Analysis for Improvement of Simultaneity of Shuttering in an Ultra High-Speed Framing Camera

Y. Ito, Y. Katoh, M. Kagata, S. Tomioka, and T. Enoto

***Abstract*—We suggest a method to improve the shuttering characteristics of an ultra high-speed camera that consists of a proximity focused image intensifier with a micro channel plate (MCP) and an external transparent electrode (ETE). Over a range of the gating times of the several tens of picoseconds, using this apparatus, there are two obstacles to the system's simultaneity, i.e., accuracy of photographing phenomena. First, the time required for the shuttering pulse to propagate on the electrode creates a time delay between different areas of the image photons passing through the ETE. Second, the photoelectrons do not reach the MCP simultaneously. If we attempt to speed-up the gating time using nonlinear operation of the MCP, the latter problem has an undesirable effect on the resulting image. Our proposal is to compensate for the latter problem and improve the simultaneity of the arrival time of photoelectrons at the MCP input surface by controlling the electric field between the photocathode and the MCP. This is achieved by optimizing the shape of the electrode. Further analysis by FDTD and an electron trajectory tracking method verified that the variance of arrival time is reduced from 30 ps to 5 ps with the altered electrode shape.**

***Index Terms*—Cameras, FDTD methods, microstrip, particle tracking, photomultipliers.**

I. Introduction

THE taking of measurements from two-dimensional images is an essential method in many fields. Ultra high-speed cameras with a micro channel plate (MCP) are used for measurements of various high-speed phenomena. Utilizing the x-ray region, such cameras are used in examining inertial confinement fusion targets [1]–[4], taking synchrotron radiation measurement [5], measuring the size of a pinched relativistic electron beam to clarify the mechanism of production of the ion beam [6], and taking beam profile measurements of a linac. In the visible light region, it is used in many fields to record various phenomena, like the combustion process, discharge phenomena, fracture events, etc. In this paper, we focus on the shuttering characteristics of an ultra high-speed framing camera using a proximity focused image intensifier (PFII) in the visible light region.

There are two different types of the ultra high-speed cameras, the framing cameras and the streak cameras. The latter has a superior temporal resolution compared to the former. At the present, the limit of the time resolution of the streak camera is several hundred femtoseconds. It is possible to record the two-dimensional images using a multi-imaging streak camera [7]. Though the limit of the time resolution of the framing camera is about 30–40 ps [1], the spatial resolution is significantly better than that of a multi-imaging streak camera. The time resolution of the x-ray spectrum ultra high-speed framing camera used for diagnosing laser-driven implosions is 40 ps–80 ps time resolution using the nonlinear operation of the MCP [4]. The technique using this operation is needed for speedup of gating time, because it is difficult to generate an ultra high-speed pulse with the high-voltage (e.g., 10 ps FWHM, 1000 V). Over a range of the gating times of the several tens of picoseconds, we can not disregard the difference of the temporal information in each place of the image, which is generated due to the time delay of the gating pulse as it propagates on the electrode. In other words, the simultaneity of the image is not maintained. For the same reason, a difference of the arrival times of the photoelectrons at the MCP input surface is also generated, and this has a negative effect on the nonlinear operation of the MCP. These two problems have not been clearly defined or treated up to the present since the effects were previously considered negligible in the range of sub-nanoseconds time resolution. In this paper, we propose to improve the simultaneity of the arrival time of the photoelectrons by controlling the acceleration electric field, and analyze the numerical model of this camera.

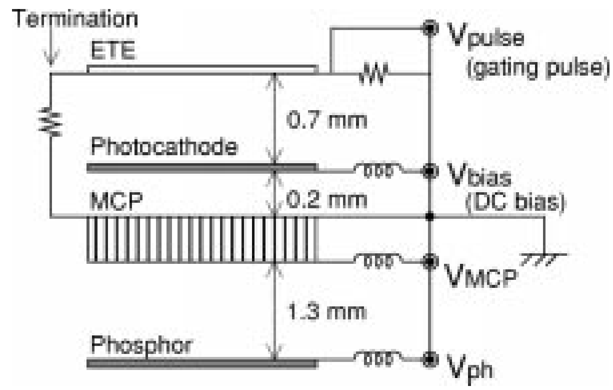

Fig. 1. Schematic of PFII with ETE.

