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

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ABSTRACT

The next generation magnetic spectrometer in space, AMS-100, is designed with a geometrical acceptance of 100 m^{2}sr for a ten year operation at Sun–Earth Lagrange Point 2. The purpose of AMS-100 is to improve the sensitivity for the observation of new phenomena in cosmic rays by at least a factor of 1000 compared to AMS-02.

The AMS-100 detector consists of a high temperature superconducting solenoid, an electromagnetic calorimeter, a tracking system made out of silicon and scintillating fibre modules and a time-of-flight system based on plastic scintillators readout by silicon photomultipliers.

We will present the AMS-100 project. In the framework of the related R & D-programme, measurements with a test coil made out of 8 layers HTS tape will be shown. Time resolution measurements with a ToF-prototype in the temperature range of +30 °C to −40 °C will be discussed. The first produced 12-layer fibre mat made out of 125 μm thick scintillating fibres and the quality control measurements will be shown.

1. Introduction

The next generation magnetic spectrometer in space, AMS-100 [1], is designed to have a geometrical acceptance of 100 m^{2}sr. It serves as a cosmic ray observatory operated for at least ten years at Sun–Earth Lagrange point 2 (L2). The success of recent space missions in the last decade, in particular of the AMS-02 experiment [2] on the International Space Station, have revealed several unexpected new features in the cosmic ray matter [3,4] and antimatter fluxes [5,6]. Due to the strong dependence of the cosmic ray flux on the energy of the cosmic rays, an extension of the energy reach for all the cosmic ray measurements of AMS-02 by a factor of ten requires an increase in acceptance by a factor 1000. The instrument will monitor most of the sky continuously for γ-ray astronomy and will orbit around the Sun in one year, together with Earth and L2.

2. AMS-100 detector

The AMS-100 detector (Fig. 1) is located behind a sun shield to guarantee operation at cryogenic temperatures. The rear radiator removes the heat from the instrument. In front of the sun shield, it is equipped with solar panels, electrical propulsion system and a space craft service module. The key element of the instrument is the magnet. Its design is based on second-generation (2G) rare-earth barium copper oxide (ReBCO) high temperature superconducting tapes (HTS) [7], which allow the construction of a thin solenoid with a thickness of the HTS of 0.7 mm. The length of the solenoid is 6.3 m and its diameter is 4.2 m creating a homogeneous central magnetic field of 1 T in the tracking volume. Thermal studies (Fig. 2) show that the magnet is cooled passively to 50 K to 60 K while the sub-detectors are operated at 200 K. An expandable compensation coil balances the magnetic moment of the solenoid and allows the attitude control of the instrument within the heliospheric magnetic field.

The centre of the inner detector consists of a Lutetium–Yttrium oxyorthosilicate (LYSO) crystal calorimeter with an outer radius of 40 cm. The central calorimeter has a depth of 70 radiation lengths and 4 nuclear interaction lengths. It is followed by a pre-shower detector and a silicon tracker (Fig. 3). The silicon tracker is assumed to have a single point resolution of 5 μm in the bending plane for $|z| = 1$ particles, similar in design to the AMS-02 silicon tracker [8]. It consists of six double layers arranged in cylindrical geometry leading to a maximum of 24 measurement points for a single track. This instrumentation will allow probing, with high statistical power and high precision, the separate positron and electron spectra and the antiproton spectrum to 10 TeV, and the nuclear cosmic ray component to 10^4 TeV, beyond the knee in the cosmic ray flux. The main solenoid is instrumented on the inside and on the outside with three layers of scintillating fibre tracker (SciFi) modules. The SciFi tracker is assumed to have a single point resolution of 40 μm. A four layer Time-of-Flight (ToF) system is located between the SciFi-modules and the inner side of the magnet. These two sub-detectors will provide fast time, position and charge information

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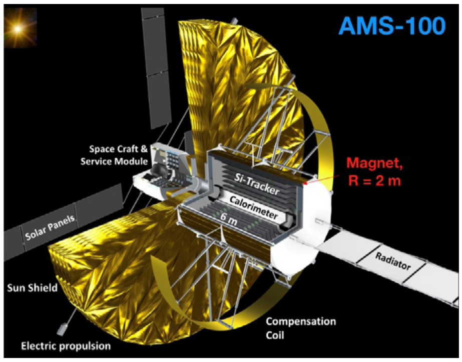

Fig. 1. AMS-100 detector concept.

