The AMS-02 TRD
for the International Space Station

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***Abstract*— The Alpha Magnetic Spectrometer (AMS-02) is an experiment which will be mounted on the international space station (ISS) to measure primary cosmic ray spectra in space. A key element is a transition radiation detector (TRD) to extract an e^+ or p^- signal reducing the p^+ or e^- background by a rejection factor $10^2 - 10^3$ in an energy range from 10 to 300 GeV. This will be used in conjunction with an electromagnetic calorimeter to provide overall p^+ rejection of 10^6 at 90% e^+ efficiency.**
The detector consists of 20 layers of 6 mm diameter straw tubes alternating with 23 mm layers of polyethylene/polypropylene fleece radiator. The tubes are filled with an 80%:20% mixture of $\mathrm{Xe:CO_2}$ at 1.2 bar absolute from a recirculating gas system designed to operate >3 years in space. There are in total 5248 straw tubes which are read out by a custom-made DAQ system in less than $70\,\mu s$. The electronics must be low in power consumption and sustain the stringent requirements of operation in space. The construction of the detector and its electronics is presented in this paper.

***Index Terms*— AMS, TRD, ISS, space science, space electronics, gas detectors, proton rejection, transition radiation**

I. INTRODUCTION

THE Alpha Magnetic Spectrometer is an experiment which will be mounted on the International Space Station (ISS) to measure primary cosmic ray spectra in space for three years. It will measure cosmic ray spectra of individual elements up to Z $\leq$ 26 and up to TeV region, high energetic γ-rays up to hundreds of GeV.

A. The AMS-02 subdetectors

The AMS-02 spectrometer consists of a ”Silicon Tracker”, a ”Time of Flight” (TOF), a ”Ring Image Cherenkov Counter” (RICH), an ”Electromagnetic Calorimeter” (ECAL), a ”Amica Star Tracker” (AST), ”Anticoincidence counters” (ACC) and a ”Transition Radiation Detector” (TRD).

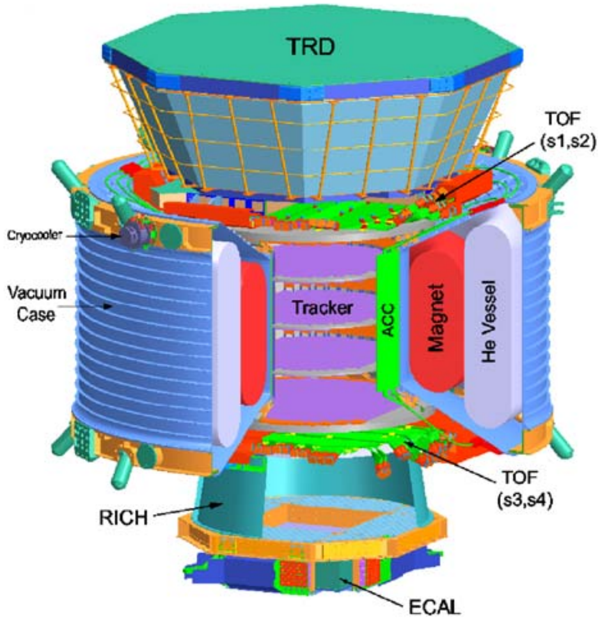

Fig. 1. Cross section of AMS-02. The TRD in AMS-02 is the uppermost detector. Its conical octagon shape allows a big acceptance of 0.5 $m^2 sr$ with minimal weight.

AMS-02 provides excellent particle identification capabilities. It measures the charge of the traversing particle independently in Tracker, RICH and TOF subdetectors. The velocity is measured by the TOF, TRD and RICH subdetecors.

The Tracker measures the particle’s momentum in a magnetic field with $0.8\,Tm^2$ bending power, which is provided by a superconductive magnet. It is composed of 2300 double-sided silicon sensors arranged in 8 circular layers transverse

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to the magnet axis. Its accuracy is $10\,\mu$m in the bending direction and $30\,\mu$m in the non-bending one, allowing the determination of the particle's momentum up to 2 TV rigidity. It also provides information about he particle's energy loss.

