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

Prof. S. Schael

**AMS-100**

A Magnetic Spectrometer with an acceptance of 100 m² sr in Space

Structural- & Thermal Design, Service Module, Sunshield & Magnet


S. Schael RWTH Aachen University
November 2022
We have only one magnetic spectrometer in space: AMS-02
TRD Construction at RWTH

TRD Gas System
Thermo Vacuum Test at RWTH
AMS-02 TRD

5248 Readout Channels,
482 Temperature Sensors,
8 Pressure Sensors,
24 Heaters.
In total, 7.2 m out of 7500 m of total wire length are ineffective, i.e. 99.9% of the TRD are working as expected.
The TRD will run out of Xe gas in ~2040.
Tracker Thermal Control System with UTTPS

**Tracker**

- **Evaporator**
  - +10°C
  - 120W

- **Working fluid**: CO₂
  - Two-phase
  - Single phase

**Radiators**

- **Condensers**
  - 120W

- **Magnet**
- **Evaporator**
- **Accumulator**
- **Fill/Refill Vessel**
- **Filter**
- **4 Pumps in parallel**
- **Add. Pump Caps**
- **Fill Port Cap**
- **Radiator**

Diagram showing the flow of the thermal control system with various components and connections.
The UTTPS was constructed at RWTH Aachen with strong support from NASA and MIT

4 years - 70 Scientists and Engineers
With the new tracker plane on top of AMS-02 its acceptance will be increased by 300%.
It took 600 Physicists and Engineers from 16 Countries and 60 Institutes 17 years to construct the Alpha Magnetic Spectrometer.

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 weights 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.
Example of Thin Solenoids using Low Temperature Superconductors (Nb-Ti) at T = 4 Kelvin

The coil weighs 43 kg and has a radial thickness of 3.4 mm and was build at KEK, Japan.

The coil weighs 5.5 tons and has a radial thickness of 4.5 cm and was build at Toshiba, Japan.
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.
• A thin solenoid provides a magnetic field of 0.5 Tesla.
• The solenoid is operated at 60 K behind the sunshield in thermal equilibrium with the environment.
• A compensation coil balances the magnetic dipole moment of the solenoid.
• The solenoid is instrumented on the inside with a silicon tracker and a calorimeter system.
The Expedition to Lagrange Point 2

Vehicle and Launch:
- Target launch year: ~2035.
- Operational for 10+ years.
- Total estimated mass of AMS-100: 40 Tons
  - ~4 Tons for the magnet system,
  - ~16 Tons of detector equipment,
  - ~20 Tons of auxiliary equipment and cabling.
- Launched with SpaceX’s Starship rocket.

Starship’s 8 m (26 ft) diameter payload dynamic envelope
SpaceX

- In 2019, the cost per launch for Starship was estimated by SpaceX to be as low as US$2 million.
- Elon Musk has said in 2020 that, with a high flight rate, they could potentially go even lower, with a fully-burdened marginal cost on the order of US$10 per kilogram of payload launched to low Earth orbit.
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AMS-100 Solenoid - a non-insulated coil

90 km of High Temperature Superconducting Tape

Thickness: 18 x 0.04 mm = 0.72 mm!

B = 0.5 Tesla
L = 0.29 H
E = 14 MJ

Stack of 18 Tapes
12 mm wide; Fujikura, 700 A @ 77K, SF
Active Radiation Shielding
6 + 1 Expansion Coil Architecture

Habitat & Compensator Coil Launch
Six-Coil Launch
Orion Spacecraft
Helium Vapor Cooling System

Habitat View
Logistics Module
Habitat Module
Exploration Propulsion Module

NASA Innovative Advanced Concepts
Variable Specific Impulse Magnetoplasma Rocket (VASIMR®)
### Commonwealth Fusion Systems (CFS)

