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**SERIES-PRODUCED HELIUM II CRYOSTATS FOR THE LHC MAGNETS:
TECHNICAL CHOICES, INDUSTRIALISATION, COSTS**

A. Poncet, V. Parma

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The specific technical requirements of the generic systems of the cryostat (vacuum, cryogenic, electrical distribution, magnet alignment) are briefly recalled, as well as the basic design choices leading to the definition of their components (vacuum vessels, thermal shielding, supporting systems). Early in the design process emphasis was placed on the feasibility of manufacturing techniques adequate for large series production of components, optimal tooling for time-effective assembly methods, and reliable quality assurance systems.

An analytical review of the costs of the cryostats from component procurement to final assembly, tests and interconnection in the machine is presented and compared with initial estimates, together with an appraisal of the results and lessons learned.

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KEYWORDS: cryogenics, LHC.

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INTRODUCTION

The superconducting magnets of the Large Hadron Collider (LHC) operate in a bath of pressurized 1.9 K superfluid helium, and are cooled via a separate cryogenic distribution line (QRL) [1]. The cryostats have been designed to mechanically support and position precisely the superconducting magnets and minimize the static heat inleak to the cold

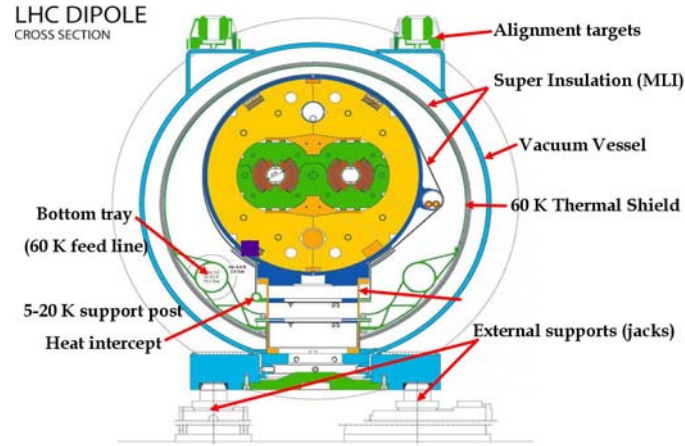


FIGURE 1. Standard schematic cross-section of the LHC Cryostat

masses at 1.9 K in the most efficient and economic way, while having to house, sectorise and interconnect a number of utilities such as vacuum, electrical distribution, magnet instrumentation and cryogenic distribution. The LHC cryostat main constituents (Fig. 1) contributing to the static heat load are the carbon steel vacuum vessels, the Glass Fiber Reinforced Epoxy (GFRE) magnet support posts, the 60 K thermal shielding, the Multi Layer Insulation (MLI), the 1.9 K conduction and radiation shielding (MLI). To these have to be added the magnet Instrumentation Feedthrough Systems (IFS) and the 20 K beam screens present for each magnet, the insulating Vacuum sectorisation Barriers (VB) every two SSS, corrector magnet Current Feedthroughs (DCF), QRL jumpers every two SSS, 20K-cooled Beam Position Monitors (BPM) supports, beam vacuum feedthroughs and cryogenic modules at each SSS.

TABLE 1. LHC arc cryostat main components and the total computed static heat loads.

<i>cryostat components</i>	<i>quantities</i>	<i>overall length (m)</i>	<i>overall budgeted static heat loads</i>		
			50-75 K [W]	4.6-20 K [W]	1.9 K LHe [W]
1) <u>LHC continuous arc cryostat (sum of 8 sectors), composed of the following main components:</u>		22'564			
Dipole vacuum vessel (14.6 m unit length)	1'232	17'938			
SSS vacuum vessel (6 m average)	438	2'617			
Interconnection sleeve (1.185 m average)	1'695	2'009			
Service Module QQS	438			4	53
Longitudinal Vacuum Barrier VB	104		5'081	13	186
Magnet support post	4'620		32'890	2'053	225
Thermal shield sub-assembly	3'365		62'278		
Radiative insulation sub-assembly	3'365			178	2'329
Instrumentation feedthrough system (IFS)	1'670				888
<i>2) Ancillaries (not described in this paper)</i>					
Beam Screen	3'340				334
Beam vacuum feedthrough	432		526		92
Dipole corrector feedthrough (DCF)	324		2'786	526	117
Beam position monitor (BPM)	680			203	132
TOTAL			103'052	2'976	4'355



FIGURE 2. Series production of cryostat vacuum vessels : standard tube, forged cradles, and storage of finished vessels.

Table 1 gives the quantities of main components of the LHC cryostat together with the total expected heat loads at each temperature level.

