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293 K - 1.9 K SUPPORTING SYSTEMS FOR THE LARGE HADRON COLLIDER (LHC) CRYO-MAGNETS

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Abstract

The LHC machine will incorporate some 2000 main ring super-conducting magnets cooled at 1.9 K by super-fluid pressurized helium, mainly 15m-long dipoles with their cryostats and 6m-long quadrupoles housed in the Short Straight Section (SSS) units. This paper presents the design of the support system of the LHC arc cryo-magnets between 1.9 K at the cold mass and 293 K at the cryostat vacuum vessel. The stringent positioning precision for magnet alignment and the high thermal performance for cryogenic efficiency are the main conflicting requirements, which have lead to a trade-off design. The systems retained for LHC are based on column-type supports positioned in the vertical plane of the magnets inside the cryostats. An *ad-hoc* design has been achieved both for cryo-dipoles and SSS.

Each column is composed of a main tubular thin-walled structure in composite material (glass-fibre/epoxy resin, for its low thermal conductivity properties), interfaced to both magnet and cryostat via stainless steel flanges. The thermal performance of the support is improved by intercepting part of the conduction heat at two intermediate temperature levels (one at 50-75 K and the other at 4.5-20 K). These intercepts, on the composite column, are thermally connected to the helium gas cooled thermal shield and radiation screen of the cryo-magnet.

An overview of the design requirements is given, together with an appreciation of the system design. Particular attention is dedicated to the support system of the SSS where the positioning precision of the quadrupole magnet is the most critical.

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INTRODUCTION

After an intense R&D phase, which has lead to testing of several prototype supports, the main technological choices have been made[1,2,3]. The final layout of the support system is now defined within the cryostat design of the LHC Standard half cell. New prototypes for cryo-dipoles, manufactured by industry are presently undergoing testing at CERN.

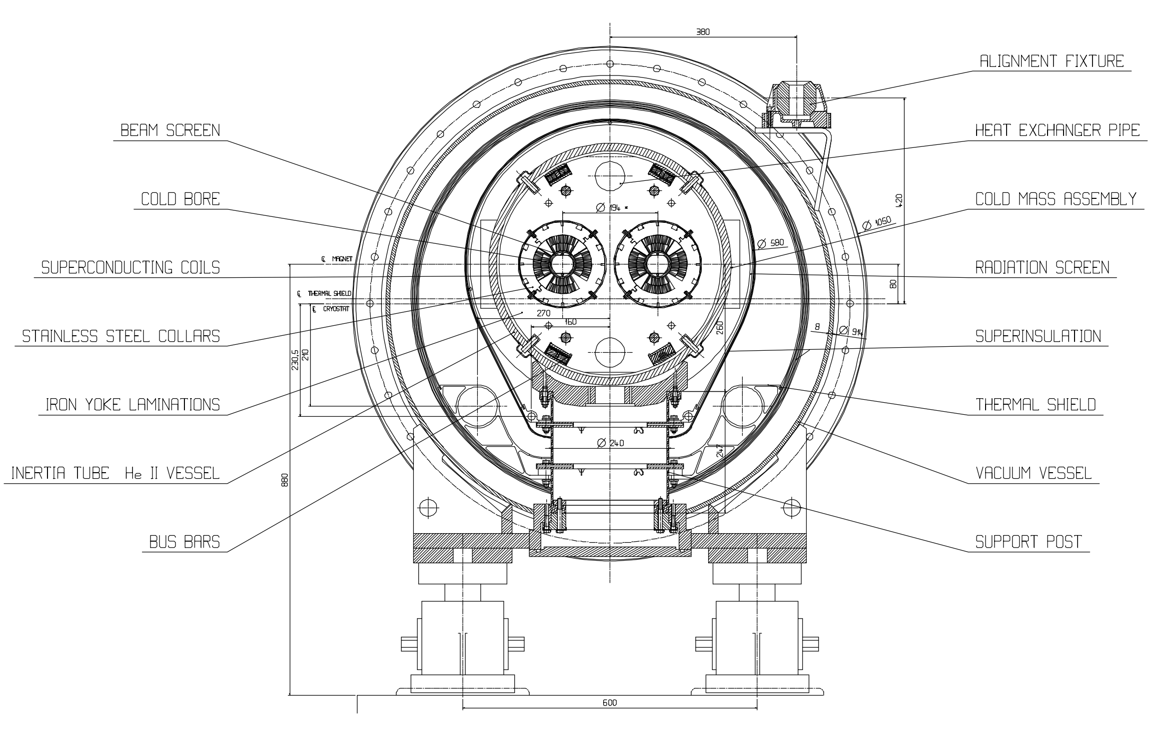

Figure 1. Transverse section SSS, fixed support.

