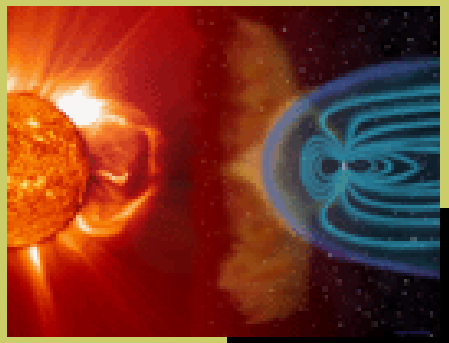
A Radiation Monitor for Future Space Missions

P.Gonçalves, M. Pimenta, B. Tomé
LIP - Laboratório de Instrumentação e Física Experimental de Partículas
Lisboa, Portugal

Space radiation environment

Earth´s trapped radiation belts

- Electrons (<6 MeV) & Protons (<250 MeV)
- Relevant only for Low Earth Orbits (LEO)

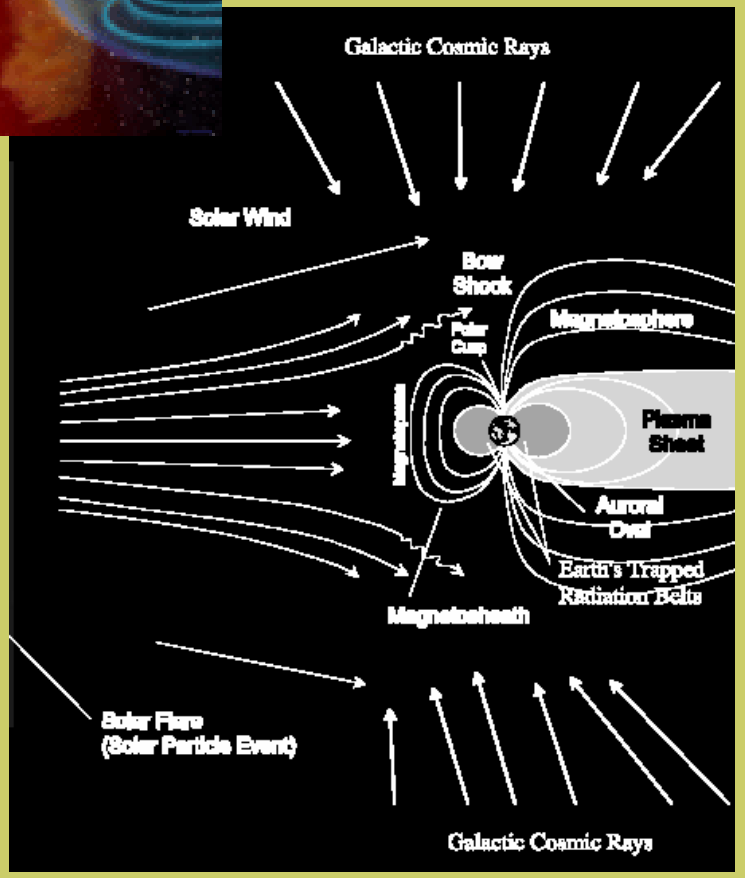


Galactic Cosmic Rays

- Energy spectrum peaked at ~1 GeV/n
- < 1 GeV/n affected by 11-year solar cycle
- Flux modulated by solar cycle (inversely proportional to solar activity)

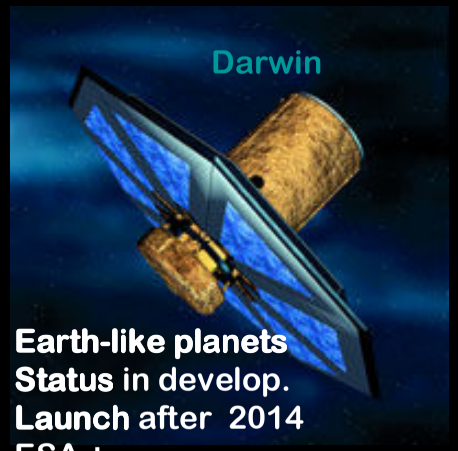
Solar Energetic Particles (SPE)

- Associated w/ impulsive solar flares and Coronal Mass Ejections
- Sudden and dramatic increase in flux – unpredictable & highly variable
- Mostly “low energy” electrons & protons ; some heavy ions
- Frequency and Magnitude strongly correlated with solar cycle

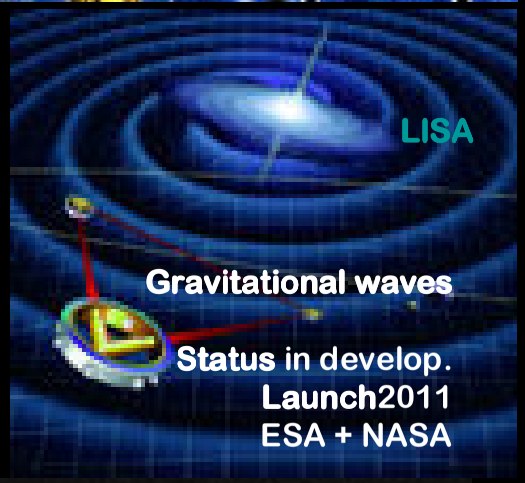


SOME FUTURE MISSIONS

X-ray Evolving Universe Spectroscopy



Laser Interferometer Space Antenna



James Webb Space Telescope

Radiation monitors for future space missions

Ancillary radiation environment information for the spacecraft :

-Trigger shielding actions

Data with scientific quality always welcome

- only non dormant instrument during the cruise phase where data of scientific relevance can be acquired (e.g. particle fluxes & spectral distributions *vs* distance to Sun)

New generation compact, lightweight space radiation monitor

electrons : ~ 0.5 MeV – 20 MeV ;
protons and ions : 0.5 MeV/n – 150 MeV/n ;

Weight: < 1 Kg, Volume ~ 5 x 5 x 5 cm3
Power consumption < 1 W

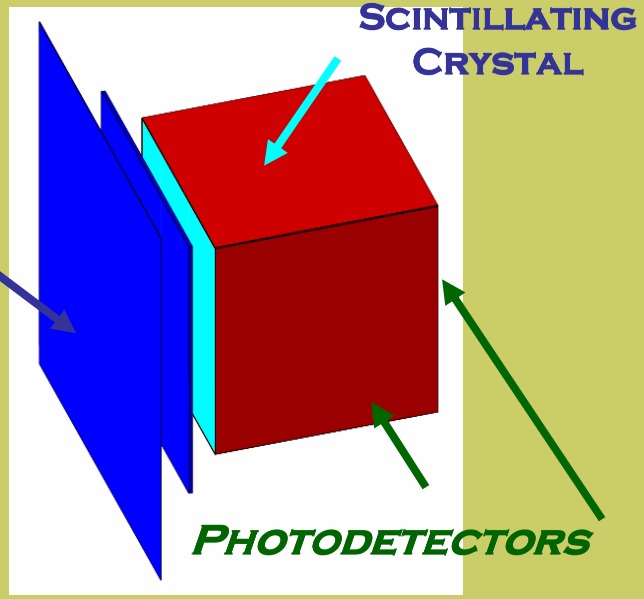
A Simple concept based on a scintillating crystal :

(A. Owens et al. (ESA-SCI/A), private communication)

- **Particle tracking**
- **Particle id. through dE/dx in trackers**
- **Energy measurement in crystal**
- **Anticoincidence shielding via phoswitching**

Similar concepts from, e.g.:

