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Development of an Ultra-Fast Photomultiplier Tube With Pulse-Dilation Technology

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ABSTRACT A pulse dilation photomultiplier tube (PD-PMT) has been developed. The photoelectrons energy is modulated by a time-dependent electric field between photocathode and ground mesh. Then, the photoelectron pulse is dilated as it transits in a relatively long drift region from mesh to microchannel plate (MCP). The dilated electron pulse is gained by the MCP and then detected by the output collector. Because the temporal width is magnified, the temporal resolution of the photomultiplier tube is better than that of the output collector alone. The result shows that the temporal resolution of the detector is improved to be 25 ps by using pulse-dilation technology, which is much better than 300 ps temporal resolution while without pulse-dilation. The ramp electrical pulse dilates the electron signal to improve the temporal response by about 10 times.

INDEX TERMS UV detector, pulse dilation photomultiplier tube, magnetic lens, temporal resolution, stretching ratio.

I. INTRODUCTION

Microchannel plate based photomultiplier tubes (MCP-PMTs) are a well-established instrument for the inertial confinement fusion (ICF) experiments [1], [2]. Combined with pump detection and compressed sensing technology [3] MCP-PMTs can also be used to explore the surface plasmons waveguides [4]–[6]. The implosion burn widths are typically 150 ps and are expected to drop as performance improves [7]. These optical signals derived from the imploding core plasmas can be recorded with MCP-PMTs but temporal resolution is limited to around 100 ps [8]. There are two aspects to have a significant influence to temporal resolution of the PMTs. One is the size of active area and the other is the design of the tapered 50Ω transmission line connecting the collector to the SMA output connector. The best temporal resolutions were obtained about 110 ps, 450 ps with a smaller and larger active area MCP-PMTs, respectively [9], [10]. In order to improve temporal resolution further, a pulse dilation technique has been used in the fast detectors [11]–[14]. Prosser first proposed the technique for increasing the bandwidth of electronic detectors by modulating electron beam velocity [15]. The pulse dilation technique is a method for slowing down an electronic signal using velocity dispersion of electrons in a vacuum drift tube. This technique converts a short-lived temporal history to a longer time scale fora limited time. A pulse dilation MCP-PMT with temporal resolution of sub-20 ps has been developed by S. G. Gales, and this detector has been used at the National Ignition Facility to improve the diagnosis of nuclear fusion burn history and the areal density of the remaining capsule ablator [11].

In this paper, a MCP-PMT detector is presented to measure the ultrashort UV laser pulse. To make the experiment easier our standard pulse dilation framing tube is modified by removing the phosphor screen and coupling with a strip line electron collector [12], [14].

II. DETECTOR DESCRIPTION

The detector shown in Fig.1(a) consists of basic components: a transmission gold photocathode (PC), ground mesh drift tube, magnetic lens, MCP, high voltage fast ramp pulse generator and charge collector. Fig.1(b) is the photograph of the

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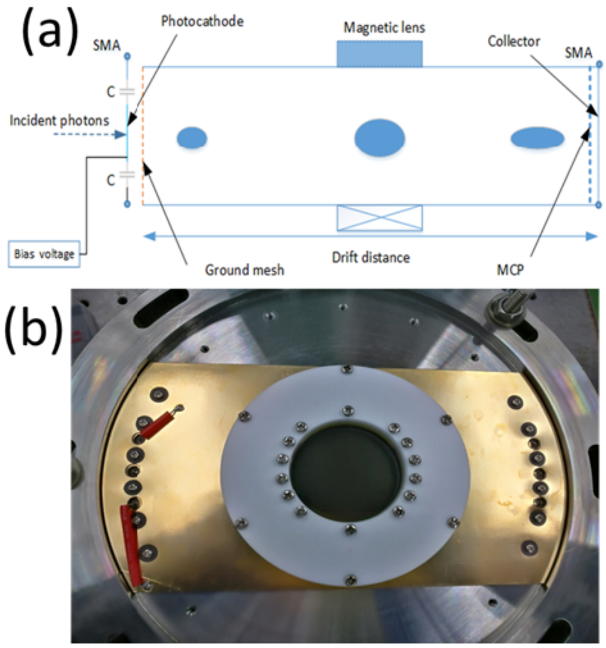

