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DEVELOPMENT OF LARGE-CAPACITY REFRIGERATION AT 1.8 K FOR THE LARGE HADRON COLLIDER AT CERN

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Abstract

CERN, the European Laboratory for Particle Physics, is working towards the construction of the Large Hadron Collider (LHC), a high-energy, high-luminosity particle accelerator and collider [1] of 26.7 km circumference, due to start producing frontier physics, by bringing into collision intense proton and ion beams with centre-of-mass energies in the TeV-per-constituent range, at the beginning of the next century. The key technology for achieving this ambitious scientific goal at economically acceptable cost is the use of high-field superconducting magnets using Nb-Ti conductor operating in superfluid helium [2]. To maintain the some 25 km of bending and focusing magnets at their operating temperature of 1.9 K, the LHC cryogenic system will have to produce an unprecedented total refrigeration capacity of about 20 kW at 1.8 K, in eight cryogenic plants distributed around the machine circumference [3]. This has requested the undertaking of an industrial development programme, in the form of a collaboration between CERN and CEA, France, for investigating specific machinery, i.e. very-low pressure cryogenic heat exchangers, volumetric and hydrodynamic compressors, as well as practical and efficient thermodynamic cycles. We report on the aims, lines of action and present progress of this ongoing programme.

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1. INTRODUCTION

CERN, the European Laboratory for Particle Physics, is working towards the construction of the Large Hadron Collider (LHC), a high-energy, high-luminosity particle accelerator and collider [1] of 26.7 km circumference, due to start producing frontier physics, by bringing into collision intense proton and ion beams with centre-of-mass energies in the TeV-per-constituent range, at the beginning of the next century. The key technology for achieving this ambitious scientific goal at economically acceptable cost is the use of high-field superconducting magnets using Nb-Ti conductor operating in superfluid helium [2]. To maintain the some 25 km of bending and focusing magnets at their operating temperature of 1.9 K, the LHC cryogenic system will have to produce an unprecedented total refrigeration capacity of about 20 kW at 1.8 K, in eight cryogenic plants distributed around the machine circumference [3]. This has requested the undertaking of an industrial development programme, in the form of a collaboration between CERN and CEA, France, for investigating specific machinery, i.e. very-low pressure cryogenic heat exchangers, volumetric and hydrodynamic compressors, as well as practical and efficient thermodynamic cycles. We report on the aims, lines of action and present progress of this ongoing programme.

2. CRYOGENIC SCHEME AND REQUIREMENTS OF THE LHC

The LHC will be installed in the underground tunnel of the present LEP collider. Cryogenics for its eight 3.3 km-long sectors will be supplied from large capacity refrigerators installed in four equidistant technical service areas. The superconducting magnets of a sector operate in static baths of pressurized helium II, the high thermal conductivity of which is exploited to transport the heat deposited or generated in the coils, up to a linear heat sink, in the form of a heat exchanger tube threading its way along the magnet string. Saturated helium II, flowing in two-phase inside this tube, gradually absorbs the heat load quasi-isothermally as the liquid phase vaporizes. To avoid excessive pressure drop in the vapour flow, this scheme is implemented in independent cooling loops extending each over 53.5 m, i.e. the length of a half-cell of the LHC lattice, and connected in parallel to feed and return headers (Figure 1). In each of these loops, the saturated helium II is produced by Joule-Thomson expansion of liquid helium prealably subcooled to the lambda point by the escaping cold vapour in a subcooling heat exchanger. The superheated low-pressure vapour is then returned to the sector cryoplant by the DN250 return header, where a set of low-pressure compressors raise its pressure from the 1.6 kPa saturation at 1.8 K, up to atmospheric.