- *G. Pasquali et. al, NIM A301 (1991)101*
- *Sensys MRM´s*
- *???*

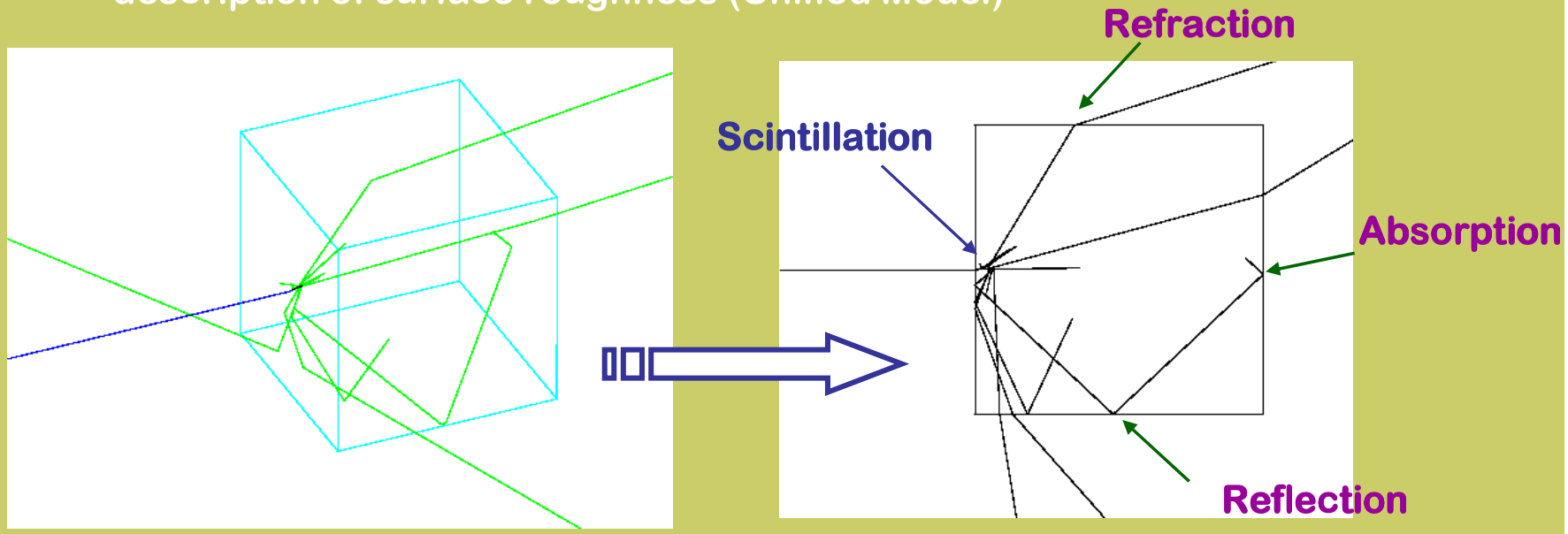


Geant 4 toolkit

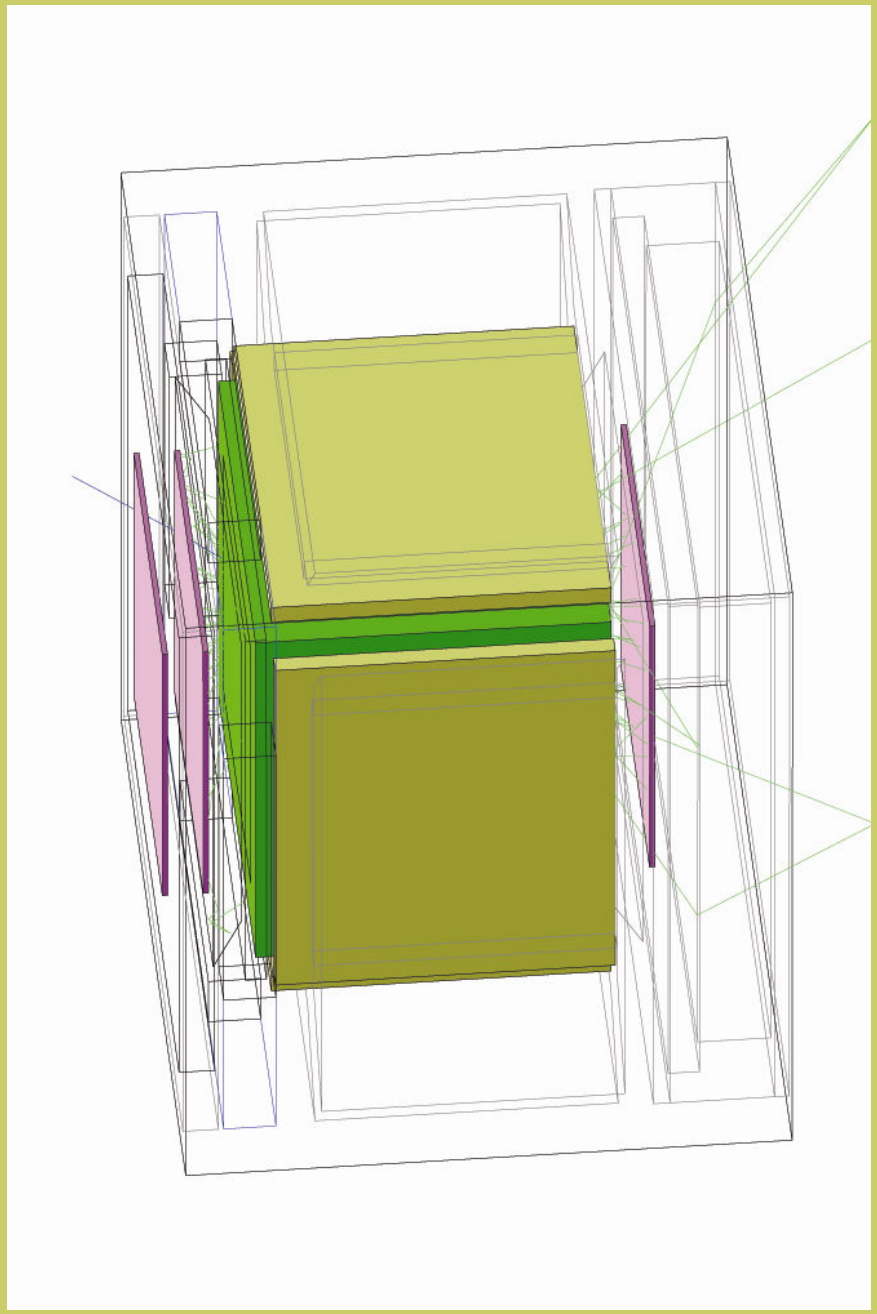
Geant4 is a toolkit for the simulation of particle transport and interaction with matter, featuring :

