New readout and data-acquisition system in an Electron-Tracking Compton Camera for MeV Gamma-Ray Astronomy (SMILE-II)

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Abstract

For MeV gamma-ray astronomy, we have developed an electron-tracking Compton camera (ETCC) as a MeV gamma-ray telescope capable of rejecting the radiation background and attaining the high sensitivity of near 1 mCrab in space. Our ETCC comprises a gaseous time-projection chamber (TPC) with a micro pattern gas detector for tracking recoil electrons and a position-sensitive scintillation camera for detecting scattered gamma rays. After the success of a first balloon experiment in 2006 with a small ETCC (using a $10 \times 10 \times 15$ cm³ TPC) for measuring diffuse cosmic and atmospheric sub-MeV gamma rays (Sub-MeV gamma-ray Imaging Loaded-on-balloon Experiment I; SMILE-I), a (30 cm)³ medium-sized ETCC was developed to measure MeV gamma-ray spectra from celestial sources, such as the Crab Nebula, with single-day balloon flights (SMILE-II). To achieve this goal, a 100-times-larger detection area compared with that of SMILE-I is required without changing the weight or power consumption of the detector system. In addition, the handling events are also expected to dramatically increase during observation. Here, we describe both

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the concept and the performance of the new data-acquisition system with this (30 cm)³ ETCC to manage 100 times more data while satisfying the severe restrictions regarding the weight and power consumption imposed by a balloon-borne observation. In particular, to improve the detection efficiency of the fine tracks in the TPC from $\sim 10\%$ to $\sim 100\%$, we introduce a new data-handling algorithm in the TPC. Therefore, for efficient management of such large amounts of data, we developed a data-acquisition system with parallel data flow.

Keywords: MeV gamma-ray astronomy, Compton camera, ETCC, electron track

1. Introduction

MeV gamma-ray astronomy is unique because nuclear gamma-ray lines in this energy range provide information about fresh isotopes in the universe, such as those produced by nucleosynthesis in supernovae [1, 2, 3], with significant contributions to particle acceleration in active galactic nuclei [4, 5, 6, 7] or gamma-ray bursts [8, 9, 10], the strong gravity potential of black holes [11, 12, 13], and the interaction of cosmic rays and interstellar matter in the galactic plane [14]. However, the observation of such gamma rays in space is difficult because of the large background noise produced by the interaction of cosmic rays with materials around the detector and the atmosphere (albedo). Therefore, MeV gamma-ray astronomy is not as advanced as astronomy in other energy bands. In fact, while EGRET and *Fermi*-LAT found 270 and ~ 3000 sources over 100 MeV, respectively [15, 16], COMPTEL loaded on the *Compton Gamma Ray Observatory* (*CGRO*) discovered only about 30 steady gamma-ray sources in all-sky observations [17]. Thus, the advancement of MeV gamma-ray astronomy requires better imaging and more efficient background rejection.

To address this need, we developed an electron-tracking Compton camera (ETCC), which measures the direction of the recoil electrons in the gaseous time-projection chamber (TPC) event by event. Figure 1a shows a schematic view of the ETCC [18]. By detecting the direction of the recoil electron track, the

21 direction of each incident gamma ray is determined by a point instead of by an
 22 event circle. The residual angle α (see Figure 1a) between the scattered gamma
 23 ray and the recoil electron provides a robust kinematical background rejection to
 24 evaluate the measured angle with that calculated on the basis of the kinematics
 25 of Compton scattering. In addition, the energy-loss rate of charged particles
 26 in the TPC identifies the recoil particles, which means that the ETCC can
 27 select only fully contained electrons, while suppressing escaping electrons, run-
 28 through charged particles such as cosmic rays, and neutron-recoil protons. To
 29 detect gamma rays from celestial objects, detectors must be deployed at the top
 30 of the atmosphere by a balloon or satellite to avoid atmospheric effects. In 2006,
 31 we launched the first balloon-borne experiment, called the “Sub-MeV gamma-
 32 ray Imaging Loaded-on-balloon Experiment I (SMILE-I)”. The detector for this
 33 mission comprised a small ETCC with a $10 \times 10 \times 15$ cm³ TPC and 33 pixel
 34 scintillator arrays (PSAs) [2112 Gd₂SiO₅:Ce (GSO) pixel scintillators]. This
 35 detector obtained good background noise rejection and observed the spectra of
 36 both diffuse cosmic and atmospheric gamma rays in the energy range from 100
 37 keV to 1 MeV [19]. In addition, this detector provided good performances for
 38 medical applications [20].

