# Ultrafast pulse-dilation framing camera and its application for time-resolved X-ray diagnostic.

**Authors:** Houzhi Cai, Qiuyan Luo, Kaixuan Lin, Xuan Deng, Junkai Liu, Kaizhi Yang, Dong Wang, Jiajie Chen, Jiaheng Wang, Jinghua Long, Lihong Niu, Yunfei Lei, Jinyuan Liu, Yunfei Lei, Jinyuan Liu

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## Abstract

An ultrafast framing camera with a pulse-dilation device and a microchannel plate (MCP) imager as well as an electronic imaging system is reported. The camera achieves a temporal resolution of 10 ps by using a pulse-dilation device and a gated MCP imager, and a spatial resolution of 100  m by using an electronic imaging system composed of combined magnetic lenses. The spatial resolution characteristics of the camera are theoretically and experimentally studied. The results show that the camera with combined magnetic lenses could reduce field curvature and acquire a larger working area. A working area 53 mm in diameter has been achieved by applying four magnetic lenses to the camera. Furthermore, the camera is used to detect X-rays produced from a laser targeting device. The diagnostic results show that the width of the X-ray pulse is about 18 ps.

## Full Text

## Preamble

### Ultrafast Pulse-Dilation Framing Camera and Its Application for Time-Resolved X-Ray Diagnostic

Houzhi Cai, Qiuyan Luo, Kaixuan Lin, Xuan Deng, Junkai Liu, Kaizhi Yang, Dong Wang, Jiajie Chen, Jiaheng Wang, Jinghua Long, Lihong Niu, Yunfei Lei, and Jinyuan Liu

Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China

An ultrafast framing camera incorporating a pulse-dilation device, a microchannel plate (MCP) imager, and an electronic imaging system is reported. The camera achieves a temporal resolution of 10 ps through the use of a pulse-dilation device and gated MCP imager, and a spatial resolution of 100  m via an electronic imaging system comprising combined magnetic lenses. The spatial resolution characteristics of the camera were studied both theoretically and experimentally. Results demonstrate that the combined magnetic lens configuration reduces field curvature and provides a larger working area. A working area with a diameter of 53 mm was created by applying four magnetic lenses to the camera. Furthermore, the camera was used to detect X-rays produced by a laser-targeting device, with diagnostic results indicating that the X-ray pulse width was approximately 18 ps.

**Keywords:** Inertial confinement fusion, Plasma diagnostics, Framing camera, Combined lenses, Pulse-dilation

## I. Introduction

An X-ray framing camera based on a gated microchannel plate (MCP) is an essential diagnostic instrument in various fields including inertial confinement fusion (ICF) studies, Z-pinch experiments, and laser plasma physics [1-8]. Such cameras employ a microstrip transmission line photocathode (PC) deposited on the MCP surface to transmit a short gating pulse [9,10]. Temporal sampling of the signal is achieved through synchronization with the gating pulse [11,12]. The temporal resolution of such cameras is limited by the transit time spread of electrons traversing the MCP channel pore [13-15]. For an MCP with a thickness of 0.5 mm, the temporal resolution ranges from 60 to 100 ps. In ICF experiments, this resolution is insufficient for acquiring a detailed history of implosions with 100-200 ps duration [16-18]. A faster camera is required to accurately characterize implosion performance [19,20].

Recently, Hilsabeck et al. developed a dilation X-ray imager (DIXI) with pulse dilation technology [21] and achieved temporal resolution better than 10 ps [21-25]. The temporal width of the electron beam generated by the PC was dilated up to 50 times in a 50 cm drift region to achieve high temporal resolution. Because of the long transmission distance of the electron beam in the drift region, an electronic optical system is required to image the electron beam from the PC onto the MCP to achieve high spatial resolution. In the DIXI, four magnet coils were employed to achieve a spatial resolution of 510  m for the Au PC [21,22]. The single-line-of-sight camera developed by Nagel et al. used a Cu winding outside an evacuated drift tube to produce a magnetic field, achieving a spatial resolution of 35  m and a working area of 25.6 mm × 12.8 mm [26,27]. Another 4 ps dilation framing camera used a short magnetic lens to image electrons, achieving a spatial resolution of approximately 100  m with a magnification ratio of 1:1 [28]. However, variations in spatial resolution within the working area have not been reported for dilation framing cameras with short magnetic lenses. Generally, the off-axis spatial resolution is reduced because of field curvature in the electronic optical imaging system of cameras using short magnetic lenses, which limits both the working area and spatial resolution. Combined magnetic lenses were used in our framing camera to correct for field curvature. Such magnetic lenses are frequently employed to observe electron Moiré patterns or achieve high imaging quality in electron microscopes and streak cameras [29-32].

