1.8 K Refrigeration Units for the LHC: Performance Assessment of Pre-series Units

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The cooling capacity below 2 K for the superconducting magnets of the Large Hadron Collider (LHC), at CERN, will be provided by eight refrigeration units of 2400 W at 1.8 K, each of them coupled to a 4.5 K refrigerator. The two selected vendors have proposed cycles based on centrifugal cold compressors combined with volumetric screw compressors with sub-atmospheric suction, as previously identified by CERN as "reference cycle". The supply of the series units was linked to successful testing and acceptance of the pre-series temporarily installed in a dedicated test station. The global capacity, the performance of cold compressors and some process specificities have been thoroughly tested and will be presented.

INTRODUCTION

The cooling capacity below 2 K for the superconducting magnets of the Large Hadron Collider, at CERN, will be provided by eight 2400 W@1.8 K refrigeration units, each of them coupled to a 4.5 K refrigerator. The 1.8 K refrigeration units have been specified in 1998 [1] and ordered in 1999 to IHI-Linde (four units) and Air Liquide (four units) [2,3].

According to CERN technical specification and procurement scenarios, the proposed cycle and machinery had to provide the minimum investment plus operating costs [1]. This principle leads IHI-Linde to propose a process including four cold compressors and two turbines whereas Air Liquide installs three cold compressors and only one turbine. Figure 1 shows the simplified schemes of both 1.8 K refrigeration units as well as the interfaces with the LHC (header B) and a 4.5 K refrigerator (headers C and D). The 1.8 K units are composed of :

– one warm compression station (WCS) including oil lubricated screw compressors (WC) associated with the oil removal system (ORS).
– one cold compressor box (CCB) including mainly a train of cold compressors (CC), heat exchangers (HX) and turbo-expanders (Tu).

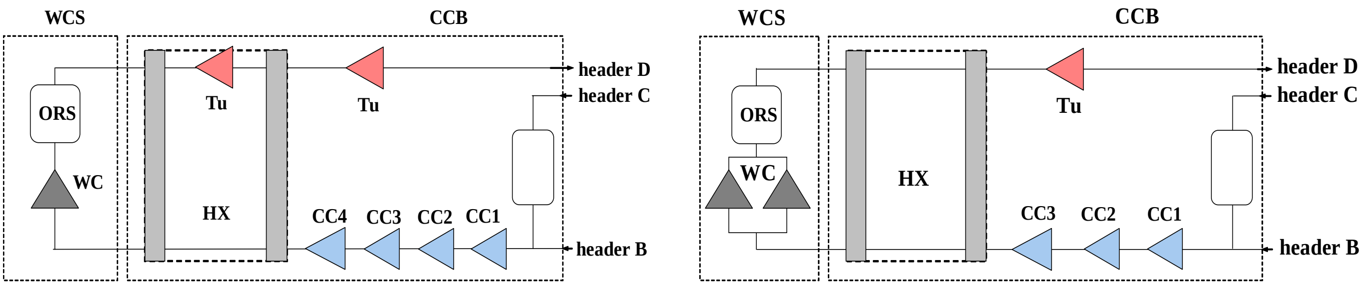


Figure 1 Simplified scheme with the LHC interfaces of a 1.8 K refrigeration unit by IHI-Linde (left) and Air Liquide (right)

In order to validate the process and components, a first unit called "pre-series unit" had to be validated by extensive testing in a dedicated test facility [4] at CERN before launching production of series unit. Acceptance tests were performed in 2002 and 2003 in order to measure and validate the overall and detailed performance of the pre-series units.

WARM COMPRESSOR STATION

IHI-Linde installed one Mycom screw compressor of two-stage compound type using slide valves whereas Air Liquide has installed two Kaeser one-stage screw compressors without any slide valve control operating in parallel. Even though sub-atmospheric conditions are required for the system, isothermal efficiency around 45 % have been successfully achieved for both screw compressors. The corresponding volumetric efficiency of each machine was higher than expected and in the range of 85 to 90 %. Figure 2 shows the measured isothermal efficiency of the screw compressors which have to compress helium gas from few kPa to high pressure (> 0.2 MPa).

