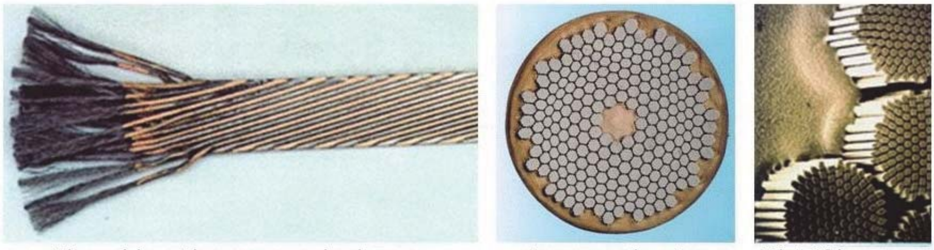

Fig. 8.8. A flat LHC cable, a strand and groups of Nb-Ti filaments in a strand [1].

The critical current of the 28-strand inner cable at 10 T is ≥ 13750 A.

The total quantity of cable procured amounted to about 7000 km (1200 t). The length of strand produced was about 270 000 km. To maintain the precision in the transverse dimensions of the strands and cables to some μm for such a production was an extraordinary industrial achievement [22].

In order to detect deviations from the specified process that could affect the strand and cable quality, strict Statistical Process Control (SPC) was applied at all steps of the production. To ensure uniformity, CERN handled the procurement of the 470 t of Nb-Ti alloy and 26 t of Nb sheet for the six suppliers of strand.

8.3 LHC Cryogenics: Quantum Fluids at Work

Philippe Lebrun

The LHC cryogenic system [23] had to face several unprecedented challenges, both qualitative and quantitative. Here we present the technological solutions developed to meet these challenges reliably, economically and efficiently.

The first challenge is the low temperature of operation of the magnets — 1.9 K — driven by the need to improve the current-carrying capacity of the Nb-Ti superconductor at high field. As this temperature is below that of the "lambda transition" between the two liquid phases of helium (Fig. 8.9), this implies operation in helium II, which exhibits particular transport properties associated with its superfluid state: very low viscosity, high heat capacity and excellent heat conductivity. These properties have been studied in detail since the discovery of superfluid helium by Piotr Kapitsa, John Allen and Don Misener in 1937, and can be profitably applied to the cooling of superconducting magnets [24]. Moreover, provided the superfluid helium can permeate the magnet coils via percolation channels designed into the electrical insulation, the stability of the superconductor

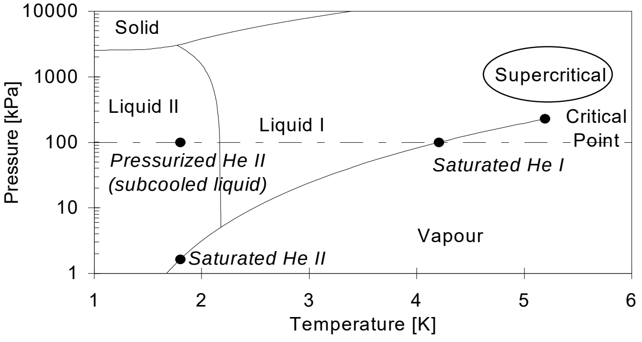

Fig. 8.9. Phase diagram of helium: the magnets operate in baths of pressurized He II, cooled by saturated He II flowing inside the heat exchanger tube.

against thermal disturbances is greatly enhanced, an essential benefit as its specific heat is an order of magnitude smaller at 1.9 K than in normal helium at 4.5 K.

It can be seen in the phase diagram (Fig. 8.9) that the saturation pressure of superfluid helium is below 5 kPa (50 mbar), which raises two concerns: (i) cryostats containing superfluid helium at saturation operate far below atmospheric pressure, with risk of air in-leaks, contamination of the helium and clogging by solid air; (ii) the dielectric strength of gaseous helium is greatly reduced at such pressure, increasing the risk of electrical breakdown. To circumvent these shortcomings, the LHC superconducting magnets operate in baths of "pressurized" He II, i.e. above saturation pressure, in fact in sub-cooled liquid at about atmospheric pressure [25]. The very large (but finite) heat conductivity of helium II ensures that each bath is quasi-isothermal; it cannot however be used to transport heat over long distances in the accelerator tunnel. The LHC magnet cooling scheme is thus composed of a heat exchanger tube [26] threading its way along the magnet chain, in which a small two-phase flow of saturated helium II gradually vaporizes as it absorbs heat from the pressurized helium II baths (Fig. 8.10).

