

Plastic scintillator detector with the readout based on an array of large-area SiPMs for the ND280/T2K upgrade and SHiP experiments

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Plastic scintillator detectors have been extensively used in particle physics experiments for decades. A large-scale detector is typically arranged as an array of staggered long bars which provide a fast trigger signal and/or particle identification via time-of-flight measurements. Scintillation light is collected by photosensors coupled to both ends of every bar. In this article, we present our study on a direct replacement of commonly used vacuum photomultiplier tubes (PMTs) by arrays of large-area silicon photomultipliers (SiPMs). An SiPM array which is directly coupled to the scintillator bulk, has a clear advantage with respect to a PMT: compactness, mechanical robustness, high PDE, low operation voltage, insensitivity to magnetic field, low material budget, possibility to omit light-guides. In this study, arrays of eight $6 \times 6 \text{ mm}^2$ area SiPMs were coupled to the ends of plastic scintillator bars with 1.68 m and 2.3 m lengths. An 8 channel SiPM anode readout ASIC (eMUSIC) was used for the readout, amplification and summation of signals of individual SiPMs. Timing characteristics of a large-scale detector prototype were studied in test-beams at the CERN PS. This technology is proposed for the ToF system of the ND280/T2K II upgrade at J-PARC and the timing detector of the SHiP experiment at the CERN SPS.

KEYWORDS: MPPC, SiPM array, Plastic scintillator, Timing detector, ToF, SHiP, ND280, T2K

1. Introduction

A study of timing properties of a detector assembled from long plastic scintillator bars which are read out by silicon photomultiplier (SiPM) arrays is presented. SiPMs are widely employed in high energy physics detectors. The fast evolution of the SiPM market opens new possibilities. Large-area sensors are nowadays available in the market at a reasonable price. When assembled in a 2D array they can cover a sizeable area, therefore they can be considered as a promising direct replacement for traditional photomultiplier tubes (PMTs). In particular, the sensors can be coupled directly to a scintillator bulk to provide a time resolution on a sub 100 ps level [1]. An obvious advantage of an SiPM array is that it can take a form of the bar cross-section, thus avoiding complex shape adiabatic light-guides.

