Superconducting Magnets for the LHC Main Lattice

Lucio Rossi

***Abstract*—The main lattice of the Large Hadron Collider (LHC) will employ about 1600 main magnets and more than 4000 corrector magnets. All superconducting and working in pressurized superfluid helium bath, these impressive line of magnets will fill more than 20 km of the underground tunnel. With almost 70 main dipoles already delivered and 10 main quadrupoles almost completed, we passed the 5% of the production and now all manufacturers have fully entered into series production. In this paper the most critical issues encountered in the ramping up in such a real large scale fabrication will be addressed: uniformity of the coil size and of prestress, special welding technique, tolerances on curvature (dipoles) or straightness (quadrupoles) and of the cold mass extremities, harmonic content and, most important, the integrated field uniformity among magnets. The actual limits and the solution for improvements will be discussed. Finally a realistic schedule based on actual achievements is presented.**

***Index Terms*—Particle accelerators, superconducting magnet, superconductors.**

I. INTRODUCTION

THE Large Hadron Collider under construction at CERN is the largest particle accelerators and the largest plant where superconductors are employed [1]–[3]. It is designed to collide counteracting intense proton beams of unprecedented 7 TeV energy and its performance depends critically on the reliable operation of its superconducting magnet most of them requested to operate at field in excess of 8 T [4], [5]. The beam must be guided and focused by strong superconducting magnets all over the 27 km long underground tunnel. The ring is subdivided into eight octants or sectors, being each octant subdivided into arcs and straight sections. The arcs contains the backbone of the collider, the regular lattice charged to guide the beam and to provide the necessary alternating gradient focusing to avoid beam blow up. Special arrangements of superconducting magnets are inserted in between the main lattice arcs to accomplish specialized function of beam optics and to arrange the beam for the interaction points [6]. The principal elements of the main lattice are the main dipoles (MB from Magnet Bend) [7] and the main quadrupoles (MQ) [8], but a variety of other superconducting magnets are required. The following table shows the number and type of magnet in the main lattice.

II. THE CHALLENGES

Many are the challenges in this part of the project: the thousands of magnets must reach operating field with very limited training in the tunnel (after the first acceptance test). Indeed, given the number of magnets, the cost would be prohibitive if only 10% of the magnets needed retraining any time the magnetic ring is warmed up and then cooled down. An unacceptable consequence of such a scenario would be the reduction of integrated luminosity for the experiments, too. However to have thousands of magnets providing transverse field and operating at 80–85% of the quench current allowing only, say, less than 1% retraining, is not at all trivial and requires sound design and controlling the construction at a level of unprecedented accuracy. The energy stored in the beam is 350 MJ (beam cross section is about 1 mm^2): the magnets must be able to operate with a continuous heat deposition of a few $\mathrm{mW/cm}^3$ as peak and must survive at a shot of a relevant fraction (a few percents) of the maximum beam energy: fortunately mis-operations are more likely during the beam injection and initial acceleration phase when less power is stored in the beam.

TABLE I
MAGNETS OF THE LHC MAIN LATTICE AT NOMINAL (ULTIMATE) PERFORMANCE

Type	No.	Value main component	Fraction of max. current	Stored energy	Magnetic length
MB dipole	1104	8.33 (9) T	86(93)%	7 MJ	14.3 m
MCS sext. corrector	1104	1630 T/m^2	50%	121 J	140 mm
MCDO octupole-decap.corr.	552	8200 T/m^3 1.2 10^6 T/m^4	34% 44%	60 J	110 mm
MQ quadrupole	360	223 T/m	80.3%	0.79 MJ	3.12 m
MS sextup.	360	4430 T/m^2	62%	5.45 kJ	455 mm
MCB dipole corrector	360	2.93 T	57%	9.08 kJ	785 mm
MO (octupole)	180	6.3 10^4 T/m^3	42%	242 kJ	320 mm
MQT/MQS tune quadr.	180	123 T/m	58%	4.54 kJ	380 mm

Being part of a lattice, the bending strength of the dipoles and the harmonic content must be equal among all magnets in within a few units (a unit being equal to 10^{-4} of the main field of the magnet). For this reason, and being powered by sector (154 dipoles all in series, or 45 quadrupoles in series), the weakest dipoles will eventually determine the energy that the accelerator can attain. A limitation, up to about 10%, on a quadrupole sector is less dramatic and it may be compensate, in principle, by higher focusing strength in the rest of the machine.