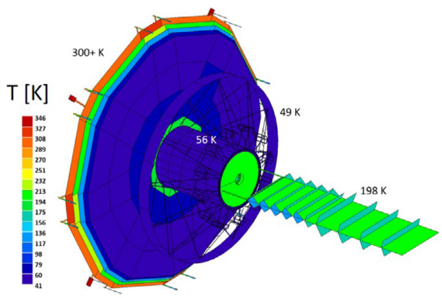

Fig. 2. Thermal model analysis of AMS-100 detector.

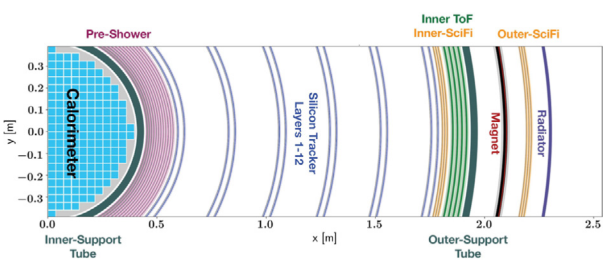

Fig. 3. Cross section of the AMS-100 detector with its cylindrical sub-detector layers.

on the incoming particles. The track segments of high energy particles reconstructed in the SciFi tracker will provide a first estimate of their rigidity up to the TeV scale. The ToF signal amplitudes will determine the particle's charge. This information will be used in the first level trigger to reject the overwhelming background of low energy protons and Helium nuclei. The weight estimate of the instrument is 40 t. It has eight million readout channels and an estimated total power consumption of 15 kW.

2.1. AMS-100: The high temperature magnet

The geometrical acceptance of 100 m^2 sr defines the dimensions of the main solenoid (L = 6.3 m, D = 4.2 m). It is constructed from HTS tapes with a typical thickness of $\approx$0.04–0.1 mm. 18 tapes are combined into a HTS cable which is reinforced with an aluminium jacket (Fig. 4) and capable to transport 13.5 kA at 60 K. The cable is wound to a coil with 450 windings on an aluminium honeycomb mandrel and enclosed with an 0.7 mm skin. The total radiation length of this coil is 11%.

Quench protection is important for the long term stable operation of such a magnet in space. A 3D thermal, electrical and magnetic nodal-network model is built using python to study the quench behaviour of this non-insulated coil [9]. The resulting hot-spot temperature (<200 K) and the mechanical load on the conductor and the supporting structure

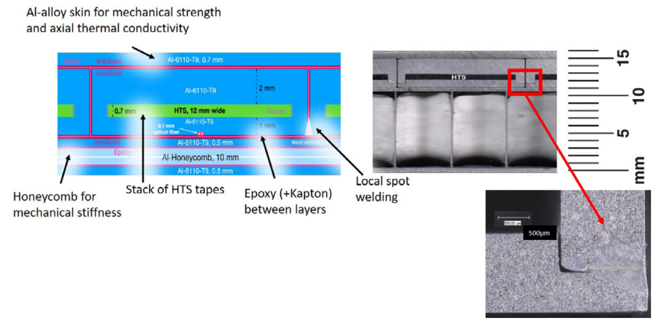

Fig. 4. Cross section of aluminium jacket and honeycomb structure for mechanical support of HTS tapes. The lower right inset shows the welding of the aluminium jacket.