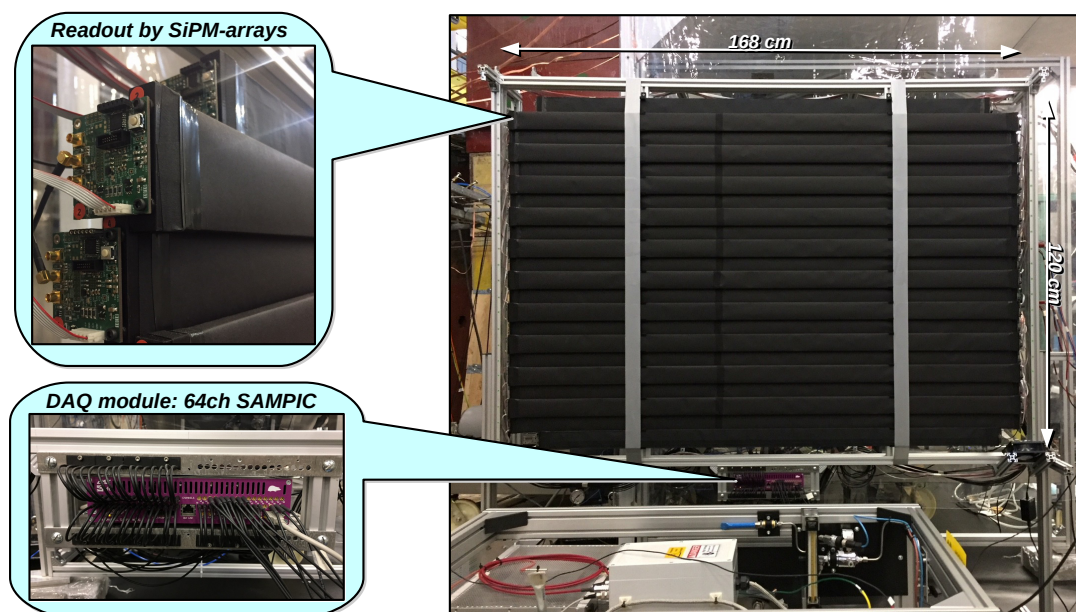


Fig. 1. A front view of the prototype detector which was assembled in summer 2018. Two inserts on the left-hand side represent a zoomed view of the eMUSIC readout board (*top*) and the 64 channel SAMPIC data acquisition module (*bottom*).

A large SiPM capacitance increases the rise time and width of a signal and thus worsens the time resolution. In this regard, a large monolithic sensor or many smaller sensors with common cathode and anode cannot be employed. An improvement can be achieved by using an independent sensor readout to isolate the sensor capacitances from each other. Signals can be amplified and summed afterwards either by a discrete circuit [2] or by an ASIC without the drawback of adding the sensor capacitances at the input. The eMUSIC ASIC [3] was adopted as an input stage of the acquisition system.

A detector configuration where SiPM arrays are coupled to long plastic scintillator bars, signals of SiPMs are read out by the eMUSIC chip and, finally, analog signals are digitized by a Waveform and TDC converter (WTDC) is proposed for the time-of-flight (ToF) system of the ND280/T2K II upgrade [4] at J-PARC and the timing detector of the SHiP experiment [5] at the CERN SPS.

2. Large-scale prototype

A 22 bar prototype, shown in Fig. 1, was assembled and exposed for one month to test beams of the CERN PS in summer 2018. In addition to the test of operating performance of the prototype itself it was also used as a time-of-flight detector for the identification of particles with momenta up to 6 GeV/c. The particles were identified via measurements of the time difference between the prototype and a beam counter, S1, installed 10.9 m upstream.

The choice of scintillator material was driven by the need to achieve precision timing by detecting as many photons as possible for interactions occurring all along the full length of a bar. The scintillator EJ-200 provides an optimal combination of a high light output, suitable optical attenuation length of about 4 m, and fast timing (rise time of 0.9 ns).

An array of 8 surface-mount devices S13360-6050PE (area $6 \times 6 \text{ mm}^2$, pixel pitch $50 \mu\text{m}$) from Hamamatsu has been mounted to a custom-made PCB, as shown in Fig. 2 (left). A charge produced in the array was sent via a high-density connector to a general purpose mini-board which was based on

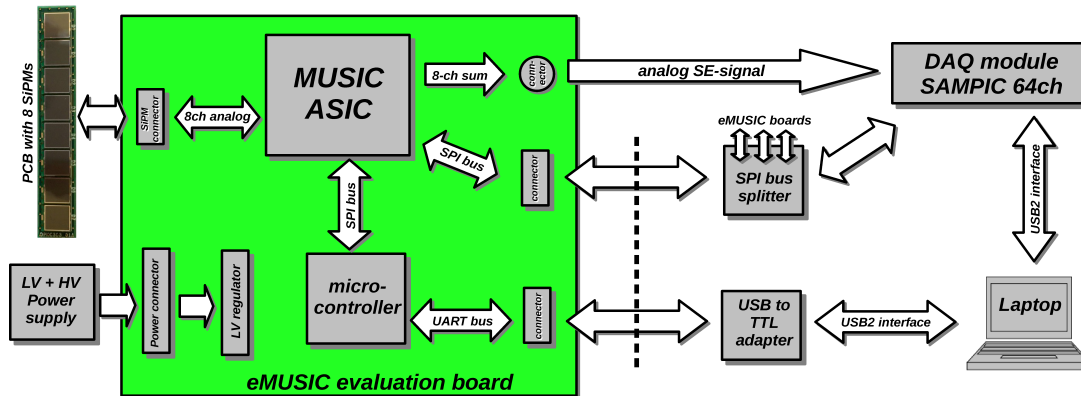


Fig. 2. A block diagram of the eMUSIC mini-board profiles (*left-hand side*) and a schematic representation of a data flow (*right-hand side*).

