Development of a High-Temporal-Resolution X-ray Diode

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Abstract

An X-ray diode (XRD) diagnostic system based on electron pulse time-dilation and energy compensation has been presented. A temporal magnifier is used to dilate the temporal width of the electron pulse, thereby significantly improving the temporal resolution. Energy compensation is performed using a time collimator to ensure measurement accuracy. Additionally, a time-resolved anode electron detector is applied to detect the processed electron pulse. Theoretical studies indicate that time-dilation technology can increase the temporal resolution of XRD from 125 ps to 5 ps. Experimental verification was also carried out using the Michelson interferometer method, measuring a temporal resolution of 9.1 ps for the XRD.

Full Text

Preamble

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Abstract

An X-ray diode (XRD) diagnostic system based on electron pulse time-dilation and energy compensation is presented. A temporal magnifier dilates the temporal width of the electron pulse to significantly improve temporal resolution. Energy compensation is performed using a time collimator to ensure measurement accuracy, and a time-resolved anode electron detector detects the processed electron pulse. Theoretical studies indicate that time-dilation technology can increase the temporal resolution of XRD from 125 ps to 5 ps. Experimental verification was carried out using the Michelson interferometer method, measuring a temporal resolution of 9.1 ps for the XRD.

Keywords

Inertial confinement fusion, X-ray diagnosis, Radiation flow measurement, X-ray diode

1 Introduction

Laser-driven inertial confinement fusion (ICF) represents a promising approach for converting deuterium-tritium fuel into clean and safe nuclear energy [1-5]. The ICF process lasts approximately 1-2 ns and requires measurement of transient plasma information generated by laser irradiation. Ultrafast diagnostic technology enables measurement of plasma temperature and density, providing essential data for analyzing transient fusion processes. Typical ultrafast diagnostic devices include X-ray streak cameras, framing cameras, fast scintillators, and X-ray diodes (XRDs). Streak cameras achieve temporal resolutions at the picosecond or even femtosecond level. The hardened streak camera employed by Lawrence Livermore National Laboratory (LLNL) provides approximately 30 ps temporal resolution, which has been used to measure time-resolved bremsstrahlung spectra for neutron yields of 4×10^{1} [6]. X-ray framing cameras based on electron pulse time-dilation technology can achieve 10 ps temporal resolution and operate in environments with neutron yields up to 7×10^{1} [7]. The new Single-line-of-Sight (SLOS) framing camera based on hCMOS is widely used in ICF experiments with neutron yields of 2×10^{1} and has been installed on the COMET laser facility [8]. Most practical scintillators offer temporal resolutions around 100 ps, though some materials achieve rise times as fast as 20 ps [9]. Scintillators are often combined with CCDs, streak cameras, or other devices to function as neutron detectors [10].

This paper focuses on XRDs, which sample radiation flux to acquire input signal waveforms and serve as oscilloscopes for neutron yields exceeding 10^{1} . In ICF experiments, X-ray radiation flow persists throughout the entire physical process, including hohlraum radiation flow physics and self-emission from compressed core plasma during implosion. Radiation flow measurement is indispensable for studying hohlraum radiation source intensity and temperature, implosion symmetry, and thermonuclear burn processes. XRDs are crucial ultrafast detectors for radiation flow measurement and core components of radiation flow diagnostic devices such as soft X-ray spectrometers and flat-response XRDs. A conventional XRD consists of a planar mesh anode and a gold photocathode (PC) evaporated onto a planar metal surface, with the PC connected to a coaxial cable via a conical connector for impedance matching. Currently, traditional XRDs achieve time responses of approximately 100 ps [8,11-13]. However, certain key physical processes such as the fusion burn stage last only 100-200 ps, necessitating XRDs with higher temporal resolution for burning plasma measurements.

