Cryogenics for high-energy particle accelerators: highlights from the first fifty years

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Abstract. Applied superconductivity has become a key technology for high-energy particle accelerators, allowing to reach higher beam energy while containing size, capital expenditure and operating costs. Large and powerful cryogenic systems are therefore ancillary to low-temperature superconducting accelerator devices – magnets and high-frequency cavities – distributed over multi-kilometre distances and operating generally close to the normal boiling point of helium, but also above 4.2 K in supercritical and down to below 2 K in superfluid. Additionally, low-temperature operation in accelerators may also be required by considerations of ultra-high vacuum, limited stored energy and beam stability. We discuss the rationale for cryogenics in high-energy particle accelerators, review its development over the past half-century and present its outlook in future large projects, with reference to the main engineering domains of cryostat design and heat loads, cooling schemes, efficient power refrigeration and cryogenic fluid management.

1. Introduction

The last fifty years have seen the emergence of applied superconductivity and ancillary helium cryogenics as key technologies to high-energy particle accelerators, the workhorses of particle, nuclear and condensed-matter physics and some of the largest scientific instruments ever built by man. This is exemplified by the evolution of the total cryogenic refrigeration capacity at liquid helium temperature installed at CERN, the European Organization for Nuclear Research in Geneva, Switzerland (figure 1). Although some fairly large helium cryogenic plants have been in use at CERN since the 1960s, mainly feeding large bubble chamber and detector magnets, it is only with the appearance of numerous superconducting components in particle accelerators – high-frequency cavities and magnets – that the installed capacity developed to the hundreds of kW at 4.5 K observed today.

It is therefore interesting to analyze this transition, taking stock of the technical progress stimulated by the diverse large accelerator projects of this period and trying to understand the development processes at work. Having lived through this change and contributed to it in his professional career, the author appears particularly well placed to draw the big picture of the emergence of cryogenics in high-energy accelerators and, in a more speculative way, to explore some of the paths of future development. This picture will evidently not be free of personal bias. But to begin with the beginning, let us first present the rationale for cryogenics in high-energy particle accelerators [1].

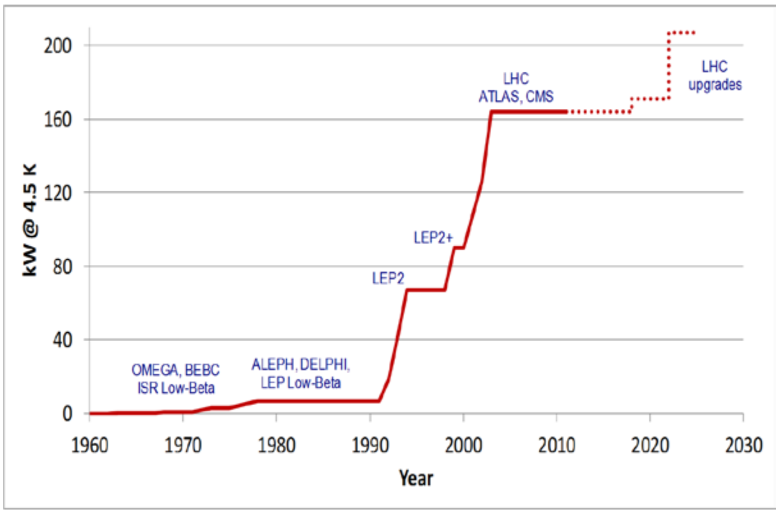

Figure 1. Installed cryogenic refrigeration capacity at CERN

2. Why cryogenics in particle accelerators?

The primary use of cryogenics in particle accelerators is to cool their superconducting components. Accelerators are electromagnetic machines, which exert forces on beams of charged particles via electric and magnetic fields for accelerating, guiding and focusing them. The absence of electrical d.c. resistance, or the limited a.c. dissipation in superconductors opens the way to produce higher fields and thus reach higher beam energy, while containing the dimensions of particle accelerators. This was historically the first reason to bring superconducting magnets in circular accelerators. More recently, with the advent of large machines, electrical power consumption became a serious issue and the choice of superconducting technology was also driven by energy efficiency. This applies in particular to "continuous-wave" linear accelerators, where most of the power is dissipated in the walls of the accelerating high-frequency structures, but also to the magnet systems of very large circular machines.

