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The Large Hadron Collider (LHC) at CERN will be the next research instrument of high-energy physics. Colliding protons at 14 TeV center-of-mass energy and high luminosity, it will probe the structure of matter down to an unprecedentedly fine scale, thus allowing to reproduce in the laboratory phenomena which occurred in the very early universe. On the technological side, the LHC makes use of high-field superconducting magnets for guidance and focusing of the particle beams around the 26.7 km circumference of the machine, to be installed in the existing LEP tunnel. The nominal bending field of 8.65 T is produced in some 1300 twin-aperture dipoles, wound with small-filament Nb-Ti conductor, and operated below 1.9 K in static baths of pressurized helium II, thus taking advantage of its specific properties as cooling fluid. We present the main technical challenges of the LHC cryogenic system, and review the actions of development and the preparatory work in progress.

INTRODUCTION

CERN is preparing to build the Large Hadron Collider (LHC), a unique research facility for particle physics [1]. This machine, to be installed close to Geneva (Switzerland) in the 26.7 km circumference tunnel of the existing LEP collider (Figure 1), will accelerate and bring into collision intense beams of protons and ions at higher energies than ever achieved before. This will allow to probe the structure of matter at the very fine scale of 10^{-19} m, i.e. to resolve the quarks which constitute the nucleons. The particle physics community now agrees that the LHC is the most adequate instrument to continue the exploration of the structure of matter and of the basic forces acting between its constituents, thus opening the way for progress beyond the range of the "standard model" of modern physics, in particular as concerns fundamental issues such as the origin of mass and the breaking of symmetry, which accounts for the predominance of matter over antimatter in today's universe. As the latest addition to the CERN accelerator complex, the LHC will make optimal use of existing resources, such as the efficient network of injectors, the infrastructure of a large laboratory and the technical expertise of an experienced staff with a long-standing tradition of efficient international collaboration.

The LHC also represents a major technical challenge for accelerator builders. It will make intensive use of high-field, twin-aperture superconducting magnets, operating in pressurized superfluid helium below 1.9 K, for guidance and focusing of the stiff hadron beams. The technical success of the project thus rests on the ability to push the key technologies of applied superconductivity and large-capacity helium cryogenics to an unprecedented scale, to develop them well beyond their present state-of-the-art, and to integrate them reliably in a high-energy accelerator with high-intensity beams.

The basic design parameters of the LHC, operating as proton collider, are listed in Table 1. The machine will reuse civil engineering and infrastructure from LEP, and is thus constrained by the existing geometry: a quasi-circular tunnel composed of eight octants, on a slope of 1.4 % and at a depth ranging from 50 to 150 m below ground, with eight evenly-spaced access areas at a distance of 3.3 km from each other. As a consequence, the LHC cryogenic system is based on eight octant cryogenic plants, each producing and distributing refrigeration to the adjacent half-octants, over a length of 1.7 km and across elevation differences of up to 22 m.

Table 1 Nominal design parameters of the LHC (proton collider mode)

Circumference	26.7	km
Bending field	8.65	T
Particle energy in collision	7.0	TeV
Particle energy at injection	0.45	TeV
Luminosity	10^{34}	$cm^{-2}.s^{-1}$
Beam intensity	2 x 530	mA
Beam stored energy	2 x 332	MJ
Synchrotron power	2 x 3.7	kW
Acceleration time	1200	s

SUPERFLUID HELIUM AS MAGNET COOLANT

The practical solution today for designing a large accelerator magnetic system operating above 8 T is to use technical superconductors based on the well-developed, mass-produced Nb-Ti alloy, and operate them below 2 K in pressurized superfluid helium. In addition to the enhancement of superconductor performance at lower temperature, dictated by the high-field requirement, this allows to benefit from the peculiar thermophysical properties of helium II - large effective thermal conductivity and heat capacity, as well as low viscosity - for heat transport and conductor stabilization. Moreover, operating in helium II at about atmospheric pressure avoids the severe drawbacks of the low saturation pressure, i.e. the risks of dielectric breakdown and contamination of the process fluid by air inleaks. Increasing the working current density in the magnet windings also results in significant savings on the mass of superconductor required, which at the present value of 1.2 x 10^6 kg represents the single largest item in the cost breakdown of the project.