The superconducting magnet is cooled by 2500 l of superfluid Helium (He II). It consists of a pair of large dipole coils together with two series of six smaller racetrack coils distributed between them. The racetrack coils increase the magnitude of the dipole field and reduce the stray field outside the magnet in order to prevent a torque on the ISS resulting from the interaction with the magnetic field of the Earth.

The TOF subdetector is composed of four layers of plastic scintillator paddles, of which two are located above and two below the magnet. It measures the time a particle needs to fly through the four layers with an accuracy of 140 ps. Apart from that it provides coordinate information and energy loss.

The RICH subdetector is mounted below the lower two TOF planes and consists of a NaF and silica aerogel radiator plane at the top and a photodetector plane at the bottom, separated by 45 cm drift space. A hole with the size of the ECAL in the middle of the photodetector plane assures that no interaction with RICH occurs before the particle crashes into the ECAL. A conical mirror encloses the drift volume to increase the acceptance. It measures the velocity of a single charged particle with an accuracy better than per mil and provides particle flight direction information.

The ECAL subdetector is placed at the bottom of AMS. It is a three-dimensional sampling calorimeter composed of 1 mm scintillating fibers sandwitched between grooved lead plates. The length of the ECAL is 15 X_0. Shower shape analysis of positrons and protons provides a way to suppress the proton background up to a level of 10^4.

The ACC subsystem surrounds the Tracker. This scintillation based anticounter system vetos against events that show signals of particles which hit the barrel of anticounters around the Tracker. Therefore only particles are selected that go straight through the detector.

The Star Tracker is a pair of optical telescopes with CCD-cameras to measure the pointing direction in space AMS-02 looks at.

The TRD subdetector is decribed in this paper. [1] [2] [3] [4] [5]

B. Physics scope

AMS-02 is designed to contribute in a wide field of astrophysics and astroparticle physics.

The precise knowledge of cosmic-ray spectra are relevant for constraining models for galactic cosmic-ray production, acceleration and propagation. AMS-02 will provide detailed and precise measurements of the most abundant cosmic-ray components with electric charges $1 \leq Z \leq 26$ in the energy range 0.1 GeV/n E_k/n $\leq$ 1 TeV/n. After three years of data taking, AMS-02 will have collected 10^8 H, 10^7 He and 10^5 C nuclei with energies above 100 GeV/n.

To investigate Gamma-ray bursts (GRBs), Active Galactic Nuclei (AGN) and gamma ejection from Pulsars, AMS-02 provides two complementary methods for photon detection. The first method is based on the identification and reconstruction of e^+e^--pairs converting somewhere in the material above the Tracker, e.g. in the TRD (*conversion mode*). The second method is based on the detection of photons in the ECAL (*single photon mode*).

A major objective in the AMS-02 physics program is the search for animatter, e.g. $\overline{He}$. The expected upper limit after three years of operation in space will reach $\overline{He}/He \simeq 10^{-9}$.

In contrast to this direct search for antimatter, the observatio of the positron, antiproton, antideuteron and gamma-ray flux provides the possibility for an indirect search of antimatter: Astrophysical observations indicate that the Universe could include a large amount of dark matter of unknown origin. It could be formed by Weakly Interacting Particles (WIMP). e.g. the Lightest Supersymmetric Particle (LSP) in R-paritiy conserving SUSY models. This Neutralino can annihilate in the Galactic Halo, providing characteristic signatures in the aforementioned fluxes. It is shown in a recent paper [6] that Neutralino annihilation can explain the shape and magnitude of the positron, antiproton and gamma-ray flux with a fitted normalization factor similar for all three fluxes.
[7] [8]

Since positrons can be mistaken for protons with different energy using only Tracker data, a way is needed to distinguish between them. To measure the positron-spectra, it is crucial to suppress the proton background, which is 10^4 times higher than the positron rate. If a precision on the percent level is desired, a proton rejection capability of 10^6 is needed. Combining the TRD rejection power with that of an electromagnetic calorimeter (Ecal in Fig. 1) located at the bottom of AMS-02 increases the p^+ rejection to the order of 10^6 at 90% e^+ efficiency.

