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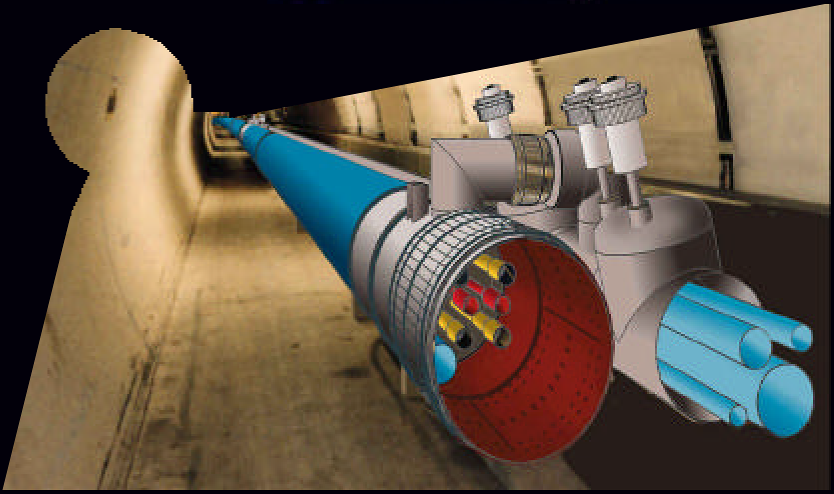
PROCEEDINGS OF THE *LHC DAYS 2001*

19-21 March 2001
Villars-sur-Ollon, Switzerland



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GIOVANNA VANDONI

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FOREWORD

My first year in office as leader of the LHC division convinced me of the acute need for a one-off briefing of our rather numerous young staff in Career Paths V, VI and VII recruited since the approval of the LHC, who had not lived through the development history of the project and therefore lacked a comprehensive and homogeneous information on its main design choices and engineering challenges. This was the very purpose of the ***LHC Training and Integration Days*** which took place in Villars-sur-Ollon in March and October 2000, attended by some 120 colleagues recruited since 1995. The success of these events rested as much on their social aspect as getting-to-know-each-other and team-building exercise, as in their basic training function, and many attendees commented enthusiastically on the interest of holding such an event on a regular basis in the future, though with a different scope.

A small, hard-working organising committee was set-up in the autumn of 2000, which rapidly identified the goals and scope of the ***LHC days 2001***: a yearly workshop addressing key topics in the current life of the LHC project, focussed on the main ring systems which constitute the *raison d'être* of our division, with topical sessions providing presentations and ample time for discussion, attended by people who contribute to the discussed topics. With the trend towards finer specialisation in scientific and technical education, compounded by the increasing pressure of daily work as we move into the industrial construction phase of a very complex and interdisciplinary project, bringing people together to learn, discuss and communicate for a few days in a nice setting is a sheer necessity, and *a posteriori* proved extremely useful, as it allowed to identify important issues, crystallise lines of action and circumvent technical and organisational blockages.

The organisation of the ***LHC days 2001*** benefitted a lot from the experience of our colleagues from the SL division who organised the LEP Chamonix Workshops over the last decade. We however decided to concentrate this event over three days, to try and maximise the number of participants attending the whole duration. A consequence of this approach is that we had to be selective in our choice of topics, which evidently did not cover all domains of activity of the division. Preference was given to "transverse" topics involving specialists from several groups or teams, as well as subjects perceived as "hot" at the time of organisation – most of which still are! The organising committee also pronounced themselves clearly in favour of asking the authors to produce short written versions of their presentations, to be posted on the Web and published: the result is now in your hands.

I take this opportunity to thank again members of the organising committee – and in particular the scientific secretary and editor of this volume Giovanna Vandoni – as well as session chairpersons and speakers, for the time and effort they devoted to make this event a success. A special mention is due to Evelyne Delucinge who coped with all aspects of the logistics in her efficient and professional fashion.

Philippe Lebrun

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EXPERIENCE WITH MB FINAL PROTOTYPES AND START OF THE PRE-SERIES - COLLARED COILS

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Abstract

The first part of this note will give a description of the lessons learnt during the execution of the prototype and short model programmes. The parts or procedures we defined will be shortly described:

- Optimisation and production of mechanical components
- Prestress of the straight part
- Collaring procedure
- Tests (magnetic, mechanical and electrical).

The second part will be devoted to the subjects where some work is under way or is still needed. The solutions foreseen or proposed will be explained:

- The coil size (spread between coils produced in the same firm and between coils produced in different firms)
- Ends (fabrication procedures and configuration)

1 PROTOTYPES AND SHORT MODELS

During the last two years six 15-m-long prototypes were assembled in industry and completed at CERN; five were tested. The first pre-series dipole was completed and tested as well and another three pre-series collared coils were delivered and are under completion at CERN. In the mean time ten twin-apertures and 20 single-aperture 1-m-long models were assembled and tested. The prototypes include several variants reflecting the evolution of the design and the need of testing and qualifying several parameters [1].

Table 1: Summary of the characteristics of the prototypes and first pre-series dipole

1. TYPE	**2. FIRM/ N^{O}**	**3. COLLARS**	**4. ENDS**	**5. END SPACERS**
Prototype	Noell 1	Hyb. Al.	Not sym.	Gen. 1
Prototype	Noell 2	Steel SA	Not sym.	Gen. 1
Prototype	Al.-Jeu. 1	Steel NS	Not sym.	Gen. 1 filed
Prototype	Al.-Jeu. 2	Steel AS	Sym.	Gen. 1 filed
Prototype	Ansal. 2	Steel UG	Sym. nest.	Gen. 1
Prototype	Ansal. 1	Steel UG	Sym. nest.	Gen. 1
Pre-series	Al.-Jeu. 1	Steel NS	Sym. nest.	Gen. 1 filed
Pre-series	Al.-Jeu. 2	Steel NS	Sym. nest.	Gen. 1 filed
Pre-series	Ansal. 1	Steel NS	Sym. nest.	Gen. 3
Pre-series	Noell 1	Steel NS	Sym. nest.	Gen. 2

Table 1 summarises the main parameters of the 15-m-long prototype and pre-series dipoles. The dipoles are reported in the sequence of delivery from the oldest to the most recent. In particular the material of the collars, the configuration of the yoke in the ends, and the end spacers changed during the production.

The first Noell was still assembled using aluminium collars. Then all the others had austenitic steel collars. Different producers were used for the steel in order to qualify the material. All the pre-series dipoles were made using the chosen steel producer after the tendering phase.

The end configuration of the yoke evolved from non-symmetric extremities (the layer jump was covered by a longer pack) to symmetric ones. Furthermore a ring of soft iron was added to surround the non-magnetic laminations; this was done to harmonise the field configuration in the ends and it is the so-called nested lamination ends.

Finally the end spacers evolved from the first design (generation 1) to a second geometry (second generation) with angles and shapes modified to have a better matching of the cable during winding. The second generation was designed taking into account the data coming from the first prototypes in industry and from the short models at CERN. The third generation includes an extra spacer after the first two turns of the second layer. This spacer reduces the field seen by the cable of the first two turns. This means an increase of the margin before quenching. One Cold Mass assembler (Alstom-Jeumont) filed the angles and the shape of their end spacers to have them better adapted to their winding technique and tooling.

If we try in few words to summarise the results of the assembly and testing of all these dipoles we can say the following:

- The straight part behaves properly in terms of quench performances but is not correct in terms of field quality (i.e. some multipolar components are out of tolerance).
- The layer jump region works correctly. Some problems were found during the first assemblies (deformation of the cold bore tube) but now the solution to avoid them is known.
- Almost all quenches are localised in the ends and especially in the second layer ends.

From this summary it is clear which are the points to improve with the work of the future months. These points will be treated in Chapter 2. The rest of this chapter will describe the achievements of the last couple of years.

1.1 Components

Extensive Monte Carlo simulations allowed us to enlarge the tolerances of the main components of the active part being confident of not loosing in performances.

The problems linked to the beginning of the production of massive quantities of components (collars, copper wedges, plastic parts for the coils) are solved or under control and a smooth and regular flux of parts has started.

As an example fig. 1 shows the process of the correction of the tooling for the fineblanking of the collars. The picture shows also the beginning of the series production (after the tooling modification). Few dimensions only are shown. The control is carried out for hundreds of dimensions for the collars.

Similar data analysis of the production is used for the other components [2].

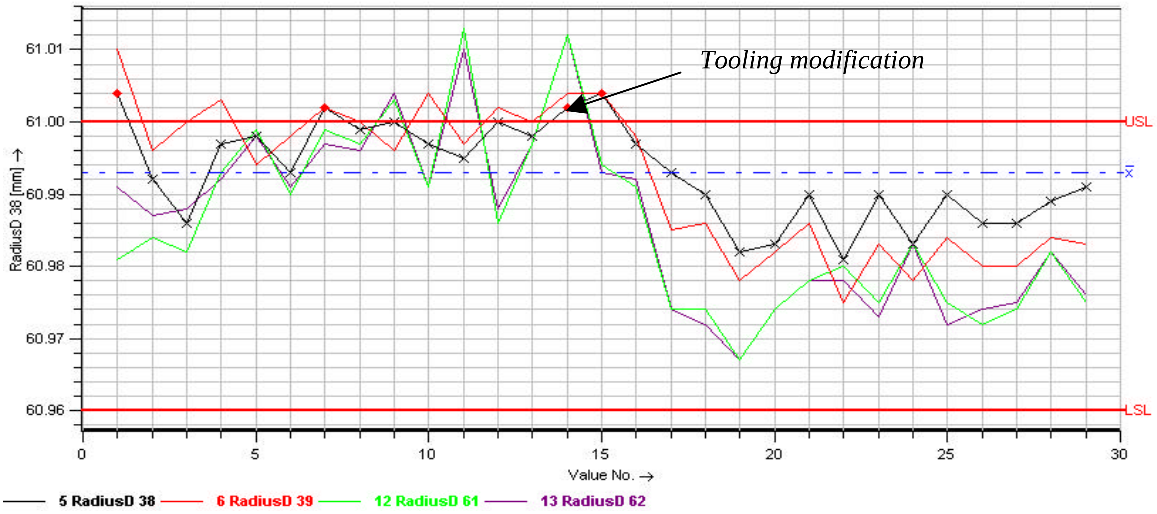

Figure 1: Evolution of some collar dimensions during the setting of the tooling and the beginning of the series. The reported dimensions are the radii of the coil cavity. The “y” axis gives the measured value. The two horizontal red lines are the upper and lower tolerance limits. The “x” axis gives the sample number. After the “tooling modification” the series production started.

1.2 Assembly of the collared coils

The winding and curing tooling for the pre-series and series is available at the three Cold mass Assembler’s premises. The winding and curing techniques are settled. Some work has to be done to understand the effects of the tooling and techniques on the performances of the ends and on the field quality.

The collaring was a real nightmare years ago during the assembly of the very first prototypes. Now the collaring tooling (the same for the three assemblers) and the experience gained make this operation standard and easy: the pressure applied on the collars is increased cyclically till the insertion of the locking rods. The operation that took days in the past lasts now a couple of hours and during the series will go even faster.

The target prestress after collaring is 75 MPa (average of the first and second layer) with a tolerance of ± 15 MPa for the straight part, 30 MPa ± 10 MPa for the ends. A smooth transition between the straight part and the ends has to be foreseen. The values reported above are the results of the experience gained with the past models and prototypes. The ± 15 MPa means ± 0.12 mm in the shim size. This is the amount available to fine-tune the field quality using the shims.

The mechanical, electrical and magnetic tests were settled during the prototype production and will be approximately the same for the series production. Some minor changes will be introduced due to the series production arrangements. A complete description of the tests carried out for the pre-series can be found in the Inspection and Test Plan of the dipole technical specification IT-2708.

2 THE FINAL TUNING

As already anticipated in Chapter 1 the two items were improvements are necessary are the control of the coil azimuthal size and the behaviour of the ends. The first item affects the field quality while the second affects the quench performances.

2.1 Coil size

The Technical specification IT-2325 (technical specification for the production of the dipoles for three octants) foresaw the following tolerances for the azimuthal size of the coils:

Tolerance on the azimuthal size of each coil: ± 0.02 mm. Waviness: ± 0.025 mm.

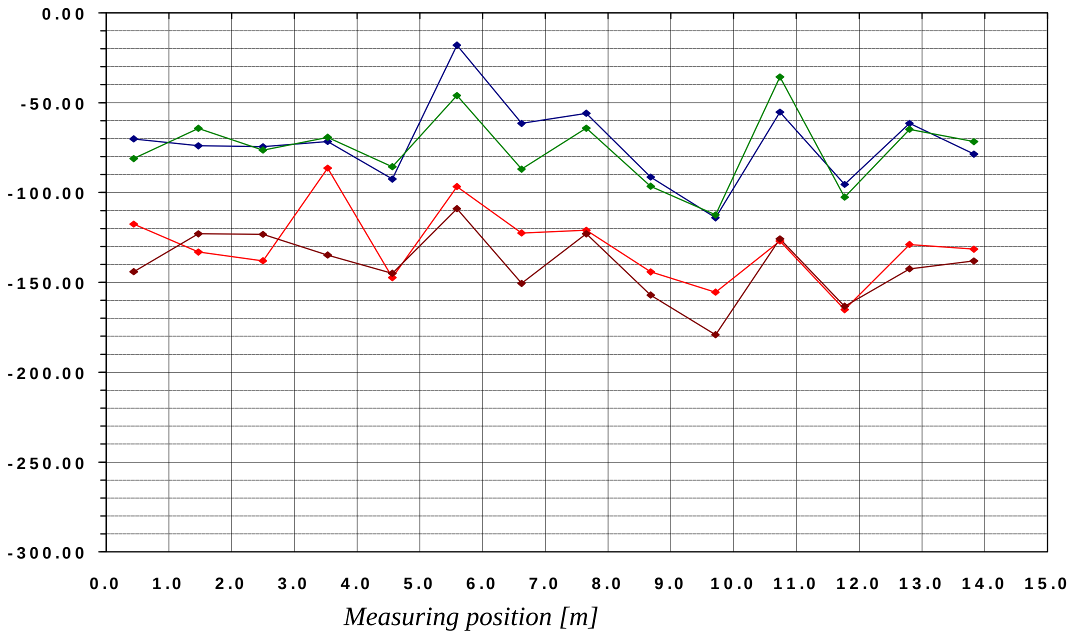

Figure 2: Coil size in µm at 100 MPa. The curves represent four inner layer coils that were used for the first Noell pre-series dipole. The size under a compression of 100 MPa is measured in several positions along the 15-m-long coil. The reported size is the difference respect to the nominal condition (0.00 line).

Furthermore a tolerance of ± 10% respect to the average was imposed for the modulus of elasticity of the coils assembled in the same dipole.

During the negotiations that followed the offers and that lead to the contract to produce 90 pre-series dipoles this part of the specification was dropped.

The first coils assembled in industries were measured and we obtained values that can be represented by the coils of fig. 2. There is a waviness of the order of ± 0.05 mm. The spread between coils of the same producer is up to 0.1 mm despite the components belong to the same batches. Furthermore a spread up to 0.1-0.2 mm has been obtained between coils of different producers.

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2.1.1 *Coil Waviness*

Since ± 0.025 mm is very difficult or almost impossible to achieve for the series of coils can we accept ± 0.05 mm? There are good reasons to answer yes. The modulus of elasticity of the coils is about 10’000 MPa, the collars and the copper wedges have a modulus equal to 190’000 MPa and 120’000 MPa respectively. Therefore during collaring the “soft” coils are “squeezed” inside a “rigid” cavity defined by the collars and the copper wedges. If we will be able to have collars and copper wedges within their strict tolerances we will be in the position of releasing the coil tolerances.

A confirmation of this is given by the first Noell pre-series dipole. The waviness of the coils is ± 0.05 mm while the waviness of the collared coils goes down to ± 0.03 mm; and this value of ± 0.03 mm includes also the tolerance on the collars.

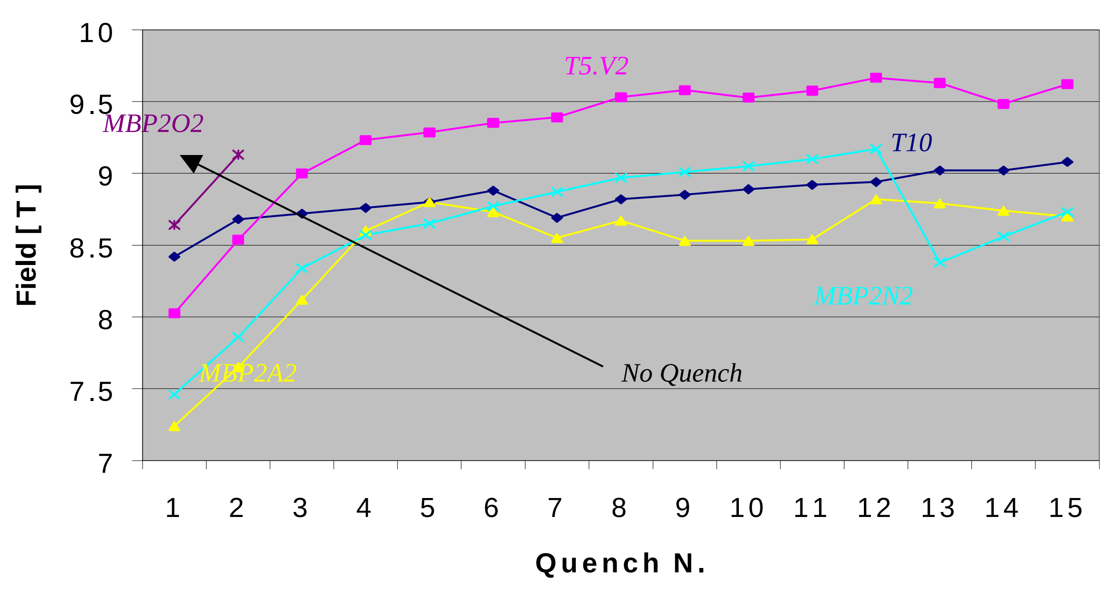

Figure 3: Training of some prototypes and short models

2.1.2 Spread

At the moment there is not a clear explanation of the spread between coils of the same producer and the spread between coils of different producers.

Possible parameters that may influence the spread are the following:

- Precision of the measurements
- Cable insulation procedures
- Coil curing procedures
- Curing tools: the press, the moulds etc.

In particular the precision of the coil measurements and the influence of the tools must be assessed. At this purpose a campaign of transversal crosschecks of the tooling and procedures is starting now. The goal is to compare and understand the differences seen in the three producers.

2.2 Ends

Fig. 3 shows the training behaviour of some 15-m-long prototypes and some 1-m-long models. The 15-m-long prototypes MBP2A2 and MBP2N2 show a relatively low quenching field at the beginning. Almost all the quenches are in the ends and a large part in the second layer. The 15-m-long prototype MBP2O2, built by Alstom-Jeumont is largely above the specifications. T5.V2 is the best 1-m-long model; it starts with a relatively low level quench but it goes quickly to high fields. T5.V2 has a mix structure with “steel main collars” – “plastic floating collars” which works as the standard “all steel collars” [3]. The largest amount of quenches of this model is on the second layer ends. Finally the 1-m-long model T10 has a starting quench at a satisfying level but the slope of the training curve is too low; all the quenches of this dipole are on the first layer ends.

All those dipoles have the same end spacer shape with two exceptions: MBP2O2 where the end spacers were modified filing them and the T10 where the second layer end spacers are the so called “third generation”. As already said the third generation end spacers are the last designed, they foresee an extra spacer after the first two turns of the second layer to decrease the field seen by the first turns in the ends.

From the analysis of these training curves it seems that the end spacer shape is important to define the quench performances but the relationship is not clear.

The same end spacer shape has given different performances in case of different assembly procedures (i.e. the training of T9 and T10 1-m-long models).

The same end spacer shape give different results in the single and double aperture 1-m-long models. In average the training curves of the single apertures are about one Tesla higher than the corresponding ones of the twin apertures. The difference is more than the double of what can be expected because of the non-symmetries in the field.

The same end spacer shape (the second generation) matches better the cable in the case of Ansaldo respect to

Noell during winding; the contrary can be said for the third generation.

For all these consideration it is not yet clear the influence of the different winding and curing techniques, tooling, and end spacer shape on the quench performances of a dipole. The work of the next months will be to understand and keep under control the different parameters.

As a final consideration it is important to mention the relationship cost/production time of the end spacers. The cost of an end spacer is directly proportional to the machining time. A given shape can be produced quickly with a single pass of a cylindrical cutter in a 5-axys machine or must be produced slowly with several passes of a spherical cutter in a 3-axys machine. It is clear that if we want to limit the costs and to follow a production rate of several dipoles per week we have to choose the "quick way". Not all the surfaces can be produced with a quick 5-axys method; it depends how the surface is designed. As an example the filed surfaces of the Alstom-Jeumont dipole can not be copied and produced with a cylindrical cutter. For Alstom-Jeumont the solution is to compute the closest 5-axys surfaces to the filed ones. This has to be done with one of the existing programs that compute the cable deformation in the ends. Doing it only with a CAD-CAM program would not warranty the correct matching of the cable and end spacers.

3 CONCLUSIONS

During the "prototype phase" considerable progresses have been made in controlling the production of components. The assembling and collaring procedures and the tests are defined and validated. The pre-series started and for the first time the dipoles are assembled using components within tolerances and that are the same for the three Cold Mass Assemblers. This will allow us to compare the results of the different dipoles and/or assemblers and fix the two points still opened: the coil size and the quench behaviour of the ends.

REFERENCES

[1] K. Artoos, M. Bajko, L. Bottura, P. Fessia, M. Modena, O. Pagano, F. Savary, W. Scandale, A. Siemko, G. Spigo, E. Todesco, J. Vlogaert, C. Wyss: "Design, manufacturing status, first results of the LHC main dipole final prototypes and steps towards series manufacture." MT-16 Ponte Vedra Beach, USA, September 1999.

[2] P. Fessia, C. Lanza, D. Perini: "Statistical approaches to follow industrial processes and their application to data from prototype dipole collars." LHC project note 246, December 2000.

[3] P. Fessia, D. Perini: "Mechanical design of a possible LHC dipole cross section with mixed plastic-steel collars." LHC-MMS Technical note 99-06.

COLD MASS GEOMETRIC MEASUREMENTS

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Abstract

This paper gives the definition of the dipole cold mass (CM) geometry based on the optical needs of the LHC machine and on the mechanical boundary conditions in the interconnection zones. The tolerances on the CM shape, the assembling tolerances on the corrector magnets and on the different components assembled on the ends are given. The 3-D optical measuring system and the measuring method is shortly described. The summary of the results obtained on the first CMes shows what we have learned from the assembly of the 6 prototypes at CERN. Making the comparison of the prototypes following the evolution of the tooling, the measuring system and method the critical aspects of the final assembly steps comes in evidence.

1 THE GEOMETRY OF THE DIPOLES

The requirements on the dipole CM geometry are arising from optical needs of the LHC machine [1] and of the mechanical boundary conditions of the interconnection zone [2]. In order to provide the largest possible mechanical aperture for the LHC beam, the dipole CMes have to match the particle's circular trajectory.

1.1. The geometry

Therefore the active part of the CM is bent in the horizontal plane, inside an apical angle of 5.0999 mrad with a bending radius of 2812.36m at room temperature. Beyond this arc, the theoretical geometric axis is prolonged along the local tangent to the arc. The shape of the two beam channels is identical. Therefore, the centre of curvature of each aperture should be 194.52 mm apart in assembly conditions. The length of the bent part is 14343mm. The theoretical geometric axes lie in a perfect plane, which will be representing the datum plane of the CM.

It is assumed that the axis of the cold bore tubes represents the geometry of the dipole.

1.2. The tolerances

The global tolerance range denotes the shape tolerance and is defined by a set of two toroidal sectors of circular section and 4 straight cylinders, all centred on the theoretical axes. The radius of the generating circle is 1mm. The tolerances on the two apertures are not independent.

The correctors, both the sextupoles and decapole/octupole combined magnets shall be positioned with respect to the straight ends of the theoretical geometric axis within a localisation tolerance of 0.3 mm.

The end covers are positioned and fixed by welding on the shrinking cylinder extremities such that the vertical axis is localised with respect to the symmetry axes within 0.5 mm, the horizontal axis with respect to the datum plane within 1 mm and perpendicular to the straight ends of the theoretical axis within 0.2 mm.

The cold bore tubes' extremities, shall be aligned to their nominal position within a localisation tolerance of 0.3 mm.

The cold feet pads are positioned at 5400 mm within a tolerance of ±1 mm. They should be at 292 mm distant from the reference plane within a tolerance of ± 0.5 mm and parallel with this plane within 0.5mm. They have to be centred on the symmetry axis within 0.2 mm. [3]

2 MEASURING SYSTEM

2.1 The measuring instrument

The geometry of the approximately 15 m long, 0.5 m diameter and 30 t weight dipole CM is verified by the measurement of the axis of the cold bore tubes. The tight tolerances imposed by the above-mentioned optical and mechanical requirements necessitate the use of a high accuracy 3-D measuring system. The assembling and alignment procedures are such that results of intermediate measurements are guiding the successive operations, implying the use of a portable system. The sole measuring system, which corresponds to all the requirements is a 3-D portable laser tracker, the LTD500[1]. The system is based on the interferometric laser technique and incorporates also a high precision absolute distance meter. The tracking interferometer follows and measures the position of a reflector. Therefor the measurements of the axis of the cold bore tubes necessitate a mechanical mole travelling along the cold bore tube inside, centred with respect to the tube wall and holding the necessary reflector. The accuracy of the measuring system is 10 ppm.