The challenge of LHC cryogenics is thus to apply the technology of pressurized superfluid helium, pioneered at CEA Grenoble (France) and implemented in the Tore Supra tokamak and a few other projects [2], to a large distributed system spreading over several kilometers. Preliminary work had explored cooling schemes exploiting thermal conduction [3] and forced convection [4] in pressurized superfluid helium, with periodic recooling by saturated baths in lumped heat exchangers, which eventually had to be abandoned. Although based on the use of single-phase helium II, the flow and heat transport properties of which may now be modelled with confidence [5,6], these schemes proved to be barely sufficient to match the increased cooling requirements of the project.

The superconducting magnets of the LHC operate in static baths of pressurized helium II at 1.9 K and about 0.1 MPa, in which the generated or deposited heat is transported by conduction to a heat exchanger tube threading its way along the magnet string. Inside the tube, a flow of saturated helium II absorbs the heat load by gradual vaporization of the liquid phase (Figure 3). The internally wetted length of this tube thus constitutes a quasi-isothermal linear cold source with a large developed exchange area, which permits to extract the magnet heat loads under a temperature difference of a few tens of mK only. In addition, this scheme provides complete hydraulic separation, as well as efficient thermal switching in case of dryout, between the magnet baths and the cooling loop. Both features prove very useful in the LHC configuration, since they preclude contamination of the helium circulating in the cooling loop and inhibit thermohydraulic quench propagation between neighbouring magnets.

Such a cooling scheme however implies two-phase flow and heat transfer in saturated helium II across the whole range of vapour quality and on a varying slope, and therefore must be validated by model work. Investigations started on a 24-m long, 25-mm diameter smooth tube with a heated central section, which showed stable horizontal or downward-sloping flow and excellent heat transfer characteristics, maintained up to dryout [7]. The next step was to implement the proposed scheme in quasi-full scale geometry, on a thermohydraulic model cryoloop equipped with modular 10-m long elements simulating magnets, traversed by a 39-44 mm diameter corrugated copper tube heat exchanger, and subject to steady and transient, localized and distributed heat loads. Tests performed with applied heat loads up to 2.4 $W.m^{-1}$ confirmed flow stability and good heat transfer, characterized by overall thermal conductance in the 100 $W.K^{-1}.m^{-1}$ range, resulting in excellent temperature homogeneity along the magnet string [8]. The influence of slope, the effect of co-current or counter-current vapour and liquid flow, and the consequence of heat exchanger dryout over a fraction of its length were also investigated, in relation with process control issues. A more detailed study of the basic hydrodynamic and heat transport processes occurring in two-phase flow of saturated helium II is under way, on a 100-m long test loop at CEA Grenoble.

In the LHC, the superfluid helium cooling scheme is implemented in independent cooling loops, each extending over 51 m, i.e. the length of an elementary "half-cell" of the magnet lattice (Figure 4). Subcooled helium I from the octant refrigerator, distributed through line A, is expanded to saturation through valve TCV1 and fed to the far end of the heat exchanger tube, along which it gathers heat and gradually vaporizes as it flows back. The low saturation pressure is maintained on the flowing two-phase helium by pumping the vapour with minimum superheat through line B, over the length of a half-octant. Line C normally supplies supercritical helium to the beam screens equipping the magnet apertures, and intercepts residual conduction at 4.5 K on the magnet supports. In normal operation, line D collects the bleed of the beam screen circuits, controlled by valve TCV2, and returns it at 20 K to the octant refrigerator. Lines E and F circulate high-pressure helium which intercepts primary heat loads on magnet supports and thermal shield between 50 and 75 K.

