Commissioning of cooling system AIRCOOLER SPLIT before installation for TOTEM detectors

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Abstrakt

Cílem této práce bylo sestavit měřicí trať pro ověření správné funkce nového modelu chladicího zařízení s názvem AIRCOOLER SPLIT pro chlazení elektronických komponent částicových detektorů typu Roman Pot, využívaných experimentem TOTEM. Toto zařízení pracuje se vzduchem, jako chladícím médiem a bylo navrženo s ohledem na prostorovou náročnost této aplikace. Pro chlazení vzduchu využívá vírových trubic. Měřící trať byla vybavena senzory pro monitorování teploty, tlaku a průtoku vzduchu systémem. Pro zobrazení a ukládání měřených veličin byl využit systém sběru dat založený na software WinCC OA. Bylo provedeno první kontrolní měření s maketou detektoru typu Roman Pot, při kterém bylo dosaženo předpokládané teploty chladicího vzduchu dle dříve zjištěné charakteristiky systému.

Klíčová slova

Měření a sběr dat, chlazení vzduchem, měření teploty, tlaku a průtoku, vírová trubice, Roman Pot.

Abstract

This paper describes building of a measurement setup that verifies correct performance of a new model of cooling device AIRCOOLER SPLIT for cooling electronic components of Roman Pot type particle detectors used in TOTEM experiment. This device works with air as a cooling medium and it was designed with respect for space requirements of its application. It uses vortex tubes to cool down stream of air. There were implemented sensors for monitoring temperature, pressure and flow of the air stream in the setup. A data acquisition system based on WinCC OA software was used for monitoring and retaining measured values. First measurement with Roman Pot mock-up was carried out in order to verify lowest cooling air temperature that corresponded with previously found characteristics.

Keywords

Measurement and data acquisition, air cooling, measuring of temperature, pressure and airflow, vortex tube, Roman Pot.

1. Introduction

Aim of this paper is to describe verification measurement of a cooling device called "AIRCOOLER SPLIT" connected to Roman Pot mock-up that took place in CERN laboratory R-N14, Switzerland and was conducted between the 2nd and 14th February 2015. The AIRCOOLER SPLIT (the ACS) is the latest model in a series of cooling devices that have been developed and designed at the Department of Applied Physics. The first prototype of the device has been thoroughly tested in the mean of functionality and optimal working conditions during summer of 2014.

The ACS can produce a stream of cooled air at temperatures down to -50 °C using only low potential pressurized air (between 7 and 9 bar$_a$) as a source of energy. The pressurized air has

to be dry and without any impurities (mechanical particles, oil etc.). It is to be used to cool down two newly prepared horizontal-type Roman Pot detectors of the TOTEM experiment. This solution will enable to leave existing cooling arrangement untouched and fully functioning. In other words, the 24 Roman Pot detectors will remain to be cooled by an evaporative cooling system with compressors and evaporators using octafluoropropan as a refrigerant. The first, two AIRCOOLER SPLIT units will be installed in the tunnel of LHC sometime between 35th and 46th week of 2015.

1.1 AIRCOOLER

The ACS is used to cool down a stream of compressed air to temperatures starting from -5°C down to -60°C depending on the input air pressure and flow rate. Two mechanical devices - vortex tubes, Figure 1, provide cooling effect. The compressed air is injected into the tube through a cylindrical vortex generation chamber where a swirling motion is developed. The air stream inside the vortex tube is warmer near the tube walls and colder in the centre [3]. The warm air leaves the vortex tube on one side (hot end) and the colder on the opposite (cold end), both of which are perpendicular to the air inlet. No electricity or any other form of energy except for the pressurized air (gas in general) is required for the vortex tubes to operate.
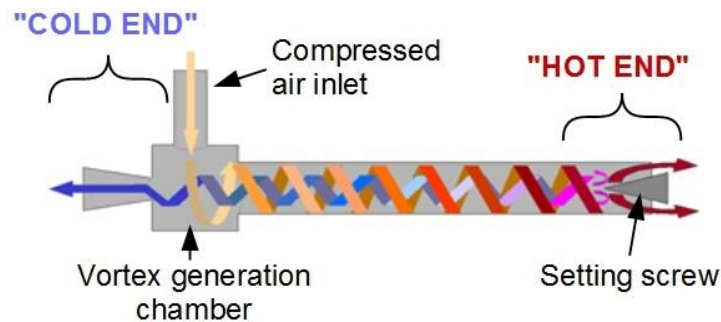

Figure 1: *Vortex tube*

The vortex tube has a setting screw located on the hot end that allows changing the ratio between hot and cold air mass flow rate. Changing the ratio also affects the temperatures of both streams. The achievable temperature difference (ΔT) between the input and the cold output changes with the flow ratio: the higher the cold airflow the smaller the ΔT. Typical ΔT between the input and the cold output ranges from 20°C up to 60°C.

The AIRCOOLER uses two vortex tubes called *precooling* and *main*. The tubes are connected in parallel through a heat exchanger (HEX), Figure 2. A more powerful vortex tube together with air-air heat exchanger is used to precool the input air for a second, less powerful tube. The second vortex tube provides cooling air to be used for desired application.

There have been three different AIRCOOLERs tested at CERN and in Prague so far. Two of them are similar design as is depicted in the Figure 2; however, one has higher cooling capacity (cooling air flow 50 l/min vs. 20 l/min) and also higher consumption of the compressed air (400 l/min vs. 250 l/min). Both these AIRCOOLERs are able to achieve -50°C at the cold output from +20°C input air at 8 bar$_a$. The third AIRCOOLER, called AIRCOOLER SPLIT, has different design. The first prototype of AIRCOOLER SPLIT has been tested during the summer of 2014. Later, two other devices have been manufactured and prepared for use in LHC tunnel. Only the function design is described in this paper since the structural design is different for the various AIRCOOLER prototypes.
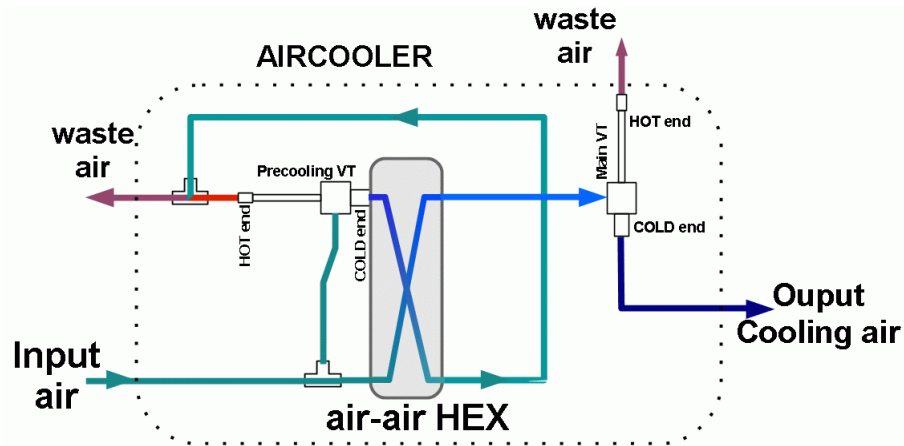
Figure 2: *AIRCOOLER "all in one box" design*

All types of AIRCOOLER devices have one input and 3 outputs. One output is the cooling air and the other two are warm air from the vortex tubes hot ends and air used for precooling in the heat exchanger. The warm air outputs are labelled "waste air" in Figure 2 and since the device is used for cooling they have no use. The cooling airflow makes only around 8 to 20% of the total air consumption. The efficiency of the system is relatively small in comparison with other cooling systems. However, AIRCOOLER's reliability, relatively low running cost, simplicity, radiation resistance and very easy and fast deployment counterbalance the small efficiency.

