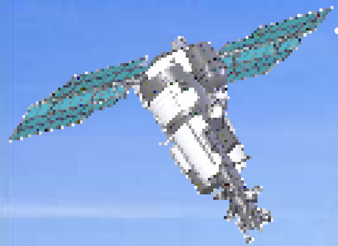


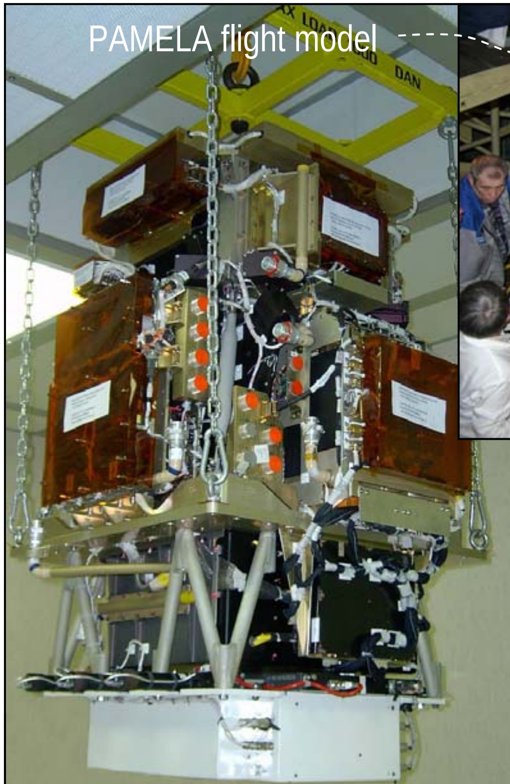
In-flight performances of the PAMELA magnetic spectrometer

Elena Vannuccini

INFN Florence

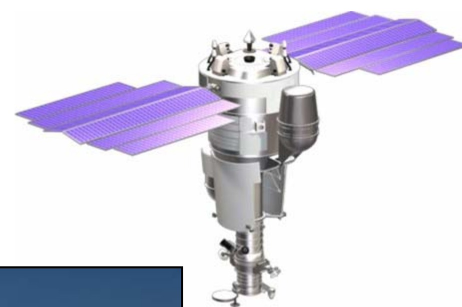
On behalf of the PAMELA spectrometer group

The PAMELA experiment



MAIN TOPICS:
- CR *antiproton* and *positron* spectra:
  - ~10^4 antiprotons → 80 MeV/c - 190 GeV/c
  - ~10^5 positrons → 50 MeV/c - 270 GeV/c
- search for light antinuclei

SECONDARY TOPICS:
- Modulation of GCRs in the Heliosphere
- Solar Energetic Particles (SEP)
- Earth Magnetosphere



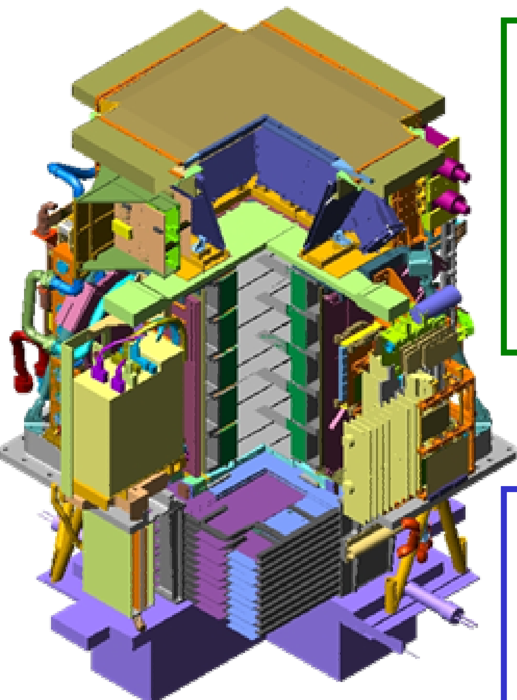
- PAMELA on board of Russian satellite **Resurs DK1**
- Orbital parameters:
  - inclination ~70^o ($\Rightarrow$ low energy)
  - altitude ~ 360-600 km (elliptical)
  - active life >3 years ($\Rightarrow$ high statistics)
- *Launched on 15th June 2006*

→ **First switch-on on 21st June 2006**
- Detectors in nominal conditions (no problems due to the launch)
- Tested different trigger and hardware configurations
- Commissioning phase successfully ended on September 15th 2006

→ **PAMELA in continuous data-taking mode since then!**

PAMELA detectors

Main requirements → high-sensitivity antiparticle identification and precise momentum measure

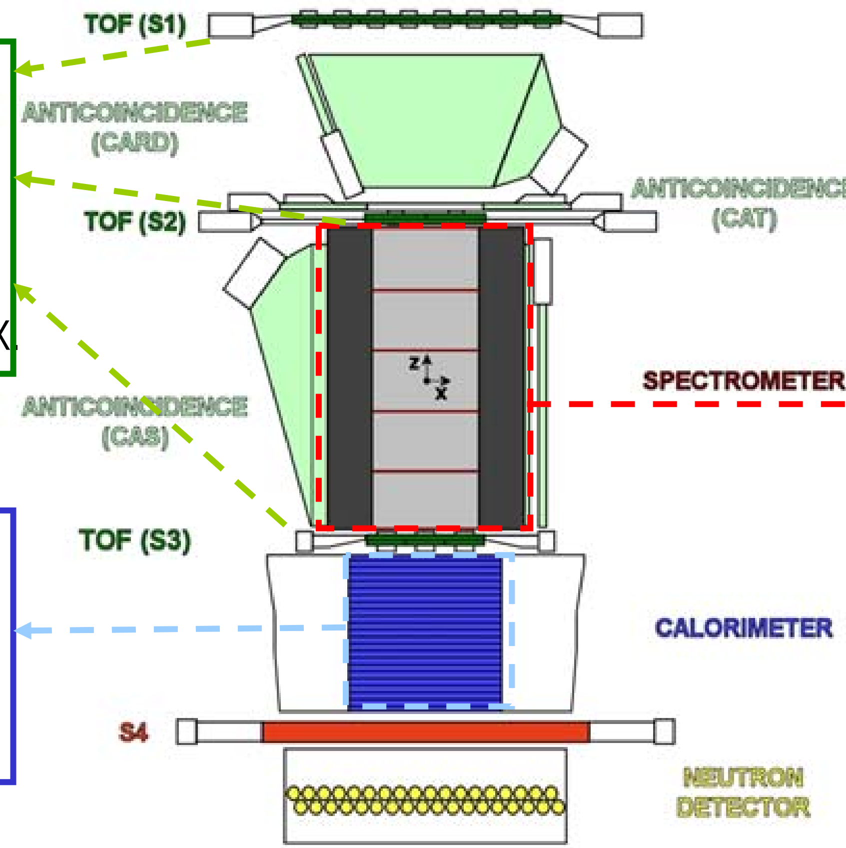


Time-Of-Flight

plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Electromagnetic calorimeter

W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

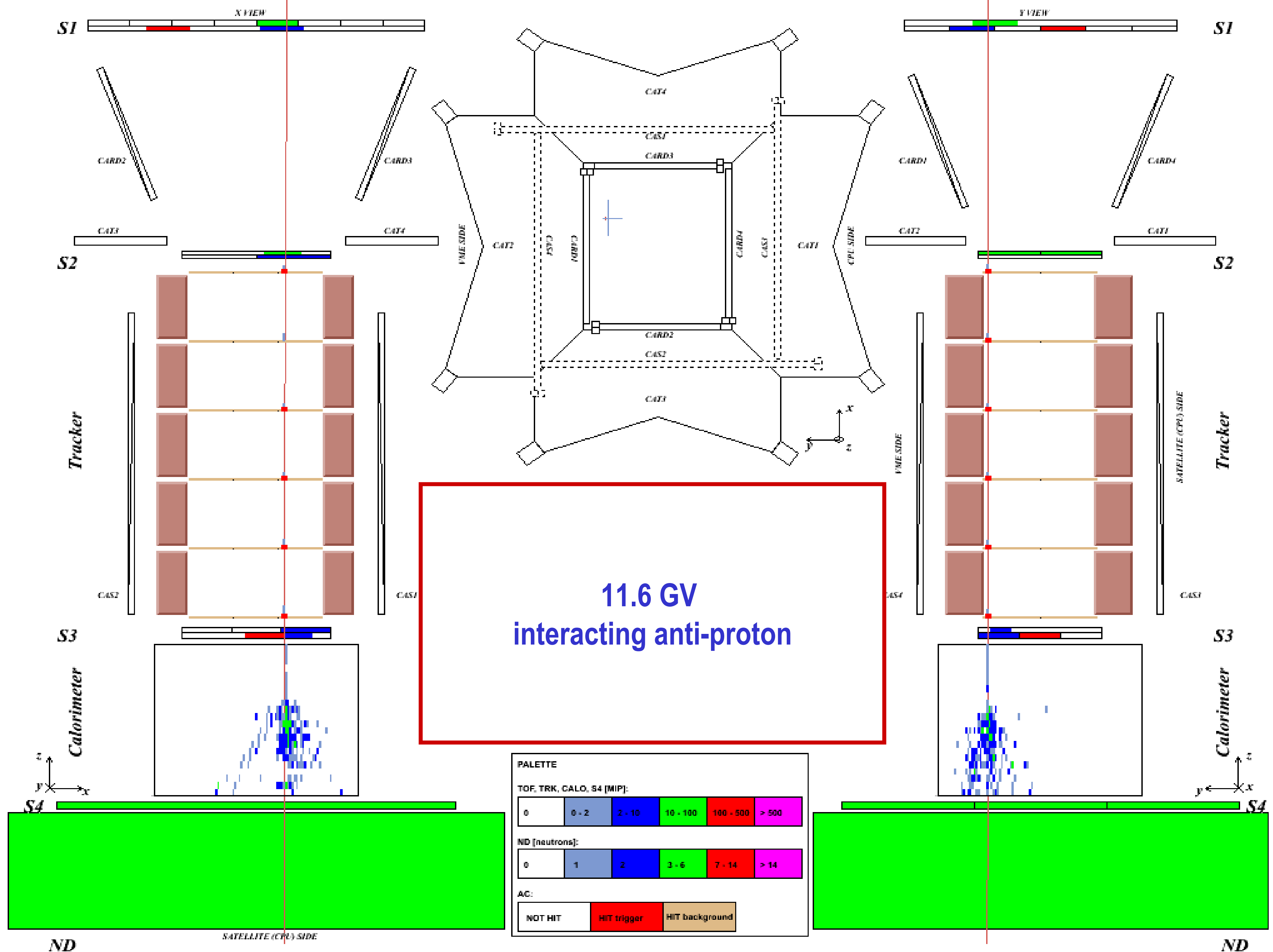


GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W

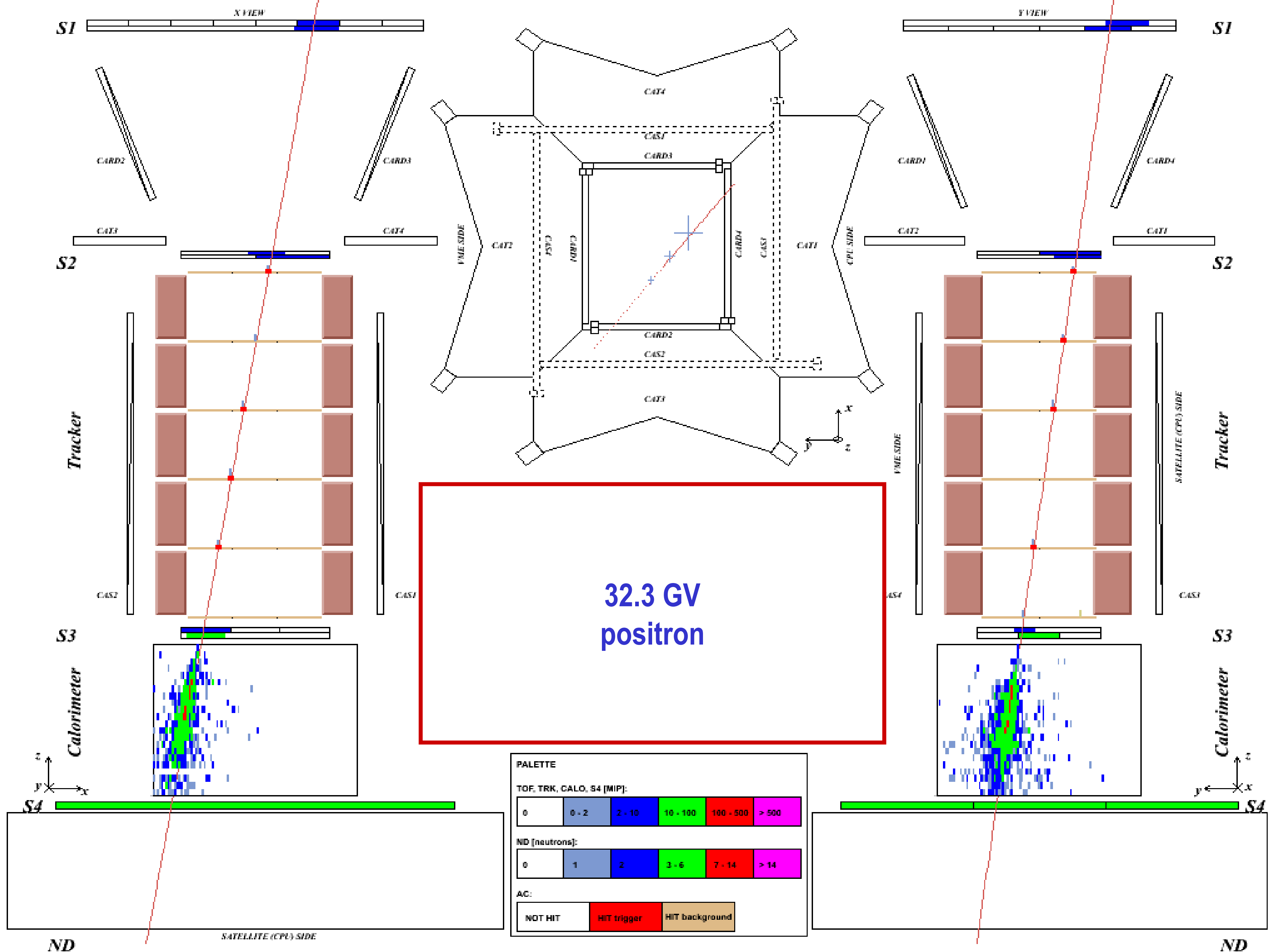
Spectrometer

microstrip silicon tracking system + permanent magnet

It provides:
- ***Magnetic rigidity*** → R = pc/Ze
- ***Charge sign***
- ***Charge value from dE/dx***



X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
11.6 GV
interacting anti-proton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background


X VIEW
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S1
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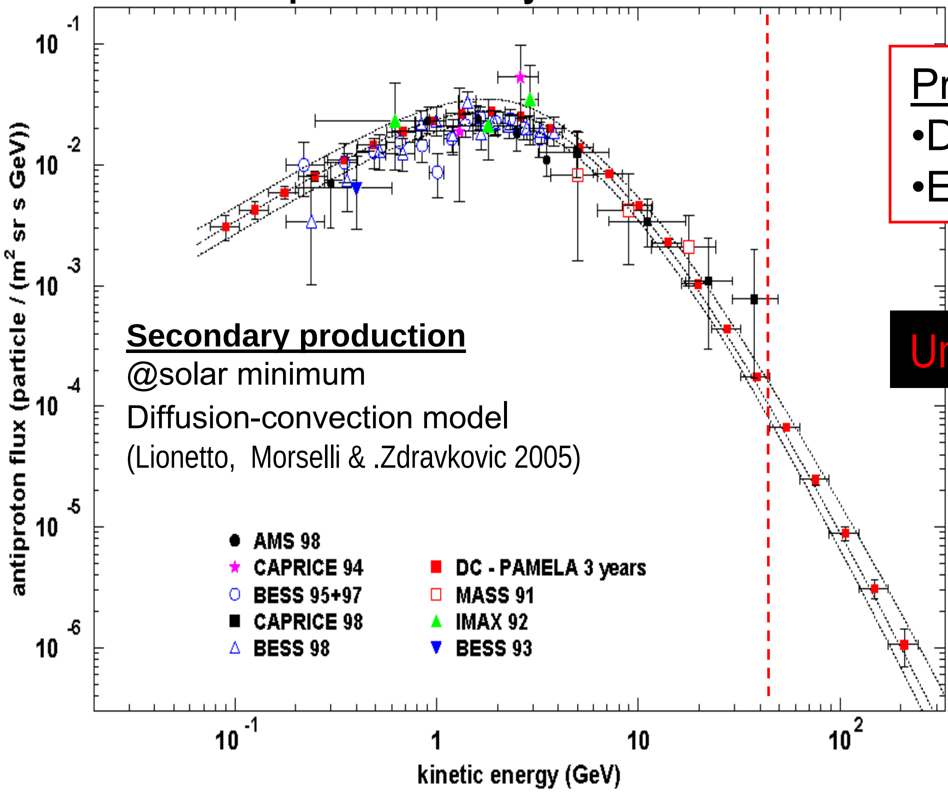
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
32.3 GV
positron
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