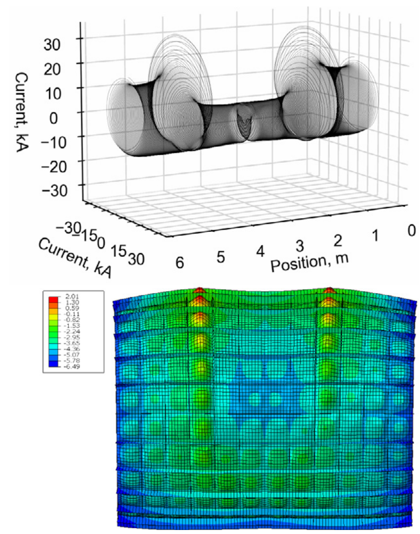

Fig. 5. Quench behaviour simulation and resulting calculated mechanical displacements.

are derived for several quench scenarios. The results from this model are analyzed in ANSYS/Abacus to evaluate the resulting mechanical response as shown in Fig. 5.

Several compact demonstrator coils have been build and studied to optimize the material selection and the soldering procedure. The starting point were small, few turn test coils to compare B-field measurements in dependence of the supply currents with simulations (Fig. 6). With the next prototype (Fig. 7, Geometry: L = 180 mm, D = 120 mm, 36 turns, 8 HTS-layers) the 3D-model will be validated by operating this prototype in a 6 T external field at liquid helium temperature at CERN. This prototype will also undergo space qualification tests. In addition high velocity impact tests on HTS tapes are performed at the Ernst-Mach-Institute in Freiburg (Germany) to study micrometeoroid impacts on HTS solenoids in space.

2.2. AMS-100: The scintillating fibre tracker

The AMS-100 SciFi tracker is following the technology [10,11] developed for the PERDaix detector [12] and which has lead to the construction of the worlds largest SciFi tracker with an area of 340 m^2, the LHCb-SciFi tracker [13,14]. These SciFi trackers are constructed from staggered layers of 250 μm thick scintillating fibres (Kuraray SCSF-78 MJ) forming a fibre mat and silicon photomultiplier (SiPM) arrays for the readout with channels covering the full thickness of the fibre mat. The pitch of the SiPM arrays follows the fibre mat pitch so that the light is spread over few SiPM channels [11].

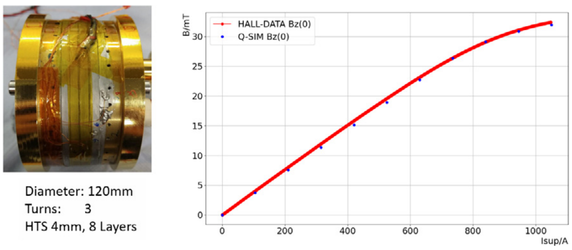

Fig. 6. Demonstrator coil: B-field measurements in dependence of the supply current compared with simulations.

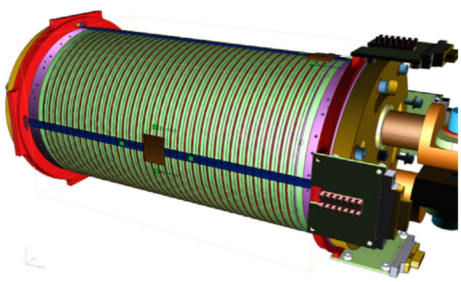

Fig. 7. Prototype coil to study the quench behaviour and compare it with a 3D-simulation and to perform space qualification tests.

