The AMS-02 Transition Radiation Detector to Search for Dark Matter in Space

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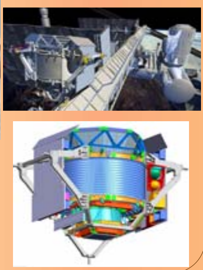
On behalf of the AMS collaboration

AMS-02

AMS-02 on ISS

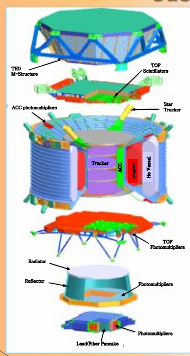
AMS-02 is a high precision magnetic spectrometer that will be mounted on the International Space Station (ISS) for a 3 years mission at a mean altitude of 400 km



The detector will perform primary cosmic ray spectroscopy allowing the direct search for antimatter and the indirect search for dark matter in the universe

The main detector features are:
Acceptance: 0.45 m² sr
Weight: 6700 kg
Dimensions: 3.5 m x 2.3 m x 2.3 m
Power: 2500 W

Subdetectors



__TRD__: e/p separation with p⁺ rejection of 10^2-10^3 in 10-300 GeV

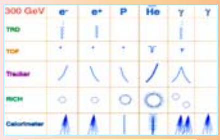
__TOF__: Main trigger σ_t = 125 ps, charge separation, β with few % precision

__Cryomagnet and Tracker:__
Bending power BL^2 = 0.85 Tm²
Resolution < 2% below 10 GV, rigidity up to 2-3 TV, charge separation up to Fe

__RICH__: Isotopes identification for A ≲ 20 in 1-12 GeV, 3σ charge separation for Z ≲ 26, β measurements with 0.1% precision

__Electromagnetic CALorimeter:__
$e^{\pm}$, γ detection
3D sampling lead/scintillating fibers
p⁺ rejection > 10^4 in 10-300 GeV

Physics

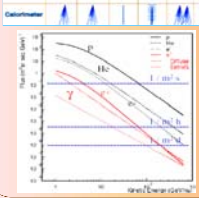


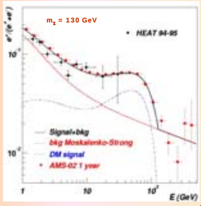
AMS-02 will perform primary cosmic ray spectroscopy for energies up to TeV. The main goals are:
- direct search for antimatter
- indirect search for dark matter

The detection of heavy antimatter nuclei, like $\overline{He}$ and $\overline{C}$, constitutes an important information about the existence of antistars and antigalaxies

Annihilation of neutralinos χ, the major SUSY dark matter candidates, could produce an excess in the positrons spectrum in the range between 10 GeV and 300 GeV

$$\chi\chi \to W^+W^- \to e^+ + \nu_e + W^-$$
$$\chi\chi \to b\bar{b} \to e^+ + X$$





HEAT observed such an excess in the region above 5 GeV; AMS will explore this region with higher energy resolution and a high statistics

Since the cosmic ray spectrum is dominated by protons
a protons rejection factor of 10^6 has to be achieved to detect positrons with a 90% efficiency

This will be reached with the joint use of the Electromagnetic CALorimeter and of the Transition Radiation Detector

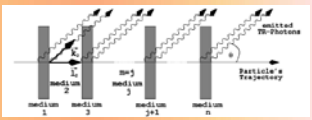
Transition Radiation Detector

Transition Radiation

The transition radiation (TR) is a soft X ray emission generated when a charged particle crosses the boundary between two materials having different dielectric constants

The intensity of transition radiation is proportional to the Lorentz factor γ so its detection allows an efficient separation between light and heavy particles

The probability of emission at a single surface is of the order of 10^{-2} so a fleece radiator is necessary to enhance the X ray emission



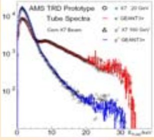
An efficient detection of transition radiation requires a low Z radiator material to minimize the absorption of the transition photons produced. On the contrary, the detection medium should have high Z to allow the best photons absorption. Since the emission angle is of the order of $1/\gamma^2$ ionization losses will be detected together with transition radiation; this requires a thin enough detection medium to limit the ionization loss of the charged particle

AMS-02 TRD

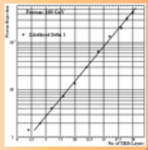
The TRD consists of 20 layers of straw proportional tubes interleaved with a fiber fleece radiator material

The tubes are arranged in modules of 16 straws each

The modules are placed in a conical octagon support structure in alternate projections to provide 3D tracking



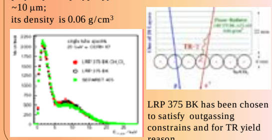
The different energy deposits in a TRD prototype have been studied at a test beam comparing 20 GeV electrons to 160 GeV protons



Moreover the proton rejection as a function of the number of the active layers in the detector has been studied