39 As a next step, we have proceeded a balloon experiment SMILE-II to cer-
 40 tificate the sufficient capabilities of background rejection and clear imaging for
 41 detecting celestial MeV gamma-ray sources by the observation of bright celestial
 42 sources such as Crab Nebula or Cygnus X-1. For this purpose, a medium-sized
 43 ETCC having approximately 100 times larger effective area than that of SMILE-
 44 I with the angular resolution of <10 degrees at 662 keV is necessary to observe
 45 these targets during single-day balloon flights where the observation time is be-
 46 tween 4 and 8 h [21]. Hence, we developed the medium-sized ETCC with a
 47 (30 cm)³ TPC and 108 PSAs (6912 GSO pixel scintillators) for SMILE-II [22].
 48 The SMILE-II ETCC also benefited from more efficient tracking of recoil elec-
 49 trons compared with that of SMILE-I: the $\sim 10\%$ efficiency of SMILE-I [19]
 50 was improved to $\sim 100\%$ efficiency by improving the readout electronics and the
 51 algorithm for finding tracks in the TPC [23]. Together, the larger detection

Figure 1: (a) Schematic view of the SMILE-II ETCC system [18], and (b) the base part of the TPC comprising the μ -PIC and GEM.

52 volume and improved tracking method led to the significant increase in effective area, while keeping the weight and power consumption similar to those of
 53 SMILE-I. This is important due to the limitations of the balloon experiments.
 54 The medium-sized ETCC thus provides more readout channels and generates
 55 more data. In addition, the number of triggered events dramatically increases
 56 because of the 100-times-greater effective area. As a result, SMILE-II required
 57 the redesign of the data acquisition system to handle the 10-times-larger data-
 58 transfer rate, all with a similar live-time ratio of $>70\%$. To do this, we improved
 59 the entire readout and data acquisition system, including the data-transfer al-
 60 gorithm of the TPC.
 61

62 This article first describes the concept of the ETCC and then presents in
 63 detail the hardware used for the readout electronics and the algorithm of the new
 64 data-acquisition (DAQ) system. Finally, results of observations with SMILE-II
 65 ETCC are given.

Figure 2: (a) Correlation between energies obtained by PSAs and by TPC upon gamma-ray irradiation from ^{137}Cs (662 keV). The Compton events are distributed along the dashed line (calculated correlation) with total energy of 662 keV. (b) Energy spectrum measured by combined ETCC.

Figure 3: Scatter plot of track range versus energy deposited in the TPC (dE/dx map) due to an intense radiation field created by irradiation of a water target by 140 MeV protons, where event clusters are clearly grouped into Compton electron stopping in the TPC, minimum-ionizing particles such as cosmic rays and high-energy electrons escaping from the TPC, and protons scattered by fast neutrons. The dashed and solid lines show the energy deposited by minimum-ionizing particles and by fully contained electrons in a 1 atm Ar gas, respectively. The detailed experimental conditions are reported in reference [35].

Figure 4: Schematic views of background events in a Compton camera. (a) Electron-escaping event, (b) multiple-scattering event, (c) chance coincident event, and (d) neutron event. An ETCC can reject these background events using Compton kinematics energy-loss rate in the TPC to determine the angle α and identify the particle, respectively.

66 2. SMILE-II ETCC

67 An ETCC comprises a three-dimensional gaseous electron tracker for mea-
68 suring the Compton scattering point, energy, and direction of the recoil electron
69 as well as a position-sensitive scintillation camera constructed from PSAs for
70 measuring the energy and absorption point of the scattered gamma ray. An elec-
71 tron tracker is a TPC based on a micro pixel chamber (μ -PIC) [24], as shown in
72 Figure 1b. A μ -PIC, which is a two-dimensional micro pattern gaseous detector
73 with pixel electrodes at a density of 400 μm , has a fine-position resolution of 120
74 μm (root-mean square (RMS)) and a high, stable gas gain of ~ 6000 [25]. Since
75 the pixel anodes and cathodes are connected perpendicularly to strip readout
76 electrodes, a $30 \times 30 \text{ cm}^2$ μ -PIC has 768 anode strips and 768 cathode strips [26].
77 Since this gain is insufficient for detecting a minimum-ionizing particle, a gas
78 electron multiplier (GEM) [27, 28] is set above the μ -PIC with the low gain
79 operation of about 10, so that this hybrid system provides an adequate and
80 stable gain of approximately 20000 with the gas at normal pressures (Ar 95%,
81 CF_4 3%, iso- C_4H_{10} 2%). A hybrid μ -PIC-GEM also reduces ion feedback to
82 the drift electrodes to less than 1%. To increase the cross section for Compton
83 scattering, Xe or CF_4 gas could be used in the ETCC, although this calls for a
84 higher voltage across the electrodes [29]. In the PSA, we used the GSO scintil-
85 lator, which is known as a good scintillator material for use in space due to its
86 nonhygroscopicity and radiation hardness. The PSA pixel size is $6 \times 6 \text{ mm}^2$ (13
87 mm in height), and one PSA consists of 8×8 pixels [30]. This scintillator ar-
88 ray was matched to a multianode flat-panel photomultiplier tube (PMT) H8500
89 (Hamamatsu Photonics), which has 8×8 pixels ($6 \times 6 \text{ mm}^2$ per pixel) and a total
90 geometrical area of $52 \times 52 \text{ mm}^2$ (89% active area). To reduce the number of
91 readout circuits, we used a resistor matrix for each PMT, where the position
92 of the hit pixel was obtained based on the center of the gravity of four sig-
93 nals from the corners of the resistor matrix. The average energy resolution is
94 approximately 11% at full width at half maximum (FWHM) for 662 keV [31].

