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Cryogenic tests of time of flight and Scintillating Fibre Tracker prototypes read out by SiPMs for the AMS-100 experiment

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ABSTRACT

The AMS-100 Experiment, the next generation magnetic spectrometer in space, will use plastic scintillators read out by silicon photomultipliers (SiPM) as a time of flight (ToF) detector. The ToF will be operated in vacuum at cryogenic temperatures. The Scintillating Fibre Tracker (SciFi) for AMS-100 and the planned LHCb Upgrade II will use scintillating fibre mats read out by SiPM arrays. The SiPMs will be operated in vacuum at cryogenic temperatures.

We will present time resolution and signal shape measurements with a ToF-prototype in the temperature range of 303 K to 77 K. Long term tests of a ToF prototype in vacuum will be shown.

Thermal studies and light yield measurements of a SciFi tracker prototype at room temperature and at 77 K in vacuum will be presented.

1. Introduction

The Magnetic spectrometer with a geometrical acceptance of 100 m^2sr, AMS-100 [1], is a proposed follow-up experiment for the AMS-02 experiment [2]. It serves as a cosmic ray observatory operated for at least ten years at Sun–Earth Lagrange point 2 (L2).

The success of the AMS-02 experiment on the International Space Station in the last decade, has 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. One purpose of AMS-100 is to observe antideuterons in cosmic rays for the first time and measure their spectra with high precision. A precise knowledge of the spectrum will allow the differentiation between antideuterons created in secondary processes or during the annihilation of dark matter. To distinguish between these two possible sources of antimatter, antideuterons with energies of up to 10–20 GeV need to be resolved. In order to achieve the necessary resolution, a time resolution of the AMS-100 ToF system of 20 ps is desirable.

2. AMS-100 detector

The AMS-100 detector is located behind a sun shield (Fig. 1). Thermal studies showed that the magnet is cooled passively to 50 K to 60 K. 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. A compensation coil balances the magnetic moment of the solenoid and allows the attitude control of the instrument within the heliospheric magnetic field. Due to the heatload of the detector components the sub-detectors are operated at approximately 190 K. When the detector components are turned off, AMS-100 will not be actively heated, so the components need to survive cryogenic temperatures. The detector components will be operated in vacuum at L2.

This cylindrical spectrometer (Fig. 2) is rotationally symmetric and measures particles that pass through the lateral surface of the cylinder. The key element of the instrument is the high-temperature superconducting solenoid with a length of 6.3 m and a diameter of 4.2 m creating a homogeneous central magnetic field of 0.5 T in the tracking volume. The centre of the inner detector consists of a crystal calorimeter, followed by a pre-shower detector and a silicon tracker [7]. The main solenoid is instrumented on the inside and on the outside with three layers of scintillating fibre tracker (SciFi) modules. 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 on the incoming particles. The track segments of high energy particles reconstructed in the SciFi tracker will provide a first

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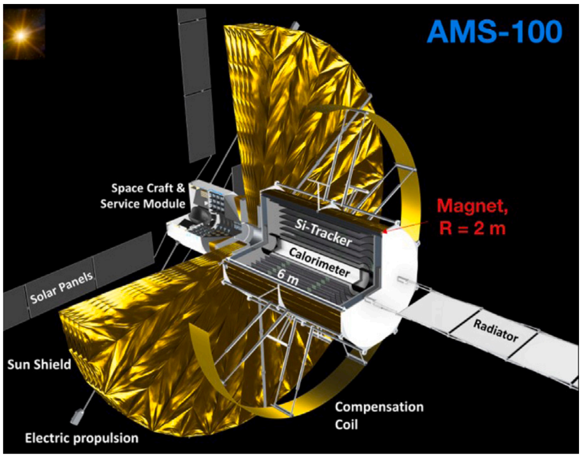

Fig. 1. AMS-100 detector concept.

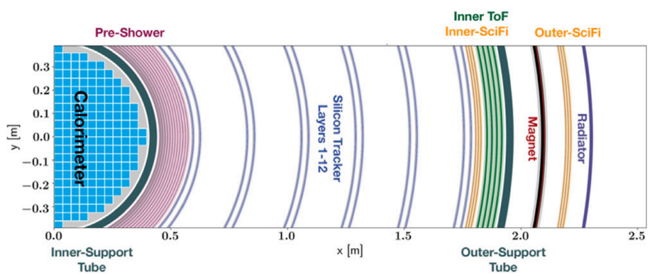

Fig. 2. Cross section of the AMS-100 detector with its cylindrical sub-detector layers.

estimate of their rigidity up to the TeV scale. The ToF signal amplitudes will determine the particles' 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.