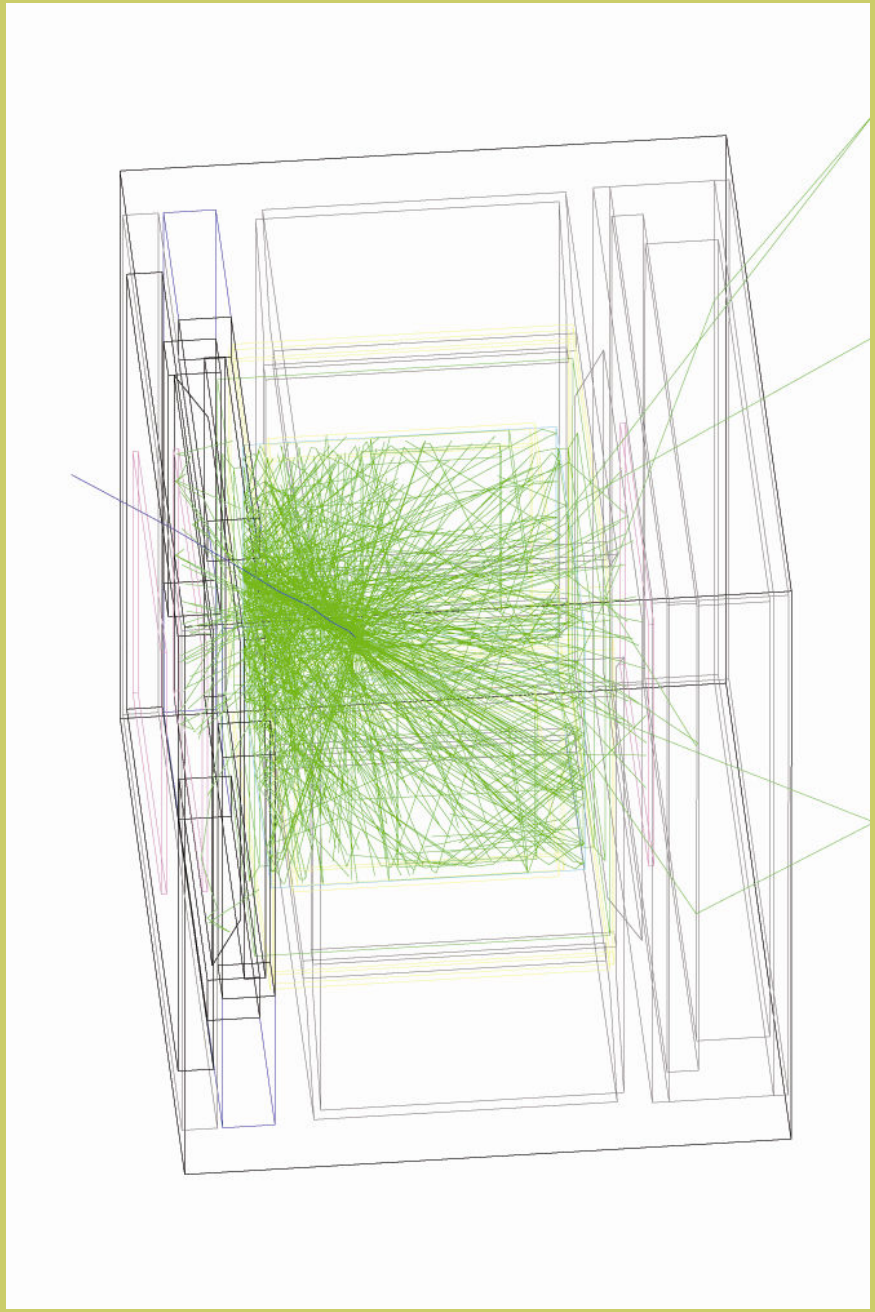
- Description of geometries of arbitrary complexity.
- Simulation of Hadronic, Electromagnetic and Optical physics processes.

  + Cerenkov & Transition radiation, Rayleigh scattering
  + description of surface roughness (Unified Model)



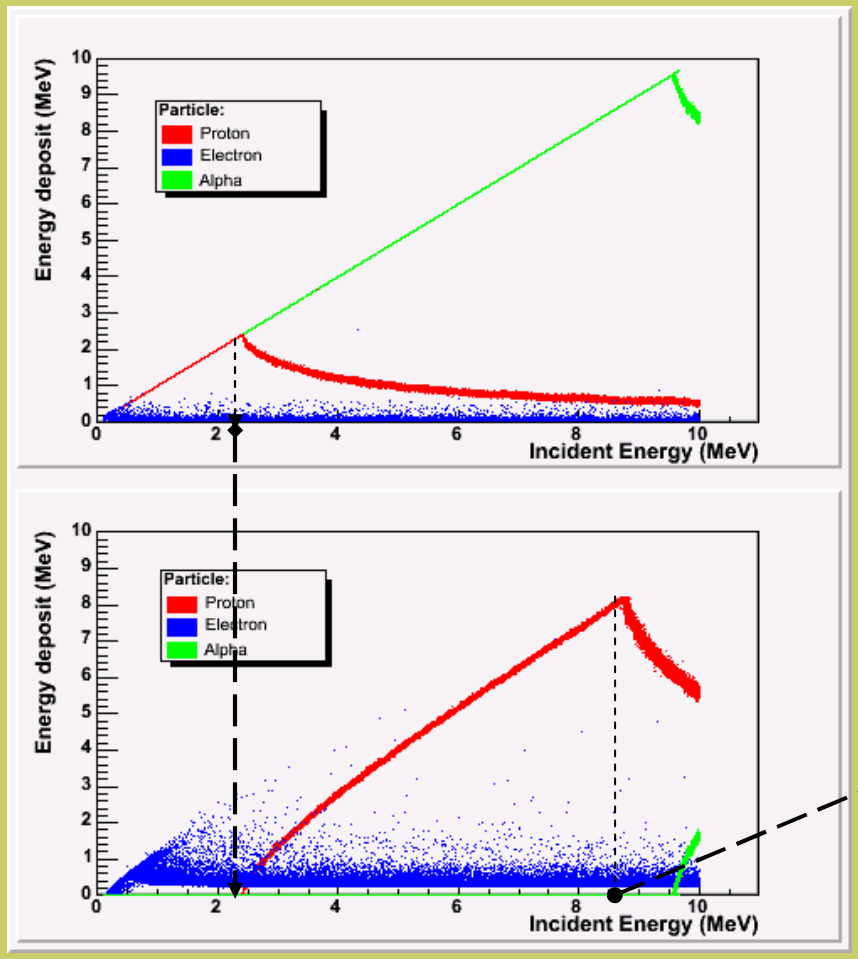
- OO design, allowing the implementation of flexible simulation applications.
- New physics processes categories easily plugged-in (openness & extensibility of the code).





Some illustrative results from Geant4 simulation

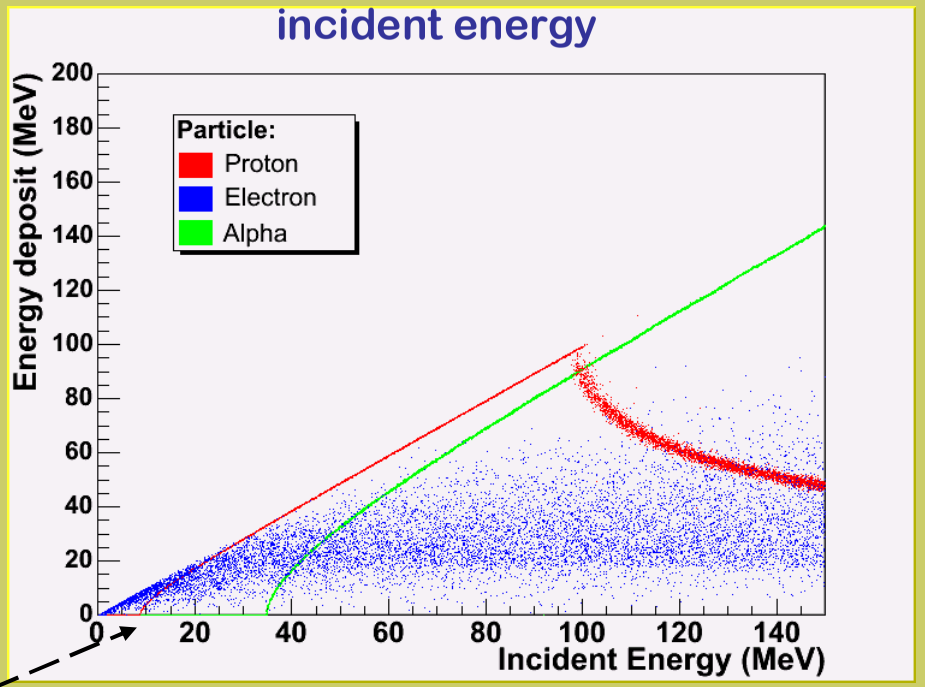
Energy deposition in trackers *vs* incident energy