the eMUSIC chip [3] providing either an individual SiPM readout or an analog sum of all eight SiPM channels. The outputs of the chip could be easily monitored via coaxial RF connectors as a differential or single-ended signals. The eMUSIC chip has several configuration parameters accessible via an SPI protocol, i.e. a tunable pole-zero cancellation providing output signals with less than 10 ns FWHM; two different gain options; a bias voltage of every SiPM could be controlled using an internal DAC with 1 V dynamic range; any of channels could be powered-off.

A block diagram of the eMUSIC mini-board is presented in Fig. 2. There are two ways to modify and upload parameters to the ASIC.

- (1) A limited programmability profile (UART). In this case, the eMUSIC board has to be connected to a PC via an external UART-to-USB adapter. An in-board microcontroller is used as a bridge to send configurations to a non-volatile memory of EEPROM. The microcontroller dumps this configuration to the eMUSIC chip as soon as the board has been switched on.
- (2) A full programmability profile (SPI). In this mode, the embedded microcontroller is bypassed and the external master takes control of the SPI bus. This profile is suitable for applications where a frequent reconfiguration of the eMUSIC chip is required. In this mode, the control is taken by an FPGA of the DAQ module. An SPI bus from multiple eMUSIC mini-boards is propagated to the DAQ module using SPI-splitter boards.

A 64 channel SAMPIC module [6] was used to digitize the signals (see Fig. 1). SAMPIC is a 16 channel ASIC implementing a novel type of digitizing electronics which performs both the function of a TDC and a waveform sampler based on a switched capacitor array. Having the waveforms recorded, one can extract various kinds of information such as baseline, amplitude, charge and time. The SAMPIC circular buffer contains 64 cells which makes possible to cover a 20 ns time window at the sampling frequency of 3.2 GS/s. In addition to the TDC, the ASIC contains one on-chip ADC per cell which makes the charge digitization particularly fast. Each SAMPIC channel integrates a discriminator which can trigger itself independently of other channels. It is an important feature for neutrino experiments which do not have triggers induced by incoming particles.

The time resolution of a bar was determined by placing two reference counters of $20 \times 20 \text{ cm}^2$ size up- and and downstream of the bar as described in Ref. [1]. The time defined by the reference counters (resolution of 20 ps) was subtracted from the time measurement of the bar. The time resolution of two bars with dimensions $230 \times 12 \times 1 \text{ cm}^3$ and $168 \times 6 \times 1 \text{ cm}^3$ is shown in Fig. 3. The resolution evolves from 80 ps for the crossing point located near the sensor, to 310 ps (230 cm bar) and 180 ps (168 cm bar) for the crossing point located at the opposite end of the bar to that of the sensor, due to light propagation along the full length of the bar. The resolution, calculated as a weighted mean between

