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Characterization of plastic scintillator Detector prototypes for the HERD experiment

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on behalf of the HERD Collaboration

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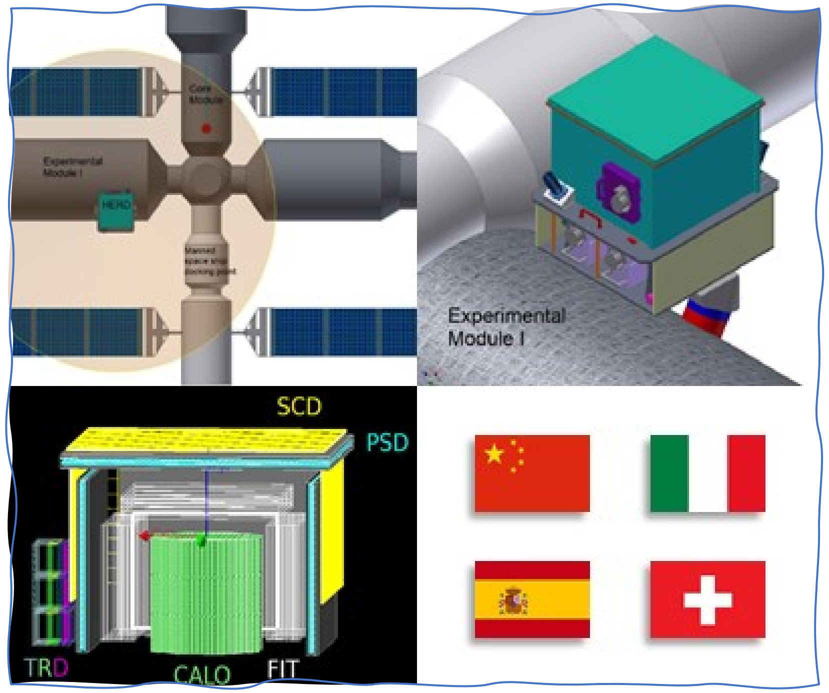
HERD Overview

- The **High Energy cosmic-Radiation Detection** (HERD) facility is a China-led international space mission that will start operation around 2026.
- **Main scientific goals:**
  - Cosmic Rays: Precise CR spectra and mass composition up to the PeV range
  - Gamma – ray astronomy and transient studies (e.m. counterpart of GW)
  - Electron spectra (and anisotropy) up to tens of TeV (nearby sources, ...)
  - Indirect Dark Matter searches with high sensitivity

- **HERD Subdetectors:**
  - **CALO**: *The HERD core is a 3D, homogeneous, isotropic and finely-segmented calorimeter*
    - Energy Reconstruction
    - e/p Discrimination
  - **FIT**: *The CALO is surrounded by Fiber trackers (FiTs) (except the bottom)*
    - Trajectory Reconstruction
    - Charge Identification
  - **PSD**: *The CALO and the FIT are covered by the plastic scintillator detector (PSD)*
    - Charge Reconstruction
    - γ identification
  - **SCD**: *The silicon charge detector (SCD) is the outermost detector*
    - Charge Reconstruction
  - **TRD**: *A Transition Radiation Detector (TRD) will be located on the lateral side*
    - Calibration of CALO
    - response for TeV proton



Plastic Scintillator Detector (PSD)

- PSD provide γ-**identification** (VETO of charged particles) and **nuclei identification** (energy loss∝ Z^2)

  - highly segmented for the back scattering → *Tile/Bars geometries*

  - Overall High efficiency and low dark noise for charged particles rejection
  - Good energy resolution for better charge particle detection
  - High dynamic range for high Z identification
  - Low power consumption for space application

  → *SiPM based read-out system for the scintillator light emission*

Two layout configuration are under investigation

Bars

- Each layer made by two staggered sub layer to increase hermeticity
- Read-out with up to 6 SiPM (up to 3 for each end)