95 The SMILE-II ETCC shown in Figure 1a uses a 30 cm^3 TPC comprising

Table 1: Specifications of FE2009bal.

Process	0.5 μm CMOS
Number of input	16 ch
Preamplifier gain	0.6 V/pC
Peaking time	30 ns
Sum amplifier gain	0.8 V/pC
Dynamic range	-1 to +1 pC
Cross talk	< 0.5%
time walk	~ 6 ns (10 fC to 1 pC)
ENC ($C_d = 100$ pF)	~ 6000 e $^-$
Power consumption	18 mW/ch

96 a 30×30 cm 2 μ -PIC with a GEM foil stacked above the μ -PIC, and 108 PSAs
 97 surround the bottom and four sides of the TPC. Figure 2a shows how the energy
 98 obtained by the PSAs correlate with that obtained by the TPC under gamma-
 99 ray irradiation from ^{137}Cs (662 keV) with a calculated correlation (dashed line
 100 in this figure), and Figure 2b shows the summed energy spectrum. Figure 3
 101 shows the energy-loss rate (dE/dx) of charged particles in the TPC as a map
 102 of the track range versus the energy deposited in the TPC per particle. This
 103 plot clearly distinguishes event clusters such as Compton-electron stopping in
 104 the TPC, minimum-ionizing particles such as cosmic rays and high-energy elec-
 105 trons escaping from the TPC, and protons scattered by fast neutrons. Thus,
 106 the background events depicted in Figure 4 can be removed using Compton
 107 kinematics to identify the fully contained Compton electron.

108 3. New CMOS ASIC for TPC Readout

109 For the readout electronics for the SMILE-I TPC, we used an amplifier-
 110 shaper-discriminator (ASD) integrated circuits that were developed for the AT-
 111 LAS detector in the large hadron collider [32] and a position-encoding system
 112 constructed from eight field-programmable gate arrays (FPGAs) clocked at 100

Figure 5: Photograph of fabricated chip (left) and block diagram of FE2009bal CMOS ASIC chips (right).

Figure 6: Distribution of the 6-bit DAC for 384 channels in 24 FE2009bal chips.

Figure 7: (a) Measured analog sum pulse from FE2009bal. The input charge is -0.5 pC. (b) Measured peak output-pulse voltage of the analog sum pulse from FE2009bal vs input charge.

113 MHz [33]. Each strip consumes 130 mW. However, a $(30 \text{ cm})^3$ TPC with 1536
 114 readout strips is required to keep the total power consumption similar to that
 115 of SMILE-I, which corresponds to 40 mW/strip. For this requirement, we de-
 116 veloped a new $16 \times 16 \text{ mm}^2$ CMOS ASIC (FE2009bal).