In this paper, an ultrafast framing camera with pulse-dilation technology and combined magnetic lenses is presented, and an X-ray diagnostic experiment is described. Four magnetic lenses were combined in the camera to reduce field curvature, and a spatial magnification ratio of 1:1 was designed. The temporal resolution of the camera was measured using a femtosecond laser and fiber bundle. The electronic optical imaging characteristics of the camera, such as spatial resolution, field curvature, and sensitive area, were also analyzed. Furthermore, the camera was used to detect X-rays produced by a terawatt laser targeting system.

## II. Camera Parameters

The ultrafast pulse-dilation framing camera consisted of a pulse-dilation device, an MCP imager, a combined lens imaging system, and a pulse generator; its schematic and photograph are shown in Figs. 1(a) and (b), respectively. The pulse dilation device included three microstrip X-ray PCs, an anode mesh, and a drift tube. The PCs were developed by coating an Au film with a thickness of 80 nm onto a (C8H8)n film. Each PC was 12 mm wide, with a gap of 10 mm between neighboring PCs. The PCs converted X-rays into electrons and functioned as a microstrip transmission line to transmit the dilation electric pulse. The anode mesh was mounted 1.8 mm from the PC and connected to ground. A high direct current (DC) voltage was applied to each PC strip, overlaying the dilation pulse, which provided a varying PC voltage. The energy of electrons arriving at the mesh was obtained by varying the PC voltage. An electron emitted from the PC earlier possessed higher energy and speed than those emitted later, resulting in an electron energy spread that caused temporal magnification of the electron pulse in the 550 mm drift tube.

The MCP imager consisted of an MCP, a phosphor screen, and a charge-coupled device (CCD). The thickness, diameter, and pore diameter of the MCP were 0.5 mm, 106 mm, and 12  m, respectively. Three microstrip transmission lines were formed by depositing 500 nm Cu overlaid with 100 nm Au on the MCP input surface. The entire MCP output surface was also deposited with Cu and Au with the same thicknesses and connected to ground. A width of 12 mm for each microstrip transmission line and a 10 mm gap between adjacent lines were formed. The phosphor screen was biased with a +3.4 kV DC voltage and positioned 0.5 mm from the MCP. The CCD was fiber-coupled with the phosphor screen to capture visible light images.

The drift region for electron pulse dilation, from the mesh to the MCP, was 550 mm. Electrons traveling in the drift tube were imaged from the PC to the MCP by an axially symmetric nonuniform magnetic field produced by the combined magnetic lenses [28,33]. Four identical annular magnetic lenses were used to form the combined-lens imaging system. Each magnetic lens was composed of a soft iron frame and 2320-turn copper coils with an outer diameter of 256 mm, inner diameter of 160 mm, and axial length of 50 mm. In the inner cylinder, a 4 mm circular slit was formed to release the magnetic field from the soft iron to the drift tube.

The output of the pulse generator consisted of three PC dilation pulses and three MCP gating pulses. The pulse generator comprised a transistor ramp pulser and pulse-width-shortening diode circuit. In the transistor ramp pulser, eight avalanche transistors were stacked in a string, and seven strings were configured in a Marx-bank circuit. The transistor ramp pulser produced six ramp pulses, three of which were used as PC dilation pulses to drive the three PCs, while the other three were used to separately drive the diode circuit to produce three MCP gating pulses [28]. Each PC dilation pulse had an effective rising time of approximately 400 ps, as shown in Fig. 1(c), with a slope of approximately 2.5 V/ps. The MCP gating pulse had an amplitude of −2 kV and a width of 325 ps, with the corresponding waveform shown in Fig. 1(d).