PRO
- Less number of readout channels

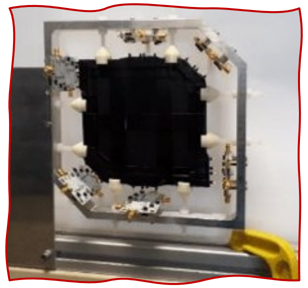
CONS
- Higher Back-scattering problem

Squared tiles

- Two layer of tiles to increase nuclei identification power
- Each tile is readout by 6 SiPM (3 per side on two opposite sides)

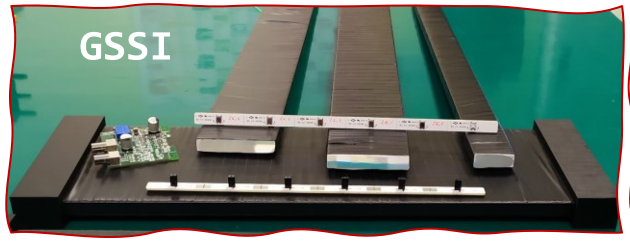
PRO
- Reduce back-scattering problem

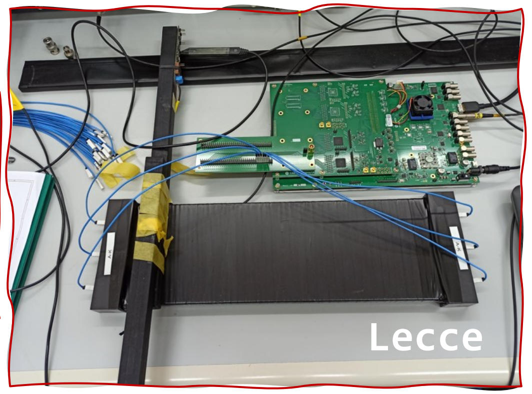
CONS
- Higher number of readout channels

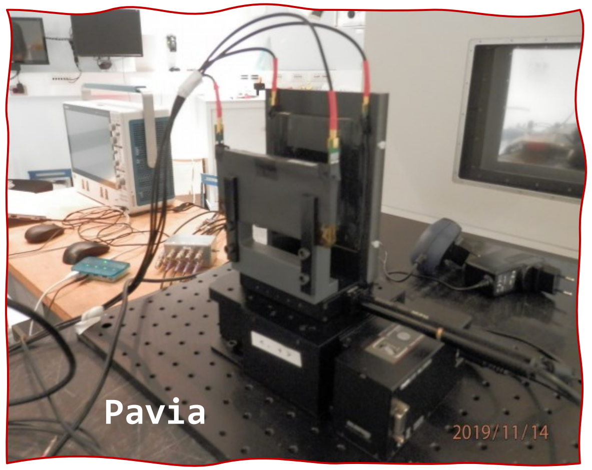


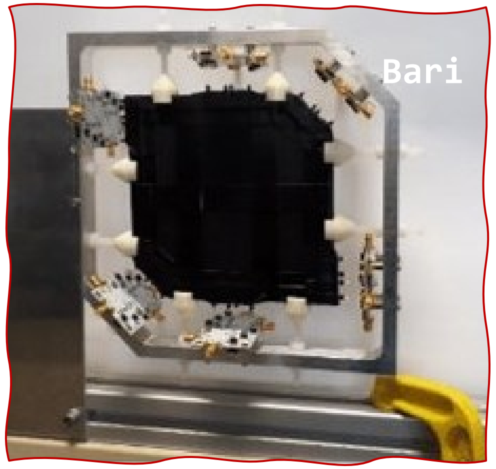
Built prototypes under testing

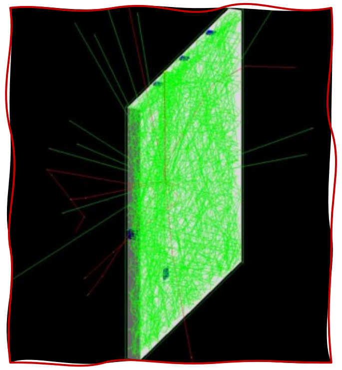
- We built several tile and bar prototypes, and we are testing them in different configurations:
  - Test with protons and ions @ CERN
  - Test with CR in lab
  - Test with radioactive sources in lab
  - Test with ions @ CNAO (PV)
- We have also developed full customizable simulation tool based on GEANT4 that tracks every optical photon generated by scintillation in tiles/bars
  - The simulation purpose is to study the best tile/bar geometry and the best design for the SiPM-based readout system

