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# SUPERCONDUCTIVITY AND CRYOGENICS FOR FUTURE HIGH-ENERGY ACCELERATORS

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High-energy particle accelerators are used to create new forms of matter, probe its structure at very small scales, reproduce in the laboratory very high temperature conditions naturally present in astronomical or cosmological objects, and generate high-brilliance electromagnetic radiation. To accelerate, guide and focus beams of charged particles, they produce electrical and magnetic fields in RF cavities and electromagnets. Economically attaining higher fields is an essential condition for sustaining development of performance while containing increase in size, capital and operating costs. Superconductivity and cryogenics have therefore become and will remain enabling technologies for high-energy accelerators. After discussing the rationale for their use, we present several projects of future machines, under construction or under study, with emphasis on their specific requirements, constraints and adopted solutions.

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## INTRODUCTION

High-energy particle accelerators are the largest scientific instruments built by man. Invented at the end of the nineteenth century, almost contemporary with the concept of elementary particle, they have accompanied the development of "modern" physics – relativity and quantum mechanics – to become very large facilities constructed at the supranational and even global level, serving thousands of users in many scientific domains. The sustained development of their performance over the years was made possible by timely adoption of emerging technologies, often developed for other markets but sometimes stimulated by this very application. Superconductivity and cryogenics, which are also the products of the late nineteenth and early twentieth centuries, constitute the most recent example of this cross-development process. After describing how nature can be investigated with high-energy particle beams, we briefly present the principles and techniques of particle acceleration, and the particular role of superconductivity and cryogenics in these machines. We then proceed to review several projects of future accelerators and colliders, in construction or under study, with emphasis on their specific requirements, constraints and solutions in these technologies.

## RESEARCH WITH HIGH-ENERGY PARTICLE BEAMS

There are basically four classes of reasons to use high-energy particle beams as research tools, all finding their rationale in basic laws of "modern" physics.

The first one is to explore matter at small scale, by probing it with radiation of a wavelength smaller that the dimension one wishes to resolve. Since de Broglie and the advent of quantum mechanics, we know that the wavelength associated with a particle is inversely proportional to its momentum, hence the need for high-energy beams to resolve small dimensions. In this respect, high-energy accelerators can be seen as powerful microscopes. While electrons and X-rays in the 10 keV range are sufficient to resolve structure down to the atomic scale ($10^{-10}$ m), beam energies of GeV are needed to probe matter at the nucleon scale ($10^{-15}$ m), and investigating the quarks which constitute the substructure of nucleons at $10^{-18}$ m requires TeV beams.

The second reason is the ability to produce new, massive particles in high-energy collisions thanks to the mass-energy equivalence postulated by Einstein. In high-energy accelerators, particles get highly relativistic, i.e. their mass-energy is orders of magnitude larger than their rest mass. When released in the collisions, this energy can produce many new particles, with mass-energies much larger than the rest mass of the incoming particles. This mechanism was that used to produce all elementary particles other than the few stable ones available in ordinary matter, up to the discovery of the “top” quark with a mass of 175 GeV (almost as heavy as a gold nucleus) by colliding protons and antiprotons with a rest mass of only about 1 GeV each, accelerated to some 900 GeV in the Tevatron collider at Fermilab (USA).

A third applicable relation is that established by Boltzmann between particle mean energy and temperature. Accelerators can impart energy to particles and nuclei to locally reproduce in the laboratory the very high temperatures occurring in stars or in the early universe, and to investigate nuclear matter in these extreme conditions. This enables us to explore the confines of the nuclear “valley of stability”, both along the valley (superheavy nuclei) and on its sides (proton-rich and neutron-rich radioactive nuclei), and to generate intense, pulsed beams of neutrons by spallation from heavy nuclei bombarded with proton beams. At higher temperature (corresponding to an average energy of 170 MeV), quarks and gluons get deconfined from nucleons and the onset of a “quark-gluon plasma” such as occurred when the universe was less than 1 ms old could recently be observed and is investigated at machines like RHIC at Brookhaven (USA) and soon at the LHC at CERN.

