# ASSEMBLY AND QUALITY CONTROL OF THE LHC CRYOSTATS AT CERN: MOTIVATIONS, MEANS, RESULTS AND LESSONS LEARNT

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*Abstract*

In 2001, the project management decided to perform at CERN the final assembly of the LHC superconducting magnets with cryostat parts and cold masses produced by European Industry in large series.

This industrial-like production has required a very significant investment in tooling, production facilities, engineering and quality control efforts, in contractual partnership with a consortium of firms. This unusual endeavour of a limited lifetime represented more than 850,000 working hours spanning over five years, the work being done on a result-oriented basis by the contractor.

This paper presents the reasons for having conducted this project at CERN, summarizes the work breakdown structure, the production means and methods, the infrastructure specially developed, the tooling, logistics and quality control aspects of the work performed and the results achieved, in analytical form. Finally, the lessons learnt are outlined.

## INTRODUCTION

The 1232 superconducting dipoles and 474 lattice superconducting quadrupoles of the Large Hadron Collider (LHC), currently in its final installation phase at CERN, have been manufactured in European Industry (France, Germany and Italy). These magnets, together with very wide variety of correction magnets, are enclosed in so-called large (up to 15 m) and heavy (up to 30 t) cold masses containing pressurized super fluid helium used as coolant. The cold masses are assembled into cryostats, also of a wide variety, satisfying tight specifications in terms of heat loads and geometric stability [1]. The magnetic, electrical and thermo-mechanical performance of the LHC magnets imposed a thorough and complete testing at cold conditions at CERN and prior to installation.

If, in the early days of the project, the possibility to order from Industry completely assembled cryomagnets was studied, logistics, financial and quality reasons lead to the decision to assemble the cryomagnets at CERN.

The sequence of assembly, testing, preparation for cold test and installation represented a formidable logistical challenge, entailing a tight and strict control of buffer stocks, duration of activities and management of non-conformities which would have rendered the externalization of the work extremely difficult and costly. In addition road transport of these heavy and delicate assembled structures on thousands of kilometres would have been expensive and risky.

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 application.

## THE WBS (WORK BREAKDOWN STRUCTURE)

Assembly and preparation activities for the two main families of cryomagnets (cryodipoles and Short Straight Sections -SSS- housing the quadrupoles) were split into 18 work packages, 9 for each family, whose sequential structuring led to the main contractual assembly work flow (see Fig. 1).

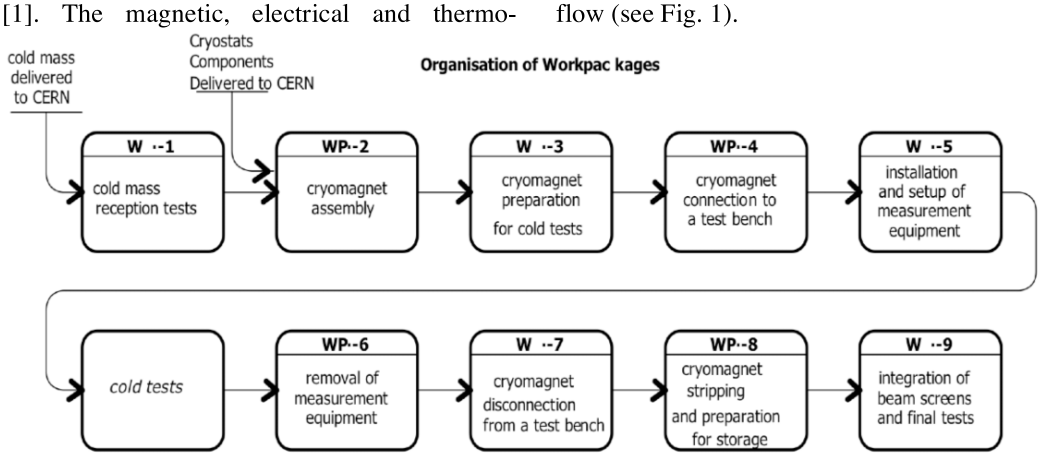


Figure 1: Main sequence of work packages for cryomagnet assembly, tests and preparation