The 54 standalone superconducting magnets of the so-called matching sections installed in the long straight sections of the LHC tunnel are not part of the arc cryostat and are not accounted for in Table 1. However, they also use standard cryostat components which were procured on the same contracts.

Details on the design and thermal validation of the LHC He II standard arc cryostats can be found in [2].

LARGE-SCALE SERIES PRODUCTION OF THE MAIN CRYOSTAT COMPONENTS

Given the very large quantities of components entering the cryostat assemblies, the emphasis at the design stage was put on conceptual and technical choices permitting cost minimization, taking advantage of large series manufacturing techniques involving a consequent investment in tooling. The examples, given in this report, concern the main cryostat components.

Cryostat vacuum vessels

The vacuum vessels (Fig. 2) consist of long (14 m) cylindrical tubes made from alloyed low carbon steel, stress relieved by vibration to ensure mechanical stability. The outer diameter (914 mm -36 inches-) and the wall thickness (12 mm) have been chosen to match the dimensions of industrial standard tubes in order to benefit from low costs. Forged steel cradles serve to locally reinforce the vessel to allow the loads induced by the



FIGURE 3. Production of cryostat 60 K thermal shield assemblies: extruded profile, aluminium to stainless steel transition, assembled thermal shield.



FIGURE 4. Production of GRFE cold mass support posts: assembly of the lay-ups, mould hardware and finished support post equipped with heat intercept flanges.

weight of the cold mass to be transmitted to the external jacks while minimizing deformations of the vessel structure. The tubes are made of cryogenic steel grade DIN GS-21 Mn5 (MB485, American Pipe Association), giving an adequate energy absorption (28 J/cm^2) at -70 C , which is the minimum temperature attainable in case of accidental rupture of the insulation vacuum. The tooling costs represented 20 % of the total amount of the vacuum vessel production contracts.

Cryostat thermal shield assemblies

The thermal shield assembly of the LHC cryostats (Fig. 3) intercepts heat radiating from the vacuum vessel and heat conducted through the cold mass support posts. The choice of material (aluminium) and of the design features result from production cost considerations and efficiency in heat interception. It is composed of a long double-walled tray formed from two extruded profiles in series 6060 aluminium alloy welded together. The tray incorporates two tubular channels. One of these channels is used for the passage of gaseous helium at a temperature of about 60 K. At each end of this cryogenic line, industrially available aluminium-alloy-to-stainless-steel pipe transition elements with an internal diameter of 80 mm are welded on. To complete the shield, curved pure aluminium sheets are welded onto the tray, via slits extruded together with the profile. At three (for the 15 m dipole) or two (for the SSS) locations along the length of the tray, passages are machined for thermal anchoring of the cold posts supporting the cold masses to the heat intercepts. Thermalisation of the cold post flanges is ensured by welded flexible aluminum strips. The tray assembly of a cryostat is a structural element: it has to support the shield and its Multi Layer Insulation (MLI), and withstand the bellows interconnection forces between the cryostats. The tooling for extrusion and automatic welding and machining of the profiles, designed for large series production, represented 15 % of the total amount of the production contracts.

Magnet cold mass support posts

A magnet cold mass is supported within its cryostat vacuum vessel on three (dipole) or two (SSS) support posts, one fixed and two (or one) sliding support posts. The LHC cryomagnets required 4622 Glass Fibre Reinforced Epoxy (GFRE) support posts in total. A support post is composed of a main monolithic 4 mm-thick tubular column made of Glass Fibre Reinforced Epoxy resin (GFRE), integrating a top and a bottom flange, serving as mounting interfaces onto the cold mass and the vacuum vessel respectively. Resin Transfer Moulding (RTM) was chosen as manufacturing method, because it is suitable to a large-scale industrial production of high quality components. This technique presents the major advantage of being highly automated and less sensitive to the skill of the labour as



FIGURE 5. Details of large series production of cryostat MLI blankets: lay-up structure, fully automatic blanket assembly table, blankets fitting on a dipole thermal shield.

compared to other processes like pre-preg moulding, thus reducing production costs while maintaining the required quality [3].

Prefabricated Multi Layer Insulation (MLI) blankets

The vacuum vessel of the cryostats contains the cold mass operating at 1.9 K, which is wrapped with one MLI blanket, and a thermal shield assembly operating at 60 K around which are wrapped two MLI blankets. In order to maximise the thermal insulation and to ease the installation of MLI, the thermal shield and the cold masses need individual blanket assemblies, i.e. pre-fabricated blankets with a low packing factor. The blanket around the cold mass is manufactured from lay-ups composed of 10 layers of double face reflective film (each 6 μm thick with a 400 angström-thick aluminium layer on each face), interleaved with 9 layers of spacers. The thermal shield is equipped with two superimposed blankets with lay-ups composed of 15 layers. For ease of installation of the blankets and to reduce assembly costs, these are equipped with Velcro^{®1} fasteners made of polyamide, stitched to the edges of the blankets. An important investment in tooling for series production of blankets allowed the manufacturer to reduce manpower costs (Fig. 5).

