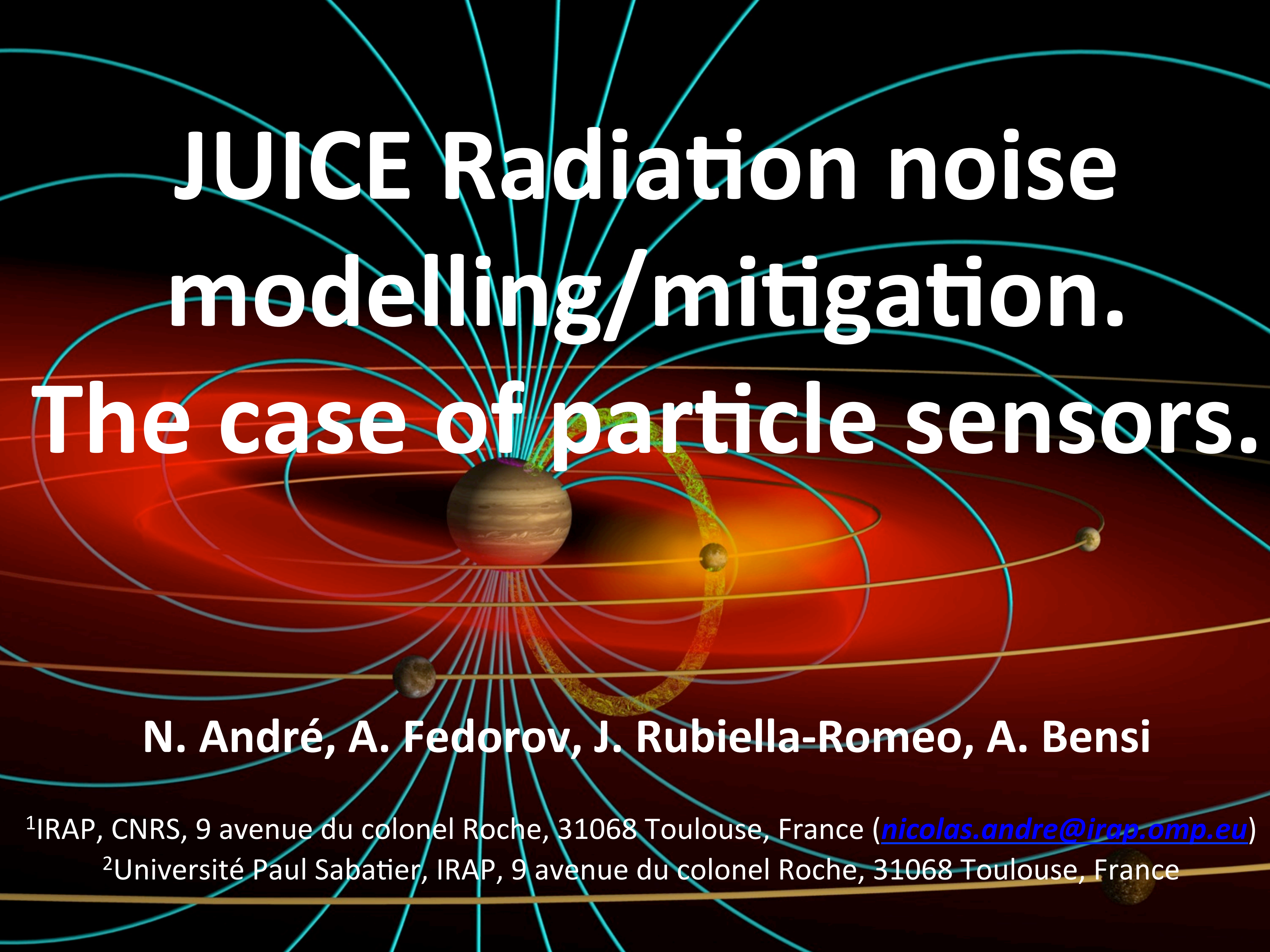

JUICE Radiation noise modelling/mitigation. The case of particle sensors.

N. André, A. Fedorov, J. Rubiella-Romeo, A. Bensi

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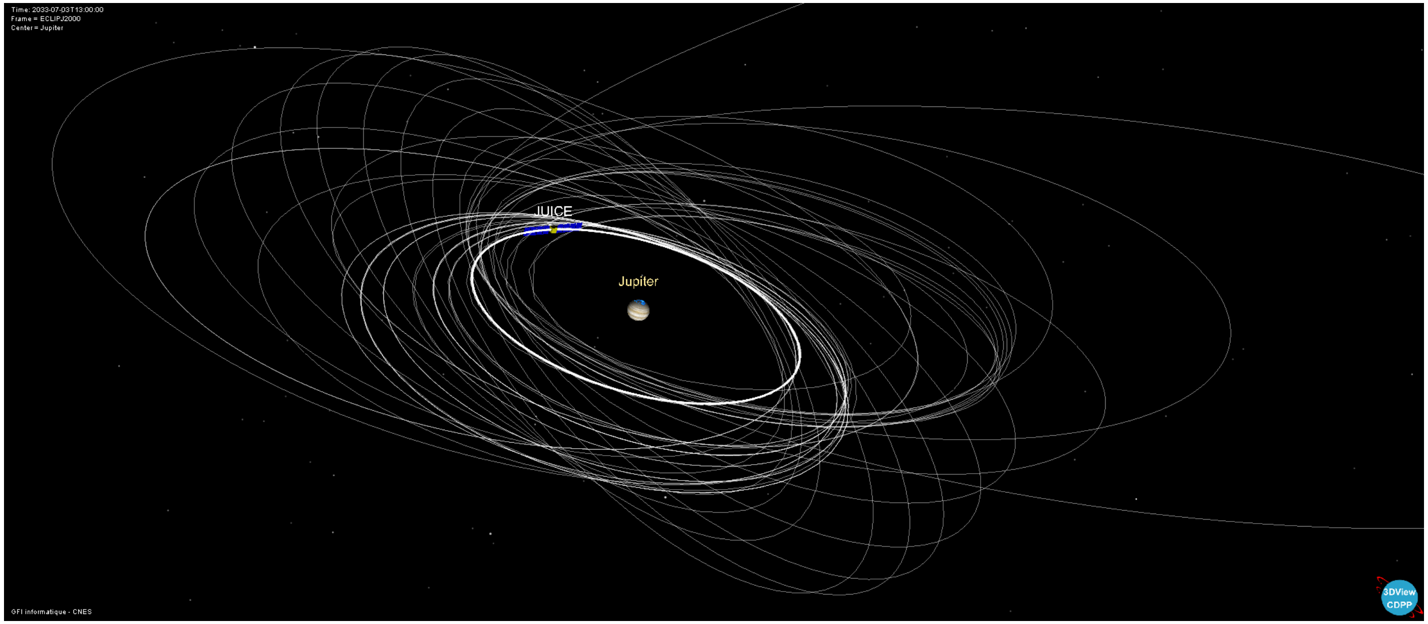
[2]Université Paul Sabatier, IRAP, 9 avenue du colonel Roche, 31068 Toulouse, France

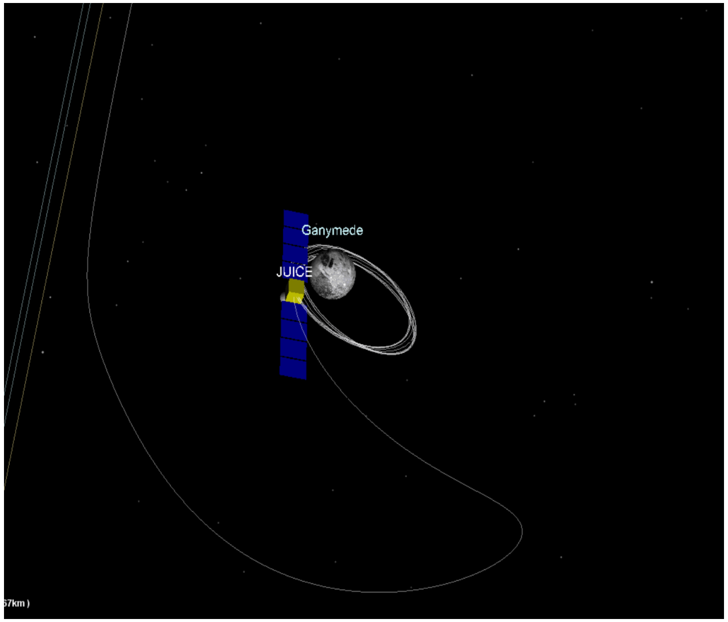
Outline

1. Particle sensors and background noise
2. Passive shielding – GEANT4 modelling
3. Laboratory tests and validation of shielded and unshielded detector's response
4. JUICE Radiation Noise modelling (GEANT 4)
5. The need for active shielding
6. Conclusions

JUICE



N.B.: JUICE trajectory (later attitude, contextual data) added to our <u>3DView/CDPP Tool</u> for our own instrument operation planning and now available to the benefit of the broad science community (http://3dview.cesr.fr/)



Outline

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JUICE Model Payload

Imaging	
Narrow Angle Camera (NAC)	10 kg
Wide Angle Camera (WAC)	4.5 kg

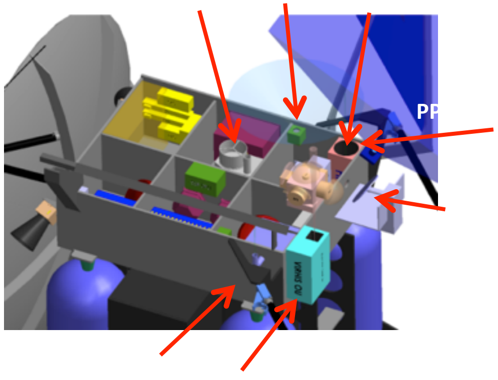
Spectroscopy	
Visible Infrared Hyperspectral Imaging Spectrometer (VIRHIS)	17 kg
UV Imaging Spectrometer (UVIS)	6.5 kg
Sub-mm Wave Instrument (SWI)	9.7 kg

In situ Fields and Particles	
Magnetometer (MAG)	1.8 kg
Radio and Plasma Wave Instr. (RPWI)	11.2 kg
Particle and Plasma Instrument - Ion Neutral Mass Spectrometer (PPI-INMS)	18.2 kg

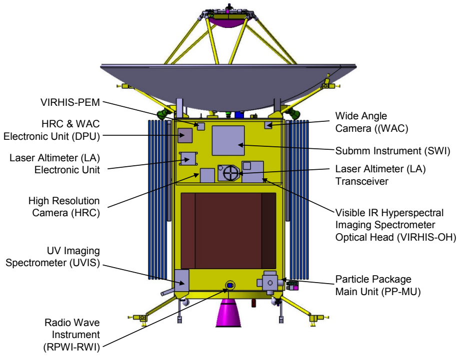
Sounders & Radio Science	
Laser Altimeter (LA)	11 kg
Ice Penetrating Radar (IPR)	10 kg
Radio Science Instrument (JRST+USO)	4 kg

Total mass: 104 kg

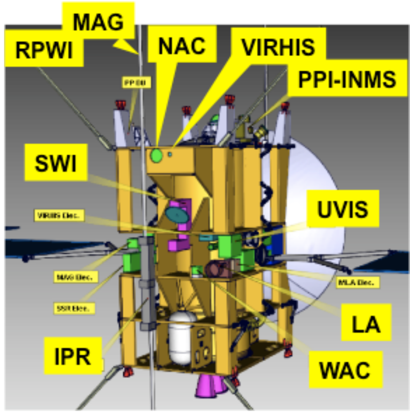
Option 3



Option 2



Option 1

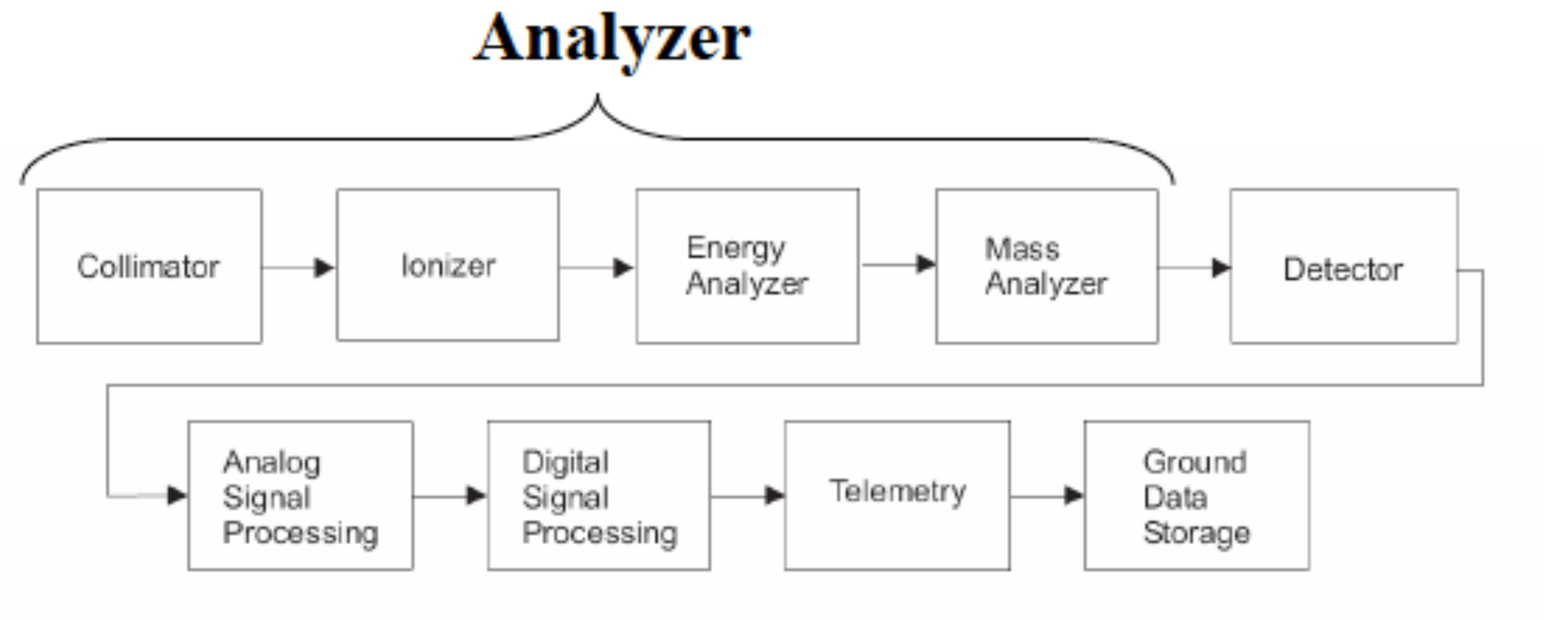


Model payload is based on heritage:

BepiColombo, Juno, Mars Express, Double Star, Venus Express, Rosetta, Dawn, Cassini, etc…

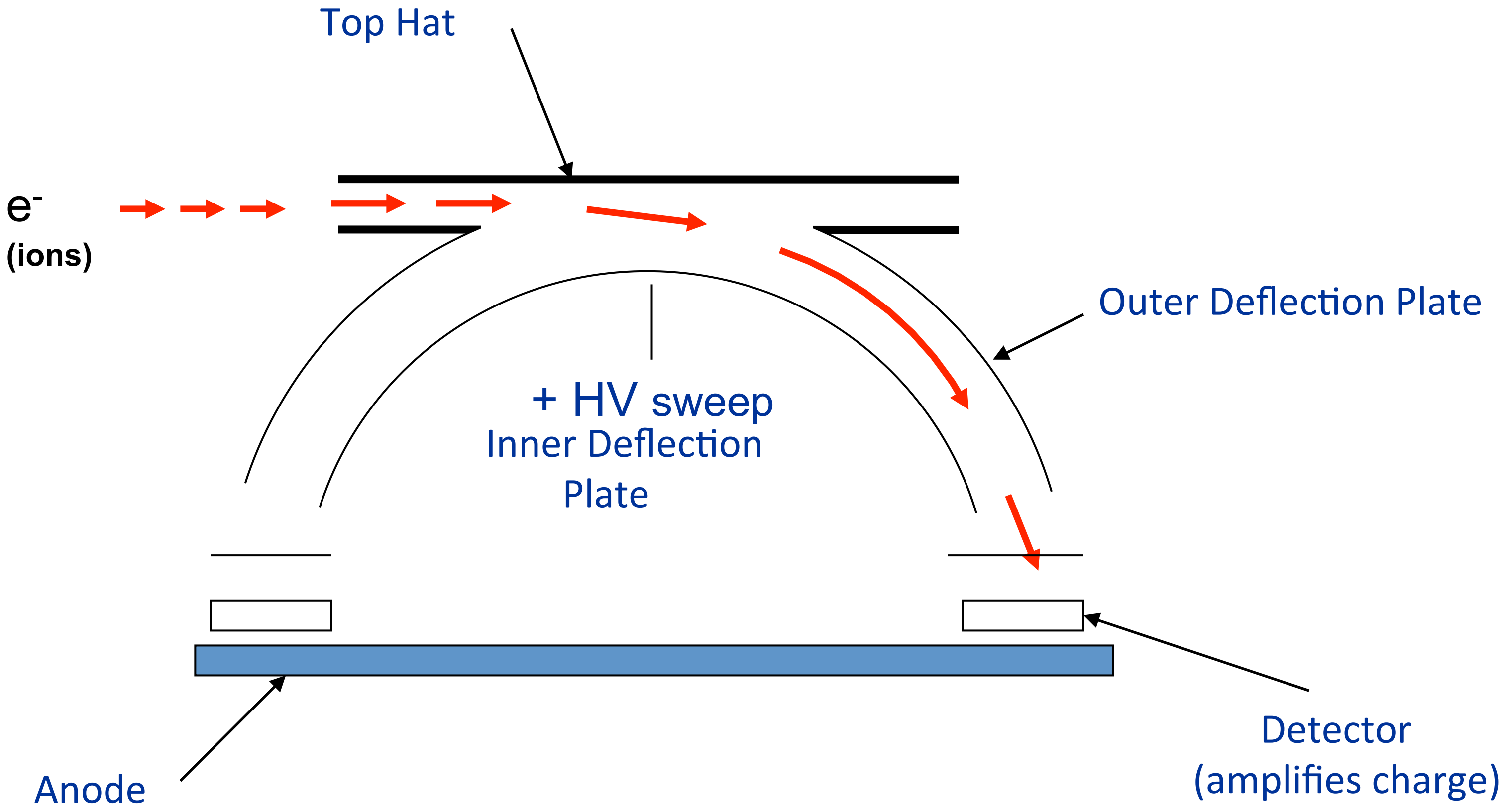
(Charged) Particle sensors

- Principle of operations



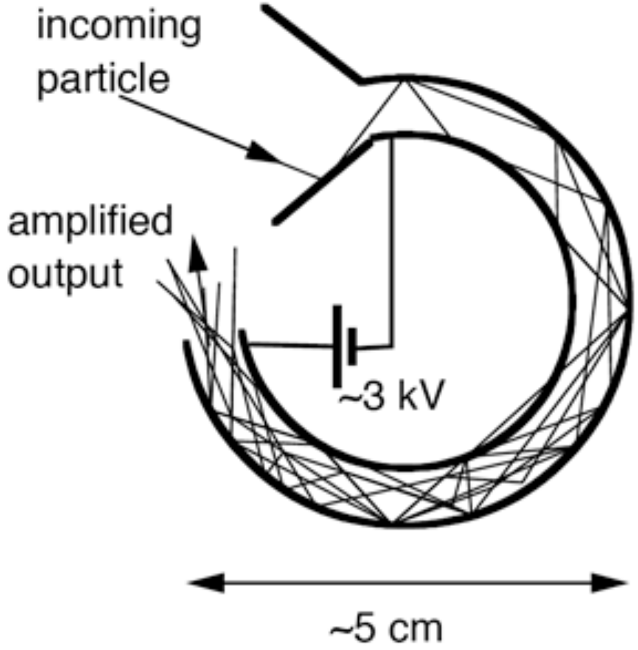
Top-Hat Analyzer

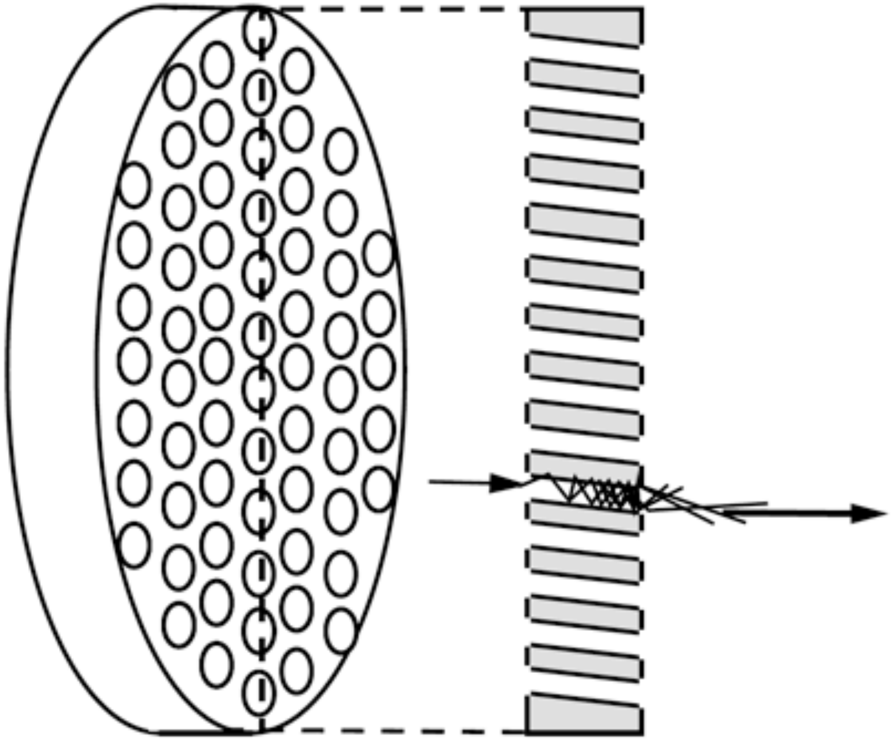
- Enables simultaneous angle-resolved measurements over 360° FOV
- Selects particles by E/q (e.g., 1 eV-30 keV)



Detectors

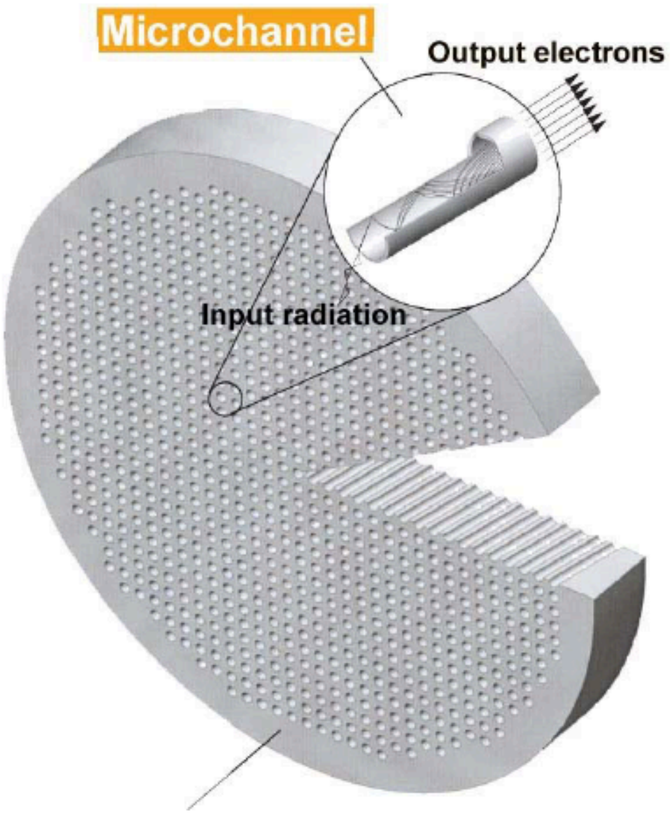
- Channeltrons (CEM) / MicroChannel Plate (MCP)





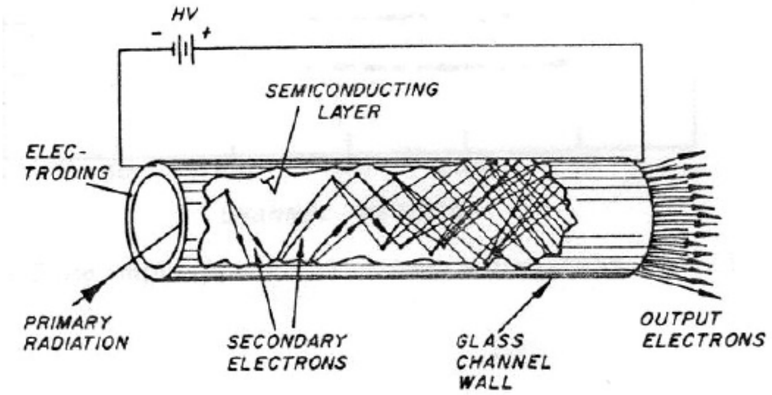
- Secondary electron multiplication from one incident particle

MCP Micro-Channel Plate



Miniaturized electron multipliers parallel to each other
(treated glass)

Diameter 10-100 μm
Length/diameter 40-100.



