1 Study of the timing performance of micro channel plate photomultiplier for use as
2 an active layer in a shower maximum detector.

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4 A. Ronzhin^{a*}, S. Los^a, E. Ramberg^a, A. Apresyan^b, S. Xie^b, M. Spiropulu^b, H. Kim^c
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6 ^a*Fermilab, Batavia, Il 60510, USA,*

7 ^b*California Institute of Technology, Pasadena, CA 91126, USA*

8 ^c*University of Chicago, Chicago, Il 60637, USA*

9 **Abstract**

10 We continue the study of micro-channel plate photomultiplier (MCP-PMT) as the
11 active element of a shower maximum (SM) detector. We present test beam results obtained
12 with Photek 240 and Photonis XP85011 MCP-PMTs devices. For proton beams, we obtained
13 a time resolution of 9.6 ps, representing a significant improvement over past results using the
14 same time of flight system. For electron beams, the time resolution obtained for this new type
15 of SM detector is measured to be at the level of 13 ps when we use Photek 240 as the active
16 element of the SM. Using the Photonis XP85011 MCP-PMT as the active element of the SM,
17 we performed time resolution measurements with pixel readout, and achieved a TR better
18 than 30 ps, The pixel readout was observed to improve upon the TR compared to the case
19 where the individual channels were summed.

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23 **Keyword**

24 Microchannel plate photomultiplier or MCP-PMT

25 Shower maximum or SM

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28 * Corresponding author. Tel.: 1 630 840 8630

29 E-mail address: ronzhin@fnal.gov (A. Ronzhin)

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1. Introduction

The goal of the article is to describe our latest results of the study of MCP-PMT as a possible device for a fast and highly radiation resistant active layer for a shower maximum (SM) detector. In our previous work [1] we obtained data indicating that the shower particles were registered through the Cherenkov radiation in the input window of the Photonis XP85011 MCP-PMT, as well as through direct interaction with its MCP. We presented results of the MCP direct shower particles detection in [2].

The paper is organized as follows. Section 1 is an introduction. In Section 2 we describe the experimental setup and test beam results obtained with Photek 240 and Photonis XP85011 MCP-PMTs. Photonis XP85011 MCP-PMT was tested in two readout configurations: one with the sum of the 16 central pixels, and the other with individual pixel readout. Discussion of the results and conclusions are presented in Section 3.

2. Setup. Test beam results.

The setup is described in detail in Refs. [1, 2]. The setup includes detectors, placed in a dark box lined with copper foil for RF shielding, a data acquisition (DAQ) system based on DRS4 waveform digitizer, HV power supplies, and equipment to monitor and control test beam parameters. The box was placed on a moving table located at section MT6.2B of the Fermilab Test Beam Facility (FTBF). The table can be moved in both horizontal and vertical directions in the range of ~ 300 mm, with better than 0.5 mm accuracy. The event selection and analysis is also described in detail in Refs. [1, 2]. Few changes were made with respect to the previous work [1]. The trigger was based on a 1.7×2 mm² scintillation counter. The three detectors (two Photek 240 and the Photonis XP85011 MCP-PMTs between them) were placed in line, as shown in Fig. 1. A differential Cherenkov counter is placed upstream of our detector, and is used to select electron events.

Fig. 1. Dark box with MCP-PMT detectors inside. The Photonis XP85012 MCP-PMT is placed on a X-Y moving stage between two Photek 240 MCP-PMTs. The Cerenkov counter is not shown in the picture. The red arrow shows the direction of the incoming particle beam.

The Photonis XP85011 MCP-PMT was located on an X-Y moving stage, which allowed movement in both X and Y directions by ± 15 mm. In order to detect showers from high-energy particles, we placed absorbers composed of tungsten or lead plates of varying thickness close to the face of the Photonis XP85011 MCP-PMT. The stage was operated remotely from the test beam control room. The accuracy of the Photonis XP85011 MCP-PMT alignment with respect to the stack of absorber material located close to its front face was ~ 30 μm for both X and Y directions.

The Photonis XP85011 MCP-PMT was removed when measuring the time resolution with only two Photek 240 MCP-PMT (for the 120 GeV proton beam, as in Fig. 2), or when using the second Photek 240 MCP-PMT as the active layer of SM detector, as in Fig. 3.

Fig. 2. Setup to measure the time resolution with two Photek 240 MCP-PMT devices. A time resolution of 9.6 ps was obtained with the 120 GeV proton beam. The red arrow shows the direction of the incoming particle beam.

Fig. 3. Setup to measure the SM time resolution and the signal amplitude (SM longitudinal profile) as a function of the amount of lead absorber, placed between the two Photek 240 MCP-PMT. The red arrow shows the direction of the incoming particle beam.