C. Challenge of Operation in Space on the ISS

Operation in space on the ISS implies that the detector needs to withstand the harsh conditions in space and to fulfill the stringent requirements of the ISS. During the start of the space shuttle, vibrations of up to 6.8g can occur. So all detector components need to be tested on a vibration table. The weight of the whole TRD is limited to 480 kg, due to a weight budget of around 7000 kg for whole AMS. Temperature variations of TRD outer casing range from $-180°$C to $+50°$C. As a consequence all components need to be tested in a thermo-vacuum-chamber. A multilayer insulation foil (MLI) assures

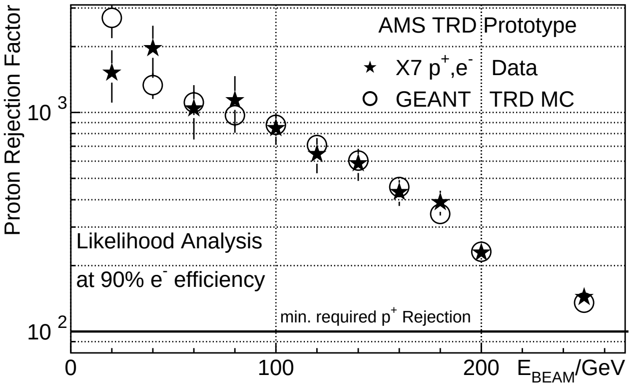

Fig. 2. TRD proton rejection factor measured in an X7 Testbeam at CERN using a 20 layer jig to simulate the final detector. Also GEANT 3 simulation points are given in this figure showing the perfect agreement between measurement and simulation in the energy range 20 to 250 GeV.

that the temperature of the TRD will remain in the range of $0°\mathrm{C}$ to $20°\mathrm{C}$ keeping the temperature gradient within $1°\mathrm{C}$ across the volume of the TRD. AMS-02 has a limited power consumption budget of 2000 W, from which the TRD takes a part of less than 185 W. Strict electromagnetic interference limits need to be fulfilled near the ISS. During the expected operation time it needs to be maintenance free.

II. THE TRANSITION RADIATION DETECTOR

Transition radiation (TR) consists of soft x-rays which are emitted when charged particles traverse the boundary between two media with different dielectric constants. In the momentum range from 10 to 300 GeV/c, light particles such as electrons and positrons have much higher probability of emitting TR photons than heavy particles such as protons and antiprotons. At a single boundary, the probability of emission is still very small, on the order of 10^{-2}, but this is enhanced by using fleece as a radiator made of polyethylene/polypropylene, which is divided into twenty 23 mm thick layers and 6 mm diameter straw tubes, filled with an 80%:20% $\mathrm{Xe}:\mathrm{CO_2}$ gas mixture to detect the photons. In this way a rejection factor of $10^2 - 10^3$ for p^+ and e^- can be achieved against e^+ and $\overline{\mathrm{p}}$ in the aforementioned momentum range.

Fig. 2 shows the proton rejection factor measured in a CERN X7 testbeam with a 20 strawtube layer prototype detector. The results show good agreement with the GEANT 3 simulation. It can be seen, that in an energy range from 10 to 250 GeV the proton rejection factor lies clearly above the minimal required factor of 10^2. [9]

III. MECHANICAL STRUCTURE

The conical octagon structure (width from 1.5 m at bottom to 2.2 m at top) is built of a carbon fiber and aluminum honeycomb sandwich material, both for the sidewalls, with slots machined with a precision of $200\ \mu\mathrm{m}$, and the top and bottom covers (Fig. 3). The dimensions are verified on a high precision optical measuring machine.