In 2016, J. D. Hares et al. integrated electron pulse time-dilation technology into XRDs by employing a ramped cathode pulse paired with an extended drift region, establishing a transit time dependency on photoelectron emission timing and enabling development of a time-dilation XRD (TD-XRD) prototype [14]. The time-dilation mechanism applies a time-dependent ramp to a photocathode-mesh structure, generating a time-varying photoelectron accelerating potential that induces axial velocity dispersion in emitted photoelectrons. As the photoelectron pulse traverses a drift region, it undergoes temporal dilation before reaching the anode electron detector. An anode electron detector with ultrafast temporal response then measures the temporally stretched electron pulse, significantly enhancing TD-XRD temporal resolution. In 2018, S. G. Gales et al. advanced the TD-XRD system, demonstrating that electron pulse time-dilation technology improved temporal resolution from 85 ps to 20 ps [14]. In 2020, LLNL further improved TD-XRD temporal resolution to 10 ps and applied it to ICF experiments [15-17], successfully measuring a fusion burn width of 90 ps [18].

Electron pulse time-dilation produces temporal dilation while simultaneously increasing the energy of leading electrons and decreasing the energy of trailing electrons [11,19-24]. When an electron pulse with gradually decreasing energy bombards the microchannel plate (MCP), the MCP gain decreases over time because MCP gain depends on the energy of incident electrons. If two X-ray pulses with identical intensity but different emission times are diagnosed, this causes the anode output pulse amplitude to decrease gradually over time, resulting in measurement errors. To improve system measurement accuracy, enhancing MCP gain uniformity is essential. J. D. Hares applied an impulse voltage to the MCP output surface, creating an increasing voltage between the two MCP faces. This caused MCP gain to increase gradually, compensating for gain reduction caused by decreasing electron energy [24]. However, this compensation method causes electron energy to decrease gradually when reaching the anode, as the pulse voltage reduces the acceleration voltage between the MCP output surface and anode mesh over time. Electrons with decreasing energy induce current pulses with diminishing amplitude on the anode, introducing new measurement errors for incident X-ray amplitude information.

To increase MCP gain uniformity without introducing new measurement errors, this paper proposes a time collimation technique to compensate for electron energy, ensuring that electron energy incident on the MCP remains nearly constant. The time collimator consists of an input electrode and an output electrode. The input electrode, placed at the end of the drift region, features a microstrip transmission line structure, while the MCP input surface serves as the output electrode. The input electrode center is hollowed out and covered with a mesh. By applying a collimation pulse to the input electrode with the output electrode grounded, a time-varying accelerating electric field is created between the electrodes. Electrons with lower energy flying behind receive greater additional energy from the time collimator than higher-energy electrons in front, resulting in all electrons having nearly identical energy after passing through the collimator.

This paper presents a drift tube XRD diagnostic system utilizing electron pulse time-dilation and energy compensation. Theoretical analysis was performed for the drift tube XRD, and its temporal resolution was assessed. The drift tube XRD system described here differs from the TD-XRD developed by J. D. Hares et al. not only in enhancing MCP gain uniformity but also in anode electron detector design. Hares employed a conventional conical structure [11,23], using a conical piece to connect the anode with an effective diameter of 10 mm to the coaxial cable for impedance matching. This paper proposes a novel coplanar waveguide-type anode structure with broadband response, using an impedance tapered line to achieve impedance matching between the anode and coaxial cable. This optimized design significantly improves anode temporal response characteristics. The coplanar waveguide structure is typically utilized for high-frequency signal transmission, recognized for its low dispersion, wide bandwidth, and ease of characteristic impedance adjustment. Furthermore, this paper implements three independent anode structures, enabling a drift tube XRD diagnostic system to operate as three separate XRDs. This configuration extends system time recording length, improves radiation flow measurement duration, and enables simultaneous measurement at three distinct energy points. Moreover, an input signal reconstruction algorithm is proposed to overcome nonlinear dilation and inconsistent MCP gain, further improving XRD system measurement accuracy. The algorithm uses the detected anode electrical pulse signal, electron pulse temporal dilation factor D(t), and MCP gain G(t) to reconstruct the input optical signal.

In summary, this article offers several innovations compared to previous work by J. D. Hares et al. First, it proposes electron pulse time collimation technology, which compensates for electron energy loss during time-dilation. This compensation method achieves electron energy consistency to improve MCP gain uniformity and ultimately enhances system measurement accuracy. Second, it introduces an innovative anode structure design, proposing a wideband-responsive coplanar waveguide anode to achieve ultrafast time response and improved temporal resolution. By using three independent anodes, a drift tube XRD diagnostic system is equipped with three sets of XRD functions, extending radiation flow measurement duration. Third, an input signal reconstruction algorithm is proposed to further improve XRD system measurement accuracy.