We started by measuring the electronic time resolution of about ~ 3 ps on the beam line by using an improved calibration method, which is described in detail in Ref. [3]. We then proceeded to measure the time resolution (TR) for proton beams of 120 GeV using the configuration shown in Fig. 2. The TR is the jitter of the “time difference” between the two Photek 240 MCP-PMTs signals. We measured the TR of 9.6 ps as shown in Fig. 4. This is the best time resolution we have obtained with a time of flight (TOF) high aperture system (41 mm diameter) and DRS4 readout. A few experimental issues impact this measurement. The largest impact is from high frequency noise. A low pass filter algorithm was applied to the digitized waveform of the signal pulses to obtain the best result. Without the use of this noise filter, the time resolution degrades to about 17 ps. The requirements on the signal pulse amplitude also has an impact, as the signal to noise ratio is improved. Our result is obtained by requiring at least 50 mV in both Photek 240 MCPs. Lowering the amplitude threshold to 20 mV degrades the time resolution to about 12 ps, due to worse signal to the noise ratio.

Fig. 4. Time resolution (TR) of 9.6 ps was obtained with two Photek 240 MCP-PMTs with the 120 GeV proton beam.

Next we measured the time resolution and longitudinal profile of electromagnetic showers using beams of 8 GeV electrons as in the setup shown in Fig. 3. The mean value of the amplitude or pulse height (PH) distribution is shown in Fig. 5 as a function of the absorber

thickness expressed in units of the radiation length for both tungsten and lead absorbers. The radiation lengths of tungsten and lead are 3.5 mm and 5.6 mm, respectively. We observe very similar longitudinal shower profiles for both lead and tungsten absorbers. For each thickness of the lead and tungsten absorber, we also measure the time resolution. The time resolution dependence on the absorber thickness is shown in Fig. 6, and is relatively constant as a function of the absorber thickness ranging from 2 to 12 radiation lengths. An example of the histogram showing the time resolution is presented in Fig. 7.

Fig. 5. The longitudinal shower profile is shown, giving the dependence of the average Photek 240 MCP-PMT signal amplitude on the absorber thickness for lead and tungsten absorber. The measurements at zero absorber thickness were performed by placing the Photek 240 MCP-PMT before the absorber plate.

Fig. 6. The dependence of the Photek 240 MCP-PMT time resolution on the absorber thickness for lead and tungsten absorber is shown.

Fig. 7. SM time resolution (TR) for 8 GeV electrons. The first Photek 240 MCP-PMT serves as a start counter, and its brass enclosure serves as an absorber of ~ 2.3 radiation lengths. The stop counter is the second Photek 240 MCP-PMT.

The time resolution measurements using the Photonis XP85011 MCP-PMT as the shower maximum photodetector were published in Ref. [1]. In Ref [1] the sum of the sixteen central pixels was used for the readout, and we obtained a time resolution of ~ 37 ps that was relatively constant as a function of the thickness of the lead absorber.

In the following we present the measurements with the same Photonis XP85011 MCP-PMT, but using individual pixel readout. The signal trace from an individual pixel as recorded by a Tektronix oscilloscope is shown in Fig. 8.

Fig. 8. A trace for an individual pixel from the Photonis XP85011 MCP-PMT is shown for illustration. Each time division is 1 ns.

We placed the Photonis XP85011 MCP-PMT on the X-Y moving stage for the measurements. The Photonis XP85011 MCP-PMT was placed furthest upstream and the reference Photek 240 MCP-PMT device was removed from the beam to avoid inducing an early electromagnetic shower. An early shower induced by the 2.3 radiation lengths of brass inside the Photek 240 MCP-PMT device can cause a significantly larger transverse shower size and is undesirable for our intended measurements as such showers could exceed the size of the sensitive area of our detector. We used 4 X_0 of tungsten absorber, also with the purpose to minimize the transverse shower size as the Moliere radius for tungsten is significantly smaller than that of lead. We estimate that the accuracy of the position of the Photonis XP85011 MCP-PMT relative to the beam is better than 30 μm . A diagram of the pixel matrix for the Photonis XP85011 MCP-PMT is shown in Fig. 9 and the pixels that were connected to and read out by the DRS are labeled in red. Two DRS units were used in order to accommodate signals from all four pixels, the reference MCP-PMT, and the Cherenkov counter. We split the reference MCP-PMT signal and connected the split signals to both DRS units. These split signals were used to synchronize the time between the two DRS units.

