Cryogenic design of the new high field magnet test facility at CERN

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Abstract

In the framework of the R&D program related to the Large Hadron Collider (LHC) upgrades, a new High Field Magnet (HFM) vertical test bench is required. This facility located in the SM18 cryogenic test hall shall allow testing of up to 15 tons superconducting magnets with energy up to 10 MJ in a temperature range between 1.9 K and 4.5 K. The article describes the cryogenic architecture to be inserted in the general infrastructure of SM18 including the process and instrumentation diagram, the different operating phases including strategy for magnet cool down and warm up at controlled speed and quench management as well as the design of the main components.

1. Introduction

For a future upgrade of LHC a new generation of high field magnets is required. New components as well as new magnet technology have to be validated for these new LHC magnets. The design of the new test bench shall provide efficient cool down from 300 K to 80 K and warm up to 300 K, recuperation of helium after a quench, and high cooling capacity at 1.9 K in order to quickly recuperate the nominal conditions after a quench.

The HFM test set-up will be installed in the CERN cryogenic test hall SM18. It will be connected to the existing cryogenic infrastructure; Benda et al. (1996). Its key element is the helium refrigerator with a power of 6 kW at 4.5 K. This refrigerator is used as a liquefier delivering about 27 g/s of saturated liquid helium (LHe) at 1.6 bar. This LHe is collected in a 25 m³ dewar from which it is distributed to the various test stands or clients. The refrigerator can produce also supercritical helium and in parallel supply saturated LHe to the dewar by reducing the inlet pressure. Cooling power at 1.9 K is obtained by two warm pumping units of 6 g/s pumping capacity at 10 mbar each. Both pumping units can be boosted by dedicated “cold compressors”. In this case the pumping speed of each unit is 18 g/s at 30 mbar as the cold compressor compresses helium from 10 to 30 mbar.
At the inlet of each warm pumping unit a very low pressure heater of 32 kW is installed. The pre-cooling of heavy superconducting magnets is achieved via the circulation of temperature controlled helium gas at about 4 bar. There are two pre-cooling units in SM 18 of 120 kW each, in which pressurized gaseous helium (GHe) is cooled down by liquid nitrogen. Circulation is ensured by two compressors with a flow of 90 g/s each. Both pre-cooling units and their associated compressors can be connected in parallel. The pre-cooling system is used to cool down the magnets from 300 K down to 80 K and for their warming up from 5 K up to 300 K. The refrigerator, the cold compressors, the very low pressure heaters and the pre-cooler units are located in the SM18 hall, while the compressors and the warm helium pumping units are located in separate noise-isolated buildings next to the SM18 hall. This cryogenic infrastructure is shared by the horizontal and vertical magnet test facility, radio frequency cavity test facility and two test benches requiring supercritical helium.

The HFM test set-up will be integrated into the vertical test facility [Bajko M. et al. (2012)] with a link to the pre-cooling system of the horizontal magnet test facility [Axensalva J. et al. (2004).] In addition a quench buffer for the recuperation of the helium after a magnet quench will be installed.

2. HFM functional description

The required functions including objectives of maximum duration are summarized in the Table 1.

Table 1. HFM functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Duration</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purge of the system including a leak test</td>
<td>2 h</td>
<td></td>
</tr>
<tr>
<td>Magnet cool down from 300 K down to 80 K</td>
<td>10 h – 200 h</td>
<td>magnet cooling speed limitation</td>
</tr>
<tr>
<td>Magnet cool down from 80 K down to 4.5 K</td>
<td>10 h</td>
<td>with a flow of LHe of 15 g/s</td>
</tr>
<tr>
<td>Cryostat filling with saturated LHe at 1.3 bar</td>
<td>5 h</td>
<td>with a flow of LHe of 15 g/s</td>
</tr>
<tr>
<td>Magnet cool down from 4.5 K down to 1.9 K</td>
<td>24 h</td>
<td></td>
</tr>
<tr>
<td>Nominal conditions during magnet test at 1.9 K or 4.5 K if required</td>
<td>one week</td>
<td>at least</td>
</tr>
<tr>
<td>Quench recovery</td>
<td>24 h</td>
<td>depending on quench energy</td>
</tr>
<tr>
<td>Evaporation of LHe from the system after a magnet test</td>
<td>5 h</td>
<td></td>
</tr>
<tr>
<td>Magnet warm up from 5 K to 300 K including all related equipment</td>
<td>12 h – 200 h</td>
<td>magnet warming speed limitation</td>
</tr>
</tbody>
</table>