**SPARC AMS-100**

<table>
<thead>
<tr>
<th>Feature</th>
<th>SPARC</th>
<th>AMS-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-Field</td>
<td>20 Tesla</td>
<td>0.5 Tesla</td>
</tr>
<tr>
<td>Temperature</td>
<td>20 K</td>
<td>55 K</td>
</tr>
<tr>
<td>(I_{\text{op}})</td>
<td>40 kA</td>
<td>10 kA</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>110 MJ</td>
<td>14 MJ</td>
</tr>
<tr>
<td>HTS Length</td>
<td>270 km</td>
<td>85 km</td>
</tr>
</tbody>
</table>

16 HTS coils

[https://cfs.energy](https://cfs.energy)
Table of properties for the AMS-100 main solenoid and compensation coil.

<table>
<thead>
<tr>
<th></th>
<th>Main</th>
<th>Compensation</th>
<th>Combined</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil radius</td>
<td>2.0 m</td>
<td>4.0 m</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>Coil length</td>
<td>6.0 m</td>
<td>1.5 m</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>Tape width</td>
<td>12 mm</td>
<td>12 mm</td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Stabilizer</td>
<td>Al-6063</td>
<td>Al-6063</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cable thickness</td>
<td>2.85 mm</td>
<td>2.85 mm</td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Cable width</td>
<td>16 mm</td>
<td>16 mm</td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Layers</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turns</td>
<td>376</td>
<td>94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inductance</td>
<td>286 mH</td>
<td>114 mH</td>
<td>287 mH</td>
<td>mH</td>
</tr>
<tr>
<td>Number of tapes</td>
<td>18</td>
<td>18</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Total tape length</td>
<td>85 km</td>
<td>43 km</td>
<td>128 km</td>
<td>km</td>
</tr>
<tr>
<td>Operating current</td>
<td>10.0 kA</td>
<td>-10.0 kA</td>
<td></td>
<td>kA</td>
</tr>
<tr>
<td>Cable mass</td>
<td>1090 kg</td>
<td>545 kg</td>
<td>1635 kg</td>
<td>kg</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>14.3 MJ</td>
<td>5.7 MJ</td>
<td>14.4 MJ</td>
<td>MJ</td>
</tr>
<tr>
<td>Energy Density*</td>
<td>14 kJ/kg</td>
<td>11 kJ/kg</td>
<td>9 kJ/kg</td>
<td>kJ/kg</td>
</tr>
</tbody>
</table>

*Considering only the mass of the cable.
Design **B-field of 0.65 T** in the center, ~1 T on the conductor at the edge of the solenoid.

**B-field of 0.5 T** when the compensation coil is on.

Operating temperature range of 50 to 60 K:
- \( \Delta T \) of 12 K @ 55 K

Large temperature margin is important:
- cooling power is very limited,
- high energy density,
- no intervention possible.

**Smart spacing of the conductor / additional HTS tape** is envisioned at the coil extremities to reduce the peak field. And allow possible operation at higher current/magnetic field.

The field homogeneity is not an operation critical parameter.
AMS-100

Main Support Cylinder
1.0 mm CFRP - 30 mm Al-Honeycomb - 1.0 mm CFRP

Radiator & Debris shield: 0.5 mm Al 6110, 50 mm Al-Honeycomb, 0.5 mm Al 6110

SciFi-Tracker: 0.5 mm CFRP - 10 mm Nomex

Magnet Interfaces

GFRP Magnet

MLI

MLI

inner-stringers, AL 6063
10 mm x 25 mm

outer-stringers, AL 6063
5 mm x 130 mm

X₀=1.8%

X₀=14.7%, NIL=2.8%
(without MLI)

100 cm

10 cm
Dangers of Space: Micrometeorite Impact

ø2.8 mm Al sphere
7.06 km/s

Micro-Meteoroid

5724
25.5 µs
Magnet survives and operates after minor degradation -> No Insulation HTS
Conductor and Coil Layout

**Current conductor layout:**
- Stack of eighteen 12 mm wide HTS tapes
- HTS stack is soldered to tin-coated aluminum (6000 series) conductor stabilizer.
- Conductor thickness of 2.75 mm.
- Outer surface anodized / varnished to provide turn-to-turn insulation.

