Cryogenic upgrade of the low heat load liquid helium cryostat used to house the Cryogenic Current Comparator in the Antiproton Decelerator at CERN

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Abstract. The Cryogenic Current Comparator (CCC) and its purpose built cryostat were installed in the low-energy Antiproton Decelerator (AD) at CERN in 2015. A pulse-tube cryocooler recondenses evaporated helium to liquid at 4.2 K filling the helium vessel of the cryostat at an equivalent cooling power of 0.69 W. To reduce the transmission of vibration to the highly sensitive CCC, the titanium support systems of the cryostat were optimized to be as stiff as possible while limiting the transmission of heat to the liquid helium vessel. During operation the liquid helium level in the cryostat was seen to reduce, indicating that heat load was higher than intended. To verify the reason for this additional heat load and improve the cryogenic performance of the cryostat, an upgrade was undertaken during the 2016 technical stop of the AD. This article presents the studies undertaken to understand the thermal performance of the cryostat and details the improvements made to reduce heat load on the liquid helium vessel. Also discussed are the procedures used to reduce the diffusion of helium to the vacuum space through ceramic insulators. Finally the upgraded cryogenic performance of the cryostat is presented.

1. Introduction
The CCC cryostat was installed in the Antiproton Decelerator (AD) at CERN during 2015 to house the cryogenic current comparator (CCC) [1]. The CCC uses a superconducting quantum interference device (SQUID) to calculate the AD beam intensity by measuring the distribution of its magnetic field [2], [3]. Operating at 4.2 K the CCC is cooled using liquid helium (LHe) supplied by a pulse tube re-liquefier which provides an equivalent cooling power of 0.69 W at 4.2 K [1].

The SQUID is highly sensitive to mechanical vibrations [4] so the cryostat was designed with a special titanium support system to minimize the transmission of vibration [1]. During its first period of operation, it was not possible to keep a stable level of LHe in the cryostat due to a heat load of 1.04 W on the helium vessel (HV), 0.47 W higher than intended by design [1].

To improve the cryogenic performance of the cryostat and ensure a stable LHe level, an upgrade was undertaken during the shutdown of the AD at the start of 2016. During commissioning, gaseous helium (GHe) was found to be diffusing through the ceramic insulator integrated in the HV beam tube, reducing the performance of the insulation vacuum of the cryostat. This article discusses the improvements made to reduce heat load on the HV and thermal shield (TS), as well as the procedure put in place to manage the effect of diffusion of helium through the ceramic insulators.
2. Improvements to the thermal design of cryostat

The following modifications were made to the cryostat to reduce heat load on the HV and TS:

2.1. Titanium support rods: Removal of strain gauges and cables

To verify the pre-loading of the support rods and monitor loading during cooldown a strain gauge was fitted to each support rod. Due to schedule pressure during assembly, the routing and material of the copper cables were not thermally optimized, adding significant heat load. During the first cooldown of the cryostat, the mechanical behavior of the support system was as expected, reducing the need for monitoring. Therefore, it was decided to completely remove the strain gauges and all associated cables.

2.2. Titanium support rods: Reduction of cross sectional area

The design of the cryostat aims to optimize thermal and mechanical performance to retain a stable amount of LHe. The support rods were designed to be as stiff as possible to avoid mechanical resonance with harmonic oscillations originating in the AD complex or from the re-liquefier (1 to 2 Hz and 50 Hz), while having a small cross section to limit heat load from thermal conduction [1].

The mass of the CCC installed in the cryostat was 36 kg, 19 kg less than originally specified, meaning that the stiffness of the support rods could be reduced while still obtaining a similar dynamic response. The cross sectional area of the HV and TS support rods was reduced from 20 mm² to 16 mm² and 20 mm² to 13 mm² respectively. This area reduction was calculated to reduce the conductive heat load on the HV and TS by 0.06 W and 1.04 W respectively, while reducing their first modes of vibration by 1.1 Hz and 2.4 Hz respectively. Further details of the changes in the mechanical performance of the cryostat before and after the upgrade can be found in table 1.

2.3. Multi-Layer insulation (MLI): Addition of MLI along support rods

The heat load due to radiation on the surface of the support rods was not originally considered. However, due to the complexity of the support system, the total surface area of the 24 support rods is approximately 0.14 m². Assuming that the surface temperature of each support rod varies linearly from 300 K to 75 K the total heat load from radiation may be as much as 3.8 W.

To reduce the heat load from thermal radiation 5 layers of MLI were added around each support rod as shown in figure 1. To reduce heat transfer by conduction through the MLI, the length of each layer was staggered and thermalized to a decreasing temperature, the outer layer being the longest.