2 Drift Tube XRD Diagnostic System

A schematic diagram of the drift tube XRD diagnostic system based on electron pulse time-dilation and energy compensation is shown in Fig. 1(a) [Figure 1: see original paper]. The system comprises an electron pulse temporal magnifier (including a microstrip PC, mesh 1, and electron drift region), a time collimator (consisting of an input electrode and the MCP input surface serving as the output electrode), an MCP, an anode electron detector (including mesh 2, an anode, and external circuits), a high-voltage pulse generator (producing cathode and collimation pulses), a magnetic lens, and a high-speed oscilloscope.

The electron pulse time-dilation and time collimation system consists of an electron pulse temporal magnifier, time collimator, and high-voltage pulse generator. Its function is to dilate electron pulse time width, achieve temporal dilation, and compensate energy of subsequent electrons, ensuring nearly uniform energy when all electrons are incident on the MCP. The electron pulse temporal magnifier comprises three microstrip PCs, an anode mesh, and an electron drift region. A transmissive microstrip PC structure is formed by evaporating 80 nm-thick Au onto a polystyrene film. The three microstrip PCs measure 20 mm in length and 12 mm in width, spaced 6 mm apart. Microstrip PCs serve dual functions: converting incident light into photoelectrons and functioning as microstrip transmission lines to transmit cathode pulses, thereby creating a time-varying electric field between the microstrip PC and mesh 1 (1 mm away) that results in electron pulse temporal dilation. A grounded metal nickel mesh with spatial frequency of 10 lp/mm is used. By applying a negative DC high voltage to the microstrip PC and superimposing a positive high-voltage ramp cathode pulse, a time-varying electric field is generated between the PC and mesh 1. ICF plasma X-ray pulse radiation synchronized to the cathode pulse rising edge generates photoelectrons on the microstrip PC. Photoelectrons produced at different times acquire varying energies, leading to electron velocity dispersion [24-25]. A schematic diagram illustrating cathode pulse transmission on the PC is depicted in Fig. 1(b). The cathode pulse travels from left to right on the PC, with voltage at each photoelectron emission point changing over time. As illustrated at point A in Fig. 1(b), in addition to a DC bias voltage of -2.5 kV, a cathode pulse with voltage A was superimposed at time t , and voltage A at time t . Since A exceeds A , the total voltage between point A and mesh 1 decreases over time, and the accelerating electric field gradually diminishes. Consequently, earlier-emitted photoelectrons obtain higher energy and drift at faster velocity. After drifting through the 50 cm electron drift region from mesh 1 to the time collimator input electrode, the electron pulse temporal width is magnified, achieving temporal dilation.

As analyzed above, electron energy decreases over time as the electron pulse reaches the MCP. When an electron pulse with progressively diminishing energy directly strikes the MCP, MCP gain gradually decreases over time because MCP gain depends on electron bombardment energy. If two X-ray pulses with identical intensity but different emission times are diagnosed, this causes anode output pulse amplitude to decrease gradually over time, resulting in measurement errors. To enhance MCP gain uniformity and improve measurement precision of the drift tube XRD diagnostic system, electron pulse time collimation technology is presented to offset electron energy loss. The time collimator comprises input and output electrodes spaced 1 mm apart, with the input electrode being a polytetrafluoroethylene high-frequency circuit board and the MCP input surface serving as the output electrode. Three copper microstrip transmission lines are fabricated as the input electrode on the polytetrafluoroethylene substrate, each measuring 20 mm in length, 12 mm in width, and spaced 6 mm apart. A 10 mm-diameter hole is created at the center of each microstrip transmission line and covered by a plane mesh with density of 10 lines per millimeter. The mesh connects to surrounding microstrip transmission lines, allowing the input electrode to transmit the collimation pulse while permitting electron pulse passage.