The measurements are guided with and made systematic by a Visual Basic script developed at CERN[2], based on the Axyz[3]. This script permits to use the Axyz

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[1] Made by Leica Geosystem

[2] Script developed in collaboration between LHC/MMS and LHC/IAS

[3] Software developed by Leica Geosystem

software in a limited and semi-automated way. It is adapted for our special application in industry for the series production of the dipole magnets in order to minimise the human errors and to reduce the time of execution.

2.2. The measuring method

In order to determine the reference plane of the CM, with the best possible accuracy, the axes of the cold bore tubes have to be measured. The measurements matrix, built with the 3-D co-ordinates of the centres of the two cold bore tubes, is best fitted with the theoretical geometry in the least square sense, expressed in a similar matrix by a general method of transforming co-ordinates using seven geometrical transformation parameters. In this way, any translation of the origin, rotation of the axes and scale change may be accommodated. The general formulation of this transformation is usually attributed to the German geodesist 'Helmert'. Once the co-ordinates of the theoretical points and those of the measured points are superposed in a common co-ordinates system, the true geometry of the CM can be checked with respect to the theoretical one. The different components are aligned with respect to this common co-ordinate system of the reference plane.

3 RESULTS ON THE MAGNETS

During the assembly of the prototype CMes at CERN in the Build. 181, we gained our experience on the final assembly steps, guided by 3-D measurements. The 6 prototypes, and two magnets of the series contain the collared coils coming from the 3 different contractors. They have been finished with the same measuring equipment, slightly changing measuring and assembling processes and with aligning tools that were designed in parallel with the assembly and based on the accumulated experience. Some of the most important results from the geometrical point of view are summarised in a qualitative way in the Table 1. The qualification of the shape includes the vertical straightness and the horizontal curvature. The Cold Bore Tube (CBT) summarises the positioning of the 4 ends while the Corrector Magnets (CM) gives information on the 2 sextupoles and on the 2 decapoles if there is any. The Interconnection Zone (ICZ) summarises all alignment parameters related somehow to the interconnection zone: end covers, overall lengths and cold feet pads. The qualifications given in the table are obtained summing logically the results of the components of each specified family. Therefore, if there is at least one of the composing parameters out of tolerance the specified family is qualified out of tolerance.

Table 1: Results obtained on the magnets

Magnet	Shape	CBT	CM	ICZ
MBP2N1	o.k.	out	out	out
MBP2N2	o.k.	o.k.	out	o.k.
MBP2O1	o.k.*	o.k.	o.k.	out
MBP2O2	o.k.	o.k.	o.k.	o.k.
MBP2A2	o.k.*	out/o.k.	o.k.	out
O1[4]	o.k.	o.k.	o.k.	o.k.
O2[5]	o.k.*		o.k.	

4 CRITICAL ASPECTS

Following a detailed analysis of the results shown here one can make 3 categories of critical aspects: one regarding the components, one regarding the alignment tools and one the process itself. As the geometry of the dipole is fully determined by the inertia of the CM assembly, the most critical component is the shrinking cylinder. Bad shape half cylinders will cause errors on the shape and on the ends of the CM. These errors can be corrected as far as the shape is concerned but it is not always possible for the ends. However it is important to note that during the assembly of those magnets an effort was made to optimise the production of the shells, which includes also the optimisation of the geometry based on our experience [4].

The second category of critical aspects is related to the positioning tooling which were developed during the last 2 years. There is a significant improvement on the alignment of the corrector magnets as from the MBP2O1 magnet, the first on which a dedicated alignment tool was used. There is an aligning tool for the cold feet pad which can be used as a temporary support and allows the positioning of the feet in normal working position of the CM, reducing the handling of the CM. There is still a need for tooling development, especially for the positioning of the end cover and of the orbital cutting machine.

This category of critical aspects is also related to the third one: the process optimisation. An automatisation of the complete process is needed for the series production, in view of achieving an acceptable repeatability of the operations, of reducing the time of execution and of having a perfect uniformity of the process in the different sites.

REFERENCES

[1] W. Scandale, "From tolerances to alignment", LHC days 2001, Villars, March 2001

[2] J.Ph. Tock, "Cryomagnet interconnect and connection to the cryogenic distribution line", LHC days 2001, Villars, March 2001

[3] Technical Specification for the Supply of 90 Cold Masses of the Superconducting Dipole Magnets for the LHC Collider (Rev. 1.1 of Doc. No. IT2324 LHC-MMS/98-198

[4] F. Savary, "Cold Mass Assembly", LHC days 2001, Villars, March 2001

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[4] HCMBB_A001_01000001

[5] HCMBB_A001_01000002

MQ PROTOTYPES AND START OF SERIES

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In total five quadrupole cold masses have been developed and constructed by CEA-Saclay in the frame of two collaboration agreements during the last 12 years. The two first ones were successfully cold tested at CEA and one of them integrated into the string one.

In the frame of the special contribution of France to the LHC Project, three more quadrupoles and their cold masses of the most recent and definitive design have been built by CEA and tested in Saclay and at CERN. All three magnets performed according to their specification or even better from the point of view of training. The field quality measured, both at warm and cold conditions, is close to the announced requirements. What is encouraging is the fact that the multipoles over the six apertures measured show a high degree of consistency. Only minimal 'tuning' of the coils is presently envisaged for the series. This will be achieved by reducing the thickness of the protection sheets by 0.05 mm. This will not have any significant influence of the coil pre-stress which in the prototypes has been at the upper range.

The focusing and defocusing function of the quadrupoles for the two beams, together with the different combinations of corrector magnets, MO, MQT, MQS, plus the four types of MSCBs must be combined with the variants originating from the different cryogenic function of the SSS cold masses. Respecting the presence or not of the vacuum barrier interface and of the helium flow restriction plugs as well as the different connections to the QRL, one arrives at a total of 40 different cold masses. The fabrication of the cold masse variants will have to follow the sequence of the installation of the short straight sections into the tunnel. Any faulty cold mass would entail the provisional leaving out in the tunnel. A certain buffer storage of SSS units may in some cases allow avoiding this kind of gap.

While initially it was envisaged to entrust two firms with the construction of the 400 MQ magnets and the assembly of their cold masses, the call for tender came out such that only one was finally selected. This is justified by the low price, which was offered compared to second bidder, and by the fact that the follow up in one firm is expected to be simpler and costing less manpower. After difficult negotiations, ACCEL, near Cologne in Germany, was selected and the contract signed in July 2000. Similar to the dipole contracts, but to a lesser extend, a number of components and equipment has to be delivered by CERN. We have there to distinguish between components, which go directly into the cold mass and those which have to go to a sub-contractor, especially for insulation (cable) or fine-blanking (collar and yoke steel sheets). For the first type of components a lead time for delivery before cold-mass assembly of three month is assumed, for the second type of component this assumption counts six month lead time.

Our colleagues of CEA-Saclay will ensure the technical follow up. Two CEA technicians, highly experienced from the construction of the MQ prototypes, will be detached quasi permanently from CEA. Their function will be to provide the technology transfer and to serve as inspectors during the series fabrication. The technicians will be backed up by three engineers of CEA and their drawing office.

ACCEL has rented two factory halls and is presently in the final state of adapting them to the needs of the fabrication. In one of the halls a five metre deep pit has been constructed allowing for the required free height under the crane and thus for the vertical assembly of the standard MQ cold masses. In the frame of an amendment to the contract, a further three metre deep hole has already been made in addition. This in order to keep open the option of entrusting ACCEL with the assembly of the MQ cold masses for the dispersion suppressor regions.

The start of installation of the prototype tooling from CEA is scheduled for the beginning of April. ACCEL has still to order further sets of tooling and to subcontract the fabrication of the components. ACCEL's cold mass fabrication planning is based on CERN's installation planning as it was valid more than a year ago. It has taken ACCEL more time than initially foreseen to renew and adapt the factory halls to the needs of the quadrupoles. However, ACCEL, for the time being, does not announce any delay with respect to their contractual planning. Thus, the delivery of the first two magnets, not assembled into their cold mass, is scheduled to start in mid December 2001. These magnets are to be tested in the new vertical cryostat in block 4 and will be used for the cold masses of the dispersion suppressors. Thereafter the delivery of completed cold masses is envisaged. The sequence of deliveries will follow the forthcoming new installation planning. Contrary to the earlier one, this planning will feature the installation of each arc to start at its middle point, i.e. at Q34, and not at the beginning of the arcs.

PERFORMANCES OF MAIN DIPOLE AND QUADRIPOLE PROTOTYPES AND FIRST PRE-SERIES MAGNETS

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Abstract

The cold tests performed on Main Quadrupole (MQ) and Main Bending (MB) dipole prototypes of the last generation (3rd generation, 15-meters long, 6-block structure) and the first pre-series magnets will be summarised. The main results concerning the cryogenics operations, the field quality and the quench performance will be presented with their interpretation.

1. INTRODUCTION

The experimental program on the 10-m long two-in-one LHC Main Bending (MB) dipoles started on the turn of 1989-1990. Since then seven magnets of the 1st generation and five of the 2nd generation were built in industry and tested at CERN. The design and main test results of these magnets were described in several earlier publications [1], [2]. In summer 1998, CERN has lunched fabrication of six 3rd generation, final design, full-scale dipole prototypes (i.e. 15-meters long with 6-block structure) collared in industry. These collared coils have been subsequently assembled into cryo-dipoles at the CERN Magnet Assembly Facility and tested at the CERN Super-conducting Magnets Test Plant (SMTP). The main test results of the first three dipoles prototypes of the last generation including quench performances, magnet protection, and field quality were already discussed in terms of the design parameters and the aims of the full scale dipole prototypes program [3].

Concerning the Main Quadrupole (MQ) prototypes, the review of the experimental program can be found in the reference [4]. The Short Straight Sections SSS3 and SSS4 were tested at cold at the CERN SMTP, whereas SSS5 was tested at CEA-Saclay. A part of the results of the cold tests of the SSS3 was already published [5].

In this paper, a summary of the results concerning the quench performances and the field quality obtained on MQ and MB prototypes of the 3rd generation and 1st pre-series magnets is presented after a short description of the cold tests performed on these cryo-magnets.

2. TEST PROCEDURES

2.1 Generality

The cold test programs (procedures and aims) for MQ and MB superconducting cryo-magnets are similar. They will be different for the series magnets phase with respect to the prototype one. More precisely, the investigations performed for prototypes are more closely related to an experimental approach than to a tests phase with a priority given to the feedback to magnet builders and designers to improve the design of the MBs and MQs. This phase was also used to define procedures for the final quality control tests (i.e. the series tests at cold condition) and to prepare the tools for data-bases. For the series magnets phase, the approach will be changed and the priority will be given to the characterisation of the performances of cryo-magnets with feedback to magnet builders in case of drifts during the production. During the pre-series magnets phase, the feedback to magnet designers will be carried on at the beginning for the final tuning of the MQ and MB structures. This “smooth” transition period toward the “true” tests phase of series cryo-magnets will also be used to install the automatic supervision of tests at the SMTP [6] and to improve quench diagnosis methods [7].

2.2 Cold tests flow diagram, case of the prototype magnets phase

The summary of the layout of cold tests including the preparation phase is given in Fig.1. After the installation on the test bench, the electrical integrity of the main and auxiliary cryo-magnets is checked prior to connect them to the CFU (Cold Feed Unit). This step includes mainly :

- electrical continuity tests with Direct Current (DC),
- AC-transfer function measurements of the coils (with frequencies for the AC in the range of 1 to 20000 Hz),
- High-Voltage (HV) insulation tests between the different components (coil-ground, heaters-coils and heaters-ground for the MBs and MQs).

The maximum applied voltage for the prototype phase at ambient temperature was 1 kV if the coil was not immersed into He gas before. The electrical and cryogenics circuits of the magnets are then connected to the CFU before to proceed to the leak and pressure tests. When the magnet temperature is 1.9 K, the electrical tests are repeated to check that no degradation occurred during the cool-down. Then a discharge of the magnet current is triggered at 1 kA and a quench is provoked at 6 kA to verify respectively the proper functioning of the energy extraction system and the quench heaters efficiency. The characterisation of the magnetic field quality (harmonics measurements) starts with a so-called virgin load line up to 9 kA. It is followed by the alternation of training quenches and harmonics measurements during load lines to study the training of the cryo-magnets and related effects on the field quality.

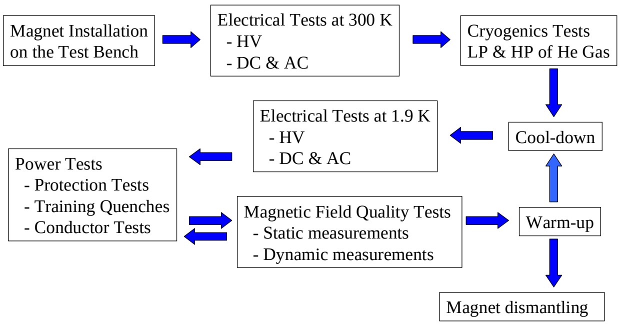

Figure 1: Summary of the cold tests flow diagram of prototype cryo-magnets. LP and HP mean Low Pressure and High Pressure respectively.

The different types of power tests performed after this standard first part are mainly composed of :

- provoked quenches to study the heaters efficiency (heaters delay as a function of the magnetic field B, Miits versus B without energy extraction),
- the study of the ramp rate effect on the quench performance,
- RRR measurements (Residual Resistive Ratio of the copper of superconducting cables),
- measurements of the electrical resistance of the connections,
- loss measurements as a function of the ramp rate,
- natural quenches around 4.3 K to measure the short sample limit of the superconducting cable.

Concerning the field quality study, the program of cold tests mainly focused on :

- the loadline and the magnetic transfer function,
- the integrated field and the magnetic length,
- the field direction and the magnet twist,
- DC and AC magnetisation effects,
- harmonics decay and snap-back, and
- the correlation between measurements performed at room temperature.

Details results concerning all the cold tests mentioned above cannot be presented in this paper. They can be found at the home page of the LHC/MTA group[1].

Two types of thermal cycle were performed during the tests campaigns of prototypes. One with a “slow”cool-down and an other with a “fast”one. The total duration of a fast cool-down to 1.8 K is around 24 hours, with a maximum temperature gradient of 30 K/m coming from the 80 K He gas which is directly injected into the cold mass.

2.3 *Case of the pre-series magnets phase*

For the pre-series cryo-dipoles, the cold tests flow diagram is closely related to the one planned for the series tests and can be found in the reference [8].

3. RESULTS OF TESTS PERFORMED ON SHORT STRAIGHT SECTIONS

3.1 Quench performances

The result of training quenches of all pre-serie MQs namely the SSS3, SSS4 and SSS5 are summarised in the Table 1. Significant lower quench performance was obtained for the SSS5 [9]. For all these MQs the ultimate field was reached without quench after the thermal cycle (satisfactory memory effect).

Table 1: Quench performance

	Number of quenches to reach the	
	Nominal (223T/m)	**Ultimate** (240T/m)
SSS3	1	3
SSS4	0	1
SSS5	1	7

3.2 Field Quality

The results of the field quality measurements of the SSS3 and SSS4 were already reported in references [10] and [11]. The main parameters outside tolerances concerning both these SSSs are :

- the angle of the main field component of the MQs,
- the dodecapole components (i.e. b_6) of the MQs at the injection and at the nominal current in the harmonic decomposition of the field,
- the mutual axis alignments of octupoles and sextupoles correctors with respect to MQs, and
- the mutual field directions of octupoles correctors with respect to MQs.

The mutual field directions of sextupoles correctors with respect to MQs are within specifications.

4. RESULTS OF TESTS PERFORMED ON MAIN DIPOLES

4.1 Quench performances

4.1.1 MB Prototypes

The training curves of the five prototypes of the final generation tested to day are shown in Fig.2. All prototypes passed nominal field but all of them also experienced the detraining effect. This effect is associated to a thermomecanical instability and is found in general, to be more pronounced for cryo-magnets exhibiting a weak training performance (Fig.2).

The summary of the localisation of quench origins are also given in Fig.2. Compared to the 5-block structure of the 2nd generation prototypes, the quench location of the 3rd generation has changed and is now concentrated in the magnet ends. The problem of mechanical stability of coil

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[1] http://mtauser.home.cern.ch/mtauser/

ends is less pronounced in Alstom cryo-dipoles which display a better training performance.

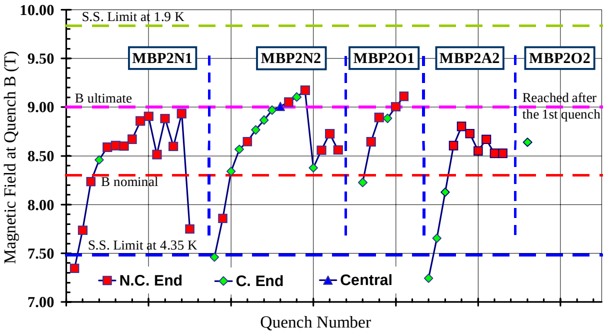

Figure 2 : Training curves of the prototypes of the 3rd generation. N.C. End and C. End mean Non Connection End and Connection End respectively.

Concerning the memory effect, the field value of the first quench after a thermal cycle lies between 87 and 98% of the previous maximum quench value. This effect is found in general, to be more pronounced for cryo-magnets exhibiting the best “virgin” training behaviour.

4.1.2 MB first pre-serie

The training performance of the 1st pre-serie LHC-dipole (HCMBB_A0001-01000001) fulfilled the specification but is lower than the one of MBP2O2 with a single quench at 8.31 T before to reach the ultimate field. After the provoked quenches at the nominal field foreseen in series tests [8], the cryo-dipole suffered from a detraining and three quenches were then needed to re-train the magnet up to the ultimate field. This degradation of the quench performance was probably du to a defect induced during the collaring process [12]. After the “standard” thermal cycle defined for series tests [8], this dipole reached the ultimate field without quench. The same provoqued quenches at the nominal field were performed and no detraining was then observed on this dipole.

4.2 Field Quality

4.2.1 MB Prototypes

The averaged transfer functions containing ends measured on cryo-dipoles coming from each company are given in Fig.3. The difference observed between dipoles has several origins. Around 30% of this difference comes from ends contribution whereas the remaining part can be explained by the use of different components such as the ferromagnetic yoke and the inserts.

The harmonic decompositions of the magnetic field produced at the nominal current by all prototypes are shown in Fig.4. The components outside tolerances which should be mentioned are the normal and the skew quadripole (b_2, a_2), the normal sextupole (b_3) and the normal decapole (b_5) terms.

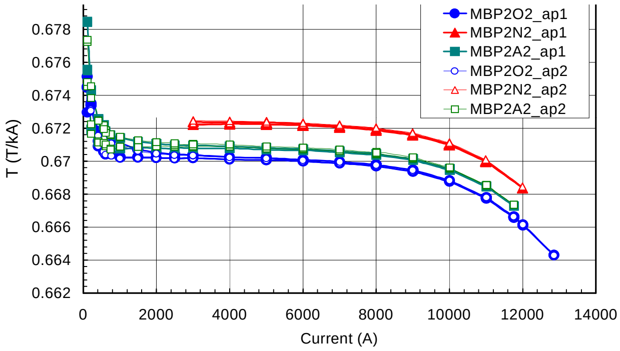

Figure 3 : Averaged transfer function contening ends of dipoles. The magnetic lengths measured are equal to 14.28 m for MBP2O2 and 14.31 m for both other prototypes.

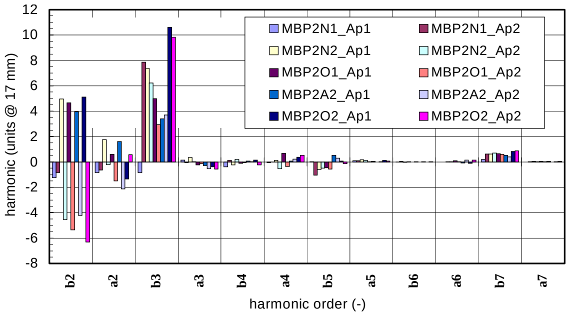

Figure 4 : Harmonic decomposition of the field produced by MB prototypes at the nominal current (ends included).

4.2.2 MB first pre-serie

The harmonic decomposition of the magnetic field still displays too large b_3 and b_5 components at the nominal field. The b_2 component is found to be significantly reduced (maximum for the 2nd aperture around 1 unit at the nominal field) in comparison to prototypes. This improvement of the field quality can be explained by the modifications of the inserts.

4.2.3 Interpretation of the b_3

The expected values from the shims size of the b_3 component were calculated according to the method given in the reference [13]. The results [14] were plotted on Fig.5 as a function of measurements of the geometric b_3. The linear regression is better when the data concerning the prototype MBP2O2 are not considered. In that case, the value of the geometric b_3 obtained with nominal shims is equal to 4.5 units. It can be compared to the corresponding b_3 value of 5.5 units calculated with the Roxie program package [15] and obtained without considering the new inserts, neither the anti-ovalisation nor the deformation processes. If a correction of +0.5 unit is applied to the calculated values of the 1st pre-serie dipole to take into account the new inserts contribution [15], the

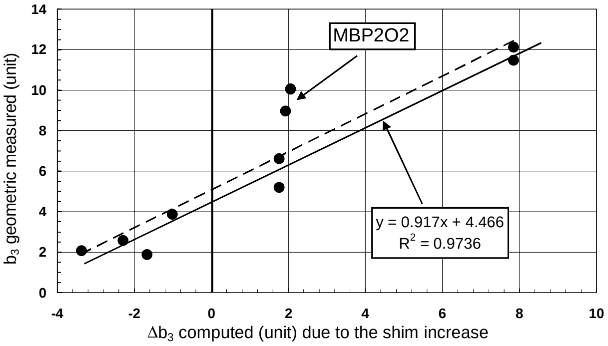

Figure 5 : Geometric b_3 measured in both apertures of the four last prototype and the 1st pre-serie dipoles versus the values calculated from the size of shims. The dotted line corresponds to the linear fit of all data.

slope of the linear regression is found, as expected, being closer to 1 (fit value equal to 0.96).

5. CONCLUSION

No difference in quench performance neither in field quality can be detected on prototypes when a slow or a fast thermal cycle was performed. This investigation will be carried on 1st pre-series cryo-magnets with the standard thermal cycle to study in particular the mutual alignment between the main and the auxiliary coils.

The mechanical stability of the dipole coil ends is the best for Alstom magnets. It is most probably due to a better end-spacers adjustment associated to more compact coils.

The high b_3 values observed for the 1st pre-serie dipole were predictable from the size of the shims but this explanation cannot be used for the case of the last prototype MBP2O2 tested ("3±1 σ effect" where σ represents the standard deviation of the data dispersion around the linear regression) and more investigation are needed.

Concerning b_5, the constraint in the field quality at the nominal field (re)starts to be a delicate problem with the foreseen decapole corrector strength.

From a more general point of view and as it was already mentioned [3], the performance of prototypes and the first pre-serie MB seems to be predominantly affected by the particular assembly process different at each company. In view of the serie production of the LHC main dipoles, a standardised and homogeneous manufacturing processes controlled by strict assembly and quality assurance procedures should be strongly reinforced.

ACKNOWLEDGEMENT

I would like to thank all members of the MTA group for the fruitful continuous collaboration, especially A. Siemko, S. Sanfilippo, N. Smirnov, L. Bottura, for fertile discussions and G. D'Angelo, M. Gateau for their devotion during the tests of the cryo-magnets.

REFERENCES

[1] J. Billan, M. Bóna, L. Bottura, O. Pagano, R. Perin, J.L. Perinet-Marquet, D. Perini, L. Rossi, F. Savary, G. Spigo, A. Siemko, J. Vlogaert, L. Walckiers, "Manufacturing features and performances of long models and first prototype for the LHC project", *LHC-Project-Report-224*.

[2] J. Billan, M. Bóna, L. Bottura, D. Leroy, O. Pagano, R. Perin, D. Perini; F. Savary, A. Siemko, P. Sievers, G. Spigo, J. Vlogaert, L. Walckiers, C. Wyss, L. Rossi, "Test Results on the Long Models and Full Scale Prototype of the Second Generation LHC Arc Dipoles", *IEEE Trans. Appl. Sup.*, 9(2), pp. 1039-1044, 1999.

[3] L. Bottura, P. Pugnat, A. Siemko, J. Vlogaert, and C. Wyss, "Performance of the LHC final design, Full-scale superconducting prototypes ", *LHC-Project-Report 452*.

[4] T. Tortschanoff, "MQ Prototypes and Start of Series", *This Proceeding*.

[5] T. Tortschanoff, J. Billan, L. Bottura, V. Remondino, A. Siemko, M. Peyrot, J. M. Rifflet, F. Simon, "Performance of serie-design prototype main quadrupoles for the LHC ", *LHC-Project-Report 428*.