FIGURE 1. **(a) Schematic diagram of the detector. (b) Photograph of the MCP.**

MCP. The PC, ground mesh, drift tube, MCP and collector are located in a high vacuum chamber. The transmission photocathode with a microstrip line structure is coated with a 800 nm thick layer of Au on a fused silica substrate. The width and length of the microstrip line are 8 mm and 35 mm, respectively. A 1mm accelerating gap is formed between the PC and the mesh. The nickel mesh is 20 lp/mm and the open area is 60%. The drift distance is 490 mm from the ground mesh to the MCP. The MCP is 0.5 mm in thickness and 56 mm in diameter with microchannel holes diameter of 12 μm and a bias angle of 6°. The input and output surfaces of the MCP are coated with 500 nm Cu overlaid by 100 nm Au. A microstrip line charge collector with about 50Ω impedance is fabricated on a printed circuit board (PCB) of 0.5 mm thickness. The width, length, and thickness of the microstrip line are 2 mm, 200 mm, and 3 μm, respectively. The distance from the output surface of the MCP to collector is about 1 mm. The electrodes of the photocathode and collector are connected with vacuum sealed SMA connectors. Two capacitors ($C = 470$ pF) are connected in the broken taped photocathode electrodes to block DC bias voltage. An axi-symmetric magnetic lens with 16 cm inner diameter and 10 cm axial length is placed on the outer surface of the drift tube. The magnetic lens has a soft iron shield enclosing the outer surface of the coil windings, with a lens gap of 4 mm in the inner circumference.

In the pulse dilation MCP-PMT, the photoelectrons produced by the UV sensitive photocathode are accelerated by a negative DC high voltage overlap by a positive ramped pulse between the photocathode and the anode. Electrons emerging early from PC are accelerated by a higher voltage than electrons emerging late. This results in that the electron bunch dilates in time axis during travelling in long drift region. The photo-electrons are focused on MCP by a magnetic lens. After amplified by MCP, the electron signal is collected by the charge collector and measured by an oscilloscope with 6 GHz bandwidth (SDA 760Zi-A LeCroy).

III. EXPERIMENT

The experimental setup of the temporal resolution measurement is shown in Fig.2. The Ti-sapphire laser outputs two laser beams with wavelengths of 266 and 800 nm. The 800 nm laser pulse width is about 130 fs. A Michelson interferometer is used to generate two 266 nm UV laser pulses with variable interval time. The 266 nm laser pulses illuminate PC to create photoelectrons The 800 nm laser pulse is used to illuminate the $p-i-n$ detector to generate synchronization electrical pulse The electrical pulse is delayed by the delay circuit and then used to trigger the high voltage pulse generator to produce a fast ramped pulse to drive the strip line PC electrode from one side, another side of strip line PC electrode is connected with an absorbing resistor($R1=50\Omega$). This results in a time varying electric field between the PC and ground mesh to dilate the electron bunch as described above. The laser spot size on the photocathode is about 2 mm in diameter. The electron image magnification ratio from the PC to MCP is set to 1:1 with the magnetic lens.

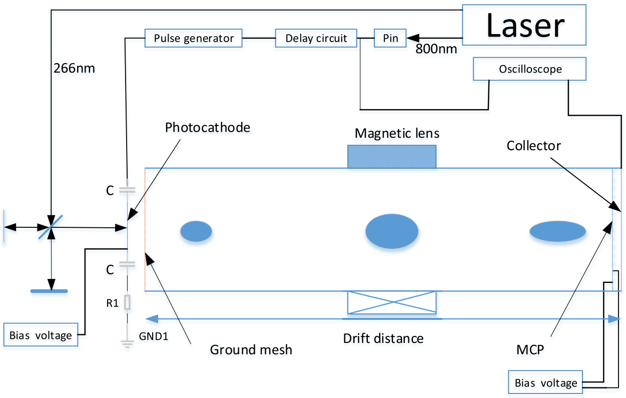

FIGURE 2. **The experimental setup of the temporal resolution measurement. The electron signal is axially dispersed as it transits the drift tube.**

The interval time of the two UV pulses from Michelson interferometer is set to 75 ps. The pulses energy is about 10μJ, 30μJ, respectively. While the bias voltages of PC, MCP input surface and MCP output surface are -3kV, -775 V and 25 V, respectively, the output waveforms of collector without pulse dilation are shown in Fig.3. The pulse from ARM1in Michelson interferometer (red line) comes earlier than that from ARM2 (black line) by 75 ps. The pulse waveform (blue line) is result of the two pulses overlapped. It is clear that the two pulses cannot be resolved. The pulse widths of ARM1 and ARM2 are 261ps, 392ps, respectively. The pulse width of ARM1 is much shorter than that of ARM2. It believes that is due to the space charge effect. It means

