The cryogenic system of the Large Hadron Collider (LHC) under operation at CERN has a total helium inventory of 140 t. Up to 50 t can be stored in gas storage tanks. The remaining inventory will be stored in a liquid helium storage system consisting of six 15-t liquid helium tanks in 4 locations. The two liquid helium tanks of specific low heat inleak design and the required infrastructure of the first location were recently commissioned. Four additional tanks shall be operational end 2010. The paper describes the features and characteristics of the liquid helium storage system and presents the measurement of the thermal performance of the two first tanks.
INTRODUCTION

In order to store at CERN about 30 t of LHC helium inventory a liquid helium storage system was erected close to the 18 kW refrigerator located at LHC Point 18. This system consists of two horizontal 15-t liquid helium tanks installed on a solid foundation designed in accordance with safety analysis including seismic, a 11 m³ liquid nitrogen tank, a combined liquid helium line (supply liquid helium/return cold helium gas) including a distribution box, liquid nitrogen distribution lines, low pressure and high pressure lines for gaseous helium and related instrumentation. Four other 15-t tanks to be installed in a similar way at three other LHC Points will complete by end 2010 the 90-t required LHC liquid helium storage capacity.

ARCHITECTURE

The tanks are connected to the 18 kW LHC refrigerator via a combined cryogenic helium line which allows helium transfer from the LHC to the tanks and back. The tanks are equipped with bayonets in order to transfer helium from or to mobile containers to adjust LHC helium inventory when required. The liquid helium tanks are equipped with two active thermal shields in order to minimize heat inleak. The first shield is kept at 80 K by liquid nitrogen, the second one at about 20 K by cold helium vapor. A view of the 30-t liquid helium storage system located at LHC Point 18 is shown on Fig. 1.
RISK ANALYSIS

As the stored volume of liquid helium is exceptional, a comprehensive risk analysis [1] according to EU rules was performed. Risk was assessed according to items listed in Table 1.

Table 1, General and specific risks

<table>
<thead>
<tr>
<th>Items related to general risk</th>
<th>Items related to specific risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology and seismology</td>
<td>Over pressure</td>
</tr>
<tr>
<td>Meteorology</td>
<td>Degradation of vacuum insulation</td>
</tr>
<tr>
<td>Fire</td>
<td>Oxygen deficiency</td>
</tr>
<tr>
<td>Collision with a truck</td>
<td>Noise</td>
</tr>
<tr>
<td>Plane fall</td>
<td>Jet of cryogen</td>
</tr>
</tbody>
</table>

ELEMENTS DESCRIPTION

Liquid helium tanks [2]
The required parameters of each horizontal tank are listed in Table 2.

Table 2, Required parameters of horizontal tanks

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of liquid helium</td>
<td>120 m³</td>
</tr>
<tr>
<td>Design pressure</td>
<td>3 bar</td>
</tr>
<tr>
<td>Maximum loss rate</td>
<td>0.52 g/s</td>
</tr>
<tr>
<td>Maximum flow of filling and withdrawal</td>
<td>200 g/s</td>
</tr>
</tbody>
</table>

The basic construction for the inner vessel and related pipes is low carbon austenitic stainless steel. Outer vessel is in carbon steel. All low temperature parts are vacuum insulated and thermally protected by multilayer insulation.

Each tank is equipped respectively with level meter pressure sensor and a temperature sensor is installed on helium outlet shield line, see Fig. 2.

Liquid nitrogen tank and line
The liquid nitrogen tank installed at LHC Point 18 is a standard vertical tank with a volume of 11 m³, a design pressure of 18 bar and a working pressure of 1.25 bar. The tank is equipped with a pressure sensor and a level measurement, see Fig. 2.
A semi-rigid line supplies liquid nitrogen from the nitrogen tank to the nitrogen shield of the helium tanks.

**Combined cryogenic helium transfer line**
The combined line [3] transfers helium between the 18 kW refrigerator of LHC Point 18 and the helium tank in both directions:
- From the refrigerator to the helium tanks as saturated liquid helium,
- From helium tanks to the refrigerator as gaseous helium at 5 K.
The line consists of four concentric corrugated pipes of an external diameter 150 mm. The length of the line is about 100 m. The internal pipe is dedicated to transfer of liquid helium, inter-circular space between 2\textsuperscript{nd} and 3\textsuperscript{rd} pipe to cold return gaseous helium.

Integral part of the line is a distribution box. This box splits helium between tanks. The box is equipped with a by-pass cryogenic valve allowing the independent cool-down of the line and with a thermometer T which is installed in the helium gas return line.

**Warm helium lines**
High pressure line (HP) brings gaseous helium to pressurize the tank to empty it to a transport container or to vapourize liquid helium to transfer cold helium gas to the 18 kW refrigerator. The line is also used to pressurize a mobile container to transfer liquid helium from the container to the tank. As the pressure in the HP line can vary from 3 to 20 bar, pressure reducers are installed to set the inlet pressure to the tanks and the containers at about 2 bar.

