**Nationaal Lucht- en Ruimtevaartlaboratorium**

National Aerospace Laboratory NLR

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# AMS02 Tracker Thermal Control Cooling System Test Results of the AMS02 Thermal Vacuum Test in the LSS at ESA ESTEC

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## Executive summary

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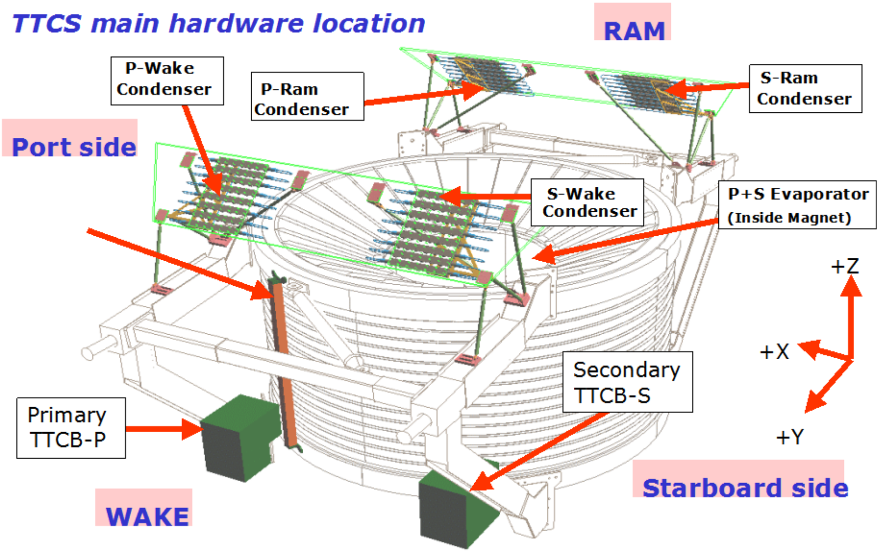

**Problem area**
The AMS02 Tracker Thermal Control System (TTCS) is a two-phase cooling system developed by NLR, INFN, SYSU, AIDC, and NIKHEF. The TTCS is a mechanically pumped two-phase CO2 cooling loop used for accurate (< 3 K) thermal control of the AMS02 Tracker instrument. The TTCS is part of the Alpha Magnetic Spectrometer (AMS-02) experiment a state-of-the-art particle physics detector designed to operate as an external module on the International Space Station and launched with the space shuttle Endeveour STS-34 May 16 in 2011.
The TTCS basically consists of a mechanically pumped two-phase loop, where 140 Watt heat is collected at two evaporators routed along the Tracker front-end electronics deep inside the AMS02 detector. The heat is transported to two radiators where it is rejected to deep space. Results show TTCS fulfils all requirements.

**Description of work**
The paper describes the TTCS TV test results of the AMS02 TV test in the Large Space Simulator (LSS) at ESTEC, the Netherlands. Results are presented on the Tracker temperature stability, pump super-critical start-up and on freezing and de-frosting of the TTCS freeze-proof condensers.

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NLR-TP-2013-312

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This report is based on paper presented at the International Conference on Environmental Systems (ICES2012) in San Diego, July 15-19, 2012.

## Results and conclusions

Results show TTCS fulfils all requirements. The paper concludes with an outlook of new developments in two-phase mechanically pumped loops.

## Applicability

Two-phase cooling systems are applicable for aerospace and industrial electronics cooling requiring accurate temperature control.

## ICES Conference

This report is based on a paper presented at the International Conference on Environmental Systems (ICES2012) in San Diego, 15-19 July 2012.

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## Summary

The AMS02 Tracker Thermal Control System (TTCS) is a two-phase cooling system developed by NLR, INFN, SYSU, AIDC, and NIKHEF. The TTCS is a mechanically pumped two-phase $CO_2$ cooling loop used for accurate (< 3 K) thermal control of the AMS02 Tracker instrument. The TTCS is part of the Alpha Magnetic Spectrometer (AMS-02) experiment a state-of-the-art particle physics detector designed to operate as an external module on the International Space Station and launched with the space shuttle Endeveour STS-34 May 16 in 2011.

The TTCS basically consists of a mechanically pumped two-phase loop, where 140 Watt heat is collected at two evaporators routed along the Tracker front-end electronics deep inside the AMS02 detector. The heat is transported to two radiators where it is rejected to deep space. The paper describes the TTCS TV test results of the AMS02 TV test in the Large Space Simulator (LSS) at ESTEC, the Netherlands. Results are presented on the Tracker temperature stability, pump super-critical start-up and on freezing and de-frosting of the TTCS freeze-proof condensers. Results show TTCS fulfils all requirements. The paper concludes with an outlook of new developments in two-phase mechanically pumped loops.

# Contents

# Nomenclature

*AIDC* = Aerospace Industrial Development Company, Taiwan
*AMS* = Alpha Magnetic Spectrometer
*APS* = Absolute Pressure Sensor
*DPS* = Differential Pressure Sensor
*ESA* = European Space Agency
*ETS* = European Test Services
*HX* = Heat Exchanger
*INFN* = Instituto Nazionale di Fisica Nucleare, Italy
*LSS* = Large Space Simulator at ESTEC in Noordwijk, The Netherlands
*MIT* = Massachusets Institute of Technology
*NIKHEF* = National Institute for Subatomic Physics, The Netherlands
*NLR* = National Aerospace Laboratory, The Netherlands
*P* = Primary
*S* = Secondary
*SERMS* = Laboratory Study of Radiation Effect on Materials for Space application, Italy
*SYSU* = Sun Yat Sen University, Peoples Replubic of China
*TTCB* = Tracker Thermal Control Box
*TTCS* = Tracker Thermal Control System
*T* = Thermostat
*TV* = Thermal Vacuum
*USS* = Unique Support Structure

# 1 Introduction

The Tracker Thermal Control System (TTCS) is part of the Alpha Magnetic Spectrometer (AMS02), a space born detector for cosmic rays built by an international collaboration, lead by Nobel prize laureate S.C. Ting. AMS02 is launched on May 16 2011 with the STS-134 mission of the Space Shuttle Endeveaour for a 10 year mission on aboard the truss of the International Space Station (ISS), collecting several billions of high-energy protons and nuclei[1]. The main goal is to search for cosmic antimatter, for dark matter and lost matter. The heart of the AMS02 experiment is the Silicon Tracker. It measures particle trajectories through AMS's strong magnetic field. In a magnetic field, charged particles do not move in straight lines, but rather in arcs. A particle with positive charge will bend to the right, a particle with negative charge will bend to the left. The higher the particle's momentum, the smaller the deflection.

