

Direct measurement of cosmic rays above the atmosphere (balloons & space missions)



BESS launch, McMurco, Antarctica

Magnetic spectrometer

momentum measurement

particle in magnetic field $\frac{mv^2}{\rho} = evB$ and $\rho = \frac{p}{eB}$

deflection angle ($\rho \gg L$) $\theta = \frac{L}{\rho} = \frac{L}{p} eB$

measured momentum $p = eB\rho = eB \frac{L}{\theta}$

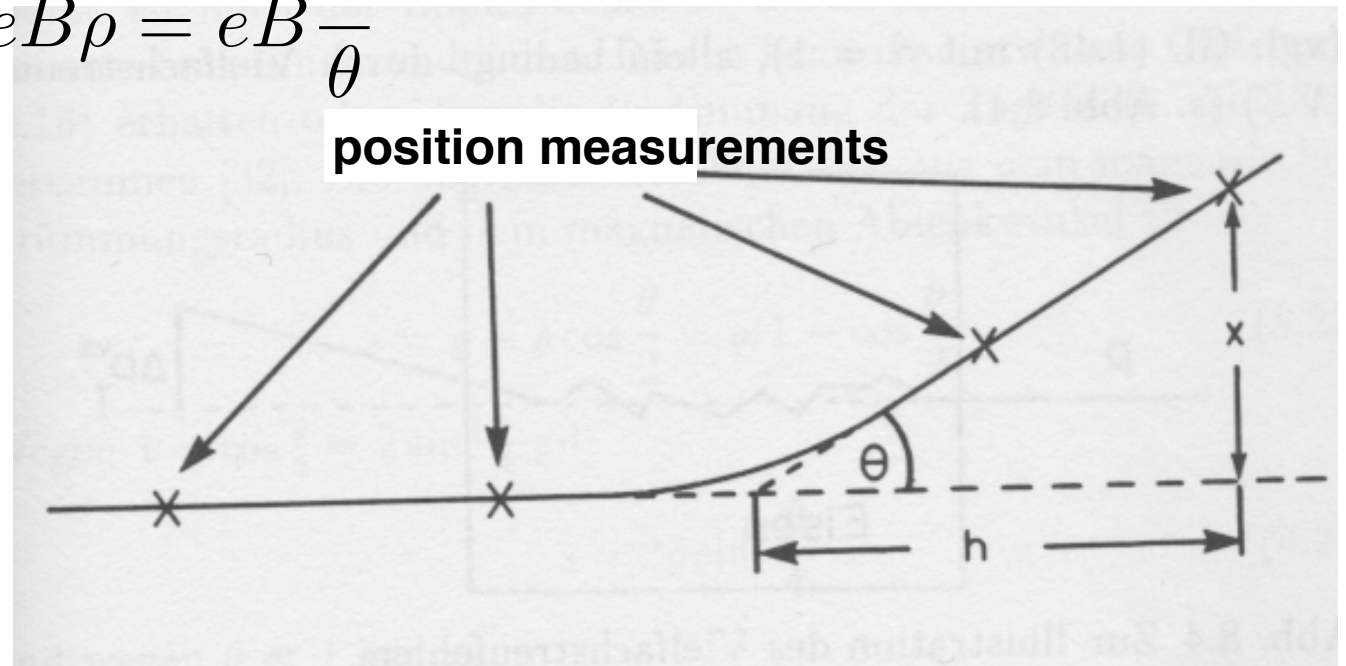
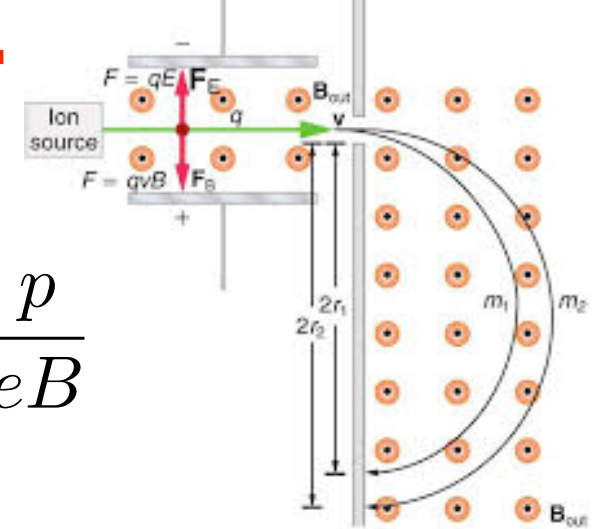
$$\left| \frac{dp}{d\theta} \right| = eBL \frac{1}{\theta^2} = \frac{p}{\theta}$$

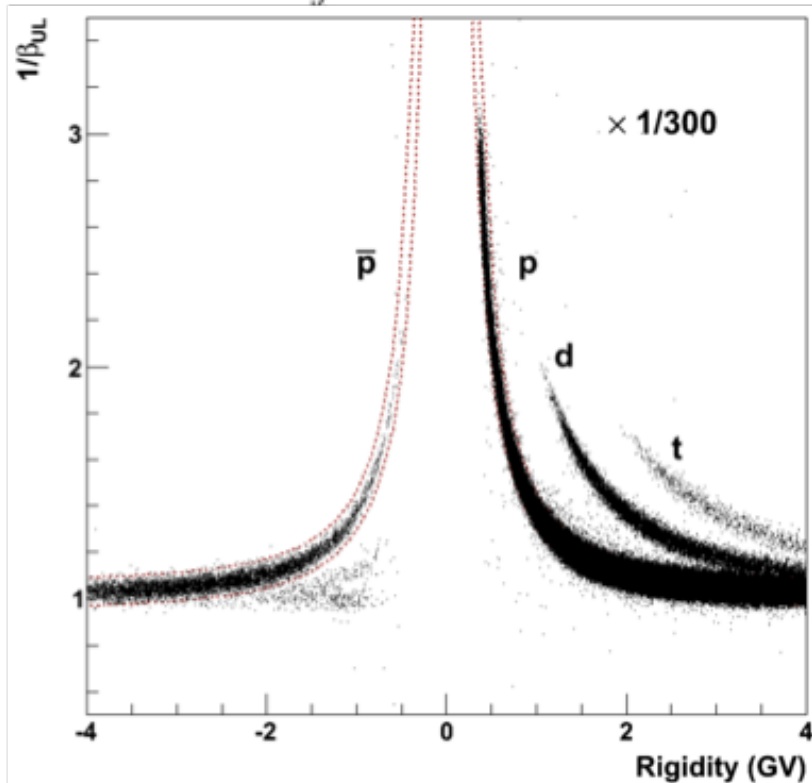
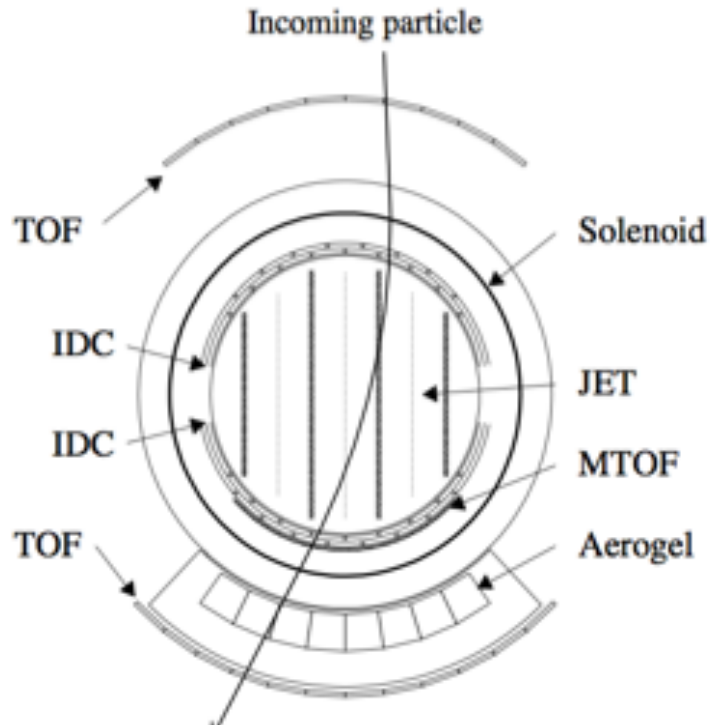
momentum resolution

$$\frac{\sigma(p)}{p} = \frac{2\sigma(x)/h}{eBL} p$$

$$\sigma(p) \propto p^2$$

maximum momentum: $\frac{\sigma(p_{max})}{p_{max}} = 1$



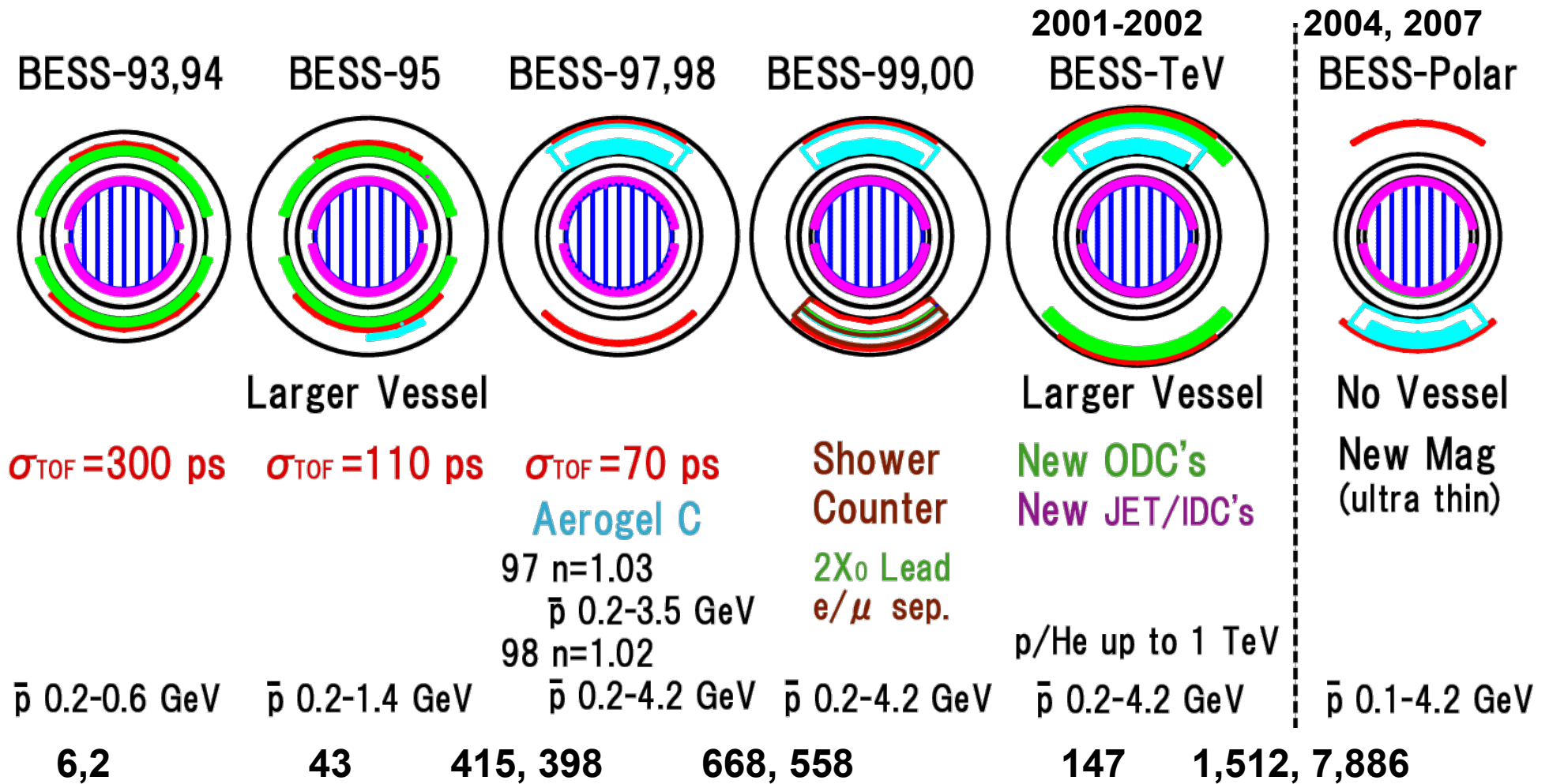


- Balloon-borne Experiment with a Superconducting Spectrometer
- Measures **charge, charge-sign, mass, and energy**
- Superconducting magnetic spectrometer: **momentum** from magnetic rigidity
 - Thin solenoidal superconducting magnet
Gives very uniform field
 - Fully active “JET” and “IDC” drift chambers with 54 points on trajectory, $\sigma < 130 \mu\text{m}$
 - MDR: 200 GV BESS; 1400 GV BESS-TeV; 240 GV BESS-Polar
- Time-of-flight system (TOF): **velocity** and **charge**
- Silica-aerogel Cherenkov detector (ACC, $n=1.02/1.03$): **background rejection**

$$m = \frac{RZe}{\gamma\beta c}$$



- Nine northern latitude flights (1+ days) 1993-2002 and two Antarctic flights in 2004 (8.5 days) and 2007 (24.5 days)
- Including BESS-Polar I 3757 antiprotons reported 0.2 - 4.2 GeV



BESS Instrumentation

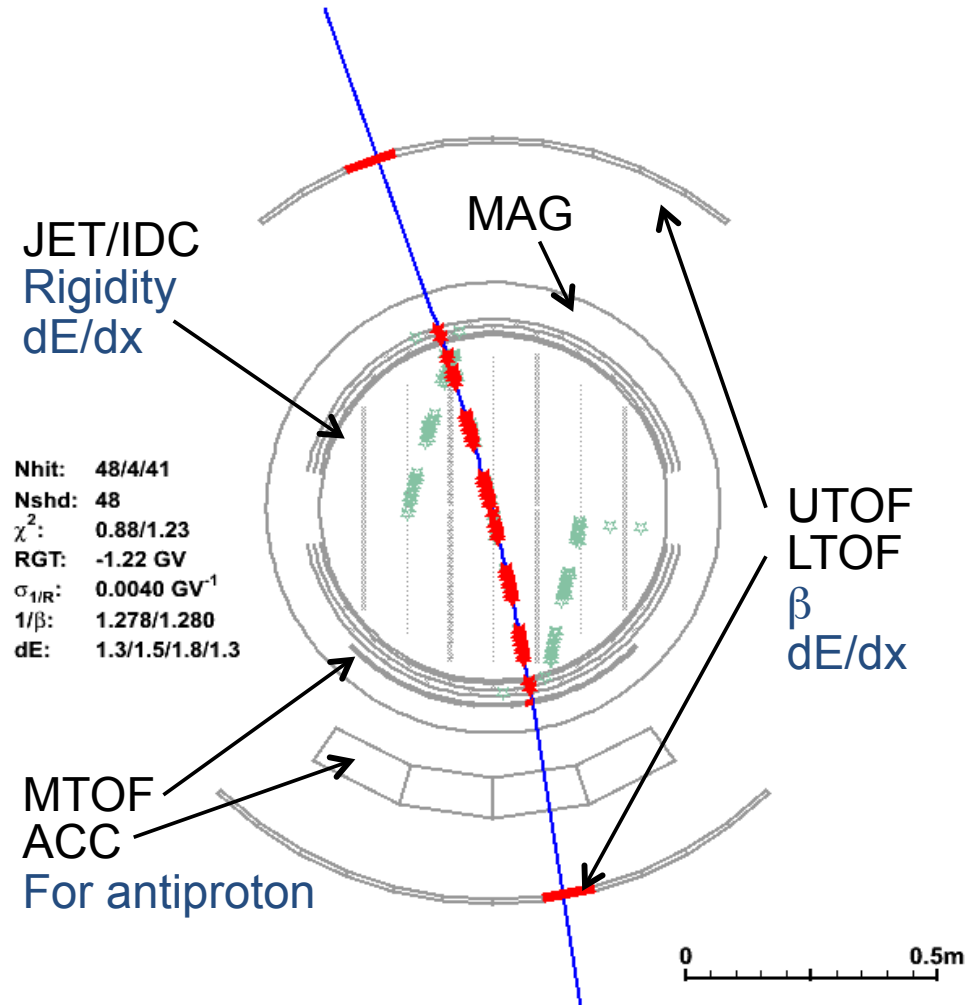
BESS-PolarII

../bessp_ext.root.sel_04-90-1171

Event Time: 02.07.54.364

Run: 095 Event: 4200488 (5A) Size: 2897 FADC: 1944 FEND: 904

Trigger: 001001011 JET: 71 IDC: 4 UTOF: 1 MTOF: 1 LTOF: 1



Event display with reconstructed Antiproton track is shown.

Rigidity (MDR:240GV)

Solenoid: Uniform field ($\phi=1\text{m}$, $B=0.8\text{T}$)
Thin material (2.4 g/cm^2)

Drift chamber: Redundant hits
($\sigma\sim 150\mu\text{m}$, $32\sim 48+4\text{hits}$)

Charge, Velocity

TOF, Chamber: dE/dx measurement
($Z = 1, 2, \dots$)

TOF: $1/\beta$ measurement ($\sigma\sim 1,2\%$)

$$m = ZeR\sqrt{1/\beta^2 - 1}$$



a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

Physics Reports 544 (2014) 323–370



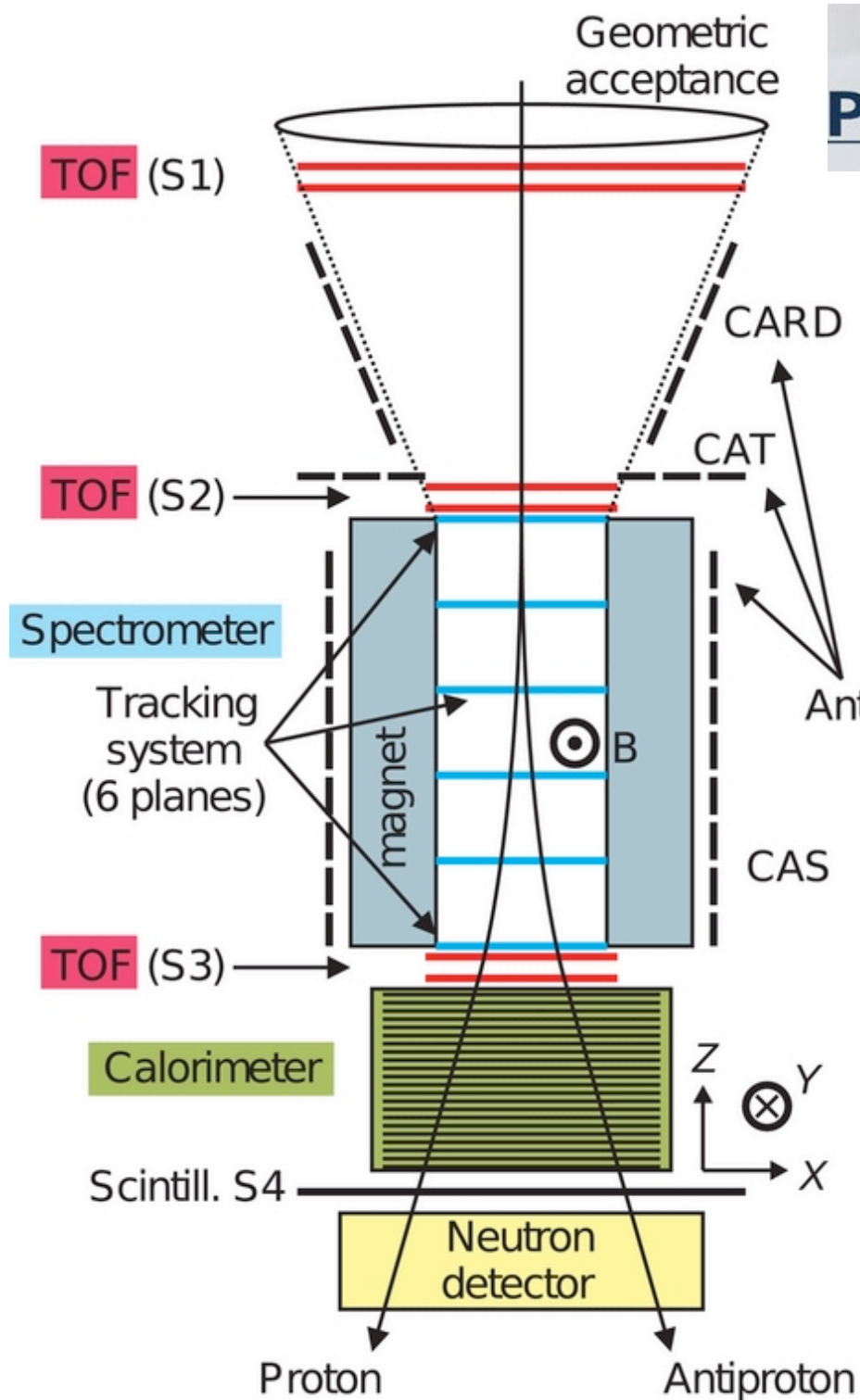
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The PAMELA Mission: Heralding a new era in precision cosmic ray physics



Energy measurement - calorimeter

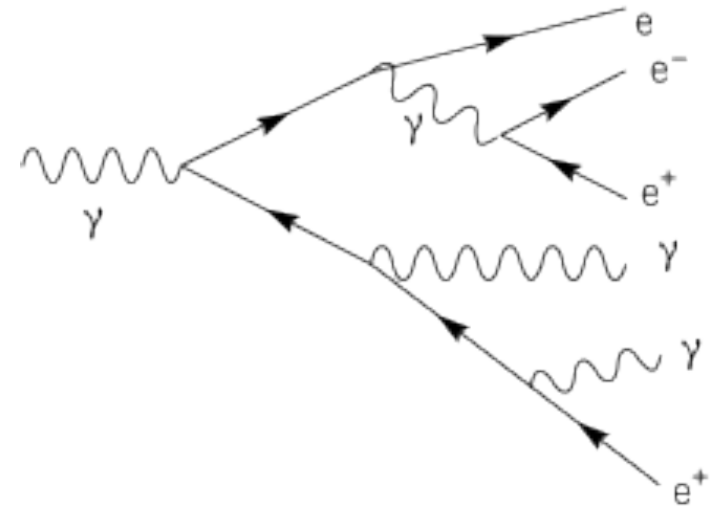
electron-photon calorimeter

at high energies (>GeV):

electrons loose energy through Bremsstrahlung

photons loose energy through pair production

--> electromagnetic cascade

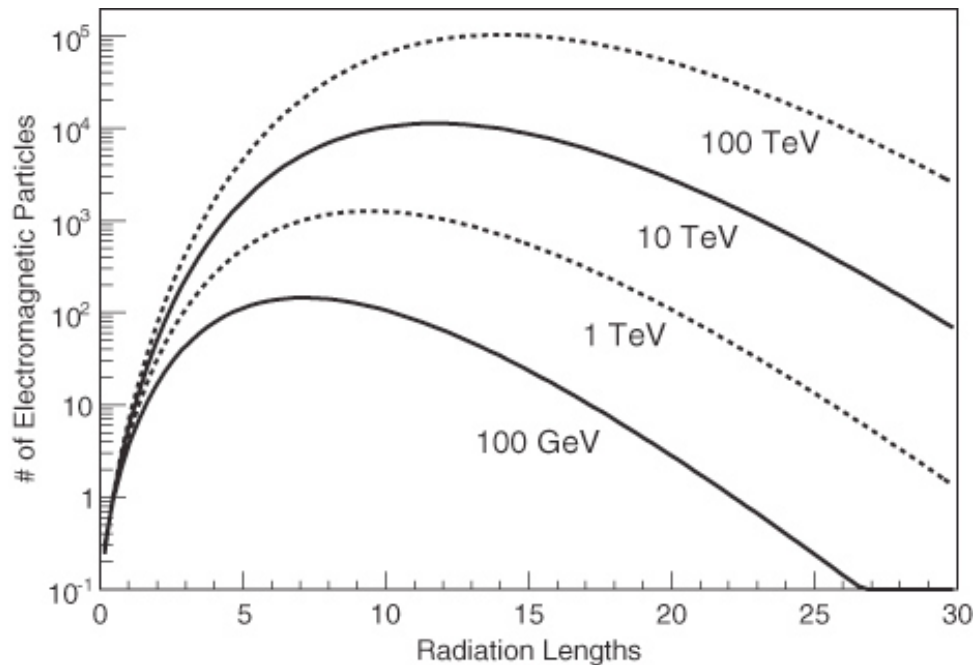


longitudinal shower development/energy loss

$$\frac{dE}{dt} = \text{const} \cdot t^a e^{-bt}$$

$$t = x/X_0$$

depth in material in units of the radiation length



depth of maximum depends on energy as

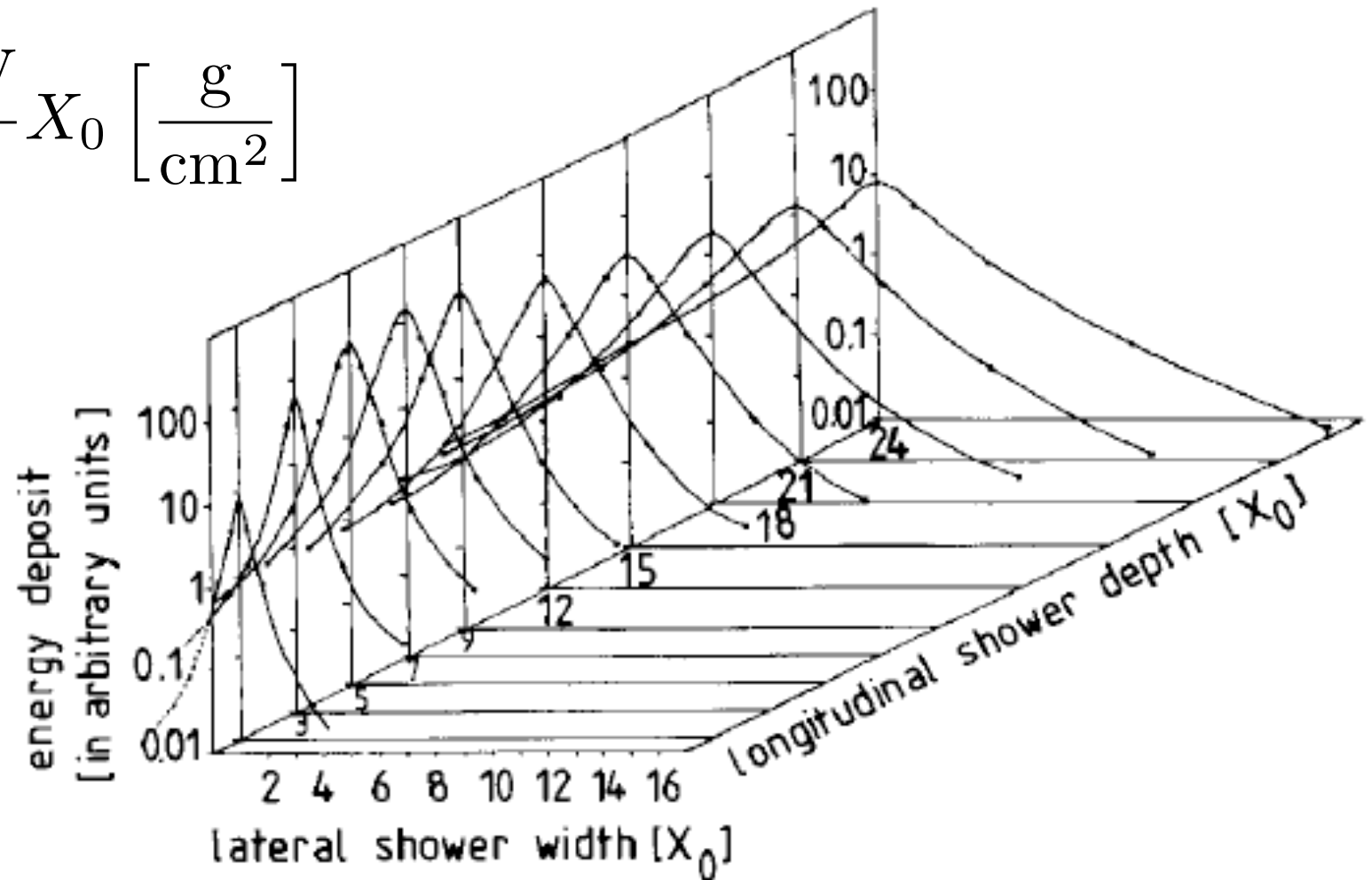
$$t_{max} \propto \ln \frac{E}{E_c}$$

Energy measurement - calorimeter

electromagnetic cascade

lateral extension of the cascade
mostly caused by multiple scattering
and characterized by **Molière radius**

$$R_m = \frac{21 \text{ MeV}}{E_c} X_0 \left[\frac{\text{g}}{\text{cm}^2} \right]$$

