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Performance Assessment of Industrial Prototype Cryogenic Helium Compressors for the Large Hadron Collider

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Abstract

In order to develop the technology of large-capacity refrigeration at superfluid helium temperature, essential for the LHC project, CERN has procured from industry three prototype single-stage hydrodynamic cryogenic helium compressors, based on different construction choices, and tested them in the laboratory. After recalling the common functional specification, as well as the main design features of the three machines, we present comparative performance results, and draw conclusions as concerns future full-scale machines for the LHC.

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Performance Assessment of Industrial Prototype Cryogenic Helium Compressors for the Large Hadron Collider

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In order to develop the technology of large-capacity refrigeration at superfluid helium temperature, essential for the LHC project, CERN has procured from industry three prototype single-stage hydrodynamic cryogenic helium compressors, based on different construction choices, and tested them in the laboratory. After recalling the common functional specification, as well as the main design features of the three machines, we present comparative performance results, and draw conclusions as concerns future full-scale machines for the LHC.

1 INTRODUCTION

The high-field superconducting magnets of the Large Hadron Collider (LHC), the 26.7 km circumference, high-energy particle accelerator under construction at CERN [1], will be cooled by superfluid helium below 2 K. In total, the LHC will require about 20 kW of cooling power at 1.8 K, to be produced in eight stations located around the machine circumference [2]. In view of the low saturation pressure of helium, the key technology to the production of large-power refrigeration at this temperature, consists in hydrodynamic compressors operating at cryogenic temperature [3]. This technology, pioneered on previous projects such as the Tore Supra tokamak in Cadarache (France), and the CEBAF accelerator in Newport News (USA), needed to be further developed by industry in preparation for the LHC cryogenic system, which will eventually require eight multistage compressor systems [4]. For this purpose, CERN has procured from three industrial firms, in Europe (Air Liquide [5] and Linde [6,7]) and Japan (IHI [8]), single-stage hydrodynamic cryogenic helium compressors (CCU), handling a nominal flow-rate of 18 g/s cold gaseous helium at 1 kPa and 4 K, and operating with a pressure ration of 3. These CCUs, matched to the operating range of the existing volumetric warm pumping unit for ambient temperature helium, which equips the LHC magnet test station [9], will also be used to triple the corresponding refrigeration capacity [10]. After recalling the main specifications and design boundary conditions of the prototype compressors, we summarise the results of the test campaigns, and draw conclusions towards procurement of final machines to be used in the LHC.

2 DESIGN SPECIFICATIONS

Each CCU must be integrated in the existing pumping system, the flow scheme of which is shown in Figure 1. Helium to be compressed is vaporised either in the helium test cryostat or in the magnet test station. In nominal conditions, the CCU must handle a flow-rate of 18 g/s @ 1 kPa inlet pressure, with a pressure ratio of 3 and an isentropic efficiency better than 0.60. The compliance of the system must allow to handle a lower flow-rate continuously varying over the range from 6 to 18 g/s, with a pressure ratio of 1 to 3 and an isentropic efficiency better than 0.50. For a given mass-flow, the gas inlet temperature may vary depending upon the number of test stations in operation. Table 1 summarises the main specifications of the CCU.

Table 1 Main specifications of CCUs

			Nominal	Low-capacity
Helium flow rate	m	[g/s]	18	6 to 18
Suction pressure	Pin	[kPa]	1	≤ 1
Suction temperature	Tin	[K]	3.5 to 4.4	5.3 to 3.5
Pressure ratio		[-]	3	1 to 3
Isentropic efficiency		[-]	≥ 0.60	≥ 0.50