Circular accelerators have developed along two different lines in order to handle stiffer and stiffer high-energy beams (figure 2): increasing their diameter, and hence the radius of curvature in bending magnets, and increasing the field produced by these magnets. Normal-conducting magnets are iron-dominated, and hence practically limited to below 2 T by the saturation of their magnetic iron yoke. In superconducting magnets the ampere-turns cost little – as long as the conductors remain in the superconducting state – and the field is directly produced by the current distribution, without the need to concentrate the flux in an iron yoke. The magnets are therefore limited by the "critical surface" in the temperature/field/current density space of the superconductor used to wind their coils or equivalently, at any given temperature, by the "critical curve" in the field/current density plane. In order to obtain sufficient current-carrying capacity at high field, the superconductor must then be operated at a fraction of its "critical temperature", in practice half of it or below. Hence normal-boiling helium at 4.2 K appears an adequate coolant for most magnets wound with niobium-titanium superconductor, which has a critical temperature of about 9.5 K. If however one wishes to produce fields in the 8 to 10 T range with niobium-titanium, one has to operate the magnets at lower temperature, e.g. below 2 K in superfluid helium in order to maintain sufficient current-carrying capacity at high field. Conversely, normal-boiling nitrogen at 77 K appears not quite cold enough to cool magnets made of today's high-temperature superconductors. The d.c. superconducting magnet system of a particle collider does not show any steady-state dissipation, other than the power consumption of the cryogenic refrigeration system, which scales approximately with the circumference of the machine, irrespective of the bending field. The specific power consumption (kW per GeV of beam energy) of the superconducting magnet system – including cryogenic refrigeration – therefore scales as the inverse of the field (figure 3). High-energy circular machines thus need to be superconducting both for reasons of compactness and of energy efficiency.

