The AMS-100 experiment:
The next generation
magnetic spectrometer in space

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on behalf of the AMS-100 group

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AMS-02 is the only magnetic spectrometer in space:

**Operational on the ISS since May 2011**

- **Weight:** 7 t
- **Magnet:** $BL^2 = 0.15 \text{ Tm}^2$
- **Acceptance:** 0.1 $\text{m}^2\text{sr}$
- **MDR:** 2 TV
- **Calorimeter:** $17 \chi_0, 1.7\lambda$

Recorded more than 198 Billion cosmic rays and will continue through the lifetime of ISS.
AMS-02 found:
8 $^3\text{He}$ and 2 $^4\text{He}$ candidates,
But no hits in outer tracker layer

\[
\text{Momentum} = 33.1 \pm 1.6 \text{ GeV/c} \\
\text{Charge} = -1.97 \pm 0.05 \\
\text{Mass} = 2.93 \pm 0.36 \text{ GeV/c}^2 \\
\text{Mass (}^3\text{He}) = 2.83 \text{ GeV/c}^2
\]
AMS-02 Upgrade: Search for Anti-Helium Nuclei

AMS-02 Upgrade: New tracker layer

AMS-02 upgrade: Find Anti-Helium candidates with hits in all tracker layers?

Only a next generation magnetic spectrometer in space will be able to experimentally resolve the questions about Dark Matter signals in cosmic ray anti-matter.
The cosmic ray flux follows a power law $\Phi \approx C E^{-3}$

Increase in energy by a factor 10 requires an increase in acceptance by 1000.

Design Requirements for a superconducting magnet spectrometer operated at Lagrange Point 2:

- Max detectable rigidity of 100 TV
- Geometric acceptance of 100 m$^2$sr $\rightarrow$ 1000 times the acceptance of AMS-02
- Measurement of cosmic nuclei with energies up to the cosmic-ray knee
AMS-100: The Expedition to Lagrange Point 2

- Total estimated mass of AMS-100: 40 t
  - Magnet system: 2t
  - Detector equipment: 18 t
  - Auxiliary equipment: 20 t
- Launch with SpaceX’s Starship rocket
  - Mass-to-orbit: 100+ t
  - Payload to L2 with refueling on-orbit
AMS-100: Physics with cosmic rays at Lagrange Point 2

- Position at Sun-Earth Lagrange Point 2
  - No heat radiation from sun or earth
  - Allows cryogenic experiments
  - Gaia, Herschel, Plank, WMAP, James Webb S. Telescope, Queqiao, eRosita
- Starting at around 2035 - 2040
- Collecting data for min. 10 years
AMS-100: High Temperature Superconducting Magnet, Compensation Coil

Interplanetary Magnetic Field

\( B > = 6 \text{ nT}, \) Variation \( B = 0-37 \text{ nT} \)

→ large volume solenoid with a B-Field of 1 Tesla in interplanetary Magnetic Field results in a Torque of 0.4 Nm

→ Current in Compensation Coil adjusted such that total magnetic dipole moment of the system is reduced to 1/10000

→ Remaining angular momentum is balanced by reaction wheels

<table>
<thead>
<tr>
<th></th>
<th>Main Coil</th>
<th>Dipole Compensation Coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>6.3 m</td>
<td>1 m</td>
</tr>
<tr>
<td>Diameter</td>
<td>4.2 m</td>
<td>12.6 m</td>
</tr>
<tr>
<td>Number of Turns</td>
<td>450</td>
<td>71</td>
</tr>
<tr>
<td>HTS Layers</td>
<td>18 @ 50 – 60 K</td>
<td>3x2 @ 50 K</td>
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<tr>
<td>Current</td>
<td>13500 A</td>
<td>9500 A</td>
</tr>
<tr>
<td>B-Field</td>
<td>1 T</td>
<td>-0.06 T @ z=0, R=0</td>
</tr>
</tbody>
</table>
AMS-100:

Planned Design:

• 3 mm high temperature superconducting solenoid (HTS tapes) → 1 T in a volume of 75 m³

• Solenoid operated at 50 – 60 K behind the sunshield in thermal equilibrium with the environment

• Expandable high temperature superconducting compensation coil (Ø 12 m) balances magnetic dipole moment of solenoid

• Solenoid is instrumented on the inside with a silicon tracker and a calorimeter system (70 X₀, 4 λ₁)

• SciFi-tracker

• Time-of-flight (ToF) system

AMS-100 Detector

Calorimeter & Pre-Shower: Measurement of E and Z

Silicon-Tracker Measurement of R and Z 2 x 12 Space Points, 5µm resolution.

