EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN AT / 92-32 (CR)

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*Invited paper to ICHEP 92: XXVI International Conference on High Energy Physics
5-12 August 1992, Dallas, TX, USA*

Geneva, Switzerland
September 1992

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Abstract

Low-temperature superconductivity, and hence helium cryogenics, have become key technologies for high-energy accelerators and colliders, through the extensive use of superconducting magnets and acceleration cavities. The race towards higher energy and luminosity has resulted in ever-increasing demands on the ancillary cryogenic systems, both qualitatively (temperature levels, efficiency, reliability) and quantitatively (refrigeration power, size, cost). Recent trends in accelerator cryogenics are discussed with reference to existing machines or planned projects.

INTRODUCTION

Applied superconductivity, and its ancillary helium cryogenics, have now become basic technologies for high-energy accelerators and colliders. Since the pioneering Tevatron¹ at FNAL, all new hadron machines, i.e. HERA² at DESY, RHIC³ at BNL, UNK⁴ at IHEP, SSC⁵ at SSCL, and LHC⁶ at CERN make use of high-field superconducting magnets for guiding and focussing their ever stiffer beams. Lepton storage

rings, the design of which is dominated by synchrotron radiation losses, can only reach economically high energy and luminosity by means of superconducting acceleration cavities; this is the case for LEP200⁷ at CERN. Such cavities also find application in high intensity linacs (e.g. CEBAF⁸) and future linear colliders, such as TESLA⁹. In fact, almost all new or future high-energy machines will be superconducting and thus require large cryogenic systems (Figure 1).

Figure 1. Emergence of superconductivity as a basic technology for high-energy accelerators and colliders.

For both kinds of devices the practical working range is limited to a fraction of the critical temperature of the superconductor. Large-scale projects, which require high tonnage of material, may only be based on technically available, industrially produced superconductors, i.e. essentially Nb and NbTi alloys. As a consequence, helium is the sole cryogen to be considered today, both as process fluid in the refrigeration cycles and as cooling medium in the superconducting devices, and it is worth recalling first some of its relevant properties.

High-energy accelerators are characterized by their huge number of components, large size, underground implantation and limited number of access points. These features have direct consequences on the cryogenic systems, in terms of heat load budgets, refrigeration capacity, sectorization of cryoplants and distribution of cooling power along the machine, not to mention more mundane aspects such as cryogen storage. Only a systems approach, which integrates all these issues, may lead to globally optimized and thus technically acceptable solutions for the large-scale cryogenics of modern accelerators.

Detailed technical information on refrigeration systems has been presented in recent reviews^{10,11,12}, and this paper will limit itself to discuss trends in accelerator cryogenics, with reference to the above mentioned projects.

HELIUM AS A COOLING FLUID

The working domains of interest for cooling superconducting devices are shown in Figure 2, superimposed on the phase diagram of helium. The straightforward practice of using helium I at saturation, either in pool boiling⁷ or forced flow, combines the advantages of fixed temperature irrespective of heat load and high boiling heat transfer; it may however lead to flow instabilities in long piping and phase separation in case of large elevation differences. For these reasons, supercritical (monophase) helium has been mostly used for forced-flow cooling of long magnet

strings, making use of the sensible heat of the fluid. High flow-rates and continuous^{1,2,4} or periodic^{3,5} recooling with saturated helium are then required, in order to limit the temperature rise along the string.

Increasing the current-carrying capacity of high-field magnet conductors and limiting high-frequency losses in acceleration cavities calls for lowering the working temperature to below 2 K, and thus operate in helium II, either saturated^{8,9} or pressurized⁶. This allows to benefit from the low viscosity and high thermal conductivity of the superfluid phase, an important asset for superconductor stabilization. The higher thermodynamic cost and technological difficulties of low-pressure operation can be successfully handled in large systems, as demonstrated by experience gained on the TORE SUPRA tokamak¹³.

Figure 2. Phase diagram of helium, showing practical working domains.

HEAT LOADS AND REFRIGERATION DUTIES

The first task facing the cryogenic designer is the definition of temperature levels and the

assessment of the corresponding cryogenic heat loads. Besides well-known conductive and radiative insulation techniques, such as generalized use of multilayer reflective insulation, the basic approach to minimizing the total entropic load, and hence the required refrigeration capacity, consists in intercepting heat at the highest possible temperature level. The cryostats of accelerator devices^{14,15} integrate one or several active shields, which intercept heat inleaks from

the environment or beam-induced losses (synchrotron radiation, eddy currents in beam pipe); the main conduction paths, such as cold mass supports¹⁶ and current or instrumentation feedthroughs, also feature several levels of heat interception. The progress in cryostat design and insulation techniques has indeed permitted the refrigeration requirements of large projects to increase less than the size of the accelerators (Figures 3 and 4).

Figure 3. Size and installed refrigeration of hadron accelerators and colliders.

Figure 4. Linear refrigeration loads of hadron accelerators and colliders.

Besides nominal operation, the superconducting devices are subject to a variety of steady-state and transient modes, e.g. cold standby, current ramp and discharge, cooldown and warmup, quench and recovery, associated with strongly varying heat loads, which the cryogenic system must handle. This results in large dynamic range requirements (Figure 5), both for lepton and hadron machines.

A problem specific to hadron colliders is the cooldown and warmup of the large magnet cold mass (Figure 6); the large cooling power required in a limited period of time may only be economically generated by vaporization of liquid nitrogen, and the thermal stresses developed in the magnet structures must be kept under close control. The cooldown of a large machine typically takes one to a few weeks.

Figure 5. Dynamic range of large cryogenic systems.

