P2-104

2014.1.9-10
宇宙科学シンポ

ERG 衛星搭載低エネルギー粒子分析器 (LEPe/LEPi) の開発

Development of low-energy plasma particle instruments (LEPe/LEPi) onboard ERG

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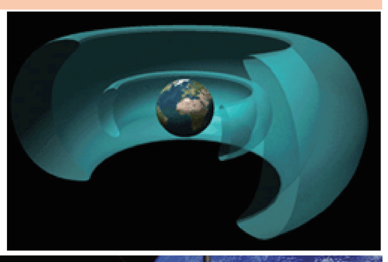
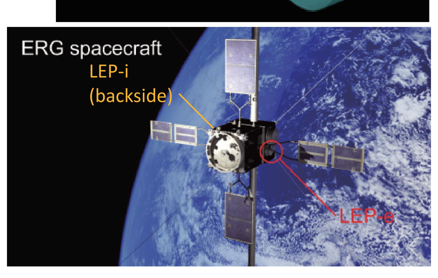
ERG Mission

- ERG is a JAXA's radiation belt observation mission.
- Goal: to understand the dynamics of the Earth's radiation belts

1. Which process produces energetic electrons, external supply or internal acceleration?
2. What mechanism accelerates electrons to a MeV range?
3. How energetic electrons are lost at the beginning of a storm?



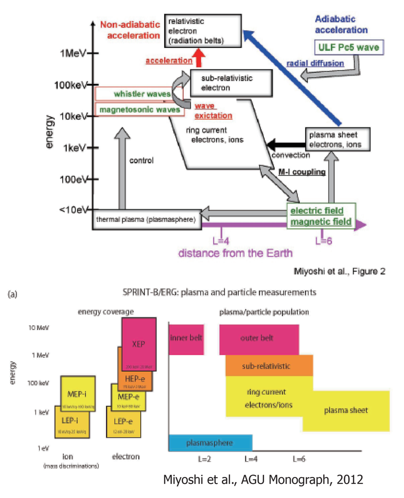


- Launch: December, 2015
- Life: >1 year
- Apogee: 5.5 Re (geocentric)
- Perigee: 300 km (altitude)
- Inclination: 31 degrees

Low-Energy Particle Measurement

Wonder of MeV-range electron existence

- MeV-range electrons are produced by radial diffusion or local wave-particle interactions???
- The inner magnetosphere has particles with a wide range of energies: 0.1eV up to 10MeV.
- ERG has a set of particle instruments to cover the wide energy range.
- LEP-e/LEP-i measure low-energy (10—20000eV / 10 — 25000eV/q) electrons/ions, which are dominant in flux and form the background for phenomena.



Miyoshi et al., AGU Monograph, 2012

Summary

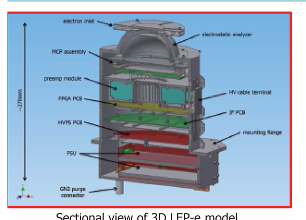
- We are developing a low-energy electron instrument LEP-e and a low-energy ion mass spectrometer LEP-i for the radiation belt observation spacecraft ERG.
- LEP-e/LEP-i will be carried into a orbit in FY2015 winter, and will give us information about radiation belt structure and dynamics.
- Laboratory experiments show good agreement with the results of numerical simulations.
- Further performance test and environmental test will be done with EM.

LEP-e Specs

Parameter		Unit	Remark
G-factor			w/o mesh
coarse	9.56e-4	cm2 sr keV/keV	@22.5deg
fine	1.51e-4	cm2 sr keV/keV	@3.75deg
Energy range	~10—19,000	eV	@4kV HV
Energy resolution	8.8	%	FWHM
Field of view	2.86 x 360	deg	
Angular resolution			
coarse	2.86 x 22.6	deg	EL x AZ, FWHM
fine	2.86 x 3.75	deg	EL x AZ, FWHM
Sub-channel coverage	80.3	%	% for 3.75deg channel width