[6] A. Raimondo and H. Reymond, "The Test Master, Functional specifications", *LHC/IAS Internal Note IAS-LS-00-003*.

[7] P. Pugnat, B. Khomenko, A. Rijllart, S. Sanfilippo, and A. Siemko, "Statistical diagnosis method of conductor motions in superconducting magnets to predict their quench performance", *LHC-Project-Report 455*.

[8] A. Siemko, *This Proceeding*.

[9] F. Simon, *Private communication*.

[10] N. Smirnov, Z. Ang, L. Bottura, P. Schnizer, "Magnetic measurements of SSS3 in cold condition ", *LHC/MTA Internal Note 2000-138*.

[11] N. Smirnov, S. Amet, L. Bottura, P. Schnizer, "Magnetic measurements of SSS4 in cold condition ", *LHC/MTA Internal Note 2001-153*.

[12] G. Spigo, *Private communication*.

[13] Z. Ang, L. Bottura, S. Russenschuck, A. Siemko, D. Tommasini, L. Walckiers, "Coil Size and Geometric Field Quality in Short Model Dipoles for LHC" *LHC-Project-Report 359*.

[14] S. Sanfilippo, *Private communication*.

[15] S. Russenschuck, *This Proceeding*.

MAGNETIC TARGETS

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This subject will make the object of an extensive Project Report entitled:

Field Quality Specification for the LHC Main Dipole Magnets
by Stéphane Fartoukh and Oliver Brüning

to be issued soon.

Evolution of the Dipole Design since the ”Yellow Book” Version

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Abstract

The design of the main dipole for the LHC has undergone a considerable evolution since the version proposed in the “Yellow book” (1995), i.e., a change from a coil with 5 blocks to a 6 block coil-layout, a change of the collar shape and material, and subsequent engineering changes to facilitate assembly, among others. This results in a nominal b_3 field component of about 6 units (in 10^{-4} at 17 mm reference radius) for the pre-series magnets. The paper explains the evolution of the design and gives the latest estimates for the field errors of the collared coil as well as the cold mass assembly.

1 THE “YELLOW BOOK” DESIGN (1995)

The Yellow Book design, as shown in fig. 1, featured a 5-block coil design, a beam separation distance of 194 mm and combined collars with a ferro-magnetic insert (MBP1). The 5-block coil was, however, originally designed for a magnet with separated collars and a beam separation distance of 180 mm. The advantage of the 5-block coil is that it provides the highest possible average quench margin (of both inner and outer layer). The results for the lower order multipole field components (as a function of the excitation) is given in fig. 2. All the calculations were recently repeated using the CERN field computation program ROXIE and the BEM-FEM coupling method. The finite element meshes were generated with the automatic, quadrilateral mesh generator that was implemented in the year 2000 [1].

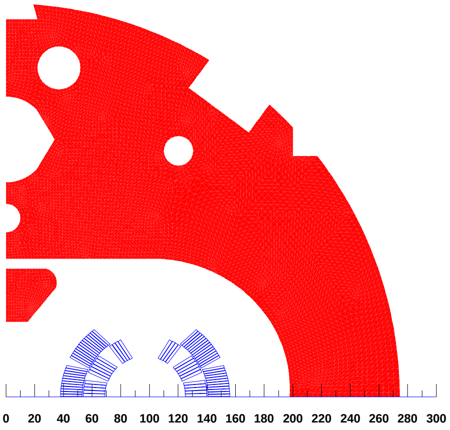

Figure 1: “Yellow book” design (1995) with 5-block coil, 194 mm beam separation distance and combined collars with ferro-magnetic insert (MBP1).

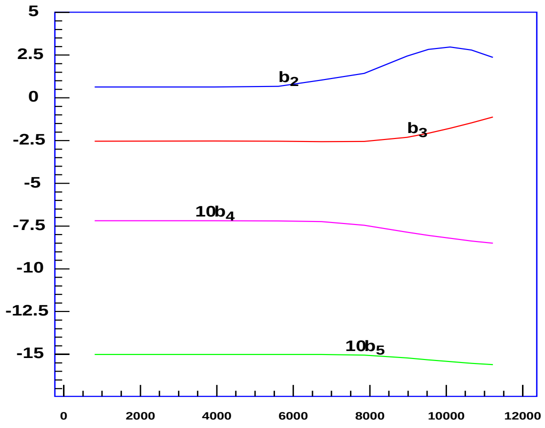

Figure 2: Lower order (relative) multipole field components (as a function of the excitation) for the “Yellow book” dipole design. Units in 10^{-4} at 17 mm reference radius.

2 THE “V6-1” COIL (1997-1998)

Changes to the 5 block coil were carried out in 1996 that made the coil very inflexible to (even small) adjustments. The changes were motivated mainly by a request from SL-AP for part-compensation of persistent currents (reduction of b_3 at injection from - 4.8 to - 4.0 units (at 10 mm) which is equivalent to a b_3 of 2.3 units at 17 mm). Additionally, the thickness of the ground plane insulation and the conductor insulation, adjustments at the cable’s narrow edge, and the ferro-magnetic insert in the combined collars had made the 5-block coil very inflexible [2]. However, flexibility is needed to compensate the lower order (odd) field harmonics due to deformations during manufacturing and cool-down. Additional objectives which were taken into account for the coil re-optimization included a lower b_{11} field component, an increase in quench margin (inner layer coil), better mechanical support (conductors placed as radially as possible) and lower sensitivity to manufacturing tolerances. The coil design was found using genetic optimization algorithms and a subsequent (detailed) study of 3 different design options [3]. This led to the so-called V6-1 coil design (6 block coil with 40 turns; one turn less than in the 5 block coil version). The V6-1 coil remained unchanged since autumn of 1998 and a final adjustment was foreseen, once sufficient data from the prototype phase would have been gained. Fig 3. shows the variation of the lower order field harmonics as a function of the excitation between injection and nominal field level for the V6-1 coil in the MBP1 iron yoke.

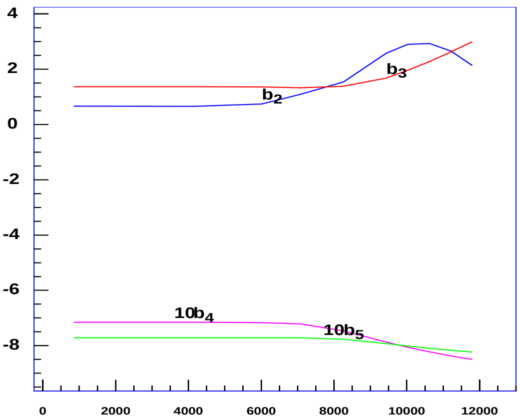

Figure 3: Lower order multipole field components (as a function of the excitation) for the V6-1 coil in the MBP1 iron yoke. Units in 10^{-4} at 17 mm reference radius.

3 THE MBP2 YOKE DESIGN (1999)

The re-design of the iron yoke was triggered by mechanical considerations, i.e., manufacturing problems with the ferro-magnetic insert. Additional objectives were a lower variation of the b_2 and b_3 field components versus excitation and a reduction of the b_4 component at injection field level [4]. Fig. 4 and fig. 5 show the geometry and the variation of the lower order field harmonics, respectively.

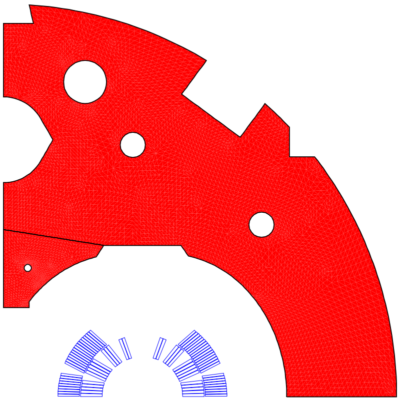

Figure 4: V6-1 coil in the MBP2 iron yoke.

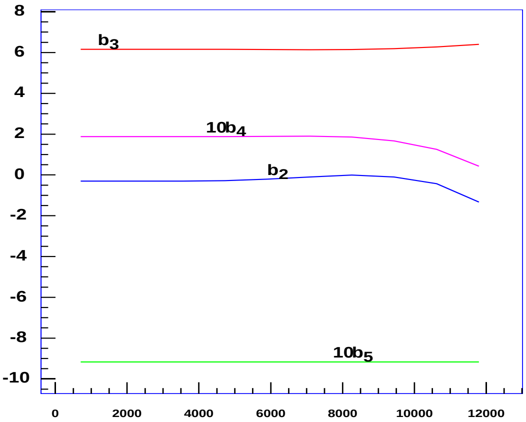

Figure 5: Lower order multipole field components for the V6-1 coil in the MBP2 iron yoke. Units in 10^{-4} at 17 mm reference radius.

4 THE PRE-SERIES MAGNETS

The MBP2 yoke design had subsequently undergone engineering changes in order to improve tooling and manufacturing and to enhance the rigidity of the structure. A re-optimization of the shape of the iron yoke or the coil block configuration was not performed. Changes include an increased “nose” in the insert, cut-offs for the compensation of b_2 and b_4 drifts due to this nose, and the change of collar material to stainless-steel with a relative permeablity of 1.0022. As the design of the magnets is now frozen and the computational tool allows the modelling of very fine details, a refined numerical ROXIE model was created that takes into account the modified shape of the iron yoke and the stainless steel collars. Fig. 6 shows the geometry and fig. 7 shows the variation of the lower order multipole components for this design. Table 1 gives the field errors at injection and at nominal field level for the pre-series magnets (cold-mass).

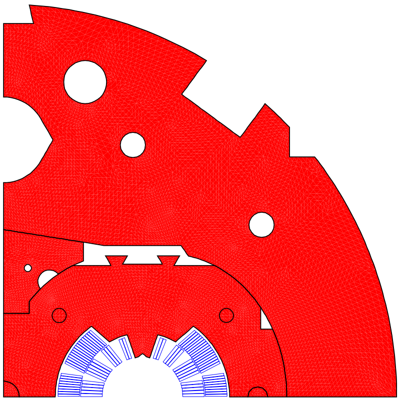

Figure 6: ROXIE model of the pre-series magnets with modified insert geometry and stainless steel collar.

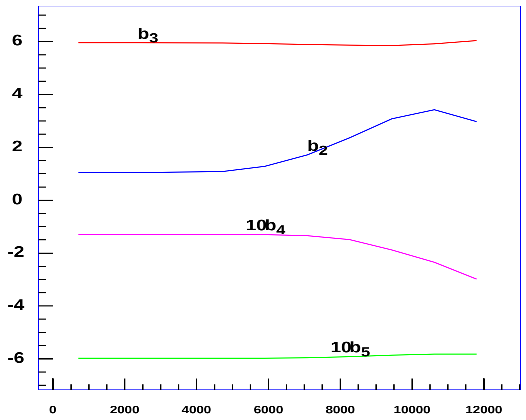

Figure 7: Variation of the lower order multipole field components in the pre-series magnets. Units in 10^{-4} at 17 mm reference radius.

Order	Injection	Nominal	Max. variation
2	1.04	2.97	2.37
3	5.95	6.03	0.18
4	-0.13	-0.30	0.16
5	-0.59	-0.58	0.01
6	0.01	0.00	0.00
7	0.57	0.58	0.00
8	0.00	0.00	0.00
9	0.10	0.10	0.00
10	0.00	0.00	0.00
11	0.62	0.63	0.00

Table 1: Geometrical field errors at injection and nominal field level for the pre-series magnets.

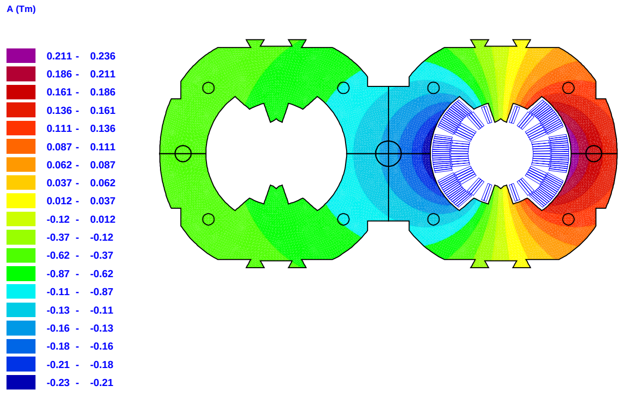

Figure 8: Geometrical model and vector-potential for the collared coil (one coil powered).

Order	Units in 10^{-4}
2	-0.239
3	2.742
4	-0.012
5	-0.733
6	0.000
7	0.687
8	0.000
9	0.119
10	0.000
11	0.735

Table 2: Expected field errors for the warm field measurements of the collared coils.

5 FIELD ESTIMATES FOR THE COLLARED COILS

At the manufacturer(s), warm field quality measurements of the collared coils will be performed. With the permeability of the stainless steel collars and the powering of only one coil at a time, an asymmetric magnetic field is observed. Collared coils also differ in the b_3 and b_5 values as compared to the cold mass. Fig. 8 shows the vector-potential in the collars when only one coil is powered. Table 2 gives the estimate of the field harmonics measured for the collared coils (considering nominal coil size and shims, while neglecting any deformations due to the collaring process, anti-ovalization of the collars etc.).

6 CONCLUSION

The nominal b_3 and b_5 field errors in the pre-series dipole magnets amount to about 6 units and -0.6 units, respectively. This is not within the requirements for the machine operation, but results from changes in the collar and yoke geometry. These changes were implemented after the re-optimization of the coil that remained unchanged since autumn of 1998. A final adjustment of the coil layout will have to be made when sufficient data on manufacturing tolerances and the coil deformations (due to the collar shape, the collaring procedure and cool-down) are available.

7 REFERENCES

[1] Aleksa, M., Russenschuck, S., Völlinger, C. : Parametric Quadrilateral Meshes for the Design and Optimization of Superconducting Magnets, LHC-Project-Report-448.

[2] Russenschuck, S.: A modified dipole cross-section for the compensation of persistent current effect, Private Communication, July 23, 1996

[3] Working Group on Field Components and Machine Performance: Summary of the meeting held on the 28 May 1997.

[4] MB working group: Minutes of the meeting N. 14, 2.09.97.

FIELD QUALITY CONTROL IN THE LHC DIPOLES

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Abstract

We analyse the present state of field quality in the dipole prototypes and in the first pre-series magnets. Limits to field quality control are estimated and compared to the values tolerable for beam dynamics. Corrective strategies to optimise the nominal cross-section field-shape and to control it during the production are analysed.

1 INTRODUCTION

Field-shape imperfections are expressed using the standard multipolar expansion of the magnetic field

$$B_y + iB_x = B_0 \sum_n (b_n + i a_n) \frac{(x+iy)^{n-1}}{R_{ref}^{n-1}} . \qquad (1)$$

The odd normal terms b_3, b_5, ... are due the four-fold symmetry of the dipole coil cross-section, plus the influence of the iron yoke. Even normal multipoles b_2, b_4, ... are driven by the insert and by the yoke contribution. Other asymmetries gives rise to skew components a_2, a_3, a_4, ...

We assume that eight different production lines are characterised by the same sigma (random part), and by different averages. The sigma of these averages is the uncertainty, and the average of the averages is the systematic part.

Magnetic measurements are carried out in the industry, at room temperature, at the level of the collared coil and of the assembled cold mass. At CERN final assessment of field quality is given by measurements at 1.9 K.

Field quality control is carried out in the industry, to have an early detection of drifts or specific problems of a given magnet. Moreover, one has to analyse and follow the chain of correlations from the measurements of the collared coil to tests at cryogenic temperature and at different fields.

Corrective actions are taken to act on normal multipoles with two main aims: reduce the uncertainty as much as possible (i.e., have the same averages in all producers) to have less constraints for the installation, and steer the systematics as close as possible to the optimal values.

2 FIELD QUALITY CONTROL LIMITS

The main limit to a control of field-shape comes from the reproducibility of multipoles from magnet to magnet; this limits our capability of precisely steering the average. The main sources of this variability are the geometric tolerances, that even if they are tighter than 0.1 mm, they give rise to relevant random components. Then, one has variability in the persistent current contribution, reproducibility of end effects, of warm-to-cold correlations, and of iron saturation. We restrict the analysis to the geometric part at warm, that dominates over the persistent.

The second limit to field quality control comes from discrepancies between the model used to determine corrective actions and the behaviour of the real magnet. Therefore, models provide a quantitative estimate of the available handles, but dedicated experiments are used to test the correction strategies. Two dedicated experiments have been carried out: changes of the insert to minimise even multipoles [1, 2], and effect of shim thickness variations on odd multipoles [3].

Measurements were post-processed to evaluate the standard deviation. Preliminary results relative to the prototypes and to the first pre-series magnet are given in Tab. 1, first column. These estimates are in agreement with the expected random component [4] (second column). In the third column we show the 'wish list' for the systematic components with the allowed window [5]. The b_5 control is very critical, since the average must fit within 1/3 of the standard deviation; this will probably require some feedback during production. On the other hand, the situation for b_3 and b_4 is less critical, since the average must be kept within two sigma.

	Sigma measured	Sigma expected	Preliminary bound on systematics (geom.)
b_2	0.55	0.68	
b_3	1.5	1.5	$-3.0 < \bar{b}_3 < 3.0$
b_4	0.15	0.49	$-0.4 < \bar{b}_4 < 0.4$
b_5	0.45	0.42	$-0.5 < \bar{b}_5 < -0.2$
b_7	0.07	0.22	$-0.4 < \bar{b}_7 < 0.4$

3 SITUATION FOR ODD MULTIPOLES

In Fig. 1 we show the data relative to the magnetic measurements of the collared coil at room temperature, average along the straight part, for b_3 in the P2 prototypes and in the first four pre-series magnets. In the lower part of Figure 1 we post-process the measurements to substract the contribution due to non-nominal shims that have been used [6], and have a strong impact on field quality. The strong variability observed in experimental data is reduced when the contribution of the non-nominal shims is taken out. The same happens for b_5 (see Fig. 2). The dotted line shows a preliminary estimate of the optimal values for b_3 and b_5, and the solid lines give the allowed window for the average. One observes that for a magnet with nominal components one has an offset in b_3 of around +2 units, and of 0.7 to 1.0 units of b_5.

These offsets are due to a coil cross-section aiming at a partial compensation of persistent currents with geometry, which is no more needed [5], to a sequence of changes in the dipole geometry and components (collar material, collar shape, iron yoke shape, insert shape) [see [7] for a review], and to the effect of coil deformations.

Whilst for the b_3 the situation could be tolerable, the average b_5 is out of tolerance (see Table I).

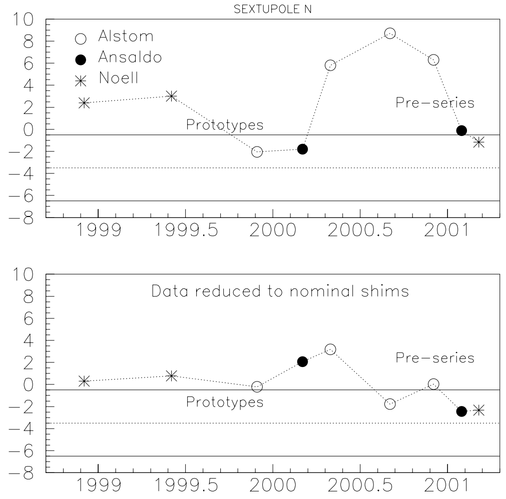

Figure 1: b_3 measured in prototypes and pre-series magnets

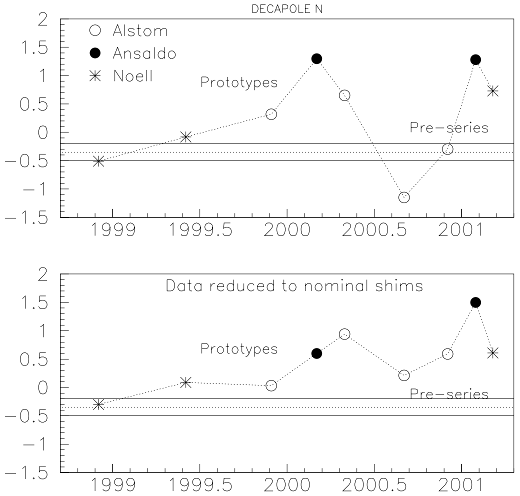

Figure 2: b_5 measured in prototypes and pre-series magnets

4 CORRECTIVE ACTIONS

Change of the shim thickness can provide a handle to vary b_3 and b_5. One has two degrees of freedom: the internal shim, mainly acting on b_3 and b_5, and the external one (b_3 only). The prestress constraint within a window of ± 15 MPa gives an allowed shim thickness variation of ± 0.12 mm of shim [3]. This allows variations of ± 4 units of b_3, ± 0.35 units of b_5 as computed in simulations and measured in dedicated experiments [3].

Mid-plane shims could be inserted to have more freedom to act on odd multipoles. Since they are not foreseen in nominal design, a feasibility analysis and impact on production should be re-evaluated. They would provide two degrees of freedom, with a stronger impact on b_3 and on b_5 [8]. Since they could provide a useful additional handle for fine tuning, we propose to test them on a short model.

Wider multipole changes can be obtained by a modification of the position of two conductor blocks in the inner layer, keeping the same coil shape. This would avoid modifications of the coil tooling, minimising the changes to the copper wedges and to the end spacers [9].

A high value of b_2 (around 4-5 units) was discovered in the first two prototypes, due to a mismatch between magnetic and mechanical design. Three insert modifications to act on b_2 and b_4, compatibles with mechanical constraints, were installed in the second Ansaldo prototype. One finds a good agreement between experimental measurements and simulations made with the BEM-FEM module of Roxie [2]. A final insert configuration has been chosen to minimise both b_2 and b_4; its impact on odd multipoles is negligible. Insert modifications could be used to control the average of b_4 within ± 0.1 units during the production.

5 CONCLUSIONS

Corrective actions to start the production centred on the right values have been already taken for the even multipoles. A large b_2 was corrected by changing the insert, together with a further optimisation of b_4. We propose to correct the mismatch in b_3 and b_5 by changing the copper wedges; data relative to a few more magnets would be welcome to have a better estimate of the present situation, especially for the b_5, and to analyse warm-to-cold correlations, end effects, and iron saturation in magnets with the final design and components.

During the production, a fine tuning of b_4 can be provided by changes of the insert shape. Tuning of b_3 and b_5 can be realized by small variations of the shim thickness. Mid-plane shims would add a very useful additional knob to have a wider possibility of acting on these multipoles.

The use of shim thicknesses different from the nominal ones of up to 0.1-0.2 mm induces very strong variations of field quality. This is presently done to match the right prestress, since the azimuthal coil length is not within tolerances [6]. The control of the systematic b_5 within present specifications will probably require additional feedback actions during the production.

6 REFERENCES

[1] F. Savary, "Cold Mass Assembly", this Workshop.

[2] P. Ferracin et al., LHC Project Report 467.

[3] D. Tommasini et al., in preparation.

[4] L. Walckiers, 9901 table, Field Quality Working Group.

[5] O. Bruning, these proceedings.

[6] D. Perini, these proceedings.

[7] S. Russenschuck, these proceedings.

[8] L. Bottura, private communication.

[9] P. Fessia, these proceedings.

USING THE CONTROL KNOBS:
IMPACT ON THE INDUSTRIAL PRODUCTION OF THE LHC MAIN DIPOLES

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Abstract

The possible actions that can be implemented in order to steer the field quality of the LHC Main Dipoles are examined. The aim is to provide a first evaluation of the impact in term of costs and time. The selection and the efficacy of each of the knobs on the field quality are not the object of this document [1].

Acronyms:

CMA: Cold Mass Assembler
CWM: Copper wedge manufacturer
ESM: End Spacer Manufacturer
RT: Reaction Time as the interval of time between the moment when a modification is decided and when the first cold mass (collared coil) including that modification is completed

1 THE USABLE KNOBS

The identified knobs are the following:

1. Actions on the shim thickness
2. Modifications of the copper wedge geometry
3. Modifications of the magnetic insert geometry

1.1 The shims

The shims are used to pre-compress the coils inside the collars in order to guarantee their mechanical stability during the different phases of the energization. They are computed from the measured values of dimensions and Young modulus of the coils and they are dimensioned in order to achieve a predefined pre-stress. After the taking off phase, during the series production, the dimensions of the coils should be very well controlled and therefore large batches of shims could prepared in advance respect to the use.

1.2 The copper wedges

The copper wedges are very precise profiles, which allow achieving the desired cable distribution in the cross section. They are made of copper that is extruded through ad hoc designed die-plates and the tight dimensional tolerances are achieved thanks to the last rolling stage. In order to minimise the impact of the changes it is assumed that the necessary tuning of the field quality is achieved thanks to modifications that keep constant the azimuth length of the 1st and 2nd layer coils. This means that no modifications are necessary on the components surrounding the coils. The production of the copper wedges is managed in batches.

Drawings n. LHCMB__A0052, LHCMB__A0054, LHCMB__A0056, LHCMB__A0058

1.3 The magnetic insert

The magnetic insert is made of the same iron of the laminations and it completes the magnetic circuit. It is fine blanked, procedure that allows keeping tight tolerances.

Drawing n. LHCMB__A0148

2 THE COST AND IMPACT OF ACTING ON THE KNOBS

2.1 The shim thickness

In order to modify the filed quality it is possible to change the thickness of the shim according to the results of the previously measured collared coils and basing the modification on sensitivity matrixes and on models.

