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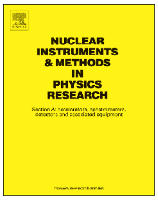

Direct tests of a pixelated microchannel plate as the active element of a shower maximum detector

A. Apresyan [a],*, S. Los [b], C. Pena [a], F. Presutti [a], A. Ronzhin [b], M. Spiropulu [a], S. Xie [a]

[a] *California Institute of Technology, Pasadena, CA, USA*
[b] *Fermi National Accelerator Laboratory, Batavia, IL, USA*

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ABSTRACT

One possibility to make a fast and radiation resistant shower maximum detector is to use a secondary emitter as an active element. We report our studies of microchannel plate photomultipliers (MCPs) as the active element of a shower-maximum detector. We present test beam results obtained using Photonis XP85011 to detect secondary particles of an electromagnetic shower. We focus on the use of the multiple pixels on the Photonis MCP in order to find a transverse two-dimensional shower distribution. A spatial resolution of 0.8 mm was obtained with an 8 GeV electron beam. A method for measuring the arrival time resolution for electromagnetic showers is presented, and we show that time resolution better than 40 ps can be achieved.

1. Introduction

In order to collect large datasets needed for precise characterization of the Higgs boson, and in order to increase new physics discovery potential, future high-energy hadron colliders, as well as the High Luminosity LHC (HL-LHC) upgrades are expected to deliver peak luminosities in excess of $5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. With the increased instantaneous luminosity the simultaneous interactions per bunch crossing (pileup) increase the likelihood of confusion in the reconstruction of particles from the hard scatter interaction with those produced in different pileup interactions. The ability to discriminate jets, photons, and electrons produced in the events of interests from pileup becomes significantly degraded.

One way to mitigate the pileup confusion effects, complementary to precision tracking methods, is to perform a time of arrival measurement associated with a particular layer of the calorimeter, allowing for a time assignment for charged particles and photons. Achieving such a time measurement with resolution better than 20–30 ps can effectively reduce the impact of pileup by a factor of 5. The ultimate goal is to develop an electromagnetic calorimeter with the same capabilities as the ones used in the CMS and ATLAS experiments, but with the enhanced capability to achieve time measurements at precisions of 20–30 ps. In this paper we continue our investigation of the development of such a calorimeter [1–4].

The use of micro-channel plates (MCP) as the active element of a shower-maximum detector or a calorimeter has been studied in the past [5,6]. These studies demonstrated the linearity in the multiplicity of secondary shower particles that have energies that the MCP can detect. Such detectors are also a promising option for achieving time measurement precision at the level of a few tens of picoseconds [2–4,7]. Moreover, such devices are intrinsically radiation hard and thus would tolerate the harsh radiation environment at future hadron colliders, particularly when operated without the reliance on a photocathode. In reference [4], we have demonstrated that the intrinsic fluctuations of electromagnetic showers induce jitter on the time measurement that is less than 10 ps, removing one important potential fundamental limitation. A further advantage of MCP's is their capability for highly segmented readout, allowing for the possibility of a highly granular calorimeter with sub-millimeter spatial resolution. Such high-granularity calorimeters have been studied in the context of detector concepts for the ILC [8] and the HL-LHC upgrade of the CMS experiment [9], indicating that such calorimeters have promising potential for substantial improvement in physics reach at the TeV scale. In this paper, we complement our past results [1–4] with additional studies of the position and time resolution for a calorimeter prototype with highly granular readout.

In this and the three previous papers we used three different MCP-PMTs:

- Photek 240: our most performant device, which provides the best time resolution, and excellent uniformity across the

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* Corresponding author.

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detector. The main parameters of the Photek 240 were reported in Ref. [2]. The pore size is 10 μm and the distance from the photocathode to the first amplification stage is 5.3 mm. The Photek 240 has a 41 mm^2 circular sensitive area, and it was operated 4.8 kV high voltage (HV). The gain at this voltage is about 10^6. The non-uniformity of the time response of the signal is limited to below 3.9 ps across the full sensitive area.

- Photonis XP85011: the anode of this MCP is composed of 64 pads, arranged as an 8×8 matrix. The size of each pad is $6 \times 6\ \text{mm}^2$. The pore size is 25 μm. The non-uniformity of the time response across the photocathode is 37 ps [2,4]. The HV applied to the Photonis XP85011 was 2.4 kV, with a corresponding gain of 10^6.
- Photonis XP85012: mostly identical to XP85011, also composed of 64 pixels arranged as an 8×8 matrix. Additionally it can be operated in a mode with a reverse voltage applied to photocathode, which enables us to effectively turn off any signals from the photocathode. When operated in this mode, the only signals are directly from secondary shower particles [3].