II. Principle of Apparatus

Generally, the temporal resolution of the framing-camera with PFII is determined by the propagation characteristics of the gating pulse. Fig. 1 shows a schematic of the device. PFII consists of a photocathode, a MCP and a phosphor. We briefly explain the principles of operation of the PFII. An incident image of the visible light is converted to an equivalent image

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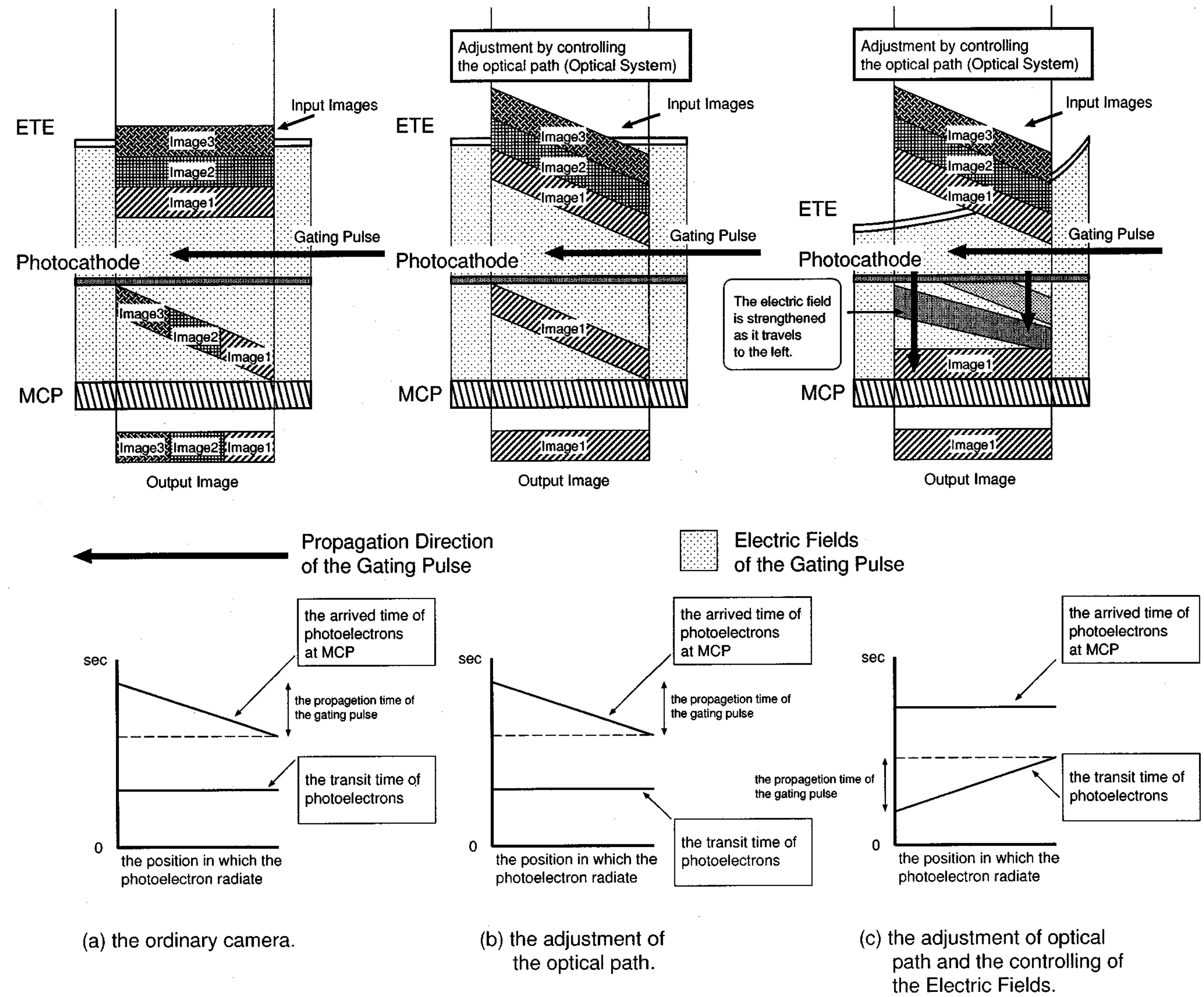

Fig. 2. Schematic of the proposal to improve the shuttering characteristics of the ultra high-speed framing camera with ETE.

of photoelectrons by the photocathode. These photoelectrons are amplified in the MCP, further the amplified image is reconverted to an image of the visible light spectrum by the phosphor screen. To reduce the surface resistance and the capacitance that prevent the propagation of the gating pulse, we apply an external transparent electrode (ETE) to PFII [8]. The gating pulse is applied between the ETE and the MCP.

Because of the time delay of the shuttering pulse, it is not possible to maintain simultaneity in two meanings as described in the introduction. A detailed description of the reason to maintain the simultaneity of the arrived time of the photoelectrons which reach the MCP input surface is given below.