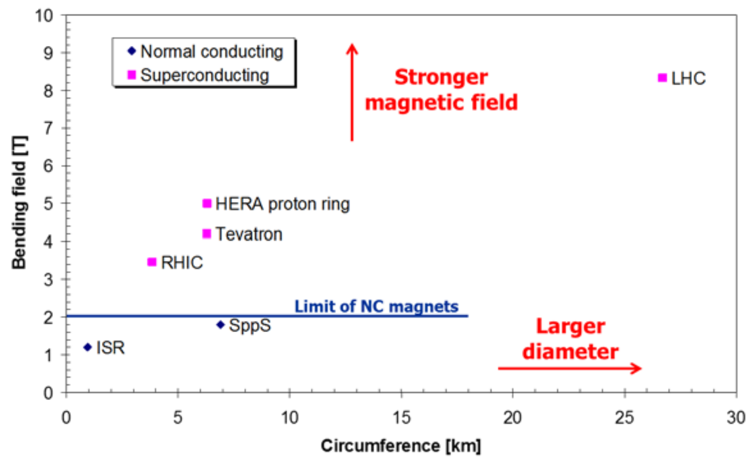

Figure 2. Development of circular hadron colliders

The case of linear accelerators, mostly composed of high-frequency accelerating cavities, is different. Such cavities are resonators for which one wishes to maximize the quality factor in order to reduce the power dissipation in the wall, characterized by its surface resistance. While copper cavities at room temperature show typical quality factors of few 10^4, superconducting cavities can reach quality factors of several 10^9, with a reduction in power dissipation more than offsetting the power consumption of the cryogenic refrigerator. This applies particularly for "continuous-wave" high-frequency systems, in which the cavities are continuously energized. Moreover, the surface resistance of superconducting cavities, which controls the quality factor and hence the power dissipation, has a component which scales with the square of frequency and the exponential of the ratio of critical to operating temperature. As a consequence, and in spite of the higher thermodynamic cost of refrigeration at lower temperature, it may be advantageous to operate high-frequency superconducting cavities at temperatures lower than the normal boiling point of helium, e.g. in superfluid helium below 2.2 K. With today's niobium cavities, this typically applies for frequencies above 700 to 800 MHz. The use of niobium with lower residual resistance displaces the optimum towards lower temperatures. Conversely, building the cavities out of higher-temperature superconductors, or coating their wall with such materials, would reduce the exponential term when operating them in normal boiling helium.

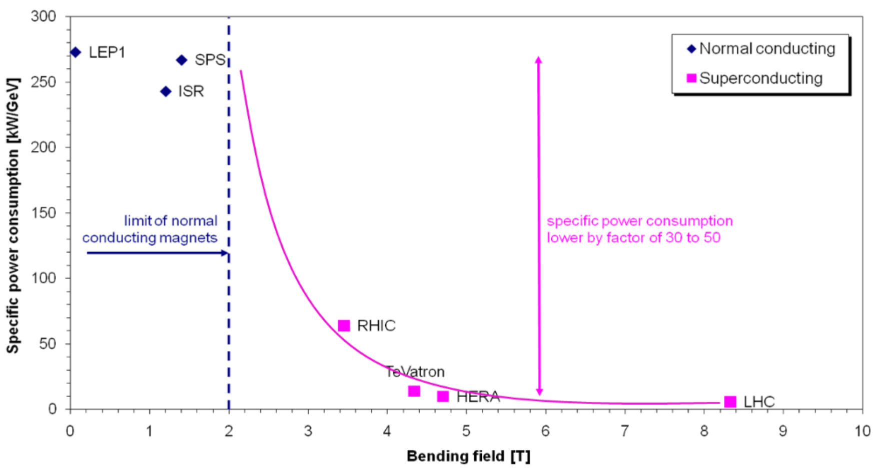

Figure 3. Specific power consumption of circular colliders

Other arguments for the use of cryogenics in particle accelerators are not driven by superconductivity, but by the interactions of the circulating beams with their environment, i.e. the wall of the beam pipe and the residual gas pressure in it. The circulation of charged particles induces currents in the metallic walls of the beam pipe, producing fields which act on the particles. This interaction, characterized by an impedance proportional to the wall resistivity, leads to power dissipation and in some cases to beam instabilities. It is important in large accelerators with small aperture, and can be compensated by feedback provided the rise time of the instability is long enough, i.e. the impedance can be kept low. This sets constraints on the choice of material and operating temperature for the first wall seen by the beam. In the Large Hadron Collider (LHC), the beam screen is coated with copper and maintained below 20 K [2].

Maintaining the beam pipe at low temperature also provides excellent cryopumping of most residual gas species. The saturation pressure of all gases, except helium, vanish at cryogenic temperatures (figure 4), so superconducting accelerators which have to be cooled at liquid helium temperature may benefit from this feature. In cases when the residual pressure in the beam enclosure must be kept very low, such as accelerators of highly-charged heavy ions, a cold beam pipe may become the driving factor for the use of cryogenics.

