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A two-dimensional position-sensitive ion detector based on modified backgammon method with weighted-coupling capacitors

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Abstract

Properties of a two-dimensional position-sensitive charged-particle detector based on “modified backgammon method with weighted-coupling capacitors (MBWC)” are described. Procedure to optimize its position resolution and image linearity is discussed. (Int J Mass Spectrom 215 (2002) 141–149) © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

A microchannel plate (MCP) is a glass plate having many regularly and densely spaced holes each of which acts as a channel electron-multiplier. An assembly of two or three MCPs and a suitable readout anode serves as a charged-particle detector with unique properties, i.e., position sensitivity with resolution of the spacing of holes, and sub-nanosecond timing resolution. These properties are realized only when the adopted readout anode has such capabilities, and the performance in each property also depends on the readout anode. Many techniques for this anode have been developed. Among them the modified backgammon method with weighted-coupling capacitors (MBWC) method, first suggested and developed by Mizogawa et al. [1–3], has several advantages: (1) two-dimensional position-sensitivity with essentially distortionless image, (2) relatively few readout signals, (3) fast and simultaneous rise of signals and thus good timing property, (4) good position resolution, and (5) simple structure and economy in manufacturing.

One of the preceding techniques, i.e., the wedge and strip (W&S) method [4] may share these features, but the MBWC method is superior to the W&S method at least in the above points (4) and (5). In fact we have shown that each of the channels on the first-stage MCP of a tandem-MCP-based detector is clearly resolved by an MBWC anode [3].

To attain the maximum performance of the MBWC anode, however, we should adopt several precautions for the problems caused by the nature of an MCP, which may need further study. For some conditions we have studied such problems and given a brief report

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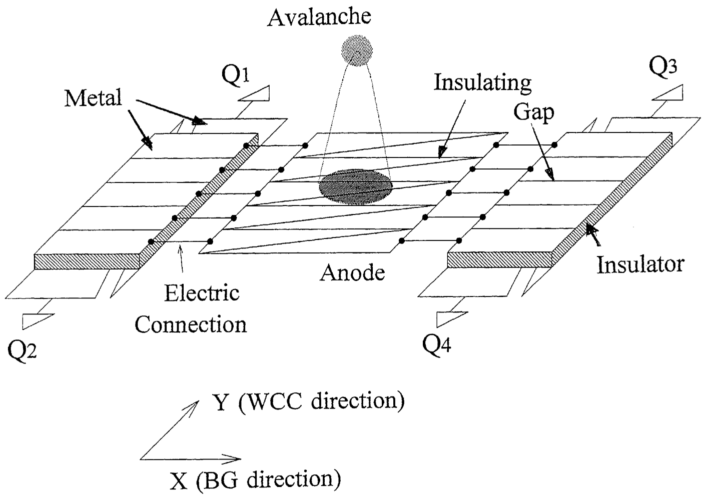

$$X=\frac{Q_3+Q_4}{Q_1+Q_2+Q_3+Q_4}, \quad Y=\frac{Q_1+Q_3}{Q_1+Q_2+Q_3+Q_4}$$

Fig. 1. Function of the MBWC anode.