Parameter		Unit	Remark
Dimension			
upper part	180DIA x 205H	mm	Cylindrical shape
lower part	170D x 180W x 90H	mm	Rectangular shape
Mass	5.92	Kg	
Power Consumption	7.3	W	w/o PSU's efficiency
Raw data production	197 [25]	Kbit/spin [Kbit/s]	32K×(12+12)EL×16AZ*16bit

Current Status

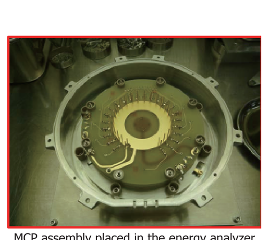


Sectional view of 3D LEP-e model.

Manufacturing an EM is ongoing:
- The energy analyzer part including its MCP assembly has been manufactured and are now under testing.
- The lower part is being manufactured now.
- The preamp PCB was developed and passed an initial test.
- The FPGA, interface and HVPS PCBs are being developed now.

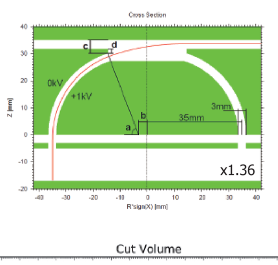
A preamp PCB connected to an anode pin

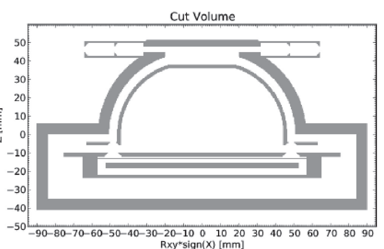
Blackened tophat-type energy analyzer.



MCP assembly placed in the energy analyzer.

Designing the Analyzer





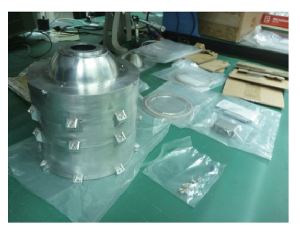
We have carefully designed the sensor geometry by parameter surveys to meet the requirements.
1. Parameterize a tophat geometry
2. Calculate E field by a Poisson equation solver (SOR)
3. Trace electron trajectories by a motion-of-equation solver (RK4+AS)
4. Estimate the performance
5. Repeat steps #2—#4 until the design meets the requirements.

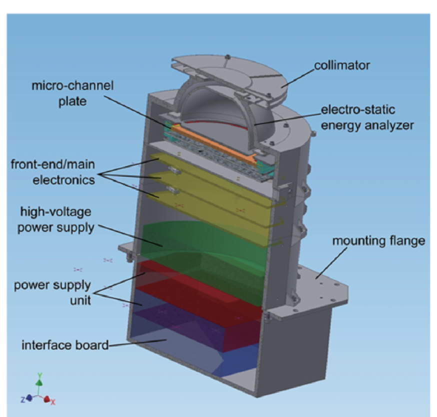
Finally, modifications are made for photon suppression and radiation shield.

Test Model Manufacturing

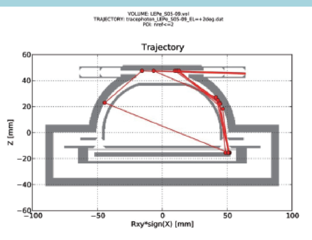
For performance verification and environment test, we are now manufacturing a test model (TM).

- The energy analyzer, MCP assembly and part of the cylindrical housing have been manufactured.
- The lower part of LEP-e is being detail-designed now.
- Developing the electronics is also on-going.





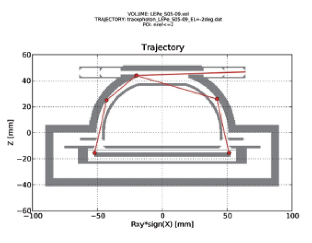
Photon Suppression

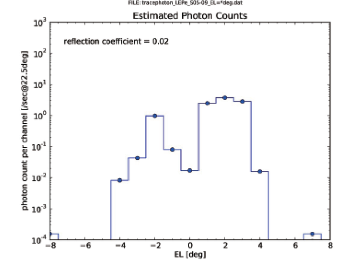


Photon suppression is important because MCPs are sensitive to UV photons as well as particles. CuS Blackening is applied on surfaces inside the sensor.