Table 1. Calculated modes of vibration before and after upgrade.

| No. | Modes before cryogenic upgrade | Modes after cryogenic upgrade |
|-----|--------------------------------|-------------------------------|
|     | Frequency (Hz) | Mode shape | Frequency (Hz) | Mode shape |
| 1   | 60.9            | HV transverse           | 59.8          | HV transverse |
| 2   | 62.5            | HV vertical & TS axial | 60.1          | HV & TS axial (in phase) |
| 3   | 64.3            | HV & TS axial (in phase) | 61.1          | HV vertical & TS axial |
| 4   | 72.1            | HV & TS axial (out of phase) | 66.5          | HV & TS axial (out of phase) |
| 5   | 73.1            | SQUID feedthrough pipe  | 72.8          | SQUID feedthrough pipe |
| 6   | 77.9            | Heater tower transverse rocking | 77.8          | Heater tower transverse rocking |
| 7   | 79.1            | Heater tower axial rocking | 78.9          | Heater tower axial rocking |
| 8   | 97.0            | HV rotation about transverse axis | 90.1          | HV rotation about transverse axis |
| 9   | 98.6            | HV rotation about vertical axis | 91.0          | HV rotation about vertical axis |
| 10  | 135.2           | TS transverse           | 118.7         | TS rotation about transverse axis |
| 11  | 135.4           | TS rotation about transverse axis | 145.4          | TS rotation about vertical axis |
2.4. MLI: Improving the continuity of the MLI

There are 39 locations inside the cryostat where support rods, cryogenic piping and braided thermalisation strips pass through the MLI. Each time the continuity of the MLI is broken small levels of thermal radiation can pass, increasing the heat load on the HV and TS by an amount which is difficult to quantify. To prevent the passage of thermal radiation, 3 discs cut from an MLI blanket were installed around the component breaking the MLI as shown in figures 2 and 3. The discs consist of 5 layers of MLI, supplier by Jehier, which were stacked sequentially with the MLI bundles of either the HV or TS. The MLI used consists of layers of double-aluminized Mylar separated with an insulating polyester mesh, in all cases a layer of insulating mesh was left on the outer surfaces of each MLI disc to minimize thermal conduction between the discs and the MLI layers.

2.5. MLI: Addition of MLI on warm surfaces of vacuum vessel (VV) beam tube

As explained in [1], 10 layers of MLI were installed on the cold inner surfaces of the HV and TS beam tubes, in both cases the MLI was held in place using an expanding G10 tube. Due to the compression of the MLI by the G10 tube, it was suspected that its thermal performance may be diminished. To mitigate this issue, 10 additional layers of MLI were installed on the outer surface of the warm VV beam tube, increasing the total number of layers between the TS and VV to 20, see figure 4. To reduce the emissivity of the G10 tubes, 1 layer of MLI was fastened to their inner surfaces with double sided tape as shown in figure 6.
2.6. Summary of calculated heat loads

Table 2 shows the calculated heat loads before and after the upgrade, indicating reductions of 9% and 10% on the HV and TS respectively. The values calculated for thermal radiation neglect the effects of the modifications described in sections 2.3, 2.4 and 2.5, which are difficult to quantify. Columns 3 and 4 show the effect of the heat load from the strain gauge cables, which are calculated to increase the temperature of the TS by 15 K. This increase in TS temperature causes an increase to the conductive and radiative heat loads on the HV. Columns 5 and 6 show the heat loads after the upgrade, indicating a possible reduction of 6.16 W and 0.22 W on the TS and HV respectively.

Table 2. Calculated heat load on HV and TS before and after upgrade.

|                  | Before upgrade - Design (TS = 75 K) | Before upgrade - Inc. strain gauges (TS = 90 K) | After upgrade - Design (TS = 75 K) |
|------------------|------------------------------------|-----------------------------------------------|-----------------------------------|
|                  | TS (W) | HV (W) | TS (W) | HV (W) | TS (W) | HV (W) |
| Thermal radiation|        |        |        |        |        |        |
| Thermal radiation| 2.84^a | 0.12^a | 2.52^b | 0.20^d | 2.91^a | 0.12^c |
| Support rods     | 4.61^ef| 0.26^f | 4.21^ef| 0.34^ef| 3.57^ef| 0.20^f |
| Bayonet connection| 0.49^g | 0.05^g | 0.45^g | 0.05^g | 0.49^g | 0.05^g |
| Safety valve line| 0.56^g | 0.02^g | 0.50^g | 0.03^g | 0.56^g | 0.02^g |
| SQUID Feedthrough| 0.53^g | 0.06^g | 0.48^g | 0.07^g | 0.53^g | 0.06^g |
| Instrumentation  | 0.06^h | 0.04^h | 0.06^h | 0.04^b | 0.06^h | 0.04^h |
| Heater line      | 0.09^g | 0.01^g | 0.09^g | 0.01^f | 0.09^g | 0.01^g |
| Strain gauge cables|  -    | -      | 6.07^i | -      | -      | -      |
| Total            | 9.17   | 0.57   | 14.38  | 0.74   | 8.22   | 0.52   |

^a Assumes that the radiation heat flux from 300 K to 75 K is 1.2 W/m² on outer diameter and end faces (25 layers of MLI) and 3.1 W/m² on beam tube (10 layers of MLI).

^b Assumes that the radiation heat flux from 300 K to 90 K is 1.1 W/m² on outer diameter and end faces (25 layers of MLI) and 2.8 W/m² on beam tube (10 layers of MLI).