When the dilated electron pulse enters the time collimator, the input electrode begins loading a negative collimation pulse. With the output electrode grounded, a time-varying acceleration field is created between the collimator electrodes. The electron pulse synchronizes with the collimation pulse falling edge, undergoing acceleration. The energy increase for lower-energy electrons behind exceeds that for higher-energy electrons in front. By employing an appropriate collimation pulse slope, all electrons achieve nearly identical energy when reaching the MCP input surface. The collimation pulse and cathode pulse are temporally delayed, with delay approximately equal to electron flight time in the drift region. Since the input electrode only begins loading the collimation pulse when the electron pulse is about to reach the collimator, the collimation pulse' s impact on electron pulse movement in the drift region is negligible. Furthermore, the electron pulse passes through the collimator for only a few tens of picoseconds before entering the MCP, and the grounded MCP input surface acts as a shield, having almost no effect on electron multiplication within the MCP. Therefore, employing time collimation for electron energy compensation can improve MCP gain uniformity without generating new measurement errors.

Both cathode pulses applied to the microstrip PC and collimation pulses loaded onto the time collimator are generated by a high-voltage pulse generator. This generator comprises an avalanche transistor ramp pulse circuit and a field-effect transistor (FET) negative high-voltage pulse circuit. A cascaded avalanche transistor produces the fast-leading edge of an ultrafast ramp pulse serving as the cathode pulse. A Marx circuit structure composed of FETs generates a negative high-voltage pulse acting as the collimation pulse.

After exiting the time collimator, the electron pulse possesses nearly uniform energy and subsequently enters the MCP for electron multiplication. The multiplied electrons are then accelerated toward the anode electron detector by the electric field between the MCP output surface and mesh 2. An anode electron detection system, including an anode electron detector and high-speed oscilloscope, detects MCP-amplified electron pulses. The electric field between mesh 2 and the anode accelerates the electron pulse toward the anode, inducing charges on the anode and generating induced current in the output circuit. The high-speed oscilloscope records the ultrafast current pulse waveform.

The anode electron detection system comprises an anode, bias circuit, two energy storage capacitors C, mesh 2, and output circuit. The bias circuit, including a high-voltage DC power supply and 1 MΩ current-limiting resistor R, applies DC bias voltage Vb to the anode and DC voltage Vm to mesh 2. This creates an acceleration field between mesh 2 and the anode while charging two energy storage capacitors C. The energy storage capacitors store energy as charge to compensate for energy losses due to induced current during anode electron detector operation. Furthermore, capacitor C isolates bias voltage Vb from the high-speed oscilloscope, ensuring Vb is applied solely to the anode and protecting the oscilloscope. Concurrently, capacitor C acts as a short circuit for high-frequency induced current signals, channeling the downward-flowing induced current into the high-speed oscilloscope.

The anode is constructed from three Au microstrip transmission lines fabricated on a high-frequency printed circuit board. These lines measure 20 mm in length, 12 mm in width, 70 μm in thickness, and are spaced 6 mm apart, as shown in Fig. 1(c). When the electron pulse is accelerated toward the anode from mesh 2, pulse current is induced on the anode. This pulse current propagates both upward and downward on the anode with consistent waveforms. To prevent upward-propagating pulse current from reflecting and causing oscillations in the pulse voltage waveform on the oscilloscope, a 50 Ω resistor RL absorbs the upward-propagating pulse current. The downward-propagating pulse current is transmitted to the high-speed oscilloscope by the output circuit, consisting of a tapered transmission line, 50 Ω vacuum SMA connector, and coaxial cable. Due to impedance differences between the anode and SMA connector, a tapered transmission line between them ensures impedance matching during pulse current transmission, reducing pulse current attenuation. The SMA connector transfers the pulse signal from the vacuum chamber to the outside and delivers it to the 50 Ω high-speed oscilloscope via a 50 Ω coaxial cable for pulse waveform recording. With impedance matching maintained throughout the induced current path from anode to oscilloscope, the oscilloscope obtains an almost undistorted induced current waveform. Since the electron pulse is temporally dilated, the drift tube XRD diagnostic system can achieve very high temporal resolution even with a lower temporal-resolution anode electron detector.