117 The requirements for the FE2009bal were low power consumption (less than
 118 20 mW/ch, which is a half of the total readout power consumption of 40
 119 mW/ch), high integration (16 ch per chip), wide input dynamic range with
 120 both polarities (-1 to $+1$ pC), and low noise (equivalent noise charge (ENC)
 121 $< 6000 \text{ e}^-$ at a signal capacitance of 100 pF). To satisfy these requirements,
 122 we designed an ASIC chip using the SPICE simulator with a $0.5 \mu\text{m}$ CMOS
 123 process. The chip was fabricated by the Taiwan Semiconductor Manufactur-
 124 ing Co., Ltd. and contains 16 channels in a 100-pin package (Figure 5). The
 125 parameters of the manufactured chips are listed in Table 1. Figure 5 shows
 126 a photograph and a block diagram of a FE2009bal chip, which has 16 input
 127 channels, generates a 16-ch-summed analog signal (AOUT), and discriminates
 128 CMOS 2.5 V digital outputs for each input (DOUT). The chip requires ± 2.5
 129 V power and consumes 18 mW/ch, which satisfies the requirements set out for

130 this chip. The gains of the preamplifier and sum amplifier are measured to be
 131 0.6 and 0.8 V/pC, respectively, and the peaking time of preamplifier is 30 ns.
 132 In the comparator, each amplified signal is compared with a common threshold
 133 voltage (V_{th}). Since the input bias voltage of a MOS FET transistor generally
 134 varies in each channel, each comparator has a 6-bit digital-to-analog converter
 135 (DAC) to compensate for its baseline. Each 6-bit DAC was iteratively adjusted
 136 until the counting rate of background noise was equal across all channels, and
 137 a serial communication interface was used at each startup to set the data of
 138 each DAC. Figure 6 shows the distribution of the 6-bit DACs for 384 channels
 139 in 24 chips. The results show that the DACs have too much variation to use a
 140 single DAC value for all strips. Figures 7a and 7b show the analog sum pulse
 141 measured from a FE2009bal chip and the measured peak output-pulse voltage
 142 vs input charge, respectively. The latter allows us to determine the dynamic
 143 range over which the above requirement of linearity is satisfied. In addition, the
 144 gain is measured to 0.8 V/pC, which is about twice the gain of the previous
 145 ASD chip.

146 4. Data Acquisition System

147 4.1. TPC readout board

148 The new TPC readout board [34] contains 4 flash ADCs, an Ethernet port,
 149 a FPGA, and 8 CMOS FE2009bal ASIC chips, as shown in Figure 8. All
 150 discriminated signals from 128 input channels are fed to the FPGA. In the
 151 FPGA, the hit patterns of the anode or cathode electrodes are individually
 152 synchronized with 100 MHz (10 ns) clocks; hence, the timing resolution of the
 153 hit signals of the TPC is determined to be $(10 / \sqrt{12}) \simeq 3$ ns RMS from the
 154 central limit theorem. The analog sum signals from each chip pair are summed
 155 and fed to 10-bit, 50 MHz flash ADC, with the digitized data are sent to the
 156 FPGA. These ADCs continuously digitize the waveform of the summed signal at
 157 this clock rate. In the FPGA, the 10-bit 50 MHz waveforms are converted into
 158 8-bit 25 MHz waveforms [35]. In the FPGA, the 128-bit synchronized hit pattern

Figure 8: Photograph and block diagram of the new readout boards for the TPC, which contain 8 CMOS ASIC chips (FE2009bal), an FPGA, 4 Flash ADCs, and an Ethernet port.

Figure 9: Schematic to define TOT.

Figure 10: Distribution of the number of hit strips of the TPC for recoil electrons for 662 keV gamma rays.

Figure 11: Typical examples of the projected track of a recoil electron, where both hit points are depicted.

159 and 4-ch digitized waveforms are saved to ring buffers. For the determination of
 160 the Vth and 6-bit DACs in FE2009bal as mentioned in the section 3, SiTCP [37]
 161 for the use of TCP/UDP protocol via the Ethernet is installed in the FPGA.
 162 The values obtained for Vth and 6-bit DACs are stored in the main VME CPU
 163 and are downloaded via Ethernet to all chips on the readout board at every
 164 startup.

165 Once a trigger signal is input to the FPGA, it stops writing to the ring buffer
 166 and starts transferring the formatted data saved over $10\ \mu s$ before the trigger
 167 signal to a first-in first-out (FIFO) buffer in the FPGA. The process signal is
 168 output from the FPGA to the trigger-control unit (TCU), while it reads the
 169 ring buffer (the TCU is explained in section 4.3). If the hit pattern exists in the
 170 ring buffer, the TPC readout board sends a data-exist flag to the TCU. At the
 171 end of the process signal, the TCU orders all TPC readout boards to start data
 172 transfer from the FIFO to the VME memory module. It stores data from several
 173 thousand triggered events to reduce the dead time due to the latency of the main
 174 DAQ-system CPU and due to data transfer from the VME memory. Upon data
 175 transfer from the ring buffer to the FIFO buffer, a trigger identification number
 176 (trigger ID) is attached to the top of the data. However, if no readout board

Figure 12: Track length vs the energy deposited for (a) the old (SMILE-I) and (b) new (SMILE-II) reconstruction methods. The dashed and solid lines represent the energy deposited by minimum-ionizing particles and fully-contained electrons, respectively.

