Measured performance of four new 18 kW@4.5 K helium refrigerators for the LHC cryogenic system

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The cryogenic system for the Large Hadron Collider (LHC) under construction at CERN will include four new 4.5 K-helium refrigerators, to cover part of the cooling needs of the LHC at the 4.5 – 20 K and 50 -75 K levels. Two refrigerators are delivered by Air Liquide, France, and two by Linde Kryotechnik, Switzerland. During the last three years, all four refrigerators have been installed and commissioned at four different points along the LHC. The specified requirements of the refrigerators are presented, with special focus on the capacities at the various temperature levels. The capacities of the refrigerators were measured using a dedicated test cryostat, and the measured performance for all four installations is presented, and compared to the guaranteed performance in the original proposal of the suppliers. Finally, the process design of the two supplies is compared, and their differences and similarities briefly analysed.

INTRODUCTION

The total cryogenic capacity necessary for the operation of the Large Hadron Collider (LHC) [1] will be delivered by eight refrigerators supplying cooling capacity down to a temperature of 4.5 K and eight refrigeration units that are coupled to each of these refrigerators supplying cooling capacity down to a temperature of 1.8 K [2]. Of the eight refrigerators four will be recovered from the now decommissioned LEP accelerator and upgraded for the LHC needs. Four new refrigerators supplying an equivalent capacity of about 18 kW at 4.5 K were specified by CERN in 1997 [3] and purchased from European Industry in 1998. Two of these refrigerators have been supplied by Air Liquide, France [4] and two have been supplied by Linde Kryotechnik, Switzerland [5]. The first of these four new refrigerators was commissioned in 2001, the last at the end of 2003.

SPECIFIED COOLING NEEDS OF THE NEW LHC REFRIGERATORS

During LHC operation, the refrigerators will work for a large portion of the time far from the maximum capacity. Therefore, CERN specified to test the refrigerators not only in its design capacity mode, called "installed" but as well in a turn-down mode called "low intensity". The capacities required for these two operation modes are also listed in Table 1.

Table 1 Specified capacity of the refrigerators

Operation mode	**4.5 K isothermal**	**4.5 – 20 K non isothermal**	**50 -75 K non isothermal**	**20 – 280 K non isothermal**
	[W]	[W]	[W]	[W]
Installed	4400	20700	33000	55400
Low intensity	1600	7700	22000	36500

The non-isothermal load between 20 and 280 K corresponds to the current leads cooling and, together with the corresponding fraction of the 4.5 to 20 K load, is seen as a liquefaction rate by the refrigerator. This liquefaction rate corresponds to 41 g/s for the installed mode and 27 g/s for the low intensity mode.

PROCESS DESIGN OF THE MANUFACTURERS

Independent of CERN, the two suppliers chose the same compressor manufacturer. Except for the final oil removal system, the compressor station from the two suppliers are therefore identical, operating at three pressure levels, a high pressure (HP) of 20 bar, a medium pressure (MP) of 3.9 bar, and a low pressure (LP) of 1.05 bar. Figure *1* shows the principle arrangement of the compressors.