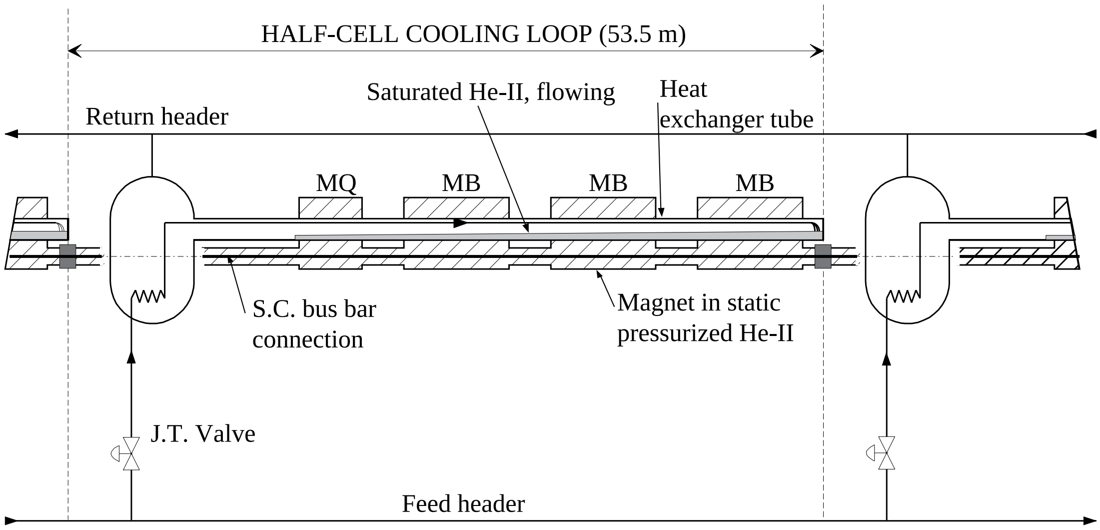

Fig. 1 The superfluid helium cooling scheme of a LHC half-cell

In view of their high thermodynamic weight, the heat loads applied to the 1.8 K level are tightly budgeted and, when possible, intercepted at higher temperature. Residual heat inleaks from ambient may be reduced to below 0.2 W.m^{-1} by a combination of active thermal shielding, multilayer reflective insulation and low-conduction supports with intermediate heat intercepts [4]. Dynamic heat loads produced by resistive dissipation in the conductors, or deposited by inelastically scattered particles from the circulating beams are absorbed at 1.8 K, but other beam-induced loads, such as synchrotron radiation losses, can be intercepted at higher temperature by beam screens. Although transient heat loads due to current ramp and discharge in the magnets are mostly buffered by the large heat capacity of the pressurized helium II bath, the demands in refrigeration at 1.8 K of the LHC will vary over a dynamic range of 2:1 (Table 1).

Table 1: Heat loads and installed refrigeration capacity at 1.8 K in LHC sectors [kW]

Mode	Low-load sector	High-load sector
Standby	0.9	0.9
Nominal	1.4	1.7
Installed	2.5	2.5

3. LOW-PRESSURE HELIUM COMPRESSORS

To maintain a saturation temperature of 1.8 K on the heat sink, the low-pressure helium vapour must be compressed up to atmospheric with a pressure ratio of 80. At moderate mass-flow rate, primary vacuum pumps, i.e. rotary-vane, Roots [5] or liquid-ring [6] appear suitable, in spite of the large volumetric capacity imposed by the low density of the helium at ambient temperature. A practical limit for vapour compression at ambient temperature seems to be reached at around 20'000 m^{3}.h^{-1}, when the size of the machines becomes prohibitive (Figure 2). The need for larger cooling power has triggered the development of cold compressors, which handle helium vapour at higher density and thus are more compact machines. Cold helium compressors must be non-lubricated, non-contaminating and thermodynamically efficient, since the heat of compression is rejected at low temperature.

