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THE ASSEMBLY OF THE LHC SHORT STRAIGHT SECTIONS AT CERN: WORK ORGANISATION, QUALITY ASSURANCE AND LESSONS LEARNED

N. Bourcey, P. Campos, R. Lopez, A. Poncet, and V. Parma

Abstract

After 4 years of activity, the assembly of approximately 500 Short Straight Sections (SSS) for the LHC has come to an end at the beginning of 2007. This activity, which was initially foreseen in European industry, was in-sourced at CERN because of the insolvency of the prime contractor. While the quadrupole cold masses were produced in industry, the assembly within their cryostats was transferred to CERN and executed by an external company under a result-oriented contract. CERN procured cryostat components, set up a dedicated 2000 m^2 assembly hall with all the specific assembly equipment and tooling and defined the assembly and testing procedures. The contractor took up responsibility for the delivery, on time, of assemblies according to the required quality. A dedicated CERN production and quality assurance team was constituted. A specific quality assurance plan was set up involving 2 additional contractors responsible for weld inspections on a total of about 20'000 assembly welds and the execution of about 3300 leak detection tests.

This paper presents the organizational aspects of the activity and the experience gained throughout the production. The learning curves and statistics by type of non-conformities detected and general quality assurance aspects are presented and discussed. The main lessons learnt are summarized, in an attempt to draw some conclusions which could be useful in making strategic choices for the cryostat assembly in future large-scale accelerators.

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ABSTRACT

After 4 years of activity, the assembly of approximately 500 Short Straight Sections (SSS) for the LHC has come to an end at the beginning of 2007. This activity, which was initially foreseen in European industry, was in-sourced at CERN because of the insolvency of the prime contractor. While the quadrupole cold masses were produced in industry, the assembly within their cryostats was transferred to CERN and executed by an external company under a result-oriented contract. CERN procured cryostat components, set up a dedicated 2000 m^2 assembly hall with all the specific assembly equipment and tooling and defined the assembly and testing procedures. The contractor took up responsibility for the delivery, on time, of assemblies according to the required quality. A dedicated CERN production and quality assurance team was constituted. A specific quality assurance plan was set up involving 2 additional contractors responsible for weld inspections on a total of about 20’000 assembly welds and the execution of about 3300 leak detection tests.

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KEYWORDS: cryogenics, LHC.
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INTRODUCTION

The design of the 474 lattice quadrupoles of the Large Hadron Collider and assembly within their cryostats, to form the so-called Short Straight Sections (SSS), was the result o

FIGURE 1. Views of the SSS assembly hall at CERN: Cryostat assembly benches (lefts), and Technical Service Modules assembly benches (right).

more than 10 years of collaboration effort between CERN and the French institutes CEA and CNRS [1-3]. The manufacture of the 392 cold masses housing the main quadrupoles was contracted, after a competitive tender, to a German firm, while, due to their small number but large variety in types it was preferred to carry out the assembly of the remaining cold masses with the insertion quadrupoles at CERN.

The initial strategy was to outsource the assembly of the SSS in industry; but due to the insolvency, at an early stage of the contract, of the firm selected, the LHC project management decided, in December 2002, to in-source the procurement of cryostat components and the assembly of the SSS, in order to avoid schedule slippage due to re-tendering [4].

To react to this sudden change in strategy, an important re-organisational effort was initiated. A network of suppliers of the cryostat components, including more than 10 European firms, formerly managed by the contractor, had to be re-established. To gain time, re-negotiation of contracts with the original suppliers was necessary for the long-lead time components; but for some components, re-tendering was unavoidable.

Meanwhile, a dedicated industrial-like facility was set-up at CERN on a floor area of 2000 m^2 for the assembly of the SSS (Figure 1). The general infrastructure was upgraded, including the installation in the building of new overhead cranes and all the required services. Specific assembly tooling and ancillary equipment was designed, procured and set up in the building.