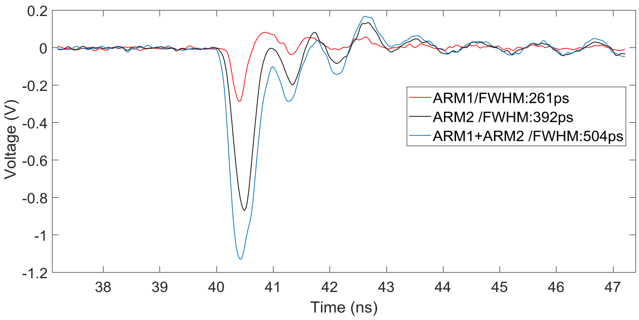

FIGURE 3. **Collector output signal without dilation pulse.**

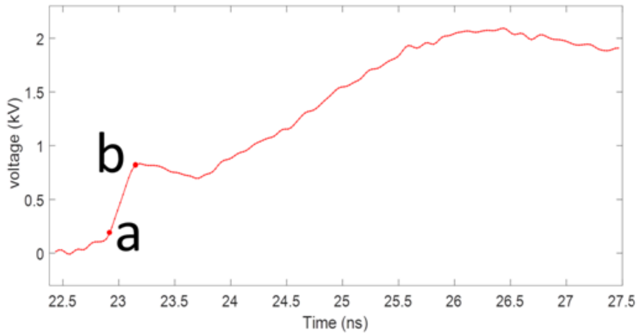

FIGURE 4. **Waveform of the high voltage fast ramped pulse applied on the PC. The time between points b and a is about 200 ps, the voltages amplitude of b and a are 775 V and 175 V respectively.**

that temporal resolution of the MCP-PMT is about 300 ps while the pulse dilation technique is not used. The pulse amplitude of ARM2 is three times greater than that of ARM1. There are some ringing noises at the end of main pulse. The ringing period time is about 850 ps. It is caused by the impedance mismatch between the two vacuum feed through SMA connectors located in both sides of strip line collector

The pulse generator produces positive pulse which is used to drive the gold PC [16]. The pulse wave form to drive the PC is shown in Fig.4. The time between point *a* and *b* is about 200 ps and the voltage is about 600 V The ramped pulse slope is 3V/ps approximately. This part is used to dilate an electron bunch. The ramped high voltage pulse governs the time of the useful dilation window and stretching ratio.

The electron bunch stretching ratio is determined by three factors: the PC bias voltage, the gradient of the PC driving pulse and the drift length. In the limit of small accelerating gap, ignoring any birth energy spread and space charge effect, the photoelectron enters the drift region at time t_i and reaches the MCP input surface at time t_i':

$$t' = d/\sqrt{2eu_i/m} + t_i \tag{1}$$

where m is the electron mass and e is the electron charge. u_i is the cathode voltage at the moment when the front end of the electron beam enters the drift region. d is the length of the drift region.

The time at which the front end and the end of the electron beam enter the drift region are t_1 and t_2, respectively.

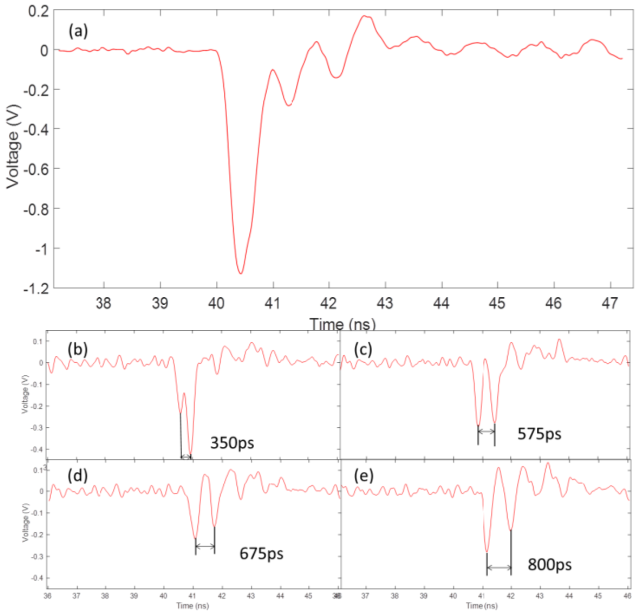

FIGURE 5. **MCP-PMD output. (a) The laser pulses arrive before the ramp pulse, (b)(e)the dilation progresses as the laser pulses move through the ramp pulse.**