Computer simulation is made to evaluate photon count rates under assumption:
- random reflection, r~0.02
- solar Ly-α flux ~ 3×10^{11} /cm^2 sec
- MCP's photon efficiency ~ 1%

Estimate count rates are <~4 /sec per channel, comparable to background counts.

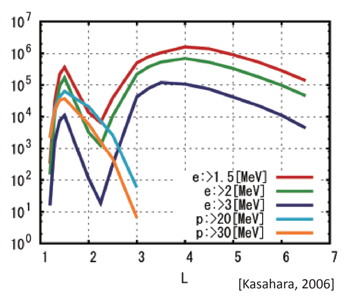




Contamination due to High-Energy Particles

- Significant background noise is detected due to high-energy particles in the earth's radiation belt and planetary magnetosphere.

⇒ High-energy particles can penetrate into and transmit through a wall of instrument. It is noise if detected.
⇒ Countermeasure should be necessary.

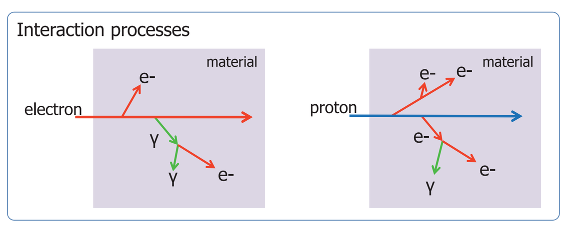


[Kasahara, 2006]

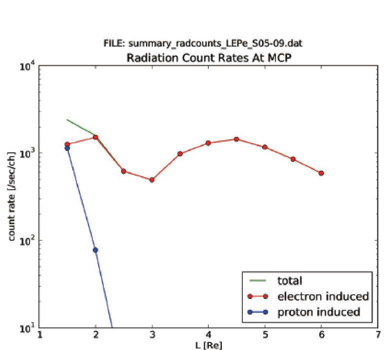
Particle-Material Interaction Processes

particle	process	
proton (p+)	ionization excitation	p+ → p+ + e- p+ → p+ (+ e-*)
electron (e-)	Bremsstrahlung ionization excitation	e- → e- + γ e- → e- + e- e- → e- (+ e-*)
positron (e+)	pair annihilation ionization excitation	e+ + e- → γ γ e+ → e+ + e- e+ → e+ (+ e-*)
gamma ray (γ)	photoelectric effect Compton scattering pair production	γ → e- γ → γ + e- γ → e+ + e-

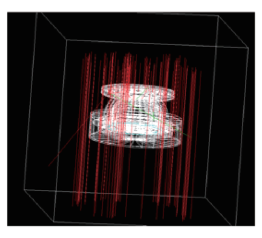
- High-energy electrons and protons can interact instrument structures.
- The particle-material interactions create secondary particles, which create noise counts on the detector (MCP).
- **We have to estimate the noise counts to design the instrument.**



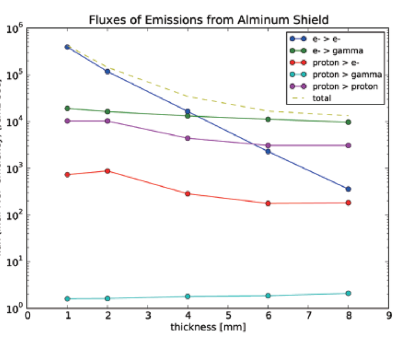
Radiation Count Estimation



MCP counts due to radiations are estimated by GEANT4 with fully-featured 3D LEP-e structure.
- MCP sensitivity:
  - 1% for gamma
  - 10% for electron/positron
  - 10% for proton
- Cut value = 10um
- AE-8/AP-8
- 4-pi isotropic radiation
- Expected radiation count rate: ~2400/sec at 1.5 Re, ~1400/sec at 4.5Re
- LEP-e has a `background' channel to monitor radiation count rates to subtract.