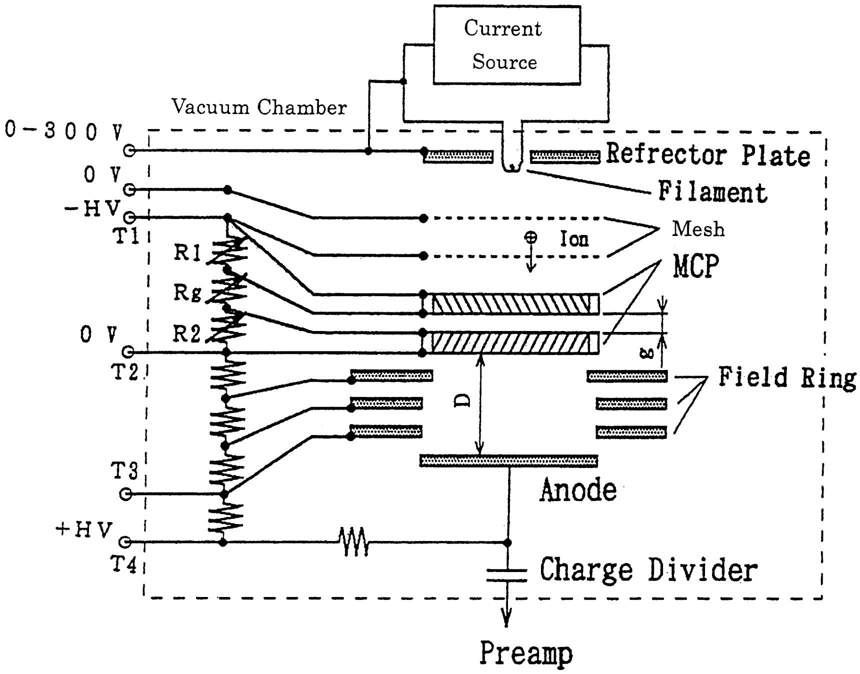

Fig. 2. MCP–anode assembly and a beam source.

[3]. In this paper we describe the study and later work in more detail, and attempt to clarify the procedure to accomplish best performance of two-dimensional position-sensitive charged-particle detectors based on MCPs and the MBWC method.

2. Experimental

The principle of the MBWC method is illustrated in Fig. 1. The pattern on the anode and the capacitive couplings divide the avalanche charge into four parts, and the position of the avalanche centroid is determined from the ratios between pulse-heights of signals. More detailed description of the principle and performances of the MBWC method have been already given [1,2].

The MCP–anode assembly of the present work is shown in Fig. 2. Two stages of MCP with the effective area of 20 mm diameter are adopted. A mesh is used in front of the MCPs to form pre-acceleration field. Several field rings are placed between the output face of the rear MCP and the MBWC anode. A gap between the front and rear MCPs, and a mesh between the MCP rear face and the anode, are introduced in the course of seeking conditions for better performances of the detector. Potentials for several essential parts can be applied from the outside of vacuum chamber to find the optimum operation conditions. One of the several kinds of masks, which are used for image-distortion tests or position resolution measurements, are placed

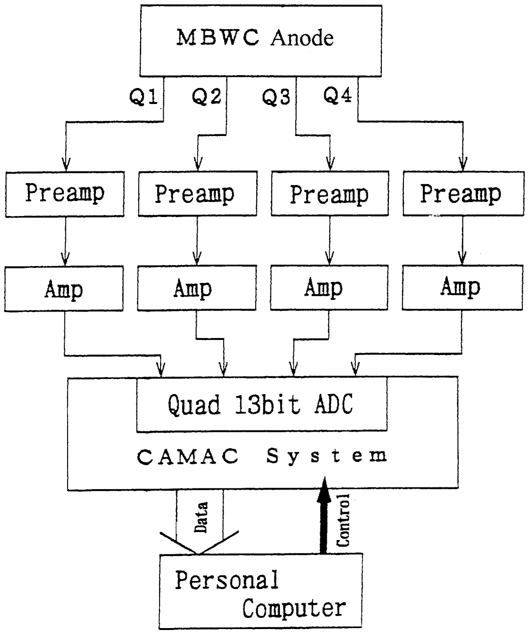

Fig. 3. Block diagram of the present electronics system.

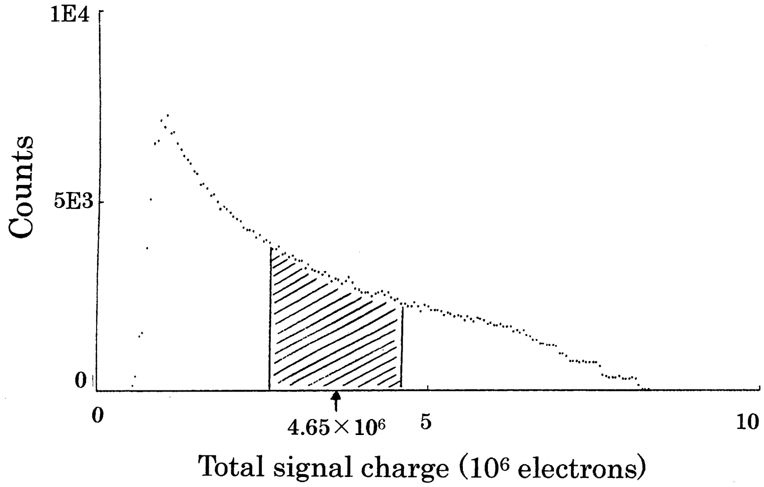

Fig. 4. Pulse-height distribution of the present tandem-MCP. When determining the position resolution as a function of the pulse-height, some range of the distribution is sliced and the central value is related to the obtained resolution.