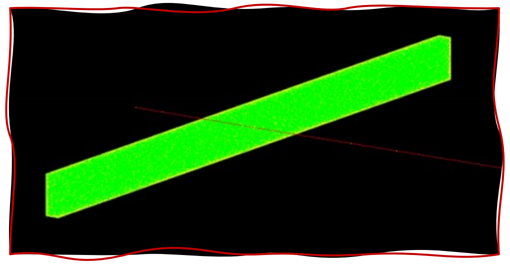






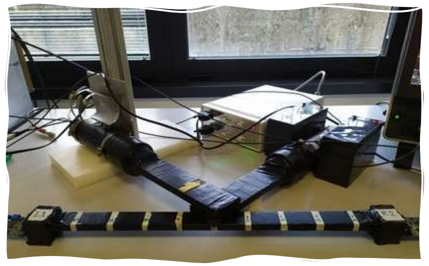


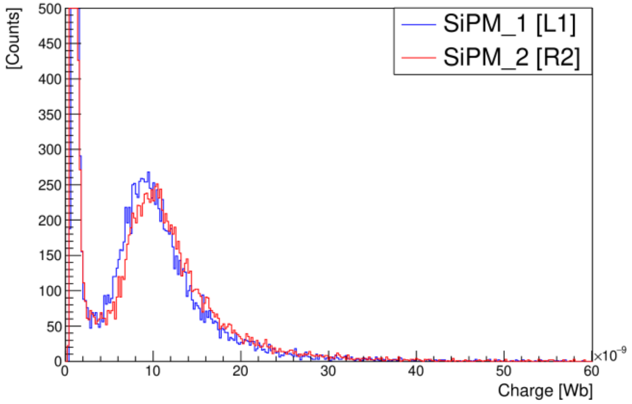




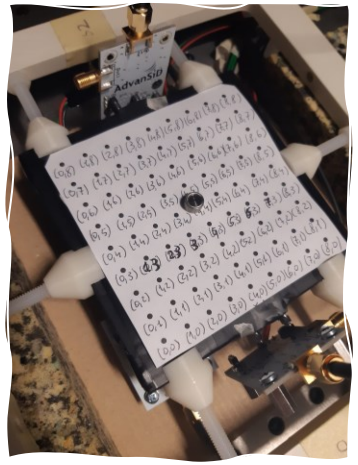
Lab tests

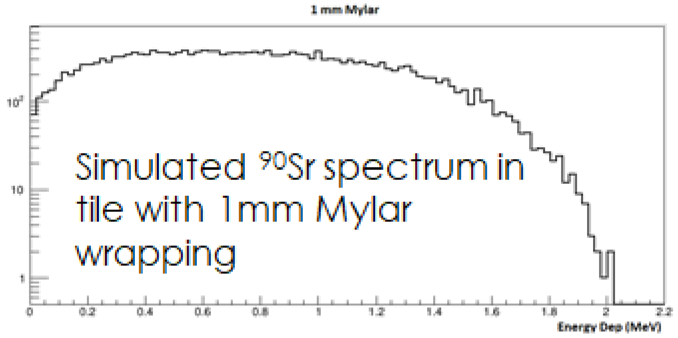
- Test with cosmic rays
  - Different EJ–200 scintillator bars coupled with 1,2 or 3 AdvanSiD / Hamamatsu SiPMs per side