The purpose of this study is the improvement on the temporal characteristics using a nonlinear mode of operation of the MCP. The MCP consists of a large number of micro-channels that operate as an electron multiplier. The pulse of photoelectrons gated by the electrically controlled shutter pass into the channels of the MCP, then the nonlinear operation of the MCP shortens the pulse width. For this operation, it is necessary that each channel of the MCP is treated as an individual avalanche phenomenon occurring simultaneously. The photoelectrons are assumed to pass into each channel of the MCP at the same time to remove the interference among neighboring channels. In our study, we attempt to control the electric field between the photocathode and the MCP to adjust the time at which photoelectrons arrive at the MCP. This is achieved by altering the shape of the electrode on which the gating pulse propagates. By optimizing the electrode shape, the characteristics of nonlinear mode operation of the MCP are improved significantly. To maintain the simultaneity of the time at which electrons arrive at the MCP, we alter the shape of the microstrip line of the ETE.

III. Simultaneity of Arrival Time of Photoelectrons

The proposal described in this paper is schematically shown in Fig. 2(a)–(c). The ordinary camera which consists of the PFII and ETE is shown in Fig. 2(a). This example considers input images which change at intervals of 100 ps, while the propagation

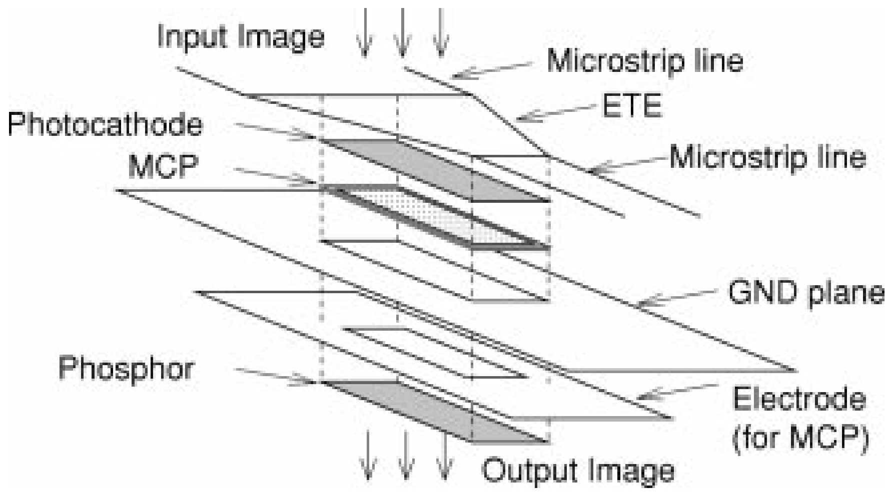

Fig. 3. 3D-model. (Each part is spaced as Fig. 1).

time of the gating pulse is 300 ps. (Each image is corresponding to "Image1," "Image2," and "Image3" in Fig. 2. The incident image is assumed to be parallel light in the visible light region.) The aim is to obtain "Image1" by applying the gating pulse of the 100 ps width. However, in Fig. 2(a), when the pulse has propagated across 1/3 of the electrode, the image which is converted in the photocathode changes from "Image1" to "Image2." Therefore, it is not possible to obtain "Image1" in Fig. 2(a). Instead, the resulting image consists of a mixture of the three images. It is shown as the output image in Fig. 2(a). The simultaneity of the spatial image is not maintained, which is the first problem we have described earlier in this paper. This problem can not be disregarded if the propagation time of the gating pulse is near to the time in which the targets change. In this region ($<$ about 100 ps pulse width), it is not possible to consider that we can obtain a faster image simply by applying a shorter gating pulse. On the other hand, the flight time is constant for all photoelectrons to travel from the photoelectrode to the MCP input surface in Fig. 2(a), (b), but all photoelectrons will not be released simultaneously, due to the gating pulse delay. Thus, the photoelectrons will reach the MCP input surface with linearly increasing delay, in direct relation to the time required for the gating pulse to propagate across the ETE. This is the second problem described earlier in this paper.