Detailed “build-to-print” specifications were prepared, covering the assembly of the SSS in all their complexity and variants. A “result-oriented” procurement was established by extending an existing contract with a consortium of firms for the assembly of the dipole cryostats. In the frame of this contract, CERN was responsible for the supply, on time, of cold masses and cryostat components, making available the production facilities and infrastructure, including all specific tooling and handling equipment. Considering the complexity of the work and the large variety of assembly types, CERN retained responsibility for the detailed assembly procedures and management of the Quality Assurance.

The assembly work could finally start at CERN in July 2003, only 6 months after the decision to in-source, though it took a further 9 months before production would actually take-off.

WORK ORGANISATION

Activities Description and Work-Flow

The assembly activity featured mechanical fitting and sheet-metal work on heavy cryostat equipment, often to precisions of a few tenths of a millimetre. Helium leak-tight welding was extensively employed to assemble vacuum and cryogenic equipment; a total of more than 6 km of helium leak-tight welds on stainless steel and aluminium cryogenic circuits, most of which designed for 20-bar pressure, were executed, according to high qualification standards and requiring severe QA inspections. Leak detection using helium mass spectrometry, was extensively used to check the tightness of the circuits to rates better than 10-9 mbar.l/s; about 3300 tests were made. The SSS assembly also included electrical connections on magnet superconducting cables and instrumentation wires, requiring competence in brazing and soldering techniques. Extensive electrical checks, including standard continuity and high-voltage tests, but also specifically developed polarity tests, were carried out throughout all phases of the assembly.

Besides the technical complexity of the work, managing the assembly of the large variety of SSS types was an organisational endeavour. The 474 units include 87 cold mass variants, resulting from various combinations of main quadrupole and corrector magnets, and 55 cryostat types, depending on the specific cryogenic and electrical powering schemes required by the topology of the LHC. About 370 components of different types, ranging in size and weight from several meters and tonnes down to a few centimetres and kilograms, were employed.

To streamline the work and avoid assembly errors, precise guidelines concerning execution of the work were given to the contractor. A considerable effort was made by the CERN team to provide complete documentation. Detailed assembly procedures, drawings and process sheets, detailed lists of parts to be assembled based on the Assembly Break-down Structure (ABS) documents were prepared. Work progress was reported and regularly cross-checked by the QA team on so-called *travellers* in the form of paper files accompanying every unit throughout all the steps of assembly. Hold points for QA checks were introduced at all critical steps to ensure the execution of configuration controls, dimensional checks, weld inspections, leak detection tests, and electrical tests. All relevant measurements were recorded into the CERN EDMS system [5], which also provided the necessary tools for the rapid treatment of non-conformities.

Figure 2 illustrates the main work-flow phases and the interactions with the activity centres. The main work sequence included reception tests on the cold mass, its assembly, after equipping it with thermal shields and MLI, into a cryostat, and the assembly of the Technical Service Module housing a variety of electrical, cryogenic, and vacuum devices depending on the type of SSS. These include the magnet Instrumentation Feed-through systems (IFS), the corrector magnet current feed-throughs (DCF), the insulating vacuum sectorization barriers (VB) for some SSS types, helium phase-separators with level and pressure gauges, cryostat links (so called “jumpers”) of the SSS to the LHC cryogenic distribution line, and beam vacuum feed-throughs, just to mention the most important components. Final testing (pressure/leak and electrical tests) were made prior to declaring the SSS ready for magnet cold testing, after which, the preparation of the magnet extremities for interconnection in the tunnel and final electrical testing were performed. While *cold mass reception testing* and *cryostat assembly* took 2-3 days on average per unit, the longest activity was the *assembly of the Technical Service Module* which would take between 2 and 3 working weeks, depending on the complexity of the SSS type. An additional 3 days on average would be needed for *final testing* and *cryostat final preparation & tests*.

