed, so T_{MCP} is constant. The temporal magnification factor M depends mainly on the drift tube, PC voltage, and driving pulse slope. In the limit of a small accelerating gap from the PC to the anode mesh and neglecting the initial energy spread of electrons emitted from the PC, an electron entering the drift tube at time t_i reaches the MCP at time [**?**]:

$$t'_i = t_i + \frac{L}{\sqrt{2e\phi(t_i)/m}}$$

where L is the drift tube length (50 cm), and e and m are the electron charge and mass, respectively. The temporal magnification factor M between two time steps is [**?**]:

$$M(t_{i+1}, t_i) = \frac{t'_{i+1} - t'_i}{t_{i+1} - t_i} \approx 1 + \frac{L}{\sqrt{2e/m}} \frac{\phi(t_{i+1})^{-1/2} - \phi(t_i)^{-1/2}}{t_{i+1} - t_i}$$

For small time steps, this becomes:

$$M(t) \approx 1 + \frac{L}{\sqrt{2e/m}} \frac{d}{dt}[\phi(t)^{-1/2}]$$

The derivative of the PC driving pulse voltage is:

$$V'_P(t_{i+1}, t_i) = \frac{V_P(t_{i+1}) - V_P(t_i)}{t_{i+1} - t_i}$$

The DIXD time resolution T and MCP signal sampling part time resolution T_{MCP} can be measured experimentally. With these known values, only two unknowns remain: $V_P(t)$ and $V'_P(t)$, which are related through the equations above. Therefore, $V_P(t)$ can be obtained from the system of equations, allowing the PC driving pulse waveform to be acquired.

III. EXPERIMENTAL MEASUREMENT

Figure 2. (a) Schematic of the time resolution measurement setup. (b) Photograph of the fiber bundle. (c) Output port array of the fiber bundle. The fiber

labeled number one has the shortest length, with length increasing by 2 mm for each increment of 1. The gap between each two adjacent fibers is 0.2 mm.

Time resolution is measured using a Ti:sapphire laser system and fiber bundle, as shown in Figure 2(a). The system outputs two beams: a 266 nm UV beam and an 800 nm infrared beam. Total reflection mirror M1 first reflects the UV laser beam (130 fs pulse width), and concave lens L1 enlarges the spot size to exceed the fiber bundle diameter. The UV beam then reaches the fiber bundle, which consists of 30 fibers with equal length differences. Photographs of the fiber bundle and schematic of the fiber array are shown in Figures 2(b) and 2(c). Fiber length increases in 2 mm steps with error less than 0.2 mm, producing 30 UV laser pulses that exit the fiber bundle at various times. The delay time between adjacent fibers is 10 ps. Lenses L2 and L3 image the UV laser pulses onto the PC to generate 30 photoelectron pulses. The infrared beam reflects from total reflector M2 to a positive-intrinsic-negative (PIN) diode, producing an electrical signal that triggers the fast pulse generator to produce the driving pulse on the PC and ultrashort pulse on the MCP. A delay circuit precisely adjusts the trigger time to ensure synchronization between the 266 nm laser pulses and PC driving pulse. The 30 photoelectron pulses with different emission times are accelerated by a varying electric field, achieving electron velocity dispersion to magnify the electron signal time duration. Finally, the ultrashort pulse samples the magnified electron pulse on the MCP, producing a time-dilated gating image.

Figure 3. (a) Static image of the 30 laser pulses, with the PC subjected to a static DC bias of −3 kV and the MCP to a static DC bias of −700 V. (b) Gating image without time dilation, with −3 kV DC bias applied to the PC and an ultrashort pulse plus −300 V DC bias applied to the MCP. The ultrashort pulse has a width of 220 ps and amplitude of −1.8 kV. (c) Lineout of the gating image without time dilation in (b).