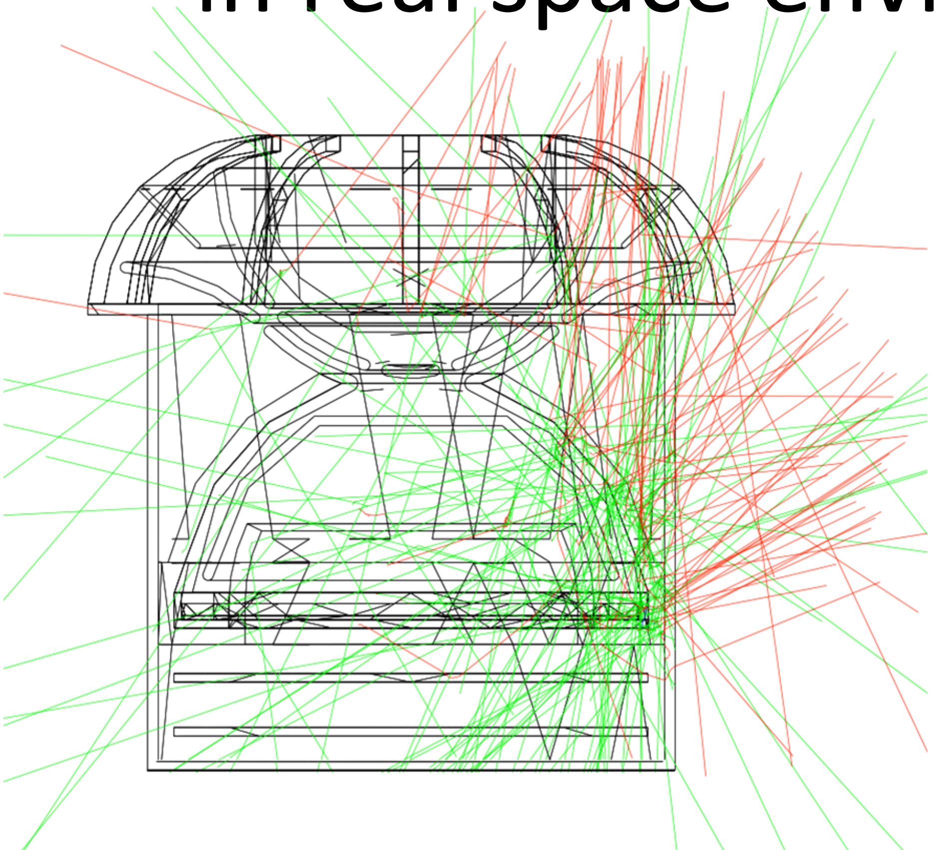
Detectors

- E.g., MicroChannel Plate (MCP)
  - Also used for X-ray spectrometers
  - Also used for UV Imagers or Spectrometers
  - …

Pro(s)/Con(s):

MCP have smaller time constant and gain than CEMs

Penetrating particles/Background noise in real space environment



Method: GEANT-4

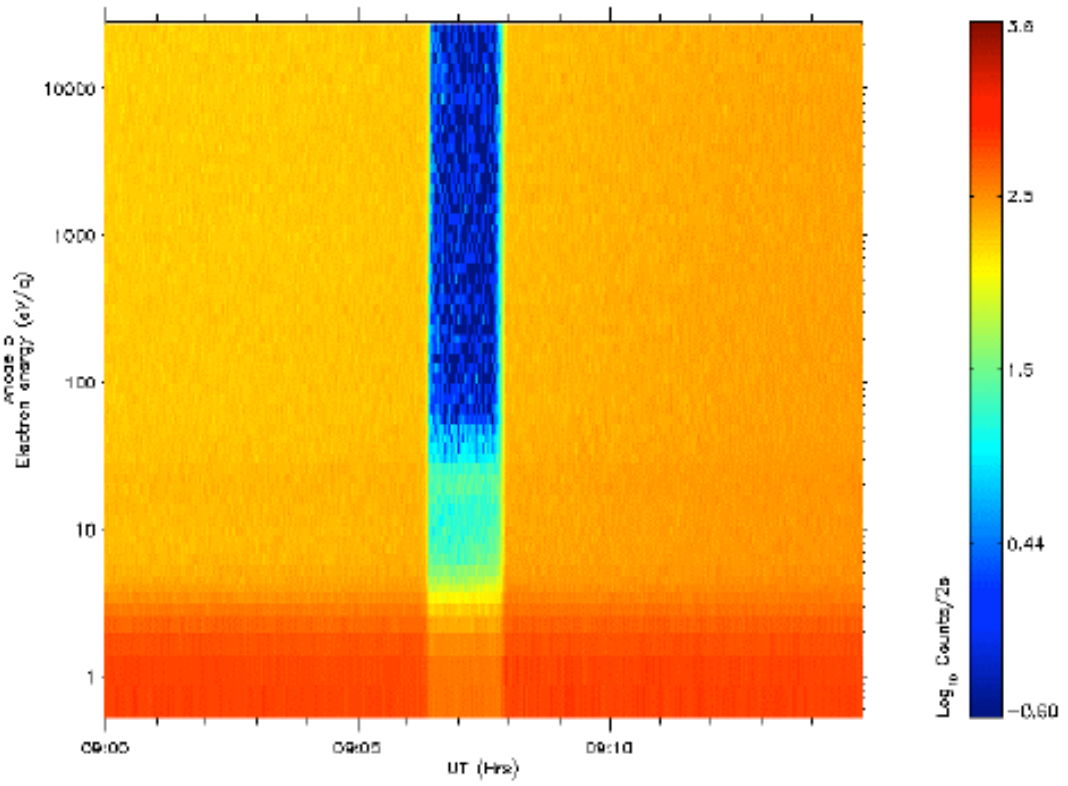
in red: electrons.
in green: photons.

• Signal (to be enhanced):	particles in a well-defined energy range
• Background Noise: (to be decreased)	high-energy incident penetrating particles + secondary electrons (interactions) + photons - X-rays, gammas (interactions)

Why to care so much ?

Let’s have a look at <u>real measurements</u>

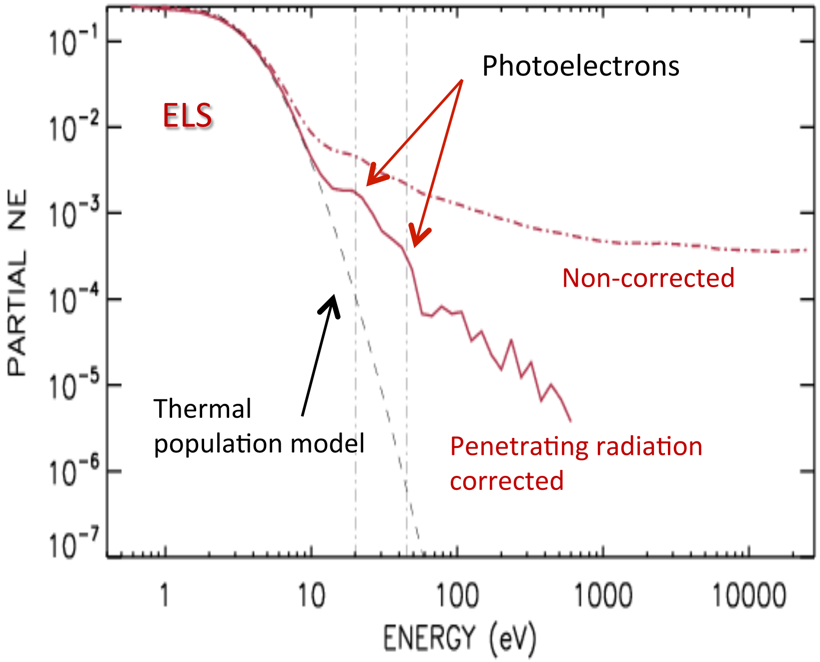
Radiation Environment within Saturn's Inner Magnetosphere and Cassini/CAPS



e.g., Enceladus flyby

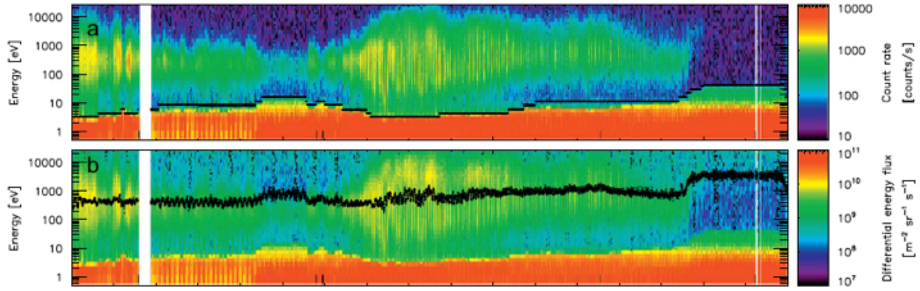
Need for efficient (reliable) background substraction techniques

Identification of ‘hidden’ plasma populations



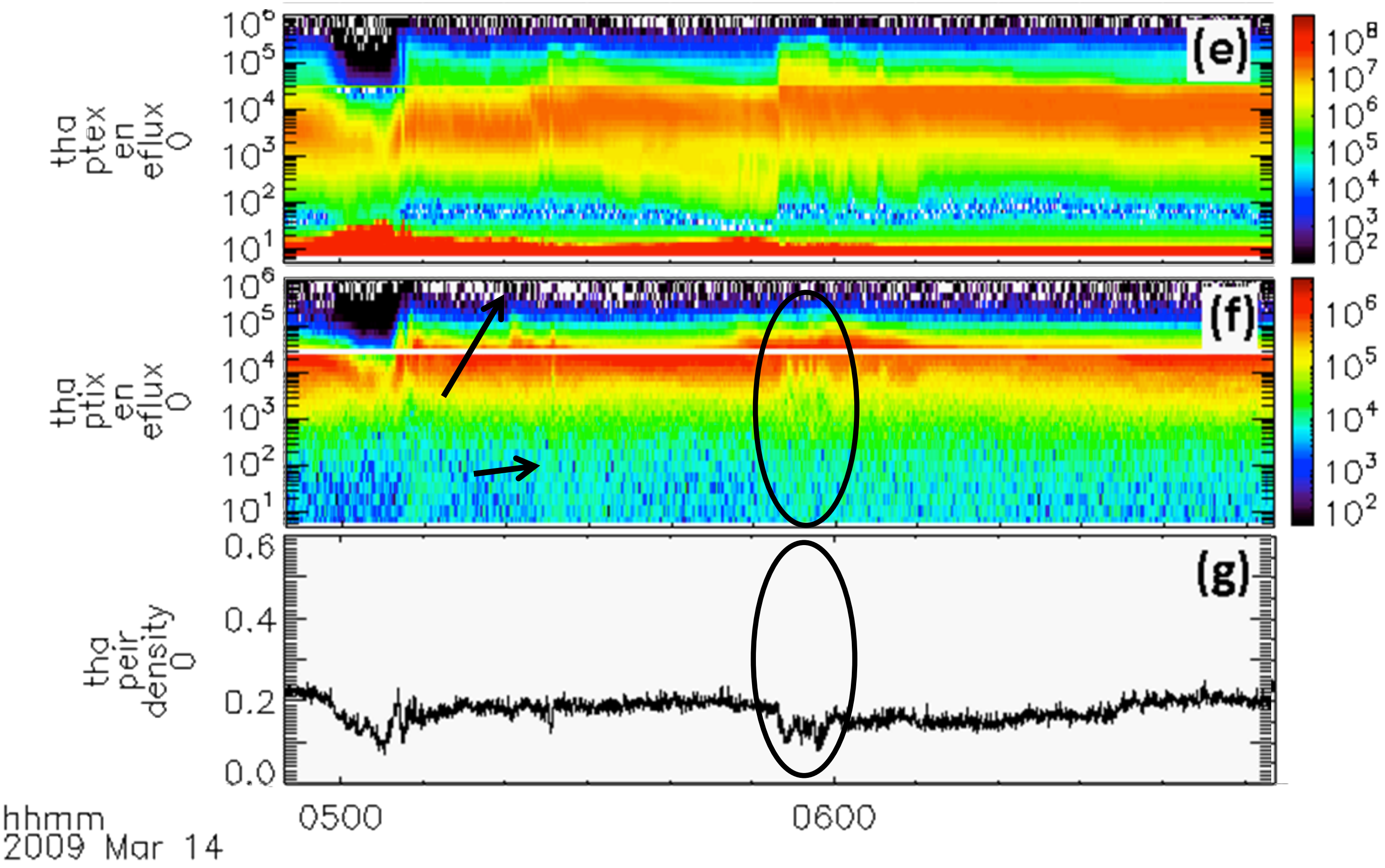
Penetrating particles
Schippers et al., 2009

Fluid moment calculations



Radiation noise (Cassini RTGs)
Arridge et al., 2009

THEMIS-ESA

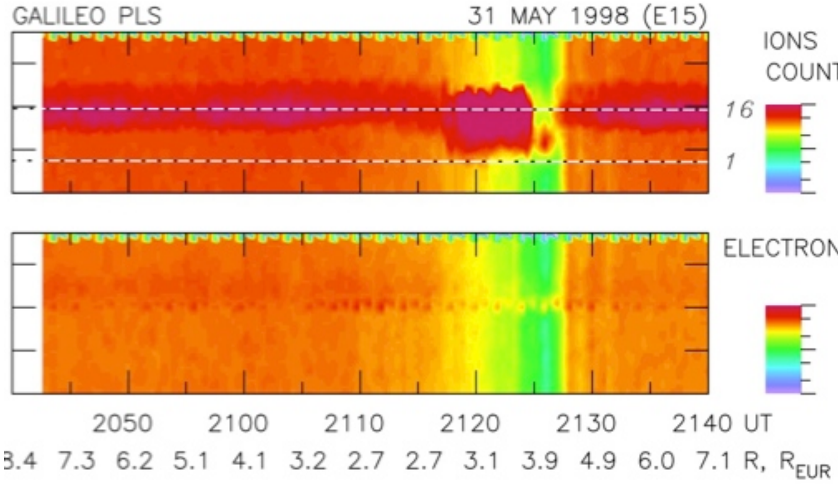


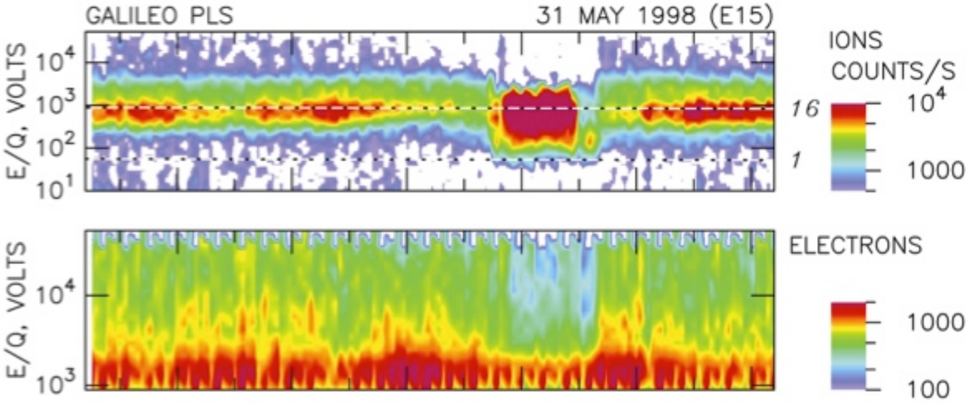
Courtesy Laurianne Palin, IRAP

PLAN

- CONTEXTE
- MOYENS EXPÉRIMENTAUX
- PHENOMENE DE DISSIPATION D'ENERGIE DANS LA QUEUE
  - Dipolarisations observées avec THEMIS
    - Observations dans la queue proche
    - Observations sol
  - Observations queue lointaine (THEMIS ARTEMIS)
  - Disruption/ reconnexion observées avec Cluster et Double Star
- CONCLUSIONS ET PERSPECTIVES

Lessons learnt from Galileo PLS





Although there was a substantial background due to penetrating energetic particles, the signature of the thermal plasma can sometimes *almost* be resolved

N.B.: A *Jupiter Magnetospheric Plasma Active Archive* has been built in the CDPP/AMDA Tool for our own needs and now available to the benefit of the broad science community (in preparation for JUICE, http://cdpp-amda.cesr.fr/)

Mitigation techniques

- Maximal reduction of the penetrating flux striking the detector

  Passive shielding

- Maximal reduction of the sensitivity to high energy electrons and X-rays (while keeping maximal efficiency for the targetted energy range)

  Careful choice of detector
  Minimization of detector size

- Use of 'Active' shielding to reach workable SNR

Outline

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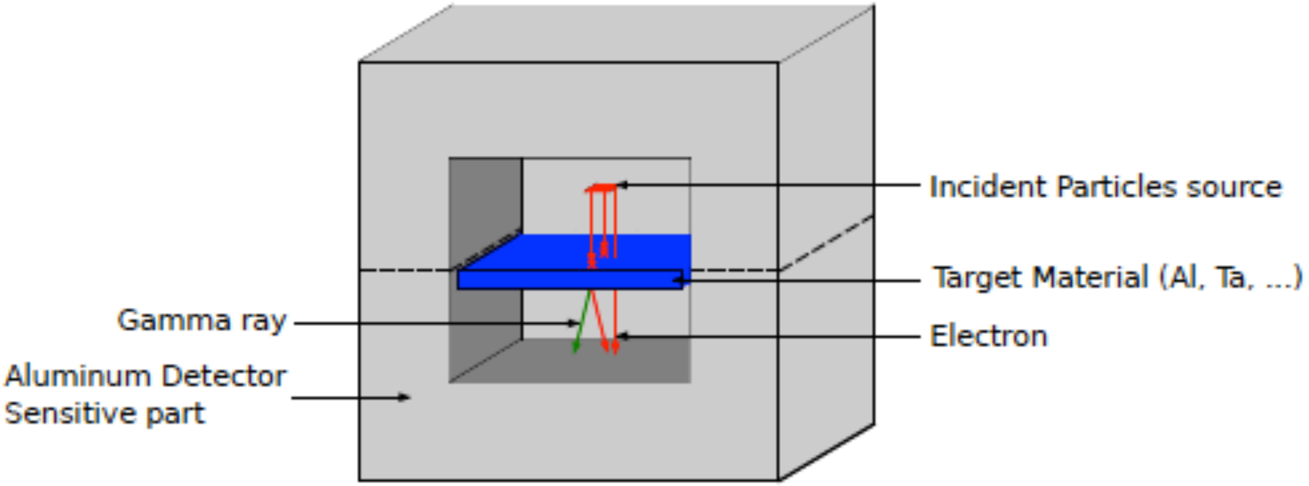
Understanding (physics) particle-matter interactions

1) Response of a simplified model (slab) under an electronic or photonic beam (effects of material and thickness)

2) Combination of different layers of different material and thickness (multi-layered shielding) under realistic environmental conditions

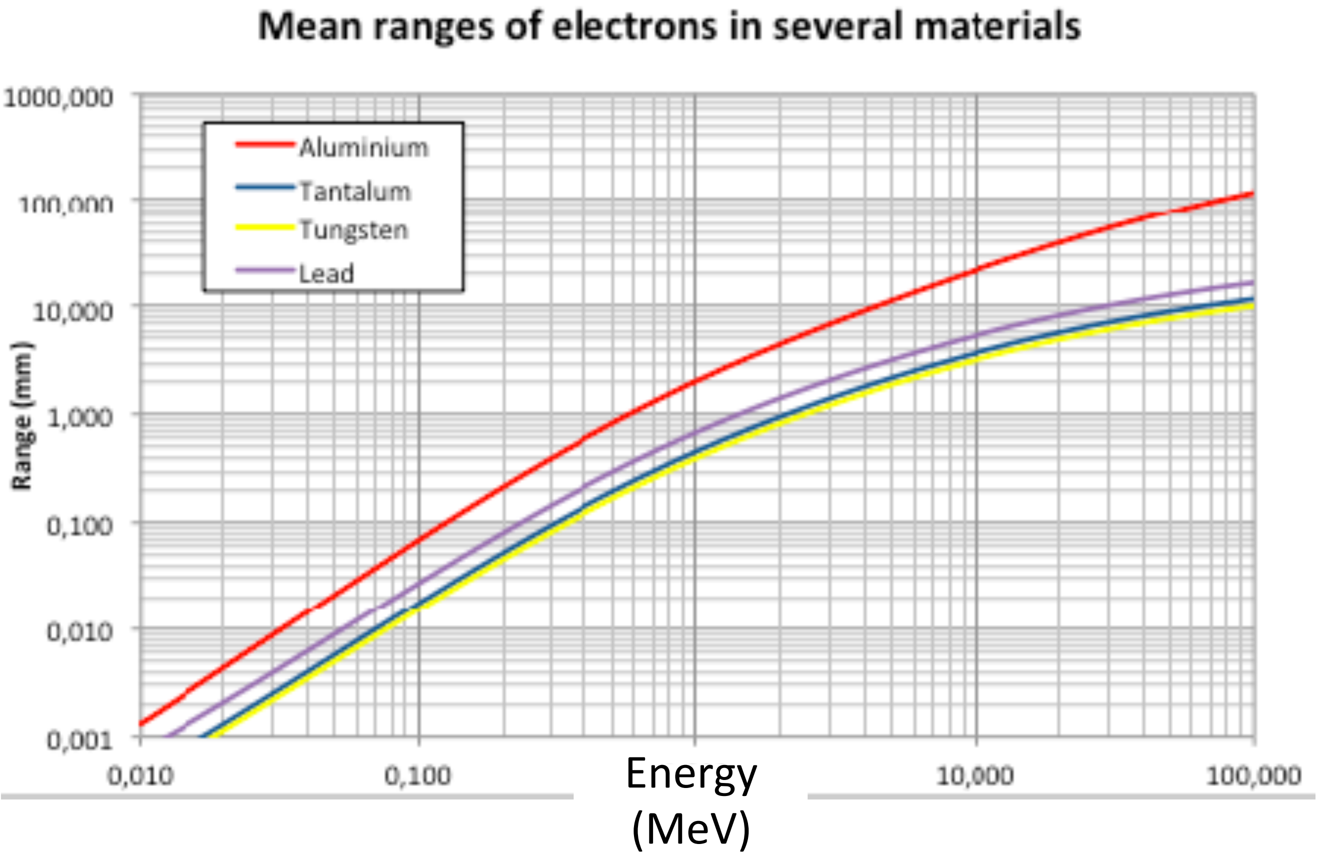
3) Integration of the identified shielding strategy into a modelled sensor and worst-case analysis

Understanding (physics) particle-matter interactions



Method: GEANT-4
Source: Planar
Incident particle: Isotropic, electrons or photons
Target: Semi-infinite slab with variable material and thickness
Detector: Thick hollow cube of Aluminium