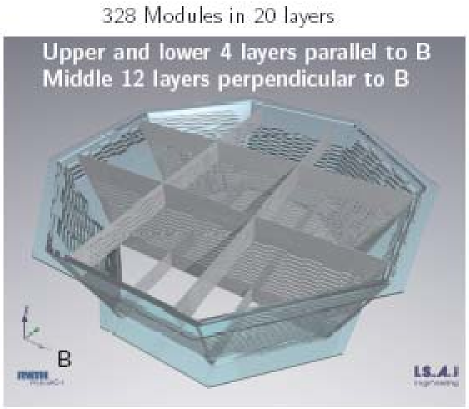

Fig. 3. Sketch of the conical Octagon.

The octagon is supported by an aluminum M-structure which is mounted on the universal support structure (USS). The USS holds AMS-02 in the space shuttle and finally fixes it to the ISS. Detailed finite element calculations have been performed to verify that the large TRD octagon structure and support satisfies all dimensional and safety requirements.

The straw tubes are built as modules of 16 tubes. The modules are arranged in the conical octagon structure, such that the upper and lower 4 layers of tubes run along the B-field direction and the 12 central layers in the perpendicular direction. In all, there are 328 modules, for a total of 5248 straws. The length of the straw modules varies from 0.8 m to 2.0 m. The wall material of the straws is a $72\ \mu\mathrm{m}$ kapton foil and the sense wires are $30\ \mu\mathrm{m}$ gold plated tungsten. During production single straws have to be tested for gas tightness. After the manufacturing of a module it has to pass stringent tests concerning gas tightness, high voltage stability and signal homogenity.

IV. DAQ AND SLOW CONTROL ELECTRONICS

The electronics for the TRD (Fig. 4) consists of the front ends (attached to the detector), the data aquisition electronics, the slow control electronics, the high voltage system (inside U-crate) and the DC/DC converters (inside UPD-box). The ”U” in the abbreviations for all detector specific electronic boards stands for the German word ”Übergangsstrahlung”, meaning ”transition radiation”. A list with the meaning of all the abbreviations is given in table I.

The front end electronic boards (UFE), which are mounted on the walls of the octagon, consist of Ideas VA32 chips, which multiplex the signals from 4 straw tube modules, and serial ADCs (AD7476) providing a read out rate of 10^6 samples per second (Fig. 5). The time to read out the 5248 channels of the TRD is less than $70\ \mu s$, which is well below the requirements for an expected data rate of max. 2 kHz.

