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The AMS-TOF and ECAL thermal tests in vacuum at SERMS

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ABSTRACT

The AMS-02 experiment is a space-born instrument designed to perform high precision measurements of cosmic rays and γ-ray fluxes on board of the International Space Station (ISS). All the components of the AMS experiment are designed to withstand the mechanical stresses in the launch phase and to operate in vacuum in a wide range of temperatures. In order to verify the performance of the hardware in harsh conditions like the flight ones, all the components of the AMS instruments undergo a severe qualification procedure before the integration into the detector. In this paper, we will report on the thermo-vacuum tests on the L-TOF (Lower Time of Flight) and ECAL (Electromagnetic CALorimeter) detectors, successfully performed in the SERMS laboratory in June and September 2006, respectively.

INTRODUCTION

The Alpha Magnetic Spectrometer (AMS-02) is a space-borne experiment that may lead to a significant step forward in the comprehension of cosmic rays and γ-ray fluxes in space. It is under construction by a world wide international collaboration and will be part of the scientific program on board the International Space Station (ISS) where it will collect data for three years. AMS-02 has been designed to investigate fundamental open questions in current astroparticle physics, including the existence of cosmological antimatter and the physical nature of the dark matter, content of our galaxy. AMS magnetic spectrometer measures the momentum, the charge, the velocity and the energy of a particle using a super-conducting magnet and complementary detectors, shown in Figure 1 and 2. The core of the AMS detector is a superconducting magnet (B=0.8 T) enclosing the silicon tracking system. Placed in pairs above and below the tracker, four planes of plastic scintillators constitute the Time Of Flight (U-TOF & L-TOF) system. A transition radiation detector (TRD), a Ring Imaging CHerenkov (RICH), a 3D Electromagnetic CALorimeter (ECAL) complete the instrument. The detectors are supported mechanically by the USS (Unique Support Structure) which also provides the connection to the Space Shuttle or the International Space Station (ISS).

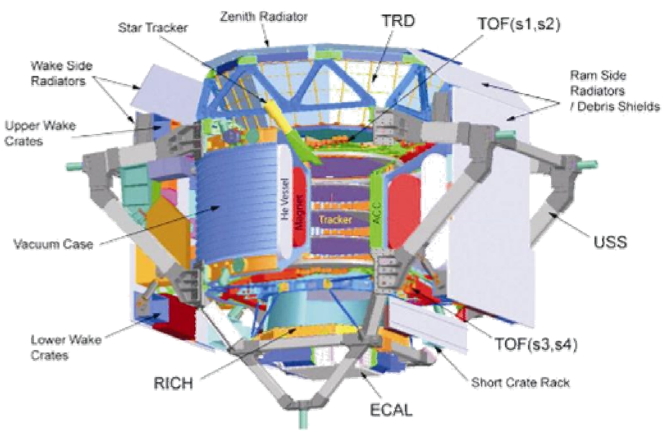

Figure 1 – The AMS Detector.

Two star trackers (AMICA Star Tracker – AST) allow it to know the AMS orientation. AMS measures the rigidity of a particle, its charge and the sign of the charge independently. The rigidity is measured mainly by the tracker. The energy deposition in the silicon tracker, the TOF, the ECAL and the TRD also provide independent measurements of the charge of the particle, as well as the measurement in the RICH. The sign of the charge is determined from the bending due to the magnetic field generated by the tracking system. The velocity is measured by the TOF, the TRD and the RICH subdetectors. The multiple measurement of the same physical quantity using different techniques allows for cross-checks. All the detectors must fulfill the requirements imposed by their operation in space over several years. So they must undergo a qualification procedure before the final integration into the detector. Aim of the qualification campaign is to certify that the hardware (and software, as applicable) design is suitable and conformed to the specification requirements. The qualification program includes functional and environmental tests (vibration test, shock test, electro magnetic compatibility, thermal vacuum test). The thermal verification of a detector constitutes an important step in the qualification process.

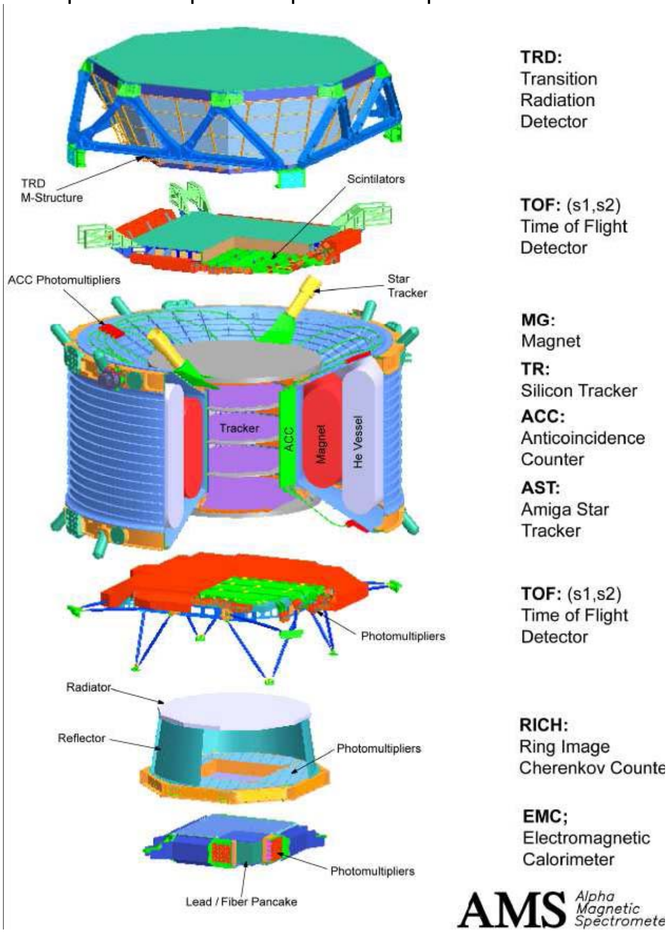

Figure 2 – An exploded view of AMS-02 detector.

In the following sections, after a brief overview of the thermal design, the thermal testing on the ECAL and L-TOF detectors are presented, which took place in the SERMS laboratory in June and September 2006, respectively, are presented. Both detectors have undergone up to 4 thermal cycles, according to their operative and non-operative temperature ranges, in vacuum (p ~ 10^{-5} mbar) for approximately 10 days each. Environmental parameters in the chamber, as well as the temperature of the devices, have been continuously monitored in ~ 70 points along the whole test and used to validate the thermal models of the detectors.

THERMAL DESIGN OF A SPACE DETECTOR

The ECAL and TOF thermal design has followed the typical development procedure: the requirements on the sensitive items composing the detectors, have been identified. In parallel, the environment, to which the detector will be exposed in orbit, has been characterized in terms of orbital fluxes on the external surfaces (direct sunlight, albedo and infrared). A thermal control system (TCS) has been designed to maintain the detectors within allowable temperature limits in the environments encountered on-orbit. The thermal control hardware specifications have been collected for driving the detailed TCS design. The performance of the design has been checked through a modeling and analysis activity. Finally, the TCS elements have been designed and manufactured. The successive phase, subject of this paper, has been the testing campaign on the thermal control system, both to correlate thermal mathematical model with the test results, and to demonstrate that the design is suitable and conformed to the requirements.

CORRELATION CRITERIA

In order to achieve a successful correlation between the thermal model and the test results, three criteria must be fulfilled.

<u>Average temperature criterion</u>

The sum of all temperature differences divided by the number of analysed points shall be less than 2 K in modulus.

$$\Delta T = \left| \frac{1}{N} \sum_{i=1}^{N} \left(T_{Mi} - T_{Pi} \right) \right| \leq 2K$$

Where
ΔT = global temperature deviation
N = number of temperature points considered for correlation
T_{Mi} = measured temperature
T_{Pi} = calculated temperature with simulation program

<u>Standard deviation criterion</u>

The standard deviation of all temperature differences (measured value minus analytical value) shall be less than 3 K.

$$\sigma = \frac{1}{N-1} \sqrt{\sum_{i=1}^{N} \left[\left(T_{Mi} - T_{Pi} \right) - \Delta T \right]^2} \leq 3\text{K}$$

Where σ is the standard deviation.