First, the time resolution of the MCP signal-sampling part T_{MCP} is measured. The static image of the 30 laser pulses and gating image without time dilation are shown in Figures 3(a) and 3(b). A −3 kV static DC bias is used for the PC and −700 V for the MCP. The static image is shown in Figure 3(a), where the shortest fiber is imaged at the top right and adjacent images are separated by 0.5 mm. Figure 3(b) shows the gating image without time dilation, obtained by applying −3 kV DC bias to the PC and an ultrashort pulse plus −300 V DC bias to the MCP. The images in Figures 3(a) and 3(b) are raw. To avoid influence from uneven light intensity distribution, the results in Figure 3(b) were calibrated using the static results in Figure 3(a). The lineout of the calibrated results in Figure 3(b) is shown in Figure 3(c). The solid points are calibrated experimental results fitted with a Gaussian curve representing intensity versus time, whose FWHM defines the time resolution. Without electron signal dilation, Figure 3(c) shows the time resolution is approximately 78 ps, which is T_{MCP}.

Next, the time resolution T is obtained as a function of synchronization position. Since the laser pulse arrival time at the PC is constant, the delay circuit is adjusted to synchronize the UV laser pulse with the rising edge of the PC driving pulse. A schematic of the synchronization position is shown in Figure 4. Point t_1 is delayed by approximately 200 ps relative to the PC driving pulse start time. The time increases by 62.5 ps as the subscript increments by one until t_{11}. Thus, point t_2 is approximately 262.5 ps after the pulse beginning, t_3 is approximately 325 ps, and t_{11} is approximately 825 ps. Point t_{12} occurs approximately 1200 ps after the beginning. The measured gating image with time dilation at synchronization position t_1 is shown in Figure 5(a). To obtain this image, the MCP voltages from Figure 3(b) are retained while applying a −3 kV DC bias overlapped by a driving pulse to the PC. The lineout of the measurement results in Figure 5(a) is shown in Figure 6, revealing that the DIXD time resolution T is approximately 39 ps with time dilation at synchronization position t_1.

Figure 4. Schematic of the synchronization position for the laser pulse with the driving pulse rising edge on the PC. The synchronization position is adjusted at points t_1 to t_{12} in turn.

Figure 5. Gating images with time dilation while the synchronization position of the laser pulse and PC driving pulse is changed from point t_1 to t_{12}. A −3 kV DC bias overlapped by a driving pulse is applied to the PC, and MCP voltages consist of a −300 V DC bias plus the ultrashort pulse. Images (a)-(l) correspond to synchronization points t_1-t_{12}.

Figure 6. Lineout of the gating image with time dilation in Figure 5(a) at synchronization position t_1, 200 ps after the pulse beginning.

To adjust the synchronization position to point t_2, the PC driving pulse delay time is changed, and the resulting time-dilated gating image is shown in Figure 5(b). The synchronization position is adjusted sequentially to points t_3 through t_{12}, with gating images obtained for each position as shown in Figures 5(c)-5(l). The variation in time resolution T with synchronization position is then obtained from Figures 5(a)-5(l) and shown in Figure 7. The time resolution differs across synchronization positions, with the best resolution of 12 ps achieved at position t_5, which is 450 ps after the pulse beginning.

Figure 7. DIXD time resolution T varying with synchronization position.

In the DIXD, the magnetic lens images photoelectrons from the PC to the MCP. A corresponding magnetic lens coil current is required to clearly image photoelectrons of a certain energy onto the MCP; thus, when electron energy changes, the magnetic lens coil current changes accordingly. We can therefore use the coil current to determine electron energy and the potential difference between the PC and anode mesh. At synchronization position t_1, a coil current of 0.33 A produces the clear spot image shown in Figure 5(a). An experiment was performed to determine the photoelectron energy corresponding to 0.33 A coil current. Only the PC voltage was changed while maintaining other conditions from Figure 5(a). A DC bias without PC driving pulse was applied to the PC and adjusted precisely to obtain a gating image decoupled from time dilation. When the PC DC bias was approximately -2.88 kV, the gating image without time dilation was as clear as the spot image in Figure 5(a). Therefore, 0.33 A coil current corresponds to a photoelectron energy of 2.88 keV.

In Figure 5(a), the PC is applied with a -3 kV DC bias overlaid by a driving pulse, and the photoelectron energy is 2.88 keV. Therefore, the PC driving pulse is approximately 120 V at synchronization point t_1. Using the measured parameters at synchronization point t_1—$T(t_1) = 39$ ps, $T_{MCP} = 78$ ps, and $V_P(t_1) = 120$ V—we can calculate $V_P'(t)$ from Equations (1)-(8), obtaining a value of 0.37 V/ps. The parameters for point t_2 are $V_P(t_1) = 120$ V, $T(t_2) = 17$ ps, and $T_{MCP} = 78$ ps, yielding $V_P(t_2) = 199$ V and $V_P'(t_2) = 1.26$ V/ps from Equations (1)-(8). Subsequently, the variations in $V_P(t)$ and $V_P'(t)$ with time t can be acquired, as shown in Table 1.