1-4244-0917-9/07/$25.00 

The main work sequence included reception tests, assembly into their cryostat and preparation for cold tests of the industrially produced cold masses, installation of measurement equipment, removal of cryomagnets from test benches, preparation of magnet extremities for interconnection, as well as installation of the beam screens into the magnet cold bores. At each production step, detailed control procedures were applied and results of measurements were recorded into the CERN EDMS system [2], which provided also the necessary tools for the rapid treatment of non-conformities.

## INFRASTRUCTURE AND TOOLING

Three main work sites representing a total of about 10,000 $m^2$ 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. 2a and 2b). The SMA18 Hall, the assembly site for the 30 t dipole cold masses into their cryostats and the SM18 cryogenic test hall, used specially designed mobile cranes for handling and precise positioning on assembly benches and transport between these two neighbouring halls. The other production buildings, SMI2 and 904, respectively used for final assembly prior to descent into the LHC tunnel and SSS cryostat assembly, used classical overhead cranes.

Figure 2a: Cryodipole assembly bench.

In view of the large series involved and to reduce production costs, a special technical and financial effort was devoted to the procurement of assembly tools, some motorized, as for example, the so-called dipole "cryostating" benches (see Fig. 2a). A wide panoply of assembly and positioning stands, fixtures and jigs was also designed and procured by CERN, the contractor being in charge of standard tooling procurement and consumables (orbital welding and cutting machines, light tooling, etc.)

Figure 2b: SSS assembly hall 904.

## PRODUCTION STATISTICS AND LEARNING CURVES

The activity on the two main lines of cryomagnet assembly benches for the 1232 cryodipoles and 474 SSS spanned 5 years (2002-2007), representing approximatively 850,000 hours of work, of which 87% was done on a fixed cost basis with a peak of 145 operators and technicians. Due to delays in the delivery of the magnet cold masses, the two first years were used to transfer the know-how to the contractor, to consolidate tooling, procedures and logistics and for works outside the initial scope of the contract. During this initial period, longer than originally foreseen, the contractor was paid on spent-hour contractual rates. As production ramped up and non-conformities not attributable to the contractor tapered down, the work was done on a fixed cost basis.

The graphs in Figs.3a and 3b summarize the total production for the two families of magnets, together with the manpower used, and the required time per magnet (learning curve).

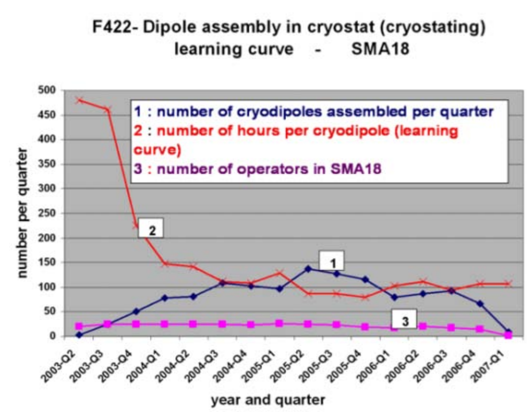


Figure 3a: Cryodipole production rates and learning curve.



 

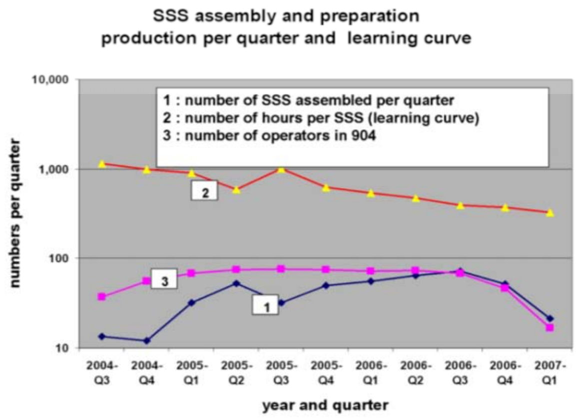


Figure 3b: SSS production rates.