1.2 AIRCOOLER SPLIT (ACS)

The ACS was specifically designed for the use in the LHC tunnel where it will cool down detectors in the Roman Pots, Figure 3. In this design the precooling stage takes place inside a metal chassis (hereafter abbreviated as BOX) and is connected via a flexible tube with the main stage (main vortex tube). The BOX will be placed on side of the Roman Pot unit, while the main vortex tube will be integrated on the top of the Roman Pot flange, Figure 3. The reason for the SPLIT design is that it is highly inconvenient to place the AIRCOOLER SPLIT BOX right next to the Roman Pot. This arrangement allows reaching lower temperatures of the output cooling air in comparison with the "all-in-one-box" design (Figure 2) with the same components.
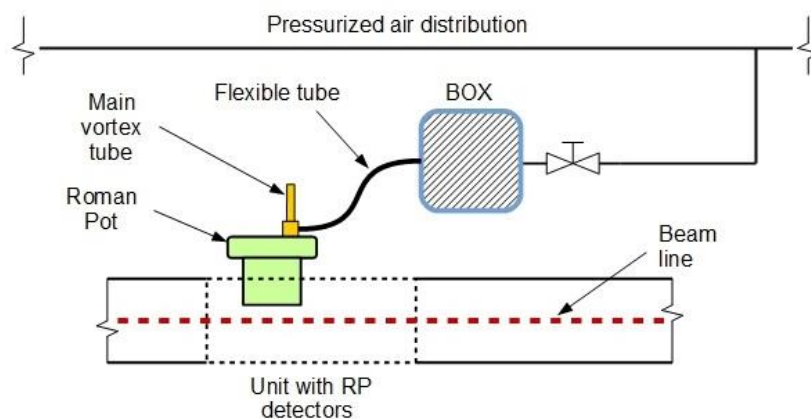

Figure 3: *Application of AIRCOOLER SPLIT*

The distance between the precooling box and the main vortex tube is determined by length of the interconnecting tube used, which is approximately 1.4 m (estimated; 1.1m interconnecting

tube plus connections) and should be kept as short as possible. The flexible (interconnecting) tube (can serve as a heat exchanger) is described in paragraph 2.1.
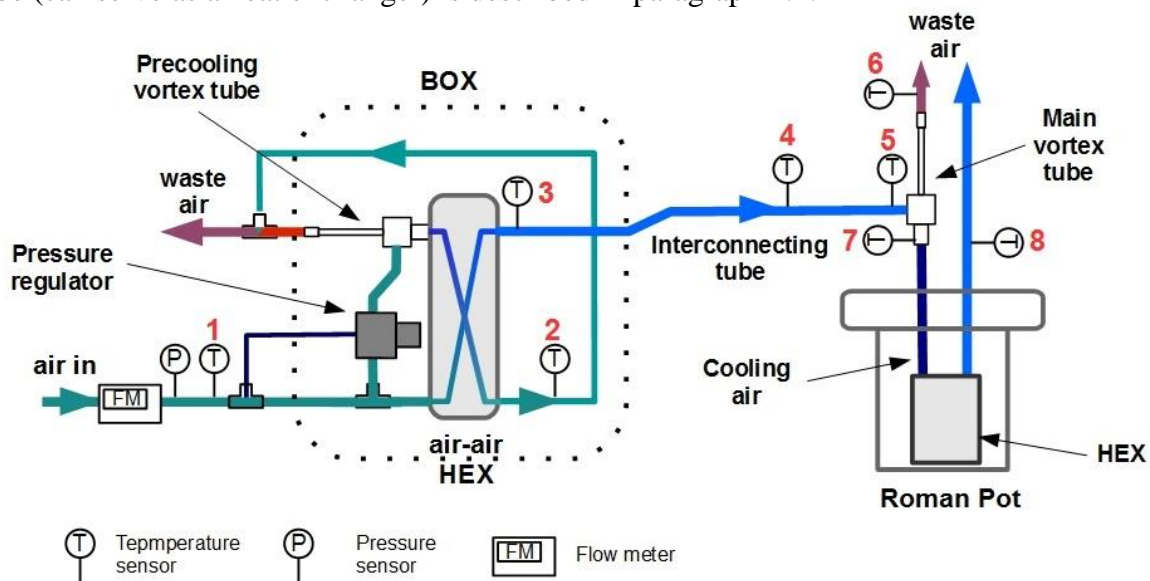

Figure 4: The scheme of setup with position of sensors (temperature sensors labelled with numbers)

Lower temperatures can be reached inside the Roman Pot since the unwanted temperature rise over the interconnecting tube between the BOX and the Roman Pot, caused by heat ingress from the ambient air, is smaller for the split design. The loss of cooling power and subsequently the temperature rise are smaller since the precooled air with higher flow rate and only mildly low temperature passes through this tube instead of the very cold air flow directly used from the main tube in case of the "all-in-one-box" design. The whole setup of AIRCOOLER SPLIT cooling system is shown in Figure 4.

A new structural design for the ACS has been developed. It is significantly smaller and lighter than the previous prototype and therefore more suitable for the target application. Two of these ACS devices were manufactured and assembled in DUO.CZ, Czech Republic and delivered to CERN, where they will be subsequently installed in the LHC.
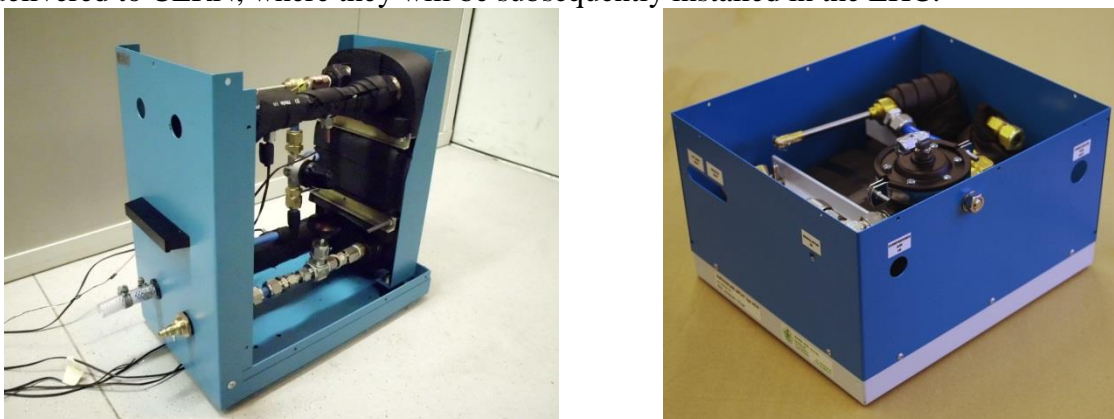

Figure 5: Comparison of prototype (left) and the AIRCOOLER SPLIT box designs (right)

Unlike in the prototype, there is a pressure operated (pilot air) pressure regulator in the ACS instead of manual regulator valve regulating input pressure to the precooling vortex tube. The purpose of the pilot air regulator is to control output temperature (cooling air to Roman Pot) by changing the ratio of airflow to the precooling vortex tube. When specific output temperature is set (higher than the lowest achievable) the precooling vortex tube consumes

less air and therefore less energy is used for cooling effect. A control system for the output temperature is being prepared and the pilot air regulator is currently connected directly to the air input line (fully opened; see Figure 4). Basic technical parameters of ACS are listed in Table 1.