Figure 13: Photographs of readout module. The Clear Pulse Model 80256 is on the left and the VME processor (Clear Pulse Model 80057), which manages four readout modules via Ethernet, is on the right. Six PSAs are mounted on each readout module.

Figure 14: (left) Photograph of PSA components: a H8500 photomultiplier and a GSO crystal array (8×8 pixels). (right) Schematic view of resistor matrix attached to a PSA. Each resistor matrix has 8×8 ch inputs from a PSA (red points) and 4 ch outputs.

Figure 15: Distribution of hit position in PSA for 662 keV gamma rays. This distribution is derived from the calculation of the center of the gravity of four signals from the corners of the resistor matrix (cf. figure 14).

Figure 18: Photograph of TCU, which comprises a main FPGA board, 2 TPC-I/O boards, 3 PSA-I/O boards, a GPS-I/O board, and a power board. Each board measures $100\text{ mm} \times 120\text{ mm}$.

Figure 19: Flow chart of the ETCC mode in the SMILE-II DAQ system. DAQ system mainly comprises 2 parts: front-end system and VME-bus system including main CPU.

177 has hit data, the TCU sends a clear signal to all readout boards. When the
 178 TPC readout boards finish data transfer or receive a clear signal, they are all
 179 reset and start recording the hits and waveforms of TPC to the ring buffers
 180 again. Since the VME memory stores the data from several thousand events,
 181 a VME CPU can reduce the number of accesses to the VME memory for data
 182 transfer to storage, because the CPU interrupt for accessing the VME system
 183 requires a longer latency time (of the order of ms). For SMILE-II, we used an
 184 800 μm pitch readout that involved grouping two adjacent anode and cathode
 185 electrodes; we found that this approach provides a position resolution similar
 186 to that of a 400 μm pitch readout due to the improvement of the signal-to-
 187 noise ratio. This strategy results in reduced power consumption and cost. The
 188 total power consumption of the readout electronics in the TPC is 45 W (30
 189 mW/strip).

190 The new TPC readout system was designed to handle the new read-out
 191 algorithm for TPC data encoding. The encoding method [33] for the SMILE-I
 192 TPC was developed for a $\mu\text{-PIC}$ high counting X-ray imaging device used in
 193 intense synchrotron X-ray sources. In the SMILE-I TPC, when the rising edge
 194 of the anode hit coincided within 10 ns to that of a cathode, the addresses and
 195 clock counts of the two were automatically encoded and transferred to the CPU.
 196 However, a 10 ns gate is too restrictive for the coincidence between the anode
 197 and cathode signals of $\mu\text{-PICs}$, mainly due to the slow rise time of the amplifiers
 198 (16 ns) and to the difference in delay timing in the circuit path of each channel
 199 in the FPGA, which caused considerable loss of hit points. In particular, this
 200 loss is quite problematic for the ETCC because low-energy recoil electrons of
 201 few tens of keV in Compton scattering have only several hit points in the TPC.
 202 Actually, the efficiency of $\sim 10\%$ obtained in the previous ETCC is one order of
 203 magnitude less than that calculated from the Compton scattering cross section
 204 of the gas in the TPC. To recover almost all the hit points in the TPC, all
 205 hit-strip addresses on anodes and cathodes are transferred with the hit timing
 206 to the memory module without the coincidence in the encoder. In the off-line
 207 analysis, an adequate gate width is applied to anode and cathode hit strips using

the hit timing. In addition, as depicted in Figure 9, the time between the rise and fall of the hit pulse is recorded as the time-over-threshold (TOT), which is roughly proportional to the pulse height or charge.

Figure 10 shows the distribution of the number of hit strips of the TPC for recoil electrons due to irradiation of gamma rays from ^{137}Cs (662 keV). Recoil electrons are clearly separated from the electrical noise. When five hits in one track are required, the electrical noise can be perfectly rejected. Figure 11 shows a typical projected track of a recoil electron, where both hit points are depicted. Note that the electron track obtained by the new algorithm indicates the Bragg peak at the track end point by the TOT, reducing misassignment of the scattering point in the previous method due to the loss of hit points. This new reconstruction method provides a much better detection efficiency of $\sim 100\%$. Figures 12a and b show how the track range relates to the energy deposited for the old and new reconstruction methods. The new method better identifies recoil electrons that stop in the TPC and separates them from cosmic rays and penetrating high-energy recoil electrons escaping from the TPC, both of which are minimum-ionizing particles. This result is quite consistent with the calculated curves in the figure. Although this new algorithm provides a satisfactory improvement in TPC performance, it also increases the quantity of TPC data, requiring a new TPC readout system with about five-times-faster data transfer capacity than SMILE-I. For this, we adopted the VME memory module for multi-event buffering.