Antiprotons

PAMELA expectation in 3 years



Primary sources ?
- Dark matter
- Extragalactic primordial p-bar

Unexplored Region

Maximum energy set by
proton spillover background
(wrong determination of charge sign)

Spectrometer required performances:

4 μm resolution on the bending view (x) → MDR = 740 GV → spillover limit **190 GeV**

(MDR = Maximum Detectable Rigidity → ΔR/R=1 @ R=MDR)

Outline

- Summary of spectrometer design
- In-flight performances (main focus on relativistic protons):
  - Basic performances
  - Position reconstruction
  - Momentum measurement
  - Preliminary results
- Conclusions

Spectrometer design

PAMELA scientific objectives require extremely good momentum resolution:

- silicon detectors → low noise electronics → *spatial resolution ~μm*
- reduced amount of traversed material → *minimize multiple scattering effect*

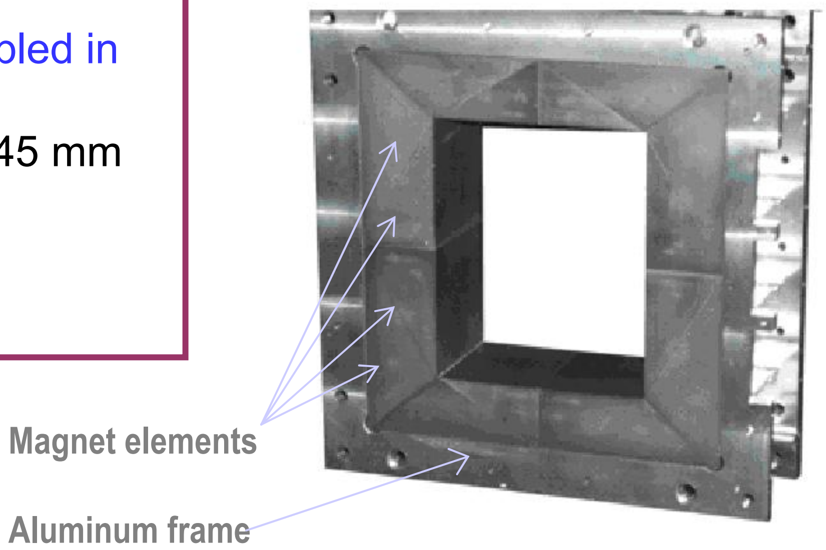
Satellite constraints:

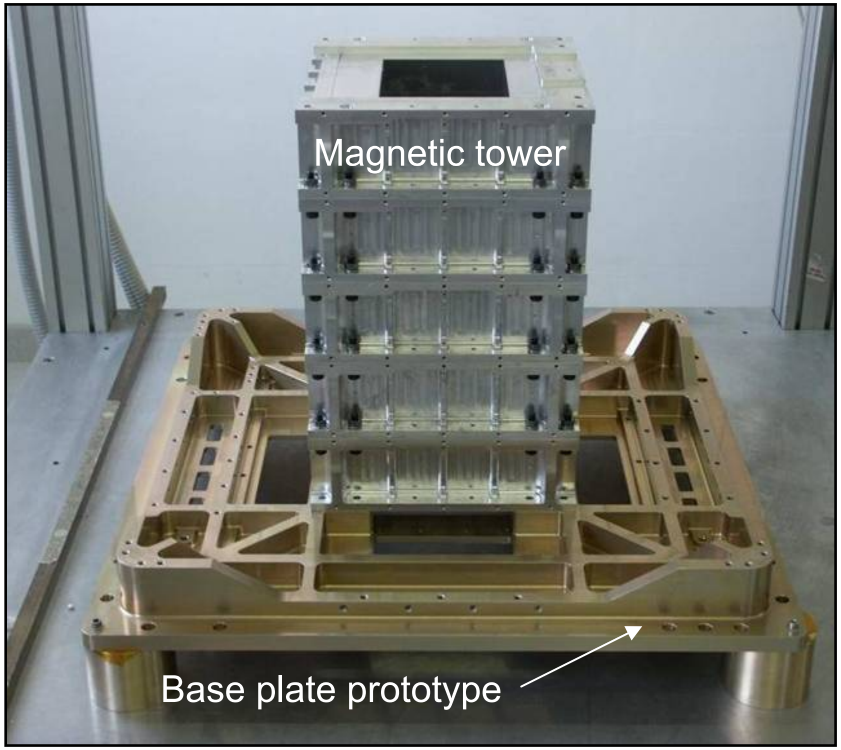
- mechanical stresses during launch phase (7.4 g rms, 50 g shocks)
- thermal variations (5-35 ^{o}C)
- small power consumption
- redundancy and safety
- protection against highly ionizing cosmic rays
- limited telemetry

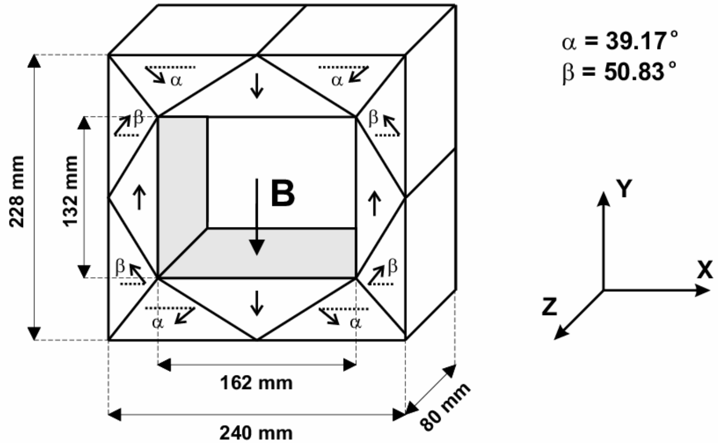
The magnet

- 5 magnetic modules
- Permanent magnet (Nd-Fe-B alloy) assembled in an aluminum mechanics
- Magnetic cavity sizes (132 x 162) mm^2 x 445 mm
- *Geometric Factor*: **20.5 cm^2sr**
- Black IR absorbing painting
- Magnetic shields

Magnetic module



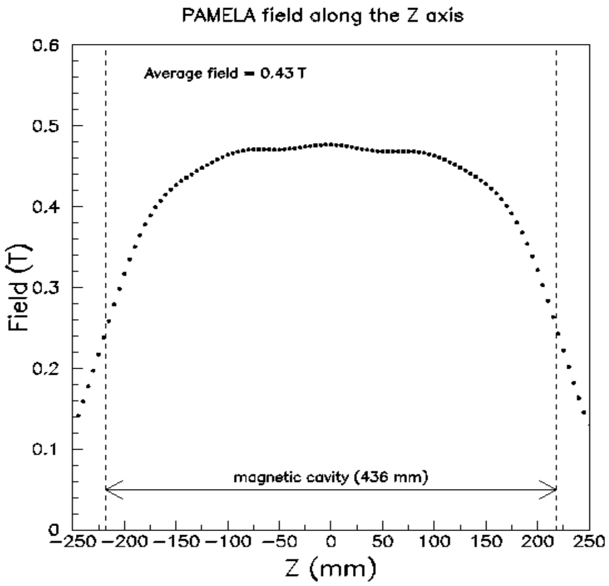


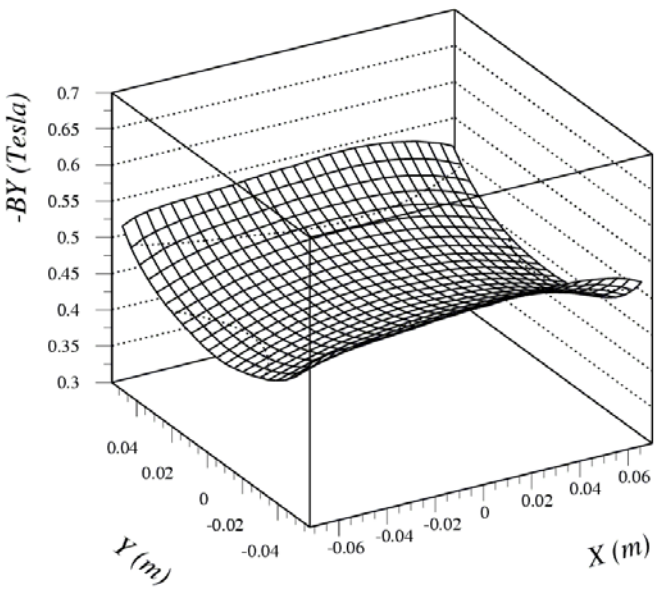


The magnetic field

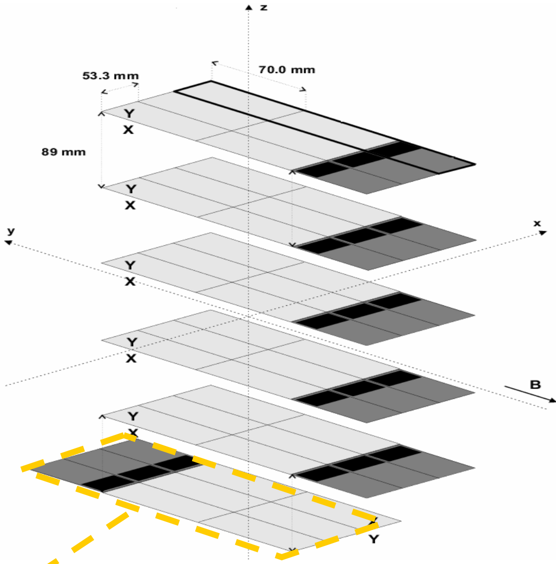
<u>MAGNETIC FIELD MEASUREMENTS</u>

- Gaussmeter (F.W. Bell) equipped with 3-axis probe mounted on a motorized positioning device (0.1mm precision)
- Measurement of the three components in 67367 points 5mm apart from each other
- Field inside the cavity:
    - **0.48 T** @ center
    - Average field along the axis: **0.43 T**
- **Good uniformity**
- External magnetic field: magnetic momentum < 90 Am^2





The tracking system

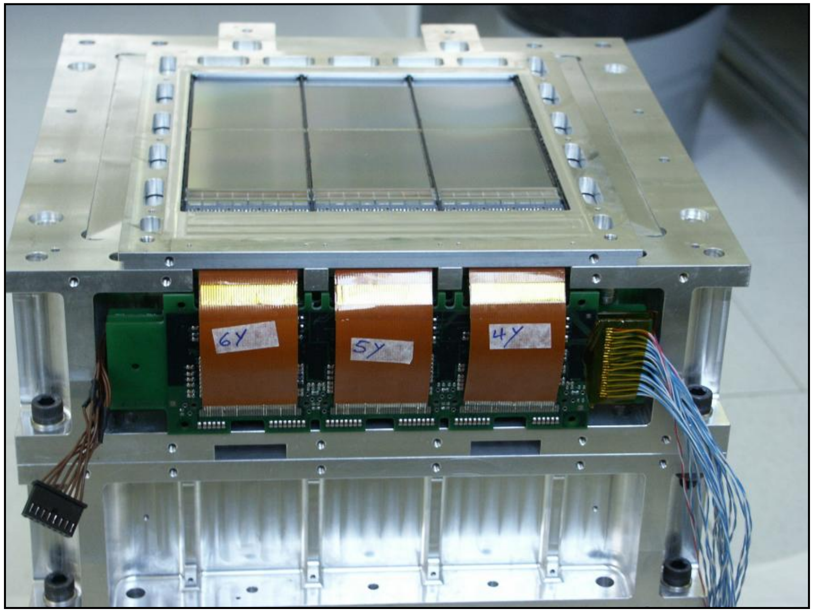


6 detector planes, each composed by 3 ladders

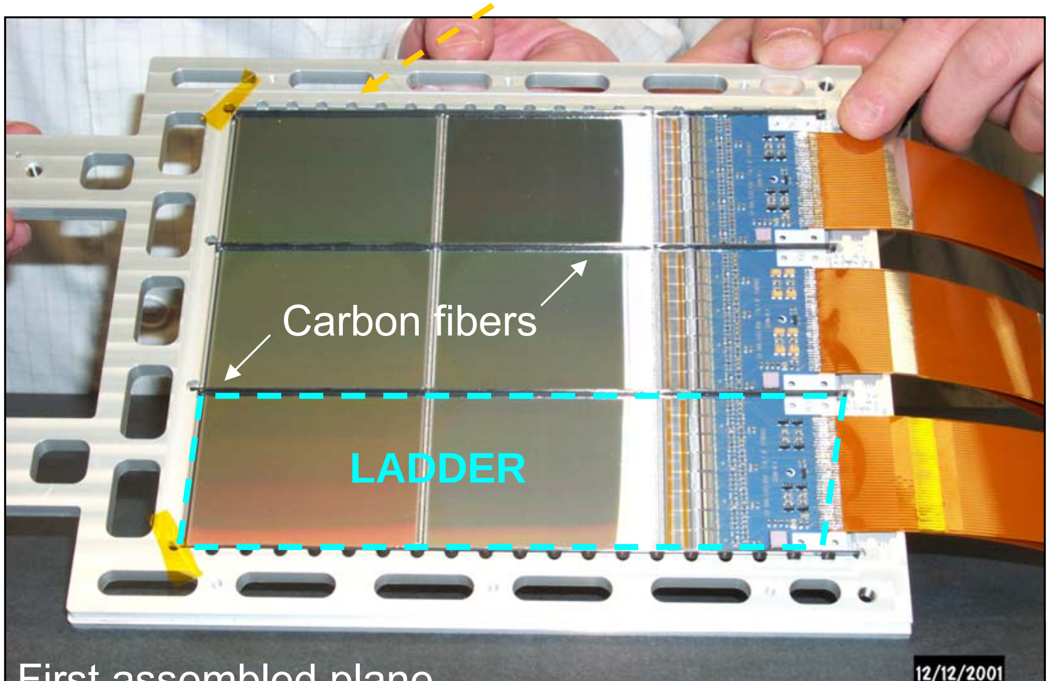
Mechanical assembly

- aluminum frames
- carbon fibers stiffeners glued laterally to the ladders
- no material above/below the plane