in contact with the input face of the front MCP. A tungsten filament is used as a source of electron beam. We found that the filament also emits some ions if a positive potential was applied. We, therefore, sometimes used it as a test beam, although the identification of the ions was not made.

The electronics used is based on the NIM and CAMAC standard modules. The block diagram is shown in Fig. 3. The signals from the detector are first received by the charge-sensitive pre-amplifiers and secondly by main amplifiers, digitized by the 13 bits ADC, and finally fed into the computer via the CAMAC bus. The data are stored by event-by-event mode and analyzed after a measurement.

Fig. 4 shows a pulse-height spectrum of the MCP constructed from the stored data. It shows a monotonically decreasing curve as a function of the pulse-height. This property of the MCPs was used by us, and some of the results of the present work may be valid for this type of MCP. The other type tandem-MCP assembly shows a peak in its pulse-height spectrum, for which further research is required.

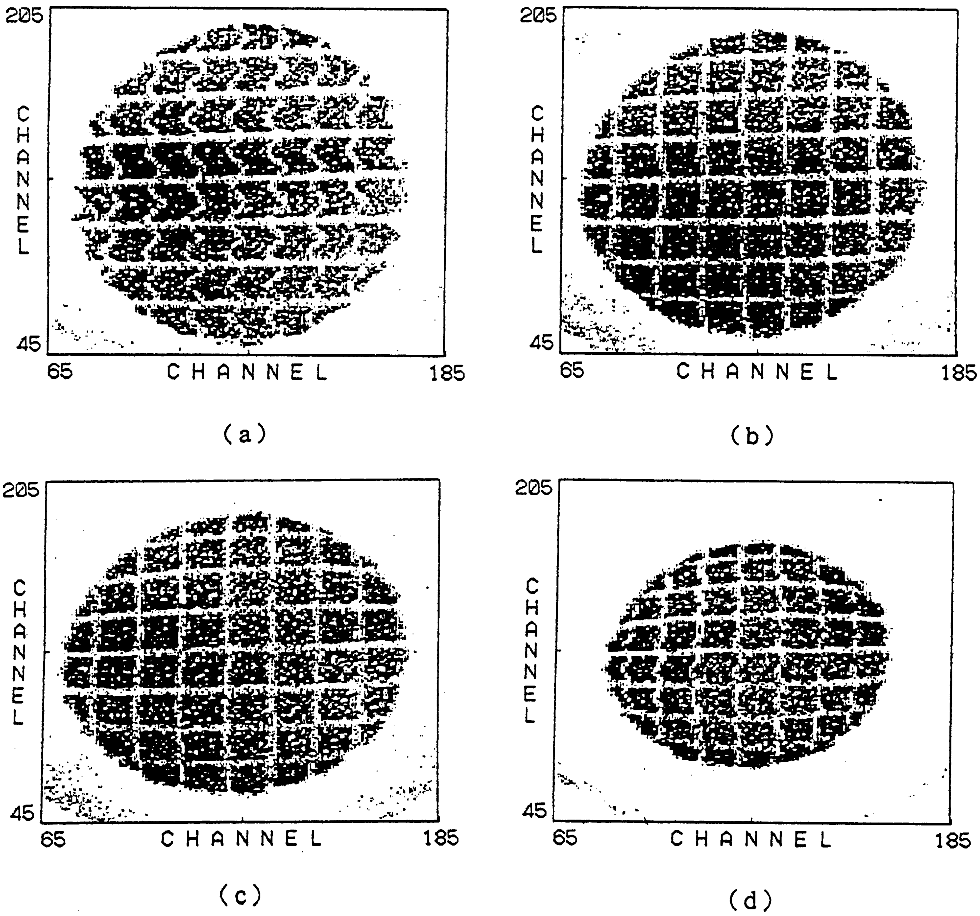

Fig. 5. Lattice image for various electric fields. Short MCP–anode distance is 6.6 mm. Electric field between the rear MCP and the anode is (a) 45 V/mm, (b) 18 V/mm, (c) 9 V/mm, (d) 4 V/mm. The lattice pitch is 2.5 mm, and the line width is 0.5 mm.