The pressure and temperature conditions in all these lines are listed in Table 2, for different modes of operation of the cryogenic system. Cooldown and warmup of each half-cell is achieved by forced circulation of high-pressure gaseous helium, supplied at variable temperature by line C, tapped through valve CFV, and returned to the refrigerator through valve FV and line D. In case of magnet resistive transition ("quench"), the resulting pressure rise [9] is contained below the 2 MPa design pressure of the cryostat helium vessel, by opening valves SRV on the quench trigger and discharging helium into line D, at flow-rates of up to 11 kg.s^{-1} per cryomagnet [10]. The low hydraulic impedance of this 150-mm diameter pipe, normally maintained at 20 K, proves very helpful in containing the helium discharge, and buffering its subsequent release to gas storage vessels [11].

Full-scale testing of these operating modes will begin at the end of 1994, on a 50-m long test string composed of prototype superconducting magnets delivered by European industry.

Table 2 Pressure and temperature conditions in cryogenic lines

Mode	A	B	C	D	E & F
Normal Operation	LHe 0.13 MPa 2.2 K	GHe 1.6 kPa 1.8 K	SHe 0.25 MPa 4.5 K	GHe 0.13 MPa 20 K	GHe 2 MPa 50-75 K
Cooldown/Warmup	-	-	GHe 2-0.6 MPa 290-4.5 K	GHe 0.5-0.1 MPa 290-4.5 K	GHe 2 MPa 290-50 K

HEAT LOAD BUDGET AND CRYOSTAT DESIGN

The thermodynamic cost of refrigeration below 2 K imposes keeping the heat loads at the lowest temperature level to a minimum. For this purpose, the design of the cryostats is based on a staging of temperatures, from ambient to 1.9 K, matching the points of interface with the existing LEP cryogenic plants. The main features of the dipole cryostat [12], a transverse cross-section of which appears in Figure 2, are:

- the integration of all pipes distributing refrigeration along the half-octant, inside the vacuum jacket and insulation system, which avoids the need for an external cryogenic line, at the cost of increased complexity in the interconnections,
- the supporting and positioning of the large cold mass by cylindrical posts made of non-metallic composite materials, with two levels of heat interception [13],
- the generalized use of multilayer reflective insulation, wrapping the thermal shield as well as the cold mass and pipework assembly, thus limiting the residual heat flux to below 50 mW.m^{-2} at the cold boundary and attenuating the consequences of a degradation of the insulation vacuum [14, 15].

The first prototype dipole cryomagnet, delivered by Italian industry in the framework of a CERN-INFN (Italy) cooperation programme, has been successfully tested in the spring of 1994 [10].

The short-straight section cryostat [16], based on the same design principles, also includes an insulation vacuum barrier and a technical service module housing the local cryogenic components of the half-cell cooling loops, as well as electrical feedthroughs for the independently-powered orbit correction magnets. The heat inleak budgets for these cryostats, estimated from detailed construction drawings, and including parametric sensitivity studies [17], lead to the average values listed in the first line of Table 3. The validity of such calculations is comforted by calorimetric measurements performed on critical components [18], on prototype cryomagnets [19, 20], as well as on a dedicated, full-scale thermal model [21].

Table 3 also displays the other sources of distributed heat loads, namely resistive dissipation in the non-superconducting cable splices, as well as beam-induced loads produced by synchrotron radiation, beam image currents, and loss of particles by nuclear inelastic scattering with residual gas. The largest fraction of these dynamic heat loads is intercepted at 4.5 to 20 K by the beam screens. In addition to the distributed heat loads discussed above, some sections of the machine circumference, e.g. around the high-luminosity collision areas, are subject to specific, localized steady-state heating. Moreover, current ramp and discharge generates transient dissipation in the 1.9 K baths, which is thermally buffered by the large heat capacity of the 20 $l.m^{-1}$ superfluid helium inventory.

