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A broad-application microchannel-plate detector system for advanced particle or photon detection tasks: large area imaging, precise multi-hit timing information and high detection rate

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Abstract

New applications for single particle and photon detection in many fields require both large area imaging performance and precise time information on each detected particle. Moreover, a very high data acquisition rate is desirable for most applications and eventually the detection and imaging of more than one particle arriving within a microsecond is required. Commercial CCD systems lack the timing information whereas other electronic microchannel plate (MCP) read-out schemes usually suffer from a low acquisition rate and complicated and sometimes costly read-out electronics. We have designed and tested a complete imaging system consisting of an MCP position readout with helical wire delay-lines, single-unit amplifier box and PC-controlled time-to-digital converter (TDC) readout. The system is very flexible and can detect and analyse position and timing information at single particle rates beyond 1 MHz. Alternatively, multi-hit events can be collected and analysed at about 20 kHz rate. We discuss the advantages and applications of this technique and then focus on the detector's ability to detect and analyse multiple hits. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Microchannel plate (MCP) assemblies are widely used to detect electrons, ions and photons and to carry out spectroscopy of their impact position ("imaging") and/or time-of-flight ("timing") with respect to an external trigger. There are different approaches to retrieve the two-dimensional (2d) position and time information from the MCP for single particle counting [1]. Often both time and position decoding of a detected particle or even a particle shower (e.g. for imaging fragment patterns of a particle breakup) is important. Such tasks are found in atomic and

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molecular science [2] as well as in surface and material science applications [3].

An MCP stack will respond to multiple hits, i.e. a shower of particles arriving within a short period, in almost any case in an adequate way. That means it will deliver spatially and timely well-defined charge clouds for each particle. However, the read-out concept needs to be specially designed to presume this information.

All common techniques based on phosphor screen readout cannot be applied here as the read-out scheme is much too slow. Pixel anodes with fast and independent read-out electronic channels can handle high rates and multi-hits, but with increasing position resolution demands, such techniques become inefficient as the number of electronic channels increases at least linearly with the position resolution dynamics in each dimension. Also, charge integrating read-out schemes as used by the wedge-and-strip or the resistive anode, fail to detect multiple hits as their read-out electronic's shaping times must be in the order of 1 μs to ensure sufficient position resolution. These detectors are unable to handle more than one particle in this time period and will thus also be limited in the particle rate to be collected.

A promising approach combining most desired features of an MCP read-out scheme, good position and timing resolution at high particle flux, including the ability to analyse multiple-hit events is the delay-line technique [4].

2. MCP detector with delay-line readout

The principle behind the delay-line technique is to take advantage of the delay that a signal experiences when travelling on a transmission line which is preferably meander-shaped or helical to introduce an effective propagation speed $v_{\perp}$ in a given direction (i.e. position dimension, see Fig. 1). Sometimes, discrete electronic delay-circuits are implemented in the transmission line. A signal induced somewhere on the delay line will propagate in both directions towards the ends where impedance adjusted circuits pick it up for further processing. One can perform a position determination by measuring the time between the signal arriving on both ends of the transmission line for a respective direction. For 2d-imaging, a second delay-line structure has to be implemented with perpendicular orientation, also receiving a share from the charge cloud.

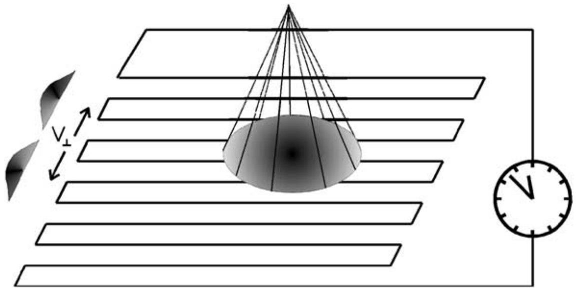

Fig. 1. Scheme of a delay-line readout for one dimension: A meander-shaped transmission line collects the charge cloud, the induced signals propagate with effective speed $v_{\perp}$ towards the ends. The time difference is proportional to the pickup position in direction $v_{\perp}$.

If the charge cloud is spread out over several of the discrete pickup structures, it is possible to achieve a position resolution which is not limited by the pitch distance or width. Unlike in discrete (pixel) readout, one can interpolate the centre-of-mass of the collected charge cloud (corresponds to the impact position of the particle on the MCP). Thus, a continuous imaging (and timing) can be achieved with a quasi-discrete anode pattern that is electronically read out.

For each dimension, the respective position is directly proportional to the time difference $t_1 - t_2$, where t_1 and t_2 are the arrival times at the two ends of the line measured with respect to a time zero. We define the time zero now as the moment when a particle hits the MCP stack and gives rise to a signal at the MCP. The time sum $T_{\text{sum}} = t_1 + t_2$ is a constant for *all* positions and equals the transmission time of a signal over the whole delay-line anode (of course, the effect of additional cable delays needs to be subtracted). We find the width ΔT_{sum} of the time-sum peak for a number of acquired events to be 1 ns or less. The *relative* time resolution for the position determination $t_1 - t_2$ is much better in our application, only limited by the time-to-digital converter (TDC) resolution. Having two time sums per particle for a crossed wire 2d delay-line anode allows consistency checks for the validity of the acquired position information, especially if more than one particle needs to be detected in a shower.

