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Development of a silicon micro-strip detector for tracking high intensity secondary beams

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ABSTRACT

A single-sided silicon micro-strip detector (SSD) has been developed as a tracking detector for hadron experiments at J-PARC where secondary meson beams with intensities of up to 10^8 Hz are available. The performance of the detector has been investigated and verified in a series of test beam experiments in the years 2009–2011. The hole mobility was deduced from the analysis of cluster events. The beam rate dependence was measured in terms of timing resolution, signal-to-noise ratio, and hit efficiency. This paper describes the detector with its read-out system, details of the test experiments, and discusses the performance achieved.

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1. Introduction

Silicon micro-strip detectors are widely used in particle physics [1], and they are now a common tool also in the other experimental fields such as nuclear physics [2,3] and astro physics [4,5]. Such detectors offer the advantage of combining precise position resolution with low particle hit occupancy due to their fine segmentation. The former is suitable for measurements of short life-time particles, and the latter opens a door for accepting high intensity beams.

The single-sided silicon strip detector (SSD) was developed as a tracking device at the K1.8 beam line of the J-PARC Hadron Experimental Facility. The beam line is designed for systematic study of hypernuclear systems and strangeness physics where the highest intensity secondary meson beam ever can be provided at the final focus (F.F.): 1 MHz kaon beam with purity $K/(\pi+\mu)$ of 3.5 under the primary proton beam condition of 30 GeV to 9 μA as well as pion beam of more than two orders of magnitude higher intensity [6]. So far, wire chambers have been used as a tracking detector for these experiments. However, due to the discharge effect, among others, the incident beam rate of $\sim 10^5$ Hz/wire for an anode pitch of 1 mm is a limit for the stable operation, which is equivalent to a beam rate of ~ 4 MHz at the F.F. of the K1.8 beam line for the typical beam profile. To stand such beam rate and beyond, the SSD was developed. It was designed to be installed near the F.F. where the beam rate per unit area becomes high and the precise position resolution is desirable.[1]

The requirements for the SSD are summarized as follows:

- The sensor should have enough radiation tolerance (5×10^{11} particles/cm^2).
- The effective acceptance of the sensor should cover the typical beam spread of 56×28 mm^2 (FWTM) around the F.F. of the K1.8 beam line.
- The position resolution should be better than that of conventional wire chambers (about 200 μm in r.m.s.).
- The hit time resolution must be less than 5 ns even under high-intensity beam condition ($>10^7$ Hz) to reduce accidental hits.

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[1] The SSDs were used during the J-PARC E10 experiment [7] as a tracking detector.

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- The signal-to-noise ratio should be exceed 10 for minimum ionizing particles (MIPs), considering the pedestal fluctuation.
- The hit efficiency should be more than 95%.

The first three issues are associated with the selection of the silicon sensor itself, whereas the remaining issues are essential performance requirements of the SSD to be verified. Experience with utilizing silicon detectors under high-intensity beam condition for fixed-target experiments are reported in Refs. [2,3,8]. We describe the performance of the fabricated SSD depending on the beam rate, studied in several test experiments in 2009–2011.

The introduction of the detector hardware and the readout system for the SSD is presented in Section 2. The experimental setup, the data analysis procedure, and the main results are described in Section 3.

2. Hardware and readout system

2.1. Silicon sensor

The silicon sensor, originally developed by the ATLAS SCT collaboration [9], is a p-in-n type single-sided silicon strip detector of 300 μm thickness fabricated by Hamamatsu Photonics K. K. It has a total of 768 strips with a strip pitch of 80 μm and the full acceptance of $62.0^W \times 61.6^H$ mm^2 which covers the typical beam spread around the F.F. of the K1.8 beam line. The radiation tolerance was investigated that a total dose of 3×10^{14} protons/cm^2 was still the range of operational lifetime [9]. This guarantees that the sensor can be used for more than one year with continuous 10 MHz beam irradiation at J-PARC though a replacement of the detector may be necessary when the sensor deteriorates as there is no cooling system. The full depletion voltage (+80 V) for an undamaged sensor was determined from a current–voltage characteristics scan. The bias is applied from the n-side electrode while the p-side electrodes are grounded.