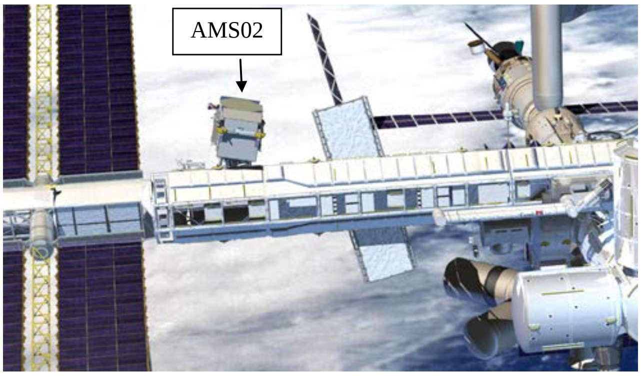


**Figure 1: AMS02 Location on ISS (picture by NASA)**

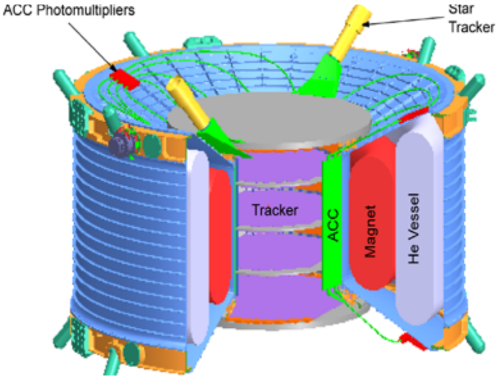


**Figure 2: The heart of AMS02 with Silicon Tracker (picture by R. Becker MIT)**

The tracker consists of eight large, thin sheets of silicon. The silicon sheets have millions of tiny aluminium stripes on them; each stripe generates an electrical signal when struck by a particle. By looking at the hits on all eight planes, it is possible to follow the track of the particle by combining the hits on the several planes.

Around the 8 silicon planes detecting front-end electronics are located. These dedicated electronics provide the accurate measurements (10 microns) needed. To achieve this accuracy the electronics need to be stable in temperature (< 3 K) while dissipating 144 Watt of heat. This temperature stability combined with the stringent requirement to use a minimum of metal inside the magnet lead to the development a dedicated mechanically pumped two-phase $CO_2$ cooling loop. Conventional space thermal hardware and working fluids would lead to large metal structures inside the magnet which is detrimental to the AMS02 experiment[5].

## 2 Tracker Thermal Control System

The TTCS is a mechanically pumped two-phase carbon dioxide cooling loop collecting the heat from the inside of the Tracker and transporting it to two dedicated Tracker radiators on top of the AMS02 experiment as schematically shown in figure 3. The layout of the TTCS-loop is shown in figure 4. By following the loop routing the loop operation is explained. At the pre-heaters stage the working fluid temperature is lifted to the saturation temperature. The working fluid enters the evaporator therefore with a quality slightly above zero, ensuring a uniform temperature along the complete evaporator. Due to the widely distributed front-end electronics the evaporator consists of two parallel branches collecting the heat at the bottom and top side of the Tracker planes. With an overall mass flow of 2 g/s the mean vapour quality at the outlet of the evaporators is approximately 30%. The two-phase flow of both branches is mixed and led through the heat exchanger where heat is exchanged with the incoming sub-cooled liquid. In this way the Tracker waste heat is re-used and therefore the pre-heater power could be reduced by 80%[5]. Behind the heat exchanger the two-phase line (red) is split. One branch leads to the condenser at the RAM heat pipe radiator and the other is lead to the condenser at the Wake heat pipe radiator, where the heat is rejected to space. The sub-cooled liquid of both liquid lines is mixed. In principal this flow distribution is self-adjusting[5]. The flow to the branch with the highest quality will induce the largest pressure drop. Hence a larger part of the condenser flow will be directed to the opposite condenser branch. At the end of the condensers the fluid is sub-cooled well below the saturation point so it arrives in liquid phase back at the pump.