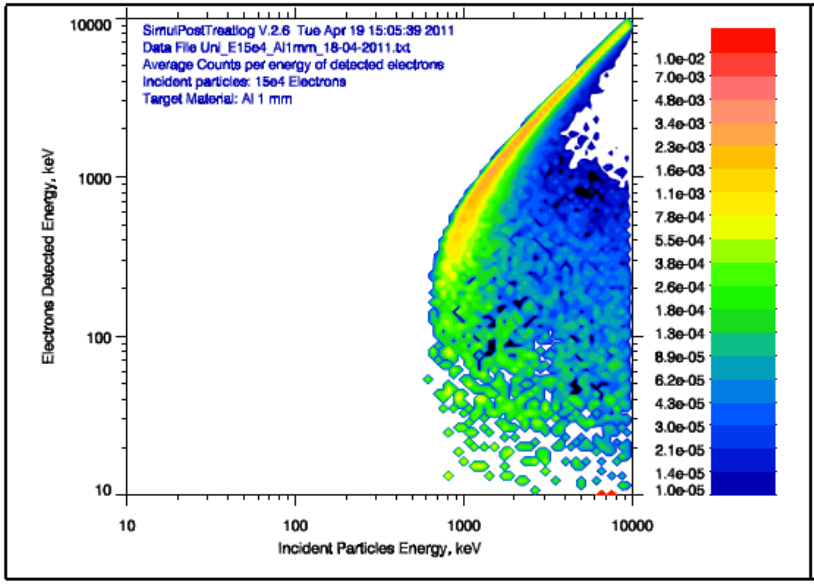
Choice of material



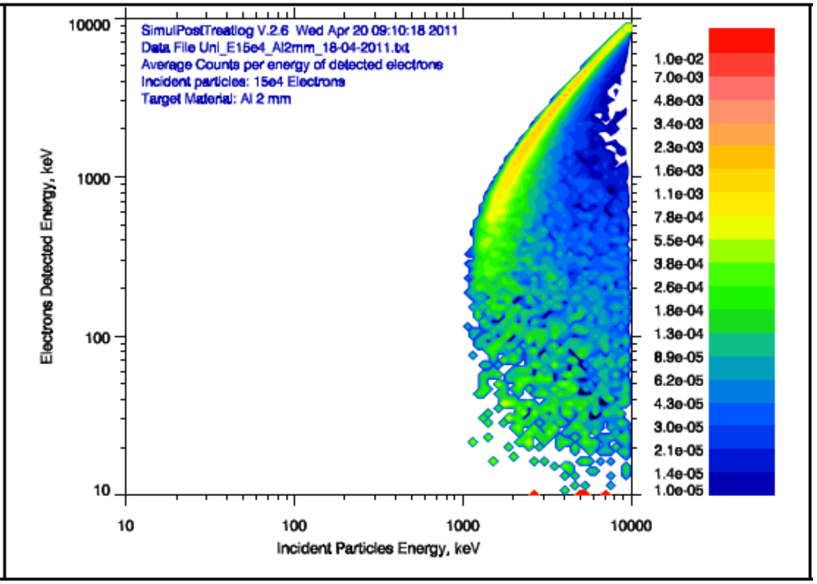
The case of Aluminium

1a. Electron beam

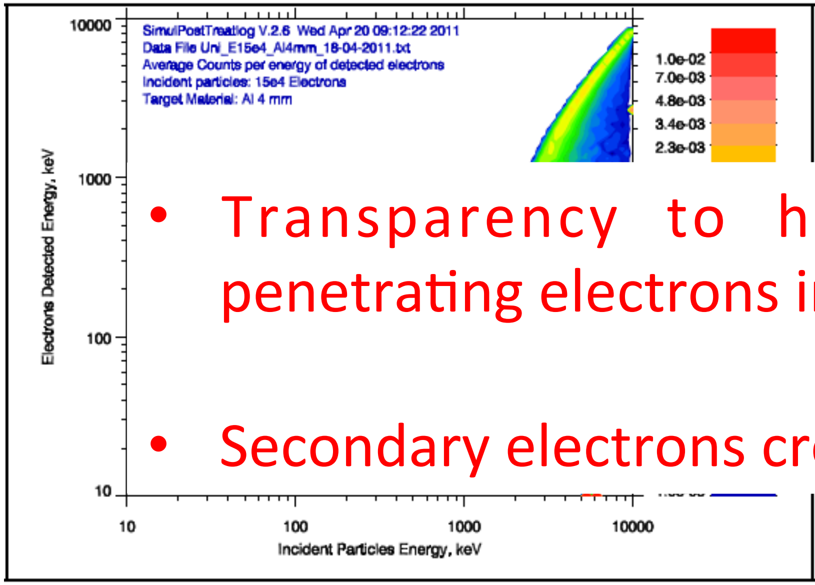
1b. Photon beam



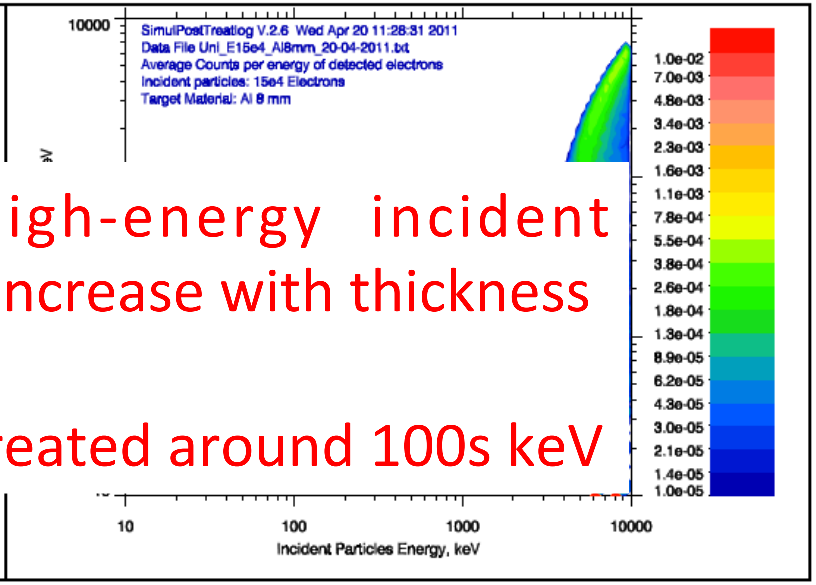
Al 1mm



Al 2mm

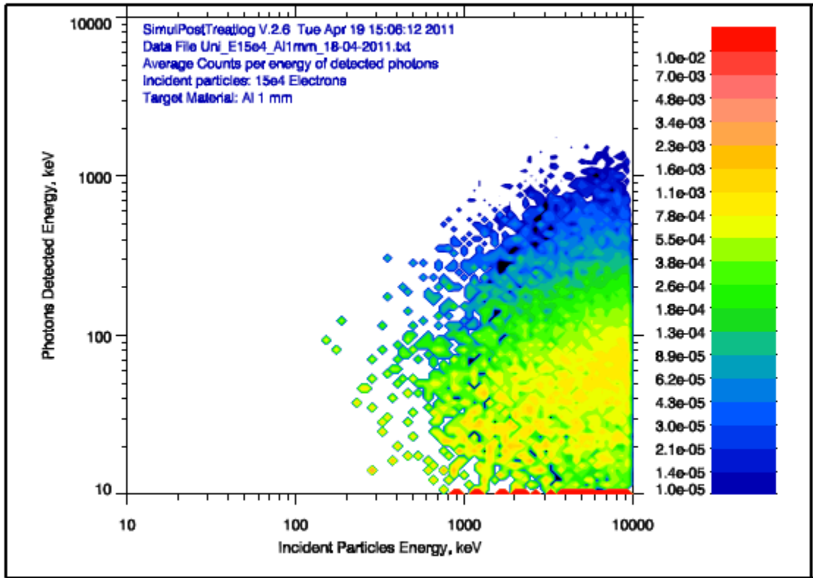


Al 4mm

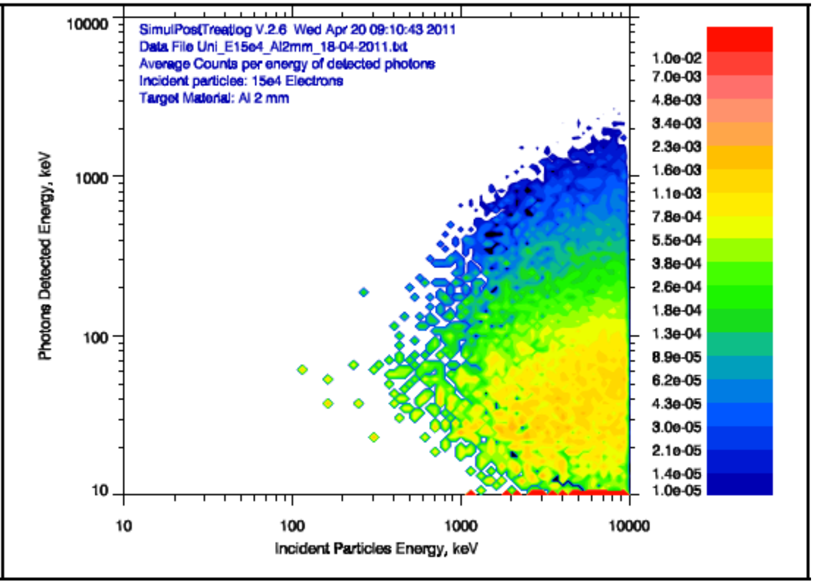


Al 8mm

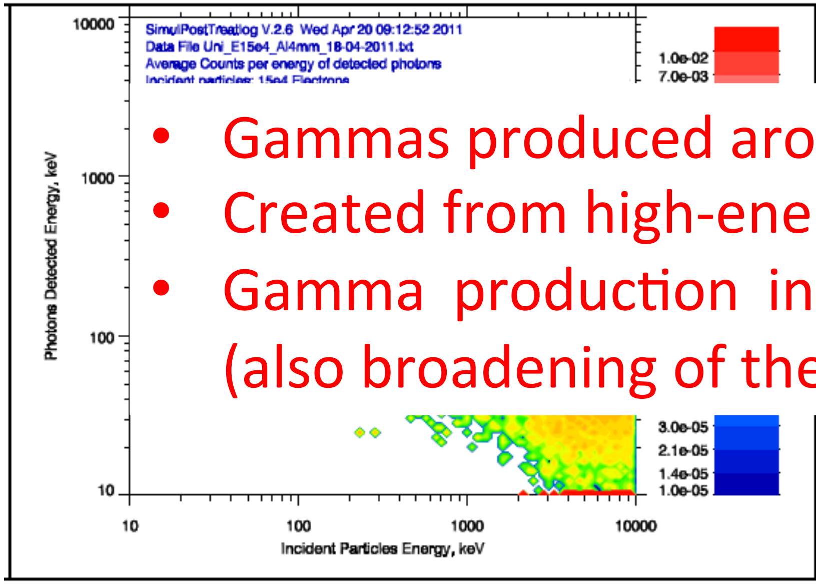
- Transparency to high-energy incident penetrating electrons increase with thickness
- Secondary electrons created around 100s keV



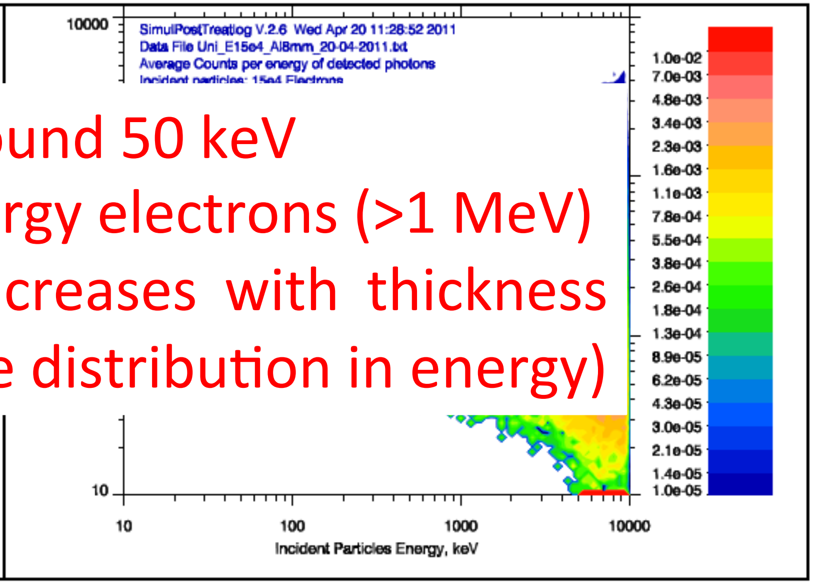
Al 1mm



Al 2mm

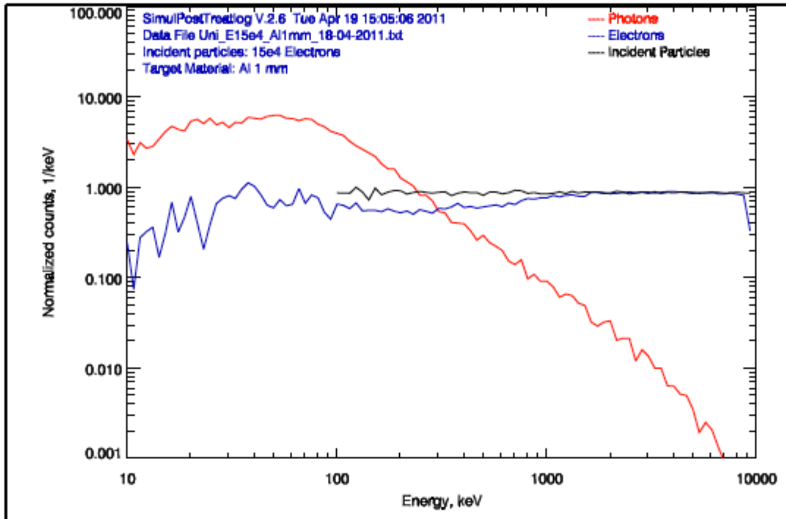


Al 4mm

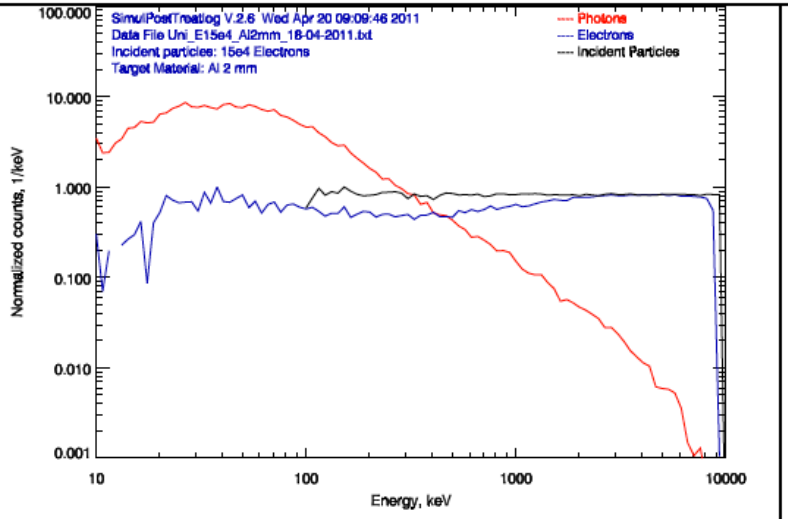


Al 8mm

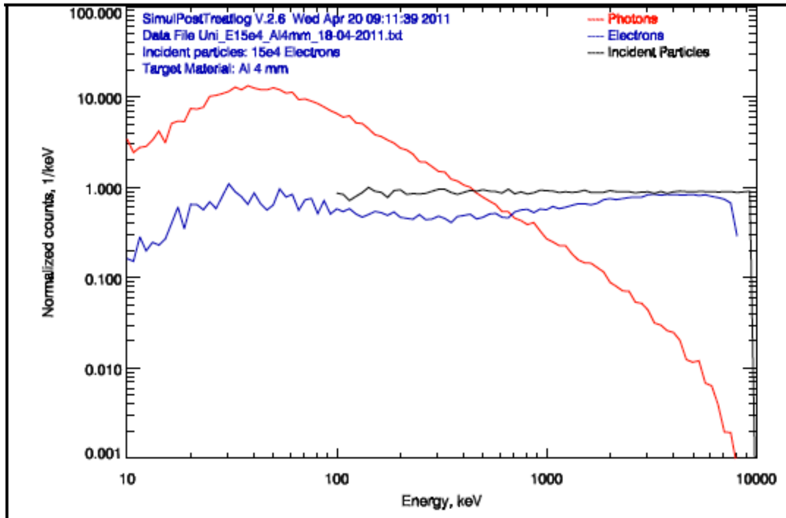
- Gammas produced around 50 keV
- Created from high-energy electrons (>1 MeV)
- Gamma production increases with thickness (also broadening of the distribution in energy)



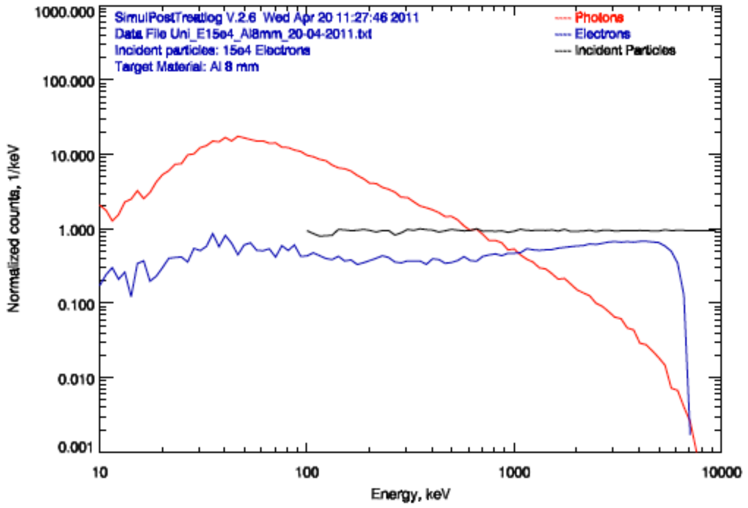
Al 1mm



Al 2mm



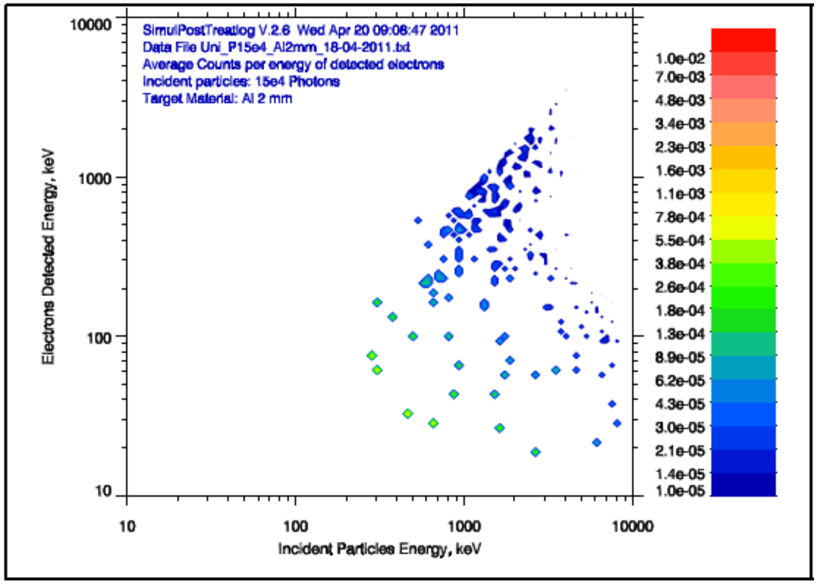
Al 4mm



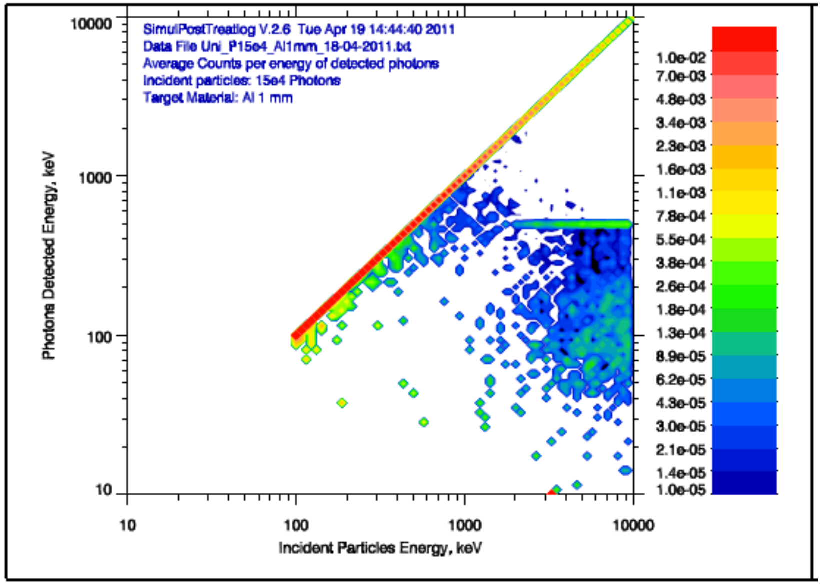
Al 8mm

The case of Aluminium

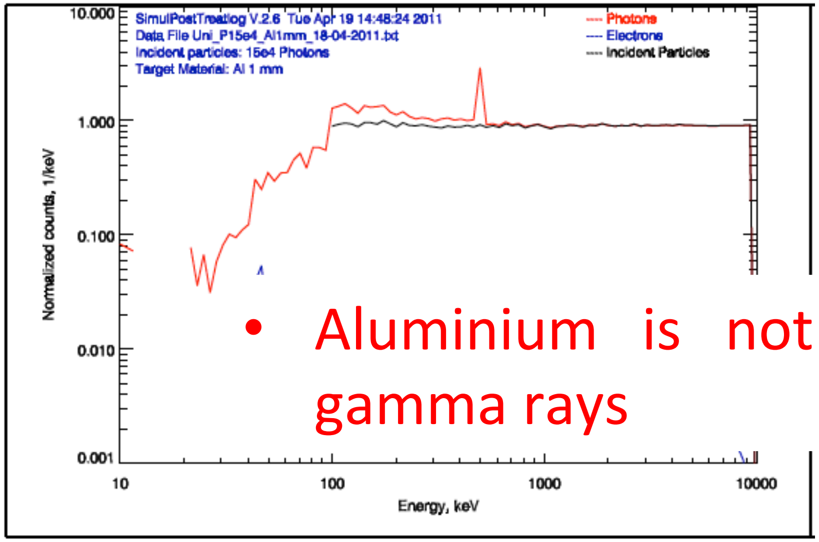
1a. Electron beam
1b. Photon beam



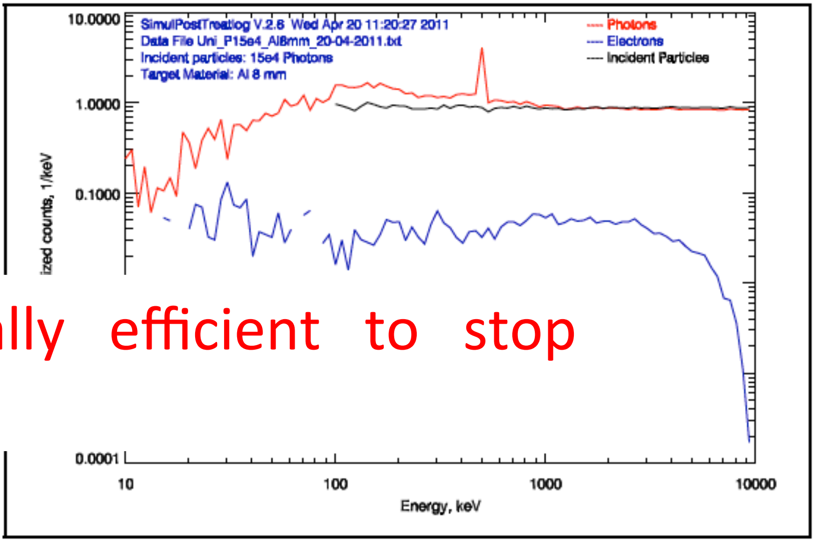
Al 1mm



Al 1mm



Al 1mm

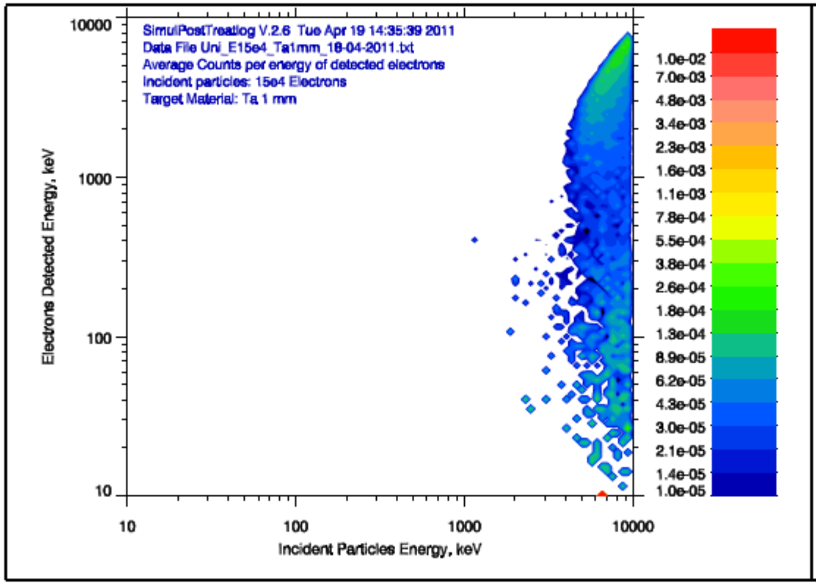


Al 8mm

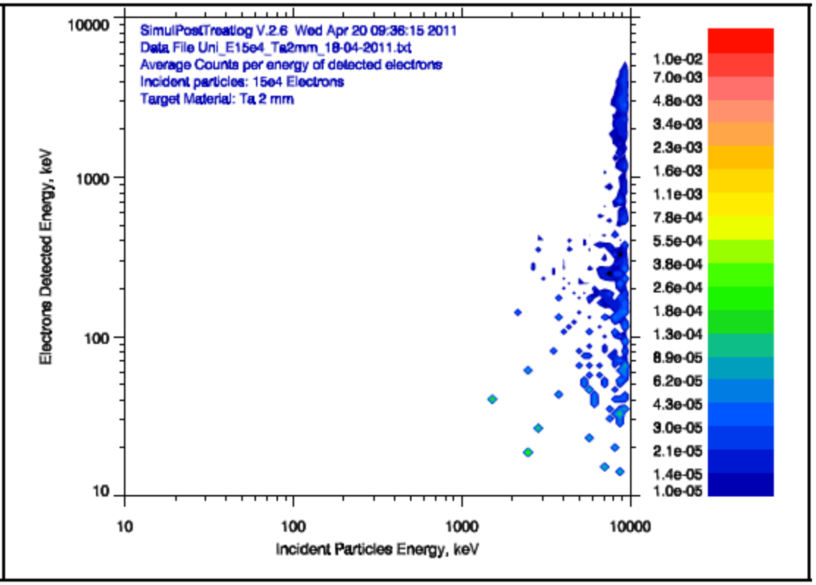
- Aluminium is not really efficient to stop gamma rays