3. Image-distortion sources due to MCPs

The image-distortions intrinsic to the MBWC method have been party described [2]. It has been shown that some of them are limited near the fringes, and the others are avoidable by suitable design and/or choice of operating conditions. Therefore, the MBWC method is essentially distortion-free imaging technique. When applying the technique to a special detector system, however, the other distortion sources due to characteristics of the detector itself should be examined. As for the present MCP-based detector, the behavior of the avalanche charge falling from the rear MCP to the anode may cause distortions, because some distance is necessary in this region to expand the avalanche over several pitches of the zigzag pattern, to determine the centroid with better precision than the pitch.

The dimensions of the present MCPs are as follows. Effective diameter is 20 mm, thickness is 0.5 mm, channel diameter is 12 μm, and bias angle of the channels is 5° (Hamamatsu photonics F1094-01).

First we set a relatively small distance, 6.6 mm, between the rear MCP and the anode and attempt to

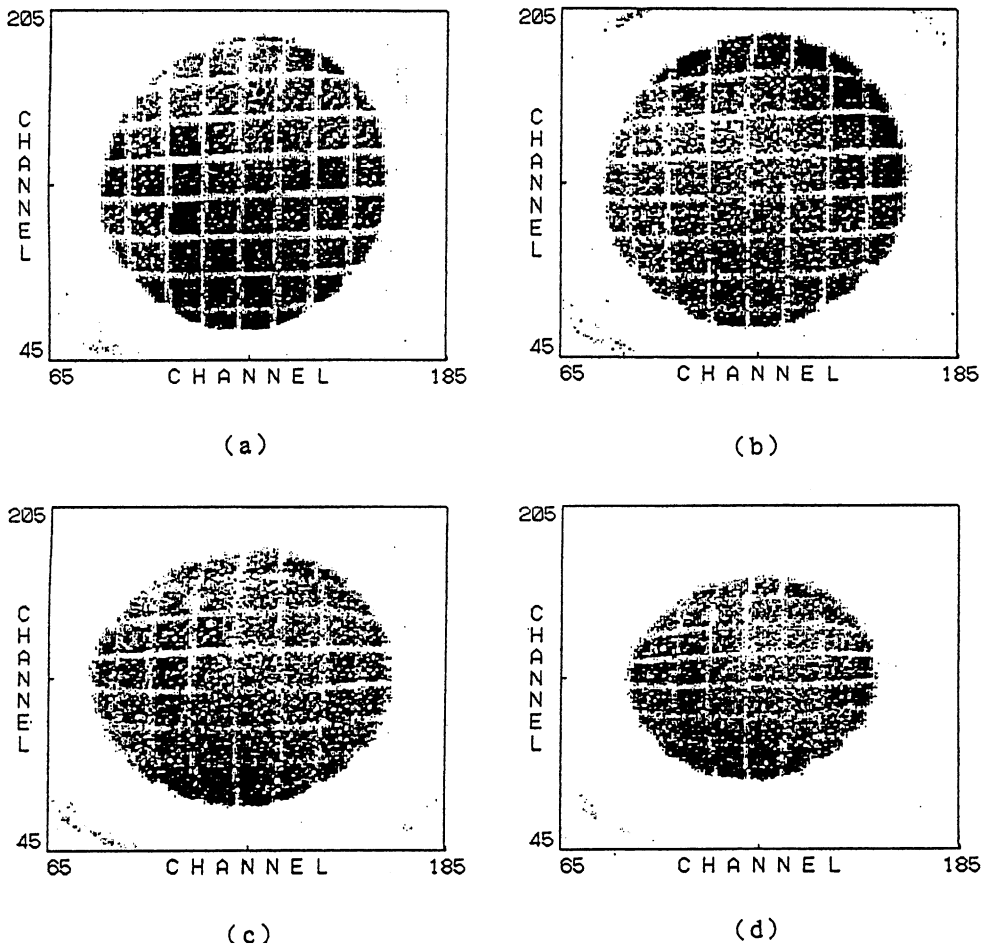

Fig. 6. Lattice image for various electric fields. Long MCP–anode distance is 17.2 mm. Electric field between the rear MCP and the anode is (a) 47 V/mm, (b) 30 V/mm, (c) 11 V/mm, (d) 5 V/mm.

find the best condition for image linearity with changing electric-field strength. Examples of the results are shown in Fig. 5. For the strong field a periodic distortion with a pitch of zigzag pattern on the anode is seen. This is caused by insufficient expansion of the avalanche footprint on the anode. One the other hand, if too small an electric field is applied, whole of the MCP image becomes small and the shrinking becomes strong near the edge. This means that the charge distribution is too large and a fraction of the charge falls outside the zigzag pattern. The periodic distortion appears again for the weakest field, which may be due to the image-force interaction between the falling charge and the anode pattern itself. A relatively good image is obtained in the second figure. It is apparent that the optimum field strength exists as a results of compromise between three needs: (1) the charge distribution should be large to avoid the periodic distortion, (2) the distribution should be small enough compared to the size of the effective area, (3) the field should be strong