  1 plane = **0.3% X_0** → reduced multiple scattering
- elastic + rigid gluing

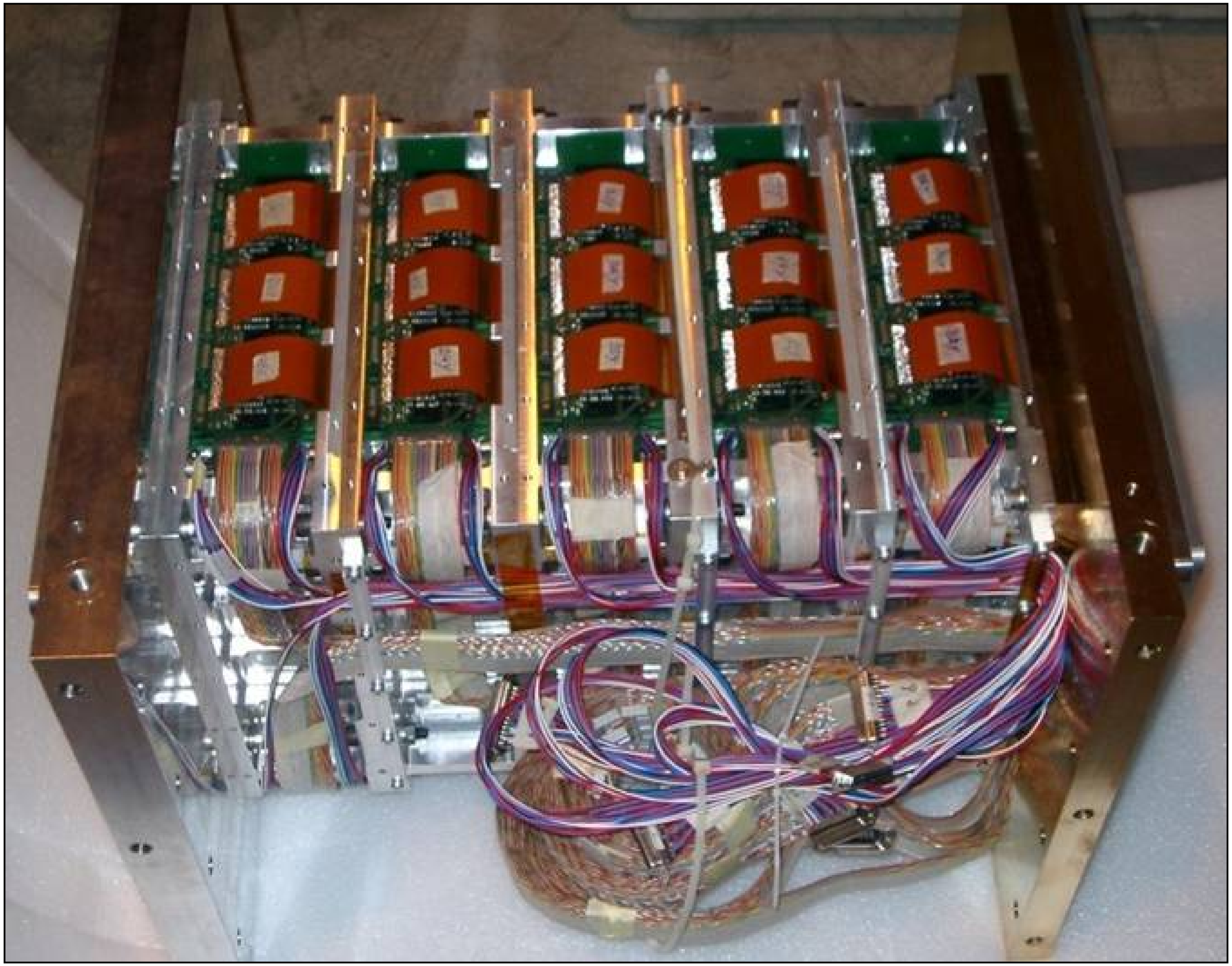


Test of plane lodging inside the magnet

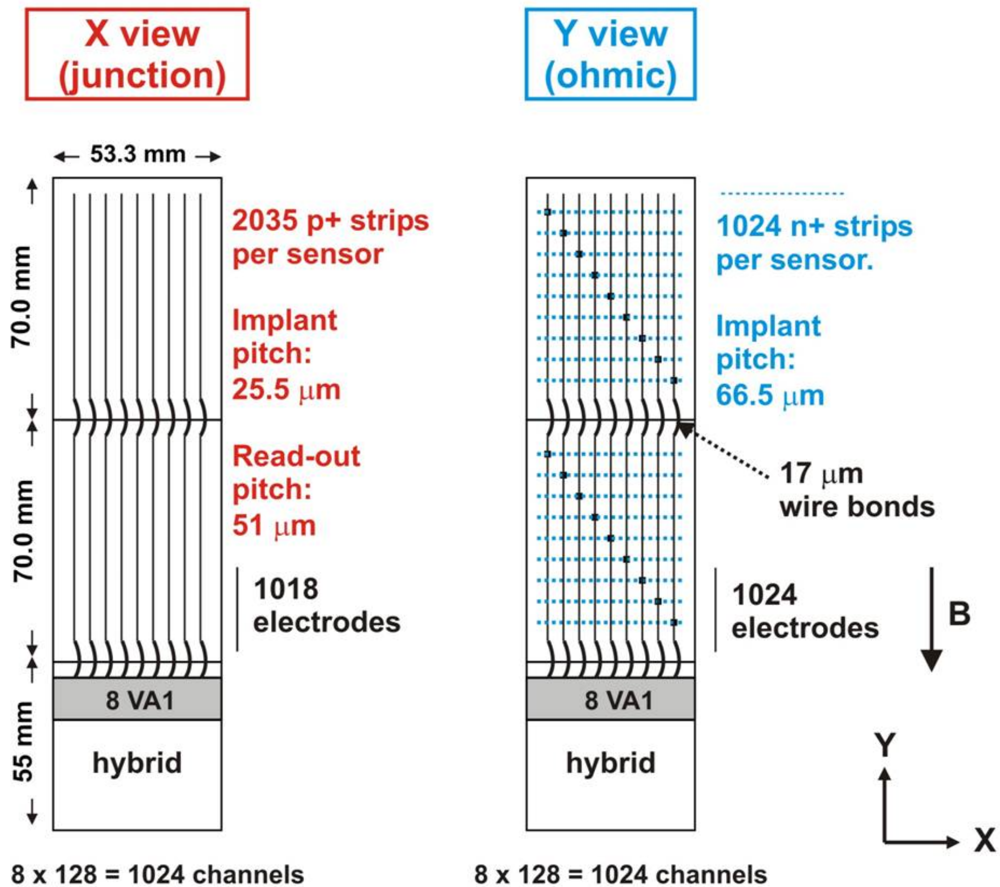


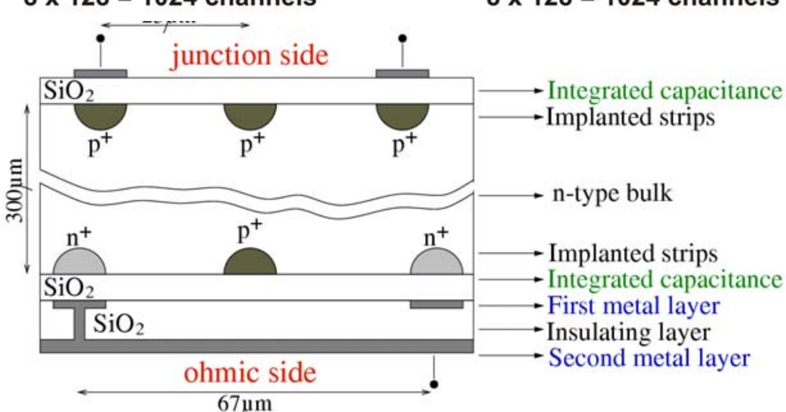
First assembled plane

The flight model



Silicon detector ladders





- **2 microstrip silicon sensors**
- **1 "hybrid" with front-end electronics**

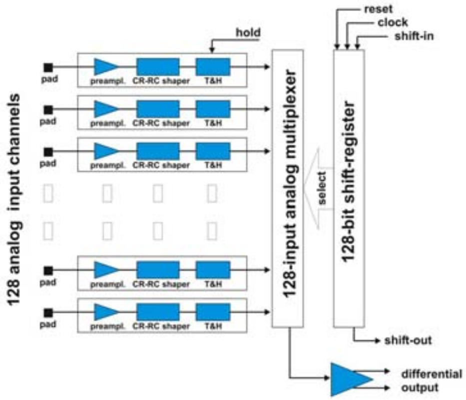
<u>Silicon sensors (Hamamatsu)</u>:

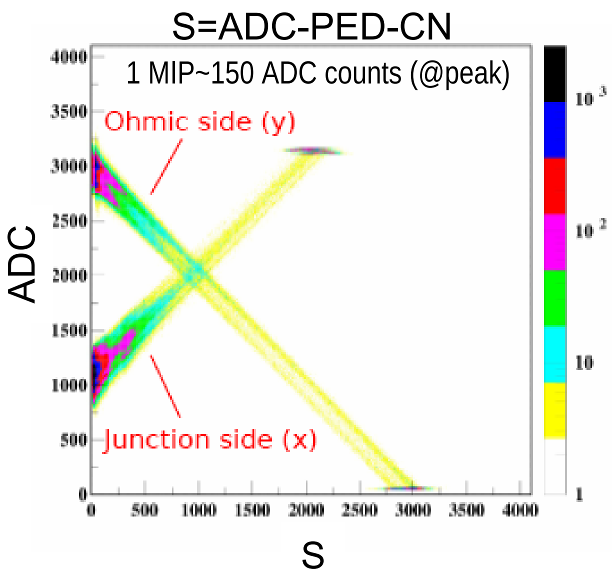
- **300 µm, double sided - x & y view**
- **AC coupled** (no external chips)
- **double metal** (no kapton fanout)
- 1024 read-out channels per view
  - strip/electrode coupling ~ 20 pF/cm;
  - channel capacitance to ground:
    - junction: < 10 pF
    - ohmic: < 20 pF

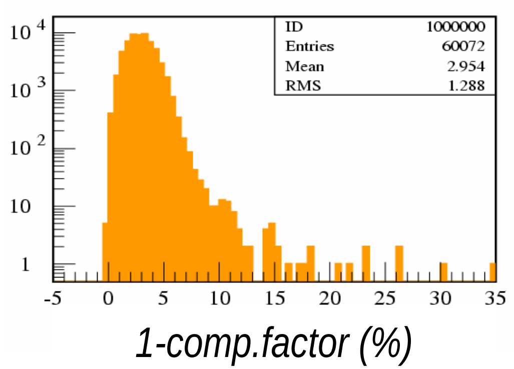
<u>Bias</u>:

- VY -VX = + 80 V fed through guard ring surrounding the strips
- Bias resistor:
  - junction: punch-through, > 50 MΩ;
  - ohmic: polysilicon, > 10 MΩ.
- Leakage current < 1 µA/sensor.

Readout electronics







Front-end → **VA1 chips**:

- 16 chip/ladder → 288 chips
- 1.2 μm CMOS ASIC (CERN - Ideas, Norway);
- 6.2 mm · 4.5 mm chip area; 47 μm input pad pitch
- 128 low-noise charge preamplifiers
- shaping time 1 μs
- operating point set for optimal compromise:
  - -Po wer consumption 1.0 mW/channel → *total dissipation 37 W for 36864 channels;*
  - - voltage gain 7.0 mV/Fc → *dynamic range up to 10 MIP*

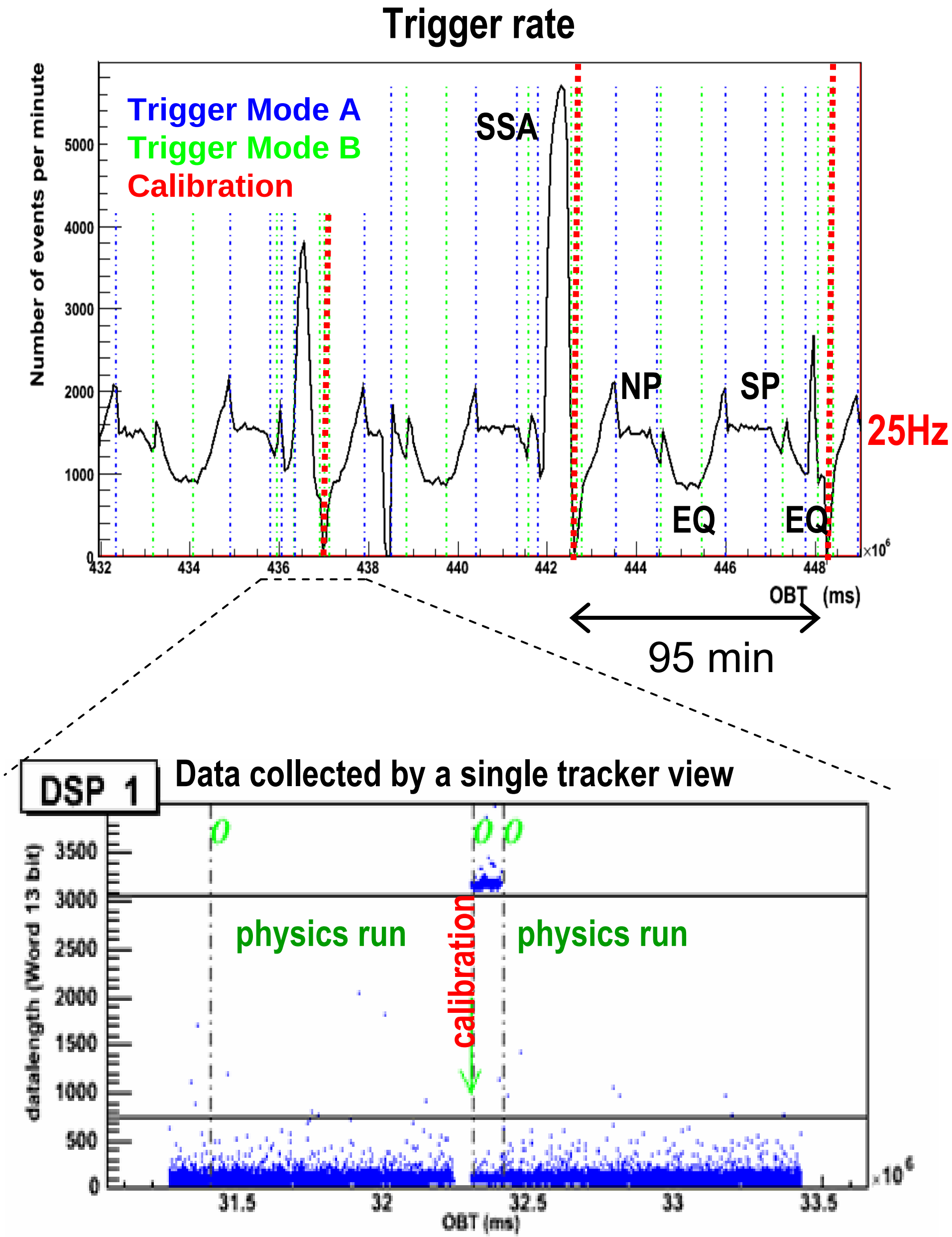
ADC:

- 1 ADC/ladder → 36 ADCs
- event acquisition time 2.1 ms.

DSP:

- 1 DSP/view (ADSP2187L) → 12 DSPs
- control logics on FPGA chips (A54SX)
- *on-line calibration* (PED,SIG,BAD)
- *data compression*:
  - - compression factor **> 95%**
  - - compression time **~1.1 ms**

Orbital environment and in-flight operation



- Particle rate:
  - -maximum at the poles (cutoff <100 MV)
  - -minimum at the equator (cutoff ~15 GV)
- Instrument operates also inside radiation belts

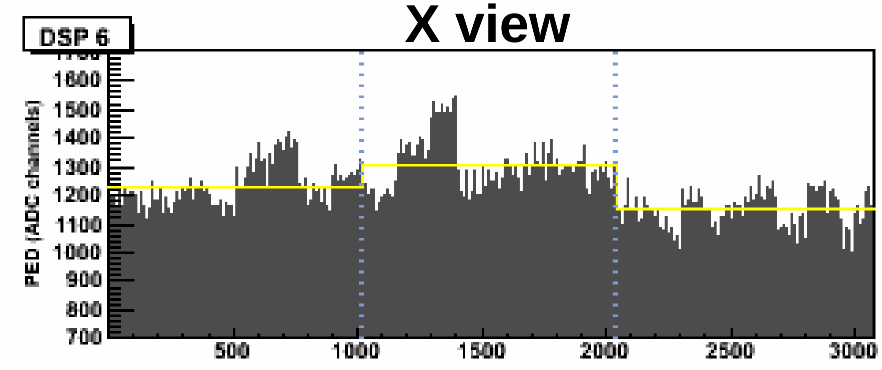
Tracker operations:

- Calibration performed every 95 min, soon after ascending node
- Data acquisition
  - Special run after calibration → *full mode*
  - Physics run → *compressed mode (~5%)*
  - 12 x 250 B ~ **3 kB/ev** → 5 kB/ev (all detectors)
- Slow controls , eg temperature sensors:
  - →~21° @ power up, **~28°** @ regime
  - → < 1° C variations along orbit
- Remote controls:
  - → DSP configuration