The case of Tantalum

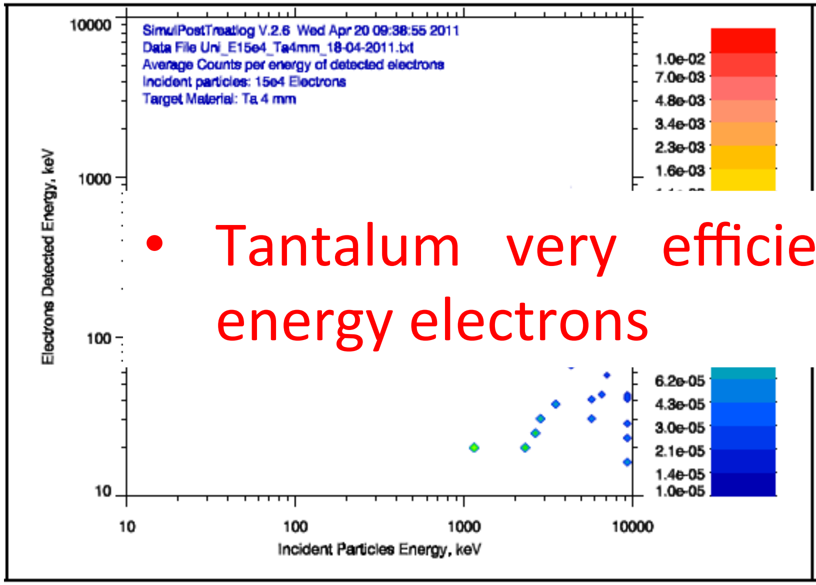
1a. Electron beam
1b. Photon beam



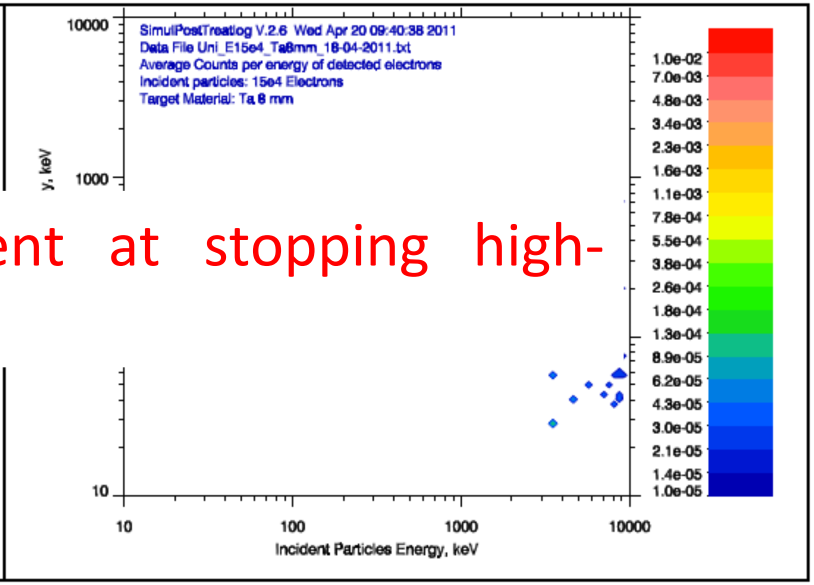
Ta 1mm



Ta 2mm

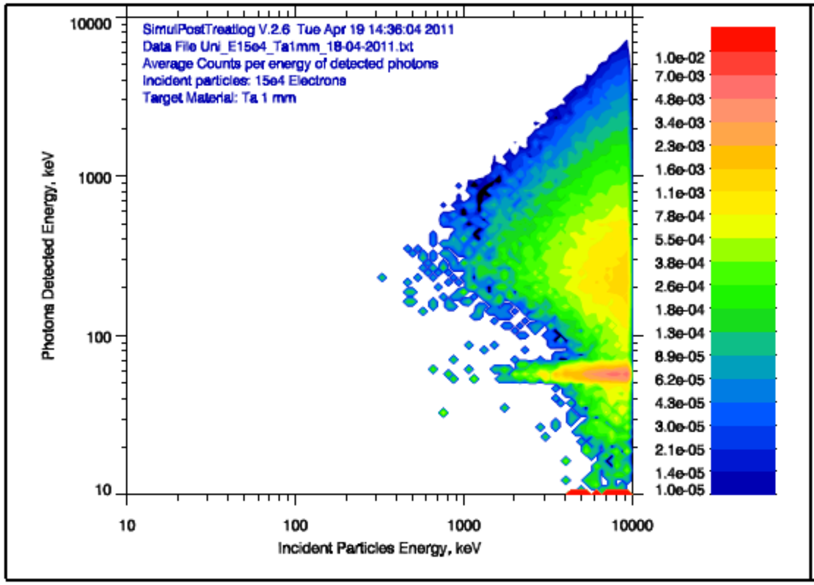


Ta 4mm

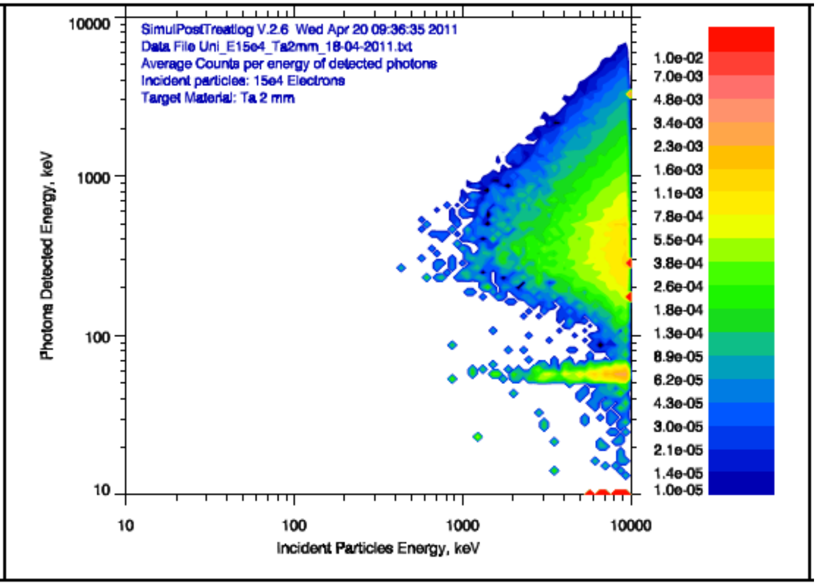


Ta 8mm

- Tantalum very efficient at stopping high-energy electrons



Ta 1mm



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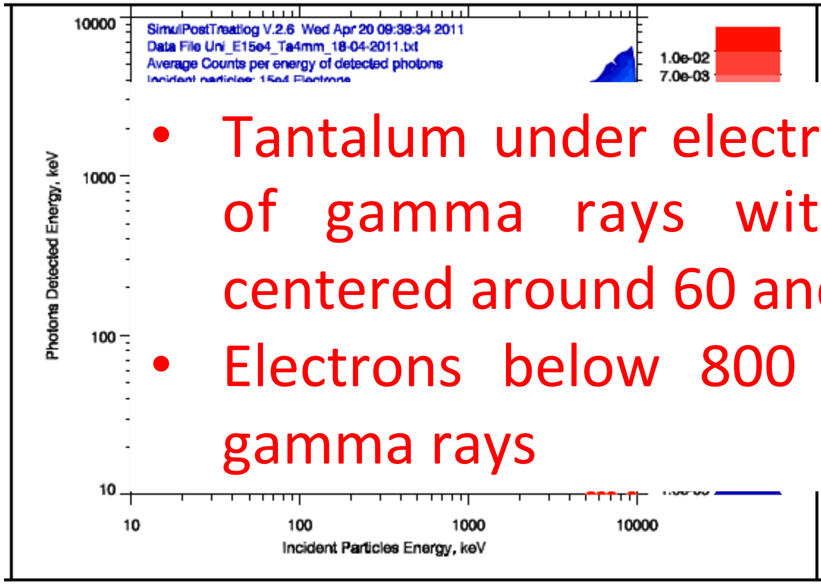
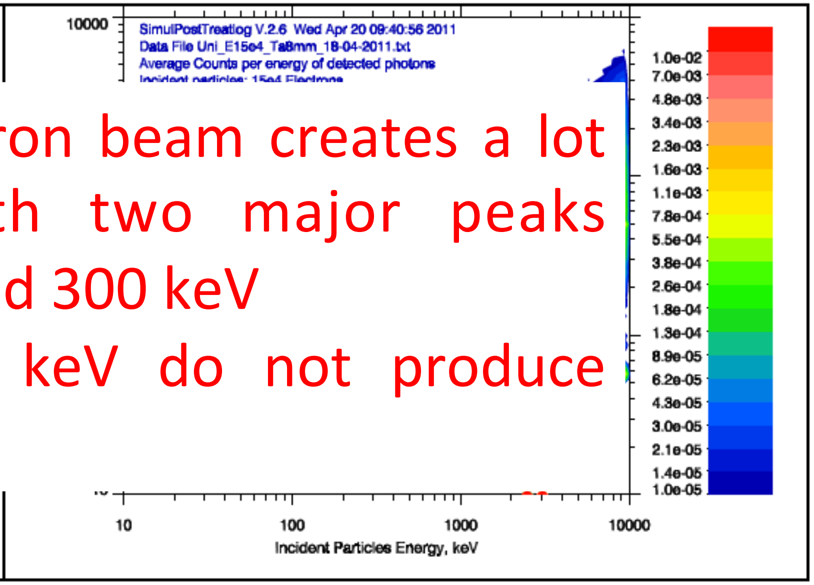
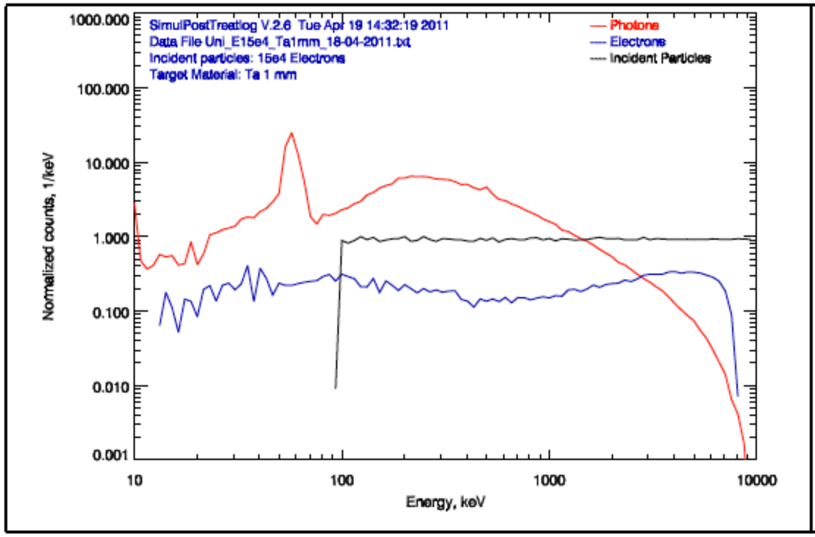




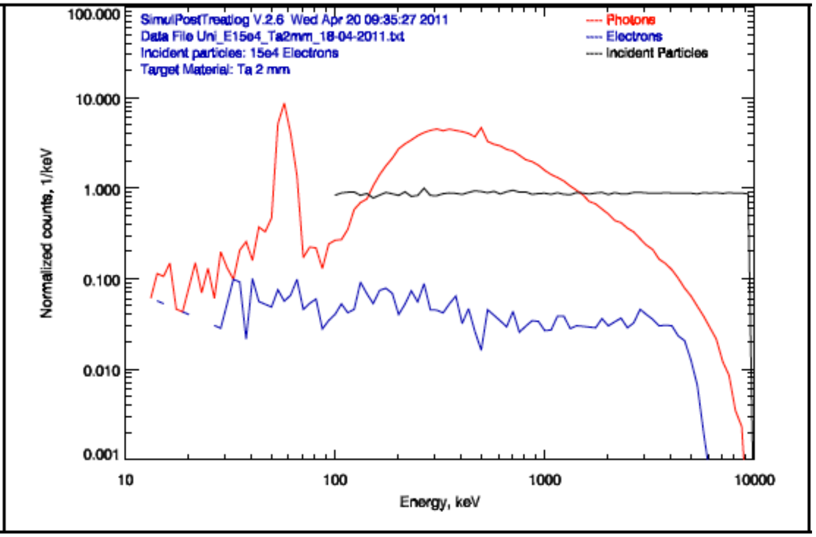
- Tantalum under electron beam creates a lot of gamma rays with two major peaks centered around 60 and 300 keV
- Electrons below 800 keV do not produce gamma rays

Ta 4mm

Ta 8mm



Ta 1mm



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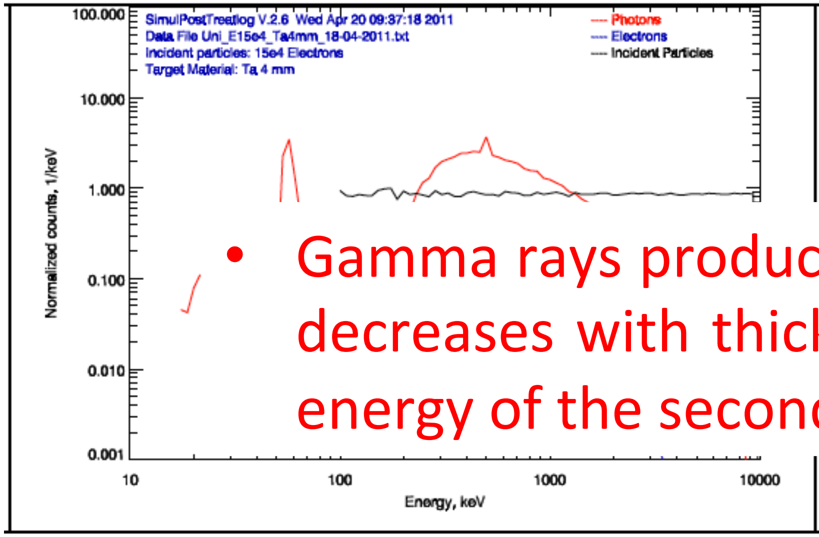
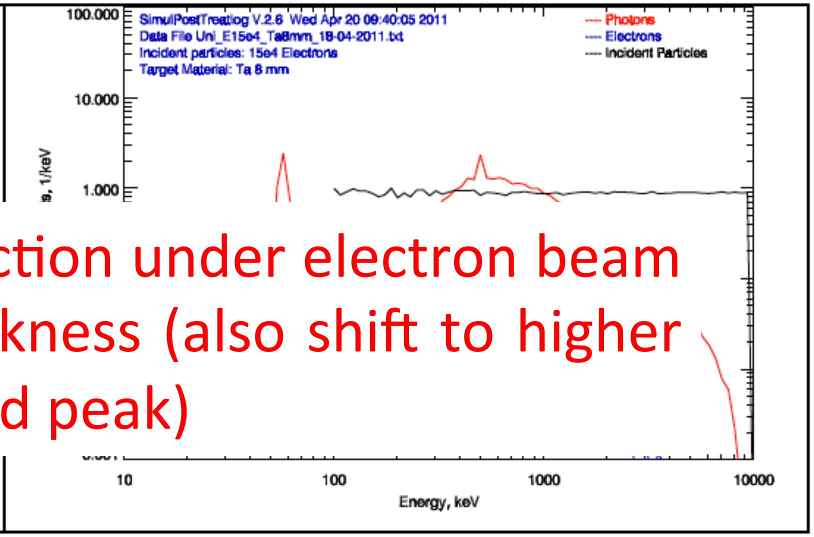


Ta 4mm



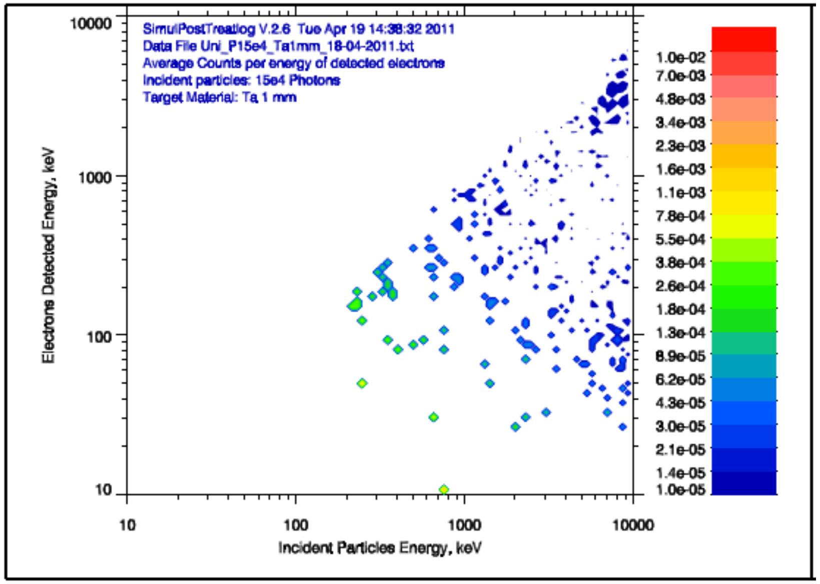
Ta 8mm

- Gamma rays production under electron beam decreases with thickness (also shift to higher energy of the second peak)

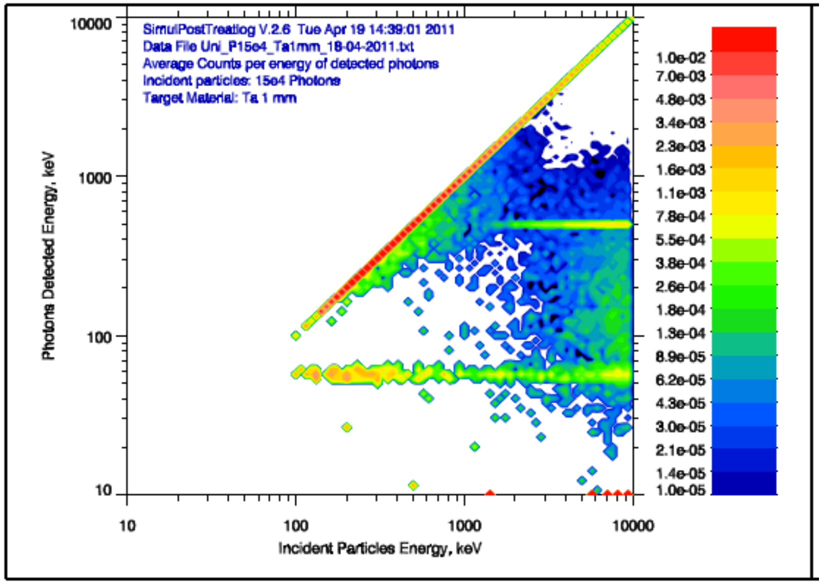
The case of Tantalum

1a. Electron beam

1b. Photon beam



Ta 1mm



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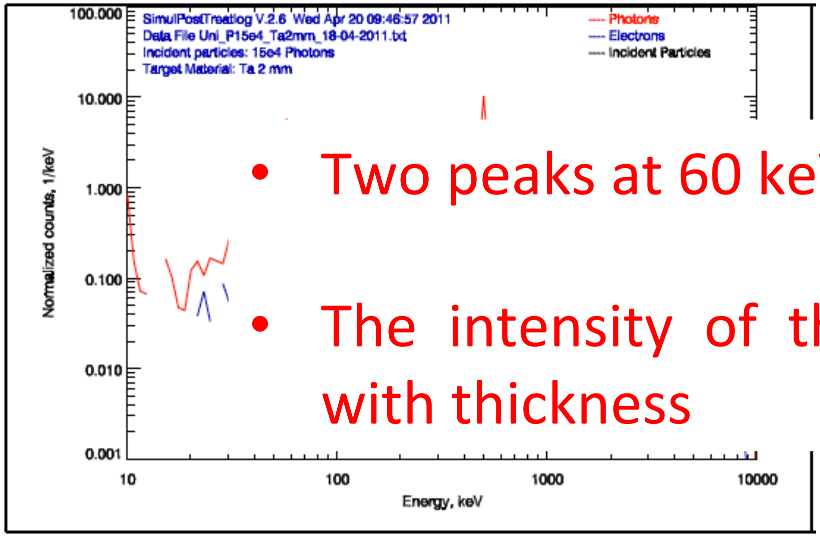
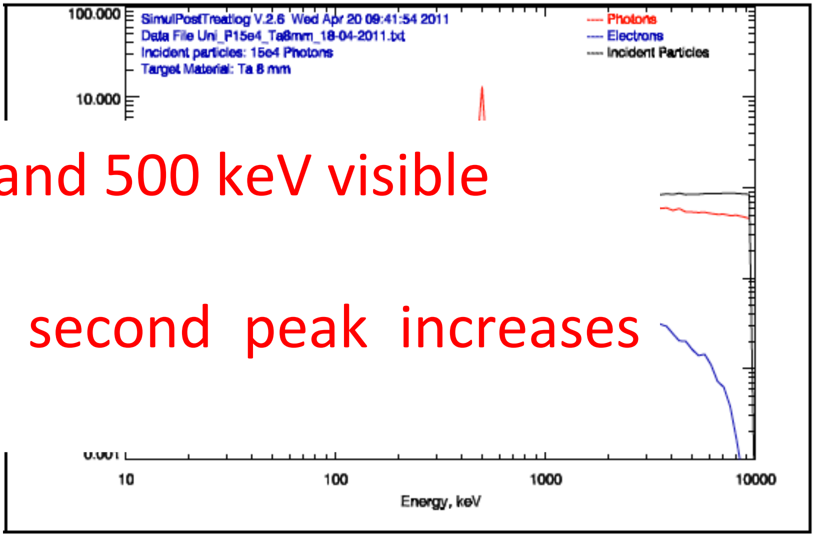


Ta 1mm

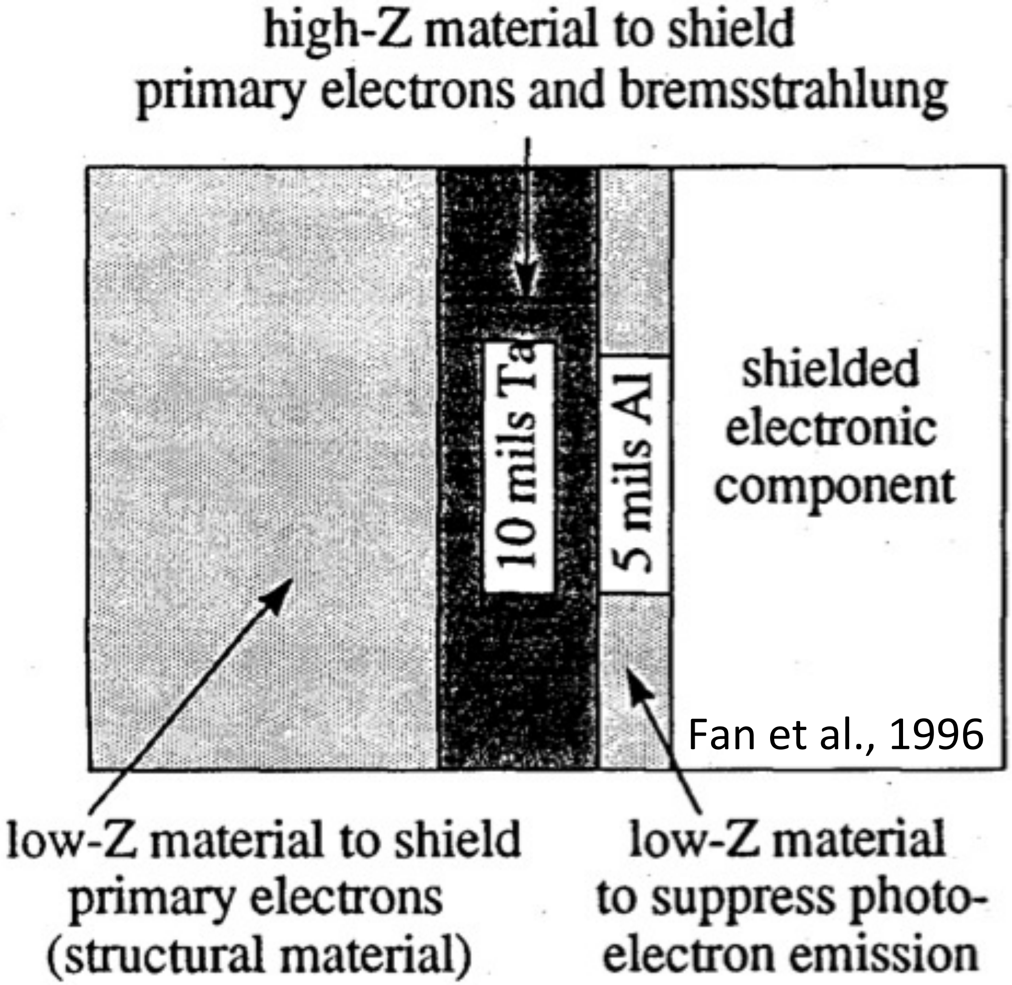


Ta 8mm

- Two peaks at 60 keV and 500 keV visible
- The intensity of the second peak increases with thickness