Radiation Shield Thickness

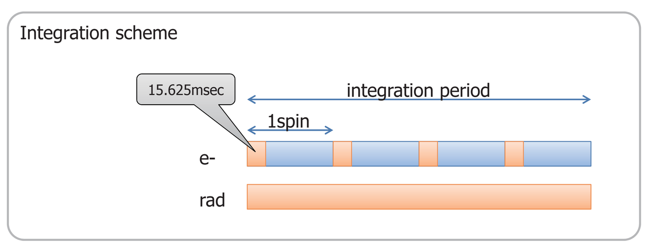


thickness	1mm	2mm	4mm	8mm
e- range	0.72 MeV	1.3 MeV	2.3 MeV	4.3 MeV
p+ range	~10 MeV	~20 MeV	~30 MeV	~40 MeV

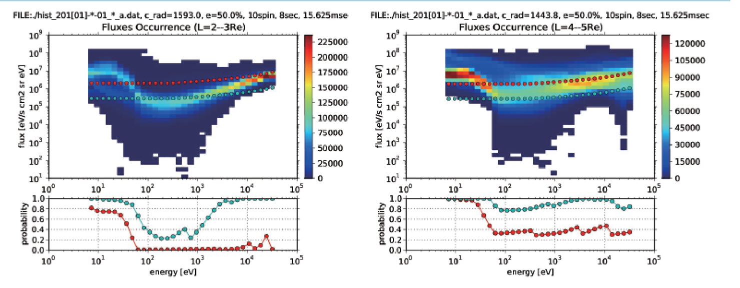
- MCP radiation counts are estimated using the GEANT4 tool kit.
- Assumption:
  - AE-8/AP-8 radiation model
  - ΔS=0.41cm2, ΔΩ=2π
  - ε(MCP,e-), ε(MCP,p+)= 10%
  - ε(MCP,γ)= 1%
- The results shows that electrons and gamma rays are dominant.
- The flux of electron-induced electrons decrease as the energy increase; The flux of electron-induced gamma rays shows roughly constant over energy.
- An aluminum plate with thickness of 6 mm can be a good compromise, because gamma rays cannot be easily stopped in a material.

Comparison of Radiation-Electron Counts

- THEMIS-A, `peer' data, 2010-12-01 – 2011-12-31 (13 months)
- Background subtraction (TDAS default setting with '/bgnd_remove')
- Histograms in (energy, energy flux) for each S/C location bin
- Comparison criteria
  1. Cele ~ Crad
  2. Δ(Ctotal – Crad)/(Ctoral – Crad) ~ 50%
     - N=10 spin, Tspin=8 sec, Tsample=15.625 msec



Result of the Comparison



- Due to harsh radiation environment of the radiation belts, radiation counts are frequently more than electron counts.
- By subtracting radiation, electron counts can be estimated.

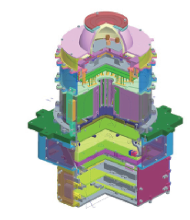
LEP-i Specs

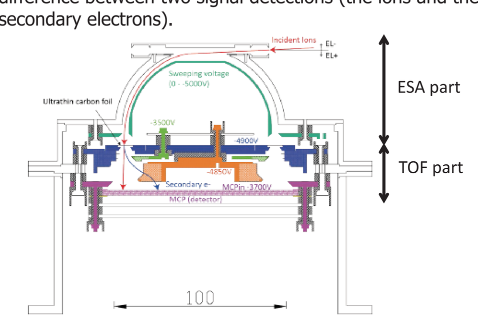
Parameter		Unit	Remark
G-factor	2.0e-3	cm2 sr keV/keV	@22.5deg
Energy range	~10—25,000	eV/q	
Energy resolution	13	%	FWHM
Mass resolution	> 4		M/ΔM
Field of view	5 x 290	deg	
Angular resolution	5 x 22.5	deg	EL x AZ, FWHM
Time resolution	8 (nominal)	sec	spacecraft spin period