The PC driving pulse waveform from points t_1 to t_{12} measured by the DIXD is obtained from Table 1 and represented by the red curve in Figure 8. The blue curve shows the PC driving pulse waveform measured using a high-speed oscilloscope. The waveforms from points t_1 to t_{12} measured by the DIXD and oscilloscope are almost identical, with differences within 6%, validating the oscilloscopic capability of the DIXD.

Table 1. $V_P(t)$ and $V_P'(t)$ vary with synchronization position, which is the point at the rising edge of the PC driving pulse t ps later than the beginning.

Point	t (ps)	$V_P(t)$ (V)	$V_P'(t)$ (V/ps)
t_1	200	120	0.37
t_2	262.5	199	1.26
t_3	325	287	1.41
t_4	387.5	376	1.41
t_5	450	465	1.41
t_6	512.5	553	1.41
t_7	575	642	1.41
t_8	637.5	730	1.41
t_9	700	819	1.41
t_{10}	762.5	907	1.41
t_{11}	825	996	1.41
t_{12}	1200	1470	1.41

Figure 8. PC driving pulse waveform measured by a high-speed oscilloscope, and the waveform from point t_1 to t_{12} measured by the DIXD.

The limiting time resolution of the DIXD is considered equal to the physical time resolution T_{phys} [?]. The red curve in Figure 9 shows the variation in limiting time resolution with potential difference between the PC and mesh (with 1.8 mm spacing between grounded anode mesh and PC). Larger potential difference reduces electron transit time dispersion in the PC-to-mesh region and improves limiting time resolution. When the DIXD is used as an oscilloscope, the relationship between its maximum theoretical bandwidth and potential difference is shown by the blue curve in Figure 9. The bandwidth is limited by the potential difference; at 3.4 kV potential difference, the theoretical limiting bandwidth is 1000 GHz, increasing with larger potential difference.

Figure 9. Limiting time resolution and maximum theoretical bandwidth of the DIXD oscilloscope varying with potential difference between the PC and mesh.

IV. CONCLUSIONS

A DIXD composed of a temporally magnified electron pulse device, sampling MCP imager, magnetic lens, and fast pulse generator has been developed. The temporally magnified device achieves electron signal dilation, improving DIXD time resolution from 78 ps to 12 ps. A DIXD oscilloscope has been presented and theoretically analyzed.

Typically, time resolution depends on factors including PC voltage, PC driving pulse slope, MCP signal sampling part time resolution, and drift tube length. In the DIXD, the MCP signal sampling part time resolution is 78 ps and the drift tube is 50 cm, both invariant. Therefore, the slope and voltage of the PC driving pulse determine time resolution and can be obtained from time-resolution measurements. The PC driving pulse waveform can then be reconstructed from DIXD time resolution, demonstrating that the DIXD functions as an oscilloscope. An experiment demonstrates the DIXD oscillographic application by adjusting the synchronization position between the laser pulse and PC driving pulse at different points and obtaining time resolution T at each position. The PC driving pulse voltage and slope at each synchronization position are then derived from the measured time resolution, yielding the waveform from points t_1 to t_{12}. The DIXD-measured waveform and high-speed oscilloscope measurement are almost identical, with differences within 6%. The maximum theoretical bandwidth of the DIXD oscilloscope varies with potential difference between the mesh and PC; the bandwidth is limited by this potential difference, reaching 1000 GHz at 3.4 kV. Larger potential difference yields higher bandwidth, so the DIXD oscilloscope bandwidth can be improved by increasing the potential difference.

This study provides a novel approach for developing new high-speed oscilloscopes.

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Supported by the Program for National Natural Science Foundation of China (NSFC) (11775147); Guangdong Basic and Applied Basic Research Foundation (Nos. 2019A1515011474 and 2019A1515110130); Shenzhen Science and Technology Program (Nos. JCYJ20210324095007020, JCYJ20200109105201936, and JCYJ20190808115605501).

Note: Figure translations are in progress. See original paper for figures.