Overview of the air liquide cryogenic systems designed for CERN LHC

Dauguet P., Briend P., Delcayre F., Hilbert B., Mantileri C., Marot G., Monneret E., Walter E.

Advanced Technology Division, Air Liquide, BP 15, 38360 Sassenage, France

The 27-km-long Large Hadron Collider (LHC) will make use of superconducting magnets. It requires refrigeration systems at temperatures ranging from 1.8 K to 80 K. Two refrigerators delivering 18 kW equivalent power at 4.5 K were installed and commissioned. Connected to these refrigerators, the pre-series unit of the so-called Cold Compression System was installed and commissioned. These systems are able to absorb up to 2.4 kW at 1.8 K. An overview of these projects is given. Other related cryogenic equipments are also delivered for the LHC project and are listed at the end of the present paper.

LHC CRYOGENIC ARCHITECTURE

The LHC cryogenic architecture is presented in Figure 1.

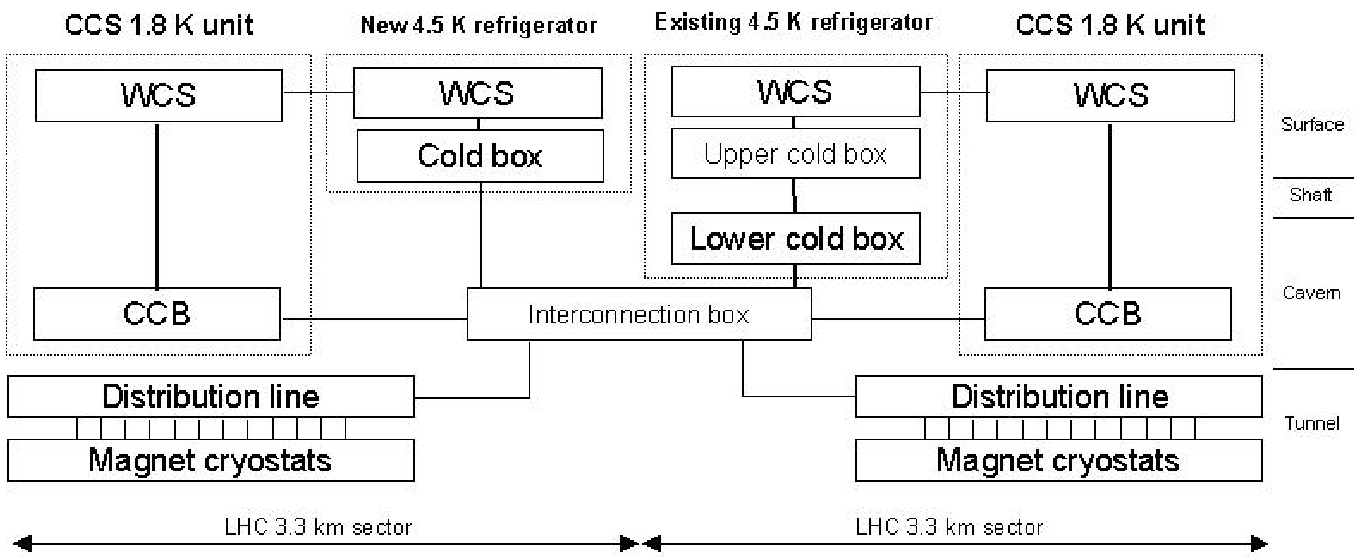

Figure 1 LHC cryogenic architecture

THE 18 kW AT 4.5 K REFRIGERATORS

The cryogenic duties to be provided by each 4.5 K refrigerator are presented in Table 1. Each refrigerator has to fit very different operating loads. A large flexibility of operation of the machine is thus requested. As the CERN call for tender was giving a very high importance to the electrical consumption of the plant as adjudication criteria, the choice of a very efficient cycle was mandatory [1]. The third request to be taken into account in the design of the machine is the high availability of the cryogenic system needed by the LHC project. This is insured by the choice of reliable and technically proven components. The cycle design presented hereafter is a compromise between efficiency, flexibility and reliability of operation.

The cycle design

The cycle design is presented in Figure 2. The cycle design has already been described in details in [2].