Table 1: *Overview of technical parameters of AICOOLER SPLIT ACS*

AIRCOOLER SPLIT ACS technical parameters	
Input air temperature	10-25 °C
Optimal input air pressure	8 bar$_a$
Maximal input air pressure	10 bar$_a$
Box dimensions (width x depth x height)	274 x 324 x 220 mm
Box weight	11 kg

The optimal performance of the system depends mostly on the setting of the vortex tubes setting screws. The optimal setting for both vortex tubes used in the tested AIRCOOLER SPLIT has been adjusted thanks to many previous measurements performed on earlier versions of AIRCOOLER devices. The optimal position of the setting screws is defined as a portion of cold air mass flow $\dot{m}_{cold}$ over total air consumption of the vortex tube $\dot{m}_{tot}$ in percent. Table below describes technical specification of both vortex tubes as well as the value of airflow ratio for ideal position of the setting screws.

Table 2: *Description of vortex tubes used*

Vortex tube designation	Type	Max. input air pressure [bar]	Air input connection size	Nominal air consumption (@ 6.9 bar) [Nl/min]	Setting air flow ratio [%]
Precooling	106-2-H	10.3	1/8 G (F)	57	38
Main	106-8-H	10.3	1/8 G (F)	226	31

A static characteristic of the system (Figure 7) was measured for this specific vortex tubes setting. Two other members of our team, Martin Doubek and Michal Haubner, have carried out those measurements. It was obtained on the AIRCOOLER SPLIT prototype during summer of 2014 in CERN. It allows us to approximately determine temperature of the cooling air as a function of input air pressure and see whether the system behaves correctly.

The static characteristic of the system is represented by following values (as seen in Figure 6): input air pressure (P), input air flow (Q_1), input air temperature (T_1), precooled air temperature (T_2), cooling air flow (Q_2) and cooling air temperature (T_3).
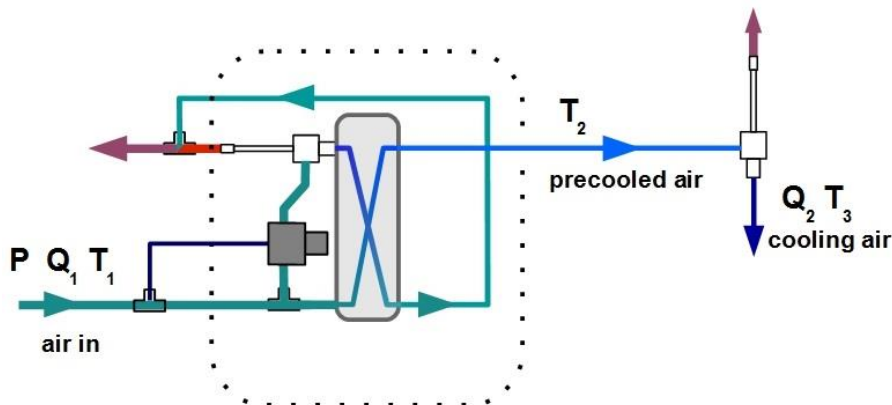

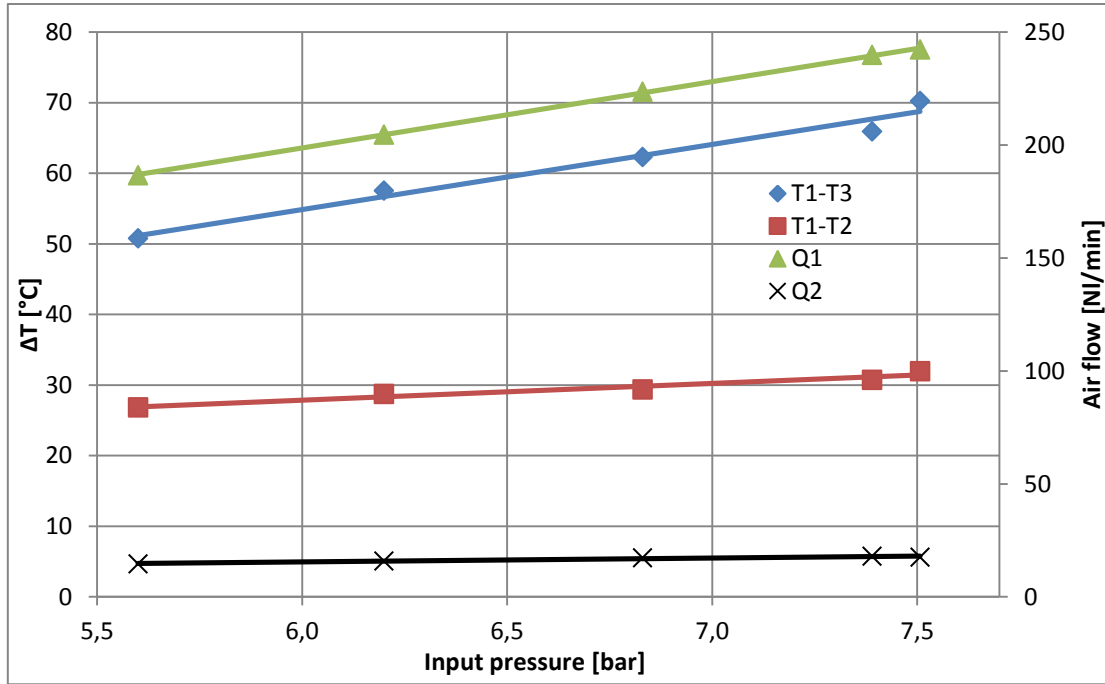***Figure 6:*** *Variables used for static characteristic measurements*

Figure 7: *Static characteristic of AIRCOOLER SPLIT*

1.3 Roman Pot detectors

The Roman Pot is experimental equipment used primarily by the TOTEM experiment at CERN for measuring the total proton-proton cross-section and to study elastic and inelastic proton-proton scattering processes. The detectors are placed inside a secondary vacuum vessel, called pots, and moved forward the beam through vacuum bellows. One Roman Pot unit contains two vertical and one horizontal pot [4], [5].

The ACS will be used for cooling down electronic components of timing detector inside of the two newly and additionally installed horizontal Roman Pots. The purpose of the timing detector is to track time of flight of protons and therefore improving the measurements made by TOTEM/CMS experiments cooperation [6].

The timing detectors will be placed in a Roman Pot of a new design. It includes a very thin $(0.2 \div 0.3$ mm) window groove. It can only withstand overpressure of 1 bar_a and thus some precautions, like installing rapture discs, will be made to prevent destruction of the Roman Pot in case of ACSs failure. The Roman Pot also contains a ferrite ring for absorbing electromagnetic field generated by passing beam particles. It heats up during runs and in the case of reaching its curie temperature (375 °C for ferrite material TT2-111R used) loses its electromagnetic properties. It is therefore desired to use the ACS for cooling not only detector electronics but the ferrite ring as well.