The magnetic measurements, performed on the collared coils, have to be sent to CERN where it is decided if it is necessary to act and which is the modification that has to be applied.

In order to determine the RT the following stages and issues have to be considered:

1. Number of collared coils that have to be measured before taking a decision. This depends on the statistical significance of the sample and also from the magnitude of the correction that has to be applied. This amount of cold masses will be not taken in account in the forecasts about the efficiency of the cycle.
2. Time necessary to process the results of the measurements and to determine the modification to be applied. The duration of this phase is determined by the automation degree of the process. If the whole process relies on the human intervention the time necessary to complete the operation can be some days. If instead it is possible to achieve a high degree of automation this time can be reduced to one day or even less. This objective can be reached leveraging on the experiences in the LHC division in fast and efficient treatment of the measurement data. The advantages from a point of view of efficiency and cost savings are evident.

3. Time necessary to implement the modification at the CMA. This time will depend on the extent of the applied modification and to reduce it would be possible to ask to the CMA to keep in stock some shims smaller of the previously used ones of 0.1-0.2 mm and a series of shims of 0.05 mm. In this way it would be possible to compose a modular shim for a first, quick reaction to the requests of CERN.

In conclusion considering:

- Information transmission from the CMA to CERN and vice versa: 0.25 day
- Treating of the information at CERN: 0.5 day
- Reaction time at the CMA:0.25 day

The RT 1 working day. This would mean 1-2 collared coils produced in the old configuration (CMA producing 1 cold mass per day). One extra collared coil is considered because, probably, when the information will arrive to the CMA, one collared coil will be already ready to go under the press.

If the process is not automated, but it relies fully on the human intervention, probably the RT will be increased up to 2.5 days with a consequent number of collared coils produced according to the old specification around 3 or 4. From the cost point of view the material cost is negligible.

2.2 *The copper wedge geometry*

Modifications of the copper wedge geometry, keeping the total length of the coils constant, can be applied. Two main components, involved in the collared coils assembly, are affected: the copper wedges and the end spacers.

The phases to implement the modification are the following considering that the new geometry of the copper wedge has been finalised:

Copper wedges

1. CERN drawings: 5 days
2. The CWM's drawing are available, approved at CERN and sent back to the CWM: 10 days
1. New tooling: 30 days
3. Production: 20 days
4. Acceptance and expedition to the CMA 5 days

Total 70 days

End spacer:

1. CERN design and computation: 5 days
2. CAM processing at the ESM 5 days
3. New tooling: 5 days
4. Production: 40 days
5. Expedition to CERN, acceptance of the batch, delivery to the CMA: 11 days

Total 66 days

It is important to remember that the end spacer will be responsibility of the CMA during the series production. It is possible to estimate RT around 75-80 days (70 days + time necessary to prepare the new winding programs and perform some tests with the new geometry at the CMAs). This time interval is equivalent to a production of 70 collared coils plus the coils for other 10 magnets if the CMA is producing 1 cold mass per day.

Costs for the change of the 1st layer:

- Copper wedge modification 8000 CHF/profile
- End spacer modification: 15000 CHF for layer
- Chips and wedge tips 40000 CHF 1st layer
- Machined chips to start production before having the injected pieces 20000 CHF
- Winding software update: 30000 CHF

Total 1st layer change: 130000 CHF

It is important to remark that, in order to speed up the process, it is considered that the ESM will start working without paper drawing, but on the basis of CAD 3D files. The same procedure cannot be applied for the copper wedges.

2.3 *The magnetic insert geometry*

The geometry of the magnetic insert can be modified without impact on other components of the magnet and being completely transparent for the CMAs. On the other hand the mechanical functionality of the insert have to be respected. The phases, to implement the changes, are the following:

1. CERN drawing 5-10 days
2. Approval manufacturer drawing 5 days
3. New tooling 10 days
4. Production 10 days
5. Acceptance and final expedition to the CMA 8-14 days.

RT 38-48 days

This elapse of time is equivalent to 40-45 cold masses. It has to be taken in account that, due to the technology used (fine blanking), due to the tight tolerances and due to the tooling conception (coupling between the lamination and the insert) it is possible that modification on the insert could perturb the precision achieved on the insert itself and on the lamination. In this case the time necessary to have the new components would increase a lot. The cost could be estimated between 30000 CHF and 50000 CHF.

CONCLUSION

Due to the RT time and the production constraints it looks like the only action that can be implemented on more or less regular basis during the production is the modification of the shim. The modification of all the cross section (changing the coils length and therefore affecting the collars) has not been taken in consideration due to the large time needed to implement it.

REFERENCES

[1] Ezio Todesco et al., "Field quality control in the LHC dipoles", EPAC'96 and this Workshop.

THE MB MARKET

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Abstract

This contribution covers the content of the presentation given during the Villars LHC Days 2001, in Session 2 "Main magnets tomorrow" about "The Main Bending market". The presentation was covering the following subjects:

1. ***The LHC Dipole Technical Specification**:*
   - *1.1 History of "Pre-series" revisions (Rev.1.0&1.1)*
   - *1.2 The next step: The "Series" revision (Rev.2.0)*
2. ***Cold Mass and Component delivery Scenario:***
   - *2.1 Cold mass delivery model and constraints*
   - *2.2 Components delivery status and constraints.*

1. THE LHC DIPOLE TECHNICAL SPECIFICATION:

1.1 History of "Pre-series" Technical Specifications revision (Rev.1.0 & 1.1)

Listed here below are the main milestones regarding the Technical Specification (T.S.) for the "pre-series" contracts of the LHC Dipole cold masses:

- *December 1998*: The Technical Specification for 468 LHC Dipole cold masses (3 octants + 6 spares c.m.) was released as the LHC Doc. No: LHC-MMS/98-198 Rev. 1.0.
- *November 1999*: Assignment of three contracts for 30 c.m. each. This production of 90 LHC Dipole cold mass was then called "The Pre-Series",
- *November 1999*: Release of the "Pre-series" Technical Specification (Rev. 1.1 of the previous mentioned LHC Doc.). The Rev. 1.1. was:
  - Coherent with the new Scope of the Supply
  - Coherent with the technical and contractual agreements taken with the Contractors (e.g. supplied components, assembly activities at CERN, Acceptance Criteria for the first 10 produced c.m).
  - Coherent with c.m. design changes occurring in the elapsed year between the two releases:

Comparing to the Rev.1.0, the Rev.1.1 we can find the following differences (not exhaustive list):

1. The coil protection sheet thickness was increased from 0.3 to 0.5 mm. The dimension of the collar's internal cavity was changed consequently in order to leave unchanged the coil dimensions (and consequently the coil production tooling).

2. The Instrumentation of the c.m. was changed as following:
   - suppression of the flux loop around the cold bore tube
   - reduction of the total number of voltage taps from 54 to 24
   - 2 new current taps for the diode
   - cryogenic heater to be mounted inside the connection side (C.S.) end cover
   - quench heaters to be bridged at the N.C.S.

3. The STT method was selected for the first pass of the longitudinal welding.

4. The welding of the six "N-line" supports was added.

5. Several CERN delivered components were modified:
   - shrinking half-cylinders delivered already bevelled.
   - collars, yoke lamination, polyimide, etc. tolerances were revised.
   - bi-metallic (non-magnetic/magnetic nested laminations) to lower the magnetic field at the coil ends and to close the stray magnetic field at the extremities.
   - appearance of the Octupole/decapole in the Spool pieces family.

6. The delivery of two new "CERN delivered tools" was decided:
   - a small press for the end measurements
   - a small press for the electrical check under pressure of coil layers and poles (later abandoned because shown to be unnecessary).

Many other aspects (new definition of cold mass "type A" and "B", tests procedures, target values for pre-stress after collaring, clarification on Acceptance Criteria, etc.) were updated.

The optimisation activity on the cold mass design was pursued throughout the year 2000 with the following "major change" on the general configuration of the cold mass "as delivered" (change following the conclusions of a series of working meetings called "Series Magnet Tests SM18"):

In order to facilitate the cold test activity at CERN the cold mass configuration was changed from the so-called "Tunnel" configuration to the "Cold tests bench" configuration. (This change was announced to the c.m. Manufacturers but not yet officially transmitted due to the large number of drawings to be revised and created, and procedures yet to be prepared).

The "actual status" (March 2001) for the "pre-series" T.S. (and drawings) is, in conclusion, the following:

- Main text of the Tech. Specs. fully updated.
- Assembling Procedures, Test Procedures, Components, tooling descriptions, etc. Fully updated up to the "He-vessel limit" (welded cylinder and end covers).
- The manufacturing drawings were officially released to the Contractors up to the "He-vessel limit".
- The last set of drawings (concerning the c.m. extremities in the new "Cold tests bench" configuration) and the respective assembling procedures are under finalisation and are expected to be available at the beginning of April 2001 for the official release to the Contractors.

NOTE: for practical reasons of the CDD approval procedure, this last set of drawings will be released under the title of "Magnet Bending: Manufacturing SERIES…" (even if they will be the completion of the PRE-SERIES set of manufacturing drawings.)

1.2 The next chapter: The "Series" T. S. revision (Rev.2.0)

The decision to go out for the 2nd Call for Tender (for "8 Octants plus spares" less the 90 Pre-series cold masses) in Spring 2001 was taken by CERN. In consequence, a new revision (Rev. 2.0) for the LHC Dipole cold mass T.S. is under preparation. (The revision is of course based on the most "actual" design of the cold mass).

Compared to the "pre-series" Rev.1.1 the major "Changes & Addition" will be (non-exhaustive list):

a) Implementation in the T.S. of the changes relative to the "Cold tests bench" configuration (not yet implemented in. the "pre-series" revision).

This change has the following major consequences as changes in the external aspects of the delivered c.m:

1. Presence at the C.S. of a hydraulic and electric loop connecting the flanges M1, M2 with the "line N" (that will be utilised as part of the cooling circuit during the cold tests). (The hydraulic loop of M1-M2-Line N, such as the other welded cups at the C.S. could be recuperated and re-used a certain number of times, so acting as "pieces navette").
2. All the flanges at the C.S. (the c.m. side not connected to the CFU during the cold tests) will be of welded type.
3. Presence of the Instrumentation Feedthrough System (IFS or "Capillary").
4. Short circuits in order to test the Spool Pieces as following: Sextupole and Decapoles through one pair of bus bars (circuit 1) and Octupoles through another pair of bus bars (circuit 2).

b) Two different types of c.m. configurations are foreseen:

- "STANDARD Test Configuration": (No "Cold Test" at CERN of auxiliary busbars and corrector magnets).
- "FULL Test Configuration": ("Cold Test" at CERN of ALL the auxiliary busbars and correctors magnets. Configuration foreseen for max. 10% of the production).

c) Installation of the protection diode at the Manufacturers premises.

d) Implementation of the Quadrupole Connected Dipole (QCD) geo-magnetic measurements at the Manufacturers premises (new current taps + procedures).

NOTE: the changes mentioned in points a), b), c) & d) have an important impact in several assembling and testing (e.g. electrical) procedures that will be consequently updated.

e) A "cold mass flushing procedure" will be added as a type-test.

f) The policy of the "CERN delivered components" for the cold mass will be revised as following:

1. CERN will be no longer responsible for the direct supply of some components like:
   - End Spacers
   - Coil Inter-layers
   - Auxiliary pieces for the layer-jump region (glass fiber wedges, Ultem™ boxes, etc.)
     NOTE: The Technical Specification of these components and the list of qualified supplier or (where necessary) the component's "Mandatory Supplier" name will be included and indicated into the Spec or in the Tender documents.
     The c.m. Manufacturers will deal directly with the procurement of these components
     .
2. CERN will also supply:
   the cold bore tubes already insulated (new design).
   - The protection diode
   - The tube for the "N line"

g) The policy for the "Acceptance Criteria" is under evaluation. The actual proposal seems to move along the following lines:

- "Hard" acceptance criteria for:

1. Electrical Integrity.
2. Leak tightness and pressure tests.
3. Geometry.
4. Field quality (by tables with multipoles limit).
5. Capability in reaching the Ultimate Field (U.F.).

- “Bonus-Malus” acceptance criteria for the Quench Performance. Numbers and acceptance procedures are under discussion but let’s look at an example:

- c.m. reaching the U.F. in 2 quenches: “Bonus” (could be in “real money” distributed at the “workshop level”)
- c.m. reaching the U.F. in 3-5 quenches: “Standard” (no actions)
- c.m. reaching the U.F. in 5-7 quenches: “Malus” (penalty proportional to the “extra cold tests” costs at CERN).

NOTE 1: The final definition & confirmation of the “Bonus-Malus” parameters must take into in account the results of the first 30 (probably the best 20 of the 30) preseries c.m. (This will also guide the acceptance criteria for the remaining pre-series c.m. N. 30 to 90.

NOTE 2: this proposed Acceptance Scenario was informally announced to the three Suppliers who have reacted positively.

1.2.1 Structure of the Technical Specification

Similarly to the previous releases, the T.S. will be structured as following:

1. MAIN TEXT: Covering the subjects as presented in the Official LHC Technical Specification template.

2. ANNEXES: (The “real technical core” of the T.S.) structured as following:

Annex A:	Drawings	[~535]
Annex B:	Assembly Procedures	[36]
Annex C:	CERN Delivered Components	[18]
Annex D:	QA Procedures and Doc.	
Annex E:	CERN Supplied Main Toolings	
Annex F:	General Doc. (Performances & Results Obtained for Prototypes And Preseries)	
Annex G:	Reference Technical Specification For Components (Provided By CERN Or under Responsibility Of The Contractors)	

Drawings status:

The total set of drawings delivered with the Tech. Specs. will consist of ~ 535 drawings subdivided in the following “big” families:

1. Active Part:	193 draws.
2. He vessel:	186 draws.
3. Electr. Connect.	99 draws.
4. Busbars	42 draws.
5. Miscellaneous	15 draws.

A Flow Chart of the “drawing sub-families” will be released in order to help the orientation in “The Drawing Labyrinth”.

The Tech. Specs. will contain instruction on how to transfer and submit for approval, the Manufacturers drawings in the CDD (via the LHC QA doc. N. LHC–PM-QA- 609 rev. 1.0)

2. COLD MASSES AND COMPONENTS DELIVERY SCENARIO:

2.1 Cold mass delivery model and constraints

The “Delivery rate model” necessary to fulfil the Official Installation Plan for the LHC construction, was presented. An important point to be underline is that, following this model, in the full production phase, about 9 cold masses per week are expected at CERN.

The expected delivery schedule for the pre-series until fall 2001 was presented. The delivery schedule for the following of the production is under preparation and will strictly bond with the following aspects:

- availability of components
- availability of main tooling
- no modification of the actual design.

2.2 Components delivery status and constraints.

2.2.1 CERN delivered components

Following is the list of “CERN delivered components for the “pre-series”. For the “series” the procurement of the components marked with a * will be done directly by the Manufacturers (as previously explained).

C1: Superconducting cables (for inner & outer layers)
C2: Polyimide tapes for cable and Cu wedges insulation (two types)
C3: Copper wedges (4 types)
*C4: End spacers, chips and wedge-tips sets (for inner & outer layers)
*C5: Coil inter-layers assembly
*C6: Layer-jump boxes
*C7: Layer-jump filling pieces
*C8: Cable stabilisers (3 types)
C9: Quench heaters
C10: Polyimide (in rolls) for the coils ground insulation
C11: Collars (6 types)
C12: Cold Bore tubes (now insulated)
C13: Low carbon steel half-yoke & insert laminations
C14: Non-magnetic steel half-yoke & insert laminations
C15: Busbars subassemblies
C16: Shrinking half-cylinders
C17: Spool pieces (sextupole and decapole/octupole correctors)
C18: End covers
C19: Helium heat exchanger tube
C20: Interconnection bellows

C21: Instrumentation for the Cold Mass
C22: Quench Protection Diode
C23: Tube for the auxiliary busbar line “N-line”

2.2.1 Contractor procured components

No critical aspects seem present.

The magnetic permeability of the minor components of the straight part (in responsibility of the Manufacturers) is a delicate aspect. For this reason, a “Mandatory table” for the permeability of these components was added to the T.S. The table will contain information like the following one:

Items	“μ rel” value
Coil prot. sheets & Shim ret.	≤ 1.005
Collaring rods	≤ 1.005
Collar pack rods	≤ 1.005
Iron insert shim	≤ 1.005 *
Tie rod yoke	Not spec.
Bearing pipes	Not spec.
Tap rod	Not spec.
Insert pack rods	Not spec.
Iron insert slide-sheet	Not spec.**

* Austenitic steel or non ferrous metal (Copper, Brass, Cu/Be) could be proposed.

** The permeability should be close to the one of the iron laminations (Annex C13)

(NOTE: the components for which the “μ rel” was not specified (“Not spec.”) have the a mandatory steel grade required).

3. DISCUSSION

T. Taylor – What is a geo-magnetic measurement ?

M. Modena – A combined measurement of the magnetic and mechanical axis using AC excitation in quadrupole configured dipole (QCD) mode.

Ph. Lebrun – Many items in the specification for series production (e.g. diode) should be already implemented for pre-series. What is the situation, and what is the contractual event that will bring these modifications into force ?

M. Modena – Diodes are not yet implemented in the production. The last set of final drawings will be given to the manufacturers in April this year. The implementation will be an amendment to be negotiated with the firms after issuing the specification for the series production.

L. Rossi – How many shifts are assumed in the production scenario ?

M. Modena – The assumption is 2 shifts/day, 5 days/week, 44 working weeks/year.

A. Poncet – 50 magnets by the end of 2001. Is this realistic ?

M. Modena – The model presented is based on the official installation plan for the LHC issued in summer 2000. A more realistic delivery plan covering the beginning of the production (pre-series and series) is in preparation on arrival of further information on components and main tooling availability (welding presses).

L. Rossi – Are quench heaters critical ?

M. Modena – At the moment, yes. The delivery rate is critical.

R. Saban – Is the “bonus/malus” principle accepted by the firms ?

C. Wyss – Based on preliminary discussions, in principle the firms are willing to accept this.

P. Sievers – “A malus” foreseeing many quenches in a magnet entails consequences for testing capability, if several magnets are below average it will be impossible to train all of them to ultimate field.

O. Bruening – Is the field quality specified for series production ?

M. Modena – Yes.

L. Walckiers – The maximum production rate is estimated at 420 magnets/year ?

M. Modena – Yes.

MAGNET QA FOR DIPOLES

P. Liénard
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Abstract

The quality assurance program for LHC dipole production will be reviewed. The talk will focus on the quality control system implemented by CERN to follow the production at different steps of the process. The traveller as a traceability tool will be presented. Following issues will be presented:

- Merging of QA plan from manufacturers and QA imposed by CERN for dipoles manufacturing.
- Inspection and test plan part of the technical specification
- Process workflow diagram.
- Assembly breakdown structure and traveller structure.
- Configuration management and traceability
- Components QA.
- Tracing non-conformities.
- Deal with changes notices.
- Test data transfer to CERN and responsibilities.
- The role of quality inspectors at firm.

1 INTRODUCTION

The LHC cryo dipole is the result of a long and close cooperation between CERN and industry. During the design and prototype period, many configuration changes were made, requiring flexibility from both sides, in order to reach the best performance for the LHC magnets as requested by CERN.

Now, this period is over as the series production is starting. The context is completely different. CERN and manufacturers are requesting a frozen design and well defined manufacturing procedures to reach the production level in the time schedule specified by CERN.

With this contract, CERN is in the position of component supplier and end user of the manufactured product. For contractual reasons, the traceability of each component delivered by CERN is very important.

CERN wants to be sure that the dipoles manufactured correspond to the technical specification and meet all required performances.

The fact that the production is shared amongst different manufacturers, is an important aspect for traceability and Q.A. application.

2 WHAT QUALITY ASSURANCE PLAN?

Each firm has a well-defined Quality Assurance Plan (Q.A.P) concerning organization, internal procedures, manufacturing and traceability. This Q.A.P is generally inheritated from the work done in Nuclear Power plants and is fully adapted to the needs of the nuclear industry.

The manufacturing contract is shared amongst different manufacturers who will deal with different Q.A.P's. As a consequence, CERN will receive information concerning traceability, manufacturing procedures and tests in different formats not directly usable by CERN responsible engineers.

The LHC Division has established well in advance a Q.A.P based on the ISO 9000 Standard.

To conform with LHC Q.A.P, CERN imposes to the manufacturers a certain number of rules concerning the Q.A.P. for the manufacture of LHC components.

For manufacturers, it means the application of both their internal procedure and rules defined by CERN (drawing numbering, drawing format, parts identification, test reports, Non-Conformance reports, change notice reports, documents and electronic format imposed by CERN).

3 PARTS IDENTIFICATION

CERN imposes the part identification numbering. Rules for part numbering are defined in the LHC-PM-QA-206.00 document. The numbering follows the drawing numbering scheme to avoid confusion. Parts are registered with serial numbers or batch number in case of large quantities (Collars, Laminations).

Manufacturers should use the parts number as defined by CERN.

The part number will be used in the Traveller as reference for component traceability. (see next paragraph).

4 MANUFACTURING PROCEDURES

The reference document for the manufacture of the cryo dipole is the Technical Specification. The manufacturing procedure and tests sequence are described in two documents:

4.1 Inspection and Test Plan

This document summarizes all tests mandatory in the appropriate sequence during the manufacture of the dipole. Tests steps are defined and references to the test procedure are given.

4.2 Work Flow Process Diagram

The Workflow Process Diagram is the graphical representation of the manufacturing process. It indicates all procedures and tests to be performed at each manufacturing step in accordance with the Inspection and Test Plan. The tests marked with "**T**" are mandatory and their results shall be recorded and transmitted to CERN.

The file in EXCEL^{TM} format is imposed by CERN and shall be sent to CERN via electronic mail (EMAIL) or File transfer (FTP) to the engineer responsible for approval and data storage.

5 TRAVELLER AND TRACEABILITY

An electronic traveller designed at CERN and based on the Assembly Breakdown Structure (A.B.S) will allow the storage of identification and characteristics of each component. The traveller tree structure is the software representation of the Assembly Breakdown Structure.

The traveller allows pointing to tests performed either on component or on C.M and stored in a repository. It will maintain up to date the list of Non-Conformity reports, their status and all applicable Change Notices.

5.1 Components traceability

All bibliographical references should be numbered and listed at the end of the paper in a section called "REFERENCES". When referring to a reference in the text, place the corresponding reference number in square brackets[1].

5.2 Test traceability

Tests performed at the manufacturers as defined in the I.T.P. will be sent to the CERN responsible engineer for approval. After validation, test results will be saved in a repository for later analysis if needed. The test data format is imposed by CERN in order to have coherency between manufacturers.

Tests results shall be recorded in the EXCEL ^{TM} format impose by CERN. These test results will be sent to CERN via electronic mail (EMAIL) or File transfer (FTP)

These files shall be sent to CERN in due time (for example: after winding, after curing, after collaring, after the welding of the Cold Mass and the final assembly.

The sending sequence will be agreed in due time between CERN and manufacturer.

5.3 Non Conformity

In case of non-conformance discovered during the manufacture either on component or on test, the manufacturer should open a non-conformity report and send to CERN the Non-Conformity report document specified by CERN.

This document in electronic form shall be sent via Email to the CERN Engineer responsible for appropriate action. This information will be saved and be accessible by the traveller.

5.4 Change Notice(configuration management)

If case of any deviation from the manufacturing procedure (design, components, tooling, manufacture or test procedure), a Change Notice report form shall be prepared and sent to CERN via Email to the Engineer responsible for approval. This information will be saved and be accessible by the traveller.

6 DELIVERY TO CERN

Before C.M shipping to CERN, the manufacturer will attach all relevant information (electronic and paper) concerning the documentation of the Cold Mass.

An identity document shall be produced (template is given by CERN) and shall contain the C.M. components identification, all test references, all non-conformities discovered and resolved and all related change notices.

7 DATA TRANSFER TO CERN AND RESPONSIBILITIES

Practice shows that for the time being the usage of WEB page in industry and especially for data recording cannot be generalized for many reasons.

It has been decided that all tests reports, Non-Conformity reports, Change Notice reports will be sent to CERN via email (EMAIL) or file transfer (FTP) to the CERN responsible Engineer.

The standard format is defined as EXCEL TM and all contractual documents will be scanned and transfer to CERN under PDF format.

It is the responsibility of the designated CERN responsible Engineer (or his assistant) to verify the data coherency, the validity of test data before the storage in the repository.

He will authorize the manufacturer to proceed to the next manufacturing step.

8 ROLE OF QUALITY INSPECTOR AT MANUFACTURERS

The role of the Quality Inspector at firm is to verify the correct execution of the Technical specification. He will ensure that manufacturing procedures, tooling used are conforming to the specification and that all tests are done with correct and calibrated equipment. He will also ensure that all procedures, all test are supervised and signed according the organisation chart diagram in place at manufacturer.

The Inspectors will act as observers. They will not be authorised to accept or to negotiate any changes within the frameworks of the contracts between CERN and the different manufacturers. They will be the CERN witnesses for the correct execution of the manufacturing sequences, manufacturing procedures, test methods, test performance and test reports during the series production of the above items. They will report to the responsible CERN engineer as defined in the relevant contract.