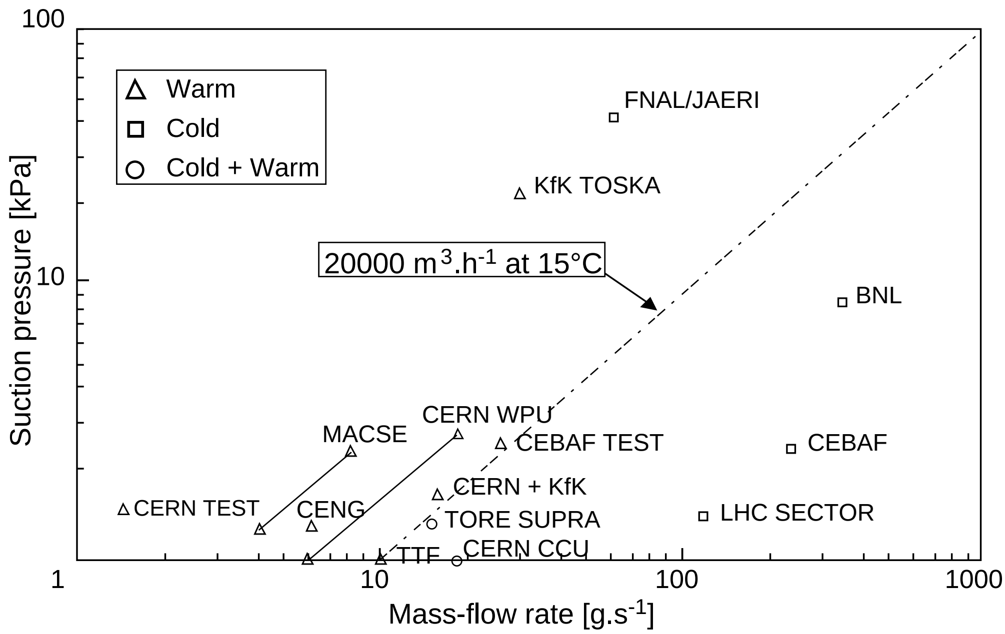

Fig. 2 Range of application of low-pressure helium compressors

A class of machines well adapted to these requirements is hydrodynamic, i.e. centrifugal and axial-centrifugal compressors [7]. However, the limited pressure ratio achieveable per stage imposes to use a multistage arrangement, with series coupling of several machines, thus compounding the problems of limited operating range (within stall, surge and choke limits), loss of efficiency away from the design point and adaptation to variable flow-rate and fluid inlet density [8, 9]. Besides these intrinsic limitations, cold hydrodynamic compressors also present several technological challenges, as concerns wheel and housing tolerances, mechanical drive, bearings, and thermal design. The use of centrifugal unshrouded rotors, with active magnetic bearings and variable-frequency electrical motor drive, operated at liquid nitrogen temperature, proved a satisfactory, although expensive solution in existing projects [10, 11]. As alternatives, we have procured from European industry and are presently investigating the performance of centrifugal and axial-centrifugal machines, with hydrostatic or ceramic-ball bearings, and gas turbine or electrical motor drives operated at ambient temperature [12]. The specifications of these machines are given in Table 2.

Table 2: Specifications of prototype hydrodynamic cold helium compressors

Mode	Nominal	Reduced capacity
Mass flow-rate [g.s^{-1}]	18	6 to 18
Suction pressure [kPa]	1	£ 1
Discharge pressure [kPa]	3	0.9 to 3
Suction temperature [K]	3.5 to 4.4	5.3 to 3.5
Isentropic efficiency [%]	≥ 60	≥ 50

In view of the potential of volumetric compressors for easy load adaptation, alone or in combination with hydrodynamic machines, we have conducted exploratory studies aiming at selecting a type of volumetric compressor suitable for operation at low temperature. The best candidate appears to be the scroll compressor, and we are presently conducting the development, in liaison with specialized industry, of a prototype scroll compressor with a capacity of 20 $g.s^{-1}$ at 2.5 kPa, 5 K. The possibility of subatmospheric operation of volumetric machines at ambient temperature, e.g. vacuum pumps and screw compressors, has also been investigated as a means to alleviate the pressure ratio to be produced by the cryogenic compressors, and thus reduce the number of cold stages.

4. LOW-PRESSURE HEAT EXCHANGERS

Attaching a 1.8 K refrigeration cycle to a source of 4.5 K helium at atmospheric pressure, requires a subcooling heat exchanger for lowering the temperature of the liquid down to the lambda point, and thus improve the yield of the subsequent Joule-Thomson expansion to saturation. The main difficulty lies in the low-pressure vapour pass, where good heat transfer and low pressure drop (typically 50 Pa) are simultaneously required. In addition to the subcooling heat exchanger, intermediate-pressure heat exchangers spanning much larger temperature differences must equip 1.8 K refrigeration cycles which involve ambient or intermediate-temperature compression, for enthalpy recovery of the cold vapour stream.

Several construction techniques for such heat exchangers, suitable for handling the mass-flow rates of up to 120 $g.s^{-1}$ corresponding to the refrigeration capacity for LHC sectors, are being investigated, and experimentally tested on scale models of 6 $g.s^{-1}$ in the laboratory. Perforated copper plate [13] and thin stainless steel plate heat exchangers provide compact designs, while distributed heat exchangers can be built of helix-in-tube construction.

5. PROCESS CYCLE OPTIMIZATION

One of the aims of the development programs presented above on compressors and heat exchangers, is to provide the cycle designer with realistic performance and efficiency characteristics of these components, thus opening the way for their optimal arrangement in refrigeration cycles. Criteria for rating such cycles stem from thermodynamics, e.g. entropy generation, as well as from technological constraints, e.g. coupling to existing 4.5 K refrigerators or simplicity of operation.

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