<u>Individual unit success criteria</u>

The differences (measured value minus analytical value) for single point measurements shall be less than 8K before thermal balance test.

ECAL THERMAL DESIGN AND QUALIFICATION

The electromagnetic calorimeter (ECAL) of the AMS-02 experiment is a fine grained lead-scintillating fiber sampling calorimeter, that allow precise, 3-dimensional imaging of the longitudinal and lateral shower development, providing the particle tracking.

ECAL DESIGN OVERVIEW

In ECAL active volume, a particle passing through scintillating fibers, produces light which is collected by photomultipliers installed all around. The active volume is contained in a mechanical support frame which holds the light collection system in position and connects the detector to the lower part of the USS. Two main constraints in the design were the limits on weight (about 640 Kg) and on power consumption (about 70 W). These figures, associated with the detector size (~0.3 m^3) turn out to be non-typical for a space system, providing an average density of more than 2000 Kg/m^3. and thus a quite large time constant. The sampling device has been built employing lead-scintillating fibers composite material. The active volume results as a pile up of 9 “superlayers” each 1.85 cm thick. The ECAL mechanical assembly supports the active volume, the light collection system and the related electronics.

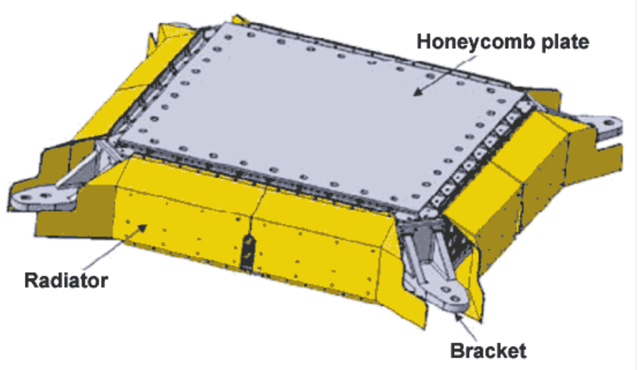

Figure 3 – The AMS-02 electromagnetic calorimeter.

ECAL has been designed in order to minimize the weight with a first resonance frequency above 50 Hz, to withstand accelerations up to 14g in any direction, and to have thermal characteristics limiting the temperature gradient in the detector. The optimization of the mechanical design has been carried out using finite element analysis techniques. The final project has led to an aluminum alloy support frame, composed of a top and a bottom honeycomb plates, four lateral panels lodging the light collection system, and four brackets for connections to the main AMS-02 supporting structure (USS). Thermal requirements have been chosen to guarantee a good PMT (Photo Multiplier Tube) gain stability. The operating temperature shall be in the range -20°C to +40°C and the temperature shall change less than 5°C over one orbit while the non-operating temperature range shall be between -30°C and +50°C. Simulations have shown that these temperature extremes are exceeded during some phases of the on-orbit life; in particular, the minimum temperature would be lower than -30°C during the switch on phase in a coldest orbit: this puts a constraint to the environmental conditions when the switch-on can be done. The superposition of the hot orbital environment with maximum dissipation would bring the PMT above their design limit for less than 5% of the mission time, thus requiring to switch off the detector for the corresponding timeframe.

THERMAL CONTROL CONCEPT

The ECAL thermal control concept is based on heat rejection to deep space by means of silvered-teflon coated aluminum alloy radiators , while limiting the heat rejected to the other AMS-02 subdetectors using MLI blankets. There are four radiators, each one 0.257 m^2, placed around the lateral panels of the detector where the PMTs are hosted. Their position is shown in Figure 3. The radiator aluminum panel thickness is 2 mm. MLI blankets are used both to insulate the ECAL from the nearby subdetectors, thus preventing mutual thermal interactions with them, and to minimize the amount of absorbed solar flux. MLI is positioned on the nadir and zenith ECAL covers, and over the mounting brackets, in between the winglets of two adjacent sides (see Figure 4).

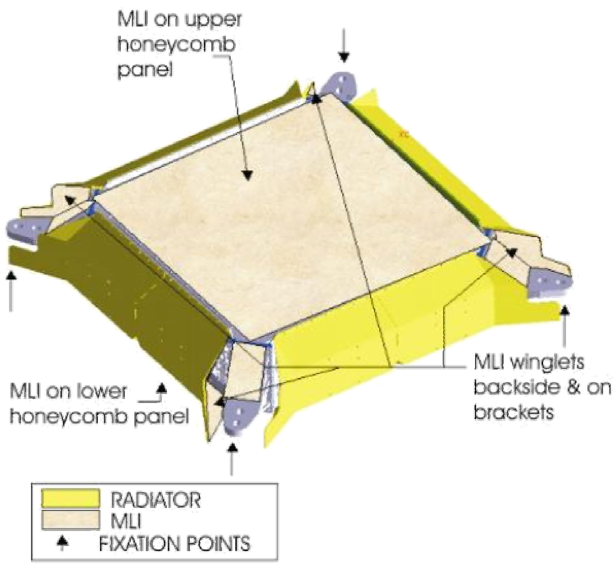

Figure 4 - Thermal control concept, Radiator and MLI locations and fixation brackets.

The ECAL is fixed on the Unique Support Structure (USS) by means of four aluminum brackets visible in Figure 4, located at the four corner of the ECAL squared shape. In order to insulate the ECAL from its mechanical support (which are not thermally controlled, and hence reach extreme temperatures during the orbit), 4 teflon pads are placed on the ECAL brackets. In addition, this provides a better mechanical performance, giving the necessary compliant mount, permitting the feet to slide when subjected to excessive thermally-induced strain.

Heaters

70W of heater power is needed for the ECAL to allow proper operations during all the mission phases. The heaters are located on the ECAL radiators backside; 4

heater dual-element patches, made of a Kapton film, are located on each radiator, for a total of 16 items. In Figure 5 the location of heaters on a radiator is shown. A main and a redundant feed at 120 VDC are present, each one controlled by a thermostat.

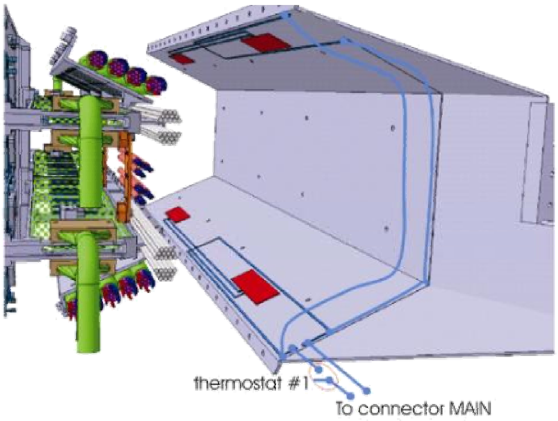

Figure 5 - Heaters patches on the radiator; only the MAIN part of the circuit is shown. The redundant circuit is symmetrical top-down, and controlled by the second thermostat.

In Figure 6 the thermostat location on the back panel is shown, nearby the mounting brackets. This is the location closer to the coldest PMT.

THERMAL LOADS

The thermal loads that have applied to the ECAL detector, can be divided into Internal and External loads.

Internal loads

Totally 49.6 W are dissipated on 324 PMTs (0.153 W each) when they are fed at maximum power. Additional 17.76 W are dissipated on the 36 EIBs.

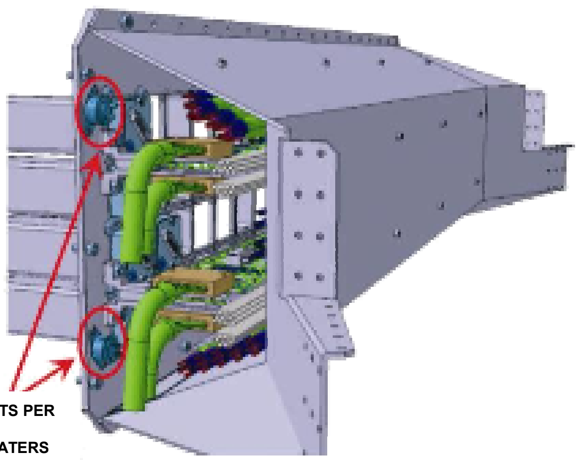

Figure 6 - Location of the thermostat (main and redundant) on the back panel.