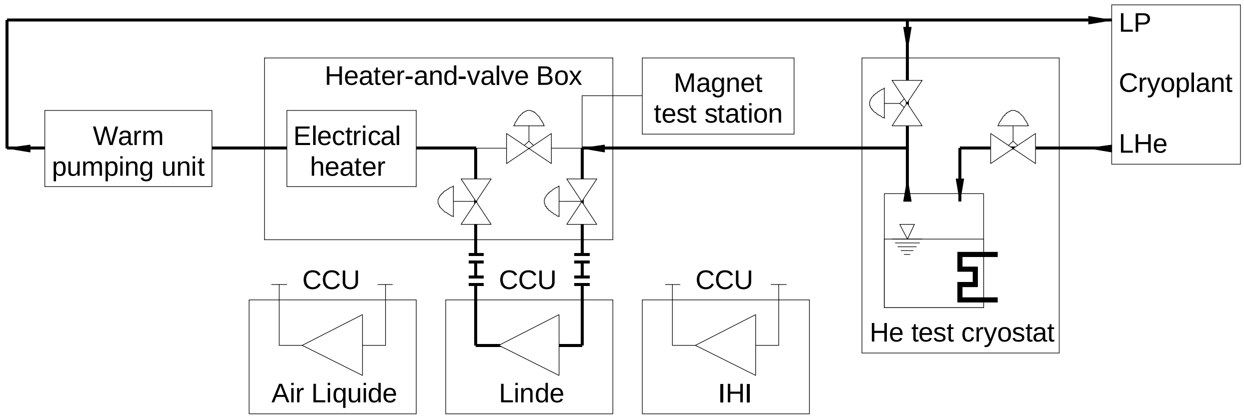

Figure 1 Simplified flow scheme of the pumping system used for CCU tests

3 CONSTRUCTION CHOICES

Three prototypes have been ordered, all based on the same technical specification, but with different features and characteristics. The original Air Liquide CCU is based on a centrifugal impeller driven by a turbine with static gas bearings. The IHI CCU features an axial-centrifugal impeller driven by an electrical motor with active-magnetic bearings. The Linde CCU has an axial-centrifugal impeller driven by an electrical motor with ceramic-ball bearings. Some prototypes were later used as test beds for improvements. By replacing the initial centrifugal impeller by an axial-centrifugal one, Air Liquide has improved the performance of their prototype, which now performs as specified. In order to cope with size limitations imposed by the former impeller, the new impeller has been designed for only 12 g/s. By changing the diffuser and the casing support, Linde has improved the efficiency performance (+ 0.07 on isentropic efficiency) of their prototype [11] at the cost of a small reduction in operating margin with respect to the stall line. The IHI prototype has reached its performance without additional improvements. Table 2 gives the final CCU characteristics.

Table 2 Main characteristics of CCU

	Air Liquide	IHI	Linde
Impeller type	Unshrouded axial-centrifugal	Unshrouded axial-centrifugal	Unshrouded axial-centrifugal
Impeller diameter [mm]	113	120	118
Diffuser	Vaned	Vaned	Vaned
Bearings	Static gas (@ 300 K)	Active magnetic (@ 300 K)	Ceramic ball (@ 300 K)
Drive	Turbine (@ 300 K)	Electrical motor (@ 300 K)	Electrical motor (@ 300 K)
Nominal speed [Hz]	476 (438)*	408 (408)*	390 (390)*
80 K heat intercept	No	Yes	No
Bearing-impeller tightness	pumping chamber	no ΔP	no ΔP
Subcontractor	-	Koyo	ATEKO, PBS, GMN

( )*: Expected

In steady-state operation, the compressor suction pressure is controlled by adjusting the motor or turbine drive speed. Efficiency assessment of the cold compressor requires two calibrated temperature sensors and two precision pressure gauges at inlet and outlet. The error on efficiency assessment, which depends on uncertainties on temperature and pressure measurements, is estimated to ± 0.02.

4 MEASURED PERFORMANCE

For each prototype, Figure 2 shows the measured operating field, which displays the pressure ratio as a function of the reduced flow m* and reduced speed N* defined as follows:

$$m^* = \frac{m}{m_0} \cdot \sqrt{\frac{Tin}{Tin_0}} \cdot \frac{Pin_0}{Pin} \qquad \text{and} \qquad N^* = \frac{N}{N_0} \cdot \sqrt{\frac{Tin_0}{Tin}} \qquad \text{with subscript 0 for design conditions}$$