Although the field ramp rate from beam injection 0.54 T to beam collision regime, 8.33 T for nominal or 9 T at ultimate operation, is a moderate 6.5 mT/s, the field quality is sensible to coupling and persistent current effects, especially at low field. The necessity to strictly control the filament distortion and the critical current all over the production as well as the quality of cabling (shape, size and interstrand resistance) make the superconducting cable construction (400 tons of NbTi) a key challenge inside the project [9].

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The author is with CERN-Accelerator Technology division. He is currently on leave from the University of Milan—Physics Department (e-mail: lucio.rossi@cern.ch).

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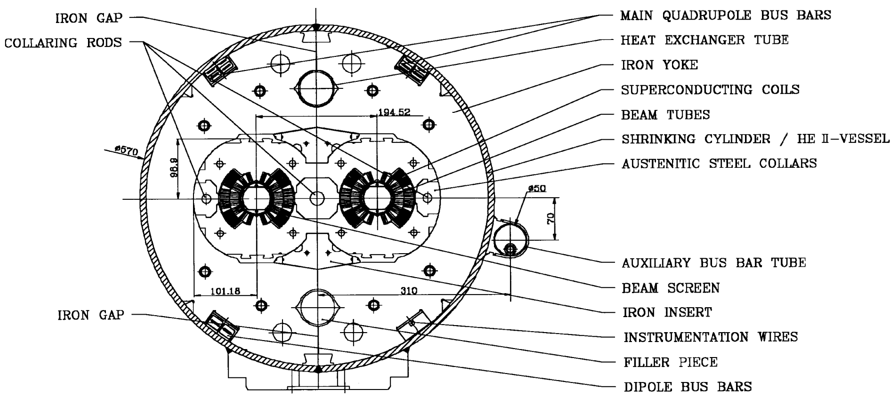

Fig. 1. Cross section of the LHC dipole cold mass.

Finally all this must be accomplished by using Industrial environment for the manufacture, since given the size of the project the magnets cannot be built at CERN. This put challenges of technology transfer but also of proper manufacturing technique, capable to meet Industrial standard avoiding to be unnecessary restrictive and expensive. The combination of sound construction of such a high tech object with financial limitation is actually one of the most interesting aspects of the challenge: the main lattice magnetic system alone is by far the most expensive item of the LHC, and it amount to about half of the cost of the whole project, civil engineering included.

III. MAGNET CHARACTERISTICS

Accelerator magnets and their characteristics have been described and discussed elsewhere [4], [10]–[15] and a description of the final features of the LHC main magnets can be found in [5], [16]. For the scope of the present paper is sufficient to recall a few of the main characteristics.

Common features of MB and MQ magnets are:

- Winding based on NbTi copper stabilized superconductor operating in atmospheric bath of superfluid helium, at 1.9 K.
- large current, almost 13 kA at ultimate field, for coil protection reason, that lead to a Rutherford cable 15.1 mm width. The Rutherford cable is insulated with polyimide tapes with a barber-pole wrapping to favor HEII permeation. We require control of the average thickness of the 15 m long coil package (many layers of insulated Rutherford cable) to ±50 micron and the variation along the 15 m length to about 30 microns. These figures have been set in order to have uniform prestress and accurate positioning of conductor (both for field quality and for quench performance).
- The coils for the two beam channels inserted in the same cold mass (two-in-one design), kept by strong laminated collars in austenitic steel. Collaring is always a critical operation since at peak the relatively soft coil package is prestressed at 150 MPa (120 for quadrupole). Between collars and the coils there are the coil protection sheets, the ground insulation and the quench heaters. The components involved in the collaring operation like collars pairs, pin rods and dowel rods, and their assembly must respect tolerances of a few tens of microns. Quench heaters strips must be free of any cutting edge effect. An analysis of the impact of the components and assembly tolerance on the LHC dipole field quality can be found in [17].

