Development of an Electron-Tracking Compton Camera with a Gaseous TPC and a Scintillation Camera for a Balloon-borne experiment (SMILE)

Kazuki Ueno, Toru Tanimori, Hidetoshi Kubo, Kentaro Miuchi, Shigeto Kabuki, Atsushi Takada*, Hironobu Nishimura, Kaori Hattori, Shunsuke Kurosawa, Chihiro Ida, and Satoru Iwaki

Cosmic-ray group, Kyoto University, *ISAS/JAXA

Abstract

We have developed an Electron-Tracking Compton Camera (ETCC) based on a gaseous micro Time Projection Chamber (μ–TPC) which measures the direction and the energy of the Compton recoil electron and a GSO(Ce) scintillation camera which surrounds the μ-TPC and measures the Compton scattered gamma ray. Measuring the direction of the recoil electron reduces the Compton cone to a point, and thus reconstructs the incident direction completely for a single photon and realizes the strong background rejection. Using the ETCC with a detection volume of about 10cm×10cm×15cm, we had a balloon-borne experiment in 2006 for the purpose of the observation of diffuse cosmic and atmospheric gamma rays. The experiment was successful. On the basis of the results, we are developing a large size ETCC in order to improve the effective area for the next balloon experiment. In this poster, we introduce the balloon experiment and report the fundamental performances of the large size ETCC.

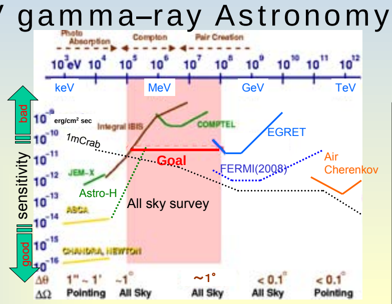
1. Observation in MeV gamma–ray Astronomy

➢ Past observations

❒COMPTEL (CGRO)[1]
Classical Compton Imaging
Detected ~30 steady sources

❒IBIS, SPI (INTEGRAL)[2]
Coded Aperture Imaging
In MeV gamma-ray region, sensitivity is worse than that of COMPTEL.

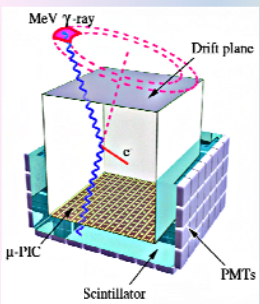
Because these methods cannot determine the direction by 1 photon, the sensitivity were restricted by the large background in MeV gamma-ray region[3].



Sensitivity gap in MeV gamma-ray region

2. Electron-Tracking Compton Camera

➢ Electron Tracking Compton Camera (ETCC)



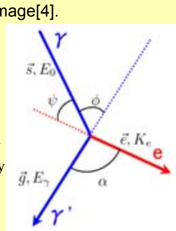
Schematic view of ETCC

The camera consists of a gaseous time projection chamber (TPC), which detects the 3D-track and the energy of the recoil electron, and a scintillation camera, which detects the absorption point and the energy of the scattered gamma ray. By using these four pieces of information, we can completely reconstruct the Compton scattering event by event, and obtain a fully ray-traced gamma-ray image[4].

$$E_0 = E_\gamma + K_e$$

$$\vec{s} = \left(\cos\phi - \frac{\sin\phi}{\tan\alpha}\right)\vec{g} + \frac{\sin\phi}{\sin\alpha}\vec{e}$$

E_0 : Energy of incident gamma ray
$\vec{s}$: unit vector of incident gamma ray
$\vec{g}$: unit vector of scattered gamma ray
$\vec{e}$: unit vector of recoil electron
ϕ : Scattered angle
α : Angle between $\vec{g}$ and $\vec{e}$



➢ Event selection with α cut

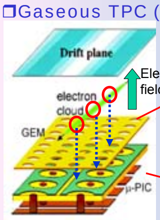
The angle α is described by the definition (α_{geo}): $\cos\alpha_{geo} = \vec{g}\cdot\vec{e}$

On the other hand, α is described by the Compton kinematics (α_{kin}): $\cos\alpha_{kin} = \left(1 - \frac{m_e c^2}{E_\gamma}\right)\sqrt{\frac{K_e}{K_e + 2m_e c^2}}$

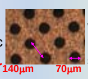
Comparing these angles, we can select Compton scattered events and strongly reject background.

3. Gaseous TPC and scintillator

❒Gaseous TPC (μ-TPC)

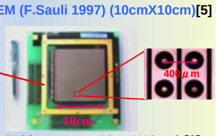


Schematic view of μ-TPC



We use the GEM as a pre-amplifier to obtain stable high gain.