The simplified HFM flow scheme is shown on Fig. 1. After the purge and the leak and electrical tests, the system is cool down from 300 K down to 80 K by the above mentioned pre-cooling system. Three circuits are cooled down in parallel: the main (magnet) circuit including the quench buffer via the lines C2 (in) and D (out), see the dash line in Fig. 1, the whole chain of the thermal shield via the lines E (in) and F (out), and the 1.9 K pumping circuit via the lines A (in) and B (out). The same procedure is used during the warm up from 5 K to 300 K. When the magnet reaches 80 K the pre-cooling phase is finished and the cool down to 5 K with liquid helium starts. This phase is ending with the filling of the test cryostat with LHe. The magnet operates in a static bath of pressurized superfluid helium (LHeII) at 1.9 K and 1.3 bar, cooled by a liquid/liquid heat exchanger (L/L HX) fed by saturated LHeII. The LHe is withdrawn from the phase separator, flows through the gas/liquid heat exchanger (G/L HX) and the line A where it is cooled down to 2.2 K, is then expanded before incoming in the L/L HX where the helium is maintained in saturated condition at 1.9 K by pumping via the line B. The layout of the installation is presented on Fig. 2. The HFM functional specification is detailed in Benda V. (2014).

![Fig. 1. HFM simplified flow scheme](image-url)
3. HFM main sub-units

3.1 Test cryostat

The vertical test cryostat [Vande Craen A. et al. (2013)] is horizontally divided by the lambda plate in two parts. The lower compartment is holding the magnet operating in a static bath of pressurized LHeII, cooled by the L/L HX with a saturated helium flow. The upper part of the cryostat, above the lambda plate, is filled with saturated LHe at 1.3 bar. Communication between these two volumes is arranged by a valve which performs also a safety function in case of quench. The upper and the lower volumes are independently supplied with LHe via the lines C1 or C2.

The powering of the magnet is ensured by two pairs of current leads of 10 kA and 20 kA. Their cold terminals are immersed in the saturated LHe of the upper compartment. Superconducting cables connect the cold terminal of the current leads and the magnet bus bars passing tightly the lambda plate.

3.2 Distribution valve box

This valve box separates the incoming helium in gas and liquid into the phase separator and distributes LHe to the test cryostat. The gas leaving the phase separator is cooling down the thermal shield of the whole system via the line E. The distribution valve box contains 11 cryogenic valves, the phase separator, the liquid/gas heat exchanger, the cold buffer and 3 electrical heaters out of which one is in the phase separator. Five cryogenic transfer lines are connected to the valve box.

3.3 Quench buffer

In case of magnet quench the evaporated helium is transferred to the quench buffer via the line D. To keep the quench buffer cold during nominal operation it is actively shielded. The inner vessel is kept at low temperature by a small flow of cold GHe. The quench buffer is connected to the distribution valve box via the quench line.

3.4 Pre-cooling valve box and related lines

The function of this valve box is to control the flow, the pressure and the temperature of the GHe during the cool down from 300 K to 80 K or the warm up from 5 K to 300 K. The pre-cooling valve box is connected to the distribution valve box and to the existing pre-cooling system via the pre-cooling lines.

