Multiple Applications of Electron Tracking Compton Camera (ETCC) and Planning for a Circum-Polar Flight of the Balloon-borne ETCC

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Contents of this talk

• Principles of ETCC … A Little bit “Physics”. How ETCC works?

• Applications of ETCC … For / To what ETCC is used / will be applied?

• Balloon-borne ETCC and the SMILE-II project
Principle of ETCC

- **Compton scattering**
  (incident: ~MeV gamma-ray, target: electron of gas-medium)

- **Tracking a recoil electron**, by using Time Projection Chamber (TPC)

*From www-cr.scphys.kyoto-u.ac.jp/*
Principle of ETCC – TPC

- **TPC** consists of a Gaseous Electron Multiplier (**GEM**) and a MicroPixel Chamber (**μ-PIC**).
- Both GEM and **μ-PIC** are Micro-pattern Gaseous Detectors (**MPGD**), and **μ-PIC** has been invented by CR-group.

*From Kurosawa (GCOE-Sympo., 2011)*
Principle of ETCC – $\mu$-PIC

- To detect recoil electrons with higher spatial resolution
- Advantages: 1) less electrode destruction due to discharge and 2) stable and large gain ($\sim 2 \times 10^4$) of gas amplification
Principle of ETCC – TPC/µ-PIC

GEM
TPC vessel
TPC/Drift cage
µ-PIC/Anode Read-Outs

All pictures taken by Sachiko
Principle of ETCC
– Advanced Compton Imaging

Compton circle by
cventional Compton method

Identification of *incident direction* of gamma-ray by independent measurements of:

\[ \cos \alpha_{geo} = \vec{g} \cdot \vec{e} \]

\[ \cos \alpha_{kin} = \left(1 - \frac{m_e c^2}{E_\gamma}\right) \sqrt{\frac{K_e}{K_e + 2m_e c^2}} \]
Principle of ETCC
– Advanced Compton Imaging

流逝 Imaging of two gamma-ray sources: Left – using the electron tracking method.
From Kurosawa (GCOE-Sympo., 2011)

Principle of ETCC
– Advanced Compton Imaging

Principle “limitations” for determining incident direction of gamma-ray (and thus resultant angular resolutions, SPD and ARM, in Compton circle) are due to

1. **Doppler broadening** due to unresting electron, and it is reflected in ARM.

2. **Multiple scattering** of recoil electron, and it is reflected in SPD.

ARM: Angular Resolution Measure
SPD: Scatter Plane Deviation
Summary (1)

- ETCC has nominally a sensitivity for gamma-rays of the energies ranging from sub-MeV (~100 keV) to (several) tens of MeV.
- ETCC is based on the two principles of physics: **Compton effect** and **Pair production**.
- FOV of ETCC is ~3 sr (~50% of half-sphere)!
- New tool for **Gamma-ray Imaging**.

*From Knoll (WILEY, 2001)*
ETCC Application – Radiation Therapy

- Proton beam (140 MeV) for reducing damage (energy deposit) on healthy tissues
- Detecting prompt gamma-rays (continuum) and annihilation (line, 511 keV) from targeted nuclei (tumour) – **Gamma-ray Imaging**
- At present, testing with water phantom (as a dummy of human body)

*From Kurosawa (PhD thesis, 2011)*
ETCC Application – Radiation Therapy

- Reducing random coincidence (neutron emissions)
- Improvement of image reconstruction method, f.ex. the Maximum Likelihood-Expectation Maximization (ML-EM).

*From Kurosawa (PhD thesis, 2011)*

Measurement

463 – 559 keV

0.8 – 2 MeV

Simulation
ETCC Application
– Neutron Imaging

- Using $\mu$-PIC with high position resolution ($<$0.4 mm) and time resolution ($\sim$10 ns), together with high DAQ rate ($\sim$ MHz)

- **Radiography** (Bragg edges), **Resonance**, **Small-angle scattering**

*From Parker (CR internal)*
ETCC Application
– Medical Imaging

- PET (positron emission tomography) – $E=511$ keV, FOV=Compton circle

- SPECT (single photon emission computed tomography) – $E<370$ keV, FOV=collimated front

$0.3 \text{ keV} < E < 1.3 \text{ MeV}$, FOV$\sim 3$ sr with ETCC

From www-cr.scphys.kyoto-u.ac.jp/
Summary (2)

- Several applications of ETCC: Radiation (Proton) Therapy and Medical Imaging as Gamma-ray Imaging, Neutron Imaging for new spectroscopy in Material Science.

- However, we do not establish image reconstruction method/technique, such ML-EL, yet. We need experts on this issue.
Balloon-borne ETCC – Overview

- Originally, to calibrate the ETCC using celestial gamma(X)-ray sources (Crab Nebula and Cyg X-1) is planned.
- Now, Bremsstrahlung-X associated with relativistic electron precipitation (REP) can be detected by means of balloon-borne ETCC.