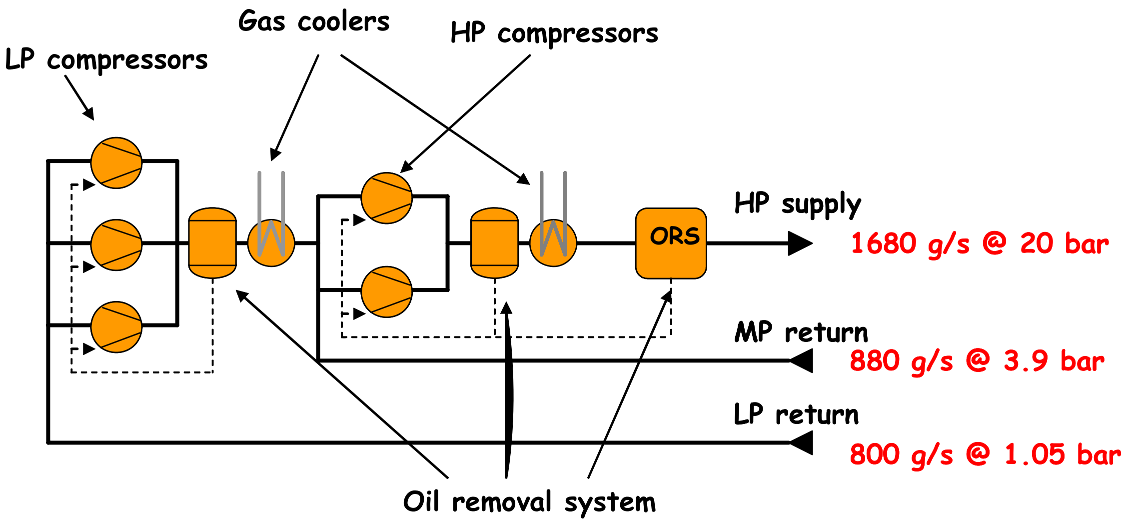

Figure 1 Compressor system of the four refrigerators

In addition to the capacity mentioned above, the typical flow scheme of a refrigerator cold box was specified, including switchable adsorbers at the 80 K level, one adsorber at the 20 K level, liquid nitrogen precooler, and a 4.5 K phase separator including a helium sub-cooler.

From a process point of view the design of the two refrigerator cold boxes are almost identical down to the 20 K level. The main compressor flow is sent through a heat exchanger, and part of it is branched of through a turbine circuit working between the HP and MP levels. Linde uses three turbines in series while Air Liquide has two turbines with heat exchange in between. After the 80 K adsorbers, a second heat exchanger block coupled with two turbine strings brings the temperature down to 20 K.

The principle flow diagram of the process realised by Linde Kryotechnik is shown in Figure 2, the one realised by Air Liquide in Figure 3.

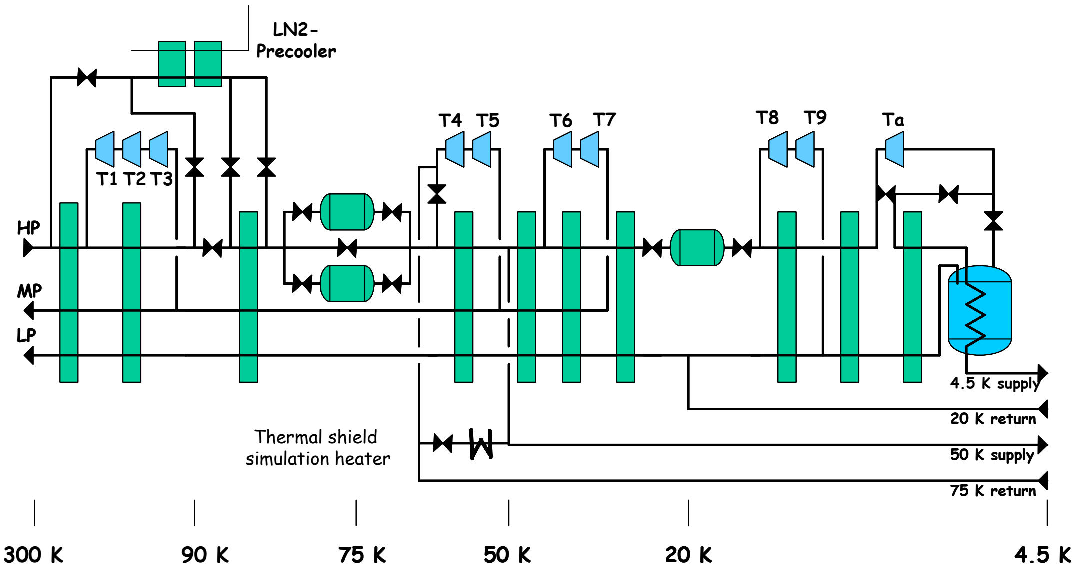

Figure 2 The Linde process with ten cryogenic turbines

As the helium supplied to the LHC (235 g/s) at 4.5 K is returned at 20 K, the lower end heat exchangers will see a considerable unbalanced flow, requiring several turbines to compensate for this.

To produce the required cooling capacity at low temperature, both suppliers use a turbine string (T8 and T9 for Linde, T7 for Air Liquide) working between HP and LP, down to a temperature of 10 K.

For Linde, the main helium flow is then sent through the last turbine, after which part of it is sent through a Joule-Thomson-Valve down to approx. 1.3 bar and fed into the phase separator. There it is used to sub-cool the helium that is supplied to the LHC at 4.6 K and 3 bar.