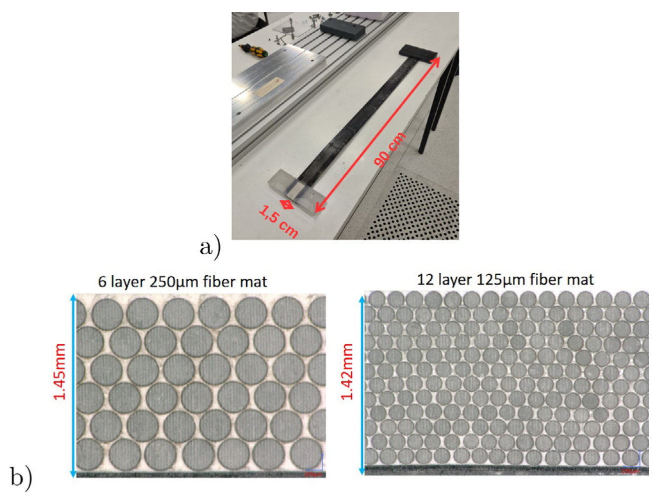

Fig. 8. (a) First 12-layer fibre mat made out of 125 μm thick scintillating fibres. (b) Optical scan of a 6-layer fibre mat with 250 μm thick fibres compared to the 12-layer fibre mat with 125 μm thick fibres.

The 6-layer fibre mats for the LHCb SciFi tracker have a length of 242 cm and a width of 130 mm. Fibre mats with a similar geometry will be used in AMS-100. With these parameters the AMS-100 SciFi tracker has a maximum detectable rigidity (MDR) of 3 TV. With fibre mats constructed from 125 μm thick scintillating fibres (Kuraray SCSF-78MJ) a spatial resolution of 13 μm could be achieved and would allow the usage of such SciFi trackers also in other sub-detectors in AMS-100. The handling of such thin fibres is significantly more challenging. In the winding process of the fibre mat the force on the fibre had to be reduced from 20 cN used in the construction process for LHCb down to 5 cN. Kuraray managed to produce a first test sample of 125 μm scintillating fibres in 2020. From this a first 12-layer fibre mat prototype has been built with a length of 90 cm and a width of 15 mm (Fig. 8a). An optical scan of the cross section of this fibre mat in comparison to a standard LHCb fibre mat is shown in Fig. 8b. The average distance between a perfect grid and the actual fibre position over the 12-layer was found to be RMS = 13.3 μm. This would result in a spatial resolution of 19 μm for such a 12-layer fibre mat.

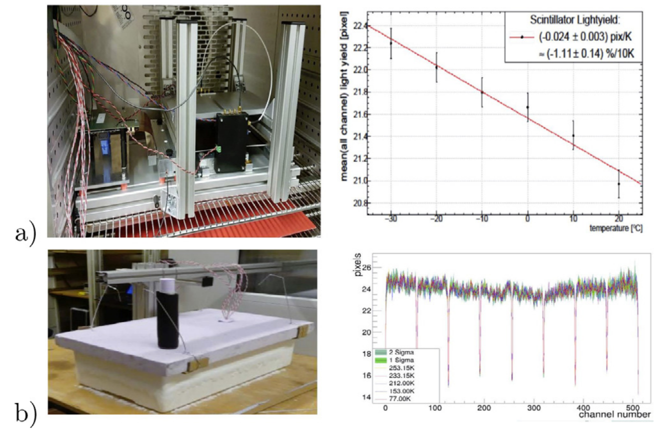

Fig. 9. (a) Light yield measurement of a 6-layer fibre mat with 250 μm thick fibres in the temperature range of −30 °C to 23 °C in a climate chamber. (b) Light yield measurement at room temperature after dipping the fibre mat in a bath with liquid nitrogen.

The measured light yield of this fibre mat using a ^{90}Sr-source to excite the fibres at the far end of the SiPMs is 10.4 photoelectrons. With a measured attenuation length of the 2.5 m for the 125 μm thick fibres a light yield of 14.6 photoelectrons was expected. This is an indication that the scintillation light production in this test sample from Kuraray is smaller then in the high quality fibres used for the construction of the LHCb SciFi tracker. Further optimization steps would therefore be necessary for an application of this technology in particle detectors.

Both in AMS-100 and in LHCb upgrade 2 the SciFi trackers need to be operated at cryogenic temperatures. Therefore the temperature dependence of the SciFi detector performance was investigated. The light yield measurements of a 6-layer fibre mat made out of 250 μm thick fibres in the temperature range of 23 °C down to −30 °C is slightly increasing by 0.11%/K (Fig. 9a). No change of the performance of the fibre mat was observed after placing the mat in a bath filled with liquid nitrogen at a temperature of 77 K and remeasuring the light yield at room temperature (Fig. 9b).