Finally, high-energy particle beams may be used not for themselves, but for the electromagnetic radiation which they emit when accelerated, particularly when their trajectory is curved by a magnetic field (centripetal acceleration). When the particle beams are highly relativistic, the radiation is emitted in a narrow forward cone, tangential to the trajectory, thus producing short bursts of light in any given direction: “synchrotron” radiation. Repeated bending in wiggler and undulator magnets yields high brilliance and narrow spectrum of the beam by constructive interference, and under some conditions coherence in so-called free-electron lasers (FEL). In synchrotron and storage-ring based light sources, recycling the beam conserves energy but degrades its emittance, and hence the characteristics of the radiation. As an alternative, energy recovery linacs (ERL) in which the beams are single-use but their energy is recovered in the RF cavities, are under study. Such instruments produce very intense, ultra-short pulses of radiation, opening new windows of observation of condensed matter structure, spectroscopy of excited atomic and molecular states, as well as dynamics of chemical reactions, biomolecules and nanomaterials.

## THE ROLE OF SUPERCONDUCTIVITY AND CRYOGENICS IN ACCELERATORS

Accelerators are electromagnetic machines, acting on charged particles – electrons, protons and their antiparticles – and ions by application of electrical and magnetic fields. A particle of charge q moving with velocity $\boldsymbol{v}$, subject to an electrical field $\boldsymbol{E}$ and a magnetic field $\boldsymbol{B}$, will undergo a Lorentz force $\boldsymbol{F}$ given by

$$\boldsymbol{F} = q\,(\,\boldsymbol{E} + \boldsymbol{v}\wedge\boldsymbol{B}\,)$$

Thus the electric field, acting along the direction of motion, will modify the momentum of the particle (i.e. the common meaning of “acceleration”), while the magnetic field, producing a force orthogonal to the particle velocity, will curve its trajectory (bending or focusing action). Particle accelerators combine RF cavities producing electrical fields and magnets producing magnetic fields, in highly evacuated beam channels. As the beams become more rigid at high energy, stronger fields are needed to contain the size of the machines, i.e. the length of single-pass linear accelerators or the diameter of multi-pass synchrotrons. The energy attainable in a linear accelerator is directly proportional to the electrical field produced in the RF cavities, and to their active length L.

$$E_{\mathrm{beam}}\,[\mathrm{MeV}] = |\boldsymbol{E}|\,[\mathrm{MV/m}]\;L\,[\mathrm{m}]$$

That attainable in a synchrotron is proportional to the field in the bending magnets and the radius of curvature r of the machine.

$$E_{\mathrm{beam}}\,[\mathrm{GeV}] \simeq 0.3\,|\boldsymbol{B}|\,[\mathrm{T}]\;r\,[\mathrm{m}]$$

Superconductivity, which allows generation of high electrical and magnetic fields, is a powerful means of kerbing the expensive increase in real estate of accelerators. The highest energy accelerator ever built, the LHC at CERN [1], has a beam energy $10^8$ times that of Lawrence’s first cyclotron, but a diameter only $10^5$ times larger (Figure 1), thus showing a factor of 1000 increase in compactness.