TABLE 1 Cryogenic loads of the LHC refrigerators in main operating modes

Loads / Operation mode	4.5 K – 20 K (W)	20 K – 280 K (W)	50 K – 75 K (W)
Installed	25100	55400	33000
Normal	15000	36500	22000
Low Intensity	9300	36500	22000
Injection Standby	6900	14900	22000
75 K standby	0	0	22000

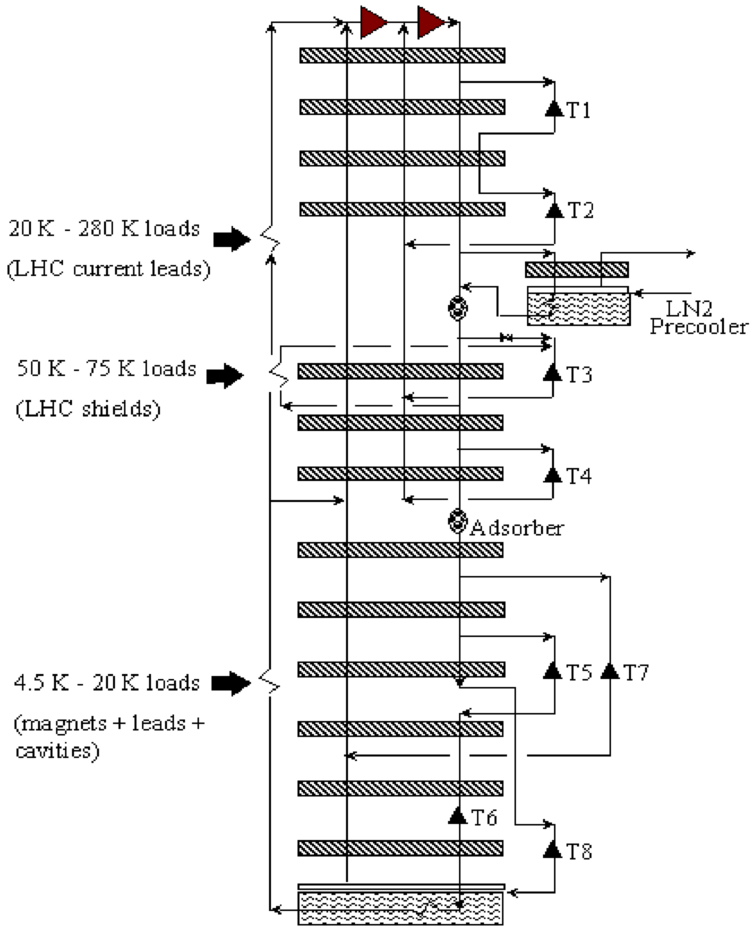

Figure 2 LHC 4.5 K refrigerators cycle design

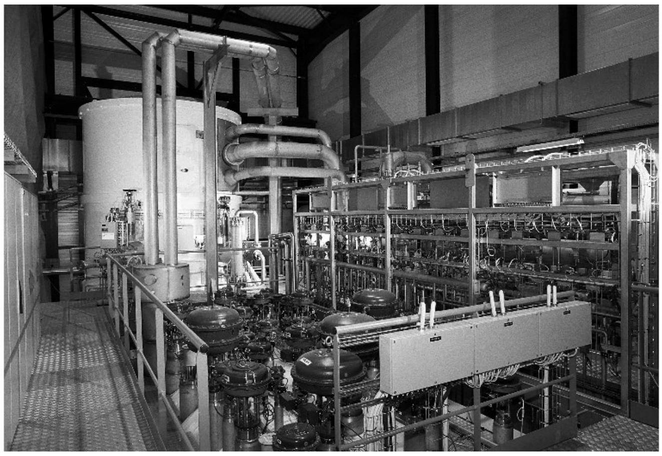

Figure 3 The compressor stations

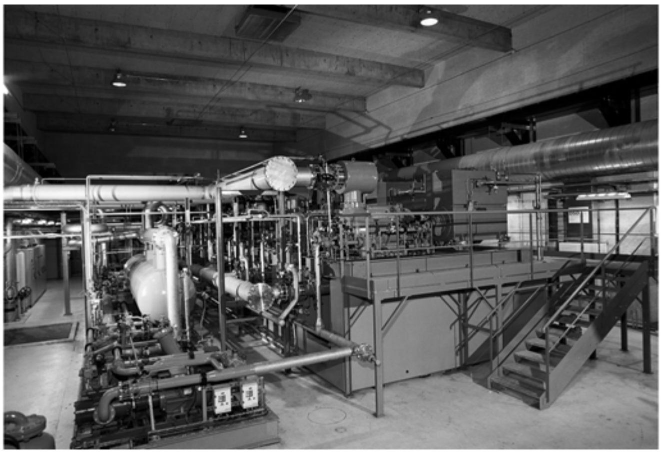

Figure 4 The cold boxes

Measured Performances

The refrigerators have been successfully operated in all the operating modes necessary to the LHC operation, as requested in the CERN specifications. Transitory situations between the static operating modes defined in the CERN specification have also been tested.