Prototype supports for the SSS will be ordered in autumn 1997. Testing on dedicated facilities will validate the thermal and mechanical design, before they are mounted in the new generation of cryo-magnets. Tests will then follow on the magnet test bench facility and finally in a string of magnets representative of a complete cell of the LHC machine, which will become operational in the year 2000. Figure 1 shows the transverse section of the SSS and its fixed support.

SUPPORT SYSTEM REQUIREMENTS

The accurate positioning of magnets to meet the alignment requirements for the LHC machine lattice imposes the most critical design constraint on the support system, as it is closely related to magnet performance and machine beam dynamics. Misalignments introduce perturbations similar to those from magnetic field errors resulting in a reduction of machine aperture and their correction would significantly increase the power requirements of closed-orbit correcting magnets[4]. In synchrotron machines, using traditional magnets, the alignment fiducials are mounted directly on the yoke. The LHC super-conducting magnets housed in cryostats, inaccessible during operation, are aligned via external cryostat-mounted fiducials. This alignment, after machine installation, is therefore carried out “blindly”, and implies that the positioning of the magnets is adequately guaranteed by the supporting system.

A thermo-mechanically optimised solution is therefore a compromise satisfying both the minimum stiffness required for precise alignment and the stringent heat load budget of the LHC.

Table 1. Main requirements for the support systems for cryo-dipole and SSS

Requirement	Cryo-dipole	Short Straight Section
Positioning accuracy:		
(after cryo-magnet assembly)		
x (radial)	± 1 mm	± 0.5 mm
y (longitudinal)	± 2 mm	± 1 mm
z (vertical)	± 1 mm	± 0.5 mm
Positioning reproducibility-stability:		
(in operation, during lifetime)		
x (radial)	< ± 0.3 mm (3σ)	< ± 0.3 mm (3σ)
y (longitudinal)	< ± 1 mm (3σ)	< ± 1 mm (3σ)
z (vertical)	< ± 0.3 mm (3σ)	< ± 0.3 mm (3σ)
θ_y (radial tilt)	< ± 0.3 mrad (3σ)	< ± 0.3 mrad (3σ)
Thermal requirements		
(indicative heat loads, steady state)		
1.9K level	< 0.15 W	< 0.10 W
4.5-20K level	< 1.5 W	< 1 W
50-75K level	< 15 W	< 10 W

The accurate positioning of the magnets inside their cryostats must be assured for machine operation in cryogenic environment during an estimated lifetime of 20 years. Support system design must take into account long-term *position reproducibility* after repeated thermal cycling, and position *stability* with respect to *parasitic loads*. These loads may be caused by interconnect bellows and misalignment, jumper connection to the CDL line, *stick-slip* on the sliding interfaces, and to the 1.4% inclination of the LEP tunnel.

It is expected that all the SSS, demanding the most precise machine alignment, but only a fraction of the cryo-dipoles will undergo cold magnetic measurements and geometrical survey before installation in the machine. Therefore, all cryo-magnets and their support systems must be assembled to tight mechanical tolerances and demonstrate repeatable thermal contraction behavior. Manufacturing tolerances and positional *reproducibility* after thermal contractions of the series production units are main items to be addressed in the compilation of a strict Quality Assurance plan.

The main requirements for the cold support system are summarised in Table 1. *Positioning accuracy* and *reproducibility-stability* of the cold mass are given with respect to the cryostats. *Reproducibility-stability* are taken to be within the precision of re-alignment between cryostat vacuum vessels which is of 0.1 mm (*r.m.s.*) in the vertical-horizontal plane and 0.1 mrad (*r.m.s.*) radial tilt[5]. The maximum values are taken with 3 σ confidence.

SYSTEM DESIGN

Layout

A three-point support configuration was chosen for the 15m-long, 25,000 kg dipole cold mass, where the inter-support spacing limits the maximum vertical sagitta, due to self weight, below 0.3 mm and the angular deflection of the extremities to acceptable values for magnet interconnect assembly[6]. Two support points are sufficient for the shorter (6 m) and lighter (6,000 kg) cold mass of the SSS to keep the maximum vertical self weight sagitta below 0.25 mm. Further details on the cryostat assemblies can be found in Reference[7,8].