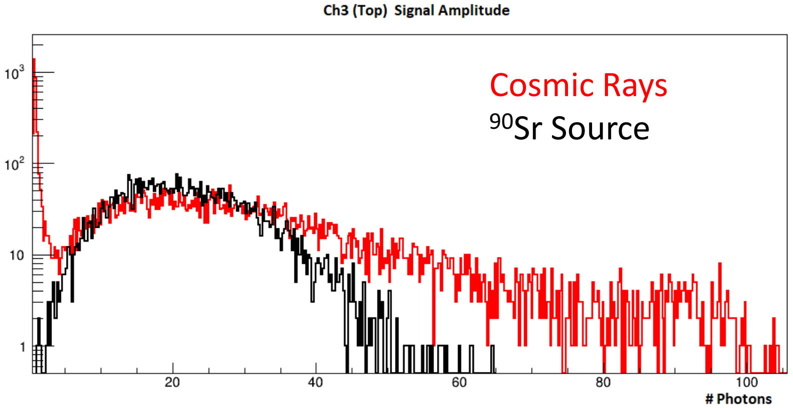


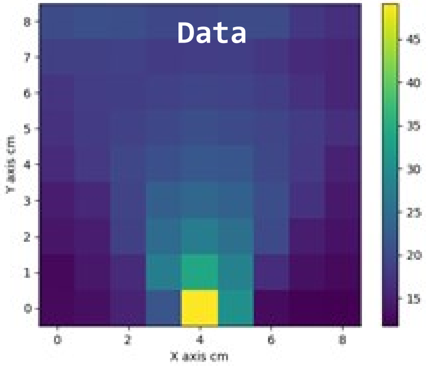


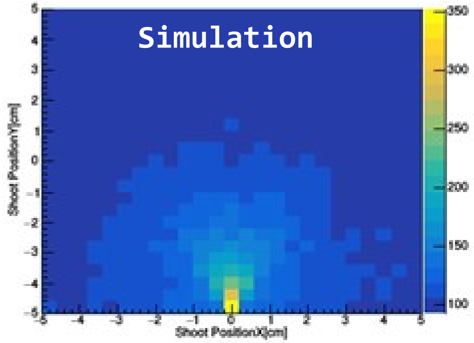
- Test with ^{90}Sr radioactive source
  - $10\text{x}10\text{x}1\text{cm}^3$ BC-404 scintillator tile tested with a ^{90}Sr radioactive source to study the uniformity in light collection







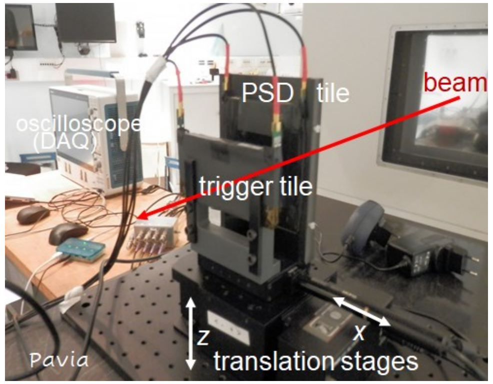




The measured photon distribution is compatible with simulations. The absolute number of collected photons is different since simulations does not take into account the SiPM photon detection efficiency (PDE) and a not perfect optical coupling of the tile with SiPMs