A mock-up bottom part of Roman Pot was used instead of the real Roman Pot for this measurement due to safety reasons (described above). However, the same Roman Pot top flange can be used for both measurement and final application in LHC. Measurements with the real bottom part of Roman Pot are yet to be carried out before installation of the system.

2. Setup description

The setup for commissioning of the ACS system has been installed in CERN laboratory R-N14. Scheme of the setup is shown in Figure 4. Pressurized air was distributed from the mains through a distribution manifold with mechanical flowmeter, pressure regulator and air filter. Despite several attempts to raise the input air pressure from mains, pressure of only 6.3 bar_a was achieved. This pressure value is sufficient for operating the ACS but it doesn't

meet its optimal design parameters, so the lowest cooling air temperature and maximal cooling performance have not been reached during the test.

The whole setup includes besides ACS system, Roman Pot mock-up and air supply manifold also a DAQ system (sensors, ELMB, KVASER and PC, chapter 2.4), power sources (one for DAQ electronics and one for heater attached to a heat exchanger inside Roman Pot mock-up, chapter 2.2, to simulate heat dissipation) and a vacuum pump for evacuating the Roman Pot mock-up inner volume.
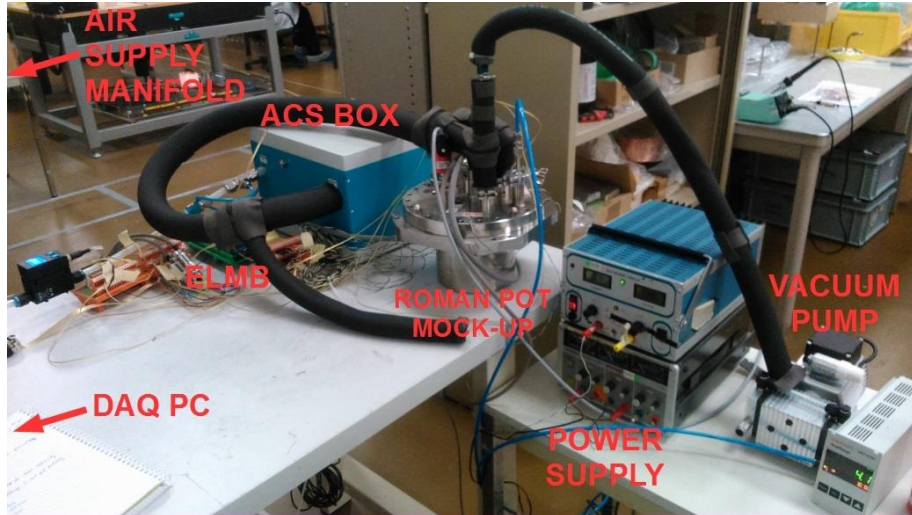

Figure 8: Setup for commissioning in CERN laboratory R-N14
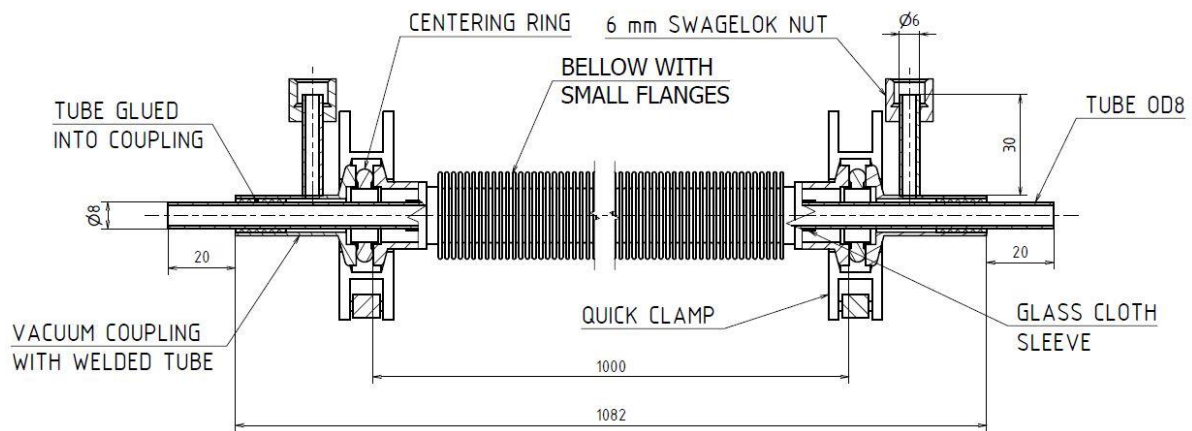
2.1 Interconnecting tube

Figure 9: Schematic drawing of interconnecting tube assembly

An interconnecting tube, which connects ACS BOX precooled air output with main vortex tube placed on Roman Pot, has been assembled. The main part is a bellow with small flanges that is secured with vacuum couplings via centering rings with O-ring seals and quick clamps. An 8 mm OD plastic tube (material of this particular plastic tube is allowed to use in strict conditions of the tunnel of LHC) is glued into the couplings on both side to create a double jacket tube (Figure 9) and it therefore cannot be disassembled. The inner plastic tube is overlaid with glass cloth sleeve to prevent the plastic tube from directly touching the outer bellow improving its thermal resistance. The whole tube is also insulated with ARMAFLEX insulation sleeve.

This interconnecting tube can be operated in two different modes (see Figure 10):

1) One connection of vacuum coupling closed with a cap and the second one is connected to a vacuum pump to enhance the insulation effect.

2) The connection on the vacuum coupling on the side of main vortex tube is connected to the outlet of cooling air from the Roman Pot. A counter flow passing through the outer jacket of interconnecting tube is established and the interconnecting tube works as a counter flow heat exchanger. The airflow from the coupling outlet on the side of box is then wasted.
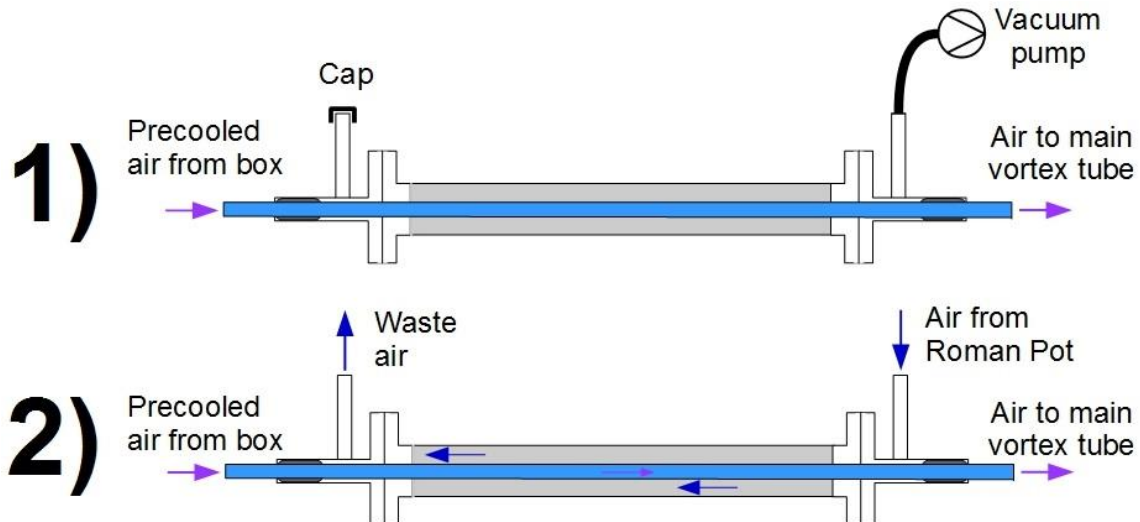

Figure 10: *Different operational modes of interconnecting tube*

Since the air flow exiting the Roman Pot outlet is in most cases colder than the precooled air from the BOX (depending on the heat power dissipation), the second operational mode is more efficient in the mean of lower precooling air heat ingress. Downside of this arrangement is higher cooling air temperature stabilization time. It is caused by positive feedback loop connection of interconnecting tube and main vortex tube.