The cryogenic load that the refrigerators are able to deliver is 105% of the defined “Installed” exergetic power, that is more than 18kW.

Performances obtained in term of cycle efficiency have been precisely measured during contractual reception tests, in “installed” and “stand by mode”. The results are presented in Table 3. The measured values of electrical power consumptions are a few percent more than the expected values, and about 1% more than the guaranteed values of the contract. The reason is that the efficiency of the room temperature screw compressors is around 5% less than expected. The efficiency of the cold box however, conforms to expectations.

TABLE 2 Expected electrical power consumptions of each LHC refrigerator versus the cryogenic load.

Operating mode	Cryogenic load (Exergetic equivalent at 4.5 K) kW and (% of max value)	Electrical consumption kW and (% of max value)	Factor of merit (W/W) (electrical consumption divided by cryogenic load)
Installed	17.5 (100)	4200 (100)	240
Normal	10.7 (61)	2800 (67)	260
Low Intensity	7.6 (43)	2300 (55)	300

TABLE 3 Expected, guaranteed and measured performance of the refrigerators

Operating mode	"Expected" power consumption (kW)	"Guaranteed" power consumption (kW)	"Measured" power consumption (kW)
Installed	4200	4275	4297
Low Intensity	2300	2461	2491

Conclusion

A very high efficiency cycle has been custom designed for the LHC accelerator. The factor of merit of this cycle at maximum cryogenic power is 245 W/W, which corresponds to an efficiency of 27 % compared to Carnot ratio. The way the plant is operated for reduced cryogenic duty enables it to keep a high cycle efficiency even at partial loads down to 40 % of the installed power.

THE 2.4 KW AT 1.8 K "COLD COMPRESSOR SYSTEM"

The Large Hadron Collider (LHC) at CERN makes intensive use of superconducting magnets operated below 2 K. It requires high-capacity (i.e. 2.4 kW) 1.8 K refrigeration systems, the so-called "Cold Compressor System" (CCS). Air Liquide's Advanced Technologies Division designed and built a pre-series of these CCS for CERN - to be followed by three additional series. This pre–series unit was manufactured in 2001 and installed at CERN during the first 2002 trimester. It has been commissioned over the spring of 2002 and has been tested during 2002 / 2003. The 1.8 K refrigeration units are described in more details in [3, 4].