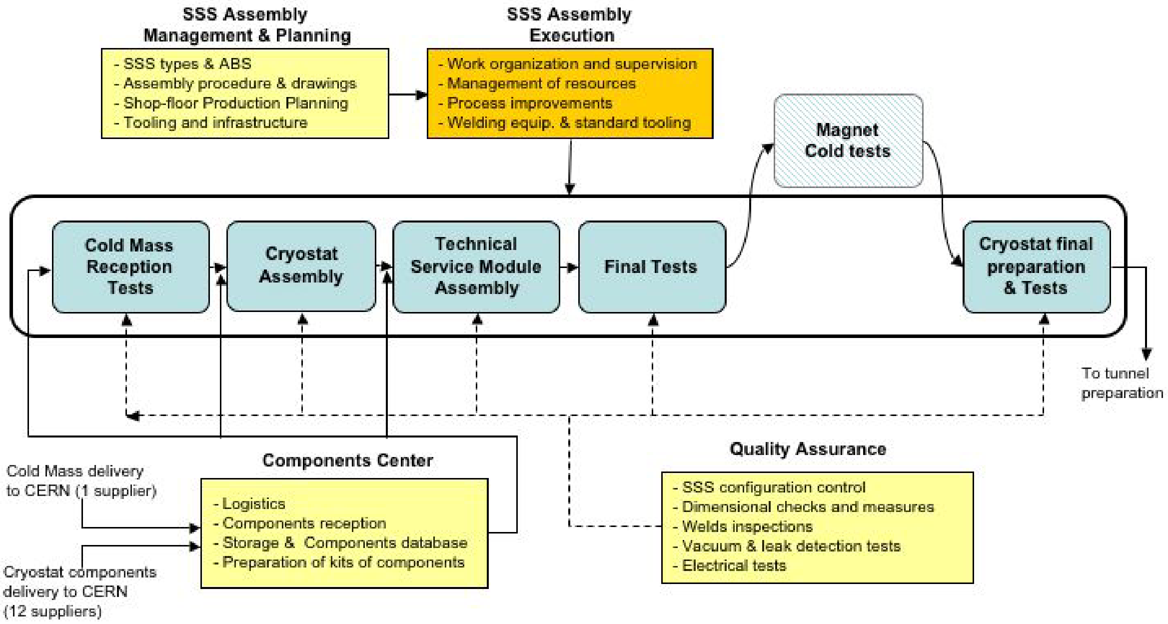

FIGURE 2. Assembly work-flow and main shop-floor activity units.

The activity was managed through two levels of planning: *long* and *short term*. The *long term planning*, covering the overall activity, and detailing quarterly assembly objectives, was the contractual basis. Project tracking and steering was made on the basis of this planning via regular technical coordination meetings every 3 weeks, and monthly contractual meetings. The *short term planning*, tracked and updated bi-monthly, detailing activities on a weekly basis, was discussed in shop-floor meetings and was a very efficient tool for managing the activity on the basis of work contingencies, availability of execution and QA team resources, availability of cold masses and cryostat components and usage of the assembly tooling. It also allowed taking into account and coping with changes in magnet cold testing and tunnel installation needs.

Components Logistics and Storage

Despite an initial belief that components could be delivered *just-in-time* to satisfy assembly needs, experience showed that anticipating their delivery and managing logistics and storage through a dedicated components centre was an absolute necessity. To guarantee a continuous supply of components to the assembly facility, depending on the type of SSS, kits of components were prepared in advance, to be assembled and transported to the assembly stations were they would be needed. Kits were prepared weekly, two weeks ahead of need, based on the *short term planning*, and stored in dedicated racks or storage areas; they were then dispatched to the assembly stations on a daily basis. Incoming inspections on the components coming from industry could be done ahead of need; non-conformities or damage to components due to transport could be detected at an early stage, in time to intervene with repair or new supplies thus avoiding disruption to the assembly. Before their use in the assembly, additional testing was also introduced on some components for which quality control in industry had turned out to be weak. A timely preparation of the components, to cater for a large variety in types, also allowed the risk of making a wrong choice to be minimised.

Another major advantage of having an in-house stock of components was the flexibility it yielded in adapting the assembly planning to cope with the magnet cold testing and tunnel installation needs.

Assembly Hall, Tooling and Infrastructure

A former workshop at CERN, composed of two bays of 1000 m^2 each, was refurbished and equipped with two overhead cranes. A first bay, dedicated to the cryostat assembly activity, was equipped with three cryostat assembly benches specifically designed to cover the six variants in cold mass and vacuum vessel lengths. For the sake of simplicity, these benches were designed to be operated manually and, even at the maximum production rates, the activity on these benches, efficiently operated by a dedicated team, was never on the critical path.