Figure 11: *Detail of connection of Roman Pot and interconnecting tube*

The Figure 11 shows detail of connection of the flexible tube to the flange of the Roman Pot. This is not the final shape, because the Roman Pot and the ACS BOX next to the Roman Pot unit may have different arrangement.

2.2 Heat exchanger

A thick-finned, aluminium alloy heat exchanger (HEX) is used for commissioning measurements. It has one input and one output connected with many channels inside (Figure **13**). It is installed vertically inside the Roman Pot cavity due to its dimensions. Even though it was designed for electronic components cooling, its use inside Roman Pot is most likely temporary. A final design of the detector electronic components will probably require a modified heat exchanger to achieve proper cooling down.
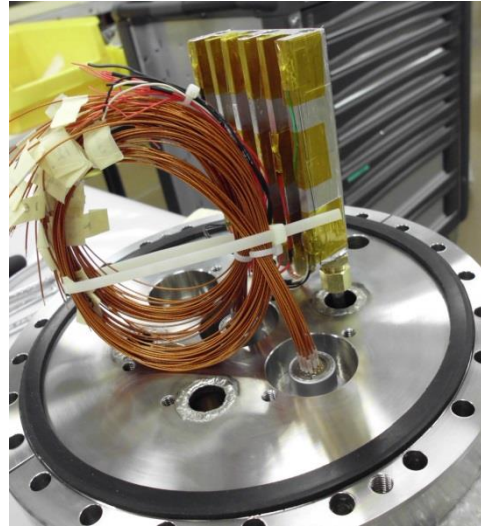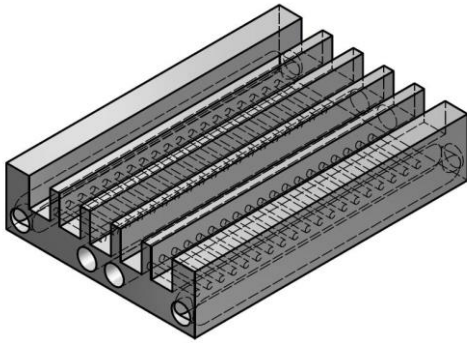

Figure 12: HEX: 3D drawing (left) and detail of HEX mounted on Roman Pot flange (right)

There have been already 9 temperature sensors (Pt 1000) and a heater attached to it from previous measurements with the AIRCOOLER SPLIT prototype. Position of the sensors is described further in next chapter.

2.3 Sensors

Pressure, flow and temperature sensors have been installed in the setup in order to monitor the performance of the system (Figure 4).

A thermoelectric flowmeter FESTO SFAB 600U and a HUBA CONTROL 510 pressure voltage transducer are installed on the input of pressurized air to the system.

In total there are 3 sets of temperature sensors placed in the system: sensors measuring the overall setup (Pt 1000), sensors on HEX inside Roman Pot (Pt 1000) and sensors on the Roman Pot flange (NTC).

When measuring temperature of a flowing fluid,

Table 3: Name of temperature sensors on setup (see Figure 4)

Sensor number	Sensor name
1	AIR IN
2	ON HEX
3	BOX OUT
4	ON INT TUBE
5	AIR TO MAIN VT
6	MAIN VT HOT
7	AIR TO RP
8	POT OUT

sensors should be in general placed directly in the flow. In this case it was decided otherwise to avoid creating more unnecessary junctions in the system. It doesn't significantly affect the temperature measurement but it takes more time to measure stabilized values.

Temperature sensors measuring the overall setup (names of sensors are listed by number in Table 3**:** Name of temperature sensors on setup) are placed on metal parts of the system (fittings, cold end of vortex tube etc.), except sensor MAIN VT HOT, which is placed directly in the air flow (waste air from main vortex tube hot end).

Position of temperature sensors on heat exchanger is shown in Figure 13. There is a flat silicone coated heater with nominal resistance of 182 Ω placed on its backside. Changing supply voltage on the adjustable power source can easily set the actual heating power.
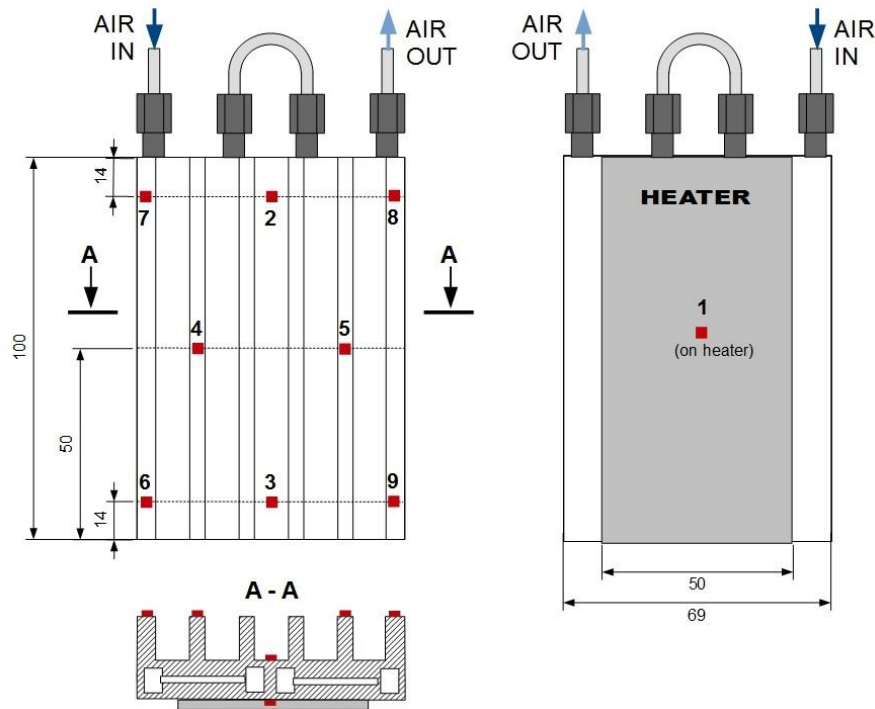

Figure 13: Position of temperature sensors on HEX

The sensors and heater are connected to the DAQ system and power supply through vacuum cable feedthroughs placed on the Roman Pot flange. They aren't connected directly to the feedthroughs, but via a simple PCB placed inside the Roman Pot cavity (Figure 14). The PCB can accommodate also RADMON detector, however, it has not been yet placed on the PCB since there is no use for it. Three cables in total are used:

1. Cable C1 for readout of the RADMON detector and one temperature sensor (Pt 100) that will be placed on the PCB. This cable is not connected yet.
2. Cable C2 for readout of temperature sensors on HEX (Pt 1000). Since 8 channels were available on this cable, only sensors 1 to 8 (see Figure 13) are connected.
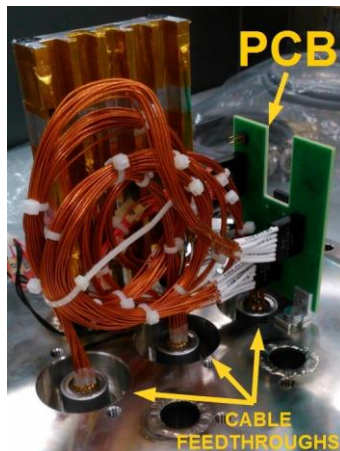3. Cable C3 for power supply (heater on HEX).