Energy deposition in crystal

vs

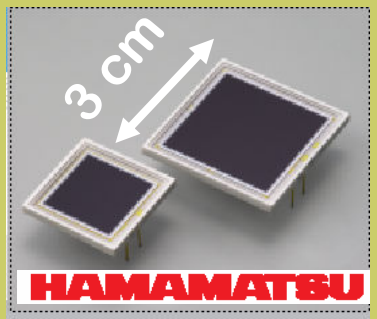
incident energy



Detector design

300 µm thick PIN diodes

- **S3584** (35,6mm frame side, 28 mm active area)



- High quantum efficiency
- Low voltage
- Low power dissipation

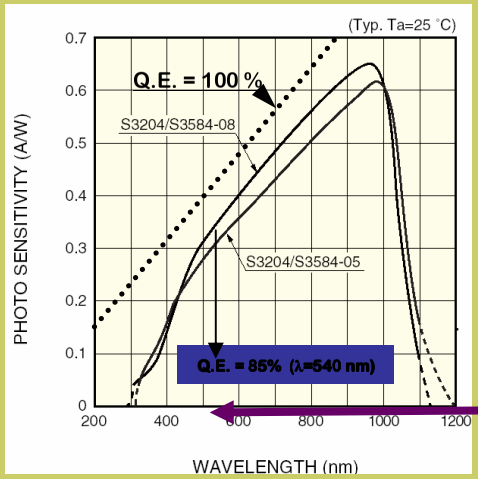
3 cm

300 µm thick trackers

3x3x3 cm3 Crystal

PIN diode

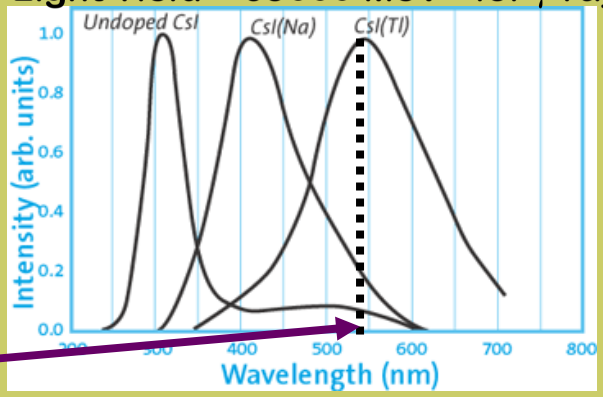
Assuming:
Top surface reflectivity : 95%
Crystal-PINdiode transmissivity : 95%



CsI(Tl)

Scintillator : CsI(Tl)

Light Yield = 65000 MeV^{-1} for γ-rays



Fast instrument simulation using Geant4 as benchmark

Protons, Electrons and Alphas

analytical Transfer Funcions based on the Physics and on the geometry

Crystal

Description of the signal arriving at each PIN diode:

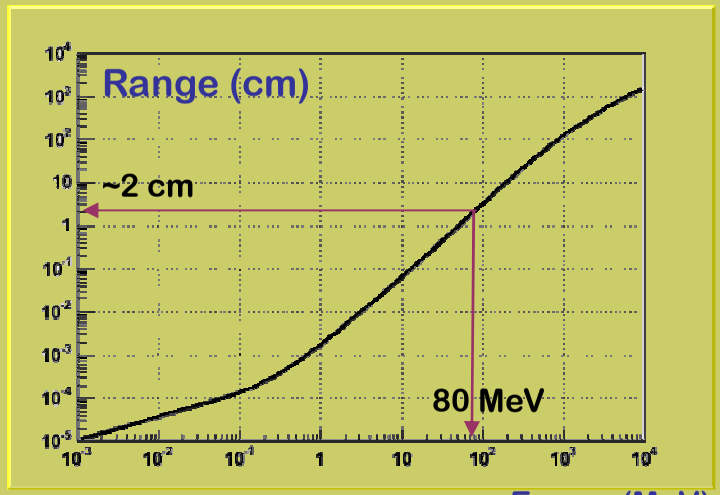
- Evaluations of the **solid angle** seen by each PIN diode.
- **dE/dx** approximation : dE/dx ~ β-2
- Account for **reflections** in crystal walls.

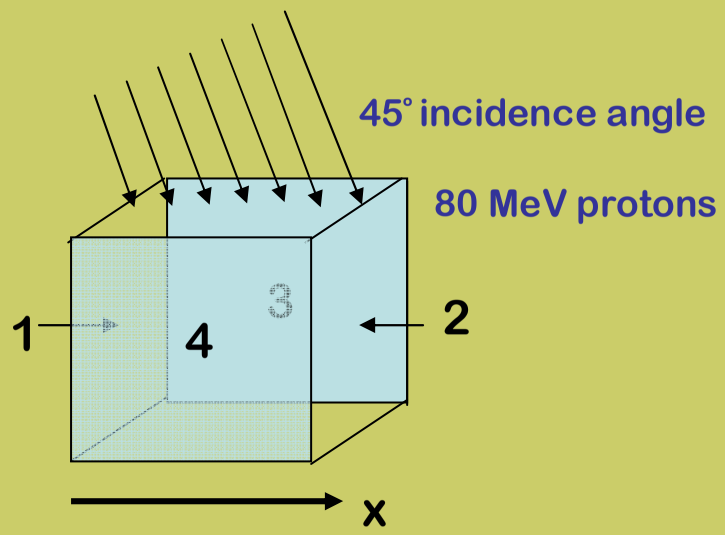
Trackers

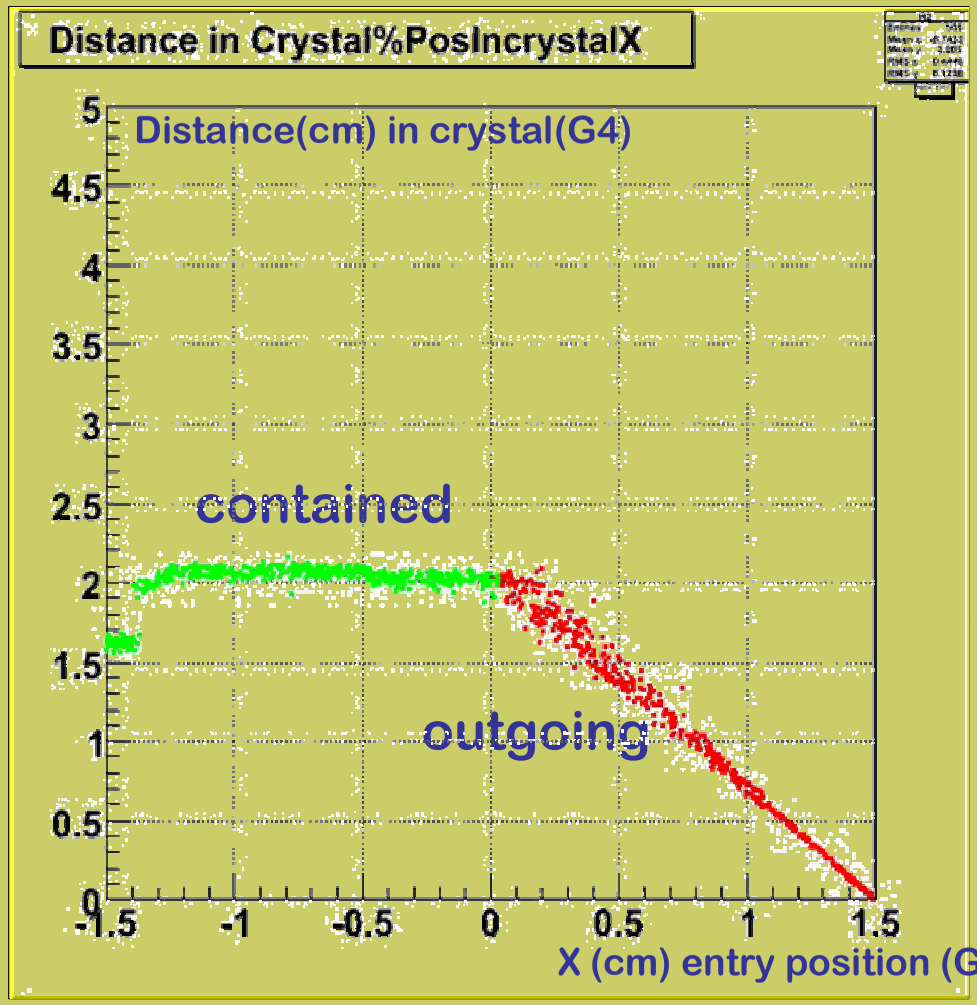
Evaluation of the energy loss in the trackers: dE/dx
Energy -> Charge