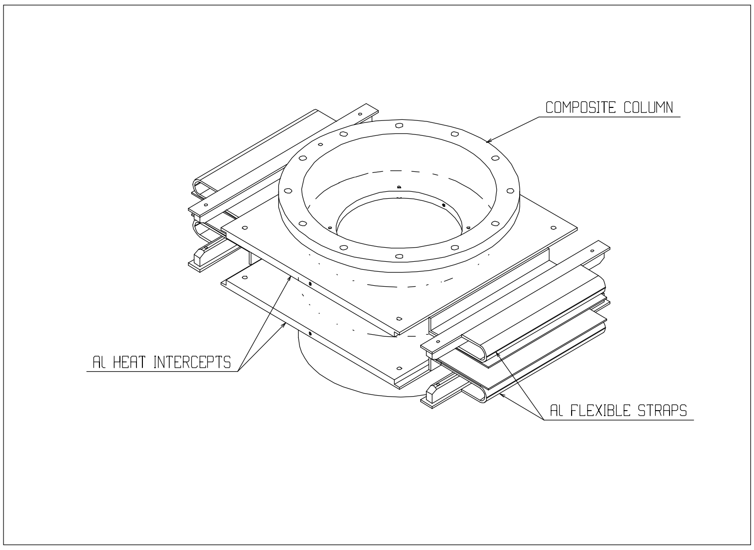

Figure 2. Support post assembly

Support post assembly and integration

Each support point is composed of a main non-metallic composite thin-walled column, bolted to stainless steel pads previously welded along the cold mass. The interface to the vacuum vessel allows the support to slide, leaving the thermal contraction of the cold mass unhindered. A simple support on the vacuum vessel and a key insert permits sliding in only one direction. The weight of the cold mass guarantees that lifting does not occur under any envisaged load case. A low-friction material plate (*Glacier DU*™) reduces stick-slip effects on the vessel. For the cryo-dipoles, the two lateral supports are free to slide longitudinally on the vacuum vessel, whereas the central support is longitudinally fixed but free in the radial direction, to allow possible changes in magnet curvature (due to excitation or repeated thermal cycling). For the SSS, one support is completely fixed, bolted to both the cold mass and vacuum vessel, as the longitudinal pressure force introduced by the insulation vacuum barrier (mounted in the SSS) would tend to lift the cold mass.

Moreover, an additional function requested to the columns of both cryo-dipoles and SSS is to support the thermal shield and radiation screen structures in the cryostat while allowing their differential thermal contractions with respect to the cold mass. The two aluminium heat intercept plates mounted on the composite column to thermalise the support at intermediate temperatures, additionally fulfill this function. An assembly view of a cold support is shown in Figure 2.

The estimated initial *positioning accuracy* of the SSS cold mass, with respect to the vacuum vessel interfaces of the supports, is less than ±0.2 mm in the transverse plane and ±1 mm in the longitudinal direction. The chain of tight mechanical tolerances achieves this precision. The *positioning accuracy* for the dipole cold mass, with respect to the vacuum vessel interfaces, is ±1 mm in the transverse plane, achieved by shimming during cryostat integration. Angular errors between the vacuum vessel and cold mass interfaces, in the order of ±0.3mrad, can be accommodated by the bending flexibility of the columns.

The assembly design for the support system is based on the use of standard tooling and on the simplicity of operations, with a view to maintaining the high assembly rate of the series production (2 cryo-dipoles per day) carried out by European industry. Road transport of the cryo-dipoles to CERN will be a critical phase for the integrity of the supports. Past experience from other similar accelerator machines has shown that blocking devices are required. Special reinforcing steel columns, mounted inside and concentric to the composite column are foreseen, unloading and stiffening the supports during transport, and finally removed when the cryo-dipole is positioned in the tunnel. An experimental program is underway to measure effects of road transport on a 15m cryo-dipole during delivery to CERN. The SSS, proposed to be assembled in the vicinity of CERN, will not mount reinforcing devices to avoid any mechanical perturbation of survey measurements. Also this strategy will need to be confirmed by tunnel transport testing.