In the hot cases the total ECAL dissipation is 72 W. In the cold cases analyses, the dissipation on each PMT is 0.107 W, the other dissipation remaining the same, so a total power of 52 W is to be considered.

External Loads

ECAL is located at the bottom of the AMS-02 experiment, which experiences typical external ISS payloads environmental conditions and fluxes in Low Earth Orbit (LEO). In order to consider the radiative loads impinging over ECAL surfaces due to the presence of the Sun and the Earth, the data in Table 1 have been input in the GMM.

Parameter	Hot cases	Cold Cases
Solar constant	1424.3 W/m^2	1322 W/m^2
Albedo	0.4	0.2
Earth flux	266.5 W/m^2	245.5 W/m^2
ISS orbit height	150 nmi	270 nmi
Thermo-optical database	EOL	BOL

Table 1 - Parameters influencing external loads.

ECAL location makes it subjected not only to these direct impinging fluxes, but also to reflections of the aforementioned contributions by other ISS elements.

GMM - GEOMETRIC MATHEMATICAL MODEL

The geometrical mathematical model has been used in the ECAL detailed model to find the internal radiative couplings. Part of the geometric model is presented in Figure 7: the brackets are shown in yellow, the MLI covers are violet, and the radiators light blue. A radiator has been removed to show the END CAPS arrays behind them (in green, with arrows indicating the active radiating surface). The optical properties used in the radiative model are listed in Table 2; only the ε is given, since it is the only relevant property in absence of direct solar radiation.

Location	**Material**	ε
Radiator back side Brackets End Caps	Clear Anodized	0.84
MLI inner face	Aluminized Polyimide	0.05

Table 2 - Optical properties used for the various items in the ECAL detailed geometrical model

TMM- THERMAL MATHEMATICAL MODEL

A Thermal Mathematical Model, using the SINDA code, has been generated, consisting of 1962 nodes for the representation of the items.

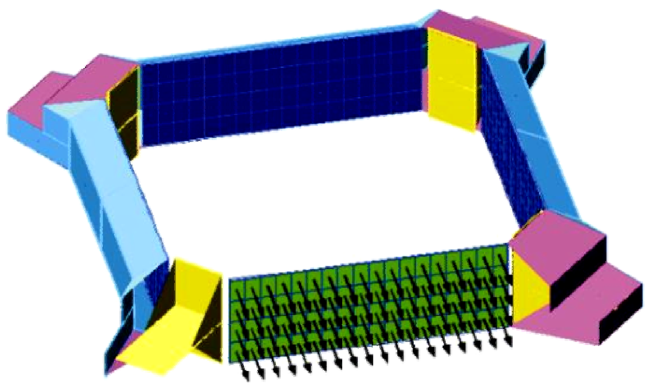

Figure 7 - Ecal detailed geometrical mathematical model: the submodels represented are the MLI (violet), the radiators (light blue), the fixation brackets (yellow) and the End Caps (in green). A radiator has been removed. The pancake is missing, since it does not participate to the radiative heat exchange.

ECAL THERMO-VACUUM TEST

The ECAL has been subjected to a Thermal-Vacuum Cycling, to investigate the thermal behavior of the detector. The test article has be composed of the FM (Flight Model) radiators (equipped with FM thermal hardware, i.e. heaters, tape and thermal filler), and the QM (Qualification Model) detector. The main objectives of the test have been:

- to test the internal thermal design of ECAL: conductive and radiative links within the QM and from the QM to the radiators
- to test radiators sizing
- to define the minimum environmental temperature that the non-operative ECAL can withstand
- to validate the thermal mathematical models (TMM and GMM).

Four thermo-vacuum cycles have been performed.

<u>Test configuration</u>

ECAL QM detector has been placed inside the Thermal Vacuum Chamber (TVC) by means of a crane and a dedicated support structure fixed to the chamber rails (Figure 8).

Interfaces

A dedicated support structure has been used for the 4 attachment points at the corner brackets. The structure has been designed in order to minimize the heat exchange by conduction between ECAL brackets and the chamber structure (less than 10% of the heat had to be transferred conductively through the corner brackets). Four Teflon insulating support have been used to insulate the mounting brackets from the aluminium test adapter and the chamber rails (see Figure 9 for details). Radiation-wise, the ECAL QM has been equipped with MLI blankets, covering both top and bottom honeycomb panels (see Figure 8 and Figure 10). The four radiators, one for each side of the ECAL, have been in view with the chamber shroud, which is painted black, and whose temperature has been controlled. The radiative interface through radiators has been the main path for heat exchange between the detector and the thermo-vacuum chamber.

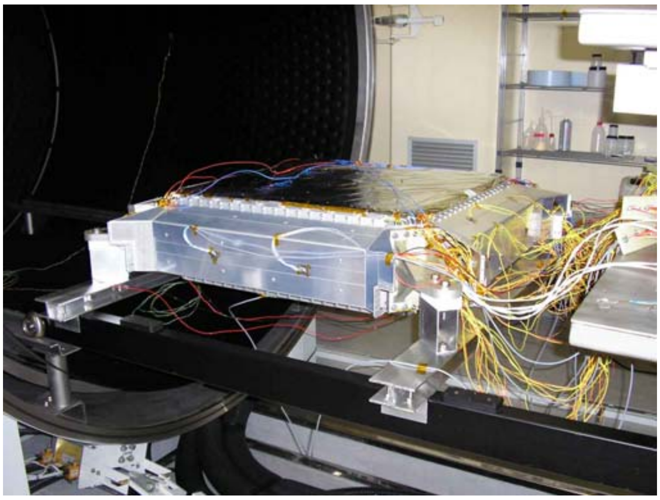

Figure 8 – Positioning of the ECAL detector inside the TVC.

<u>Temperature sensors</u>

Detector monitoring

A total of 64 Thermal Sensors have been installed on the ECAL unit. All the sensors have been placed using both a Kapton and Aluminium tape as shown in Figure 11.

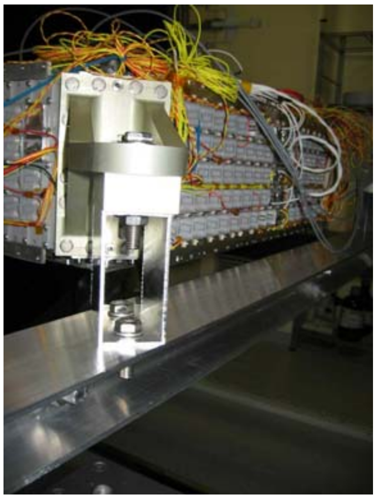

Figure 9 – Detail of support structure with the Teflon insulating support used.

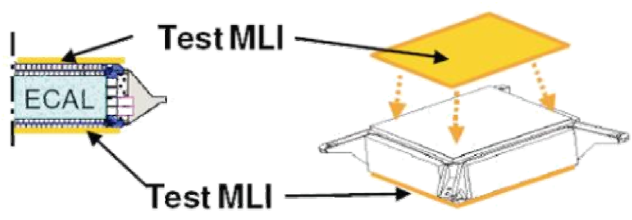

Figure 10 - ECAL MLI coverage for thermal vacuum test.

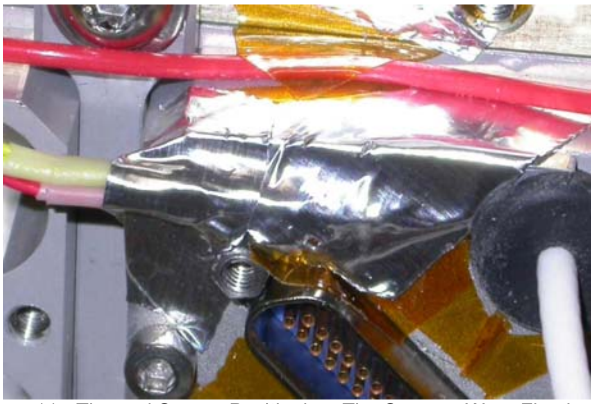

Figure 11 - Thermal Sensor Positioning: The Sensors Were Fixed Using A Kapton Tape And Then Covered With A Layer Of Aluminum Tape.