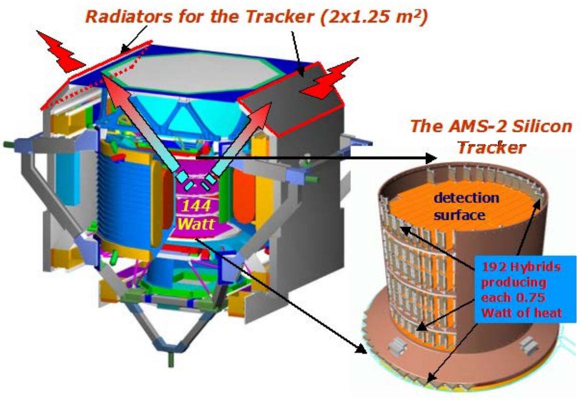


**Figure 3: Schematic of the Tracker and TTCS**

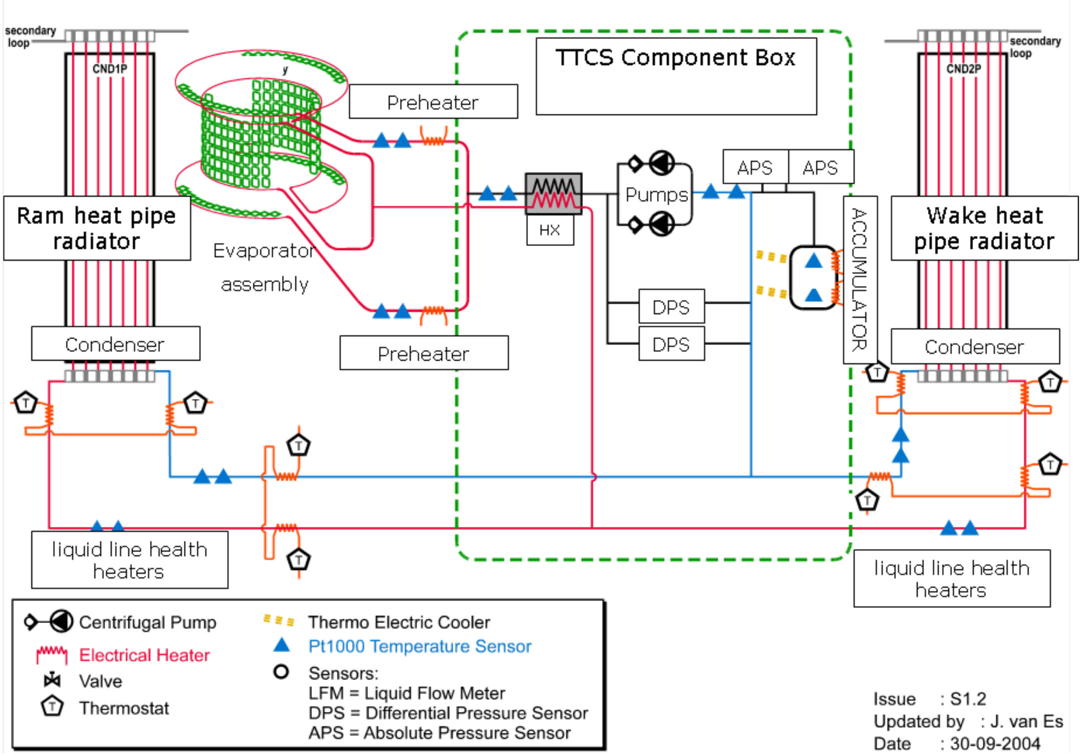


**Figure 4: Simplified Tracker Thermal Control System Loop Schematic**

Downstream the pump the sub cooled liquid is pre-heated again by exchanging heat with the returned two-phase flow from the evaporator. In most cases the heat exchanger lifts the sub cooled liquid to saturation. Only in extreme cold orbits additional 8 W pre-heater power per branch is needed to create saturation.

The set-point control of the TTCS is done by the accumulator. The accumulator is the largest two-phase volume in the loop and it therefore dictates the saturation (and thus evaporation) temperature in the loop. The accumulator is controlled by heaters and thermo-electric cooling. Breadboard test results showed that a stability <1K can easily be met[5].

## 2.1 TTCS Hardware

The TTCS hardware is widely distributed over the AMS02 experiment. This is illustrated in figure 5 where the location of the TTCS hardware on AMS02 is shown. Two complete redundant systems are integrated. The primary loop is located on the port side and the secondary loop is located on the starboard side. Both systems use the same radiators to radiate the heat to deep space located on top of AMS02

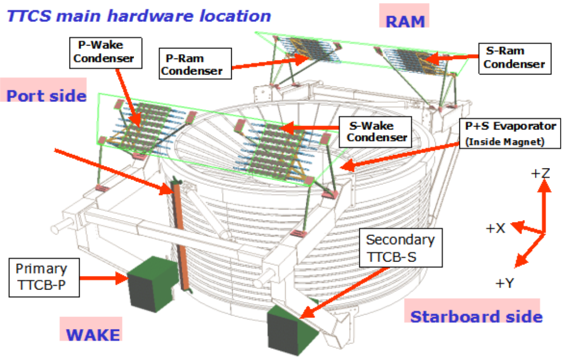


Figure 5: TTCS Hardware locations on AMS02

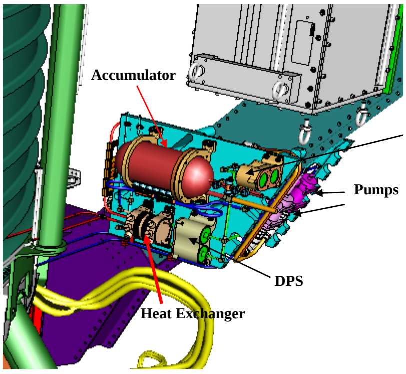


Figure 6: TTCS box on starboard side of AMS (Picture by C. Gargiulo INFN)

### 2.1.1 Thermal Tracker Control Boxes

The main component boxes, called the Thermal Tracker Control Boxes (TTCB), are connected to the Unique Support Structure (USS) of AMS02. The boxes are covered in Multi-Layer Insulation (MLI) and thermally decoupled from the USS by titanium washers. A box without cover and MLI is shown in figure 6. The main box components are indicated. Apart from the accumulator and pumps the box contains the Differential (DPS) and Absolute Pressure Sensors (APS) to monitor respectively pump health and system health. Further the TTCB contains the Heat eXchanger (HX), the pre-heaters (PR1 and PR2), start-up heater (SUP) and cold-orbit heater (COH).

During TTCS operation the temperature of the TTCB is mainly defined by the sub-cooled liquid from the condensers. In non-operational periods the TTCB slowly follows the stable temperature of the large aluminium USS structure, which always stays above -40°C to avoid $CO_2$-freezing. In extreme hot cases however the USS temperature can increase above the $CO_2$ critical temperature of +33°C. In such cases the TTCS start-up will become time consuming as the pump has to suck cold $CO_2$ from the condensers to the TTCB by pumping low-density vapour. To reduce the chance to end-up in such situations the pumps are located on special start-up radiators at the side of the TTCB radiating to the inside of the AMS02 Wake radiator. This ensures that the pumps have the lowest possible temperature. For the few hot cases in which the pumps will still reach supercritical temperatures a vapour start-up test during the thermal vacuum test is defined, which is described in the TV test section of this paper.

### 2.1.2 Evaporator

The evaporators are located inside the AMS02 magnet. The evaporators of the primary and secondary TTCS run exact the same route one just above the other. In figure 7 an overview of the evaporator lay-out is shown. Each evaporator has a top and bottom ring which are parallel branches. The inner diameter of the evaporator is 2.6 mm and the total length is 9 m. Heat collected at the inner tracker planes is transported by thermal bars to the top and bottom evaporator ring. In figure 8 the inner ring of te top evaporator is presented, showing the widely distribution of the tracker front-end electronics. The temperature along the evaporator should stay within a 3 °C band and the temperature difference between the inner Tracker planes and the evaporator should be smaller than 10 °C. The stability of each individual front end electronics should be better than ±3°C. The stability verification is one of the objectives of the thermal vacuum test.

