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CRYOGENIC EFFICIENCY AND SUSTAINABILITY ASPECTS FOR PARTICLE ACCELERATORS & DETECTORS

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Abstract

Cryogenics is a key enabling technology for present and future particle accelerators and detectors, providing the conditions required for the operation of superconducting magnets, superconducting RF cavities, vacuum systems, and particle detection devices. However, extracting heat at very low temperatures requires large amounts of energy, often representing a major share of the total energy demands of the facilities. This article presents the main factors driving energy consumption, the status of the technology for a large spectrum of temperatures, and possible developments for improving the efficiency of cryogenic systems. It discusses the impact of cryogenic cooling configurations and the potential of new superconducting materials towards improved sustainability of future accelerators and particle detectors.

INTRODUCTION

Since the 1950's cryogenics has played an essential role in particle physics, with first the liquid hydrogen bubble chambers for particle detection and then the progressive introduction of superconducting magnets and RF cavities in particle accelerators and detectors [1,2].

Given the large scale of many future accelerator and detector projects, cryogenic systems play a major role in both capital and energy costs. Table 1 shows the power and energy consumption of the LHC accelerator [3,4] and of two variants of the future FCC accelerator currently under study [5-7]. As it can be seen, cryogenics accounts for between 20% and 60% of the total energy, with yearly consumption of several hundred GWh. From these figures it appears that the cryogenic systems for any future accelerator must be optimized for high energy efficiency in design, construction, and operation. Public acceptance of such large scientific infrastructures is more and more dependent on the demonstration that sustainability aspects, like the energy consumption are considered. Cryogenic energy efficiency is essential to ensure the technical, financial, environmental, and societal viability of these projects.

HEAT EXTRACTION AND CRYOGENIC ARCHITECTURE

The second law of thermodynamics requires that extracting heat at low temperature and rejecting it at a higher (ambient) temperature needs energy in the form of work. This work is usually used to compress a gas that is then expanded with extraction of work. For an ideal process, the work required to extract a Q amount of heat at temperature T_0 and rejecting it at T_{amb} is given by the Carnot equation

Table 1: Electrical Power and Energy for the LHC and the FCC Study

Power	LHC	FCC-ee (ttbar)	FCC-hh (1.9 K)
Total Power (MW)	100	360	350
Cryogenics (MW)	39	46	206
Cryogenics (%)	39%	13%	59%
Energy per year			
Total (GWh)	700	1800	2340
Cryogenics (GWh)	295	400	1360
Cryogenics (%)	42%	22%	58%

$$W = Q \cdot (T_{amb} / T_0 - 1)$$

For example, extracting 1 W at 4.5 K and rejecting it at 25°C requires at least 65 W of work. When heat is extracted over a temperature range, an exergy analysis can be used to determine the required work [8]. In real processes, there are many sources of irreversibility and even the most efficient refrigerators, like the ones of the LHC [4], can only achieve less than 30 % of the Carnot efficiency. Table 2 gives the electrical power needed for the extraction of 1 W for various cryogenic heat loads commonly found in

Table 2: Indicative Electrical Power for Some Typical Heat Loads. "Equivalent at 4.5 K" power is also provided.

	Temp. Level [K]	Equ. @4.5 [W]	Elec. power [W]*	Description
"cost / Watt" (per W)	50 – 75	0.07	18	Screen cooling, 18.5 bar
	4.5 – 20	0.55	138	LHC beam screen, 3 bar
	20 – 25	0.18	45	Typical MgB2, 1.3 bar
	4.5	1	250	LHe boiling 1.3 bar
	1.8	3	750	LHe II boiling 16 mbar
liquef. (per g/s)	4.5–290	100	25000	Liqu. of He (per g/s)
C. Leads (per kA)	4.5–290	5.5	1375	Norm. cond. lead (per kA)
	20–290	2.3	580	Feed at 20 K (per kA)
	50-290	1.2	312	Feed at 50 K (per kA)

* assuming 250 W electric power per watt isothermal @4.5 K

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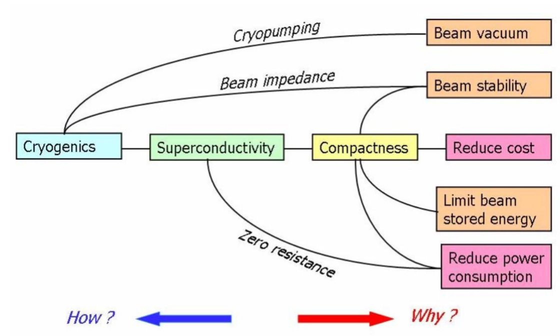

Figure 1: Rationale for using superconductivity and cryogenics in particle accelerators [2].

accelerators and detectors. The table also provides the electrical power needed for helium liquefaction (per g/s) and for current leads (per kA) and provides the "equivalent power at 4.5K" for scale comparison.