Main Temperature Sensors (TS) have been:

- 2 TS located internally at the PMT
- 4 TS located on PMT End Cap (Ram radiator). These have been the temperature reference points.

In Figure 12, the picture of one of the temperature sensor, used as reference, after positioning is shown. Externally, PT100 sensors have been placed on radiator panel, behind the radiator mounting flange, on honeycomb panels and on mounting bracket.

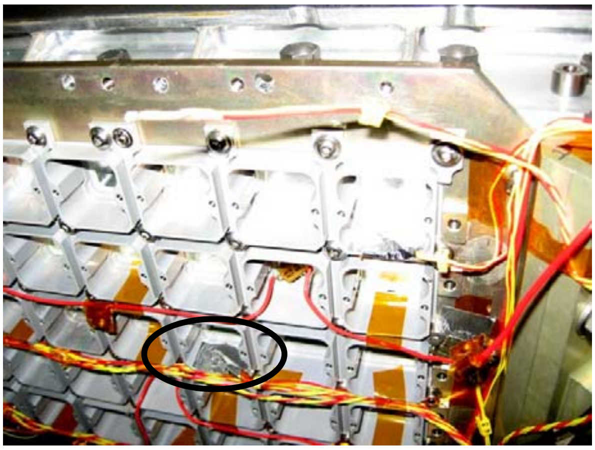

Figure 12 – One of the Temperature Reference Points.

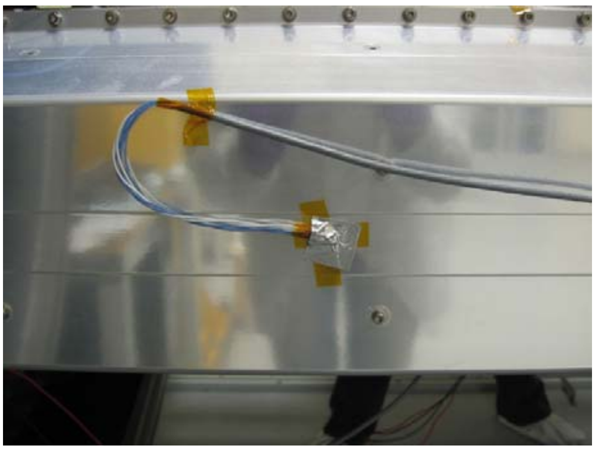

Figure 13 – Sensor placed externally on one of the four radiator.

Monitoring of the chamber

A total of 9 Temperature Sensors (TS) have been used to monitor the environmental conditions of the test:

- 6 TS (naming scheme A-B-C-D-E-F) have been placed in different shroud locations
- 1 TS has been placed on the fixture
- 1 TS has been placed on the test MLI blanket covering top honeycomb panel
- 1 TS has been placed on one radiator opposed to heaters location.

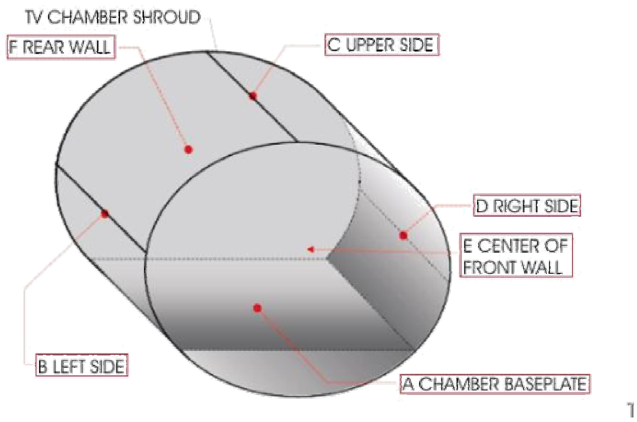

Figure 14 - Chamber Sensors Positioning (On Shroud).

Test profile

The test consisted of 4 cycles in vacuum; the last cycle has been extended in duration, in order to attain a stabilization for thermal balance purposes. Data for correlation are relative to the last hour of the thermal balance hot and cold plateaus. The cycles sequence is schematically presented in Figure 15.

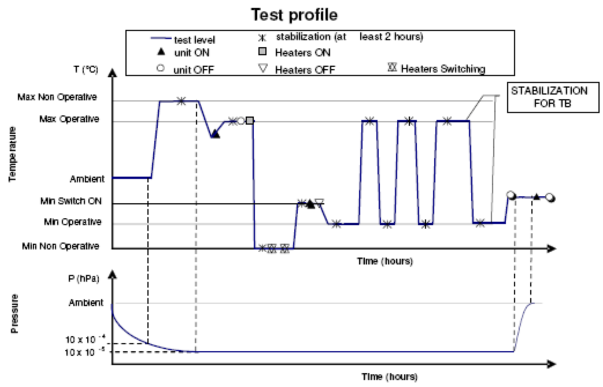

Figure 15 - Test Temperature And Pressure Profile.

The maximum and minimum qualification temperatures are summarized in Table 3 and they have been measured on the TRPs.

AMS02-ECAL	PMT temperature requirements
Maximum Protoflight Qualification Operating	+40°C
Minimum Protoflight Qualification Operating	-20°C
Maximum Protoflight Qualification Non Operating	+50°C
Minimum Protoflight Qualification Non Operating	-30°C
Minimum Switch ON Temperature: not specified, taken equal to Minimum Protoflight Qualification Operating	-20°C

Table 3 – Temperature for ECAL TRPs.

The thermal balance phase has been the part of test where ECAL reaches the equilibrium temperatures. It has been characterized (in the HOT case) by following requisites:

1. the temperature of the hottest TRP had to reach 40 °C and it had to stay in a range between of 40 °C and 43 °C during all the stabilization duration
2. every sensor had to show a gradient of temperature less than of 0.5 °C/h during thermal balance phase
3. every sensor had to stay in a windows 1 °C wide
4. The above mentioned conditions had to be maintained for at least 5 hours.

The criteria have been similar for the COLD balance case, with the target temperature of the TRP in the range -20°C÷-23°C.

Test graph

In this section, the graphs summarizing the evolution vs. time of all measured quantities during the whole test period, are reported.

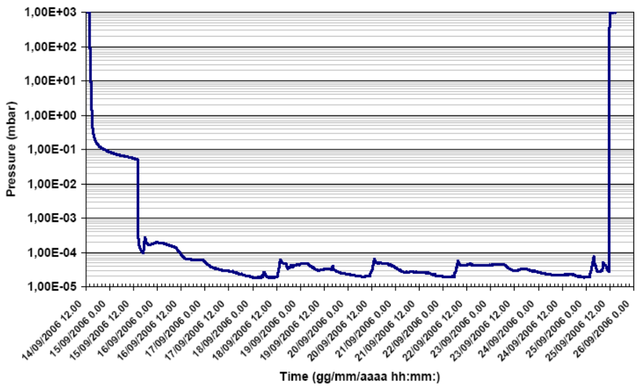

Figure 16 – Pressure profile.

Thermo-vacuum test on ECAL detector has been successfully performed at SERMS laboratory, using a space simulator. The test lasted 13 days: from September 12th to September 25th 2006. Two days have been needed to reach the required vacuum conditions. All the test objectives have been fulfilled. In particular, concerning the temperature range and requirements, the test has demonstrated that:

- The minimum operative temperature conditions have been met whenever the ECAL has been powered in a radiative environment at -60°C in average
- The minimum non operative temperature conditions have been met whenever the system has been switched off in a radiative environment at -60°C in average
- The maximum operative temperature conditions have been met in a radiative environment slightly lower than 40°C.

After the test, it has been calculated the total time the detector might need to be switched off is 2.8% of the total time, compared to the 5% requested.