Assembly at CERN of the dipole and SSS cryostats

If, in the early days of the project, the possibility to order from Industry completely assembled cryostats was studied, logistics, financial and quality reasons lead to the decision to assemble the cryostats at CERN [5]. A detailed “build-to-print” specification was written and a procurement “cost and fee” contract was established with a consortium of firms after competitive tendering. Within the frame of this contract, CERN provided the production facilities with heavy tooling infrastructure and handling means, and the procurement of parts (cold masses, cryostat components, etc.). It provided also the detailed procedures and Quality Assurance management tools, the consortium being in charge of its



FIGURE 6. Cryostats assembly halls at CERN, and dipole cryostat assembly bench (center)

¹ Velcro[®] is the Registered Trade Mark of Velcro Industries B.V

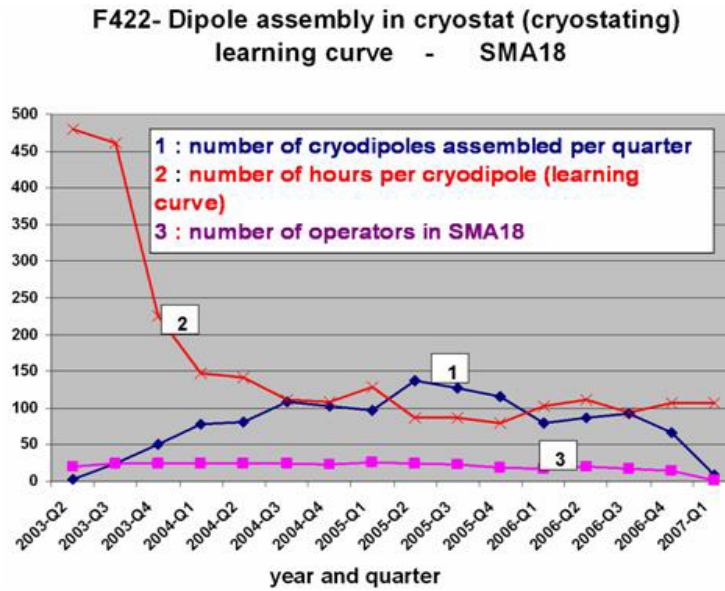


FIGURE 7. Production rates for dipole cryostat assembly, test and preparation, and learning curve.

application. Three main work sites, representing a total of about 10,000 m² of assembly halls, were attributed to the contractor, fully equipped with heavy handling and logistical means plus all the necessary specialized tooling for assembly (Fig. 6). The activity on the two main lines of cryomagnet assembly benches for the 1232 cryodipoles and 474 SSS spanned 5 years (2002-2007), representing approximately 850,000 hours of work, of which 87% was done on a fixed cost basis with a peak of 145 operators and technicians.

The assembly of LHC cryostats at CERN in contractual partnership with a consortium of firms, has been a good strategic choice, in consideration of the difficulties in managing “just in time” intricate sequences of assembly, tests, preparation, quality control and management of non-conformities. Fig.7 illustrates the production rate achieved, and the gain in productivity during the assembly period (learning curves) for 1232 dipole cryostats.

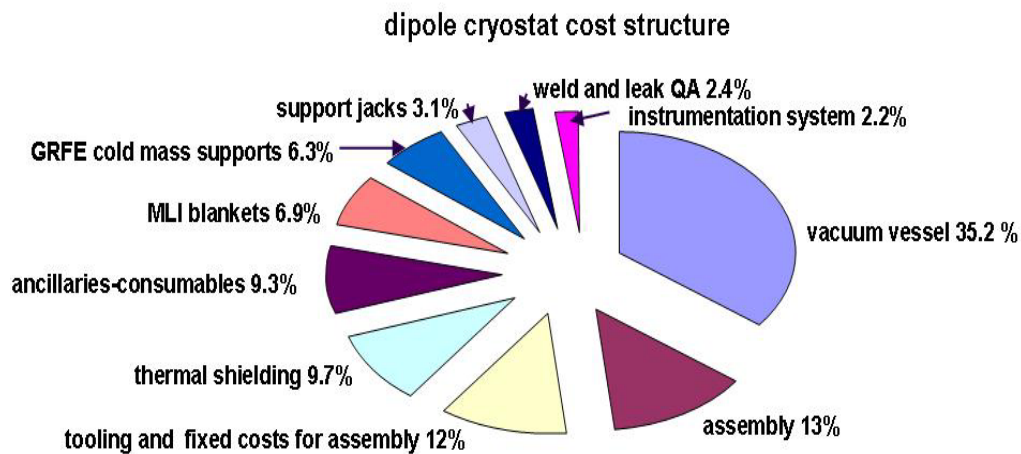


FIGURE 8. Dipole cryostat cost structure.

