ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Perugia

INFN/TC-99/12
13 Luglio 1999

THE POWER SUPPLY SYSTEM OF THE TRACKER DETECTOR FOR THE STS-91 FLIGHT OF THE AMS EXPERIMENT

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Abstract

The AMS experiment is designed to search for the antimatter components of cosmic rays, the products of the annihilation of dark matter particles and to perform additional cosmic-ray measurements like spectrum of light nuclei, antiprotons and positrons as well as Iso-topic composition for light elements. The complete AMS instrument will be installed on the space station Alpha in year 2003. A preliminary version of the apparatus has flown in June 1998 on the Space Shuttle mission STS-91.

The power supply system of the tracker, described in this paper, has been con-structed optimizing noise performances, following space qualification criteria for a ten day mission on the shuttle and considering the operation in the fringe magnetic field of the spectrometer. This paper also includes a short description of tracker electronics to be powered. Optimisation and qualification tests on the complete power supply system are also reported.

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1 The AMS apparatus for the STS-91 flight

The main goal of the preliminary flight of the AMS experiment [1] is intended to test the functionality of the magnetic spectrometer in a space environment. It is the first time that such an instrument has been operated in space. However, this configuration of the AMS apparatus can achieve three main physical objectives: a measurement of the antiproton spectra up to 3 GeV, a limit for antihelium and anticarbon flux better than current measurements [3] [4] and the spectra of light ions up to about 100 GV total rigidity [2].

The STS-91 AMS apparatus shown in fig. 1 is composed of:

- A cylindrical magnet weighting 1.9 tons made out of 6000 premagnetized rare earth Nd-Fe-B blocks. It has a dipolar magnetic field of about 1.5 kG. The fringe field is very low (below 3 G at 260 cm) in order to avoid disturbances to the shuttle orbit due to interactions with the earth magnetic field.

- A tracker detector made with 6 layers of double sided silicon detector having 2.4 m^2 total surface (the largest silicon tracker detector ever built). The measured space resolution is around 10 μm on the bending side and 30 μm on the non-bending side. The MDR (Δp/p= 100%) of the spectrometer is about 500 GV. The silicon tracker will also give the sign of the charge and the measurement of its absolute value for nuclei up to Oxygen by measuring the dE/dx.

- A set of anticoincidence counters located on the inner walls of the magnet to reject the background induced by the interaction of charged cosmic-ray particles with the magnet.

- A time of flight system based on 4 layers of scintillators having time resolution of about 120 ps to provide first-level trigger, velocity measurement, up/down separation and additional dE/dx measurement for low charge nuclei.

- An aerogel Cherenkov detector having a refraction index n = 1.055 to identify low energy antiprotons up to about 3 GeV.

The AMS apparatus was launched on the 2nd of June 1998 from Kennedy Space Center (Cape Canaveral) for the ten day precursor flight STS-91 on board of the Shuttle Discovery. The mission was successful; 152 orbits were completed at 370 km of altitude and $\pm 52^0$ inclination collecting about 100 million cosmic ray triggers.