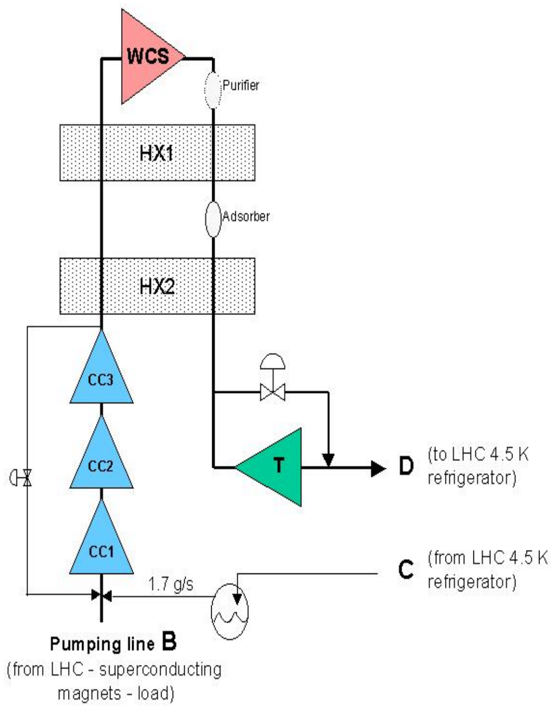

Figure 5 LHC/CCS Air Liquide cycle design

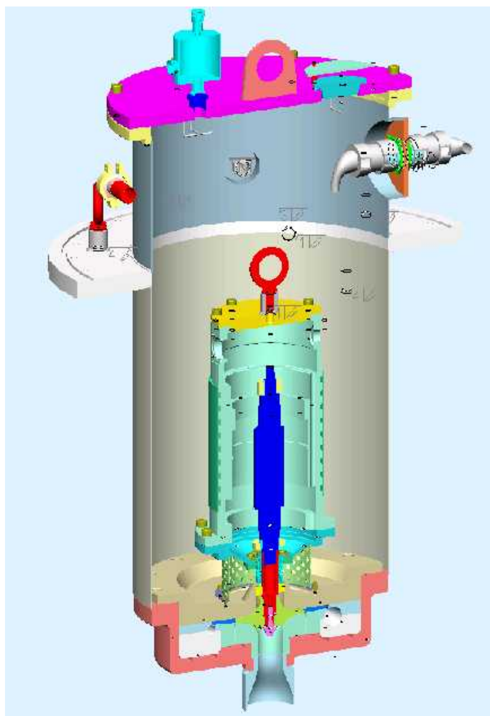

Figure 6 Cryogenic centrifugal-compressor simplified cross-section

Cycle design :

Figure 5 shows the Air Liquide CCS cycle. The very low pressure (1.5 kPa) needed on the He II saturated bath at 1.8 K is obtained using three cryogenic centrifugal compressors (CC) coupled with a one-stage ambient temperature (warm) compressor station (WCS) in a series arrangement. This article focuses on experimental results only. More details on the CERN specification and the Air Liquide cycle design are given in [3,4].

Compression at cryogenic temperature using centrifugal compressors :

Cryogenic centrifugal-compressors fitted with magnetic bearings (see Figure 6) -already successfully used in Tore Supra (CEA Cadarache, France) and CEBAF (TJNAF, USA) installations - turn out to be the key technology for achieving temperatures less than 2.17 K on a large scale (these units allow high rotation speeds, up to 600 Hz in the present case). All of these units uses 3D (axial-radial) impeller, designed in collaboration with the Czech company PBS. Their measured and guaranteed efficiencies in the different operating modes are given in Table 4.

TABLE 4 Measured parameters of the WCS for the main operating modes [3]

Operating mode	**Installed**	**Normal**	**Low Intensity**	**Injection sb**	**Cold sb**
Mass flow rate [g/s]	126	85,2	63,3	43,2	38.3
Inlet pressure [kPa] (compressor flange)	35	24	18	12,7	11,4
Pressure ratio	12,6	11,5	12,8	17,7	19,6
Measured volumetric efficiency	**0,81**	**0,80**	**0,79**	**0,77**	**0,76**
Expected power consumption [kW]	529	384	363	283	271
Expected isothermal efficiency	0.38	0.33	0.27	0.25	0.24
Measured power consumption [kW]	**446,5**	**316**	**267,5**	**250**	**246**
Measured isothermal efficiency	**0,45**	**0,41**	**0,37**	**0,31**	**0,29**

Conclusion

The CC measured efficiencies are better than expected. The required stability (i.e. +/- 0,05 kPa maximum pressure variation at the CC1 inlet in steady state regimes) and mass flow ramp-ups (i.e. +/- 6 g/s per min) could be demonstrated. The system is now in operation at CERN. Air Liquide is selected for the series which is now under way. Three other CCS are now under construction.

OTHER PROJECTS

Air Liquide also delivers for LHC project : the 27 km transfert lines to distribute the requested cryogenic power around the accelerator, a 600 mm vacuum jacketed transfer lines with a 5 pipes in 1 design, the 5 interconnection valve boxes connecting the refrigerators with the cryogenic lines and including each a 600 kW heater, the CMS particle detector helium refrigeration system, the ATLAS particle detector nitrogen refrigeration system, and also 12 test benches for the LHC magnets.

REFERENCES

1. Claudet S. et al., Specification of four new large 4.5 K refrigerators for the LHC, Advances in Cryogenic Engineering (1999) 45 1269-1276
2. Dauguet P. et al., Design, construction and start up by Air liquide of two 18 kW at 4.5 K helium refrigerators for the new CERN accelerator , Advances in Cryogenic Engineering (2003) 49
3. Claudet S. et al., Specification of eight 2400 W @ 1.8 K refrigeration units for the LHC, ICEC 2000 proceedings, Mumbai, India
4. Hilbert B., et al., Air Liquide 1.8 K refrigeration units for CERN LHC project, Advances in Cryogenic Engineering (2003)49