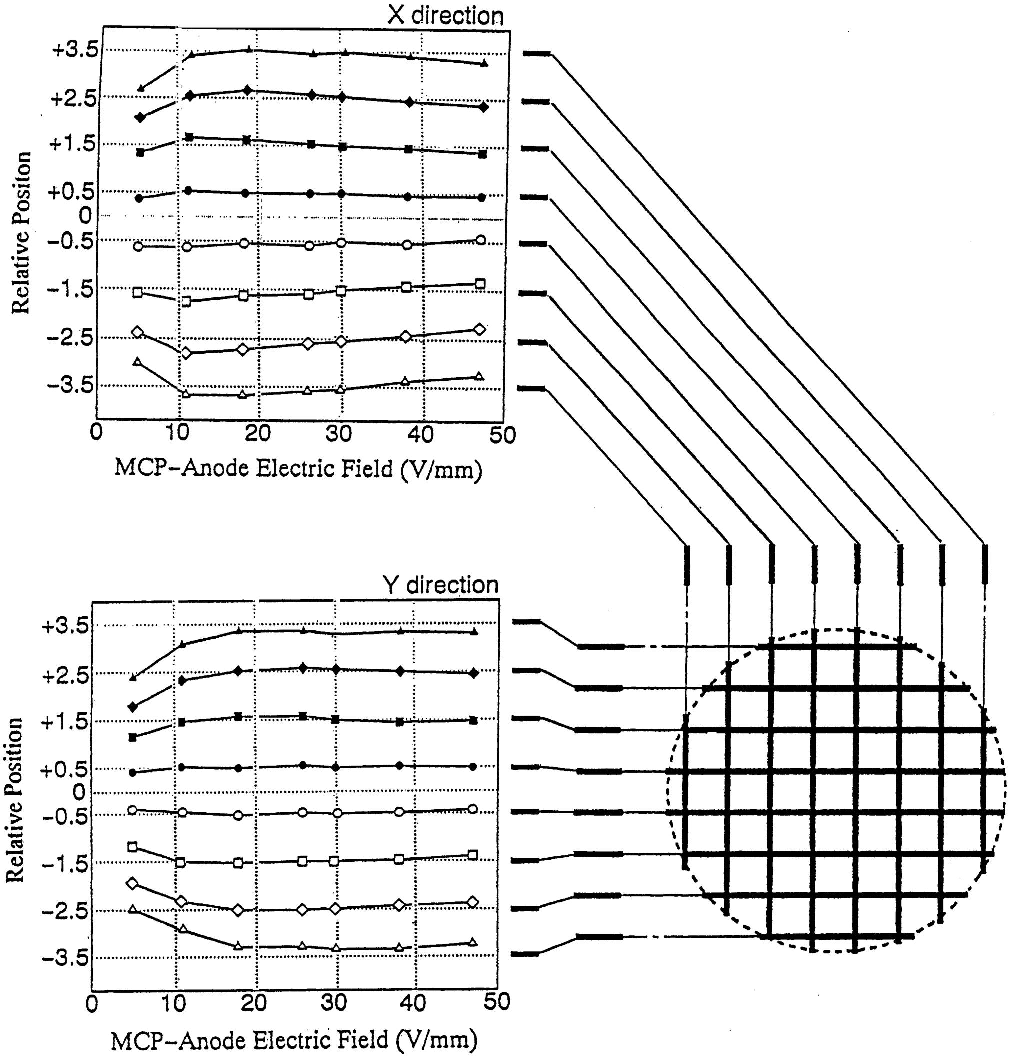

Fig. 7. Image–lattice distance vs. electric field.

enough to avoid the image-force effects. In this our first setting of the MCP–anode distance, the optimum exists but is too narrow, and even the best image is not satisfactory. To improve this situation we adopted a longer distance, 17.2 mm, between the MCP and the anode. Examples of the results are shown in Fig. 6. We even find for the strongest field, 47 V/mm, the image obtained is free from the periodic distortion, although shrinking, similar to the short-distance case, is observed at small field. More systematic illustration is given in Fig. 7. Distances of the rows and columns of the grid mask in the reconstructed image are plotted as a function of the electric field. As shown in the figure, good linearity is maintained over the range of electric field down to 20 V/mm and up to 50 V/mm, excluding the linear change of the X distances, which may be due to some electric lens effect, and the shortening of the uppermost and the lowermost Y distance, which may be a fringe effect intrinsic of the MBWC technique.

Recently, the semiconductor anode with wedge-and-strip capacitive readout from the rear face of the anode has been reported [5]. Such method may assure the expansion of the induced charge over the suitable number of the pattern pitch automatically, and will unnecessary make the adjustment of the field strength or the large distance between the MCP and the anode. The MBWC method can be adapted, of course, to such a rear-face readout technique as well as the wedge-and-strip method.

4. Factors affecting position resolution due to MCPs

Intrinsic position resolution of the MBWC anode will be analyzed with some suitable model for its capacitor network elsewhere. Here we note that it has been already shown to be the order of microns [3], which is actually good enough. The overall position resolution of the MCP-based charged-particle detector is, however, influenced by additional factors due to nature of MCP. For example, the importance of minimizing an image-force effect has been already suggested briefly [3]. Here, we describe in detail our study to find the procedure to optimize position resolution of the MCP-based detector.