The total signal duration (“signal length”) from the MCP or the anode wires is below 10 ns. Front-end electronics such as timing amplifiers and discriminators have similar pulse widths and dead times. Thus this read-out scheme can cope with very high particle fluxes. As also the signal dwell time on the anode is about 100 ns or less, no “pile-up” of signals on the anode or in the read-out electronics is to be expected. A repetition count rate of 10 MHz can thus be handled. This is also the upper rate limit of standard MCP-stacks. The fast read-out scheme for single particle counting is also the reason for a very high multi-hit capability which will be discussed in the next chapter.

The favourable properties of the delay-line technique can only be fully exploited if the digital read-out chain following the front-end electronic circuits can keep up with the signal flow and if the time digitisation is also as fast. Wilkinson-type TDCs cannot be used for high-rate or multi-hit applications as the slow analog signal-processing step will reduce the speed advantage of the delay-line technique. In recent years, a new TDC concept has been developed with the advent of faster and faster chips. The new TDC generation measures a time span by simply counting clock pulses that fall within the time interval defined by a “start” and a “stop” signal. This number is then stored in a register. No time consuming analog–digital conversion is required. With this technique, multiple intervals marked by multiple start or stop signals can also be analysed likewise and there is virtually no limitation in time range or number of hits to be detected.

Of course, there are practical limits to this technique due to switching cycles, and memory handling, but a pulse pair dead-time of 10–20 ns and time resolution bin below 100 ps has already been achieved in commercial systems, with sufficient range, hit numbers and number of TDC channels to be combined for most applications.

Still there is usually a bottleneck to overcome on the way to the “perfect” readout. It is the communication speed between a CPU and the information-bearing numbers in the TDC registers.

We have developed a PC-controlled stand-alone large-area delay-line detector system which is complete in the sense that all components, from the MCP to the data treatment software, are mutually adapted. The system features the most desirable properties of an MCP detector system including multi-hit processing taking advantage of very recent technical developments and it is sufficiently flexible and cost-efficient to be applied in many fields.

Fig. 2 shows some imaging properties of our detector system. Details on the system's components and its general performance have been reported in detail earlier [5]. In brief summary, for 80 mm active detection diameter, we achieve a position resolution well below 100 μm. The time resolution for time-of-flight (TOF) is below 1 ns and multi-hit events can be handled with about 20 kHz event acquisition speed in list mode. If only single particles need to be counted (with position and time information) the read-out speed can be extended to over 1 MHz.

3. Multi-hit detection with delay-line anodes

We define a multi-hit event as a shower of particles that arrive within 10 μs. Although this number is arbitrary, there are two reasons for the choice: First, all high-resolution imaging single particle counting anodes with slow readout will fail at about the corresponding particle rate of 100 kHz. Second, many experimental techniques of particle spectroscopy require to analyse events with two or more particles in about such time span. The general ability of our technique to be applied for such multi-hit experiments has been demonstrated [6–8]. Here, we want to discuss the potential and the limitation on a mere theoretical basis but which is empirically proven by these experimental results.

As discussed earlier, the MCP stack response for particle showers, i.e. its ability to deliver well-

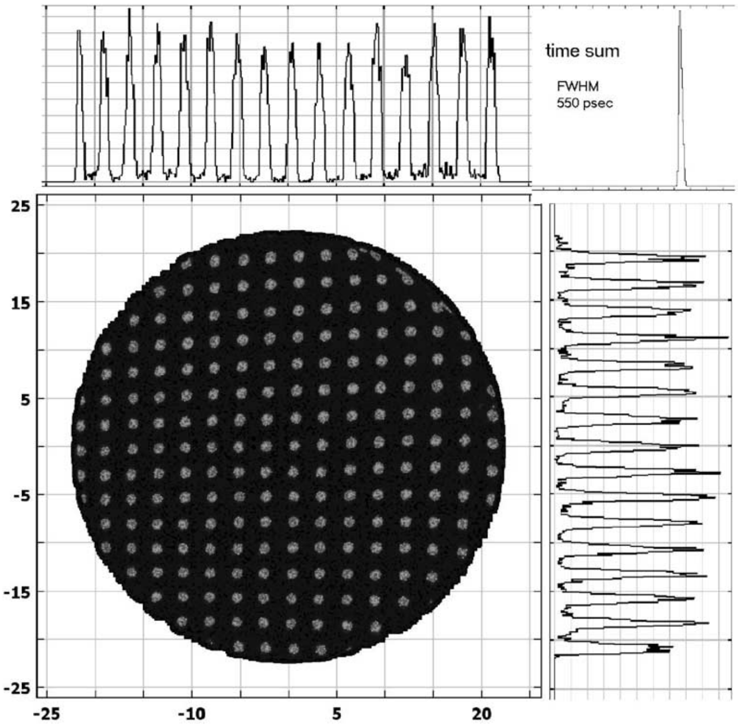

Fig. 2. The image of a shadow mask obtained with a 45 mm active diameter MCP at a single particle (3 keV Cs^+) rate of 470 kHz. For details about the imaging performance, see Ref. [4].