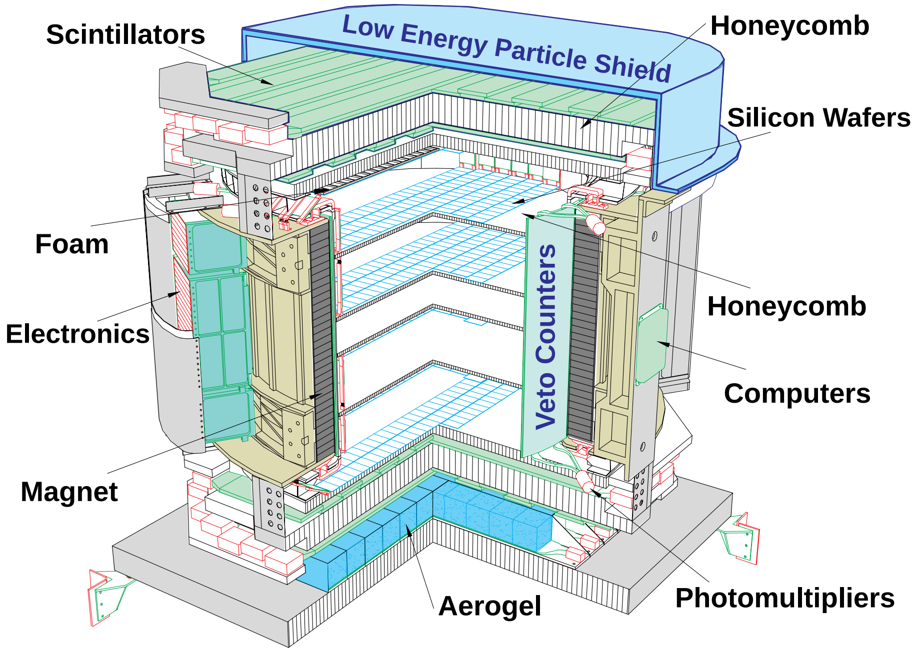

Figure 1: The AMS apparatus for the Shuttle flight STS-91

2 The Tracker Detector

The tracker detector for the precursor flight [5] is a reduced version of the tracker that will operate on the space station that is described in ref. [6] [7] . The tracker is composed of 6 silicon planes; 4 located inside the magnet volume and 2 outside (one on top and the other on the bottom). In the STS-91 flight, the sensors cover the plane surface only partially while in the space station mission the planes will be fully covered. The tracker is built from silicon sensor ladders. Each sensor [8] has the following dimension: 70 x 40 x 0.3 mm^3 . The sensor is segmented into strips on both sides oriented orthogonally. On the n-side the strip pitch is 52 μm on the p-side it is 55 μm. When biased, a sensor draws 5.47 μA on average.

Silicon sensors are assembled to form ladders; each ladder is a row of detectors bonded on the long (70 mm) side. Depending on the location in the tracker, a ladder is formed by 7 to 15 sensors. The n-side of each ladder will be glued onto a Upilex cable connecting the strips together. Due to the different resistivity of the silicon sensors used in the production, the tracker has been divided in two halves; one half has been assembled using high resistivity sensors and has a bias voltage of around 50 V and the other half has lower resistivity detectors having a bias voltage of around 95 V.

The readout of the ladder is accomplished by several 64 channel chips called VA_hdr64 [9]. The chips are glued and bonded on 2 PCBs, one for the n-side and the other for the p-side. The two PCB are glued onto an alumina substrate to improve heat dissipation; this assembly is called TFE (Tracker Front End). There are 10 chips reading the p-side which is connected with one channel every two strips (readout pitch of 110 μm) and 6 chips for the n-side of each ladder. The readout pitch on the p-side is 208 μm (one channel every 4 strips).

The VA_hdr64 chip includes a low noise CMOS charge preamplifier, CR-RC semi-gaussian shaper, a sample-and-hold and an analog multiplexer. The VA_hdr64 is connected to the silicon strips through a decoupling capacitor chip that is not able to withstand the applied bias voltage; the readout for the n-side has therefore to be referred to a voltage close to the biasing potential.

The front-end electronics requires $\pm$ 2 V and a reference ground voltage. We measured total power consumption of 45 mW/chip. Currents drawn by the chip will come to a total of 24.58 mA; about 20.05 mA from the -2V input and 4.53 mA on the +2 V input. On a TFE we also have the receiver circuit for the digital signal, several filters and a thermal sensor but the current drawn by those elements is negligible. The reference ground voltage for the p side will be 0 V while for the n side it will be +50 V or +95 V. The biasing voltages for the detectors will be referred to the same ground reference. For the p-side (dVp) the bias voltage will range from -2 to -7V. For the n-side it will have the fixed value of -1.2V (dVn) in addition to the reference +50 V or +95V. A total of 57 ladders constituted the tracker detector for the STS-91 precursor flight corresponding to a total of 733 sensors installed.

