An international group of scientists and engineers has started to work on the next generation magnetic spectrometer in space.

Prof. S. Schael

Stefan Schael

RWTH Aachen

 AMS-100

A Magnetic Spectrometer with an acceptance of 100 m² sr in Space
We have only one magnetic spectrometer in space: AMS-02
AMS-02 has recorded more than 135 Billion cosmic rays and will continue through the lifetime of ISS.
The AMS-02 Transition Radiation Detector was build at RWTH Aachen
October 2007
The 200 kg \textit{Upgraded Tracker Thermal Pump System} for AMS-02 was built at RWTH Aachen and will be brought to the ISS in October 2019.
AMS-02 Results
A. Kounine, NextGAPES-2019, Moscow

The cutoff energy $E_c = 810^{+310}_{-140}$ GeV is established with a confidence of more than 0.9999.

AMS-02 Antiproton
AMS-02 Positron

Pulsars or Dark Matter
Positrons from Cosmic Ray Collisions

AMS positrons

Positrons

Energy [GeV]

$E_{p_{\alpha}}(E) = \frac{E_{p_{\alpha}}^2}{E^2} C_0(E/E_0)^{1/4} + C_1(E/E_0)^{1/2} \exp(-E/E_0)$

Charge $\ = -2$, Mass $\ = 2.96 \pm 0.33$ GeV/c$^2$
Charge (He) $\ = +2$, Mass (He) $\ = 2.83$ GeV/c$^2$
It took 600 Physicists and Engineers from 16 Countries and 60 Institutes 17 years to construct the Alpha Magnetic Spectrometer.

![Diagram of the Alpha Magnetic Spectrometer](image)

- **Dimensions:** 5m x 4m x 3m
- **Weight:** 7 tons
- **Electronic Channels:** 300,000
- **Silicon Layers:** 7
- **Photo Sensors:** 11,000

We have to start now to work on the next generation magnetic spectrometer in space!
- The cosmic ray flux follows a power law $\Phi \approx C E^{-3}$.
- An increase in energy by a factor 10 requires an increase in acceptance by 1000. AMS-02 weighs 7 tons.
- Both PAMELA and AMS-02 have a telescope-like geometry.
- Just scaling such a geometry does not allow to increase the energy reach by a factor 10 and simultaneously the acceptance by a factor 1000.
• The design of AMS-100 was inspired by the BESS Ballon Experiment.
• A thin solenoid instrumented on the inside with a tracker like a classical collider experiment has an angular acceptance for cosmic rays of $4\pi$, if operated in space far away from earth, superior to any telescope like geometry.
• The B-Field of a long solenoid depends only on the number of turns, the current and the length, but not on the radius.
• Increasing the radius will therefore quadratically increase both the energy reach and the acceptance of the spectrometer at the same time.
James Webb, the next generation space telescope will be operated at Lagrange Point 2, and this is also the only option to significantly extend the AMS-02 physics program.
\( \vec{B} = 6 \text{ nT} \)
\( B = 0 - 37 \text{ nT} \)

For a large volume solenoid with a B-Field of 1 Tesla one typically has a Magnetic Moment of 70 MAm$^2$ which results in a Torque of:

\[ \vec{T} = \vec{M} \times \vec{B} \approx 0.4 \text{ Nm} \]
This large angular momentum can not be balanced by reaction wheels or gyroscopes!
The current in the Compensation Coil is adjusted such that the total magnetic dipole moment of the system is zero.
A 3 mm thin solenoid provides a magnetic field of 1 Tesla in a volume of 75 m$^3$.

The solenoid is constructed from HTS tapes and operated at 50 K behind the sunshield in thermal equilibrium with the environment.

An expandable compensation coil with 12 m diameter balances the magnetic dipole moment of the solenoid.

The solenoid is instrumented on the inside with a silicon tracker and a calorimeter system ($70 X_0$, $4 \lambda_i$).