A. Main Dipoles

Once obtained a collared coil, called "twin" for the dipoles since two apertures are collared together, and once finished quench heaters and instrumentation connections, the yoke—in two halves—is put around them. The yoke is composed of 1.5 m long packs of fine blanking laminations which are pressed to obtain a 98.5% packing factor. Then the 600 mm wide yoke assembly is enclosed by two 10 mm thick, 316 LN steel half shells. These shells should be curved a little more than final magnet radius. The whole is inserted into a wide aperture press where the welding operation of the half shells along the 16 m length is carried out simultaneously on both sides under a squeeze of 400 tonnes per meter length. By welding, a proper shrinkage of the shells (now forming a cylinder) occurs and all is designed to assure that the collared coils are always sustained by the shrinking cylinder, through the yoke, to make the structure surrounding the coils extremely rigid. Here again, to assure such contacts the components and assembly tolerances are pretty tight [5], [18]. The cylinder serves also as HEII container, so the welding are not only under stress but have to assure an adequate barrier against the superfluid.

Then the magnet is taken out of the press, the curvature is measured and a lot of finishing operations are carried out at the extremities, including the assembly of the corrector magnets. Afterwards the HEII enclosure is completed by welding to the extremities of the cylinders the end covers and by alignment of the various that serve for cryogenic and electric powering of the various circuits. The finishing of the extremities requires a lot of welds, also to connect them to special bellows that accommodate thermal contraction and the assembly mismatch among magnets.

A cross section of the dipole cold mass is shown in Fig. 1.

B. Main Quadrupoles

The MQ follows a different procedure. Once obtained two collared coils—here single coils are collared—they are inserted together inside the yoke composed of one single lamination rather than two halves as it is in the dipoles). This is possible because there is no interference among yoke and collars, since the collars alone can contain the whole e.m. forces, which in a quadrupole are less than in a dipole of correspondent peak field and bore. Then the yoke is fit into a 16 mm thick stainless steel inertia tube, the main difficulty being to assure the proper alignment of the single coils, obtained through a system of dowels and pins from collars to inertia tube via the yoke [19].

Other are the difficult operations are encountered in finishing the assembly of a quadrupole cold mass, including the assembly on the inertia tube of the corrector magnets, that are bigger than the ones for dipoles: The rest of the procedure does not differs significantly from a dipole assembly.

C. Correctors

We'll not address in this papers issues pertinent to correctors construction [20]: it suffices to say that the principle was to design them capable to attain their field at 4.2 K and, by inserting them in a main magnet cold mass they would profit of the reduced temperature. However, they are potted magnet and the gain in stability, although present, is not as beneficial as it might be hoped because of drop in heat capacity; moreover the indirect cooling impedes exploitation of the superior heat removal properties of HEII.

More relevant is the point of their assembly in the cold mass. They are encapsulated in a support and its must lie within 0.3 mm from the axis of the dipoles. For the quadrupoles the correctors and main axis is 0.2 mm.

All correctors are part of the main magnet cold mass and therefore they are on the critical path of the main magnet construction.

IV. CONSTRUCTION STRATEGY

The construction of the main magnets has been entrusted to four companies: the French consortium Alstom MSA-Jeumont for 1/3 of the dipoles, the Italian Ansaldo Superconduttori, 1/3 of the dipoles, the German Babcock Noell Nuclear for the remaining 1/3 of the dipoles and the German Accel for the whole of the main quadrupoles. It is worth remarking that all these companies are involved in other important LHC projects and in particular Alstom produce more than 40% of the superconducting cable, Ansaldo two types of corrector magnets, Accel the big wide aperture quadrupoles for insertions [6] and BNN is involved in cryogenics and logistics contracts.