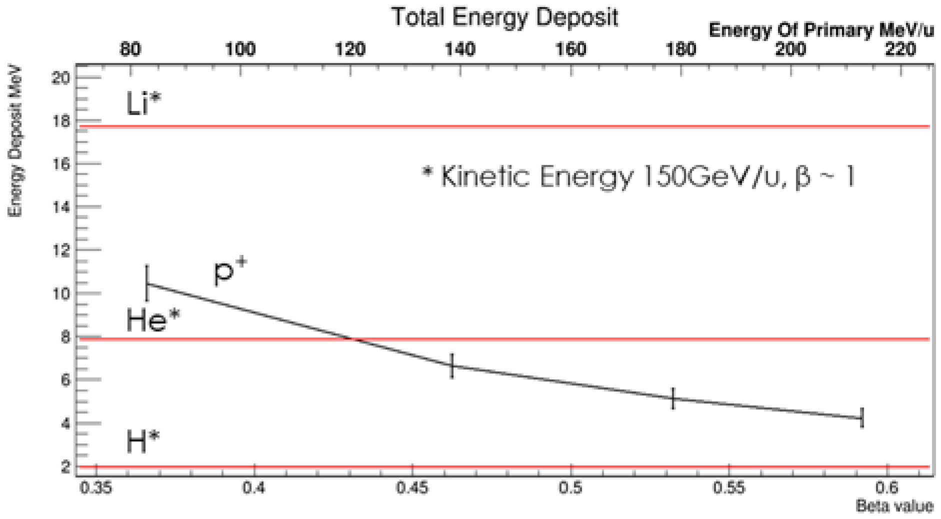
CNAO beam test

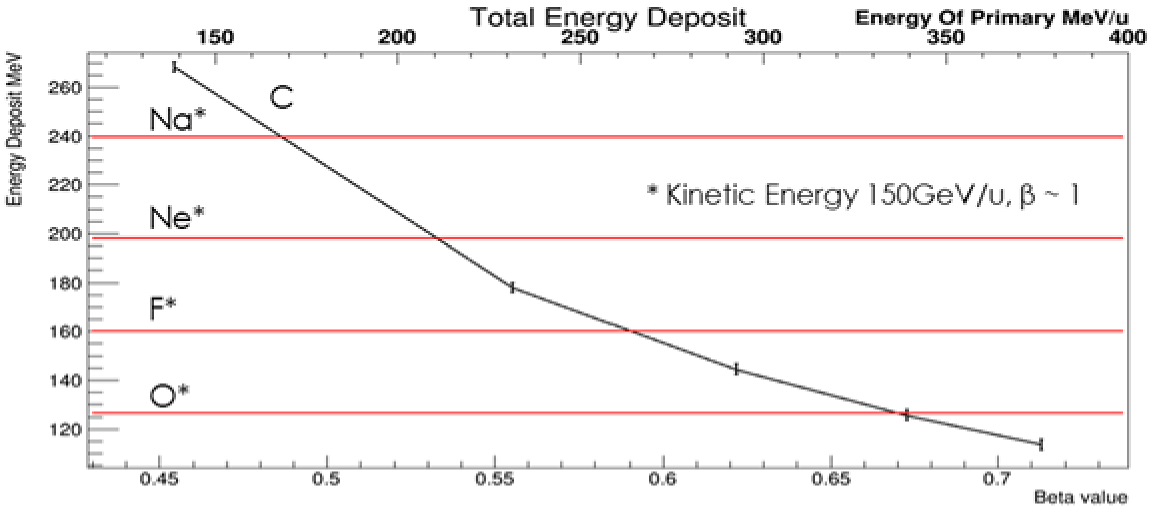
- Beam test at CNAO (Pavia) in July 2020
  - Tile prototypes coupled with different Hamamatsu SiPMs (15 and 50 μm cell size)
  - The CNAO (National Centre for Oncological Adrotherapy) is a facility for hadron therapy for treating solid tumors using beams of proton and carbon ions located in Pavia.



- Beam composition and energy:
  - p 60-250 MeV
  - C 120-400 MeV/u
- Beam transverse size $\sigma_{x,y}$~ 5 mm
- The intensity of beams for therapy is very high:
  - up to 10^{12} for protons
  - up to 10^{9} for C ions

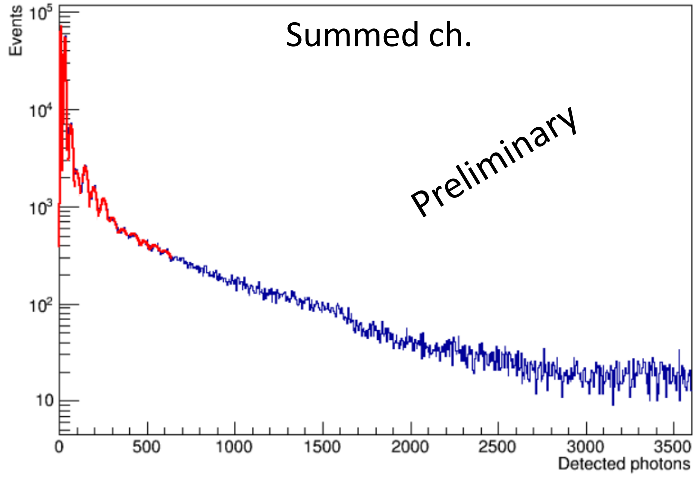
The high energy ion (m.i.p.) interaction with scintillator can be mimicked by low β ions.
Scanning β allows to study Birks' law: saturation of light yield in presence of large local energy release.