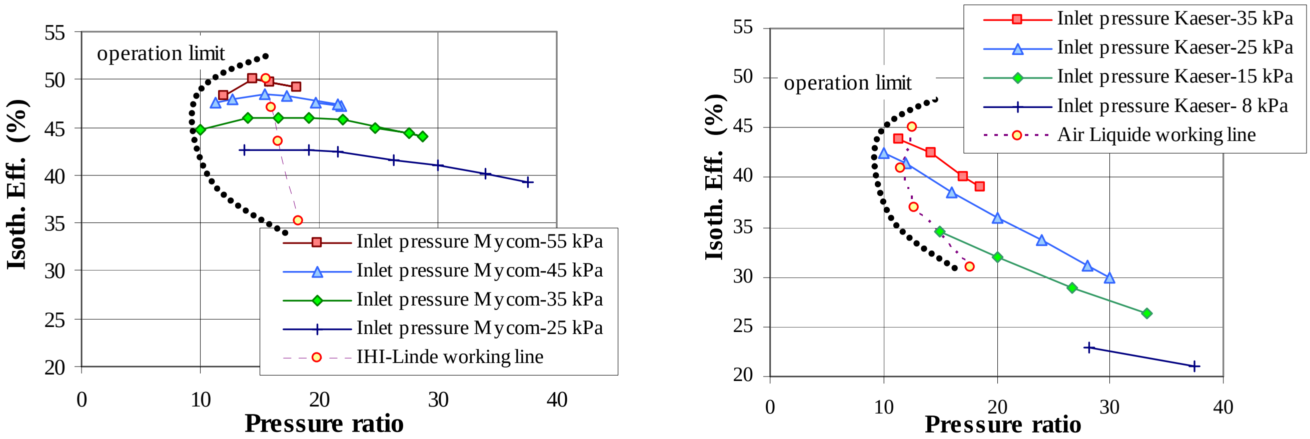


Figure 2 Isothermal efficiency of the warm compression station for IHI-Linde (a) and Air Liquide (b) pre-series units

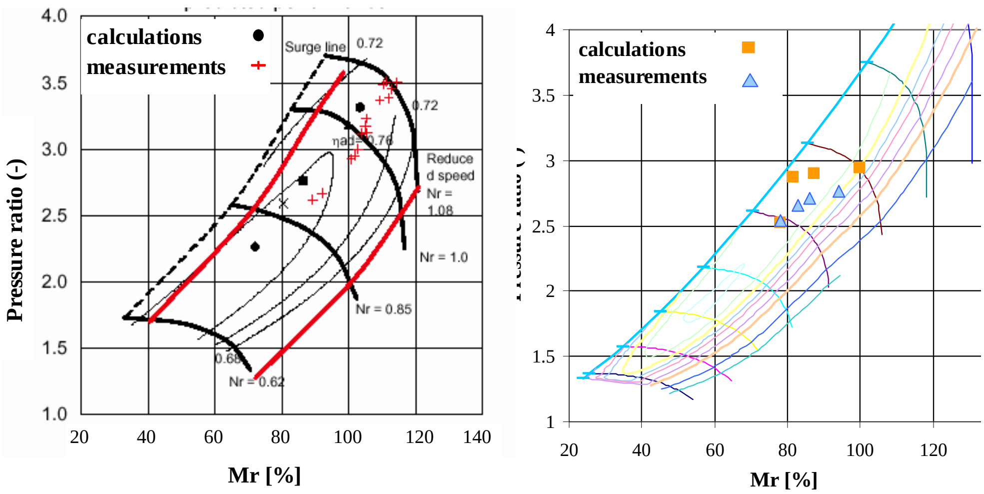
One can note that the IHI-Linde cycle is defined for the optimum efficiency of the Mycom compound compressor (Pressure Ratio PR ≅ 15) and that operating margins are comfortable. The Air Liquide cycle operating at lower warm compressor suction pressures imposes a pressure ratio higher than the usual optimum for single stage machines (PR ≅ 7). The operation margins are kept at the minimum acceptable.