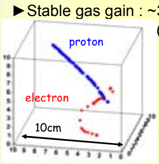
GEM (F.Sauli 1997) (10cmX10cm)[5]



μPIC(prototype:10cmX10cm) [6]

2D-readout (μPIC 400μm pitch) + Drift time (100MHz)
→ 3D-track and energy

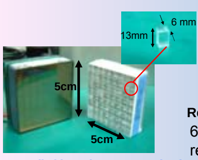
- ►Volume : 10cm×10cm×15cm (prototype)
- ►Position resolution : 400μm
- ►Stable gas gain : ~30000 (μPIC ~3000 GEM ~10)



Example of 3D-tracks of the electron and the proton in the μ-TPC

Readout system Signals from anode and cathode electrode strips are pre-amplified, shaped, and digitized. All digital signals are individually fed to FPGAs, and the two dimensional position of electrodes is synchronously calculated with a 100MHz clock.

❒Scintillation camera

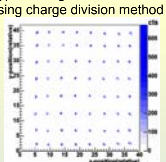


H8500 (left) and 8×8 GSO(Ce) pixel array (right) [7]

Multi Anode PMT + Pixel Scintillator Array → Scintillation camera

- ►Scintillator : GSO(Ce)
- ►Photon sensor : H8500 (HPK)
- ►Position resolution : 6mm
- ►Energy resolution : ~11%(FWHM) @ 662keV

Typical image from ^{137}Cs using charge division method



Readout system
64 anodes of H8500 are connected with resistors and reduced to 4ch. Obtained 4ch data are pre-amplified, shaped, and digitized by discrete modules.

4. SMILE project

➢ SMILE *Sub-MeV gamma-ray Imaging Loaded-on-balloon Experiment*

For the sub MeV to MeV gamma-ray observation in astronomy, a detector must be launched in the space. Then, we have planned the balloon experiments, SMILE. At the first step, using the (10cm)^3 ETCC, we confirmed the gamma-ray detection by the observation of diffuse cosmic and atmospheric gamma rays[8]. At the second step, we are developing the (30cm)^3 ETCC in order to enlarge the effective area for the observation of a blight source. In the future, we will construct the larger ETCC and have all sky survey with some balloons or a satellite

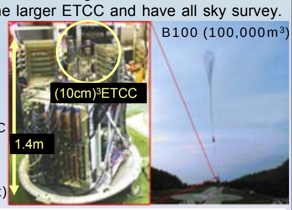
(10cm)^3 ETCC@Sanriku (Sep 1, 2006) — SMILE-1
❒Operation test of ETCC @ 35km
❒Measurement of Diffuse cosmic and atmospheric gamma rays
expectation: 0.1~1MeV
~200photons @ 35km, 3hours

(30cm)^3 ETCC @Japan 6hours (2011) — SMILE-2
Observation of Crab or Cyg X-1

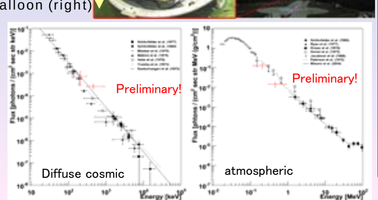
(40cm)^3 ETCC
Super pressure balloon~10days

(50cm)^3 ETCC All sky survey
Orbiting balloon (~30days) or satellite

Roadmap of the SMILE



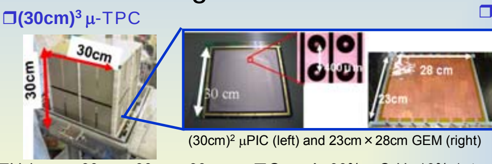
(10cm)^3 ETCC and readout system (left) and our balloon (right)



Obtained flux(red) and preceding measurement (error bar is statistical sigma) →

5. Enlargement of the ETCC

❒(30cm)^3 μ-TPC



(30cm)^2 μPIC (left) and 23cm×28cm GEM (right)

❒(30cm)^2 Scintillation camera

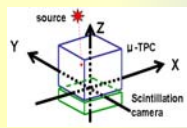
►36 scintillation cameras (see section 3)

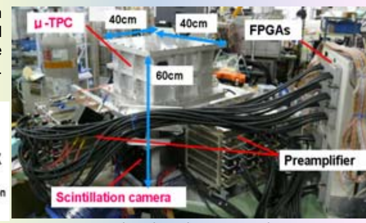
■Volume : 30cm×30cm×30cm ■Gas : Ar 90% + C_2H_6 10% 1atm
■Energy resolution : 46%(FWHM)@31keV ■Position resolution : 400μm
■Stable gas gain : ~30000(μPIC ~3000 GEM ~10)