## III. Performance Measurement Results

### 3.1 Spatial Resolution Measurement

The spatial and temporal resolutions of the camera were measured. A tailored Au PC was used instead of an X-ray PC to measure spatial resolution at different off-axis distances. The Au PCs were fabricated by depositing an 80 nm Au film on a quartz substrate. Photolithography was used to develop a resolution mask for each PC [34]. The resolution mask comprised several slits with dimensions of 3 mm × 3 mm, featuring various spatial frequencies: 500, 200, 100, 66, 50, 40, 33, and 28 m. For each spatial frequency, two slits were used with directions parallel and perpendicular to the PC transmission line. Eight spatial frequencies with sixteen slits formed a slit group, and several slit groups were deposited repetitively along each PC to measure spatial resolution at different off-axis distances.

The spatial resolution of the camera, determined by the combined magnetic lenses and MCP imager, can be expressed as [19,22]:

$$\delta = \sqrt{\delta_{\mathrm{drift}}^2 + \delta_{\mathrm{MCP}}^2}$$

where $\delta_{\mathrm{drift}}$ is the spatial resolution of the combined magnetic lenses, $\delta_{\mathrm{MCP}} = 50\ \mu\mathrm{m}$ is the spatial resolution of the MCP imager, and the spatial magnification ratio $M_s$ is 1. As $\delta_{\mathrm{MCP}}$ and $M_s$ are fixed, $\delta$ is primarily influenced by the combined magnetic lenses.

Static images on the Gaussian plane of the middle transmission PC were obtained for cameras with different numbers of magnetic lenses. When the camera consists of one magnetic lens, the static image is shown in Fig. 2(a). Static images for cameras comprising two, three, and four magnetic lenses are shown in Figs. 2(b), (c), and (d), respectively. The spatial resolution is obtained from the static image, and the modulations of the slits for different spatial frequencies are calculated using:

$$M = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

where $I$, $I_{\max}$, and $I_{\min}$ denote the intensity of the slit image, maximum intensity, and minimum intensity, respectively. The measured and simulated results were compared.

The spatial resolution was simulated using Lorentz3DEM software. The electromagnetic field from the PC to the MCP of the camera was modeled, and the resulting electron trajectories were traced. The spatial resolution at each off-axis position was obtained using the Rayleigh criterion. Two photoelectron beams were emitted at specific positions on the PC, and their corresponding image points on the MCP were obtained. The minimum distinguishable distance between the two image points was determined using the Rayleigh criterion, and the corresponding gap between the two photoelectron beams on the PC was defined as the spatial resolution.

Static spatial resolution measurements were performed using a DC ultraviolet source. A static DC voltage was applied to both the PC and MCP. The PC converted incident ultraviolet light to a photoelectron image with a mask, which was then imaged onto the MCP by the combined magnetic lenses and converted to a visible image by the MCP imager. Finally, a CCD captured the visible images.

The spatial resolution characteristics of cameras with different numbers of magnetic lenses were compared by increasing the number of lenses and obtaining the corresponding static images. The 200  m mask images for various off-axis distances and magnetic lens numbers are shown in Fig. 3(a), with corresponding modulations shown in Fig. 3(b). Lines and points represent simulated and measured results, respectively. The camera with one magnetic lens exhibits the worst imaging quality, with modulation decreasing rapidly as off-axis distance increases. It cannot resolve 200  m when the off-axis distance exceeds 13.5 mm. Cameras with two, three, or four magnetic lenses exhibit considerably better imaging quality than the single-lens camera. The camera using four magnetic lenses demonstrates superior spatial resolution compared to those using two or three lenses. With four magnetic lenses, the entire effective working area with a diameter of 60 mm delivers spatial resolution better than 200  m. Measurement and simulation results are consistent, showing that modulation worsens with increasing off-axis distance, indicating that spatial resolution decreases with off-axis distance.

