CaloCube
a new approach to calorimetry in space-based experiments for high-energy cosmic rays

Gabriele Bigongiari
University of Siena and INFN-Pisa
on behalf of the CaloCube Collaboration

7th International Conference on New Frontiers in Physics
Kolymbary, July 12th 2018
Outline

• Cosmic rays
• The Calocube project
  - Simulations
  - Prototypes
• The TIC project
Cosmic Ray physics
Cosmic rays

Open problems
- Identification of astrophysical sources responsible for acceleration
- Understanding of acceleration, propagation and interaction mechanisms
- Location of the transition region between galactic and extra-galactic origin
- Search for dark matter sources

Direct Measurements
**Advantage**
Individual particle identification

**Disadvantage**
Payload limitation ⇒ small statistics

Indirect Measurements
**Advantage**
Large arrays ⇒ large statistics

**Disadvantage**
Large model systematics
Satellite experiments

In order to improve past measurements and extend them to higher energy, future space experiments must fulfill several requirements.

Protons and Nuclei up to 3 PeV/n
\[ \sigma_E/E < 40\% \]
\[ G_{\text{eff}} \times T > 2.5 \text{ m}^2 \text{ sr} \times 5\text{yr} \]
Dynamic Range > $10^7$
\[ \sigma_Z < 0.2-0.3 \text{ e} \]

Electrons and positrons up to 30 TeV
\[ \sigma_E/E < 2\% \]
\[ G_{\text{eff}} \times T > 3.6 \text{ m}^2 \text{ sr} \times 5\text{yr} \]
Dynamic Range > $10^5$
e/p separation > $10^{6}$

Geometric factor
\[ G = \frac{dN_{\text{detected}}}{dt} / I \]

Typical limitations
- Mass \(~10^3\text{ Kg}\)
- Power \(~10^3\text{ W}\)
- Down link \(~10^2\text{ Gb/d}\)
- Volume \(~1 \text{ m}^3\)

Effective geometric factor
\[ G_{\text{eff}} = \epsilon_{\text{sel}} \times G \]

Need to find new design for future experiments in order to fulfill requests.
The Calocube project
**The Calocube project**

**Calocube** is an R&D project financed by INFN for 3+1 years in 2014

The aim of the project is the design and optimization of a *calorimeter for the direct measurement of high-energy cosmic rays in space*

The project includes a wide range of *expertises*: calorimetry, CR physics, VLSI analog design, crystals, polymeric coatings.,.,,

The *participants* to the project include several institute in Italy:

- INFN: Catania, Firenze, Milano (Bicocca), Pisa, Pavia, Trieste
- CNR-IFAC Firenze
- CNR-IMM-MATIS Catania
- IMCB-CNR Napoli
The Calocube idea

- Deep homogeneous isotropic calorimeter
- Cubic geometry with 5 face detection
- Shower imaging with 3D segmentation
- Good energy resolution
- Large geometrical acceptance
- Good e/p rejection, identification of shower axis and of shower starting point

- Photodiodes
- Signal read by two PDs and double gain electronics
- In case of CsI, N=20, side=3.6 cm, L=39X_0 (1.8 \lambda_i)
Simulations
Implementation

Simulations of a cubic calorimeter made of $N \times N \times N$ crystals taking into account:

- conversion of the energy deposited in the crystal to the number of photoelectrons (p.e.) in the photodiode (PD) considering light yield, light collection and quantum efficiency

- estimation of the signal due to direct ionization in photodiodes

- energy deposited in passive layers (carbon fiber support structure)

Particles are injected from top surface in an uniform and isotropic way:

- electrons of 100 GeV - 1 TeV
- protons of 1, 10, 100, 1000 TeV

In case of CsI:Tl

<table>
<thead>
<tr>
<th>$N \times N \times N$</th>
<th>20$\times$20$\times$20</th>
</tr>
</thead>
<tbody>
<tr>
<td>crystal side (cm)</td>
<td>3.6</td>
</tr>
<tr>
<td>crystal volume (cm$^3$)</td>
<td>46.7</td>
</tr>
<tr>
<td>gap (cm)</td>
<td>0.3</td>
</tr>
<tr>
<td>mass (kg)</td>
<td>1685</td>
</tr>
<tr>
<td>number of crystals</td>
<td>8000</td>
</tr>
<tr>
<td>size (m$^3$)</td>
<td>0.78$\times$0.78$\times$0.78</td>
</tr>
<tr>
<td>depth (R.L.)</td>
<td>39$\times$39</td>
</tr>
<tr>
<td>&quot; (I.L.)</td>
<td>1.8$\times$1.8$\times$1.8</td>
</tr>
<tr>
<td>planar GF (m$^2$sr) *</td>
<td>1.91</td>
</tr>
</tbody>
</table>