ToF Measurement of β=P/E and Z 2 x 4 Measurements, <20 ps resolution.

SciFi-Tracker Measurement of R and Z 2 x 6 Measurements, 40µm or 13µm resolution.
Thermal Analysis of AMS-100:

Thermal analysis shows:
Magnet-radiator temperature of 50-60 K,
Detector components @ 200 K

David-Sharif Kohlberger, FH Aachen, Faculty of Aerospace Engineering
AMS-100: High Temperature Superconducting Magnet

- Length: 6.3 m, Diameter: 4.2 m
- Number of Turns: 450
- Operating at 50 K – 60 K
- Current: 13500 A
- B-Field: 1 T
- 107 km of HTS Tape
- Thickness: 18x0.04mm = 0.72mm
- Stored Energy: 39 MJ
- Radiation Length: 0.11 $X_0$
- Total Weight: 2200 kg

AMS-100 magnet system faces many design challenges due to its

Ultra-thin 1T HTS coil,

Design B-field of 1 T in the center of the solenoid.

Operating temperature range of 50 to 60 K:
Large temperature margin is important:
- cooling power is very limited via external radiators,
- large stored energy 39 MJ
- no intervention possible.

Requirement to survive high-vibration launch conditions

Requirement to fit the magnet and its compensation coil(s) inside a rocket
AMS-100: High Temperature Superconducting Magnet, non insulated Coil

- Al-alloy skin for mechanical strength and axial thermal conductivity
- HTS cable welded in aluminum jacket

Al-6110-T9 skins paired with a honeycomb structure to increase the magnet’s stiffness.

- Honeycomb structure increases the effective thickness of the object with minimal increase in radiation length.
- Magnet becomes more resistant to buckling.
- Al-6110-T9 alloy: provides a compromise between mechanical strength (yield stress > 500 MPa) and good thermal conductivity.
End-Flanges (grey):
Mechanical support of the magnet during manufacturing, launch and operation. Circular, allows quench-back.

Rib (yellow):
Mechanical support of the magnet during operation and quench events. Circular, allows quench-back.

Stringers (blue):
Mechanical support for during launch.

Quench model is under development:
→ Predicting quench behavior of main solenoid, resulting hot-spot temperature and mechanical load on conductor are studied for several quench scenarios.
→ Quasi 3D thermal, electrical and magnetic nodal-network model is built using python.
→ Results from this model are analyzed in ANSYS/Abacus to evaluate the resulting mechanical response.
AMS-100: High Temperature Superconducting Magnet

Several compact demonstrator coils are envisioned and in preparation.

- Test of materials and preparation procedures.
- Optimize soldering procedure
- Validate models and results (mechanical, electrical and thermal)
- Starting with small, few turn demonstrator coils, later moving to larger coils.
- Larger Coils will undergo space qualification tests

Diameter: 120mm
Turns: 3
HTS 4mm, 8 Layers

Length: 180 mm
Diameter: 120mm
Turns: 36
HTS 4mm, 8 Layers
AMS-100: Time of Flight System

- Required ToF-Single Counter time resolution: 20 ps
- Z measurements from the signal height
- Provides the trigger and measures $\beta = \frac{v}{c}$

Anti-Deuterons are the most sensitive probe for New Physics in Cosmic Rays

AMS-100 would observe thousands of Anti-Deuterons in Cosmic Rays

$\Delta t^* = \frac{(t_1 - t_2)}{2}$
AMS-100: Time of Flight System

- Scintillator rods with SiPMs operating at 200 K
- Scintillator dimensions 90 x 25 x 6 mm³
- Expected time resolution for one rod: 20 ps
- Similar to the PANDA Barrel TOF
  → Reached 50ps resolution
  But matching factor $\approx 0.25$

\[
\sigma_t = \sqrt{\frac{\sigma_{\text{scint}}^2}{k} + \sigma_{\text{SiPM}}^2 + \sigma_{\text{elec}}^2}
\]

$\sigma_{\text{scint}}$ intrinsic time resolution of scintillator with full coverage