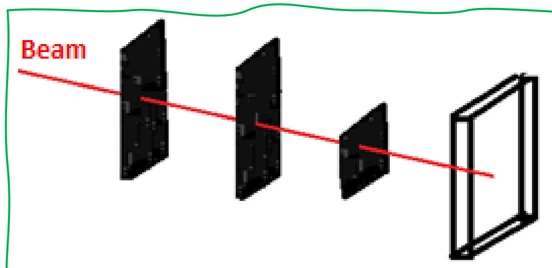




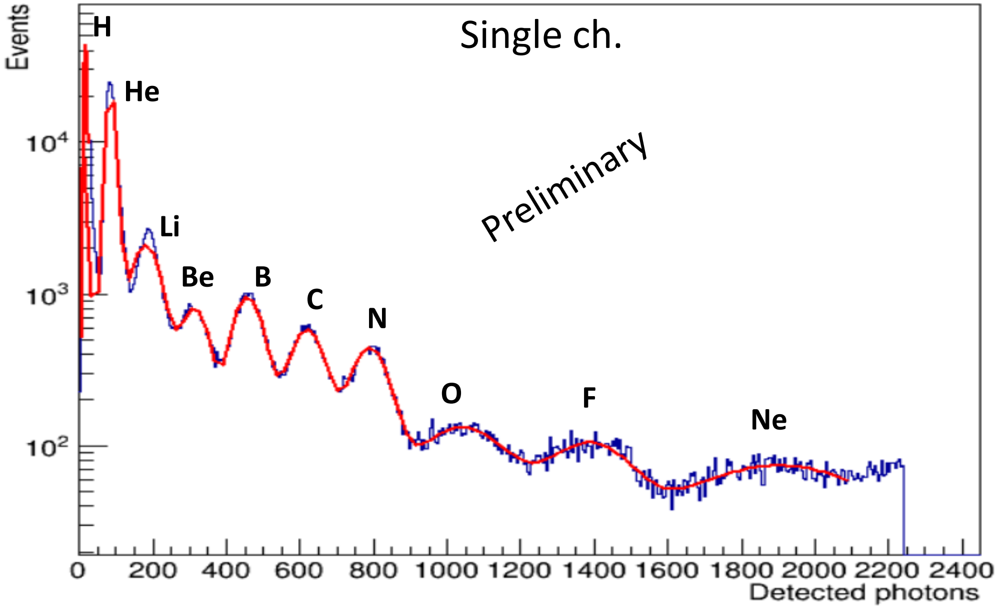
CERN SPS-H4 beam test

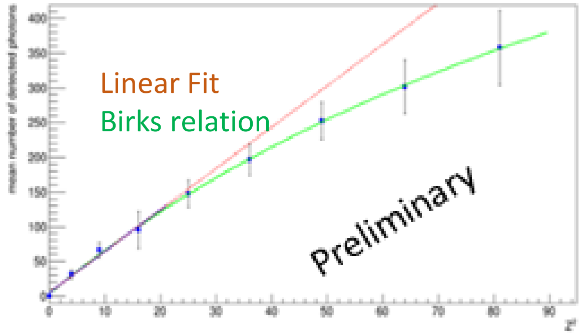
- Test beam at CERN SPS-H4:
  - Beam line with a beam of selected momentum of 330 GeV/Z, coming from a primary beam of lead, with energy 150GeV/A, impinging onto a Beryllium target.
  - The scintillator irradiated in the central position by a beam of 1 cm diameter: Capability to discriminate ion charge.
  - Improvement obtained by summing together the signals from SiPMs