## COST BREAKDOWN

Logistics infrastructure and heavy tooling costs, some quality control costs such as leak detection and weld inspections, were supported by CERN independently of the assembly contractor within the frame of the laboratory facilities for an approximate 30% of the cost of the whole project (not including CERN staff salaries). The total amount of the assembly contract consisted of fixed costs (F) covering management staff, tooling and consumables, direct production costs (E) covering fixed price work packages, and additional costs (A) regrouping hourly costs inferred to non-conformities not attributable to the contractor, direct work costs during knowledge transfer, and variations to the contract for unforeseen additional work. The graphs of Figure 4 give the split between F, E and A and the evolution of costs showing the continuous improvement of the ratio between the work package set price (E) and hours spent on non-conformities and variations (A).

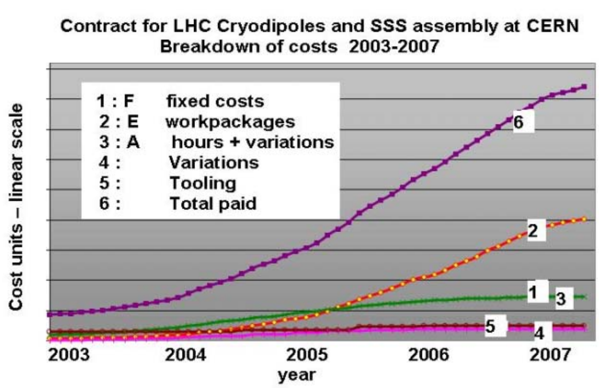


Figure 4: Breakdown of F, E and A costs (top) and their evolution with time (bottom)

## NON CONFORMITIES

The treatment of non-conformities on components received from industry and quality problems encountered during assembly, from a significant fraction of the total assembly times in the first two years of the contract, finally tapered down to an average of 5-7 % of the production hours in the last year of production. This evolution is illustrated in Figure 5.

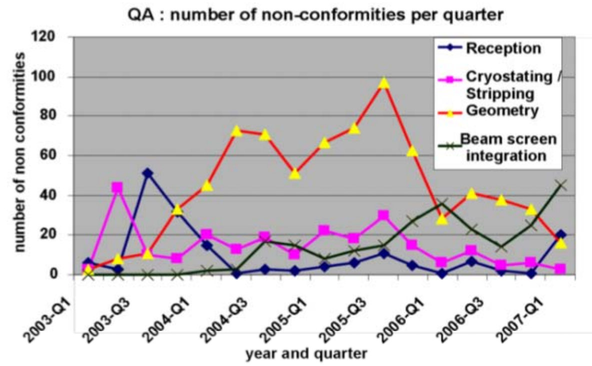


Figure 5: Quarterly evolution of non-conformities.

## LESSONS LEARNT

CERN had neither the facilities nor the competence to house a large series production of complex superconducting magnets. Circumstantial events such as delays of the project and failure of some contractors, as well as proper consideration of the difficulties in managing “just in time” intricate sequences of assembly, tests, preparation, quality control and management of non-conformities, pushed the management in the right direction, i.e. assembly of the cryostats at CERN [3]. A strong element contributing to the success was to sign a procurement contract on a fixed cost basis (after competitive tendering) rather than a service contract based on controlled expenses. The significant added value for the consortium of firms yielded a strong involvement of its management and production staff, with as a result a full partnership and much flexibility in solving the unavoidable additional work due to delays, mishaps and technical problems. In this context, it is reasonable to conclude that assembly of LHC cryostats at CERN has been a good strategic choice.

## ACKNOWLEDGMENTS

A large number of CERN staff and in-house services must be praised for their participation to this successful endeavour.

## REFERENCES

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