Parameter		Unit	Remark
Dimension			
upper part	192DIA x 207H	mm	
lower part	235D x 230W x 155H	mm	
Mass	6.9	Kg	
Power Consumption	21.2	W	including 3.1W consumed by CPU board and PSU conversion efficiency
Raw data production	614 [77]	Kbit/spin [Kbit/s]	32K×15EL×16AZ*5M*16bit

LEP-i Design

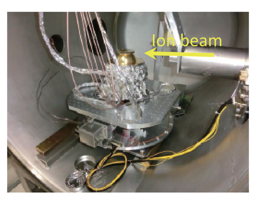
- ESA (electrostatic analyzer) provides energy analysis.
- A TOF (time-of-flight) method is applied to measure particle velocity, and then, its mass.
- Secondary electrons emit from an ultrathin carbon foil when ions pass through it.
- Particle velocity can be deduced by measuring a time difference between two signal detections (the ions and the secondary electrons).

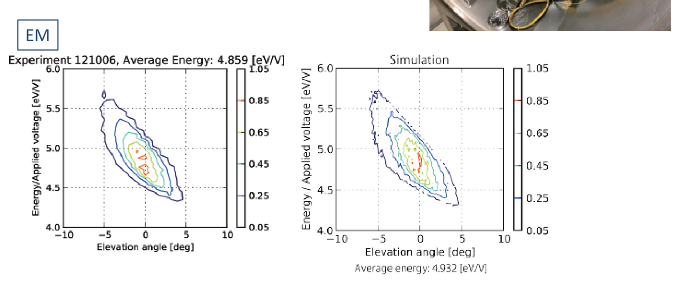




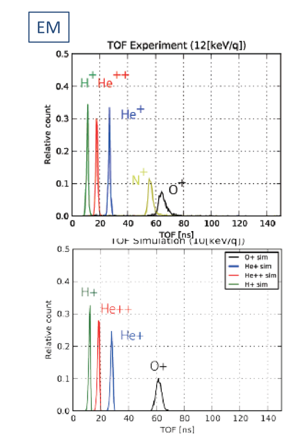
Analyzer Response

- Analyzer response for incident particles is verified by laboratory experiments.
- Ion beams are irradiated to the sensor.
- Results show good coincidence between experiments and numerical simulations.



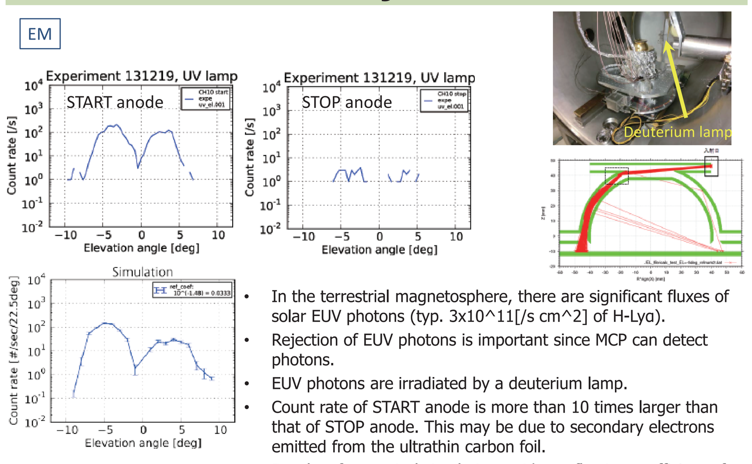


TOF (Mass) Analysis



- Mass resolution is verified by ion beams (H+, He++, He+, N+, O+).
- Results show good coincidence between experiments and numerical simulations.