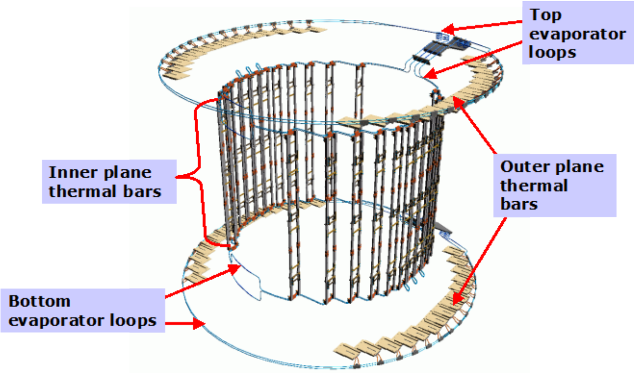


Figure 7: Evaporator lay-out with thermal bars

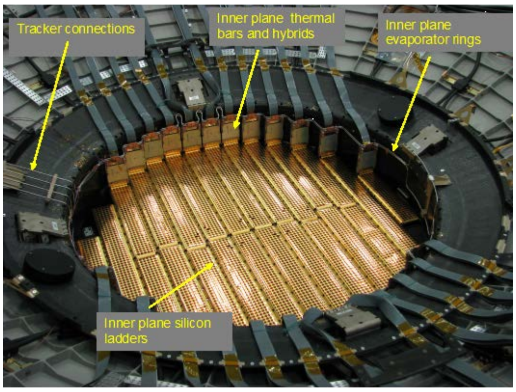
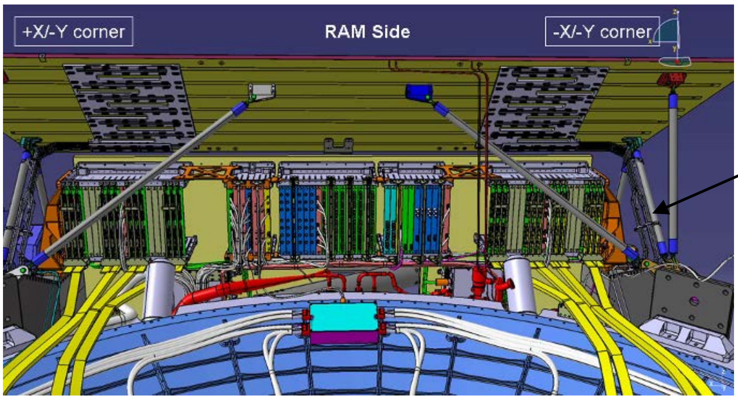


Figure 8: Top evaporator
(Picture by NIKHEF)

### 2.1.3 Condensers

Each TTCS loop has two parallel condensers, one located on the WAKE Tracker radiator and one on the RAM Tracker radiator. The location of the condensers on the RAM heat-pipe radiators is shown in figure 9. The condensers are the only TTCS parts which can freeze. The rest of the TTCS is connected to the USS or the magnet flange which will stay above -40 °C, well above the -55°C $CO_2$ freezing temperature. The condenser design is shown in figure 10 and consists of 7 parallel tubes of Inconel 718 which allowing freezing and uncontrolled thawing upto -5°C with inner pressures upto 300 MPa[2]. The design can withstand 1200 MPa by design and is tested upto 1000 MPa.



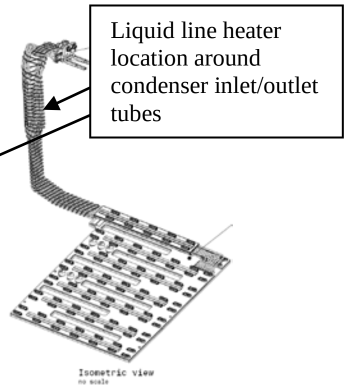


Figure 9: Condenser location on the heat pipe radiators
(Picture by F. Cadoux, University of Geneva)

Figure 10: Condenser design
(Picture by NLR)

To recover from a frozen situation, in case of a complete AMS02 power down the condenser inlet and outlet are equipped with so-called liquid line health heaters which de-frost the condensers inlet tubes from the manifolds connected to the USS until the radiator. This is to be sure that the inlet and outlet are liquid before the radiators will be de-frosted. When the liquid inlet lines reach temperatures above -40°C the radiator heaters can be switched on to also defrost the condensers attached to the radiator. The heater design is inherent safe as the radiator heaters are switched by thermostats with a set-point of -15 °C well below the maximum design temperature of -5°C.

During the TV test the condensers will be frozen to verify the defrosting procedure and to demonstrate defrosting with TTCS integrated on AMS02.

# 3 Thermal Vacuum Test

The AMS02 thermal vacuum test was performed in the Large Space Simulator (LSS) at ESTEC the Netherlands in March 2010. Inside the LSS, AMS02 was located in a special U-shaped TV test rig in order to rotate the complete set-up before the start of the test. The final test orientation is shown in figure 11 and figure 12.