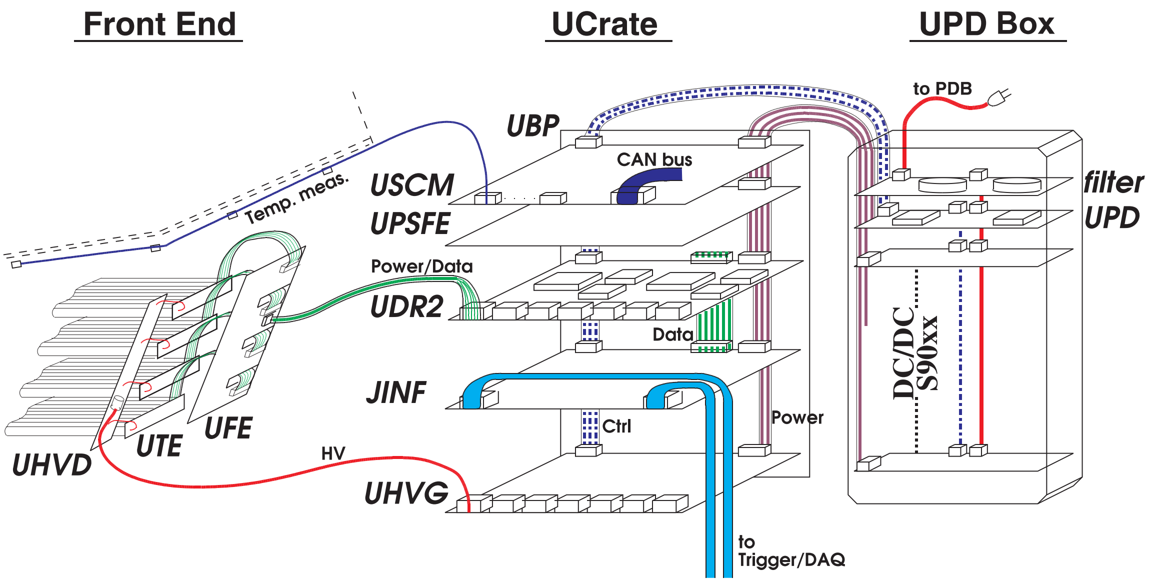

Fig. 4. Scheme of TRD DAQ electronics. The TRD DAQ electronics consists of three spatial separated parts: the front ends, the U-crate and the UPD-box. The front end part in the picture is mounted at the walls outside the octagon close to the mounting slots for the strawtube modules. It consists of the front end boards (UFE) connected to the tube end boards (UTE) and the HV distribution boards (UHVD). The boards of the U-crate are explained in the text. The U power distribution box (UPD-box) houses 9 DC/DC converters and their control electronics. The "U" in the abbreviations for all detector specific electronic boards stands for the German word "Übergangsstrahlung", meaning "transition radiation". For the meaning of all the abbreviations see Table I.

TABLE I

U-ELECTRONICS ABBREVIATIONS

Abbreviation	Name
U-crate	TRD electronics crate
UPD	TRD power distribution box
UBP	TRD backplane
UDR2	TRD Data Reduction Board
UPSFE	TRD Power Supply for Front Ends
UHVG	TRD High Voltage Generator
UFE	TRD Front End
UTE	TRD Tube End
UHVD	TRD High Voltage Distributor
JINF	data concentrator and link to higher DAQ
USCM	Universal Slow Control Module

The power for the UFE-Boards is controlled and regulated by the USPFE (U power supply for front ends). It consists of 14 linear regulators, two Actel FPGAs and slow control circuitry to switch on and off its linear regulators and other boards in the crate. 6 UPSFEs are located in one crate, each providing power for 14 UFE-Boards. Two UPSFEs are connected in parallel to gain double-redundancy, one of them remaining off in normal conditions.

The raw data of the TRD at a 2 kHz trigger rate is approx. 168 MBit/s. This in combination with the data of the other detectors amounts to approx. 7 Gbit/s. To cope with that large amount of data, each subdetector has its own data reduction board. All boards of this type are built up similarly, based on a common digital part (CDP). For the TRD the UDR2 boards (U data reduction board) comprise two CDPs for redundancy plus an interface for 7 UFEs. Each CDP consists of an FPGA (A54SX32A) and a DSP (ADSP2187), where data is zero-subtracted and buffered. In this way the data of 7 front ends is collected and reduced in one UDR2 board. 6 UDR2 boards are existing in one U-crate. Upon request the JINF board (data concentrator and link to higher DAQ), which itself is built up of two CDPs, collects the event data of all the 6 UDR2 boards and transfers it to the main AMS DAQ system for storing on the ISS and downlinking to earth.