* GF only for one surface
Dependence on scintillating material and gap size

The best value of $\sigma_{E}/E$ is obtained using low $\lambda_{c}$ crystals. The maximum $G_{\text{eff}}$ has a small dependence on the material. LYSO is the best candidate.

Larger gap increases $G_{\text{eff}}$, Smaller gap improves $\sigma_{E}/E$

A compromise is needed.

The points corresponds to different selection efficiency.
Electron performances

Selecting a shower length of at least $22 X_0$:
- $\varepsilon \sim 36\%$
- $G_{\text{eff}} \sim 3.4 \text{ m}^2\text{sr}$
- resolution $\sim 2\%$

Direct ionization in photodiodes is about 1.7% of the total signal
Prototypes
Different prototypes have been built among the years, both increasing the size and upgrading the system.
CsI:Tl scintillator

### Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>4.51 g/cm³</td>
</tr>
<tr>
<td>Wavelength @ max</td>
<td>550 nm</td>
</tr>
<tr>
<td>Light output</td>
<td>54 ph/keV</td>
</tr>
<tr>
<td>(45 % of NaI(Tl))</td>
<td></td>
</tr>
<tr>
<td>Primary decay time</td>
<td>1.25 μs</td>
</tr>
</tbody>
</table>

- **3.6 cm**
- **produced by Amcryx**
- **Good to be read** making use of photodiodes sensors
- **Good compromise between acceptance and resolution**
- **Good intensity of the light signal** (1 MIP ~ 20 MeV ~ 10⁶ photons)
- **Vikuiti ensures the best light collection efficiency**

- **2012 prototype and 2013 prototype**
- **Am 5.5 MeV α**

- **2013 upgrade and 2016 prototype**
Photodiodes

VTH2090
Area ~ 86.64 mm²
MaxSignal ~ 30 nC
Maximum detectable energy release in the crystal is ~ 30 GeV

VTP9421H
Area ~ 1.6 mm²
MaxSignal ~ 0.3 nC
Maximum detectable energy release in the crystal is ~ 3 TeV

The combination of photodiodes ensures a dynamic range of ~ 10⁶

LARGE PD

SMALL PD

The combination of photodiodes ensures a dynamic range of ~ 10⁶
Front-end electronics

CASIS (HIDRA) chip
- R&D project by INFN
- Developed by INFN-Trieste
- Designed for silicon calorimetry in space

Specification
- 16 (28) channels
- charge sensitive amplifier + correlated double sampling
- double gain (1:20)
- automatic gain control

Performances
- High Dynamic range = 52.6 pC
- Low ENC = 2280e^- + 7.6e^- /pF
- Low Consumption = 2.8 mW/ch
Prototype v2

Geometry
- 18 layers of 5x5 CsI:Tl cubes
- Scintillators wrapped in Vikuiti
- Light collected by Small and Large PD

Shower containment
- 2.5 Moliere radius
- $35 \times X_0$
- $1.6 \lambda_I$

Beam tests

<table>
<thead>
<tr>
<th>Date</th>
<th>Version</th>
<th>Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep 2016</td>
<td>v2.0</td>
<td>$\mu$, $\pi$, $e$ 50-75-150-180 GeV</td>
</tr>
<tr>
<td>Aug 2017</td>
<td>v2.1</td>
<td>$\mu$, $\pi$, $e$ + Ions</td>
</tr>
</tbody>
</table>
Event view of a 200 GeV electron

Combining the Large and Small PDs we can improve the linearity and resolution.

Saturation in crystals where shower development is maximum.

The information of Large PDs saturated channels can be recovered using Small PDs.