To measure the position resolution a mask with several pinholes is placed in contact with the input face of the front MCP. The center pinhole is 20 μm in diameter, the broadened image of which is used to determine the X and Y position resolutions. The other pinholes are used mainly to calibrate the length in the reconstructed image, and to check the soundness of the whole system.

First we summarize the problem concerning the image-force effect described before [3]. We tested a commercially available tandem assembly of MCPs, in which two MCPs are in contact with each other. We have found that the position resolution first improves with increasing charge size of avalanche but again becomes worse above some charge size. The minimum is not better than roughly 100 μm (FWHM). This has been interpreted as an effect of the image-force between the output face of the MCP and the ejected charge, i.e., uncontrollable scattering of the charge cloud by the image field $\sim 10^4$ V/mm caused by the charge size $\sim 10^7$ electrons at a distance ~ 10 μm. To minimize this effect the introduction of a suitable gap between the two MCPs has been suggested. The gap is expected to expand the charge over many channels of the rear MCP and thus to make the image-force effect less important by averaging the scattering and minimizing the charge size for each of the rear channels. After the introduction of the gap the position resolutions at higher charges have been improved dramatically.

Fig. 8 shows the detailed results when the gap width is changed without potential difference between the front MCP's rear face and the rear MCP's front face. Both X and Y position resolutions have minima ~ 60 μm at the gap width of 60 or 120 μm.