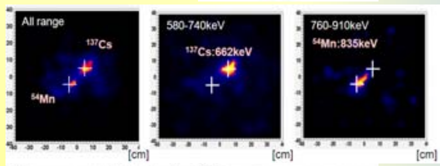
❒(30cm)^3 ETCC

We have constructed the (30cm)^3 ETCC which consists of (30cm)^2 μPIC, 23cm×28cm GEM, and 36 scintillation cameras. Using the ETCC, we have investigated the first performances of that[9].

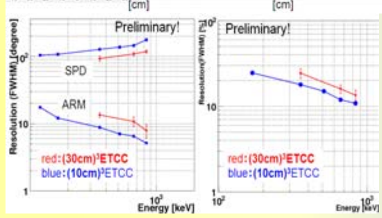
We placed some gamma-ray sources at about 50cm from the ETCC as shown in right figure. Then, we obtained the images, the angular resolution, and the energy resolution.

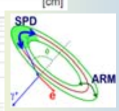






← obtained two point sources (Cs-137 and Mn-54) image (left) and the images in the energy range with 580-740keV (center) and 760-910keV (right). The white crosses show the positions of sources. XY-axis shows XY position indicated above.





❒Angular Resolution Measure (ARM) is the accuracy of the scattering angle.
❒Scatter Plane Deviation (SPD) is the accuracy of the determinant of the scattering plane.

← Angular (left) and energy (right) resolutions of the (30cm)^3 ETCC.

❒Energy resolution : 16.0%(FWHM)@662keV
❒ARM : 10.8 deg, SPD : 109 deg (FWHM)@662keV

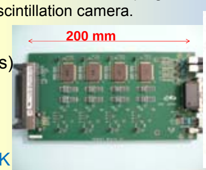
5. Low-power readout system

With the enlargement of the ETCC, larger power consumption is needed. However, the power is limited in the sky for the balloon experiment. Then, we are also developing readout systems with low power consumption for the gaseous TPC and the scintillation camera.

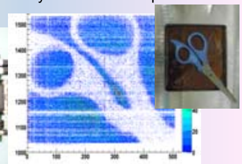
❒Readout system for μ-TPC

old: ATLAS TGC ASD (Bipolar process)
59mW/1ch
Goal: 20mW/1ch

FE2007(0.5μm CMOS ASIC) with KEK
30mW/1ch



FE2007 64ch board



Imaging with X-ray using FE2007

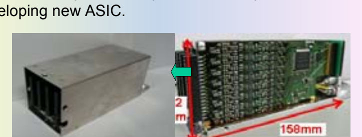
We have developed CMOS ASIC for μ-TPC with KEK and improved the power consumption. However, we need more improvement and are developing new ASIC.

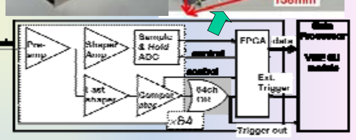
❒Readout system for scintillation camera

old: discrete modules(NIM and VME)
2.7W/1PMT
Goal: 400mW/1PMT

CP80068(IDEAS VA/TA) with Clear Pulse
1.4W/1PMT (including data processor(VME))
narrow dynamic range(30pC) (see [10])

CP80190(discrete modules) with Clear Pulse
1.55W/1PMT(including data processor(VME))
wide dynamic range(800pC) (see [11])

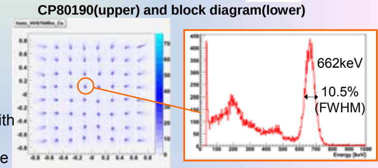




CP80190(upper) and block diagram(lower)

CP80190 + resistor chain(see section 3)
100mW/1PMT

We have developed new compact readout system with low power consumption and wide dynamic range not using ASIC, and we succeeded in improvement of the readout system for scintillation camera.



Typical image from ^{137}Cs using charge division method (left) and spectrum(right) with CP80190 and resistor chain

6. Future work

- ►Tuning : improve the ARM and the energy resolution to those of (10cm)^3 ETCC.
- ►Test : widen the dynamic range and investigate the detection efficiency and FOV.
- ►For the next balloon : start the design of next flight model of the ETCC. improve the low-power readout system.
- ►Furthermore : enlarge the ETCC to (50cm)^3 for a super pressure balloon or a satellite experiment.

[References]
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