All ladders are read by Tracker Data Reduction (TDR) cards housed into crates and connected to the TFEs via shielded multicoaxial flat cables. All TDRs are housed into VME 6U crates having 19 slots and a custom (non-standard) backplane. The crates includes 12 TDRs, 8 for the p-side and 4 for the n-side, 6 power supply cards that will be described in the forthcoming sections, and a JDQT cards that collects all data from the TDRs and controls and monitor the PS System. There are 2 crates for the entire tracker, one for the side biased at 50 V the other for the side biased at 95 V. The data stream from each crate is sent to the general DAQ system of the apparatus.

3 The power supply system of the AMS tracker

The power supply cards for the AMS detector are integrated inside the electronic crates which are also used for the readout electronics. Each crate has an additional power supply named PSB (Power Supply Box). Each PSB contains DC-DC converters from Modular

Devices Inc. (MDI) [10], that provides a 5.2V output for powering the control electronics and also the fuses for the primary 120V power line.

Each PS card is made of 4 building blocks:

1. **DC-DC converters.** Transforming the input 120 V to a voltage close to the required value.

2. **Filters.** Cutting common mode and differential mode noise.

3. **Monitor and control system.** For the control and monitoring of each PS card.

4. **Linear regulators.** For adjusting the voltage to the correct value and for current limiting.

There are 6 power supply cards per crate and there are 3 different types of card, distributed as follows:

- 1 TBS (tracker bias supply) provides the bias for the detectors and the reference ground for the electronics in the non-bending side (n side). It takes power from the 120 Volts primary line and +5.2V from the PSB for the digital control electronics. It comes in two different models depending on the output voltage: the TBS50 giving a reference ground of 50V and the TBS100 giving a reference ground of 95 V. Power output is negligible and power dissipation is below 5 W.

- 4 TPSFEs (tracker power supply - front end) provide power for the front end circuits. Each card will power 8 front-end circuits (full ladders p and n side).It takes the +120 V primary line, the reference ground from the TBS and +5.2 V from the PSB for the control electronics giving ± 2 volts, and a ground return for both the p-side and the n-side.It has 6.4 W of output power, (assuming 55% efficiency), 11.6 W input power and 5.2 W internal dissipation.

- 1 TPSR (tracker power supply - readout) provides power for the readout electronics; each card will power 12 TDR cards, 8 referred to ground (TDRS) and 4 referred to bias (TDRK). It takes power from the +120 V input voltage primary line, the reference ground from the TBS and the +5.2 Volts for supplying the control logic from the PSB. The output voltages are ± 6 V and ground return. The output power for this card is 39W, assuming an efficiency of 76%; the input power is 51 W with an internal dissipation of about 12 W.

The DC-DC converters used in each card to distribute power to the tracker subsystems are produced by MDI (Modular Devices Inc.). They have the same basic design philosophy (current flyback) even if each kind of PS card has its own different voltage and power outputs. They are custom-made hybrids enclosed in an metal shielding box. They accept on the input a voltage between 86 and 158 VDC . The circuit in the hybrid includes (see block diagram fig. 2) a common mode filter on the input line, a two-stage LC input differential filter, a current flyback DC-DC converter with a highly compact transformer and a chip-on-board mounted FET, an LC differential filter and a common mode filter on the output lines [11] .

This circuit is guaranteed by the manufacturer to operate in a maximum static magnetic

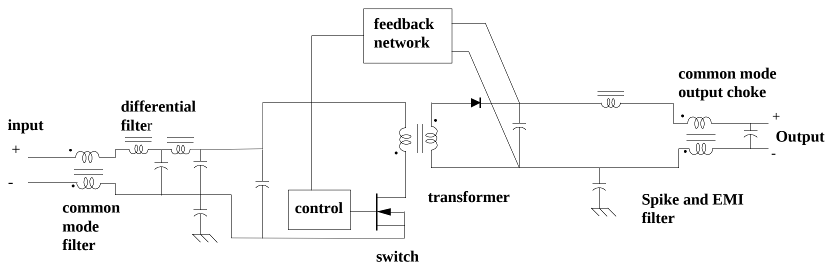

Figure 2: block scheme of an MDI DC-DC converter

field of 500 G. This performance has been tested within the AMS collaboration by ETH Zurich. No change in efficiency and output ripple was observed in the static magnetic field range from 0 to 500 G. Additional attractive features of this module are: operating temperatures at full efficiency -55 ^{0}C to 85 ^{0}C, with a linear derating up to 115 ^{0}C, shock resistance up to 50 g, acceleration resistance up to 500 g and vibration resistance up to 30 g.