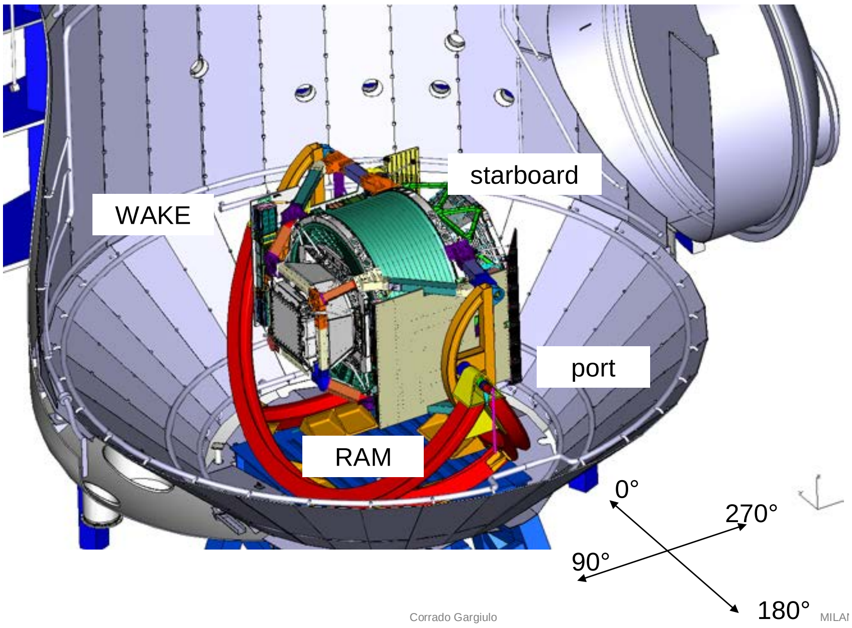


**Figure 11: AMS02 TV test set-up in the LSS  (Picture by Corrado Gargiulo INFN)**

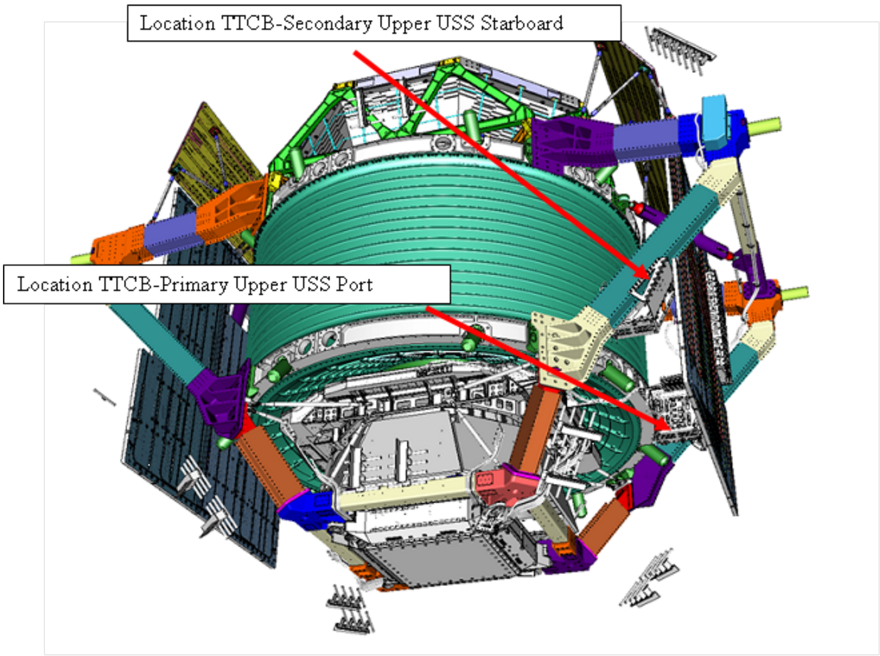


**Figure 12: TTCS location AMS02 in the TV test set-up in the LSS (Picture by Corrado Gargiulo INFN)**

## 3.1 TTCS LSS Test set-up

The TTCS is integral part of AMS02. The AMS02 orientation is such that the TTCS primary system is located at the bottom side and the TTCS secondary at the top side. The Tracker radiators are located with the heat pipes in vertical orientation. This means that the the primary system works with Tracker heat pipe radiators in thermosyphon mode and the secondary system in anti-gravity mode. Therefore only the primary system can be used to show evaporator performance and stability. The secondary system can only be operated without the thermal load of the Tracker to avoid dry-out of the radiator heat pipes. This “liquid” mode of operation is sufficient to perform functional checks on components.

The TTCS data acquisition system used for the TV test handles two data streams. First it handles the flight data which will also be available in orbit. The flight data rate can be varied by setting the priority of the TTCS data in the downlink. The maximum rate is approximately 1 Hz used to support TTCS tests in which fast changes are monitored. The second data stream is the data from dedicated LSS thermocouples attached to strategic TTCS locations. This data is used to verify the temperature profiles at additional locations and to monitor the temperatures when TTCS and/or AMS are switched off. The temperature sensor locations in the loop are shown in the detailed TTCS loop schematic in figure 14.

A special TV test heater is implemented in both TTCB’s (see figure 13) to keep the TTCB’s above the minimum health limit of -30°C during the AMS02 cold thermal balance testing. The heater is controlled by one of the LSS thermocouples located on the pump radiator but can also be switched manually.