3. AMS-100 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 consists of small scintillator rods (scintillator dimensions $90 \times 25 \times 6$ mm^3) read out by SiPM arrays on both sides, covering 100 % of the rod front faces. The AMS-100 ToF-system is targeting for a time resolution of 20 ps for such a single scintillator rod.

A test setup to measure the time resolution of such a ToF-prototype is described in detail in [8] and first results were presented in [7,8]. To measure the time resolution at cryogenic temperatures, the ToF-prototype setup is placed in a light- and air-tight box. The box can be flushed with dry air to avoid condensation and ice building up during the cool-down. Inside the box nine Pt-1000 sensors are used to monitor the temperatures (Fig. 3a). A radioactive ^{90}Sr-source is used to excite the EJ-228 scintillator. The box has a feed-through for the temperature readout, bias-voltage supply, ToF signals and radioactive source heater. Outside of the box the temperature sensors are monitored constantly with a Keithley 2701 [9] and the ToF signals are measured with a DRS4 [10].

The light-tight box is attached to a cable winch above a liquid nitrogen dewar and then lowered slowly into the liquid nitrogen (Fig. 3b). By slowly evaporating the liquid nitrogen, the temperature inside the box rises. Time resolution measurements were performed during warm-up between 77 K and room temperature.

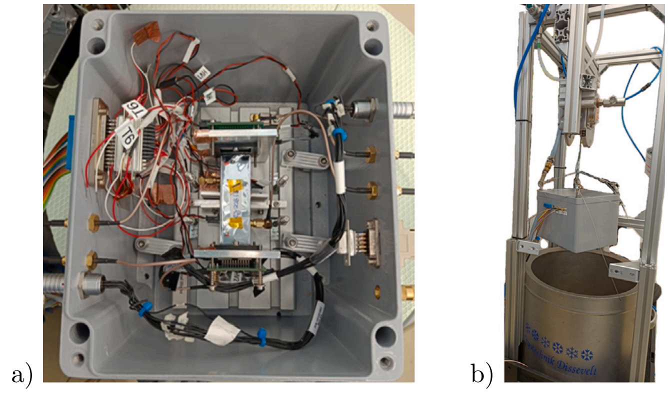

Fig. 3. (a) ToF-prototype positioned in light- and air-tight box. (b) Box inside the liquid nitrogen bath.

The measurements were performed with the different SiPMs arrays Broadcom AFBR-S4N66C013, Hamamatsu S14160-6050HS, Hamamatsu S14161-6050HS-04 and Hamamatsu S13370-6075CN. Following the specifications the Broadcom AFBR-S4N66C013 did not survive the cryogenic test due to cracks on the surface of the SiPMs starting at 230 K. The signal shapes of the Hamamatsu S14160-6050HS and S14161-6050HS-04 change at lower temperatures. The slow decay times of the signals increase due to the temperature dependence of the poly-silicon quench resistors (Fig. 4a). The Hamamatsu S13370-6075N SiPMs with a metal quench resistor have a more stable signal shape (Fig. 4b). Due to the signal shape changes the amplitudes of the investigated SiPM arrays decrease and lead to degradations in time resolution (Fig. 4c). The best time resolution of $\sigma_t = (39 \pm 1)$ ps at the AMS-100 operating temperature of 190 K is achieved with the S14161-6050HS-04 arrays.

After the measurements at cryogenic temperatures the entire ToF-prototype made out of EJ-228 scintillator and read out with the Hamamatsu S14161-6050HS-04 SiPM array is placed inside a vacuum chamber and the time resolution is measured in vacuum (Fig. 5). The clamps press the lid down evenly. The chamber is evacuated with a rotary pump and a turbo-molecular pump. Pressure and temperature are monitored constantly. Feed-throughs in the chamber wall allow for power supply of the SiPMs from outside the chamber and a signal transfer to an outer DRS4. The time resolution did not change during the measurement time of 20 weeks.