The power supply cards are connected to the TDR through the custom backplane bus and not directly to the front-end electronics since cables are foreseen only between the front-end and the TDRs. .

4 The TPSFE

The TPSFE card (fig. 3) provides power for the 8 TFE circuits on both sides (8 p side and 8 n side). Its output voltages are: $\pm$2 volts (regulated) and ground (referred to 0V) for the p-side and $\pm$2 V (regulated) and ground (referred to +50V or +95 V) for the n-side. A TPSFE provides a total of 48 (3 x 2 x 8) separate output voltage lines.

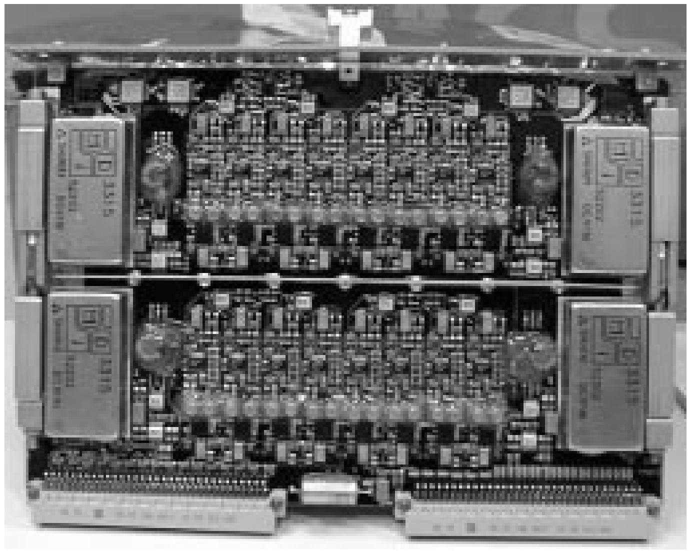

Figure 3: The TPSFE

This card includes 4 Modular Devices Inc. (MDI) DC-DC converter, 16 dual linear regulators, 4 filters and a control and monitoring circuit. The switching Power supply we have adopted is based on a hybrid module by Modular Devices Inc. model 3315, especially designed for the AMS experiment. They provide an output voltage of $\pm$2.6 V. Among these 4 converters two of them powers 8 p-side TFEs and the other two 8 n-side TFEs. Since this module operates at a typical output power (for the supply of p-side TFEs) of 2.6 W, much below their maximum capability of 5.5 W, their failure rate will be very low and no spare modules are foreseen in any of the TPSFE cards. The efficiency for these converters is around 69%. The outputs of the switching DC-DC converters goes to the low-drop linear regulators. A linear regulator section also includes a foldback current limiter; the current limit of the foldback is placed at 3/2 of the expected current.

The monitoring circuit for this card is connected to the output of linear regulators and checks if there is an overcurrent. The control circuit can kick the DC-DC converter issuing a reset in case of stalled output.

5 The TPSR

The TPSR (fig. 4) provides $\pm$6 V (unregulated) and ground level referred to 0 V for 8 TDRs for the readout of the p-side TFEs and $\pm$ 6 V (unregulated) and ground level referred to 50/95 V for 4 TRDs for the readout of the n-side TFEs. It takes power from the +120 V primary line.

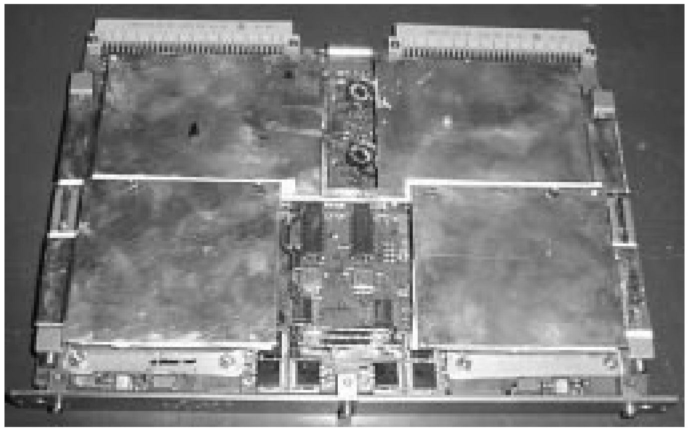

Figure 4: The TPSR

The card is divided in two halves:

- The $\pm$ 6 V converter section referred to 0 V
- The $\pm$ 6 V converter section referred to 50/95 V

Like the TPSFE, this card also includes its control and monitoring circuitry and a flyback DC-DC converters from MDI is also employed. For the section referred to 0 V a modified version of the 3051M-T06, named 3318, is used. The maximum output currents for this module are: 4.2 A on +6V and 0.8 A on -6V. The efficiency for these modules is about 72%. The $\pm$6 V converter section referred to 0 V is composed of 2 (1 active 1 spare) of these modules. Voltage regulators producing $\pm$ 5 V are placed inside each single TDR board.

The $\pm$ 6 V converter section for the TDR reading the n-side TFEs is composed of 8 active modules with no spares since they are used at below half of the maximum power they can provide. These modules are MDI-3317 derived from 12578M-D06. They can provide 0.624 A on the +6V line and 0.084 A on the -6V with an efficiency of about 70%. Each of these modules powers half a TDR for the readout of the n-side TFEs. Each module has its ground referred to the 50/95 V bias.

Since the power dissipation of this card is 12 W the card has been designed with 0.46 mm of internal heat dissipating layers and a heat sink on top of each converter connected to the crate through the wedge-lock.

6 The TBS

The TBS (tracker bias supply fig 5) provides the guard ring voltages for the detectors (dVn, dVp) and the reference ground for the readout and front-end electronics in the bending (p-side) and non-bending side (n-side).

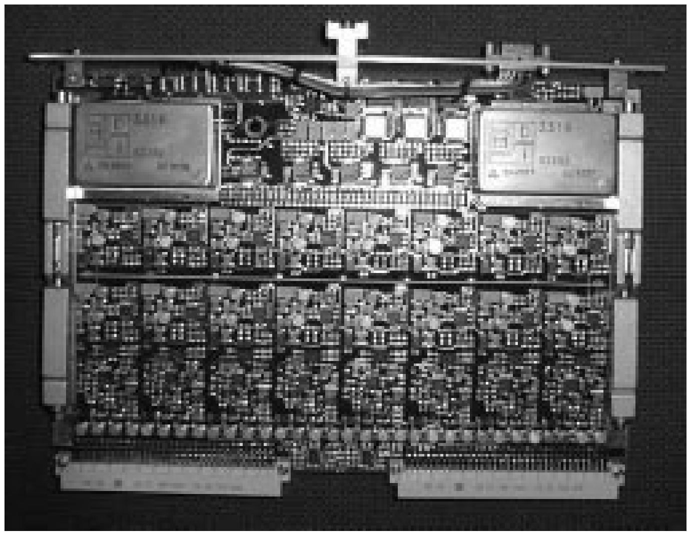

Figure 5: The TBS

Each card supplies 32 ladders and provides a reference bias to 4 n-side TDR cards and to 8 p-side TDR cards. The TBS card takes power from the 120 V primary line and the 5.2 V power lines of the PSB for monitoring and controls. It produces the following voltages:

- dVp voltage that can be tuned from -2V to -7V. This is used to bias the guard rings of the p-side of the sensors on 32 ladders.
- dVn Fixed voltage -1.2 V referred to Vgnd. This is used to bias the guard rings of the n-side of the sensors on 32 ladders.
- Vgnd Provides ground reference (at +50V or at +95 V) for 4 TPSFEs, 1 TPSR, 4 TDRs.
- Common ground reference to all cards in a crate

The switching DC-DC converters are MDI-3316 derived from MDI-3060M-T9. They can provide +60 V with a maximum current of 0.2 A and -9V with a maximum current of 0.12 A. In the TBS50 we have two of these modules in parallel both working at less than half the maximum current they can provide. Because of this implemented redundancy, if one of the two DC-DC converters fails the other can provide the current for the entire card. In the TBS100 the two 3316 housed inside the card are connected in series and the relevant output voltages are -9V from the DC-DC converter referred to 0V and 120V from the converter referred to +60V. To implement the redundancy in the DC-DC converter two additional 3316 are mounted inside the PSB and connecter to the TBS100 via a cable. A block scheme of TBS50 is given in fig. 6. The DC-DC converters are connected to two sets of linear regulators.