Figure 14: Detail of connection of temperature sensors and heater

In addition, there are 6 sensors (NTC) placed on top and bottom of the Roman Pot flange (Figure 15). They can monitor how the Roman Pot is outer shell is being cooled down by mechanical junction of the main vortex tube to the Roman Pot flange. It can be either beneficial or undesirable, depending on how much heat power is needed to dissipate from the detector inside the Roman Pot or from the ferrite ring placed underneath the Roman Pot flange.
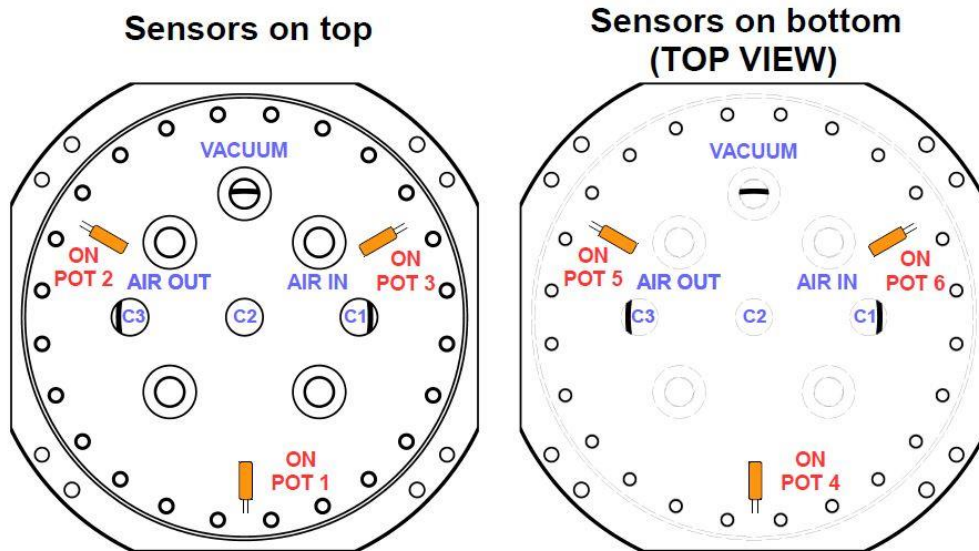

Figure 15: Position of temperature sensors placed on Roman Pot flange

2.4 DAQ system

The DAQ system for sensor analogue output signal readout is based on the ELMB (Embedded Local Monitor Board). It is a universal I/O module with both digital and analogue input and digital output. It can read up to 64 input signals using different adaptors for each sensor type (measuring resistance, voltage or current). The adaptors are placed at the bottom of the board and can be changed easily. One adaptor usually covers 4 channels [7].

The ELMB is than connected to PC indirectly, using a CAN/USB converter called KVASER. The measured data is read on the PC via the CANOpen OPC Server.

The SCADA (Supervisory Control and Data Acquisition) software called WinCC OA is used to display and archive measured data. It features run-time database, archiving, graphical editor, application programming and more. A previously developed user interface has been used and modified for our purposes.
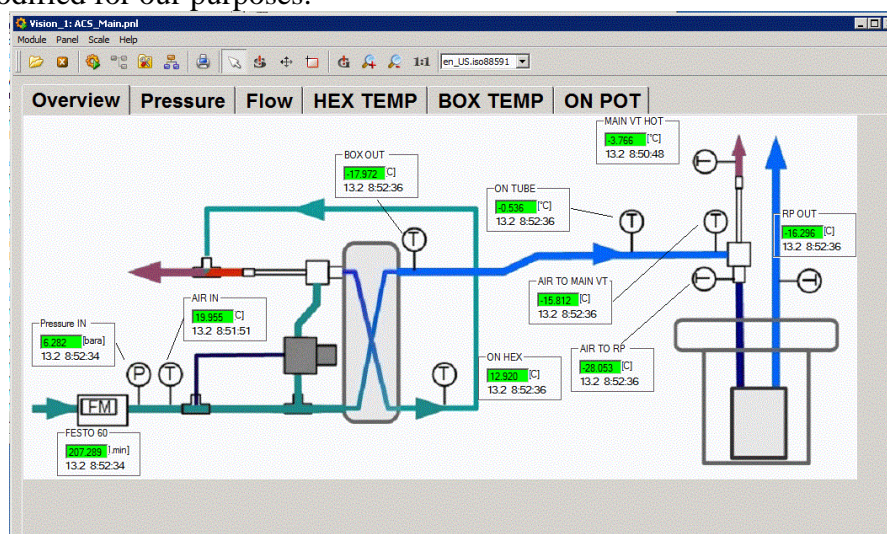

Figure 16: Visualization of actual measured values

3. Performance verification measurement

Various measurements have been executed to test function and performance of the AIRCOOLER SPLIT ACS system together with Roman Pot mock-up.

Parameters of the input air (i.e. pressure, flow and temperature) are listed in the Table 4. Both input air pressure and air flow remained constant during the measurement, room temperature (sensor AIR IN) ranged between 19.6 and 21 °C. Its change over measurement duration (21 hours) isn't significant and therefore can be considered constant with its average value of 20.1 °C.

Table 4: *Input air parameters*

Commissioning measurement input air parameters	
Input pressure [bar$_a$]	6.29
Input air flow [Nl/min]	207
Input air temperature (avg.) [°C]	20.1

The ACS system is designed to operate nominally at input pressure around 8 bar$_a$ and relevant input air flow around 280 Nl/min in order to give the best performance.