AMS-100 has a geometrical acceptance of 100 m$^2$ sr and a maximum detectable rigidity of 100 TV.
### Current and upcoming rockets

<table>
<thead>
<tr>
<th>Name</th>
<th>LEO [kg]</th>
<th>other [kg]</th>
<th>First flight</th>
<th>Agency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ariane 5</td>
<td>21,000</td>
<td>10,730</td>
<td>GTO 2002</td>
<td>ESA</td>
</tr>
<tr>
<td>Falcon Heavy</td>
<td>63,800</td>
<td>26,700</td>
<td>GTO 2017</td>
<td>SpaceX</td>
</tr>
<tr>
<td>Long March 5</td>
<td>25,000</td>
<td>8,000</td>
<td>TLI 2016</td>
<td>CALT</td>
</tr>
<tr>
<td>Long March 9</td>
<td>130,000</td>
<td>50,000</td>
<td>TLI 2025</td>
<td>CALT</td>
</tr>
<tr>
<td>SLS Block 1B</td>
<td>105,000</td>
<td>39,100</td>
<td>TLI 2022</td>
<td>NASA</td>
</tr>
<tr>
<td>SLS Block 2</td>
<td>130,000</td>
<td>45,000</td>
<td>TLI 2025</td>
<td>NASA</td>
</tr>
</tbody>
</table>

**Operational**

**Under development**

- **LEO**: Low Earth orbit
- **GTO**: Geostationary transfer orbit
- **TLI**: Trans-lunar injection

AMS-100: 40 t
<table>
<thead>
<tr>
<th>Component</th>
<th>Measurement Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>SciFi-Tracker</td>
<td>Measurement of R and Z</td>
</tr>
<tr>
<td></td>
<td>2 x 6 Measurements, 0.040 mm resolution.</td>
</tr>
<tr>
<td>Silicon-Tracker</td>
<td>Measurement of R and Z</td>
</tr>
<tr>
<td></td>
<td>2 x 12 Space Points, 0.005 mm resolution.</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>Measurement of E and Z</td>
</tr>
<tr>
<td>Pre-Shower</td>
<td>Measurement of E and Z</td>
</tr>
</tbody>
</table>

Radiator
- Outer SciFi, Layer 1 - 3
- Outer ToF, Layer 1 & 2

Magnet
- Inner ToF, Layer 1 & 2
- Inner SciFi, Layer 1 - 3
- Si-Tracker, Layer 11 & 12

ToF
- Measurement of $\beta = P/E$ and Z
- 2 x 4 Measurements, <20 ps resolution.

Measurement of E and Z
Scintillating Fiber - Tracker: First & Fast Measurement of $R$ and $Z$
Provides 2x6 Measurements with 0.040 mm resolution.
MDR: 3 TV

Light nuclei with $R<200$ GV will be mostly rejected.

Protons

Cosmic Ray Rate [1/s]

- AMS-100 Readout Design, SF= 1.5
- AMS-100, $A= 341m^2sr$
- AMS-100 L2 trigger rate

$R_{min}$ [GV]
- Linear Silicon-Photomultiplier Arrays with 0.25 mm readout pitch are attached to the end of the fiber mat.
- The other end is covered by a high reflective mirror.
- The fiber mats have a width of 13.5 cm and a length of 2.4 m.
- 350 m² of Scintillating Fiber Tracker Modules have just been produced in the past 2 years by an European Collaboration for the new LHCb Tracker.
- 500 of the 1500 fiber mats were produced at RWTH Aachen.
- The sensor size for a silicon tracker is 10 cm x 10 cm, with $\sigma_{\text{Cor.}}=0.01$ mm. For the new SciFi-Tracker of LHCb the sensor size is 13.5 cm x 240 cm, i.e. more than 30 times larger, with $\sigma_{\text{Cor.}}=0.05$ mm.
Both SciFi-Tracker and ToF have been tested already successfully 2010 in an ESA Balloon Flight.

November 23rd, 2010 07:50 am
09:18 Liftoff

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**Radiator**
- Outer SciFi, Layer 1 - 3
- Outer ToF, Layer 1 & 2
- Magnet
- Inner ToF, Layer 1 & 2
- Inner SciFi, Layer 1 - 3
- Si-Tracker, Layer 11 & 12

**Si-Tracker**
- Layer 9 & 10
- Layer 7 & 8
- Layer 5 & 6
- Layer 3 & 4
- Layer 1 & 2

**Pre-Shower**

**Calorimeter**

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**Time-of-Flight**
- Provides the Trigger and measures $\beta = v/c$
- Provides 2x4 time and Z measurements
- Time Resolution per Scintillator-Rod: < 20 ps

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**Separate Anti-Protons from Deuterium**

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**Graph**

- Acceptance [m$^2$ sr]
- $E_{\text{kin}}$ [GeV]
AMS-100 ToF based on the PANDA Barrel ToF Design

- Two scintillating rods read out on two sides each.
- Scintillator dimensions 87 x 29.4 x 5 mm$^3$

PANDA Barrel ToF

- Scintillation Tile Hodoscope for the PANDA Barrel Time-Of-Flight Detector

Time Resolution 50 ps

- Sensor board (single sided)
- Sensor board (double sided)
- Scintillator

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Willkom Netli, Ken Suzuki, Stefan Meyer-Institut, CERN on behalf of the PANDA Barrel-TOF(SaTi) group

12.06.2018, ICANP2018
\[ \sigma_T \propto \frac{1}{\sqrt{N_{pe}}} \]

- Larger SiPM's could increase the Surface coverage and hence improve the time resolution.
- Further improvements can be expected from faster scintillators and new SiPM's with higher photon detection efficiency.