Although the image-force effect is minimized by broadening the inter-MCP gap, it causes a new trade-off relation as shown by the existence of minima in Fig. 8. Apparently a large gap leads to statistical fluctuation of the charge centroid at the input stage of the rear MCP, where the charge size is in the order of $\sim 10^3$ electrons. This is demonstrated in Figs. 9–11

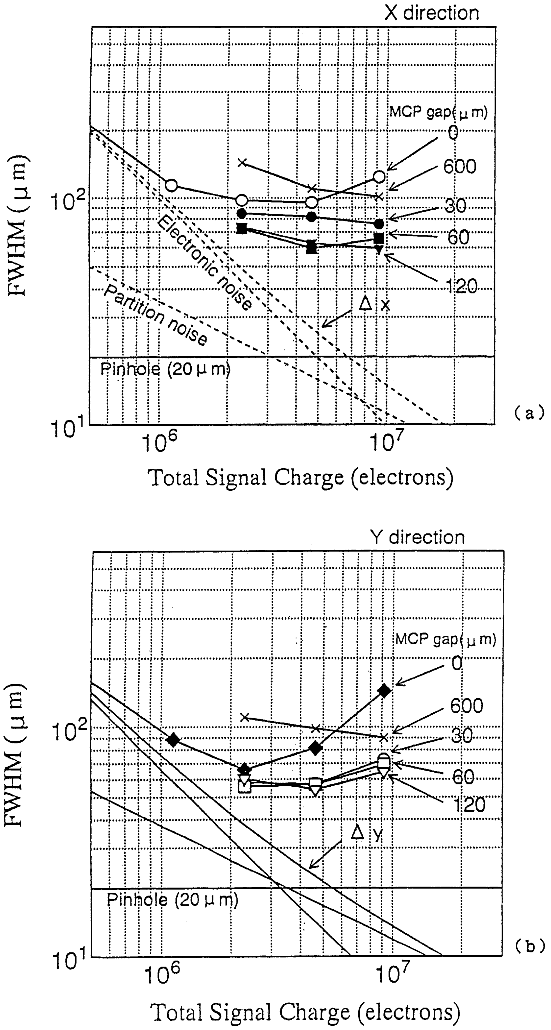

Fig. 8. The effect of the spacing between two MCP plates on the position resolution.

where the ratio of the voltages, applied to the front and the rear MCPs, changed from 4:5 (Fig. 9) to 3:2 (Fig. 11). Here the same potential was given to the front MCP's rear face and the rear MCP's front face. Apparent improvement in the resolution is seen with increasing relative gain of the front MCP. This can be interpreted by the centroid fluctuation at the front face of the rear MCP which decreases with increasing electrons there, although the final avalanche size at the rear face of the rear MCP is the same.

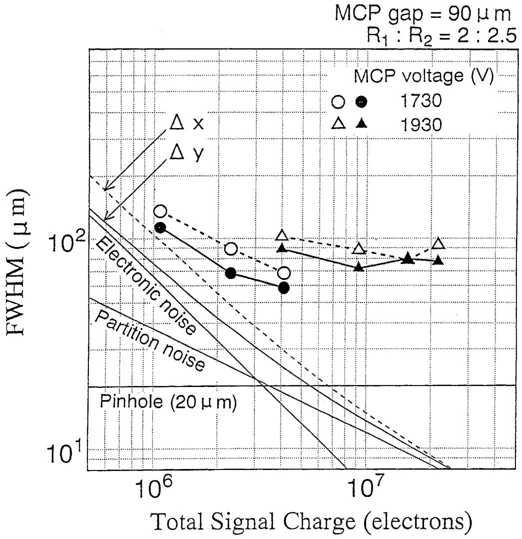

Fig. 9. Effect of changing the ratio of high-voltages for the front and rear MCP. HV for the front is smaller than the rear.