For the dipoles there has been an about 10 year long R&D period, carried out involving Industry for long magnet at an early stage. However, after the first generation of dipoles built entirely in Industry, whose success brought to the approval of the LHC Project by CERN council in 1994 [21], it was felt that in order to arrive to a solid design suitable for a mass production, many variants had to be explored, properly defined and finalized, in particular for the cold mass finishing. For this reason Industry was asked to produce mainly collared coils that were then assembled into cold mass at CERN in a hall equipped with proper tooling.

At end of 1999 the companies were awarded a contract for 30 dipole cold masses each, called preseries, while in the first half of 2002 the contracts for the whole series were signed, for further 386 dipoles each. The MQ contract was awarded in 1999, too.

V. TOOLING

Between 1998 and 2002 CERN has designed, validated, procured and installed an impressive number of tooling, like the strong presses for collaring and the huge presses for longitudinal welding. The fact that CERN provided some of the main tooling, and some of it in parallel with the tendering process created a situation where the interfaces have been very difficult with a less clear definition of the responsibility. On the other side some tooling required a long procurement time (2 years or more) and we could not have afforded to wait two years more to launch the main tenders. Somehow this was a consequence of the too long R&D phase and of late definition of the final process.

The installation of the tooling took longer time than foreseen at the beginning but also technology transfer and training was harder than foreseen.

In general for tooling we have seen a difference among tooling that exists in Industry and need to be adapted to our use and tooling conceived and built for our specific use.

In the first category falls, for example, the laser tracker that is used to measure the curvature of the magnets and the positioning of the extremities (end covers, flanges to be welded, etc.). The geometry and alignment of the LHC is critical and difficult to measure since one has to explore the 16 m long cold bore tube, 50 mm of inner diameter, measuring the curvature of 2.8 km with an accuracy of better than 0.1 mm. This laser tracker, a new conception model issued by Leica, was selected at the end of 1999 and it took more than two years to make it suitable to our assembly procedure and to obtain the necessary accuracy and reliability. We gave considerable feed back to Leica for the operation of the machine, the software was modified, and on the top a layer of software guiding the operator during the assembly and automating many operations was put. The laser trackers were then transferred from CERN to Industry: the first months were painful, with people of CERN that had to stay permanently at the companies and many software modification were required (also triggered by different operating conditions). However, after solving the adaptation problems, the time needed for these measurements was getting down to the expected figures as shown in the Fig. 2.

The case of the welding presses is different. Here the main installation, the press itself, has been quite successful, but the functions that render these presses unique: i) heavy and precise mechanics; ii) integration of two synchronous (left-right) welding equipments; iii) reading of the welding gaps through laser camera; all were difficult to integrate in a normal industrial cycle, that suffers when fine tuning and errors can block a full chain with consequences on the time of the whole process. Somehow each of the sub-process had to be tuned to actual industrial environment and the solution has been found in adapting the welding equipment and the welding parameters to components (half shells) that we couldn't get with the expected quality, and this required in time longer than foreseen. The graphs of the occupation time of a magnet in the press is shown in Fig. 3. The trend is positive but clearly a serious effort is still required by the company that is already at 15% of the production.