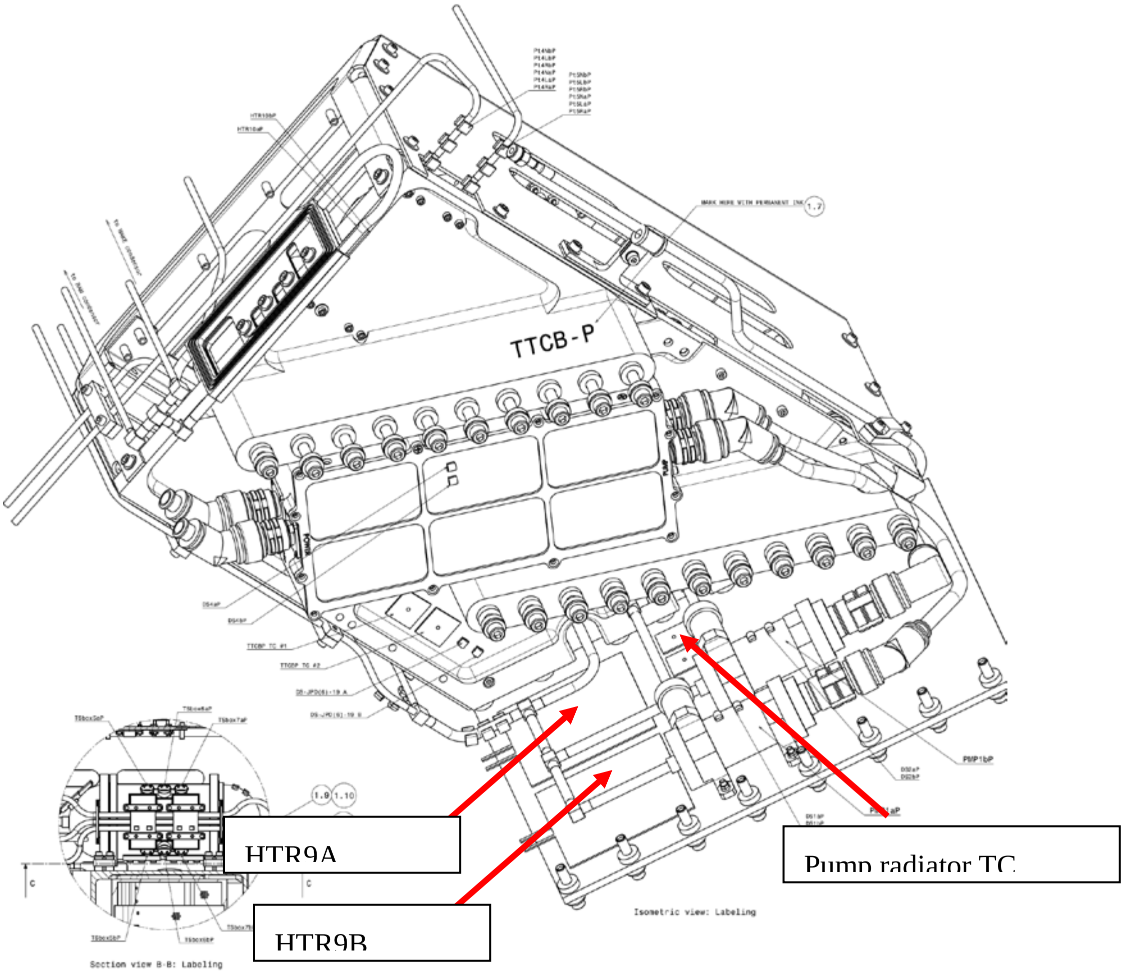


**Figure 13: Location of the TTCB LSS support heater**

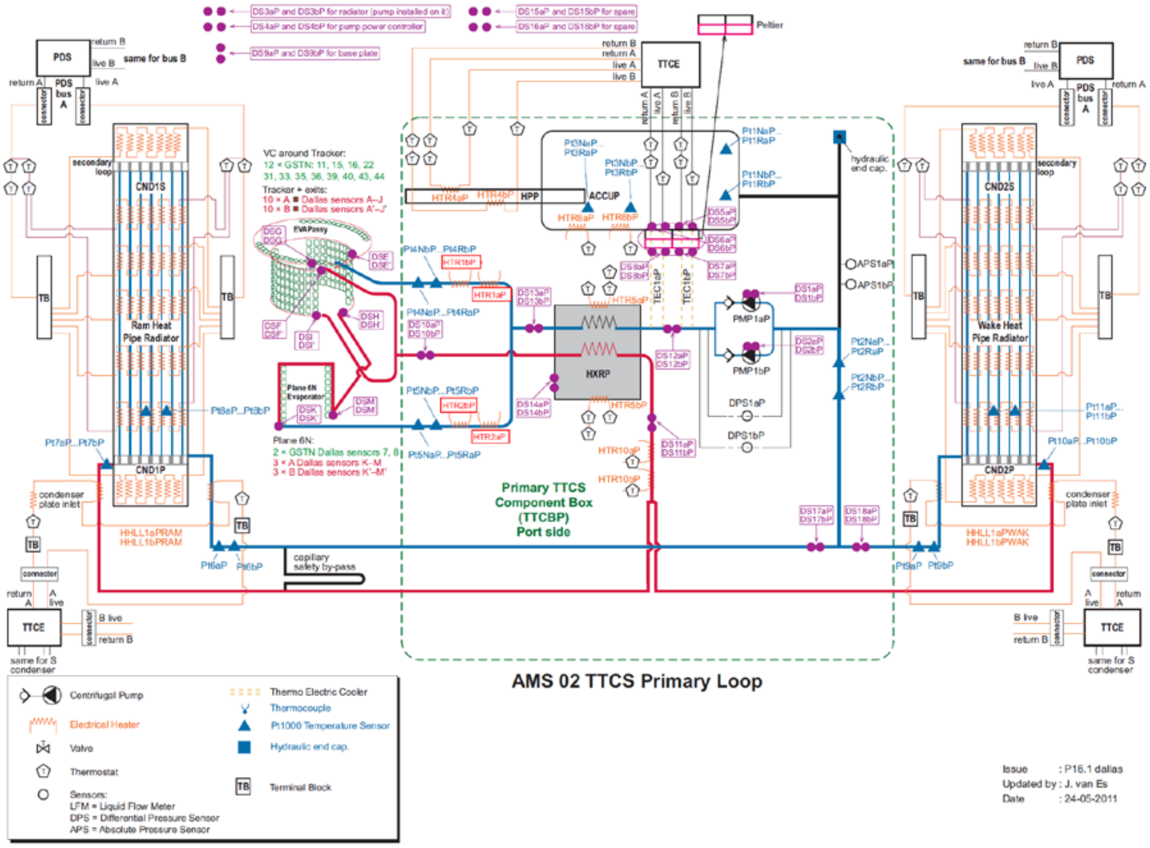


**Figure 14: TTCS Schematic with temperature sensor locations**

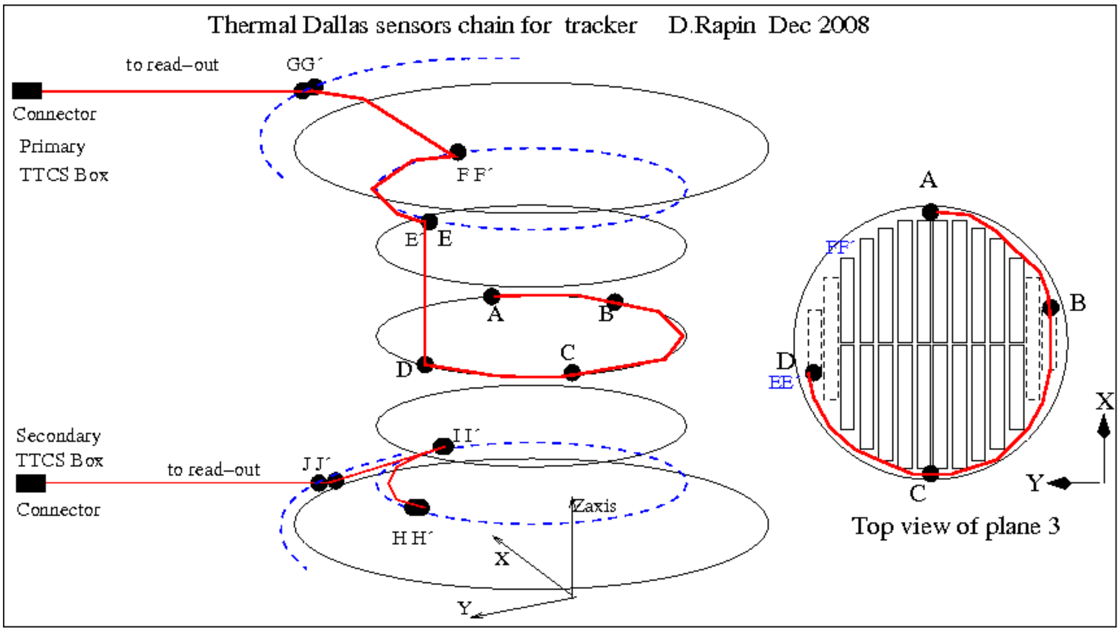


**Figure 15: Physical location of temperature sensors inside the Tracker evaporator**

## 3.2 TTCS TV test objectives

The TTCS TV test objectives are:

- Verify the health of all components by performing functional checks in hot, nominal and cold conditions
- Verify the performance (thermal stability and cooling capability) of the TTCS thermal control in in hot, nominal and cold conditions
- Verify the function of implemented control loops
- Demonstrate the TTCS capability to de-frost the condensers and to verify the de-frost procedure
- Demonstrate the TTCS capability to start-up in vapour conditions

The TTCS tests are performed in the course of the AMS02 TV test.

## 3.3 TTCS TV test results

The general conclusion from the intensive TV LSS test campaign was that the TTCS passed the test without problems. All functional tests of the TTCS components were completed successfully except for one pre-heater due to a bad connector. After the test this pre-heater is replaced by a flight spare and operates now flawlessly in space. Due to the available redundant heater the heater failure had no effect on the execution of the TV test. The implemented control loops for the accumulator temperature, on/off control of the pre-heaters, start-up heaters and the cold orbit heaters were verified. Some small control set-point changes were made to reduce cold-orbit heater switching in cold conditons. In the next subsections the thermal performance test results, the condenser de-frost test results and the pump start-up in vapour conditions are described in more detail.

### 3.3.1 TTCS Thermal Performance test results

The thermal performance of the Tracker is verified by a set of Dallas sensors in the evaporator glued on copper blocks connected to the evaporator. The locations in the loop are shown in figure 14. Test results for cold orbit are presented in figure 15. The accumulator set-point is -15°C, the evaporator temperatures are extremely stable and show variations of only ±0.2°C. Similar stable results were shown for nominal and hot conditions and during ramp-up after the cold thermal balance test.