Air Liquide has chosen a different concept to compensate for the unbalanced heat exchangers. A part of the flow bypasses the lower end heat exchangers through T8, effectively making the coldest heat exchangers balanced, and avoiding the inherit losses of unbalanced heat exchange. The flow from T8 is fed directly into the phase separator to sub-cool the helium supplied to the LHC.

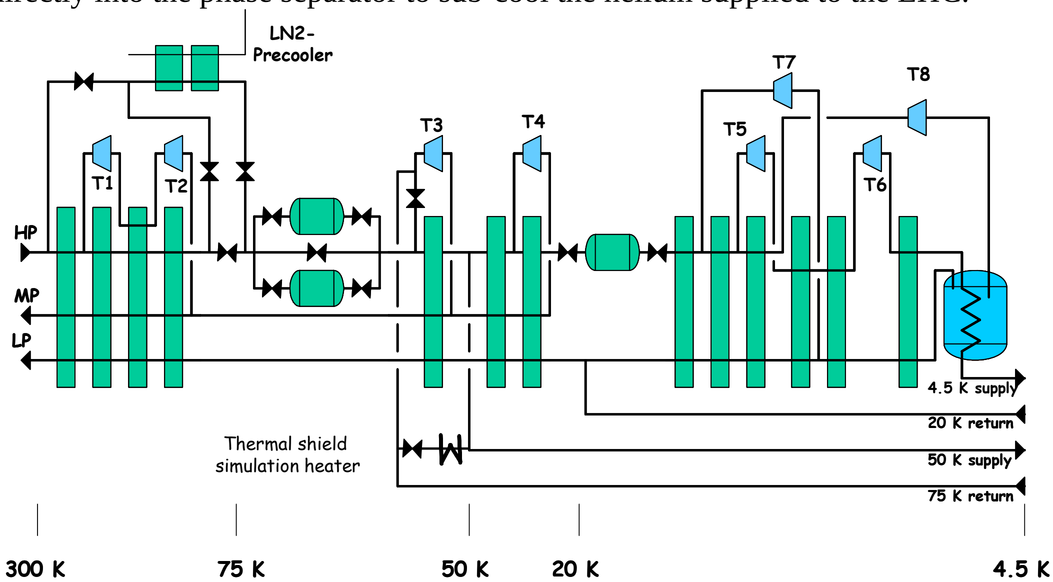

Figure 3 The Air Liquide process including eight turbines

CERN asked for guaranteed values for the power consumption for each installation from the two suppliers. These guaranteed values for the compressor station in the two operation modes described above can be found in Table 2.

Table 2 Guaranteed power consumption for both suppliers

Mode	Air Liquide	Linde
Installed	4204 kW	4275 kW
Low Intensity	2262 kW	2461 kW

Please note that the values in Table 2 only take into account the power consumption of the compressors themselves, and not that of utilities.

TEST CRYOSTAT

To verify the capacity and power consumption in all four installations, a dedicated test cryostat was built and has been used for all four installations. It simulates the thermal loads of the LHC and has been used for the two operational modes described above.

In Figure 4 a schematic lay-out of this test cryostat can be found. Dedicated heaters are installed to simulate the heat loads at the 4.5 K (Q10), 4.5 – 20 K (Q11) and the current lead flow at 20 – 280 K (Q13). Together with the shield simulation heater in the cold box, the conditions represented in Table 1 can be re-produced for the capacity tests. Heaters Q10 and Q11 are slowly ramped up to their nominal