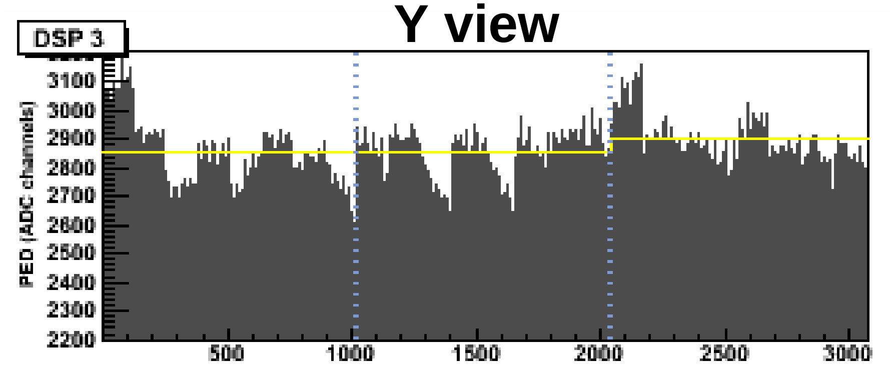
Calibration

Pedestal

X view

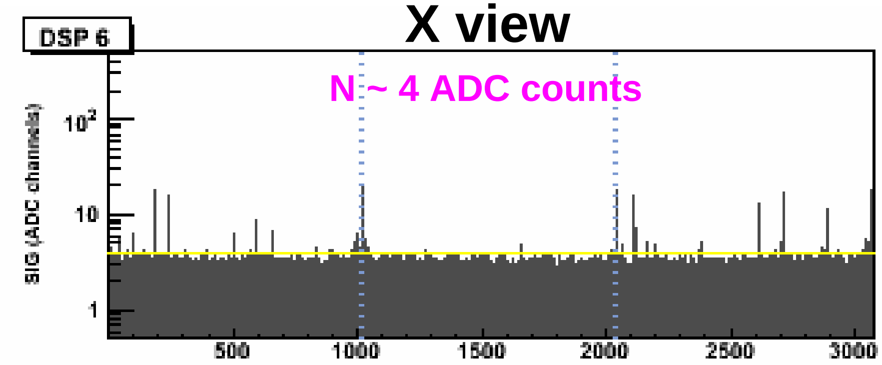


Y view

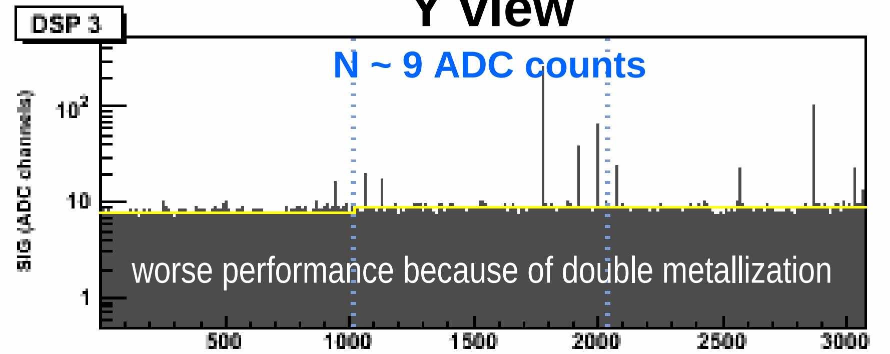


Noise

X view

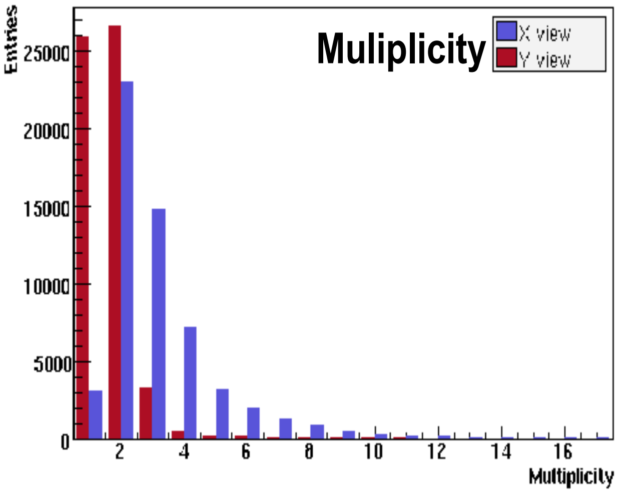


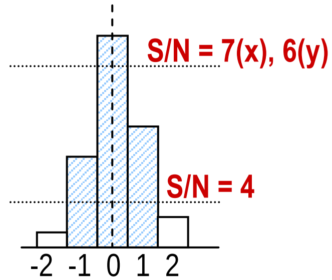
Y view

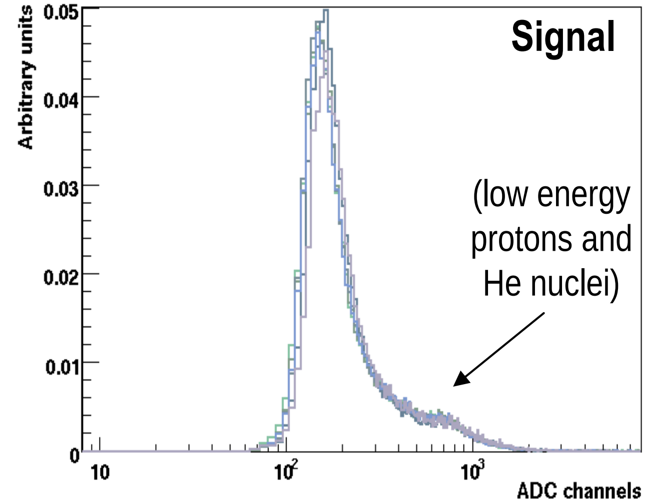


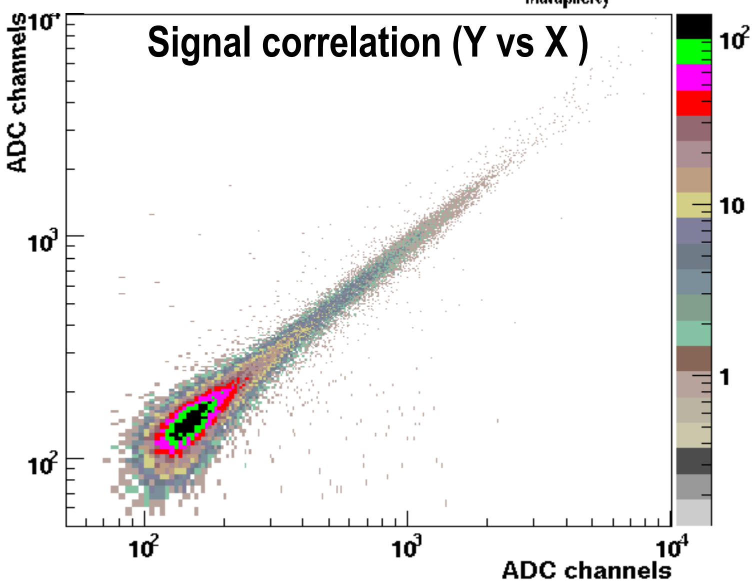
→ Noise performance is nominal

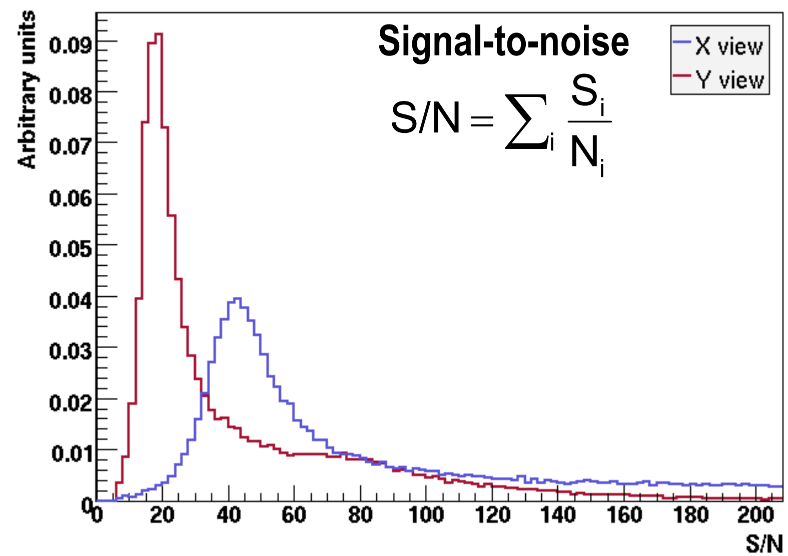
Cluster signal







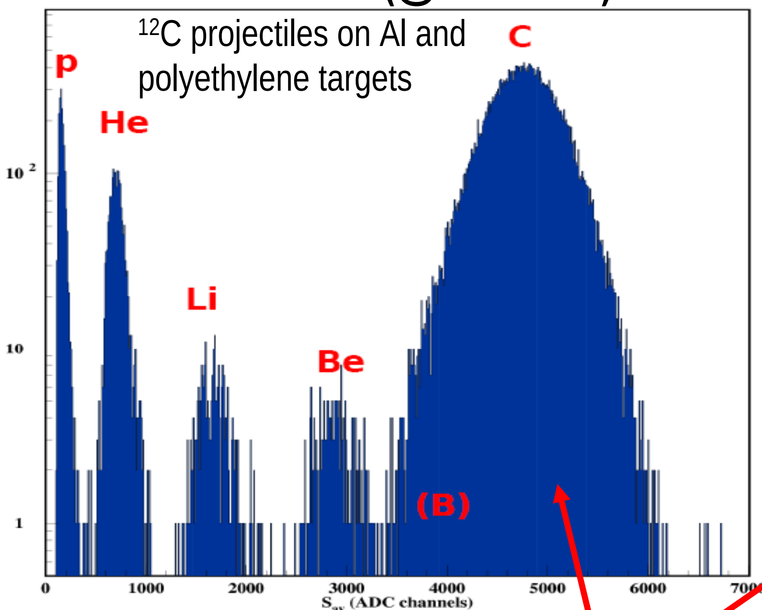




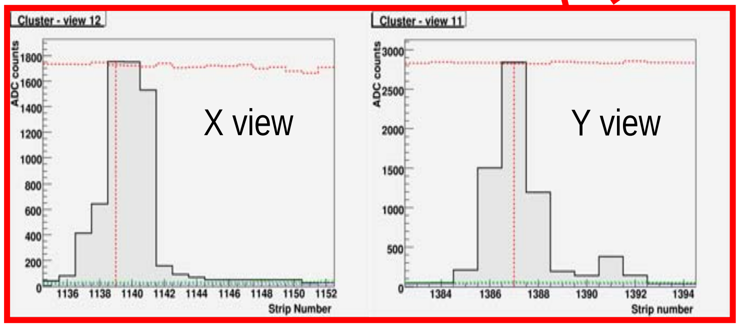
→ Cluster characteristics are nominal

Charge identification capabilities

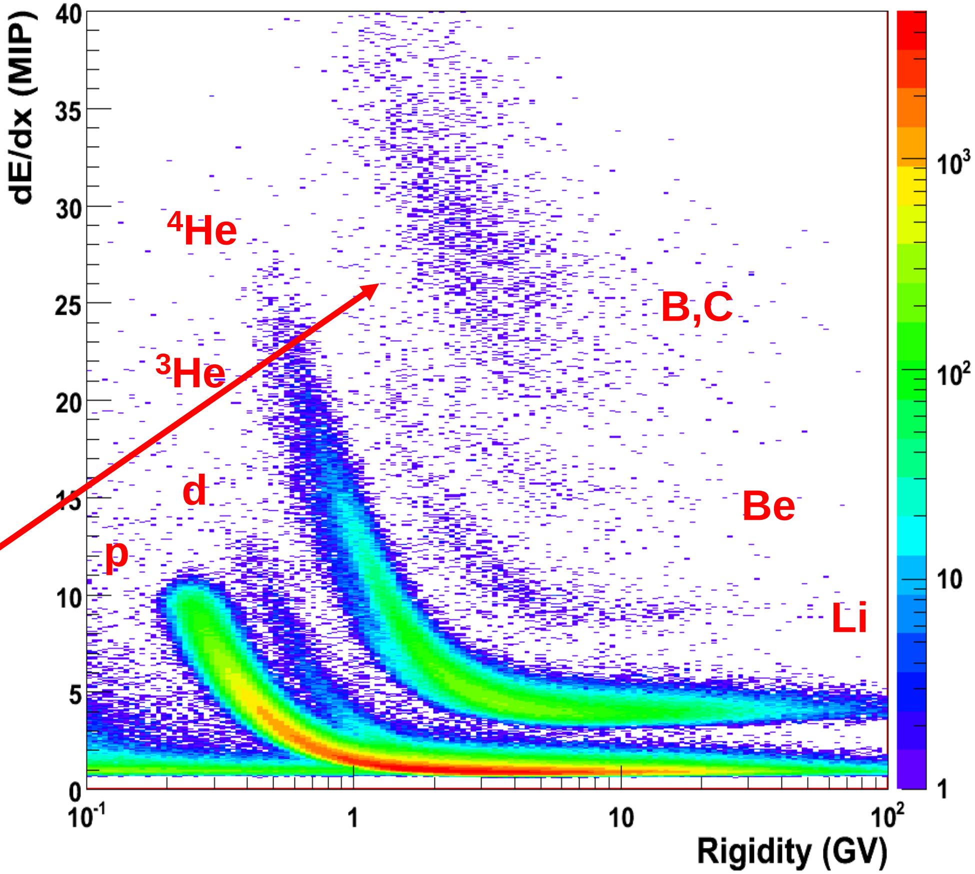
Beam-test data (@GSI 2006)



Saturated clusters

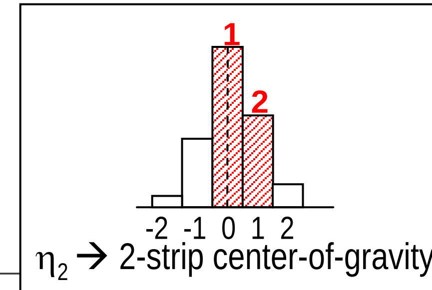


flight data (preliminary)

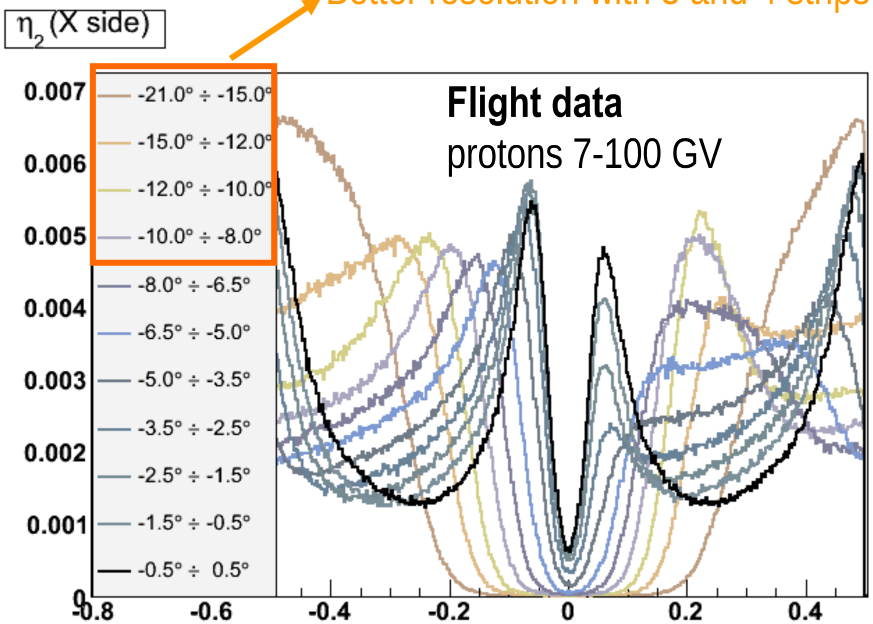


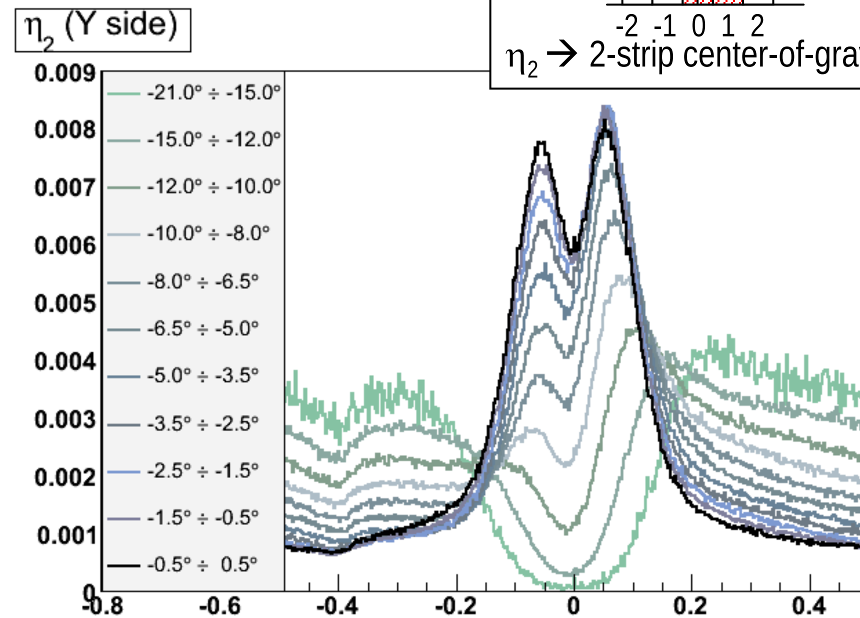
- Good charge discrimination of H and He
- Single-channel saturation at ~10MIP affects B/C discrimination