The modulations of 100 m masks on the Gaussian plane versus off-axis distance are shown in Fig. 3(c). Visibility of the 100 m mask reduces as off-axis distance increases. The 100 m mask can be distinguished within a radius of 4.5 mm when one magnetic lens is used. Imaging quality improves significantly when the camera uses four magnetic lenses. However, the 100 m mask at a PC off-axis position of 26.5 mm does not exhibit visible modulation. Therefore, the camera cannot maintain a working area with a radius of 26.5 mm for 100 m spatial resolution on the Gaussian plane. Furthermore, modulation for the 100 m mask descends faster than that for the 200 m mask along the off-axis distance.

Off-axis spatial resolution is primarily influenced by field curvature, an aberration that transforms an imaging plane into a curved surface. The curvature near the axis is approximately spherical. In the magnetic lens imaging system, the curvature radius $r_p$ of the image surface is given by [35]:

$$\frac{1}{r_p} = \frac{e}{m}\int_{-\infty}^{+\infty}\frac{B^2}{V}dz$$

where $e$ and $m$ are the electron charge and mass, respectively; $V$ is the voltage between the PC and the mesh; $B$ is the magnetic field strength in the drift tube; and $z$ is the axial direction variable.

Field curvature is a complex parameter because the curvature radius $r_p$ varies with off-axis distance. The imaging surface was simulated using Lorentz3DEM software. The curved imaging surfaces for cameras consisting of various numbers of lenses and their two-dimensional projections are shown in Fig. 4(a) and Fig. 4(b), respectively. Lines represent simulation results for a PC with a simulation area diameter of 60 mm. The parameter $L$ is the distance from the imaging surface to the PC along the axis, representing the position of the imaging surface for each off-axis point. Simulation results show that the imaging surface is curved when the PC voltage is fixed. Although the object point has a larger off-axis distance, its corresponding $L$ is smaller, indicating that the imaging point is located closer to the PC for farther off-axis object points.

In the experiment, the imaging surface was detected using a planar MCP, and the distance between the PC and MCP was fixed in the camera. Therefore, the position of the imaging point for each off-axis object point could not be obtained simultaneously in a single experiment with the same PC voltage. The imaging-point positions were obtained from different experiments using different PC voltages. The PC voltage was adjusted sequentially, resulting in a sequence of the clearest image areas on the MCP. Subsequently, the PC voltage for each object point on the PC that was imaged clearly on the MCP was obtained. In the camera with four magnetic lenses, experimental results demonstrated that the distance between the object plane and image surface reduced by approximately 0.14 mm when the PC voltage increased by 1 V. Similar results were obtained for other magnetic lens imaging systems. Therefore, variation in PC voltage can be used to obtain the imaging point position of each PC object and its corresponding variation [35]. Experimental results for the imaging point position versus the off-axis distance of the PC object point are shown in Fig. 4(b). In Fig. 4, lines and points represent simulation and experimental results, respectively, which are consistent.

The imaging point moves toward the PC when the off-axis distance of the object point increases, leading to a curved imaging surface. However, the detector of the curved imaging surface is a planar MCP; consequently, spatial resolution varies with the off-axis distance of electrons emitted from the PC, reducing the uniformity of spatial resolution over the entire sensitive area.

In Fig. 4(b), plane A is the Gaussian plane, and the curved imaging surfaces are the Petzval surfaces [35]. $S_1$, $S_2$, $S_3$, and $S_4$ are the axial deviations between the Gaussian plane and Petzval surface with an aperture radius of 30 mm. The maximum deviation in the camera with one magnetic lens, $S_1$, is approximately 13 cm. The deviation $S_2$ decreases to 5 cm when two magnetic lenses are used. Better curvature is achieved with three magnetic lenses, with deviation $S_3$ approximately 2.5 cm. Field curvature further improves in the camera with four magnetic lenses, with deviation $S_4$ improving to less than 2 cm. The improvement in field curvature enhances spatial resolution with an increasing number of magnetic lenses, which explains the experimental results shown in Fig. 3.