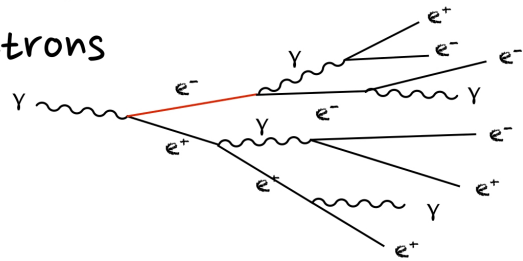


Particle identification - calorimeter

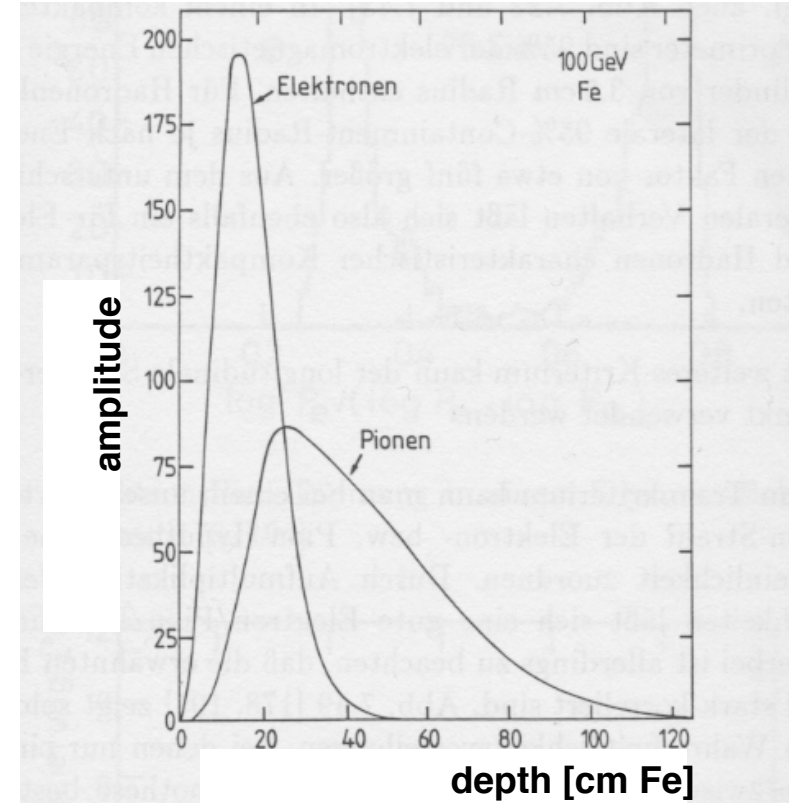
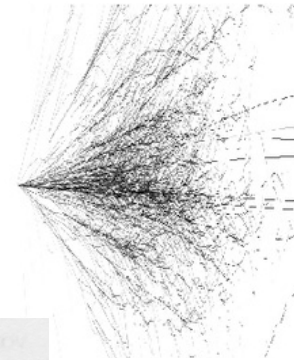
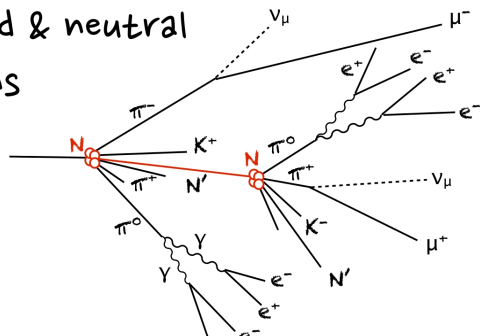
in calorimeters there are different shower responses for electrons and hadrons

Photons

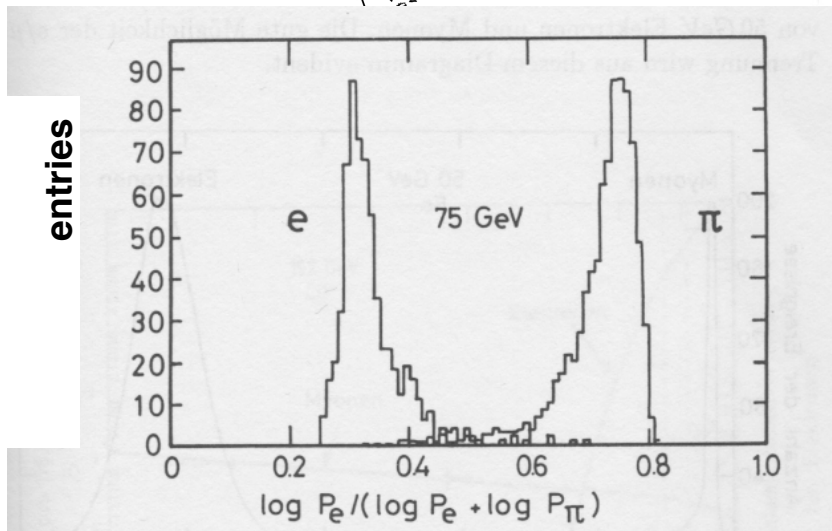
Electrons



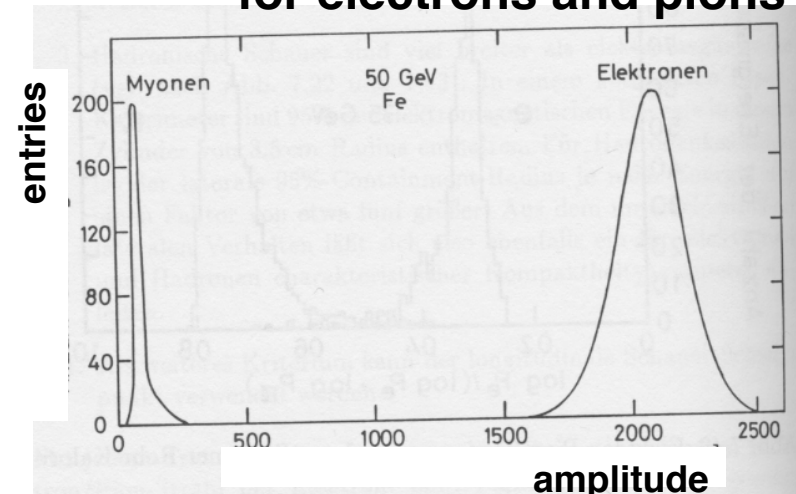
charged & neutral hadrons



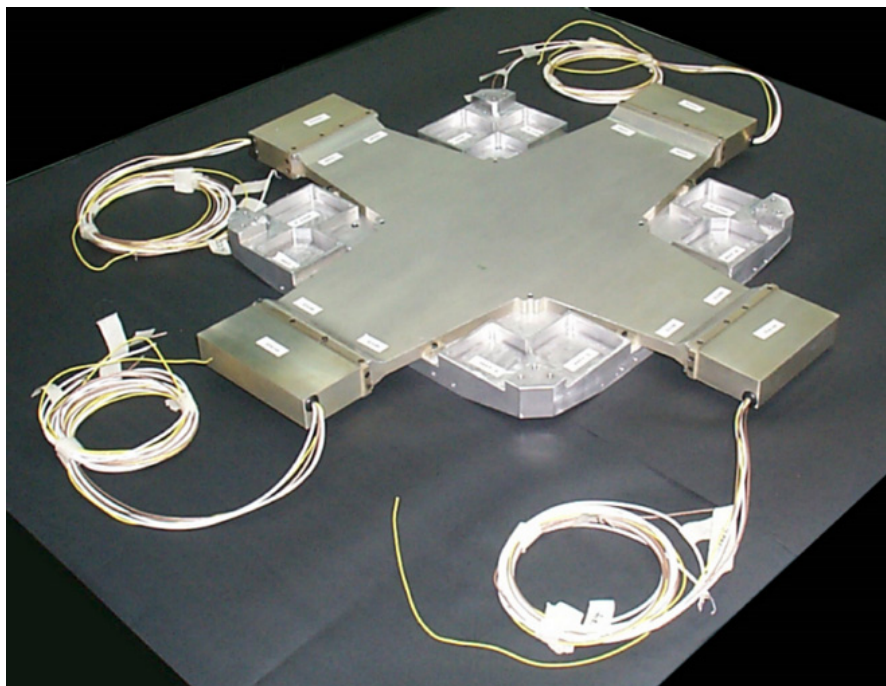
longitudinal shower development for electrons and pions



energy deposit for electrons and pions



energy deposit for muons and electrons



The PAMELA Mission: Heralding a new era in precision cosmic ray physics



O. Adriani^{a,b}, G.C. Barbarino^{c,d}, G.A. Bazilevskaya^e, R. Bellotti^{f,g}, M. Boezio^h, E.A. Bogomolovⁱ, M. Bongi^{a,b}, V. Bonvicini^h, S. Bottai^b, A. Bruno^{f,g}, F. Cafagna^g, D. Campana^d, R. Carbone^{d,h}, P. Carlson^{j,k}, M. Casolino^l, G. Castellini^m, M.P. De Pascale^{l,n,1}, C. De Santis^{l,n}, N. De Simone^l, V. Di Felice^l, V. Formato^{h,o}, A.M. Galper^p, U. Giaccari^d, A.V. Karelin^p, M.D. Kheymits^p, S.V. Koldashov^p, S. Koldobskiy^p, S.Yu. Krut'kov^l, A.N. Kvashnin^e, A. Leonov^p, V. Malakhov^p, L. Marcelliⁿ, M. Martucci^{n,q}, A.G. Mayorov^p, W. Menn^r, V.V. Mikhailov^p, E. Mocchiutti^h, A. Monaco^{f,g}, N. Mori^{a,b}, R. Munini^{h,j,k,o}, N. Nikonov^{i,l,n}, G. Osteria^d, P. Papini^b, M. Pearce^{j,k}, P. Picozza^{l,n,*}, C. Pizzolotto^{h,s,t}, M. Ricci^q, S.B. Ricciarini^{b,m}, L. Rossetto^{j,k}, R. Sarkar^h, M. Simon^r, R. Sparvoli^{l,n}, P. Spillantini^{a,b}, Y.I. Stozhkov^e, A. Vacchi^h, E. Vannuccini^b, G.I. Vasilyev^l, S.A. Voronov^p, J. Wu^{j,k,u}, Y.T. Yurkin^p, G. Zampa^h, N. Zampa^h, V.G. Zverev^p

Fig. 2. A picture of the S2 plane of the time of flight system. The sensitive area is $15 \times 18 \text{ cm}^2$ segmented into 2×2 orthogonal bars.

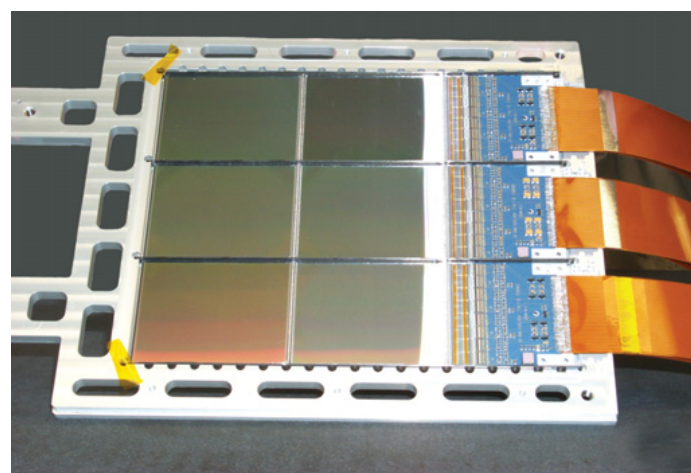
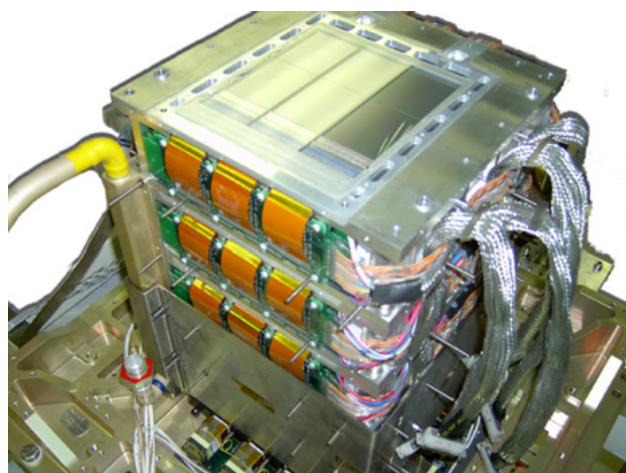


Fig. 3. Left: an overview of the magnetic spectrometer showing the top silicon plane. The magnet cavity has dimensions $13.1 \times 16.1 \text{ cm}^2$. The lower part of the magnet canister is covered by a magnetic screen. Right: a silicon plane comprising six silicon strip detectors and front-end electronics.

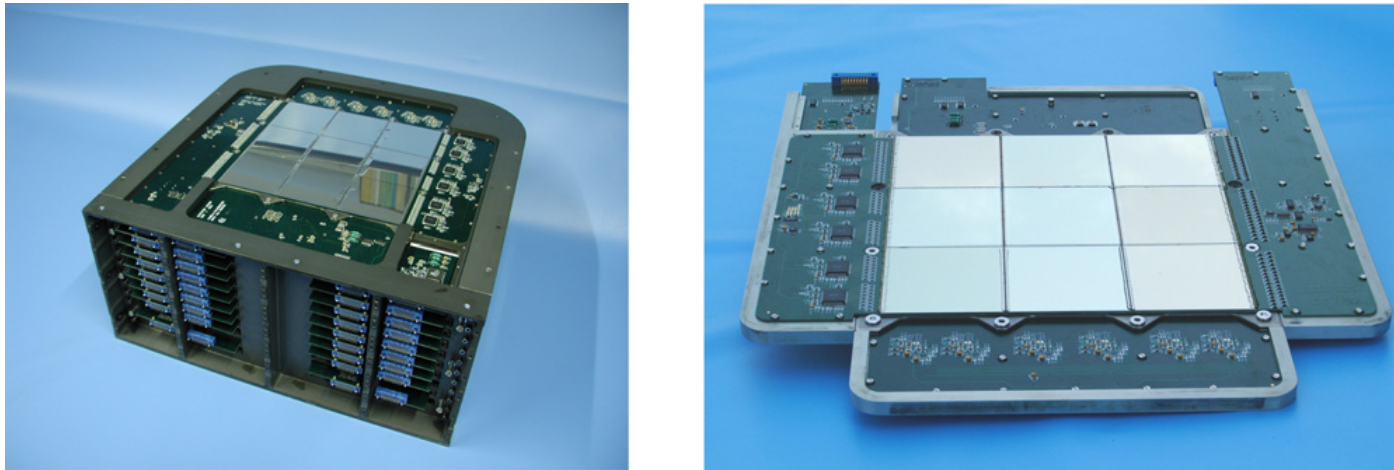


Fig. 4. Left: The PAMELA electromagnetic calorimeter with the topmost silicon plane visible. The device is ~ 20 cm tall and the active silicon layer is $\sim 24 \times 24$ cm² in cross-section. Right: Details of a single calorimeter module comprising two tungsten layers each sandwiched between two silicon detector planes.

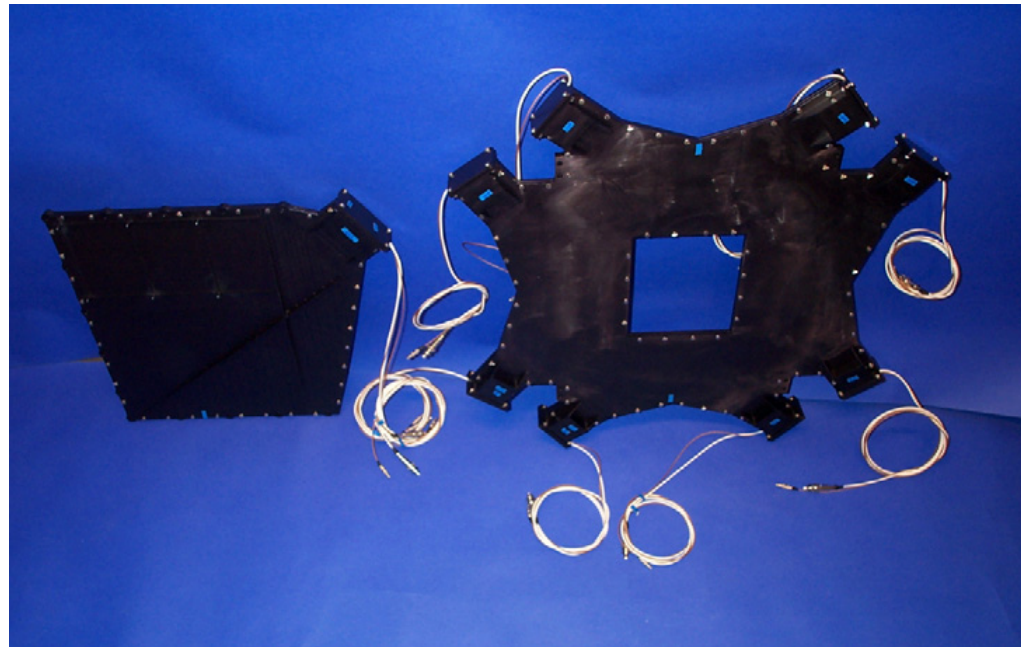


Fig. 5. An overview of the anticoincidence system. The CARD system is not shown but the design closely follows that of CAS. The CAS scintillator (on the left) is approximately 40 cm tall and 33 cm wide. The hole in the CAT scintillator (on the right) measures approximately 22 cm by 18 cm.

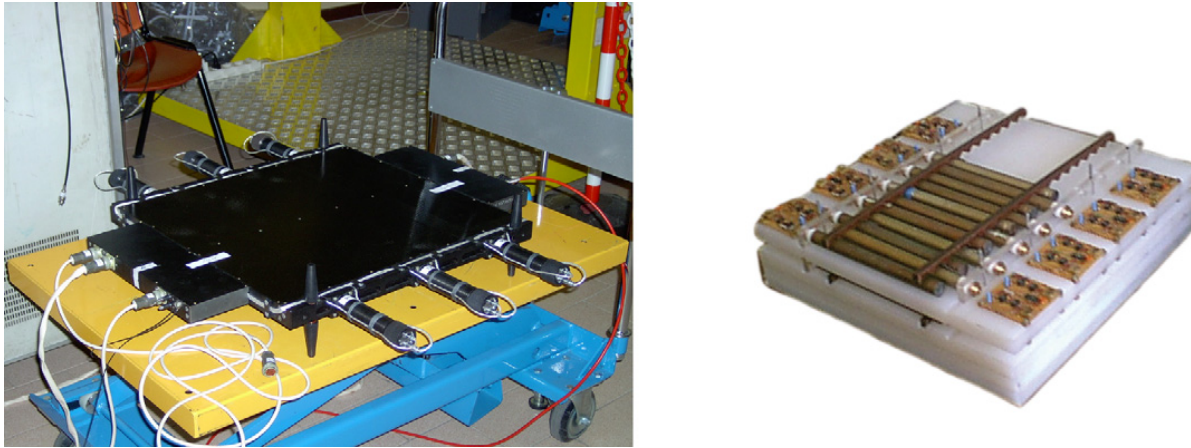


Fig. 6. Left: the shower tail catcher scintillator S4. The scintillator has dimensions $48 \times 48 \text{ cm}^2$. Right: The neutron detector equipped (partially in the figure) with ^3He proportional counters. The neutron detector covers an area of $60 \times 55 \text{ cm}^2$.

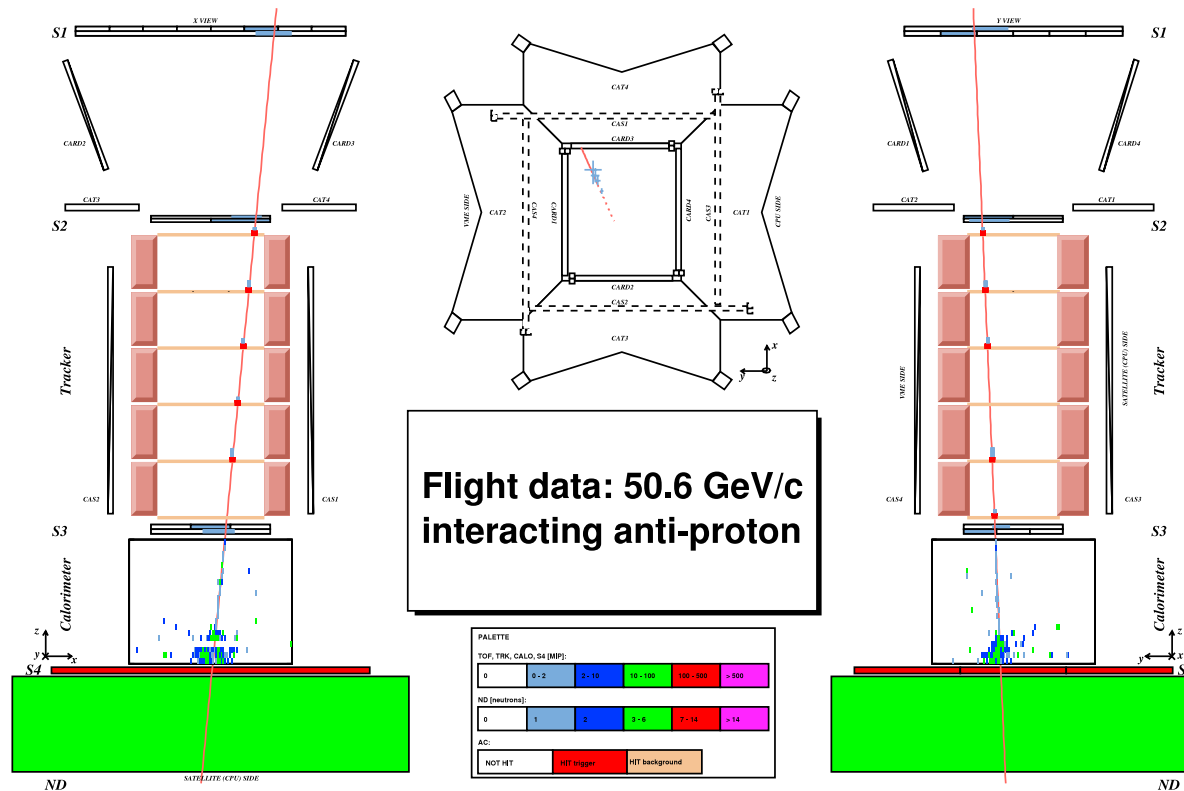


Fig. 7. A particle identified as an antiproton in the PAMELA detector. The charge sign and the rigidity are obtained from the information of the magnetic spectrometer. A hadronic shower is visible in the calorimeter; the neutron detector records neutrons from the hadronic cascade.