Charge collection



Better resolution with 3 and 4 strips





- Non-linear charge collection → best estimate of impact coordinate given by η-algorithm:

$$x(\eta) = x(\eta_0) + \int_{\eta_0}^{\eta} H(y)dy \xrightarrow[x(\pm 0.5)=\pm 0.5]{} x_s(\eta) = -0.5 + \int_{-0.5}^{\eta} H(y)dy$$

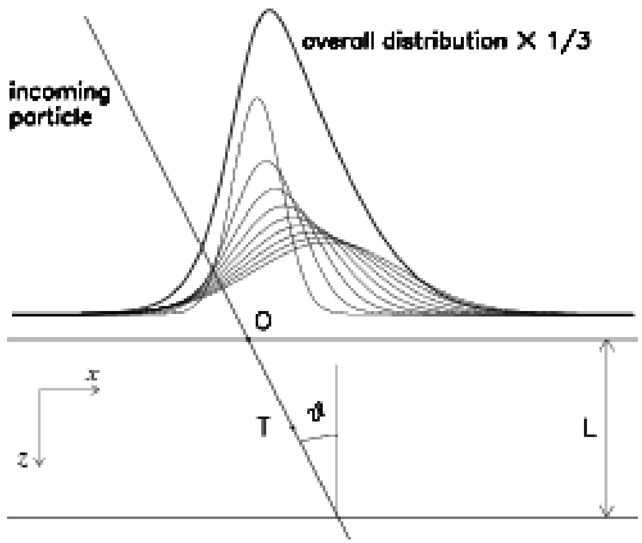
Experimental η-distribution

(standard implementation)

- for small angles (<10°) 2-strip algorithm gives best resolution → $x_s(\eta_2)$

Angular systematic

Standard implementation of the η-algorithm relies on the assumption of symmetric signal distribution → condition not satisfied in case of inclined tracks



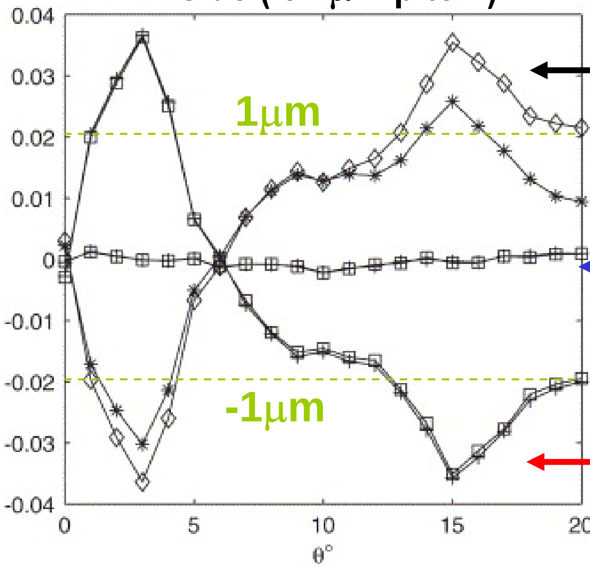
$$x(\eta) = x(-0.5) + \int_{-0.5}^{\eta} H(y)dy = x_s(\eta) + \underbrace{x(-0.5) + 0.5}_{\Delta}$$

Asymmetry of the signal distribution introduces a systematic error in the standard application of the h-algorithm

Angular correction

Angular effect studied in ref. ***Landi G., NIMA, 554 (2005) 226***:
- study of discretization effects on position reconstruction with silicon microstrip detectors, by means of analytical model (signal theory) and Monte Carlo simulation (both tuned on PAMELA tracker sensors)

X side (51 μm pitch)



correction

$$\Delta = \langle \eta_4 - \eta_1 \rangle$$

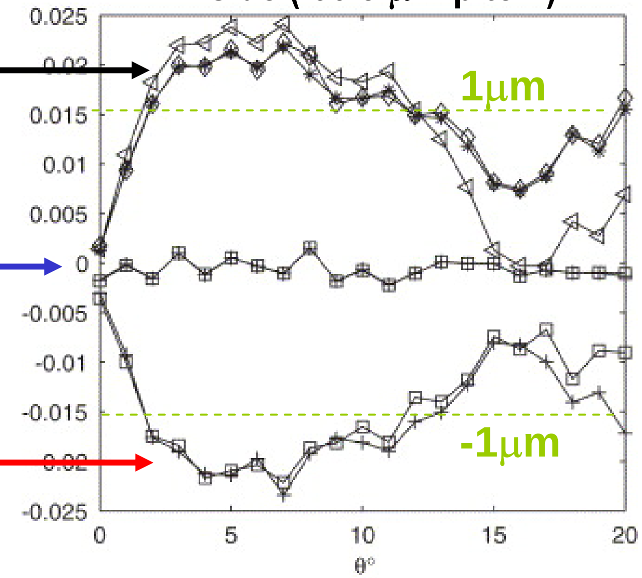
corrected

$$\langle x_s(\eta_{2,3}) + \Delta - x \rangle$$

systematic error

$$\langle x_s(\eta_{2,3}) - x \rangle$$

Y side (66.5 μm pitch)

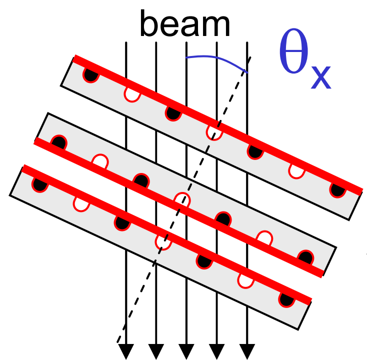


Results:

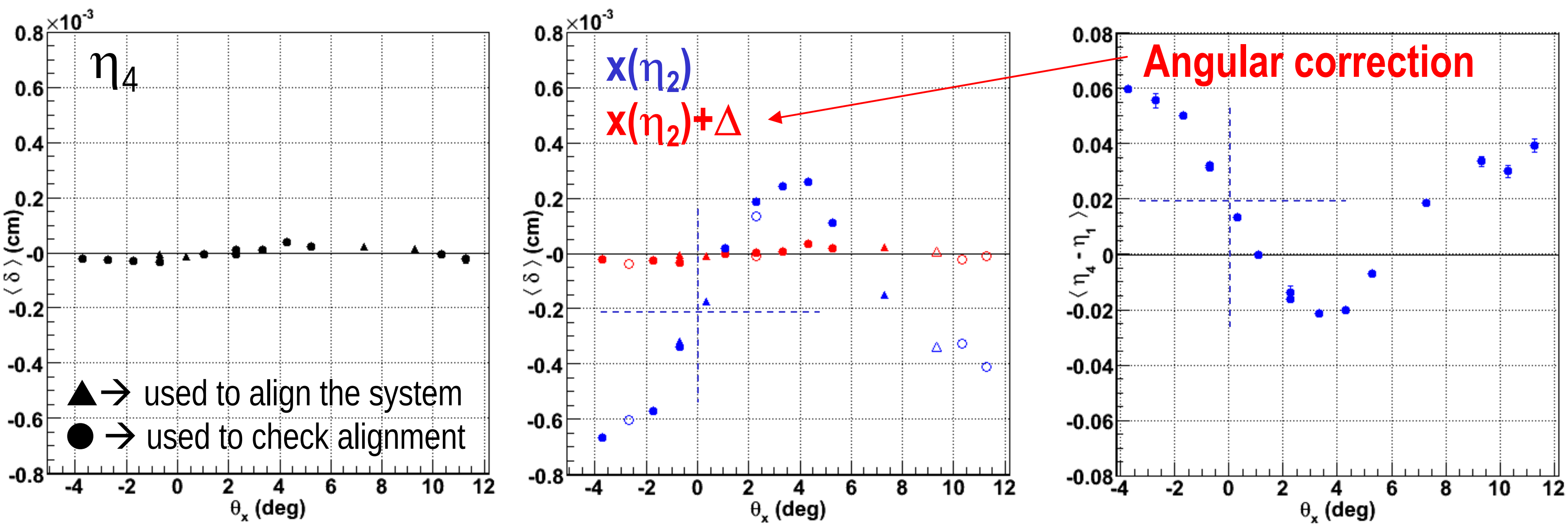
- Standard η-algorithm has a systematic error up to ~2μm → significant on the x view!
- Correction can be derived from data itself
- (Center of gravity with 4 strips (or more) has no systematic (but worse resolution))

Angular systematic (beam test)

On 2006 test of detector prototypes @SPS (protons 50-100-150 GV/c)

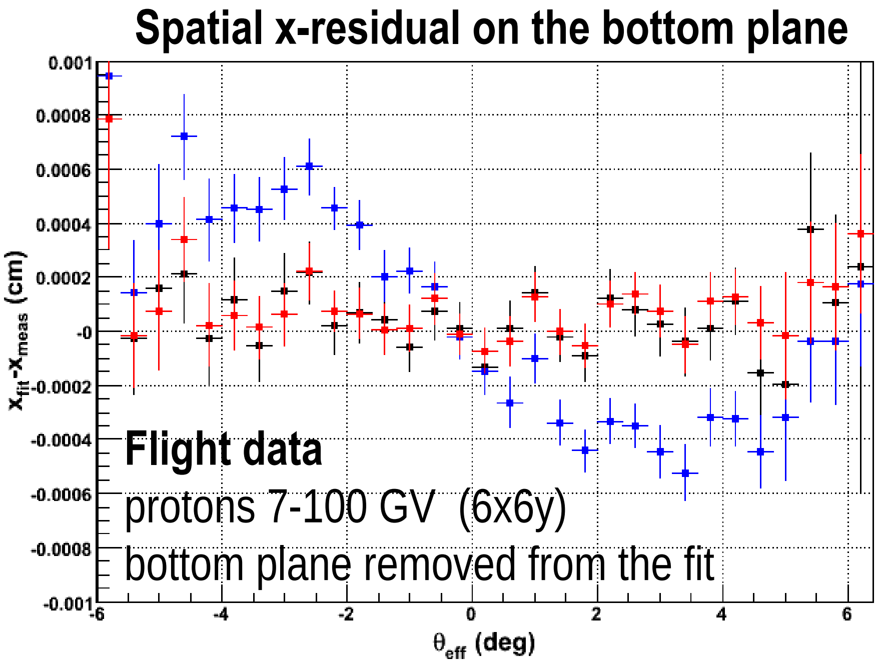


Angular systematic has opposite sign on the x view of the middle plane

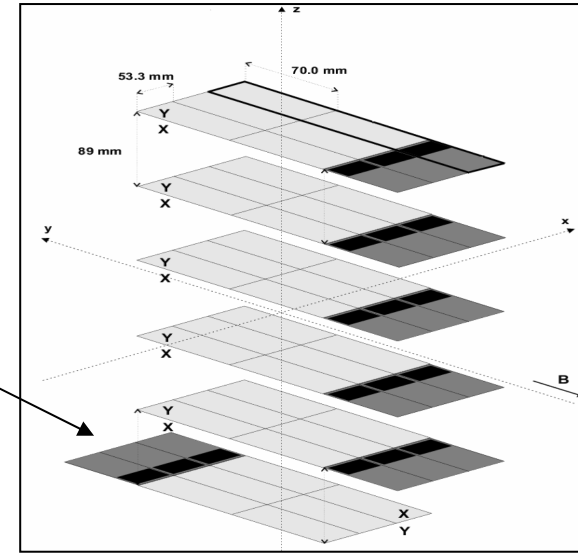


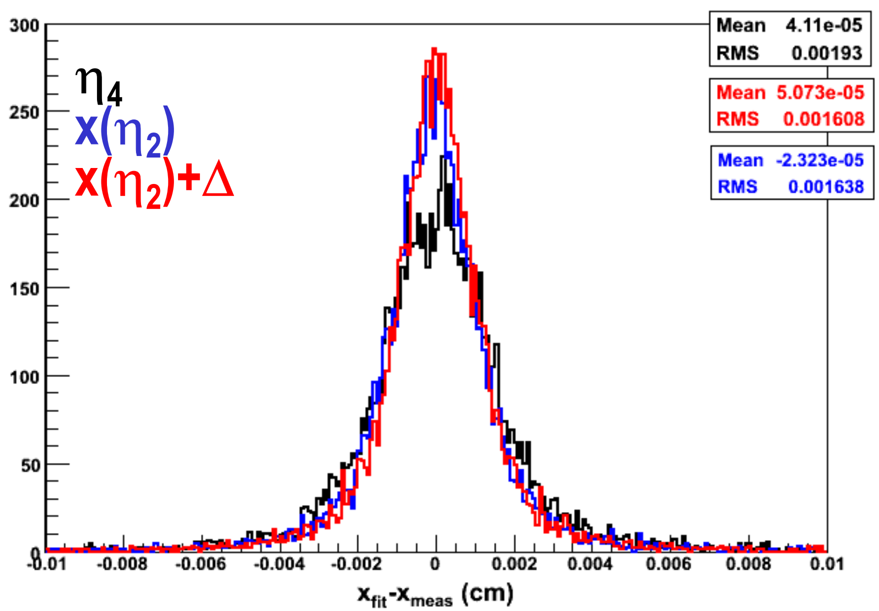
- Theoretical results confirmed
- Correction account also for intrinsic asymmetries

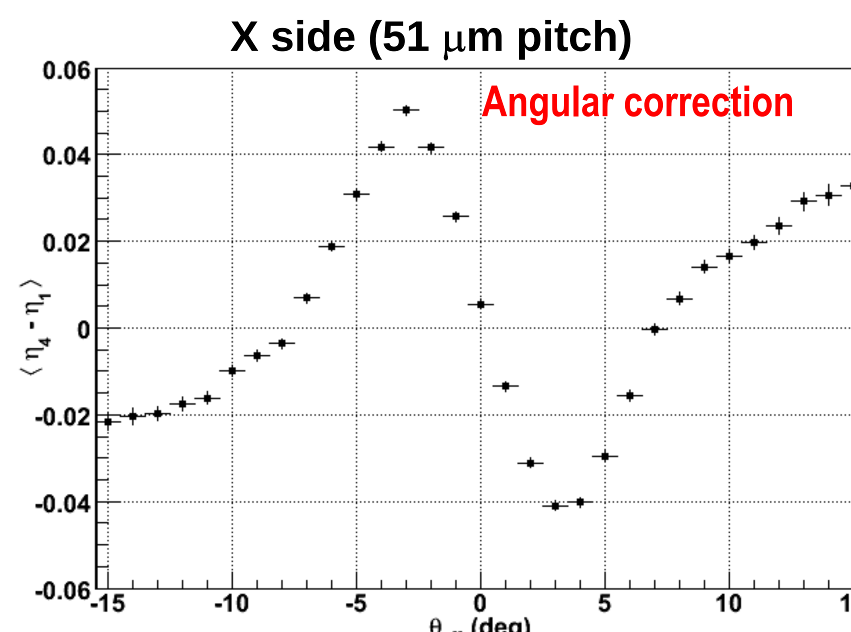
Angular systematic (flight data)