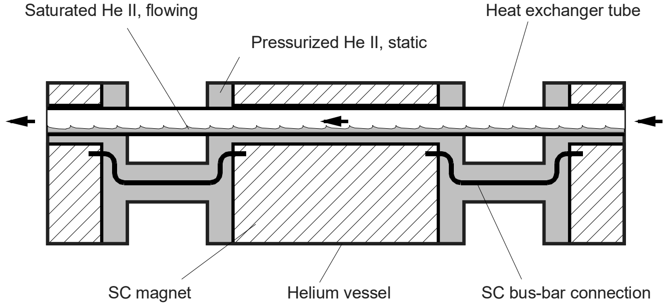

Fig. 8.10. Principle of the LHC superfluid helium cooling scheme [1].

This scheme combines the benefit of magnets operating in static, isothermal superfluid helium close to atmospheric pressure, with that of fixed temperature imposed by the saturated helium II inside the tube. Moreover, the small, stratified two-phase flow inside the tube can be driven solely by gravity (in the sloping LHC tunnel) and/or by flowing vapour, thus avoiding the use of circulation pumps. Finally, 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 neighbouring magnets.

The second challenge of the LHC cryogenic system, a novelty for hadron accelerators, stems from the dynamic heat loads induced by the circulation of the particle beams, due to synchrotron radiation, dissipation of image currents in the resistive wall of the beam pipes, loss of particles scattered by the residual gas as well as by the collisions in the interaction points (only affecting the sections of the accelerator close to the experiments), and deposition of energy by electrons resonantly accelerated in the electric field of the circulating bunches, the so-called "electron cloud". In nominal operation, the beam-induced heat loads can be up to 1.7 W/m, i.e. an order of magnitude higher than the allowed heat in-leak at 1.9 K. To reduce their thermodynamic impact, it is therefore necessary to absorb most of these losses on beam screens [27] fitted in the magnet apertures and cooled at higher temperature, from 5 K to 20 K by forced circulation of supercritical helium. The beam screen tubes, made of non-magnetic austenitic stainless steel to resist eddy-current forces at resistive transitions of the magnets, are internally coated with 75 μm of high-conductivity copper to reduce the wall impedance seen by the beam and slotted to act as cryopump baffles, shielding the 1.9 K pumping surface of the cold bore from radiation and particles lost from the beams (Fig. 8.11).

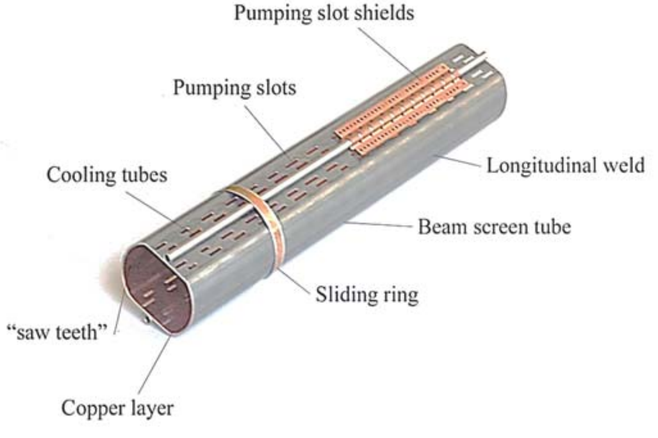

Fig. 8.11. The LHC beam screen.

The large size of the collider, impacting heat loads and refrigeration duties, and its underground implantation, limiting access to eight points around its perimeter, with sector lengths of 3.3 km in-between access points and depths exceeding 100 m below ground, constitute a third challenge. The LHC ring is cooled by eight large-capacity cryogenic plants, located at five points around the perimeter, each normally cooling a 3.3 km sector, but able to serve two adjacent sectors to provide some redundancy at partial load. Each plant (Fig. 8.12) 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. Low-pressure helium vapour 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 issue of cryogen supply and inventory management [30] completes this brief overview. The system 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. 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 litre vacuum-insulated liquid tanks at atmospheric pressure. The rest is re-injected in the market via "virtual storage" contracts with the gas vendors. This strategy allows receiving the amounts needed for operation in due time, while limiting the capital expenditure. Liquid nitrogen is used for precooling the 37 500 t mass of the magnets, a task incommensurable with the installed capacity of the cryogenic plants. For this purpose, 10 000 t of liquid nitrogen supplied by 50 m^3 semi-trailers are vaporized at rates of up to 40 t per hour, to produce 4.8 MW of precooling power down to about 100 K, thus permitting to bring the whole machine from room to cryogenic temperature in about three weeks.