4.2. PSA readout module

The PSA-data-handling system comprises a readout module (Clear Pulse Model 80256 [31]) and a VME processor (Clear Pulse Model 80057) that manages four readout modules via Ethernet. Six PSAs are mounted on each readout module, which includes 24 preamplifiers, 24 shapers, 24 12-bit ADCs, and 6 comparators, as shown in Figure 13. A resistor matrix is attached to each PSA, as shown in Figure 14, and the 8×8 channels from the PSA reduce four signals from the four corners of the resistor matrix. The hit position within a PSA is

238 calculated from the weighted average of four signals. Figure 15 shows the hit
 239 distribution obtained by this method for 662 keV gamma rays. A threshold for
 240 each PSA is set in the readout module via the VME processor module. High
 241 voltages for the six PSAs per readout module are supplied by the high-voltage
 242 supply board set at the back of the readout module. The photograph of this
 243 board is shown in Figure 16; the three high-voltage generators (one generator
 244 supplies the same high voltage to two PSAs) are mounted and controlled via
 245 RS-232 by the micro processor chip on the same board.

246 When a dynode signal from a PSA exceeds the threshold, the readout mod-
 247 ule sends a hit signal to the TCU and the TCU immediately replies with a
 248 start signal to all readout modules to activate the digitization of PSA signals
 249 regardless of any coincidence with a hit in the TPC. The threshold is set via the
 250 VME processor by the main DAQ CPU. When the TCU receives a data-exists
 251 signal from the TPC readout boards, the TCU generate a valid signal for all
 252 PSA readout modules for data transfer. If the TPC readout boards have no
 253 data, the TCU sends a clear signal to all PSA readout modules, and the PSA
 254 readout module are reset and begin to wait for the next PSA hit signal.

255 *4.3. Trigger-Control Unit*

256 Figure 17 shows a block diagram of the SMILE-II DAQ system, which com-
 257 prises 2 main parts: the front-end system (TPC, PSA, and TCU) and the
 258 VME-bus system (which includes main CPU). Each system works individually.
 259 In the front-end system, the TCU shown in Figure 18 controls starting/stopping
 260 of data acquisition and trigger making. The TCU comprises a main board, 2
 261 TPC-input/output (I/O) boards, 3 PSA-I/O boards, GPS-I/O boards, and a
 262 power board. The main board has a FPGA and an Ethernet port and is con-
 263 trolled by the DAQ CPU via Ethernet. The FPGA on the main board controls
 264 all DAQ signals from the front-end system with a 100 MHz clock. In addi-
 265 tion, the DAQ dead time is measured by a clock counter in this FPGA. The
 266 TCU main board operates TPC readout boards and PSA readout modules via
 267 TPC-I/O boards and PSA-I/O boards, respectively. A TPC-I/O board can

268 communicate with 4 TPC readout boards, and a PSA-I/O board can operate 6
 269 PSA readout modules. The current front-end system is operated with 2 TPC-IO
 270 boards and 3 PSA-I/O boards. Moreover, the TCU offers the option of increas-
 271 ing the number of TPC-I/O and PSA-I/O boards to improve the effective area
 272 by incrementing the number of TPC readout boards or PSA readout modules.
 273 A GPS-I/O board has a serial input to obtain the global time, a PPS signal
 274 input as a force trigger, and 5 veto trigger inputs for charged particle rejection.
 275 All boards are powered by the power board.