**Shorting turns by (EB / laser) point welding.**
- 1 mm² weld provides a turn-to-turn resistance of about 3e-5 Ω.
- AMS-100 -> 1250 mm² per turn (10 % of the circumference) covered with point welds of 1 mm² -> τ = 10 hours.
- Provides mechanical strength and provides thermal/electrical path.
- Shorts are within the envelope of the conductor pack.
- To be tested and to be demonstrated.
Structure of the Main Solenoid

Al-alloy skin for mechanical strength and axial thermal conductivity

Local spot welding

Stack of HTS tapes

Honeycomb for mechanical stiffness

Epoxy between layers

$X_0 = 10.2\% = \text{Thickness of structure} / \text{Radiation length}$
Conductor Testing: Single- and Multi-Tape Samples

- Single tapes have been extensively characterized.
- Many short samples of Al-alloy stabilized multi-tape HTS conductors are in preparation.
- Few-tape samples in good agreement with expectations.
- Next: more tapes, bending, micro-meteorite impact testing, etc.

Preparing a robust, radiation transparent HTS cable with minimal amount of solder and proper bonding is still a major challenge!
at 77 K and self field
Tape:  $I_c = 175 \text{ A}$
Stack: $I_c = 643 \text{ A}$
**Thermal-ElectroMagnetic Quench Model**

**Quench behavior of the non-insulated AMS-100 main solenoid**

- Quench behavior of the AMS-100 main solenoid is 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.
- Model studies the effect of slow thermal runaway and consequently a fast quench as function of a small defect.
- Not enough resolution at the moment for sudden and very local defects (due for e.g. micrometeorite impact).
- Other structural elements, such as end-flanges and ribs, are not yet included in the model.
- Simulations performed using a previous design iteration: 428 turns, an operating current of 13.5 kA and a field of 1 T.
Simulated Quench Behavior and Survival

428 turn main solenoid, $I_{op} = 13.5$ kA, $B = 1$ T.

$t = 0.2428$ s

Simulations indicate that the main solenoid is thermally self-protected.

Peak hot-spot near extremities

NZPV of $\sim 4$-8 m/s
End-flanges, Ribs and Stringers

**End-Flanges** *(grey)*: Mechanical support of the magnet during manufacturing, launch and operation. Circular, allows quench-back.

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

**Stringers** *(blue)*: Mechanical support during launch.

Mechanical load on the conductor is exported from the thermal-electrical model to Abaqus.
Mechanical Quench Analyses

- Shell model set-up in Abaqus to calculate stress in the HTS, Al-alloy conductor and structural components.
- Model includes the conductor, ribs and stringers.
- Stress in the conductor is almost tripled during a quench due to enormous induced current.
- Ribs locally reduce the stress in the conductor.
- Stress in the conductor due to thermal gradients not critical, strength of the epoxy to be validated experimentally.
- Peak stress (~300 MPa) caused by radial Lorentz force.
- Support structure requires optimization.

Boundary condition: outer rings fixed to circular shape, free thermal shrinkage
THERMAL DESIGN | HEAT SOURCES

- Service module & payload data handling
  - ~8000 W
- Inner detector
  - ~8000 W
- Solenoids
  - ~15 W
AMS-100: Structural Model

1\textsuperscript{st} Mode: 14 Hz

AMS-100: Thermal Model

\begin{align*}
T \, [K] \\
\text{351} & \rightarrow \text{332} \\
\text{312} & \rightarrow \text{293} \\
\text{274} & \rightarrow \text{255} \\
\text{236} & \rightarrow \text{217} \\
\text{198} & \rightarrow \text{179} \\
\text{160} & \rightarrow \text{141} \\
\text{122} & \rightarrow \text{103} \\
\text{84} & \rightarrow \text{64} \\
\text{45} & \rightarrow \text{200 K}
\end{align*}
AMS-100