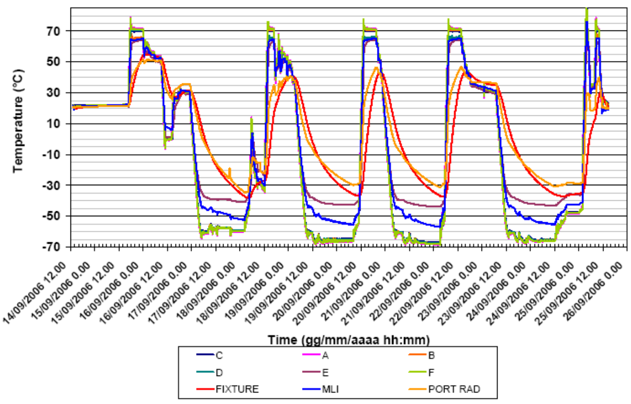

Figure 17 – Chamber sensors temperature profile.

TEST CORRELATION MODEL DESCRIPTION

Prior to any model correlation activity, the ECAL model had to be aligned to the test configuration (MLI covering, test support structure with Teflon, etc.). In this first phase, the test conditions were simplified with an equivalent, isothermal sphere at the average temperature attained during the test.

CORRELATION

The thermal model has been analyzed imposing at the boundary nodes the measured test conditions. Results have been satisfactory in the hot case, but not in line with the correlation criteria in the cold phase.

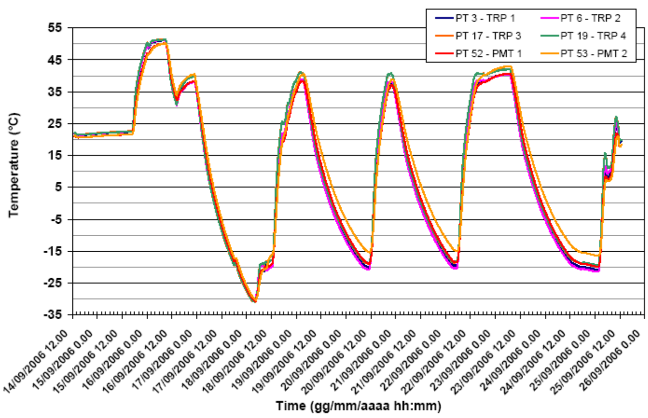

Figure 18 – Temperature reference points profile.

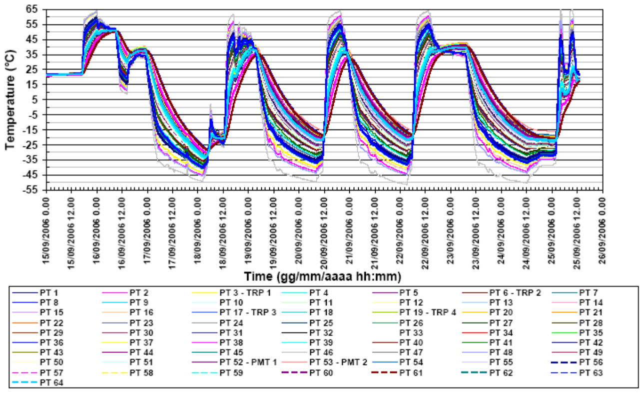

Figure 19 - Temperature Profile For all the Ecal Temperature Sensors.

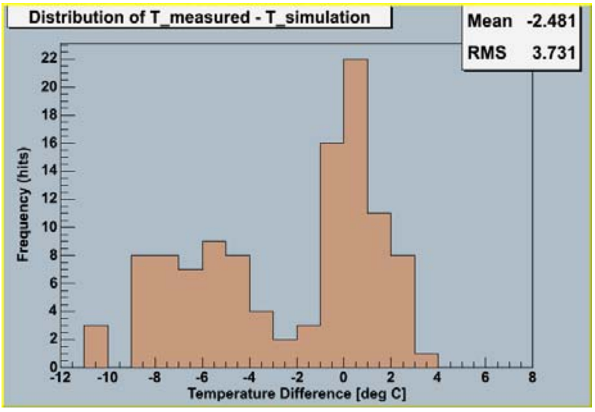

Figure 20 - Hot & Cold cases, temperature differences distribution between mathematical model and test (DT=Model-Test).

The non-correlated model shows the following deviation form the test data:

Average = - 2.48 °C   Sigma = 3.73 °C

A refining activity has to be performed in order to:

1. improve the agreement of model predictions to test data. This means a better modeling of the chamber environment, which had been initially modeled as an isothermal sphere; more radiative surfaces were included in the model, to take into account some parts which had not been perfectly covered by MLI due to integration constraints (see Figure 21). Three main areas have been selected to represent the chamber temperature distribution. These temperatures have been used for the mathematical model correlation, applying them to three boundary nodes, representative of chamber environment. These nodes represent:
   1. the shroud
   2. the front wall of the Thermo-Vacuum Chamber
   3. the structure where the ECAL has been mechanically mounted, mimicking the USS in the Flight configuration.
2. An overall model debugging activity and the tuning of the most uncertain parameters; some inconsistencies have been found in the model (e.g. material properties of aluminium 7075 has been used instead of the 5051 ones). The uncertain parameters have dealt mainly with the contact conductance.

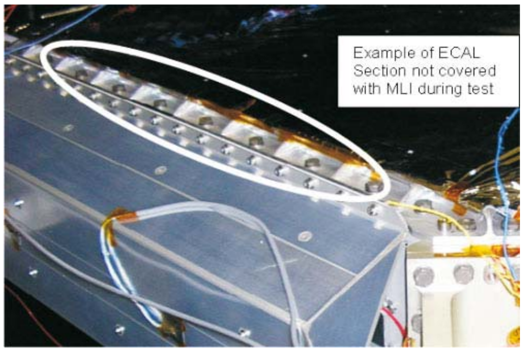

Figure 21 - Highlighted in red, an example of an ECAL section not covered with MLI during test.

CORRELATION AFTER REFINEMENT

After the refining activities, the model has been run and the temperature results have been compared to the test data, with the following results:

Average(HOT) = 0.328 °C   Sigma (HOT)= 1.081°C

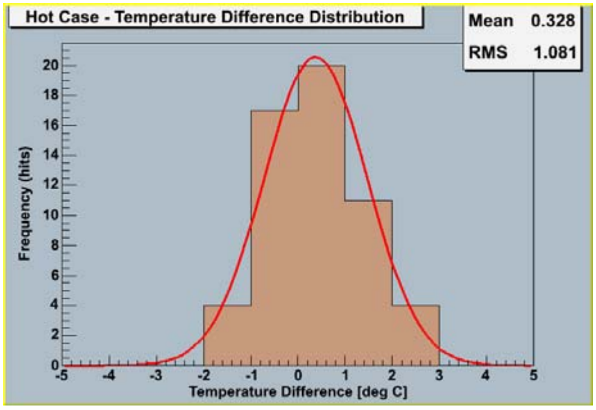

Figure 22 - Test model correlation final results for hot case.

First the correlation has been done for the hot case with very good results, then the same model has been used for the correlation in the cold case.

Average (COLD) = -1.681 °C   Sigma (COLD)= 2.248°C

The results obtained have been considered satisfactory: no further modification and refining activities on the model have been needed.

FLIGHT PREDICTION

After the model has been correlated, the new flight predictions have been generated. The first step has been putting the correlated model back to flight configuration;

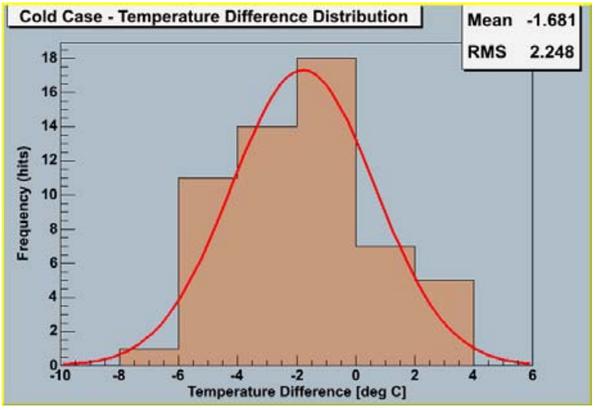

Figure 23 - Test model correlation final results for cold case.