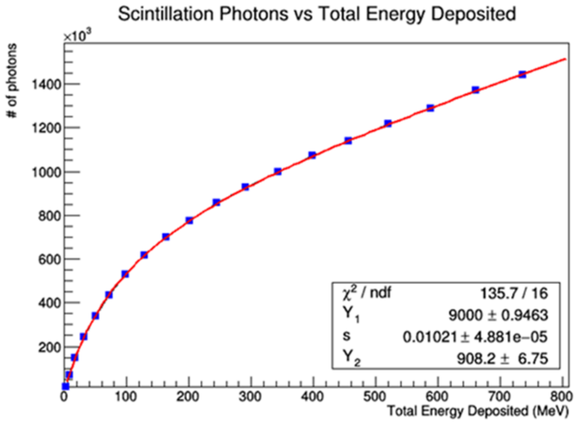
Set-Up:
S0: Scintillator of 1 cm thickness
Sh: Scintillator of 1 cm thickness
S4: Scintillator of 2 mm thickness
S0, S4, Sh coupled with a PMT
Trigger: S0 AND S4

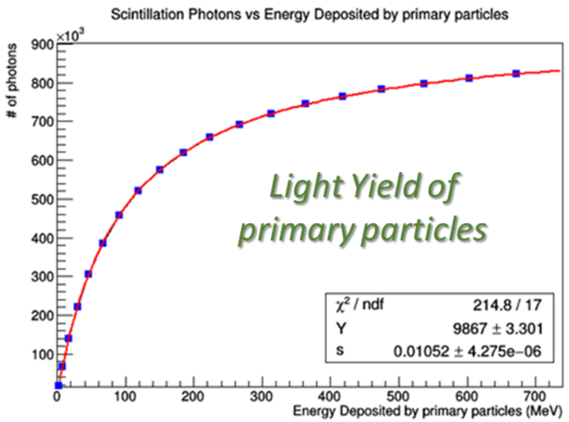


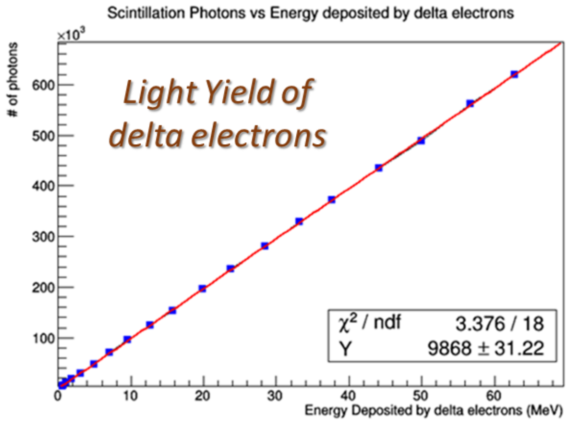


Simulation overview

- We developed a GEANT4-based package to simulate customizable plastic scintillators equipped with SiPMs. The user can:
  - Set all the main geometrical settings:
    - Scintillator shape, size, width and material (BC-404, EJ200 ..)
    - Wrapping thickness and material
    - SiPMs size, width and position …
  - Turn ON/OFF the Cerenkov/Scintillation photon production
  - Set the bulk and the surface optical properties:
    - Light Yield and attenuation length of the scintillator material; the refractive index; The surface optical properties of the wrapping: e.g. a polished or rought-cut wrapping
  - The Birk's Law for the energy lost is also implemented with the possibility to set manually the Birk's parameter.







$$\Delta N = \frac{Y_1 \cdot \Delta E}{1 + s \cdot \Delta E} + Y_2 \cdot \Delta E \quad = \quad \Delta N = \frac{Y \cdot \Delta E}{1 + s \cdot \Delta E} \quad + \quad \Delta N = Y \cdot \Delta E$$

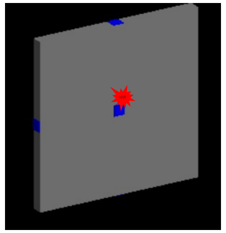
Study of the SiPMs read-out performances with the simulation tool