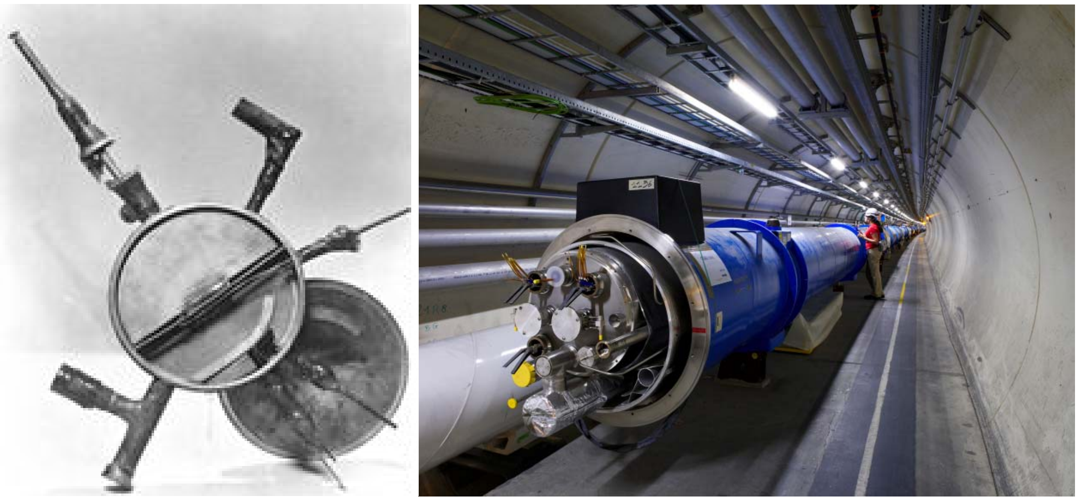

Figure 1 Development of accelerators from E.O. Lawrence’s first 80 keV cyclotron, 12.7 cm in diameter (1930) to the 7 TeV LHC, 8.5 km in diameter (2007)

For circular accelerators, compactness has another virtue than just lower capital cost. The energy stored in the circulating beam U can become very large, when particle energy $E_{beam}$, beam current $I_{beam}$ and circumference C are high, thus rendering beam handling and discharge very critical. Making a machine compact limits the beam stored energy, as it varies proportional to the circumference.

$$U\ [\mathrm{kJ}] \simeq 3.34\ E_{beam}\ [\mathrm{GeV}]\ I_{beam}\ [\mathrm{A}]\ C\ [\mathrm{km}]$$

With particle energy of 7 TeV, beam current of 0.58 A and a circumference of 26.7 km, the LHC will have an energy of 362 MJ stored in the beam - enough to melt half a ton of copper – thus requiring an elaborate and very reliable beam discharge system [2]. In a larger machine, this problem would become even more acute.

Besides compactness and capital cost, superconductivity is also a means of reducing electrical power consumption which dominates operation costs of accelerators and eventually limits their feasibility. High-energy, high-intensity machines produce beams with MW power, so that conversion efficiency from the grid to the beam must be maximized by reducing ohmic losses in RF cavities and electromagnets. In d.c. electromagnets, superconductivity suppresses all ohmic losses, so that the sole power consumption is that of the associated cryogenic refrigeration. Typical values for specific electrical power consumption in accelerator electromagnets are given in Table 1, showing net advantage for superconductivity. Thus superconductivity reduces power consumption of synchrotrons through two compounding processes, by enabling to make them smaller, and by reducing power per unit length of electromagnet. If the LHC, which is 26.7 km in circumference and will consume 40 MW electrical power for cryogenic refrigeration, had been built with normal conducting magnets, its circumference would have increased to about 100 km and its power consumption to some 900 MW. The rationale is similar for RF cavities, in which superconductivity reduces wall resistance and thus increases the Q factor of the resonator. The wall resistance of superconducting cavities subject to varying fields does not however drop to zero, but varies exponentially with the ratio of operating to critical temperature $T_c$ [3]. This imposes to operate at a temperature well below $T_c$, in practice the result of a compromise between residual dissipation and thermodynamic cost of refrigeration. The use of RF superconductivity in linear accelerators results in substantial improvement of the overall grid-to-beam power efficiency, typically from less than 10 % for conventional cavities, up to about 20 % for superconducting machines such as the ILC and SPL.

Table 1 Typical characteristics of normal conducting and superconducting accelerator magnets

| | Normal conducting | Superconducting (LHC) |
|---|---|---|
| Field strength [T] | 1.8 | 8.3 |
| Current density in windings [A/mm$^2$] | 10 | 400 |
| Electrical power consumption [kW/m] | ~10 | ~2* |

* for cryogenic refrigeration

The charged beams circulating in accelerators produce an electromagnetic field which interacts with the walls of the vacuum chamber. This interaction, characterized by an impedance when the wall has non-zero resistance or at abrupt changes in vacuum chamber cross-section, can lead to beam instabilities. Large circular machines are particularly prone to the transverse resistive-wall instability, which needs to be compensated by active feedback.