The second bay was dedicated to the assembly of the *Technical Service Modules*. Two main types of bench were required. Since the duration of this activity was by far the longest, several benches of the same type were installed.

The layout of the hall was studied to group as far as possible similar operations, in order to optimize the use of portable equipment and reduce the number of handling operations. Ergonomics and safety issues were also taken into consideration. A delimited safety area, where pressure tests were carried out on the SSS during normal working hours, was set up.

Handling of the SSS between the various stations was undertaken using specifically designed girders, which could be adapted to the changes in geometry and center of gravity occurring at various stages of assembly. Transfer between two adjacent bays was done on a shuttle trolley. On average, the assembly of each SSS demanded 10 handling operations, thus justifying 3 full-time handling operators during peak production.

The layout of the hall and the tooling installed evolved to meet production needs. To catch-up with a sluggish start-up of the assembly, additional Technical Service Module benches became necessary. Also, activities initially unforeseen in the hall, such as cold mass reception and SSS geometrical measurements, taking additional space and increasing the number of handling operations were added. Finally, experience showed that having to treat difficult and lengthy non-conformities on a regular basis, required a dedicated so-called *hospital* area, where the *sick* SSS could be segregated and treated independently, and thereby freeing the assembly benches for routine production.

The initially foreseen assembly rate of 4 SSS/week, increased up to about 6 SSS/week (with peaks of 9 SSS/week), during full production. Space was extremely tight at this stage, requiring a strict streamlining in the production flow. Buffer areas, outside the hall, for storing incoming and outgoing SSS, were used to absorb fluctuations in the assembly activity.

Transfer of know-how to the contractor

The 55 types of SSS assemblies were grouped in 4 main categories, types A, B, C and D in increasing level of assembly complexity. A staged transfer of know-how from CERN to the contractor took place starting from type A in the first year of production and then gradually passing to the most complex types. 3 SSS of type A, rising to 5 SSS of type C were assembled “hand-in-hand” with the contractor before he could assume full autonomy and take-up a “result oriented” execution responsibility. For these first units the contractor was paid on an hourly basis. Due to the complexity and particularly large variety of the SSS variants under type D (41 variants out of 50 units) [6], it was preferred to keep the execution work under direct control of CERN, and the contractor was paid on an hourly basis at contractual rates.

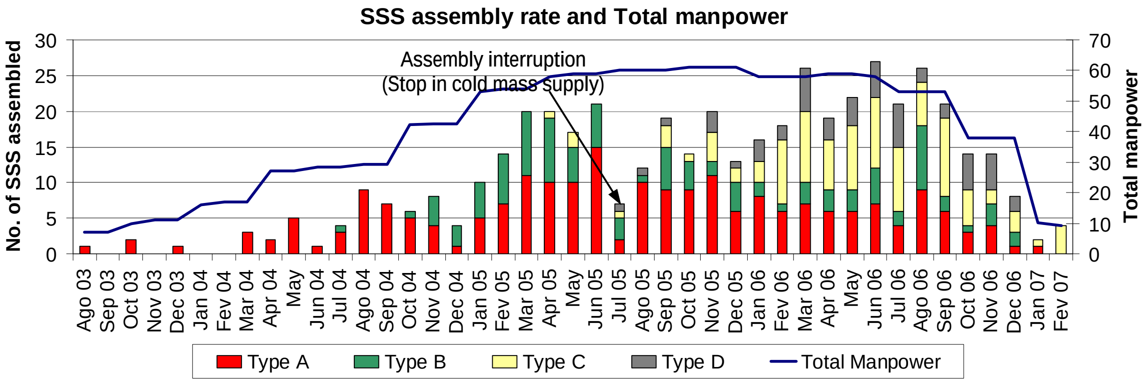

FIGURE 3. SSS assembly rates and manpower (assembly workers, QA and components center personnel).