The temperature of the ECAL PMT (where the requirements have been set) changes is shown in Table 4. As one can see, all the temperature differences are always below 3.1 °C. Therefore, the previous analysis presented has been confirmed by the new model. Previous results can be considered a conservative estimation of the on-orbit behavior, both in hot and in cold conditions.

HOT CASE	Data from correlation activity (°C)	Correlated model flight prediction (°C)	Delta T
ECAL RAM PMT, average	50.2	49.5	-0.7
ECAL WAKE PMT, average	55.7	53.4	-2.3
ECAL PORT PMT, average	49.9	48.7	-1.2
ECAL STARBOARD PMT, average	59.0	56.5	-2.5
ALL PMT AVERAGE temp.	**53.7**	**52.0**	**-1.7**
ECAL PEAK temperature (MAX)	**59.7**	**57.5**	**-2.2**
COLD CASE			
ECAL RAM PMT, average	-11.6	-10.0	1.6
ECAL WAKE PMT, average	-13.0	-9.9	3.1
ECAL PORT PMT, average	-11.3	-9.2	2.1
ECAL STARBOARD PMT, average	-13.3	-11.2	2.1
ALL PMT AVERAGE temp	**-12.3**	**-10.1**	**2.2**
ECAL PEAK temperature (MIN)	**-14.3**	**-11.9**	**2.4**

Table 4 - Temperature results for the worst hot and cold cases for the ECAL, before and after the model correlation.

LOWER-TOF THERMAL DESIGN AND QUALIFICATION

The Time Of Flight serves as a fast trigger to the AMS-02 experiment for charged particle, to measure the particles traversing the detector to a resolution sufficient to distinguish between upward and downward traveling particles and to measure the absolute charge of the particle.

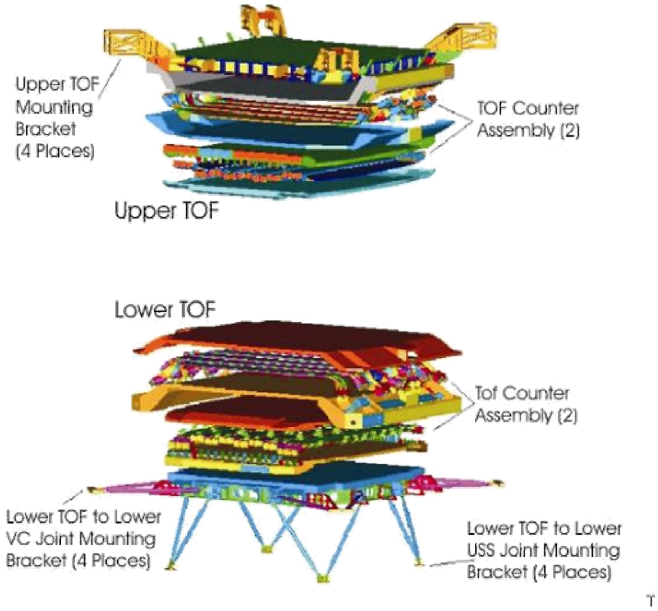

Figure 24 – The AMS-02 Time Of Flight system.

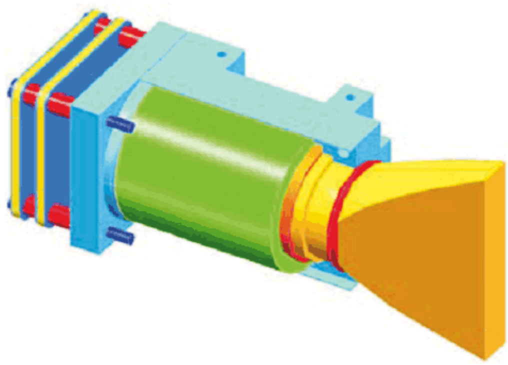

Figure 25 – TOF PMTs construction.

TOF DESIGN OVERVIEW

The TOF system is composed of four roughly circular planes of plastic scintillators paddles with a sensitive area of 1,2 m^2 each. One pair of planes is placed above the AMS tracker and one pair below (as shown in Figure 2). Between two adjacent planes of one detector, the paddles are perpendicular giving a granularity of about 12 x 12 cm^2 for trigger purposes, with an efficiency of about 100%. Each individual detector paddle is made of polyvinyl toluene (a Plexiglas-like material), it is 12 cm wide and 10 mm thick. Each detector paddle is wrapped in aluminized Mylar and enclosed in a cover made of carbon fiber. At the ends of each panel there are light guides which direct the light of scintillation to photo multipliers. The TOF is instrumented with 144 Hamamatsu R5946 photomultipliers, used to detect the scintillating light. The Hamamatsu R5946 PMT is within a PMT housing, as shown in Figure 25. The PMTs are mounted on the TOF structure at orientations that minimize the impact of the magnetic fields on the PMT operations. Light guides have complex curves to orient the light from the paddles into the carefully oriented PMTs (see Figure 28). Two large flat aluminum honeycomb panels are used to support the scintillators counters. The lower TOF honeycomb is supported by the lower USS-02. The honeycomb panels are roughly circular with a 1540 mm equivalent outside diameter. The thickness of the honeycomb aluminum core is 50 mm and the aluminum skin is 1 mm thick. The total weight of the TOF system is less than 130 Kg and the power consumption less than 4 W. The operating temperature shall be in the range -32°C to +43°C while the non-operating temperature range shall be between -35°C and +50°C. Subject of the next subsections will be the L-TOF detector thermal control system.

THERMAL CONTROL CONCEPT

Similar to ECAL, the L-TOF thermal control concept is based upon passive rejection of heat. The L-TOF PMTs and paddles are enclosed within a carbon fiber box. The heat is generated inside the PMTs electronics (see Figure 29). The dissipated heat is conducted and radiated to the carbon fiber box and in turns radiated to the external environment. 120 VDC heaters and thermostats are needed for the L-TOF to allow proper operations during all the mission phases.
The heaters are needed to:

- keep electronics above the minimum non-operative temperature when L-TOF is switched off
- bring electronics to the minimum switch-on temperature during cold cases.

Dual elements Kapton foil heaters are located on the TOF carbon fiber box (as shown in Figure 30) while the thermostats are located near the PMTs (see Figure 31).

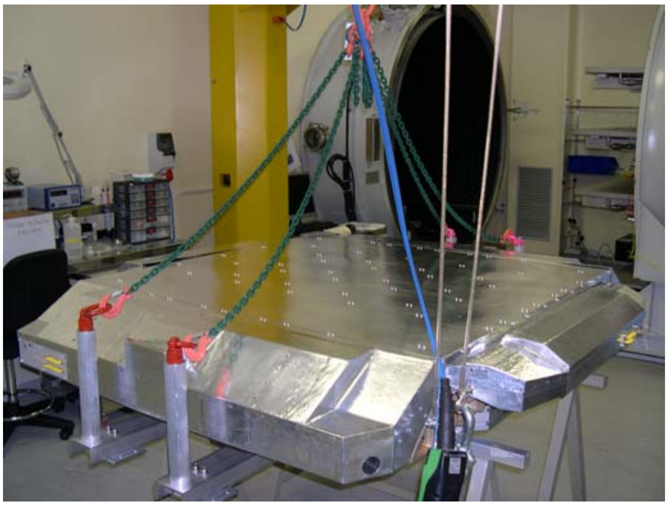

Figure 26 – Lower TOF for AMS-02.

Figure 27 – PMTs inside the TOF.

Figure 28 – Detail of PMTs inside the Lower TOF detector. The upper part of the photo shows the light guide.

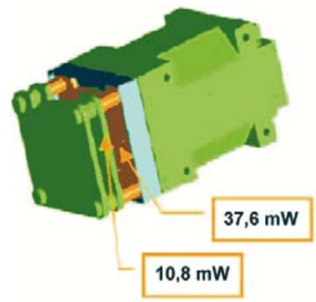

Figure 29 – Detail of the power dissipated by one PMT of the Lower TOF.