Low-pressure (LP) line collects boiled off helium leaving tanks via helium shield line. This cold gaseous helium is heated up to ambient temperature with an atmospheric heater. The low-pressure line is equipped with a flowmeter F allowing to measure the heat consumption of the tanks.

**Basement**
Basement for helium tanks of LHC Point 18 were dimensioned on the basis of a seismic analysis. Both tanks are supported in two points. Fixed one is close to the distribution manifold and sliding one on the other end. Each of four concrete blocks is designed for horizontal load of 100 t (70 t weight, 30 t seismic) and vertical one perpendicular on tanks axis of 36 t (seismic). Two blocks for fixed points must withstand in addition 72 t (seismic) in direction of tanks axis. The design of longitudinal girders of different shapes and depth was motivated by the potential lateral and transversal strains that the structure would bear in case of an earthquake. The foundation including embedded metallic plates is dimensioned for eventual future installation of two additional tanks above the existing ones. Attained precision of the plates was better than ± 15 mm from a theoretical position.
Simplified Process and Instrumentation Diagram is shown on Fig. 2. The control of the storage is handled by a dedicated PLC and a SCADA system. The control system [4,5] allows operating the liquid helium storage in a few automatic modes. The six enabled operating modes are as follows: tank cool down, nominal stand-by, filling from truck, emptying to truck, filling from refrigerator and emptying to refrigerator. According to the chosen mode, valves can be operated only under relevant conditions, i.e. they are not blocked by neither a hardware or software interlock.

COMMISSIONING OF THE 2 FIRST TANKS

The complete system was pressure and leak tested, all circuits were flushed by dry gas, and all helium circuits were purged by clean gaseous helium, while content of humidity and oxygen were monitored. Tightness of all valves was checked. All instrumentation and logic system were tested.

Cool down
Tank 1 was cooled down and filled via a transport container. It was cooled down during 4 weeks. The speed of cool down was limited by lack of liquid helium.
Tank 2 first cool down was stopped as during cooling process the tank was seriously damaged. Nitrogen shield consists of three cylindrical sections welded together. Liquid nitrogen cooling pipes are longitudinally welded to the shield. As the welds between the sections were not fully penetrated stresses during the cool down exceeded an allowable strength which caused the shield
to collapse breaking the nitrogen cooling pipe. Cool down restarted a few months later after consolidation of the tank. The weak welds were reinforced and stresses were reduced. In order to control the stresses 10 thermometers and 2 displacement sensors were installed in the tank. These sensors measured relative displacement between the inner vessel and nitrogen shield. The tank 2 was cool down and filled in 2 weeks via the tank 1. During cool down temperature of gaseous helium leaving tanks was monitored by thermometer T.

Thermal performance measurement
Heat in-leak of the tanks was measured by boil-off method. Mass of evaporated helium leaving the tank helium shield circuit was monitored by a flow-meter F. The tanks were thermalised for more than 6 weeks after its first filling. During this period the boil-off rate was stabilized. Boiled-off helium was leaving the flow-meter directly to atmosphere in order to ensure a stable pressure not disturbed by compressor pressure oscillation. The atmospheric pressure slowly fluctuated at intervals ± 5 mbar. Measurement was done with both tanks full. During normal operation, helium shield outlet gas temperatures were 68 K and 29 K for tanks 1 and 2 respectively. Temperature of the tank 2 helium shield was 10 K. Measured results are shown on Fig. 3. Comparison of specified and a measured heat inleak is shown in Table 3. In the Table a correction was applied due to measurement at decreasing level.

Table 3, Comparison between specified and measured heat inleak

<table>
<thead>
<tr>
<th>Heat consumption [g/s]</th>
<th>Specification</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank 1</td>
<td>&lt;0.5</td>
<td>0.13±0.02</td>
</tr>
<tr>
<td>Tank 2</td>
<td>&lt;0.5</td>
<td>0.35±0.05</td>
</tr>
</tbody>
</table>

Figure 3, Measured values, boil-off is not corrected
CONCLUSION

The storage for about 30 t of liquid helium was erected at CERN for a part of the LHC helium inventory. The whole system was commissioned in spring 2009. The measurement confirmed that the required parameters were fulfilled. On the basis of successful repair of the tank 2 based on reviewed calculations, the design of following tanks has been improved. In order to store the whole LHC helium inventory at CERN it was decided to install 4 additional liquid helium tanks. These tanks shall be in operation end 2010.

ACKNOWLEDGEMENTS

The tank 1 was delivered and immediately installed as the first component. All other key components except the tank 2 were delivered later on. Whole system was ready for a cool down only 10 weeks after delivery of the tank 1, thanks to all internal and external participants cooperating on the project with an outstanding effort. Thanks also to all involved on the repair of the tank 2 specifically to Ph. M. Santos Silva for a finite element model.

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