Composite technology

The composite columns are made of a 4-mm thick 240-mm external diameter tube with integrated top and bottom flanges. A glass-fiber/epoxy composite system is chosen for its high stiffness-to-thermal-conduction ratio, allowing minimization of the cross section and, as a consequence, of conduction heat loads. A long-fiber, woven fabric lay-up technology is chosen to achieve the highest stiffness. Either pre-impregnation or resin transfer mold (RTM) technologies are equally valid. Other materials and manufacturing methods such as short-fiber charged ULTEM™, ISARYL™ or ULTRAPEK™ thermoplastics have been exploited to improve thermal performance, but none of these provide a satisfactory combination of stiffness, and low thermal conductivity. Filament winding was also widely tested, however it requires glued flanges and due to the uncertain behavior of glued interfaces at cryogenic temperature over the estimated 20-year life of the accelerator, this technology has been abandoned for the SSS, which undergoes the highest shear loads. Filament winding is however interesting for its low cost of manufacture (up to 50% lower than other technologies), and is being reconsidered for the cryo-dipoles.

MECHANICAL PERFORMANCE

During machine operation, the support posts are mainly subject to vertical load due to cold mass weight (10,000 and 3,000 kg per support on cryo-dipoles and SSS respectively). In addition, the supports may be subject to residual and unpredictable *parasitic* loads, which are estimated up to 2500 N per support in the radial direction and that lead to the minimum design stiffness to fulfill position *stability*. Under this load, a 0.27 mm radial displacement and 0.35 mrad tilt[9,10] are calculated for the axis of the SSS cold mass. Displacement *stability* is achieved but with little safety margin, whereas angular deflection is slightly too high. Mechanical testing on prototypes is needed to confirm these values.

The mechanical strength of the supports is not critical during machine operation. Testing on former prototypes has shown that the supports can withstand up to 200% of the nominal loads without failure. Calculation shows high safety margins with respect to static strength and buckling[11].

Although *creep* is a difficult phenomenon to master for composites, and extreme care must be taken for the LHC supports, testing of prototype cryo-magnets over 3 years (with 30% time at room temperature) does not show any evidence of viscoelastic effects (Figure 3). Also *relaxation tests* on compressed samples at room temperatures show a limited (6%) relaxation effect when loaded at 4 times the nominal compression load[11]. *Reproducibility* requirements are fulfilled with respect to thermal cycling; for the vertical contraction this is better than 50 µm, the dispersion observed is within the precision of the measurement system[12,13].

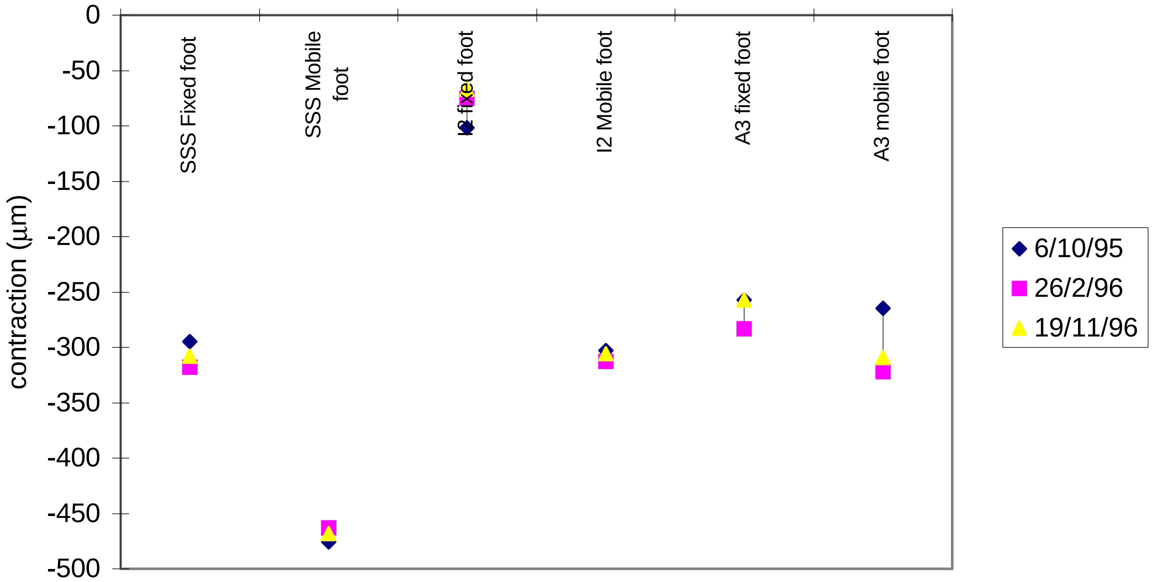

Figure.3: Supports vertical contraction, 1.9K

The thermal contraction of the supports (Figure 3) shows appreciable differences however (up to 0.2 mm). This is explained by the different technology applied by manufacturers (fiber/resin ratio, fiber orientation, etc.). The series production will need to be closely surveyed by a rigorous Quality Assurance plan to limit this uncertainty.