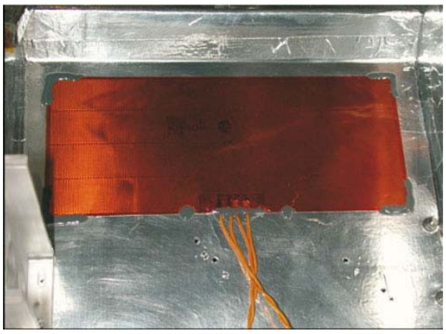

Figure 30 – Kapton foil heater used for Lower TOF detector TCS.

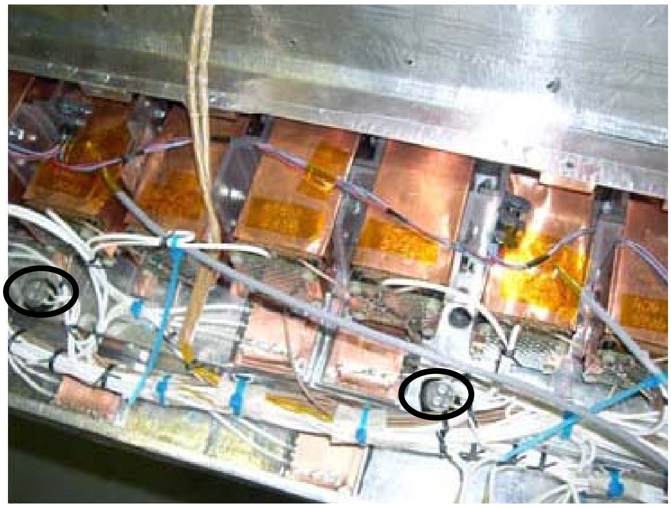

Figure 31 – Highlighted, thermostats placed near the PMTs.

L-TOF THERMO-VACUUM TEST

To investigate the thermal behavior of the L-TOF, the detector has been subjected to a Thermal-Vacuum Cycling. The test article has been a flight unit. The main objectives of the test have been:

- To test the internal thermal design of the TOF (conductive and radiative links within the flight unit) in hot and cold conditions
- To verify the heater power budget and the thermostats performances
- To verify the performance of the detector at the extreme temperatures it can experience.

Four thermo-vacuum cycles have been performed.

Test configuration

L-TOF FM detector has been moved into the Thermal Vacuum Chamber (TVC) using a dedicated support structure fixed to the chamber rails (see Figure 32 and Figure 33). The L-TOF has been thermally coupled to the shroud of the TVC only by radiation, as this will be the typical heat transfer during flight conditions.

Figure 32 – TOF detector in the thermo-vacuum chamber.

Interfaces

L-TOF detector has been tested without the FM MLI. The MLI blankets will be shared with other subdetectors and cannot be physically installed on the standalone L-TOF. It has been supported, inside the TVC, by means of 4 insulating feet, put on the chamber rails. Figure 35 shows the support structure that has been made of an aluminium frame and Teflon insulating supports, sized in order to minimize the conductive heat exchange between the detector and the TVC rails. The chamber temperature has been set in order to simulate the temperature inside the flight MLI enclosure, and to check the temperatures onto the TRPs, which are the PhotoMultipliers Tubes (PMTs).

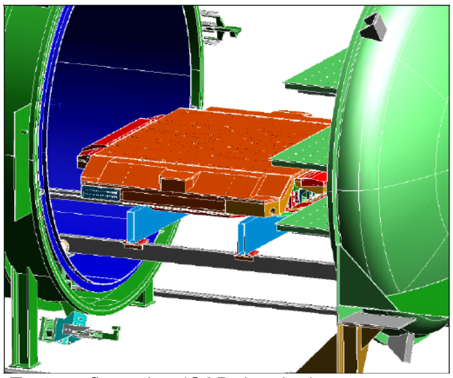

Figure 33 – Test configuration (CAD drawing).

Figure 34 – Test configuration.

Figure 35 – Photo of TOF positioning inside the TV chamber.

Temperature sensors

Three different kind of thermal sensors have been used during the test:

- 16 Flight Dallas Sensors located internally on PMT Copper Shield
- 14 Test Sensors (PT100) located internally in the same position of the Flight Dallas sensors, in order to verify the correct calibration of the flight sensors. The sensors on the PMT Copper Shield have represented also the TRPs of the test
- 44 Test Sensors (PT100) located externally

Similar to ECAL, to monitor the environmental conditions of the test, a total amount of 13 Temperature Sensors (TS) have been placed inside the TVC (as shown in Figure 14):

- 8 TS (naming scheme A-B-C-D-E-F-G-H) have been placed in different shroud locations and on rails
- 5 TS have been placed in different locations of the Cold Plates (CP).

All sensors have been placed using a Kapton tape.

Figure 36 – One TRP placed on the copper shield of the PMT body.

Test profile

The maximum and minimum TRP temperatures are summarized in the following table:

AMS02 L-TOF Detector	**TRP temperature During Tests**
MAXIMUM OPERATING	+43°C
MINIMUM OPERATING	-32°C
MAXIMUM NON OPERATING	+50°C
MINIMUM NON OPERATING	-35°C

Table 5 – Temperature value for the TRPs.

The minimum and maximum temperature values have been chosen considering the aging effect on the PMTs.

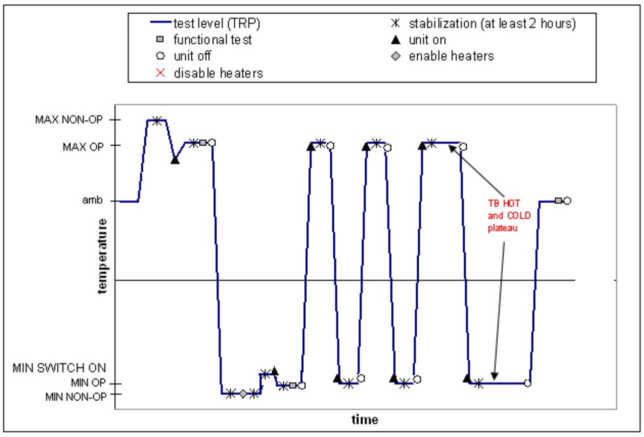

Figure 37 - Thermal Vacuum Cycling and Thermal Balance Test profile.

The first part of the test has been used for:

- heaters and thermostats verification
- verification of the minimum environmental temperature that non-operative L-TOF with heaters can be experience
- verification of the minimum environmental temperature that allows the L-TOF switch-ON.

The test had also a thermal balance (TB) phase, that has been used for thermal model correlation. The stabilization criteria have been the same used for the ECAL.

Test graph

In this section, the graphs summarizing the evolution vs. time of all measured quantities during the whole test period, are reported. Thermo-vacuum test on L-TOF detector has been successfully performed at SERMS laboratory, using a space simulator. The test lasted from May 26th to June 9th 2006 (14 days). All the test objectives have been fulfilled:

- heaters and thermostats nominal operations (in terms of dissipation and duty cycle) have been checked
- minimum switch-on temperature has been reached using the heaters in a cold environment of -35°C
- internal thermal design has been verified, showing the internal heat dissipating sources are well sunk to the TOF body, hence showing small delta-T
- acquisition of temperatures of TOF in hot/cold stabilized condition (TB test) for sufficient number of relevant points for thermal mathematical model correlation purposes
- the thermal balance stabilization criteria has been met.

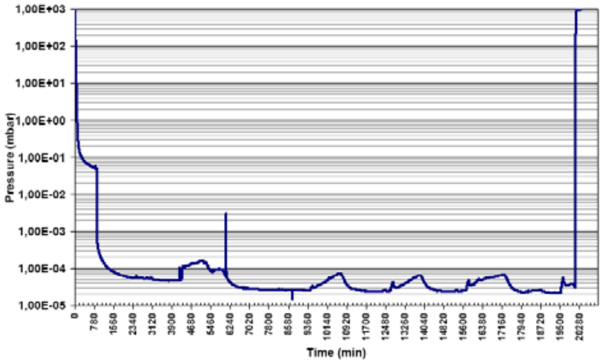

Figure 38 - Pressure profile.