276 The TCU has 3 DAQ modes: the ETCC mode, the PSA calibration mode,
 277 and the TPC calibration mode. Figure 19 shows the flow chart of the SMILE-II
 278 ETCC mode. In the ETCC mode, if any PSAs in the standby state detect a
 279 signal above the threshold, the TCU sends a trigger signal (GSO trigger) to
 280 all PSA readout modules via PSA-IO boards. The trigger for all TPC readout
 281 boards is delayed for 8 μ s with respect to the GSO trigger. As mentioned
 282 above, the PSA readout modules immediately start the digitization. However,
 283 the TPC readout board checks its ring buffer and confirms whether any TPC
 284 hit-position data were created within 10 μ s, which is longer than the drift time
 285 of 6 μ s for the use of the Ar based gas in the TPC. When the TCU accepts the
 286 data-exists flag (c.f. section 4.1) from the TPC readout board, the TCU sends
 287 a valid signal for all systems in the ETCC. However, if no signal is transmitted
 288 from the TPC, the TCU sends the clear signal, and all readout boards erase
 289 their data and return to the standby state. Once a valid signal from the TCU is
 290 accepted, all TPC readout boards and PSA readout modules send their data to
 291 memory-buffer boards or data-processing boards. After sending their data, they
 292 return to the standby state. The VME CPU can read data from the buffers and
 293 write the data into the storage after data for several thousands of events are
 294 accumulated in VME memories. This approach reduces the interrupt latency
 295 of the main VME CPU. In addition, as mentioned above, the TPC and PSA
 296 systems operate independently and their data are sent in parallel to each VME
 297 memory module. The quantity of data for one event in SMILE-II is similar to
 298 that for SMILE-I [35]. In PSA, the ADC data for all pixels are recorded event-

by-event to recover the precise total energy by considering the small leakage around the main hit peak below the threshold. In addition, the SMILE-II trigger rate in the balloon experiment is expected to increase to approximately 100-200 Hz at middle latitudes from ~ 25 Hz for SMILE-I. In this case, the new DAQ system has to manage about several megabytes per second continuously (ten times the rate of SMILE-I).

For any Compton camera, the resolution of the energy of an incident gamma ray is determined by the combined resolutions of the forward and backward detectors. In addition, the resolution of the angular resolution measure (ARM), which is the accuracy with which the Compton-scattering angle is measured, is determined mainly by the energy resolution. Thus, the energy resolution of both the TPC and PSAs is quite important. For example, even a slight variation in gain of the multianode PMT corrupts the absorption position of a scattered gamma ray in the PSAs, and any variation in the TPC gain shifts the energy-loss rate, which seriously deteriorates the detection efficiency. Thus, calibration of the energy measurements of both the TPC and PSA modules is very important to ensure the proper performance of the ETCC. Thus, the TPC and PSA have to be calibrated every day. To do this, all calibrations were managed by the TCU. To calibrate the PSAs, the TCU generates an event trigger as soon as they receive a hit signal from the PSAs without waiting for the hit signal from the TPC. To calibrate the TPC, the TCU treats the hit signal from the FE2009bal chips as an event trigger and sends a ring-buffer-stop signal to the TPC readout board. The PSA readout module and the TPC readout board in both calibration modes work the same as in the ETCC mode.

5. Performance of the New Data Acquisition System

The accuracy of the energy measurement of the scattered gamma-ray is important for all Compton cameras. However, the gain of the H8500 is not sufficient uniform (the ratio of the maximum to the minimum for a single PMT is 2-3); hence, we must calibrate the energy response of PSAs for each pixel.

Figure 20: Distributions of (a) gain and (b) energy resolution for 6912 GSO pixel scintillators.

Figure 21: Energy resolution of entire scintillation camera as a function of incident energy.

Figure 22: Clock-count distribution, which represents the time between the TPC-hit time and the ring-buffer-stop trigger. The clock count at the ring-buffer-stop trigger is 1023.

328 The distribution of gain for all GSO pixel scintillators in the SMILE-II flight
 329 model ETCC is $\pm 25\%$ at 1σ , as shown in Figure 20a. The energy resolution
 330 for each pixel is then distributed from 10% to 14% at 662 keV (Figure 20b).
 331 Figure 21 shows the energy resolution of the entire scintillation camera as a
 332 function of the incident energy. The energy resolution of the entire scintillation
 333 camera is approximately 11% at 662 keV.

334 To certificate the performance of the new DAQ system, we operated the (30
 335 cm)³ ETCC with the ETCC mode with using the TCU, TPC readout boards,
 336 and the PSA readout modules. Figure 22 shows the distribution of the clock
 337 count, which represents the time between TPC-hit time and the TPC trig-
 338 ger. The timing at the stopping ring buffer is at 1023. Because the waiting
 339 time between the GSO trigger and the stopping ring buffer is 8 μ s and the
 340 encoding clock is 100 MHz, the rising-edge timing of the GSO trigger is ap-
 341 proximately 220. Therefore, the events distributed within the clock count of
 342 230-750 are coincidence events between TPC and PSAs. The width of the coin-

Figure 23: Typical gamma-ray event obtained by SMILE-II ETCC.