defined charge clouds towards the anode, will not degrade as long as the total particle rate is not exceeding a certain rate limit (usually beyond 1 million particles per second) and two particles are not hitting the same spot on the MCP within fractions of a millimetre and within 1 ms. The anode will collect such charge clouds and will transmit the signals independently. All signals have similar shapes (few nanoseconds width) but different heights. Each signal produced from a single charge cloud is picked up from the four anode contacts (two for each dimension) and from the MCP contact. The current read-out technique with analog timing electronic front-end circuits detecting the pulse arrival times introduces a pulse-pair dead-time (Δt_e) of about 10 ns. The pulse-pair dead-time of the fastest commercially available TDC is also 10 ns.

The pulse-pair dead-time will define the actual limit in the multi-hit operability of a detection system. However, due to redundancy in the readout, a high degree of signal recovery is inherent. Potentially, there are two signals available on both wire ends per particle and dimension. With the additional MCP "start" signal, two time-sum values per particle can be calculated.

In the following, we will discuss only *pairs* of particles with given pulse-pair distance Δt_{pp}. Similar conclusions will hold for more than two particles if each two of them do not exceed Δt_{pp}. We also assume here that the TDC range and number of hit registers of the actual TDC impose no limit. Four cases can be distinguished.

(a) If $\Delta t_{pp} > T_{sum} \gg \Delta t_e$, only one particle's signals propagate on the delay line at a time. Thus the signals from individual particles will be collected in the same order as the particles arrive on the detector.

(b) If $T_{sum} > \Delta t_{pp} > \Delta t_e$, it can happen that a signal from the "late" particle arrives at a certain delay-line end contact before the "early" particle's or both arrive within Δt_e due to the relative position in the x or y direction. Then at some ends of the delay lines, signals are lost or the time order is reversed. As Δt_{pp} is known from the MCP signals, one can always restore the signal order, since only the correct signal combination will yield time-sum values equal to T_{sum} and $T_{sum} + \Delta t_{pp}$ for the first and the second particle, respectively. If one delay-line end delivers only one hit due to signal overlap it should be rejected for the calculation. Still, the signals on the other corresponding end must then be separated by more than Δt_e and in proper sequence. The lost time values (t_1 or t_2) of the particles can than be recovered from the known respective time-sum values T_{sum} and $T_{sum} + \Delta t_{pp}$. Note, that all events can be recovered, even when signals are lost in both dimensions. However, the position resolution for a particle with recovered coordinates is reduced as ΔT_{sum} is now defining the time resolution for the position determination.

(c) If $\Delta t_e > \Delta t_{pp} > \Delta T_{sum}$, it is required for an unambiguous recovery that at least in one dimension all signals of the pair arrive on the respective delay-line anode ends due to sufficient separation Δs in position, i.e. $\Delta s > v_\perp(\Delta t_e + \Delta t_{pp})$. Then T_{sum} and $T_{sum} + \Delta t_{pp}$ can be determined without the MCP signal. Additionally, the separation in the other dimension must be $> v_\perp(\Delta t_e - \Delta t_{pp})$. The lost signals in this other dimension can be recovered according to case (b). However, a cross-shaped "dead zone" around the first particle remains for this case where the second particle must not arrive if the event is to be fully recovered. In practice, it turns out that the second condition is a little weaker and one can further reduce the forbidden zone at the cost of position and timing resolution. This will be discussed in detail in a future paper.

(d) If $\Delta t_e < \Delta T_{sum}$, a recovery is not possible any more and the complete event should be rejected. Even if a sufficient spatial separation in both dimensions allows to determine T_{sum} and all position coordinates in the x and y direction can be recovered, it is impossible to decide which x–y combination corresponds to the respective particles. Again, even this can be overcome as we will show in a future publication.

From the above considerations, it becomes clear that an increase of the delay-line size is beneficial as the troublesome cases (c) and (d) in the "dead" position areas are reduced as $v_\perp$ increases, also improving the position resolution. Of course, if the MCP size and thus the usable image area also grows, there is an additional improvement in the position resolution dynamics (number of digital position pixels) and eventually also for the relative number of particle pairs being too close in time *and* position to be recovered.

4. Conclusion and outlook

We can conclude that the design and performance of our existing system makes it already a unique tool for many applications whenever single particle imaging with time information at high particle rates is needed. Also, the present degree of multi-hit acceptance allows applications in fields where multi-hit detection is crucial and so far only poorly resolving pixel anodes or complicated hybrid detector systems could be applied.

We expect further improvements in the electronic dead-time limit as electronic circuits will become even faster in the future.

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