3.5 Helium rack

The helium rack is the assembly of all the instrumentation at ambient temperature required to manage the cryogenic system. It is holding the following main parts:
- A current leads manifold including flow meters and control valves to control each lead
- A purge collector including the pumping, injection of pure helium and event lines
- A helium guard which is a vessel with pure helium at 1.1 bar holding all the instruments connected to the sub-atmospheric helium circuits in order to prevent suction of air in case of leak

The rack is connected to the distribution valve box and the test cryostat via warm pipes.
4. Magnet test requirements

The magnets are to be tested in vertical position, and quickly installed and dismantled. Heat in-leak shall be minimized and cool down from 4.5 K to 1.9 K shall be less than one day. No helium shall be lost after a quench. Process control shall be fully automatic. The operation shall be safe and simple. The main required parameters of the test bench are summarized in Table 2.

Table 2. Required parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working temperature</td>
<td>1.9 K ± 0.01 K (up to 4.5 K)</td>
</tr>
<tr>
<td>Maximum weight of the cold mass</td>
<td>15 t</td>
</tr>
<tr>
<td>Maximum energy of the magnet</td>
<td>10 MJ</td>
</tr>
<tr>
<td>Maximum magnet diameter and length</td>
<td>D = 1.5 m; H = 2.5 m</td>
</tr>
<tr>
<td>Maximum number of quenches/thermal cycles</td>
<td>10 000/1 000</td>
</tr>
<tr>
<td>Life time</td>
<td>20 years</td>
</tr>
</tbody>
</table>

5. Design strategy

5.1 Magnet cool-down/warm up

The magnet pre-cooling from 300 K to 80 K and warming up to 300 K will be supplied by the existing pre-cooling system. There is already experience with similar process with the 25 tons LHC dipoles [Axensalva J. et al. (2004)].

5.2 Quench recovery

Table 3. List of symbols related to quench recovery

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_q$</td>
<td>Energy of the magnet quench incoming in the helium</td>
</tr>
<tr>
<td>$M$</td>
<td>Mass of LHe in the cryostat</td>
</tr>
<tr>
<td>$U_0$</td>
<td>Original internal energy of helium before the quench</td>
</tr>
<tr>
<td>$\rho_1$</td>
<td>Density at the first step</td>
</tr>
<tr>
<td>$\rho_2$</td>
<td>Density when the buffer volume is included</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Adiabatic exponent</td>
</tr>
</tbody>
</table>

The cold GHe after a magnet quench is collected in a quench buffer which is kept permanently in cold condition. The required buffer volume was calculated in three steps. At the first step we consider that the magnet LHe bath is closed which means that $V=\text{const.}$ and $dV=0$. Applying the first law of thermodynamics:

$$dq = du + pdv \quad \text{for} \quad dv = 0 \quad \text{thus} \quad dQ = dU$$

The dissipated internal energy in the helium after a magnet quench is:

$$dU = Q_q/M$$

The total internal energy after the quench will be:

$$U_1 = U_0 + dU$$

From the total internal energy $U_1$ and the given density ($v=\text{const.}$), the pressure $p_1$ and the temperature $T_1$ can be derived. At the second step the buffer volume is connected and the corresponding pressure reduction can be calculated as an adiabatic expansion:

$$p_2 = p_1 (\rho_2/\rho_1)^\kappa$$

The temperature $T_2$ can then be derived. During the third step the preliminary values of $p_2$ and $T_2$ shall be corrected to take into account that $pv/rT \neq 1$. $\kappa$ is to be corrected accordingly. On this basis the final pressure and temperature can be obtained. Applying this procedure a quench buffer volume of 15 m$^3$ was determined in order not to exceed a pressure of 4 bar in the system after the quench.

5.3 G/L and L/L heat exchangers

For a quick and thermodynamically efficient cool down to 1.9 K, adequate gas/liquid (G/L) and liquid/liquid (L/L) heat exchangers (HX) have to be used.