Angular systematic has opposite sign on the x view of the last plane



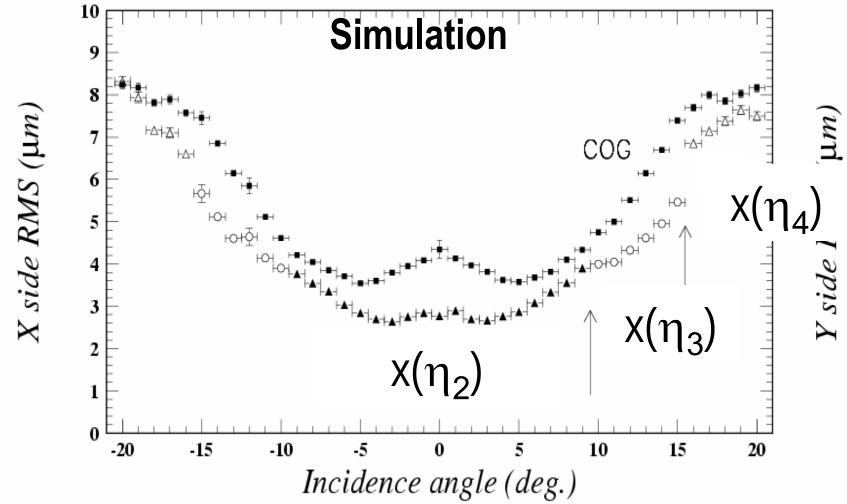


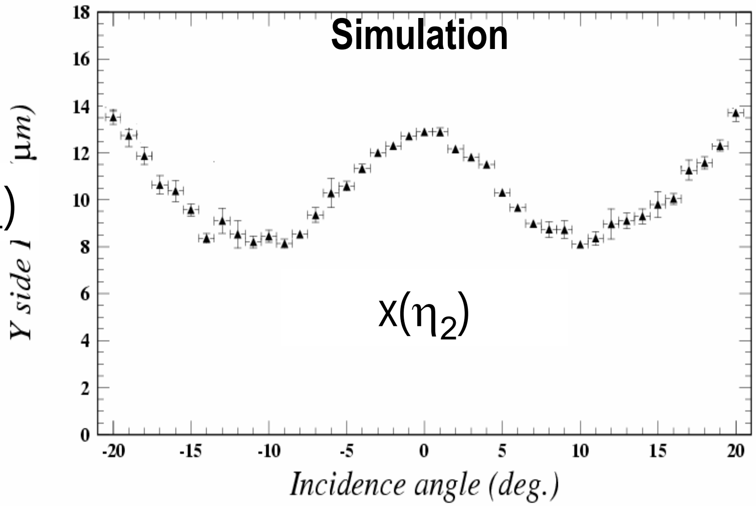


Spatial resolution

Sensor instrinsic resolution

Spatial resolution studied by means of beam-test of silicon detectors and simulation





- junction side (X): 3 μm @0°, < 4 μm up to 10° (→ determines momentum resolution)
- ohmic side (Y): 8÷13 μm

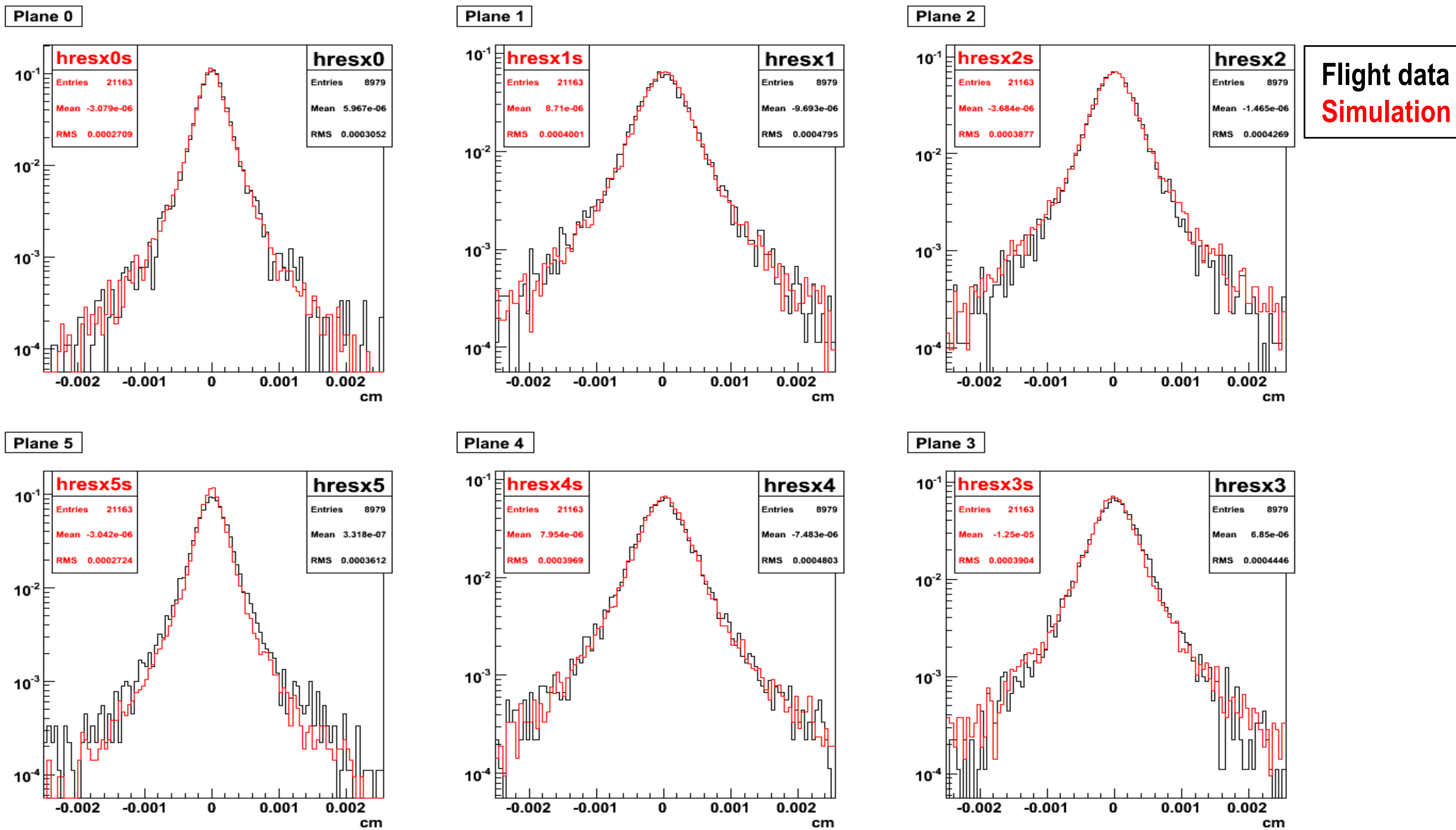
Sensor alignment

Track-based alignment: minimization of spatial residuals as a function of the roto-traslational parameters of each sensor

- Proton beam (@CERN-SPS 2003) and atmospheric muons (cross-check) → **~100±1 μm**
- In-flight corrections with protons → **~10 μm**

Spatial residual (x side)

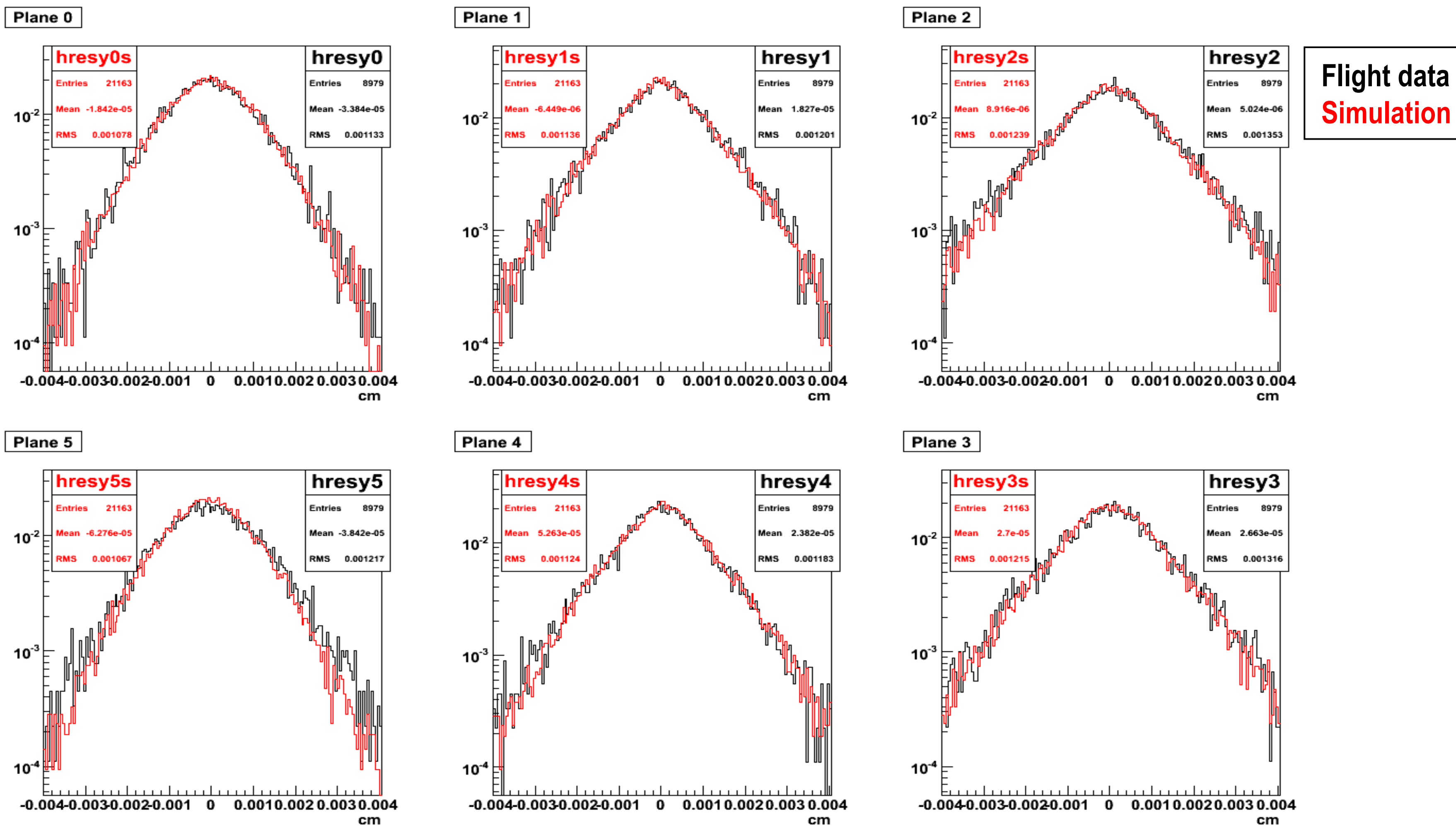
Flight data - protons 7-100 GV (6x6y, all plane included in the fit)



→ Spatial resolution is nominal

Spatial residual (y side)

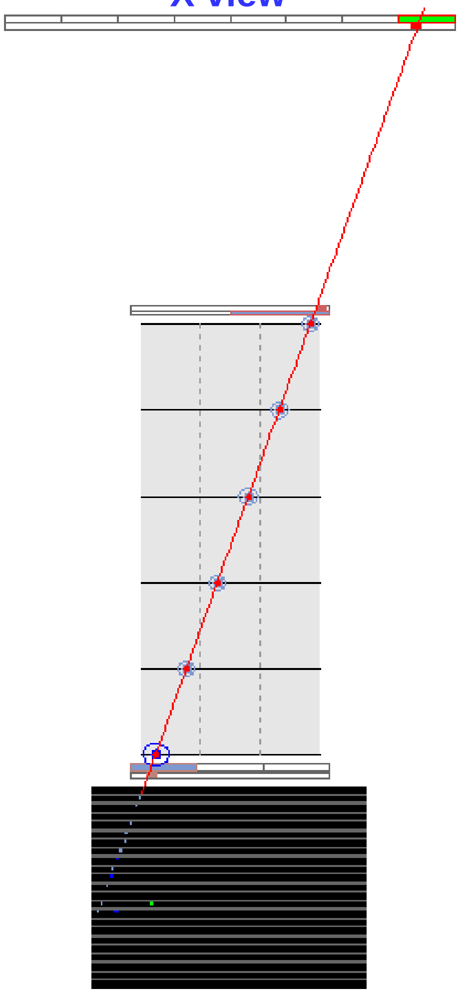
Flight data - protons 7-100 GV (6x6y, all plane included in the fit)



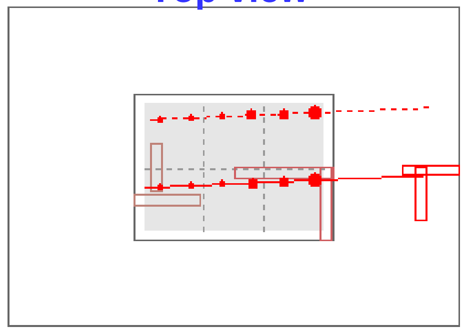
→ Spatial resolution is nominal

Track recognition

X view

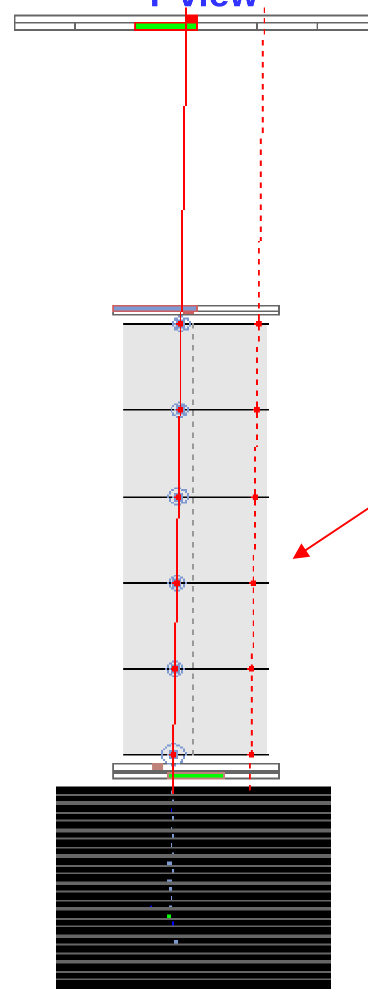


Top view

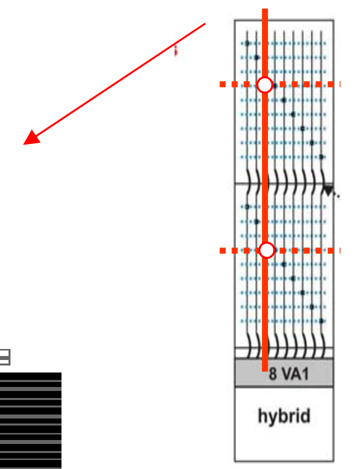


R = 23.2 GV
η = -0.043 GV^{-1}
χ^2 = 0.36
β = 1.08

Y view



Y-view ambiguity

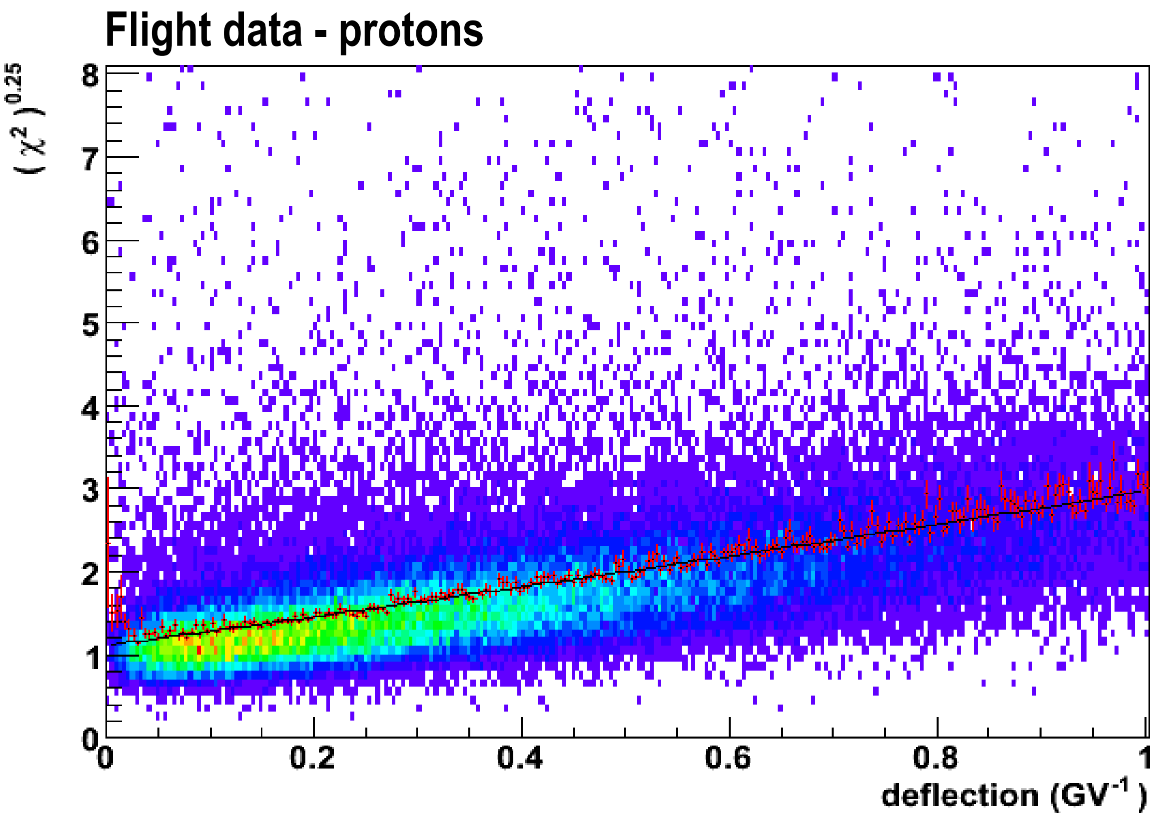


- <u>Hough transform</u>: circle sector (X) + straight line (Y)
  → Track recognition efficiency close to nominal value (sensor geometry)
- Ambiguity on Y view solved with help from ToF and calorimeter information