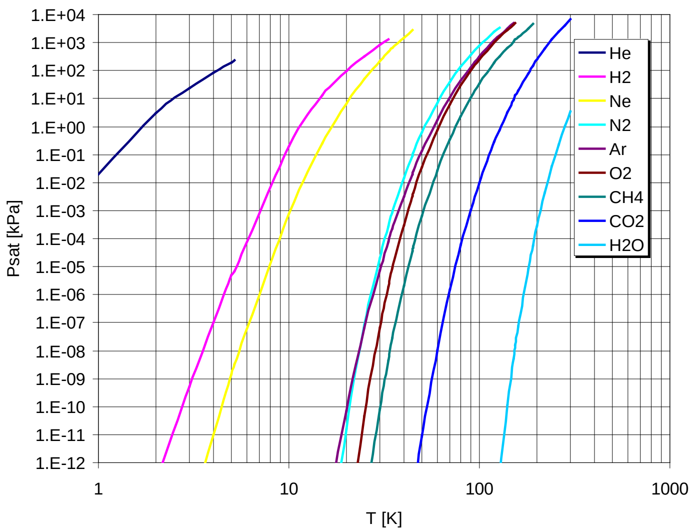

Figure 4. Saturation pressure of gases as function of temperature

3. The first fifty years: projects and progress

Although the idea of using superconductors to build high-field magnets had been formulated by H. Kamerlingh Onnes soon after the discovery of superconductivity, it is only with the advent of type-II superconductors that it could be put into practice: a 1.5 T superconducting magnet wound with molybdenum-rhenium alloy was built and patented by J. Kunzler in 1960, and the niobium-titanium alloys which became the workhorse of applied superconductivity were discovered in 1961 [3].

The potential of superconductivity for improving linear accelerators, including the option of superfluid helium cooling of the high-frequency cavities [4] was identified in the 1960s. In the same period, the benefits of using superconducting magnets in proton synchrotrons were clearly formulated and quantified, in relation to future projects of the time [5]. In these years CERN was considering building a 300 GeV proton synchrotron: following a first design study based on normal-conducting magnets in 1964, the German Atomic Energy Advisory Committee asked for a redesign using “modern techniques”, and a new proposal was issued in 1970 preserving the option of superconducting magnets, the development of which was entrusted to the GESSS European collaboration [6]. Decision to build a 400 GeV synchrotron with all normal-conducting magnets was eventually taken in 1973 and the CERN SPS accelerated its first proton beams in 1976 without the use of superconductivity.

In the following, we present projects which can be considered as important milestones in the development of superconductivity and cryogenics in particle accelerators. Rather than attempting to give a complete description of these projects or of their cryogenic system, we single out their specific features which have resulted in progress in the field.

The first system of superconducting magnets to be routinely operated in an accelerator were the eight quadrupoles of the high-luminosity insertion at the CERN Intersecting Storage Rings (ISR), strongly focusing the beams around one collision point and more than doubling the luminosity of the collider [7]. The magnets, individually powered, operated in stand-alone liquid helium bath cryostats, fed from a liquefier located some 50 m away via flexible, vapour-screened transfer lines [8]. The boil-off from the baths was used locally to intercept heat on current leads, cryostat neck and thermal shields. Although *a priori* less favourable from a thermodynamic point of view, this choice greatly simplifies the cryogenic distribution, cryostat pipework and control system, thus reducing parasitic heat in-leaks, regaining overall efficiency and improving reliability (all active cryogenic components are located in radiation-free area) [9]. The cryogenic plant made use of turbo-expanders with helium gas bearings, a technology mostly developed in Europe which had by then superseded the piston expansion engines of the old Collins-type refrigerators.

In order to preserve helium purity, the cryogenic plant for the ISR high-luminosity insertion was powered by a dry piston compressor. Shortly after came a revolution in helium refrigeration, with the use of oil-injected screw compressors similar to those employed in higher-temperature refrigeration (figure 5), with the benefits of much lower capital and maintenance expenditure. This was made possible by the development of efficient oil removal from helium, both aerosol and volatile compounds, down to a fraction of ppm level through the use of coalescing filters in series with a charcoal adsorber bed [10], a solution implemented on the satellite refrigerators of the Tevatron at Fermilab [11] which soon became the world standard.