The replies for the call for Tender are now fully analysed. The next phase concerns a more detailed discussion with a particular firm and the preparation of documents for the Finance Committee that will take place next June

Inspectors should arrive at CERN this summer for their initial training and should be operational 2 months later, ready to join their final assignment.

9 DISCUSSION

L. Rossi – Is a double collaring a non-conformity ?

P. Liénard – Yes. If any assembly procedure needs to be repeated, it means that there was a non-conformity detected. A non-conformity report should be issued. For tests that are giving unexpected results, after investigation (calibration procedures) the test result should be stored. If the results are originated from the assembly a non-conformity should be issued detailing the action taken to cure the problem.

P. Lebrun – At the moment there is no inspector at the firms to verify production and testing (the Inspection and Test Plan). Who is responsible ?

P. Liénard – The project engineer. This works, many non-conformities are dealt with.

L. Bottura – When will the system be in place and operational ?

C. Wyss – The system is already in place and is operational. There is room for improvement which will happen in the next months, especially on communication aspects.

T. Taylor – Several components are “commodities” by the time they are built into a magnet, and full information is redundant. A number for identification should be enough ?

P. Liénard – Yes, provided that traceability of the origins of the part is guaranteed so that eventually potential problems can be found by examining detailed information.

L. Bottura – Magnetic measurements, LTD and QCD measurements are delicate. Are they responsibilities of the firms ?

C. Wyss – Yes, trained technicians in the firms will perform these measurements.

MAGNET QA FOR QUADRUPOLES

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Abstract

The design, tooling and procedure definition and prototype assembly of the Main Quadrupole magnets (MQ) and Short Straight Sections (SSS) Cold Masses was entrusted to CEA-Saclay in the framework of the special French contribution to the LHC. The contract for industrial fabrication of these LHC components has been signed between CERN and the German firm ACCEL in July 2000. This is a "Built to print package" where CERN not only gave the order but provides some basis components and tooling, and where CEA-Saclay will have to transfer its technology and follow the series fabrication.

In such a "tripartite" contract, the responsibilities are split and must be clearly defined.

This paper describes how, in this context, it is planed to:

- Transfer the technology
- Establish and use manufacturing documentation: process plans, travellers, data and inspection sheets
- Manage modifications and non-conformities and trace them
- Follow the series fabrication and pronounce acceptance according to the defined criteria

1 INTRODUCTION

In July 2000, the contract for the series fabrication of 400 twin aperture quadrupole magnets and 368 cold masses has been signed between CERN and the German firm ACCEL. The design, tooling and procedure definition and prototype assembly of the Main Quadrupole magnets (MQ) and Short Straight Sections Cold Masses was entrusted to CEA-Saclay in the framework of the French contribution to the LHC. After the successful cold tests of the 3 prototypes built in CEA-Saclay, the cold mass design is considered as ready and will be subject to only a few adjustments.

The contract linking ACCEL to CERN is then a "built to print" package where responsibilities are shared between CERN, ACCEL and CEA.

The preparation work [1] has started in fall 2000 and comprises not only the preparation of the fabrication halls but also the documentation and quality assurance work needed to fulfil the requirements of the LHC machine.

2 RESPONSIBILITIES

CERN and CEA work together on the customer side while ACCEL acts as a furnisher. This implies that a strong collaboration between CERN and CEA is established. The contract is a "tripartite" contract where responsibilities are clearly defined.

2.1 CERN responsibilities

As customer, CERN must be implied in any discussion, which could lead to a change to the contract finances. It also has to define, in accordance with the machine installation planning, the production sequence for each of the 400 items of 40 different types.

It also must take care that any change will neither induce difficulties in other CERN's contracts nor have an impact on the LHC machine performances.

Some raw materials to be transformed under ACCEL responsibility are provided by CERN. For these materials, CERN is responsible of the delivery in due time and of the conformity to the specification:

- Non-insulated superconducting cable
- Insulation films
- Austenitic steel for the collars
- Low carbon steel for the yoke laminations

Some components ready to assemble are also delivered by CERN. For these components, CERN is responsible of their acceptance and for the their delivery in due time. On the other hand, ACCEL must check that they can be mounted before the start of their integration. These are:

- Busbars
- Insulated cold bore tubes
- Helium heat exchanger tubes
- Sensors and wires for instrumentation
- Corrector magnets
- Interconnection bellows
- Quench heaters
- Cold diodes

Finally, CERN is responsible for the provisional acceptance, which is pronounced after the cold tests performed in the CERN test facilities.

2.2 CEA responsibilities

CEA is responsible for the design. Any change must then be agreed by CEA, which will adapt the drawing, before it becomes effective.

CEA is responsible for technology transfer and series fabrication follow-up. For that purpose, two technicians, who already built the three last prototypes, will spend at least one year by ACCEL. At the beginning, they will "teach" ACCEL people and progressively, they will become "controllers”: They must check that the defined procedures are respected, verify the mandatory tests results, inspect the data sheets and inform CERN and CEA of any difficulty in the fabrication hall.

In addition three engineers from CEA are ready to travel to Troisdorf, where the ACCEL fabrication hall is installed, as often as needed.

2.3 ACCEL responsibilities

CERN and ACCEL signed the contract after a call for tender based on a technical specification [2] written by CERN for the commercial part and by CEA-Saclay for the technical aspects. Because ACCEL did not make the design and because key components are furnished by CERN, ACCEL is responsible neither for the design nor for the performances of the magnets at high field.

However, ACCEL, as furnisher, is fully responsible for the fabrication and its quality. This means that ACCEL is responsible for components non-furnished by CERN, for tooling (including the tooling used for the CEA's prototypes and sold by CERN to ACCEL), fabrication planning, fabrication quality and documentation.

3 DOCUMENTATION

ACCEL is actually preparing its Quality Assurance (QA) plan, based on a fully computerised system. Each workstation will be equipped with a terminal. This terminal will allow technicians to consult the travellers, open the process plans, see the reference documents and fill in the data sheets. The system will control the validity of each used tooling and component by using bar code and will identify the people involved in the fabrication.

All the fabricated items (individual coils, collared apertures, quadrupole magnets, and cold masses) will be followed with travellers. Unique number identifies items and the traveller for one item gives its fabrication status. When opening one item’s travellers, one can see where it is in the fabrication sequence and if there are particularities. By clicking on a particular fabrication step, the associated process plan open.

31 process plan documents have been written by ACCEL and submitted to CEA for correction. They refer to all sub-documents, like part lists, tool lists, etc. and all relevant process instructions.

The process plans will also link to the data sheets. The data sheets, will then allow for the identification of items, sub-components, tooling and measurement devices as well as involved people. They will also be used to store all the measurement results. In addition, all measurement results will be compared with reference values and the process will be stopped if a measurement is not within predefined limits.

4 MODIFICATIONS AND TRACING

No modification can occur without the writing of a Technical Change Request (TCR) and, if needed, an official CERN’s Engineering Change Request is issued. A modification flow-chart has been agreed between CERN, ACCEL and CEA. It takes into account the sharing of responsibilities:

- No change can occur without the technical agreement of CEA
- CERN is informed of any change and can stop the process if necessary when finance, interfaces or machine performances are touched.

Two actions ensure the tracing of the modifications:

- The relevant drawings are modified by CEA and stored in the CERN drawing database.
- Each monthly CERN-ACCEL-CEA meeting report contains the list of the TCRs.

5 NON-CONFORMITIES HANDLING

Non-conformities handling has not yet been defined correctly. It will conform to the LHC QA plan and be treated before the start of the fabrication.

6 ACCEPTANCE CRITERIA

The acceptance criteria are defined in the technical specification [2] and will not be detailed here. They are based on mandatory fabrication tests, which allow for the rejection of any non-conforming item as early as possible, and on the provisional acceptance tests at CERN.

The mandatory fabrication tests include impedance, mechanical, insulation and dimensional controls, magnetic measurement and pressure and leak tests.

At reception at CERN, any of the previous tests can be repeated at room temperature and the reception tests at liquid helium temperature are carried out:

- Leak test
- Electrical integrity
- Quench heaters performances
- Magnetic field measurement
- Quench performance. If a quench problem occurs between 6000 A and the ultimate value, CERN has to demonstrate that ACCEL has made an assembly fault.

7 CONCLUSIONS

Although some work has still to be done during the next few months, the positive attitude of ACCEL gives us confidence that a good quality level can be achieved, which is probably not sufficient but necessary to get good magnets and cold masses.

8 DISCUSSION

L. Rossi – Is ACCEL free to choose sub-contractors ?

J.M. Rifflet – Yes, but sub-contractors must be approved by CERN.

T. Taylor – How many drawings are produced for the quadrupoles ?

J.M. Rifflet – Approximately 250.

B. Skoczen – Will the traveller contain the same information as for the MB’s, and in particular the cartography of the ends ?

J.M. Rifflet – Yes, but the format still has to be specified.

P. Faugeras – For non conformities the experience of CMS is very relevant.

L. Bottura – Originally the specification for SSS production did not foresee alignment assisted by survey. What is the logic now, and what is the use of the Laser trackers ?

J.M. Rifflet – The magnets will be built according to tolerances and checked using the LTD. The LTD could assist in the machining of the inertia tubes. Alignment verifications are not in the specification, they must be defined and must be included through an amendment of the specification. Responsibility for the definition is not yet clarified.

P. Sievers – What are the acceptance criteria ? Multipoles, strength, direction, alignment ?

J.M. Rifflet – Multipoles and magnetic length are specified. No acceptance criteria has been specified on gradient and alignment.

REFERENCES

[1] T. Tortschanoff, “MQ Prototypes and Start of Series”, these proceedings

[2] LHC-LQM-CI-0001, “Technical Specification for the Supply of the Main Superconducting Quadrupoles and Assembly of the Cod Masses for the LHC Short Straight Sections”, CERN document, October 1999

THE QUALITY ASSURANCE OF SUPERCONDUCTING STRAND AND CABLE FOR LHC

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1 INTRODUCTION

The purpose of this paper is to describe the main aspects of the quality assurance programme for superconducting strand and cable for LHC. The most important goals of the quality assurance programme is to prevent and detect superconducting strand defects, to reduce and control the manufacturing process variability and to achieve overall uniformity of cable performance. The programme designed to meet these goals includes the implementation of Statistical Process Controls (SPC) at each level of the manufacturing process. The introduction of SPC by controlling statistically significant shifts in the process should improve the traditional approach to superconducting strand and cable manufacturing.

2 CONTRACTORS's QUALITY ASSURANCE PROGRAMME

To achieve quality assurance goals, a well characterised manufacturing process containing clearly defined and measurable controls throughout the process was established by each contractor before starting production. To reduce and control the manufacturing process variability and to produce strands and cables that exhibit a high degree of uniformity, SPC methods have been requested by CERN. At each level of the manufacturing process, key parameters have been identified in order to control performance variables such as critical current, Cu:Sc and number of strand breakages per billet. A plan for the application of SPC to detect any variability in the process was prepared by each contractor and was implemented from the beginning of the production.

All the results of tests performed by the Contractors are sent to CERN in a digital form and are transferred to the LHC cable ORACLE database. The information collected is used to verify performances of the strands and cables and to monitor the magnitude of manufacturing variation that which is essential for establishing confidence in the stability of the Contractor's process.

3 CERN's QUALITY ASSURANCE SYSTEM

The quality assurance system implemented at CERN to follow the manufacture of superconducting strand and cable relied on systematic tests performed by CERN on strand and cable samples to assure the cable requirements. The strand samples sent to CERN are cut from every strand piece length and are adjacent to the samples used by the contractor for the Ic test. They are used to perform acceptance tests at CERN and to cross-check the measurements done by the contractor. The strand fabrication and electrical data transmitted by the Contractor and the results of tests at CERN are collected in the LHC cable database to monitor the strand performances and to give CERN's approval to use the strands from a billet for cabling.

The CERN's approval to use the strands from a billet for cabling is the first holding point imposed on the Contractor during manufacturing. To go ahead with the cable production, the Contractor must also receive CERN's approval of the cable strand maps. The last holding point is to get CERN's approval for the shipment of the cables. To get this approval, the Contractor must send a cable sample taken from each continuous length of cable, the cable fabrication and electrical data, the graphs of the cable dimensions and a certificate of conformity for every unit length of cable. The holding points imposed to the Contractor at the end of the strand manufacturing are essential, from a quality assurance perspective, to control at key steps the manufacturing in order to assure the required performance of the LHC cables.

Management tools have been developed in the ORACLE environment to give CERN's approval for billets, cable strand maps and cable shipments and to generate electronic messages sent upon the registration of the decision in the database. These tools provide a common method and identical acceptation criteria to follow the cable contracts split among six Contractors. A complete traceability of the approval process is also guaranteed. In addition, data analysis tools are being developed and implemented for statistical analysis and graphing.

4 CONCLUSION

An appropriate quality assurance system has been implemented at CERN to follow the manufacturing of superconducting strands and cables and to assure overall strand and cable performances, with emphasis on SPC methods applied to the Contractor's manufacturing process. CERN's requirements for computerized data and procedures for data transfer were clarified with each Contractor and management tools were developed to follow the manufacturing. As a result of this work the LHC cable database is fully operational and provides an efficient follow-up tool in the CERN's quality assurance system.

5 DISCUSSION

L. Rossi – For the approval of the strand map of a cable it should be checked that the billet has been approved as well. Is this automatically done ?

L. Oberli – Yes. Several other checks are also done (e.g. that the length of a given strand is consistent with the declared piece length taking into account the lengths already used).

P. Lebrun – Data must be made available to magnet assembler. How is this done ?

L. Oberli – For magnet assembler it will be possible to retrieve data from the Oracle database in a special view with open access that contains parameters necessary for the magnet construction. The conformity certificate is delivered with the cable. In addition parameters relevant for the LHC operation will be available.

T. Tortschanoff – Is the cable production for quadrupoles following the same profile as the production for dipoles ?

L. Oberli – Yes.

R. Saban – Up to which point is data confidential ? For example, the manufacturer name.

L. Oberli – This data is not confidential, it is coded but it is available.

FROM TOLERANCE TO ALIGNMENT

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1 INTRODUCTION

The requirements of beam dynamics and the features of the magnet-to-magnet interconnections impose severe constraints to the geometry of the LHC main magnets. Additional constraints stem from the two-in-one design of the magnets and from the slow movement of the tunnel ground, observed during the 11 years of operation of LEP. The dipoles are bent to follow closely the curvature of the circulating particles and hence to provide the largest mechanical apertures with the minimum coil size. Small correctors are welded at the ends of the dipole cold mass assembly (CMA) to compensate the effect of persistent current during the injection plateau. As recommended by the Working Group on Alignment (WGA), the dipole assembly procedure is assisted by high precision survey measurements based on laser trackers. By this we hope to limit to ±1 mm the positioning error between the mechanical axis and the beam reference orbit and to ±0.3 mm the error at the ends. The quadrupoles instead are straight. They are installed in a so-called Short Straight Sections (SSS), also containing orbit correctors, chromaticity sextupoles, Landau damping octupoles and other magnetic lenses required to steer the circulating beams. The alignment of the SSS should be guaranteed by compliant tolerance components, with a precision of ± 0.3 mm everywhere.

2 BASIC ASSUMPTIONS

We study the geometry and the alignment of the LHC magnets, taking into account all the known sources of errors and trying to disentangle systematic from random effects. We assume that global systematic misalignments result from the sum of the individual systematic errors of different origin. We also assume that the various sources of random errors are independent to each other, hence we compute the global error adding in quadrature the individual standard deviations. In principle, we should be able to prevent or correct large realisations of random misalignments, in the tails of the error distribution assumed to be Gaussian. Thus, we fix to $\pm 3\sigma$ the range of allowed geometric tolerance, σ being the global rms error.

3 MAGNET GEOMETRY

The specification of the geometry of the dipole CMA is based on three main constraints:

- The CMA is to be bent around the beam orbit, to maximize the mechanical aperture, whilst minimizing the aperture of superconducting coils.
- The corrector magnets (MSC, MOC and MDC) in the CMA ends must be co-linear to the dipole axis and the dipole axis co-linear to the reference orbit, to reduce the feed-down effect.
- The radial displacement of the bellows should not exceed 4 mm. This issue is critical for magnet installation and implies accurate monitoring of the ground motion during LHC operation.

Each SSS contains a MQT or a MO (0.38 m long), a MQ (3.25 m long) and a combined MS and CB (1.26 m long). The geometry of the SSS should be straight and will be fully determined by tolerance compliant components. The inertia tube ensures the stiffness of the structure. Four arrays of 16 holes in orthogonal positions at 45 degrees respect to the horizontal-vertical planes are used as the mechanical reference. Keys inserted in the holes determine the position of the magnetic centers of the quadrupole and of the associated correctors.

3.1 Geometrical parameters

The LHC ring contains 1232 dipoles, the main geometrical parameters of which are given in Table 1.

Table 1: Geometrical parameters of the LHC dipole

	1.9 K	300 K
Magnetic length [m]	14.300	14.343
Bending angle [mrad]	5.099988	5.099988
Sagitta [mm]	9.12	9.14
Bending radius [m]	2803.928	2812.360
Axes separation [mm]	194.00	194.52

During LHC operation at 1.9 K, two counter-rotating beams follow flat straight trajectories, which become circular along the 14.3 m long active part of each dipole. The two orbits are separated by 194 mm, i.e. the nominal distance between the twin-coil axes. For each beam, the reference orbit is a sequence of straight lines and arc of circles closing upon itself. Its average value over the two beam trajectories is used to model the accelerator geometry defined by dipoles and straight sections (*not by quadrupoles)*. In assembling conditions at 300 K, one has to take into account the thermal effect, which is assumed to leave unchanged the dipole curvature, of about 5 mrad, identical to the bending angle of the circulating protons. This brings to 14.343 m the magnetic length and to 194.52 mm the distance between the coil axes. The vertical shape of the dipole should be straight. In fact, it is distorted by ~0.3 mm, between the three supporting pads, by the effect of the self-weight and of the flexural inertia. During production, the originally straight dipoles are curved. The resulting shape of the cold bore axes is measured with a high precision 3-D laser tracker. The data are used to fit the position of the reference orbit of the two beams and to identify the horizontal and vertical planes of the CMA [1].

3.2 Beam physics constraints

To partially compensate the field-shape errors in the dipole, at the connection end of the CMA there is a sextupolar corrector MSC about 150 mm long and at the lyra-side end, there are combined octupolar-decapolar correctors, MOC and MDC, about 110 mm long. Since they are very close to the source of error, they can be very efficient on the condition that they are well aligned to the beam channels. Indeed, a multipolar lens of order *n* traversed off-axis by a charged particle can be described by an appropriate combination of multipolar terms of order *k*, with $k \leq n$. This effect is referred to as the feed-down of the multipolar harmonics.

Table 2 Alignment tolerance for the dipole CMA

		Tolerance		
		systematic	random (1 σ)	Uncertainty (1 σ)
MB	x	0.14 mm	0.29 mm	0.47 mm
	y	0.14 mm	0.42 mm	0.29 mm
	roll	0.5 mrad	0.5 mrad	-
MSC	x	0.1 mm	0.34 mm	0.31 mm
	y	0.1 mm	0.61 mm	0.19 mm
	roll	1 mrad	1 mrad	1 mrad
MOC	x	31.9mm	1.9 mm	2.2 mm
	y	20.1 mm	1.6 mm	1.9 mm
	roll	1 mrad	1 mrad	1 mrad
MDC	x	0.4 mm	0.64 mm	1.3 mm
	y	1.1 mm	0.50 mm	1.7 mm
	roll	1 mrad	1 mrad	1 mrad

Table 3 Alignment tolerance for the SSS components

			Tolerance	
	Error		systematic	random (1 σ)
MQ	orbit excursion	x	-	0.37 mm
	orbit excursion	y	-	0.37 mm
	coupling	roll	0.3 mrad	1.0 mrad
MS	tune/ß-beating	x	0.1 mm	1.0 mm
	coupling	y	0.1 mm	0.8 mm
	chromatic. coupling	roll	2.0 mrad	1.5 mrad
MO	chromaticity/ DA	x	0.16 mm	1.9 mm
	chromatic coupling	y	0.1 mm	0.5 mm
	(2,-2)resonance	roll	1.0 mrad	1.5 mrad
CB	coupling	roll	0.6 mrad	0.6 mrad

In presence of misalignment, dipoles and associated correctors can have unequal displacements from the reference orbit. In this case the feed-down harmonics of a given multipolar error of order *n* and of the corresponding corrector are different, except at the order *n* itself. Consequently, the compensation is still very good at the order *n* itself, but it is imperfect at the lower orders. In Ref. [2] there are estimates of feed-down stemming from field-shape harmonics and misalignments expected in the lattice version 4.0. Updated estimate of the geometric tolerance is shown in Table 2 [3]. The alignment tolerance for the short straight section (SSS) depends on the limits imposed by beam dynamics on orbit excursion, linear coupling, ß-beating chromaticity, chromatic coupling, resonance strength, dynamic aperture (DA). Estimates of tolerance are shown in Table 3 [4].

3.3 Interconnections

The magnets to magnet interconnections impose geometrical constraints to the position of the beam pipes and of the bus-bar tubes. In Table 4 [5] we show the tolerance imposed on their localization. There is a limit also to the tolerable offset and roll along the beam axis between two consecutive magnets. The values are given in Table 5 [6].

Table 4. Errors on the geometry of the prototype CMA

	V beams	M bus-bar	E/C' external
X-Horizontal [mm]	±1	±0.5	±2
Y-Vertical [mm]	±1	±0.5	±2
S-Longitudinal [mm]	±1	±1	±2
Hortogonality [mm]	0.2	0.2	0.2/0.1
Roll [mrad]	1	1	1

Table 5. Tolerance on bellows

	V beams	M bus-bar	E/C' external
Permanent offset [mm]	0.5	2.0	5.0
Occasional offset [mm]	4.0	4.0	10.
Permanent roll [mrad]	1	1	1
Occasional roll [mrad]	2	2	2

4 REQUESTED MEASUREMENTS

The dipoles are crystated at CERN after the delivery of the CMA, whereas the SSS containing the quadrupoles are cryostated in the industry. In the two cases, the checks of the geometrical shape are rather different.

4.1 Dipole

The geometric and magnetic axes of all the dipole CMA will be measured (and recorded in the traveller) before shipping them at CERN. Up to 10 % of them is to be measured again at CERN with the same instruments and the same procedure as in the industry, to check the conformity of the measurements in the industry and of the traveller.

In the cryostat, the geometry of the cold mass depends on the level of central support. Without the central jack, the charged cryostat has a vertical sagitta of ~ 4 mm. Its correction is equally shared between the internal and the external supports. A spacer of 2 mm is added to the central cold post and the final leveling is made with the external central jack. Routinely, the correct leveling of the cryo-dipole is based on conformity of components. This operation is assisted by metrology only on 10 % of the cases.

During the cold-tests, the field level and the field-shape are routinely measured. However, in 10 % of the case, the absolute position of the magnetic axis is also recorded. After the cold-tests, all the cryo-dipoles are equipped with fiducials. During this operation, one will measure the geometric and the magnetic axes at room temperature, identify the reference orbit by a best fit and determine the relative position of the fiducials. The base-line is to fix the virtual planes of the reference orbit from the measurement of the mechanical axis, since the spool-pieces are aligned to the average mechanical axis and the warm measurements of the field-shape harmonics are compensated for the feed-down respect to the average mechanical axis.

Once the cryo-dipole is equipped with beam screens and interconnection bellows, one will establish and record the cartography of the bellows welded at the dipole ends and of the three reference plots marked in each dipole end-cup.

This is the last operation before shipping the cryo-dipole in the LHC tunnel. It is still undecided if there will be supplementary checks in the tunnel itself, just before the final positioning of the cryo-dipoles.

4.2 SSS geometry

After the assembly of each SSS, the Contractor shall measure the following parameters:

- Position of the fix and sliding support post plates.
- Dimensions of the support plates and position of the 16 support holes.
- Parallelism of the support plates.
- Position and perpendicularity of the end covers.
- Position of the cold bore tube respect to the centre of the cold mass, using the external inertia tube reference points.
- Position of the heat exchanger tubes.
- Position of the beam position monitor (BPM) support studs respect to the horizontal and vertical symmetry planes of the MQ.
- Position of the bus bar.
- Position of the instrumentation wire passage on the flat end cover.
- Position of the cryogenic pipe socket, where present.
- Position, dimension and perpendicularity of the vacuum barrier ring.
- Transverse position of the support pads for the tube of the auxiliary bus bar.

The program of geometrical verifications on the components themselves is the responsibility of the Contractor. However the Contractor shall control at least the position of the alignment holes before the cold mass assembly. Checks on the global alignment of the SSS are not yet planned in the industry.

6 WHERE DO WE STAND?

Systematic measurements are made in the recently produced magnets to check the conformity of the geometrical shape. The results relative to the dipoles at the end of the assembly procedure are rather good, as shown in Table 6. The mechanical axis has always been found within the tolerance. On the other hand, the magnetic axis measured with the system of Ref. [7] is superposed to the mechanical axis within a tolerance of ±0.2 mm. There is still some difficulty to position the end-cups within the tolerance of Table 4. Indeed, the bus-bar lines M are some times more than 1 mm off from the nominal position. In the prototypes, also the position of the correctors was often out of tolerance. The assembly procedure has been modified to improve the situation in the pre-series dipoles.