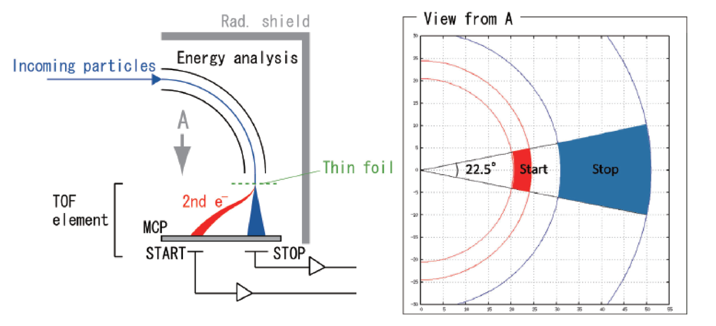
EUV Rejection



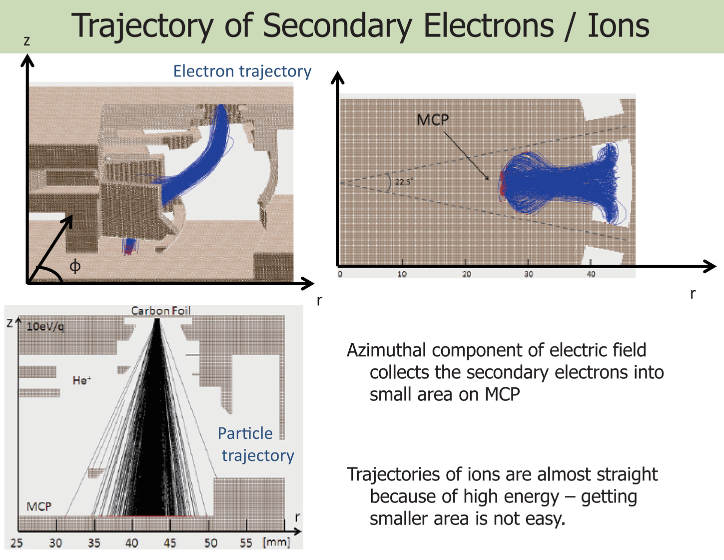
- In the terrestrial magnetosphere, there are significant fluxes of solar EUV photons (typ. 3x10^11[/s cm^2] of H-Lyα).
- Rejection of EUV photons is important since MCP can detect photons.
- EUV photons are irradiated by a deuterium lamp.
- Count rate of START anode is more than 10 times larger than that of STOP anode. This may be due to secondary electrons emitted from the ultrathin carbon foil.
- Results of numerical simulations with a reflection coefficient of 0.033 generally agree with the experiments (START anode).

Countermeasure for High-Energy Background

(1) Small detection area for START electrons
(2) Coincidence with TOF
(3) Passive shield



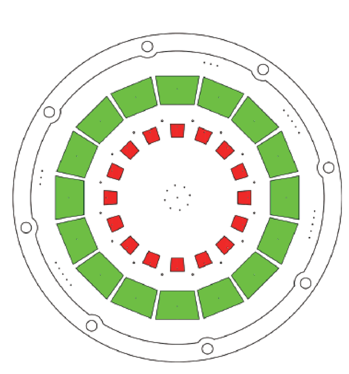
Trajectory of Secondary Electrons / Ions



Azimuthal component of electric field collects the secondary electrons into small area on MCP

Trajectories of ions are almost straight because of high energy – getting smaller area is not easy.

Small Detection Area

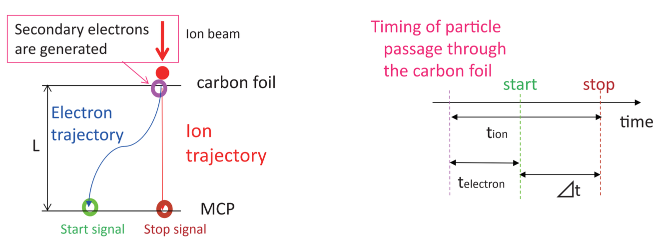


start anode
0.25 cm^2 / 22.5deg
4-5 times smaller
The area is separated for each 22.5deg sector.

stop anode
1.66 cm^2 / 22.5deg
The area is separated for each 22.5 deg sector.