Due to large transmission distance in the drift region, the electron pulse experiences radial space divergence. To obtain the same electron pulse spot diameter as the PC on the time collimator, a magnetic lens images the electron pulse from the microstrip PC onto the time collimator with a 1:1 imaging ratio [25-27].

3 Theoretical Research

In the anode electron detector, electrons are accelerated toward the anode by the electric field as they pass through mesh 2. The transit time of electrons between mesh 2 and the anode could be expressed as, where d represents the distance between mesh 2 and the anode, e represents electron charge, U represents DC voltage applied to mesh 2, U represents DC voltage applied to the MCP output surface, E represents electron energy as it exits the MCP, m represents electron mass, and U represents DC voltage applied to the anode.

The leading edge of the anode output pulse depends on electron transit time, whereas the trailing edge depends on discharge circuit time constant. The oscilloscope’ s equivalent resistance is 50 Ω, equal to absorption resistance RL. The anode and mesh 2 can be equivalent to capacitor Canode, thus the anode electron detection system can be equivalent to the circuit shown in Fig. 2(a) [Figure 2: see original paper].

The discharge time constants of the RC circuit, composed of Canode, 2C, 0.5RL, and Cm, are given by, = 0.5. The equivalent capacitance Canode between the anode and mesh 2 could be expressed as, where represents dielectric constant (1 for vacuum), S is relative area between anode and mesh 2, k is electrostatic force constant, and d is distance between mesh 2 and the anode.

The discharge time of the circuit is,. The temporal resolution of the anode electron detector is, = 2.75 = 0.5 퓔. The temporal resolution of the anode electron detector is simulated. In the simulation, the anode and mesh 2 are spaced 1 mm apart, with mesh 2 voltage Vm set at 1.8 kV, energy storage capacitor C at 50 pF, anode dimensions of 20 mm length and 12 mm width, and absorption resistor RL at 50 Ω. The MCP has 0.5 mm thickness, 12 m channel diameter, and 8° slant angle, with the MCP input surface grounded and output surface voltage at 0.8 kV spaced 1 mm from mesh 2. With discharge capacitance Cm connected to mesh 2 at 2 pF, the relationship between anode electron detector temporal resolution and voltage difference between anode and mesh 2 is depicted in Fig. 2(b). Temporal resolution increases with increasing voltage difference. As anode bias voltage Vb increases from 0.8 kV to 4.8 kV, the voltage difference between anode and mesh 2 increases from -1 kV to 3 kV, improving anode electron detector temporal resolution from 88 ps to 52 ps.

When discharge capacitances Cm are 10 pF and 10 nF separately, temporal resolution variation with voltage difference is shown by red and blue curves in Fig. 2(b). Furthermore, Fig. 2(b) demonstrates that smaller discharge capacitance Cm yields higher temporal resolution. With -1 kV voltage difference and Cm of 10 nF, theoretical temporal resolution is 125 ps.

To further improve temporal resolution, an electron pulse time-dilation and time collimation system is employed for the drift tube XRD diagnostic system. The temporal dilation factor of the electron pulse time-dilation system is simulated. The temporal dilation factor is primarily determined by PC bias voltage, cathode pulse rising edge slope, and electron drift region length. Electron pulse time-dilation is achieved through energy dispersion. When a linear cathode pulse is used, electron energy changes linearly, but electron velocity changes nonlinearly, resulting in nonlinear temporal dilation of electron pulse width. To improve XRD measurement accuracy, a curved pulse is necessary to drive the microstrip PC, achieving linear electron velocity change and resulting in linear temporal dilation, achieving a result where the cathode pulse has the same temporal dilation factor at each slope position [28].

When the microstrip PC is applied with a curved cathode pulse having a rising edge slope of 4.5 V/ps at the starting point and -2.5 kV bias voltage as shown in Fig. 3(a) [Figure 3: see original paper], each ramp position achieves 16× electron pulse temporal dilation factors. With a rising edge slope of 14.6 V/ps, temporal dilation factors improve to 50×.

When the electron pulse reaches the time collimator, its temporal width is magnified. The collimator' s input electrode is then applied with a collimation pulse, as depicted in Fig. 3(b), resulting in all electrons having identical energy while passing through the collimator. The falling edge slopes of -0.278 V/ps and -0.291 V/ps at the starting point correspond to 16× and 50× temporal dilation, respectively.