From the thermodynamic point of view, it is evident that the single most efficient way to reduce energy consumption is to extract the heat at the highest possible temperature. This can be achieved by minimising the heat load at the lowest temperatures and by choosing configurations and materials that allow operation at higher temperature as exemplified by a recent study for the FCC-hh accelerator, with an operation at 4.5 K providing a reduction of the electrical power of a factor of 1.7 [7] with respect to 1.9 K.

A careful design of the cryogenic process and of the cryogenic distribution system matching the actual cooling requirements is essential for an optimal efficiency. For any large facility, a significant portion of the refrigeration capacity and energy consumption can be lost in distribution through two fundamental thermodynamic processes: first-principle losses, including heat leaks and fluid friction within the distribution system; and second-principle losses, when the cooling provided does not closely match the actual temperature requirements of the cooled system [8].

Cryogenics for Particle Accelerators

Particle accelerators use electromagnetic fields to accelerate, steer, and focus charged particles. For Linear accelerators the maximum particles energy depends on the accelerating RF field and length, whereas for circular accelerators, the maximum energy is limited by the ring size and the magnetic field for heavy particles (hadrons, muons) and by the RF power for light particles (electrons, positrons). Superconductivity enables very high current densities in conductors with minimal losses and superconducting RF cavities provide a major improvement in efficiency and Q factor. Very low temperatures provide also an essential function for the beam stability, thanks to reduced resistance in the beam tube walls and improve vacuum quality through distributed cryo-pumping. Figure 1, from ref. [2], summarizes the main rationale for using superconductivity and cryogenics in particle accelerators.

Cryogenics for Particle Detectors

In particle detectors, since at least the 1970's, Cryogenics has been used for cooling the superconducting magnets needed to generate the required strong magnetic fields [9-12]. Cryogenics is also essential to keep gases like argon or krypton in liquid form for calorimeters [13]. Large amounts of liquid argon are also need for neutrino detectors [14] and dark matter detection experiments [15]. Cryogenics is also needed on smaller scale for fixed targets like the liquid hydrogen one of AMBER at CERN [16] and for possible cryogenic detectors like Transition Edge Sensors [17]. Large data treatment with quantum computing might also need large-scale cryogenics at very low temperature in the future.

As is the case for accelerators, most future large-scale projects for particle detectors will need significant cryogenic facilities.

STATUS OF TECHNOLOGY AND POSSIBLE DEVELOPMENTS

Refrigerators and Cryogenic Distribution

For refrigerators, as originally shown by Strobridge [18] the efficiency essentially improves with size following an exponential law with an approximate exponent of 0.23 of the refrigeration power as proposed by Green [19], with the most efficient existing cryoplants like the ones of the LHC having a 28.5% of Carnot efficiency [20]. This would tend to favour centralized cryoplants, however the cryogenic distribution needs to be carefully optimized, with low heat-inleak distribution lines and absence of cryogenic pumps or circulators providing the best performance [4]. With expansion turbines already achieving isentropic efficiencies near 80%, the potential for further improvements in cold box performance is limited. However, compression remains a weak point, with oil-lubricated screw compressors having around 55% isothermal efficiency [21]. Future improvements can potentially be achieved with a Turbo-Brayton compression cycle operating with mixed gases for temperatures down to 40 K [22]. Turbo Brayton commercial refrigerators with a cooling power of more than 150 kW are available with Carnot efficiencies of up to 40 % at 77 K [23]. The implementation of such a system is envisaged for the FCC-hh with the extraction of up to 3.6 MW between 40 K and 60 K [5,24] and for the proposed FLArE liquid argon detector at CERN [25]. Such refrigerators could also find an ideal application for cooling HTS based devices in the range 40-60 K.