To render this feasible, the rise time of the instability must be made large enough, i.e. the beam transverse impedance $Z_T(\omega)$ must be kept low.

$Z_T(\omega) \sim \rho^{0.5}\ r^{1.5}/b^3$

Since $Z_T(\omega)$ increases with the size of the machine r and the electrical resistivity ρ of the wall material and varies inversely with the vacuum chamber aperture b, usually kept as small as possible for cost reasons, the only issue in large machines is to maintain ρ low: the vacuum chamber is coated with a thin layer of copper and operated at low temperature. In the LHC, the first conducting wall seen by the circulating beams, i.e. the beam screen, is coated with 0.1 mm copper and operated below 20 K [4]. Cryogenics is therefore required for this application independent of the use of superconductivity.

Another direct application of cryogenics in accelerators is distributed cryopumping. The saturated vapour pressures of all gases, except helium, vanish at low temperatures, so that the wall of a cold vacuum chamber can act as an efficient cryopump. Moreover, while small apertures and long pumping distances result in poor conductance for lumped pumps, the cold vacuum chamber provides *in situ* distributed pumping. In high energy machines, though, the pumping surface needs to be sheltered from the impinging radiation and scattered particles from the circulating beams, which can induce desorption of the condensed atoms and provoke vacuum instabilities. The beam screen of the LHC [5], permeable to gas molecules and cooled below 20 K by forced flow of supercritical helium, protects the cold bore at 1.9 K which constitutes the prime pumping surface for the beam vacuum.

The rationale for the use of superconductivity and cryogenics in accelerators is summarised in Figure 2.

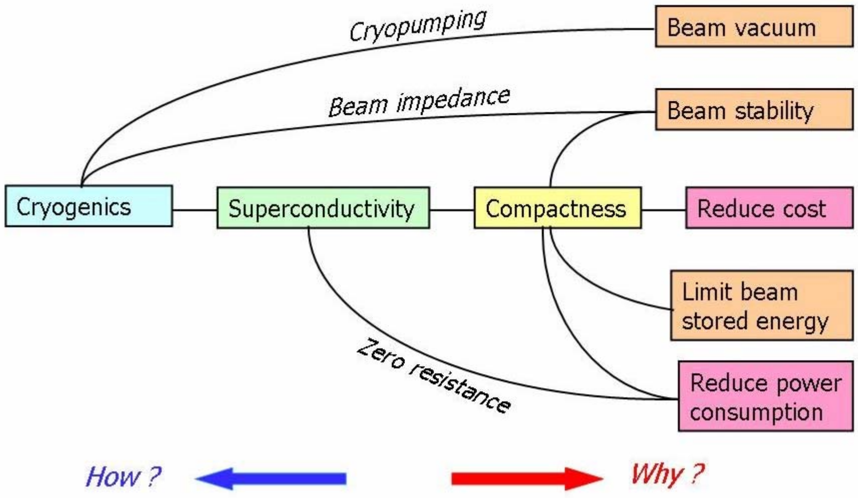

Figure 2 Rationale for the use of superconductivity and cryogenics in particle accelerators