4. AMS-100 scintillating fibre tracker

The AMS-100 SciFi tracker is following the technology [11] which has led to the construction of the worlds largest SciFi tracker with an area of 340 m^2, the LHCb-SciFi tracker [12,13]. This SciFi tracker is constructed from staggered layers of 250 μm thick scintillating fibres (Kuraray SCSF-78MJ) 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 a few SiPM channels. 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.

For very different reasons both in AMS-100 and in LHCb upgrade II the SciFi tracker need to be operated at cryogenic temperatures. Therefore the temperature dependence of the SciFi detector performance was investigated. The light yield measurements of a fibre mat in the temperature range of 300 K down to 243 K showed a slight increase by 0.11 %/K [7]. No change of the performance of the fibre mat was observed after placing the mat in a bath filled with liquid

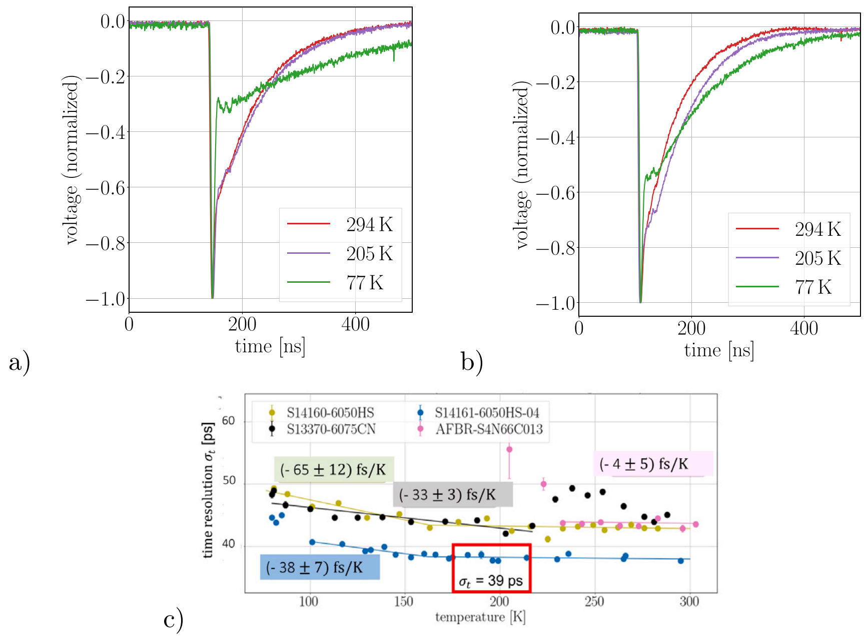

Fig. 4. (a) Signal shape at different temperatures for SiPMs with poly-silicon quench resistors, (b) Signal shape at different temperatures for SiPMs with metal quench resistors. (c) Temperature dependence of the time resolution σ_t for all tested SiPMs. The red box indicates the operational temperature range.

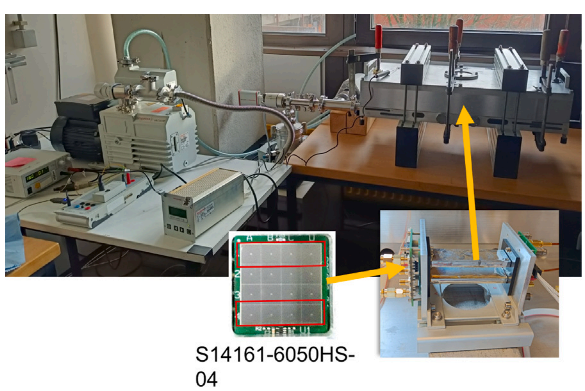

Fig. 5. ToF-prototype inside a vacuum chamber.

nitrogen at a temperature of 77 K and remeasuring the light yield at room temperature [7].

A test setup is designed to measure the lightyield of a 300 mm long scintillating fibre mat with SiPM arrays which are cooled down to cryogenic temperatures (Fig. 6a). Four 128-channel SiPM arrays from FBK or from Hamamatsu, the same which are used for tests of the LHCb SciFi tracker upgrade II [14], are placed in a vacuum-tight cold box which is traversed by an LN2 cooling pipe made out of 6 mm diameter stainless steel tube (Fig. 6c). Outside of the cold box, the LN2 line is housed in a 40 mm diameter corrugated stainless steel tube leading to a pressurized dewar vessel on the inlet and an unpressurized exit vessel on the outlet side. The scintillating fibre endpiece facing the SiPMs is enclosed in the cold box. The SiPMs are pressed against the fibre endpiece with a copper bar that is thermally connected to the LN2 cooling pipe with flexible threaded copper straps. An LN2 flow of 2 g/s was used to cool down the SiPMs to 100 K. Six Pt1000 sensors are used to monitor temperatures of the cold bar, the fibre mat, and the LN2 line inside the cold box. A vacuum below 10^{-4} mbar reduces convection to avoid dew or ice on the cold box surfaces. A feedthrough adapter board routes the SiPM signals to the external analog-multiplexed Spiroc [15] frontend readout (Fig. 6b). The single photon response is calibrated