The major constituent of the outer radiation (Van Allen) belt is relativistic electrons.

*Figure from Wikipedia*
Balloon-borne ETCC – Overview

- REP is variable due to the solar activity (acting on the outer radiation belt).
- REP is considered to affect on the polar upper atmospheric (mesosphere to upper stratosphere) physical/chemical dynamics in terms of the generations of NOx and HOx.
Balloon-borne ETCC – Overview

● When REP impinge into the atmosphere, they emit photons (of hard X-ray \(\approx\) gamma-ray) due to Bremsstrahlung (braking radiation) process.

● Above all, REP have never systematically been observed before.

Circum-polar “summer” balloon flight path.

From Esrange/SSC
Balloon-borne ETCC
– Pre-summary

• Multi-purposed plan

- **Astrophysics**: 1) large chance to detect gamma-ray bursts (GRB) due to long-term duration balloon flight, 2) to elucidate the acceleration process of relativistic particle.

- **Space Physics**: To clarify the quantities (spatial/temporal variation/distribution, flux and spectrum) on REP (probably, **first time** in the world!)

- **Atmospheric Science**: Estimation of energy deposit due to energetic particles (both REP and SPE).
Balloon-borne ETCC
– Pre-summary

• … Further, with advanced DAQ logic, we expect **solar neutron** monitoring (in neutron trigger mode), and in which **solar proton events** (SPE) can be measured together.

• This project is planned, first, for **Summer in 2013**, when the next Solar Maximum is expected to start.
Balloon-borne ETCC – for Future

- To detect/measure gamma-rays associated with lightning (so-called terrestrial gamma-ray flashes, TGF)

- Gamma-rays above 10 MeV can create electron-positron pairs (through Pair-creation mode).

From Barrington-Leigh (2001)

From Ueno (2011)
Balloon-borne ETCC
– Practical preparation

Outside Al-vessel (on gondola):
Sensors, DC-DC module, batteries

From Ueno (Master thesis, 2006)

In the case of SMILE-I (2006)

Veto-counter
TPC
Encoder
(FPGA)
NIMmodule
VME module (CPU)
various ADC
Telemetry module

From Takada (2011)
Balloon-borne ETCC  
– Practical preparation

We have started several preparations for 1) test flight (@Japan, 2012) and 2) circum-polar long-term duration flight (from Esrange, 2013), and
1. Improvement of TPC-detection mode … on-going
2. Calibration of gamma-ray absorbers (scintillators + PMTs: right figure) … on-going
3. Replacement of $\mu$-PIC board (TPC amp) … on-going
4. Design of prototype vessel and inner alignment … on-going

From Takada (2011)
Balloon-borne ETCC
– Practical preparation

5. Replacement of NIM module (to FPGA) and updating CPU and Encoder … **planned**
6. DC-DC converter (Regulator) … **under planning**
7. Battery (solar panel or Li) … **planned / under planning**
8. Inner (inside Al-vessel) and outer sensors (thermometer, magnetometer, clinometer, barometer, and GPS) … **under planning**
9. Monitor-ADC (for the sensors) … **under planning**
10. Command / Telemetry … **under planning**
Balloon-borne ETCC
– Practical preparation

The test flight in Japan will take only ~3 hours (at maximum), and therefore the balloon flight from Kiruna will be totally different from the campaign in Japan. Furthermore,

11. Shall we duplicate one more ETCC or develop a rotor for covering ~2π sr (half-sphere)? … Demand for REP-detection mode

12. On-board processing and command / telemetry protocol (for example, frequent data download) … Demand for pre-studies on satellite-borne ETCC
Balloon-borne ETCC
– Practical preparation

In Kyoto, 2 Master students (one is Space Master Karl Muller) have studied Attitude Control System during this summer (July – Sept., 2011). To make the gondola be star-guided, the team has investigated the functions of motored-rotor which determine the target angle ($\theta_2$) and consequently the resultant angle ($\theta$) of the gondola.
Balloon-borne ETCC
– Practical preparation

CPU board
Motor Driver
GPS compass

By courtesy of Matsucka
Balloon-borne ETCC

Mini-gondola test

target angle $\theta_2$

measured angle $\theta$

By courtesy of Takada
Summary (3)

- We have almost fixed the cyanotype of SMILE-II (Sub-MeV gamma-ray Imaging Loaded-on-balcon Experiment), which is planned for 2012 (in Japan) and 2013 (in Sweden), in terms of the detector (ETCC) self.

- **Peripherals for balloon experiments** should soon be studied and prepared, particularly for 2013- balloon campaigns in Sweden. *We need experts (or will develop expertise) on this issue.*

- **We have a long perspective on advancing ETCC!**