Radiator Material

The radiator material (LRP 375 BK) consists of polyethylene/polypropylene fibers with a mean diameter of ~10 μm;
its density is 0.06 g/cm³



LRP 375 BK has been chosen to satisfy outgassing constrains and for TR yield reason

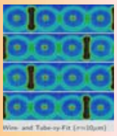
Straw Tubes

The straw tubes have an inner diameter of 6 mm and length between 0.8 m and 2.2 m

Each tube wall is a 72 μm thick kapton/aluminum sandwich

The tubes are arranged into 328 modules of 16 straws each

and will be filled with a $Xe:CO_2$ (80:20) mixture at ~1250 mbar. The modules are divided in 41 segments of 8 modules each



Each tube has a W/Au wire with a diameter of 30 μm tensioned with 100 g

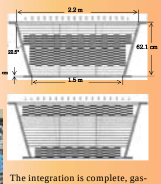
To assure the mechanical rigidity longitudinal and transversal carbon fiber stiffeners are glued onto the modules

Support Structure

The support structure has aluminum honeycomb walls covered by 2 mm of carbon fiber

The structure has a mechanical precision of 100 μm to avoid wire displacement or straw walls deformation

A Multi-Layer Insulation (MLI) is used to guarantee the thermal stability

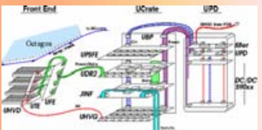


The weight of the structure is 207 kg including the external support and insulation

The integration is complete, gas-tower interconnection tubes are installed, temperature sensors mounted on the structure and tested, front end electronics tested

Front End Electronics and DAQ

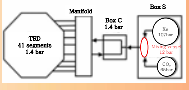
There are 82 front end units (UFE) for a total of 5248 channels powered by 20 W. They digitize the signals produced in the straw tubes. Dedicated boards (UTE) distribute the high voltage to the tubes and decouple straw signals. Two crates (U-crates) host the whole TRD gas system and contain the UDR boards dedicated to the reduction of the data coming from the UFEs



TRD Gas System

Gas System Structure

The TRD gas system stores sufficient gas for the whole duration of the AMS-02 mission, transfers fresh mixture to the TRD each day, circulates the gas through the detector and monitors the gas content continuously



The gas system consists of a supply module (Box S) to store the necessary amount of gas, a circulation module (Box C) to circulate the gas mixture through the detector and Manifolds to distribute the mixture to the straw modules

__Box S__ contains two carbon fiber overwrapped stainless steel gas tanks to store
- 49.5 kg of Xe at 107 bar
- 4.5 kg of CO_2 at 65 bar

High pressure valves allow gas transfer to a mixing vessel with a volume of 1 l where the $Xe:CO_2$ (80:20) mixture is obtained to 1% accuracy. Heaters are used for uniform and safe gas transport

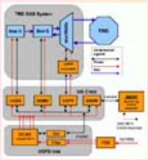
__Box C__ contains diaphragm pumps to circulate the mixture through the system. Gas gain and mixture quality are monitored through 4 calibration tubes coated with ^{55}Fe and a spirometer is used to calculate the CO_2 fraction in the mixture from transit time measurements of an ultrasonic pulse

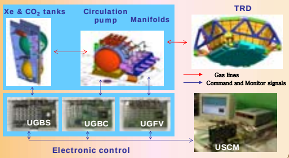
__Manifolds__ are placed as gas inlet and outlet to each TRD segment. They are equipped with differential pressure sensors to reveal pressure drops and allow to isolate leaking segments. The gas flow will be 1 l/h per gas circuit

All the main components are double redundant to assure safety and functionality in space

Gas System Electronics

The system is controlled via the electronics crate (UGcrate) that contains the double redundant control board (USCM) and dedicated boards to control box S (UGBS), box C (UGBC) and Manifolds (UGFV) and one board to supply the high voltage to the monitor tubes in box C (UHVG). The electronic control includes a main DAQ computer (JMDC) that communicates via CAN bus with the USCM and then with each board that controls the electromechanical devices.



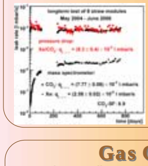


Requirements and Performances

To satisfy all the technical requirements needed for a safe and successful space mission and to achieve the expected performances, the detector must undergo extensive tests like radiation resistance, thermo-vacuum and vibration. Key point for the operation in space is the gas tightness while the accuracy of the gas mixture is crucial to obtain the expected gas gain

Gas Tightness

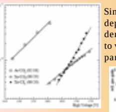
Gas tightness depends on the gas diffusion through the straw walls and from the leak rate through the modules endpieces. The straw modules are terminated with
- Polycarbonate endpieces
- AW 134 glue for potting
- Cu-Te crimp connectors to the electronic board



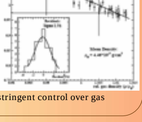
A TRD longterm test has demonstrated that gas tightness is unchanged over a period longer than 2 years. The CO_2 leak rate is about 7.7×10^{-5} l·mbar/s corresponding to 20 years of operation