Table 3 Distributed heat loads in steady operation at maximum energy and luminosity [$W.m^{-1}$]

Temperature	50-75 K	4.5-20 K	1.9 K
Heat inleakage	6.4	0.16	0.19
Resistive heating	-	-	0.06
Beam-induced losses	-	1.49	0.13
Total	6.4	1.65	0.38

HIGH-POWER REFRIGERATION BELOW 2 K

In the framework of the LEP energy upgrade project (LEP2), CERN has installed and is now beginning to operate four large cryogenic plants for supplying 192 superconducting acceleration cavities with liquid helium at 4.5 K. These plants, installed at the even-numbered points of LEP, have a refrigeration capacity equivalent to 12 kW @ 4.5 K each [22]; they have been designed and constructed - by European industry - in view of further upgrade to 18 kW @ 4.5 K, as well as adaptation to LHC cooling duties (Table 4), and feature high-efficiency cycles [23, 24]. The LEP refrigerators thus constitute the backbone of LHC cryogenics down to the 4.5 K level at the even-numbered points, while four other similar plants will have to be installed at the odd-numbered points. In addition, specific coldboxes, producing the required refrigeration at 1.8 K by means of multistage cold helium compressors, will be added to the lower temperature end of the eight 4.5 K refrigerators.

Due to the low saturation pressure of helium below 2 K, and the corresponding difficulty of designing efficient heat exchangers and prohibitive size of pumping systems operating at ambient temperature, cold subatmospheric helium compressors appear as the key technology to large-capacity refrigeration in this temperature range [25]. The reference systems, i.e. the Tore Supra tokamak [26] and the CEBAF superconducting accelerator [27], both use multistage centrifugal compressors with variable-frequency electrical drive and active magnetic bearings. In view of the vital importance of this technology for the LHC project, CERN has launched, in collaboration with CEA (France), a specific development program, with the following aims:

- exploration of technical alternatives for drive and bearing systems, through industrial development and supply of single-stage compressors with a capacity of 18 $g.s^{-1}$ at 1 kPa suction pressure,
- assessment of the potential of cold volumetric machines, and development of associated technologies, including very-low pressure heat exchangers,
- investigation of the efficiency, stability and capacity adaptation issues of a multistage centrifugal compressor system [28],

- design, construction and testing of a prototype LHC multistage cold compressor box, with a capacity of 50 $g.s^{-1}$ at 1.6 kPa suction pressure.

Table 4 Installed refrigeration and liquefaction at LHC octant

Cooling duty	50-75 K [kW]	4.5-20 K [kW]	4.7 K [kW]	1.9 K [kW]	LHe [$g.s^{-1}$]
Standard	30	5	0.1	2.0	33
High-luminosity	30	5	0.5	2.4	50

FROM R&D TO PROJECT CONSTRUCTION

This review has focused on the aspects of the LHC cryogenic system directly linked to the use of superfluid helium, which are also those requiring specific, novel development work. The R&D program on LHC cryogenics has already produced a significant set of results, on which the design and construction of a large accelerator project can be soundly and firmly based. The final success of the project will, however, also depend on the proper handling of other major, although more mundane issues, such as cooldown and warmup of the 3 x 10^7 kg cold mass, storage and management of the 10^5 kg helium inventory, and reception testing of several thousand cryomagnets [29, 30].

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Cryogenics for the LHC rallies the dedicated work of many colleagues at CERN, as well as in national laboratories and industries in Europe, a few of whom appear as authors in the following list of references.