Figure 5. Dry piston compressors in the CERN North Area in 1977 (left); oil-injected screw compressors for LEP cryogenics at CERN in 1996 (right)

In these years Brookhaven National Laboratory near New York in the USA had planned to build a 200 to 400 GeV superconducting proton collider called ISABELLE [12]. Magnets were developed, a 3.8 km circumference tunnel was excavated and a very large helium cryogenic plant was procured from industry, with a total capacity of 25 kW at 3.8 K; sub-cooling of saturated helium down to this temperature was achieved by two stages of cold hydrodynamic compressors [13]. The monitoring and control system was computer-based, and the strings of magnets in the tunnel would be cooled by forced-circulation of supercritical helium. The project was eventually cancelled, but the infrastructure, including the cryogenic plant, was later reused for the RHIC collider and has been in operation to this date.

The first fully superconducting particle accelerator was the Energy Doubler/Saver at Fermi National Laboratory near Chicago in the USA, which started operation in 1983 and later became the Tevatron proton-antiproton collider [14]. The 6.3 km circumference tunnel housed 990 main superconducting magnets with a bending field of 4.4 T. The magnets had a room-temperature iron yoke and their coils were cooled by forced circulation of supercritical helium, expanded at the end of the magnet sector and continuously re-cooled by the returning two-phase flow of saturated helium in a coaxial annular channel. Liquid helium was produced in a central liquefier and distributed via a cryogenic line circling the ring, to 24 satellite refrigerators operated in economizer mode, each feeding a magnet sector around the ring [15]. A pioneer machine, this successful project established the feasibility of large superconducting magnet systems and their associated cryogenics in accelerators, and served as reference for many years. It also trained a whole generation of experts in the construction, operation and maintenance of superconducting magnet and cryogenic systems for particle accelerators, thus preparing the future of the field.

The first superconducting accelerator in Europe was the proton ring of the HERA electron-proton collider at DESY, the German laboratory of particle physics in Hamburg. This machine accelerated beams of protons to 820 GeV, guided around the 6.4 km circumference of the ring by 416 superconducting dipoles and focused by 224 superconducting quadrupoles [16]. The magnets were designed in the laboratory and produced by industrial companies in several European countries. They featured a cold iron yoke and were cooled by forced circulation of supercritical helium at 4.4 K with continuous re-cooling by returning two-phase helium, in a way similar to the Tevatron cooling scheme. The machine was cooled by three large cryogenic refrigerators located in a single hall, each providing 6.8 kW cooling power at 4.4 K, 20.5 g/s liquefaction and 20 kW at 40-80 K for the thermal shields. The refrigerators operated on a modified Claude cycle with 14 heat exchangers and 7 expansion turbines, a configuration optimized for minimizing the temperature pinch on the heat exchange line, achieving a COP of 280 W/W and establishing a new record in thermodynamic efficiency [17]. After the closure of HERA, two of these machines are now re-used, with an additional 2 K stage, for cooling the superconducting high-frequency cavities in the linear accelerator of the European X-FEL project.

In the late 1980s, the USA launched a very large accelerator project, the Superconducting Super Collider (SSC) [18]. After several years of studies and R&D on the superconducting magnets, the construction of the 83 km circumference tunnel for this 40 TeV proton collider started south of Dallas. With almost 10’000 main superconducting magnets in the two proton rings, cost issues were critical and a large effort from several American laboratories aimed at streamlined design, technical optimization and industrialization of the magnets and their cryostats [19]. The project was eventually cancelled in 1993 after several years’ construction, but the benefits of the development work proved very valuable for future very large projects.

The late 1980s also saw the construction in the USA of the first accelerator making large-scale use of superconducting high-frequency acceleration cavities, CEBAF at the Thomas Jefferson National Laboratory in Newport News [20]. This machine accelerates electron beams by means of two recirculating linear accelerators using niobium superconducting cavities operating at 1.5 GHz, cooled at 2 K in saturated superfluid helium. CEBAF was thus the first high-energy accelerator cooled by superfluid helium, with a single large cryogenic plant nominally producing 4.8 kW at 2 K and 12 kW at 35-50 K for thermal shielding [21]. The powering of the accelerating cavities imposes strong variations on the 2 K heat load, which the cryogenic plant has to cope with. Maintaining the saturation pressure corresponding to 2 K on the helium baths of the cavity cryomodules requires four stages of cold hydrodynamic compressors in series and special procedures to handle the temperature and flow transients while maintaining the hydrodynamic machines in their operating envelope, i.e. remaining within the surge, stall and over-speed limits of the wheels. Being the first to produce superfluid-helium refrigeration in the multi-kilowatt range, CEBAF’s cryogenic system was extremely useful to the design of that of the LHC. The accelerator started operation in 1995 and is still in use today, after an upgrade to higher energy (and higher cooling capacity of the cryogenic system).