COLD COMPRESSORS

Cold compressors fitted with active bearings and equipped with individual frequency drive were already successfully used in Tore Supra [5] and CEBAF [6] installations. The cold compressor design of both suppliers are similar and based on technically proven components such as magnetic bearings, frequency drive and electrical motor cooled with water. All cold compressors are of the 3D (axial-radial) impeller type with fixed diffuser. Special attention was paid to prevent any air inleaks to sub-atmospheric helium circuits. Therefore a helium guard system (associated with high-vacuum feedthroughs) isolating the process from air is installed for IHI-Linde cartridges while Air Liquide cold compressors are mounted in individual vacuum-pumped housings. To reduce the heat inputs to the process flow, IHI-Linde has installed a cold intercept (50 to 85 K) on their short shaft, supplied with cold gas subtracted from the main HP flow. Air Liquide preferred a longer shaft and a housing design with dissociated mechanical and sealing functions.

Each cold compressor has its individual working field indicating the combination of rotating speed, mass flow, pressure ratio and suction conditions as shown in Fig. 3. In multistage configuration, the different cold compressor stages are interacting and have to enable safe operation of each compressor within their respective working field. Special automatic control strategies [3,7] based on the volumetric behaviour of the warm compressor, the variable frequency drive and (for transients) the suction temperature adjustment were developed by each supplier to keep the suction pressure below 1.5 kPa ± 50 Pa in steady-state operation or below 1.7 kPa during transient modes as specified.

The fully automatic pump-down towards 1.5 kPa is started when the cold compressor box is cold, with the screw compressor initially close to the required pressure at the inlet of first CC stage (typically 20 to 25 kPa for 64 g/s) allowing the final pump-down with the cold compressors to start. Such automatic pump down from 20 to 1.5 kPa is achieved in less than 30 min at fastest for the present pumped volume and would automatically adapt to any volume to be pumped down.



Mr Reduced mass flow
Nr Reduced speed

$$\boldsymbol{Mr} = \frac{\boldsymbol{M}}{Mo} \times \frac{Po}{\boldsymbol{P}} \times \sqrt{\frac{\boldsymbol{T}}{To}}$$

$$\boldsymbol{Nr} = \frac{\boldsymbol{N}}{No} \times \sqrt{\frac{To}{\boldsymbol{T}}}$$

with
M, P, T, N measured values
Mo design mass flow
Po design inlet pressure
To design inlet temperature
No design rotation speed

Figure 3 Typical cold compressor working field for a cold compressor cartridge from IHI-Linde (left) and Air Liquide (right)

Table 1 summarises the acceptance test results in the Installed Mode for each cold compressor train. The values were measured several times with good reproducibility (± 2 %). In most of the operation modes and for most of the cold compressors, the isentropic efficiency are above 75 %. One can note that larger pressure ratios (around 4) have been achieved without any disturbance of the cold compressors and preserving high efficiency above 70 % for any pressure ratio > 1.5.

Table 1 : Main performances of cold compressors : Pressure ratio / Isentropic efficiency for the Installed mode

Operation Mode		**IHI-Linde**					**Air Liquide**			
		CC1	CC2	CC3	CC4*	CC chain	CC1*	CC2*	CC3	CC chain
Installed mode	Pressure ratio [-]	3.26	2.9	2.55	1.61	38.75	3.13	2.96	2.76	25.56
	Isentropic efficiency [%]	77	78	75	70	66	77	74	75	65

** sensor correction required for outlet temperature of CC4 IHI-Linde and inlet temperature of CC2 Air Liquide*

The test cryostat also allows performing transient tests called "LHC daily" simulating the expected heat load change during a nominal working day for LHC physics runs. Fig. 4 shows the typical specified transients and corresponding measured values.