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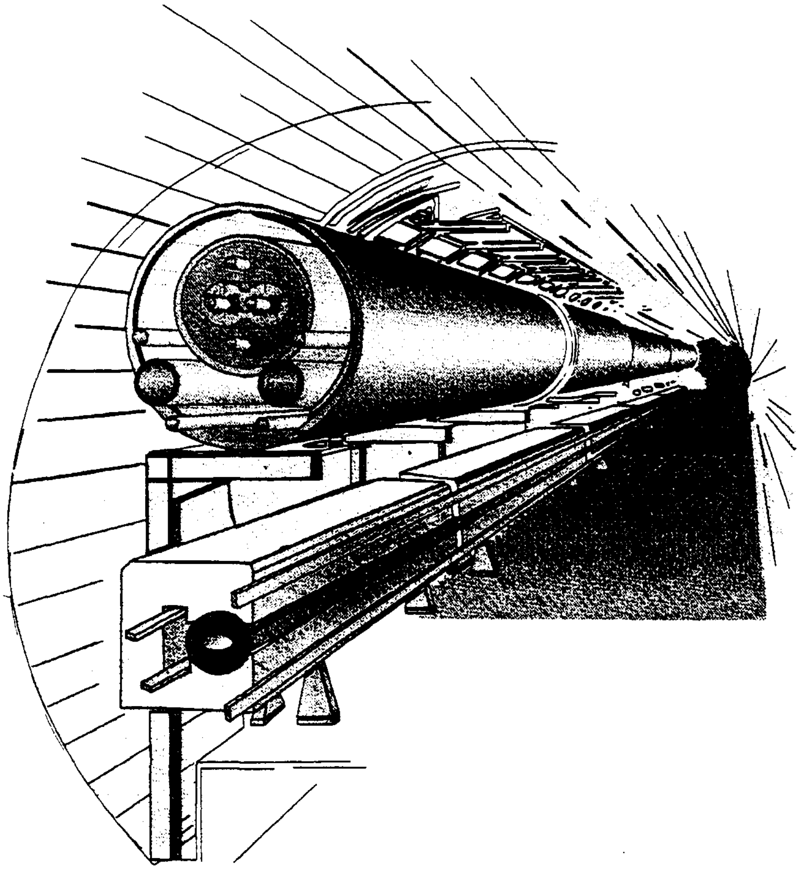

Figure 1 Schematic view of the LHC in the LEP tunnel.