Proton Range in the Crystal

Proton Range in CsI







Transfer function for the crystal

The crystal is read by 5 PIN diodes located on its side and bottom surfaces

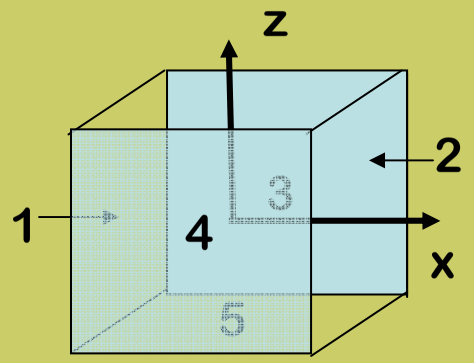
1)The signal arriving on each surface is proportional to its subintended solid angle wrt the proton trajectory inside the crystal

$$TotalSignal = \sum_{face=1}^{5} Signal(face)$$

2) The emission of scintillation photons is isotropic for each point

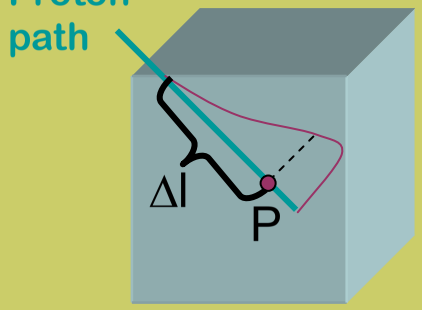
3) The number of scintillation photons at each point is proportional to dE/dx.

4) There are internal reflections in the crystal walls and absorption (ρi).



Signal(face,P) =
TotalNPhotons .r1. k1(face).[Ω(face,P) + k2(face).r2.S.Ω(top,P)]

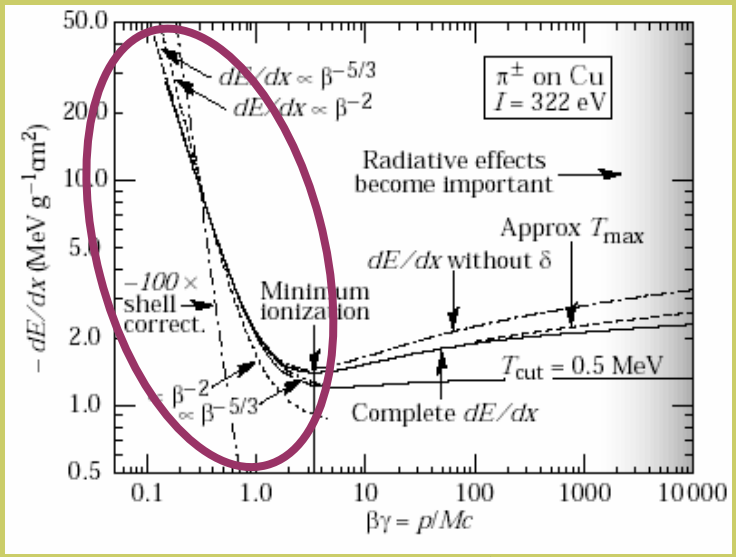
Proton path



Approximation:
calculate Ω(face) in the point along the proton trajectory corresponding to the average of the energy loss distribution

Energy loss

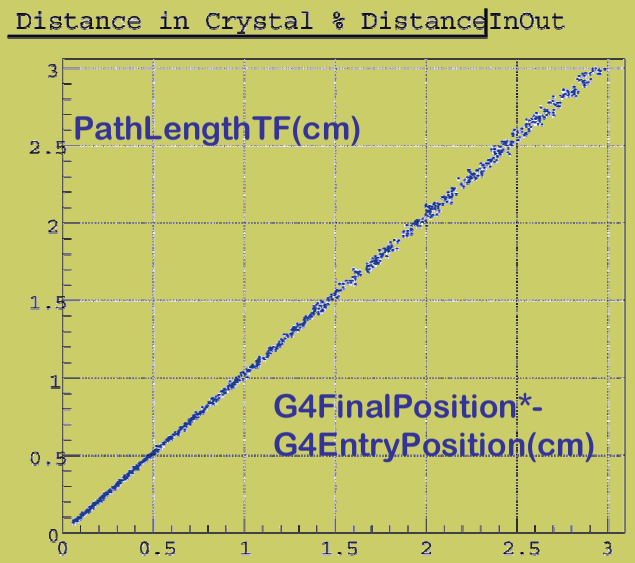
$$-\frac{dE}{dx} = kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left(\frac{1}{2}\ln\left(\frac{2m_e c^2 \beta^2\gamma^2 T_{\max}}{I^2}\right) - \beta^2 - \frac{\delta}{2}\right)$$

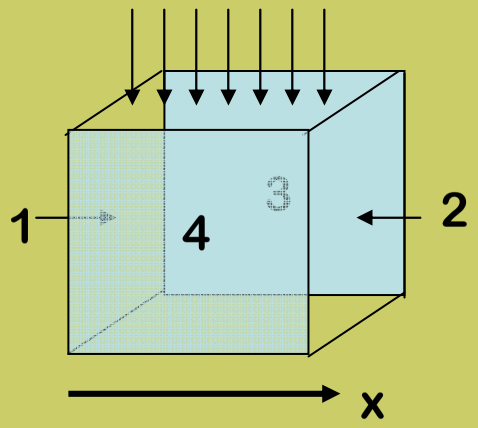


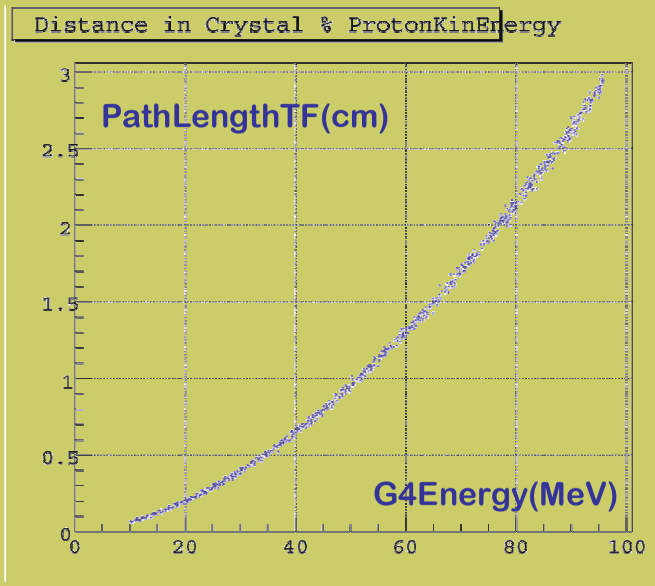
minimum ionization: $\beta\gamma$ ~3 ⇨ **protons E~3 GeV**
electrons E~1.6 MeV

approximations: $-\frac{dE}{dx} \propto \beta^{-5/3}$ **Or (?)** $-\frac{dE}{dx} \propto \beta^{-2}$