Large PDs

Small PDs

Prototype v2
Electron deposit

Prototype v2

Small PDs

Large PDs
Electron performances

By combining the information of Large and Small PDs:

- non-linearity ~ 1%
- resolution < 1.5%

Prototype v2
Hadron performances
350 GeV proton beam

By selecting showers started in the first 3 layers we have a resolution better than 40%

Similar performances found for 30 GeV/n ions with resolution improvement from 40% to 20% when considering A going from 2 (D) to 28 (Si)
Energy resolution for hadrons

Inequalized ADC counts

Shower starting within layer 5

Beam energy

Equalized counts

Energy resolution (%)

Quite good linearity up to 1.6 TeV ion energy

Instrumental effects (optical cross-talk) were mostly understood and corrected starting from prototype v1.1

\[
\left( \frac{\sigma_E}{E} \right)_A = \frac{1}{\sqrt{A}} \left( \frac{\sigma_E}{E} \right)_p
\]

Shower starting on layer 3

- Ion-beam data (Prot.v1.0)
- MC

30 GeV/n
12.8 GeV/n

\( \chi^2 / \text{ndf} = 553.3 / 18 \)

Prob = 0

p0 = 7041 \( \pm \) 716.5

p1 = 2737 \( \pm \) 12.4

(D, He, B, C, O, Mg, Si, S, Ti, Fe)
The TIC project
The TIC project

**TIC** is an R&D project financed by INFN for 1 years in 2017.

The aim of the project is the design and optimization of a tracker *integrated inside the calorimeter (Tracker In Calorimeter)*.

In a large space satellite experiment, we are interested in collecting signals from different channels: electron, proton, nuclei and γ-rays.

CaloCube was optimized for charged particles: *how about γ-rays*?

Need a good compromise between

- good angular resolution for γ-rays
- large acceptance for charged particles
The angle can be measured using two different approaches.

**Standard approach**
- Exploiting conversion of γ in e^+e^- pair in W

**TIC approach**
- Exploiting transverse profile of shower

**Tracker design**
- Standard approach
  - Tracker (Si + W)
  - Calorimeter (LYSO)

**TIC approach**
- Charge identifier (Si only)
- Tracker (Si + LYSO)
- Calorimeter (LYSO)

**Advantages of TIC design**
- Decrease the amount of mass used for passive material (W)
- Reduce hadron fragmentation in passive material
- Increase the geometric acceptance
Using full information both from calorimeter and silicon tracker, angular resolution for vertical $\gamma$ is better than $0.1^\circ$ above 10 GeV (comparable to Fermi-LAT).
A TIC prototype have been realized integrating several DAMPE spare silicon layers inside the Calocube prototype.

The prototype is currently under beam test at the CERN PS+SPS with 1-100 GeV electrons at different incident angles.

From simulation we expect an angular resolution for vertical $\gamma$ better than 0.1-0.5° above 10 GeV.
The **CaloCube R&D project** aims to develop a novel design calorimeter intended for the measurement of high-energy cosmic rays in space.

**MC simulations** were used to optimize the design of the detector in order to satisfy the scientific requirements on geometric factor and energy resolution of:

- $G_{\text{eff}} \sim 3.4 \text{ m}^2\text{sr}$ and $\sigma_E/E < 2\%$ for electrons
- $G_{\text{eff}} \sim 4 \text{ m}^2\text{sr}$ and $\sigma_E/E < 40\%$ for protons

**Several prototypes made of CsI(Tl) crystals** have been built and tested, obtaining results mostly consistent with MC simulations:

- $\sigma_E/E < 1.5\%$ for electrons up to 280 GeV
- $\sigma_E/E < 35\%$ for ions up to 30 GeV / n

The **TIC R&D project** is ongoing to study a new tracker configuration that allows good reconstruction performances both for charged particles and γ-rays.
Back Up
Past vs Future experiments

Past experiments
based on **magnetic spectrometer**

Future experiments
based on **calorimeter**

**Past vs Future experiments**

- **better resolution at high energy**
  \[
  \frac{\sigma_E}{E} \propto E \quad \text{vs} \quad \frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}
  \]

- **better geometrical acceptance**
  because of rigid geometry, it can measure particles from one direction only