This link between AMS-02 and the ISS is called HRDL (high rate data link) - an ISS specific implementation of the TAXI protocol over fiber optic cables operating at 125 MBaud. In this data stream event data and monitoring data are transmitted to the ACOP (AMS crew operations post), where data is archived for eventual retrieval by the Space Shuttle. When Ku-band is available, data can be replayed from ACOP or streamed live from the experiment to

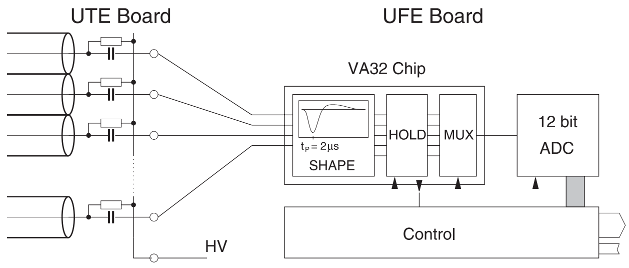

Fig. 5. Scheme of front end electronics.

Earth at an allocated orbital average of 2 Mbit/s downlink. [10]

The interconnection between the UDR2 boards to the JINF and from JINF to higher DAQ are made by a serial point-to-point protocol called AMSWIRE, based on IEEE-1355, spacewire. It provides a net transfer rate of 10 Mbyte/s.

The wires of the straw tubes are supplied with max. 1600 V generated on 6 UHVG boards per crate. The UHVG boards are build of double-redundant Cockroft-Walton HV generators with 16 stages controlled by Lecroy MHV100 chips.

The USCM (universal slow control module) boards represent electronics for slow control. They are based on a DS80C390 processor, similar to an 8051. The two USCMs in each crate are working redundantly. They are connected in parallel by Lecroy links, a serial two wire bus controlled by the Lecroy protocol, to the UPSFE and UHVG boards and to the UPD-box control electronics. Either by direct request from the slow control master computer or by decision tables stored in USCM memory, the USCM may switch redundant parts of the electronics and the power to the front ends, allowing to shut down malfunctioning boards or channels in order to save power. Furthermore it provides the communication interface between slow control master computer and UHVGs. The USCMs communicate via CAN bus with the AMS-02 slow control system, which is permanently monitored from ground via satellites.

This monitoring data is sent via the LRDL (low rate data link), which is based on the MIL-STD-1553B dual serial bus, through the ISS for transmission on the Ku-band to the ground. Available data rate is $\sim$10 Kbit/s with a duty cycle of 55 to 90 %; 10 byte/s is transmitted coninuously. [10]

All in all there are two U-crates, which house 21 VME-sized boards each. To supply these boards with their different operating voltages, the 28 V coming from a central power distribution box (PDB) inside AMS-02 have to be transformed by custom-made DC/DC converters which provide transformation efficiencies of up to $80\,\%$. For each U-crate one UPD-box houses 9 double-redundant DC/DC converters.

Due to the low power consumption of the used components and due to the high efficiencies of the DC/DC converters, the complete TRD DAQ electronics has a power consumption of less than $100\,W$. Further requirement for the components are: radiation hardness (600 rad/year) for three years mission), stability under thermal stress (-25°C to +55°C operational and -45°C to +85°C non-operational) and vibration up to 6.8g.

V. GAS SYSTEM

The TRD tubes contain $\mathrm{Xe}/\mathrm{CO}_2$ mixed 4:1 in volume at 1.2 bar. The gas has to be stored, mixed, and distributed through the TRD modules. The system is build up of a supply box (box-S) and a circulation box (box-C) (Fig. 6).

Box-S stores the Xe and CO_2 in separate vessels, which will contain 46 kg of Xe at a pressure of 115 atm and 4 kg of CO_2 at a pressure of 70 atm, 50 kg in total. This amount is sufficient for operating the TRD up to 15 years, giving a safety factor 6.7 in time. The gases are transfered in controlled amounts (by measuring partial pressures) to a mixing vessel, from which the mixture is released to box-C. Box-C contains redundant pumps to circulate gas through the TRD to ensure uniform gas properties. It also contains a CO_2 analyzer and monitor tubes for measuring the gas gain with an Fe^{55} source. Then the flow of gas splits into 41 separate gas circuits, each consisting of eight straw modules connected in series. Pressure sensors and valves located in the so-called manifolds can detect leaks and isolate a leaky segment.