$k$ is the fractional sensor coverage, matching factor

$\sigma_{\text{elec}} \sim R_{\text{amp}} \times C_{\text{SiPM}}$ and intrinsic noise of amplifier

→ full coverage of the frontface of scintillators, $k=1$
→ serial connection of SiPM cells → reduce $C_{\text{SiPM}}$
AMS-100: Time of Flight System

SiPM (Hamamatsu S14161-6050HS-04)
- Single Array Size = 6mm × 6mm
- Total Nr. Arrays = 4 × 4
- Array Connection: Hybrid
- VBR = 38V
- Peak Sensitivity (450nm, PDE=50%)
- Capacitance $C_{\text{SiPM}} = 2000$ pF

Single Scintillator Size ($D \times W \times L$) = 6mm × 25mm × 90 mm
- Matching-Factor = 1.0 (fased $D \times W$ sides to SiPM)

TOF Time Resolution ($\sigma_t$)_{req.} = 20 (ps)

4 Array signals are summed up and fed into one channel
AMS-100: Time of Flight System

External triggered / Self-triggered Setup:

Climate Chamber

SiPMs
Hamamatsu (S14161-6050HS)

Power/Signal (L)

SiPM Amplifier

Power/Signal (R)

USB2

SiPM Signals

Waveform Digitizer (DRS4)

External Trigger

USB2

Linux-PC

SiPMs

Hamamatsu (S14161-6050HS)

External Trigger

SiPM (L)

$\chi^2/\text{ndf} = 213.1/249$

\[ f(x) = a + b \left( 1 + e^{-\frac{x-t_0}{\tau}} \right) \]

\[ f_{1/2}(t_0) \]

External Trigger

Time (ns)

Amp

90%

50%

10%

USB2

SiPM (R)

\[ \chi^2/\text{ndf} = 193/247 \]

\[ a = -4.892e-05 \pm 3.243e-05 \]

\[ b = -0.0041 \pm 0.0003955 \]

\[ t_0 = 132.6 \pm 0.00262 \]

\[ \tau = 0.8395 \pm 0.01659 \]
AMS-100: Time of Flight System

External Triggered Events:

$^{90}\text{Sr}$, EJ-228 (6 mm x 25 mm x 90 mm), PCB-Ch4(Hybrid), T=23°C

Coincidence Time Resolution (CTR, $\sigma_{\Delta t}$)
For triggered MIP-particles: $\sigma_{\Delta t} = 78.7$ ps

Time Resolution ($\sigma_t$): $\sigma_t = \frac{\sigma_{\Delta t}}{2}$

$\sigma_t = (39.3 \pm 0.1\text{(stat.)} \pm 0.7\text{(syst.)})$ ps

Wrapping/Reflector Studies:

$\sigma_{t, \text{al.Mylar}} = 39.3$ ps
$\sigma_{t, \text{PTFE}} = 39.9$ ps

Next steps: Reduce $R_{\text{amp}} \times C_{\text{SiPM}}$ to improve $\sigma_t$
AMS-100: Time of Flight System

Temperature Variation:
Self triggered measurement, threshold 10 mV → 0.5 MeV e⁻

Coincidence Time Resolution (CTR, $\sigma_{\Delta t}$)

Time Resolution not significantly depending on temperature in the temperature range 23°C to -30°C
AMS-100: Scintillating Fiber Tracker

- Staggered layers of $\varnothing 250 \, \mu\text{m}$ fibres form a fibre mat
- Readout by arrays of SiPMs. 1 SiPM channel extends over the full height of the mat.
- Pitch of SiPM array should be similar to fibre pitch. Light is then spread over few SiPM channels. Centroiding can be used to push the resolution beyond $\text{p}/\sqrt{12}$.

50µm resolution
AMS-100: Scintillating Fiber Tracker

LHCb-SciFi-Tracker:

Fiber Mat Winding

→ 10,000 km of fibre in total

5m length

1152 SciFi mats, 144 Modules, 340 m² total area

See talk Lais Soares Lavra: „The Scintillating Fibre Tracker for the LHCb Upgrade“
AMS-100: Scintillating Fiber Tracker

First & Fast Measurement of R and Z; MDR: 3TV
Provides 2x6 Measurements with
40 μm resolution (using 250μm thick fibers), MDR 3TV
or
13 μm resolution (using 125μm thick fibers), MDR 9TV

$$\sigma = \text{FiberWidth}/\sqrt{12}/\sqrt{nFiber}$$
AMS-100: Scintillating Fiber Tracker

Production of 12 layer fiber mat made out of 125μm thick fibers from Kuraray, LHCb winding machine @ I. Physics Institute adapted to 125μm fibers, winding force less then 5cN.