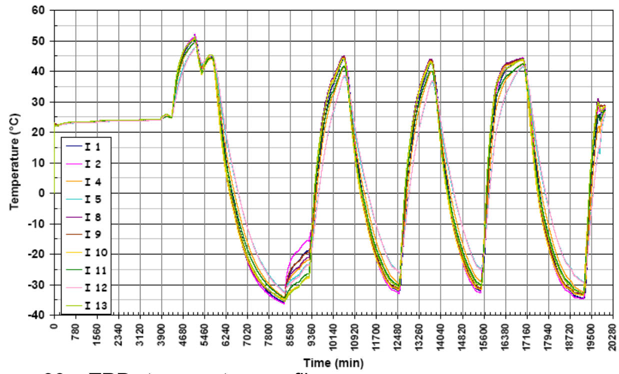

Figure 39 – TRPs temperature profile.

CORRELATION

To correlate the model to the test results, the following parameters have been tuned:

- conductance value of PMTs to their bracket from 0.006 W/K to 0.09 W/K (conduction through carbon fiber structure and glue);
- conductance of PMT bracket to the carbon fiber box of the TOF from 0.025 W/K to 0.05 W/K (glued interface);
- electronics boards thermal conductance to their sink from 1 W/K to 0.035 W/K (PCB with aspect ratio 1/7 in series with bolted interface on the long edges).

After the tuning activity, the criteria of correlation have been satisfied. The model correlation has focused on the temperatures of the TRPs (Table 6).

	HOT phase		***COLD phase***	
	NOT CORR. MODEL	**CORR. MODEL**	**NOT CORR. MODEL**	**CORR. MODEL**
ΔT AVERAGE [°C]	**-2.30**	**-1.31**	**-1.87**	**0.76**
STANDARD DEV. [°C]	**3.92**	**1.48**	**5.56**	**2.42**

Criteria: $\Delta T_{AV} < 2°C$ / STD_DEV < 3°C

Table 6 - Correlation criteria for TOF detector. Both of them are satisfied.

CONCLUSION AND LESSON LEARNT

The thermal control system of two main AMS-02 detectors (ECAL and L-TOF) has been presented, paying attention to the thermo-vacuum tests that have been the final step of the qualification campaign. The tests have been done in the SERMS laboratory using the space simulator. Test results have been presented. The results show that both the ECAL and L-TOF TCS are properly designed and the performance of the detectors fulfill all the applicable requirements. Moreover, using the test data, the correlation of the thermal model has been done. Both ECAL and L-TOF thermal model have been refined and have been used to make more accurate flight predictions. The two tested detectors represent extremes payloads from the density point of view: the ECAL detector has an average density of 2000 Kg/m^3 while the density of L-TOF is about 170 Kg/m^3, thus putting different issues in terms of handling, test set up (number of monitoring points) and test duration.

The two detectors described in this paper have different specific heat coefficients: about 130 KJ/Kg·K for ECAL and about 1000 KJ/Kg·K for L-TOF, resulting in the same order of magnitude heat capacitance: 85 kJ/K for the ECAL vs. 130 kJ/K for the TOF. The time needed to complete a cycle is in good agreement with these thermal mass figures: 42 hours for ECAL and 50 hours for L-TOF. For future tests on test articles in-between the two extremes presented in this paper, the actual specific heat will be used for an accurate interpolation of the test duration, while density will be the index for assessing test set-up duration and operations planning.

During the ECAL and L-TOF tests, several lessons have been learnt. Among them, we report the importance of tracking with particular care the view factors between the unit and the chamber; as shown in Figure 21, even small parts left uncovered with MLI lead to noticeable temperature differences.

Another important lesson learnt deal with the behaviour of L-TOF detector during the depressurization phase, before the thermal cycling and thermal balance. The first outgassing took 48 hours to reach a stable condition before the high vacuum phase ($P \sim 5 \cdot 10^{-2}$ mbar).

The chamber evacuation was repeated a few more times, each one with a shorter time needed to achieve the desired vacuum level. During the fourth depressurization test 22 hours were sufficient to reach the pressure of $P \sim 5 \cdot 10^{-2}$ mbar (see Figures 40 and 41).

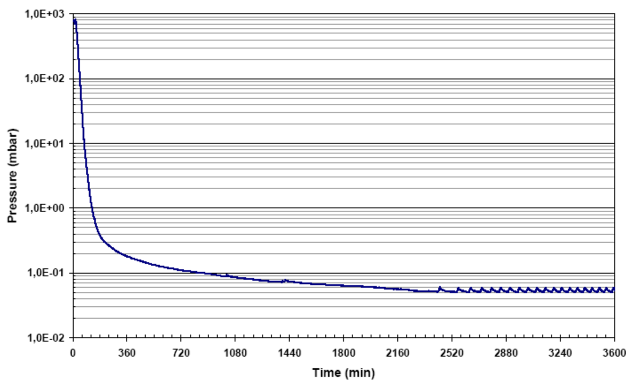

Figure 40 – Pressure profile for the first depressurization test on L-TOF detector. 48 hours have been needed to reach a stable vacuum condition (P~5·10-2 mbar).

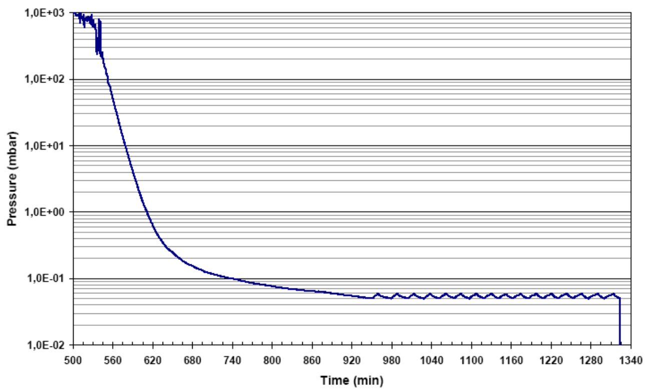

Figure 41 – Fourth depressurization test on L-TOF detector. Only 22 hours have been needed to reach a stable vacuum condition for the beginning of the high vacuum phase($P \sim 5 \cdot 10^{-2}$ mbar).

This behaviour, index of a 'memory effect' of the TOF with respect to the vacuum, is explained with outgassing, or bake-out, of the materials.

The residual time needed anyway (after backing-out) to achieve vacuum is due to the venting from the honeycomb and, most important, to the virtual leakage from Poron. Poron is a vibration damping material used inside the L-TOF, about 30 dm^3. Its volume behaves like a sponge and, depending on the time it is left at ambient pressure after vacuum, completely or partially absorbs back air in its pores; this determines a moderate memory effect: if TOF was left in air after vacuum for a longer period, a longer evacuation time was needed afterwards to recover the same vacuum level. This key behaviour will be important in estimating the test duration of the upper TOF, scheduled for June 2007.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AMS-02: Alpha Magnetic Spectrometer

AST: AMICA (Astro Mapper for Instrument Check of Attitude) Star Tracker

Correlation: correspondence between analytical predictions and test results

ECAL: Electromagnetic CALorimeter

EIB: Electronic Input Board

GMM: geometrical mathematical model; mathematical model in which an item and its surroundings are represented by radiation exchanging surfaces characterized by their thermo-optical properties

ISS: International Space Station

LEO: Low Earth Orbit

L-TOF: Lower Time Of Flight

MLI: Multi Layer Insulation

PMT: Photo Multiplier

PT100: platinum resistance thermometers; temperature sensors that exploit the predictable change in electrical resistance of Platinum with changing temperature

Qualification Test: verification process that demonstrates that hardware functions within performance specification under simulated conditions more severe than those expected during the mission

QM: Qualification Model

RICH: Ring Imaging CHerenkov

TMM: thermal mathematical model; lumped parameters model in which an item and its surroundings are represented by concentrated thermal capacitance nodes, each with one representative temperature, coupled by a network made of thermal conductors (radiative, conductive and, if applicable, convective)

TRD: transition radiation detector

TRP: Temperature Reference Point physical point located on a unit and unequivocally defined; the TRP provides a simplified representation of the unit thermal status

TS: Temperature Sensor

TV: Thermo-Vacuum Test; test conducted to demonstrate the capability of the test item to operate satisfactorily or to survive without degradation in vacuum at predefined hot and cold temperatures

TVC: Thermo-Vacuum Chamber

USS: Unique Support Structure