<table>
<thead>
<tr>
<th>thickness</th>
<th>N_{pe1}</th>
<th>N_{pe2}</th>
<th>time-resolution (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3mm</td>
<td>72.37</td>
<td>46.84</td>
<td>60.34</td>
</tr>
<tr>
<td>4mm</td>
<td>85.64</td>
<td>55.14</td>
<td>68.09</td>
</tr>
<tr>
<td>5mm</td>
<td>139.94</td>
<td>128.69</td>
<td>50.14</td>
</tr>
<tr>
<td>5mm polished</td>
<td>111.87</td>
<td>78.1</td>
<td>48.29</td>
</tr>
<tr>
<td>6mm</td>
<td>101.7</td>
<td>70.7</td>
<td>48.7</td>
</tr>
</tbody>
</table>
MPPC (Multi-Pixel Photon Counter) | S13360 series

Photosensitive area: 6.0 x 6.0 mm²
Pixel pitch: 75 μm
Fill Factor: 82%

MPPC characteristics vary with the operating voltage. Although increasing the operating voltage improves the photon detection efficiency and time resolution, it also increases the dark count and crosstalk at the same time, so an optimum operating voltage must be selected to match the application.

SiPM’s will be operated in AMS-100 at 200 K. This will allow for a larger Overvoltage and hence increase the photon detection efficiency.
AMS-100 ToF

Scintillator rods (90mm x 30mm x 6mm) with high-gain and low-gain SiPM readout arranged in 4 overlapping layers.

Side view of the SciRod

• Time Resolution per SciRod: <20 ps
• Defines the region of interest for the SciFi-Tracker readout.
High Temperature Superconducting Magnet
Provides a homogenous magnetic field of 1 Tesla in a Volume of 75 m³
Operated at 50 Kelvin in thermal equilibrium with the environment
Together with groups from Uni. Geneva and EPFL we will perform the first space qualification of a HTS magnet.
AMS-100 Magnet Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Inner Solenoid</th>
<th>Compensation Coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Radius</td>
<td>2.0 m</td>
<td>6.0 m</td>
</tr>
<tr>
<td>Length</td>
<td>6.0 m</td>
<td>1.2 m</td>
</tr>
<tr>
<td>Current</td>
<td>500 A</td>
<td>1500 A</td>
</tr>
<tr>
<td>Temperature</td>
<td>50 – 60 K</td>
<td>30 – 40 K</td>
</tr>
<tr>
<td>HTS Tape Width</td>
<td>12 mm</td>
<td>12 mm</td>
</tr>
<tr>
<td>HTS Tape Layers</td>
<td>22</td>
<td>4</td>
</tr>
<tr>
<td>$B_z$ at Center</td>
<td>1.0 T</td>
<td>-0.06 T</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>37 MJ</td>
<td>4.5 MJ</td>
</tr>
<tr>
<td>Magnetic Moment</td>
<td>70 MA m$^2$</td>
<td>-70 MA m$^2$</td>
</tr>
<tr>
<td>Coil Thickness</td>
<td>3.0 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Mass</td>
<td>1.2 t</td>
<td>0.13 t</td>
</tr>
<tr>
<td>Volume</td>
<td>75 m$^3$</td>
<td>136 m$^3$</td>
</tr>
<tr>
<td>Material budget</td>
<td>0.12 $X_0$</td>
<td>0.02 $X_0$</td>
</tr>
<tr>
<td>Wire Length</td>
<td>150 km</td>
<td>15 km</td>
</tr>
<tr>
<td>$\sigma_R$</td>
<td>-130 kPa</td>
<td>-40 kPa</td>
</tr>
<tr>
<td>$\sigma_\theta$</td>
<td>270 MPa</td>
<td>250 kPa</td>
</tr>
<tr>
<td>$\sigma_Z$</td>
<td>-140 MPa</td>
<td>-79 kPa</td>
</tr>
</tbody>
</table>
Performance of the Tracking System
The concentric 6 double layers of the Silicon Tracker provide up to 2x12 Space Points with 0.005 mm resolution and measurements of Z.
Performance of the Tracking System