12 Layer fiber mat with 125μm thick fibers produced
L = 90cm, W = 1.5cm, H= 1.42 mm

→ Production of 1st Fiber mat with 125μm thick fibers successful!
AMS-100: Scintillating Fiber Tracker

Optical Scan of 12 layer fiber mat with 125µm thick fibers

Fitted angled quadratic formula per fibre layer:
Distance between fitted and actual fiber position increases from 6 µm (1st wound layer) till 17µm (12th wound layer);
Average distance between fitted and actual fibre position: **13.3 µm**

→ Total Position Resolution ($\sigma_x$) = 13 µm $\oplus$ 13.3 µm = 19 µm → MDR 6TV
AMS-100: Scintillating Fiber Tracker

Light yield Measurements using Sr90-radioactive source to excite 12 layer fiber mat with 125µm thick fibers

6-layer Fiber mat with 250 µm thick fibers

12-layer Fiber mat with 125 µm thick fibers

\[ R_{LY} = \frac{LY_{250\mu m}}{LY_{125\mu m}} = \frac{16.1}{10.4} = 1.6 \]

\[ R_{LY \ exp. \ @0.8m \ from \ SiPM} = 1.11 \]

→ Light yield of 12 layer fiber mat with 125µm thick fibers lower than expected!
AMS-100: Scintillating Fiber Tracker

Lightyield of 6 Layers SciFi-Mat with 250µm fibers measured at lower temperatures

\[ \text{Lightyield}(T) = 0.11 \% /K \]
AMS-100: Scintillating Fiber Tracker

6 Layers SciFi-Mat (0.25mm Fibers) @ temperature range 77 K - 253K

Light yield before and after cryogenic temperatures

⟶ no significant changes in performance

⟶ LHCb SciFi-Tracker is planning to cool down SiPMs and Fibers to cryogenic temperatures for Upgrade 2
AMS-100

Precise measurements of proton, electron, positron and anti-proton flux at higher energies

Proton flux is described by a power law with several smooth breaks, inserted for the purpose of illustration (dashed curve).
As a Magnetic Spectrometer AMS-100 can separate Anti-Matter from Matter

Anti-Deuterons are the most sensitive probe for New Physics in Cosmic Rays

Z=-1 Particles in Cosmic Rays

From AMS-02 to AMS-100 Anti Helium Flux:
1 event/year -> 1000 events/year

The resolution is high enough to distinguish between the different sources for Anti-Helium
Conclusion

• AMS-100 is a powerful magnetic spectrometer detector concept
  • Acceptance 1000x higher than of AMS-02
  • MDR 100 TV – Calorimetry measurements up to the cosmic knee (PeV)
  • Sensitive to measure Anti-Matter and other rare nuclei in Cosmic Rays
  • High accuracy measurement of the positron spectrum till 10 TV
  • Continuous full sky coverage to measure gamma rays with excellent angular resolution

• New technologies
  • High temperature superconducting magnets are becoming very important for accelerators and detectors on earth (LHC. FCC) and in space
  • Detector technologies @ cryogenic temperatures

Weight: 40 t
Thin coil Solenoid: \( BL^2 = 15 \text{Tm}^2 \)
Acceptance: \( 100 \text{ m}^2\text{sr} \)
MDR: 100 TV
Calorimeter: \( 70 \ X_0, 4 \Lambda \)
Power Consumption: 15 kW
Incoming Particle Rate: 2 MHz
Number Readout Channels: 8 Million
Mission Flight Time: 10 years
Backup
Particles and nuclei are defined by their charge ($Z$) and energy ($E \sim P$). $Z, P$ are measured independently by the Tracker, RICH, TOF and ECAL.
AMS-02 Results & Open Questions: Positron Flux – Search for Dark Matter:

Diffuse term:
Low-energy part of the flux dominated by the positrons produced in the collisions of ordinary cosmic rays with the interstellar gas.

Source term:
Origin through pulsars or dark matter annihilation or an unknown source.

Cutoff ($\approx$ 300 GeV):
Gives the maximum energy of the positrons and could therefore represent half the mass of the dark matter particles.