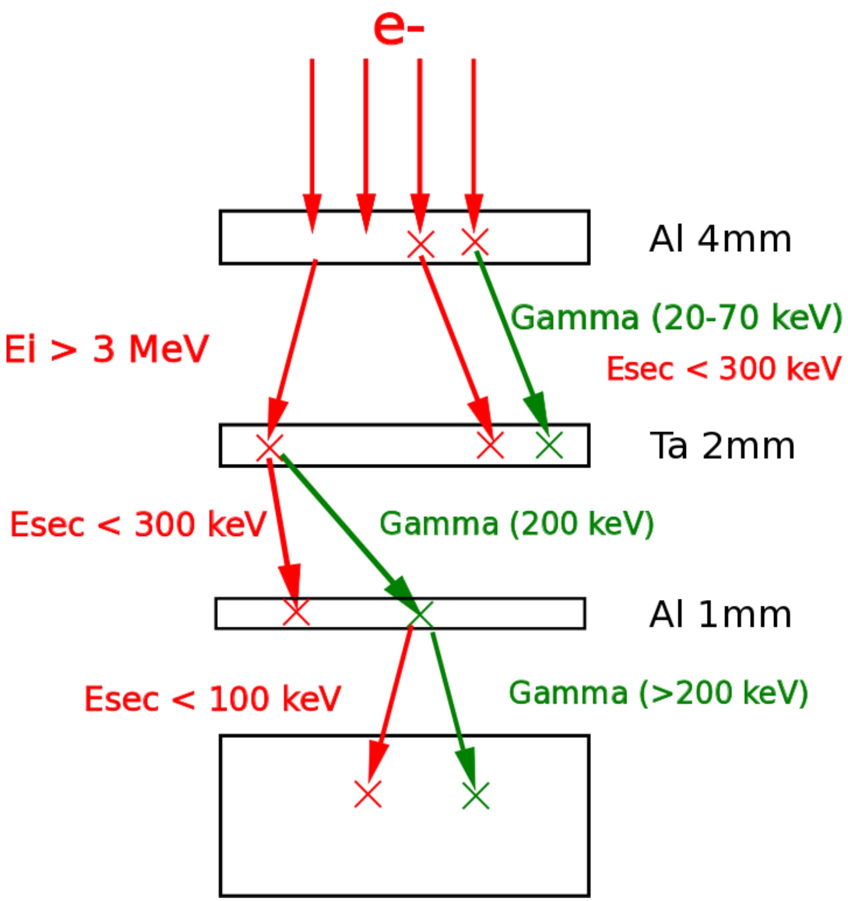
Graded-Z shielding

- Multi-layered
  - Low Z material to stop electrons
  - High Z material to suppress gammas
  - Low Z material to stop lower energy photoelectrons



Fan et al., 1996

Multi-layered shielding



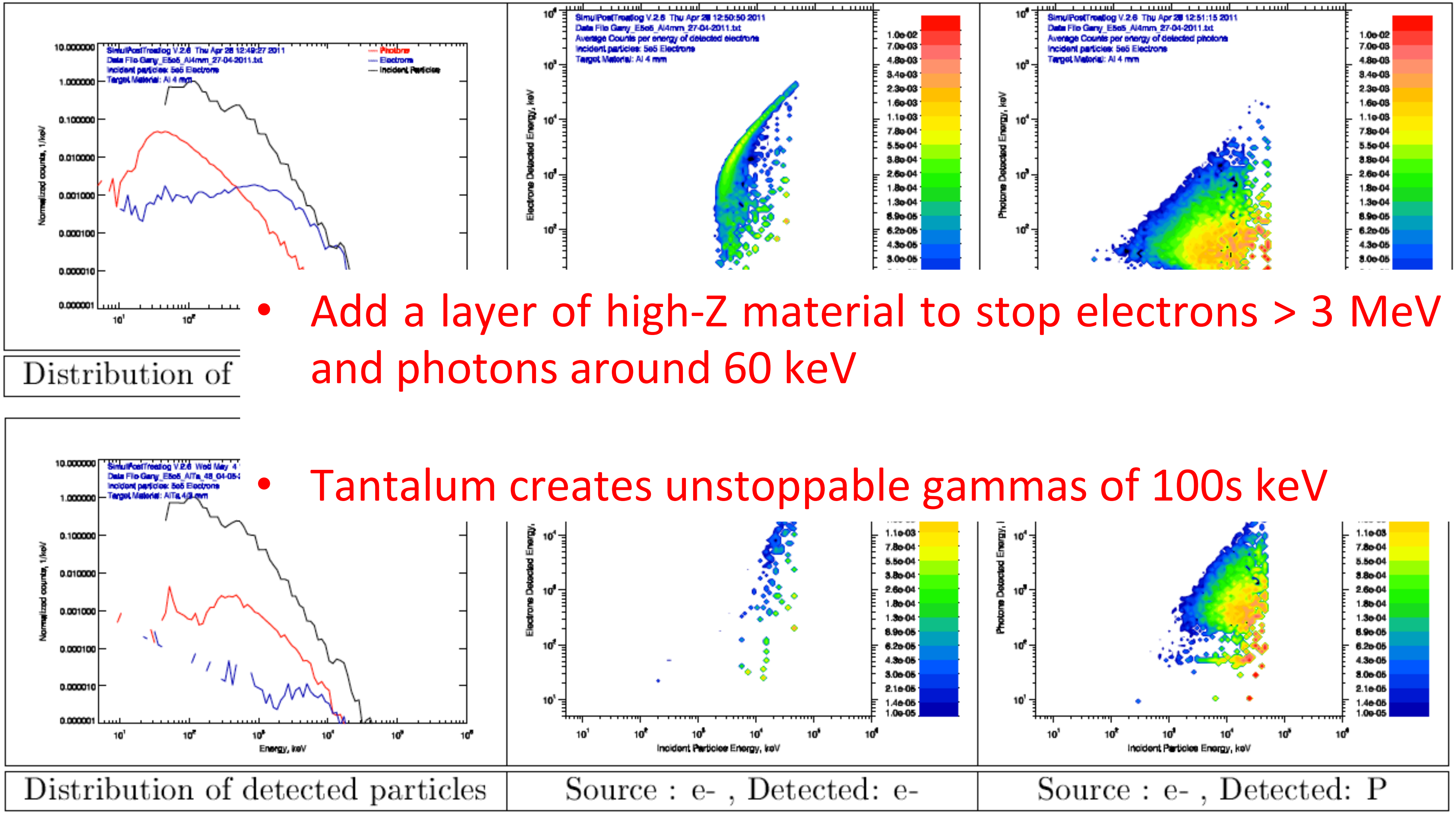
Aluminum:

- Absorbs e- of high-energies
- Produces gammas of lower energy (60-70 keV)

Tantalum:

- Absorbs e- of very high energies
- Stops gammas up to 100 keV
- Produces unstoppable high-energy gammas (>200 keV) under e- beam

Multi-layered shielding



Distribution of

Distribution of detected particles

Source : e- , Detected: e-

Source : e- , Detected: P

- Add a layer of high-Z material to stop electrons > 3 MeV and photons around 60 keV

- Tantalum creates unstoppable gammas of 100s keV

Passive shielding + Spot shielding

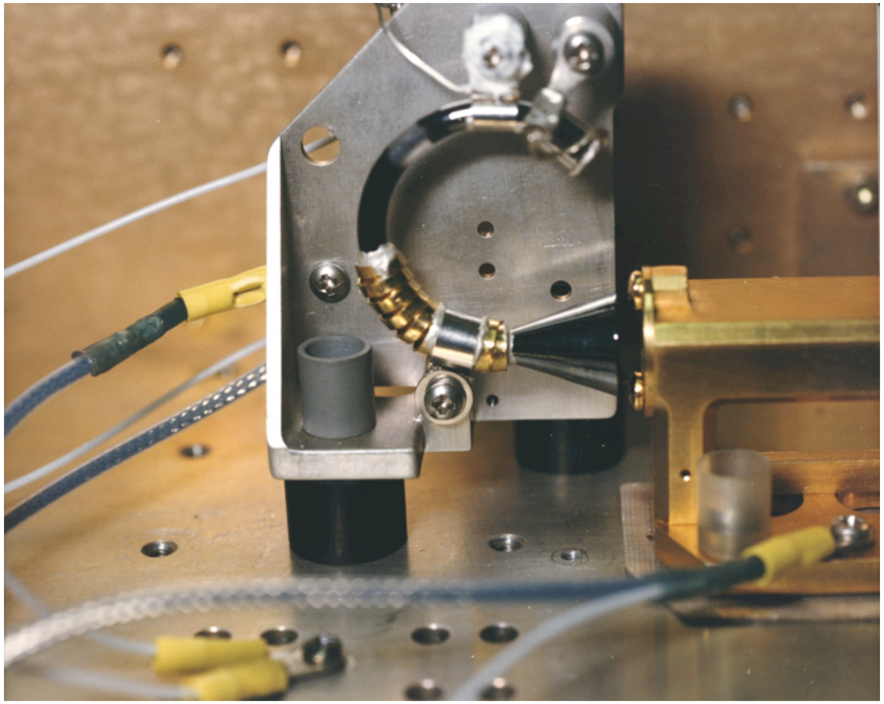
- Multi-layered shielding of the whole sensor (structural housing)

- Shielding of the detector (sensitive part) itself

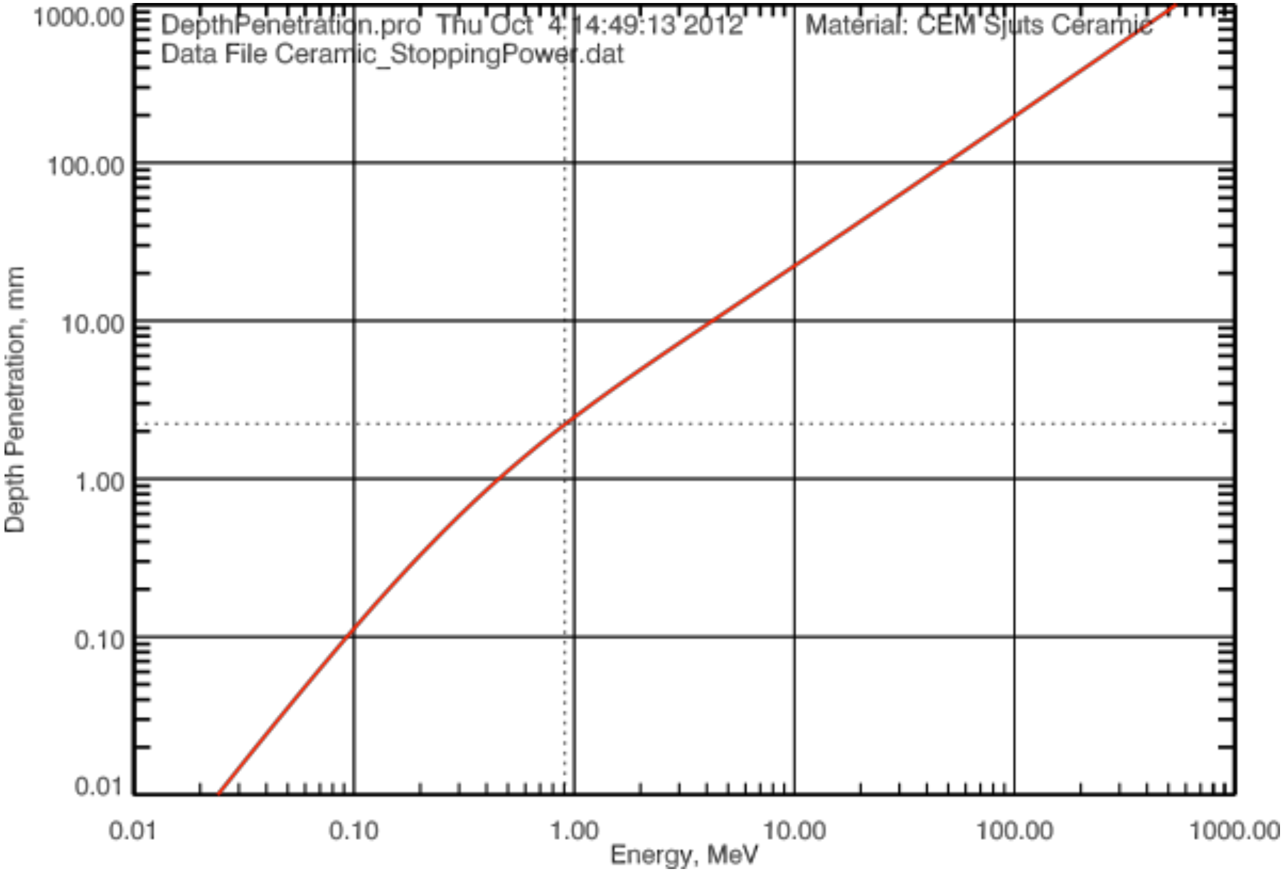
  (spot shielding)

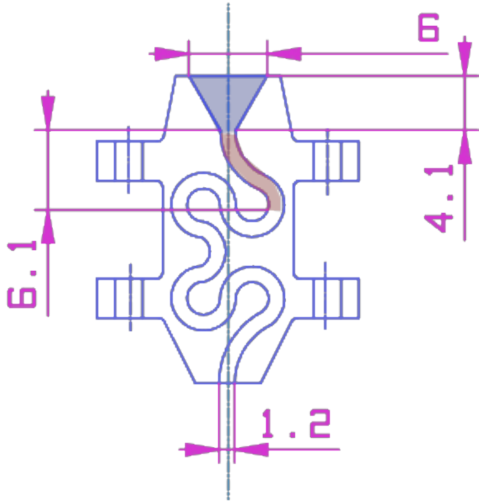
Lessons learnt from DE1-RIMS

- This small gold wrap of a C-shaped CEM was extremely effective in the radiation belts at Earth for the Retarding Ion Mass Spectrometer onboard the Dynamics Explorer-1 mission



Choice of detector - Ceramic CEMs



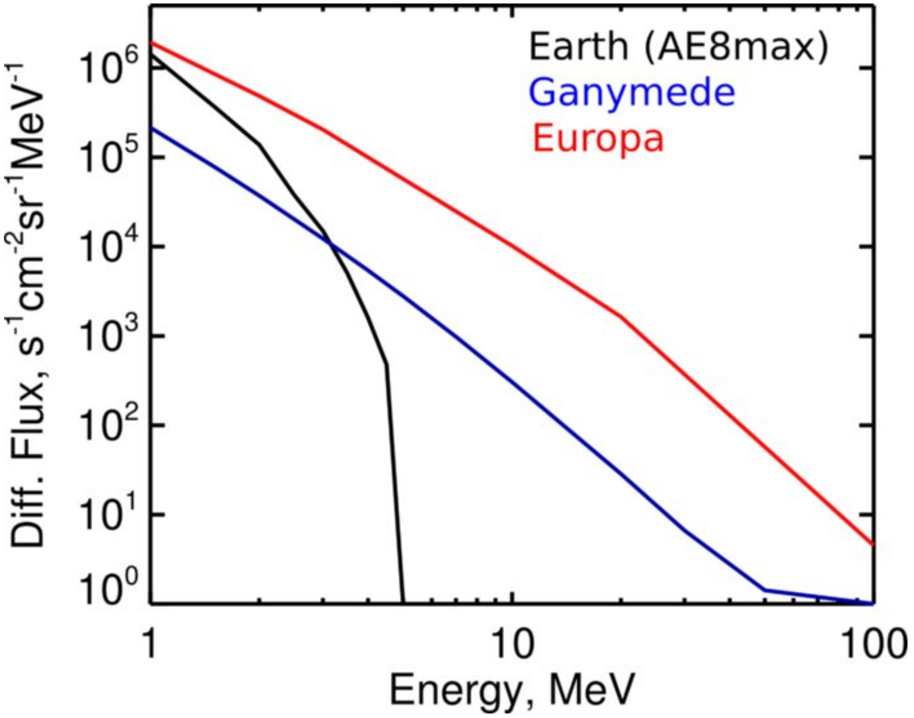


Additional benefit taken from ceramic coverage of the sensitive part (channel). This comes for free (spot shielding by construction).

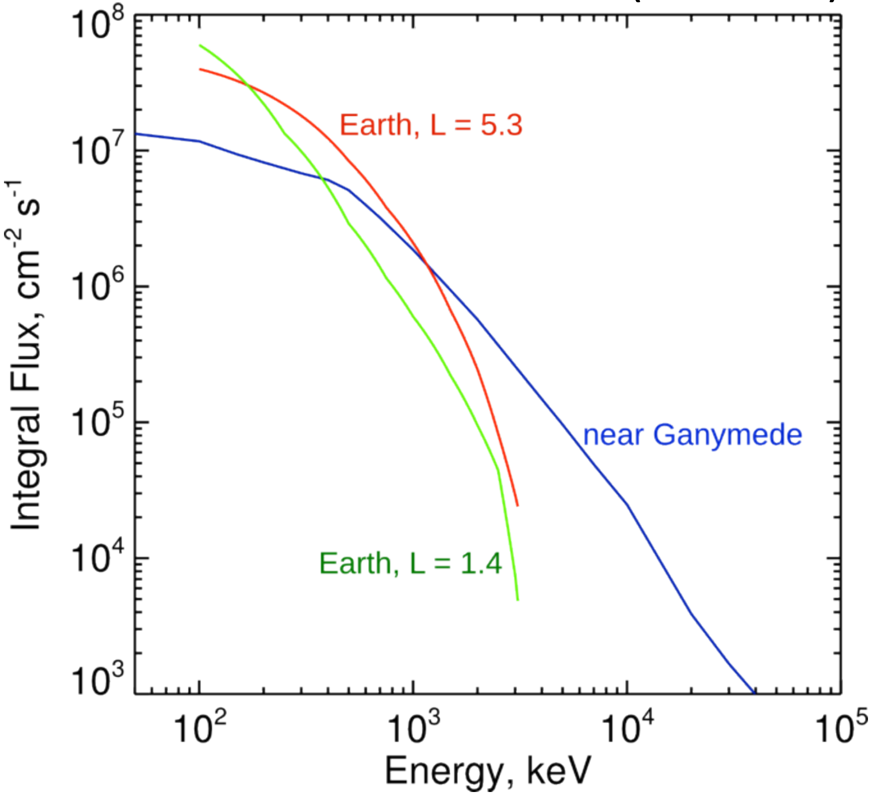
Is passive shielding *only* a good-enough solution ?

Let’s again have a look at real measurements

Jupiter vs. Earth



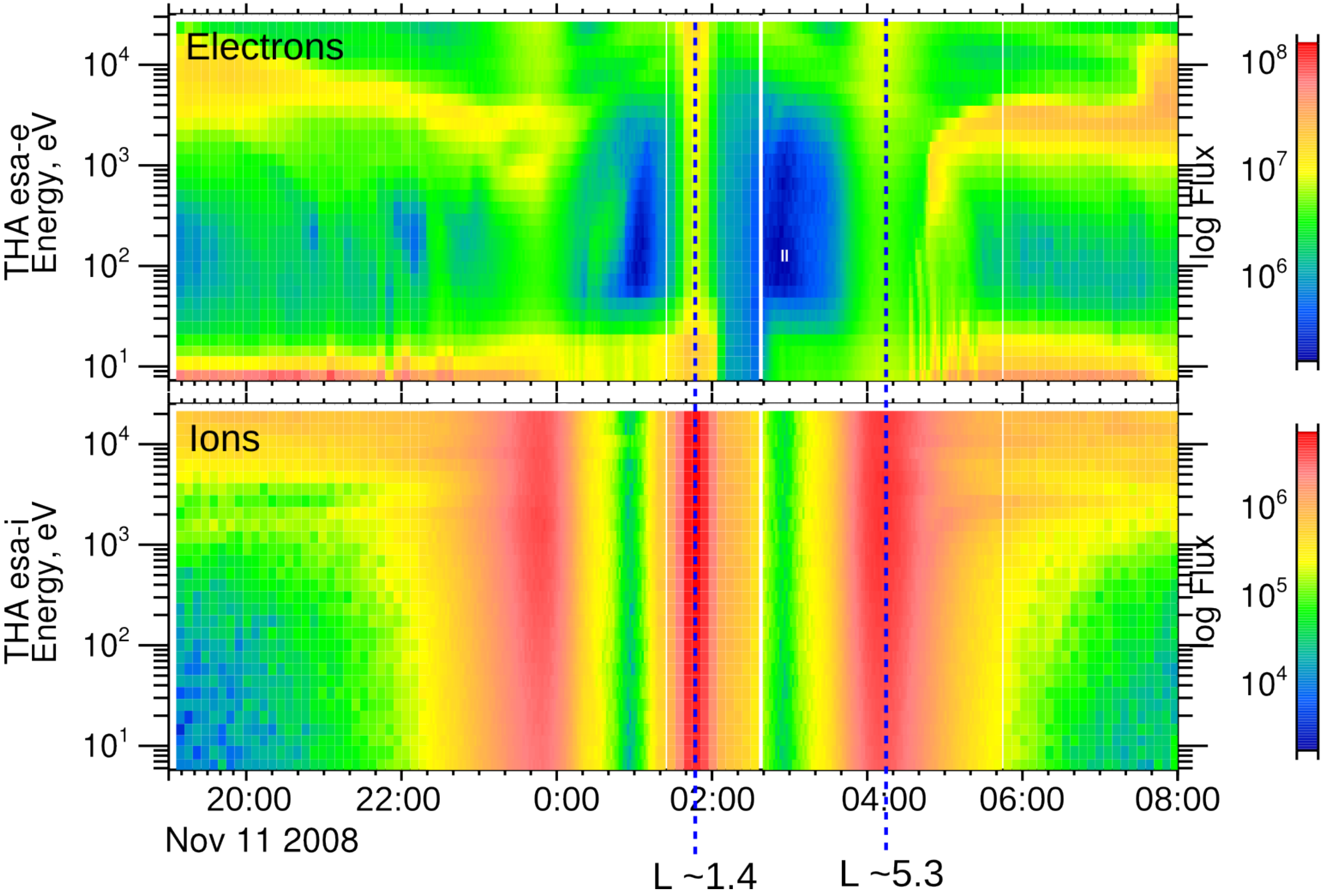
SPENVIS (AE-8min)



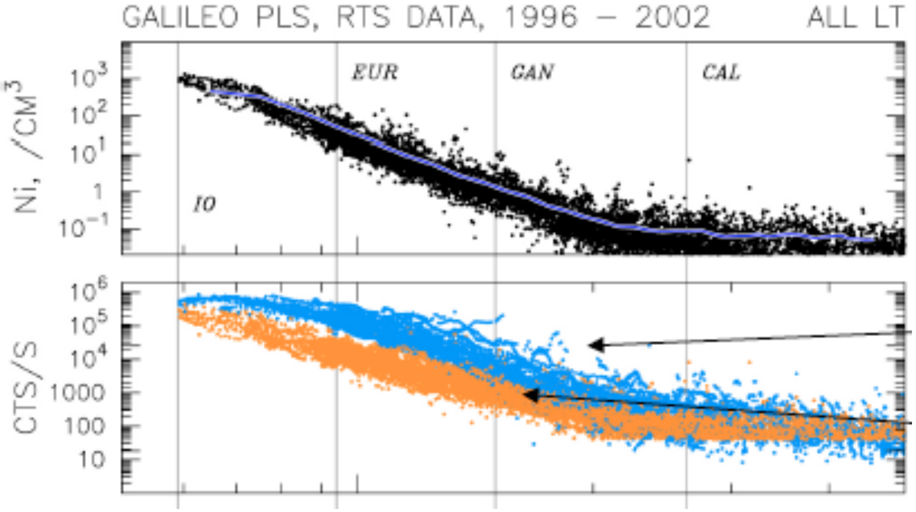
High-energy electron flux (>10 MeV) at Ganymede and Europa orbital positions very high compared to the case of Earth

Shielding against penetrating particles is a very serious (constraining) issue at Jupiter!