10 -100 MeV protons





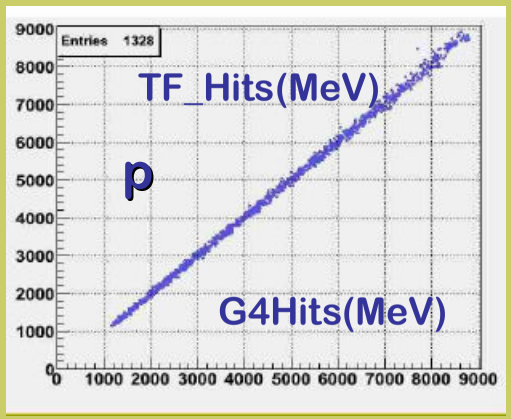


* G4FinalPosition

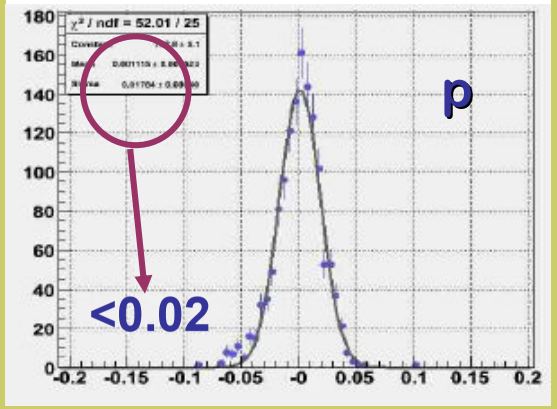
Contained:
point where proton "dies"

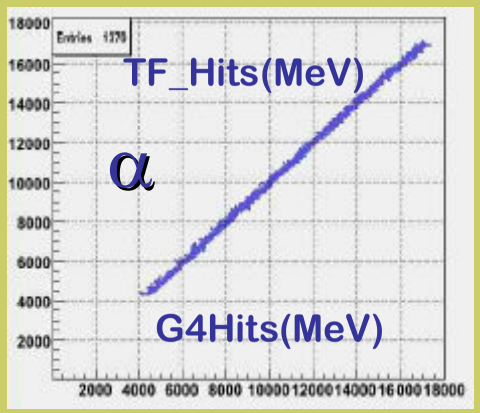
Outgoing:
point where proton leaves crystal

Protons and alphas in the Crystal

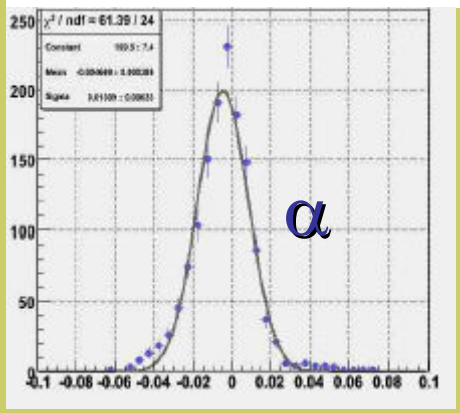


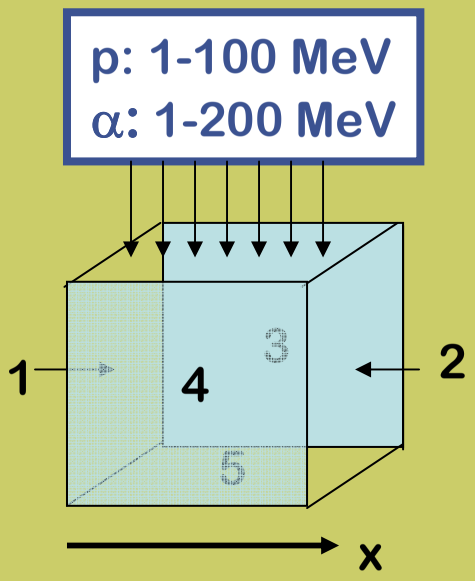
(TF_Hits – G4_Hits) /G4_Hits



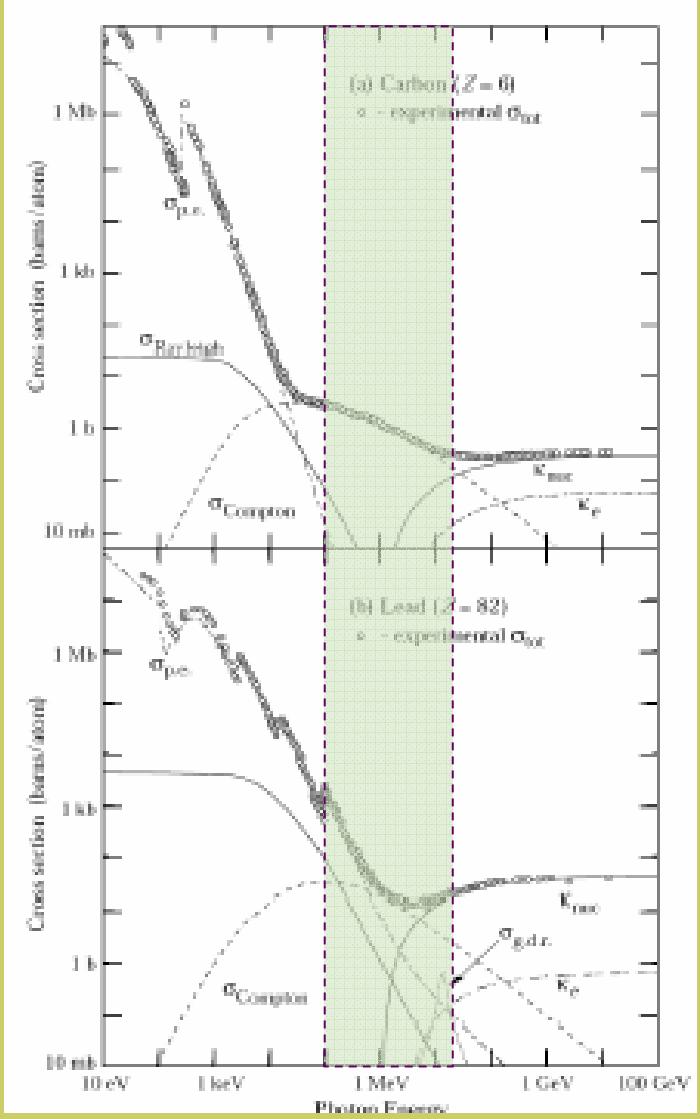


(TF_Hits – G4_Hits) /G4_Hits





Electrons



- More challenging problem due to bremsstrahlung and showers,
- Cherenkov radiation negligible wrt scintillation