$\Phi_{e^+}(E) = \frac{E^3}{E^3} \left[ C_0 (E/E_1)^\gamma + C_1 (E/E_2)^\gamma \exp(-\hat{E}/E_3) \right]$
AMS-02 Results & Open Questions: Search for Anti-Deuterons

No active or proposed instrument has the sensitivity to exclude low energy Anti-Deuterons from Dark Matter Annihilation by measuring the flux expected from secondary production.
Performance of the Silicon Tracking System:

- Expected: a **single point resolution of 5 μm** in the bending plane for |Z| = 1 particles
- Higher resolution by lowering the temperature to 200 K
- Six double layers arranged in cylindrical geometry leading to a maximum of 24 measurement points for a single track
- With a magnetic field of 1 T, the AMS-100 silicon tracker provides an MDR of 100 TV
- The structure is similar to the CMS silicon strips detectors in the barrel module but with silicon ladders instead of single strips
- Sensitive area 380 m²
- Readout: VA-140 Chip, 0.35 μm CMOS, 0.3 mW/Channel
- 5.2 \(10^6\) Channels
AMS-100: Tracking System

Performance of the Silicon and SciFi Tracking System

**Silicon Tracker**
- 2 × 12 points
- 5 μm resolution

**SciFi Tracker**
- 2 × 6 points
- 40 μm resolution

Expected of the Tracker and ToF System

\[ M = \frac{Z R}{\beta \gamma} \]
\[ \gamma = \frac{E}{M} \]

\[ \left( \frac{\sigma_M}{M} \right)^2 = \left( \frac{\sigma_R}{R} \right)^2 + \gamma^4 \left( \frac{\sigma_p}{\beta} \right)^2 \]

AMS-100: Separate $\vec{p} \leftrightarrow \vec{d}$ with 6-σ up to $E_{\text{kin}} = 15\text{GeV}$ $P = 17\text{GeV}$ $R = 17\text{GV}$

M(Deuteron)=1.876 GeV

Maximum acceptable resolution

Deuteron $\sigma_M/M$ vs $E_{\text{kin}} [\text{GeV}]$
AMS-100: Electromagnetic Calorimeter

Preshower Detector:
- 12 silicon detector layers interleaved with thin tungsten layers ($5X_0$)
- $L$=400 cm, Weight 4 t
- Measures direction of cosmic gamma rays
- Limit the backsplash of the calorimeter into the silicon tracker

Crystal Calorimeter (inspired by HEARD concept):
- 3-dimensional grid of 37740 LYSO crystal cubes ($3 \times 3 \times 3$ cm)
- $R$=40 cm, $L$= 400 cm, Weight 8.2 t
- LYSO is a Cerium doped Lutetium based scintillation crystal with a density of 7.1 g/cm3, $X_0 = 1.14$ cm, each crystal $\sim 2.6 X_0$
- Readout with large and small area photodiodes glued to one face of the cube.
- Allows reconstruction of the shower shape

Combined detectors:
- Can separate electromagnetic and hadronic showers
- Radiation length of $70X_0$
- Nuclear interaction length $4\lambda_i$
- Measurement of cosmic protons and ions with energies above 100 TV up to the cosmic-ray knee (PeV) are possible
AMS-100: Electromagnetic Calorimeter

High-Energy Gamma Rays

1. Using the calorimeter to measure directly gamma rays with an acceptance of 30 m² sr

2. Measure photons which are converted in the 3 mm thin magnet coil (0.12X₀)

3. Measure photons at low energies with the Gamma Converter at the endcap which is inspired by the GAMMA-400 design
AMS-100
Precise measurements of proton, electron, positron and anti-proton flux at higher energies

\[ R^{2.7} \Phi_p \text{ [m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GV}^{1.7}] \]

Anti – Protons

 AMS-100  
AMS-02  
BESS  
PAMELA
AMS-100
Precise measurements of proton, electron, positron and anti-proton flux at higher energies
AMS-100

Precise measurements of proton, electron, positron and anti-proton flux at higher energies

Model (a): a power law plus a source term with an exponential cutoff (blue circles, lower curve at high energy).
Model (b): power laws with spectral breaks and the last break is at 300 GeV (blue squares, upper curve at high energy).
The dashed green curve shows the contribution as typically expected from secondary production to the spectrum in model...