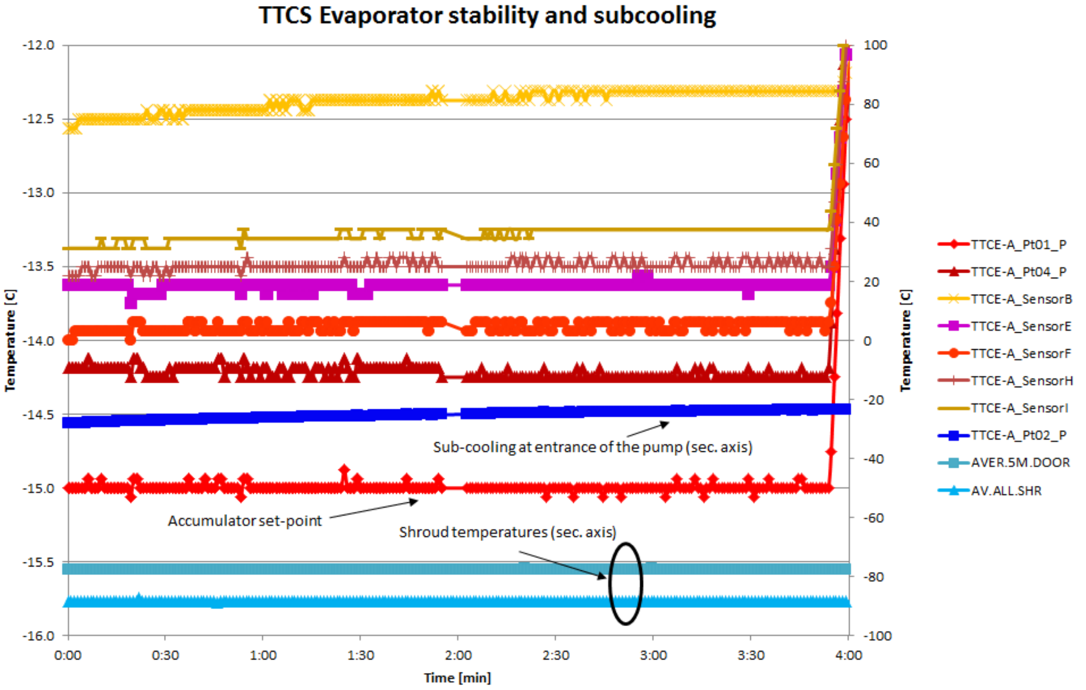


**Figure 16: Tracker temperature stability in cold conditions ($T_{shroud}$ = -90°C, $T_{Accu\ Setpoint}$= -15°C)**

The Tracker temperature with index B shows stable temperatures with an off-set. This is the temperature of the centre Tracker plane connected with thermal conductive bars to the evaporator which is also more influenced by the slow temperature changes of the magnet surrounding the Tracker.

### 3.3.2 Defrosting of the TTCS condensers

In figure 16 the freezing and defrosting cycle of the TTCS condensers is presented. In the left side of the graph it is shown that the Pt1000's on the condenser inlet tubes near the radiator (Pt07P and Pt07S) reach -60°C, well below the -55°C $CO_2$ freezing temperature. That was the start condition for the defrost procedure, consisting of defrosting the inlet and outlet of the condensers by switching on the liquid line heaters (see also figure 9) and heat them above -50°C.

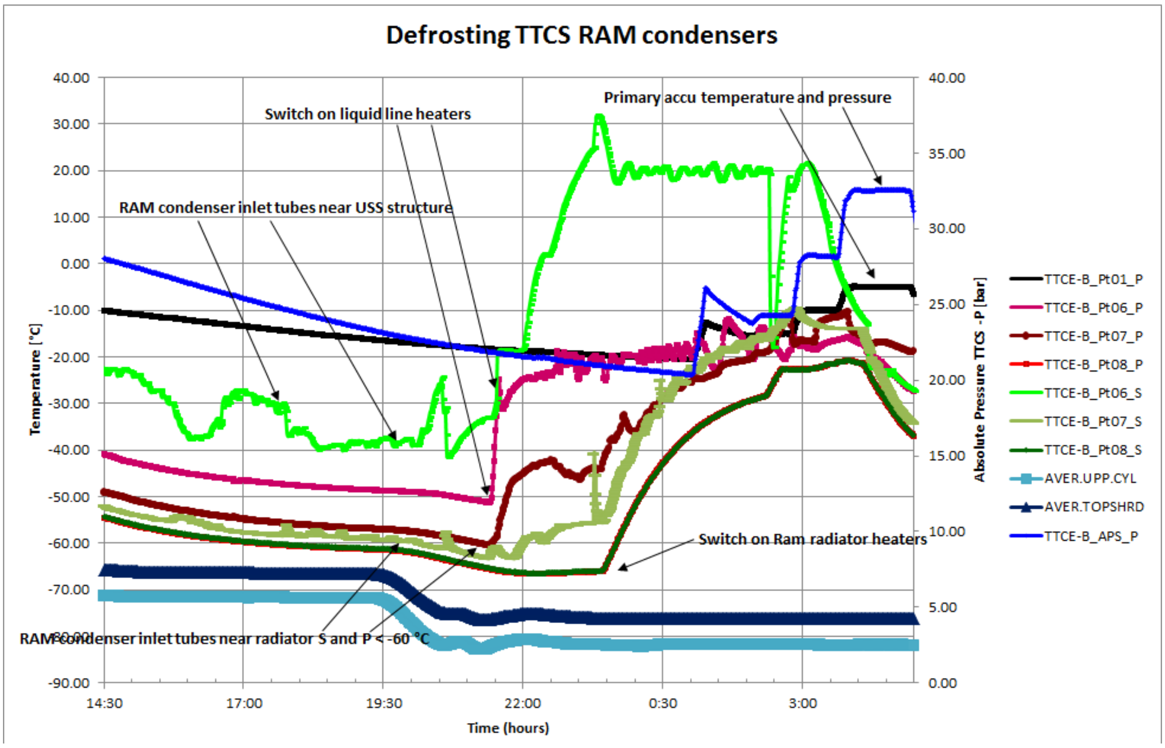


Figure 17: Freezing and defrosting cycle of the TTCS condensers RAM side

Then the Tracker radiator heaters are switched on defrosting also the condenser plate directly attached to the heat pipe radiators (see figure 9). After also the radiator temperatures have reached -50°C a normal TTCS start-up is executed. Figure 16 shows that the defrosting procedure works well and the TTCS can recover from freezing. After the RAM radiator reached -40 °C the accumulator was heated and put on a set-point of -10 °C. After that a normal TTCS start-up could be performed.