An interesting development occurred in the same period at the Joint Institute for Nuclear Research in Dubna, Russia. A 252 m circumference synchrotron accelerating heavy ions up to 6 GeV/A, the Nuclotron was built using pulsed superconducting magnets. The coils were wound with an internally

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cooled conductor, so that the magnets rest in the vacuum vessel of the cryostats, without the need for a helium vessel [22]. Magnet cooling circuits are tapped in parallel, between a header supplying liquid helium and a return pipe, and see two-phase flow of strongly varying vapor quality, a configuration prone to generate flow instabilities and possible vapor lock. The system however works, thanks to proper balancing of the hydraulic impedances of the parallel circuits and to accepting large variations in temperature and quality at the outlet of each branch. The latter are not detrimental to the operation of the magnet since they are seen mainly by the iron yoke, cooled in series with the coils. This type of superconducting magnet and cooling scheme is now used in the SIS100 proton and heavy ion synchrotron, under construction at GSI Darmstadt, Germany as part of the FAIR complex.

The largest system of superconducting high-frequency cavities built at this day is the acceleration system of the LEP electron-positron collider, built at CERN in the 1980s and upgraded in energy (LEP2) throughout the 1990s [23]. 288 niobium-on-copper cavities, installed deep underground in four long straight sections of the 26.7 km circumference ring, operate at 352 MHz in saturated helium bath cryostats at 4.5 K. They are fed from four large cryogenic helium refrigerators, each with an equivalent capacity of 12 kW at 4.5 K, later upgraded to 18 kW [24]. The upgraded LEP cryogenic plants are now reused for the LHC. They have also set, for several years, a *de facto* standard for the unit capacity of large helium refrigerators, which has seen an impressive development since the 1970s following the requirements of the market (figures 6 and 7).

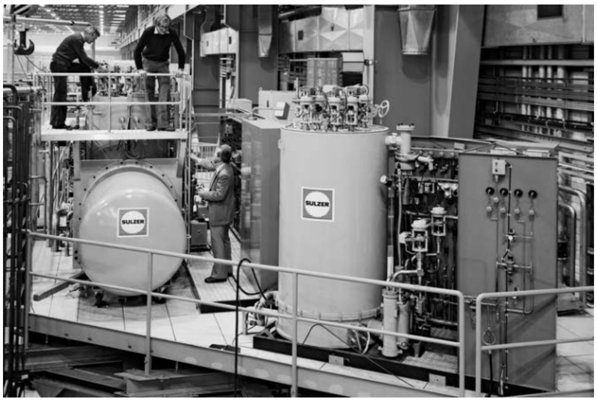

Figure 6. 400 W @ 4.5 K refrigerators (SULZER) in CERN North Area in the 1970s

Figure 7. 18 kW at 4.5 K refrigerators (AIR LIQUIDE and LINDE) at LEP/LHC in the 1990s

The deep implantation of the LEP tunnel, 100 m below ground on average, sets particular constraints on the configuration of the cryogenic system. If the large refrigerator cold boxes delivering liquid helium and recovering vapor at 4.5 K had been located integrally at ground level, a reasonable choice dictated by easier maintainability and cost of cavern volume underground, the hydrostatic head on the column of returning helium vapor of about 20 kPa (200 mbar) would have added 0.2 K on the operating temperature of the cavities. It was then decided to build the refrigerators with split cold boxes, a large upper one operating between room temperature and 20 K, and a compact lower one, installed at tunnel level, covering the 20 K to 4.5 K range. Another effect due to tunnel depth also had be taken into account, namely the work exerted by gravity on the downward flow of helium, which amounts to some 5 % of the latent heat of vaporization and therefore increases the transfer losses.