The location of the Gaussian plane A for the camera imaging system was adjusted to improve the uniformity of spatial resolution across the entire sensitive area of the PC. The PC voltage of $-3$ kV was fixed while the magnetic lens excitation currents were reduced, moving the Gaussian plane A farther from the PC. Spatial resolution differences in the working area improved when plane B in Fig. 4(b) was moved to overlap with the MCP plane. Fig. 5(a) shows the 200 m static images of the slits on imaging plane B, while Fig. 5(b) shows its modulations varying with off-axis distance. Compared to results for Gaussian plane A in Fig. 3(a), the off-axis spatial resolution at 25.5 mm off-axis is significantly improved. The 200 m mask at a radius of 25.5 mm was distinguishable in cameras with four and three magnetic lenses. Fig. 5(b) shows that changing the imaging plane from A to B improves modulation for the off-axis region, although modulation of the on-axis area decreases. Fortunately, spatial resolution differences over the entire working area improve. Comparing the modulation difference of plane B in Fig. 5(b) with that of plane A in Fig. 3(b), the modulation difference among points within a 30 mm off-axis distance in plane B is better than that in plane A. Therefore, the uniformity of spatial resolution across the entire working area for plane B is better than that for plane A.

The modulations of 100 m slits for static images on imaging plane B are shown in Fig. 5(c). The 100 m spatial resolution at a radius of 26.5 mm is distinguishable in the camera with four magnetic lenses. Multiple combined magnetic lenses produce better imaging quality than a single magnetic lens. The camera with four combined magnetic lenses achieved a spatial resolution of 100  m in a sensitive area with a diameter of 53 mm.

### 3.2 Temporal Resolution Measurement

The energy spread at the mesh results in temporal magnification of the electron pulse in the drift tube, which greatly improves temporal resolution. The temporal resolution $T$ of the pulse-dilation framing camera is mainly determined by the temporal resolution $T_{\mathrm{MCP}}$ of the MCP imager and the pulse-dilation temporal magnification factor $M$, given by [21]:

$$T \approx \frac{T_{\mathrm{MCP}}}{M}$$

The pulse dilation temporal magnification factor $M$ is determined by the PC voltage, PC dilation pulse slope, and drift tube length [26]. Because of the small distance from the PC to the mesh and negligible initial electron energy spread at the PC, electrons entering the drift tube at time $t_i$ reach the MCP at time $t_i'$ as follows [25]:

$$t_i' = t_i + \frac{L_{\mathrm{pm}}}{\sqrt{\frac{2e}{m}\phi(t_i)}}$$

where $L_{\mathrm{pm}}$ is the 550 mm length of the drift tube. Between two time steps, the temporal magnification factor $M$ can be expressed as [33]:

$$M = \frac{t_{i+1}' - t_i'}{t_{i+1} - t_i}$$

In general, the drift tube length is fixed when the pulse-dilation framing camera is designed. The temporal resolution $T$ is primarily determined by the PC voltage, PC dilation pulse slope, and MCP imager resolution [26]. As shown in Fig. 6, the variation of temporal resolution $T$ with PC dilation pulse slope and its relationship with PC voltage were studied when the temporal resolution of the MCP imager was 100 ps. Temporal resolution improves with increasing PC dilation pulse slope because the temporal magnification factor $M$ increases with the PC dilation pulse slope. In Fig. 6(a), a voltage of −2.5 kV is applied to the PC. As shown in Fig. 6(b), the PC dilation pulse slope is 2.5 V/ps. Fig. 6(b) shows that temporal resolution improves with decreasing accelerating voltage. The accelerating voltage is an important parameter for the camera because both electron transit time spread from the PC to the anode mesh and spatial resolution improve with increasing acceleration voltage [31,32]. The acceleration voltages of pulse-dilation framing cameras are typically higher than 2.5 kV [21,36].