Gas Gain

The TRD will operate at a gain of ~3000



Since the gas gain is strongly dependent on high voltage and gas density, variation in gas gain due to variations of these two parameters has to be corrected for



For example a 3°C temperature change causes a 1% gas density variation, which implies a gas gain variation of about 5%

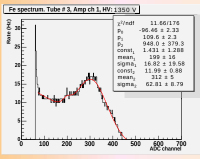
So to obtain the required proton rejection power, a stringent control over gas parameters is necessary

Gas Quality Check

The mixture quality is of fundamental importance to obtain the expected gas gain. To control the accuracy of the gas ratio the TRD uses two techniques: spirometer and monitor tubes
In particular the monitor tubes are used to analyze the gas gain variation measuring ^{55}Fe spectra

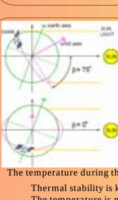
A test on the engineering model of the gas system has been performed using a premixed $Ar:CO_2$ (80:20) mixture.

The gas was flushed into an open system, thus increasing impurities on the cathode or in the mixture composition. Despite the high background due to the test conditions, the result shows that is possible to perform a good fit of the spectra using an exponential function for the background and two gaussians to describe the photopeak and the escape peak.



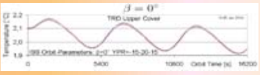
The test has also shown that is possible to control the whole apparatus successfully using the gas system electronics and slow control software

Thermal Stability



Since the gas amplification is strongly dependent on gas density it is necessary to keep pressure and temperature stable during the operation in space. In particular the temperature gradient has to be

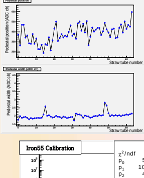
$$\Delta T < 1\ K$$



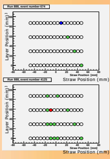
The temperature during the orbit ranges from +35 °C to 0 °C depending on the ISS orbit angle
Thermal stability is kept using multilayer insulation and heaters
The temperature is monitored with 200 Dallas temperature sensors in the whole TRD

Data Preparation for Proton Rejection Analysis

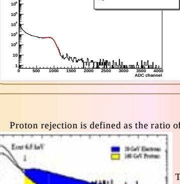
Prior to the proton rejection analysis, the raw data have to be corrected channel by channel for interfering effects like pedestal position and common baseline shift of all detector channels referred to as common mode. Also, the permanent gas amplification differences due to the finite mechanical accuracy, depending on wire displacement and shape deformation, have to be corrected for.



The first step of the data preparation is the pedestal subtraction: the pedestal positions and widths are calculated from each data sample

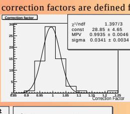


The second step is the event selection. A straight line fit is performed for each event. Several cut parameters are defined to select events with a single track in the detector



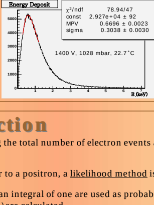
The last step is the detector energy calibration. To perform this, ^{55}Fe measurements are taken using a random trigger. The photopeak position is derived from a correlation between one of the Fermi function parameter and the σ of the Gaussian

Then channel by channel intercalibration is used to correct the data for tube to tube differences in the average signal heights. The correction factors are defined for each tube as



$$CF_i = \frac{\overline{MPV}}{MPV_i}$$

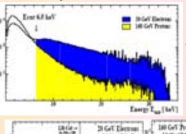
where MPV is the most probable value obtained from a Landau fit of a single tube spectrum



A cosmic test performed using a 4-layer prototype (64 channels) shows good agreement between the results and the expected value for MIP crossing ~3 mm of $Ar:CO_2$ (82:18) mixture at known density

Proton Rejection

Proton rejection is defined as the ratio of the number of incident protons to those selected, keeping the total number of electron events above 90% applying the same cuts

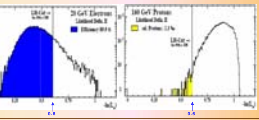


To determine whether a track belongs to a proton or to a positron, a __likelihood method__ is used

The energy spectra of electrons and protons normalized to an integral of one are used as probability distribution: for each hit on track the probability density functions $P^i_{e,p}(E_i)$ are calculated

The combined probabilities of the event are built as $W_{e,p} = \sqrt[N]{\prod_{i=1}^{N} P^i_{e,p}(E_i)}$ where N denote the number of hits on the track

The likelihood function is $L_e = W_e/(W_e+W_p)$



Low $-\ln(L_e)$ values are an indication of electron-like events

Proton rejection is calculated as the inverted percentage of proton events selected as electron-like to the total number of proton events in the sample, applying the same cut

Assuming that events with L_e < 0.6 are from light particles, a proton rejection factor >10^2 is reached up to 250 GeV with 90% electron efficiency