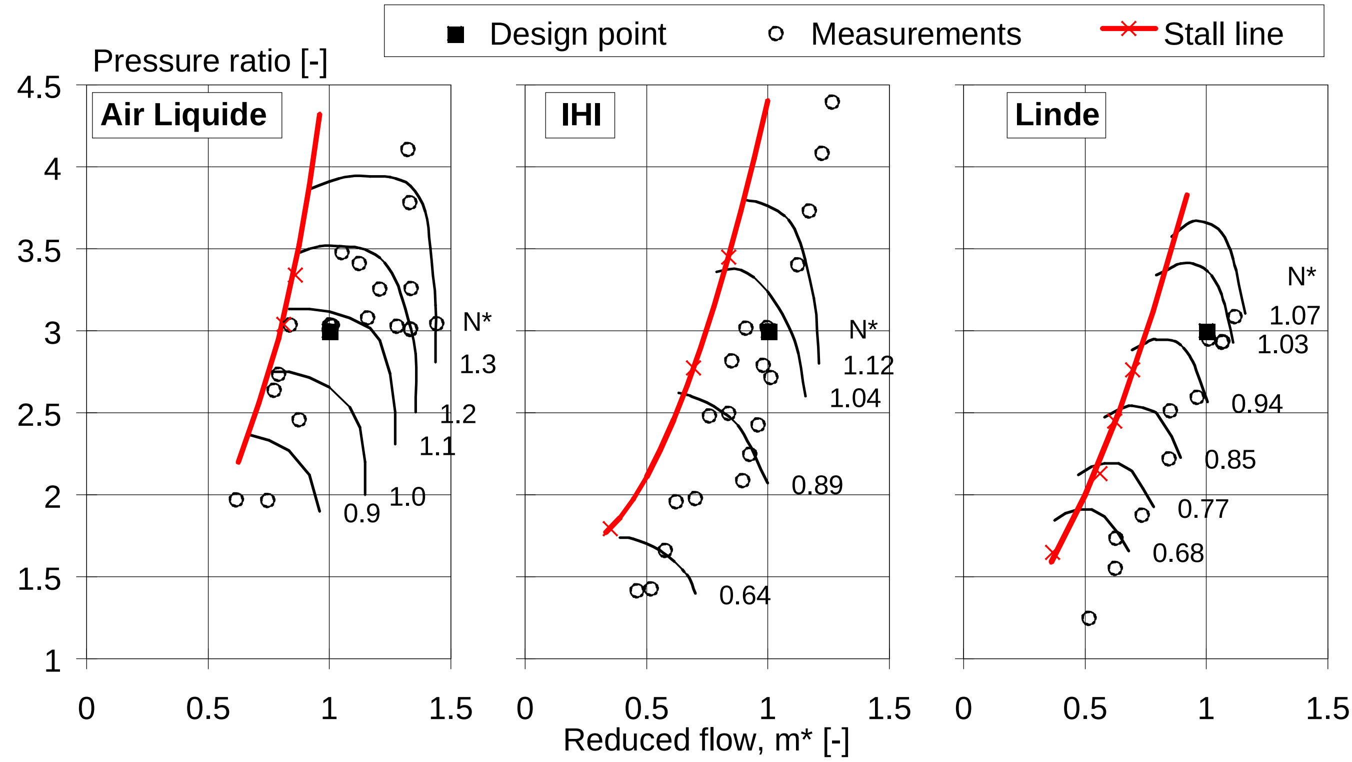

Figure 2 Measured operating fields of prototype cryogenic compressors

A well-designed compressor should have its design point precisely at reduced speed N*=1. This is not quite the case for the Air Liquide prototype, which needs to rotate faster (N*=1.08) in order to reach its design pressure ratio. The operating range is located to the right of the stall line. The operating margin between the stall line and the design point, in terms of reduced flow, varies from 21 % (Air Liquide) to 26 % (IHI and Linde). Table 3 gives the design point conditions for each prototype and the corresponding isentropic efficiency, which ranges from 0.60 (Air Liquide) up to 0.75 (IHI). The Linde prototype shows the best agreement between design and measured values of isentropic efficiency. The overall efficiency is strongly dependent on the heat inleaks which reach the cold part. Assessing the loss of efficiency due to these heat inleaks makes it possible to estimate the hydrodynamic efficiency alone, which is more relevant for comparing the impeller and diffuser design. The measured hydrodynamic efficiency of IHI and Linde are equal (0.78). Despite of its greatest design hydrodynamic efficiency (0.82), the Air Liquide prototype exhibits an hydrodynamic efficiency of only 0.74.