2.2. Frontend readout chip

The analog signals induced on the strips are read out using a frontend chip, called APV25-s1 [10]. It is an analog pipeline ASIC designed for the CMS experiment at the LHC, and each of the 128 channels consists of a CR-RC type shaping amplifier and a 192 cell deep analog pipeline. The pipeline is synchronized to a reference clock and the analog output of the amplifier is sampled and stored in the cell at each clock timing. When a trigger is issued on the chip, pre-assigned cells are read out and fed to the multiplexer in the multi-peak mode [11]. Owing to this function, timing information can be extracted by reading successive cells, as detailed in Section 3.1. The outputs of 128 channels are multiplexed and are first transferred to a repeater board which is located near the SSD, before they are sent to a VME module via an Ethernet cable of 30 m length. The repeater board is not only a bridge for transmitting signals between the readout chips and the VME system, but also a hub for supplying the electric power of the APV25 chip and the bias voltage for the sensor. One sensor is bonded to a total of six APV25 chips via a pitch adapter that matches the pitch of the strips on the wafer to the bond pads of the APV25 chip. The assembled SSD is shown in Fig. 1.

2.3. Data acquisition

The multiplexed analog data are processed by the VME system consisting of an on-board CPU controller and the readout modules, called APVDAQ. This module has been developed by the HEPHY Vienna group at the Austrian Academy of Sciences and it is specialized in the control of the APV25 chip and the management of the data stream. One APVDAQ handles four APV25 chips in parallel, therefore, two APVDAQ modules constitute the readout chain of one SSD. The incoming analog data are digitized by 10 bit FADCs and then stored in RAM on an FPGA. The implementation of the zero suppression logic and the multi-buffering system have been done by upgrading the FPGA firmware. By this improvement, the readout DAQ system can handle a trigger rate of up to 6 kHz for a single SSD with a reasonable threshold set for the zero suppression logic. The APVDAQ mounts a 40 MHz oscillator which distributes the clock timing to other APVDAQs and APV25 chips so that the whole electronics circuit is synchronized. The number of cells to be read out from one APV25 chip is controlled via APVDAQ and was set to 6 per channel throughout the test experiments as described in Section 3.

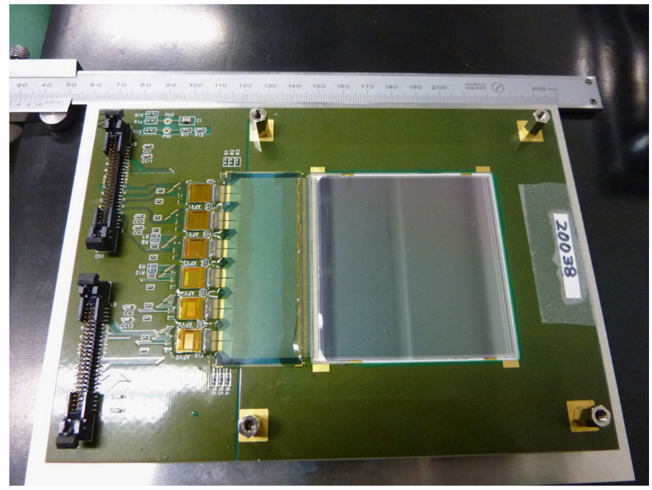

Fig. 1. Photograph of the fabricated SSD module.

3. Performance

3.1. Experimental set-up and data analysis process

The basic performance of the SSD was evaluated during the experiment E364 at the ESS course of Research Center of Nuclear Physics (RCNP) in Osaka University. The experiment was dedicated to a study of the silicon-emulsion hybrid system, which is an essential part of the double hypernuclei search experiment (E07) [12] at J-PARC. Four SSDs were stacked with the direction of X–Y–X–Y, and placed in front of an emulsion plate. The event trigger was made from the coincidence of hodoscopes surrounding the hybrid system. A proton beam with the kinetic energy of 100 MeV irradiated the SSD stack after passing an energy degrader. The average beam rate was adjusted to around 10 Hz for collecting data without the zero suppression logic. The beam tracks were perpendicularly incident on the SSD plane, and then obliquely incident by rotating ($\theta = 10^\circ$, 20°, 30°, 45°) the entire hybrid system, centering around the SSD stack. A thinner energy degrader was used for $\theta = 10^\circ$, 30° setting, which slightly changed the energy of the incident proton beam. The detector setup is illustrated in Fig. 2.

The off-line analysis to extract hit information from the SSD starts with the pedestal subtraction for each channel and a subsequent cut on the ADC. If none of the ADC values within six samples exceeded a threshold, the channel was rejected. For the remaining channels, a shape analysis was performed. The APV25 chip has a CR-RC shaper with a time constant τ of 50 ns [10], therefore the signal shape can be represented as a function

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