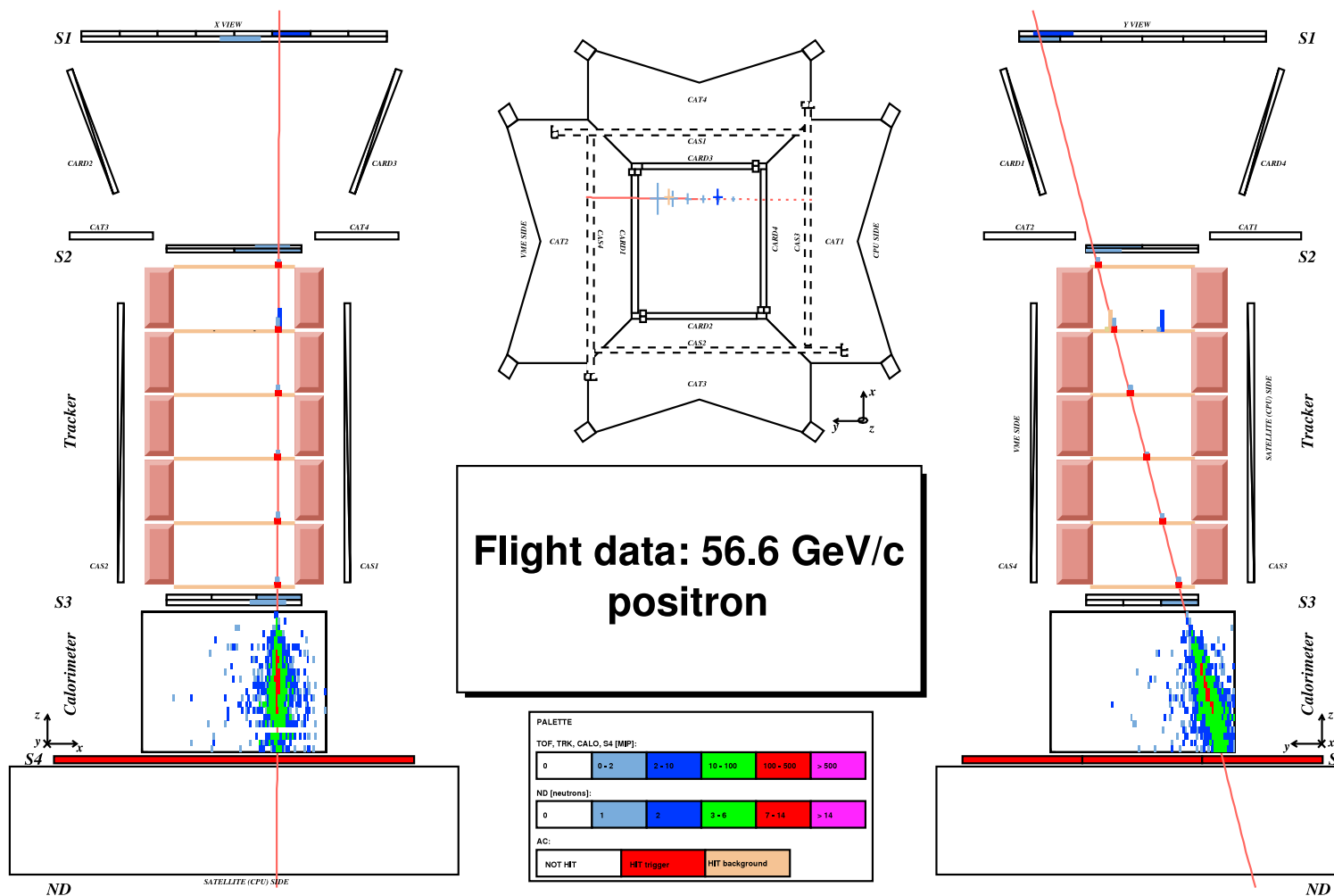


Fig. 8. A particle identified as a positron in the PAMELA detector. The charge sign and the rigidity are obtained from the information of the magnetic spectrometer. An electromagnetic shower is produced in the calorimeter, no neutrons are detected by the neutron detector.

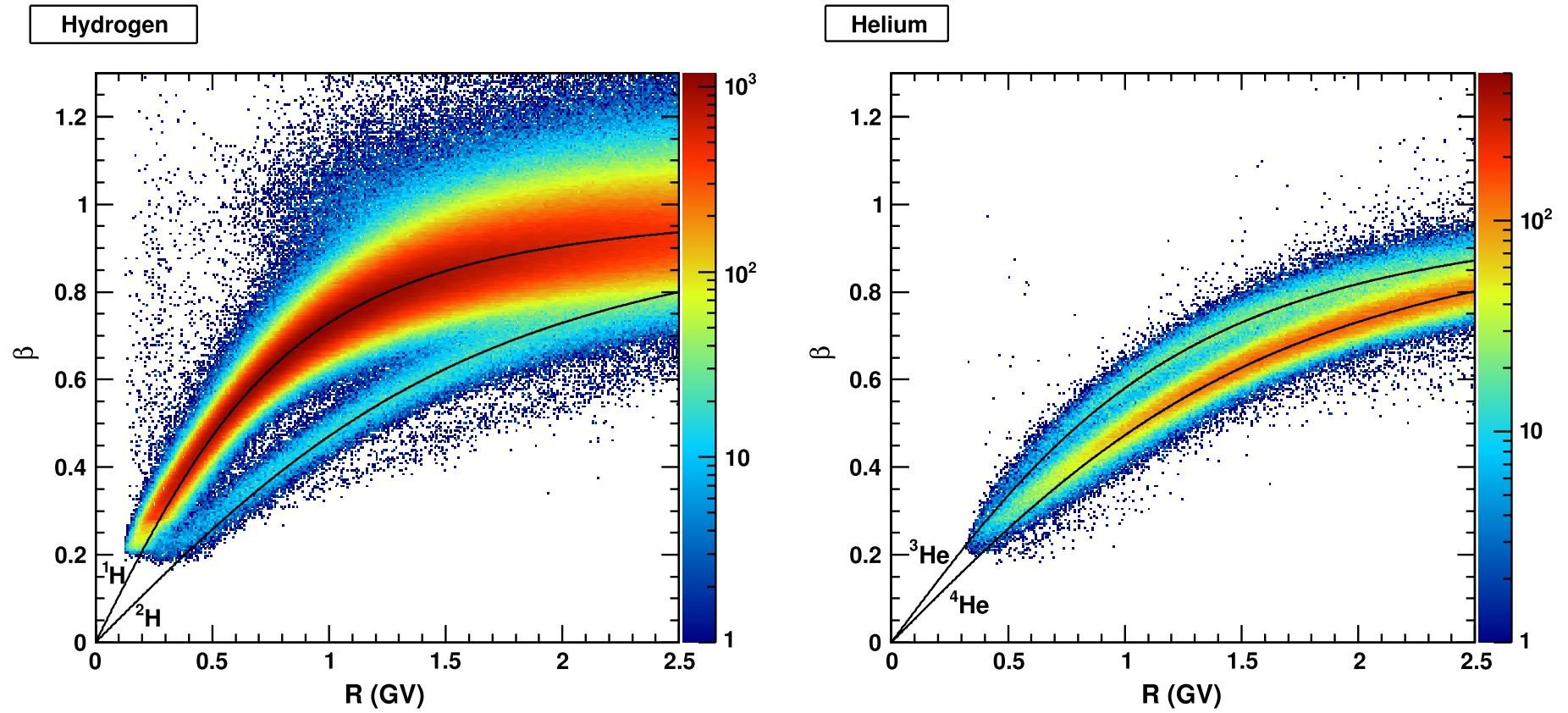


Fig. 29. Velocity versus rigidity showing the mass separation for $Z = 1$ (left) and $Z = 2$ (right) particles. The black lines represent the theoretical isotope curves.

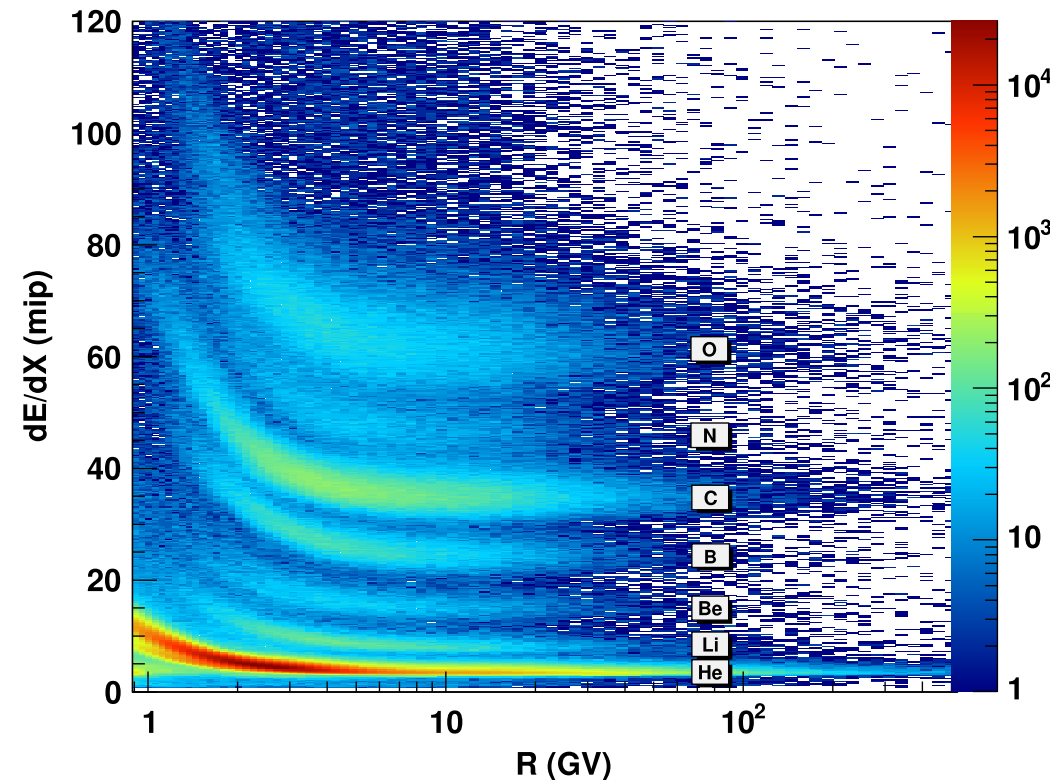


Fig. 32. The averaged dE/dx information on the middle ToF layer (S2) versus the rigidity obtained by the tracking system. Protons have been previously removed from the sample of events used to produce this figure.

The Alpha Magnetic Spectrometer on the International Space Station

Samuel Ting^a

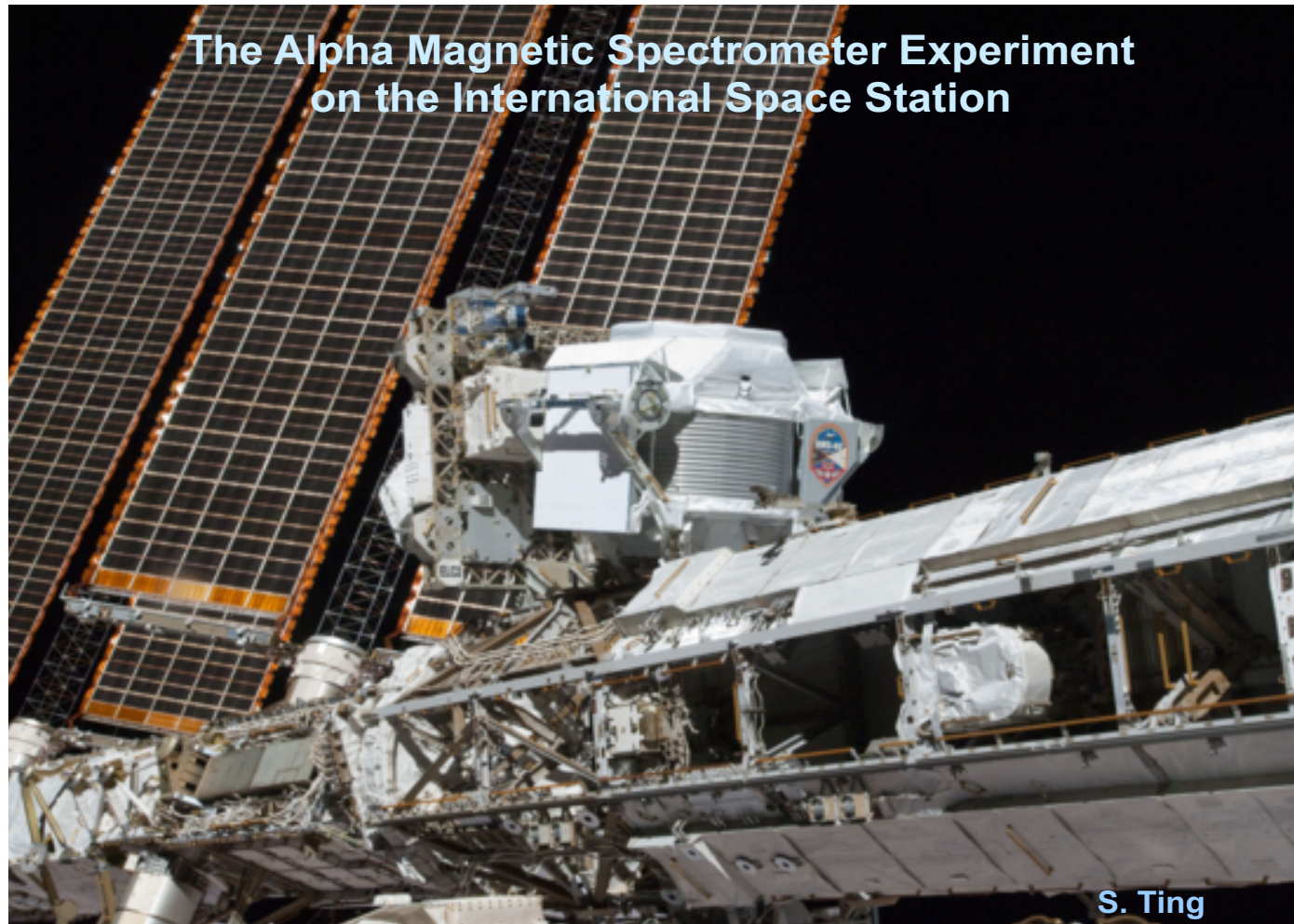
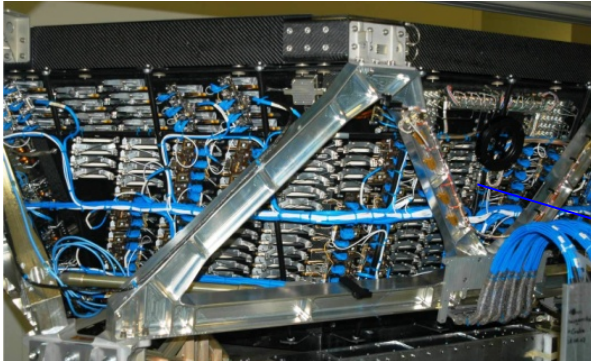


Fig. 1. AMS was delivered and installed on the ISS in May 2011.

AMS: A TeV precision, multipurpose spectrometer

TRD

Identify e^+ , e^-

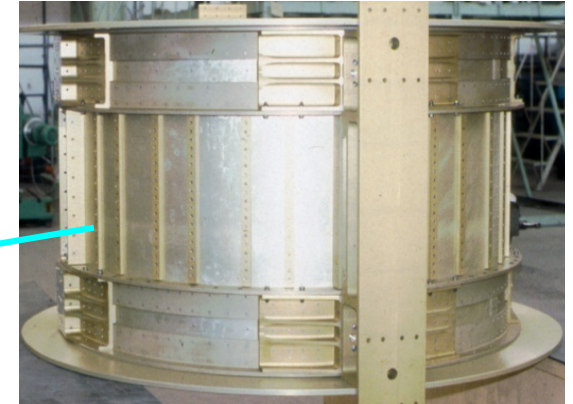


Particles and nuclei are defined by their charge (Z) and energy ($E \sim P$)

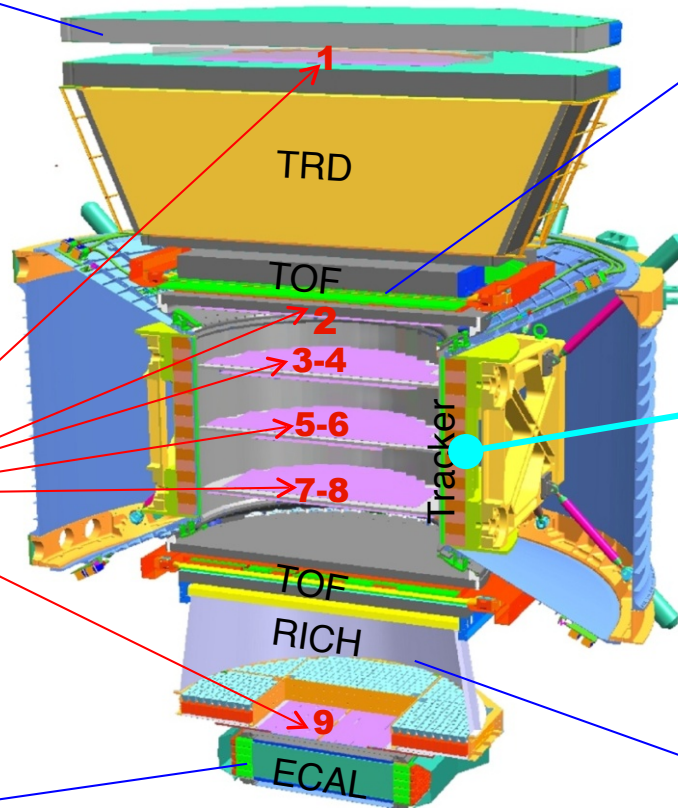
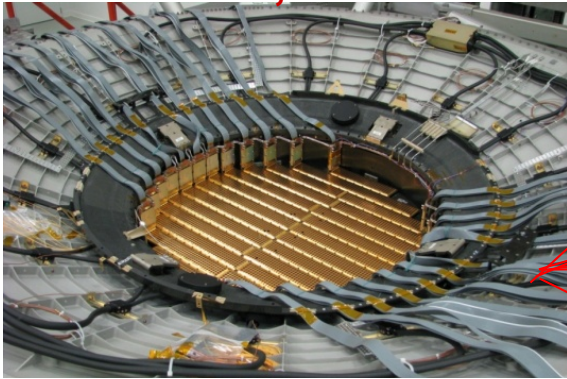
TOF
 Z, E



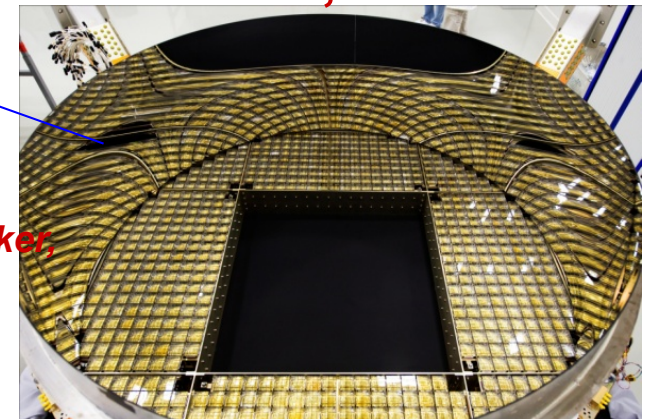
Magnet
 $\pm Z$



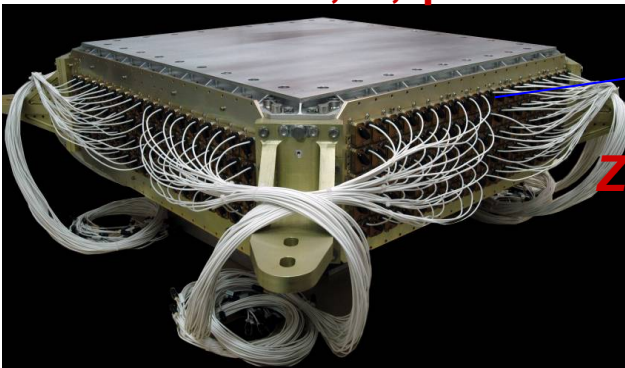
Silicon Tracker
 Z, P



RICH
 Z, E

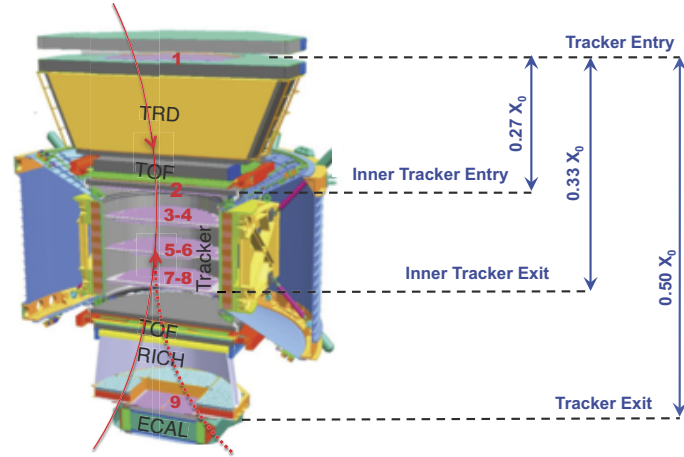


ECAL
 E of e^+ , e^- , γ



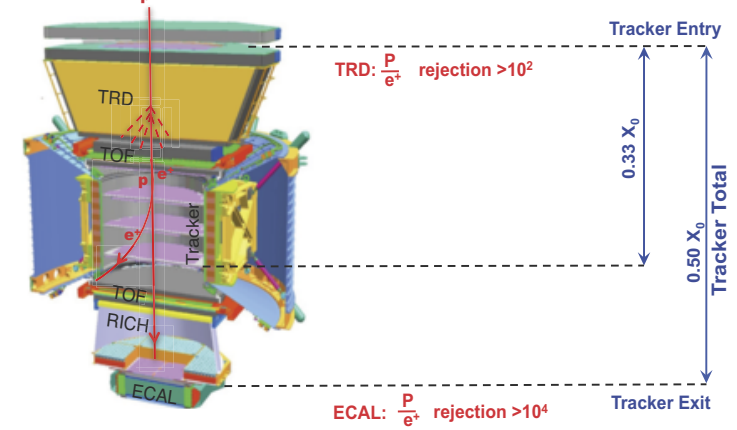
Z, P are measured independently by the Tracker, RICH, TOF and ECAL

Sensitive Search for Antimatter with $\bar{\text{He}}/\text{He} > 10^{10}$



- a) Minimal material in the detector
So that the detector does not become a source of large angle scattering
- b) Repetitive measurements of momentum
To ensure that particles which had large angle scattering are not confused with the signal.

Sensitive Search for the origin of Dark Matter with $p/e^+ > 10^6$



- a) Minimal material in the TRD and TOF
So that the detector does not become a source of e^+
- b) A magnet separates TRD and ECAL so that e^+ produced in TRD will be swept away and not enter ECAL
In this way the rejection power of TRD and ECAL are independent
- c) Matching momentum of 9 tracker planes with ECAL energy measurements

Fig. 4. High sensitivity search for antimatter is a goal of AMS.

Fig. 6. High sensitivity search for Dark Matter is a goal of AMS.

Multiple Independent Measurements of the Charge ($|Z|$)

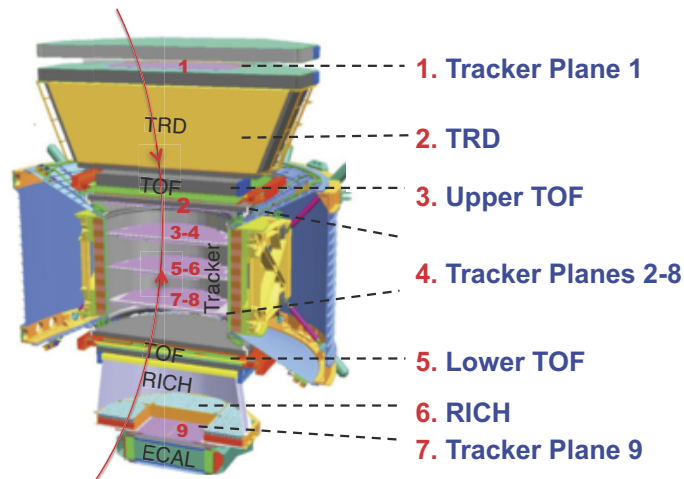
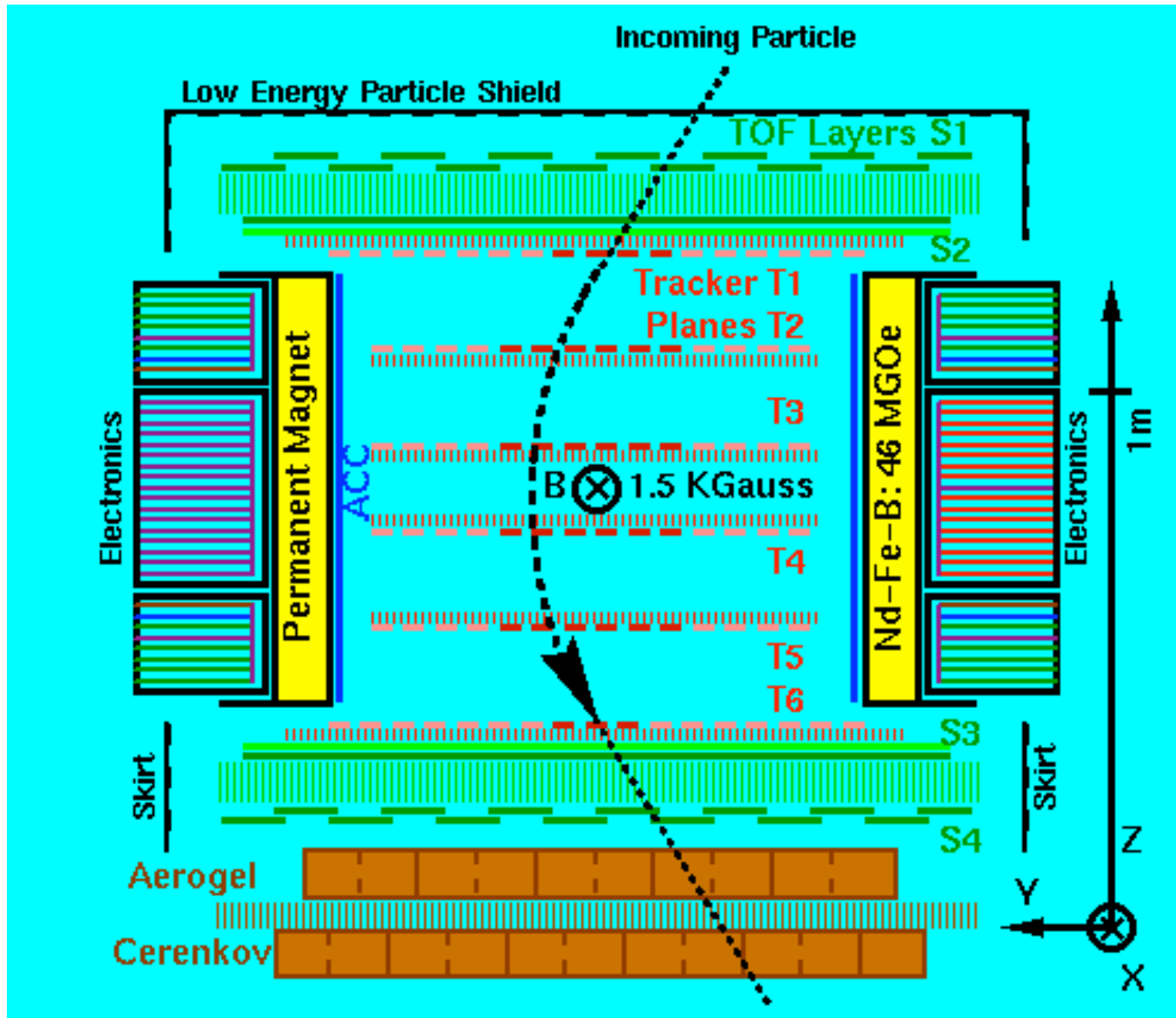


Fig. 5. Multiple independent measurements of the charge of passing particles.