The LEP tunnel and technical infrastructure were later reused in the LHC project, the construction of which stretched between 1994 and 2008 at CERN. This high-energy proton and ion collider achieves unprecedented performance thanks to more than 1700 high-field superconducting magnets, wound with niobium-titanium conductor and operated in superfluid helium at 1.9 K [25]. In addition to the lower temperature of operation, the LHC cryogenic system makes use of the peculiar transport properties of the superfluid [26]. The magnets operate in quasi-isothermal static baths of pressurized superfluid helium close to atmospheric pressure, continuously cooled by a heat exchanger tube running along the magnet string, in which a small two-phase flow of saturated helium extracts the heat. This very efficient cooling scheme is able to cool a complete 3.3 km long sector of the LHC from one end with a maximum temperature difference of 0.1 K, without the need for circulator pumps [27]. Moreover, in case of resistive transition of a magnet, the rise in temperature of the helium bath leads to dry-out inside the heat exchanger tube, thus limiting thermal propagation to neighbors.

The LHC is the first hadron accelerator in which the circulation of beams induces significant heat loads. Most of them are intercepted before they hit the 1.9 K cold mass, by means of a beam screen snugly fitted in the magnet aperture and cooled by supercritical helium between 5 and 20 K. Primarily installed for thermodynamic reasons, the beam screen also serves other important purposes for beam vacuum and beam stability [2].

The LHC ring is cooled by eight large-capacity cryogenic plants, located at five points around the perimeter, each normally cooling a sector, but able to serve two adjacent sectors to provide some redundancy at partial load. Each plant provides a mix of liquefaction and refrigeration duties at 50-75 K and 4.5-20 K, amounting to an equivalent entropic capacity of 18 kW at 4.5 K with excellent efficiency reaching 28 % of the Carnot cycle [28]. The cryogenic plants are complemented at their cold end by eight 1.8 K stages producing each 2.4 kW of refrigeration power by expansion to the 1.6 kPa (16 mbar) saturation pressure of helium. The low-pressure helium vapor is compressed by a train of cold hydrodynamic compressors up to a fraction of atmospheric pressure, followed by room-temperature screw compressors operating at sub-atmospheric suction pressure. This arrangement combines good efficiency, limited capital expenditure and compliance to the strongly variable demand resulting from the dynamic heat loads [29].

The LHC contains 135 tons of helium, of which about 60 % are in the magnets when the machine is in operation, the rest being shared between the distribution pipework, the cryogenic plants and the minimum reserve in the buffer storage vessels [30]. Helium is procured from the market and delivered to CERN in standard liquid transport containers. Upon warm-up of the machine, the helium must be stored and its purity preserved. Long-term storage is done at room temperature in 250 m^3 gas vessels at 2 GPa (20 bar), which can only accept about half of the inventory. Part of the helium can also be stored, for limited amounts of time, in 120’000 liter vacuum-insulated liquid tanks at atmospheric pressure. The rest is re-injected in the market via “virtual storage” contracts with the gas vendors, a strategy which allows receiving the amounts needed for operation in due time, while limiting the capital expenditure.

This rapid overview illustrates the impressive development of cryogenics in particle accelerators over the past half-century, following that of superconductivity. It shows how a rather exotic laboratory technique has developed into a full-fledged industrial discipline, meeting performance and reliability objectives and serving a market. Credits for this evolution are due to the pioneering work of the research centers initiating ever ambitious projects, but also to the specialized industry which has responded to the market demands through sustained technical progress. Now let us try and see how this may continue in present and future projects.