In this paper, we report on our studies of the high-granularity shower-maximum detector prototype that uses the Photonis XP85011 MCP as the active element. As demonstrated in reference [2], due to the fact that the input window is very thin, the signal in this device is dominated by direct detection of secondary shower particles, while Cherenkov photon signals contribute only 30% of the amplitude. The MCP is used to sample the electromagnetic shower induced by a beam of electrons impacting a tungsten absorber layer that has a thickness of about 4 radiation lengths (X_0). The MCP-PMT is read out with a pixelated anode, with square pixels of size $6 \times 6\ \text{mm}^2$. The energy of the electromagnetic showers is reconstructed using the total collected charge and the positions are reconstructed using a simple energy-weighting algorithm, described in Section 4. Through the use of a high-precision motorized stage, a position scan is performed during beam-tests and the position resolution of the shower-maximum detector is obtained. Finally, we investigate the precision of measuring the arrival time of electromagnetic showers with such a pixellated shower-maximum detector.

The paper is organized as follows. In Section 2 we describe the experimental setup used to perform the measurements, in Section 3 we present the event selection and pulse reconstruction, in Sections 4 and 5 the results on measured position and timing resolutions are presented.

2. Experimental setup

The experiment was performed at the MTEST location of the Fermilab Test Beam Facility using an 8 GeV beam primarily comprised of electrons. A differential Cherenkov counter, located further upstream of the MTEST location, was used to enhance the purity of electrons and to suppress pions, by requiring a signal consistent with a passage of electrons through the device. All other detectors were placed inside a dark box lined with copper foil for electromagnetic shielding. A photograph of the experimental setup within the dark box is shown in Fig. 1. A scintillator of size 1.7 mm × 2.0 mm optically coupled to two photomultiplier tubes, one on each side, was used to trigger the data acquisition and to constrain the trajectory of the electrons from the beam. Downstream of the trigger, a tungsten absorber with a thickness of about 1 cm, equivalent to about 4 radiation lengths, was placed. The Photonis XP85011 MCP-PMT with pixelated readout was set on a high precision motorized stage and placed behind the tungsten absorber. The precision of the motorized stage is about 0.1 mm. To avoid unintended early showers due to interactions with the material of the casing and MCP device, the Photek 240 MCP-PMT was placed behind the Photonis XP85011 MCP-PMT.

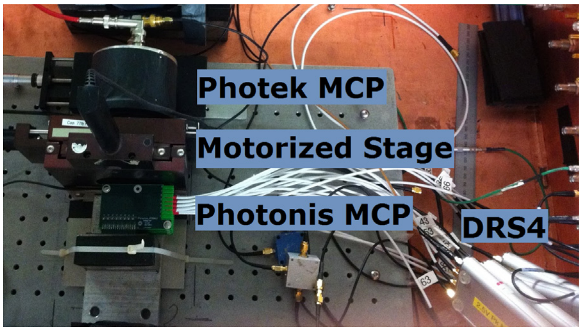

Fig. 1. The experimental setup inside of the dark box is shown. The beam direction is from the bottom of the photograph to the top. The detector elements shown in the order from upstream to downstream of the beam are: the tungsten absorber, the Photonis XP85011 MCP-PMT located on the motorized stage, and the Photek 240 MCP-PMT used as a time reference detector. The DRS4 waveform digitizers are also shown on the lower right side.

An external view of the Photonis XP85011 MCP-PMT is shown on the left of Fig. 2, and a schematic diagram is shown on the right. There are a total of 64 pixels arranged in an 8×8 square that can be read out individually. For our experiment, the nine pixels shown within the red square are used. During the course of the experiment we found that the pixel labelled 44 in Fig. 2 did not function properly and was therefore not used in the analysis of the data.

Four DRS4 high speed waveform digitizers were used to acquire the signals from the Photek 240 MCP-PMT, the cherenkov counter, and the eight operational channels from the Photonis XP85011 MCP-PMT. In order to allow a synchronized readout of four separate DRS4 units we split the signals from the Photek 240 MCP-PMT into four, and connected them to each of the four DRS4 units, thus achieving a "calibration" between the four different units.

3. Event selection and pulse reconstruction

Reconstruction of the signal pulses and timestamps is performed using the identical methods described in our past studies [1–3]. In Fig. 3, we show example pulses from one pixel channel of the Photonis XP85011 MCP-PMT and the Photek 240 MCP-PMT digitized by the DRS4.

We measure time resolution as the standard deviation of the Gaussian fit to the time-of-flight distribution $t_0 - t_1$, where t_0 is the time recorded at the "start" detector, and t_1 is that of the "stop" detector. To assign a time stamp for each signal pulse, we first determine the time position of the pulse peak. A Gaussian function is fitted to the pulse maximum using three points before the maximum of the pulse peak and four points after the maximum. The mean value of the Gaussian was used as the time stamp for each pulse. A Photek 240 MCP-PMT, whose time resolution was previously measured to be less than 10 ps [3] was used as a "start" signal, while pulses from individual pixels on the Photonis XP85011 MCP-PMT were used as "stop" signals. More details on the pulse reconstruction algorithms that we use are presented in Ref. [2]. The integrated charge for each pulse is used as a proxy for the measured energy deposit in each channel, and is computed using four time samples before and after the peak of the pulse. Each time sample is approximately 0.2 ns in time. Events containing pulses above 500 mV in amplitude are rejected as they saturate the DRS4. Only pulses with amplitude larger than 20 mV are used for time measurements, to reduce the impact of the electronics noise in the DRS4. Other event selection and pulse cleaning procedures are