Development of temperatures monitoring overall state of the setup can be seen in Figure 17. The measurement is divided into two parts. In the first part, the system is left to stabilize and cool down to its maximum. In the second part, heater attached on the heat exchanger is turned on.
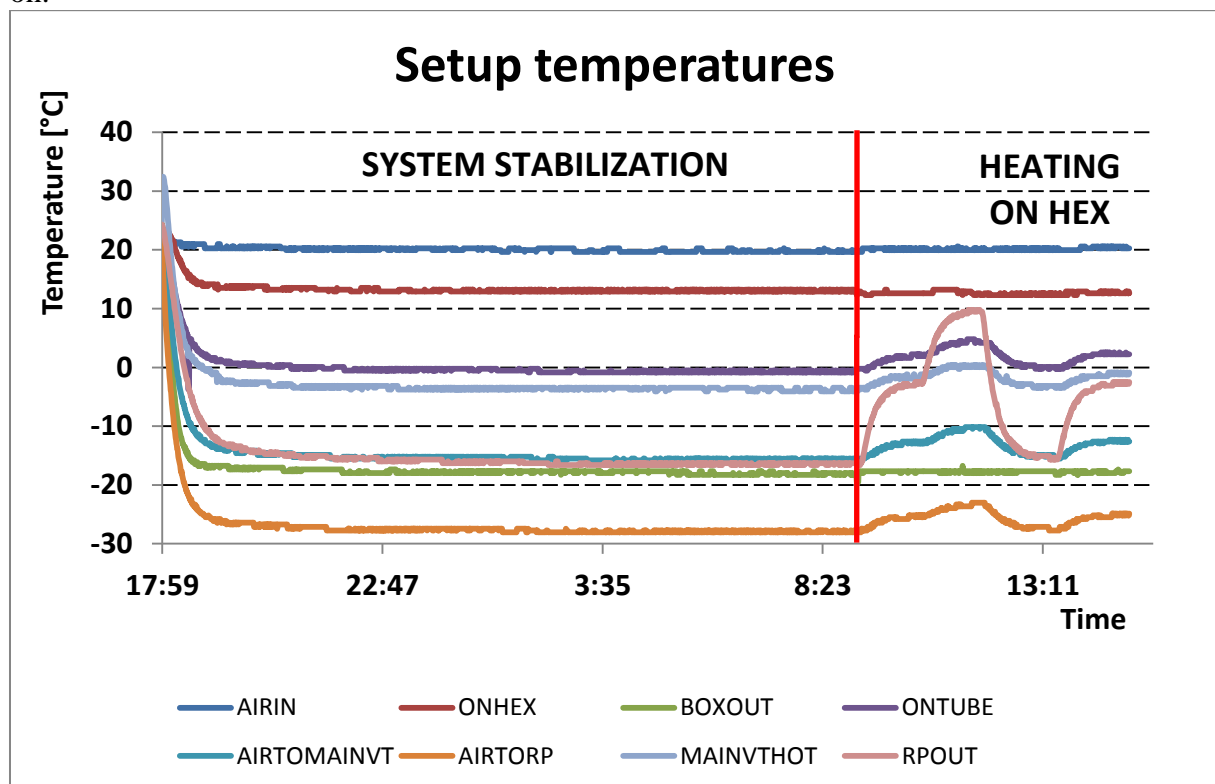

Figure 17: *Graph of setup temperatures development*

The temperature difference between AIR IN and AIR TO RP measured at the stable condition of the system is 47.7 °C. It is one of the most important parameters measured and it can represent performance of the system. It compares with the system static characteristic (in Figure 7 the temperature difference is labelled as T1-T3).

No problems such as water condensing/freezing inside the vortex tube have occurred. It would appear in the graph by sudden increase of BOX OUT and/or AIR TO RP temperatures

(outputs of vortex tubes). No visible frost on the outside structure of the system was observed due to proper insulation.

Graph of overall system temperatures measured during heating cycles is displayed in Figure **18**. It shows the influence of the counter flow flexible tube operating mode: as the temperature RP OUT rises with higher heat load, all of the other temperature values listed rise as well. Temperatures would stay at the same level in case of the first flexible tube-operating mode (outer jacket evacuated) but the system would perform worse.

The temperature of the interconnecting tube surface is important value because unwanted water condensation on its surface in the operating environment (LHC) may appear. Even though the interconnecting tube is thoroughly insulated, its surface temperature should not be lower than surrounding air dew point temperature. A measurement at full operational pressure (8 bar$_a$) needs to be carried out in order to evaluate this criterion.

The heater was turned off after 2 heating cycles at 5 and 10 W and the system was left to cool down fully with maximal capacity. The heater was later set back to 5 W to check if the system would reach the same result as before.
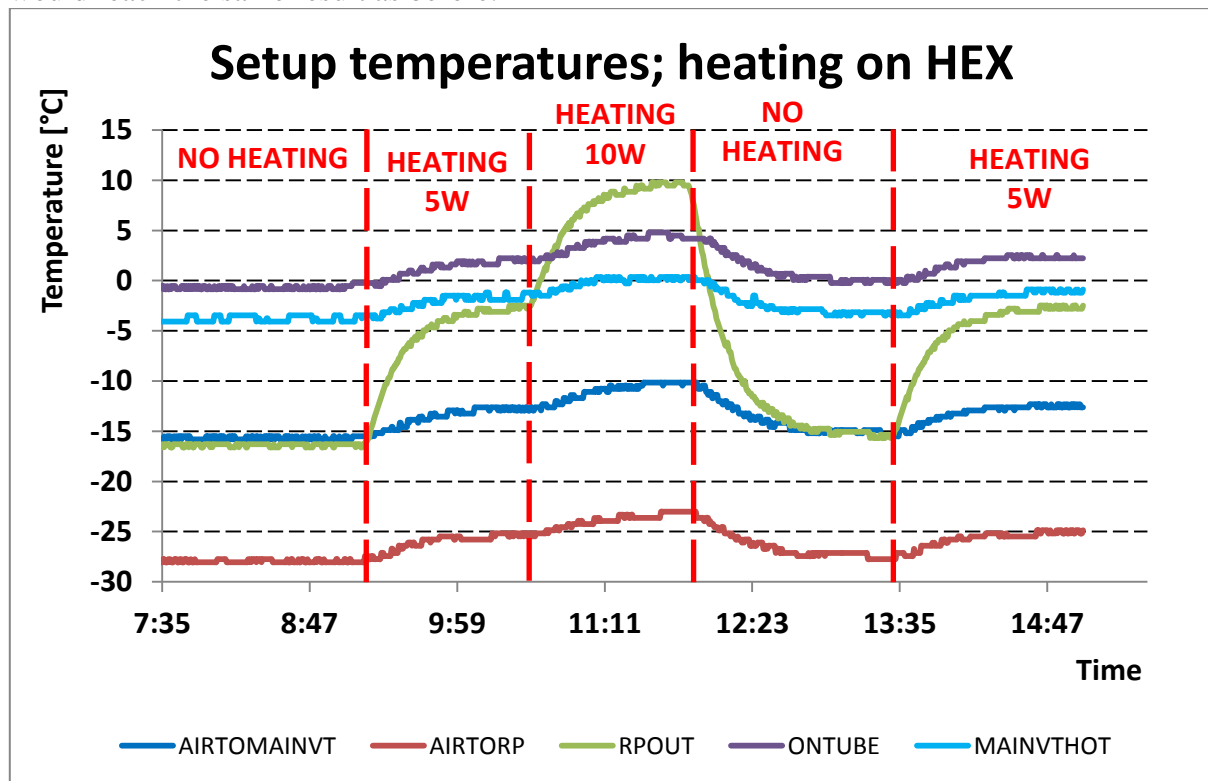