THERMAL PERFORMANCE

The thermal performance of the supports is improved by intercepting most of the residual conduction heat at two intermediate temperature levels, 50-75 K and 4.5-20 K, the precise temperature depending on the position of the cryo-magnet in the cryogenic loop of a machine sector. These intercepts consist of aluminium plates, integrated to the composite column and connected to the thermal shield and radiation screen via flexible aluminium straps. All-welded thermalisation assemblies are adopted, as past experience has demonstrated the unreliability of bolted connections for achieving low thermal impedance. Although cryostat integration and assembly limits the free choice of vertical position of the heat intercept plates along the composite column, these positions are chosen to minimize the exergetic cost of low-temperature refrigeration, according to the weighing function [14]:

$$Q_{tot} = Q_{1.8K} \cdot 1000 + Q_{5K} \cdot 125 + Q_{75K} \cdot 16$$

Where:

$Q_{1.8K}$, Q_{5K} and Q_{75K} are the heat loads at the temperature levels indicated, multiplied by their weight factors, and Q_{tot} is the exergetic cost of refrigeration in Watts.

The optimization has been achieved for both the SSS and the cryo-dipole for arc-wise averaged temperatures at the heat intercepts (10 K for the 5-20 K range and 65 K for the 50-75 K range).

Table 3: Heat loads of Standard Half-Cell support systems (±15%)

Temperature	Cryo-Dipole	SSS	% of half cell static loads
1.9 K	0.069 W	0.038 W	1.8 %
8 K	2.58 W	1.38 W	62 %
80 K	17.3 W	9.5 W	17%

A review of this optimization criterion and of the position of the heat intercepts may be required, to reduce the cooling demands at the 4.5-20 K refrigeration, presently close to the budgeted limit for the re-conversion of cryogenic equipment from LEP.

Compared with a non-thermalised version of the same support of the SSS, the two heat intercepts allow a reduction of the heat loads to 1.9 K by a factor of 100. Sensitivity analysis indicates that the thermal efficiency is strongly influenced by the temperature at the heat intercepts[15]. The 4.5-20 K heat intercept is the most critical, where an off-design temperature of ±2 K introduces a variation of ±10 % on the exergetic cost of refrigeration. Off-design temperatures are encountered during cool-down (a transient study is being made to evaluate the impact on cool-down time and peak heat loads during this phase) but could also be caused by a faulty assembly of the heat intercepts to the support. Quality Assurance will play once more a crucial role in coping with this type of problems.

Inside the supports are mounted reflective aluminum disks for the interception and extraction of radiation heat via the heat intercepts. Additionally, aluminized *Mylar*™ reflective surfaces protect the part of the support column exposed to temperatures between 293 K and 50-75 K[16].

The heat loads for the cryo-dipole and SSS support systems, extrapolated from measurements on former prototypes of different geometry, with heat intercepts at 8 K and 80 K are shown in Table 3.

Measurements on a dedicated cryogenic test facility at CERN will be made to validate these results and will allow precise measurements of the heat loads across the working temperature ranges of each heat intercept. Validation of the new all-welded flexible thermalisation straps will be also possible.

CONCLUSIONS

The system layout for the supporting of the LHC magnets inside the cryostats is retained and the main technological choices are made. An intense R&D phase has indicated the technology retained for the manufacture of the composite column (glass-fiber/epoxy pre-preg or RTM) although cost-reduction for the series production suggests continuing with further investigation on filament winding. The design of the supports is the result of a compromise between stiffness and thermal requirements. Calculations (to be validated by testing) show that stiffness is just within the positioning *stability* requirements; efforts must be therefore made towards the understanding and reduction of possible sources of mechanical misalignment. Thermal cycling over several years of operation on the first string of prototype cryo-magnets shows good position *reproducibility* with respect to thermal contractions of the cold mass inside the cryostats. However, an appreciable dependence of thermal contraction behavior on the manufacturing technology highlights the importance of limiting this dispersion by imposing a strict Quality Assurance program. Minor changes in the thermalisation design might still be introduced to reduce heat loads at the 4.5-20 K level.

New prototype supports have been manufactured by industry and are now being tested at CERN. Mechanical testing and evaluation of thermal heat loads on dedicated test facilities will validate the design. After being mounted in cryo-magnets, they will be tested first on the magnetic test-bench facility and finally in a string of magnets representative of a complete cell of the LHC machine, that will be operational in the year 2000.

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