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Study of timing characteristics of a 3 m long plastic scintillator counter using waveform digitizers

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ABSTRACT

A plastic scintillator bar with dimensions 300 cm × 2.5 cm × 11 cm was exposed to a focused muon beam to study its light yield and timing characteristics as a function of position and angle of incidence. The scintillating light was read out at both ends by photomultiplier tubes whose pulse shapes were recorded by waveform digitizers. Results obtained with the WAVECATCHER and SAMPIC digitizers are analyzed and compared. A discussion of the various factors affecting the timing resolution is presented. Prospects for applications of plastic scintillator technology in large-scale particle physics detectors with timing resolution around 100 ps are provided in light of the results.

1. Introduction

Plastic scintillator detectors have been extensively used in particle physics experiments for decades. In large-scale experiments, they are typically arranged as an array of bars covering a large surface which can provide a fast trigger signal or particle identification using the time-of-flight (ToF) technique. Depending on the bar dimensions, scintillator type and light readout sensor, the time resolution[1] for such detectors typically ranges from 50 ps (0.5 m bars of the ToF system of MICE [1]) to 350 ps (6.8 m bars of the ToF system of OPAL [2]).

In practice, bars which are made of a bulk scintillator do not exceed 3 m in length. This restriction comes naturally from light attenuation within the plastic and an uncertainty related to the dispersion of photon path lengths which becomes dominant for long bars. Moreover, this uncertainty grows exponentially with decreasing bar thickness [3]. It makes a bar cross section close to a square shape advantageous in detectors [4–7]. However, when a detector covers a large surface, for reasons of economy, the bar thickness along the beam is often chosen to be significantly smaller than its width. In this case the thickness becomes a limiting factor for the precision of the time measurement. Recent examples of detectors using this type of bars are the trigger hodoscopes system in COMPASS [8] and in the NA61/SHINE ToF detector [9].

Another example of a detector which combines the requirements of a large covered surface and an excellent time resolution is the timing detector of the proposed SHiP experiment at the CERN SPS [10]. To efficiently distinguish between vertices from random muon crossings and genuine particle decays, the SHiP timing detector needs to cover a 6 m × 12 m area with a time resolution of 100 ps or better [11] at an affordable price, which is a challenge. One option considered in the SHiP technical proposal is an array of 3 m long plastic scintillator bars with the light collected by photomultiplier tubes (PMTs) [11]. Another feature of SHiP is a software trigger running on an online computer farm, thus favoring the use of a DAQ electronics which has the particularity to tolerate relatively high event rates and at the same time allow for each channel to operate in a self-triggering mode.

Novel types of acquisition electronics which perform waveform sampling using a switched capacitor array (SCA) have only recently been employed in particle physics experiments [12,13]. The use of an analogue memory which is added in parallel with a delay line allows for analog signal sampling at a very high rate. In addition, having the waveform recorded, one can extract various kinds of information such as baseline, amplitude, charge and time. The measurements presented in this article with a 3 m bar were made with the two acquisition

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[1] In this paper, the time resolution is expressed as the rms value if not otherwise specified.

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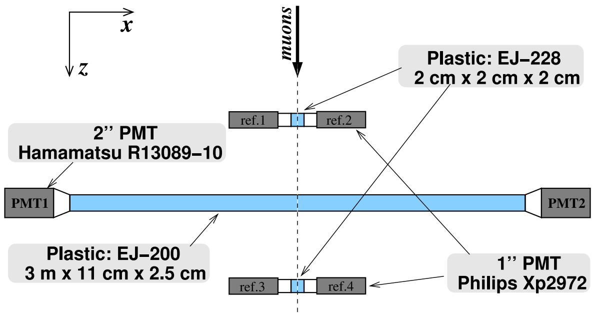

Fig. 1. Schematic top view of the experimental setup. The outputs of all 6 PMTs are connected to a single acquisition module.

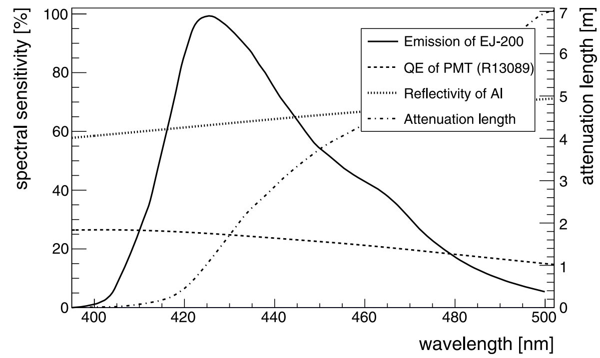

Fig. 2. Emission spectrum of EJ-200 [14] (arbitrary units) overlaid with the quantum efficiency of the PMT [15], the reflection efficiency of an aluminum foil [7] and the attenuation length[2] [16] (right axis).

modules WAVECATCHER [12] and SAMPIC [13]. The latter is proposed for the data acquisition system for the SHiP timing detector. The test-bench used here can thus be considered as a prototype for the design of the timing detector of the SHiP experiment described in the technical proposal [11].