Alpha Magnetic Spectrometer - AMS



Test Beam Results at CERN 2010

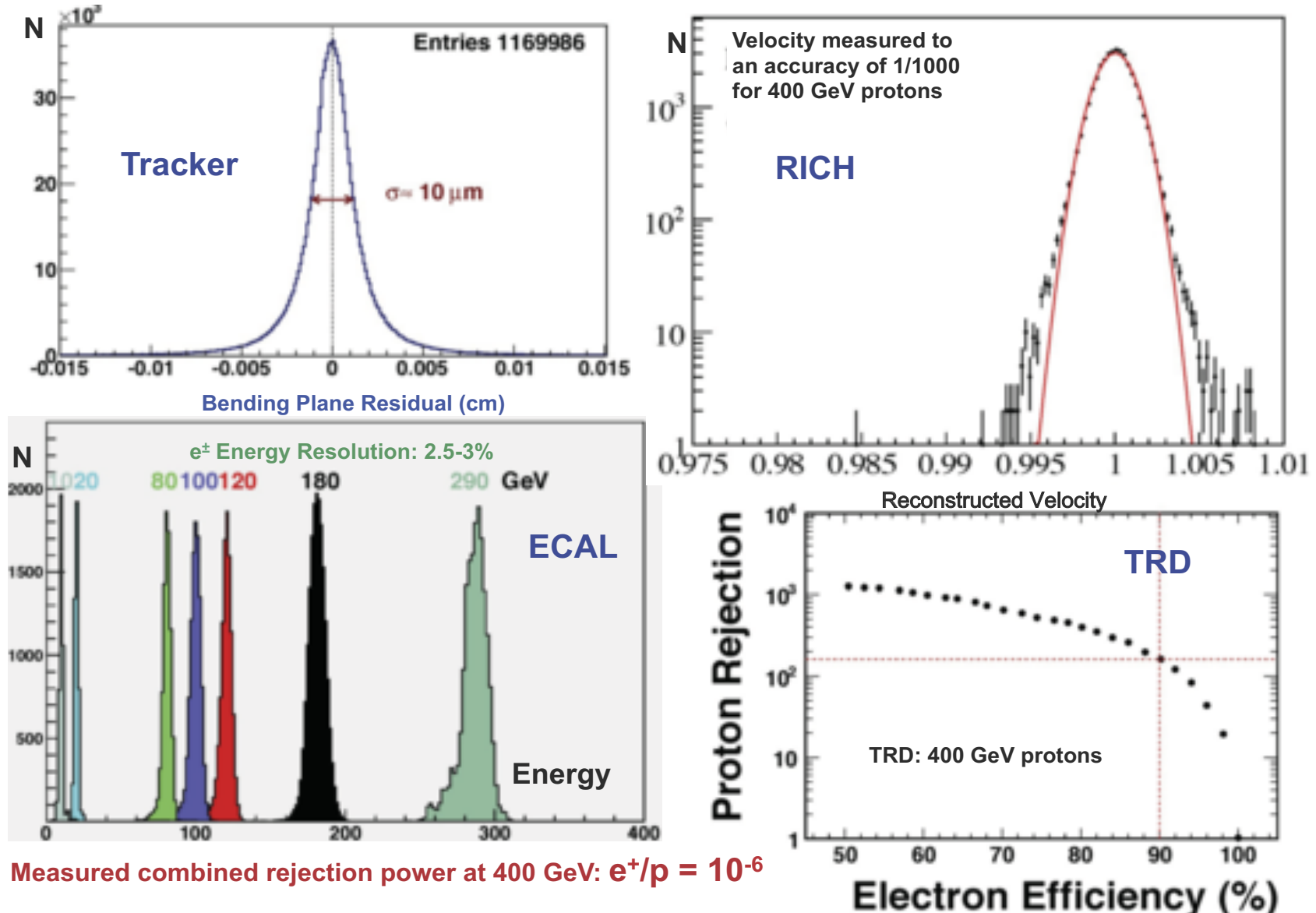
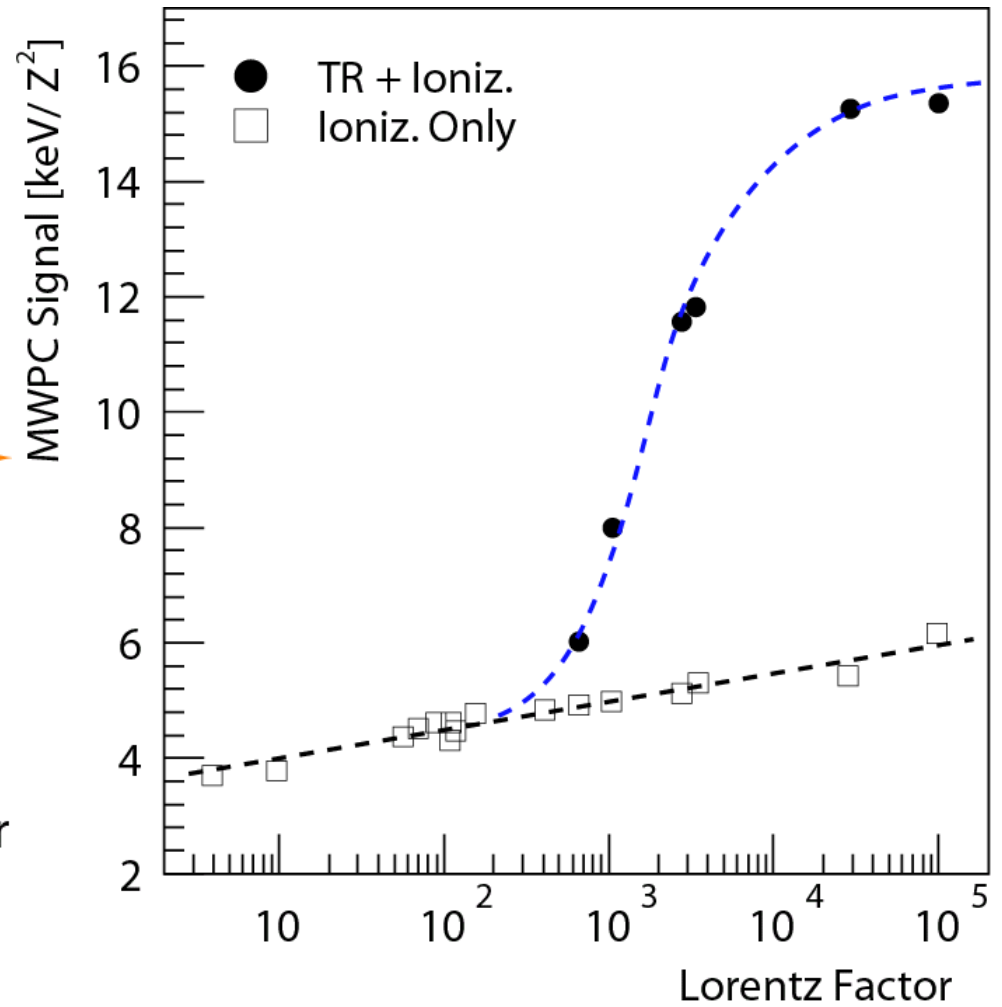
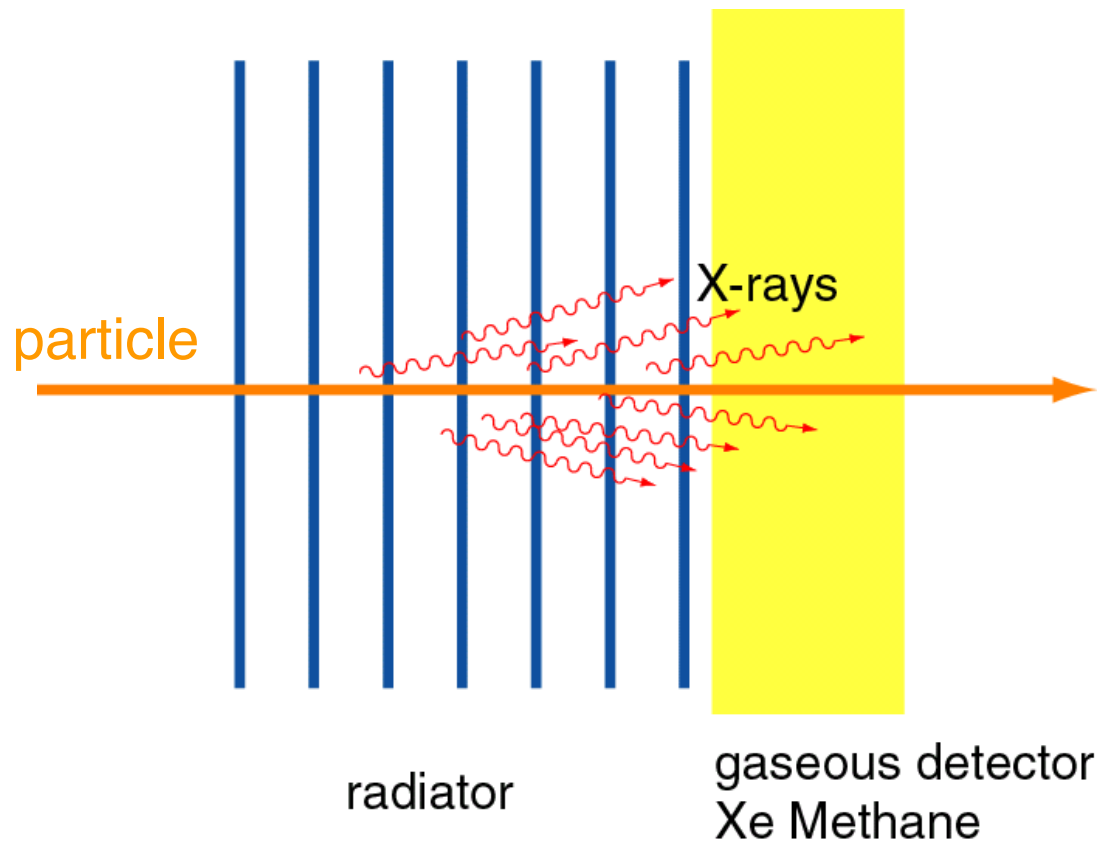


Fig. 7. Major results from the AMS test beam calibration at CERN (2010)

Transition Radiation Detector



Transition radiation

particles traversing a boundary of media with different dielectric properties
--> emission of transition radiation (below Cherenkov threshold)

differential energy spectrum of emitted x-ray photons

$$\frac{d^2 W_0}{d\omega d\theta} = \frac{2\alpha\hbar\theta^3 Z^2}{\pi} \left| \frac{1}{\gamma^{-2} + \theta^2 + \xi_1^2} - \frac{1}{\gamma^{-2} + \theta^2 + \xi_2^2} \right|^2$$

$$\xi_i \equiv \omega_i / \omega$$

**ratio of material's plasma
frequency to the emitted photon
frequency**

$$\epsilon_i \approx 1 - \xi_i^2$$

dielectric constant

emission of photons sharply peaked in forward direction $\theta \approx 1/\gamma$

total radiation yield (integrated over all angles and frequencies)

$$W_0 = \frac{\alpha\hbar Z^2}{3} \frac{(\omega_1 - \omega_2)^2}{\omega_1 + \omega_2} \gamma.$$

Transition radiation

interference effects between the emission amplitudes of all media boundaries of a radiator

for N-foil regular stack with constant spacing l_2 and foil thickness l_1

$$\frac{d^2 W_N}{d\omega d\theta} = \frac{d^2 W_0}{d\omega d\theta} 4 \sin^2 \left(\frac{l_1}{z_1} \right) \frac{\sin^2 [N(l_1/z_1 + l_2/z_2)]}{\sin^2 (l_1/z_1 + l_2/z_2)}.$$

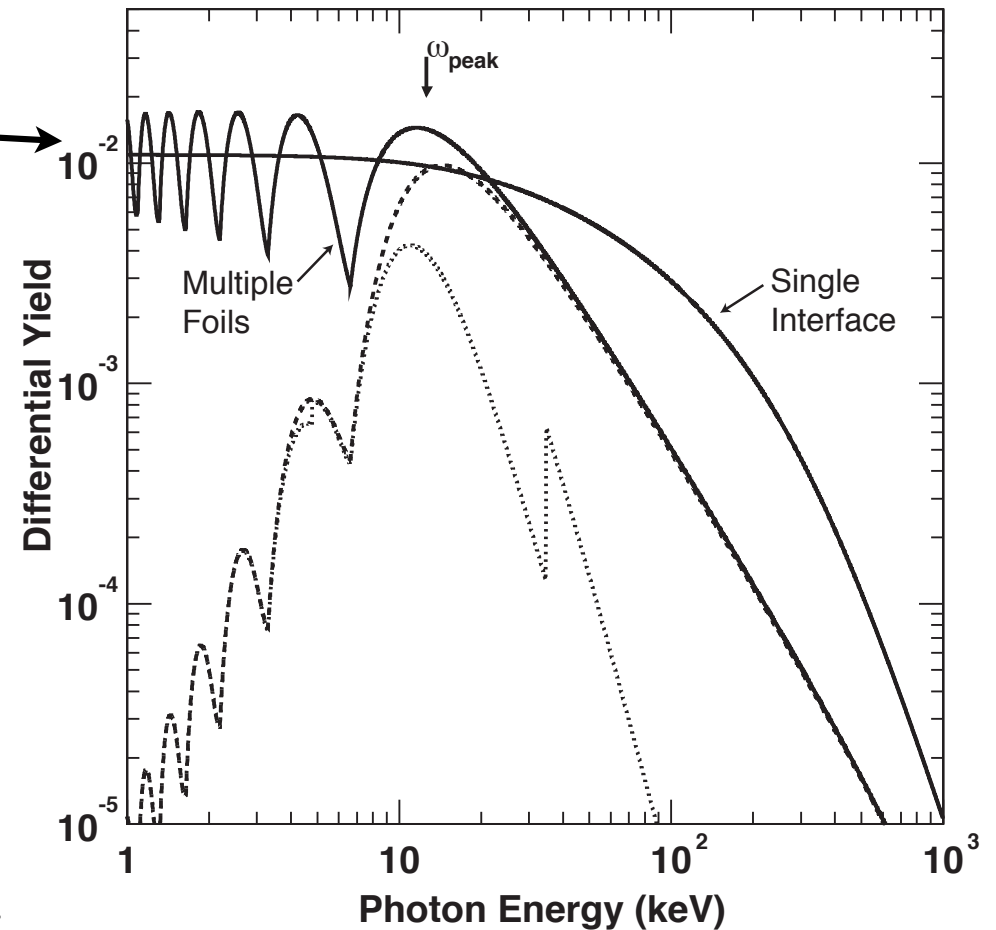
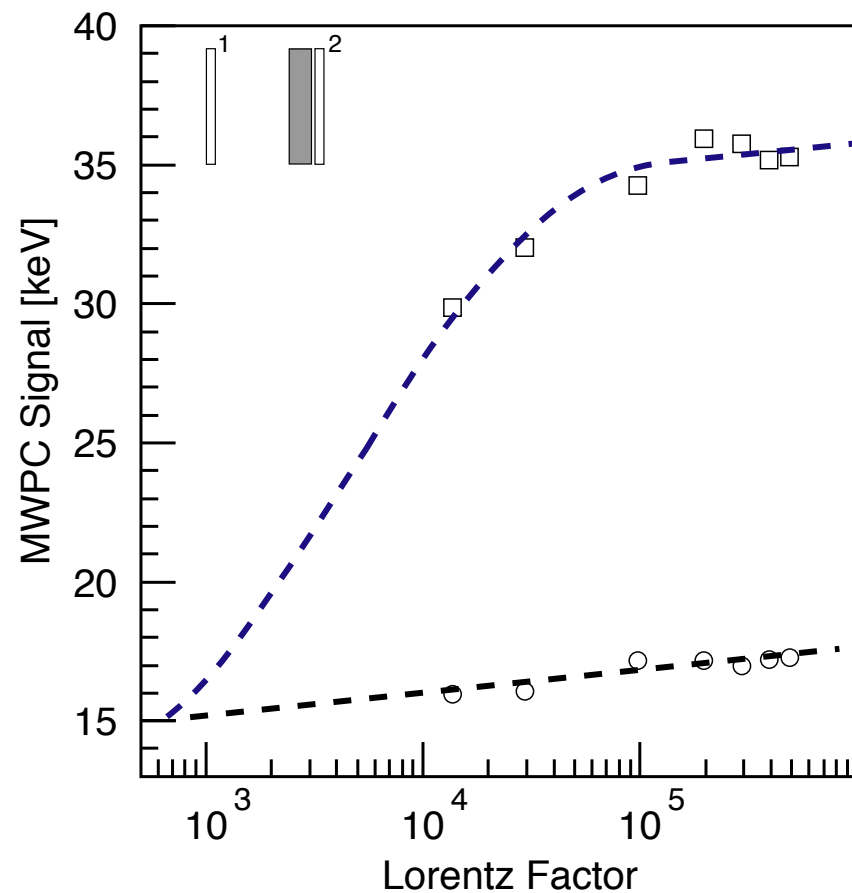


Fig. 1. Differential TR yield ($dW/d\omega$) versus Lorentz factor for several configurations. Shown are the single-interface (smooth line) and approximate multi-foil (oscillating line) energy spectra, as well as the multi-foil spectrum modified by self-absorption processes in the foil (dashed line). The dotted line shows the yield which would be captured in a single 1 cm thick layer of xenon. The characteristic peak emission energy ω_{peak} is also indicated. All spectra are normalized to a single-interface yield. The relevant parameters are $\gamma = 2 \times 10^4$, $l_1 = 35 \mu\text{m}$, $l_2 = 1000 \mu\text{m}$, $\omega_1 = 21.2 \text{ eV}$, and $\omega_2 = 0.75 \text{ eV}$.



Transition Radiation Detector

- particle identification (threshold detector)
- energy measurement (Lorentz factor)

TRD test at CERN

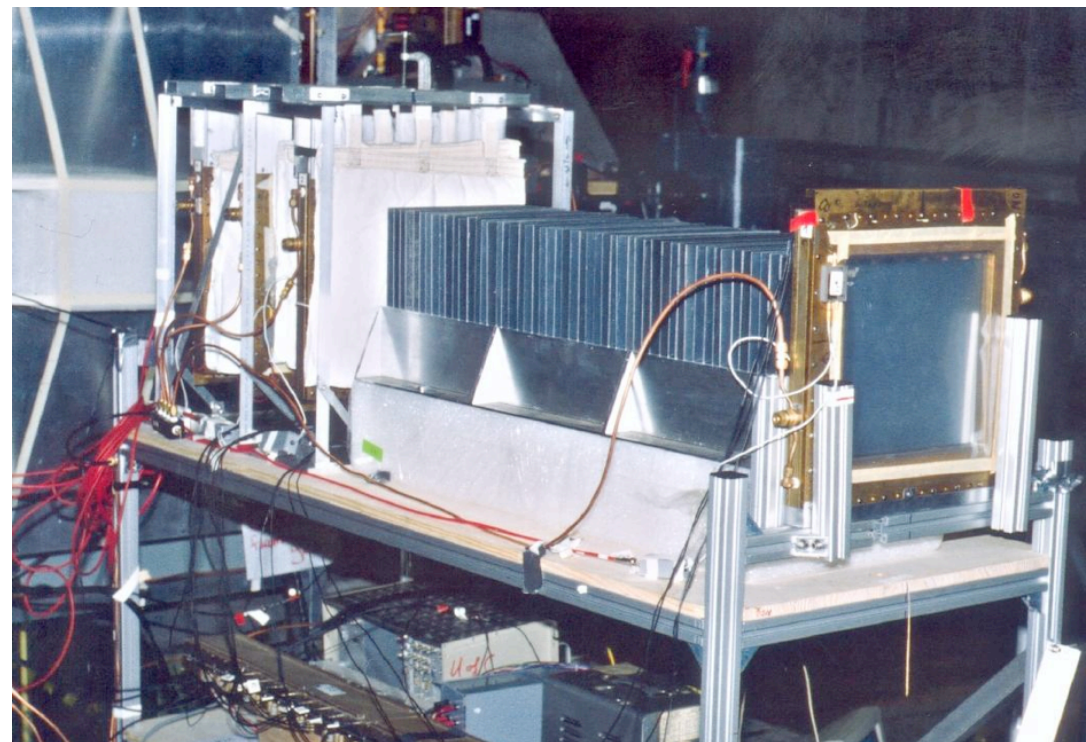
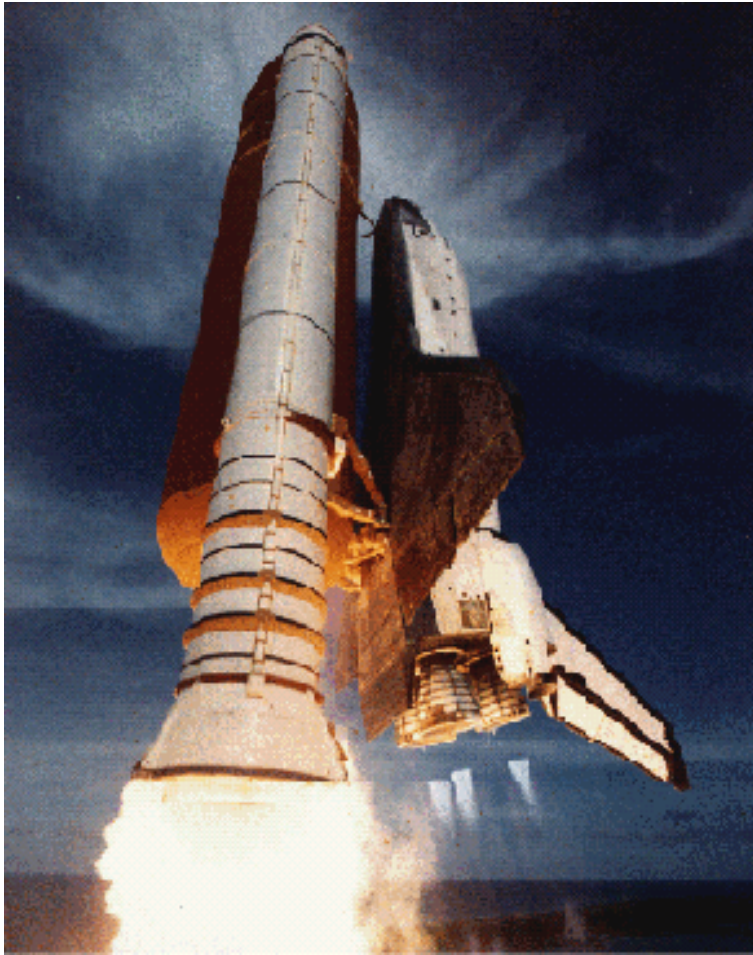


Fig. 8. Average detector signal versus Lorentz factor for a CRN-like radiator configuration. The open circles are data from MWPC 1, and the open squares are from MWPC 2, as shown in the inset schematic. The dashed lines serve to guide the eye.