The specific case of the prototype dipole MBP2O2 requires some attention. Its shape was repeatedly measured during the various production steps and the some of the results are shown in Figs.1 and 2. The vertical level of three internal and external supports was carefully adjusted to the same value during all measurements. The horizontal shape instead changes by rather large amounts, for still unknown reasons. Unfortunately, none of the other dipoles was measured with the same frequency and method to confirm if the change is an accidental or a systematic feature.

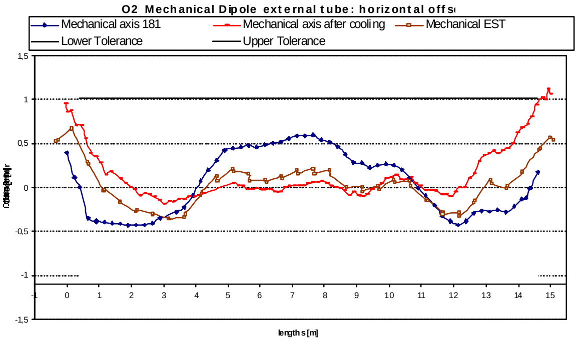

Fig 1 Horizontal shape of the dipole MBP2O2

The geometry of the so-called SSS4 prototype is shown in Ref. [8]. There are large discrepancies from the nominal reference line especially along the multipolar correctors. The situation is well outside the tolerance range. Substantial improvements will come from a more rigorous quality control plan during series production

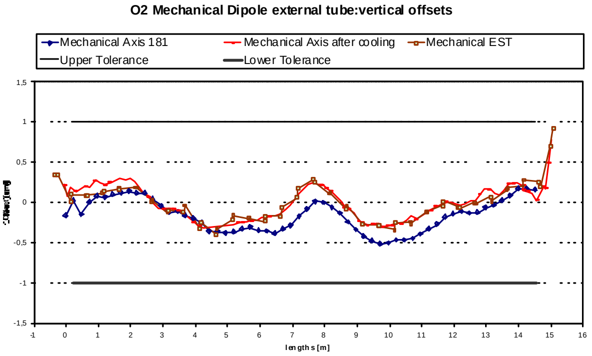

Figure 2: The straightness of the MBP2O2

Table 6. Errors on the geometry of the prototype CMA

MBP2-	N1 min/max	N2 min/max	O1 min/max
Horizontal curvature [mm]	-0.8/+0.8	-0.4/+0.7	-0.8/+1.7
Vertical straightness [mm]	-0.4/+1.0	-0.4/+0.8	-0.4/+0.4
Twist [mrad]	-1.1/+3.0	-3.0/+2.5	-2.5/+3.0
Radial offset of correctors [mm]	V2/V1 0.67/1.03	V2/V1 1.23/1.10	V2/V1 0.19/0.18

7. ALIGNMENT IN THE TUNNEL

The global tolerance for magnet alignment in the tunnel should be based on the expected errors induced By CMA geometry, by the cryostating, by the positioning procedure in the tunnel and by the ground motion over one year of continuous LHC operation. These effects have been estimated by the WGA, the results are shown in Tables 7 and 8.

Table 7 refers to dipoles, and gives the expected rms value for random misalignment of the fiducials and of the ends. The tolerance on ends is deduced from that on fiducials with an amplification factor of 1.8. The effect of central post instead is the same on ends and on core.

In Table 8 there is the tolerance relative to the quadrupole. In this case the amplification factor from fiducials to ends is equal to two.

By composing quadratically the tolerance of two consecutive magnet ends one can compute the maximum radial displacement of the interconnection bellows. Between two consecutive dipoles the maximum offset can be as large as 3.95 mm, whilst between a quadrupole and a dipole the offset can be up to 3.68 mm. The values are still within the tolerable offsets given in Table 4, however there is no margin left. Indeed, this means that the alignment procedures should be very rigorous to avoid unexpected problems. In addition this will make rather difficult to manipulate the dipoles during the routine realignment operation for which an additional margin is required by the EST-SU operators.

Table 7 Alignment tolerance (1σ) for dipoles

	Fiducials [mm]	Ends [mm]
Cold mass assembly		
Magnetic axis vs reference orbit	0.32	0.58
Cryostat		
Thermo-mechanical	0.25	0.45
deformations	0.20	0.20
Level of the central post		
Positioning in the tunnel		
Displacement over one year	0.23	0.41
Global rms (quadratic sum)	0.51	0.93
Global tolerance (= 3·σ)	1.53	2.79

Table 8 Alignment tolerance (1σ) for quadrupoles

r.m.s. misalignment	Fiducials [mm]	Ends [mm]
Quadrupole axis with respect to inertia tube	0.1	0.2
Rotation of the yoke inside the inertia tube	0	0.08
Measurement error of the field axis at 1.9 K	0.03	0.03
Position error of the external fiducials	0.15	0.3
Stability of the cryostat	0.1	0.2
Stability of the cold feet	0.1	0.2
Deformation and tilt of the cold mass supports	0.07	0.14
Alignment of the SSS in the tunnel	0.28	0.56
Position error of the drift tube (SL Note 98-048/BI)		0.29
Global rms (quadratic sum)	0.37	0.8
Total tolerance (= 3·σ)	1.11	2.4

DISCUSSION

W. Scandale – Horizontal tolerances on line M (0.5 mm) are not consistent with vertical tolerances and with other tolerances on similar lines (1 mm).

A. Poncet – These tolerances are probably wrong in the specification.

L. Rossi – What if the magnetic and mechanical axis do not coincide ?

W. Scandale – For the MB they are checked to be OK (1 magnet), for the SSS there is a mismatch larger than the tolerance, to be cleared.

O. Bruening – Who is following the alignment for the insertion magnets ?

W. Scandale – No clear contact person is specified at CERN.

L. Rossi – Some manipulation changed the alignment of O2. Do we understand why ?

W. Scandale – We do not know exactly why, and this has been observed on another magnet before. We need more check points and redundancy before and after transportation.

P. Lebrun – If the tolerances are responsible only for a part of the mis-alignment, and reproducibility is dominating, why keep tolerances so tight ? Are we too conservative with our bellows, or with our tolerances ?

O. Groebner – Can we tolerate more on the mechanical aperture ?

W. Scandale – For the moment mechanical aperture and bellows tolerances are consistent with each other.

B. Skoczen – For the bellows, the movements in the machine should go in the same direction, so that the net relative movement should be small.

J.P. Quesnel – We are not too conservative with tolerances. We should minimise what we can minimise as sources of errors.

P. Lebrun – I do not agree. It is not useful to minimise tolerances much below the expected magnet stability.

A. Poncet – Why is reproducibility of the magnet geometry much better in the vertical plane than in the horizontal one ?

W. Scandale – This is a fact, not yet explained. A possible explanation is that the curvature in vertical direction is applied “elastically” as opposed to the horizontal sagitta that results from a “plastic” deformation. Changes in sagitta due to movements can then be irreversible.

T. Taylor – A stabilizing process could be applied to the cold mass (vibration) to avoid successive changes of geometry following cold tests and transport.

A. Poncet – We have tested this and we remarked no effect.

M. Mayoud – What are the key points for alignment of SSS ?

W. Scandale – The SSS geometry relies only on tolerances. The verification is performed only late in the process, at the cold test.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the contribution to this work of the entire WGA. Several colleagues of the MMS group helped me in preparing the talk. I would like to thanks in particular J. Garcia Perez, T. Tortschanoff.

REFERENCES

[1] M. Bajko, F. Savary, W, Scandale “Geometry and Alignment requirements for the LHC main Dipole” EPAC2000,Wien.

[2] R. Bartolini and W. Scandale, “Multipole Feed-down due to Dipole Misalignments”, LHC-MMS, Internal Note 97-12, (1997).

[3] E. Wildener and A. Verdier, Private communication.

[4] O. Bruning, Private communication.

[5] Engineering Specification LHC-LI-ES-0001.

[6] B. Skoczen, Private Communication.

[7] J. Billan et al., LHC-MMS Int. Note2000-01.

[8] M. Bajko et al. LHC-MMS Int. Note 2000-16

EXPERIENCE WITH THE ASSEMBLY OF STRING 2

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Abstract

Based on the recent experience of co-ordinating the installation of String 2, after a short description of the exercise, the relevant lessons learnt (non-conformities, scheduling of activities, resources, conflict of competence, orphan components) which are applicable to machine installation are highlighted.

1 STRING 2

As for its predecessor, String 2 is built to validate individually the technical systems and investigate their collective behaviour in conditions equivalent to those in the machine. String 2 will be assembled in two phases. The facility which will be commissioned during the first phase comprises one half-cell and an additional short straight section. It will contain exclusively prototype magnets heavily instrumented for the experimental programme. It is expected to start the commissioning at the end of April 2001. Phase 2 of String 2 will include in addition three pre-series dipole magnets and will be commissioned in early 2002.

1.1 Layout

String 2 consists of two LHC half-cells terminated on the upstream end by the electrical feed-box and on the downstream end by the return box. The former is a prototype of the arc DFBs and contains the current leads through which the 15 electrical circuits are fed. The latter box contains the short circuits and the connection to the QRL simulating the jumper connection of the following cell.

With respect to vacuum, cryogenics, interlocks, protection and powering, Phase 2 of String 2 represents a full cell in the regular part of the LHC arc.

1.2 Experiments

The behaviour of the vacuum system will be monitored during the pump down, normal operation and during quenches.

The beam induced heating on the beam screens will be simulated with heaters and its effect on the regulation of the cooling loop will be studied. Furthermore, the effect, recently observed in the magnet test benches of the current in the beam screen during a quench and the associated deformation, will be studied.

The final superfluid helium cooling loop with a cylindrical heat exchanger on a horizontal portion of the machine will be validated and thermo-hydraulics of quench propagation across magnets will be studied in conjunction with the magnet protection team.

With respect to powering, String 2 is much more equipped than it predecessor where only one electrical circuit was present. Final design power converters for 15 independent circuits are installed. The recently developed digital regulation techniques will be validated as well as high precision DCCTs and dipole circuit topology. One aperture of a prototype dipole and one aperture of each quadrupole have been instrumented with fixed coils to study the tracking between the dipole and quadrupole circuits.

Prototypes of the quench detectors for LHC with local protection at the level of each magnet will be tested for the first time. The protection strategy for the high temperature superconducting current leads of the electrical distribution box and the global protection of the circuits for the spool-pieces and the lattice correctors as wells the bus-bars will be validated.

2 THE ASSEMBLY

2.1 The preparation of the site

String 2 is installed in hall 2173 (SM18) and just fits in the length of the building (120 m). Because it comprises the external cryoline an artificial difference in level was required to simulate the trench in the tunnel. This was achieved using already available concrete slabs.

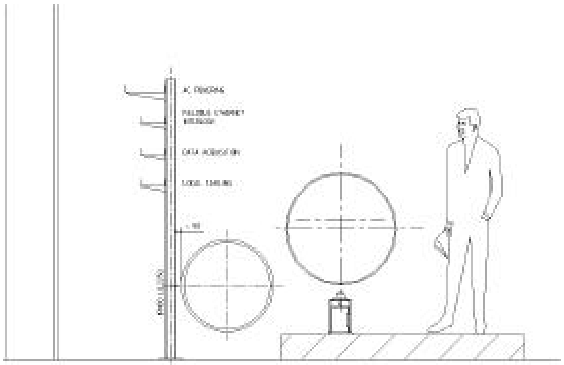

Figure 1 : Cross-section of String 2 in Hall 2173

The interface between the jacks and the floor of the hall was verified by simulating the forces in play when the vacuum vessel is evacuated.

The preparation of the site also included the pulling of the cables and the installation of the racks. In both cases the configuration as in LHC was kept separate from the

String specific configuration. All the racks which are present in the tunnel were installed under the cryostats and those dedicated to the experiments were installed behind the QRL. Although largely dominated by the String specific cabling, 17 km of cables and the associated connectors for the process control and the data acquisition were pre-installed.

The power converters for the 15 separate circuits, the energy extraction system for the dipole circuit and the lattice sextupoles were installed in the powering area situated at the north end of the String. A kicker power supply and an associated dummy load is foreseen in this area to study the electromagnetic compatibility of converters, front-end electronics, PLCs, etc. All the infrastructure particular to powering was also installed. It includes: demineralized water distribution, water and air cooled DC cables and a set of switches to modify the topology of the dipole power converter.

2.2 The preparation of the components

The five magnets installed for Phase 1 underwent extensive tests. One of the dipoles was quenched 86 times at different current levels. On one occasion, in this same magnet, the heaters failed to fire because of a short in an instrumentation feedthrough connection box.

Every magnet had to be converted from a test bench configuration to a tunnel compatible configuration. As an example, the upstream end of a dipole is shown before and after the modification.

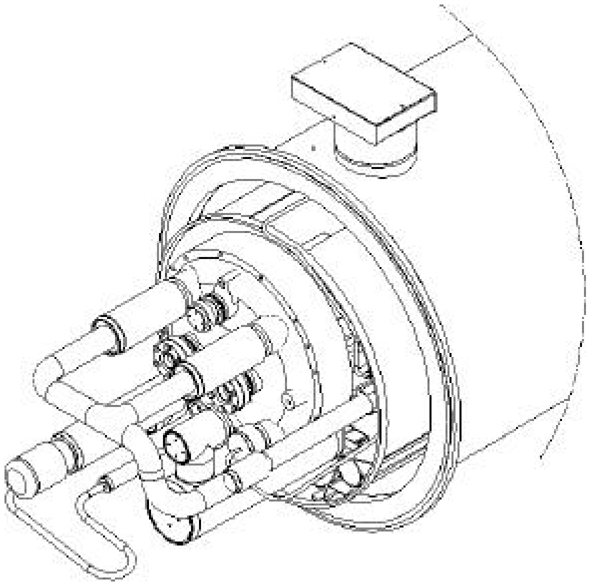

Figure 2 : Dipole upstream end in test bench configuration

Most of the modifications concerned the cryomagnet extremities; in particular the cold bores which were fitted with RF contacts and beam screens but also the M1, M2 and M3 tubes which contain the main and spool-piece bus-bars. A final design instrumentation feedthrough, the by-pass diode on every dipole were mounted. Line N, which contains the bus-bar cable for the lattice correctors, was mounted and fitted with its flexible hose.

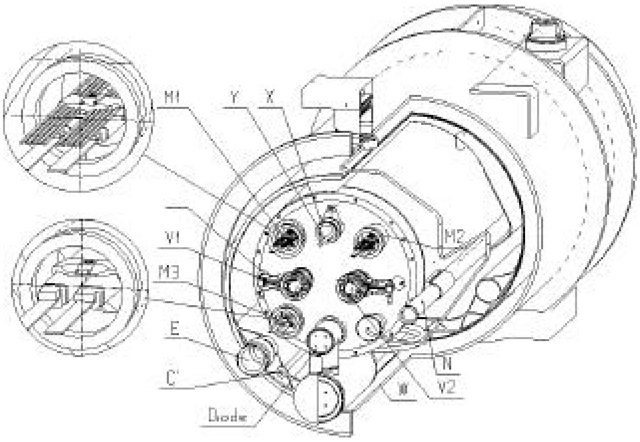

Figure 3 : Dipole upstream end in tunnel configuration

Although the learning process is clearly visible in the decreasing preparation times, it remains still above the times foreseen for the series magnets by a factor 10.

During their preparation, a number of tests were made to qualify the magnet on reception, to verify the result of an operation and finally qualify the magnet for installation. These tests included :

- the dimensional verification of the magnet extremities,
- the measurement of the cold mass position with respect to fiducials on the vacuum envelope,
- leak tests of all components before installation and after the welds,
- electrical insulation tests of the coils and the instrumentation at the reception and after the installation of the diode and the instrumentation feedthrough,
- electrical measurements of the transfer function, of the coil resistance and of the continuity of the circuit before installation.

2.3 The assembly

Before the assembly of the magnets started, the QRL was installed on its supports, welded and leak tested. The magnets were then joined by operations first performed in the innermost tubes (the cold bores) and then advancing towards the periphery.

After the cold bores were fitted with the RF contacts and welded, the main bus-bars were soldered and insulated. These were then followed by the ultrasonic welding of the spool-piece bus-bars and the welds of tubes containing the bus-bars. An electrical insulation test was performed after soldering or ultrasonic welding of bus-bars. Although these tests yield no information on the quality of the junction, at least for the ultrasonic welds a prototype automatic machine with well controlled parameters was used. The quality of these junctions can be verified on samples.

The flexible tubes of the beam-screens and the lines thermalising the support posts and the thermal shield were then welded. After all these welds, a partial leak test was performed

Line N was not welded until the bus-bar cable was inserted over the full length of the half-cell.

The learning process is also visible for the assembly operation but is still a factor close to 2 with respect to what is expected for the assembly in the tunnel.

In the assembly phase, String 2 has already yielded precious information about the mechanical design of interfaces, alignment, assembly and quality assurance procedures. It has also validated the assembly process. The presence for the first time of components like beam screens, RF contacts in the interconnects, BPMs in the short straight sections has validated the design and highlighted possible improvements for the series production.

3 INCIDENTS

A number of incidents occurred during the preparation and assembly process. Only the most important ones, in terms of consequence they had or could have had, are reported.

3.1 Leak in the cooling tubes of a beam screen

A leak in one of the cooling tubes of a beam screen developed after it was inserted in the cold bore and pressure tested. The beam screen was removed and sliced to investigate the leak. Following an extensive analysis, it was concluded that the leak had most likely been caused by remaining traces of chlorine contained in lubricants used during the manufacturing process of the cooling tubes. As a consequence of this incident, the beam screens were extensively tested after each operation during the assembly in the cold bore.

3.2 Instrumentation wires left inside the cold mass

After the measurements on the test bench, the magnets were flushed with high pressure nitrogen gas to expel eventual debris left from manufacturing or produced during the tests. This process revealed that the flux loops and the cold bore insulation did not to survive a quench: the former were abandoned while the latter was re-designed. A side effect of this process was the blowing of the wires for the test bench specific instrumentation deep inside the domed end of the dipoles. For two dipole magnets these instrumentation wires were left inside the cold mass without being insulated. During the qualification test prior to installation, the value of the coil resistance was unusually low because some of the voltage taps were in contact with the bus-bars. A visual inspection of the bus-bar tubes revealed the presence of the uninsulated wires deep inside the cold mass.

3.3 Interference of instrumentation connectors with the QRL

When the last element of the magnet string, SSS3 was installed, the connectors to instrumentation in the vacuum vessel fixed on a flange on the side of the vessel were found to interfere with one of the valve boxes of the QRL. Fortunately, the wires conveyed signals from sensors installed upstream of the vacuum barrier: the set of connectors could be moved to another opening on the vacuum vessel.

4 NON-CONFORMITIES

The following major non-conformities were encountered. They are classified according to their nature:

mechanical
  - ovalisation of beam tube in N1
  - cold-bore length in SSS4
  - incompatibility between QRL jumper and SSS type
  - leaks of the bus-bar plugs in SSS3

electrical
  - short to ground in orbit corrector of SSS4
  - damage to orbit corrector current leads in SSS3
  - short to ground in sextupole spool-piece in A2
  - spool piece corrector bus-bar positions in SSSs

instrumentation related
  - missing voltage taps in SSS4
  - broken pressure sensor in SSS3

All the non-conformities were either resolved by repairing the fault, or by-passing the faulty component (e.g. short to ground in sextupole spool-piece in A2) or else using the component as is.

4 CONCLUSIONS

The collaboration between the teams originating from different groups went very smoothly in terms of sharing of space, resources and time. During the preparation and installation of the magnets on the slabs the support of transport team in SM18 was remarkable.

A number of points can be improved for the next phase of the assembly of String 2. Namely, the definition of responsibility in border areas (e.g. installation of the diode), the definition of procedures and their sequencing (e.g. electrical tests), the optimisation of the procedures (e.g. bus-bar soldering, ultrasonic welding & insulation). Experience gained during this first phase will certainly lead to improved tooling.

The lack of a supervisor present full-time in the field and participating to the preparation and installation work across the different specialities was blatant. A number of working days were lost because of missing equipment or missing co-ordination of resources in the service divisions.

Last but not least, a work flow diagram for the preparation and assembly work which integrates the full process across group boundaries was cruelly missing. It would have improved performance and resulted in less work and shorter times. The manufacturing and test folder, MTF, for each component with the history of the component before its delivery for installation in String 2 was either incomplete or missing. For Phase 2, emphasis should be put on this document so that all the operations and tests carried-out during the assembly are also recorded in a single document. The incident of the instrumentation wires left un-insulated inside the cold mass would have certainly been avoided if all the tools aiming at quality control had been used.

5 ACKNOWLEDGEMENTS

The quality of the preparation achieved despite the shortcomings enumerated above, was remarkable in as much as many parameters were measured to be well within tolerance of what is aimed for the collider. This was possible thanks to the quality of the work of many colleagues in the CRI, ICP, MMS and VAC Groups of the LHC Division and MF Group of the EST Division.

FITTING THE INSTALLATION SCHEDULE TO THE AGREED TARGET MILESTONES

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Abstract

A revised schedule for the construction and installation of the LHC machine has been issued; it demonstrates the feasibility of the installation of this accelerator in the time frame agreed between CERN management and the spokespersons of the four LHC experiment collaborations.

1 THE AGREED TARGET MILESTONES

Following discussions between CERN management and experiment spokespersons, seven milestones and time windows were agreed (cf. L. Evans memorandum to all LHC project engineers, ref. DG/DI/LE/jf/2001-37 dated 14 Feb. 2001). These dates are recalled in table 1.

Table 1: Agreed target milestones and time windows

Sector test	01 Apr. → 30 Sep. 2004
Ring closed	31 Dec. 2005
First beam	01 Feb. 2006
First collisions	01 Apr. 2006
Shutdown 2006	01 May → 31 Jul. 2006
Run with protons	01 Aug. 2006 → 28 Feb. 2007
Run with lead ions	01 Mar. 2007 → 12 Apr. 2007

2 LEP DISMANTLING & CIVIL WORKS

Following CERN Director general's decision not to go ahead with an additional run of LEP in 2001, it was necessary to re-schedule the LEP dismantling, to take into account the additional month to LEP run 2000, the late arrival of some authorisations for dismantling LEP, and some delays in contract mobilisation. This schedule review had consequences on LHC civil works, and together with a value engineering review of civil work by package 3A contractor, and ad hoc progress review with the other civil engineering contractors, new taking over dates have been agreed. These new dates aim to limit the financial consequences of this re-scheduling exercise within the overall milestones as laid out by the management of the project. Main taking over milestones of underground works are given in table 2.

Table 2: Taking over milestones of underground works

Works	*Date*	*Contractor*
Point 1 * * related to the Machine	10 Jan. 03	#1
UJ/PM18	31 Jan. 03	#3A
UJ22	11 Jan. 02	#3A
TI2, PMI2	31 Jan. 03	#3A
UJ28, UP25	10 May 02	#3A
Sector 3·4	late 2002	"Jura"
Point 5 * * related to the Machine	22 Aug. 03	#2
Point 6 left to IP6	27 Jun. 03	#3A
Point 6 right to IP6	22 Feb. 03	#3A
RR73	28 Jun. 02	#3A
RR77, UJ82	10 May 02	#3A
UJ88	12 Apr. 02	#3B
TI8	July 02	#3B

3 CRYOGENICS

Among all the cryogenics installation works, the installation of the so called QRL (tunnel cryo-distribution line) is the most critical. LHC/ACR are targeting the September 2001 Finance committee for awarding the manufacturing and installation contract for this piece of equipment. In the technical specification associated to the first tendering phase, it was mentioned a 15-month period for completing the detail design of the QRL, for procuring components entering in the fabrication and for starting the fabrication. This leads to January 2003 for starting installing the first sector. LHC/ACR have also asked for a 18-weeks periods for installing the QRL in one sector, and an additional 9-weeks period for commissioning it (except for the first QRL sector to which a 50% duration increase has been requested). Other groups are concerned with these works, and they have asked for some weeks in between for installing their equipment and cables.

Sector 7·8 (also known as sector test) is foreseen to be the first one to be installed. The installation of the QRL in this sector is scheduled from January to May 2003, and its commissioning from May to August 2003.

For the commissioning of the eight sectors of the QRL, the corresponding QUIs (underground cryogenics interconnection boxes) need to be installed and commissioned, so do the vertical cryo-piping works and 4 K cryo-plants. The LHC installation schedule shows that the installation and commissioning of these items are feasible in the associated time windows, and are much less critical than the installation and commissioning of the QRL.

The scheduling of the QRL in the seven other sectors are constrained by the availability of resources for their commissioning. In other words, the eight QRL commissioning time windows must not overlap. The QRL installation sequence is then constrained by the commissioning sequence.