The stretching ratio M when the electron beam reaches the input surface of MCP is [17]–[19]

$$M = \frac{t_2' - t_1'}{t_2 - t_1} = 1 + \frac{d}{t_2 - t_1}\left\{\frac{d}{\sqrt{2e/m}}\left(\frac{1}{\sqrt{u_2}} - \frac{1}{\sqrt{u_1}}\right)\right\} \tag{2}$$

$$u_2 = u_1 - k(t_2 - t_1) \tag{3}$$

where k is the gradient of the ramp pulse unit in V/ps.

The PC potential is about −3.0kV, the ramp pulse gradient is 3 V/ps, the length of the drift is 490 mm. The voltage at point a of the ramp pulse is about 175 V. When the two UV laser pulses with interval time of 75 ps are synchronized between point *a* and *b* on the ramp pulse, the stretching ratio of interval time between the two pulses can be estimated to be 9∼13 times.

While the cathode bias voltage is −3kV, the MCP input surface bias voltage is −775 V, the output surface bias voltage is 25V, and the ramp pulse is applied on the PC, the collector output signal is shown in Fig.5In Fig.5(a), the collector signal is measured while the ramp pulse comes later than the laser arrival, therefore the electron pulses are not dilated. In Figs 5(b)-(e), the laser pulses are synchronized with the ramp dilation pulse at different region while the delay time is changed. It is clear that stretching ratio varies with synchronization point between the laser pulses and the ramp pulse. The interval times of the two electron pulses in Fig.5 (b)(e) are 350 ps, 575 ps, 675 ps and 800 ps respectively. The maximum stretching ratio of the two pulses can be calculated to be 10.6 times.

Since the stretching ratio is nonlinear in the dilation time window, a correction has been made with a program in our

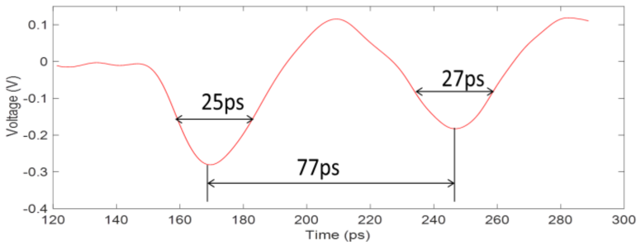

FIGURE 6. **The dilated pulses recompression temporally.**

test condition. The dilated output signal from collector can be recompressed according to the different stretching ratio in the dilation time window. Three pieces of information are needed to reconstruct the input signal from the output signal: the dilation factor, the MCP gain factor, and the impulse response function (IRF) of the MCP The imprint of the MCP-IRF on the dilated signal is minimal and a deconvolution is unnecessary. MCP gain factor at different electron energies has not been accurately measured. So the pulse recompression is limited to the time axis. Fig.6 shows the pulse recompression result of Fig.5 (e). The interval time of the two pulses is about 77 ps (interpolation was implemented between the reconstructed data points). The two pulse widths are almost same around 25 ps and much less than that without dilation shown in Fig.3. These mean that space charge effect is reduced and the temporal resolution of MCP-PMT is improved to 25 ps by using the pulse dilation technique.

IV. CONCLUSION AND DISCUSSION

A ultra-fast photomultiplier tube using the pulse-dilation technology has been developed. The pulsedilation is helpful to magnify the temporal width of the electron pulse and reduce the space charge effect in short electron bunch during travelling in the long drift region. There, the temporal resolution could be improved. The temporal resolution is measured by a short UV laser pulse, which shows that a temporal resolution of better than 25 ps is achieved. The pulse-dilation allows the temporal response to be improved by 10 times It should be noted that the temporal resolution obtained here is a semi-experiment result, because that a calculation of the pulse recompression are introduced in the data processes. The collector output signal exhibits some ringing at the end of pulse and it will influence the precision of results. The future work will be focused on the pulse ringing reduction and the stretching ratio improvement.

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