Track fitting

- Stepwise integration of motion equations by means of Runge-Kutta method (not-homogeneous B field)
- Iterative χ^2 minimization as a function of track state-vector components

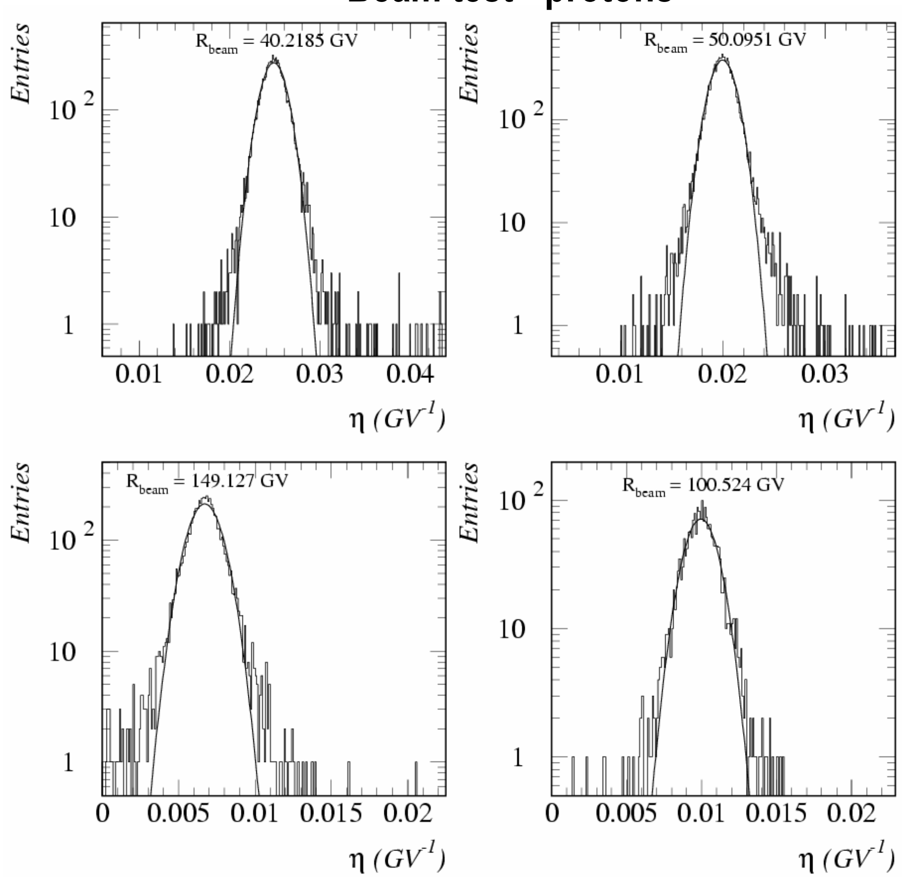
$\alpha = (x0, y0, \sin\theta, \phi, \eta)$ $\eta = 1/R$ = magnetic deflection

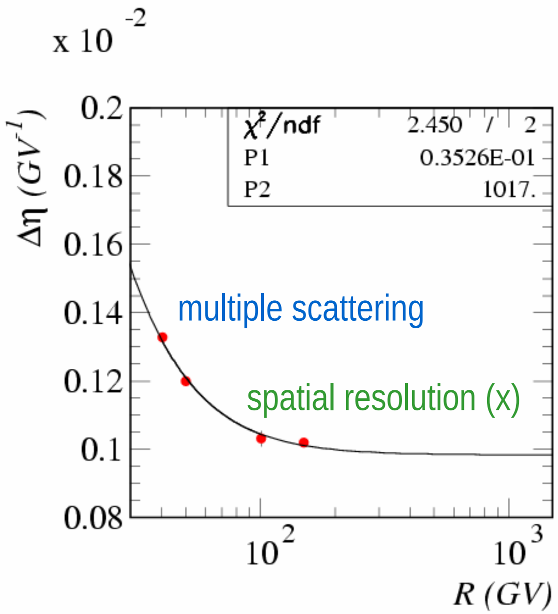


Energy dependence due to multiple scattering effects

Momentum resolution

Beam test - protons





→ **MDR ~ 1TV**

$\eta = 1/R$ → magnetic deflection

$\Delta R/R = \Delta\eta/\eta$ → $MDR = 1/\Delta\eta$

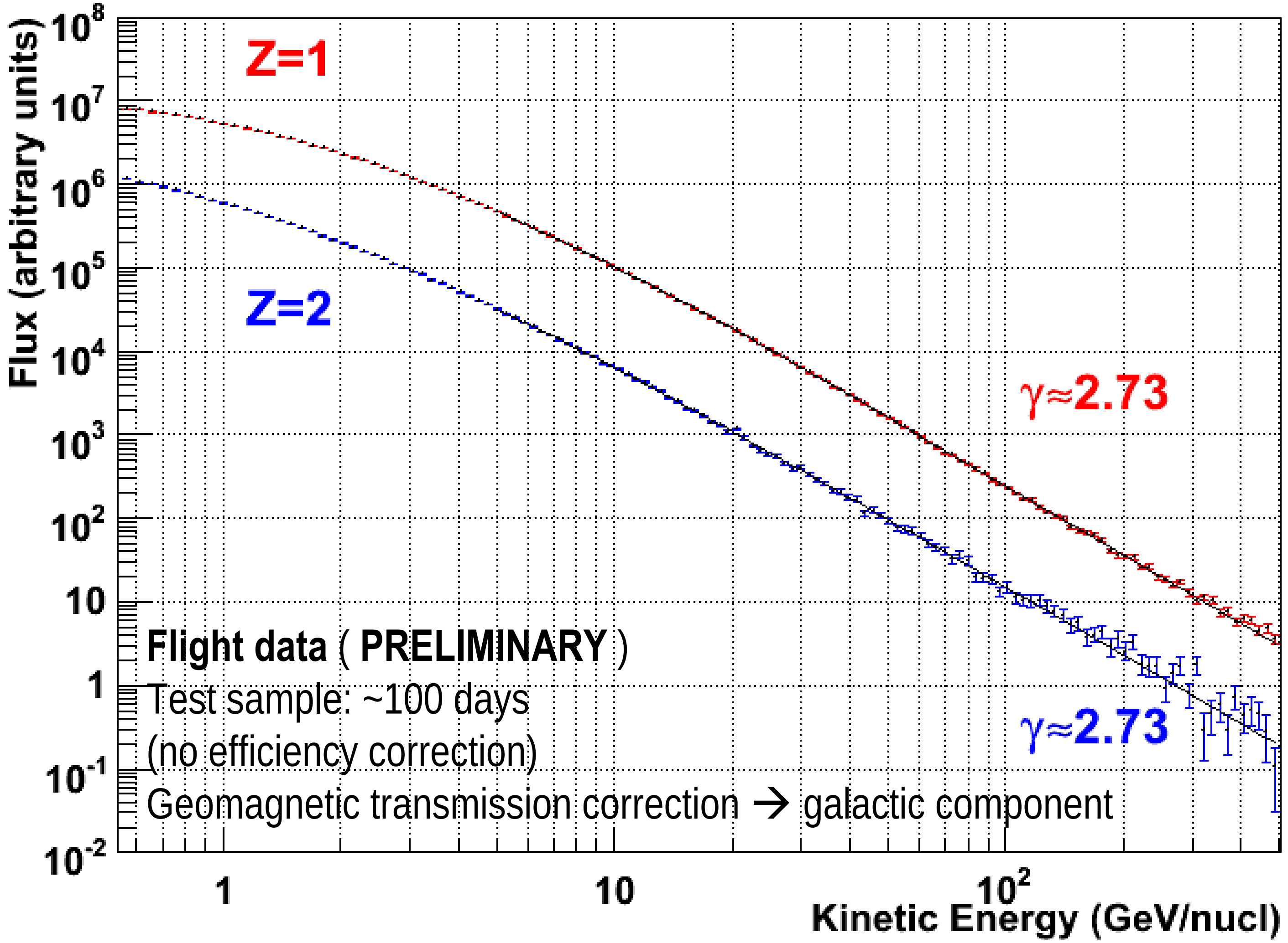
MDR = Maximum Detectable Rigidity

@R=MDR → $\Delta R/R=1$

→ Measured at beam test with protons of known momentum (CERN SPS, 2003)

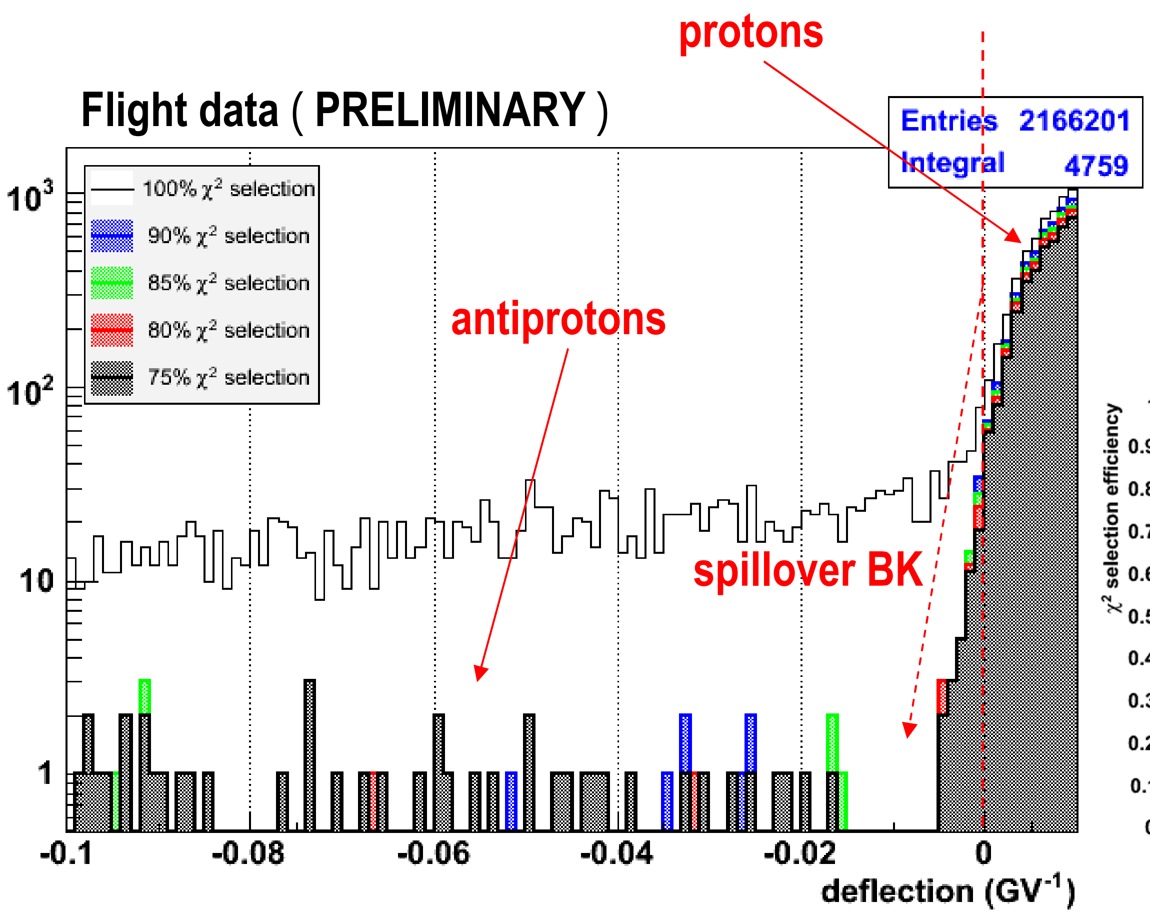
→ In-flight cross-check with e^-/e^+ (energy measured by the calorimeter), to account for residual distortions after alignment procedure → (in progress)

Hydrogen and Helium spectra



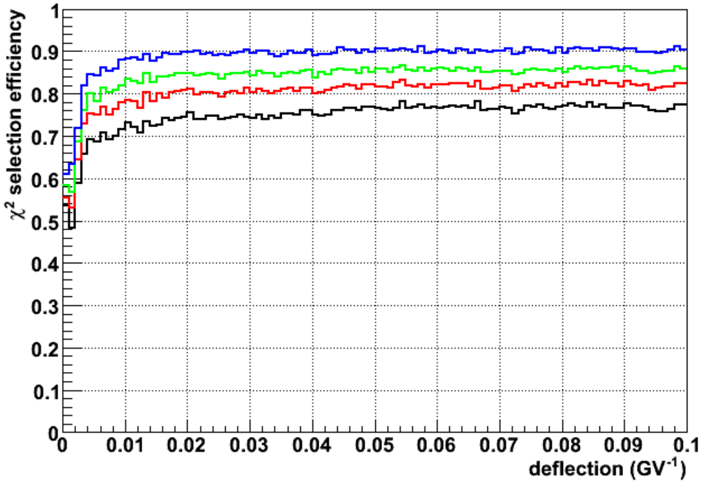
→ Good energy reconstruction over a wide energy range

Antiprotons

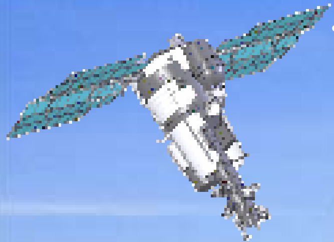


(Test sample: ~2500h)

- Tracks: 4x3y + Lever-arm 6
- Electron rejected with calorimeter
- Cut on track χ^2 (energy-dependent)



→ Spillover background under control



Conclusions

PAMELA is in space, continuously taking data since July 2006

Study of detector performances in flight is now in progress

Magnetic spectrometer:

- **basic performances (noise, cluster signal...) are nominal**
- **position reconstruction algorithm extensively studied and applied to flight data**
- **spatial resolution in flight consistent with expectations**

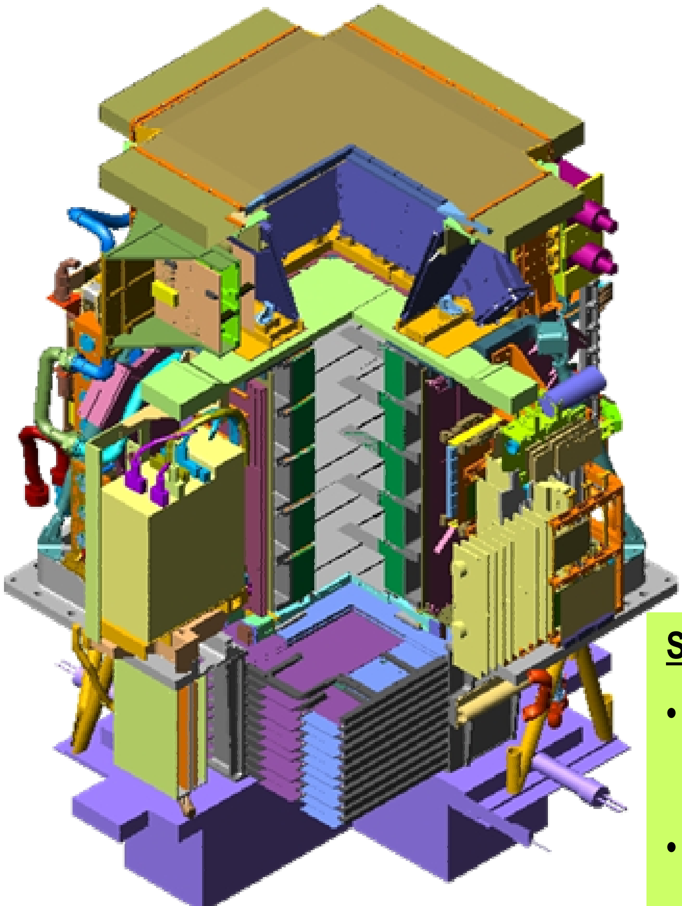
→ Spectrometer performances fulfill the requirements of the experiment!