Accelerator Magnets

Magnets for heavy particles circular accelerators (hadrons, ions, muons) are characterized by high magnetic fields and high current densities. While existing accelerators are based on NbTi conductors, at 4.5 K or 1.9 K, most future high energy accelerators plan to use Nb_3Sn conductors to achieve higher magnetic fields while still working around 4.5 K. The temperature margin provided by these conductors enables the possibility to achieve the required

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high fields without the need to operate at 1.9 K [7] with potential lower electrical consumption. On the longer term, the development of HTS conductors could enable either higher magnetic fields at 4.5 K or operating at temperatures around 20 K with reduced field.

Circular accelerators for light particles (e-, e+), like the FCC-ee, need moderate magnet fields and conventionally use resistive magnets. With the development of HTS conductors it is possible to envisage replacing the resistive magnets with HTS ones operating around 77 K [26] with greatly reduced energy consumption, with however the added complexity of cryogenics.

RF Cavities

Most existing superconducting RF cavities are either made of pure Niobium (Nb) or are made of copper coated with a thin layer of Nb. For achieving optimal performance, these cavities often need to operate at 2 K, immersed in superfluid HeII, well below the superconducting transition temperature of Nb. The main current accelerator studies are planned to stay with these temperature levels. However, in recent years, the quality of Nb_3Sn coated cavities has progressively improved, allowing to envisage them as alternatives to Nb. Since the critical temperature of Nb_3Sn is much higher than for Nb they can operate with similar properties around 4.2 K, and it can be envisaged to cool them either by conduction [27] or semi-dry cooling [28]. This opens the possibility to use cryocoolers, greatly reducing the complexity of the cryogenic system, with however questions on the overall efficiency and reliability if applied for more than a few units.

Detector Magnets

Magnets for detectors are typically characterized by a large volume, a moderate magnetic field in the range 2T – 4 T, transparency to particles and usually solenoid or toroidal fields. Most magnets in existing large experiments use NbTi conductors, operating close to 4.5 K, either in a thermo-syphon configuration [12] or in forced-flow configuration [10,11].

The development of MgB_2 and REBCO practical conductors has recently opened the possibility to operate detector magnets at higher temperatures and with different configurations like conduction cooling. As an example, the future SHiP detector at CERN is planning to use a conduction cooled MgB_2 magnet [29] at 20 K for its spectrometer and a REBCO conduction cooled magnet [30] at 30 K for its muon shield, both using cryocoolers. The future IDEA detector for FCC-ee [31] is also using REBCO conductors that will require specific cryogenics.

OTHER ASPECTS

Helium

Helium is a non-renewable resource, and it is necessary for any application requiring a cryogenic fluid below 20 K and even the more advanced facilities loose about 10% of the inventory every year [32]. While it is possible to envisage using other fluids, like hydrogen for higher temperature, all existing projects will still need helium in the foreseeable future.

The production of helium is essentially a byproduct of the extraction of LNG which is estimated to peak in the 2060's [32]. In the medium term no shortage is expected, however helium availability and price are subject to large variations due to the limited number of helium sources and inventory management adds complexity. It is therefore desirable to reduce the inventory, and efforts are being made in this direction, an example being the recent study for an FCC-hh version operating at 4.5 K [5]. Managing the transient heat loads at very low temperature could however be challenging with less buffering provided by helium.

Heat Recovery

Extracting heat at very low temperature results in the emission of large amounts of heat to the environment. The temperature at which the heat is released, typically below 100°C, makes it relatively difficult to use directly. However, most recent and future facilities are planning to include aspects of heat recovery. As an example of such approach, a multi megawatt project is currently under construction at CERN [33].

CONCLUSION

Cryogenics has been, and will be, for the foreseeable future a key enabling technology for high energy particle accelerators and particle detectors. As extracting heat at low temperature requires large amounts of energy, a systematic optimization of all the technical choices is essential for improved efficiency. Improvements in efficiency for large facilities are expected from the future introduction of Turbo Brayton compression. New configurations like conduction cooled magnets, at 4.5 K or higher temperatures have the potential to reduce the energy requirement, to simplify the cryogenic system and to reduce the helium inventory.

The recent availability of practically usable new superconducting materials like MgB_2 and REBCO opens the possibility, at first for detector magnets, of cryocooler based conduction cooling that has the potential to greatly simplify their cryogenic systems.

Efforts are also ongoing to define configurations with reduced helium inventory and for the improvement of the sustainability of cryoplants by recovering the rejected heat, with already multimegawatt projects under construction.

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