The sequence of sector installation is based on the availability of civil works, and the priority for the taking over of these works is based on the project management short term strategy, i.e. sector 7·8 installed and hardware commissioned by September 2004 for sector test. For reaching this, priority is given to TI2 and related works (lowering and transportation of magnets), TI8 and related works (injection test tunnel), and works related to the machine at points 1, 8 and 7. Consequently, the optimised sequence is the following:

7·8 → 1·2 → 8·1 → 2·3 → 3·4 → 4·5 → 6·7 → 5·6

Table 3 summarises the time periods associated to the installation and commissioning of the QRL in the eight sectors.

Table 3: QRL installation and commissioning

Sector	*Installation*	*Commissioning*
7·8	6 Jan. 03 → 9 May 03	12 May 03 → 22 Aug. 03
1·2	7 Apr. 03 → 11 Aug. 03	25 Aug. 03 → 24 Oct. 03
8·1	9 Jun. 03 → 13 Oct. 03	27 Oct. 03 → 09 Jan. 04
2·3	11 Aug. 03 → 15 Dec. 03	12 Jan. 04 → 12 Mar. 04
3·4	13 Oct. 03 → 01 Mar. 04	15 Mar. 04 → 14 May 04
4·5	8 Mar. 04 → 9 Jul. 04	26 Jul. 04 → 24 Sep. 04
6·7	17 May. 04 → 20 Sep. 04	4 Oct. 04 → 3 Dec. 04
5·6	19 Jul. 04 → 22 Nov. 04	6 Dec. 04 → 18 Feb. 05

4 GENERAL SERVICES

The refurbishing of general services and infrastructures for LHC involves several groups in the EST and SL divisions. Preliminary schedules have been issued and show that these works are feasible in a 40-week time window. This includes: the restoration of the AC distribution network (18 kV), the marking of the position of equipment by the survey group, the upgrade of the cable trays, the pulling of power and control cables by ST/EL, the pipe works by ST/CV… The general co-ordination schedule shows that these 40-week time windows can easily be fitted in the mean time left between the taking over of civil engineering underground works, and the time spans allocated for installing and commissioning QRL sectors.

5 LHC MACHINE

The following assumptions were made for installing the LHC machine in the arcs (continuous cryostats):

- Machine elements only to be installed when the commissioning periods of the QRL are completed.
- Machine elements (cryo-dipoles, SSSs and DFBAs) available for installation, at least at the rate of installation.
- Support jacks installed together with the commissioning of the QRL.
- Pit (PMI2), transport routes (TI2 downstream side, UJ22, sectors 1·2 and 8·1) and transport vehicles are operational as from mid-May 2003.

5.1 Elementary sequence for installing the LHC

An analysis of the detailed sequence of installation and interconnection of LHC machine elements was made showing that it is possible to install one element per day, and that the amplitude (see figure 1) of work is approximately equal to 50 days.

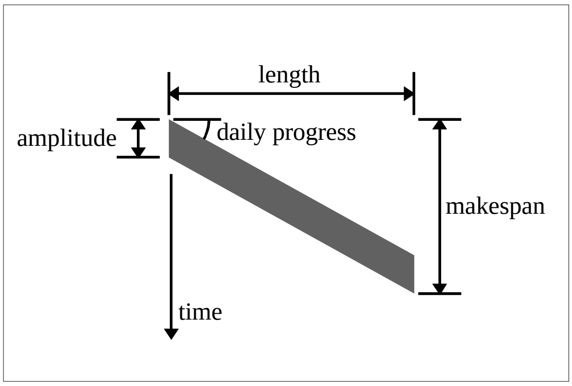

Figure 1: Determination of the makespan of a sector.

Each continuous cryostat is made of approximately of 200 elements. If one decided to start at one end of a sector, progressing to the other end, the make span required for completing one sector can be calculated as follows:

$$\text{length} \cdot \text{daily rate} + \text{amplitude} = 200 \times 1 + 50$$

to which a learning period must be added, i.e. a 20 % increase on 25 interconnects.

Following this scheme, 255 days, i.e. about one year would be required for completing the installation of a sector. This is not compatible with the agreed target milestones (see § 1.).

Hence two fronts of installation must be envisaged, with an installation starting from the middle of a sector progressing towards both extremities. With the second front of installation starting 4 weeks after the first one, this scheme leads to 175 days, i.e. approximately 8 months, which is feasible and compatible with the milestones as set out by the Project management.

5.2 Installation & commissioning in sector 7·8

The installation of sector 7·8 is scheduled to start in August 2003, and expected to be completed for hardware commissioning by April 2004.

The so called hardware commissioning period will consist in pressure testing the whole sector (elements belonging to the continuous cryostat), performing electrical checks at warm temperature, cooling down the sector, performing additional electrical checks at cryogenics temperature, performing a smooth alignment of the sector elements, commissioning the quench detection systems and other machine protection systems, commissioning the machine powering systems…

Table 4: LHC Machine installation

Sector	*Side*	*Team*	*Installation period*
7·8	L8	1	25 Aug. 03 → 25 Mar. 04
7·8	R7	2	15 Sep. 03 → 13 Apr. 04
1·2	L2	3	27 Oct. 03 → 26 May 04
8·1	L1	1	06 Feb. 04 → 27 Aug. 04
1·2	R1	2	25 Feb. 04 → 14 Sep. 04
2·3	L3	3	08 Apr. 04 → 25 Oct. 04
8·1	R8	1	12 Jul. 04 → 26 Jan. 05
3·4	R3	2	28 Jul. 04 → 24 Feb. 05
2·3	R2	3	07 Sep. 04 → 07 Apr. 05
3·4	L4	4	04 Oct. 04 → 11 May 05
4·5	R4	1	09 Dec. 04 → 15 Jul. 05
6·7	L7	2	07 Jan. 05 → 26 Jul. 05
6·7	R6	3	18 Feb. 05 → 01 Sep. 05
5·6	L6	4	24 Mar. 05 → 06 Oct. 05
4·5	L5	1	30 May 05 → 19 Dec. 05
5·6	R5	2	08 Jun. 05 → 27 Dec. 05

A five-month period (from April to September 2004) is allocated for performing the hardware commissioning of all these systems. The tests with beam is scheduled to occur in late September 2004.

5.3 Installation of the whole LHC machine

The revised LHC installation schedule shows that up to four fronts of installation are needed, to meet the "deadline" i.e. the LHC main ring closed by December 1.). This leads to the lowering and installation of up to 20 cryo-magnets per week.

Transport time for a cryo-magnet depends to its final location in the main ring. Because the transport vehicles (3 for cryo-dipoles and 2 for SSSs and special equipment) are designed to reach 3 km/h in arcs and linear sections, and 1 km/h in singularities, up to 10 hours may be needed. In case of problems, transports are also foreseen over weekends.

According to this new installation scheme, with two fronts of installation starting in the middle of a sector, the availability dates of DFBAs and of DS SSSs (Q7s to Q11s) for installation are delayed, as compared to the previous schedule. The installation of these element now starts in Dec. 03.

6 CONCLUSIONS

It is demonstrated that the installation of the LHC machine is feasible in the time span allocated, i.e. before end 2005. However this revised schedule is very tight; and no time is left to contingencies. Further investigations need to be carried out for confirming the feasibility of the installation in the allocated time scale: detailing the installation of the services and of the machine in insertion regions, and performing sensitivity analyses in order to appraise the consequence of some shortage of cryo-magnets on the machine installation overall schedule.

INSTALLATION OF THE CRYOGENIC DISTRIBUTION LINE

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N. Veillet, SOTEB, Saint-Genis-Pouilly, France

Abstract

A brief introduction to the Cryogenic Distribution Line (QRL) highlighting the installation relevant particularities with respect to the continuous magnet cryostat is given. The QRL installation concept will be described emphasizing interferences with other activities and related safety issues.

1 INTRODUCTION

The LHC cryogenic distribution scheme for each of the eight sectors, individually served by a refrigeration plant, is based on a separate Cryogenic Distribution Line (QRL) feeding helium at different temperatures and pressures to the elementary cooling loops of the magnet cryostats every full cell length (106.9 m for the arc) [1]. Each QRL sector is a continuous cryostat of about 3.3km length without any fluid header sectorisation. In 1998 CERN adjudicated contracts to Air Liquide, Linde-Babcock and HELU[1] for a 110 m long Pre-Series Test Cell. Each test cell, designed, manufactured and installed by the suppliers at a dedicated test facility at CERN [2], was extensively tested in 2000 and 2001. Final QRL contract adjudication to one or more suppliers is expected for September 2001.

2 QRL LAYOUT

The QRL is a repetitive pattern of Service Modules (QRL-SM, a few meters long) and Pipe Modules (QRL-PM, ~ 100 m long). A QRL cell inside the arc consists of one Service and one Pipe Module. The Service Modules are single elements providing via the so-called Jumper Connection the link to the machine cryostats (see Figure 1). The Pipe Modules are made up of several Straight Pipe Elements (length varies in between ~12 m and ~20 m for the three different designs) and interconnects including the bellows to compensate for the longitudinal thermal contraction in between two fixed points.

The Service Modules contain the cryogenic control valves for the local helium circuits, quench valve(s), a subcooling heat exchanger as well as the necessary instrumentation such as flowmeter, temperature and pressure sensors. The 8 QRL sectors contain 307 Service Modules of about 40 different types, of which 208 Modules of 9 different types are foreseen within the arcs and Dispersion Suppressors (DS).

Inside the tunnel the QRL is placed in between magnet cryostats and tunnel wall. Inside the arc and DS the QRL standard height above floor is 400 mm using the tunnel groove for the external supports. The outer diameter is 610 mm with a maximum envelope of 750 mm due to e.g. the interconnect sleeves including bellows. Inside the Long Straight Sections (LSS) the respective values are 650 mm and 800 mm. The QRL height above floor varies along the LSSs (e.g. 850 mm inside the RA tunnel).

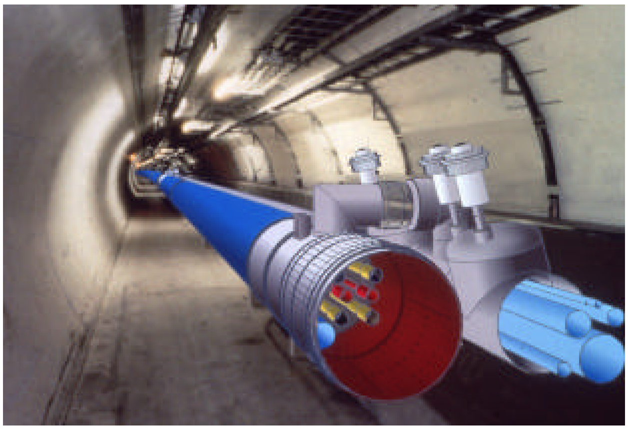

Figure 1: Perspective of Magnets/QRL in the tunnel

3 TRANSPORT AT CERN

All QRL elements will be lowered to underground via the PX shafts (∅ 10 m) at the even points and introduced from the corresponding UX caverns into the respective machine tunnel sector (exception: QRL elements for sector 2-3 will be lowered at point 4 and transferred via sector 3-4). As a mean value about 38 Service Modules (~1500 kg) and, depending on the design chosen, about 160 to 300 Straight Pipe Elements per sector will have to be lowered and distributed along the tunnel. All transport and handling equipment will be provided by the QRL contractor using CERN's installation such as overhead cranes and electrical tractors to pull the QRL elements along the tunnel. A transport simulation with one 20.5 m long Straight Pipe Element is foreseen in June 2001.

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[1] HELU consortium: Alstom, CH (leader), Kraftanlagen (D), Messer-Griesheim (D), Nexans (D) and Nordon (F)

4 QRL IMPLEMENTATION

The 3D implementation studies, done by CERN for the three different QRL designs and based on the year 2000 measurement campaign of the tunnel geometry (accuracy: ± 2 cm) revealed for the QRL eight critical cells in sector 1-2 and 4-5, where the respective QRL Service Modules are in collision with the tunnel wall by up to 33 mm. With the QRL being at nominal position the collision is due to civil engineering tolerances of the tunnel. For 22 further LHC cells the respective Service Module approaches the tunnel wall by less than 30 mm. These values do not consider the built-in Jumper Connection flexibility and Service Module adjustment capability, which allows a relative displacement of the magnet cryostats with respect to the QRL of a up to 25 mm horizontally and 50 mm vertically following magnet re-alignments throughout the LHC lifetime.

To overcome these interferences, the tunnel will have to be modified locally to enable the installation of the Service Modules concerned. The Pipe Modules on each side of these Service Modules, will have to be installed with their interconnects slightly moved towards the magnet cryostats to avoid further collisions with the tunnel wall, but keeping a minimum distance in between the QRL and the magnet cryostat of 80 mm.

The Jumper Connections link the QRL Service Module to the Technical Service Module (QQS) of the Short Straight Section (SSS) on the magnet side. This QQS/QRL assembly is the most critical area as concerns machine cryostats and QRL. At distinguished points the two machine elements approach to about 42 mm nominal minimum gap in between the QRL-SM valve boxes and the QQS including the interconnect with the adjacent dipole cryostat.

The Jumper Connection region with the horizontal bellows (part of the articulated bellows system, which enables the relative displacement of SSS and QRL-SM) and the SSS vacuum jacket feedthroughs is tight and critical for “non-hardware interferences”, such as electrical connectors, for which it might not be able to plug them in with the two elements in place.

Similar studies as well as the respective tunnel geometry database are still to be done for all Long Straight Sections, where the tunnel cross-section due an increased QRL outer diameter and a worse relative position of the elements concerned, is even more critical (nominal minimum gap of about 18 mm).

The beam dump and other (e.g. point 3 left) areas are critical for the QRL installation due to their special layout configuration.

5 QRL PLANNING ASPECTS

After contract adjudication the QRL planning considers 14 months for engineering and manufacturing of the first QRL sector to be installed, which is sector 7-8. Its installation will start beginning of January 2003. The installation of each QRL sector will take 4 months (18 weeks) and will be done by a team of about 30 to 40 people per sector during the day, with tests (e.g. X-ray examination of welds) and other special activities during the night shift. For commissioning activities and reception tests of an installed QRL sector, 11 additional weeks are foreseen (15 weeks for the first sector to be installed). Before starting the installation, access is required for a survey team of the respective QRL contractor for dedicated measurements. With the QRL contractor different CERN groups will need to work partly in parallel for installing e.g. the cable tray on top of the QRL or connecting vacuum and cryogenic instrumentation necessary for the QRL commissioning and the reception tests.

For reception testing a QRL sector, which will take place before magnet installation in the sector concerned, the Jumper Connection of each Service Module will be equipped with a test cap remaining, which will remain until the magnet installation. These elements, as they are stepping forth, will be protected by “crash barriers” against accidental damages e.g. during transport activities in that area.

6 SUMMARY

To keep the tight planning all pending machine integration studies will have to be completed on time as well as transport and logistic issues need to be concluded. The first QRL sector installation will start in January 2003.

REFERENCES

[1] W. Erdt, G. Riddone and R. Trant, “The cryogenic Distribution Line for the LHC: Functional Specification and conceptual design”, in “Adv. Cryo. Eng.” 45, Plenum Press, New York, (2000), 1387:1394

[2] J. Livran, G. Mouron, C. Parente, G. Riddone, D. Rybkowski and N. Veillet, “A Cryogenic Test Set-up for the Qualification of Pre-Series Test Cells for the LHC Cryogenic Distribution Line”, in “Proc. ICEC 18”, Narosa Publishing House, New Delhi, India (2000), 227:230

INTEGRATION AND INSTALLATION STRATEGY OF THE CONTINUOUS CRYOSTAT

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Abstract

The techniques used to study in 3-D the tunnel infrastructure and layout are presented along with some examples. It is described how we get from the finished cryomagnets available at the surface ready for descent to cryomagnets in their final position in the tunnel.

The strategy, the resources (tooling, infrastructure, personnel), the time required as well as the interference with other activities and equipment are presented in detail. Specific safety issues will also be addressed.

1 INTRODUCTION

This presentation merges two different subjects, the machine integration inside the tunnel and the installation of the continuous cryostat. General logistics, a major subject for the success of the installation of the LHC, will not be treated, except for some hints, neither the safety aspects which should not be minimised, especially in these underground activities.

2 THE INTEGRATION OF THE LHC

The integration is done via a Digital Mock-up (DMU), a 3-dimensional representation of what is inside the tunnel. It has already been presented elsewhere [1] and will only be summarised here.

2.1 Why a DMU?

A complete DMU for the LHC means a large effort, but the heavily crowded LHC tunnel justifies this. A crude comparison between a LEP cross-section and a LHC cross-section shows that the hardware of the latter occupies 4 times more space than the former. The potential interferences between systems are numerous. Any problem will slow-down the installation: modification, repair, non-standard part, etc., and will cost resources. The DMU is used to specify accurately at the time of the Invitation for Tender, is the basis for the installation drawings and should avoid costly in-situ adjustments.

2.2 Methodology

In the standard zones of the tunnel (80 % of the circumference), most of the systems are more or less periodic. Therefore, an automatic generation of the DMU has been preferred and the software is presently under preparation.

The non-standard zones have to be integrated mostly manually: each group is supposed to provide the 3-D model of his equipment based upon the initial integration layouts, then the integrator merges all the models together. This is usually done with EUCLID CAD software, but ROBCAD would be better suited for that. Interferences are then located and solved during weekly meetings (ICL), leading to local modifications, issuing of ECRs. Much iteration is needed in the critical zones before solving all the problems. Some zones are considered as very critical and no solutions have been found yet.

2.3 Problems

The major difficulty in the integration work is to use correct information, meaning an efficient configuration management of the project. Use of standards, verified and approved version of the elements, could solve this.

Tunnels are so crowded that all the civil engineering should be known accurately, much better than for the LEP. This was not the case two years ago, but the situation has improved greatly following survey campaigns; a last one is presently under way.

Surprisingly, an other difficulty is the lack of knowledge of what is inside the tunnel at a given location. This is being solved by the creation of schematic layouts for the various systems.

Finally, since the information comes from different teams, their reactivity influences greatly the pace of the integration work.

However, a DMU cannot replace the practice: handling, accessibility, training, etc. A full-scale tunnel (R) is required by many teams.

3 THE INSTALLATION STRATEGY OF THE CONTINUOUS CRYOSTAT

3.1 The continuous cryostat

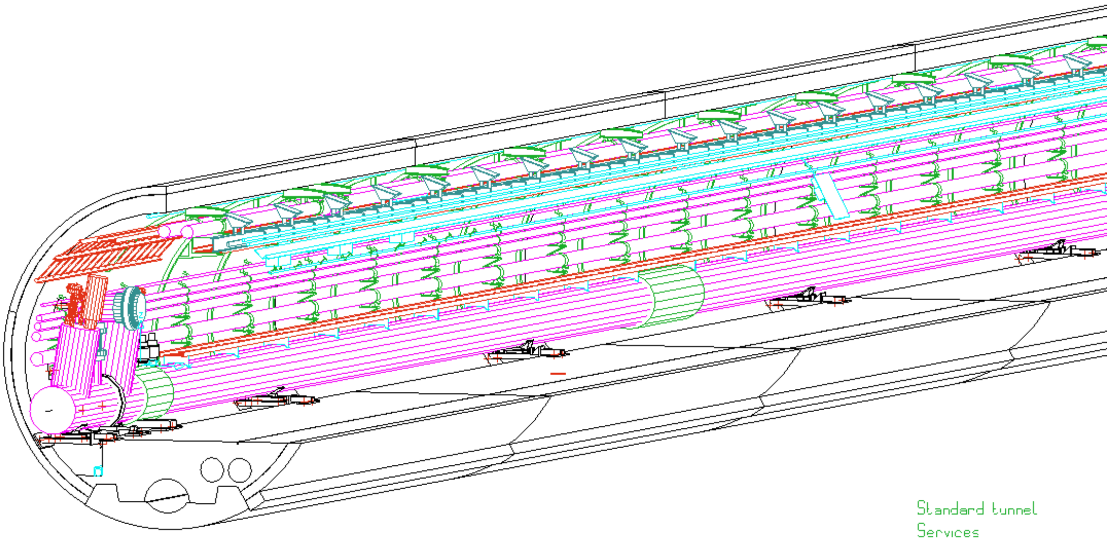
The continuous cryostat is different from one sector to the next. According to the nomenclature, it includes the ARC, the two DS, the Q7, when existing, and ends at the DFBA. In some particular cases, it may include also D3 and Q6. It ends 230 to 250 meters from the IP and therefore it is longer than the LEP ARC+DS was.

It is mainly located inside the standard tunnel (R) but this standard tunnel, designed for LEP geometry, ends usually 296 m from the IP. Therefore, part of the installation of the continuous cryostat will be done inside non-standard zones like UJ, RR and RA, leading to many particular cases (different floor slope, different beam height, specific environment).

3.2 *Preparation*

The preparation of the installation of the continuous cryostat starts underground as soon as lighting is available; the locations of the jacks are then marked on the floor. Tunnel floor has to be corrected to fulfil the transport requirements: drain covers have to be reinforced to bear the high specific loads of the transport vehicles and the steps larger than 8 mm have to be smoothened. Jacks requirements have also to be taken into account: correction of the height of the floor by grinding when it is outside the specified range (too high), local reinforcement of the trench in case of a radial offset, etc. Tunnel walls may interfere with installed equipment or transport vehicles in some zones. Local corrections (cutting, grooves, etc.) are then required. The infrastructure needed for the transport is the powering rail (so-called LEP monorail), which has to be restored all over the circumference of the LHC and the wire guiding system buried in the floor.

As soon as the QRL has been installed in a sector (Fig. 1), the jacks ground fixations are put in place, the jacks are installed, including the shimming when the floor is outside the acceptable range (too low) and the jacks' heads are positioned to correct location in space.



Standard tunnel
Services
16/03/2001
Y. Muttoni

Figure 1: The tunnel with the QRL installed.

3.3 *Installation*

The installation of the continuous cryostat can now proceed: cryomagnets are brought down to their final position one by one.

A cryomagnet is waiting in SMI2 for the clearance from the Magnet Evaluation Board. Its final location has been decided (some days in advance) and its ends prepared accordingly. Its traveller is fully completed.

The cryomagnet is lifting down the pit PMI2 and put onto a transport vehicle. It travels through the injection tunnel TI2 to and the junction chamber UJ22. There, it starts its translation around the tunnel either clockwise or anti-clockwise, avoiding the experimental halls 1,2,5 and 8 through by-passes (UA, UL and US).

After some hours at low speed, the cryomagnet arrives at its final position in the passageway, its end covers and transport restraints are then removed. The integrity of the cryomagnet is then checked.

The cryomagnet is translated sideways and installed on its jacks with the transfer table. Alignment is performed and the central jack is added in the case of a cryodipole (Fig. 2).

The cryomagnet is then ready for interconnection!

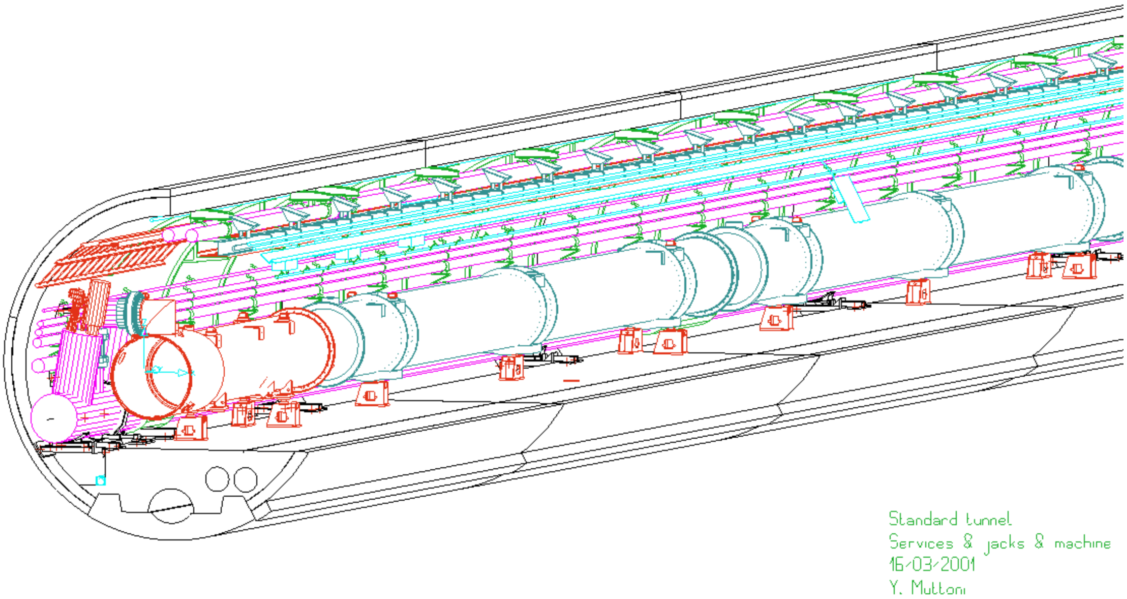


Figure 2: The tunnel with the cryomagnets ready for interconnection.

4 SOME HINTS ABOUT LOGISTICS

Transport through the tunnel will be done at very low speed and could interact strongly with the underground activities if not properly planned. Some hints on the cryomagnets transport are given below.

The transport vehicles of the cryomagnets have a 3 km/h nominal speed, which is reduced to 1 km/h in critical zones like by-passes.

