A Silicon Telescope for Applications in Nanodosimetry

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***Abstract*—The position- and energy-sensitive primary particle detectors of a nanodosimetry system are described. They consist of a telescope of silicon strip detectors, which allow the determination of the particle's position from the hit strip address and its energy from the specific energy loss. In our implementation, the energy loss is measured through the time over threshold (TOT). When testing the performance of a single silicon strip detector, it was found that between the energies of 20 and 100 MeV, primary particle energy could be determined to an accuracy of 15%, decreasing to 25% at 250 MeV. Below 20 MeV, we observed TOT saturation. It is concluded that the performance of the tested silicon strip detector is suitable for application in nanodosimetry.**

I. Introduction

The goal of our research is to develop a silicon telescope that will have applications in nanodosimetry. It will provide a precise measurement of the energy and trajectory of individual charged particles inducing ionizations within the low-pressure gas volume of a nanodosimeter (ND) (Fig. 1). The ND technique, developed at the Weizmann Institute of Science, is based on the counting of individual ions deposited by the primary charged particles or delta electrons in a wall-less sensitive volume of equivalent nanometer dimensions, thus simulating DNA segments as described in [1]–[3]. By using a gas at low pressure instead of a solid, the basic interaction of ionizing radiation with molecules can be probed on the molecular scale. Experimental results obtained to date prove the feasibility of the ion counting technique with a vacuum-operated multiplier and demonstrate the possibility of nanometer spatial resolution [3].

To enhance the measurement capabilities of the existing ND, the silicon telescope, consisting of two detector modules, placed in front of and behind the sensitive volume, will be implemented. The new system will permit correlation of ND data with primary particle energy and position relative to the sensitive volume. In this paper, we describe the module's performance with respect to measuring particle energy, which was tested with protons over a wide range of energies.

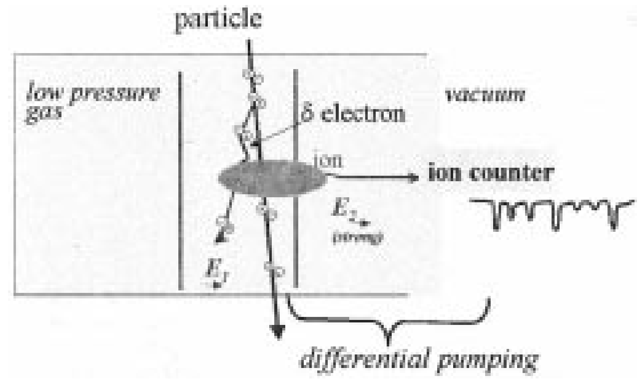

Fig. 1. A schematic diagram of the nanodosimeter based on single-ion counting. Only ions formed in the sensitive volume (shaded dark gray) are extracted with high efficiency and detected in the ion counter.

II. Primary Particle Detection Hardware

The telescope is made up of two modules, each consisting of a pair of single-sided silicon strip detectors (SSDs) with their strips oriented at right angles. These SSDs were developed for the gamma-ray large area space telescope (GLAST) and manufactured by Hamamatsu Photonics [4]. The detectors are constructed of p-on-n of 400 μm thickness, with a pitch of 194 μm, and outer dimensions of 6.4 by 6.4 cm. Fig. 2 shows one of the two modules. The SSDs provide information about the primary particle track from the strip-hit information as well as the particle's energy, which is determined via the specific energy deposition measured in each detector.

For the readout of the fast silicon detector signals, we are using a low-noise low-power front-end application-specific integrated circuit (ASIC) global trigger front end (GTFE) developed for the GLAST mission [5]. All GTFEs on one silicon detector are read out via a digital controller ASIC global trigger readout controller (GTRC) into a computer. The GTFE is a binary chip, with a threshold able to be set for every channel, and has a fast output of the time over threshold (TOT), used for energy measurement. Self-triggering is accomplished through an OR of the TOT of all channels on one detector. The GTRC also allows digitization of the TOT, yielding a measurement of the input charge through the pulse width, i.e., the TOT signal, over a large dynamic range.