For example in the case of PAMELA
- \(G = 20.5 \text{ cm}^2 \text{ sr}\)
- \(\sigma_p/p \sim 15\% \text{ for } 100 \text{ GeV } p\)
- \(\text{MDR} = 740 \text{ GV/c}\)
Chinese Space Station will be constructed before 2022. It will house the HERD payload for the detection of cosmic rays. Several universities and institutes are interested in the project. Main countries involved are China, Italy, Switzerland and Spain.
Current proposal of the HERD detector

The design of the HERD detector is going to be optimized starting from this year.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Payload</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range(e/γ)</td>
<td>10 GeV - 10 TeV (e/γ)</td>
<td>CALO</td>
<td>55 R.L.; 10^7 DR</td>
</tr>
<tr>
<td>Energy range (CR)</td>
<td>0.5 GeV - 10 GeV(y)</td>
<td>PSD&amp;CALO</td>
<td>99.9% veto effi.</td>
</tr>
<tr>
<td>Angle resolution</td>
<td>30 GeV - PeV</td>
<td>CALO</td>
<td>3 N.I.L; 10^7 DR</td>
</tr>
<tr>
<td>Charge meas.</td>
<td>0.1 deg.@10 GeV</td>
<td>STK</td>
<td>At least 3 layers, distance in between &gt; 3cm</td>
</tr>
<tr>
<td>Energy reso.(e)</td>
<td>1%@200 GeV</td>
<td>STK</td>
<td></td>
</tr>
<tr>
<td>Energy reso.(p)</td>
<td>20%@100 GeV-PeV</td>
<td>STK</td>
<td></td>
</tr>
<tr>
<td>e/p discri.</td>
<td>~10^-6</td>
<td>STK</td>
<td></td>
</tr>
<tr>
<td>G.F. (e)</td>
<td>&gt;3 m^2sr@200 GeV</td>
<td>STK</td>
<td></td>
</tr>
<tr>
<td>G.F. (p)</td>
<td>&gt;2 m^2sr@100 TeV</td>
<td>STK</td>
<td></td>
</tr>
</tbody>
</table>
Expected spectra with the HERD detector in five years from Ivan De Mitri 2017 HERD workshop

Precise measurement of the “discrepant” hardening

Detecting the knee(s)

electrons and positrons

p, He
Expected spectra with the HERD detector in five years

from Ivan De Mitri
2017 HERD workshop
Choice of Calocube layout

Different Calocube layout have been tested fixing

- total mass of detector = $2 \times 10^3$ kg
- crystal size = 1 Moliere radius
- gap size = 0.3 cm for CsI:Tl

...and using different materials as scintillator.

The ideal material is a trade-off between 

- **density** (i.e. detector acceptance) and 
- **interaction length** (i.e. energy resolution)

### Properties of crystals

<table>
<thead>
<tr>
<th></th>
<th>CsI:Tl</th>
<th>BaF$_2$</th>
<th>YAP:Yb</th>
<th>BGO</th>
<th>LYSO:Ce</th>
</tr>
</thead>
<tbody>
<tr>
<td>densità (g/cm$^3$)</td>
<td>4.53</td>
<td>4.89</td>
<td>5.50</td>
<td>7.13</td>
<td>7.40</td>
</tr>
<tr>
<td>$\lambda_1$ (cm)</td>
<td>39.90</td>
<td>30.50</td>
<td>21.78</td>
<td>22.80</td>
<td>20.90</td>
</tr>
<tr>
<td>$\lambda_1$ (g/cm$^2$)</td>
<td>180.75</td>
<td>149.15</td>
<td>119.79</td>
<td>162.56</td>
<td>154.66</td>
</tr>
<tr>
<td>$X_0$ (cm)</td>
<td>1.85</td>
<td>2.03</td>
<td>2.69</td>
<td>1.12</td>
<td>1.17</td>
</tr>
<tr>
<td>$X_0$ (g/cm$^2$)</td>
<td>8.39</td>
<td>9.91</td>
<td>14.81</td>
<td>7.97</td>
<td>8.67</td>
</tr>
<tr>
<td>$R_M$ (cm)</td>
<td>3.53</td>
<td>3.12</td>
<td>2.40</td>
<td>2.26</td>
<td>2.07</td>
</tr>
<tr>
<td>Light Yield (fotoni/MeV)</td>
<td>$5.4 \cdot 10^4$</td>
<td>$1.0 \cdot 10^4$</td>
<td>$1.8 \cdot 10^4$</td>
<td>$0.8 \cdot 10^4$</td>
<td>$3.0 \cdot 10^4$</td>
</tr>
</tbody>
</table>
Choice of Calocube layout