4. Addressing tomorrow's challenges

A number of superconducting high-energy particle accelerators are being constructed, planned or studied today in Europe, Asia and America. They will need varying amounts of cryogenic refrigeration at normal boiling helium as well as at superfluid helium temperature. The challenges ahead are therefore quantitative – higher total refrigeration capacity, larger helium inventory – but also sometimes qualitative – better energetic efficiency, lower refrigeration temperature to match the lower residual resistance of advanced superconducting materials for high-frequency cavities. Such new projects constitute a unique opportunity to push technological development, which should not be missed during their R&D phase. Taking the case of unit capacity of cryogenic helium plants at 4.5 K and below 2 K (figure 8), one can see that even projects requiring much higher total refrigeration capacity than the LHC tend to use the existing state-of-the-art rather than promoting new developments. By contrast, the Future Circular Collider (FCC) study, initiated by CERN and conducted in global collaboration [31], explores new avenues in large-capacity helium cryogenics, such as magnet cooling schemes of very long (8 to 10 km) sectors, beam screen cooling schemes using non-conventional fluids, innovative refrigeration schemes and machinery including high-efficiency turbo-Brayton cycles using helium-neon mixtures down to 40 K, impact of higher design pressures on the thermal performance of cryostats and vacuum-insulated pipelines, and design of higher unit-capacity cryogenic plants, typically 50 to 100 kW at 4.5 K and up to 10 kW below 2 K.

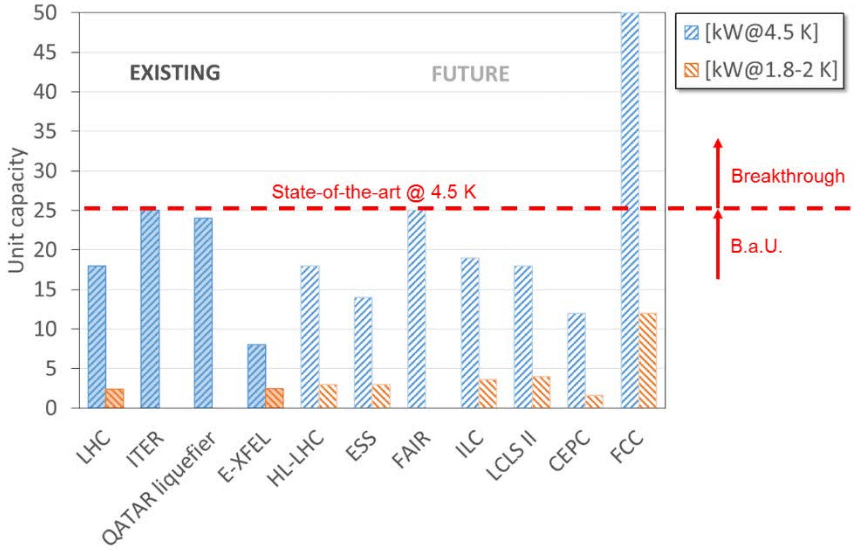

Figure 8. Unit capacity of cryogenic helium refrigerators for present and future projects

To conclude these prospective considerations, let us quote from the opening address of K. Mendelssohn, the founder of the International Cryogenic Engineering Conference series, to the first venue held in Tokyo in 1967 [32]:

There is one prediction where I feel quite safe… Cryogenic engineering, as it faces us today, requires many and diverse skills and disciplines. So far they often stand apart but they will have to co-operate and enter upon each other's field if they wish to get results.

The ambitious goals, technical complexity, managerial challenges and societal constraints of new high-energy particle accelerator projects needing advanced cryogenic systems render this prediction timelier than ever.

Acknowledgements

The projects briefly discussed here bear witness to the ingenuity, dedication and hard work of many scientists, engineers and technicians in research institutes and industry throughout the world, spanning a period of fifty years i.e. longer than a professional career. The author apologizes for not being able to give due credit to all of them in this limited article and list of references. Among them, he would like to particularly acknowledge the work of the CERN Magnet and Cryogenics groups, which he shared for many years.

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