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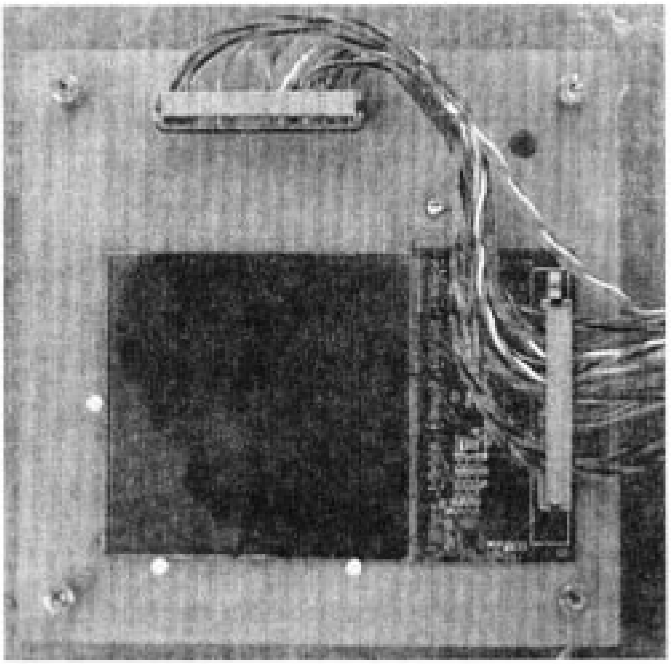

Fig. 2. One of the two silicon modules. The 6.4 × 6.4 cm SSD and the MCM with 5 GTFE and 1 GTRC ASICs are visible. Alignment of the SSDs on the two sides to each other is accomplished by the Delrin posts and the precision cutting of the SSD to 20 μm.

The measured electronic calibration of the chip TOT versus input charge is shown in Fig. 3 and exhibits a linear dependence of the TOT on the charge input up to a duration of 100 μs. At that point, saturation sets in very quickly. Thus we expect valuable energy measurement up to an input charge of 100 fC, which corresponds to the charge deposited by 20-MeV protons or about 20 minimum ionizing particles (MIPs) in 400-μm Si (see Table I). One feature of the selected ASIC is that only one TOT value is returned per detector, even if more then one strip is hit. The TOT value is the OR of all pulse widths. Thus to achieve good energy resolution, events with only one hit have to be selected, such that there is no appreciable charge sharing between strips. The TOT values for hits next to any nonfunctional strips were also eliminated because the extent of charge sharing is unknown.

Fig. 4 shows the TOT spectrum for 40-MeV protons for all events and for single-hit events and other fiducial cuts as mentioned.

III. Silicon Detector Performance

To determine the energy measurement capabilities of the silicon strip detector TOT system, we exposed silicon detectors to proton beams of various energies and recorded the TOT spectra. Table I shows the proton beam energies selected. The TOT spectra for single hits allow finding the mean and the full-width at half-maximum of the deposited charge for different incident proton energies. We used a prototype module to take TOT spectra in the proton beam of the proton synchrotron at Loma Linda University Medical Center (LLUMC). Monoenergetic beam energies of 250 and 40 MeV were selected. Beams of lower proton energies were produced by degrading the proton beam with polystyrene absorbers. In addition, we have analyzed the data taken in a 13.5-GeV proton beam during the GLAST beam test in January 2000 [4], using identical Si detectors and front-end ASICs.

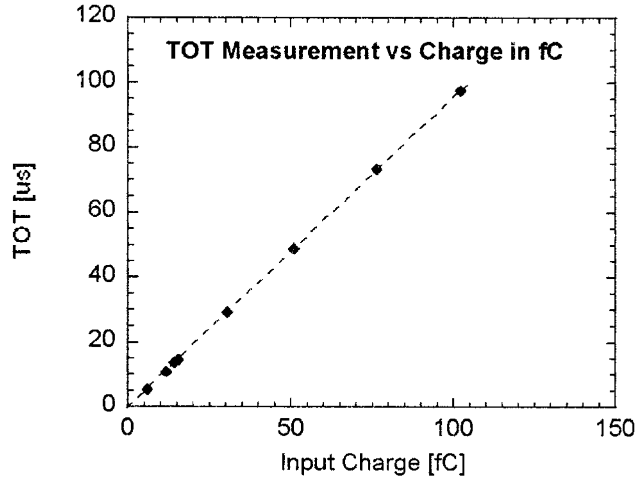

Fig. 3. The TOT calibration curve. The curve is linear below 100-fC input charge and saturates at 100 μs (not shown).