- Bremsstrahlung OK, but

The photon interaction processes/x-sections vary for the chosen energy range:

crystal absorbed energy depends on whether the photons get absorbed or leave… ->

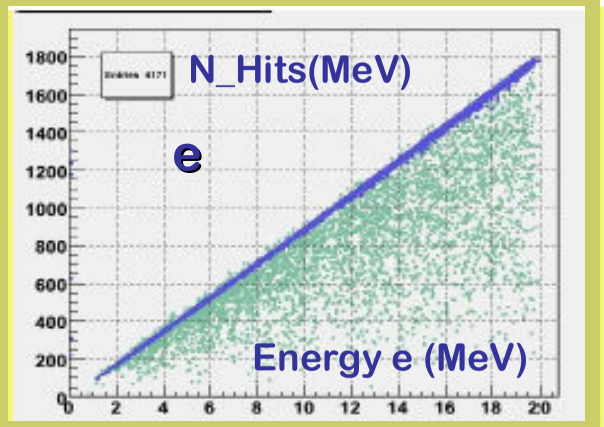
distributions:: function (electron energy)

use p.d.f./means values for Energy and Signal

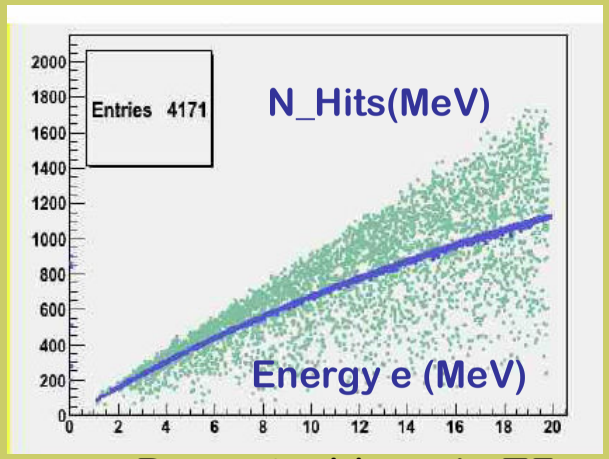
Electrons

G4 .....

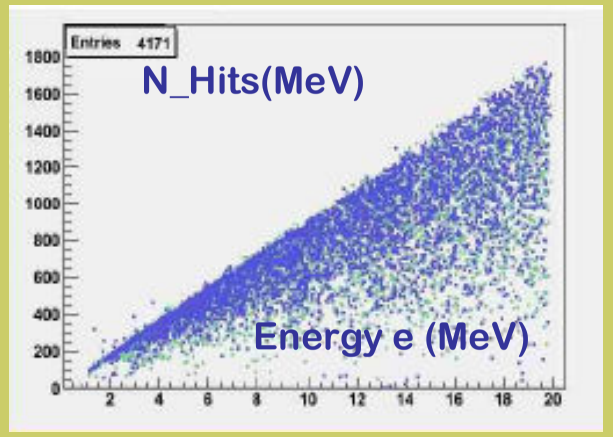
TF .....



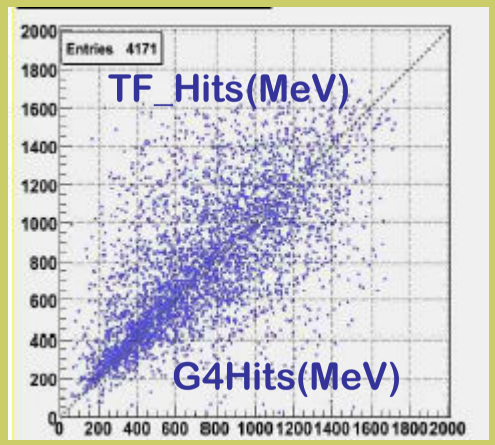
No bremstrahlung in TF



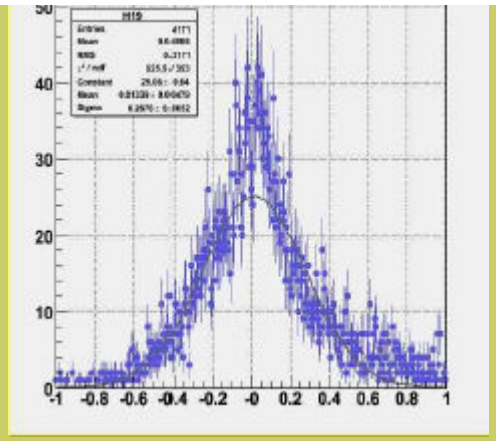
Bremstrahlung in TF

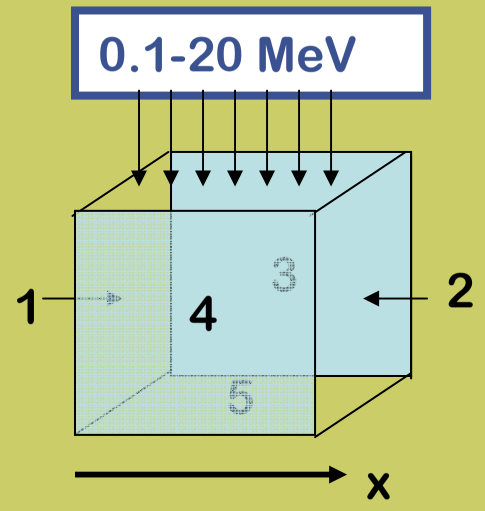


Bremstrahlung in TF+
pdf for Nhits fitted from G4



(TF_Hits – G4_Hits) /G4_Hits





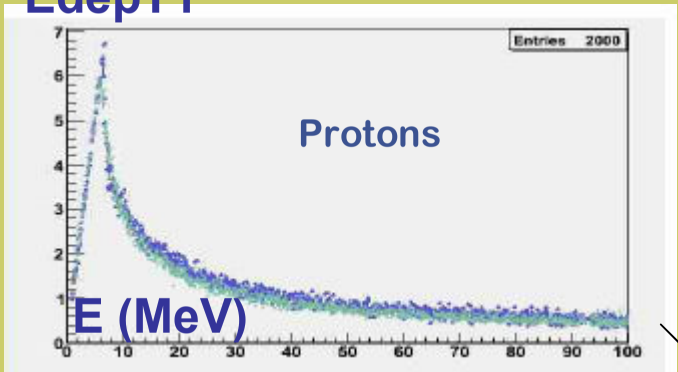
Transfer function for the tracker

Protons and alphas

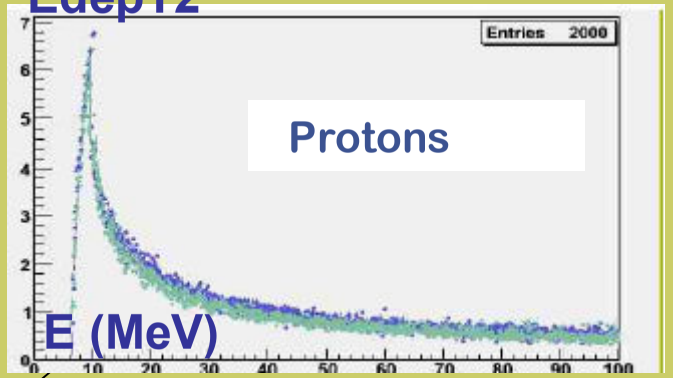
E_lost : Gaussian distribution: $dE/dx \sim \beta^{-2}$ is valid for all energies

Average value from the inverse of $\Delta x = \int 1/dE/dx\, dE$

EdepT1

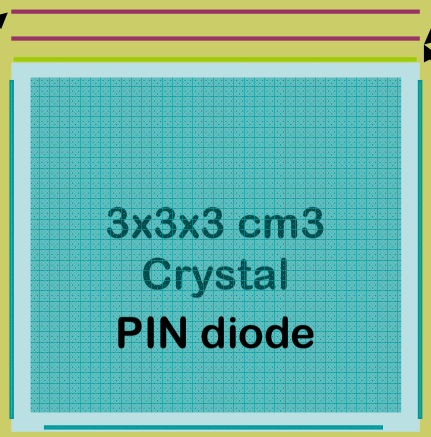


EdepT2



G4 .....