Themis A @ Earth

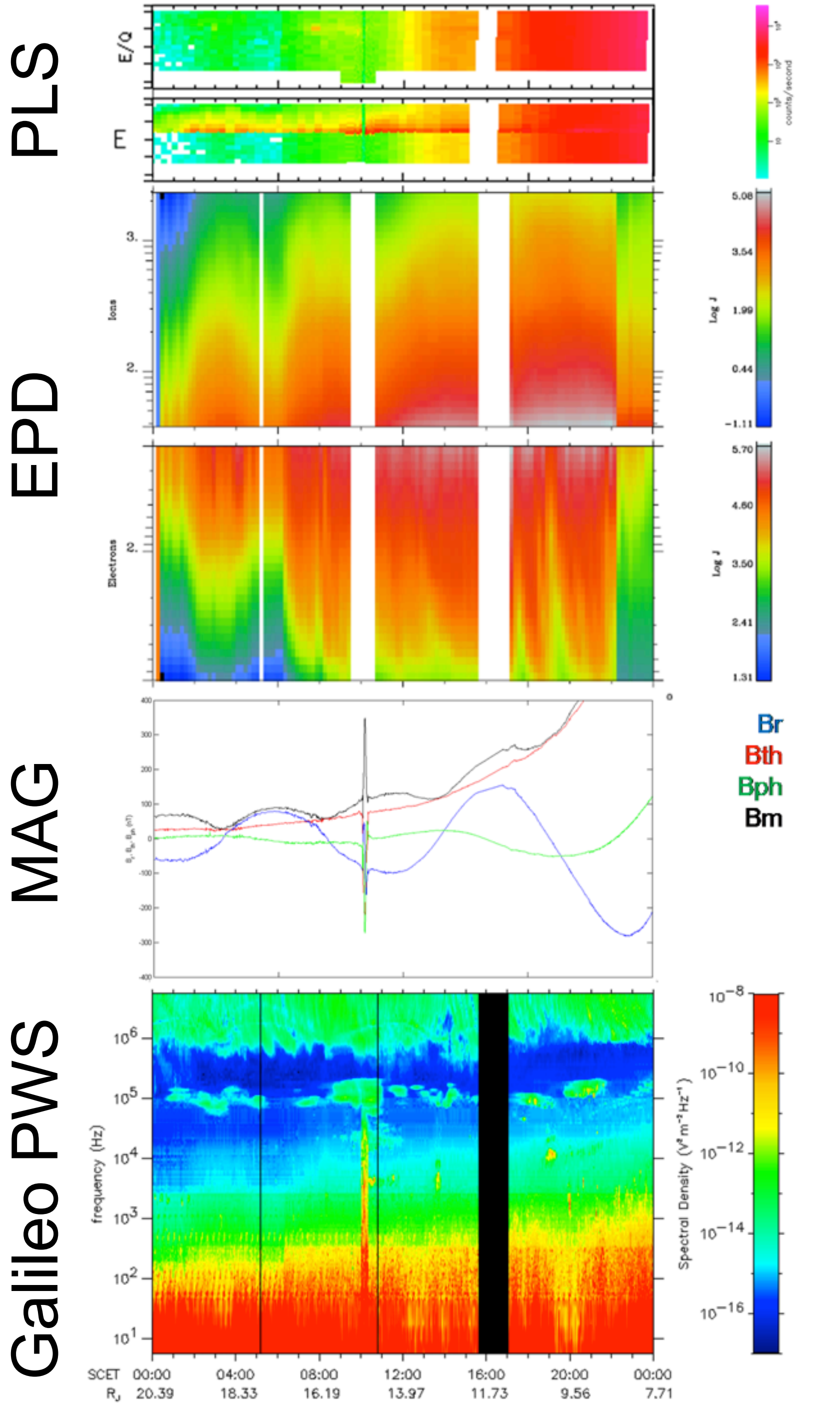


Lessons learnt from Galileo PLS



Penetrating Background

Signal



Lessons learnt from Galileo PLS

The average background rates at the orbits of the Galilean moons are listed below in units /cm^2 – s

Io	402071.3	42 SAMPLES
Europa	133236.1	483 SAMPLES
Ganymede	7786.524	325 SAMPLES
Callisto	195.9424	188 SAMPLES

Lessons 1:

Even with rather effective (passive) protection (e.g., Ta = 9 mm Al) the background noise can be unacceptable (low SNR, saturation) !

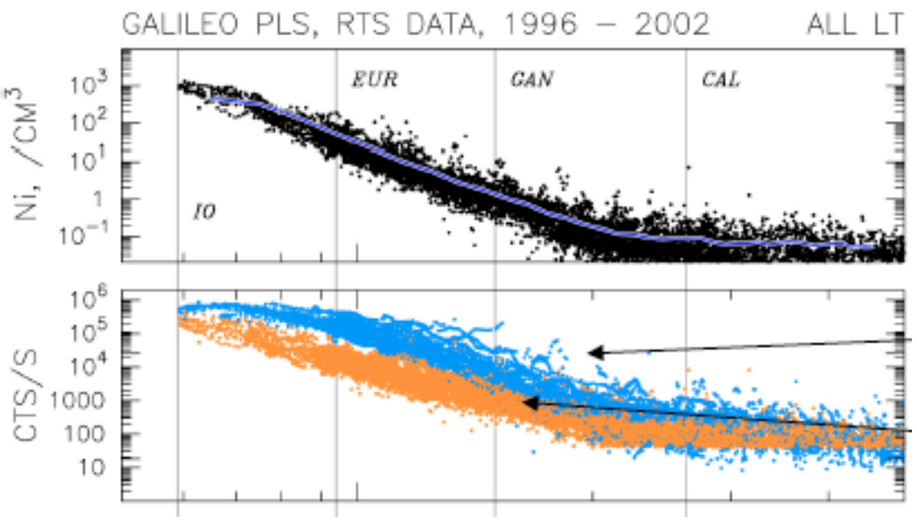
Lessons 2:

Need for reducing the size of the detector but also to keep (absolutely mandatory for science) a high geometric factor !

Geometric Factor of the sensor

- $C/v^4 = \varepsilon . Gf . f(v)$ where ε is the detection efficiency
- Gf is proportional to the sensor collecting surface

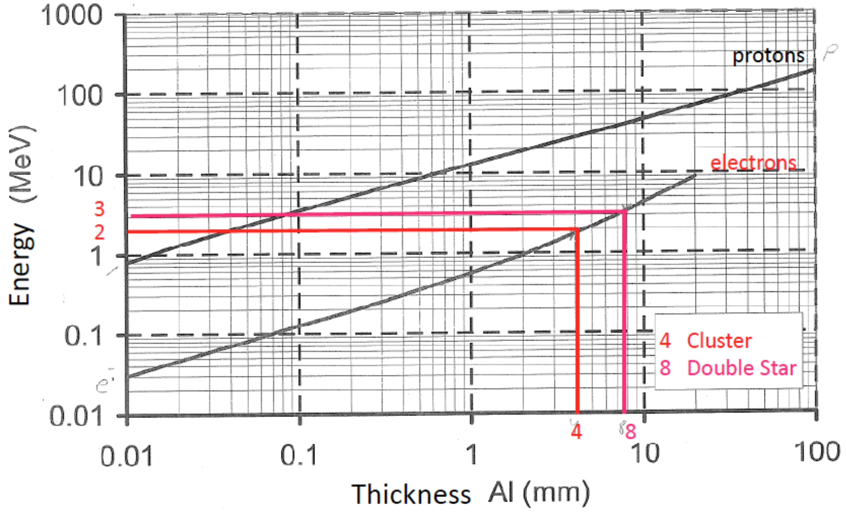
CAUTION: reducing the detector size is advantageous for noise reduction but it also alters/degrades significantly the signal level ! **To keep a high GF for the sensor is therefore mandatory.**

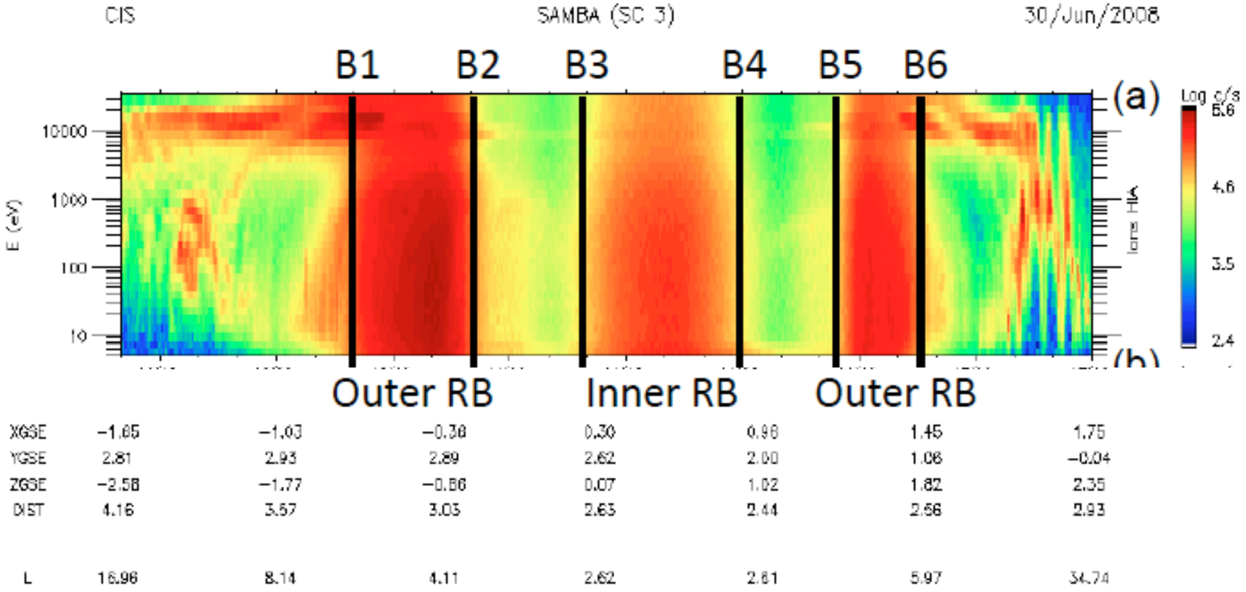


Penetrating Background

Signal

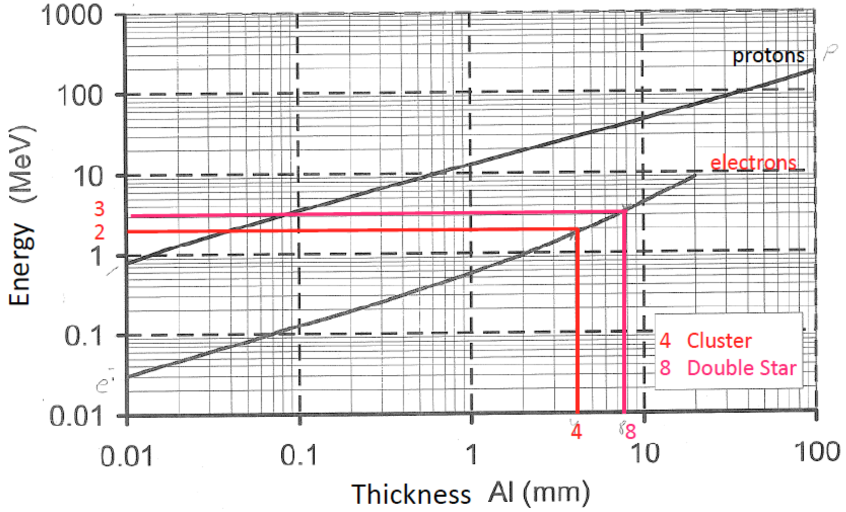
Cluster @ Earth
HIA (4 mm Al)

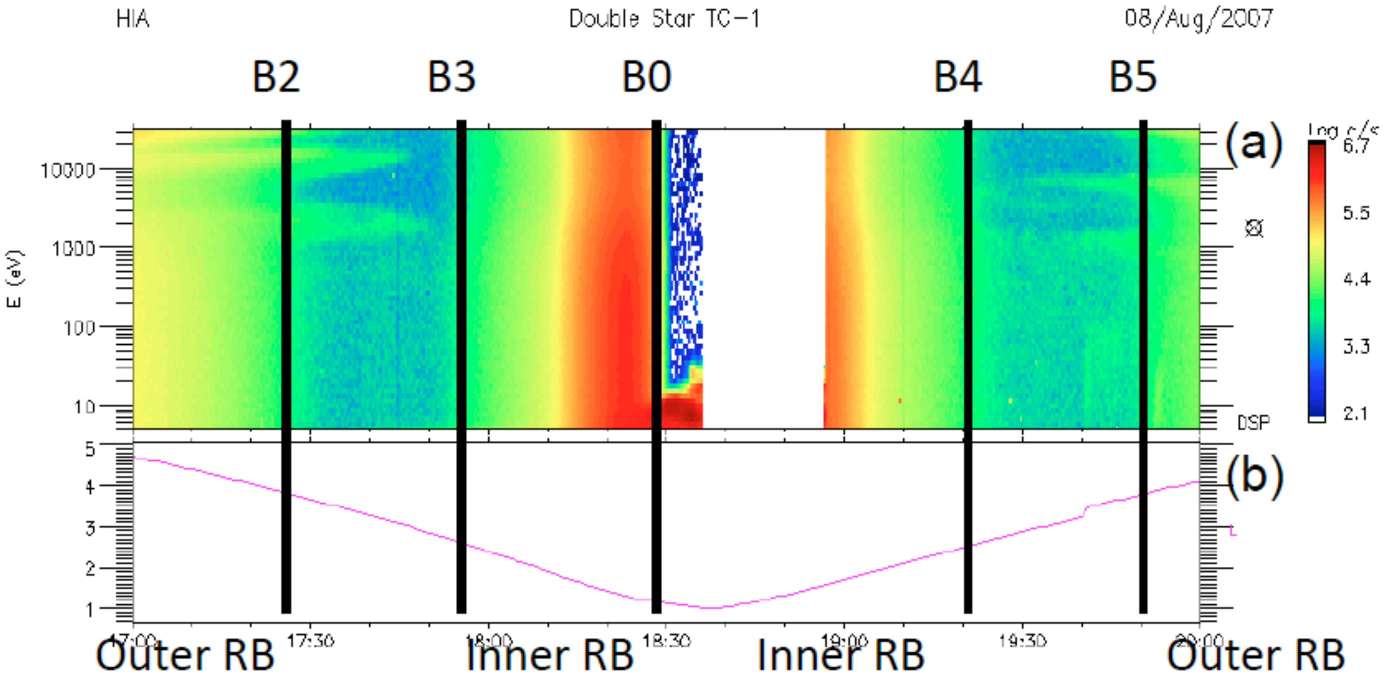




XGSE	−1.65	−1.03	−0.38	0.30	0.98	1.45	1.75
YGSE	2.81	2.93	2.89	2.62	2.00	1.08	−0.04
ZGSE	−2.58	−1.77	−0.86	0.07	1.02	1.82	2.35
DIST	4.16	3.57	3.03	2.63	2.44	2.56	2.93
L	16.96	8.14	4.11	2.62	2.61	5.97	34.74

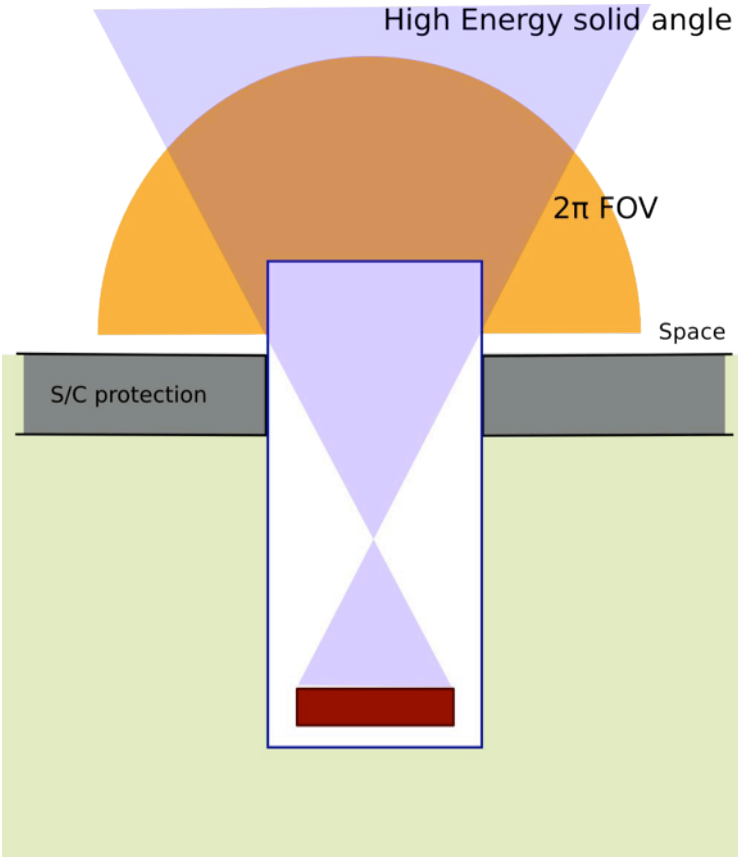
Double Star @ Earth HIA (8 mm Al)



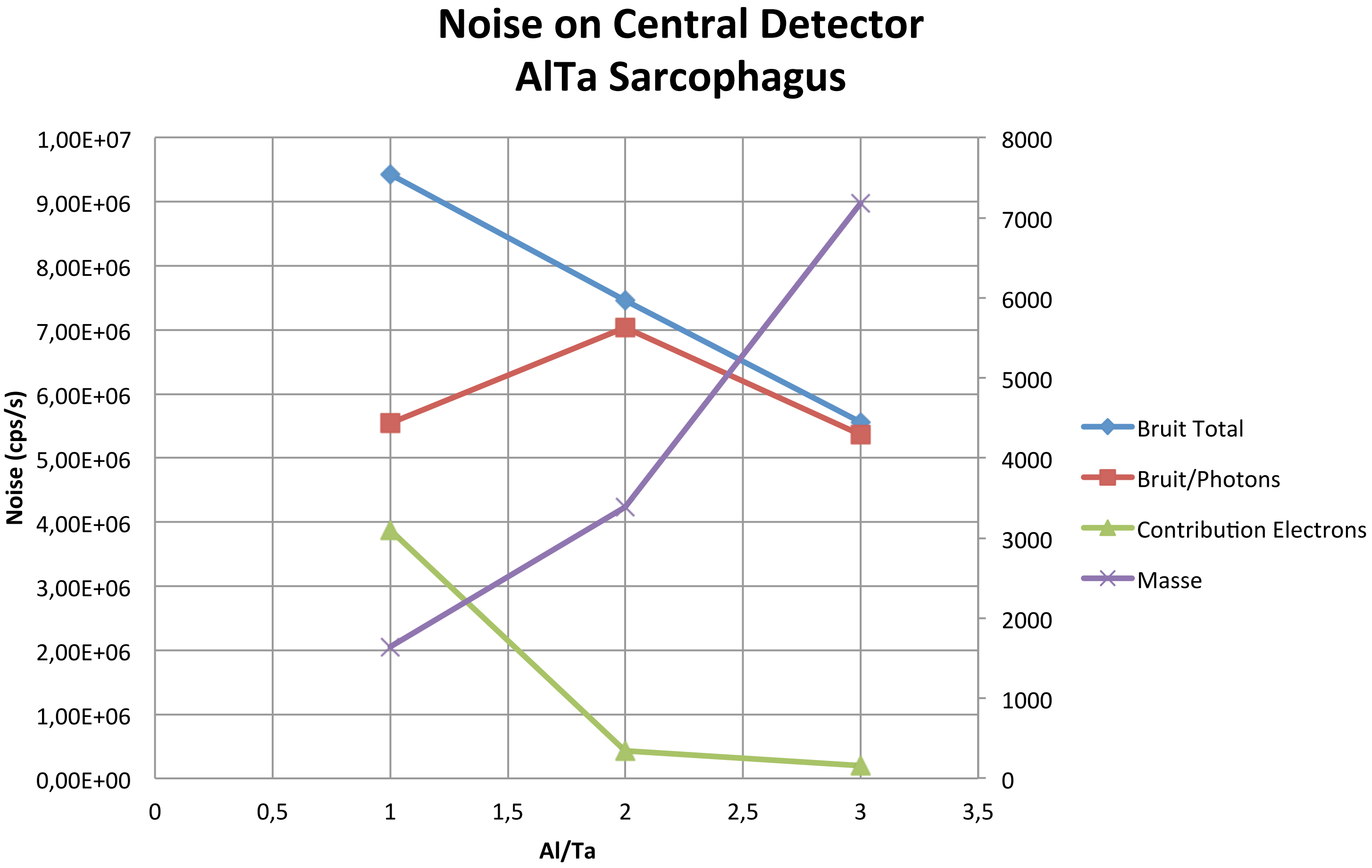


XGSM	3.57	2.90	1.92	0.19	−1.39	−1.66	−1.61
YGSM	−1.58	−0.54	0.51	1.11	−0.69	−2.52	−3.92
ZGSM	−2.64	−2.13	−1.34	−0.00	0.91	0.79	0.46
R	4.71	3.64	2.40	1.13	1.80	3.12	4.26
L	4.70	3.67	2.39	1.13	1.71	2.87	4.12

Passive shielding at sensor level



(Only) increasing the thickness of the passive shielding is not efficient enough !



Radiation noise stays high while overall mass budget unaffordable

Outline

1. Particle sensors and background noise
2. Passive shielding – GEANT4 modelling
3. Laboratory tests and validation of shielded and unshielded detector’s response
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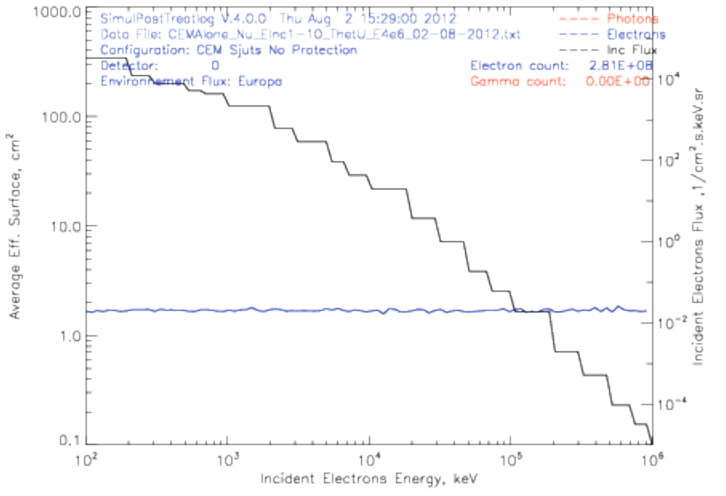
5. The need for active shielding
6. Conclusions

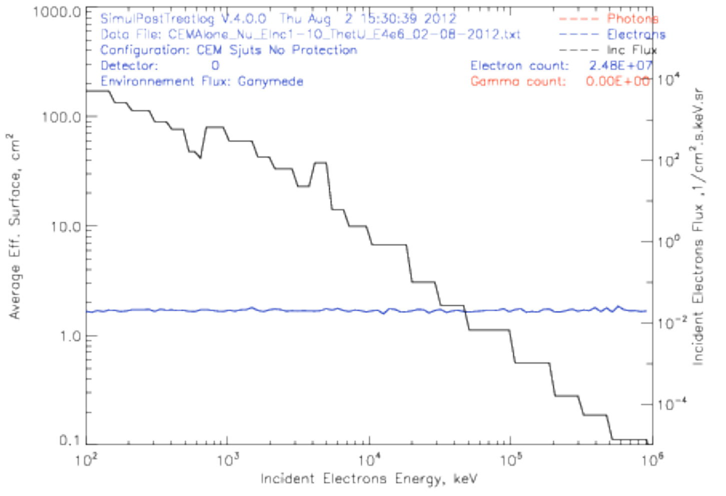
One further step required to obtain the real background noise

- GEANT-4 simulations give the electron and gammas/X-rays count rate for an ‘idealised’ detector
- Efficiency of the detector to incoming particles (heterogeneous source) to be taken into account to obtain the real background that will be measured

Effective Surface – Naked CEM



Environnement : Europe



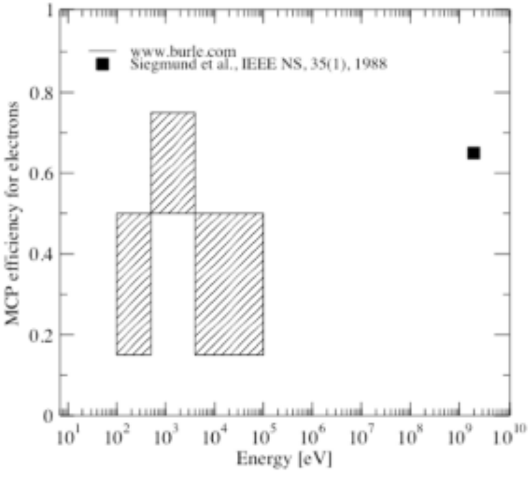
Environnement : Ganymède

Environnement	Europe	Ganymède
Coups totaux photons	0	0
Coups totaux électrons	2.81e09	2.48e07
Coups totaux	2.81e09	2.48e07

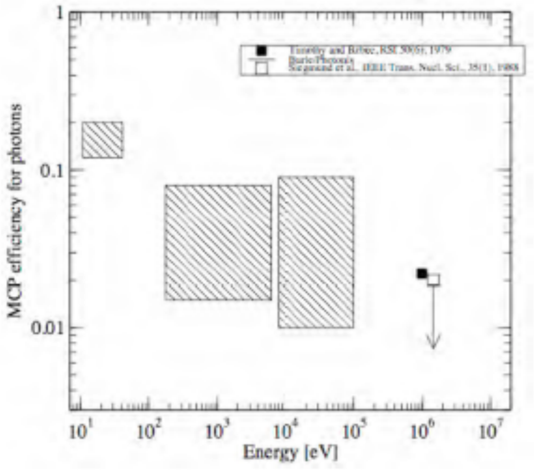
- GEANT-4 simulation/modelling of the detector itself