To attain the simultaneity of the image, we adjust the optical path in each point by correcting the optical system. As the result, we can get "Image1" as the shuttering image in Fig. 2(b). However, the simultaneity of the arrival time of the photoelectrons is not achieved yet, because the flight time for all photoelectrons to reach the MCP input surface is still constant for all points. As described in the Section II, to improve the characteristics in nonlinear mode operation of the MCP, it is necessary to eliminate the time difference in which photoelectrons radiated onto each area of the photocathode arrive at the MCP input surface. For that purpose, we alter the shape of the electrode (ETE) in order that the acceleration of the electric field is strengthened as it travels to the left. This is shown in Fig. 2(c). The purpose is to cancel the linear delay in the arrival time of photoelectrons by controlling the transit time of photoelecrons. As the result, the photoelectron in each area arrives at the MCP in the same time. In Fig. 2(c), the two problems outlined indicate in this paper have both been corrected. Below, we describe the method of maintaining the simultaneity of photoelectrons arriving at the MCP. The shape of the microstrip line of the ETE must be altered in such a way that the electric field intensity gradually grows as the gating pulse propagates. Thus photoelectrons which are radiated later can catch up with photoelectrons which are radiated earlier. Accordingly, the shape and the voltage are chosen to adjust the time at which photoelectrons arrive at the MCP in order to maintain the simultaneity of the arrival time. Therefore, we used the finite-difference time-domain (FDTD) method [9] to numerically model the pulse propagation and transient response of the electric field on the gating electrode of the camera in order to estimate the simultaneity. The transit time of each electron is calculated from the electron trajectory tracking method.

IV. Model of Calculation

We assume the 3D-model as shown in Fig. 3 which is the microstrip line structure in a tapered configuration. The photocathode is floating with respect to gating pulse in this model, and the accelerating electric field is only controlled by the shape of the ETE.

For practical reasons, it is necessary to simplify the calculation model in order to reduce the computational time per iteration. We analyze this problem with a 2D-model (Fig. 4) using FDTD. This approximation is possible when the analysis is focused on the two factors of propagation velocity and impedance. The results can be used qualitatively to estimate the improvement of the simultaneity of transit time. The transit time is calculated at every time-step using the electric field which accelerates photoelectrons. In this analysis, photoelectrons have an initial velocity, and the distribution of velocity and radiation is neglected. and the electron which return to the photocathode is absorbed. The gating pulse is applied to the right side of Fig. 4, and it propagates to the left side. The absorbing boundary condition is Mur's 1st-order condition [10]. The surrounding space other than the electrode surface is treated as a vacuum, and the photocathode and ETE are treated as dielectrics which have surface

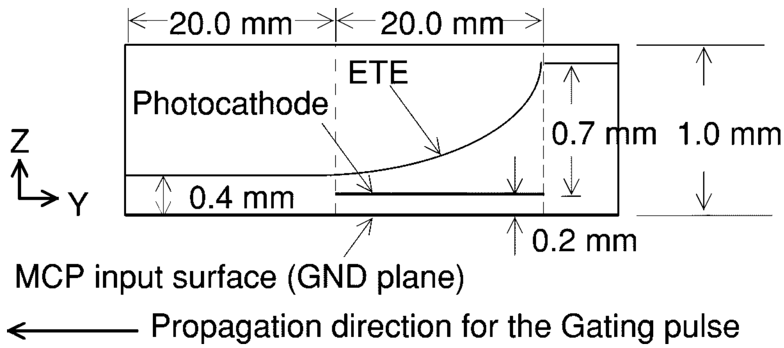

Fig. 4. 2D-model of the calculation by FDTD.

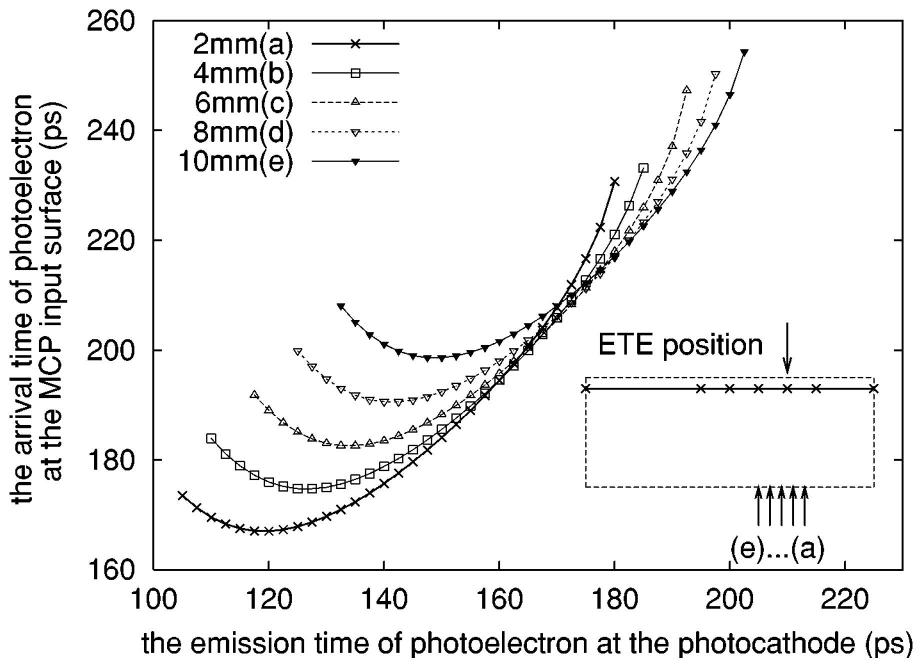

Fig. 5. The analytical results without the taper configuration. (The distance from the right end of the MCP to the locations at which each photoelectron arrives is shown in the legend.)