Temporal resolution was measured using a femtosecond laser and fiber bundle. The measurement setup included a Ti-sapphire femtosecond laser system, an optical time adjustment system, a fiber bundle, an optical imaging system, an electric trigger signal generator, an electric delay circuit, and the pulse-dilation framing camera, as shown in Fig. 7(a). Two laser beams with wavelengths of 266 nm and 800 nm were emitted by the femtosecond laser system. The 266 nm UV light was used to excite photoelectrons, while 800 nm infrared light served as a synchronous trigger signal. UV light with a pulse width of 130 fs was reflected by a total reflection mirror M1, and the spot size was enlarged by a concave lens L1. The fiber bundle was composed of 30 fibers and used to separate the input UV laser into 30 light points. The lengths of the 30 fibers were increased with an equal difference of 2 mm, with error less than 0.2 mm. Therefore, 30 UV light points were generated at various times, achieving a delay of approximately 10 ps for each pair of adjacent light points. Photographs of the fiber bundle and an array diagram of the fiber output port are shown in Fig. 7(b) and (c), respectively. The 30 UV light points from the fiber bundle were imaged onto the PC using lenses L2 and L3, generating 30 photoelectron pulses. The emission interval for each pair of neighboring photoelectron pulses is approximately 10 ps.

First, the static image of 30 laser pulses was acquired, as shown in Fig. 8(a). The PC and MCP were subjected to static DC voltages of $-3$ kV and $-700$ V, respectively. The top-right image point is from the shortest fiber, and each pair of neighboring images is 0.5 mm apart. The static image represents the light intensity uniformity of the 30 light points, which is used as a normalized background image for the gating image.

The gated image of the camera without pulse dilation (Fig. 8(b)) was measured by applying a $-2.5$ kV static DC voltage to the PC and a $-483$ V DC bias plus the gating pulse to the MCP. When a static DC bias was applied to the PC, the electron beam was not temporally dilated. The MCP was driven by the gating pulse, and the electron signal was sampled by the MCP imager, allowing measurement of the gate width of the MCP imager. Figs. 8(a) and (b) show two raw CCD images. To reduce the effect of nonuniform light intensity distribution, static results from Fig. 8(a) were used to correct the gating results in Fig. 8(b). A lineout of the corrected data is shown in red in Fig. 8(d). The solid red block points represent experimental results, which were Gaussian fitted to obtain intensity versus time. The full width at half maximum (FWHM) of the Gaussian curve is defined as the temporal resolution of the camera. Fig. 8(d) shows that without electron signal dilation, the temporal resolution is approximately 100 ps, which corresponds to $T_{\mathrm{MCP}}$ of the MCP imager.

Finally, the gated image for the camera with pulse dilation was measured, as shown in Fig. 8(c). The MCP was gated with a $-483$ V DC bias and the gating pulse. The PC was excited by a dilation pulse and $-3$ kV DC bias. Therefore, photoelectron pulses were temporally dilated and the temporal resolution improved significantly, as shown in Equation (4). To achieve pulse dilation, all or part of the 30 photoelectron pulses were synchronized with the rising edge of the PC dilation pulse. In this experiment, the arrival time of laser pulses at the PC was constant, and the timing of the PC dilation pulse was accurately adjusted using a delay circuit to synchronize with the photoelectron pulses. A good synchronization position was achieved in many experiments, approximately 235 ps relative to the starting time of the PC dilation pulse. The PC voltage at this synchronization position is approximately −2.5 kV. The measured gated image of the camera with pulse dilation at this synchronization position is shown in Fig. 8(c). The lineouts from Fig. 8(c) are indicated in blue in Fig. 8(d), showing that the temporal resolution $T$ of the pulse-dilation framing camera is approximately 10 ps. The temporal magnification factor $M$ was determined from the PC voltage, temporal resolution $T_{\mathrm{MCP}}$ of the MCP imager, and temporal resolution $T$ of the pulse-dilation framing camera. The measured $M$ was 10, consistent with the theoretical result of 10.2 calculated using Equation (6).