TF .....



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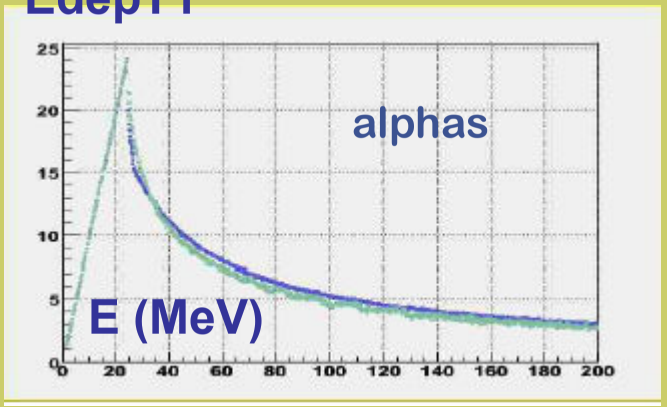
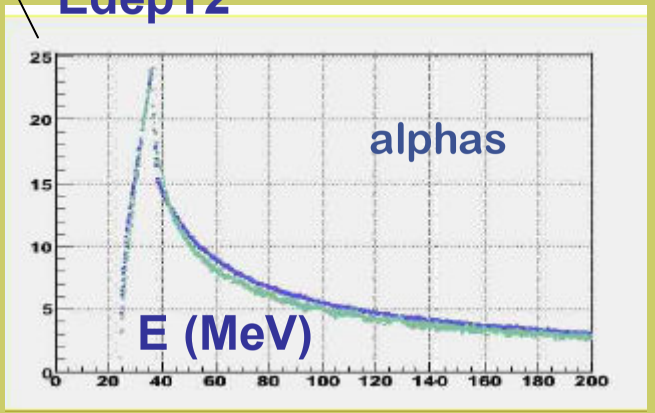


EdepT2



Transfer function for the tracker

electrons

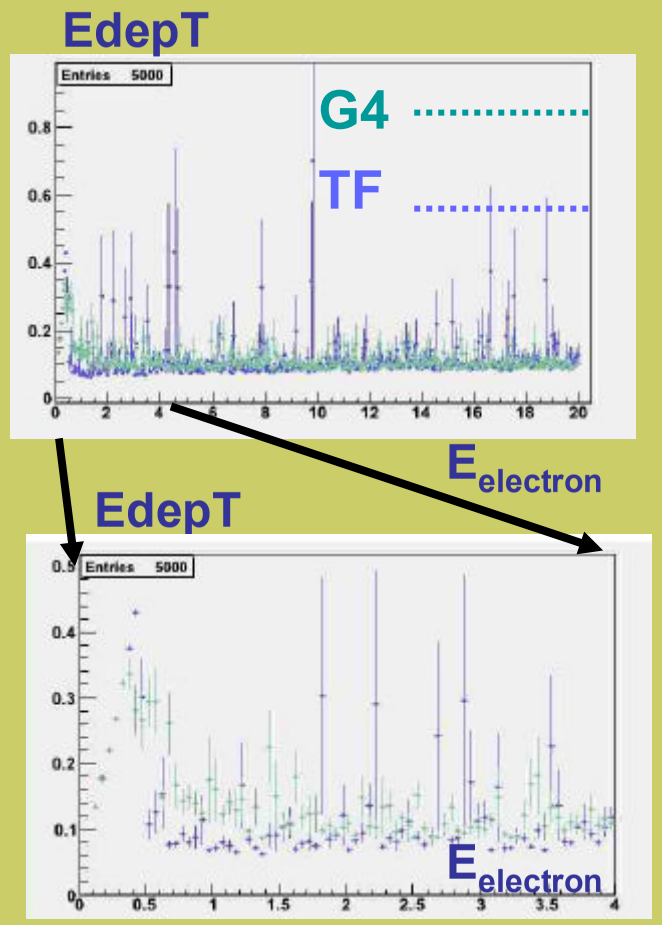
E_lost : Landau distribution

dE/dx ~ β^{-2}
is valid for Energy ~ < 1.6 MeV
average Energy value from the inverse of

$$\Delta x = \int 1/dE/dx \, dE$$

for Energy > ~ 1.6 MeV
average Energy value from

$$dE/dx * \Delta x$$



Conclusions

A new generation of compact, lightweight, general purpose radiation monitors are needed and being developed for future Space Missions (e.g. BepiColombo).

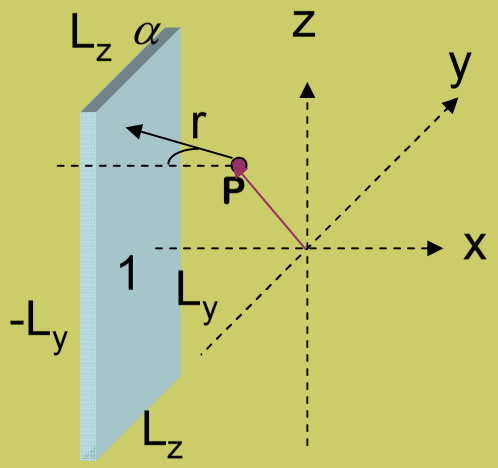
A simple concept based on a scintillating crystal was studied.

The Instrument geometry and corresponding structural model were implemented in Geant4

The Geant4 toolkit proved to be a powerful tool:

- for a standalone simulation of the instrument
- as benchmark for a fast instrument simulation

Solid angle calculation



The solid angle subtended by a surface is defined as the surface area of a unit sphere covered by the surface's projection onto the sphere.

$$\Omega = \iint_S \frac{\vec{n}\,.\,\vec{da}}{r^2}$$

For face 1 and emission point P (xp,yp,zp):

$$\begin{cases} \vec{n}\,.\,\vec{da} = \cos\alpha.dy.dz = \dfrac{x - x_p}{r} dy.dz \\ r^2 = (x - x_p)^2 + (y - y_p)^2 + (z - z_p)^2 \end{cases}$$

The solid angle corresponding to face 1 is :

$$\Omega_1 = \int_{-L_z}^{L_z} \int_{-L_y}^{L_y} \frac{(-L - x_p)}{\left((-L - x_p)^2 + (y - y_p)^2 + (z - z_p)^2\right)^{3/2}} .dy.dz$$

$$\Omega_1 = \text{atan}\left(\frac{(L_y - yp)\,(L_z - zp)}{(-L_x - xp).\sqrt{(-L_x - xp)^2 + (L_y - yp)^2 + (L_z - zp)^2}}\right) + \text{atan}\left(-\frac{(-L_y - yp)\,(L_z - zp)}{(-L_x - xp).\sqrt{(-L_x - xp)^2 + (-L_y - yp)^2 + (L_z - zp)^2}}\right) +$$

$$\text{atan}\left(-\frac{(L_y - yp)\,(-L_z - zp)}{(-L_x - xp).\sqrt{(-L_x - xp)^2 + (L_y - yp)^2 + (-L_z - zp)^2}}\right) + \text{atan}\left(\frac{(-L_y - yp)\,(-L_z - zp)}{(-L_x - xp).\sqrt{(-L_x - xp)^2 + (-L_y - yp)^2 + (-L_z - zp)^2}}\right)$$