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Spatial distributions of photons in plastic scintillator detected by multi-anode photomultiplier for heavy-ion position determination

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ABSTRACT

The spatial distributions of scintillation photons in a plastic scintillation detector were measured using a multi-anode photomultiplier H7546A coupled with 1-mm-diameter optical fibers. A row of several tens of fibers connected to the scintillator generates one-dimensional spatial distributions of photons induced by the swift passage of heavy ions. The pulse heights from each channel change depending on the beam position. This can be utilized to determine the positions of the heavy ions. To test the performance of the proposed detection method, an experiment using a ^{84}Kr beam with intermediate energies ranging from 40 to 85 MeV/nucleon was performed at the heavy-ion medical accelerator in Chiba (HIMAC). The photon spatial distributions were successfully observed. By optimizing the photomultiplier bias voltage and threshold in the pulse height analyses, a detection efficiency of 98% and a position resolution of 1.1 mm in σ were achieved simultaneously.

1. Introduction

The science of radioactive isotope (RI) beams has advanced with the development of heavy-ion accelerators and fragment separators. High-resolution heavy-ion detectors play an important role in identifying and separating secondary beams in fragment separators. Among the various types of detectors, position-sensitive detectors are important not only for beam diagnostics and tuning beam line magnets, but also for magnetic rigidity analysis in particle identification and subsequent RI-beam experiments.

Today, a variety of position-sensitive detectors have been developed and are successfully used. For example, parallel plate avalanche counters (PPACs) [1] are often utilized as beam line detectors in intermediate-energy fragment separators. The position resolution of PPACs is excellent, whereas their detection efficiency for high-energy light particles is moderate. Also fiber scintillation counters are used in precision momentum tagging of secondary beams [2,3]. The fiber technique became very popular in nuclear and particle physics experiments. A good review can be found in Ref. [4] and the references therein. The intrinsic efficiency of scintillating fibers is high, even with respect to low-Z particles; however, thin clad layers surrounding the scintillating cores directly affect the uniformity of thickness and sensitivity.

As a complementary approach, we are developing a new method for position determination of heavy ions. When heavy ions pass swiftly through a scintillator, many photons are produced and emitted in an isotropic fashion. The spatial distribution of the scintillation photons correlates with the particle position on the scintillator. This principle can be applied to position-sensitive detection. A commercially available, high-sensitivity multi-anode photomultiplier coupled with thin optical fibers realizes the sampling of photon spatial distributions in a reasonable manner. The advantage of the present detector is that the plate of the scintillator provides high sensitivity and uniform thickness. Using a CsI crystal scintillator makes the detector compatible with an ultra-high vacuum condition such as that in storage rings.

A similar detection concept was reported, in which photon distributions from a large NaI(Tl) were directly viewed by several tens of photomultipliers [5]. The position detection was successfully performed. In the present study, we have developed a prototype of such a detector using a conventional plastic scintillator, and tested its performance by using a heavy-ion beam.

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2. Detector design

2.1. Principle of position detection

Fig. 1 shows the principle behind position detection using a spatial distribution of scintillation photons generated by the swift passage of heavy ions. The photons produced in a scintillator are emitted isotropically, and are read out by a multi-anode photomultiplier tube (MAPMT) through several tens of optical fibers connected to the side of the scintillator. Owing to a difference between the solid angles of different fibers and to an attenuation length in the scintillator, the maximal pulse height is expected to be observed at the fiber channel nearest to the beam position. As the distance from the beam position increases, the number of detected photons decreases. The pulse height distribution of all the channels represents a one-dimensional projection of the photon spatial distribution produced in the scintillator. Hereafter, we refer to the developed detector as the PD^2 (PDPD: photon spatial distribution position-sensitive detector).

2.2. Configuration of PD^2

The PD^2 prototype consists of a 5-mm-thick plastic scintillator with an effective area of 100 × 100 mm^2. As shown in Fig. 2, a row of 1-mm-diameter and 200-mm-long 64 optical fibers is sequentially connected to the side surface of the plastic scintillator by using optical cement. The pitch of the fibers is 1 mm. A schematic of the prototype is shown in Fig. 2. To avoid reflection of the emitted photons, the sides of the plastic scintillator are covered with black tape. The fibers are bundled by a black acrylic block for connecting to a MAPMT, H7546A (Hamamatsu photonics), by using optical grease. To minimize the cross-talk phenomenon on the MAPMT photocathode, each fiber is carefully guided to an individual channel of the MAPMT. For practical reasons, 32 channels out of 64 fibers are read out; the pitch of the readout fibers is then 2 mm with a few exceptions, and the detailed assignment is shown as black squares in the right inset of Fig. 2. The plastic scintillator with the fiber light guide was installed in a black light-shielded box without wrapping.

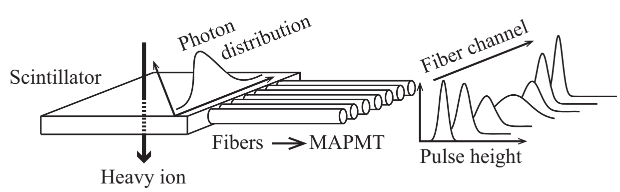

Fig. 1. Schematic of the principle of position determination using a scintillation photon spatial distribution.