The temporal resolution of the drift tube XRD diagnostic system varying with cathode pulse slope is simulated. Here, an anode electron detector with 125 ps temporal resolution is used in simulation. When the microstrip PC is loaded with -2.5 kV DC voltage and a cathode pulse, the relationship between theoretical temporal resolution of the drift tube XRD diagnostic system and cathode pulse rising edge slope is depicted in Fig. 4 [Figure 4: see original paper]. As slope increases beyond 3.5 V/ps, temporal resolution improves from 125 ps to better than 10 ps. When cathode pulse slope is further increased beyond 9.5 V/ps, temporal resolution significantly improves to better than 5 ps.

4 Experimental Results

A drift tube XRD diagnostic system has been developed and its temporal resolution measured. The temporal resolution measurement employs the Michelson interferometer method, with measurement setup schematic shown in Fig. 5 [Figure 5: see original paper]. A laser outputs ultraviolet pulses at 266 nm wavelength with 130 fs width, split into two beams by semi-reflective lens BS1. One beam passes through PIN photodiode (PIN2) to output an electrical pulse sent to a high-speed oscilloscope to monitor ultraviolet laser intensity and trigger jitter between the ultraviolet laser and cathode pulse. The other beam is first reflected by total reflection mirror M2, then reaches the Michelson interferometer comprising semi-reflective BS2 and total reflection mirrors M3 and M4, producing two light pulses with adjustable time intervals. The two light pulses are sequentially reflected by total reflection mirror M5, then attenuated by neutral grayscale mirror ND. The attenuated light pulse is expanded by concave lens L to approximately 12 mm diameter and input to the microstrip PC.

The 800 nm laser pulse is reflected by total reflection mirror M1 and directed into PIN1 photodiode to generate a trigger signal, which is delayed and used to trigger the high-voltage pulse generator to produce four pulses. Three serve as cathode pulses, and the other is sent to the oscilloscope to monitor trigger jitter between the ultraviolet laser and cathode pulse. Circuit delay is adjusted to synchronize arrival time of the 266 nm light pulse and cathode pulse at the microstrip PC, after which electron pulse temporal width is dilated. This state is referred to as electron pulse dilation mode for the drift tube XRD diagnostic system. The system' s ultrafast pulse signal output is detected by a high-speed oscilloscope. With mirror M3 fixed, mirror M4 is mounted on a high-precision displacement stage to adjust its position, thereby adjusting time interval between the two light pulses. If the time interval between the two light pulses exceeds system temporal resolution, the oscilloscope output electrical pulse exhibits two peaks. By reducing optical path difference, system temporal resolution is obtained according to the Rayleigh criterion. When the microstrip PC is biased with DC voltage without a cathode pulse, the drift tube XRD diagnostic system operates in electron pulse non-dilation mode, allowing measurement of anode electron detector temporal resolution.

When the microstrip PC is biased with -2.5 kV DC voltage without cathode pulse, the electron pulse does not undergo temporal dilation. The anode output electrical pulse waveform detected by the oscilloscope is depicted in Fig. 6(a) [Figure 6: see original paper], showing a pulse width of approximately 150 ps. Consequently, without electron pulse time-dilation technology, system temporal resolution is measured to be approximately 150 ps, representing the temporal resolution of the anode electron detector.

In the experiment measuring drift tube XRD diagnostic system temporal resolution in electron pulse dilation mode, the microstrip PC is biased with -3 kV DC voltage and a cathode pulse with 4.5 V/ps rising edge slope. Two optical pulses with 50 ps time interval from the Michelson interferometer enter the system simultaneously. When optical pulses are synchronized approximately 200 ps relative to cathode pulse starting time, the XRD diagnostic system dilates the two optical pulses, with output electrical pulse waveform shown in Fig. 6(b). The time interval between the two optical pulses is magnified to 800 ps, achieving a temporal dilation factor of approximately 16× through electron pulse time-dilation technology.