Spares

PAMELA detectors

TRD

- Threshold device. Signal from $e^{\pm}$, no signal from p, $\bar{p}$
- 9 planes of Xe/Co_2 filled straws (4mm diameter). Interspersed with carbon fibre radiators $\Rightarrow$ crude tracking.
- Aim: factor 20 rejection e/p (above 1GeV/c) (2. 10^5 with calorimeter)



Anticoincidence system

- Defines acceptance for tracker
- Plastic scintillator + PMT

Time-of-flight

- Trigger / detects albedos / particle identification (up to 1 GeV/c) / dE/dx
- Plastic scintillator + PMT
- Timing resolution = 120ps

Si Tracker + magnet

- Measures rigidity
- 5 Nd-B-Fe magnet segments (0.4T)
- 6 planes of 300mm thick Si detectors
- ~3mm resolution in bending view demonstrated, ie: MDR = 740GV/c
- +/-10 MIP dynamic range

Si-W Calorimeter

- Measures energies of $e^{\pm}$.

  DE/E = 15% / $E^{1/2}$ + 5%
- Si-X / W / Si-Y structure.
- 22 Si / 21 W $\Rightarrow$ $16X_0$ / $0.9l_0$
- Imaging: EM - vs- hadronic discrimination,longitudinal and transverse shower profile

PAMELA nominal capabilities

	energy range	particles in 3 years
Antiproton flux	80 MeV - 190 GeV	~ 10^4
Positron flux	50 MeV – 270 GeV	~ 10^5
Electron flux	up to 400 GeV	~ 10^6
Proton flux	up to 700 GeV	~ 10^8
Electron/positron flux	up to 2 TeV (from calorimeter)	
Light Nuclei	up to 200 GeV/n He/Be/C:	~$10^{7/4/5}$
AntiNuclei search	sensitivity of 3×10^{-8} in He/He	

→ **Simultaneous measurement of many cosmic-ray species**

→ **New energy range**

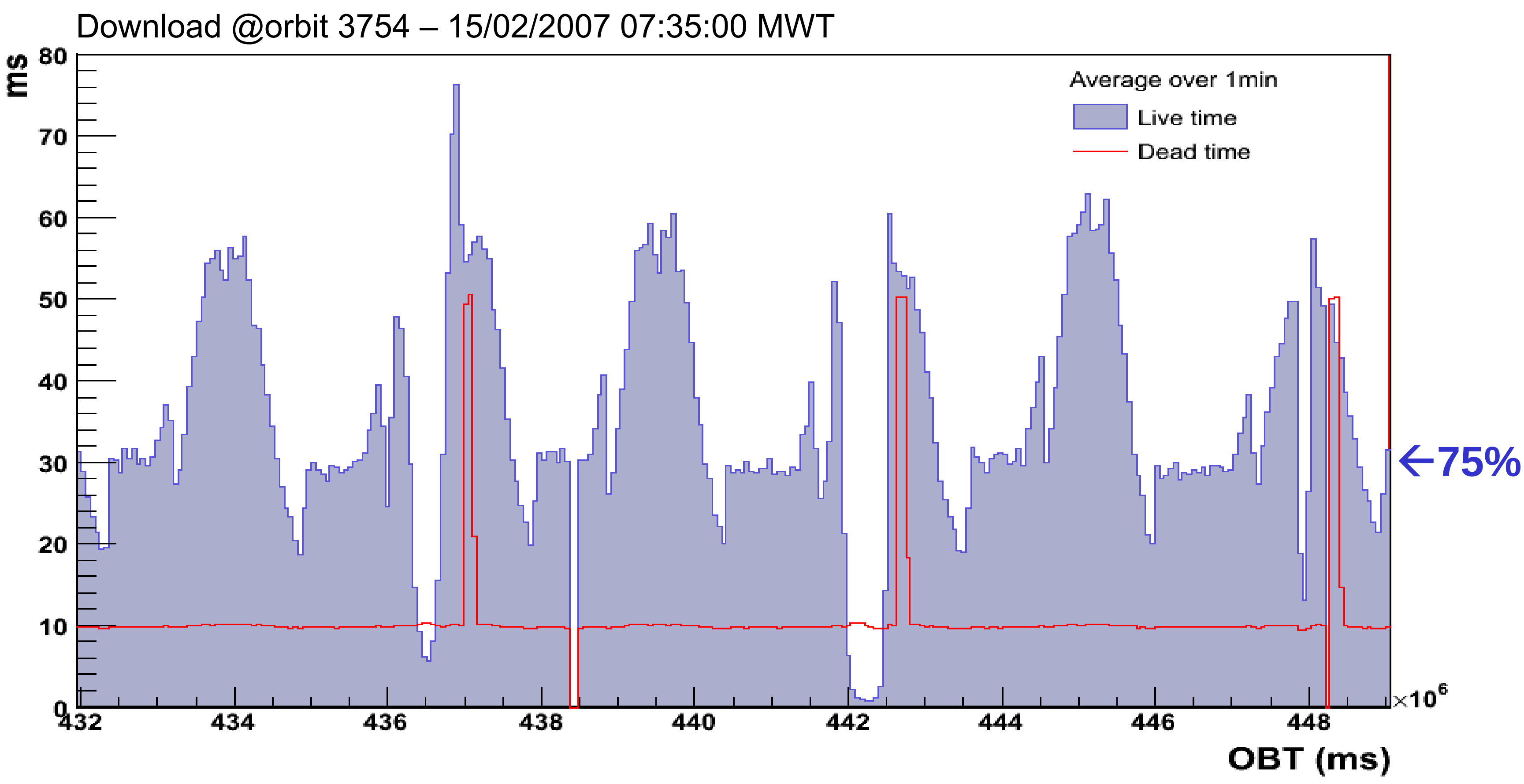
→ **Unprecedented statistics**

Taking into account live time and geometrical factor:

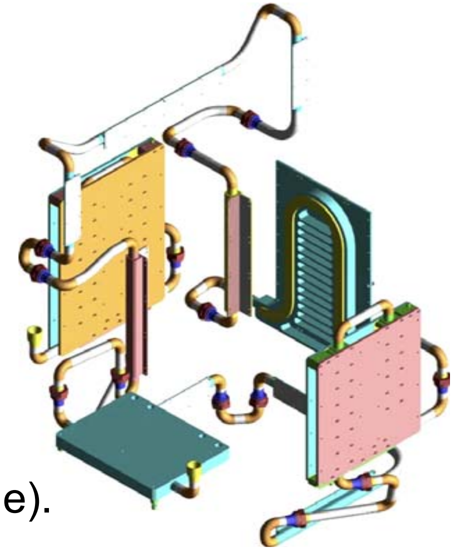
1 HEAT-PBAR flight ~ 22.4 days PAMELA data

1 CAPRICE98 flight ~ 3.9 days PAMELA data

Dead/Live time

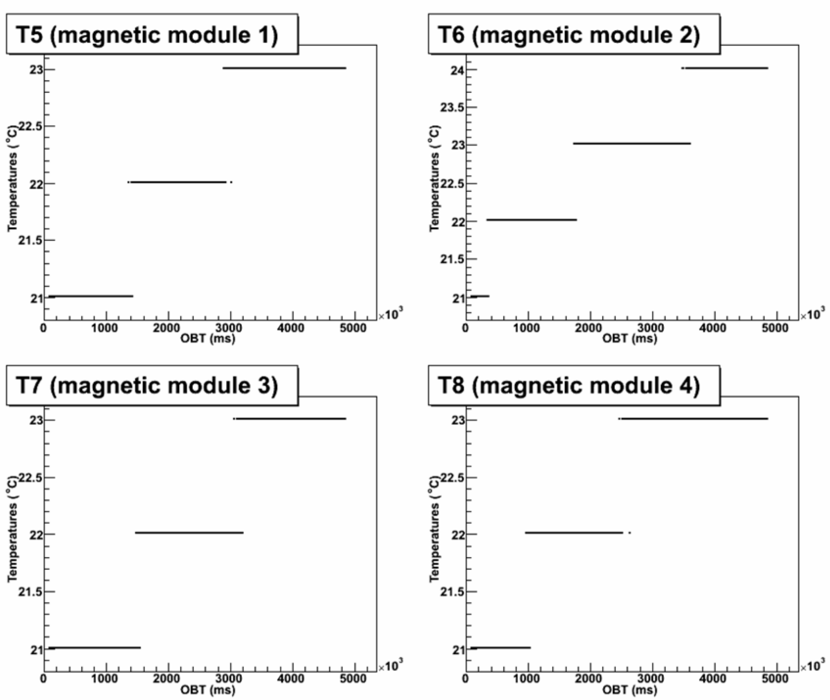


Temperatures

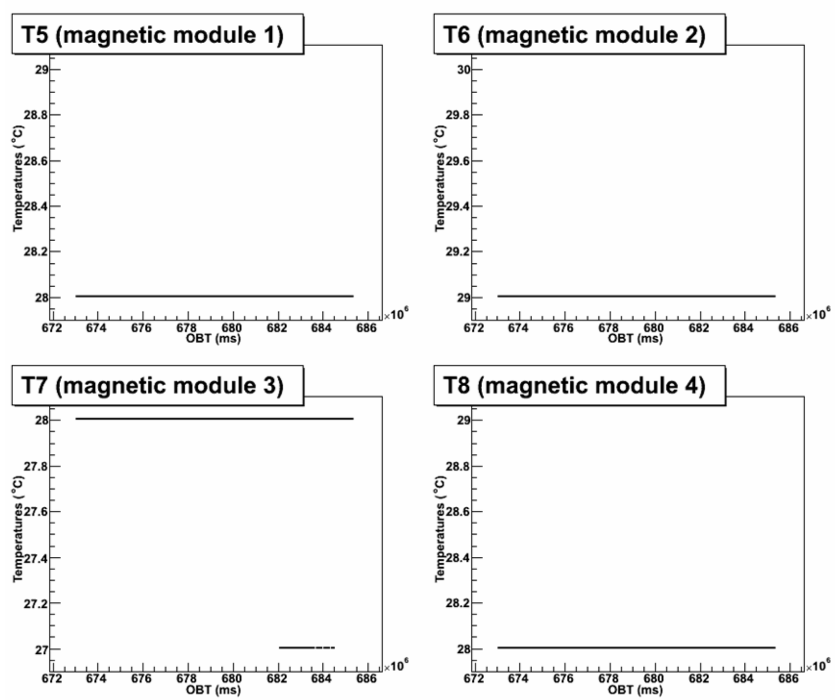


- **After power-up temperature remains stable:**
  - < 1º C variations along orbit;
  - < 10º C difference between PAMELA off and on.
- **Heat from VA1 on hybrids radiated to the magnetic tower:**
  - black IR absorbing painting on the walls;
  - heat released from magnetic tower to cooling loop (liquid iso-octane).

At power-up: 21º C
(5000 s ~ 0.9 orbits)

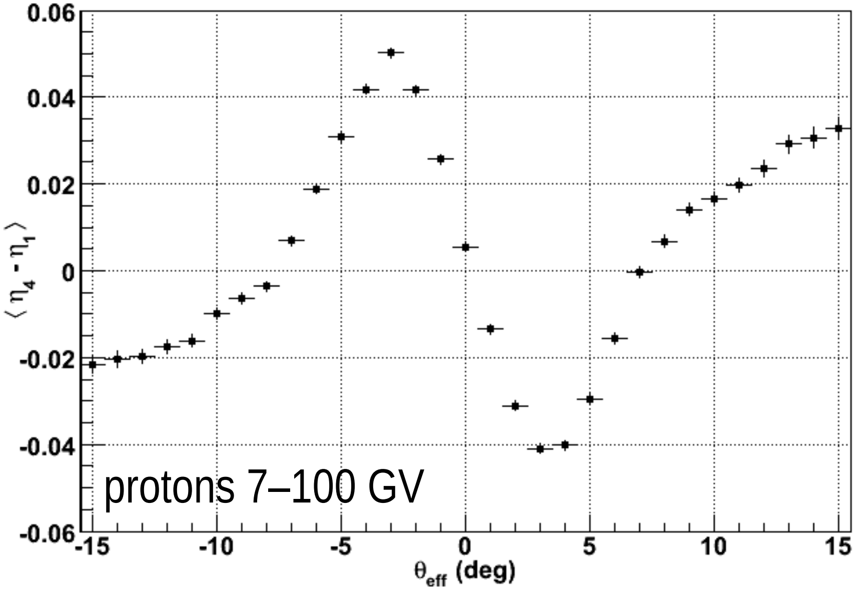


8 days after power-up: 28º C
(10000 s ~ 1.8 orbits)

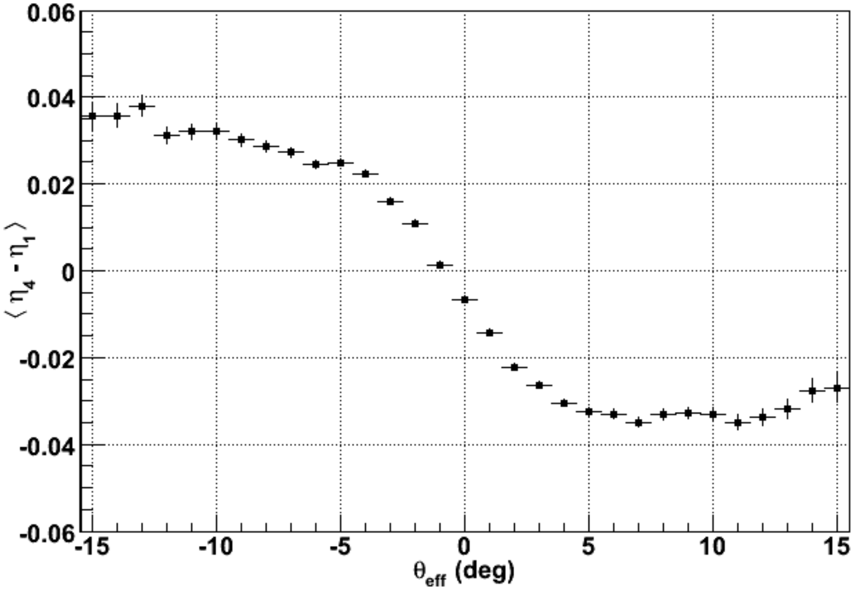


Angular correction in flight

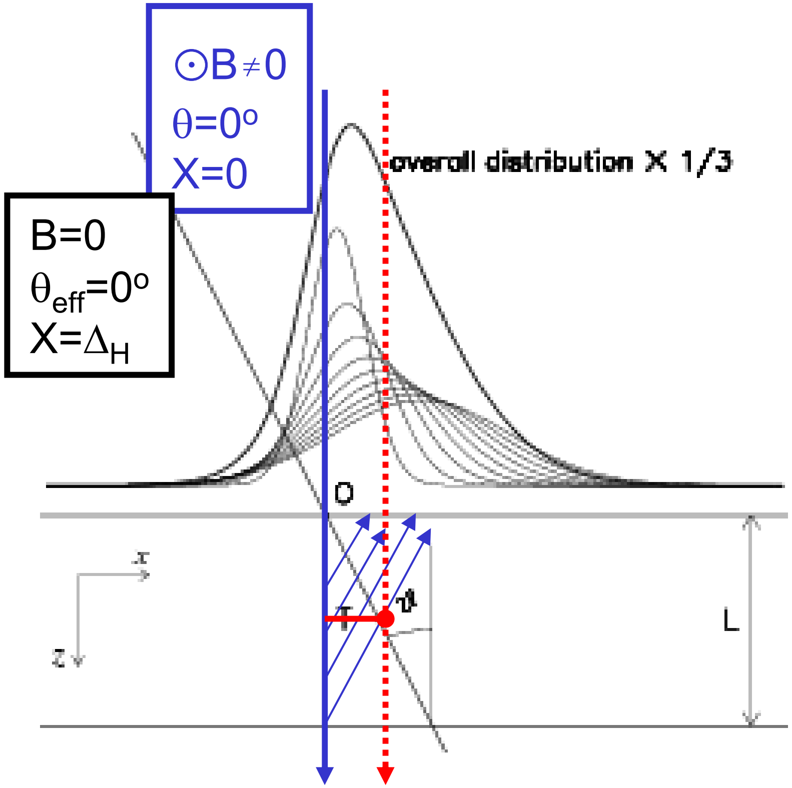
X side (51 μm pitch)



Y side (66.5 μm pitch)



Effect of the magnetic field on the reconstructed position



- Charge distribution displacement

$$\Delta_H = \frac{L}{2}\mu_H B$$

$$\rightarrow \Delta_H^h \sim 1.8\mu m$$

- Shape (almost) equivalent to that of an inclined track

$$\tan\theta_{eff} = \mu_H B$$

$$\rightarrow \theta_{eff}^h \sim 0.7^o \quad (@0^o)$$