The article is organized as follows. The experimental setup is described in Section 2. Section 3 provides a detailed description of the DAQ electronics. The analysis procedure is presented in Section 4. The results of the measurements are discussed in Section 5. Finally, a summary is given in Section 6.

2. Experimental setup

We present results of test-beam measurements which took place at the CERN PS in June 2016. The layout of the setup is shown in Fig. 1. The coordinate system is chosen such that the z axis is directed along the beam, the x axis is along the bar and the y axis is directed vertically in such a way that the coordinate system is right-handed. The origin of the system is at the left side of the bar, in the center of the yz cross section.

2.1. Plastic bar and PMTs

The scintillator bar was purchased from the SCIONIX Radiation Detector & Crystals company [14]. The bar length is 300 cm and its transverse cross section is 2.5 cm × 11 cm. The two larger surfaces of the bar (300 cm × 11 cm) were in contact with a casting form and had no other preparation. The four other surfaces were diamond milled. The choice of plastic was primarily driven by the length of the bar: EJ-200 provides an optimal combination of a suitable optical attenuation length, fast timing and high light output. The properties of EJ-200 quoted by the producer are: a rise time of 0.9 ns; a decay time of 2.1 ns; a bulk attenuation length of 4 m; and a refraction index of 1.58. The peak in the emission spectrum resides in the violet region of the visible spectrum. As shown in Fig. 2, this spectrum is compatible with the sensitivity region of the PMT and the reflection efficiency of an aluminum foil which was used to wrap the bar.

The bar is attached via tapered light guides to 2'' phototubes on both ends. The fast Hamamatsu R13089-10 PMT [15] is chosen because of its good time resolution and moderate cost. It has a linear-focused dynode structure with 8 stages and a typical anode gain value of 3.2×10^5. The voltage divider optimized for timing applications was provided by the company. The PMT output signal was coupled directly to the acquisition module. This results in a signal amplitude in the range 30–150 mV (given for the most probable value) which fits perfectly the dynamic range of the acquisition modules. The quantum efficiency of the photocathode as given by the manufacturer is 25% at the emission peak for the scintillator (see Fig. 2). Parameters relevant for the precision time measurements are a rise time of 2 ns and a transit time spread[3] of 230 ps.

The phototubes were pressed towards the light guides. The probable presence of air gaps between the photocathode and plastic may however reduce the amount of photons at large angles due to total internal reflection. Also, the cross-sectional area of the bar is larger than the area of the photocathode by about 34%. Due to phase-space conservation of the photon flux the light output should be reduced by about the same amount in the case where an interaction took place in the proximity of the PMT.

The bar and PMTs were fixed to an aluminum frame which could be moved vertically and horizontally with respect to the beam.

2.2. Beam and trigger system

Measurements were carried out using a 10 GeV/c muon beam produced by interactions of 24 GeV/c protons from the CERN PS accelerator with closed shutters at the T9 beam line of the East Hall.

The trigger was formed by the coincidence of signals from two beam counters installed 50 cm up- and downstream with respect to the bar under test as shown in Fig. 1. The counters are shaped as cubes with 2 cm sides made of a fast EJ-228 scintillator with rise and decay constants 0.5 ns and 1.4 ns, respectively. They were coupled to 1'' PMTs (Philips Xp2972) from two sides via 5 cm long light guides.

The trigger time is calculated as an average of the measurements of all four trigger PMTs. This time is used as a reference for the measurement of the counter under test. The resolution of the trigger system is derived from the width of a distribution of the time difference between the time measurements by up- and downstream counters. It is found to be 40 ps. Another contribution to the trigger time resolution is associated with a finite size of the beam counters. It was estimated to be 36 ps assuming a uniform distribution of the beam within the counter area. Both contributions are further subtracted in quadrature from the uncertainty obtained with the counter under test.

3. DAQ electronics

The major design criterion for the DAQ system is an internal time resolution which has to be much better than the expected resolution of the scintillator counter. The chosen electronics modules WAVECATCHER [12] and SAMPIC [13] are based on waveform digitizer ASICs which have been developed by LAL and IRFU teams since 1992. The technology employs a circular buffer, based on arrays of switched capacitors (SCA) which record an analogue signal at very high rate. The

[2] Measurements presented in Ref. [16] are done for BC-412 which is based on polyvinyltoluene as EJ-200.

[3] A spread of fluctuations of the transit time for a single photoelectron [15].