PRODUCTION FIGURES

Assembly rates and human resources

Figure 3 shows the assembly rates and the total manpower employed (assembly workers, QA and components center personnel) throughout the production. After a slow start up phase of almost 1 year, during which the network of suppliers of cryostat components was being organized by CERN and the contractor was still in a learning period, production ramped up in 2005 [7]. A stable production rate was kept until the middle of the year, but then dramatically dropped due a temporary rupture in the supply of cold masses from industry for technical reasons (the discovery of a faulty weld). During this period, which also corresponded to the peak of manpower, thanks to the flexibility foreseen in the “result-oriented” contract allowing for retribution on an hourly basis, about half of the workers temporarily unemployed were occupied on other CERN activities, thus limiting the financial impact of this event. A new start up followed, and since more complex assemblies were attacked, the ramp up in assembly rate was slower, but then increased to the maximum rates, indicating that the full mastery of the processes was achieved and an efficient work organization was reached. The assembly came to an end with a 6 months ramp-down period, accompanied by a drastic reduction in manpower.

Table 1 reports the break-down of personnel according to competence during peak production.

TABLE 1. Break-down of shop-floor personnel (FTE) by competence, at peak production.

Assembly Activity	No. FTE	Quality assurance	No.FTE	Components center	No.FTE
Supervision	3	SSS configuration control	2	Logistics	3
Mechanical workers	6	Vacuum technicians	5	Storage	2
Welders	6	Welding inspectors	1	Components inspections	1
Electro-mechanical workers	10	Electrical checks	2		
Electricians	7				
Sheet metal workers	3				
Handling operators	3				
Totals	**38**		**10**		**6**

Non-Conformities (NC)

Figure 4, reporting on a monthly basis, the number of NC per SSS as a function of time and of the assembly rate, illustrates the quality learning curve throughout the assembly. The high and irregular spikes in the start up phase stabilized gradually with a clear tendency to a constant reduction in the last year of activity, despite the increasing complexity of the SSS types being assembled (from type A to D, as illustrated in Figure 3) and the increasing workload.

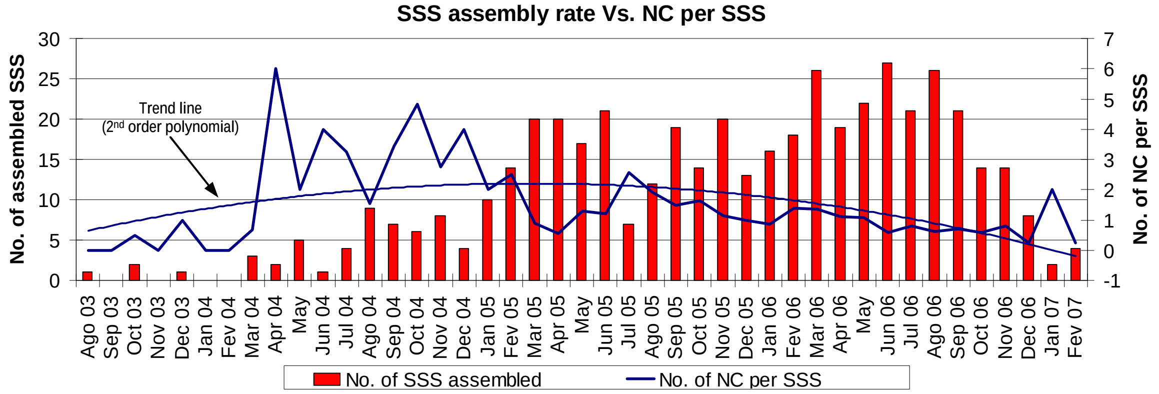

FIGURE 4. NC/SSS versus time and monthly assembly rate.

Figure 5 presents the break-down by the type of NC. A total of about 600 NC were encountered and treated. 60% came from assembly problems (geometrical, mechanical, welding, leak-tightness, and electrical) which occurred mainly while the contractor was learning, and that could be contained by process improvements and stronger QA actions (as visible in Figure 4.). A further 25% came from cold mass NC at reception (electrical, mechanical and polarity) and 6% came from quality problems on cryostat components (materials, and welding mainly), the latter demanding an additional effort for CERN's team in repeating qualification tests and inspections, sorting components and managing repair actions.