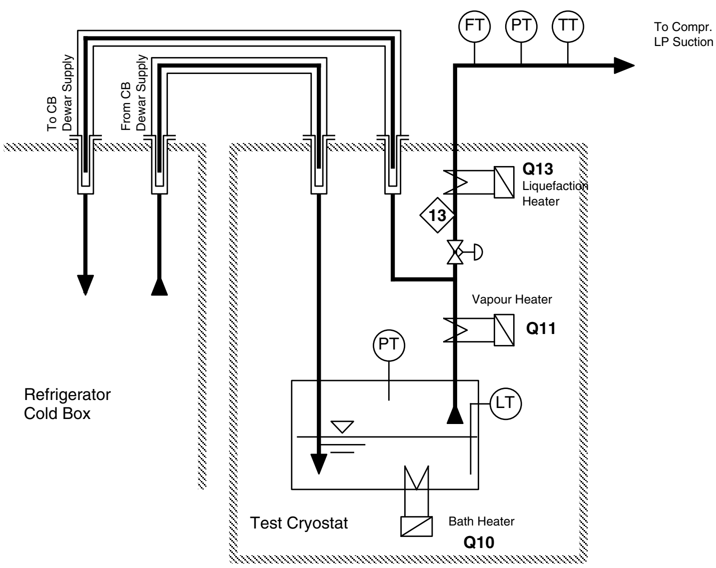

Figure 4 Flow diagram of the Test Cryostat

value and thereafter the flow and temperature of the flow through Q13 are controlled to 41 (27) g/s and 280K respectively.

MEASUREMENTS

During the commissioning, each refrigerator was connected to the test cryostat as shown in Figure 4. The refrigerators were operated in fully automatic mode for 40 to 48 hours for the installed mode and about 24 hours for the low-intensity mode. During this time, the power consumption of the compressor station was monitored, as well as temperatures and pressures in the cold box to assure that stable conditions were maintained.

During the capacity tests in installed mode one regeneration of the 80 K adsorbers and one regeneration of the 20 K adsorbers were performed. During this regeneration, the adsorbers were cooled down, which acts as an additional load on the refrigerator. The impact of this load on the overall energy consumption was noted, and the average energy consumption of the compressor station calculated. This value has been used to calculate the Coefficient Of Performance (COP).

To calculate the efficiency, or performance, of the plant, it is usual to calculate the equivalent capacity of the refrigerator at 4.5 K. The COP can then be given by the energy consumption divided by this equivalent capacity. In other words it is the number of watts consumed at the compressor station needed to produce one watt of cooling power at 4.5 K.

During the capacity test in Point 1.8, due to problems with the CERN electrical supply, it was not possible to power the heaters in the test cryostat to the specified value. In the end, the tests were accepted with about 3% less capacity than specified. Spare capacity was available, and doing an analysis as described above gives about the same COP as for the refrigerator in Point 4. For all other points the refrigerators achieved the specified capacity during the capacity tests. The energy consumption and the COP of all refrigerators are calculated using the capacities measured by the test cryostat and can be found in Table 3. These measurements and the guaranteed values for the power consumption were the basis of a commercial bonus/malus calculation.

Table 3 Measured energy consumption and COP for all refrigerators

	Point	**PA18** Air Liquide	**PA4** Air Liquide	**PA6** Linde	**PA8** Linde
Installed mode	Energy consumption (kW)	4297	4474	3964	4095
	% of Guarantee	*102*	*106*	*92.7*	*95.7*
	COP	248	247	222	231
Low Intensity mode	Energy consumption (kW)	2491	2560	2179	2203
	% of Guarantee	*110*	*113*	*88.5*	*89.5*
	COP	338	339	289	298

CONCLUSIONS

Four new helium refrigerators have been installed and commissioned on CERN during the last three years. Their capacities have been measured using a dedicated test cryostat simulating the future cooling needs of the LHC accelerator. All four refrigerators have the specified capacity. Even though their COP and energy consumption varies considerably, they are all adapted to the future needs of the LHC accelerator.

REFERENCES

1. Schmidt, R., Status Of The LHC, CERN-LHC Project Report 569, Geneva, Switzerland (2002), Eight European Particle Accelerator Conference (EPAC), Paris, France (2002),
2. Claudet, S; Gayet, P; Jäger, B; Millet, F; Roussel, P; Tavian, L; Wagner, U; Specification of Eight 2400 W @ 1.8 K Refrigeration Units for the LHC, ICEC 18 , Mumbai, India , (2000) 207-210
3. Claudet, S; Gayet, P; Wagner, U; Specification of Four New Large 4.5 K Helium Refrigerators for the LHC, ICMC '99 , Montreal, Canada , (1999)
4. Dauguet P; Guerin C and Monneret E; Construction and start up of two 18 kW at 4.5 K helium refrigerators for the new CERN accelerator; LHC, ICEC19, Grenoble, France, (2002) 187-190
5. Boesel, J., Chromec, B., Meier, A.Two large 18 kW (equivalent power at 4.5K) refrigerators for CERN's LHC project supplied by Linde Kryotechnik AG CEC 1999, Montreal, Canada, (1999), 1285- 1292