^c Assumes that the radiation heat flux from 75 K to 4 K is 0.1 W/m² (10 layers of MLI).

^d Assumes that the radiation heat flux from 90 K to 4 K is 0.16 W/m² (10 layers of MLI).

^e All or part of heat load brought to TS through thermal intercept (copper braid).

^f Integral thermal conductivity calculated from [5].

^g Integral thermal conductivity calculated from [6].

^h Including SQUID cable and Manganin cryogenic instrumentation cables.

^i Conduction only, radiation on cables is neglected.
3. Cryogenic upgrade
The disassembly, upgrade and reassembly of the cryostat was undertaken by the Cryolab at CERN with support from the CERN main workshop using the method described in [1]. It was ensured that the modifications to the MLI described in section 2 were undertaken to the highest quality. As with the original assembly, the two difficult steps were the alignment of the beam tubes and the pre-loading of the support rods, which were undertaken without the strain gauges. Figure 5 shows the rear support rods after assembly, figure 6 shows the HV and TS beam tubes and the MLI mounted inside them.

![Figure 5. MLI on support rods and TS after installation into the VV. The stainless steel support ring can be seen at the top of the image, connecting to the titanium links of the support system.](image)

![Figure 6. MLI on TS beam tube.](image)

4. Commissioning, cryogenic testing and operation

4.1. Cryogenic testing without re-liquefier
The HV was cooled to 4.2 K and filled with 46.7 liters of LHe. Once stable, the volume of LHe and the temperature of the TS were monitored for a period of 20 hours as the cryostat was left to warm up naturally, the results are shown in figure 7.

![Figure 7. Cold test: Without re-liquefier.](image)

![Figure 8. Cold test: With re-liquefier.](image)
The LHe level in the HV reduced by 16.7 liters, equating to a heat load of 0.59 W, a reduction of 43% when compared to the value of 1.04 W measured before the upgrade.

The change in temperature of the TS equates to an average heat load of 4.20 W based on the integral specific heat capacity of copper from 68 K to 95 K, much lower than calculated in table 2. The cooling of the TS is influenced greatly by the stability of mass flow through the cooling circuit. A high level of evaporation due to the lack of cooling of the HV may cause the TS temperature to be lower than expected during stable operation.

4.2. Cryogenic testing with re-liquefier

After the HV was cooled to 4.2 K and filled with 48.7 liters of LHe, the re-liquefier was turned on. It took 30 hours for the pressure in the cryostat to stabilize, at this time the increasing TS temperature began to decrease, stabilizing at 88 K. As shown in figure 8, the LHe level was relatively stable throughout the test demonstrating the successful stable operation of the cryostat (small changes in level are due to the high dependency of the density on the saturation pressure and the temperature of the LHe bath).

4.3. Diffusion of LHe into the vacuum space through the ceramic insulators

After re-installation in the AD, it was observed that the cryostat no longer retained a stable level of LHe. The insulation vacuum pressure of $9 \times 10^{-6}$ mbar measured after assembly was seen to have degraded to $1 \times 10^{-2}$ mbar. Leak testing found helium in the vacuum space which was ascertained to have slowly diffused through the ceramic insulators in the HV beam tube at the rate of $7 \times 10^{-4}$ mbar·l/s, 50 times the value expected by design. To reduce the diffusion of helium to an acceptable level, the cool down procedure was modified to take advantage of the cryogenic effect on diffusion though the ceramic insulator when its temperature drops below 70 K. After the vacuum space and process circuits are purged, vacuum pumping continues while LHe is used to cool the cryostat to 70 K achieving a vacuum of $5 \times 10^{-7}$ mbar. The re-liquefier is then activated and vacuum pumping is stopped. Cool down continues to 4.2 K using LHe and the re-liquefier, by which time the vacuum improves to $9 \times 10^{-8}$ mbar due to cryopumping. Unfortunately, the vacuum is not stable and degrades to $9 \times 10^{-7}$ mbar after 20 days, at which time it begins to affect the performance of the cryostat. To remain operational the insulation vacuum must be pumped to maintain a pressure less than $9 \times 10^{-7}$ mbar for as long as possible.

4.4. Thermo-acoustic oscillations during filling

Thermo-acoustic oscillations are still observed during filling of the cryostat [1] and have not been reduced by the addition of buffer volumes on the thermal shield return line and on the SQUID connection line. Once they begin, the oscillations can be stopped by reducing the pressure in the cryostat to 1 bar for around one minute.

5. Conclusions

The cryogenic upgrade of the CCC cryostat has reduced the heat load on the HV and TS to an acceptable level allowing operation with a stable level of LHe. Results from the CCC indicate that this result has been achieved without a significant reduction in mechanical performance.

The discovery of helium diffusing through the ceramic insulators in the HV and the subsequent degradation of the insulation vacuum has revealed a significant new source of heat load. This degradation can be managed by the application of a modified cool down procedure and monthly vacuum pumping. A permanent repair would require either coating or replacement of the ceramic insulators.

Further study is required to eliminate the thermo-acoustic oscillations apparent during filling.
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