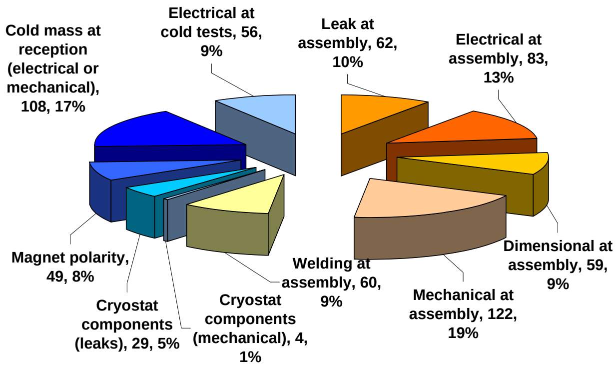

FIGURE 5. Break-down of Non-Conformities by type and number, as encountered during the SSS assembly.

Despite not being the most numerous (~90 NC), leaks were among the most time consuming NC to treat, particularly when small leaks (~10-7 mbar/l/s) were to be localized on finished assemblies. Alternative leak detection methods, using neon as tracer gases were used when helium spectrometry was ineffective due to helium background [8]. Controls on magnet polarity due to wrong routing or labelling of the corrector magnets bus-bars, were systematically introduced at reception, and were repeated at the end of the assembly. A polarity test set-up, specifically designed for this purpose, and fully automated to minimize the risk of human errors was used [9]. About 20 SSS experienced serious electrical NC (dielectric weakness, or shorts in the corrector circuits or in their instrumentation) some of which were only visible at cryogenic temperatures during magnet testing. These SSS were subjected to long and complex diagnostics, using specific techniques such as electrical signal reflectrometry using network analysers to localize discontinuities in the circuits. On 9 of them the NC was imputable to a defective assembly of electrical components during SSS assembly, and 11 turned out to be affected by NC inside the cold mass and had to be sent back to the manufacturer for disassembly and repair.

SUMMARY AND LESSONS LEARNED

The in-sourced assembly of the LHC Short Straight Sections was successfully achieved within schedule. After a slow start-up, mainly imputable to the lengthy learning of complex assembly processes, the difficulties encountered in setting up an efficient network of component suppliers, and linked to organisational matters (shop-floor layout, tooling, QA, logistics, etc.), a spectacular increase in production rate took place, indicating that the full organisational and learning maturity of this industrial-like activity had been attained. Skilled manpower was needed, in particular welders, electricians, and vacuum technicians, not always easily obtainable on the employment market.

Quality issues on components supplied by industry, including the cold masses, generated an important and underestimated additional work load. Electrical and leak-tightness NC exceeded initial expectations, and the difficulty in solving them would have seriously affected the production schedule if strong steering actions had not been taken by CERN. A dedicated infrastructure was set up for their treatment, and technically advanced methodologies, developed by CERN and mastered by in-house specialists, were made available for diagnostics; leak detection using neon, investigations on electrical circuits using network analysers and magnet polarity measurements, or ultra sound for detecting material microstructure defects, just to mention a few.

The “result-oriented” frame of the contract with an external firm was efficiently exploited by CERN; despite an important initial investment in specifying the work and in the transfer of know-how, the contractor could take up full responsibility for the execution of work and provide an effective organisation and management of its labour force thus achieving the necessary production rates with the required quality. Furthermore, the strong involvement of the contractor, resulting in a full partnership with CERN, and the flexibility foreseen in the contract in the use of the labour force, allowed the unavoidable additional work due to delays, mishaps and technical problems to be covered.

Though CERN was initially not prepared in competence and culture, nor was it equipped in infrastructure, to face a large scale industrial-like production of this type, which demanded an important learning effort, having a direct control of the activity on its premises allowed high reactivity to tackle the numerous hurdles encountered. In this respect in particular, in-sourcing the SSS assembly was the most appropriate strategy.

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