18	28	38	48	58	68	78	88
17	27	37	47	57	67	77	87
16	26	36	46	56	66	76	86
15	25	35	45	55	65	75	85
14	24	34	44	54	64	74	84
13	23	33	43	53	63	73	83
12	22	32	42	52	62	72	82
11	21	31	41	51	61	71	81

Fig. 9. Schematic diagram of the Photonis XP85011 MCP-PMT pixels. The pixel channels that were connected to and read out by the DRS4 are labeled in red, corresponding to pixels number 43, 44, 53 and 54.

The goal of the measurement was to place the Photonis XP85011 MCP-PMT at the location which yields approximately equal response in each of the four connected pixels and to measure the time resolution of each pixel in this configuration. In Fig. 10 we show the mean amplitudes in the four connected pixels. The time resolution between the individual pixel signals and the reference Photek 240 MCP-PMT signal are shown in Fig. 11.

Fig. 10. Mean amplitude in the four connected pixels are shown: #44 is 78 mV, #54 is 108 mV, #43 is 101 mV, #53 is 125 mV.

We used the X-Y stage for the alignment. The accuracy of the X-Y alignment is $\sim 30 \mu\text{m}$. An electron beam of 8 GeV was used and 4 X_0 of tungsten absorber was placed before the Photonis XP85011 MCP-PMT. The reference Photek 240 MCP-PMT was placed at the back behind the Photonis XP85011MCP-PMT detector. The time resolution between the individual pixel signals and the reference Photek 240 MCP-PMT signal are shown in Fig. 11.

Fig. 11. Time resolution between individual pixels and the reference signal, and between each other are shown.

3. Discussion and conclusion

We continue the study of MCP-PMT as the active element of SM detector. We presented test beam results obtained with the Photek 240 MCP-PMT and Photonis XP85011 MCP-PMT. We obtained a time resolution of 9.6 ± 0.3 ps for a TOF system based on two Photek 240 MCP-PMT start and stop counters and DRS4 readout using the 120 GeV proton beam. This time resolution includes the contribution of the electronic time resolution from the DRS waveform digitizer, which was about 3.6 ps. This result represents a significant achievement, as it is the first time that we achieve a TOF resolution better than 10 ps with a **devices having a sensitive area of 41 mm diameter [4]. Better time resolution (~ 5 ps) was obtained earlier, but with a smaller of the detector sensitive area ~ 11 mm (HPK R3809U-50-11) diameter [5].**

Correcting for the electronic time resolution of ~ 3.6 ps yields a time resolution of the TOF system of 8.9 ps. Unfolding to obtain the time resolution of a single Photek 240 MCP-PMT device yields 6.3 ps. The obtained time resolution is in agreement with the measured SPTR for the Photek 240 MCP-PMT, which is ~ 45 ps for 405 nm light illumination [6]. Projecting to 70 measured photoelectrons produced in the input window (9 mm of thickness) yields an expected time resolution of about 5.4 ps for a single Photek 240 MCP-PMT. The difference between the measured time resolution and the projected one can be explained by a few reasons, for example the wider spectrum of Cherenkov light in comparison to the light used for the illumination in the bench test.

The registration efficiency of the MCP-PMT to electromagnetic showers is close to 100%. The time resolution obtained for this new type of the SM detector is at the level of ~ 13 ps for Photek 240 MCP-PMT for electron beams. We do not observe a significant difference in the time resolution between lead or tungsten absorber. We also do not observe a significant dependence of the time resolution on the absorber thickness. These two new observations have important consequences. The measurements suggest that the time resolution attributed to fluctuations of the electromagnetic shower is significantly below the 13 ps level. Furthermore, they explicitly demonstrate that the placement of a timing detector layer within an electromagnetic calorimeter does not impact the time resolution performance of the detector beyond the 13 ps level.

For the measurements with the Photonis XP85011 MCP-PMT, we observe that for some pixels, the measured TR is less than 30 ps, and improves upon the 35 ps TR obtained with the sum of the 16 pixels [1]. This suggests that it may be possible to improve the time resolution obtained for the SM if we use the information of the individual pixels and perform an inter-calibration. We note that even with the four pixels that were read out (12 mm x 12 mm of the sensitive area) and using the tungsten absorber, we could not cover the full transverse shower size, as the Moliere radius for tungsten is ~ 9 mm [7, 8]. Such non-containment could degrade the TR obtained with the individual pixel readout.

For future beam tests, we are working to produce a 64-channel printed circuit board for the Photonis XP85012 MCP-PMT to allow for simultaneous readout of all pixels. Furthermore, we plan to test this device as well as other devices without a photocathode (PC). This will allow us to measure both the time and space resolution covering the full electromagnetic shower, and to evaluate the performance of detectors that are much more resistant to ionizing radiation.

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