## IV. X-Ray Diagnosis Applications

A pulse-dilation framing camera was used to detect X-rays generated by a terawatt laser target device. The experimental setup for X-ray pulse measurement was similar to the temporal-resolution measurement setup shown in Fig. 7(a), but without the fiber bundle. Two laser pulses with wavelengths of 390 nm and 780 nm and pulse widths of 100 fs were emitted from the terawatt laser system. The 780 nm laser had an energy of 650 mJ. It was first reflected by several total reflection mirrors and then irradiated onto a planar iron target to produce X-rays. The camera was placed outside the target chamber, with a distance of 71 cm between the PC and iron target. Because no component was placed between the PC and iron target, X-rays freely reached the PC to produce photoelectrons. The 390 nm laser was reflected from another total reflector to a positive-intrinsic-negative (PIN) diode, which produced a trigger signal for the pulse generator. The framing camera was operated in pulse-dilation dynamic mode. A DG535 delay generator was used to precisely adjust the trigger time to synchronize X-rays with the PC dilation pulse, and gated images with pulse dilation were obtained.

In this experiment, a middle-transmission PC was used as a monitor without applying DC voltage or dilation pulse. First, the static image of the transmission PC was measured while the PC was subjected to a −3 kV static DC voltage and the MCP was biased with −700 V, as shown in Fig. 9(a). A nonuniform intensity distribution is observed due to the nonuniform spatial distribution of X-rays. Then, the gating image of the transmission PC for the camera with pulse dilation was acquired (Fig. 9(b)) when both top and bottom PCs were subjected to a dilation pulse in addition to the −3 kV DC bias and the MCP was subjected to a −483 V DC bias plus the gating pulse. Two coaxial cables of different lengths were used to achieve two dilation pulses reaching the top and bottom PCs at different times, acquiring X-rays at various times for the two PCs. The dilation pulses on the two PCs were synchronized with the X-ray pulses, obtaining two gated images. The intensity distribution along the MCP was obtained from Fig. 9(b). Because of the 1:1 magnification ratio, the PC area related to the gated image is the same as that on the MCP. The dilation pulse was transmitted across the PC from left to right at a velocity of approximately $1.87 \times 10^8$ m/s, measured by the time-domain reflection method [36,37]. Subsequently, intensity with varying transmission times along the PC for the gating image was obtained from the gating image spatial distribution and PC dilation pulse velocity, as shown in Fig. 9(c). Final results were calibrated using static results from Fig. 9(a).

Fig. 9(c) shows intensity versus temporal distribution of the X-ray pulse. Solid points and lines represent experimental results and Gaussian fitting curves, respectively. Blue and red regions show results for the top and bottom PC, respectively. The FWHMs of the Gaussian-fitting curves are 21.3 ps and 20.4 ps. The two FWHMs are almost identical, with their difference within 5%. Each Gaussian fitting curve is the convolution result of the camera intensity versus time curve with the X-ray intensity versus temporal distribution. Considering that the FWHM of the camera intensity versus time curve was 10 ps, the FWHM of the temporal distribution of X-rays was approximately 18 ps from the deconvolution result, indicating that the X-ray pulse had a width of approximately 18 ps. Furthermore, Fig. 9(c) shows that the delay time between dilation pulses for the top and bottom PCs is approximately 132 ps.

## V. Conclusion

An ultrafast pulse-dilation framing camera combined with magnetic lenses was developed. The camera used a pulsed PC to achieve high temporal resolution and four magnetic lenses to improve spatial resolution, obtaining a temporal resolution of 10 ps and spatial resolution of 100  m. The spatial resolution characteristics of the camera were studied by applying different numbers of magnetic lenses. Both theoretical and experimental results showed that spatial resolution using a single magnetic lens was the worst, but improved significantly with combined magnetic lenses. The camera with four magnetic lenses exhibited better spatial resolution than other configurations. Furthermore, field curvatures of cameras with different numbers of lenses were measured, showing that the four-magnetic lens camera had lower field curvature, resulting in better spatial resolution and larger working area. The axial location of the imaging plane influenced spatial resolution uniformity across on- and off-axis areas, limiting the working area. An appropriate imaging plane was obtained for the camera with four magnetic lenses, achieving a working area with a diameter of 53 mm. The camera was used to detect X-rays, and diagnostic results indicated that the X-ray pulse width was approximately 18 ps.

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