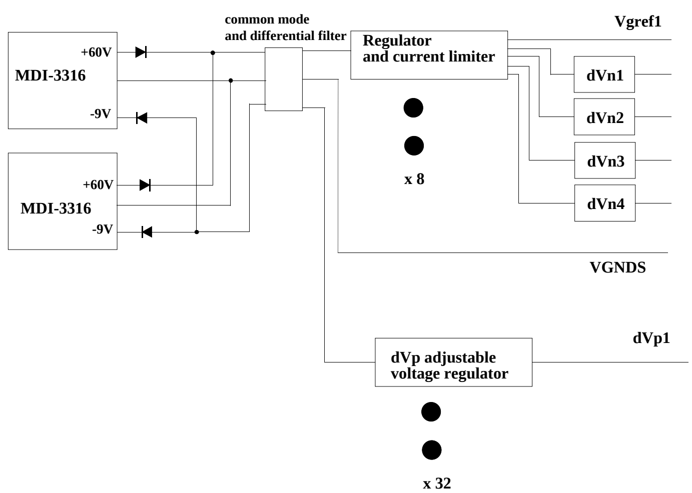

Figure 6: TBS50 block scheme

The first set is connected to the +60/120 V output of the DC-DC converters through diodes and is composed of 8 independent regulating and current limiting units each having 4 dVn outputs (+48.8/93.8 V) and 1 Vgnd output (+50/95V).

The second set of circuits is connected to the -9V outputs of the DC-DC converters and is composed of 32 independent voltage regulators for the generation of the dVp voltage which can be adjusted via fixed resistors from -2V to -7V.

The monitor circuits provide a measurement of all voltages from the regulating units and the currents from each dVp regulators. The control circuit can turn off each positive regulating unit.

7 The monitoring and control system controller

The telemetry and control part of the tracker power supplies is based on a microcomputer, placed on the JDQT card (fig. 7). This computer has 2 Motorola 68HC11 8-bit microcontrollers (MCU), one of them is a cold spare. The memories are space-qualified, radiation hard versions, so they are not redundant.

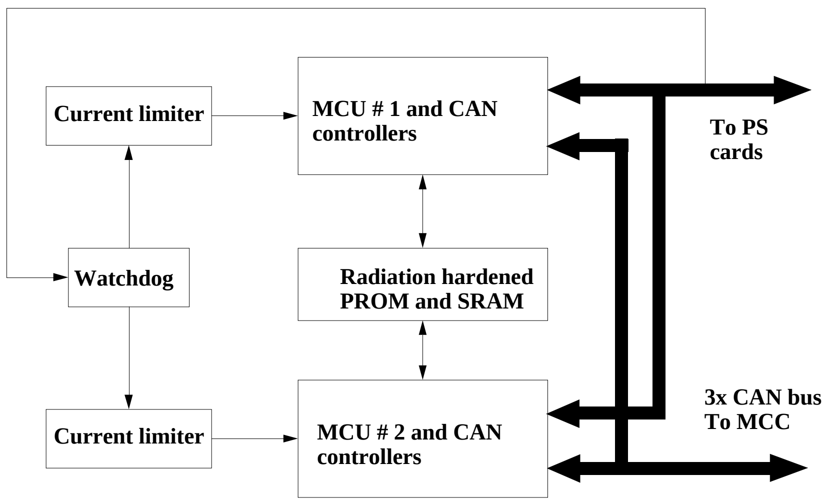

Figure 7: Block scheme of tracker power supply controller

Each CPU (and not rad-hard glue logic) has a foldback current limiter power switch, with a watchdog circuit build of discrete and LSI bipolar components. This can detect software malfunctions caused by SEU and switch the other CPU on, if the first fails to restart. The current limiters also prevent damage by SEL.