Table 3 Efficiency results and analysis

Prototype	Mass flow [g/s]	Suction pressure [kPa]	Suction temp. [K]	Pressure ratio [-]	Isentropic efficiency [-]		Impeller heat inleaks [W]		Spiral casing heat inleaks [W]		Hydrodynamic Efficiency [-]	
					D	M	D	M	D	M	D	M
Air Liquide	12	1	4.2	3	0.65	0.60	17	17	18	18	0.82	0.74
IHI	18	1	4.4	3	0.79	0.75	1.6	4	1.6	3	0.80	0.78
Linde	18	1	3.5	3	0.65	0.64	17	17	17	22	0.78	0.78

D: Design conditions, M: Measured conditions

Tests have also been conducted in off-design operation. The IHI prototype has reached a pressure ratio of up to 4.4 while maintaining isentropic efficiency better than 0.70. The Air Liquide prototype has reached a reduced flow of 1.44 with an isentropic efficiency close to 0.50. Concerning endurance, static-gas and active-magnetic bearing have already proven their reliability. For ceramic ball bearing, a dedicated test rig simulating operating conditions has gone through more than 10'000 hours [11], which is in full agreement with the required MTBM of 8'000 hours for LHC operation.

5 CONCLUSION

All three machines, in some cases after improvement, eventually perform as specified. The technical advantage of 3-D (axial-centrifugal) over 2-D (centrifugal) impellers is established. The diffuser can be optimised for high efficiency, with limited loss of operating margin. For these relatively small-flow prototypes, the thermal design is very important, in particular as concerns the heat load at compressor inlet. With similar hydrodynamic efficiency, an active 80 K heat intercept on the spiral casing and on the impeller shaft can increase the overall isentropic efficiency by 0.10. No mechanical problem on drive and bearings, whatever the solution, has been encountered, but some limitations on maximum rotating speed imposed by ceramic ball bearings and on maximum voltage on the electrical motor, are of importance for the design of larger machines. Scaling to full-scale LHC machines indicates promising efficiency values in excess of 0.75.

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7 REFERENCES

1 Evans, L., The Large Hadron Collider Project, in Proc. ICEC16, Elsevier Science, Oxford, UK (1997) 45-52

2 Lebrun, Ph., Riddone, G., Tavian, L. & Wagner, U., Demands in Refrigeration Capacity for the Large Hadron Collider, in Proc. ICEC16, Elsevier Science, Oxford, UK (1997) 95-98

3 Lebrun, Ph., Tavian, L.& Claudet, G., Development of Large-Capacity Refrigeration at 1.8 K for the Large Hadron Collider at CERN, in Proc.Kryogenika'96, Icaris, Praha, CZ (1996) 54-59

4 Millet, F., Roussel, P., Tavian, L. & Wagner, U., A Possible 1.8 K Refrigeration Cycle for the Large Hadron Collider, paper presented at CEC'97 Portland, USA.

5 Bonneton, M., Tavian, L., Gistau-Baguer, G.M., Turcat, F. & Viennot, P, A High-Reliability Gas-Driven Helium Cryogenic Centrifugal Compressor, paper presented at CEC'97 Portland, USA.

6 Schustr, P., Vins, M., Brunovsky, I. & Tucek, L., Helium Low-Temperature Compressor, in Proc.Kryogenika'96, Icaris, Praha, CZ (1996) 78-82

7 Decker, L. et al., A Cryogenic Axial-Centrifugal Compressor for Superfluid Helium Refrigeration, in Proc. ICEC16, Elsevier Science, Oxford, UK (1997) 195-198

8 Saji, N. *et al.*, A One kPa Centrifugal Cold Compressor for 1.8K Helium Refrigeration System, paper presented at this conference.

9 Benda, V. *et al.*, Cryogenic Infrastructure for Superfluid Helium Testing of LHC Prototype Superconducting Magnets, in Adv. Cryo. Eng., (1994) 39A 641-648

10 Benda, V. et al., Upgrade of the CERN Cryogenic Station for Superfluid Helium Testing of Prototype LHC Superconducting Magnets, in Proc. ICEC16, Elsevier Science, Oxford, UK (1997) 199-202

11 Decker, L. *et al.*, Operational Experience with a Cryogenic Axial-Centrifugal Compressor, paper presented at CEC'97 Portland, USA.