### 3.3.3 Pump start-up test in vapour conditions

In figure 17 the pump start-up is shown in vapour conditions. Hereto first the TV test heater connected to the TTCB start-up is switched on (heater 9 in figure 13). This heater directly heats the pump section. and it raises the pump temperatures DS1 and DS2 to +15°C well above the accumulator temperature of +5°C. As the accumulator set-point dictates the evaporation temperature in the loop, the pump is now in vapour condition.

The vapour start-up test is then started by switching on the pump on 3000 rpm. After 15 minutes the pump speed was increased to 5000 rpm. This pump speed was high enough to suck down the liquid from the condenser to the pump. It is shown that right after the pump speed increase the box inlet temperatures Pt02 is dropping slowly. After approximately another 9 minutes the liquid enters the pump. This can be seen by a rapid temperature drop of the pump. The pump has successfully sucked cold liquid from the condenser outlet by the pumping $CO_2$ vapour.This feature works for $CO_2$ with its dense vapour with a density only 10 times smaller than $CO_2$ liquid. It is however unlikely that centrifugal pumps show similar results for $NH_3$ , with density ratios upto 800.

Because a vapour start-up is time-consuming and cumbersome operational guidelines are developed to avoid that the non-operating TTCB will reach vapour start-up conditions. Well in advance the redundant loop will be operated in parallel to the running loop so the TTCB including the pumps are cooled down. This has already been tested in space and is implemented in the AMS02 operation guidelines.

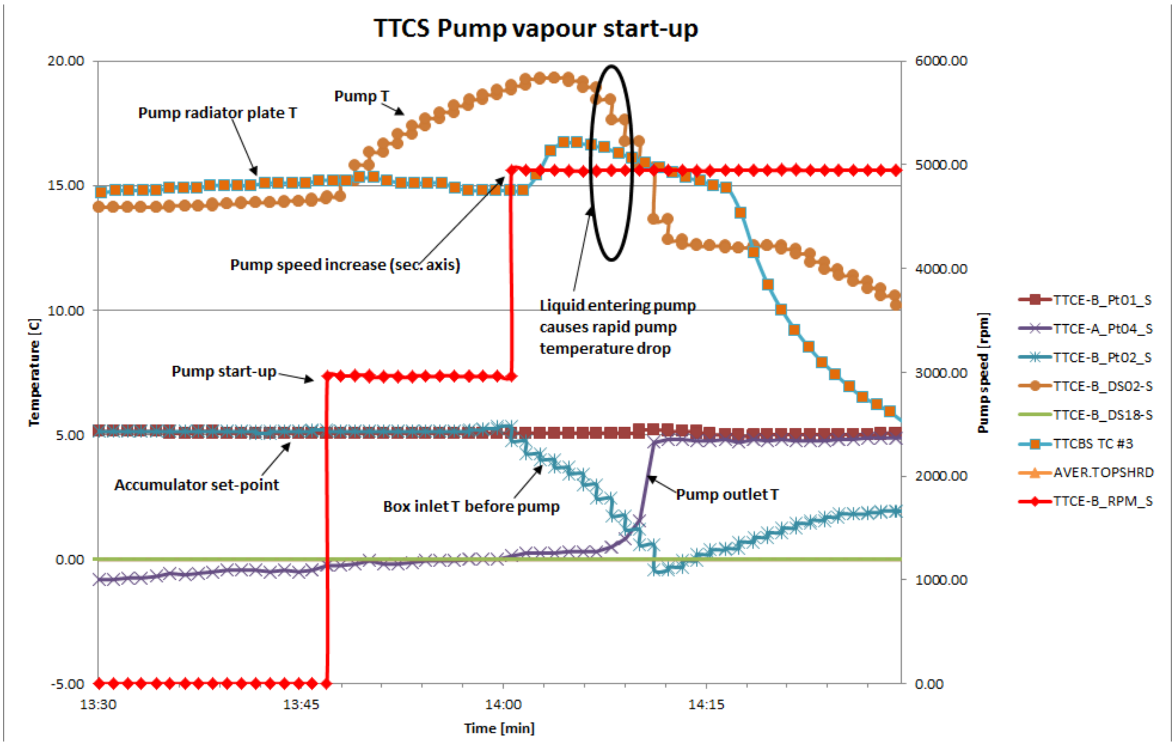


**Figure 18: Vapour pump start-up test**

# 4 Conclusion and new developments

## 4.1 Conclusions

During the AMS02 thermal vacuum test in the Large Space Simulator at ESTEC the Netherlands the TTCS showed a Tracker temperature stability of ±0.2°C in hot and cold conditions and during ramp-up and down. More than ten times better than the required ±3°C. A freeze-thaw cycle was performed on the TTCS condensers to demonstrate the capability to recover from freezing. A pump start-up test in vapour condition was performed to verify the capability of the TTCS pumps to start-up in extreme hot conditions. The TTCS passed all tests and demonstrated that a mechanically pumped two-phase system controlled by an accumulator is able to accurately set the temperature in a distant evaporator and collect heat of a widely distributed payload.

Special for $CO_2$ is the low liquid/vapour density ratio resulting in low evaporator pressure drops providing the possibility to implement tight thermal control in extremely confined areas. This unique property lead to the implementation of a TTCS-like system in the Vertex Locator (Velo) instrument of the Large Hadron Collider (LHCb) by NIKHEF[3]. This 2.5 kW system accurately controls the temperature of the detector with an accumulator on a distant location far away from the radiation which is detrimental for thermal active components. Two other large CERN experiments ATLAS and CMS are developing similar thermal control systems to improve the thermal stability of their inner detectors.

## 4.2 New developments

The successful TTCS in-orbit commissioning and the flawless TTCS operation for one year has lead to more confidence in two-phase mechanically pumped systems for space applications currently under development. Current commercial spacecraft (S/C) are running to their thermal limits meaning that the radiator area is too small to provide enough cooling capacity. Recent requests of customers will force the industry to provide deployable radiators. Firstly this will be done with capillary pumped cooling systems but for S/C requiring stable temperatures or for future high dissipative telecommunication payloads (Q>9kW), two-phase mechanically pumped systems are advantageous and a competitive alternative to complex LHP-HP networks. The first application of a 2-phase mechanically pumped loop is foreseen to cool active antennas, requiring tight and stable temperature control[4]. Because of the $CO_2$ freezing problem[2] in space and the overall better thermodynamic properties ammonia is selected as working fluid. NLR, as main lead in the TTCS-development, is involved in the development of the two-phase heat controlled accumulator for this system. A qualified system is expected not earlier than 2015.

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