VI. GAS SYSTEM ELECTRONICS

The monitoring and control crate for the gas system (UG stands for the German word ”Übergangsstrahlung Gas”) contains two redundant USCMs which run the monitor program that tests the status of the gas system against pre-conditions and executes commands, which are stored in the form of decision tables.

To control box-C, box-S and the manifolds, three different kind of boards are placed in the UG-crate:

UGBC (gas control for box-C): it controls box-C operations, i.e. running the pump, opening valves to refill the TRD and monitoring gas pressure. It shuts down the gas system safely in case of power and communications failure and generates high voltage system shutdown. In case of overpressure a relief valve is opened. For twofold redundancy two UGBC boards are placed in the crate.

UGBS (gas control for box-S): it controls box-S operations i.e. providing the correct gas mixture to refill the TRD, monitor the pressure and filling status. It shuts down the gas system safely in case of power and communications failure. For twofold redundancy two UGBS boards are placed in the crate.

UGFV (gas control for manifolds): it controls and monitors the isolation valves and pressure sensors of TRD manifolds, such that leaky gas circuits can be isolated.

The power needed for the boards in the UG-crate is converted by 4 DC/DC converters housed in the UGPD-box (UG power distribution box). Two UGFV boards are needed to control all the manifolds. For twofold redundancy 4 UGFV boards are placed in the crate.

One UHVG board is housed in the same crate to supply the monitor tubes of box-C with high voltage. [11] [12]

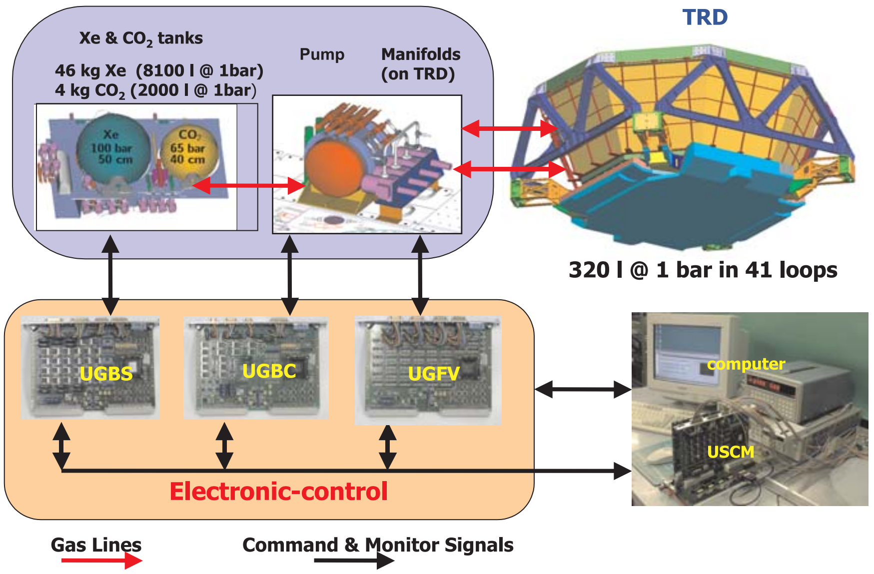

Fig. 6. Scheme of the TRD gas system electronics.

VII. CONCLUSION

In testbeam the proton rejection capability of the TRD has been demonstrated to be of the order of 10^2 up to 250 GeV. Tests of strawtube modules and electronics on a vibration table and in a thermo-vacuum-chamber show that the current design of TRD can withstand the harsh conditions in space and can fulfill the stringent requirements of operation on the ISS.

ANNOTATION

AMS-02 and its TRD subdetector is currently under construction. All information given in this paper is valid at the day of publication. But the detector and its DAQ system can be changed if regarded as necessary in the future.

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