VI. COMPONENTS AND MAGNETS ASSEMBLY

The component by far more difficult and critical to the performance of the magnets is the superconducting cables. Here we experienced a general delays by all companies, especially in the first phase. Wire breakage during drawing occurred at an unexpected rate, mainly due to the fact that mastering the process

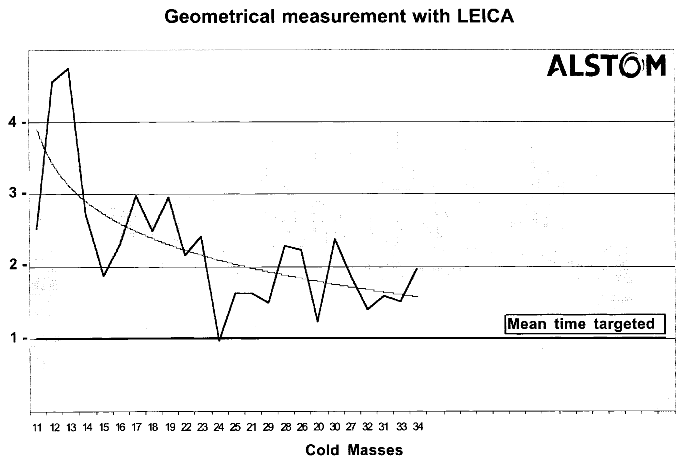

Fig. 2. Expected and actual time (arbitrary units) for geometry measurements with the laser tracker for preseries in a dipole manufacturer.

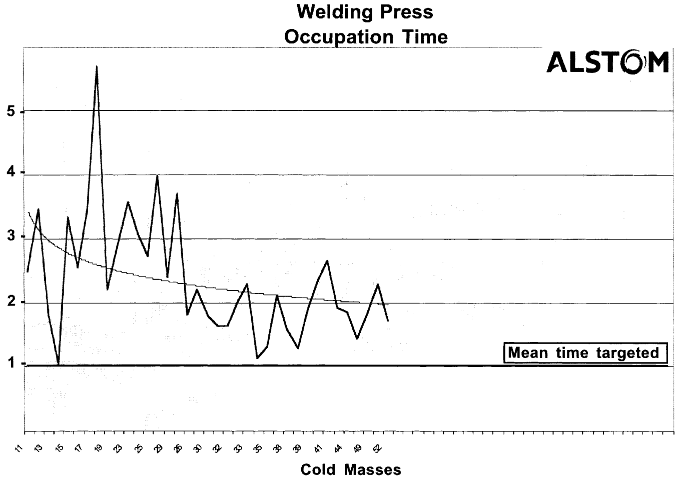

Fig. 3. Expected and actual time (arbitrary units) employed for all operations related to welding press at one dipole manufacturer: final target, actual and trend.

became hard when the quantity jumped of a factor 10 and then 100 with respect to the R&D phase. Here the main reason is that the R&D production was may be too small in quantity and the industrial lines had to be debugged in the series production: this caused some 4 to 12 months delays over the initial plan.

In the magnet factories, the assembly itself depends both on the CERN defined procedure and on the organization of the companies. A big ingredient of this is the number and the skill of the people and the necessity of proper training. Indeed companies refrains to put enough personnel when required since they are afraid to have too many people when the process is not yet fully assessed and stop and go typical of the learning phase are still possible. Then staff is increased upon pressure of need to ramp up production, so training is may be not sufficient.

In the following we discussed the points still difficult in the productions and where the targets are not fully met.

A. Coil Manufacturing

As mentioned in Section III, this is one of the key point or quench performance and it is difficult to stay in the target (±50 microns) of uniformity for the coil azimuthal width since this is linked to stability of many manufacturing steps and to tolerances of many components. Actually today the variations are approximately more than double than our targets. Few improvements have been obtained by actions on tooling and more strict control of the procedures of curing. Some scattering may also be due to winding tension, but probably variation of components play the most important role. It is difficult to disentangle the effects of the numerous key components, however cable and insulation can partially explain this even if they are found inside the requested tolerances. Quench performance [22] seems however independent on the coil size, in the this range of variation, indicating that the acceptable prestress variation is actually larger than the window of ±15 MPa today prescribed in our specifications.

One good point, as indication of good manufacturing, is the fact that the coil waviness, after some uncontrolled values in a few coils, is kept under control: all along its 15 m length, a dipole coil usually does not vary its azimuthal size more than 20–30 microns.