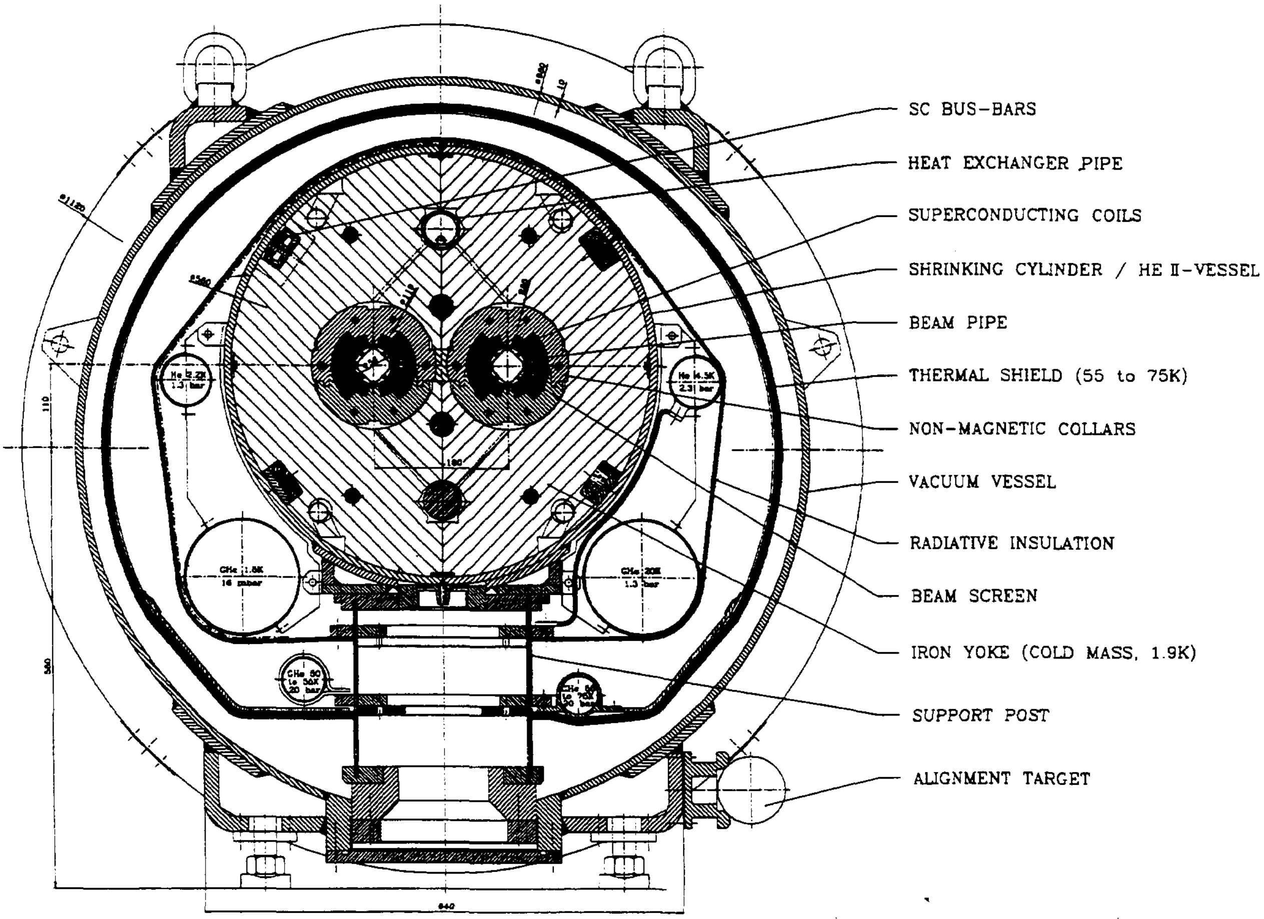

Figure 2 Tranverse cross section of LHC dipole cryomagnet.

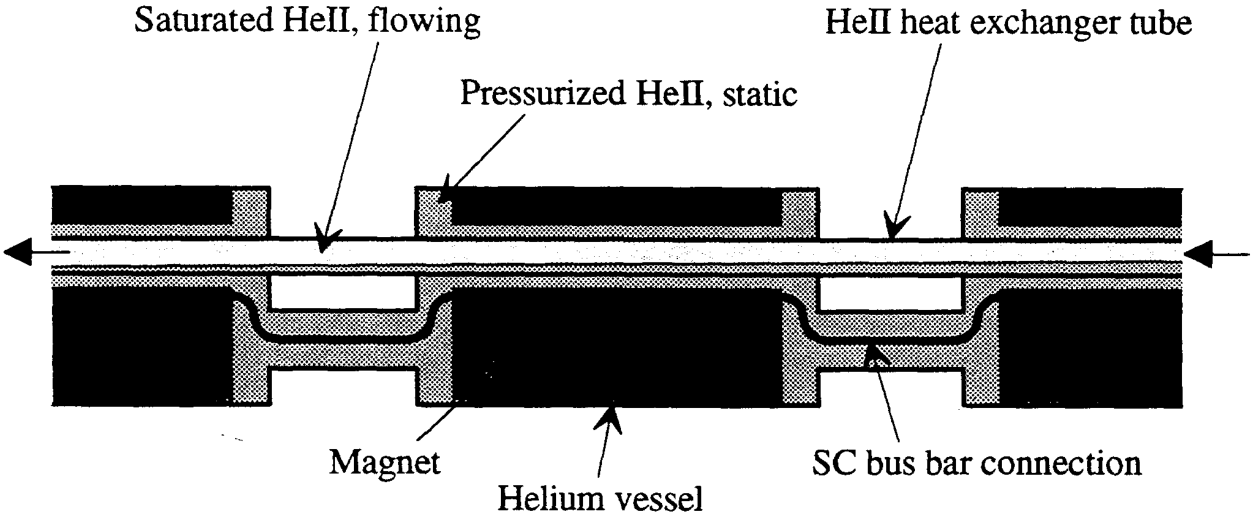

Figure 3 Principle of LHC magnet cooling scheme.