TABLE I
Energy and TOT

Proton energy [MeV]	Mean TOT [us]	RMS TOT [us]	Charge Deposition 400um Si [fC]	TOT expected [us]
13,500	7	1.4	5.3	6.5
250	12.3	2.6	13.5	13.7
39	53.4	6.4	54	55
27	70.4	7.5	67.5	69
24	78.3	8.5	76.5	78
22	84.4	9.8	81	82
17.6	105	11.5	99	101
9.5	108	15	189	105
7.4	109	21	243	105

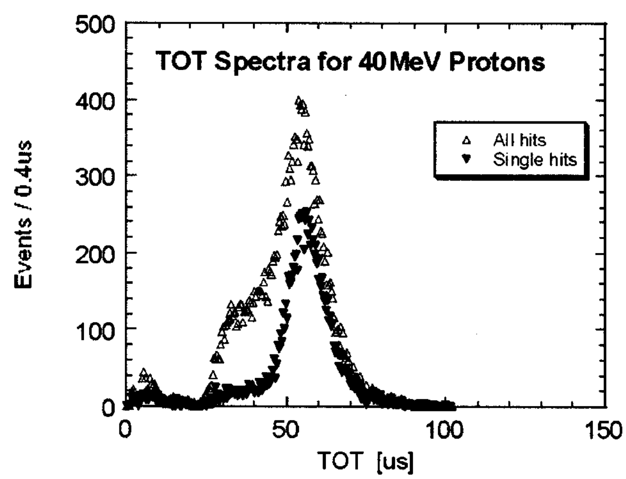

Fig. 4. TOT spectrum for 40-MeV protons. The effect of the fiducial and hit cuts is shown. Open circles: TOT in all events; open squares: TOT in events with single hits and with applied fiducial cuts.

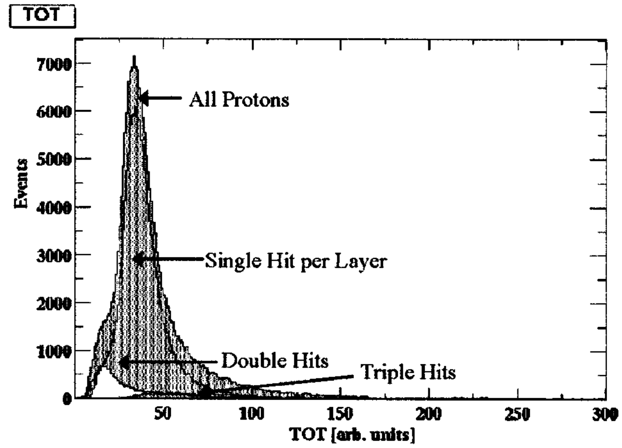

Fig. 5. TOT spectrum for 13.5-GeV protons. The effect of the hit cut is shown.

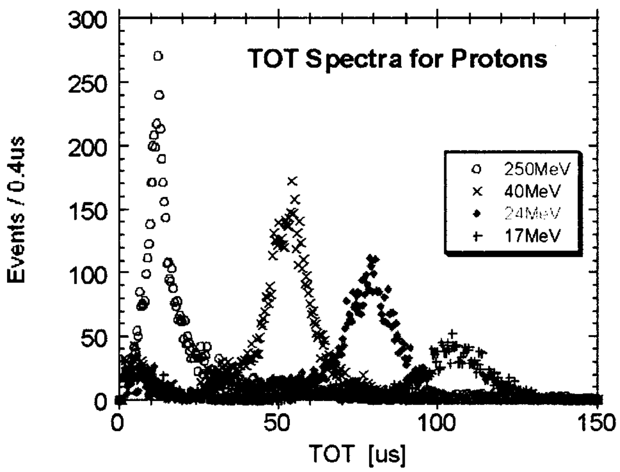

Fig. 6. TOT spectrum for two monoenergetic proton beams (250 and 40 MeV) and two degraded proton beams (24 and 17 MeV) with fiducial and hit cuts applied.

Fig. 5 shows the TOT spectrum from the SLAC beam test for all events for those with one hit, two adjacent hits, and three and more adjacent hits, respectively. The ASIC voltages $V_{\rm analog}$ and threshold settings $V_{\rm thr}$ were slightly different for the two setups, resulting in slightly different TOT calibration curves, which were taken into consideration in the data analysis. (LLUMC data: $V_{\rm analog} = 1.92$ V, $V_{\rm thr} = 5$ fC; SLAC data $V_{\rm analog} = 2.3$ V, $V_{\rm thr} = 1.4$ fC.)