Weight: 40 t
MDR: 70 TV

Readout-Channels: $8 \times 10^6$
Acceptance: 100 m$^2$ sr

Power: 15 kW
B-Field: 1 Tesla
Measurement Time: 10 years
Calorimeter: 70 $X_0$, $4\lambda$

Power: 15 kW
Measurement Time: 10 years
Calorimeter: 70 $X_0$, $4\lambda$
• In 2005 NASA canceled the AMS-02 Space Shuttle Flight.
• At RWTH Aachen a concept for a balloon experiment (PEBS) was developed to measure cosmic ray positrons.
• A new scintillating fiber tracker with SiPM readout was the key element for the tracking system.
• In 2008 the group of T. Nakada, EPFL joined the team.
• In 2010 a prototype (PERDAIX) was launched from Kiruna, Sweden. 300 000 protons and Helium nuclei were recorded at an altitude of 34 km.
• In 2014 the LHCb Upgrade I TDR was published, describing a 360 m² version of this detector build from 11,000 km of fiber.
A large international team from several institutes, including EPFL and RWTH Aachen, constructed the LHCb SciFi Tracker in the past years.
AMS-100

Weight: 40 t
MDR: 70 TV
Readout-Channels: 8 \times 10^6
Acceptance: 100 m^2 sr
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B-Field: 1 Tesla
Measurement Time: 10 years
Calorimeter: 70 X_0, 4\lambda

Pre-Shower
Silicon Tracker
Layers 1-12
Inner ToF
Inner-SciFi
Outer-SciFi
Outer-Support Tube
Magnet
Radiator

AMS-100; V6.00; 09-July-2021

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.
Positrons in Cosmic Rays

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

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

secondary production
Anti-Deuterons are a very sensitive probe for New Physics in Cosmic Rays

As a Magnetic Spectrometer AMS-100 can separate Anti-Matter from Matter.
$Z = -1$ Particles in Cosmic Rays

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

$E_{\text{kin}}$ (GeV)

AMS-02 electrons
AMS-02 $p$
BESS $p$
BESS (95% CL) $\bar{D}$
GAPS $D$
AMS-02 $D$ sensitivity
Panda
AMS-100 $D$
D from dark matter
AMS-100 $D$ sensitivity
D from secondary production

PHYS. REV. D 97, 103011, 2018
AMS-02 Measurements of Matter and Antimatter

**Matter**
- Electron: 50 M
- Proton: 7 B
- Helium: 1.3 B
- Li: 8 M
- Be: 4 M
- B: 11 M
- C: 38 M
- N: 10 M
- O: 32 M

**Antimatter**
- Positron: 3.4 M
- Anti-proton: 0.8 M
- Anti-Helium
- Anti-C
- Anti-O

Particle Number of event collected

V. Choutko
COSPAR 2022
Athens
Anti-Helium in Cosmic Rays

AMS-02 Helium Flux

AMS-02 Sensitivity @ 95 % CL

Dark Matter

AMS-100 $^3$He (10 years)

Interactions

E. Carlson et al., 2014, Phys. Rev. D 89, 076005
M. Cirelli et al., 2014, JHEP 1408, 009
Angular Resolution for Converted Photons

AMS-100
Converted Photons

\[ e^- + e^+ \]
AMS-100
Converted Photons

Crab Nebula with Chandra (blue and white), Hubble (purple), and Spitzer (pink) data.

FERMI, CTA

AMS-100

CRAB Nebula TeV - Photons
AMS-02 has collected more than 200 Billion cosmic rays since 2011 and will continue to take data for the lifetime of the ISS. It is a unique scientific instrument in Space.

AMS-100 will improve the sensitivity of AMS-02 by a factor 1000 and will explore a completely new territory in precision cosmic ray physics.