resistance. The inverse DC bias applied between photocathode and ground plane is treated as the initial value of FDTD.

The configuration of microstrip line tapering is decided by the linear interpolation of 5 points. To decide the best configuration is an inverse problem of searching for the optimum solutions among 6 parameters which consist of the position on 5 points of the ETE and the inverse DC bias voltage. In this article, we obtain the appropriate parameters by simple iterative calculations attempted while changing the value of the parameters each time. This shape of the ETE is not the optimized shape, though it is considered to be a good approximation.

V. Result of Calculation

The computation results for the Gaussian pulse (−900 V amplitude, 100 ps FWHM) with and without the tapered configuration are shown in Figs. 5 and 6, respectively. These express the relation between the emission time of photoelectrons at the photocathode and the arrival time at the MCP input surface, also the configuration of the ETE is shown in the lower right in these figures. The distance from the right end of the MCP to the locations at which each photoelectron arrives is shown in the legend of the figures. 540 V and 720 V are the inverse DC biases used for the cases of Figs. 5 and 6,respectively. The figures clearly show that the transit time increases in direct relation to the propagation of gating pulse in Fig. 5. On the other hand, in Fig. 6, the difference of the arrived time is less than 5 ps because of the controlled electric field. (i.e. optimized microstrip line shape).

VI. Conclusion

This paper proposes a method to maintain the simultaneity of the arrival time of the photoelectrons at the MCP input surface in the shutter mechanism of a high-speed framing camera by precisely controlling the electric field between the photocathode and the MCP, and also by altering the shape of the ETE to control the flight time of the photoelectrons. We demonstrate that this method is practical, and that the combined use of FDTD and the electron trajectory tracking method are effective means to achieve the required level of control. As the shape of the electrode can be easily altered by using an ETE, further research will

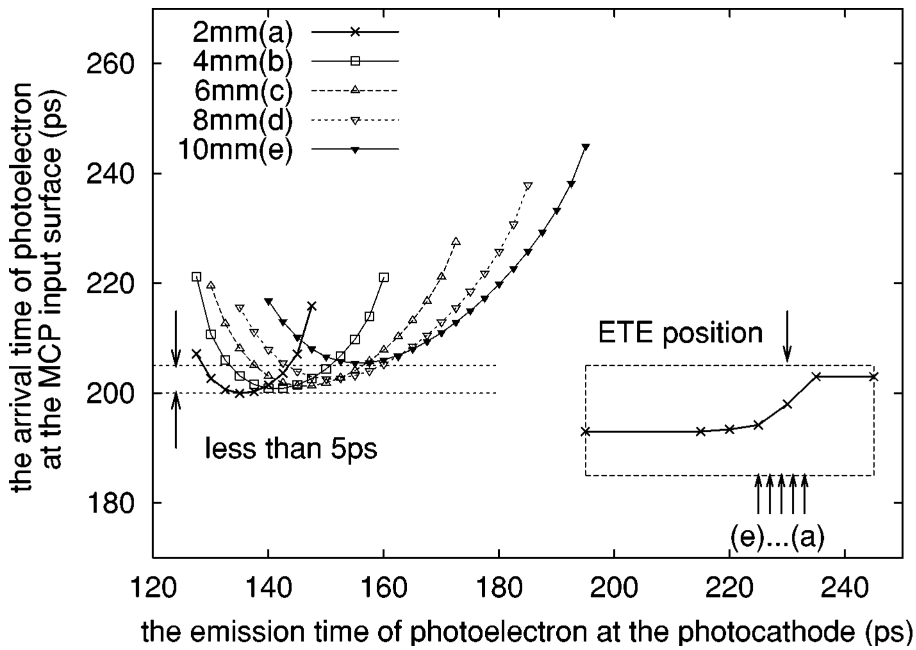

Fig. 6. The analytical results with the taper configuration. (The distance from the right end of the MCP to the locations at which each photoelectron arrives is shown in the legend.)

be necessary to develop an appropriate algorithm to optimize the electrode shape.

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