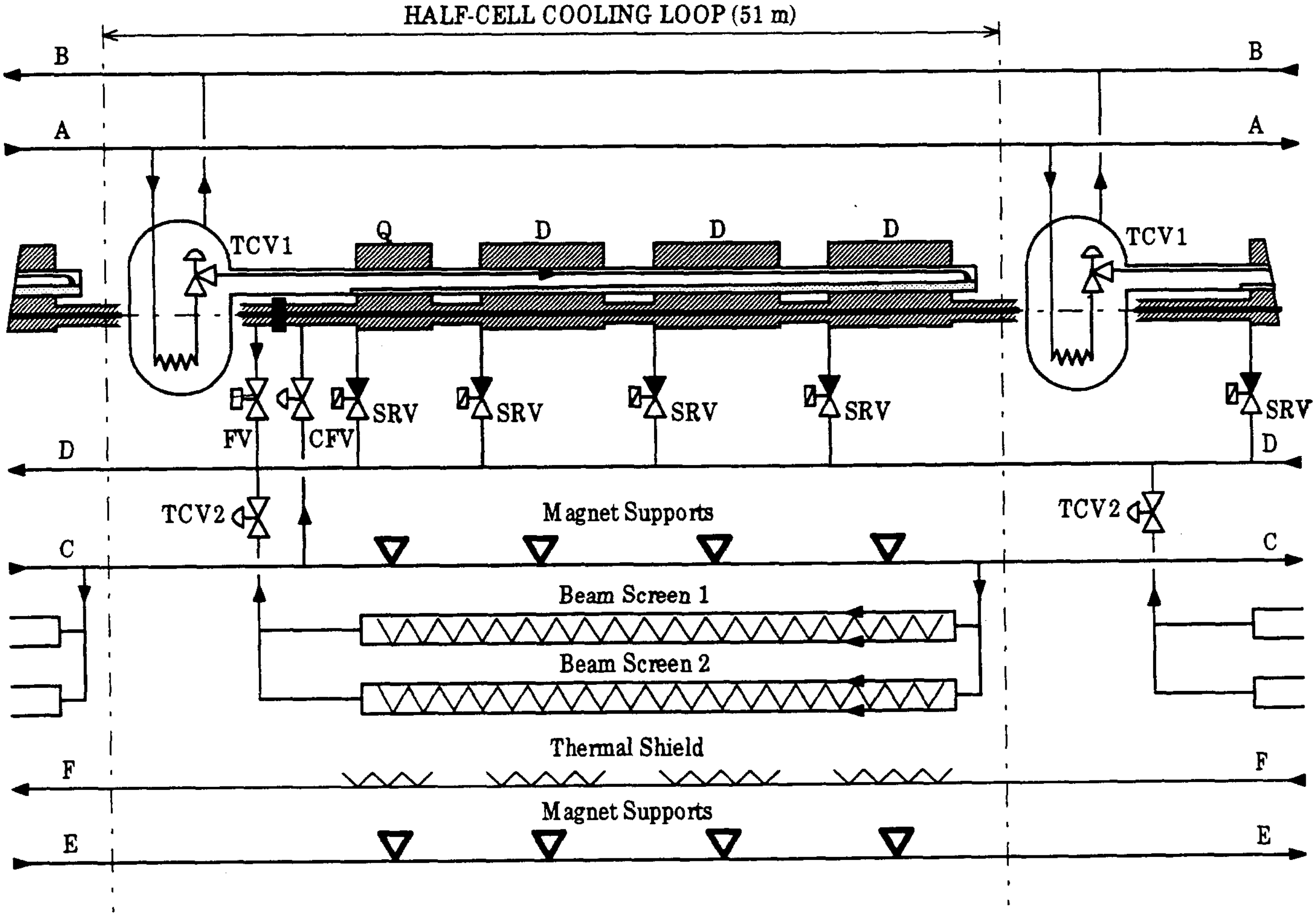

Figure 4 Cryogenic flow-scheme of LHC half-cell.