## PARTICLE PHYSICS AT THE ENERGY FRONTIER: LHC AND ILC

The Large Hadron Collider (LHC) under construction at CERN [1] is a high-energy, high-luminosity proton and ion collider, with beam energy of up to 7 TeV. It reuses the 26.7 km circumference tunnel and infrastructure from the previous LEP machine. The beams will be guided and focused by high-field superconducting magnets [6]: 1232 twin-aperture dipoles of 8.3 T, 474 quadrupoles and 7612 corrector magnets of diverse types [7]. The main magnets use 7000 km of Nb-Ti Rutherford-type superconducting cable, operating at 1.9 K in static pressurized superfluid helium [8]. All magnets, produced in industry, are assembled into their cryostats and individually cold tested at CERN before installation and interconnection in the tunnel. The machine is composed of eight 3.3 km long sectors, individually cooled and powered. Cryogenic refrigeration is lumped in five “islands” with cryoplants serving the adjacent sectors. Each cryoplant is constituted of a helium refrigerator of 18 kW @ 4.5 K equivalent capacity, feeding a 2.4 kW @ 1.8 K refrigeration unit. Subatmospheric compression of helium vapour from 1.5 kPa to 0.13 MPa is performed by multi-stage cold hydrodynamic compressors and warm volumetric compressors [9]. Cryogenic distribution in the tunnel is achieved through a compound helium line, connected to the elementary magnet strings at every 107 m cell [10]. The cold mass of the LHC amounts to 37’000 tons: it will be cooled from room temperature in 15 days by vaporizing 10’000 tons of liquid nitrogen. The helium inventory in the system is 96 tons. Powering of the 1720 independent electrical circuits, with currents from 60 A to 12 kA, will be done through 3284 current leads, of which the 1182 with higher current rating make use of high-temperature superconductors [11]. The LHC will start colliding beams in 2007, and operate for some 20 years. Over this period, its luminosity will be gradually increased by upgrading collision regions (new high-field, large-aperture superconducting quadrupoles based on Nb-Ti and $Nb_3Sn$) and injectors (new superconducting RF linac and synchrotrons using pulsed superconducting magnets).

Complementary to the LHC for making precision measurements in the TeV energy range, is the International Linear Collider (ILC), presently under study by a world-wide collaboration organized through the Global Design Effort [12]. This machine is an electron-positron collider with beam energy of 250 GeV, later upgradeable to 500 GeV. Its main subsystems are two 11 km long linear accelerators, using some 16’000 superconducting RF cavities made of Nb and operating at 1.3 GHz in saturated baths of superfluid helium at 2 K. To contain the length of the machine, an ambitious goal of 31.5 MV/m for the operating gradient has been set, requiring studies and development on new materials (large-grain, single-crystal Nb), improved surface treatments and more efficient cavity geometries. The cavities are installed in 12-m long cryomodules such as developed for the TTF project at DESY (Germany), integrating all cryogenic pipework and ancillaries and assembled in cryogenic strings of 142 m. Cryogenic sectors of 2270 m length are individually served by helium refrigerators of unit equivalent capacity 22 kW @ 4.5 K, with 4.1 kW @ 2 K. The size of these machines is comparable to that of the LHC cryoplants. To cool both linacs and damping rings, ten 4.5 K and twelve 2 K refrigerators would be required, with an installed equivalent capacity totalling 250 kW @ 4.5 K [13]. The total helium inventory is estimated to 91 tons. The ILC Global Design Effort aims at conducting focussed R&D and producing a technical design report by the end of the decade, to permit approval and construction from 2010 onwards.

## HIGH-INTENSITY PROTON LINACS: SNS AND SPL

The Spallation Neutron Source (SNS) which has just started operation in Oak Ridge (USA) is based on a 1 GeV proton linac with a beam power of 1.4 MW [14]. For energy efficiency, the 330 m long linac uses in its high-energy section, 81 Nb superconducting cavities operating at 805 MHz with gradients up to 24 MV/m. The cavities, housed in 23 cryomodules, operate in saturated baths of superfluid helium at 2.1 K. Cryogenic distribution is performed by transfer lines paralleling the linac, from which cryomodules are individually connected through removable connections. The single refrigerator, modelled after that of CEBAF in Newport

News (USA), produces 8.5 kW @ 35-55 K, 15 g/s liquefaction at 4.5 K and 2.4 kW @ 2.1 K using four stages of cold hydrodynamic compressors.

The SPL under study at CERN is a high-intensity proton linac with a beam energy of 3.5 GeV and a beam power of 5 MW [15]. The rationale for using superconducting RF is the same as for the SNS: energy efficiency. Out of the 430 m total length, 80 % would be equipped with 178 Nb superconducting cavities operating at 704 MHz with gradients up to 25 MV/m. The cavities would be housed in 24 cryomodules of a design similar to those of TTF, and operated at 2 K in static superfluid helium. The estimated equivalent refrigeration capacity would be 15.8 kW @ 4.5 K, with 4.5 kW @ 2 K.