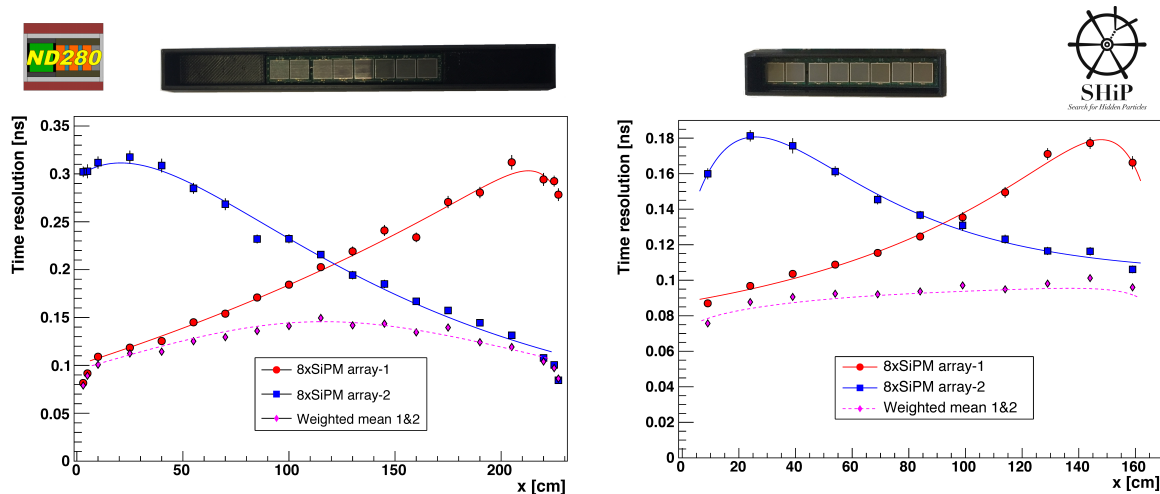


Fig. 3. Time resolution as measured by 8-SiPM arrays attached at both ends of a $230 \times 12 \times 1 \text{ cm}^3$ bar of ToF detector of ND280 (*left*) and a $168 \times 6 \times 1 \text{ cm}^3$ bar of timing detector of SHiP (*right*) as a function of the interaction point along the bar. Arrays of eight SiPMs fixed inside of light-tight cases are shown on top of corresponding figures. The sensitive area of each SiPM is $6 \times 6 \text{ mm}^2$.

SiPM-arrays located at two ends of each bar, makes the distribution more constant, i.e. 130 ps and 85 ps on average for two bars, respectively.

Some results obtained with the 22 bar prototype are presented in Fig. 4. The primary goal was to identify particles by calculating the time difference detected by the S1 counter and the prototype. A longer time was required by heavier particles to traverse this distance which could serve to identify the species. As an example, protons arrive at the prototype about 20 ns later as compared to positrons at $0.8 \text{ GeV}/c$. This interval shrinks to 3.8 ns at $2 \text{ GeV}/c$.

An ionization produced by charged particles and, in turn, an amount of optical photons generated in de-excitation processes depends on particle masses and is quite different at low momenta. The effect can be observed in the amplitude of recorded signals as shown in Fig. 4 (left). Amplitudes of the deuteron and proton signals ranges around 300 – 400 mV whereas signals of e , μ and π are spread from 50 to 400 mV. This information can also be used for the particle identification.

The technology described in this article has been proposed for two time measuring detectors which are presented in the following sections. Both detectors are located in zones of strong magnetic field.

3. Time-of-flight detector for the ND280/T2K II upgrade

The goal of the T2K experiment is to study neutrino flavor oscillations employing an off-axis neutrino beam from the J-PARC accelerator facility. The near detector of T2K, ND280, is used to study neutrino interactions aiming for neutrino cross-section measurements and reduction of systematic uncertainties in neutrino oscillation analyses.

A layout of the ND280 detector proposed for the upgrade of T2K [4] and the ToF detector itself are shown in Fig. 5. The ToF system will consist of 6 planes surrounding the active target [7] and two TPCs. Each plane will have about 5 m^2 surface area. The ToF aims at precise measurements of the crossing time of charged particles as they exit or enter the TPCs. A time resolution of 500 ps or better is required for an unambiguous determination of the flight direction of charged particles. An additional goal is to improve particle identification, requiring the time resolution of 100 – 200 ps. The whole system will be located inside the UA1 magnet which will create a field of 0.2 T. The presence