Different Calocube layout have been tested fixing

- total mass of detector = \(2 \times 10^3\) kg
- crystal size = 1 Moliere radius
- gap size = 0.3 cm for CsI:Tl

scaled according to the crystal size otherwise

...and using **different materials** as scintillator

The ideal material is a trade-off between **density** (i.e. detector acceptance) and **interaction length** (i.e. energy resolution)

### Properties of CaloCube

<table>
<thead>
<tr>
<th></th>
<th>CsI:Tl</th>
<th>BaF(_2)</th>
<th>YAP:Yb</th>
<th>BGO</th>
<th>LYSO:Ce</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\ell) (cm)</td>
<td>3.60</td>
<td>3.20</td>
<td>2.40</td>
<td>2.30</td>
<td>2.10</td>
</tr>
<tr>
<td>gap (cm)</td>
<td>0.30</td>
<td>0.27</td>
<td>0.20</td>
<td>0.19</td>
<td>0.18</td>
</tr>
<tr>
<td>N° cristalli</td>
<td>(20 \times 20 \times 20)</td>
<td>(22 \times 22 \times 22)</td>
<td>(28 \times 28 \times 28)</td>
<td>(27 \times 27 \times 27)</td>
<td>(30 \times 30 \times 30)</td>
</tr>
<tr>
<td>L (cm)</td>
<td>78.00</td>
<td>76.34</td>
<td>72.80</td>
<td>67.23</td>
<td>68.40</td>
</tr>
<tr>
<td>(\lambda_t) totali ((\lambda_t))</td>
<td>1.80</td>
<td>2.31</td>
<td>3.09</td>
<td>2.72</td>
<td>3.01</td>
</tr>
<tr>
<td>(X_0) totali ((X_0))</td>
<td>38.88</td>
<td>34.73</td>
<td>24.96</td>
<td>55.54</td>
<td>53.75</td>
</tr>
<tr>
<td>G (m(^2)sr)</td>
<td>9.56</td>
<td>9.15</td>
<td>8.32</td>
<td>7.10</td>
<td>7.35</td>
</tr>
</tbody>
</table>

For a planar surface A, the geometric factor is

\[ G = \pi A \]

In our case this is multiplied by number of active faces (5)
Resolution vs Acceptance

In case of no-full-shower-containment the resolution is spoiled by fluctuations of the shower length.

Selecting only events with large shower length improves resolution but decreases the acceptance.

Making use of integrated gamma function, it is possible to correct the energy deposit for the shower length event by event.

\[ F(x) = k \cdot \int_0^x b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)} \, dt \]

\[ E_m [\text{TeV}] = \frac{S [\text{p.e.}]}{F(x, E) [\text{p.e./TeV}]} \]
Event selection

Important quantities
- **Hit** in crystal $i$
  \[ dE_i > n \times \text{MIP} \text{ where } n = 0.80-0.85 \]
- **Shower starting point**
  crystal $i$ having $dE_i > 15$ MIP
- **Shower maximum**
  crystal $i$ having maximum $dE_i$

Basic event selection
- shower maximum must be outside of edges
- shower starting point must be defined
- $N_{\text{hit}} > 100$

The efficiency of this selection is
\[ \varepsilon_{\text{BS}} = 40-55\% \]

Because *Resolution vs Acceptance* depends on shower length, 4 different cases have been investigated, corresponding to a minimum value of shower length that ensures an additional event selection with an efficiency
\[ \varepsilon_{\text{SL}} = 25, 50, 75, 100\% \]

The effective geometric factor is therefore given by
\[ G_{\text{eff}} = G \times \varepsilon_{\text{BS}} \times \varepsilon_{\text{SL}} \]
Dependence on the primary energy

$\sigma_E/E$ is mostly independent on the primary energy
Prototype v1

**Geometry**
- 15 layers of 3x3 CsI:Tl cubes
- Scintillators wrapped in Teflon
- Light collected by Large PD
  (small PD tested on only 3 cubes)