2.3. Time-of-flight-system

A high resolution ToF-system is required to reconstruct particle masses and thus identify isotopes in cosmic rays. The design of the AMS-100 ToF-system is similar to the PANDA Barrel-ToF design [15] which is constructed from small scintillator rods (scintillator dimensions $90 \times 25 \times 6$ mm^3) read out by 4 SiPM-arrays on both sides, covering in total 25% of the rod front faces. The Panda-ToF-system reached a time resolution of 50 ps [15].

The AMS-100 ToF-system is targeting to a time resolution of 20 ps for a single scintillator rod by using SiPM arrays covering 100% of the front faces of the scintillator. In addition a reduced electronic noise is expected at the operational temperature of 200 K. These improvements should lead to a total time resolution of 15 ps for the 4-layer ToF-system.

An experimental setup to investigate this has been built and is described in detail in [16]. The measured time resolution is $\sigma_t = (39.3 \pm 0.1 \pm 0.7)$ ps (Fig. 10). No significant dependence of the time resolution on temperature was observed in the temperature range from 23 °C down to −30 °C. It is our understanding that this difference compared to the design goal of 20 ps is originating from the large capacitance of the SiPM-arrays (S14161-6050HS-04, 2000 pF) used in this test-setup. New SiPM-arrays have been delivered with a significantly smaller capacitance (S14161-3050HS-08, 300 pF) and will be studied.

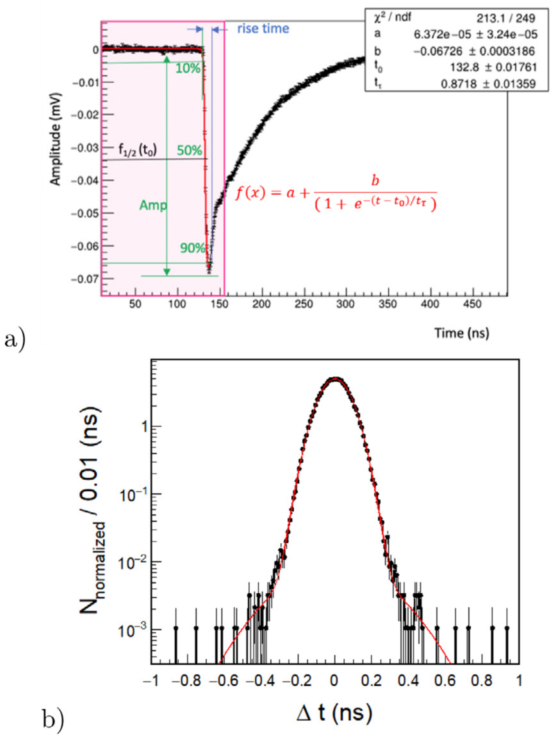

Fig. 10. (a) Signal of one of the two SiPM arrays reading out the scintillator rod. b) Measured time resolution of the ToF-prototype.

3. Conclusion

The only magnetic spectrometer in Space today, AMS-02, has collected more than 200 billion cosmic rays since 2011 and will continue data taking for the lifetime of the ISS with an expected upgrade increasing the acceptance by 300% in 2025. AMS-100 is an ambitious project for the following decade which requires pushing the actual technologies for high temperature superconducting magnets and particle detectors like scintillating fibre trackers and Time-of-Flight systems to their limits. The progress in the required technological developments has been described in this paper. Up to now no show-stopper for AMS-100 has been identified.

AMS-100 will improve the sensitivity of AMS-02 by a factor of 1000. In other words AMS-100 will reproduce 20 years of AMS-02 data within the first week of operation at Lagrange Point 2 and then will explore a completely new territory in precision cosmic ray physics.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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