The MCU communicates with the MCC (Measurement Control Computer), the main system controller of AMS through triple CAN bus, using the industrial standard CAN, and the higher level protocols designed specifically for AMS.

Due to restrictions in backplane connections, a serial line is used to control the power supply cards. Each card receives a common clock, serial data input and output signals, and has individual select lines, so the interface between the cards and the MCU used only 10 wires. Failure of the control circuit of a power supply card does not disturb the communication with the others.

On each card, there is a serial-parallel converter shift-register stage (8 bits on TPSR, 16 bits on TPSFE and 24 bits on TBS) which stores the settings for the card when the select line is active. During this active signal, the card can send 1 bit of information back to the MCU. The card settings contain power supply on/off commands and selects the input of the measurement multiplexers, so getting all the information needs many serial packets from the MCU. Controlling the ADCs on the TBS with this method was possible only at low readout speed (all measurements were done in 8 seconds), but the changes in power consumption are slow enough, and in case of a short circuit or latch-up on the TFE the built-in current limiters protect the hardware.

The initial setting on power-up enables all power outputs, so in case of MCU failure or the fuse of the control circuit is blown, the power supplies remain operational. Also, the DC/DC controller kick method provides protection against software failures, but this also means that parts of the supplies can not be kept off continuously (except for the TBS linear regulators, but cycling the +5V output of the PSB can reset the outputs if the communication with the MCU is lost).

The software of the MCU continuously scans the power supply cards for status and measurement information, constructs telemetry data blocks and sends them to the MCC on demand. The STS-91 flight version of this software did not take automatic actions to recover fault situations, but the ground controller can send commands through the MCC to switch power supplies off/on.

The on-board software was written in assembly language, resulting 3.5 kB of object code, which was stored in radiation hardened PROM, but there is a possibility of uploading new software into RAM. During the extensive testing of the equipment, bootloading of the power controller never seemed necessary.

The ground controller software was written in C language. The main window displays the main status of the power system, quckly enough to check the status of the voltages and the leakage currents of the silicon ladders. The operator can issue simple on/off commands to the power supplies, or choose the ’expert mode’, where more detailed information is displayed about the internal status variables of the on-board software, it is also possible to see the history of the currents/voltages in the last few hours. The software can also be used for off-line display of pre-recorded telemetry data. Future improvement will include better data logging and presentation possibilities, and an advisor module which explains what to do for an inexperienced operator, because the fully operational AMS will have at least 3 times more power supply data to display, and more commanding possibilities.

8 Optimization and Qualification tests

A power supply system for such a large dynamic preamplifier connected to a detector giving a charge signal in the femtocoulomb range should be powered with a very low noise power supply. In order to reach the desired noise level electronic design and noise optimization on prototypes was conducted at the same time. For this reason we connected a test ladder with 12 detectors to a breadboard prototype power supply and to 2 TDRs (one reading the p-side and the other the n-side of the ladder) directly interfaced with a computer.

The direct connection of the various DC-DC converters to the linear regulators supplying the bias and the power yielded unsatisfactory noise levels, hence an intermediate filter stage was required. We tested various filtering configuration and we also optimized the different values of the components involved. The design that was adopted in all cards is a common mode plus differential mode LC filter shown in fig. 8 where the components value changes in the various cards.

The noise performance of the design optimization readout chain was compared with the

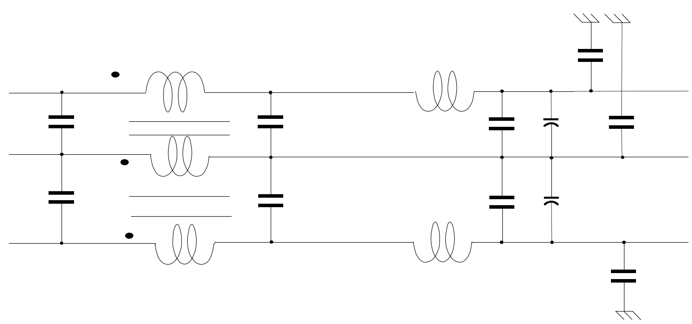

Figure 8: Most general filter configuration used at the output of each DC-DC converters, the value of each components changes in each configuration. In some configuration some components are missing

same chain powered with batteries. The results of this test are:

- Average signal-to-noise ratio of the p-side on the test ladder powered with batteries: 23.5
- Average signal-to-noise ratio of the p-side on the test ladder powered with power supply prototype: 20.8

- Average signal-to-noise ratio of the n-side on the test ladder powered with batteries: 11.5
- Average signal-to-noise ratio of the n-side on the test ladder powered with power supply prototype: 9.8

As a signal we considered the mean value of a MIP signal on silicon, as noise we considered the RMS fluctuation of the pedestal value, common-mode noise subtracted for a single channel. We considered this result satisfactory since the noise level of our power supply is less then 15% worse than an 'ideal' power supply built only with batteries.

The qualification test performed in order to test the reliability of the power supply cards operation during the shuttle flight were:

1. An initial burn-in test done at a temperature much higher than the operation temperature and close to the breakdown limit. This test has been performed in air keeping the DC-DC converter at 80 ^{0}C and the rest of the card at 70 ^{0}C for 20 hours.
2. A thermal cycle test. Performed turning on the card at 10^{-2} mbar pressure at a temperature around 0 ^{0}C and then keeping the card in vacuum at the standard operating crate temperature of 40 ^{0}C (which is the standard operating temperature on the shuttle) for about 16 hours.
3. A random vibration test with vibration spectrum displayed in fig. 9

All cards underwent the three qualification tests. Burn-in and thermovacuum tests were performed at the space qualification facility at the Department of engeneering of the Terni University (Terni, Italy), the vibration test was done at ETH Zurich (Switzerland). During the tests no failure was observed. A total of 12 TPSFE, 3 TPSR and 2 TBS50 and 2 TBS100 were built, during the integration additional noise tests contributed to the selection of the flight card set (8 TPSFE, 2 TPSR, 1 TBS50, 1 TBS100).

9 Conclusions

The power supply system built for the AMS detector worked reliably during the 10 day mission of the shuttle STS-91. No failure during the flight was observed. During the flight the boards operated at temperatures varying from 25 to 40 ^0C.

In addition, 6 months of almost continuous operation on ground for preliminary testing and post-flight calibration was also performed with no failures.

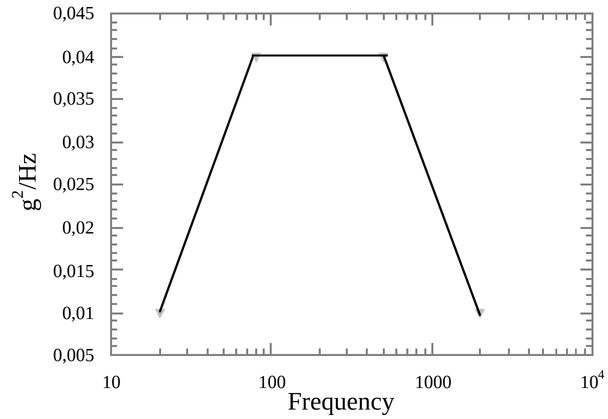

Figure 9: Random vibration test spectrum

For the future flights of the AMS experiment we will develop new, more efficient and less noisy switching power supply modules, it is also necessary to improve the efficiency on the linear regulating section by the use of lower drop regulators especially in the power supply for the readout cards (TDRs).

Since the space station mission will last for about 3 years the issue of radiation hardness will be taken into greater account in two aspects of the power supply design. The first aspect is the use of radiation hard components, wherever possible or the implementation of additional redundancies where the use of hard-rad components is not feasible. A second aspect will be the implementation of adjustable current limits controls to account for the change in power consumption of the irradiated components during the mission.

10 Acknowledgements

The authors would like to thank S. Bizzaglia and P.Levtchenko for the intallation of the power supply system in the AMS apparatus, E.M. Fiori for the help during the optimization tests. A special thanks to G.Castellini and A. Gschwindt for the useful discussions on system architecture and modularity during the early design stage of the project.

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