Missing information

MCP

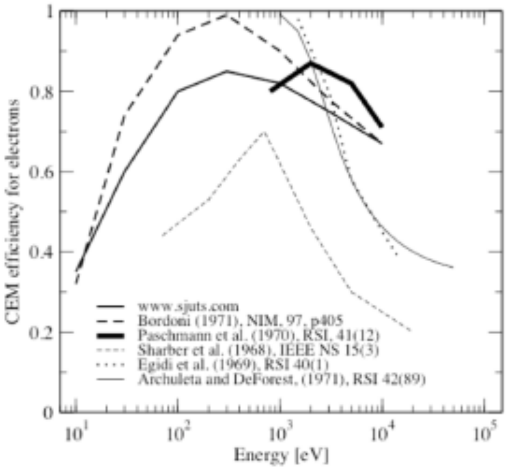


(a) électrons

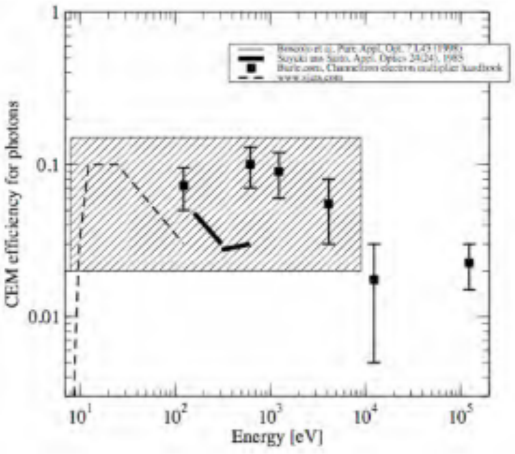


(b) photons gammas

CEM

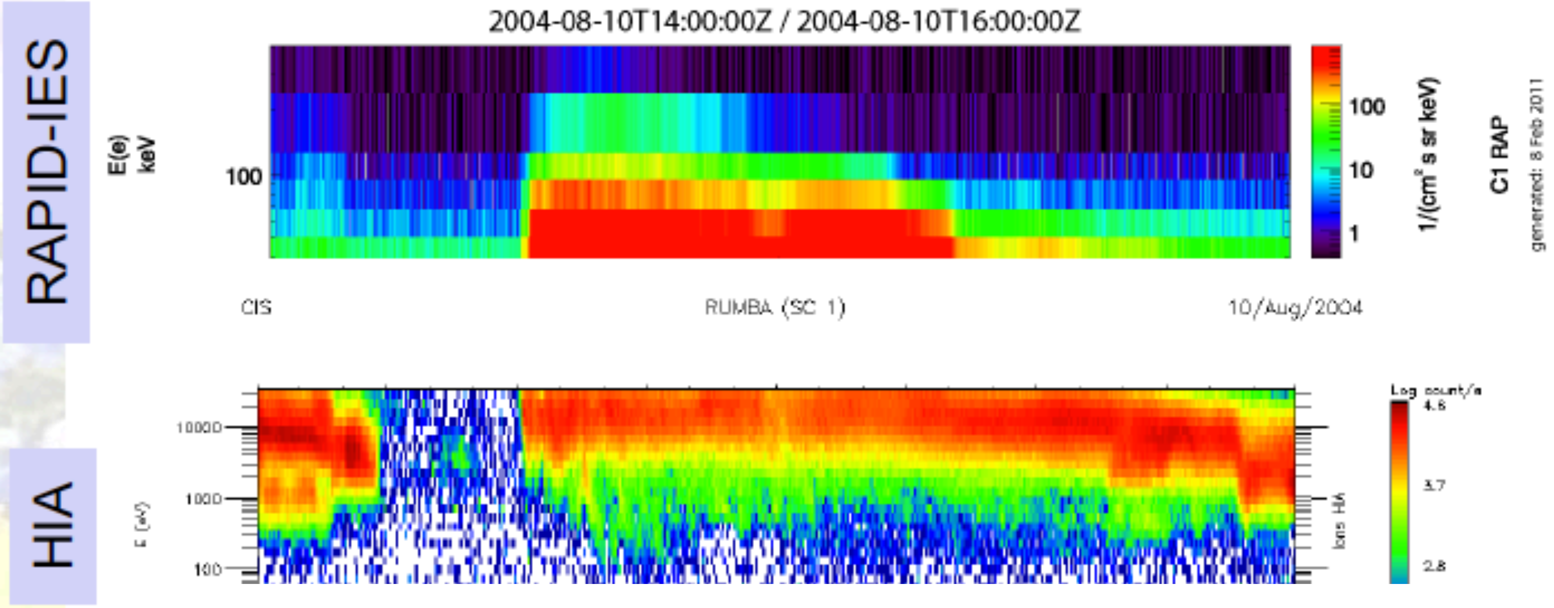


(a) électrons

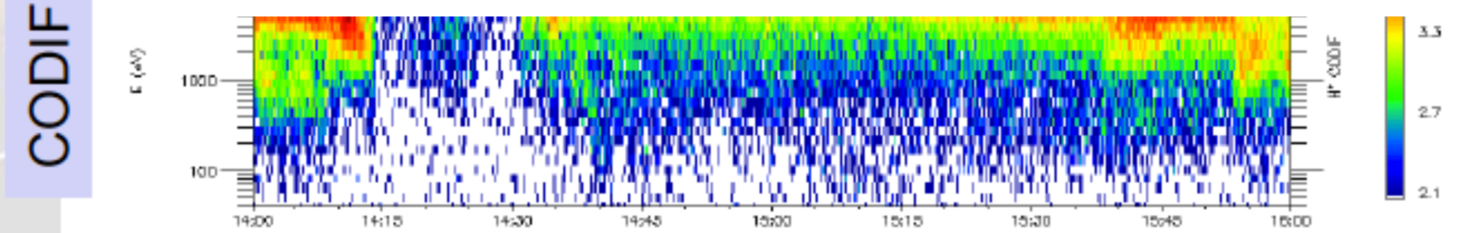


(b) photons gammas

>100 keV electrons in the pl. sheet during a strong substorm (AE=800 nT): **no background** detected by CIS => instrument sensitivity to bremsstrahlung-produced X-rays from these electrons is negligible

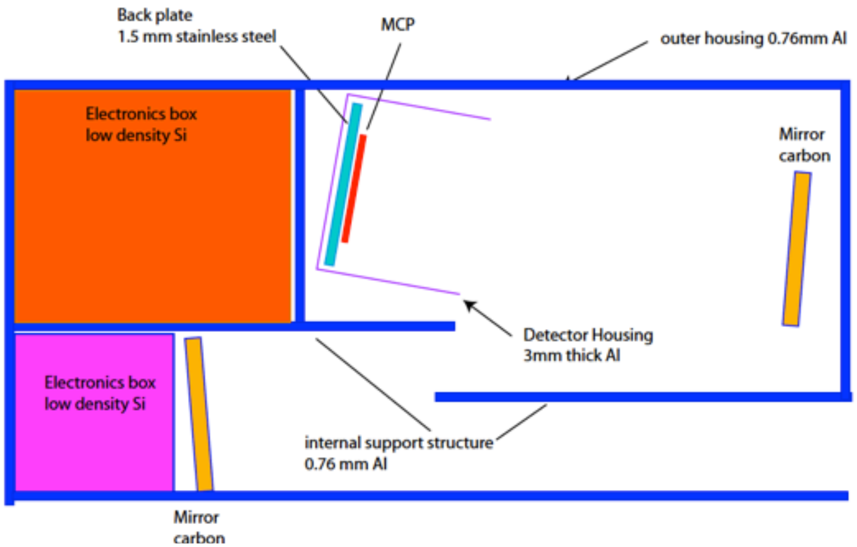


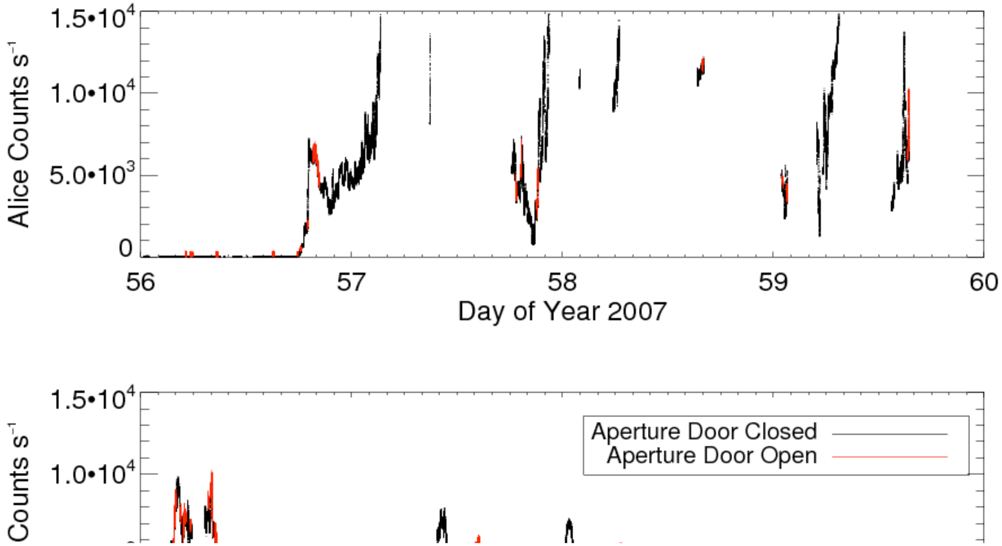
- Sensitivity of detectors (MCP, CEM) to X-rays is small



XGSE	−17.28	−17.27	−17.25	−17.23	−17.21	−17.18	−17.14
YGSE	−6.96	−6.86	−6.76	−6.66	−6.56	−6.45	−6.34
ZGSE	−4.14	−4.33	−4.52	−4.71	−4.89	−5.07	−5.25
DIST	19.08	19.08	19.07	19.07	19.05	19.04	19.02

New Horizons ALICE (UV spec.) @ Jupiter





Excellent energetic particle Detector

Laboratory testing at GSFC show a quantum efficiency of 33% for 1 MeV electrons

- Sensitivity of some detectors (e.g., MCP) to high-energy electrons can be significant

What is the exact sensitivity of detectors to high-energy electrons and gammas ?

Let’s get real experimental measurements and test them in representative environment

Tests in GEODUR at ONERA

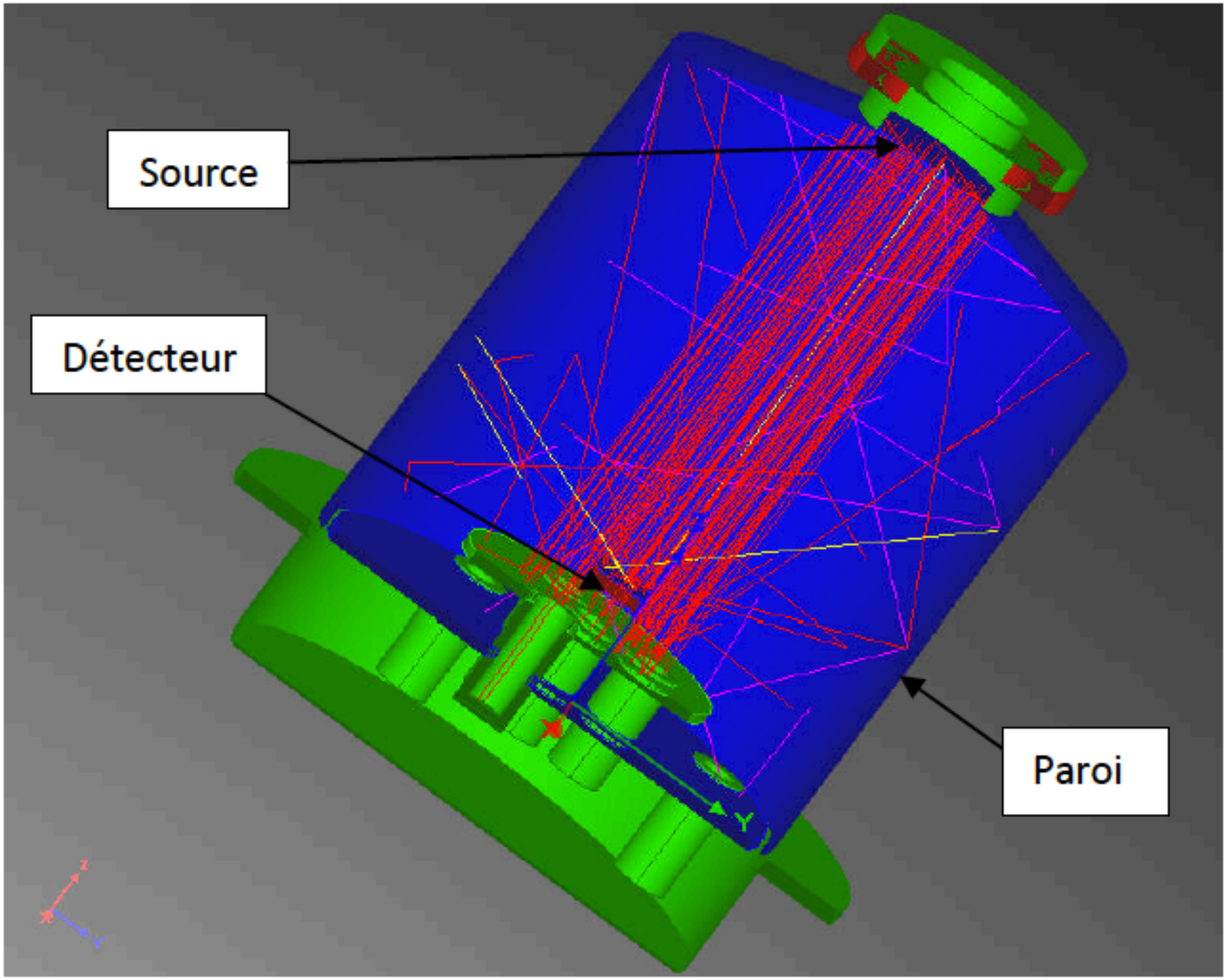
electrons

400 keV

700 keV

1 MeV

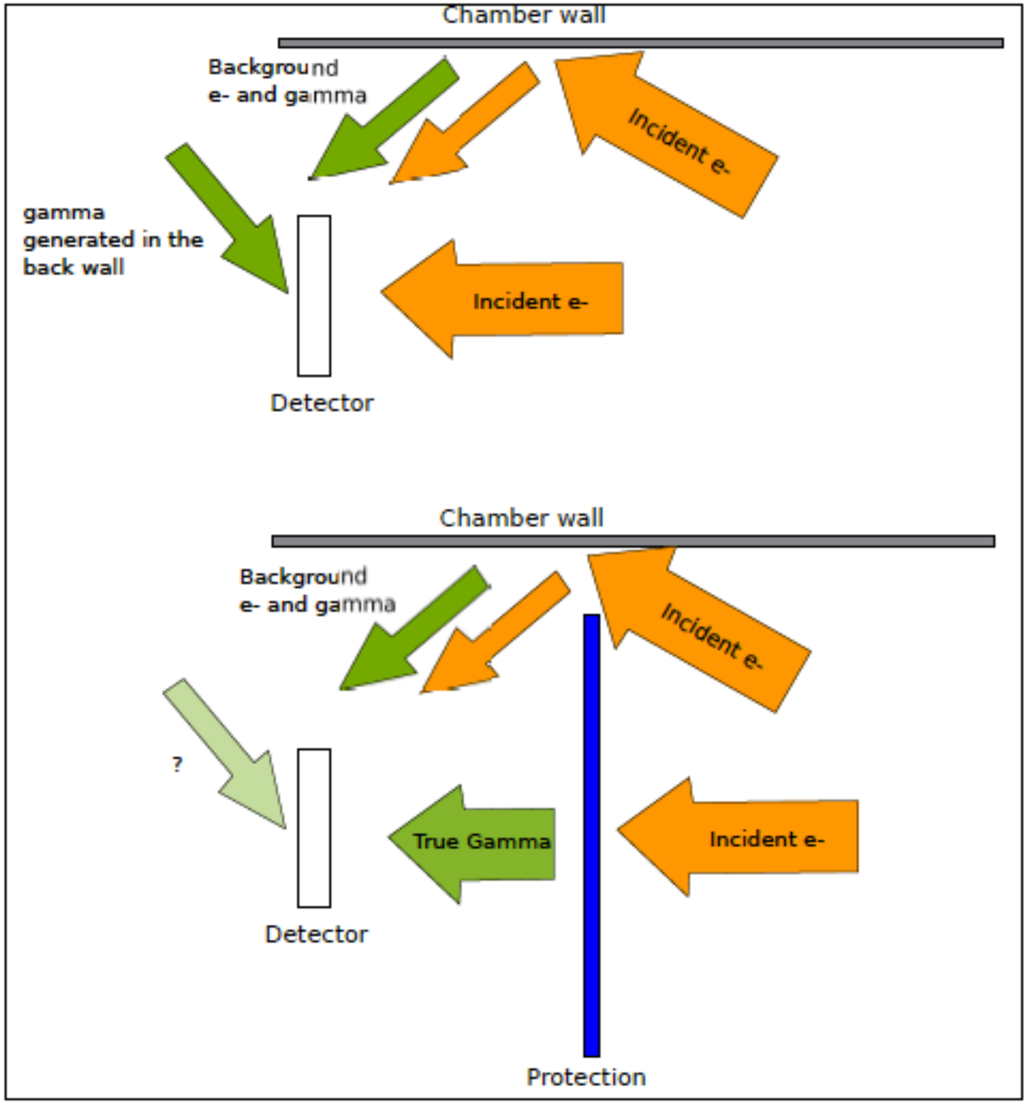
1.5 MeV



Tests in GEODUR at ONERA

Complex measurements to analyze

Good illustration for the Background noise that will come from the S/C subsys



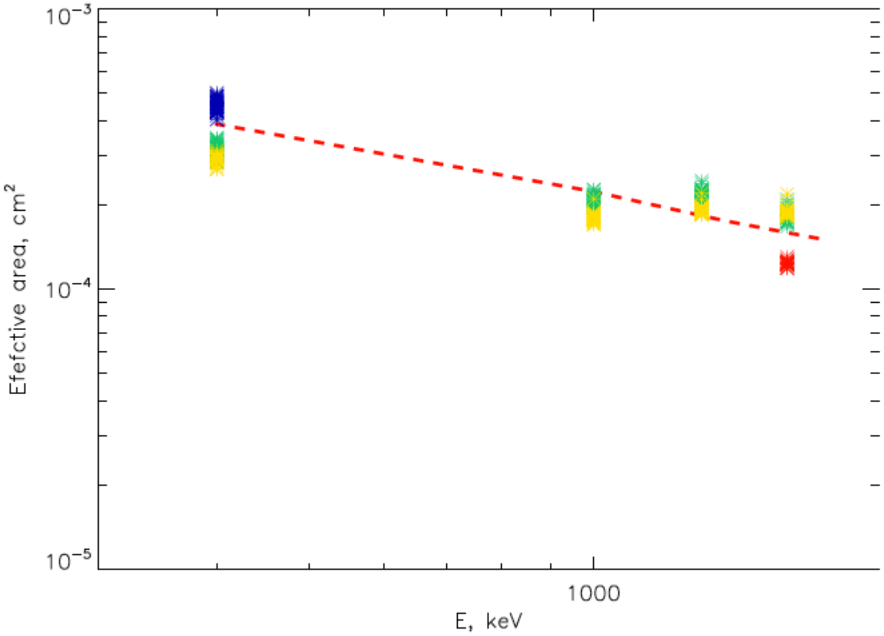
Results

$$Cnt\,[s^{-1}] = F \cdot S$$

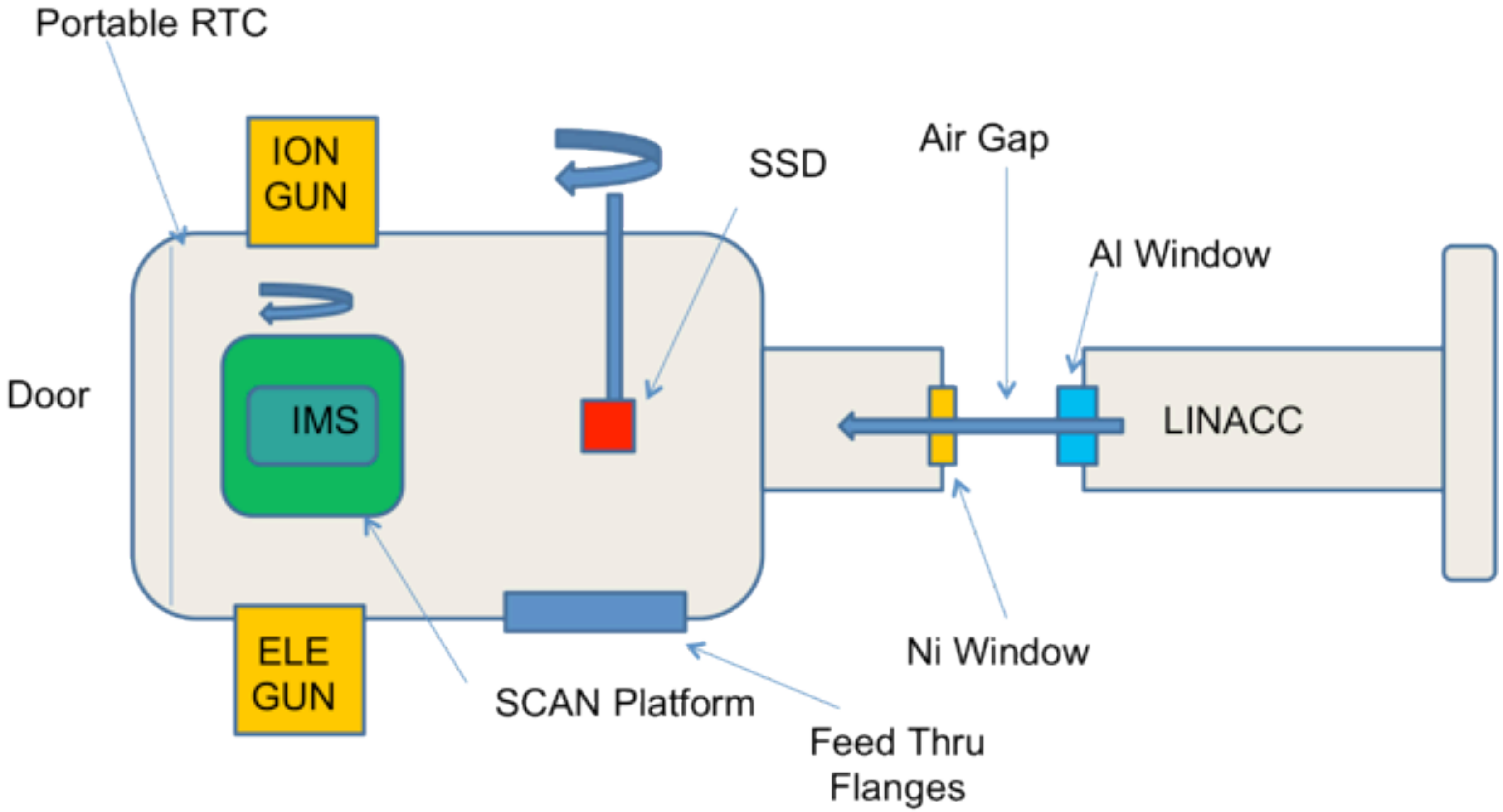
hence

$$S = Cnt/F$$

S_{Eff} [cm^2]= <Count Rate[s^{-1}]>/<Beam Flux[cm^{-2} s^{-1}>.
S effective surface of the detector determined

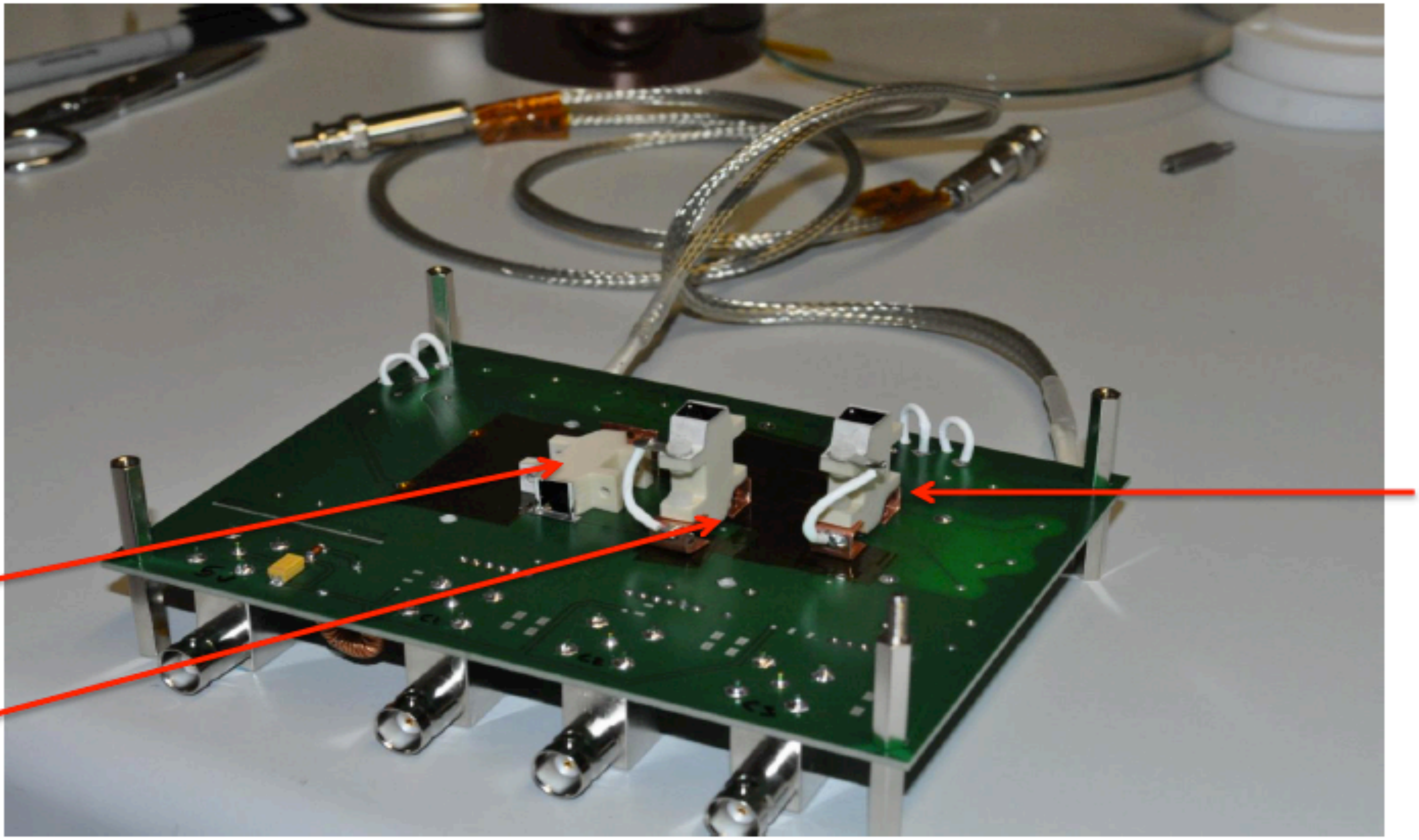


Tests in NIST/LINAC (USA)