Cosmic Ray Nuclei detector



Spaceleb 2 July/August 1985
Spaceshuttle Challenger

GAS CERENKOV C1

SCINTILLATOR T1

TRANSITION
RADIATION
DETECTORS

SCINTILLATOR T2

GAS CERENKOV C2

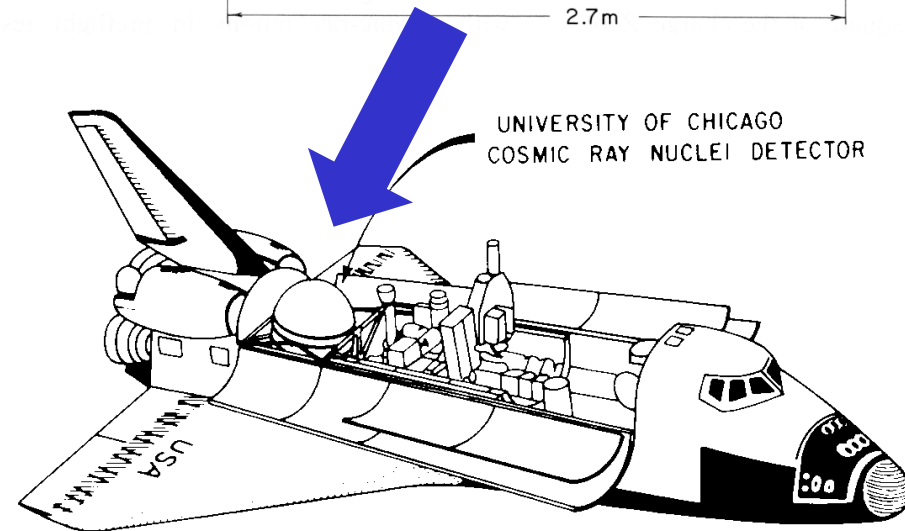
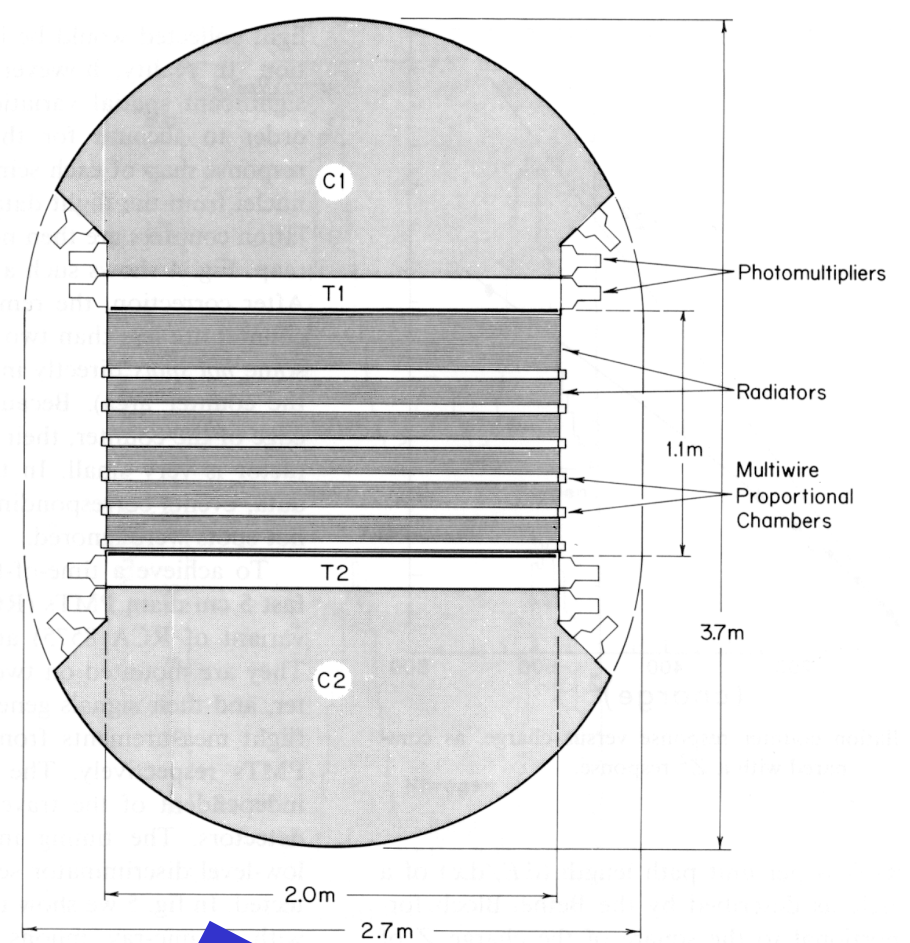
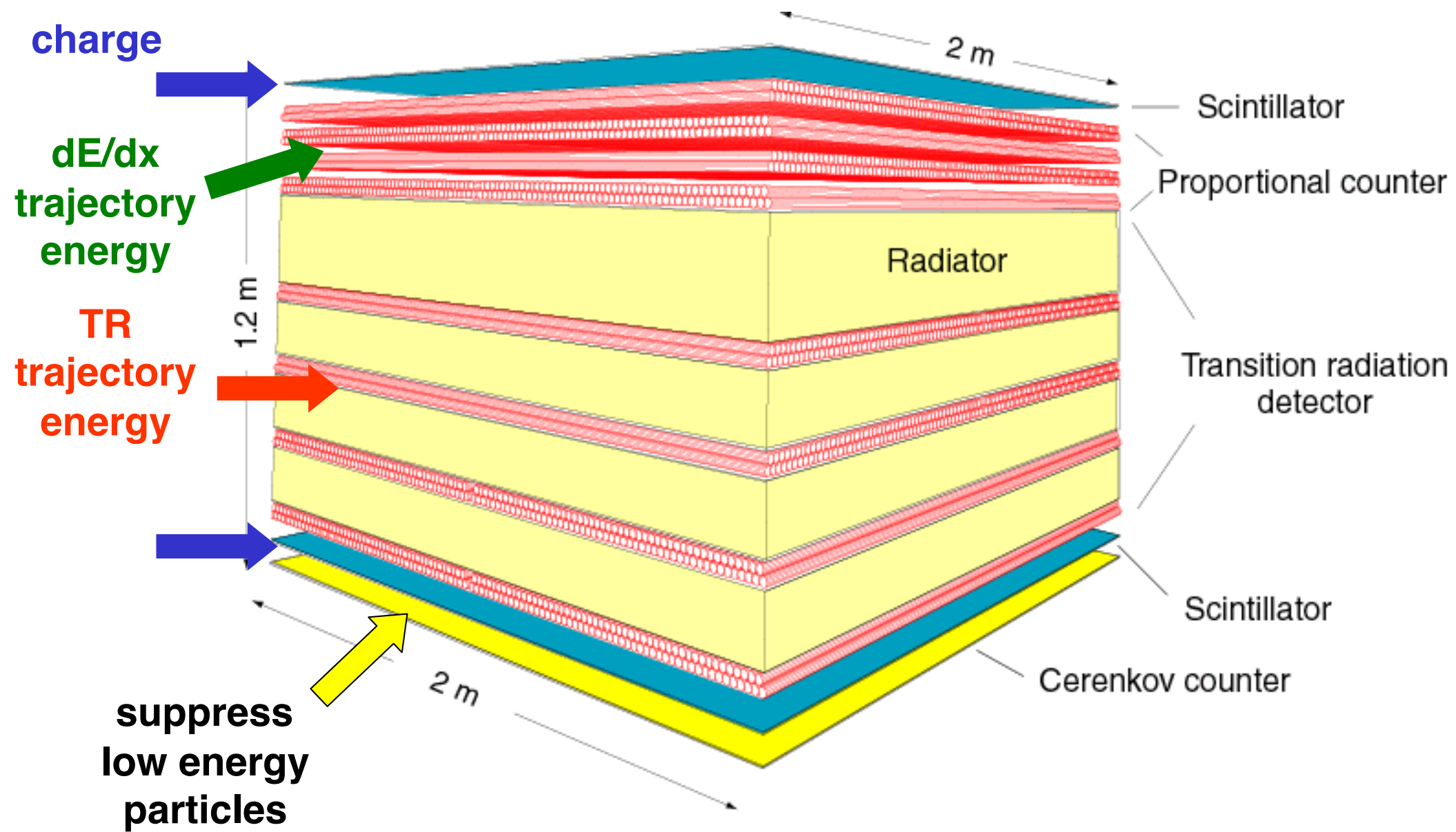


Fig. 14. Schematic view of the Spacelab-2 instruments mounted in the orbiter.

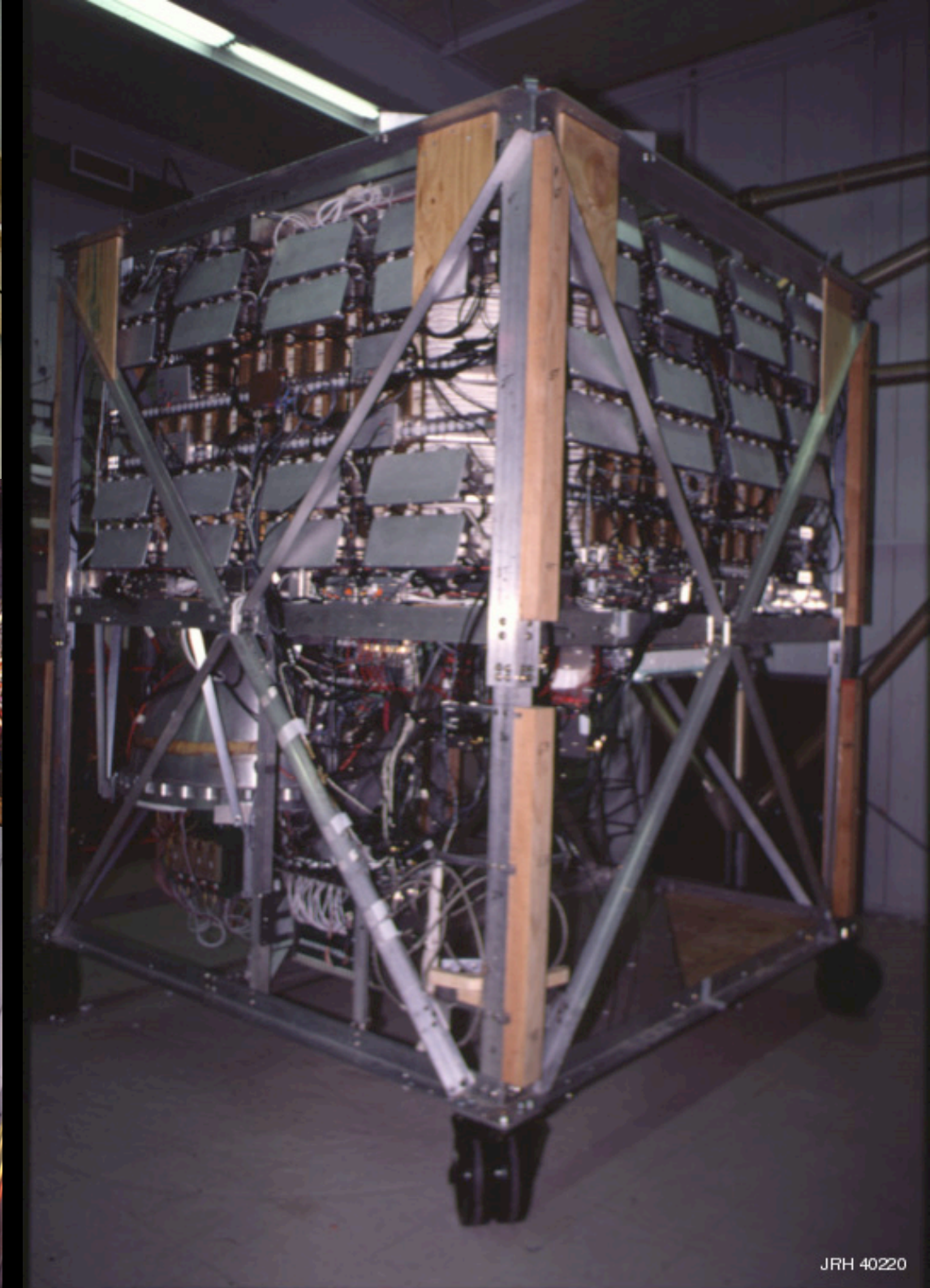
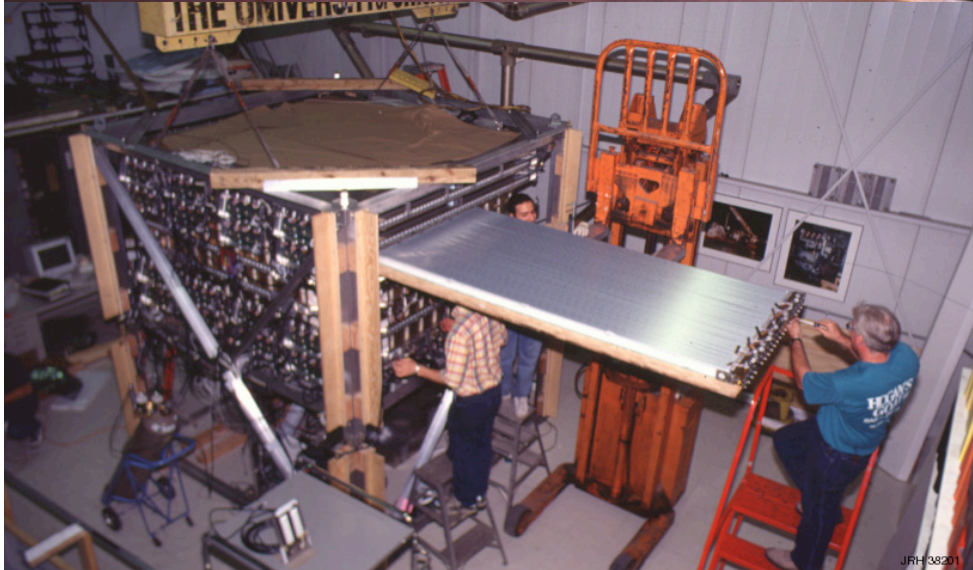
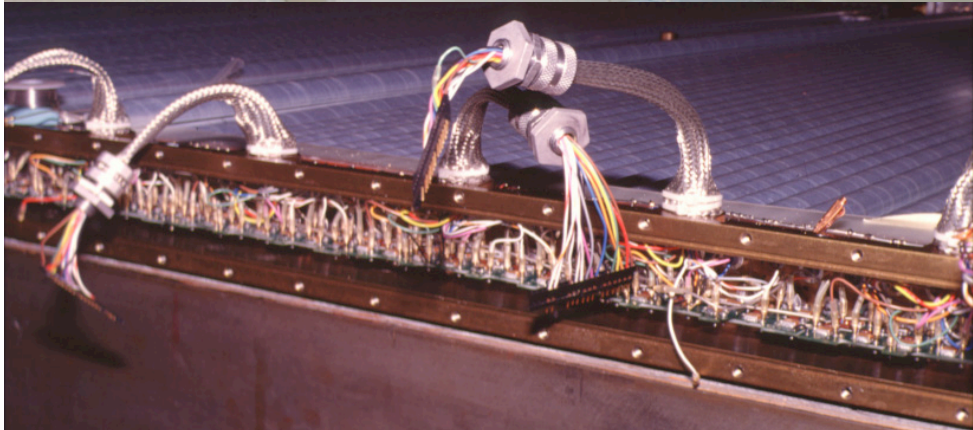


Transition Radiation Array for Cosmic Energetic Rays

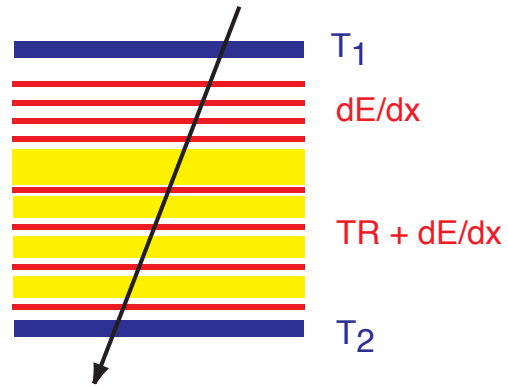


Geometric factor: 5 m² sr

1600 proportional tubes total



Data Analysis Steps:



Charge assignment:

Events with clean tracks

Fine trajectory resolution (< 1 mm)
from signal distributions in proportional tubes

Correction of scintillator signals
for position and zenith angle

Rejection of interacting particles

Energy determination:

3 GeV/n to 1000 GeV/n:

use relativistic rise in specific ionization in
gas (Xe - CH₄ mixture)

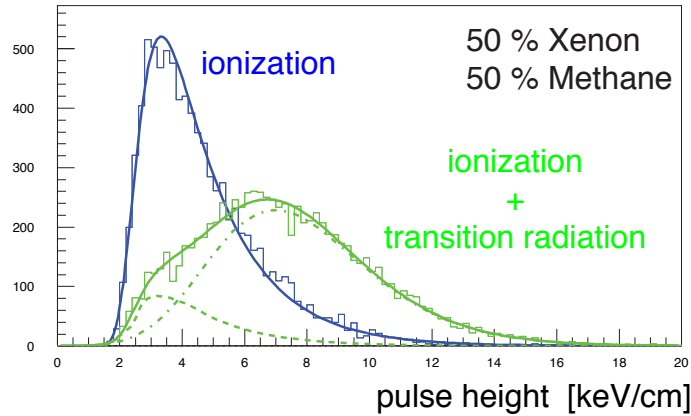
above 1000 GeV/n:

strong energy dependence of transition radiation signal,
and dE/dx signal near saturation

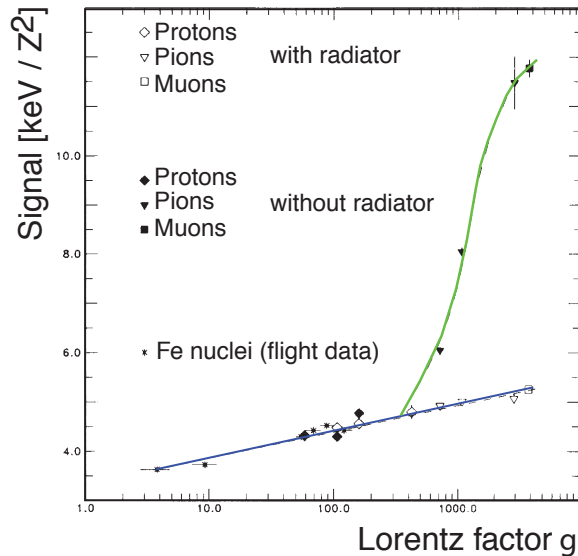
Calibration of a transition radiation detector

Measured pulse height distribution in proportional tubes

35 GeV electrons

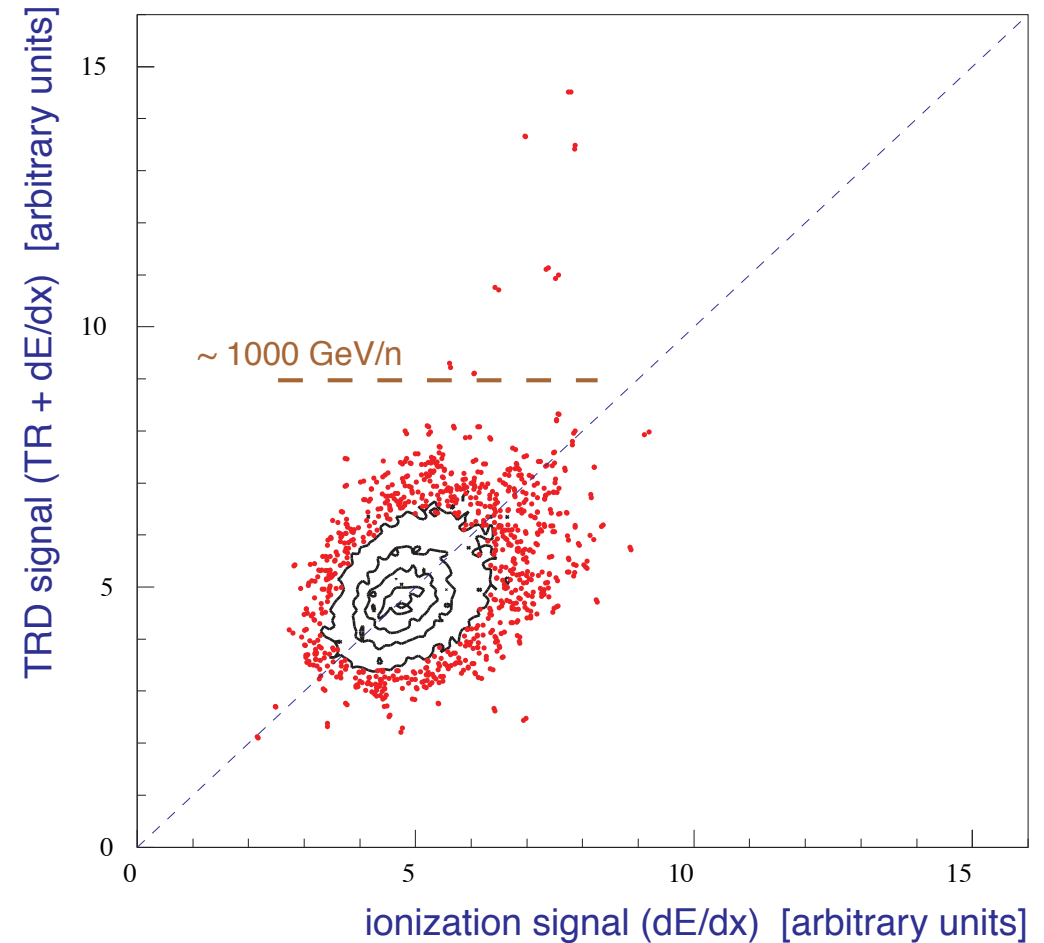


Measured detector response vs Lorentz factor

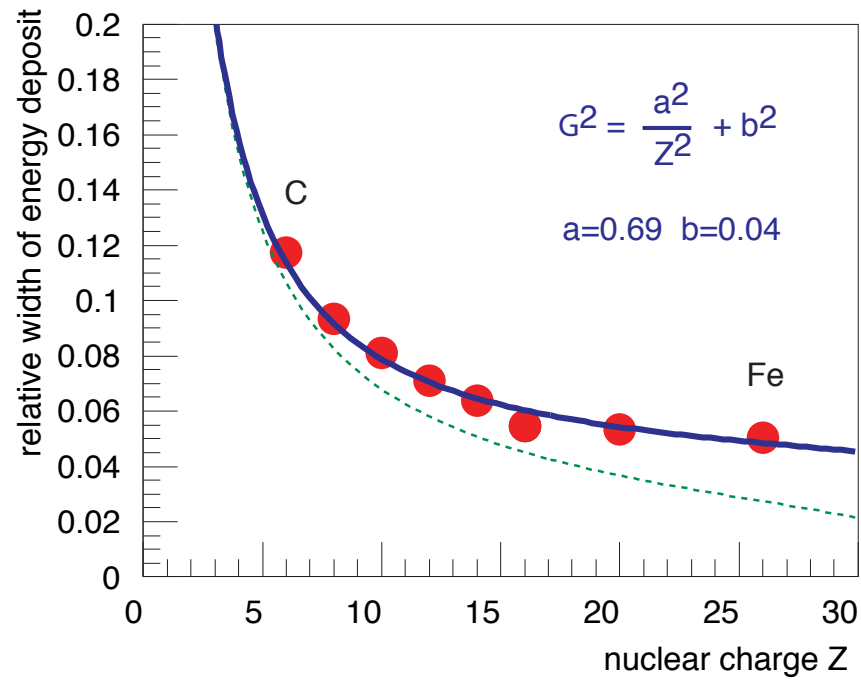


Detector Response TRD signal vs dE/dx signal

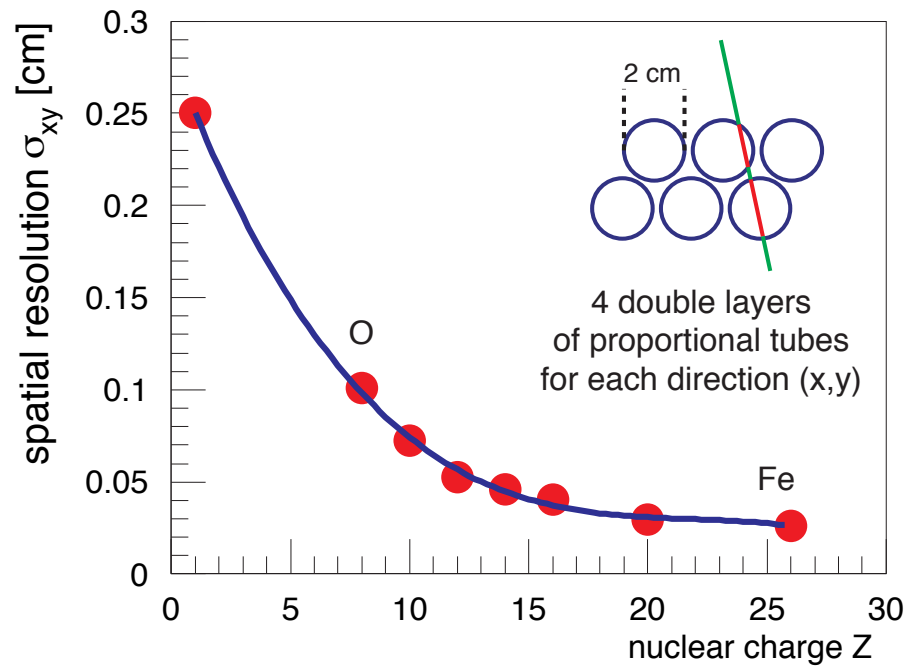
sample of flight data, oxygen nuclei



Measured relative width of the energy deposition



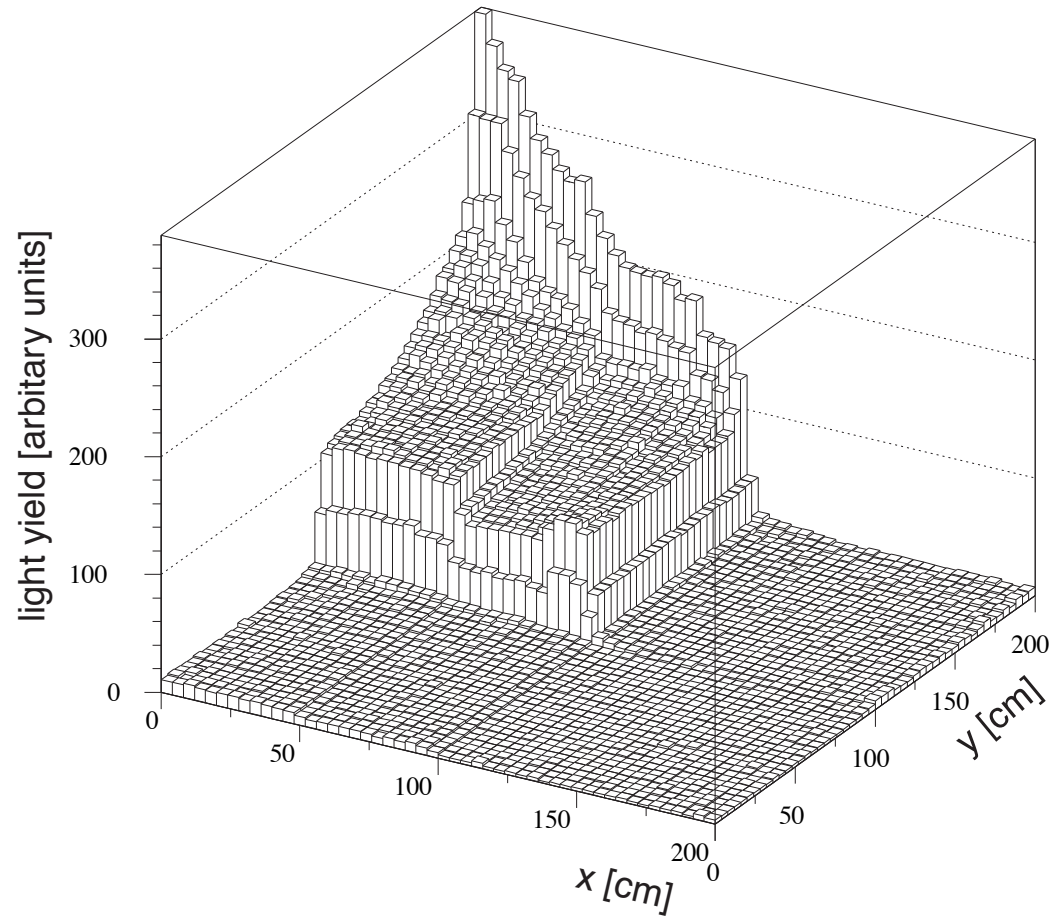
Spatial resolution of track reconstruction



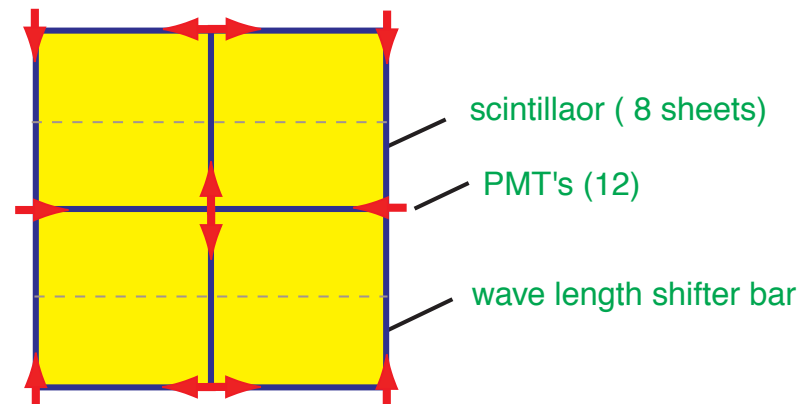
Spatial resolution dominated by (Landau-) fluctuations of energy deposit