Time-Of-Flight (TOF) Method

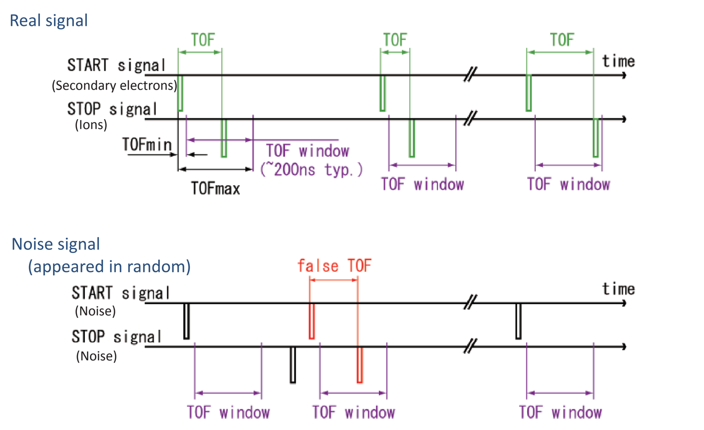
Particle velocity can be deduced by difference of appearance timings between START and STOP signals



m/q can be deduced with E/q and v

$$\frac{m}{q} = 2\left(\frac{E}{q}\right)\left(\frac{t_i}{L}\right)^2$$

Noise reduction with TOF coincidence



Noise Reduction with TOF Coincidence

N_{start}, N_{stop}: Noise count rate
Δt_{max}: Maximum value of TOF

↓

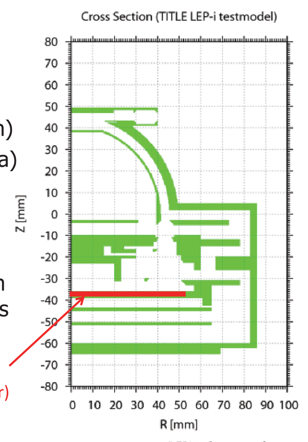
Reduced count rate $N_{reducted} = N_{start}\{1 - (1 - \Delta t_{max})^{N_{stop}}\} \sim N_{start}N_{stop}\Delta t_{max}$

Reduction is effective in case of lower noise count rate.
Smaller Δt_{max} helps the reduction also.

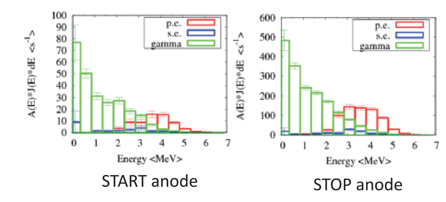
Ex.
N_{start}=1000[/s], N_{stop}=1000[/s], Δt_{max}=150[ns]
→ $N_{reducted}$ = 0.15[/s]

Estimation of Noise Count Rate

- Noise count rate due to the high-energy background is estimated by Geant4.
- Input flux: AE8Max (L=4.5), isotoropic.
- Detection efficiency of MCP: 0.1 (electron), 0.03 (gamma)
- Sensor:
  - Axis symmetric
  - Aluminum plate with thickness of 5mm is used instead of a stack of electronics boards.



Estimation of Noise Count Rate



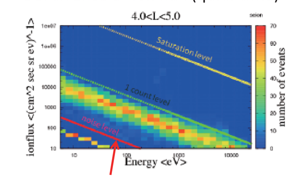
Calculated noise count rate:
START anode : Cstart = 380 [counts/s /sector]
STOP anode : Cstop = 2600 [counts/s /sector]

Cfalse = Cstart Cstop Δt
= 380 x 2600 x 1.5x10^-7
= 0.15 [/s / sector]

Cfalse: Residual noise count rate which cannot be reduced by the TOF coincidence method.

Cfalse corresponds to a flux well below the majority of ion fluxes observed by THEMIS spacecraft.

THEMIS
Occurrence of ion flux (quiet time)



Noise level (0.3 [count/sec/sector])

Estimation of Noise Count Rate

L=4.5

START anode
STOP anode

Calculated noise count rate:
START anode : Cstart = 380 [counts/s /sector]
STOP anode : Cstop = 2600 [counts/s /sector]

Cfalse = Cstart Cstop Δt
= 380 x 2600 x 1.5x10^-7
= 0.15 [/s / sector]

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