High-energy electrons 1-28 MeV

Tests in NIST/LINAC (USA)

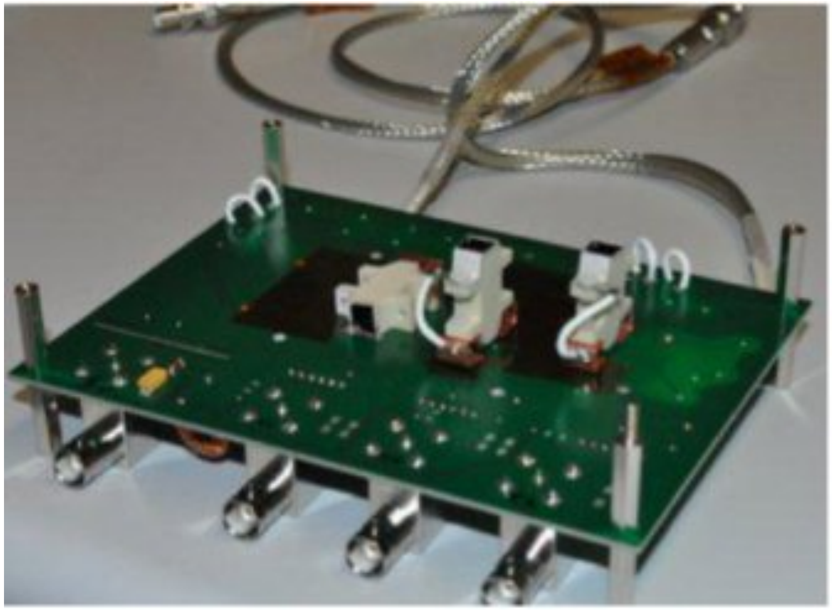


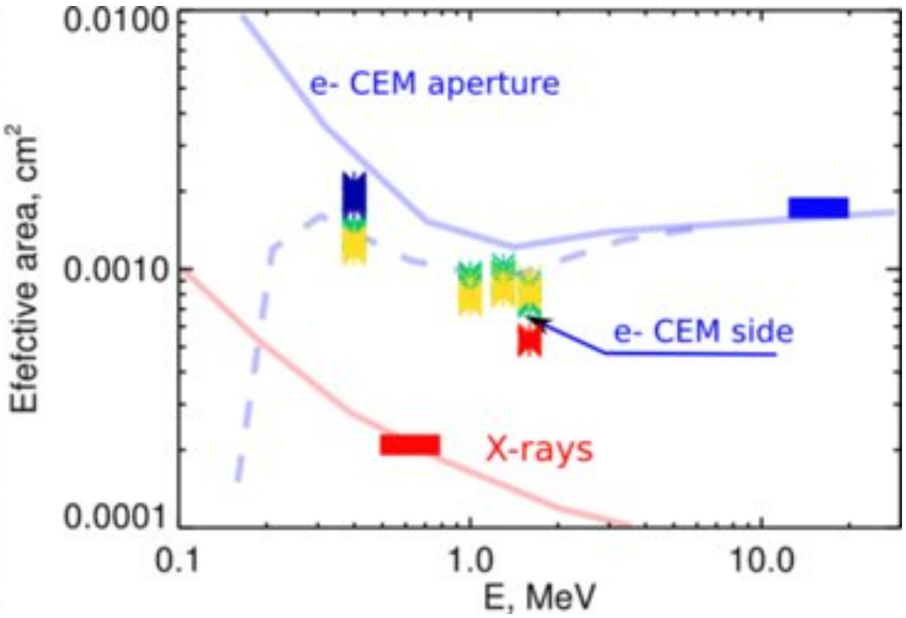
C

1

2

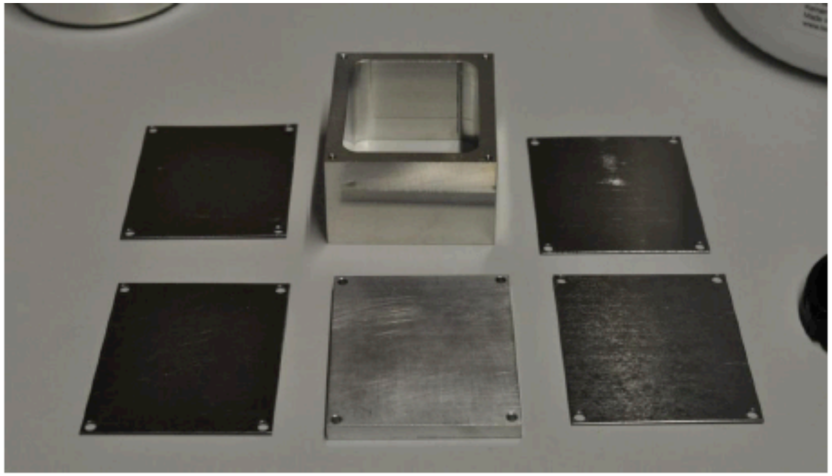
Results

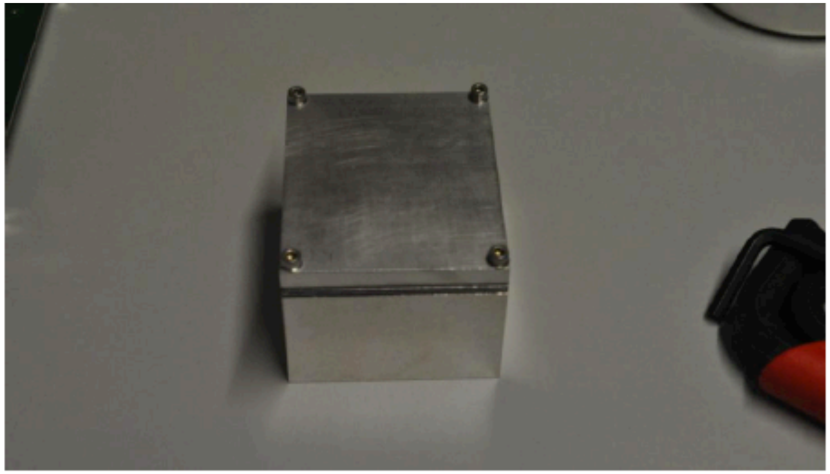


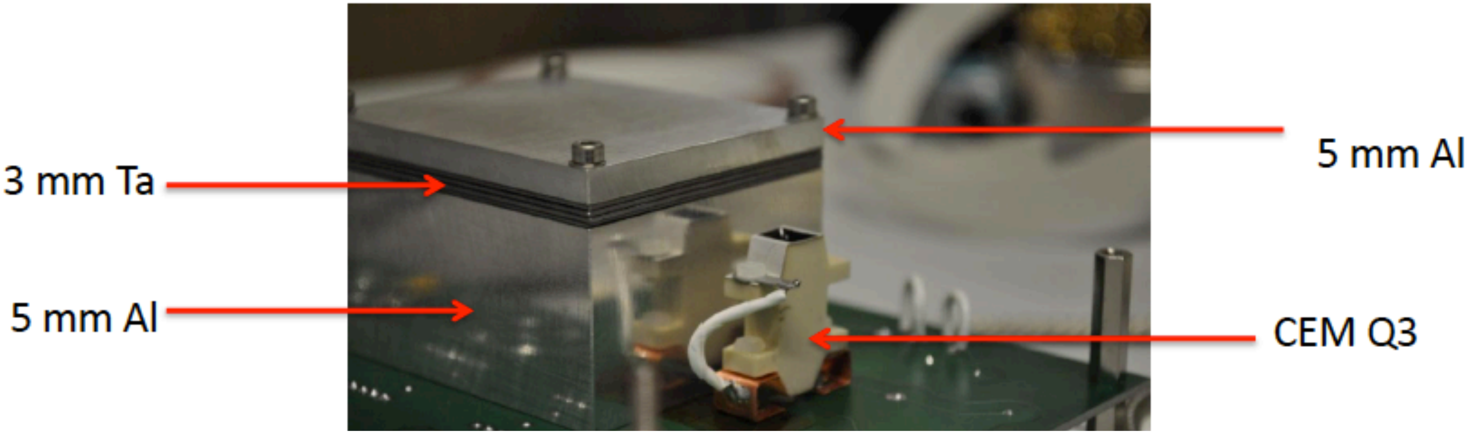


- Key (missing) parameter(s) determined

Shielded (Grad-Z) CEMs







- This enabled us to validate any passive shielding strategy with real measurements (and not only simulations/modelling) !

Comparison with measurements

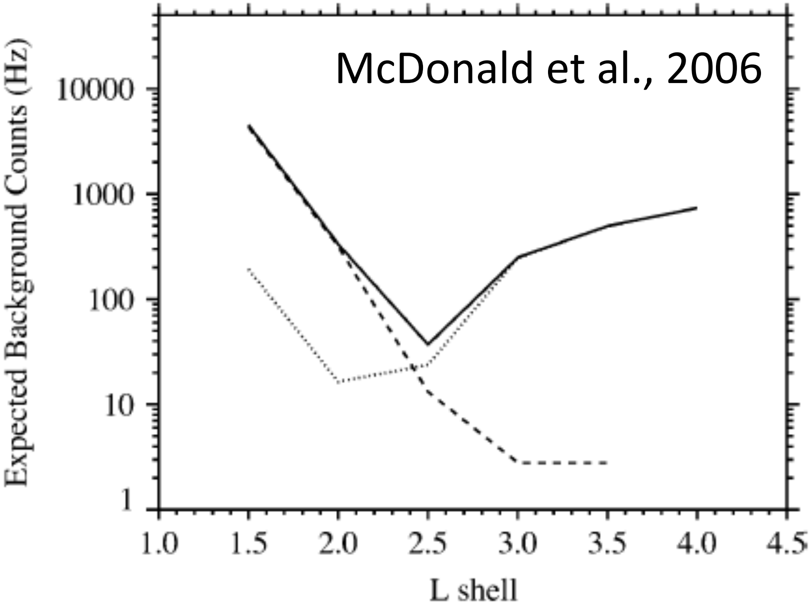
- LANL/MPA in GEO environment

Method: GEANT-4
Detector: CEM
Shiedling: 1.3 mm Aluminium

Total (raw) counts for photons : 5.25e05
Total (raw) counts for electrons : 1.55e06

With our measured effective surfaces:
Total counts for photons : 32
Total counts for electrons : 615

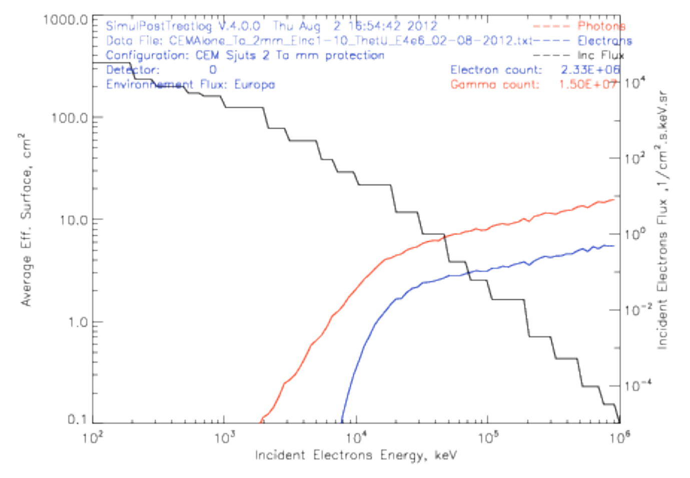
hence a background rate of 650 Hz.
This value is similar to the one deduced from the empirical model.



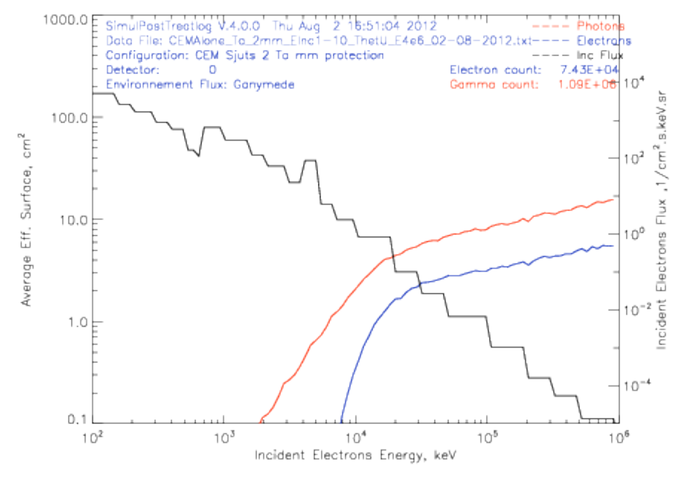
McDonald et al., 2006

Fig. 5. Expected background count-rate for an MPA-like detector attributable to penetrating electrons (dotted line), protons (dashed line), and their sum (solid line). The curves are calculated from the AP-8 and AE-8 model fluxes of protons and electrons above energies of 50 and 1.1 MeV, respectively.

Effective Surface – Galileo PLS



Environnement : Europe



Environnement : Ganymède

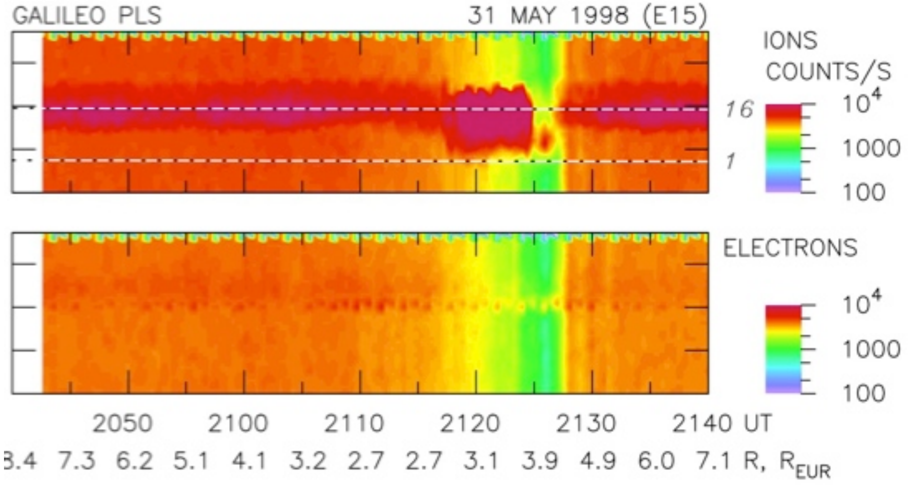
Environnement	Europe	Ganymède
Coups totaux photons	1.50e07	1.09e06
Coups totaux électrons	2.33e06	7.43e04
Coups totaux	1.73e07	1.16e06

- GEANT-4 simulation/modelling of the shielded detector

Comparison with measurements

- Galileo PLS

The background rate for one spiraltron as deduced from Galileo PLS measurements during E15 is 4 kHz.



Method: GEANT-4
Detector: CEM
Shiedling: 2 mm Tantalum

Total counts for photons : 1.5e07
Total counts for electrons : 2.33e06

With our measured effective surface:
Total counts for photons : 4050
Total counts for electrons : 629
hence a background rate of 4.67 kHz which is close to the deduced Galileo PLS value.

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6. Conclusions

Method

- Same as before (GEANT-4 simulations). Step by step approach.
- the results of the simulations are expressed as a function of the effective detector area versus the incident electron energy (The ideal detector collects any particles striking to its wall).
- Then, to calculate the real detector count rate, we have to make a convolution of this function with the incident electron distribution, and normalize the resulting count rate to the real CEM “effective aperture”.
- The results for different passive shielding strategies for the Europa environment are of the order of a few kHz.

This is still high !

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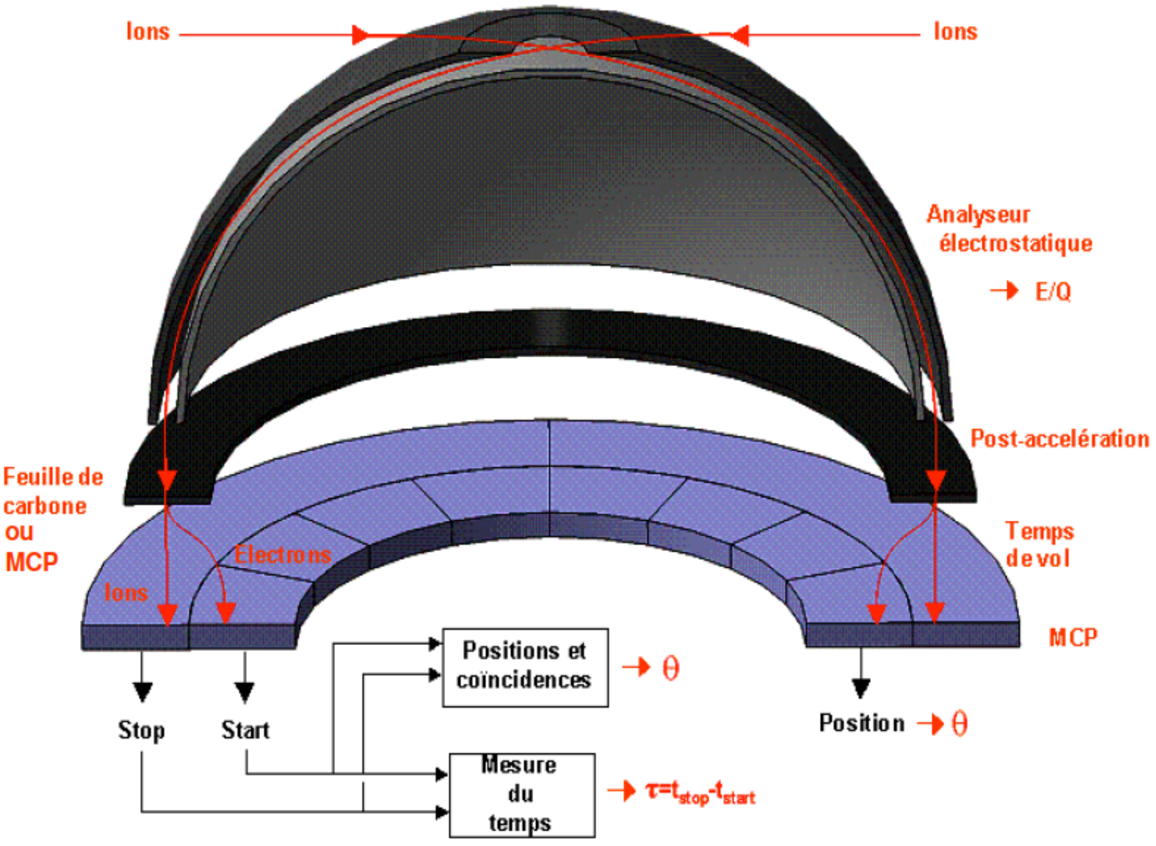
Coincidence



Rates = R_{start} x R_{stop} x $\Delta\tau$

Coincidence

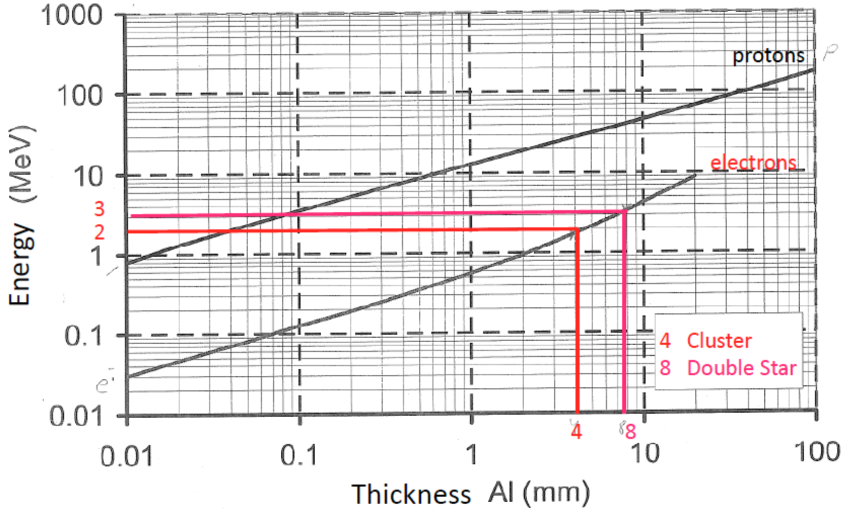
- Coincident signal between two detectors (1 START, 1 STOP)
- Rates = R_{start} x R_{stop} x $\Delta\tau$
- Simple illustration (no real sensor)

Assume background noise R_{start} = R_{stop}= 10^4 and $\Delta\tau$ = 100.10^(-9)

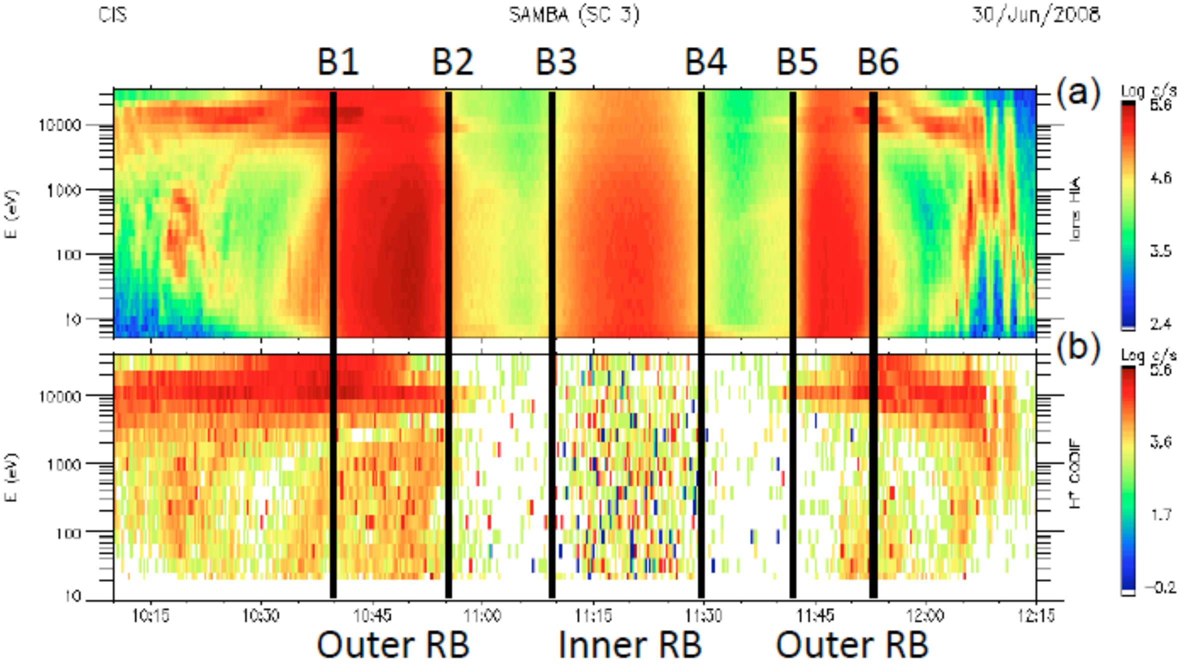
then background noise down to a few 10s Hz using coincidence

- + further reduction of (time) acceptance window ($\Delta\tau$)

Radiation mitigation



Benefices of coincidence clearly demonstrated here



XGSE	−1.65	−1.03	−0.38	0.30	0.98	1.45	1.75
YGSE	2.81	2.93	2.89	2.62	2.00	1.06	−0.04
ZGSE	−2.58	−1.77	−0.86	0.07	1.02	1.82	2.35
DIST	4.16	3.57	3.03	2.63	2.44	2.56	2.93
L	16.96	8.14	4.11	2.62	2.61	5.97	34.74

Without
the coincidence signal

Using the coincidence signal

Cluster CIS CODIF/HIA

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Conclusions

- Radiation noise and TID are very serious issues for particle sensor (and others) in the case of JUICE

- Passive shielding can significantly reduce TID and protect sensor subsystems (electronics) – this can be solved by relying on simulations (e.g., GEANT-4; FASTRAD) with the objectives of optimizing the required shielding mass

Albeit, this HAS to be DONE at SYSTEM level (therefore knowledge of S/C preliminary architecture(s) required by instrument teams)

Conclusions

- Passive shielding alone cannot reduce background noise to the low level required to fulfil ALL the ambitious scientific objectives of JUICE

  Strong limits to that approach

  This issue can be solved by relying on active shielding techniques (coincidence)