Scintillator Response

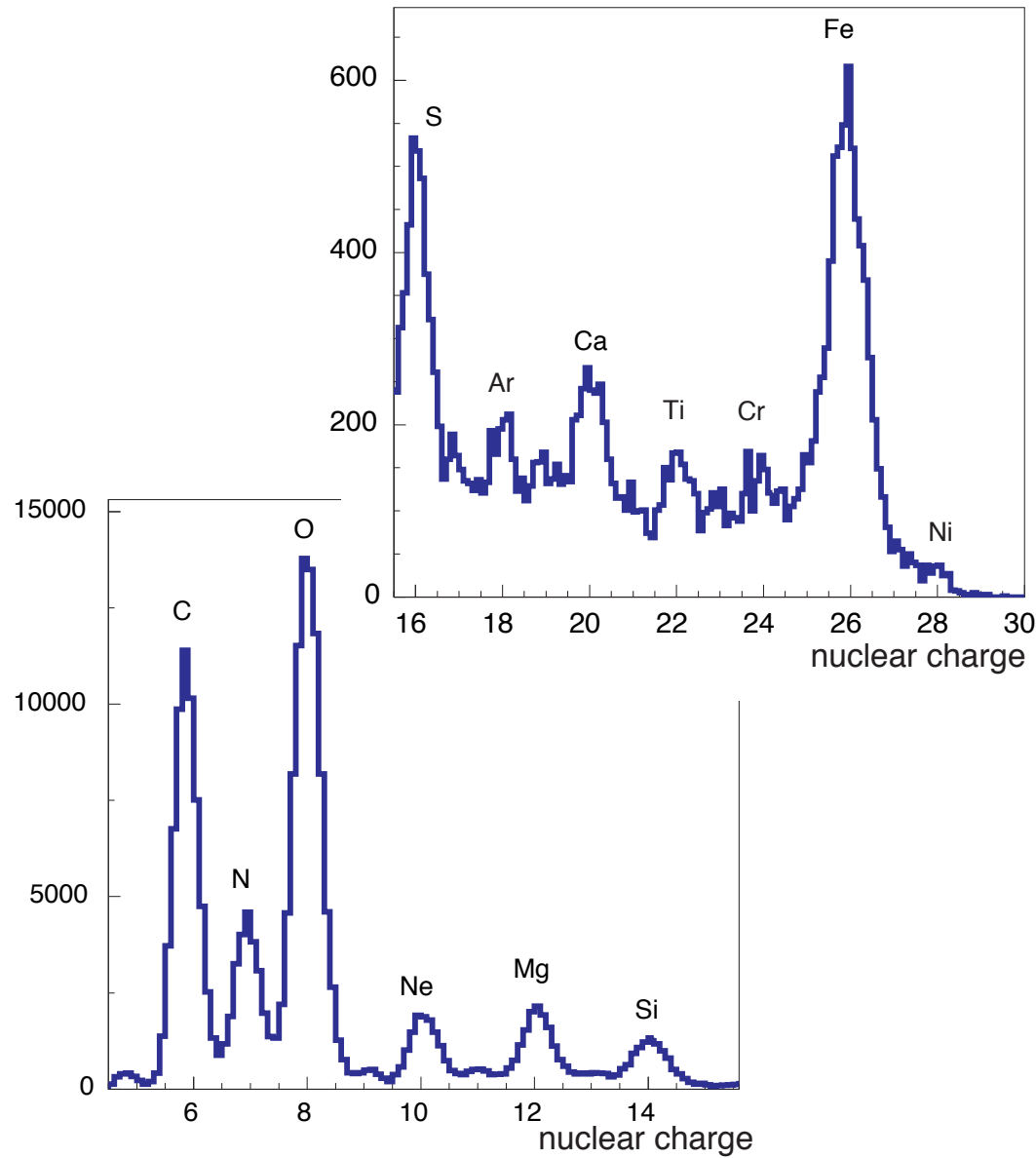
Response map of scintillators for one of 12 PMT's



schematic view of scintillator plane



Cosmic-ray charge distribution measured at instrument



obtained with two layers of scintillation counters (200 x 200 x 0.5 cm³)

resolution dominated by spatial uniformity

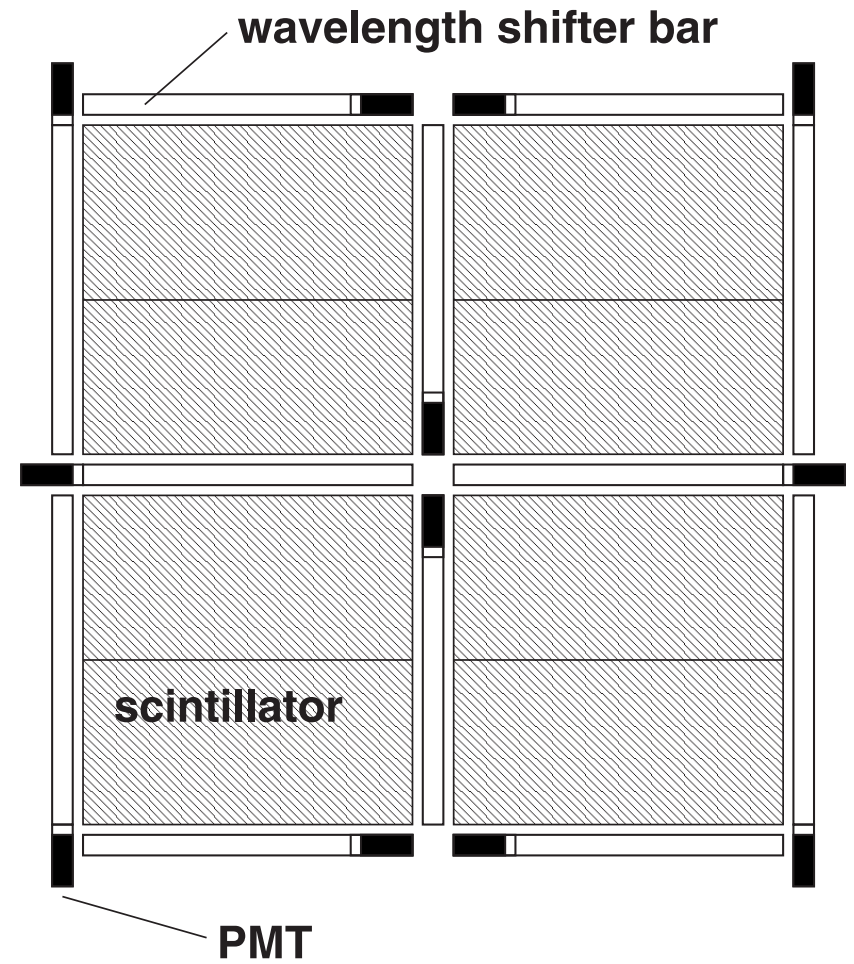


FIG. 3.—Schematic arrangement (not to scale) of scintillator sheets, wavelength shifter bars, and PMTs.

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A NEW MEASUREMENT OF THE INTENSITIES OF THE HEAVY PRIMARY COSMIC-RAY NUCLEI AROUND 1 TeV amu⁻¹

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 Enrico Fermi Institute, University of Chicago, 933 East 56th Street, Chicago, IL 60637
 Received 2003 December 6; accepted 2004 February 3

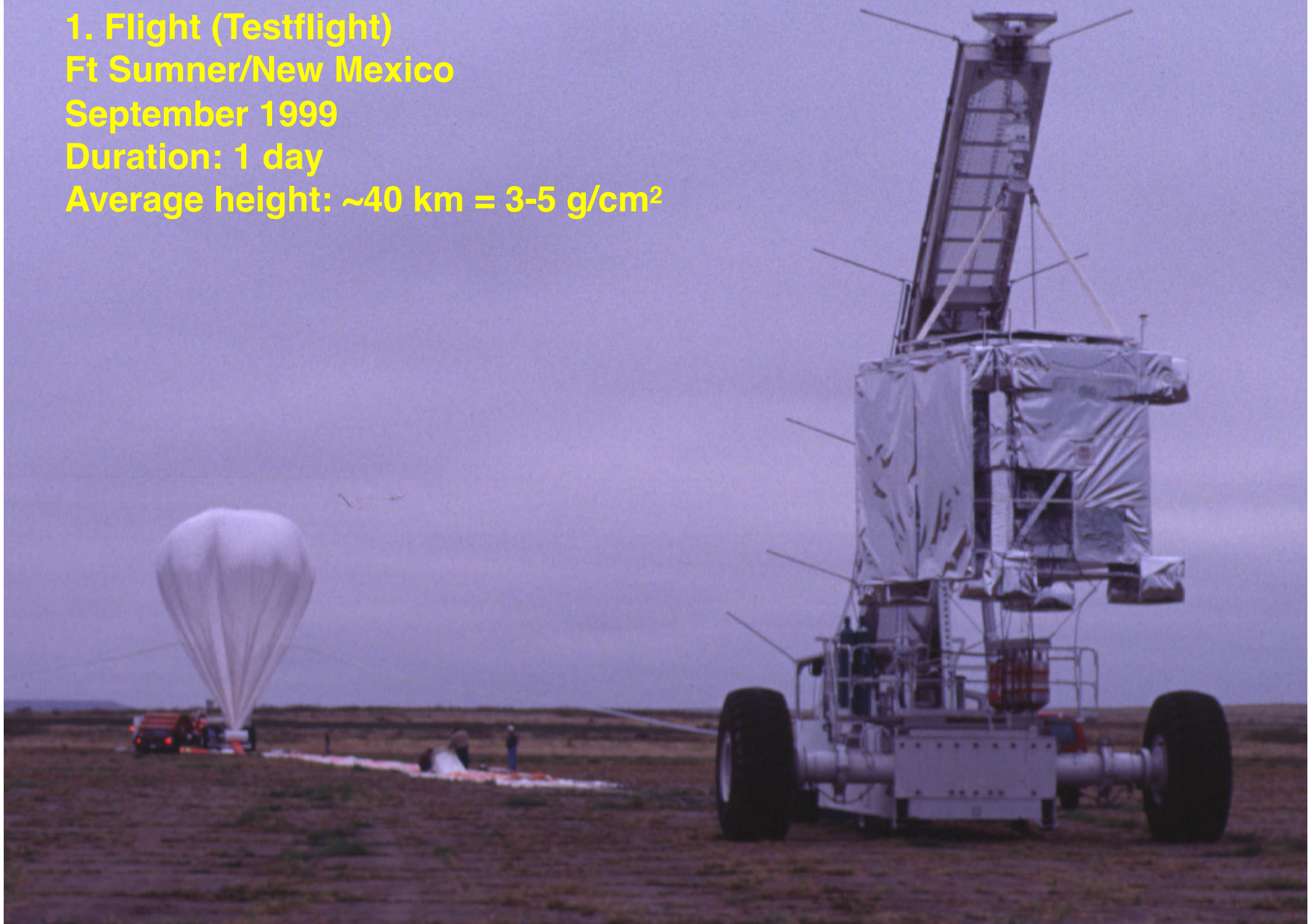
1. Flight (Testflight)

Ft Sumner/New Mexico

September 1999

Duration: 1 day

Average height: $\sim 40 \text{ km} = 3\text{-}5 \text{ g/cm}^2$



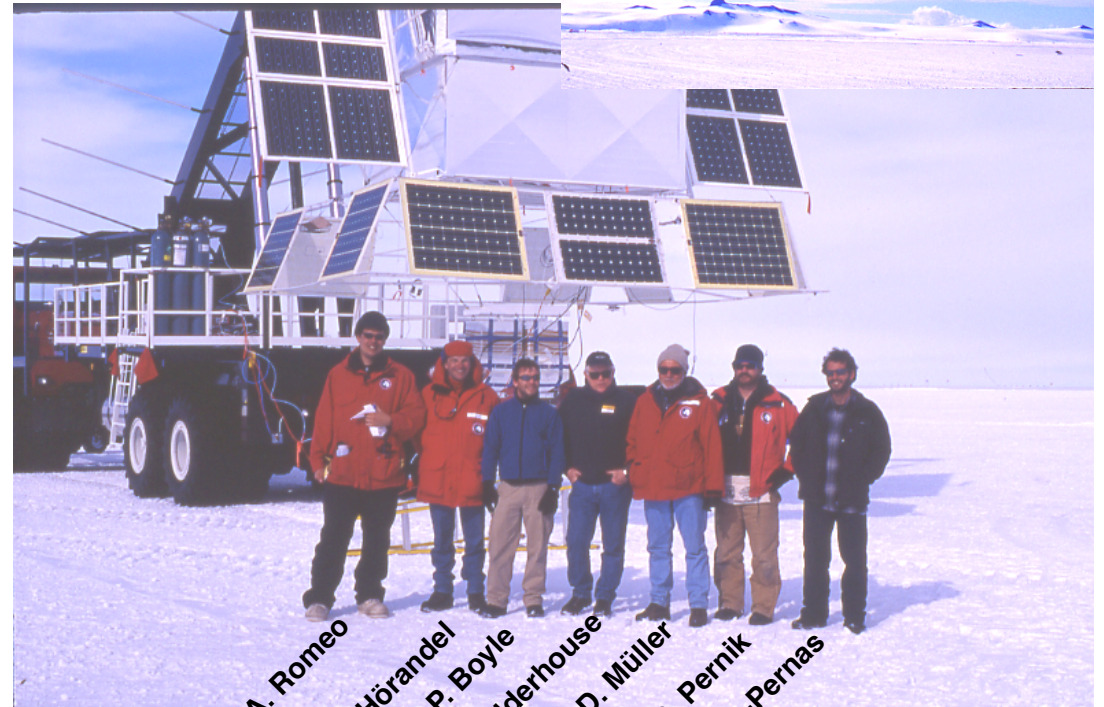
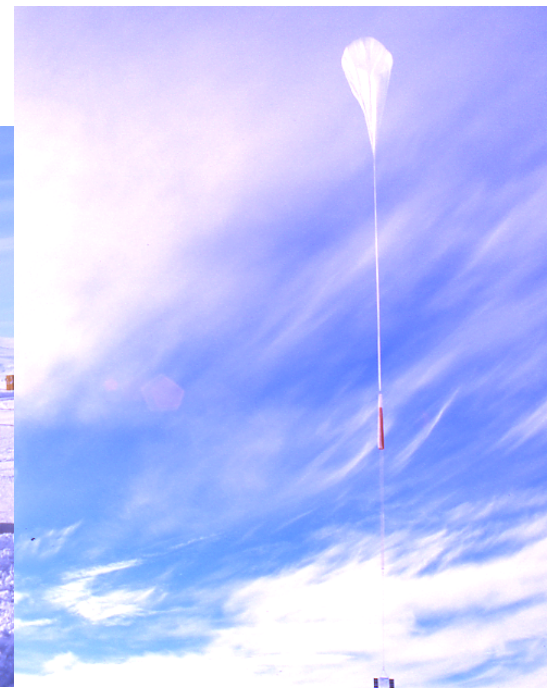
TRACER Experiment - Mc Murdo, Antarctica

flight: 12. – 26. December 2003

~ 40 km (3-5 g/cm²)



TRACER Experiment

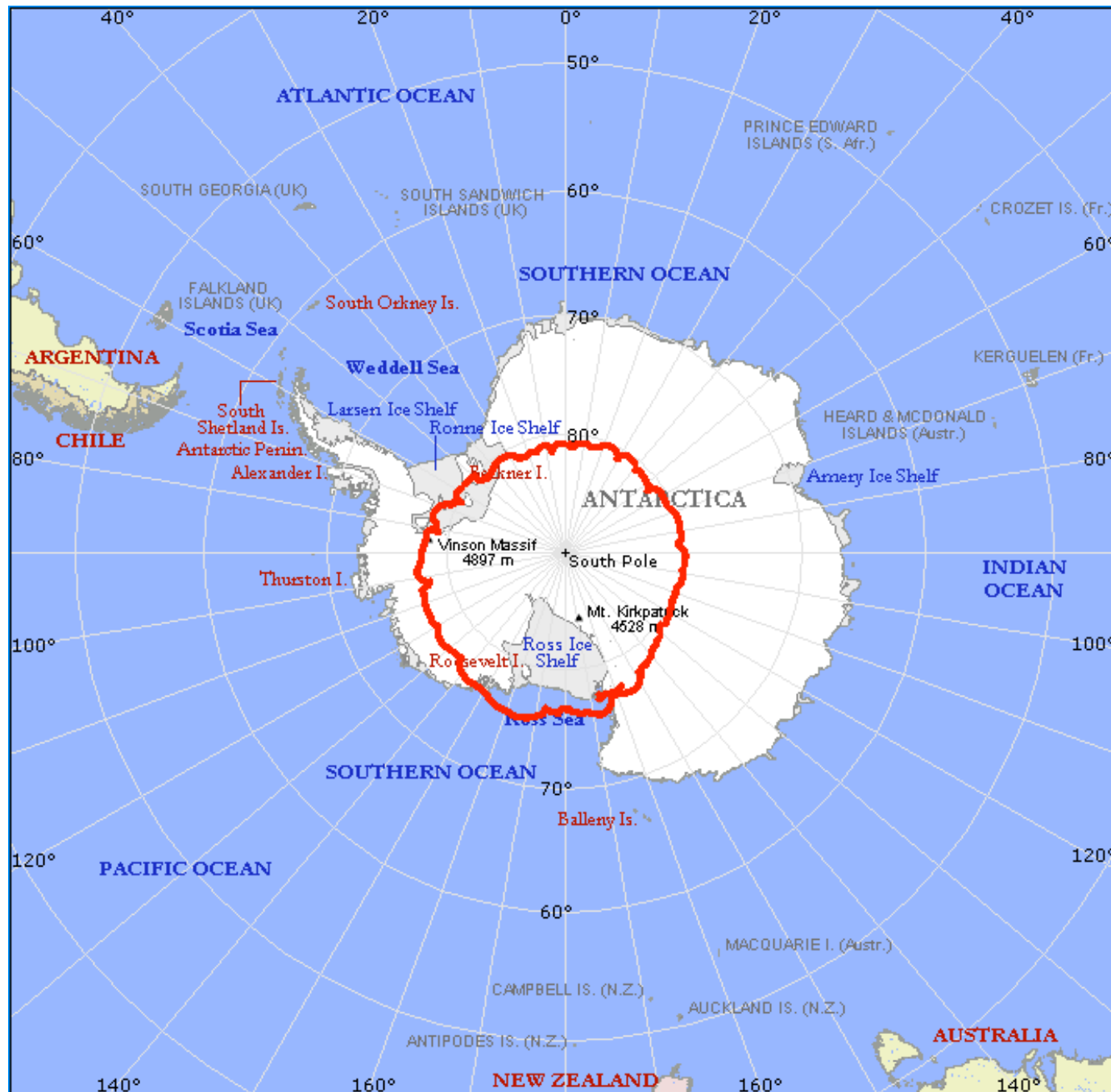


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TRACER Experiment - Mc Murdo, Antarctica

flight: 12. – 26. December 2003

~ 40 km (3-5 g/cm²)



Cherenkov Detectors

Cherenkov radiation

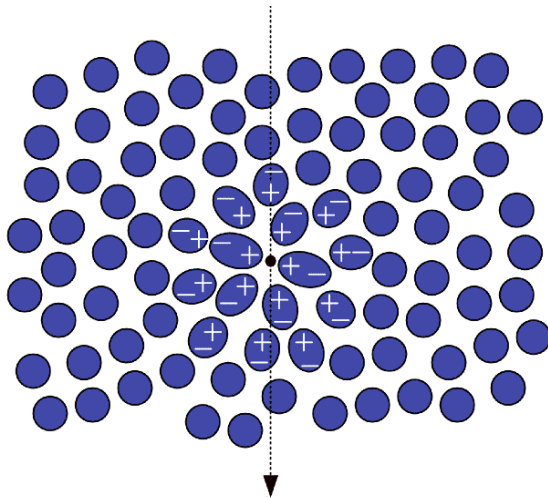
charged particles, moving in a medium with refractive index n with

$$v > \frac{c}{n}$$

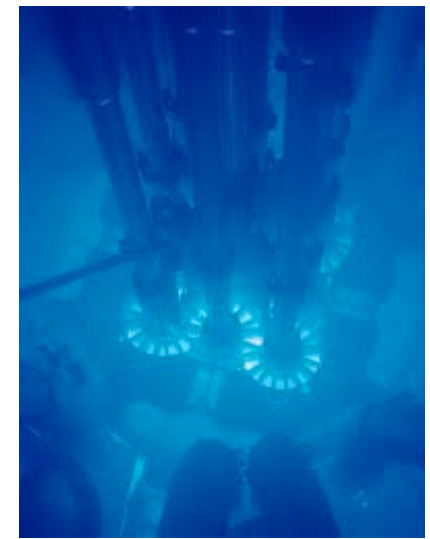
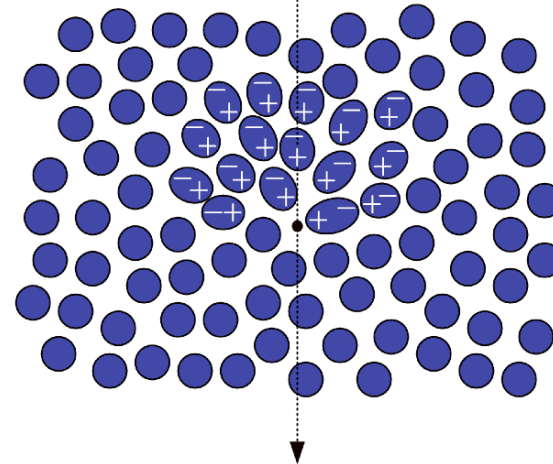
emit electromagnetic radiation --> Cherenkov radiation

electrons passing through a dielectric at

$$v < \frac{c}{n}$$



$$v > \frac{c}{n}$$



Charged particles, passing by the atoms in the dielectric, momentarily polarize them. Once the particle has passed, this polarized state collapses, causing each atom to emit Cherenkov radiation. For slow moving particles, the polarization is perfectly symmetrical, resulting in no electric field at long distances. When the particle is moving very quickly, however, the polarization is no longer perfectly symmetrical.

Cherenkov radiation

angle between the trajectory of the particle and the emitted photons

$$\cos \theta_c = \frac{c}{n\beta c} = \frac{1}{n\beta}$$

threshold for Cherenkov radiation

$$\beta > \frac{1}{n}$$

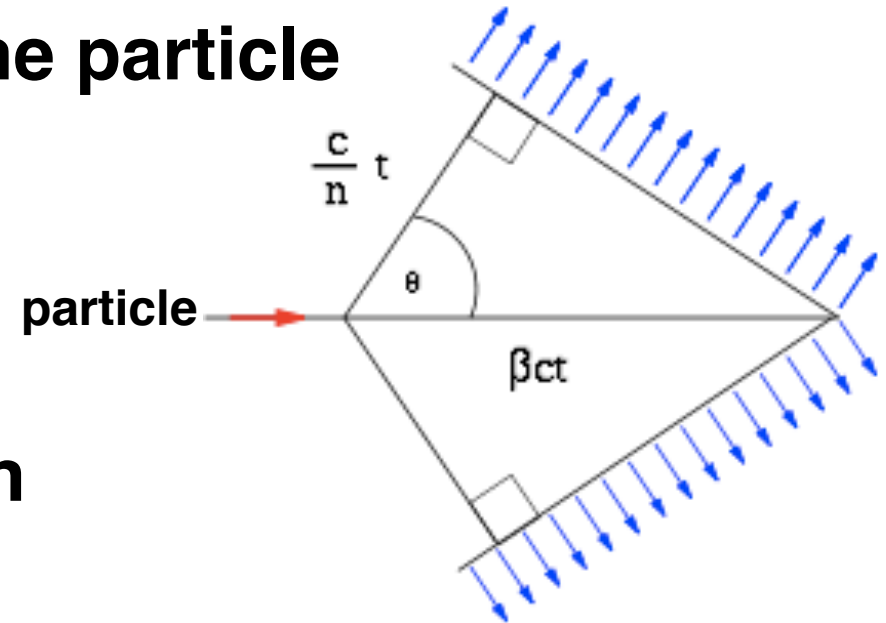
at threshold, the photons are emitted in forward direction

the Cherenkov angle increases to a maximum value

for $\beta = 1$: $\theta_c = \arccos \frac{1}{n}$

threshold energy

$$\gamma_{th} = \frac{1}{\sqrt{1 - \beta_{th}^2}} = \frac{1}{\sqrt{1 - \frac{1}{n^2}}} \quad \text{with} \quad \gamma_{th} = \frac{E_{th}}{m_0 c^2}$$