Broadening of the charge cloud at the front face of the rear MCP may be estimated from these data assuming that the electrons behave independently. For example, the centroid fluctuation of 0.1 mm with 1000 electrons implies the size of distribution $0.1 \times 1000^{1/2}$

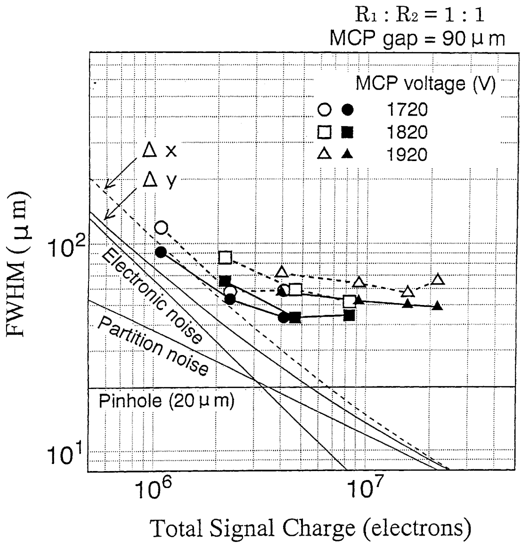

Fig. 10. Effect of changing the ratio of high-voltages for the front and rear MCP. HV for the front is same as the rear.

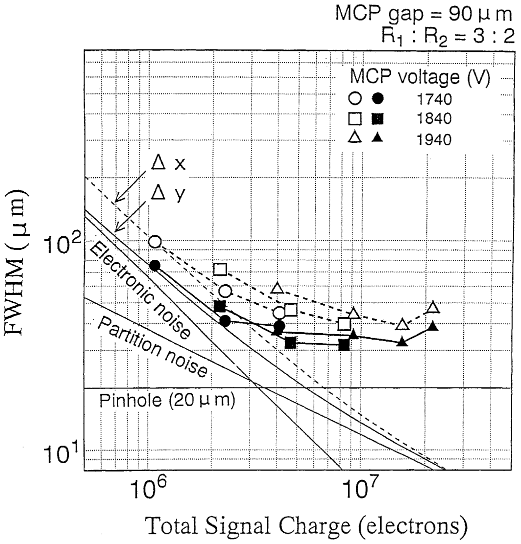

Fig. 11. Effect of changing the ratio of high-voltages for the front and rear MCP. HV for the front is larger than the rear.

~3.2 mm. This seems surprisingly large compared to the adopted gap-widths, and may suggest rather some collective fluctuations of the electrons. Further study with more different types of MCPs will be necessary at this point. The above prescription that the front MCP should bear the larger high-voltage is, however, considered to be effective in any case.

It is in general a difficult work to adjust the gap-width. Except for it, extension of the charge can be controlled by electric field with fixing the gap-width to some relatively large value. Using the gap-width of 1 mm and the electric field, 20–40 V/mm, we have obtained good results similar to Fig. 11.

Another problem to limit the position resolution is a displacement of the image with the pulse-height. This may be another image-force effect caused by the interaction between the falling charge and the anode pattern. By inserting a fine mesh between the anode and the MCP, with distance 2 mm to the anode and 13 mm to the MCP, the displacement has been minimized within ~20 μm for the charge changing from 9×10^6 to 1.6×10^7 electrons. Without the mesh and with a shorter distance between the MCP and the anode, we sometimes found the displacement over 100 μm. This problem will be less serious for an MCP, the pulse-height distribution of which shows a well-defined peak.

5. Position drift with time and other precautions

Position drift with time, ~20 μm, for both the X and Y directions are observed, which may be partly due to the gain drift in the electronics and partly due to thermal expansion of some structural parts of the assembly. To attain the extreme position resolution, therefore, temperature control and thermal equilibration are important.

6. Concluding remarks

The above described procedure to construct and operate the tandem-MCP-based charged-particle detector, utilizing the MBWC anode, enables 20–40 μm position resolution without any difficulty. Better resolution can be attained if the pulse-height distribution is sliced and only the narrow band is utilized to reconstruct the image, and a special precaution for the consistency of the room temperature is paid. In fact, the individual channels of the front MCP have been resolved [3].

Further improvement can be expected through several courses. First, a study with MCPs having a well-defined peak may be necessary. The triple-MCP assembly may enable the extreme resolution with more ease. Finally, the rear-face readout from a resistive anode may simplify the structure and operation of detectors based on the MBWC technique.

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