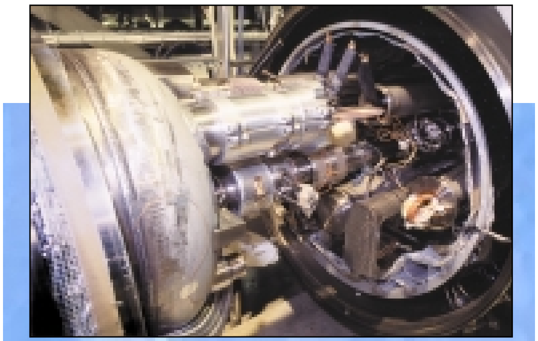
The LHC cryogenic system

The LHC will be the largest cryogenic system in the world. Why does such a particle accelerator need low temperatures?
The LHC has to use powerful electromagnets to keep its high-energy particles on a circular track. To provide the strong fields needed to grip its high-energy particles, the LHC electromagnets exploit the phenomenon of superconductivity, in which an electric current passes almost without resistance. In this way, the LHC magnets can be powered to very high fields and at minimal cost. Most materials which become superconducting only do so at liquid helium temperatures.

As well as being vitally dependent on temperature, superconductivity also depends on other factors. If the current is increased beyond a critical level, the material ceases to be superconducting. This critical current itself depends on temperature as well as on the applied magnetic field. To maintain the required high currents and avoid such problems, the liquid helium bathing the LHC's electromagnets will be cooled down to just 1.9 K, at which temperature helium is a superfluid.

Providing cryogenics on this scale calls for some very special technology, providing efficient refrigeration capacity and long-distance transport of this capacity at very low temperatures. The LHC represents a major fraction of the world cryogenic effort, not only in sheer volume but also for research and development work. Most of the world's major cryogenic suppliers are involved in the LHC effort, providing enormous amounts of high-quality materials.



Interconnections for an LHC superconducting dipole magnet. The LHC's magnets will be cooled by superfluid helium at 1.9 K.

Cooling the LHC ring

To maintain its 27-kilometre ring at superfluid helium temperatures, the LHC's cryogenic system will have to supply an unprecedented total refrigeration capacity of some 150 kW at 4.5 K and 20 kW at 1.9 K distributed around the ring. The LHC cryogenic system has been the subject of an extensive industrial development programme between CERN and the French Commissariat d'Energie Atomique (CEA). This programme benefited from experience gained in construction of the CEA's Tore Supra experimental thermonuclear fusion facility in the 1980s.

Helium compressors at the test and assembly area for LHC equipment.

About half of the refrigeration capacity used at the LHC was originally installed for LEP – CERN's electron–positron collider. There its job was to provide the liquid helium supply for the superconducting radiofrequency cavities which boosted the energy of the particle beams. For the LHC, this cryogenic supply had to be doubled in size to provide much more liquid helium, and extended to cool helium from 4.5 K down to 1.9 K using several stages of centrifugal compressors.

The LHC uses eight 18-kW cryoplants, four of them new and four upgraded from the cryogenics used for LEP. This photo shows one of the new 18-kW 4.5-K refrigerator units.

As well as being highly efficient, the compressors must not contaminate the helium in any way. After significant development work in industry, the LHC will use centrifugal compressors which operate like spin-driers, hurling helium outwards into the compressor outlets. These operate at extremely high speeds (up to 900 revolutions per second) requiring special active magnetic bearings.

For the cooling system needed to maintain the LHC ring at 1.9 K, development work focused on specially-designed low-pressure heat exchangers, volume and hydrodynamic compressors, and optimal thermodynamic cycles. Special large-scale experiments were carried out to measure the flow pattern of superfluid helium over long distances.

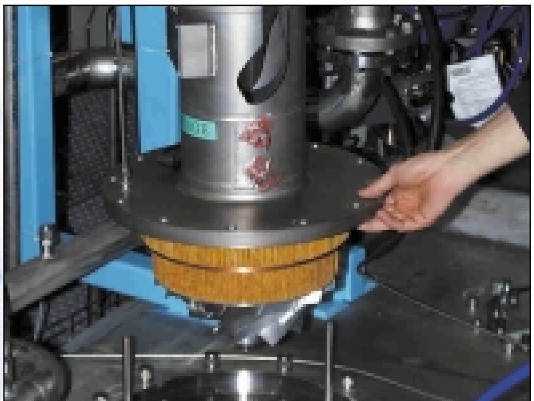
Cryogenics for the eight sectors of the machine will be supplied by eight powerful refrigerator units distributed around the ring. The superconducting magnets are bathed in static superfluid helium under pressure. This high pressure keeps air out and minimizes electrical problems due to bubbles of vapour. Superfluid helium at 1.9 K has a very high thermal conductivity and is able to conduct away heat a thousand times better than a metallic conductor like copper. With almost no viscosity, superfluid helium penetrates tiny cracks, 'soaking' deep inside the magnet coils to absorb any deposited or generated heat.