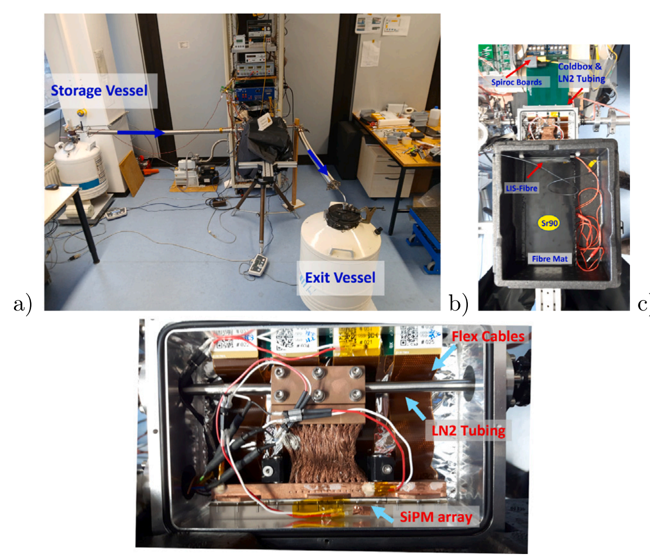

Fig. 6. (a) Test setup for light yield measurements with SiPM arrays cooled down to cryogenic temperatures, (b) light-tight box with the fibre mat, cold box with the SiPM arrays and outside the readout electronics. (c) Inside of the cold box.

individually for all SiPM array channels, and signals from neighbouring channels are grouped into clusters to obtain the cluster photon count and the cluster position across the fibre mat. The cluster lightyield measurement of the fibre mat using a collimated ^{90}Sr-source at the far end from the SiPMs showed an increase by 14.4 % at cryogenic temperatures compared to room temperature at the same overvoltages of the SiPMs (Fig. 7).

5. Conclusion

AMS-100 is an ambitious project for the next decade which requires pushing the current technologies for particle detectors like Time-of-Flight systems and scintillating fibre trackers to their limits.

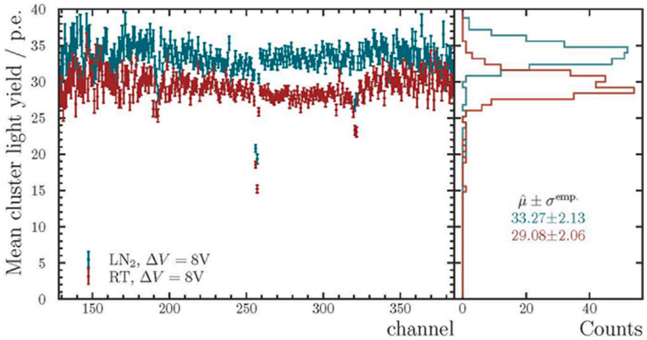

Fig. 7. Light yield measurement of a 6 layer fibre mat with SiPM arrays placed in a vacuum box before and after cool down to cryogenic temperatures.

The ToF-prototype made out of EJ-228 scintillator read out with the S14161- 6050HS-04 Hamamatsu SiPM array reached a time resolution of (39 ± 1) ps at 190 K and the operation in vacuum did not influence the time resolution significantly. Different scintillation materials with different geometries will be tested to further improve in time resolution.

The Scifi-tracker prototype made out of a 6-layer fibre mat with 250 μ thick scintillating fibres and readout with 128-channel SiPM arrays cooled down to cryogenic temperatures in a vacuum box showed an increase in lightyield of 14.4 % and was fully functional.

No show-stopper for AMS-100 has been identified during the work described in this paper. The results show that AMS-100 will improve the sensitivity of AMS-02 by a factor of 1000 and 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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