The input signal reconstruction algorithm based on electron pulse temporal dilation factor D and MCP gain G is schematically illustrated in Fig. 7(a) [Figure 7: see original paper]. Δt represents the time interval between each pair of points in the pulse signal recorded by the oscilloscope, and V is the voltage value at a certain moment on the pulse signal. The , , respectively represent the three steps of the input signal reconstruction algorithm. The cathode pulse used for pulse dilation and the electron pulse temporal dilation function D(t) are shown in Fig. 7(b). The relationship between normalized MCP gain and electron energy is depicted in Fig. 7(c). The MCP gain function G(t) is shown in Fig. 7(d).

In this experiment, photoelectrons converted from the input signal undergo processes within the drift tube XRD diagnostic system including electron pulse temporal dilation, MCP gain, and pulsed current generation at the anode followed by output. The input signal can be reconstructed using detected electrical pulse signals, electron pulse temporal dilation function D(t), and MCP gain function G(t). The input signal reconstruction algorithm comprises three steps, as illustrated in Fig. 7(a). First, the time interval Δt between each pair of points in the pulse signal recorded by the oscilloscope is divided by the corresponding electron pulse temporal dilation factor D, while the corresponding vertical coordinate voltage value remains unchanged, thereby compressing the pulse signal time axis to the time scale of the input signal without temporal dilation. Second, the voltage value of each point in the time-compressed pulse signal is multiplied by the corresponding electron pulse temporal dilation factor D. Third, the voltage value of each point in the pulse signal obtained in the second step is divided by the corresponding MCP gain G, thus obtaining the input signal waveform.

When the cathode pulse shown by the red curve in Fig. 7(b) is employed, the electron pulse temporal dilation function D(t) can be derived from the electron pulse temporal dilation model as illustrated by the blue curve in Fig. 7(b). Electron energy gradually diminishes as time increases during electron pulse temporal dilation, leading to decreased secondary electron production when electrons strike the MCP over time, causing MCP gain to decline gradually. The relationship between normalized MCP gain and electron energy was measured, as depicted in Fig. 7(c). The energy of electrons emitted at different times when reaching mesh 1 can be obtained from Fig. 7(b). Consequently, the MCP gain function G(t) can be achieved as shown in Fig. 7(d).

Using the input signal reconstruction algorithm depicted in Fig. 7, along with electron pulse temporal dilation factor function D(t) and MCP gain function G(t), the electrical pulse waveform output by the system in Fig. 6(b) was reconstructed to obtain the input signal waveform. This effectively compresses the pulse time axis back to the original time scale prior to magnification, with resulting input signal waveform displayed in Fig. 8 [Figure 8: see original paper]. Post-decompression, the two pulse widths measure 9.9 ps and 9.1 ps, respectively. Consequently, with electron pulse time-dilation technology implementation, drift tube XRD diagnostic system temporal resolution was enhanced from 150 ps to superior resolution of less than 9.1 ps. Furthermore, Fig. 8 shows that the time interval between the two input signals is 51 ps, only a 2% difference from the 50 ps gap of the two optical pulses output from the Michelson interferometer.

5 Conclusion

This paper presents a drift tube XRD diagnostic system exploiting electron pulse time-dilation and time collimation. It enhances temporal resolution by employing a temporal dilation system to stretch the electron pulse. The temporally dilated electron pulse is then energy-compensated by a time collimation system. Finally, the dilated electron pulse is measured with an anode electron detector. Theoretical studies suggest the anode electron detector has approximately 125 ps temporal resolution. When a cathode pulse with 3.5 V/ps slope excites the microstrip PC, the drift tube XRD system achieves temporal resolution better than 10 ps. As slope further increases beyond 9.5 V/ps, temporal resolution significantly improves to better than 5 ps. A drift tube XRD diagnostic system has been developed and its temporal resolution measured. Its input signal reconstruction algorithm has also been studied. Based on experimental results, a temporal resolution of approximately 9.1 ps was demonstrated for the XRD diagnostic system. Future research will focus on using curved cathode pulses to achieve linear temporal dilation of the electron pulse and applying electron pulse time collimation technology to compensate electron energy and enhance MCP gain uniformity.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of Interest

The authors have no conflicts to disclose.

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