This heat is quickly transported to a heat exchanger pipe containing a mixture of saturated vapour and superfluid helium arranged in a series of 107-metre cooling loops all around the ring. The low-pressure vapour is returned to a header, where low-pressure compressors take it to atmospheric pressure (at 1.9 K, saturated superfluid helium is at a pressure of 1.6 kilopascal, 1.6% of atmospheric pressure).

Arrival of a cold compressor box for a pre-series 1.9-K refrigeration unit for the production of superfluid helium for the LHC.

To reduce the cooling required at 1.9 K, heat is removed as far as possible at higher temperatures. The magnet supports, for example, have intermediate heat intercepts to reduce heat entering the magnet cold-masses. Electrical connections, instrumentation and the feet on which the magnets stand are the only points where heat transfer can happen through conduction. They are all carefully designed to draw off heat progressively. The feet are made of 4-mm-thick glass-fibre composite material with layers of aluminium and steel heat intercepts. Each foot supports 10,000 kg of magnet.

Making the current leads themselves superconducting minimizes the heat entering the cold system. Instead of classic materials like copper which are good thermal conductors, these current leads use newly discovered materials which become superconducting at around 80 K and which have a lower thermal conductivity.



Cold compressor cartridges ready for installation. Four stages in series will compress superfluid helium from 1.6 to 60 kilopascal.

Materials - superconductor around the world

The metallic conductors carrying the current in the LHC's superconducting electromagnets are a key element in the manufacturing process. The niobium–titanium alloy used in the LHC represents a major fraction of the total world production of superconducting raw material – 28% over a five-year period. In addition to the sheer volume of the production process, the finished product has to be of extremely high quality.

The magnet coils for the LHC are wound from 'Rutherford' cable, so called after the UK laboratory where it was developed. This cable consists of up to 36 twisted 15-mm strands, each strand being made up in turn of up to 8800 individual filaments, each filament having a diameter as small as 7 micrometres.

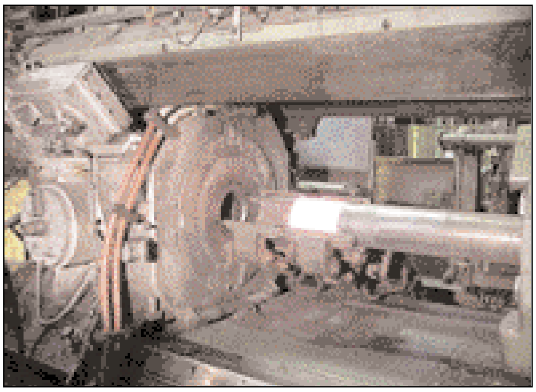
The 27-kilometre circumference of the LHC calls for 7000 km of cable, corresponding to about 240,000 km of strand – enough to circle the Earth six times at the Equator. If all the component filaments were unravelled, they would stretch from the Earth to the Sun!

The raw material for this conductor is 470 tonnes of niobium–titanium alloy and 26 tonnes of niobium sheet supplied by Wah-Chang in the USA. To make the filaments, a 110-kg billet of niobium–titanium 195 mm long and 850 mm across, protected by a niobium sheet and enclosed in a copper canister, is forced through a nozzle under pressure and then drawn out into hexagonal wires about 2 mm across. In the next stage of the process, 8800 of these hexagons are packed together in another copper can, for extrusion and drawing to the required strand size, ready for cable manufacture.

The cables are provided by specialist suppliers –four in Europe, one in the USA and one in Japan. The provision of the superconducting material to the European suppliers is covered by the USA's contribution to the LHC.

Quality control for this cable is extremely important. A few broken filaments deep inside the conductor matrix are not a problem, however large breaks would quickly ruin magnet performance. CERN therefore strictly controls all stages in the manufacture of the cable. All billets of niobium–titanium must be certified as conforming to a strict specification. Then the cabling run is checked to ensure that all strands come from previously approved billets. During the cabling run, samples are continually monitored before an approval for shipment is issued. The whole cable is then stringently checked before being made available for magnet manufacture. To handle all these complicated tests, a large array of testing equipment has been developed and built at CERN. Some tests are also carried out at Brookhaven in the USA.

During 2001, about half the raw niobium–titanium was processed, but it became clear that cable production was already running behind the schedule originally foreseen. This was mainly because of the difficulties of maintaining the required cable quality under mass production conditions. Certain supplier responsibilities were reassigned, and with cable supply being critical to the success of the whole project, such flexibility could still continue to play an important role.



Preparing LHC superconductor – a billet of niobium–titanium rods ready for insertion into an extrusion press. (Photo KME)