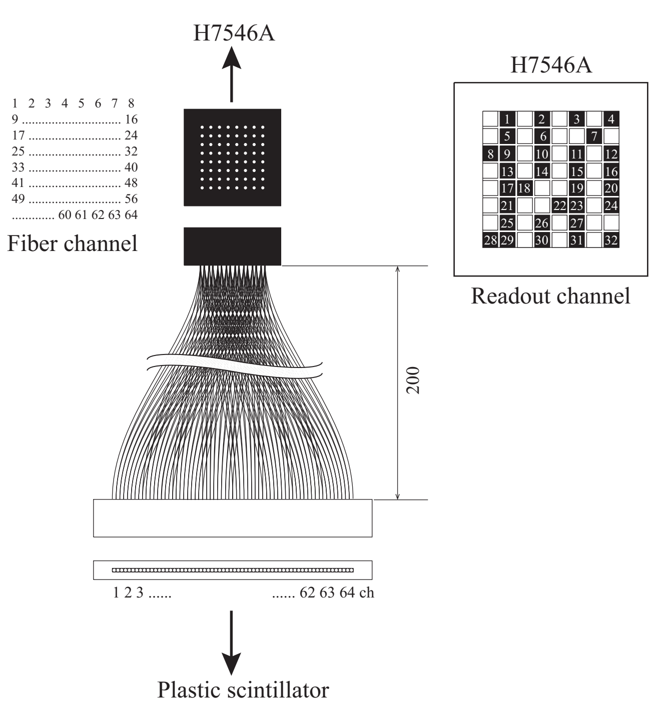

Fig. 2. Schematic of the fiber light guide of PD^2 and the assignment of readout channels (right).

3. Experimental details

To evaluate the PD^2 performance, we conducted a beam experiment at the heavy-ion medical accelerator in Chiba (HIMAC) synchrotron facility [6]. A ^{84}Kr beam with the energy of 200 MeV/nucleon was accelerated at the accelerator complex. Every 3.3 s the ^{84}Kr beam was slowly extracted from the synchrotron for about 1 s. The beam diameter was roughly 5 mm, and the beam rate was below 10^3 particles/spill. The experiment was performed at the final focal plane of the secondary beam line [7], where the detectors were set up as shown in Fig. 3.

The beam was extracted from a thin vacuum window of the beam line to air, and irradiated onto a 0.5-mm-thick plastic scintillation counter with an effective area of 100 × 50 mm^2. The coincidence signals that were read out at both ends by fast photomultipliers, H2431-50 (Hamamatsu photonics), generated the trigger signals of the data acquisition system event-by-event. A delay-line PPAC [1] (effective area of 100 × 100 mm^2, filled with C_3F_8 gas at approximately 10 Torr) in front of the PD^2 was used for determining the positions of the incident particles. The estimated position resolution of PPAC is 0.4 mm for a $Z=36$ beam quoted from Fig. 24 in Ref. [1]. A multi-sampling ionization chamber [8], located between the trigger counter and the PPAC, was placed to measure the energy resolution for a different purpose. The PD^2 that was assembled in a light-shielded box for this study was placed at the end of the beam line. The MAPMT with the fibers was arranged on the top, as shown in Fig. 3, to provide position information on the horizontal coordinate in the present setting. Note that the short ranges of Kr ions at this energy lead to the beam being stopped by the PD^2 scintillator, and the large energy deposit in the scintillator increases the detection efficiency of PD^2 relative to that of PPAC. In most cases, the energy deposit of Kr ions into the plastic scintillator was 6.4 GeV.

Fig. 4 shows a part of the block diagram of the electronics and data acquisition system based on the CAMAC platform. The signals from the 32 anodes of MAPMT were fed into fast amplifiers and then sent to the counting room. After timing adjustment by using delay modules, each signal was divided into two: one was fed into a 12 bit charge-sensitive ADC (Phillips 7166), and the other into a

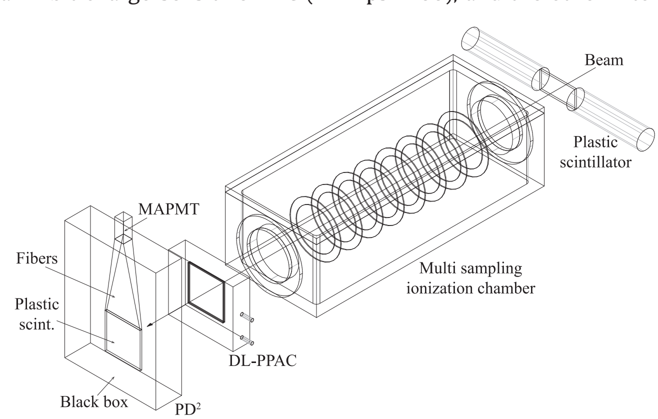

Fig. 3. Schematic of the experimental setup (not to scale).