The concentric 6 double layers of the Silicon Tracker provide up to 2x12 Space Points with 0.005 mm resolution and measurements of $Z$.
4 x Silicon Ladders
90 cm x 10 cm

4 x Front-End Hybrids
10 cm x 10 cm
- 6 Cylinders, 12 Layers
- Double-Sided Silicon Detectors, 380 m² (similar to CMS)
- Readout: VA-140 Chip, 0.35 μm CMOS, 0.3 mWatt/Channel
- 5.2 $10^6$ Channels
Pre-Shower & Calorimeter: 70 $X_0$ and 4 $\lambda_1$

Energy and Direction Measurements for Photons, Positrons and Hadrons

3D Shower Reconstruction for Particle Identification

Energy up to which the shower maximum is contained in the calorimeter.
Calorimeter
Inspired by the HERD Detector Concept

LYSO Crystal
3 cm x 3 cm x 3 cm

- LYSO is a Cerium doped Lutetium based scintillation crystal with a density of 7.1 g/cm³.
- The $X_0$ of LYSO is 1.14 cm, so each crystal is $\sim 2.6 X_0$.

LYSO Crystal with large and small area photodiodes glued to one face of the cube.

R=40 cm, L= 400 cm, Weight 8.2 t
37 740 LYSO Crystals

Pre-shower: L=400 cm, Weight 4 t,
Tungsten (5 $X_0$) instrumented with Si-Detectors

Central Support Tube
3 cm CF
AMS-100 will measure light Nuclei in Cosmic Rays up to the maximum energy that can be reached by cosmic ray accelerators in our galaxy.
Electrons in Cosmic Rays

\[ E^3 \Phi_{e^-} \text{ [m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-2}] \]

- \( e^+ + e^- \)
- CALET
- DAMPE
- FERMI
- H.E.S.S.

Electrons
- AMS-100: No Source Term
- AMS-100: Charge Symmetric Source Term
- AMS-02
- PAMELA

\[ E \text{ [GeV]} \]
Anti-Deuterons are the most sensitive probe for New Physics in Cosmic Rays

As a Magnetic Spectrometer AMS-100 can separate Anti-Matter from Matter.

AMS-100 would observe thousands of Anti-Deuterons in cosmic rays. Integral sensitivities are not useful.
$Z = -1$ Particles in Cosmic Rays

Flux ($m^{-2} s^{-1} GeV^{-1}$)

- AMS-02 electrons
- AMS-02 p
- BESS p
- BESS (95% CL) D
- GAPS D
- AMS-02 D sensitivity
- AMS-100 D
- D from dark matter
- AMS-100 D sensitivity
- D from secondary production

$E_{kin}$ (GeV)

- 20 ps
- 50 ps
- 10 ps

Phys. Rev. D 97, 103011, 2018
Gamma rays are measured in three ways:

1. Using the calorimeter the acceptance is 30 m² sr. The energy reach is limited by the flux, not by the depth of the calorimeter. For energies above ~1 GeV the whole sky is covered continuously.

2. The 3 mm thin magnet coil (12% $X_0$) is a well localized converter for photons. The angular resolution at high energies is excellent, geometrically 0.005 mm/4000 mm, covering most of the sky continuously.

3. The endcap opposite to the service module is instrumented with a dedicated photon detector inspired by the GAMMA-400 design to optimize the angular resolution at low energies.
FERMI expects to discover ~8000 Gamma Ray Sources in 12 years. It will take AMS-100 0.5 years to confirm these sources and afterwards it will explore a new territory in gamma ray physics.

**Calorimeter + Converted Photons**

**Effective acceptance for Converted Photons**
Angular Resolution for Converted Photons

68% containment (deg)

- AMS-100 barrel
- AMS-100 endcap, GAMMA-400
- Fermi-LAT

E (GeV)

Crab Nebula with Chandra (blue and white), Hubble (purple), and Spitzer (pink) data.
Weight: 40 t
MDR: 100 TV
Acceptance: 100 m² sr
Power: 10 kW
B-Field: 1 Tesla
Measurement Time: 10 years
Calorimeter: 70 X₀, 4λ

New groups who are interested to work on AMS-100 are very welcome!