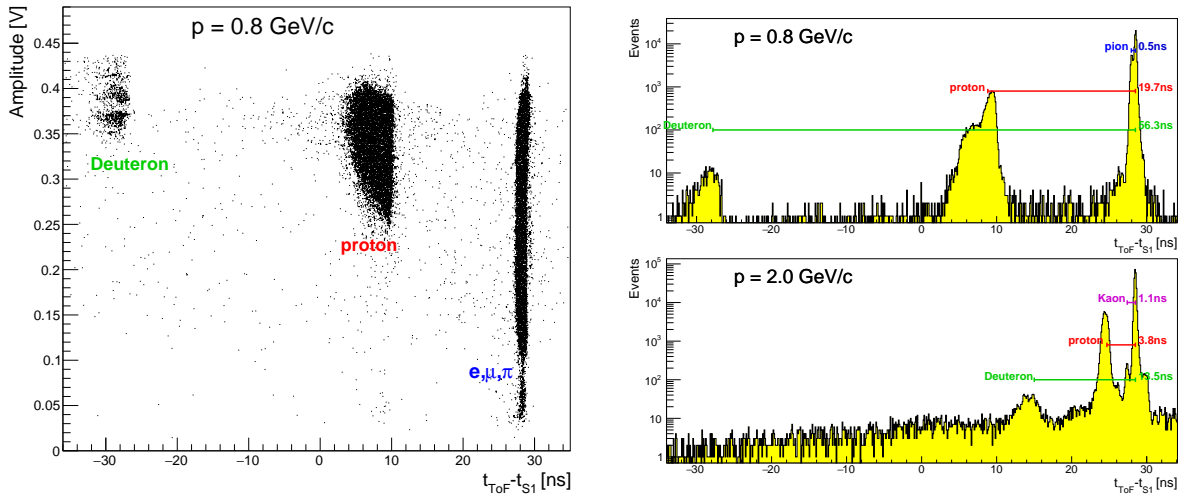


Fig. 4. *Left:* a correlation plot presenting a signal amplitude versus time required by 0.8 GeV/c particles to traverse a 10.9 m distance between the beam counter S1 and the ToF prototype. *Right:* a time required by 0.8 GeV/c and 2 GeV/c particles to traverse the distance between S1 and the ToF prototype.

of the magnetic field and a very limited space for the detector makes the use of the SiPM readout particularly advantageous. The detector will be assembled from 118 bars with a length of 2 to 2.3 m which will provide a time resolution of approximately 150 ps along the bar as shown in Fig. 3 (left). In total, the number of DAQ channels is 236 and the number of SiPMs is 1888.

4. Timing detector of SHiP

SHiP is a new general-purpose experiment [5] proposed for installation at a beam dump facility of the CERN SPS to search for hidden particles as predicted by a very large number of recently elaborated models of Hidden Sectors which are capable of accommodating dark matter, neutrino oscillations, and the origin of the full baryon asymmetry in the Universe.

The SHiP spectrometer and the timing detector are shown in Fig. 6. The timing detector will be positioned downstream of the vacuum decay vessel and will cover a $5 \times 10 \text{ m}^2$ area. The main purpose of the detector is a reduction of the combinatorial background (vertices made by a random muon crossing) by tagging particles belonging to a single event. The time resolution is required to be better than 100 ps. The detector can also be used for identification of few GeV particles. The 100 ps resolution constraint limits the possible bar length to approximately 2 m. Therefore an array of 3 columns and 182 rows assembled from 167 cm long bars is considered as a base option for the present design of the detector. Altogether, it results in 546 bars, 1092 channels and 8736 SiPMs. The test-beam measurements for a single bar resulted in about 85 ps time resolution as shown in Fig. 3 (right).

5. Conclusions

A study on a direct replacement of vacuum photomultiplier tubes by arrays of large-area silicon photomultipliers has been presented. Arrays of SiPMs were coupled to the ends of long plastic scintillator bars. An 8 channel chip, eMUSIC, was used for the readout, amplification and summation of signals of individual SiPMs. A 64 channel SAMPIC module was used for the data acquisition. Results obtained in test-beams with a 22 bar prototype detector have been presented. This technology is proposed for the ToF system of the ND280/T2K II upgrade at J-PARC and the timing detector of the SHiP experiment at the CERN SPS.