## NUCLEAR PHYSICS WITH PROTONS, ANTIPROTONS AND IONS: FAIR

The FAIR project in preparation at GSI Darmstadt (Germany) is a vast complex of synchrotrons and storage rings using 1630 superconducting magnets of diverse types [16]. Particularly noteworthy are the pulsed superconducting magnets equipping the SIS100 and SIS300 synchrotrons, each with a circumference of 1.1 km. SIS100 uses 108 window-frame magnets of 2.1 T, fast ramping at 4 T/s, based on the Nuclotron design at Dubna (Russia). The coils are made of Nb-Ti superconductor with a central cooling channel, cooled at 4.5 K by flow of two-phase helium. The 108 magnets of SIS300, of the cos θ design, operate at 6 T with ramp rate of 1 T/s. They are wound from Nb-Ti Rutherford cable conductor, with special polyimide insulation featuring cooling holes. Strings of magnets will be cooled by forced flow of supercritical helium at 4.5 K. Due to ramping losses, the cryogenic load is strongly variable over time, with the dynamic term twice as large as the static load. Two refrigerators, totalling a refrigeration equivalent capacity of 41.7 kW @ 4.4 K, will feed the synchrotrons, storage rings and beam transfer lines. In view of the geographical dispersion of the user devices, some 1.7 km of cryogenic lines are required [17]. The total helium inventory of FAIR is 11 tons. Construction is expected to start in 2007, with possible staging of the different machines.

## NEW SYNCHROTRON LIGHT SOURCES: EUROPEAN XFEL AND ERL

The European X-Ray FEL in preparation at DESY Hamburg (Germany) is a source of very brilliant, ultra-short (100 fs) pulses of X-rays down to 0.1 nm wavelength [18]. It is based on a 17.5 GeV electron linac with an average beam power of 600 kW. The 1.7 km long linac is equipped with 928 Nb superconducting RF cavities at 1.3 GHz with gradient of 23.6 MV/m. The cavities, housed in 116 cryomodules of 12 m length of the TTF type, operate in static saturated superfluid helium at 2 K. The cryomodules, which include all cryogenic pipework and ancillary equipement, are assembled in 146 m long cryogenic strings. The whole linac is cooled by a central refrigerator with an equivalent capacity of 12 kW @ 4.5 K, featuring 2.45 kW @ 2 K with four stages of cold hydrodynamic compressors. The present HERA refrigerator could be used as back-up for improved availability of the E-XFEL. Construction is due to start in 2007 and first operation is expected by 2014.

Energy recovery linacs (ERLs) are under study in several laboratories [19]. The Cornell (USA) project is based on a 5 GeV linac with a beam power of 500 MW, thus making energy recovery and acceleration efficiency an absolute necessity. It would use 390 Nb superconducting cavities at 1.3 GHz, operating at 1.8 K with gradient of 16 MV/m. The refrigeration power needed is estimated at about 10 kW @ 1.8 K. The G4LS project at Daresbury (UK) is a complex of FEL and ERL using 102 Nb superconducting cavities at

1.3 GHz, operating at 1.8 K with gradients of 15.5 MV/m. The refrigeration power needed is 3.5 kW @ 1.8 K [20]. Design and R&D work for 4GLS are presently funded.

## CONCLUSIONS

Superconductivity and cryogenics now constitute key enabling technologies of high-energy particle accelerators. With the LHC and the development of superconducting RF, superfluid helium has become a medium of choice for boosting superconductor performance and cooling extended systems. Existing large projects have required the development to industrial scale, and stimulated the emergence of *de facto* standards for materials, devices, insulation techniques, cooling methods and cryogenic refrigeration, thus permitting to mutualize R&D efforts and to create wider markets. The variety of ambitious accelerator projects under study, preparation or construction shows a bright future for these technologies.

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