Figure 6. Magnet cold mass of hadron accelerators and colliders.

CRYOGENIC DISTRIBUTION

The heat deposited or generated in the cryogenic devices all along the accelerator must be efficiently transported to the cryogenic plants, where it is eventually absorbed. This requires an adequate distribution scheme, operating with minimum temperature and pressure drops, and free from flow instabilities. The sectors served by each cryoplant in large machines may extend over several kilometers, but distributing the refrigeration power along such distances under thermodynamically acceptable temperature difference requires intermediate recooling. As a consequence, the maximum string length of cryogenically passive components does not exceed a few hundred meters, and active cryogenic equipment must be installed and operated in the machine tunnel.

Cryogenic distribution lines spanning kilometer lengths^{1,2,7,8} are expensive, both in terms of capital investment and operating costs. In the most recent projects^{5,6,9} all cryogenic distribution piping is integrated in the device cryostat and shares its thermal insulation.

A desired feature of a distribution scheme is redundancy: in case of failure or unavailability of one cryoplant, the cryogenic load of the corresponding sector must be shared by the neighbouring refrigerators. This is only possible provided sufficient reserve is available in the refrigerators and in the distribution lines, the transport capacity of which may be limited by excessive pressure drop, particularly on the low-pressure vapour return. In all cases, long-distance distribution of large refrigeration power is costly and cumbersome.

REFRIGERATION PLANTS

All large-capacity helium refrigerators operate on a modified Claude cycle, based on the combination of three elementary cooling processes: quasi-isobaric cooling in heat exchangers, adiabatic expansion with extraction of mechanical

work in turbines or piston expanders, and isenthalpic Joule-Thomson expansion in valve nozzles. These components are integrated in a vacuum-insulated coldbox, fed with high-pressure gaseous helium from a compressor set; oil-injected screw compressors, in a two-stage arrangement, have now become the industrial standard. While the capacity of the compressor set can be adjusted at wish by modular juxtaposition of similar machines, manufacturing and handling constraints practically limit the coldbox unit size to an equivalent refrigeration power of about 20 kW at 4.5 K.

Accelerator cryoplants must simultaneously perform different refrigeration duties and adapt their capacity to varying demands, while maintaining high efficiency and reliability. Matching these often conflicting requirements results in complex installations operating with elaborate thermodynamic cycles and sophisticated process control. The Carnot principle sets an absolute limit to efficiency, yielding a minimum work of refrigeration of 66 W/W at 4.5 K. Under the incentive of rising electrical power costs, the efficiency of recent cryoplants has significantly increased, up to about 30% of the Carnot limit (Figure 7). This was achieved by detailed analysis and improvement of process cycles¹⁷, as well as progress in components generating irreversibilities such as compressors, heat exchangers and turbo-expanders. The rising demand in plant capacity has also triggered studies which could lead to even higher efficiency¹⁸.

A frequent constraint on accelerator cryoplants is their underground implantation, which favours compact design. The specific volume of large-capacity coldboxes has been substantially reduced (Figure 8), thanks to wide use of computer-aided piping design, as well as increased efficiency⁷, which permits to obtain the required refrigeration capacity with lower process flow-rate.

The growing demand for large-power refrigeration below 2 K has stirred new

developments in low-pressure helium vapour compression by means of cryogenic centrifugal compressors¹⁹. Such machines already operate in two-stage configuration¹³, but four⁸- and five^{6,9}-stage operation with capacity adjustment still requires specific R & D.

HELIUM INVENTORY MANAGEMENT

The cryogenic systems of high-energy accelerators contain a large inventory of pure helium, a valuable resource which must be

Figure 7. Efficiency of large cryoplants.

Figure 8. Specific volume of large cryoplants.

conserved throughout the phases of operation (Figure 9). In particular, warmup and magnet quenches release large quantities of helium, which must be handled and stored so as to be available for swift restart of operation. The simplest and most flexible way to store helium is as gas at ambient temperature and about 2 MPa (20 bar), using the existing cycle compressors for handling and recovery; all cryogenic systems in operation today apply this technique. However, the high volume and specific cost of 2 MPa gas storage make it impracticable for systems with very large inventories⁵, which must resort to liquid storage, of much higher density and thus lower specific cost. Conserving the inventory then demands uninterrupted reliquefying, either by means of dedicated plants, or by using one or a few system cryoplants, interconnected for shuffling helium between sectors. Some gas storage volume is always required for operational flexibility.

CONCLUSIONS

Large-scale cryogenics is now a well-established technology in high-energy accelerators, for 4.5 K refrigeration of kilometer-long sectors by cryoplants in the 10 to 20 kW

capacity range. The present state-of-the-art may easily be extended to larger machines, by increasing the number of sector refrigerators and string cooling loops. Under economic and siting constraints, recent projects have displayed trends towards more compact plants with increased efficiency. Industrial-scale helium II systems appear feasible for operation below 2 K, but development is still required on multistage cryogenic compressors.

Conversely, the huge projects of high-energy physics appear as the leading field of application of large-scale helium cryogenics today.

ACKNOWLEDGEMENTS

I cordially wish to thank for their help in preparing this paper: D.P. Brown (BNL, Upton, NY, USA), G. Gistau (L'Air Liquide, Sassenage, France), G. Horlitz (DESY, Hamburg, Germany), M. McAshan (SSCL, Dallas, TX, USA), H. Quack (Sulzer, Winterthur, Switzerland), C.H. Rode (CEBAF, Newport News, VA, USA), J. Theilacker (FNAL, Batavia, IL, USA), as well as my colleagues of the Cryogenics Group at CERN.

Figure 9. Helium inventory of accelerator cryogenic systems.

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