The TOT spectra for single hit tracks are shown in Fig. 6 for selected energies of the LLUMC runs. The energies, mean, and rms of all TOT spectra are shown in Table I. In addition, the calculated deposited charge in 400-μm silicon and the expected TOT mean value are shown in Table I [6], [7]. The mean measured and calculated TOT values versus the energy of the primary protons are shown in Fig. 7. The rms of the TOT spectra derived from the core of the distributions are shown as error bars. The agreement between measured and predicted TOT values is excellent over the entire energy range from 20 MeV to 13.5 GeV. It is clear from Fig. 7 that there is less energy discrimination for proton energies above 100 MeV due to the smaller dependence of the energy loss on primary proton energy. We can derive the energy resolution of the system σ_E

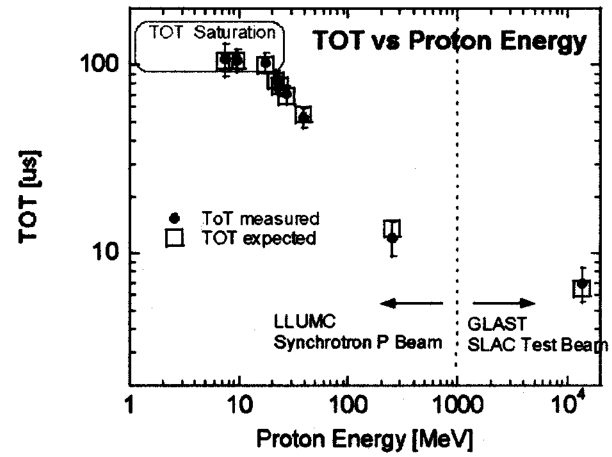

Fig. 7. Measured and predicted mean TOT signal as a function of the proton energy. The proton energy can be measured uniquely at energies above 20 MeV (and below 3 MeV, where the signal of stopping protons is not saturating the TOT). The error bars shown are the rms width of the TOT spectra in Fig. 6.

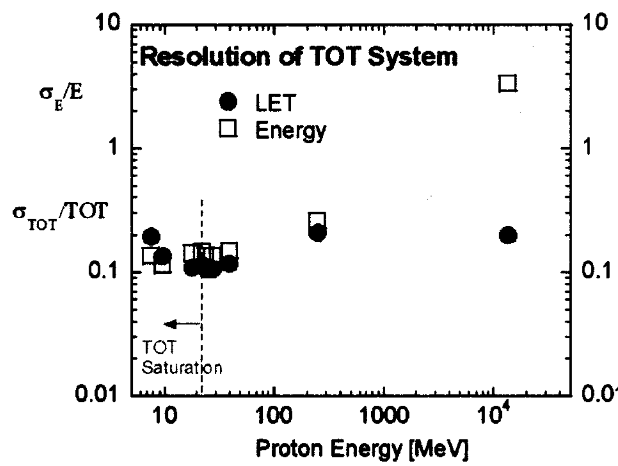

Fig. 8. Relative width of the measured TOT spectra $\sigma_{\rm TOT}/{\rm TOT}$, and derived energy resolution σ_E/E. The TOT resolution is on the order of 10–20% and represents the linear energy transfer (LET) resolution of a single plane. The energy resolution is about 15% below 100 MeV. At energies above 100 MeV, the dE/dx curve is relatively flat, which leads to a relatively low energy resolution.

from the observed TOT rms $\sigma_{\rm TOT}$ and the derivative of the TOT versus energy curve (Fig. 7)

$$\sigma_E = \sigma_{\rm TOT} \bigg/ \frac{\partial {\rm TOT}}{\partial E}\ . \tag{1}$$

Fig. 8 shows the relative width of the measured TOT spectra $\sigma_{\rm TOT}/{\rm TOT}$ and the energy resolution σ_E/E. Below 40 MeV, the energy resolution of the detector is on the order of 15%, and increases to 25% at 250 MeV.

IV. Conclusion

We have demonstrated that with the silicon telescope module described in this paper, useful measurements of the position and primary energy of the protons can be derived from their specific energy deposition using the TOT signal of a single silicon strip detector for proton energies above 20 MeV. In the energy range of 3–20 MeV, where we observed TOT saturation, the total energy deposited in the planned four detector planes (two per module) will be shared such that at least one detector will provide a measurement outside the TOT saturation range, which should permit a reconstruction of the primary proton energy. At high energies, i.e., above 100 MeV, the TOT is a relatively shallow function of the incident proton energy, which intrinsically leads to lower resolution. On the other hand, the simultaneous energy deposition information available from all four detector planes will, to a certain degree, compensate the loss of resolution. In addition, we expect that nanodosimetric cluster size distribution of protons in this energy range will be relatively insensitive to variations in energy, thus obviating the need for accurate energy measurements above 100 MeV.

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