B. Longitudinal Welds

Some problems in this area were certainly related to choice of 316 LN which is not an easy austenitic steel to be welded, and the choice of the STT (Surface tension Transfer) technique, selected for the root weld for his superior quality, which is rather new application on austenitic steel in horizontal welding with fixed speed in order to synchronize the two sides. However, even the conventional MAG filling passes creates, unexpectedly, numerous problems. Again, it was difficult to disentangle among problems coming from welding parameters, or from gap laser reading and associated electronics, or from nonconforming components (half shells geometry and bevel status) or, finally, from a non correct functioning of the press mechanics. Here a key point was to provide adequate training for Industry staff, calling the experts that built the most critical components of the welding press, i.e., coordinating an actions from four different companies all around the world. When this was done, both for the use of electronics devices and of STT machine, the welding improved considerably: for example in BNN the number of intervention for repairing, including very minor ones and repairs of repairs, went from a range of 9/4 12 (min/max) for the 20 magnets welded before the intervention campaign, down to 0/13 for the 40 magnets welded after the intervention. Of course measures to attain values near to zero, see Fig. 4, are under way in the other manufacturers, too.

C. Geometry

During R&D phase the problem of reaching the geometry has never been fully addressed. Indeed reaching the geometry with a certain stability depends on factors like having a proper and constant curvature radius of the shells, the technique of welding and the use of the final welding press: all these were simply not available during R&D.

The experimental datum is that too many dipoles exhibited a bad curvature just after weldings, and some others that are marginally in tolerances got worst during various phases. The curvature must be within required values in the LHC tunnel and stability during various phases: transport to CERN, cryostating, cold test, installation is essential, indeed.

The shape of the shells is by far worst than specified (shells has been one of the most difficult components to manufactures).

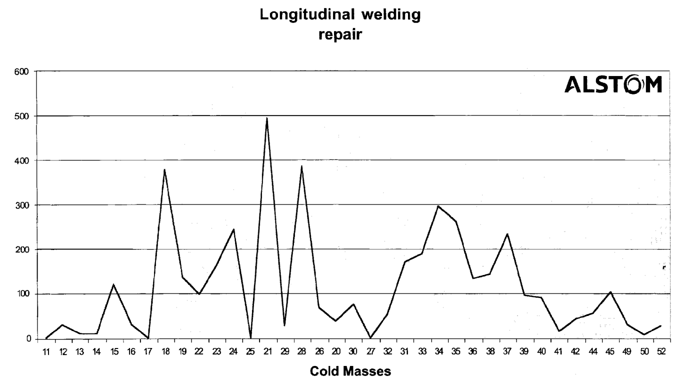

Fig. 4. Total repairs (of any type) for the welding operation vs. dipole number in a firm. The target value is basically no repair.

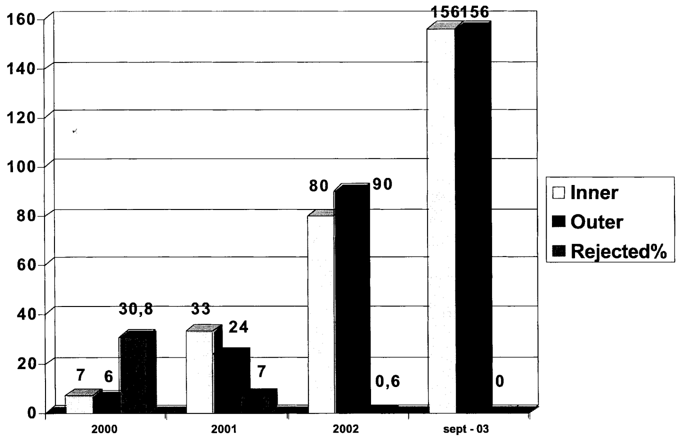

Fig. 5. Statistic of the production and quality of the coil production at ANSALDO. The big jump in quality (from a very bad situation) was accomplished through training and reinforcement of the staff.