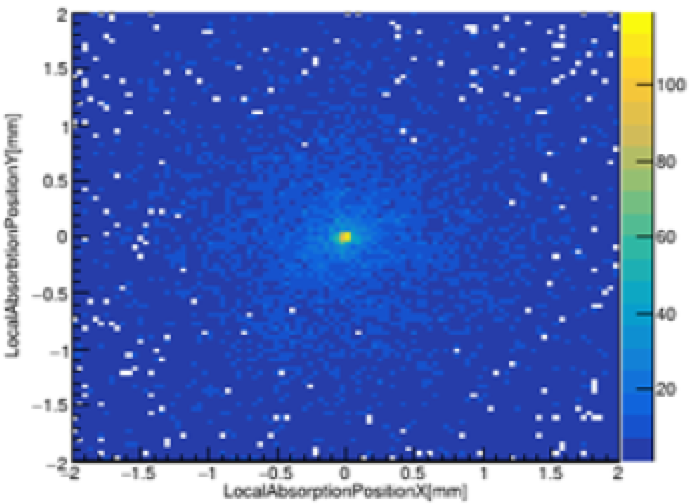
The simulation is not implemented as a facility to study in detail the real SiPMs performances, but the possibility to control all optical parameters of the plastic scintillator and to track all optical photons produced and absorbed can be used to study the response of the system in terms of:

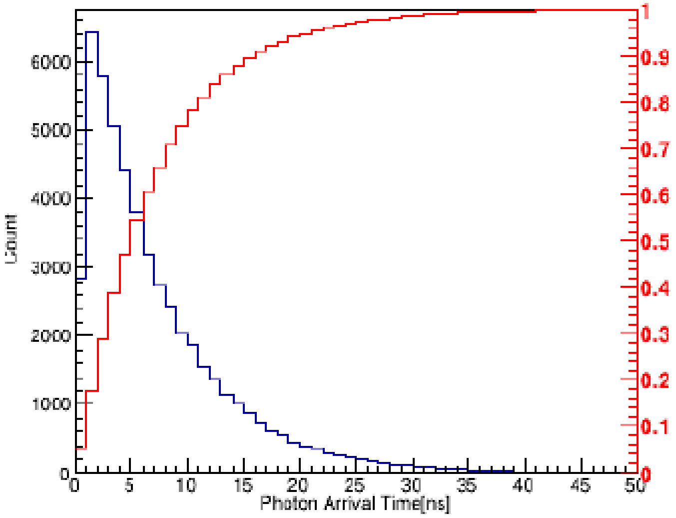
- spatial density
  - Study of SiPM's cell occupancy to optimize the SiPM design in terms of cell size in order to avoid the saturation
- collection time
  - Study of SiPM's timing response to optimize the electronic read-out

Simulation of Iron ions of 150GeV/u crossing a 10x10x1cm³ tile with TiO_2 wrapping in the central position
Studying the performance of the central SiPM:

- Cell occupancy: SiPM 4x4mm with 40um cells
  - ~ 48000 photons collected (taking into account the SiPM PDE)
  - ~ 9500 cells fired
  - smaller cells needed
- Collection time:
  50% of photons are collected in 5ns
  80% of photons are collected in 10ns







Conclusions

- The **High Energy cosmic-Radiation Detection** (HERD) will start its operation around 2026 aboard the future China's Space Station.
  - The HERD collaboration is a China-led international space mission with Italy at the forefront
  - It will provide high quality data on charged cosmic rays and gamma rays giving a valuable contribution in several scientific topics as dark matter searches, study of cosmic ray chemical composition and high energy gamma-ray observations.
- One of the main sub detector of HERD satellite is the Plastic Scintillator Detector (PSD)
- The PSD needs to have a very high detection efficiency for the charged cosmic rays, which represent the main background for the identification of gamma rays, and a very good capability in identifying charged nuclei.
  - The choice of the proper PSD geometry is a critical aspect to reach the best particle identification performances
  - The future HERD space mission will employ Silicon Photomultipliers (SiPMs) instead of classical Photomultiplier Tubes to read out the scintillator light emission to exploit their smaller sizes and lower power consumption.