Pre-cooling of the inlet LHe from 4.5 K down to 2.2 K by saturated GHe at 10 mbar is achieved in the G/L HX. This exchanger is an “LHC standard” heat exchanger designed for a maximum flow of 7.5 g/s. There are about 30 heat exchangers of this type in the LHC working for a few years without any degradation [Gilbert N. et al. (2005)].
The function of the L/L HX is to transfer heat from the pressurized magnet helium bath to the saturated helium at 10 mbar which is maintained at low temperature by pumping. Its design is based on 30 OFE-copper “U” tubes welded to a collector as it is shown on 3. The heat exchanger can extract a maximum power of 90 W, which allows the cool down of a 15 tons magnet in a 2 m³ helium bath from 4.2 K down to 1.9 K in about 1 day. The dimensions of the heat exchanger were calculated according to the following principle. No bubbles shall appear in the saturated LHeII circuit in order to transfer the maximum heat flux. The bubbles are avoided by the weight of saturated helium columns which generate a slight pressurization. On the other hand this height can limit the cooling power through a cross section of the column. On this basis the diameter of the pipe is determined [Bon Mardion G. (1994)]:

\[ A = P / 0.3 \]

In our case for a required cooling power of 1.5 W/pipe the internal diameter of the pipe is 25 mm. For this “thermo hydraulic” design the temperature difference \( dT \) between the magnet and saturated baths shall be checked on the basis of the Kapitza resistance [Pollack G. L. (1969)]:

\[ dT = dT_w + 2dT_K \]

\[ dT_K = (Q x r_K) / S. \]

In the HFM nominal conditions \( Q=25 \) W, \( r_K=2 \times 10^{-4} \) m²K/W at 1.85 K and \( S=2.1 \) m², \( dT \) is less than 0.01 K which is fully acceptable. During cool down \( dT \) will be smaller than 0.03 K.

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>cm²</td>
<td>Required cross section</td>
</tr>
<tr>
<td>( P )</td>
<td>W</td>
<td>Cooling power for one pipe at 2.15 K considering that the pipe height is &lt;0.5 m</td>
</tr>
<tr>
<td>( dT_w )</td>
<td>K</td>
<td>Temperature difference through the wall (negligible for copper)</td>
</tr>
<tr>
<td>( dT_K )</td>
<td>K</td>
<td>Temperature difference due to Kapitza resistance on the walls of the heat exchanger</td>
</tr>
<tr>
<td>( Q )</td>
<td>W</td>
<td>Required total cooling power</td>
</tr>
<tr>
<td>( r_K )</td>
<td>m²K/W</td>
<td>Kapitza resistance at the required temperature depending on the wall material</td>
</tr>
<tr>
<td>( S )</td>
<td>m²</td>
<td>Total exchange surface</td>
</tr>
</tbody>
</table>

5.4 Cryostat heat in-leak

The heat in-leak of the test cryostat at 4.5 K was minimized with, in addition to the standard active thermal shield, the help of two independent cooling systems corresponding to the thermal model shown on Fig. 5.

- an active cooled copper ring around the neck of the cryostat, see Fig. 4 and reference “TA” on Fig. 5a.
- a controlled flow of the evaporated helium rising along the neck of the cryostat ("m²", top of Fig. 5a)

To determine the position of the “branch” which will supply cold GHe to keep the quench buffer permanently cold (line D on Fig 1), the temperature of the GHe incoming into the quench buffer after a quench (about 7.5 K) has been used (see Fig. 5b).

The estimated total heat in-leak in liquid helium above the lambda plate is about 3 W [Hanzelka P. (2014)]. Current leads are not considered in this calculation.

5.5 Simple and quick magnet installation

All the cryogenic connections are performed on the side of the cryostat which simplifies the removing of the insert and of the magnet from the cryostat.
6. Status

The whole project has been split in the following work packages:

- Test cryostat
- Cryogenic valves
- Cryogenic distribution system (valve boxes & transfer lines)
- Quench buffer
- Helium rack and warm pipework

The installation is planned in 2015.

7. Conclusion

The new large test bench for the vertical testing of large and heavy magnet with big energy has been designed. The procurement is ongoing. The design has been focused on a user-friendly and safe operation, a quick cool down to 1.9 K and the recuperation of helium after a quench.

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