Cherenkov radiation

number of Cherenkov photons emitted per unit length

$$\frac{dN}{dx} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2\beta^2}\right) \frac{d\lambda}{\lambda^2}$$

z charge of particle α Sommerfeld constant in the wavelength interval $\lambda_1 \dots \lambda_2$

neglecting dispersion yields

$$\frac{dN}{dx} = 2\pi\alpha z^2 \sin^2 \theta_c \frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2}$$

which gives for a singly charged particle ($z=1$) in the wavelength range 400 to 700 nm

$$\frac{dN}{dx} = 490 \sin^2 \theta_c \quad [\text{cm}^{-1}]$$

Cherenkov detector

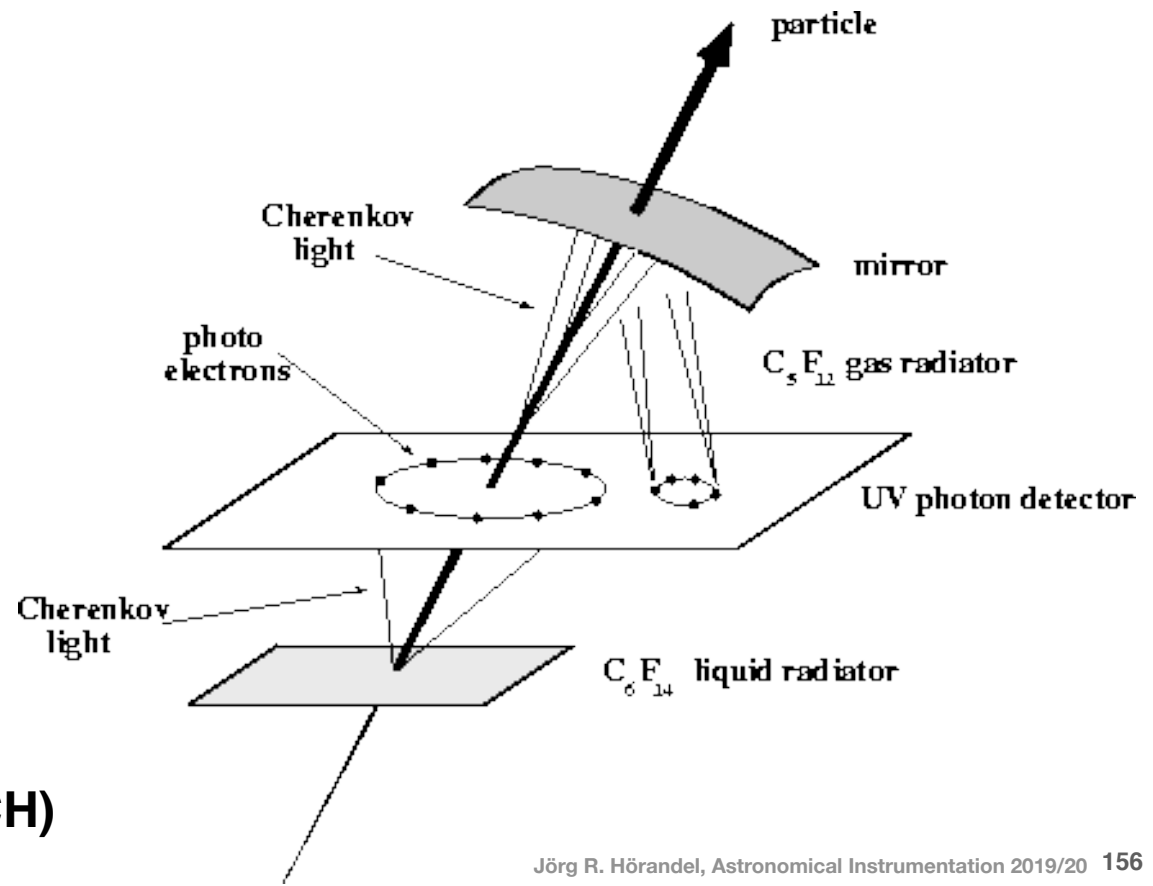
- particle identification threshold detector

$$\gamma_{th} = \frac{1}{\sqrt{1 - \frac{1}{n^2}}} = \frac{E_{th}}{m_0 c^2}$$

select material with appropriate n
--> light particles radiate

- measurement of velocity (kinetic energy)

$$\cos \theta_c = \frac{c}{n\beta c} = \frac{1}{n\beta}$$



ring imaging Cherenkov detector (RICH)

Human Eye as Cherenkov detector - SilEye-2 experiment

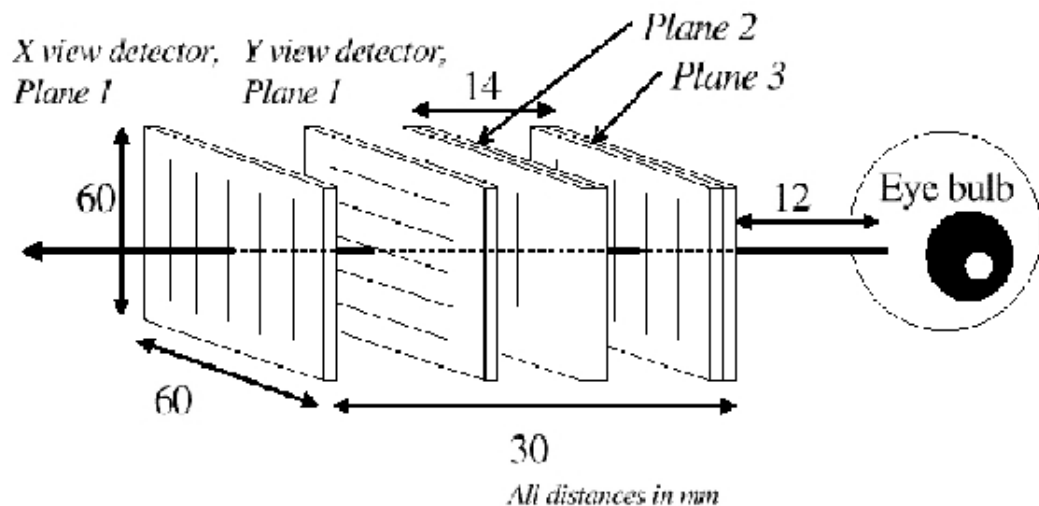


Figure 2. Scheme of the SilEye-2 silicon detector: six 16 strip silicon layers glued in pairs with strip orthogonally aligned form three planes (the two layers of the first plane are drawn separately). The position of the eye bulb is also shown.

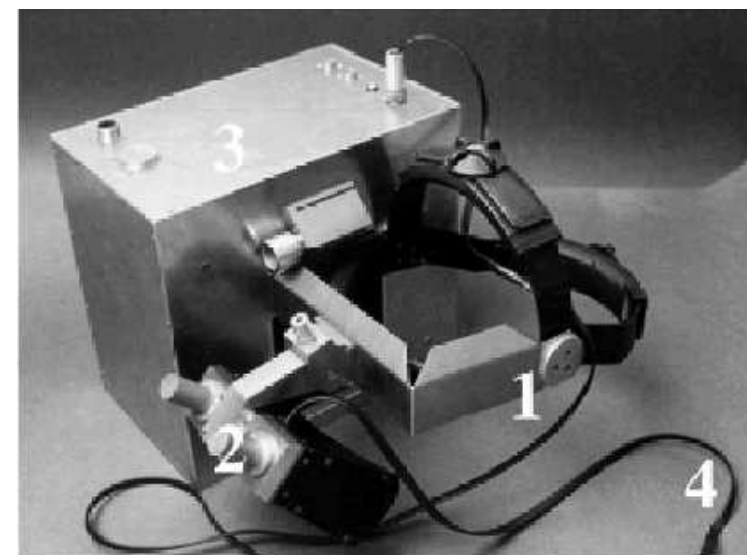
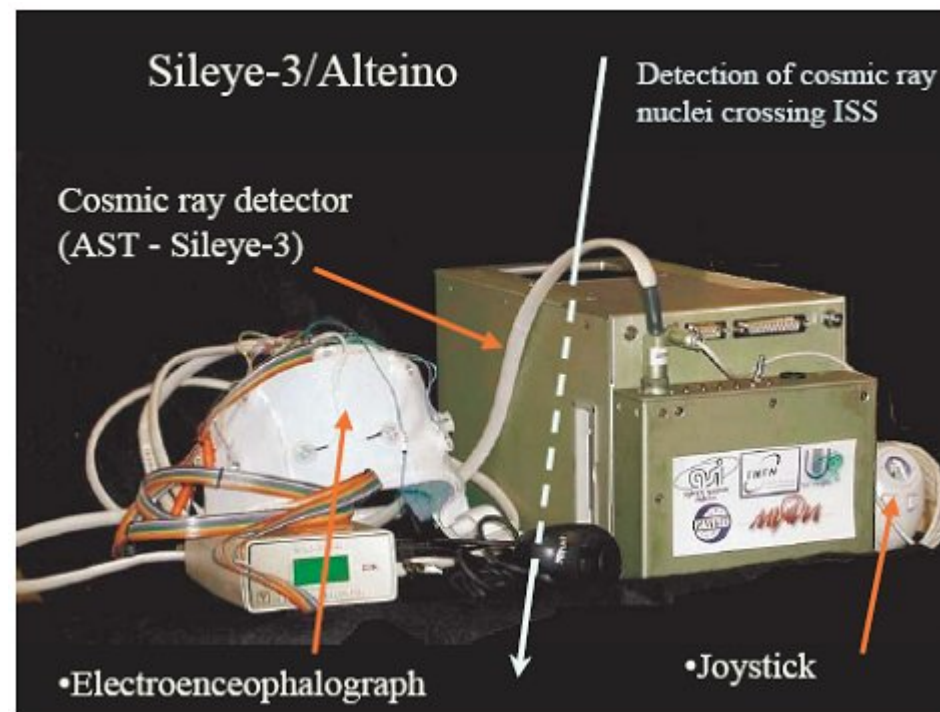
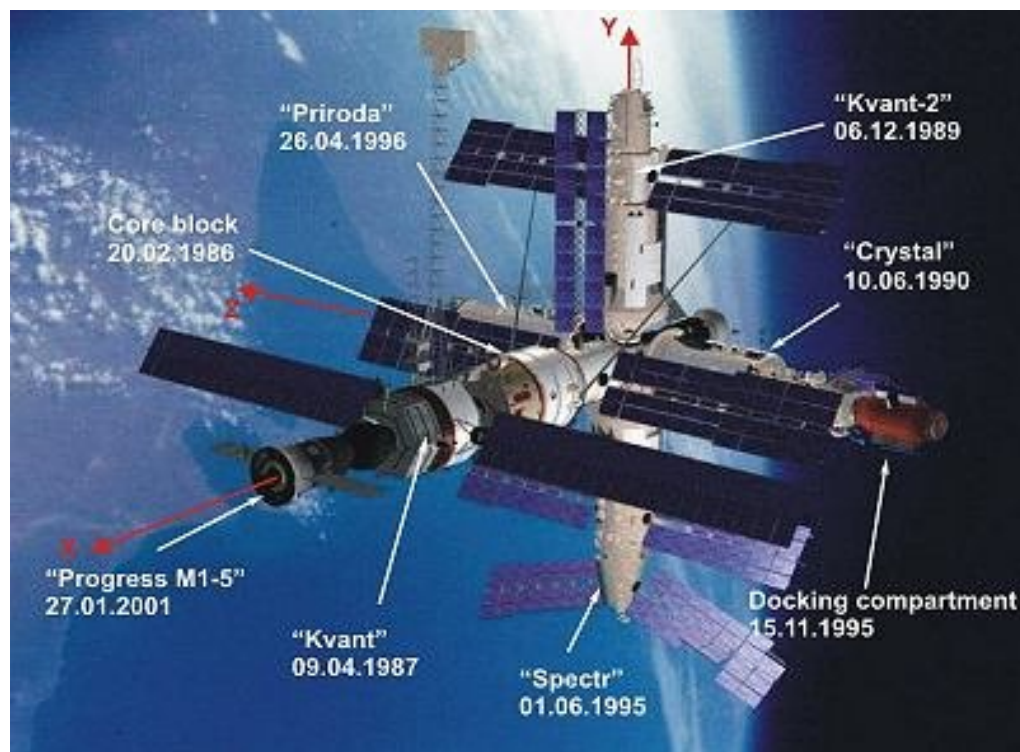


Figure 1. Photo of the SilEye-2 helmet and detector case: 1. Head Mounting. 2. Eye mask with internal LEDs. 3. Detector Box. 4. Connection cable for the LEDs used for dark adaptation tests .



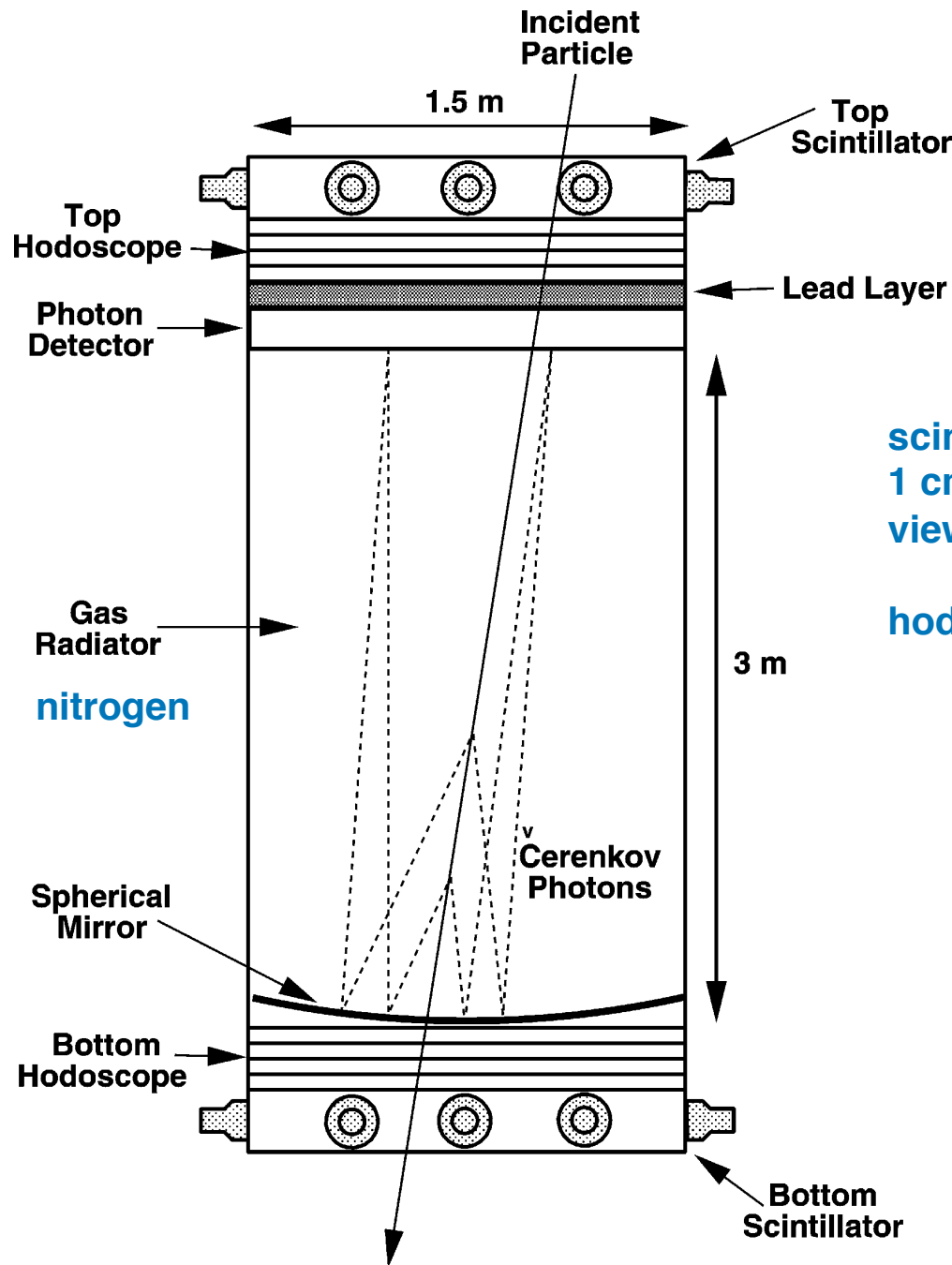


Fig. 1. Schematic cross-section of the instrument.

The energy spectrum of cosmic-ray protons and helium near 100 GeV

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Received 15 February 2002; accepted 2 May 2002

**scintillator: 1.5 m x 1.5 m NE110 plastic scintillator, 1 cm thick
viewed by twelve 12.5 cm diameter PMTs**

hodoscope filled with argon/methane 95:5

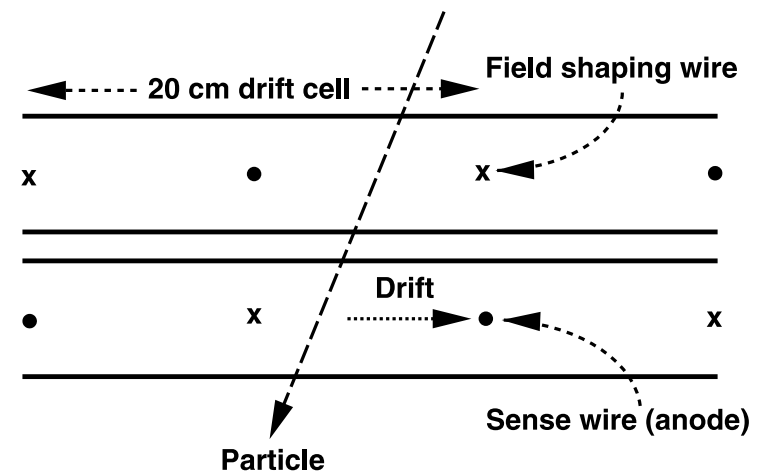
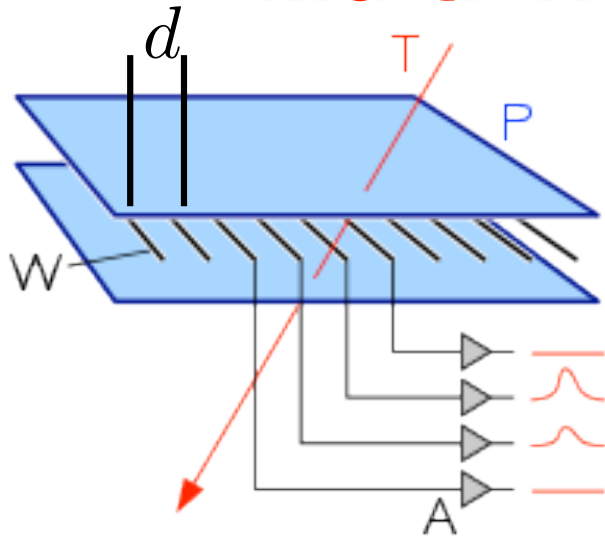


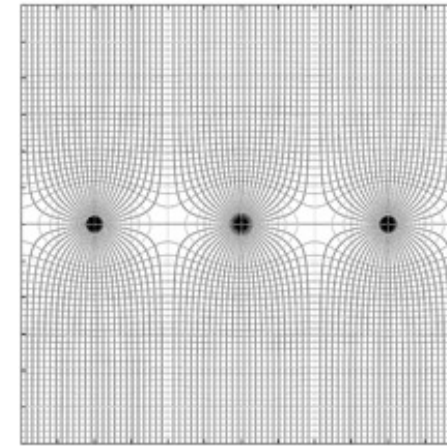
Fig. 2. Schematic cross-section view of hodoscope operation.

Multi-Wire Proportional Chamber



spatial resolution

$$\sigma(x) = \frac{d}{\sqrt{12}}$$



electric field

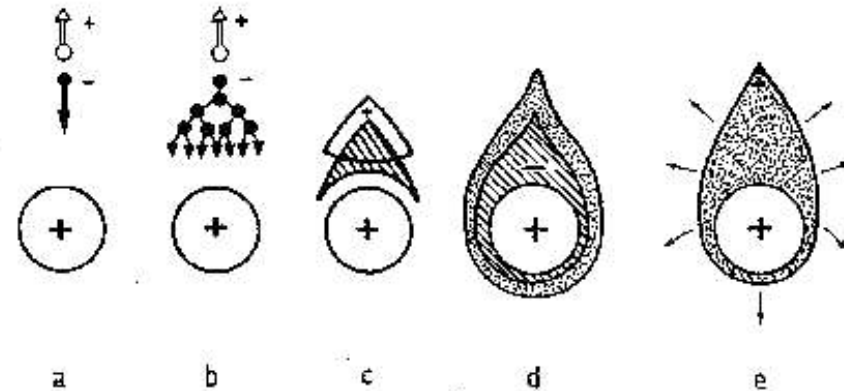
ionization liberates electrons
--> acceleration in electric field

energy gain between to electron collisions

$$\Delta E_{kin} = -e \int_{r_1}^{r_2} E(r) dr$$

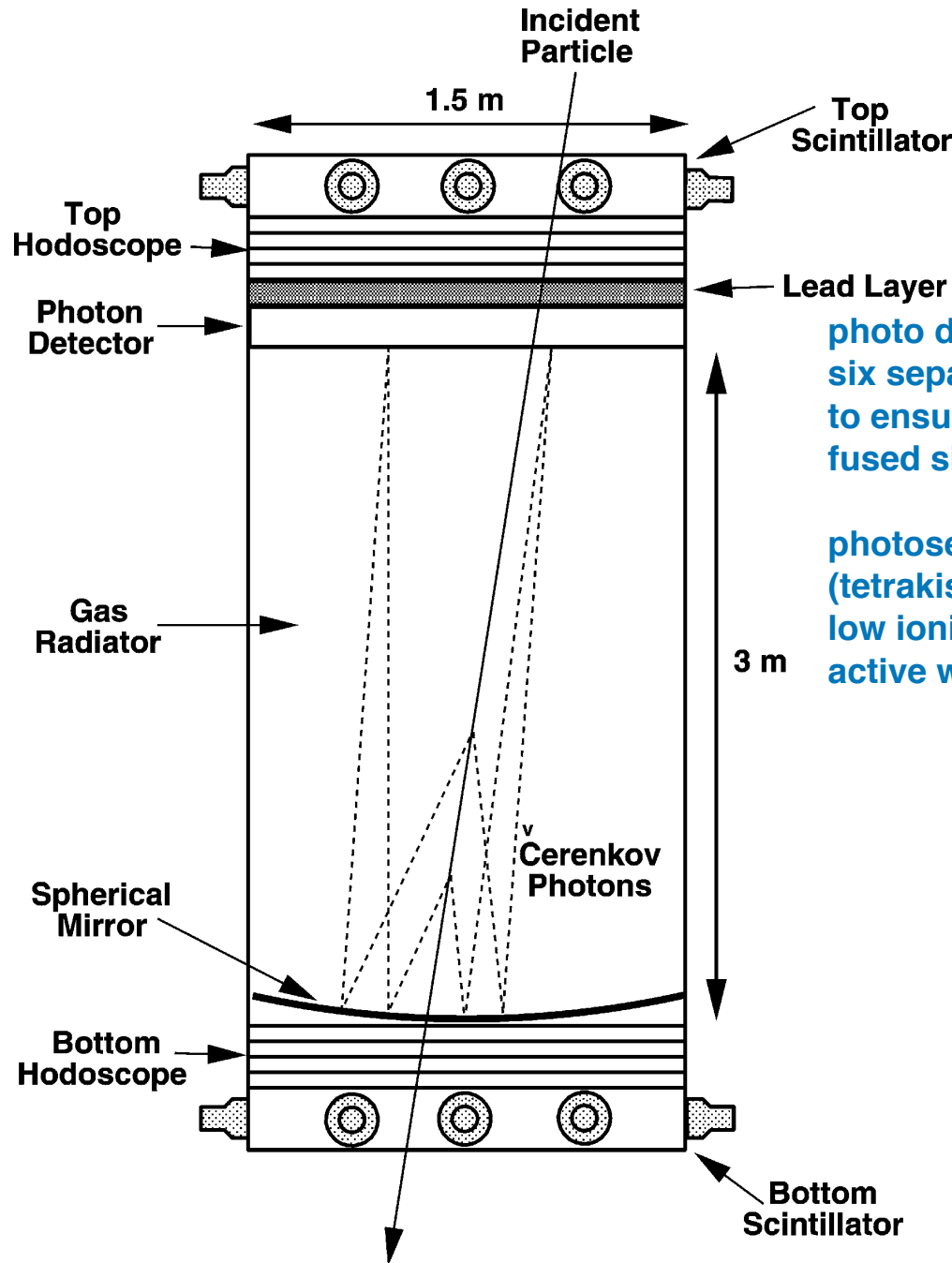
if energy gain is larger than ionization energy

--> development of electron avalanche



voltage signal $\Delta U = -\frac{eN}{C} A$

A gas amplification factor
 N charge carrier pairs
 C capacity



The energy spectrum of cosmic-ray protons and helium near 100 GeV

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photo detector:
six separate MWPCs filled with ethane to ensure the transmission of the UV Cherenkov light, fused silica is used for the entrance windows

photosensitivity is achieved with TMAE (tetrakis(dimethylamine)ethylene)
low ionization threshold 5.36 eV
active wavelength region 160 - 220 nm

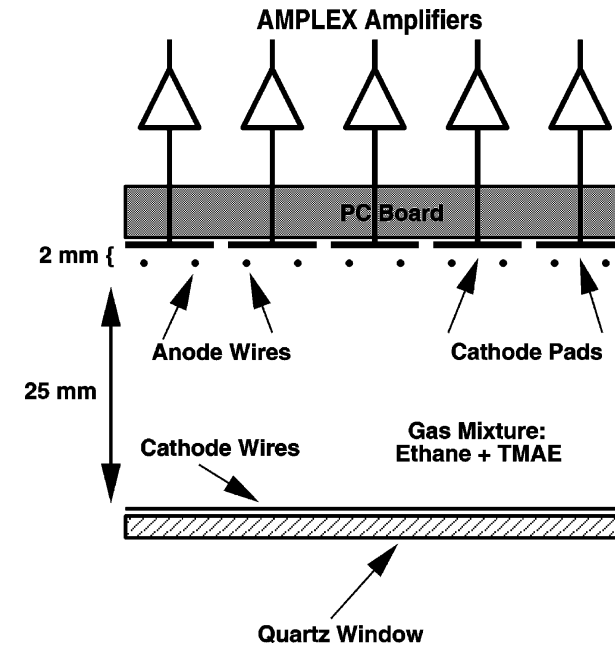


Fig. 1. Schematic cross-section of the instrument.

Fig. 3. Schematic cross-section of the photon detecting chamber.

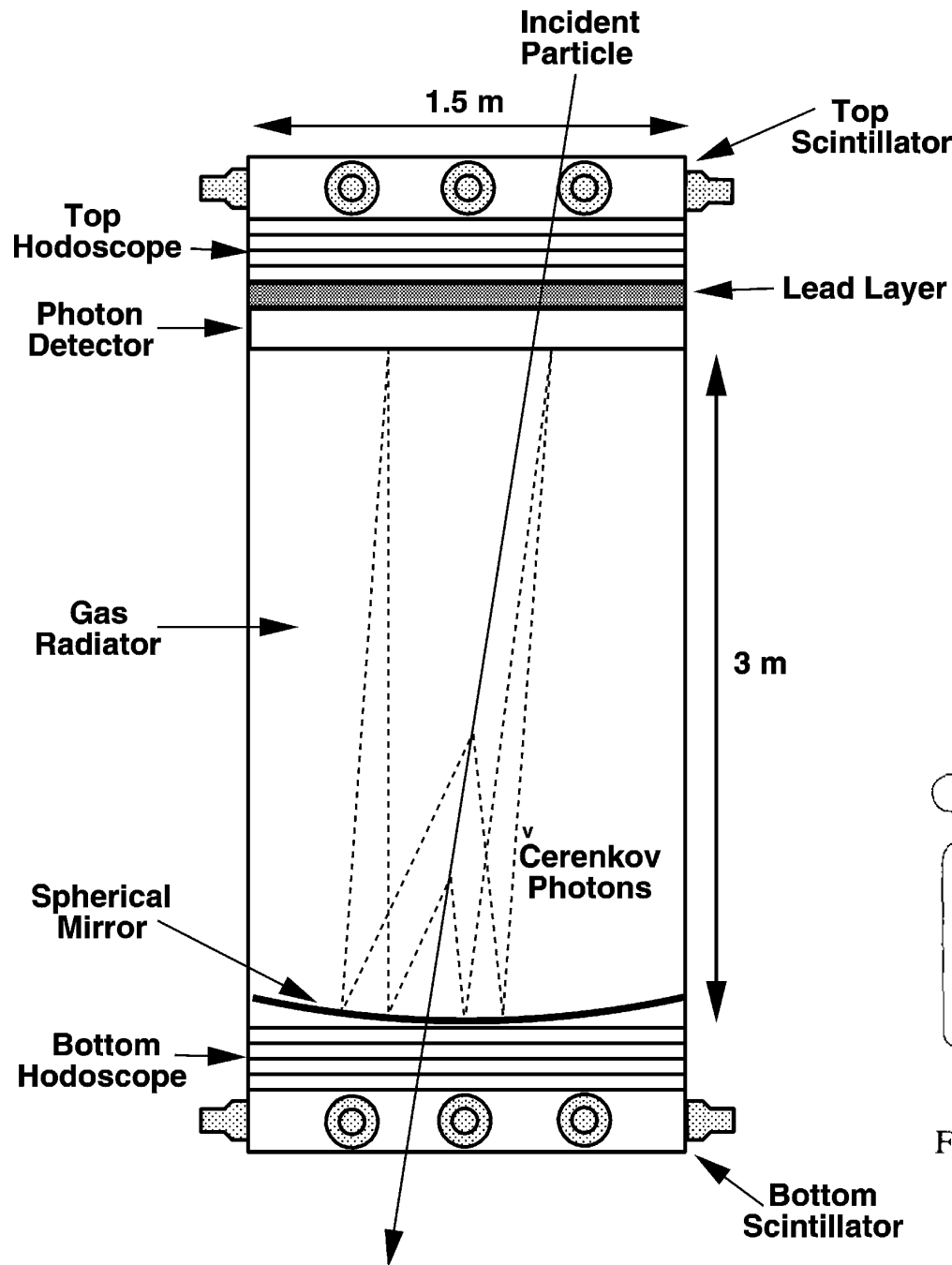


Fig. 1. Schematic cross-section of the instrument.