**Shower containment**
- 1.5 Moliere radius
- $28.4 \times X_0$
- $1.35 \lambda_i$

**Beam tests**

<table>
<thead>
<tr>
<th>Date</th>
<th>Version</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 2013</td>
<td>v1.0</td>
<td>Ions Pb+Be 13-30 GeV/u</td>
</tr>
<tr>
<td>Mar 2015</td>
<td>v1.1</td>
<td>Ions Ar+Poly 13-30 GeV/u</td>
</tr>
<tr>
<td>Aug/Sep 2015</td>
<td>v1.2</td>
<td>$\mu, \pi, e$ 50-75-150-180 GeV</td>
</tr>
</tbody>
</table>
Depedence on the ion: Csl:Tl Calocube

![Graph showing energy resolution vs. effective geometric factor for different ions. The graph includes lines for Proton, Helium, and Carbon. The y-axis represents energy resolution in percent, and the x-axis represents the effective geometric factor in m$^2$ sr. The graph shows that the energy resolution increases with the effective geometric factor for all ions.]
Signal dependence from integration time

Signal attenuation consistent with 30% of slow scintillation component having $\tau = 8 \mu s$
Computation of time correction factor

For each scintillation component

\[ S(t)_{C_{sI}(Tl)} = \int_0^{T_i-t} I_0 e^{t/\tau} \, dt = I_0 \tau (1 - e^{-T_i/\tau} e^{t/\tau}) \]

Cumulative distribution of all signals belonging to the central column normalized to the corresponding most probable value (MP)

\[ \left( \frac{ADC_{ij}}{MP(ADC)_j} \right)_{ij} \]

\[ f(t) = P_0 \cdot \left(1 + P_1 \cdot e^{t/P_2}\right) + P_3 \cdot \left(1 + P_4 \cdot e^{t/P_5}\right) \]

Time correction \[ \frac{f(0)}{f(t)} \]
Equalization of channels using muons beam

Gain dispersion among crystals $\sim$ 19%

$\text{RMS}_{\text{noise}} \sim 60/80 \text{ ADC}$

Signal/Noise $\sim 10$
Energy resolution with electrons: Prototype v1.3

Energy resolution as a function of impact position shows strong dependence of performances on the region of the crystal.

Total signal in the crystal region having best resolution gives a value of this parameter of 1.1% for 50 GeV electrons.
Shower classification

Showers are classified according to the \textbf{starting layer} representing the first interaction point.

\[ \text{max} \propto A \cdot E \]
\[ \text{ion} \propto Z^2 \]

\begin{itemize}
  \item \textbf{Ion-beam data (Prot.v1.0)}
  \item \textbf{He @ 30.0GeV/u}
\end{itemize}
Energy resolution for hadrons

Shower starting on layer 3
Quite good agreement between data and MC

Shower starting within layer 5
12.8 GeV/amu
30.0 GeV/amu
(D,He,B,C,O,Mg,SI,S,Tl,Fe)

Equalized ADC counts

Beam energy

$\chi^2 / \text{ndf} = 553.3 / 18$
Prob = 0
$p_0 = 7041 \pm 716.5$
$p_1 = 2737 \pm 12.4$

Quite good linearity up to 1.6 TeV ion energy

$\left( \sigma_E \right)_A = \frac{1}{\sqrt{A}} \left( \sigma_E \right)_p$

Instrumental effects (optical cross-talk) were mostly understood and corrected starting from prototype v1.1

30 GeV/n
12.8 GeV/n
The non linear regime starts for $Z^2 = p_2 = 1/Z_0^2$

CsI:Tl has the largest $Z_0$

LYSO has the smallest $Z_0$
Using full information both from calorimeter and silicon tracker, angular resolution for vertical $\gamma$ is better than $0.1-0.5^\circ$ above 10 GeV.
“Starting from the front of the instrument, the LAT tracker (TKR) has 12 layers of 3% radiation length tungsten converters (THIN or FRONT section), followed by 4 layers of 18% r.l. tungsten converters (THICK or BACK section). These sections have intrinsically different PSF due to multiple scattering with the PSF for FRONT events being approximately a factor of two better than the PSF for BACK events.”
Calocube angular resolution

Graph showing 68% containment angle (deg) vs. effective geometric factor (m² sr) for different energy levels:

- 1 TeV
- 10 TeV
- 100 TeV
- 1 PeV

The graph represents protons.