Figure 18: Overall system temperatures during heating cycles

Temperature on the surface of HEX was monitored on 8 spots during the measurement (Figure 19). It represents the final cooling potential available. Since there are 8 sensors in total only their maximal, minimal and average value is displayed (except for the sensor placed on heater).
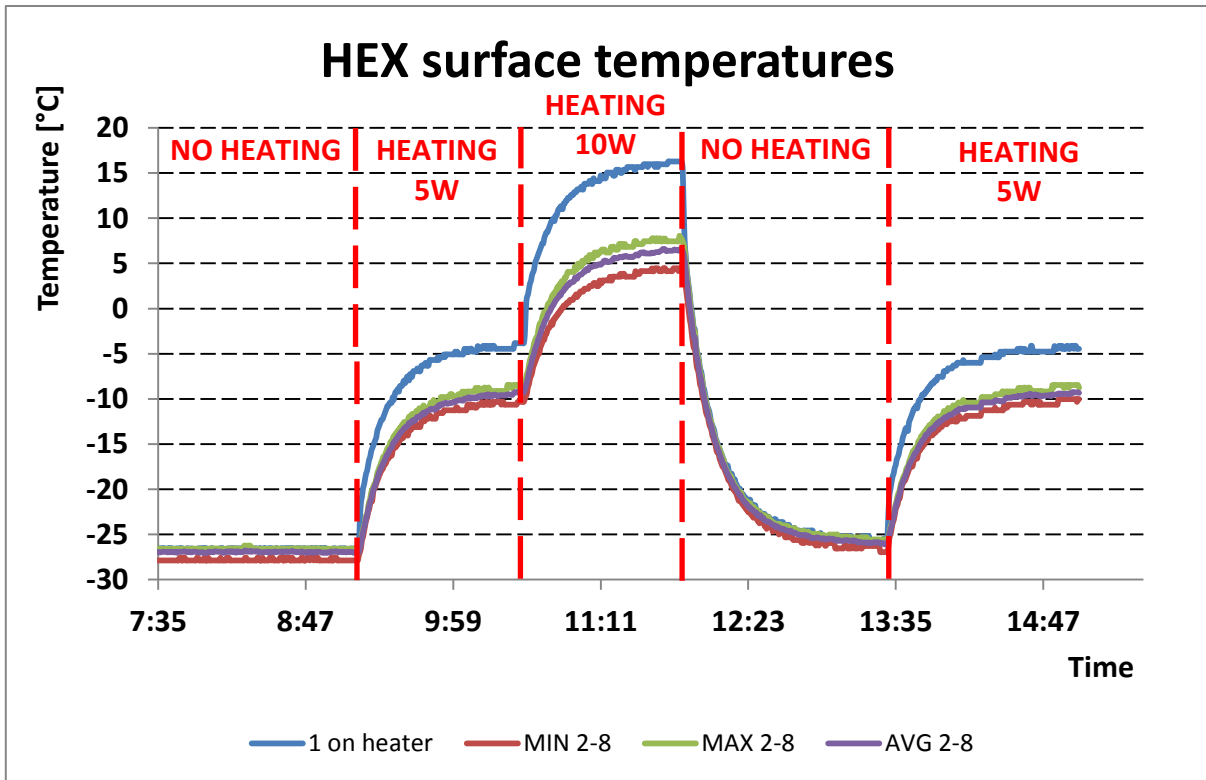
Figure 19: Temperatures on heat exchanger inside Roman Pot

The last set of temperature sensors monitored surface temperature of the Roman Pot flange (**Figure 20**). It takes a lot of time until the flange temperature is stabilized due to the large time constant. It's the main reason why stabilized temperature wasn't achieved during the heating cycles and the cool down period between them. The lowest temperature of the flange shows sensor ON POT 3 that is placed close to the cooling air input feedthrough on the Roman Pot flange (see Figure 15). The highest temperature is shown by sensors ON POT 1 and ON POT 4 placed in the opposite side of the flange than cooling air input and output.
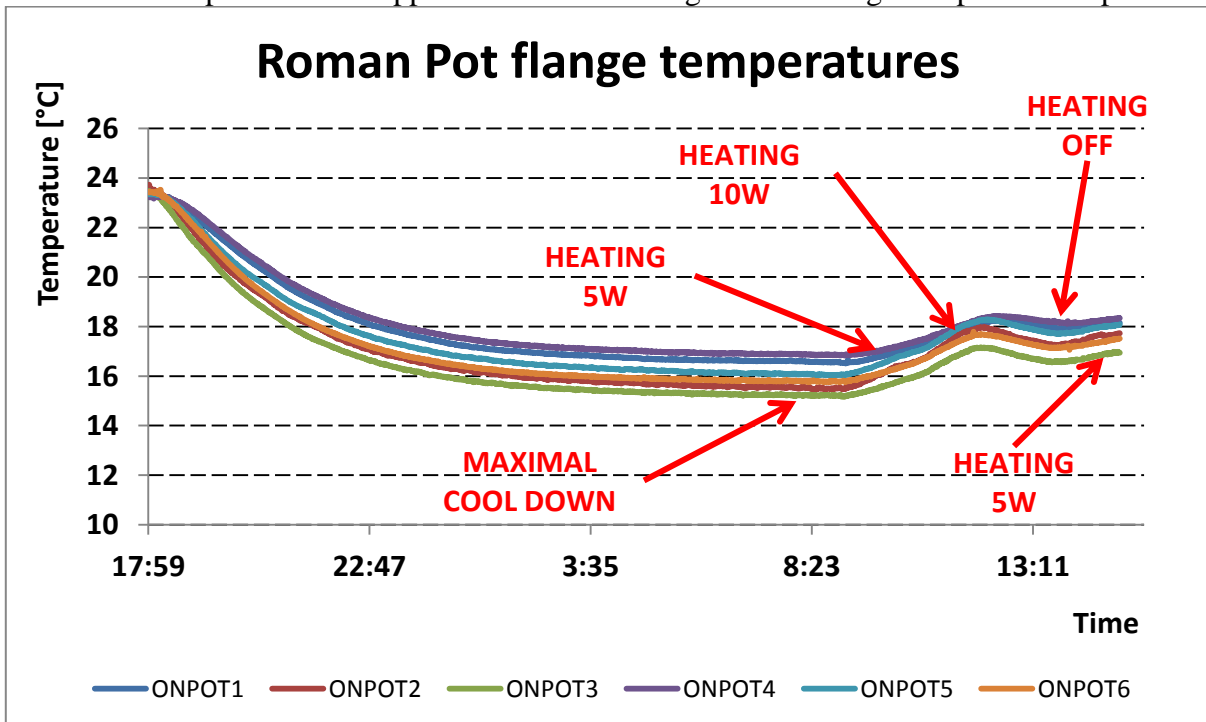

Figure 20: Graph of temperatures on Roman Pot flange surface

4. Conclusion

The new design of the AIRCOOLER SPLIT (ACS) has been tested together with Roman Pot mock up. Observed performance of the ACS met the static characteristic found with the previous AIRCOOLER SPLIT prototype. Full cooling potential of the AIRCOOLER SPLIT could not be achieved due to insufficient input air pressure.

The new improved design of interconnecting tube was deployed. It performed well and without any complications. The operating mode will be chosen by the amount of heat dissipated by cooled detector (and Roman Pot). Since no excessive heat load is expected, the second operating mode (counter flow heat exchanger) will be probably chosen for the flexible interconnecting tube.

The last tests with real Roman Pot are foreseen before installation of the two ACS devices into the LHC tunnel. The installation is planned for 35th or 46th week of 2015.

List of symbols

ΔT	temperature difference	(°C)
$\dot{m}_{cold}$	cold air mass flow	(Nl/min)
$\dot{m}_{tot}$	total air mass flow	(Nl/min)
P	input air pressure	(bar)
T_1	input air temperature	(°C)
T_2	precooled air temperature	(°C)
T_3	cooling air temperature	(°C)
Q_1	input air mass flow	(Nl/min)
Q_2	cooling air mass flow	(Nl/min)

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