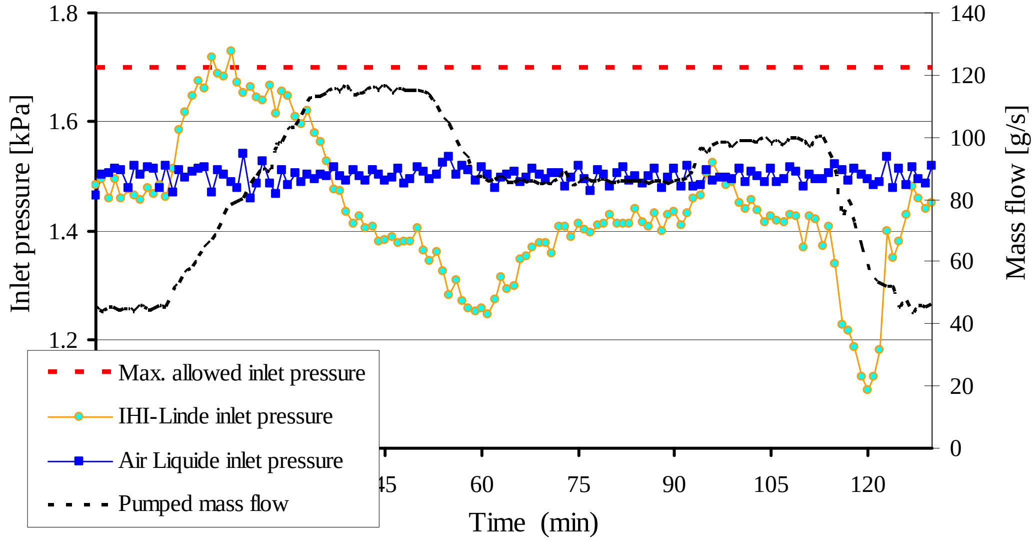


Figure 4 Typical specified transients and corresponding measured values for IHI-Linde and Air Liquide

Both solutions have provided efficient control of the mass flow variation : the suction pressure stays all the time below the specified value of 1.7 kPa. Flow variations above 8 g/s per minute were successfully tested and have shown promising capability of the 1.8 K refrigeration unit to achieve the required turn down range of 3 in less than 15 min.

THERMODYNAMIC EFFICIENCY

The thermodynamic efficiency of the 1.8 K refrigeration units is as expected and guaranteed by suppliers during the conceptual design phase. To illustrate the thermodynamic efficiency, it is usual to calculate the Coefficient Of Performance (COP) which is equal to the overall electrical power consumptions divided by the cooling power at 1.8 K. Table 2 presents, for three steady-state modes, the measured electrical power consumption of the 1.8 K pre-series units and the averaged measured values for the 4.5 K refrigerators [8] absorbing the non isothermal loads from the 1.8 K unit between 4.5 K (header C supply) and 20 K (header D return) as specified. Moreover, by reducing the header D return temperature down to 17.5 K and assuming the same COP for the 4.5 K refrigerator, the best achieved COP for the IHI-Linde 1.8 K unit is as low as 870 W/W in the Installed mode.

Table 2 : Achieved COP (W/W) for the three LHC operation modes

		Installed mode	**Normal mode**	**Low Intensity mode**
1.8 K heat loads	1.8 K isothermal heat loads [kW]	2.4	1.6	1.2
4.5 K refrigerator	COP [8] [W/W]	237	277 *estimated*	316
1.8 K refrigeration pre-series units	Non isothermal heat loads [kW]	13.45	11.26	9.33
	Equivalent iso. 4.5 K loads [kW]	7.6	5.5	4.3
	4.5 K ref. input power [kW]	1800	1530	1360
IHI-Linde / AL	1.8 K unit measured input power [kW]	427 / 466	322 / 345	272 / 290
IHI-Linde / AL	**COP [W/W]**	**930 / 940**	**1160 / 1170**	**1365 / 1380**

CONCLUSION

Two 2400 W@1.8 K refrigeration “pre-series units” have been successfully tested at CERN and accepted in 2002 and 2003. Their achieved COP are in the range of 900 W/W with cold compressor isentropic efficiency higher than 70 % for all modes and warm compressor isothermal efficiency around 45 % in sub-atmospheric conditions. Series units delivery at CERN are now finalised for IHI-Linde and are expected in the coming months for Air Liquide allowing then the acceptance tests of the series units.

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