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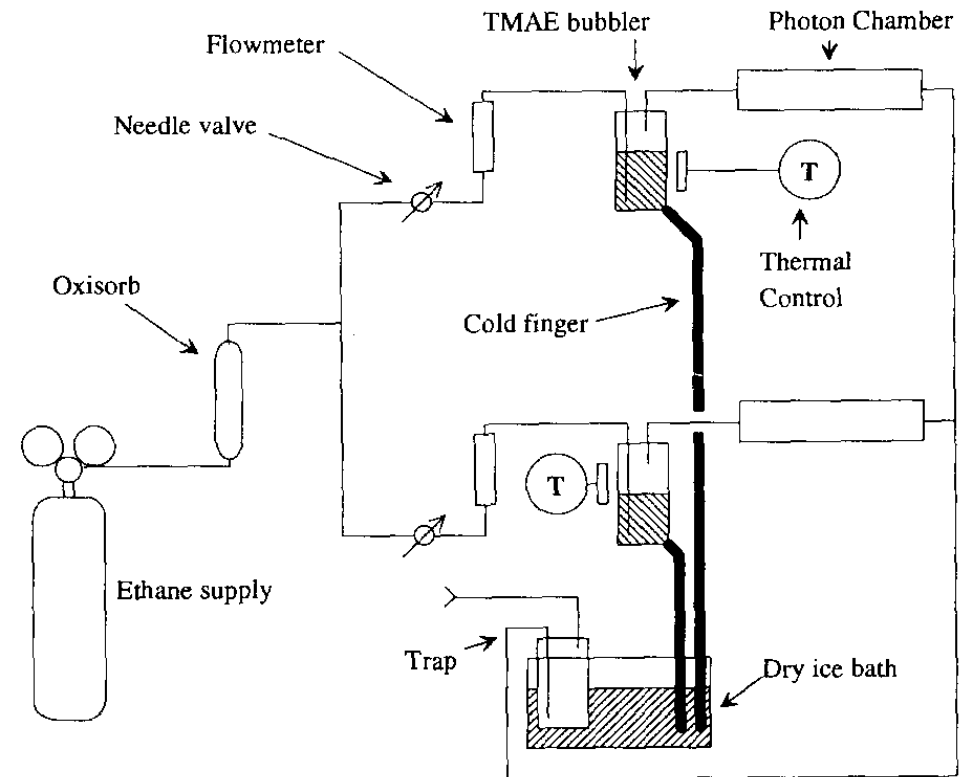


Fig. 4. Photon chamber TMAE/ethane gas system and control.

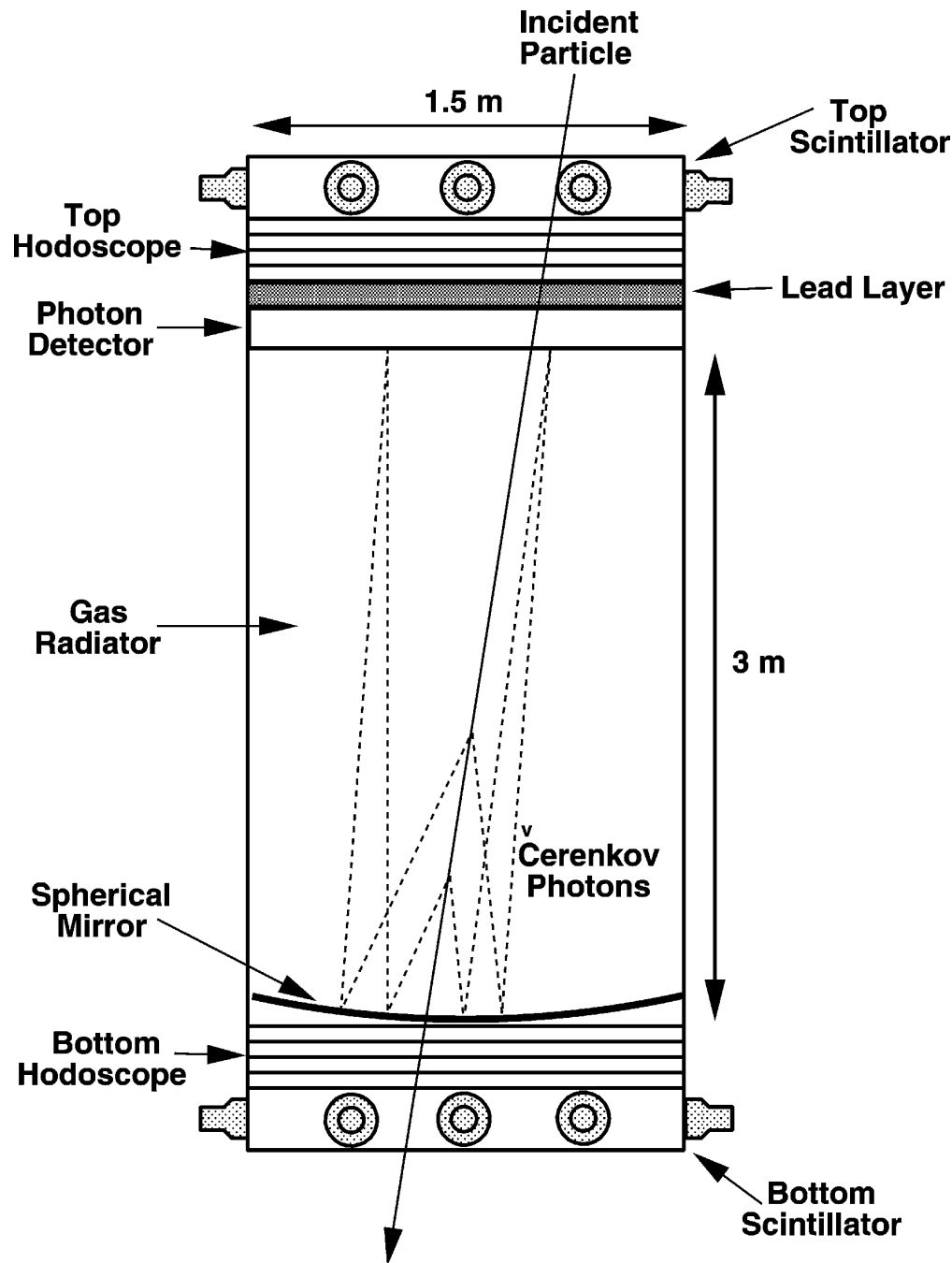


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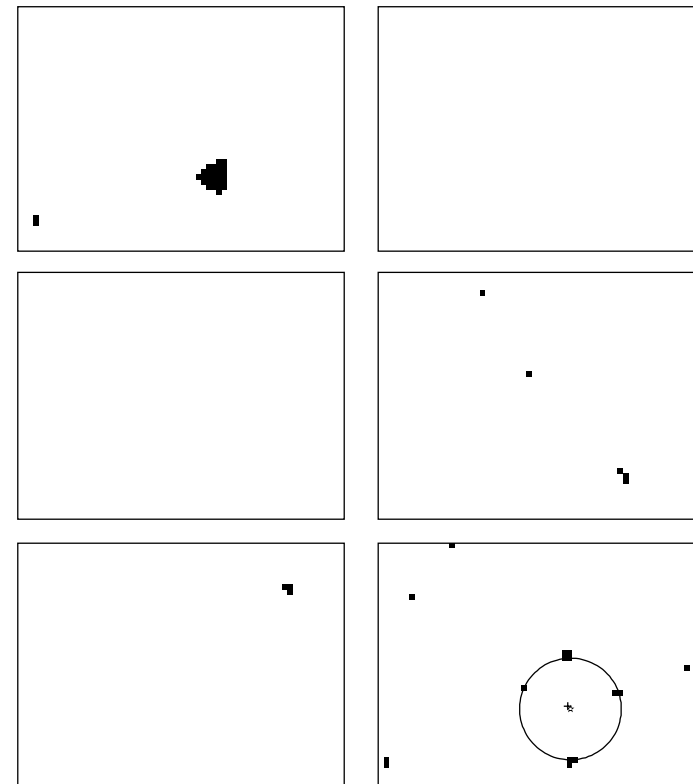


Fig. 6. A single event in the photon detecting chambers. The sensitive areas of the six chambers are shown as rectangles. Detector pads hit are shown as small black squares. The incoming particle produced a ring image of four clusters in the bottom right, the circle shows the fitted ring. The cross is the ring center predicted from the track fit, the star is the fitted center from the clusters detected. At the top left the incoming particle passed through the detector, leaving a cluster of hits. Other pads shown as hits are background.

Cherenkov Detectors **for** **particle detection in air** **showers**

Pierre Auger Observatory - Water Cherenkov Detector to measure secondary particles in air showers

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The Pierre Auger Collaboration / Nuclear Instruments and Methods in Physics Research A 798 (2015) 172–213

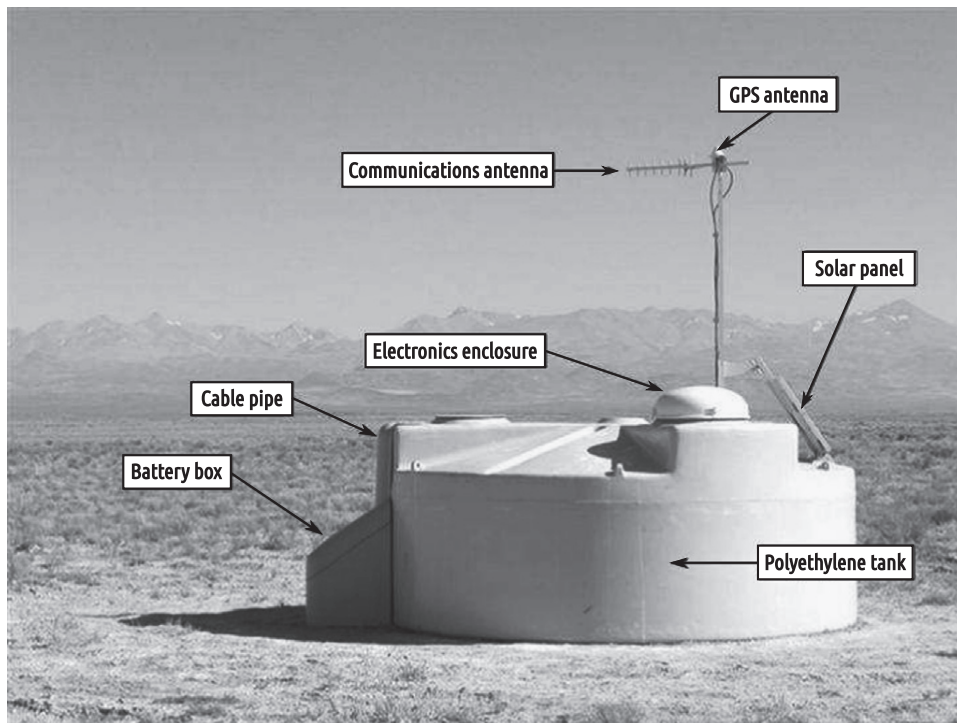


Fig. 3. A schematic view of a surface detector station in the field, showing its main components.

12000 l ultra pure water
three 9" diameter PMTs - Photonis XP1805/D1

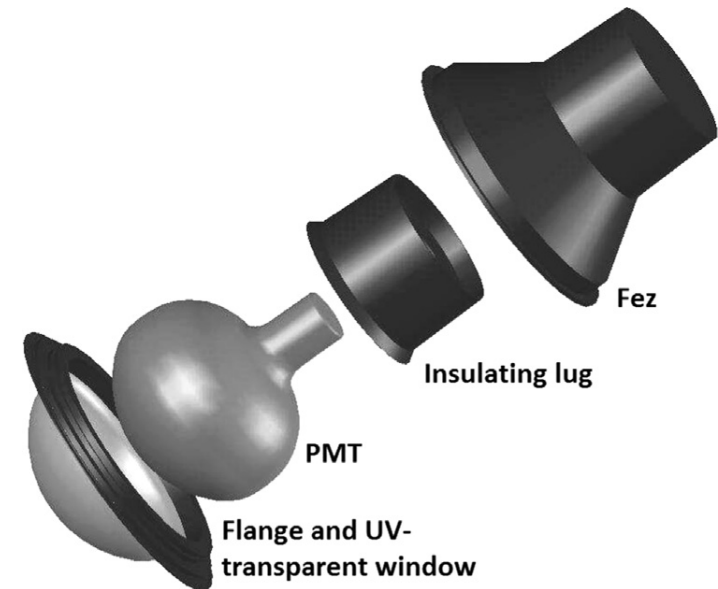


Fig. 4. Mechanical housing for the SD PMT. Top to bottom: outer plastic housing (fez), insulating lug, PMT, flange, and UV-transparent window.

expected to be available over 99% of the time. Batteries are charged through a commercial charge controller, which is epoxy encapsulated and has robust surge protection. The electronics

Pierre Auger Observatory - Water Cherenkov Detector to measure secondary particles in air showers

wireless communication system

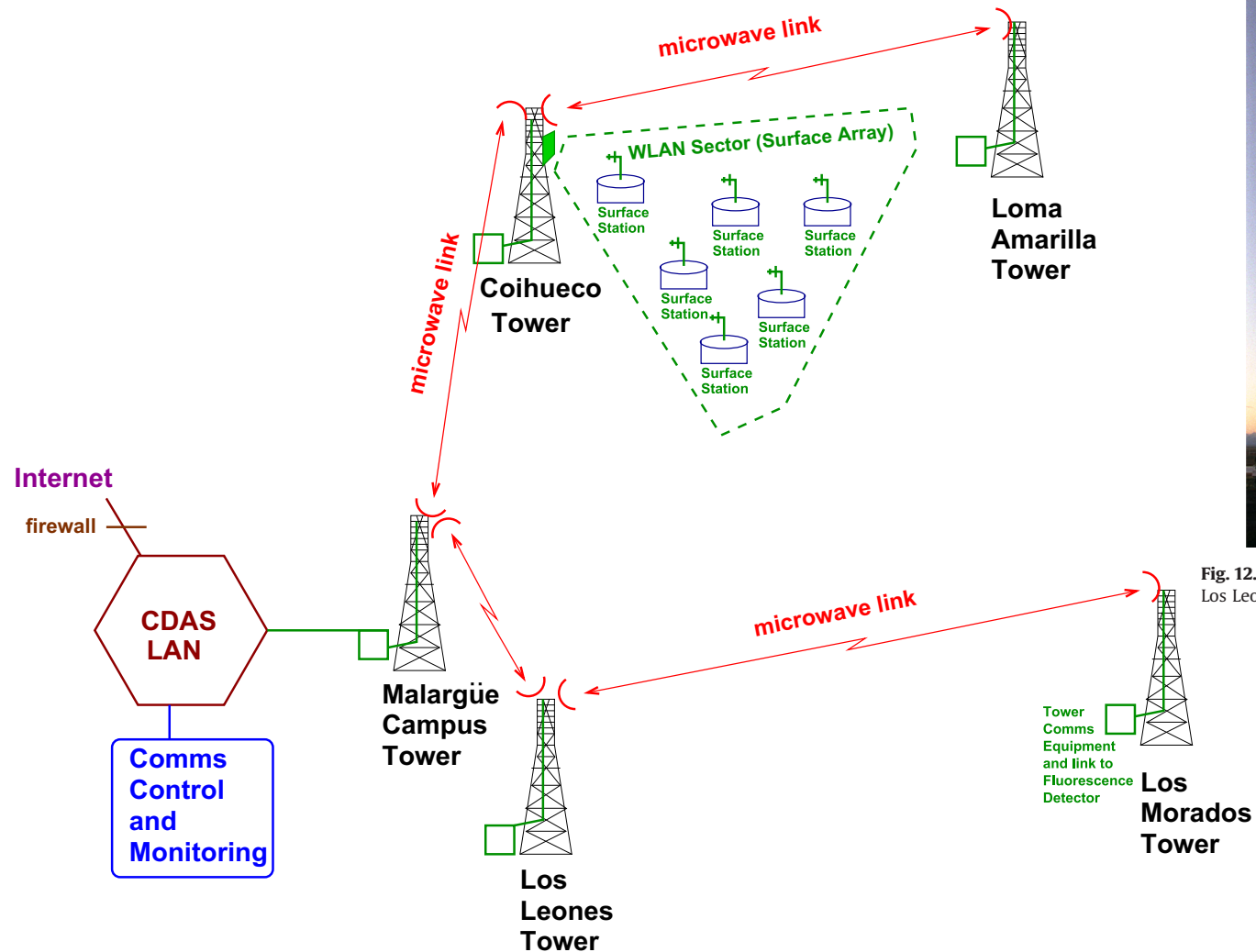


Fig. 12. One of the five communications towers: the one shown is deployed at the Los Leones site; see Fig. 11.

Fig. 11. Conceptual schematic of the overall radio telecommunications system for the Pierre Auger Observatory.

Pierre Auger Observatory - Water Cherenkov Detector to measure secondary particles in air showers

trigger system to identify extensive air showers

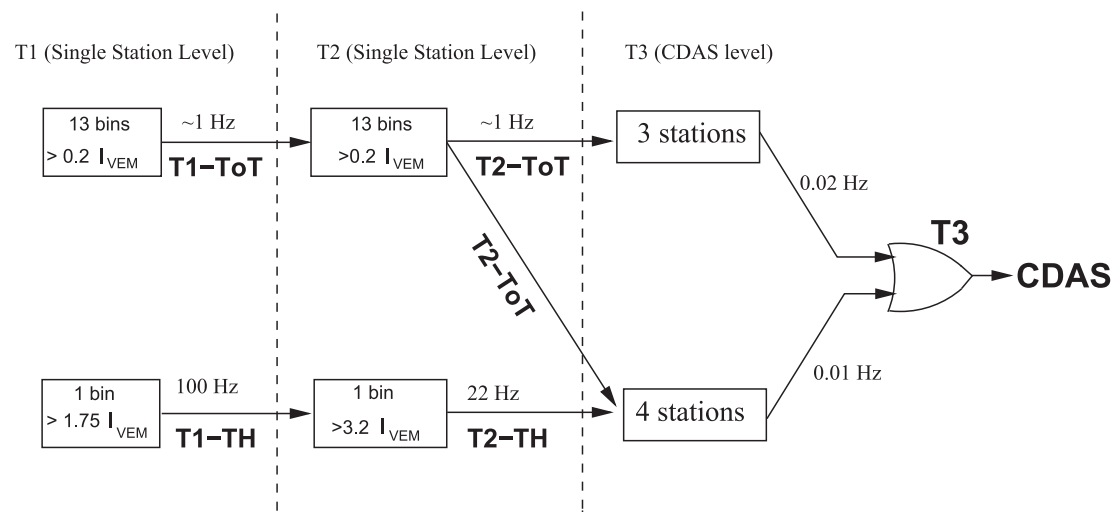


Fig. 15. Schematics of the hierarchy of the trigger system of the Auger surface detector.

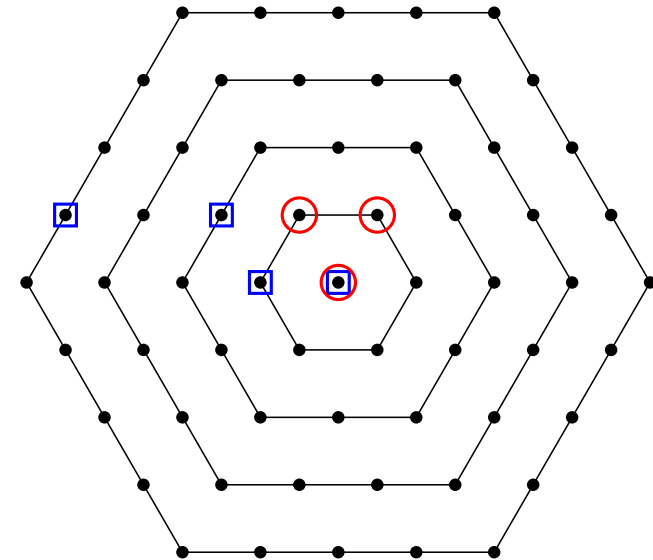


Fig. 16. Four hexagons, containing stations, are illustrated around a central surface station, for a portion of an ideal array. For a 3-fold coincidence, a T3 is issued if the 3 T2s are ToT, and if one of them is found in the first hexagon of the central station, and the other one no further than the second hexagon. A 4-fold coincidence applies to any kind of T2 and the additional station may be as distant as in the 4th hexagon. Two examples of the topology of triggers are shown: a 4-fold coincidence in which the triggered stations are identified by open blue squares, and a 3-fold coincidence identified by open red circles.

Pierre Auger Observatory - Water Cherenkov Detector to measure secondary particles in air showers

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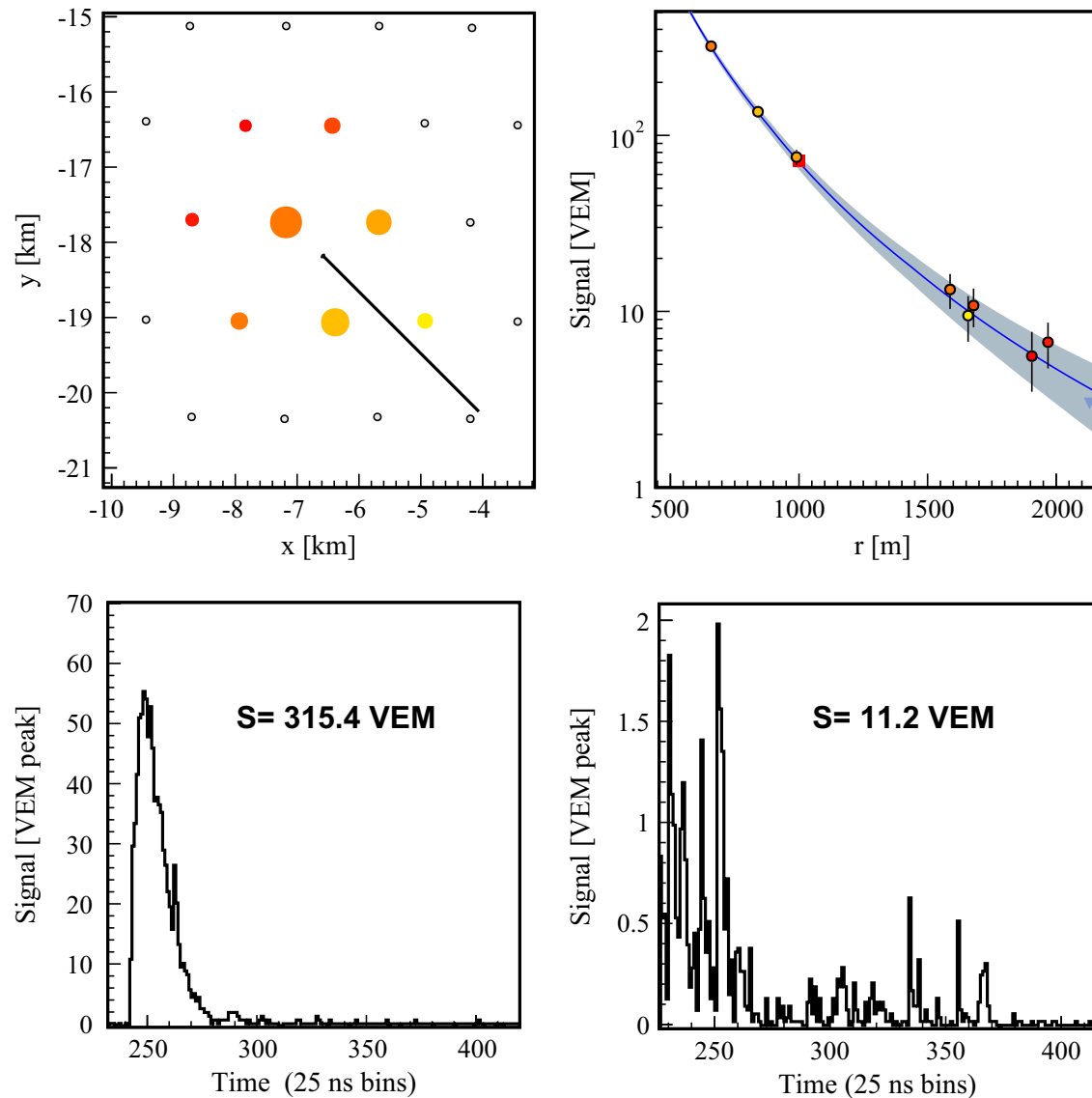


Fig. 17. Event 13357690: a typical vertical event of about 3×10^{19} eV. Top left: The array seen from above with the 8 triggered stations. Top right: The fit to the lateral distribution function (LDF) for this shower of zenith angle 28° . Bottom: The FADC traces from 2 detectors at distances of 650 and 1780 m from the shower core. The signal sizes are in units of VEM.