However it appears that the shell shape and the variation of the iron stacking factors (laminations more strictly packed might be more rigid and favor spring back of the cylinder) are not strictly correlated to variation of the curvature of the magnets. An effort to cure these problems is under way meanwhile the production is advancing. We can accept some 30% of dipoles with larger tolerance, since the mechanical aperture is larger in the middle of the lattice cell but, giving the lack of margin, it is necessary to continue the effort to improve the control of the welding operations and the uniformity of half shells and of lamination packs.

D. Learning Curves and Staff Training

The coil production is going now very well as shown in the two graphs of Figs. 5 and 6. This is not surprising since these companies are doing LHC coils since 10 years. However, as it can be seen in one companies, the most experienced, there was at the beginning of the pre-series a crisis situation due to change of people, lack of motivation and internal disorganization linked to uncertain (at that time) future of the superconductor unit inside the company.

The learning phase has been more difficult for the cold mass assembly, with the companies sometimes reproaching CERN of lack of industrialization in certain procedures and lack of realism in some tolerances. Some suggestions have been accepted and many small procedures refined and improved by proper dedicated effort. However it is today a satisfaction to see that the companies, following basically the CERN procedure, are already incredibly near to the long term objectives, as shown by Fig. 7.

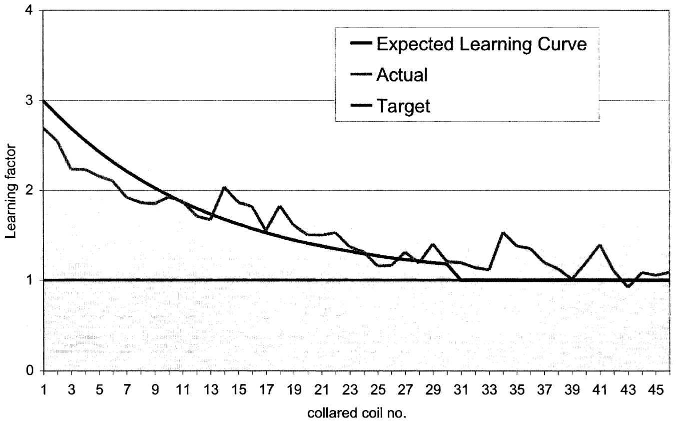

Fig. 6. Learning curve for the total collared coil production at BNN. (not included abnormal repair time). The jump up from the projected learning curve are mainly due to training of new staff.

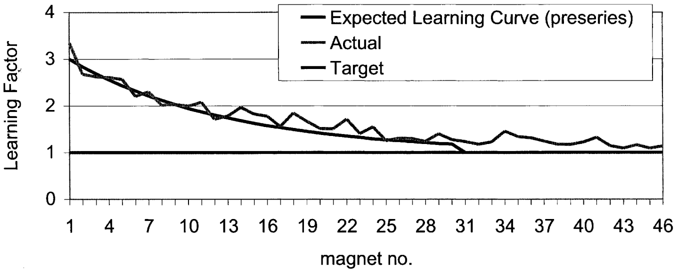

Fig. 7. Learning curve for the total CM production (i.e., collared coils and cold mass finishing, including the welding time) at BNN. Abnormal stop are excluded. Today BNN is welding 4 magnets per week and has shown an extra 25% capacity.

One point that may be obvious but it's worth discussing is the strict correlation among increase of staff and time employed per magnets.

In Fig. 8, this is very well depicted for the coil fabrication of one manufacturers. The fact that the huge peak due to entering of new staff is quickly recovered testifies that the entering was may be too sharp but also that serious effort have been done to recovery the delays. Some correlation among new recruitment and bad quench performance has been found in case of two companies, while it appears negligible with the manufacturers with more staff and with more managing structure.