COST BREAKDOWN STRUCTURE OF THE DIPOLE AND SSS CRYOSTATS

The final cost structures of the dipole and SSS cryostats, for the quantities given in Table 1 of this report, are given on Fig.8 and 9 respectively. The assembled dipole cryostat cost of 100 kCHF in 2007 value can be split between the main ingredients briefly presented in this report: vacuum vessel, assembly, tooling and fixed costs for assembly, thermal shielding mechanical parts, MLI blankets, supports.

A comparison with the initial LHC cost estimate (1996) of the dipole cryostat of 130 kCHF (2007 value), 30% above the finally achieved price, reveals significantly lower prices obtained on important items of the cost structure such as the vacuum vessel, thermal shield structure, MLI blankets, assembly work and support jacks.

The final cost of an assembled average SSS with insulation vacuum barrier of 136 kCHF reduces to 114 kCHF without vacuum barrier. As can be expected, the fraction of assembly work for the SSS, more complex and diversified, is significantly larger than for dipoles.

As for the dipole, the 1996 estimate of 117 kCHF (2007 value) was incomplete (instrumentation hardware missing, as well as numerous QQS components linked to the late decision to separate the cryogenic distribution line (QRL)).

A comparison of the finally achieved SSS cost structure is therefore only relevant for the vacuum vessel and the thermal shielding. As it is also the case for the dipole, the effective costs of the vacuum vessel and of the multilayer insulation (MLI) are by far lower than the estimates done in 1996. This applies also to the thermal shielding (mechanical parts: extruded aluminium trays, shields, C' piping), for which the design in 1996 was essentially based on stainless steel mechanical parts.

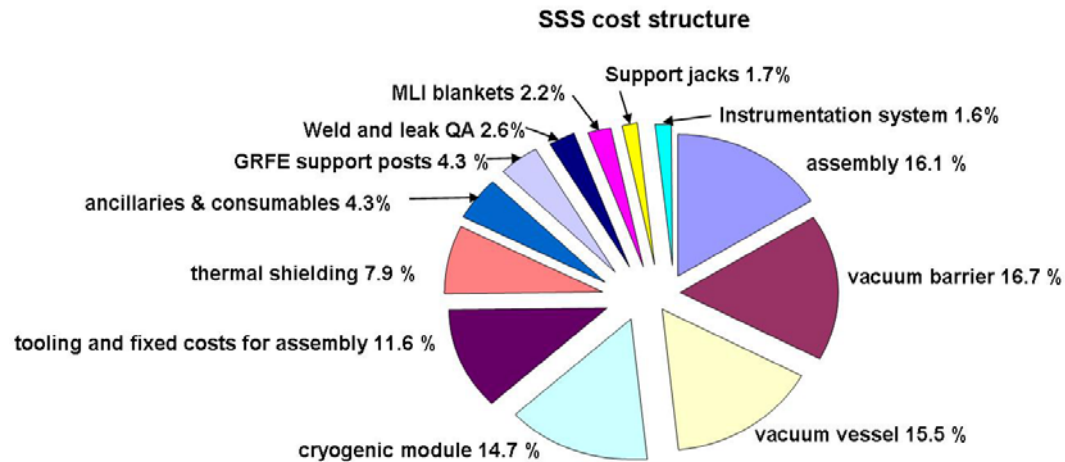


FIGURE 9. SSS cryostat cost structure.

SUMMARY

The conceptual and technical choices made in view of meeting the specific requirements of the He II cryostats for the LHC magnets while maintaining the final production costs within the LHC budget have been presented. When compared to estimates done in 1996, the relatively low costs achieved for the main items entering the cryostats cost structure such as the vacuum vessels, the thermal shielding (MLI and aluminium structure) and the assembly at CERN, are the result both of the conceptual and technical choices made in order to reduce production costs, and of the competitive tendering policy based on “built-to-print” technical specifications. This chosen policy, an alternative to the one consisting in addressing functional and performance specifications to specialized firms, was put in place at the start of the project, and aimed at identifying and pre-selecting the largest possible panel of companies having the infrastructure and the experience in large series production of similar items. It certainly allowed to achieve costs lower than was anticipated on a number of cryostat components.

At the date of writing this report, June 2007, about 90% of the nearly 23 km of continuous LHC arc cryostat have been interconnected successfully, and the thermal and mechanical performance validated after cool-down of the first sector.

ACKNOWLEDGEMENTS

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