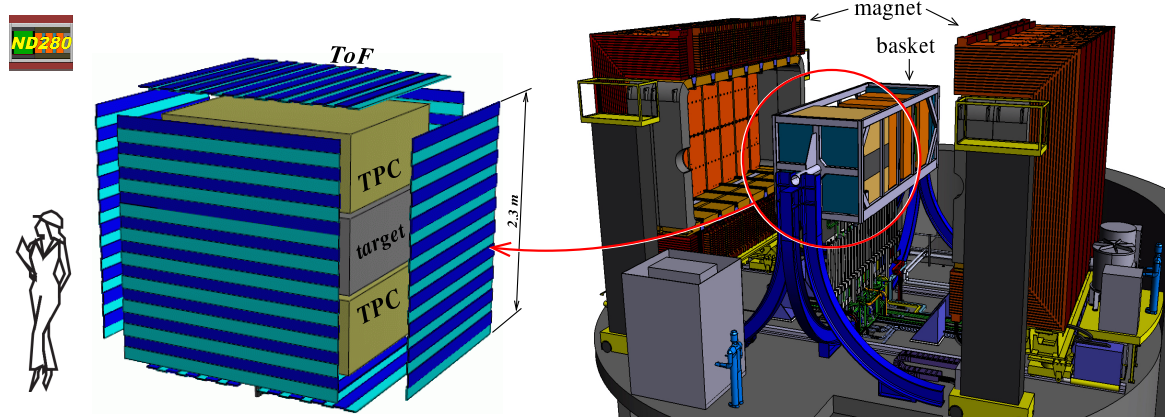


Fig. 5. Layout of the ND280 detector proposed for the T2K II upgrade, with magnets opened such as to see the inner basket (*right*). The part of the basket to be upgraded is shown *on the left*. It includes the active target and two TPCs, all surrounded by 6 ToF planes.

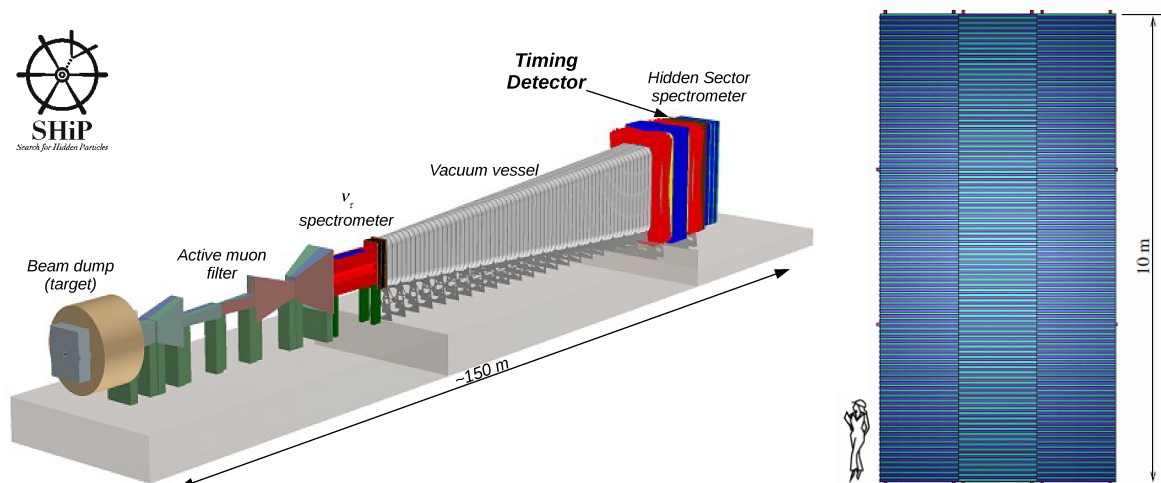


Fig. 6. *Left*: the SHiP experimental facility. *Right*: schematic view to the SHiP timing detector which will be located downstream of the vacuum vessel, in front of an electromagnetic calorimeter.

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