Figure 24: Variation of the live time of the DAQ as a function of the valid signal rate. The blue and red points show data measured in the laboratory and RCNP, respectively.

343 cidence distribution gives the maximum drift time; hence, we can measure the
 344 drift velocity at any time. In addition, we can estimate the signal-to-noise ratio
 345 by using this clock distribution, because the chance coincidence events are uni-
 346 formly distributed. Upon irradiation by gamma rays from ^{137}Cs , we searched
 347 for Compton-scattering events. The correlation between the energy deposited
 348 in the TPC and PSAs and the correlation between the track length and the
 349 gamma-ray energy deposited in the TPC are shown in Figures 2a and 12b, re-
 350 spectively. Figure 23 shows a typical gamma-ray event obtained by ETCC upon
 351 irradiation by gamma rays from ^{137}Cs . More results are described by Mizumura
 352 et al. [22] and Tanimori et al. [36].

353 To verify the background rejection and high counting rate of the SMILE-II
 354 ETCC, it was examined while exposed to intense radiation (140 MeV proton
 355 beam on a water target at Research Center for Nuclear Physics (RCNP), Osaka
 356 University). Brief reports have been published recently [35, 36], and details of
 357 this experiment and the results for background noise rejection will be presented
 358 elsewhere. Here, a 140 MeV, 0.1-0.5 nA proton beam irradiates the 20 cm ϕ $\times$ 30
 359 cm cylindrical water target, from which similar amounts of fast neutrons and
 360 MeV gamma rays emanate. The ETCC was set normal to the beam line and
 361 at 1 m from the water target. A lead shield was placed between the water
 362 target and the ETCC to block the direct particles from the target, because
 363 in space, background particles uniformly irradiate the instrument. The trigger
 364 rate was varied from 100 Hz to 1 kHz. Figure 3 shows the correlation between
 365 energy deposited and track length in the TPC at 450 Hz, in which the tangent
 366 of the curve gives the energy-loss rate dE/dx . Even under such condition of
 367 intense radiation, the cluster of Compton electrons halted in the TPC is clearly
 368 identified. This result certifies that SMILE-II operates stably even when
 369 exposed to about five times more radiation than expected in an actual balloon
 370 experiment. Figure 24 shows the variation in the DAQ live time as a function
 371 of trigger rate, where the live time of 80% at 100 Hz reduces to 20% at 1 kHz.
 372 For actual measurements with the expected trigger rate of 100 Hz, a live time
 373 of 70% is the minimum requirement which is satisfied with the present DAQ

374 system. However, the margin for safety is small considering the considerable
375 variation of trigger rates in the SMILE-II balloon experiment at 200 Hz, where
376 the live time reduces to 60%. At present, we use a relatively slow VME CPU,
377 and data transfer via Ethernet is expected to increase the data-transfer rate
378 more than several times without requiring a change of hardware.

379 6. Summary

380 We developed an ETCC technology for use in MeV gamma-ray astronomy
381 and for applications such as nuclear-medicine gamma-ray imaging. In 2006,
382 we did the first balloon-borne experiment SMILE-I and the small-size ETCC
383 detected diffuse cosmic gamma rays and atmosphere gamma rays. As a next
384 step, we developed the SMILE-II medium-sized ETCC with a 30 cm^3 TPC and
385 108 PSAs. We plan to launch this instrument on a balloon within a few years to
386 test its imaging and background noise rejection by observing bright sources, such
387 as the Crab nebula. Because of the balloon-related requirements and the larger
388 detection area, we also developed new readout electronics for both the TPC
389 and PSAs as well as a new DAQ system. In addition, to increase the effective
390 area by a factor of ~ 100 compared to SMILE-I ETCC, we improved the data-
391 acquisition algorithm to find the hit positions in the TPC efficiently and new
392 readout electronics. These allow us to obtain clearer electron-track data as
393 compared with SMILE-I. We also obtained satisfactory effective area, angular
394 resolution, and the data-handling capability for the balloon experiment [36].
395 After SMILE-II, we plan to increase the effective area to 30 cm^2 at 300 keV (over
396 30 times larger than the effective area of the SMILE-II ETCC) by increasing the
397 volume of the TPC to $40\times 40\times 40\text{ cm}^3$ and the gas pressure up to 3 atm [36]. In
398 this case, the expected trigger rate should also increase by a factor of 30; namely,
399 to a few kHz. To manage such a high trigger rate, we are now developing a
400 network data-acquisition system wherein all TPC and PSA readout boards are
401 directly connected via Ethernet.

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