VII. CONTROLS, QA AND PRODUCTION STEERING

All the measurements carried out during construction are recorded in the MTF (Magnet Test Folder) [23], the electronic traveler that is on line exchanged among manufacturers and CERN. The MTF contains also all NCR (nonconformity reports) and all other information relevant to describe the magnet construction. The ultimate tool for quality controls and steering the production toward the beam dynamic limit are magnetic measurements carried out on all collared coils and cold masses produced, both dipoles and quadrupoles. For more details see [5], [16], [24], [25]. From the point of view of the QA,

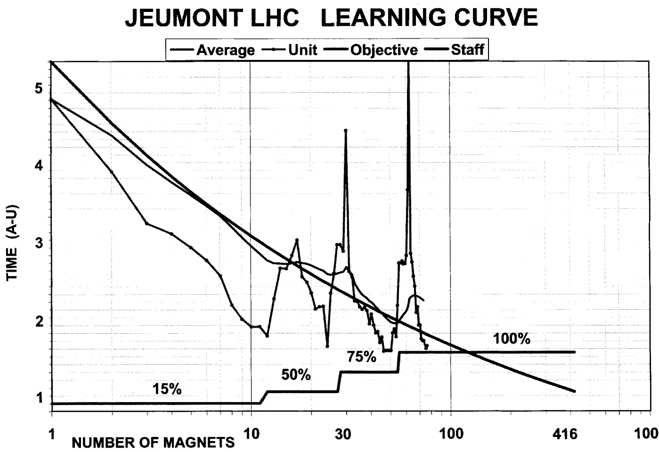

Fig. 8. Time of manufacturing of a dipole coil for one firm: comparison with expectation and correlation among staff increase (bottom curves in %) and jumps in coil production time.

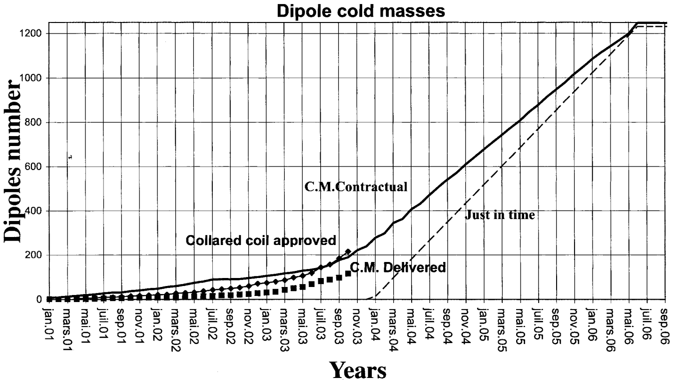

Fig. 9. Contractual delivery schedule of the main dipoles to CERN, (first 90 were pre-series, then series) compared with the actual production curves achieved for collared coils and final cold mass. Indicated is the "just-in time" limit to respect the present installation schedule.

already four serious mistakes have been detected: three have been corrected and one is under investigation. Warm magnetic measurements carried out on collared coils have allowed also to correct unacceptable drifts outside the allowed range for the main harmonics avoiding to suffers too much of the very long feed back time from cold measurements at CERN (almost one years delayed with respect to the winding operation).

VIII. Performances and Delivery

A detailed analysis of the quench performance can be found in [22]. Here we want to underline that all magnets passes nominal field, with one exception, and most of them goes straight to ultimate field after the thermal cycle. Considering that all magnets will be cold tested and that in the tunnel by nature they will have at least another thermal cycle before excitation, the situation is certainly more comfortable than it appeared at the time of the tender.

At the beginning many magnets were plagued by electrical problems, especially related to quench heaters shorts. From a percentage of 40% out of the first 10 magnets, we went down to 15% in the first 50 and now we are less than 10% and we think to be able to go down to less than 2% for the series.

The dipoles production is the controlling clock for the entire project. However, starting spring 2003 is already outside of the critical path since magnet testing is not following with sufficient speed also for delays in installing the cold benches.

The dipole delivery achieved so far and the projected curve, see Fig. 9, show that the goal of installing the last dipole by end of 2006 (for that scope we need it at CERN by November 2006) is hard but certainly feasible.

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