When unloaded, their speed is 4 km/h. Therefore, the transport duration from UJ22 to any point of the tunnel, 2-way and unloading time, could be up to 11.5 hours for a cryomagnet to be installed around point 6.

The present planning is based on the hypothesis that the transport vehicles will go through the sectors under installation only during the 8 hours night shift. Taking into account the speed of the vehicles, this means they cannot go through more than 2.5 octants in work during the night shift.

The worst conditions for the transport will occur during Q1 2005 when four teams will be working in parallel and 5 cryomagnets will have to be transported each day. Taking into account the number vehicules ordered, these conditions correspond to a daily average use of a vehicle of 14.25 hours.

5 ACKNOWLEDGMENTS

The author would like to quote the main contributors outside LHC division: EST-ME, EST-ISS, EST-SU, ST-GC, ST-CV, ST-EL

REFERENCES

[1] S. Chemli et al. – A virtual CAD Model of the LHC - 2000 European Particle Accelerator Conference (June 2000).

CRYOMAGNETS INTERCONNECTIONS AND CONNECTIONS TO THE CRYOGENIC DISTRIBUTION LINE

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Abstract

This paper is a summary of the presentation made about the cryomagnets interconnections and connections to the cryogenic distribution line in the frame of the LHC days 2001 at Villars. The presentation was included in the third session : "From working components towards complete system : installing and assembling". After giving the assumptions and a brief overview of the technologies developed to carry out the interconnections, the sequence is described step by step. The activities of the LHC-VAC group, mainly the installation of the RF modules, has been presented separately. Then the interconnection activities related to the jumper are described. Finally, as conclusion, an overview of the duration estimates is presented and open issues are listed.

1 INTRODUCTION

The design of interconnections between the cryomagnets and with the cryogenic distribution line (QRL) has been carried out by the LHC-CRI-I2 section with the support of the EST division. The scope of this presentation is limited to the standard LHC Arcs. Few adaptations are required to adapt it to the Dispersion Suppressors zones. The interconnection activities start only after commissioning of the QRL and after installation and alignment of the cryomagnets. Several interconnection configurations have been developed to accommodate the different types of cryomagnets. Pressure and leak tests are not integrated in this paper. They are treated in a separate paper. [1]

2 THE TECHNOLOGIES

2.1 Inductive soldering

This technology was developed to perform the junction of the main busbars. The main constraints and requirements are :

- High number of joints (about 10 000)
- High current intensity (up to 13 000 A)
- Low electrical resistance (< 0.6 nΩ to meet the cryogenic budget requirements)
- Limited space (both longitudinally and radially)
- High reliability and quality
- Economical and schedule constraints.

The procedure comprises the main following steps :

- Compression of the bellows and of the lyra
- Assembly of the interconnection components (Sn/Ag solder ribbons, copper pieces, ..)
- Installation of the machine on a dedicated support structure
- Inductive heating is chosen for its fast thermal transient capability. This is to preserve the super-conducting properties of the cables, the heating duration is limited to about 90 seconds between 223°C and 230°C.

A non-corrosive flux classified 1.1.1 (see ref. [2]) is used. It was selected after testing (mechanical, electrical, corrosion) carried out in the framework of the Flux Working Group. To ensure a good quality, the cable extremities must be in good conditions (cleanliness, dimensional accuracy), and stabilised beforehand. This technology is giving very good results and has been used for STRING2 interconnections. The repair procedure by unsoldering the junction has also been successfully tested.

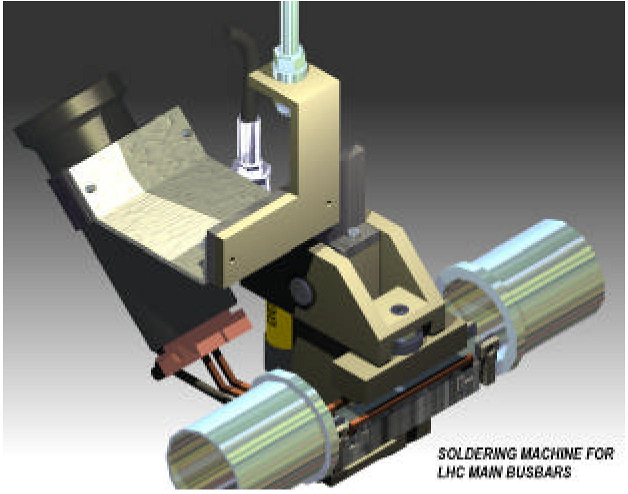

Figure 1 : Inductive soldering machine

2.2 Ultrasonic welding

This technology was developed in collaboration with LAPP (Laboratoire d'Annecy de Physique des Particules) to perform the junction of the auxiliary busbars. The main constraints and requirements are :

- High number of joints (about 50 000)
- Current intensity (up to 600 A)
- Low electrical resistance (< 18 nΩ to meet the cryogenics budget requirements)
- Limited space (both longitudinally and radially)
- High reliability and quality
- Economical and schedule constraints.

The process is controlled by on-line recording of operating parameters such as power, driving in, time, dissipated energy. This technology was also applied for STRING2 and is giving very good results.

The repair scenario consists in cutting the welded joint and welding a bridge. This makes an additional joint but the margin on the electrical contact resistance is high enough to allow this.

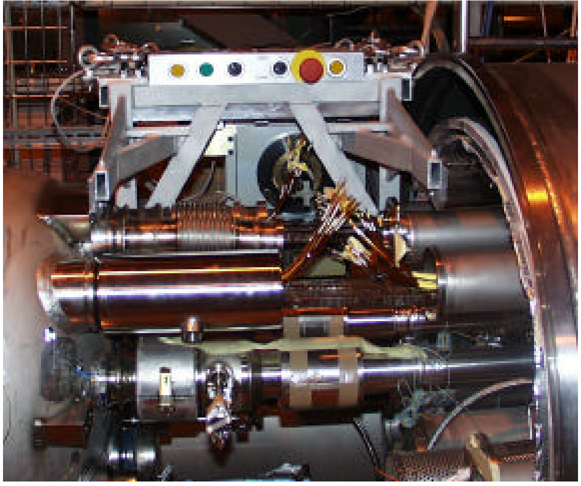

Figure 2 : Ultrasonic welding machine on STRING2

2.3 *TIG welding*

This method is selected to carry out the welds on the various cryogenics pipes because it is fulfilling the following requirements :

- High number of welds (more than 30 000)
- Limited space (both longitudinally and radially), especially radial clearance of about 45 mm.
- Must be repairable
- High reliability and quality
- Economical and schedule constraints.

The choice of TIG welding together with automatic orbital machines associated with a specific weld geometry is meeting all these requirements.

2.4 *Other technologies*

In addition to the previously described technologies, an automatic cutting machine is also used in case of repair and to remove the QRL test cap.

Some additional precautions are also taken like securing all screws and nuts, working with gloves to install MLI,…

3 THE INTERCONNECTIONS

3.1 *Introduction*

The sequence of operations necessary to carry out an interconnection has been defined following some general principles :

- From inside towards outside for ease of work
- Operations involving fragile components are carried out as late as possible
- Whenever possible, operations requiring the same tooling are performed consecutively
- The most delicate parts are protected (bellows, bus bars extremities, …)
- At some points, agreement of responsible of relevant systems is mandatory to go ahead.

In this sequence, leak and pressure tests are not taken into account because they are handled in a further document.

In the following chapters, the cryomagnets interconnections will be described then the connections between QRL and the SSS are presented.

3.2 *Cryomagnets interconnections*

After installation and alignment of the cryomagnets, the first operation is the installation of the RF modules and other components under LHC-VAC responsibility.see ref[3].

After installation of the RF modules, **two TIG welds per line** have to be performed. Protection devices are installed around the beam lines interconnection.

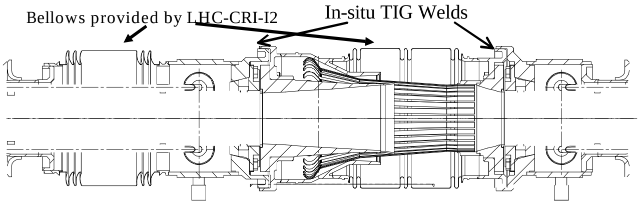

Figure 3 : Beam lines interconnection

Then, bellows and lyras of the M1, M2 and M3 lines are compressed to allow the installation of the soldering machine. The **soldering of the main superconducting cables** is performed applying the technology described in paragraph 2.1. The **electrical insulation is rebuilt**.

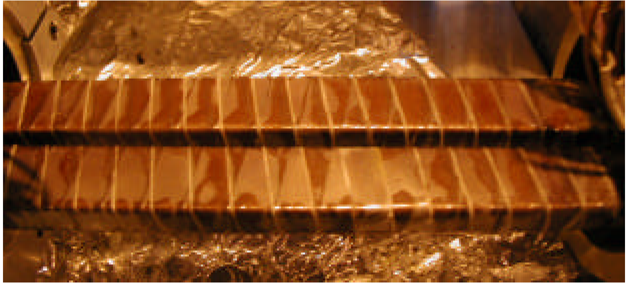

Figure 4 : Insulated busbars

After this, the **M1, M2 spool piece busbars are ultrasonically welded** applying the technology described in paragraph 2.2.

At that stage, a very important **electrical verification** must be performed. They are under LHC-ICP responsibility and are described in ref [4]. The main functions to be checked are :

- electrical continuity,
- electrical insulation
- electrical scheme.

After this, sleeves of the M1, M2, M3 lines are slid in place and the **six corresponding TIG welds** are performed.

Then, moving from inside to outside, **the two heat exchanger lines (lines Y and X) are connected**. The line Y copper tube is soldered using a non aggressive flux and the stainless steel sleeve of line X is welded at both extremities.

After this, **line C' is connected**. The TIG welding technology is applied. This system is auto-stabilised thanks to compensation loops present at both sides. Depending on the cryogenic scheme and on the location of the interconnect, the interconnection configuration is varying.

Moving outwards, the **line E expansion joint is mounted** by means of two TIG welds.

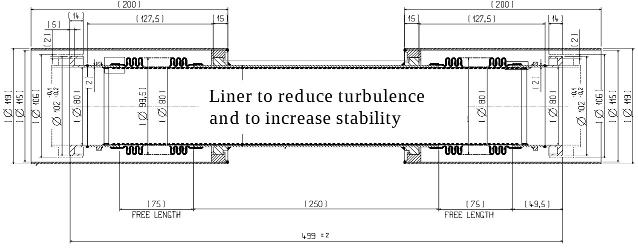

Figure 5 : Line E expansion joint

The K1,K2 hoses are TIG welded. Here also, the configuration is varying with the interconnection location around the LHC machine. Depending on the degree of preparation in surface-work, there will be 2 or 4 welds to perform in-situ.

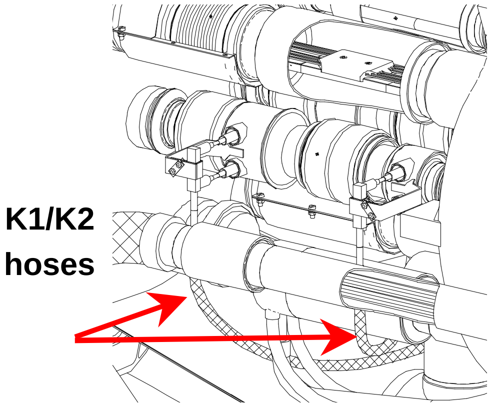

Figure 6 : Beam screen cooling hoses (K1/K2)

A that stage, a **complete visual inspection** is performed to check that all tasks have been correctly executed and that all verification parameters are recorded in the traveller.

The next operation is the **installation of the line N cable** (auxiliary busbars). This activity is carried out on one half cell. A 54-meter long portion of line N cable, equipped beforehand is inserted from the downstream side. The cable wires are ultrasonically welded (see paragraph 2.2). Up to 46 welds must be performed. The electrical connection scheme is not identical for all interconnections and its correctness is of vital importance because a mistake is very difficult to detect. Finally, the cryogenic channel is closed by four sliding sleeves (8 TIG welds).

The **interconnection area is cleaned** and it is verified that all foreign bodies (temporary protection devices, tools, tissues,…) have been removed.

Based on a check list, **all previously executed tasks are reviewed**. The approval to go ahead must be given by all involved groups. This verification is important because later, the centre of the interconnection zone is becoming less accessible.

The **radiative insulation support and the corresponding Multi-Layer Insulation (MLI) blanket (10 layers) are mounted**. MLI is assembled using Velcro fastener.

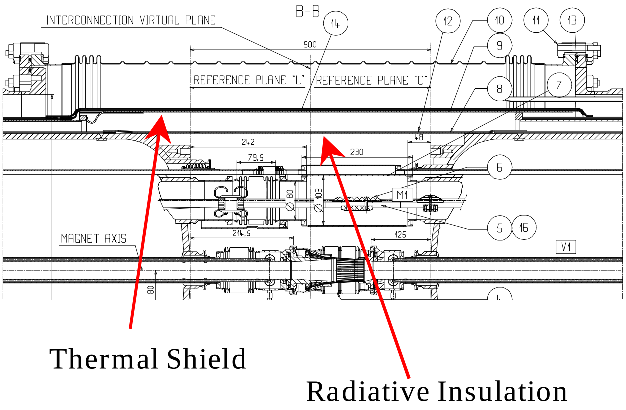

Figure 7 : Interconnection radiative insulation and thermal shield

The **thermal shield is mounted** and welded and then it is covered by two 15-layers MLI blankets. Precautions must be taken to protect MLI from catching fire.

Finally, the **W-bellows (outside sleeve) is closed** using clamps and seals.

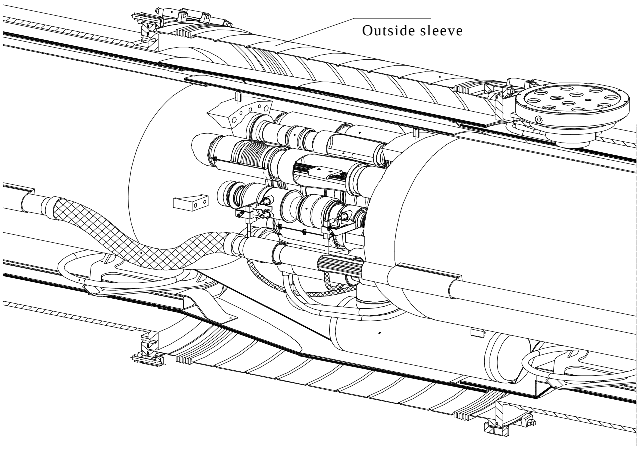

Figure 8 : MB-MB Interconnection 3D view

After completion of all the interconnection activities, a formal **review of all the aspects**, including non-conformities is organised. Its conclusion is to release the interconnection or to impose corrective actions.

3.3 Jumper interconnections

The technologies used for the jumper interconnections are a subset of the ones applied in the cryomagnet case. Only TIG welding and orbital cutting are employed.

The first activity is to **cut the QRL endcap**. This must be done prior installation of the SSS. This consists in cutting the external cap but also inner circuitry. The jumper extremity is cleaned, a provisional support template is removed and a temporary protection is mounted. Just before the SSS installation, this temporary protection is removed and the sleeves and persistent rings are selected and ounted.

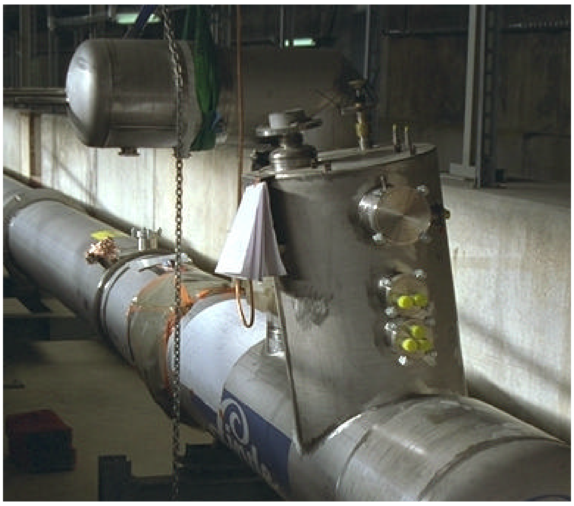

Figure 9 : QRL jumper with endcap

After SSS alignment, **the pipes are TIG welded** (about 10 welds).

Then the **interconnection is cleaned** and it is verified that all foreign bodies have been removed. Based on a check list, the completeness of work done is checked.

The **jumper interconnection radiative insulation is mounted**. The interconnection design must make the link between the QRL radiative insulation and the SSS one.

The thermal shield is mounted together with two 15-layers MLI blankets.

The **interconnection is cleaned** and a last visual inspection is performed. The **approval for closure must be given by all involved groups**. This is very important because the jumper outside sleeve is welded and the number of repairs is limited.

The jumper outside sleeve is installed and welded (2 welds).

A position monitoring device is mounted. It is still to be designed. Then, the QRL vertical bellows fixture is removed.

4 CONCLUSION

4.1 Duration estimates

Based on our experience during STRING2 assembly and on some theoretical estimates, the duration to carry out interconnection activities, after learning has been assimilated, is given in table 1. These figures will be refined after completion of phase 2 of STRING 2. As learning effect is integrated, it is obvious that the first interconnections will take longer.

Table 1: Typical durations

Scope	**Duration [hours]**
One typical interconnection (MB-MB)	≈ 70
One half cell (4 interc. + line N installation)	≈ 320
One cell (2 half cells + 1 jumper)	≈ 700

4.2 Open issues

The benefits of a **training mock-up**, simulating the tunnel environment has been underlined. The same mock-up could also be used for installation study and test. It would allow testing of the machines and tooling in a representative environment, training of the various teams (installation, interconnection, verification,…), and could also be used for demonstration and visit purposes.

As pointed out, the **preparation strategy of the K1/K2 hoses** used for beam screen cooling must be defined. To limit the number of in-situ welds to two per interconnection requires a more complex preparation in the surface (SMI2 building) and protection of the hoses. This has the great advantage to decrease the number of in-situ welds by a huge amount (about 3 500 welds) and so the risk of leaks. Moreover, the complex preparation work has anyway to be done and it is obviously easier to handle in surface workshops than in the LHC tunnel.

A **position monitoring device** is foreseen in the interconnections with the QRL (jumpers). The possibility to have a similar device between cryomagnets is studied by the Survey Group.

Most of the procedures and tooling have been validated during phase 1 of STRING2. Anyway phase 2 will be very important because cryomagnets will be more representative of the LHC machine ones. The procedures foreseen for the tunnel will be applied very strictly during phase 2 of STRING2 and this will be easier because the number of non-conformities will be hopefully lower. Electrical tests procedures must be defined and validated during phase 2. A good rehearsal exercise would be to exchange a magnet : this would allow to test also the dismounting procedures.

4.3 Acknowledgements

The work presented in this paper has been performed by the whole LHC-CRI-I2 section with the support of EST division. The author would like to thank all the members for their work and their collaboration.

5 REFERENCES

[1] P. Cruikshank, "Vacuum QA", these proceedings
[2] ISO 9454-1 Soft soldering fluxes - Classification and requirements.
[3] R. Veness, "Vacuum Equipment Installation", this Workshop.
[4] N. Siegel, "Electrical QA", these proceedings

ELECTRONICS AND INFRASTRUCTURE IN THE TUNNEL

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Abstract

A brief description of the electronics installed around the cryomagnets in the arc is given. The infrastructure required (crates, fieldbuses, networks, optical fibres, cables, etc.), the sequence of installation interleaved with other activities, and the time for installation is described. Radiation issues will not be addressed here.

1 INSTALLATION OF ELECTRONICS

Electronic crates will be located under the cryomagnets, small electronic boxes may be fixed under the lowest cable tray (N°3) and 19" crates will be inserted into the existing racks available in the alcoves.

1.1 Electronics under Cryomagnets

Under the cryomagnets space has been allocated for the survey team to access the support jacks in order to allow the adjustment of the position of the magnets. Depending on the orientation of the jacks 50 or 100 cm must be reserved for the technician and his special tools to have access to each individual jack. Taking into account this requirement up to twelve 19" crates may be housed under a dipole and four 19" crates under a quadrupole.

Under a quadrupole a Front-End crate, containing Beam Instrumentation electronics, is located close to the BPM and BLM (Beam Position and Beam Loss Monitors). In between the two support jacks of the quadrupole space is available for one Vacuum control crate and for fixed Vacuum pumps. In addition a mobile Vacuum pump group may temporarily be placed along the quadrupole and be sheltered under the connection side of the next dipole.

In a full-cell, under each dipole there are four Heater Power Supplies and a Control crate assembled in dedicated rack for the Magnet Protection system and a Control /Acquisition crate for the Cryogenics. Similarly for the Corrector Power Converters four power supply crates are assembled into another type of dedicated rack. This idea of regrouping three, four or five crates into system dedicated assemblies will facilitate their physical installation and their connection to power and control cables. In case of failure of one of the items only the corresponding crate needs to be exchanged.

Table 1 gives the summary of the electronic crates installed under the cryomagnets in the tunnel and for the various systems: Magnet Protection, Vacuum, Cryogenics, Corrector Power Converters and Beam Instrumentation.

System	Full-Cell	Sm-Cell	Arc	DispSup	TOTAL
Magnet Protect.	28 Crate 8 Contr	20 6	644 184	80 24	724 C 208 CC
Vacuum	2 Contr	2	46	8	54 CC
Cryoge.	6 Contr	4	138	16	154 CC
Corr-PS	4 Contr	4	92	16	108 CC
Beam In.	2 FE	2	46	8	54 FE
TOTAL per OCTANT			644 C 46 FE 460 CC	80 C 8 FE 64 CC	724 C 54 FE 524 CC

Table 1: Electronic Crates in the Tunnel

1.2 Electronics under Cable Trays

In order to place simple Input/Output modules close to the equipment they control it is possible to fix in a standard way these modules under the lowest cable tray (N°3); this cable tray has been reserved for the controls cables. This possibility is particularly convenient for electronics connected to the Profibus and WorldFIP fieldbuses.

The size of these modules is based on standard PLC I/O modules: 92mm width, 187mm height and a length which is user defined according to the number of I/O channels required by the equipment to be controlled.

Another type of box, which may be fixed either under the cable tray or closely onto the tunnel vault, concerns optical fibre derivation modules. For Beam Instrumentation Front-End crates, located under each quadrupole, it has been decided to use data transmission via optical fibre cables. Each BPM/BLM Front-End crate is linked to the BI data acquisition system, located in a surface building, via a dedicated optical fibre cable containing 12 individual fibres. A total of 54 such optical cables is required per octant for Beam Instrumentation. Each optical cable is inserted into a thin guiding tube. These individual tubes are regrouped into a larger plastic pipe upright each quadrupole by means of an optical fibre derivation module.

1.3 Electronics in Alcoves

The 16 underground alcoves and the eight USs contain each 15 standard ISR racks for the housing of 19" electronic crates. After evaluation and discussion in the TEWG (Tunnel Electronic Working Group) about the total space and volume required for all the systems needing space in alcoves it has been decided to keep in place the old ISR racks; their dimensions are: width

54 cm, depth 75 cm and their height 45 Units. These racks do not allow recto/verso mounting of 19" crates, nevertheless a detailed study of the required rack space for all the systems showed that all electronic equipment would fit into the 15 available racks.

This decision has been taken following: 1) the decision of the SL/BI Group to install their two racks in surface buildings rather than in the alcoves and 2) following the good radiation tests results obtained in year 2000 by SL/PO Group on their Corrector Power Converters and Controllers. Without these recent decisions it would have been necessary to replace the old ISR racks by some 360 new racks of the LEP type equipped with double sided access capabilities.

For Vacuum PLCs it is anticipated that two racks of 60 cm width will be needed instead of the existing 54cm ones.

The layout of an alcove is available in the set of transparencies of the Villars LHC Workshop.

2 EQUIPMENT INVENTORY

A detailed inventory of the electronic equipment, fieldbuses, networks, optical fibre and copper cables to be installed in the tunnel has been made by the TEWG. [1] Table 2 shows the result of this study for one octant.

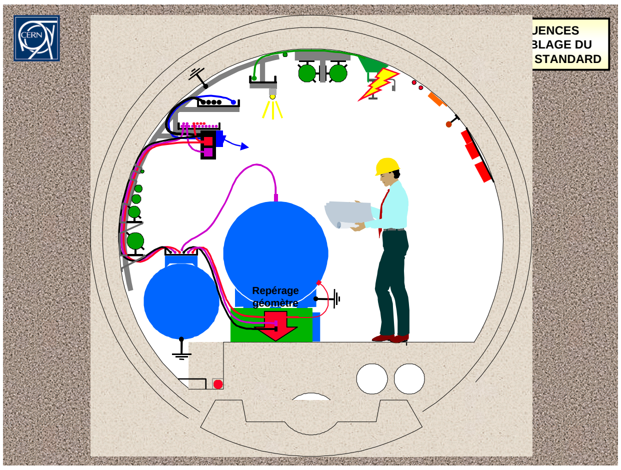
Systems	Control Crates	Fieldbus Nb-Type	Fieldbus Speed	Network Interface	Interface Location
Magnet Protect	208	8 WorldFIP	1 Mbit/s	8 PLCs	2 in IP 3+3 Alc.
Vacuum	54	12 Profibus	187.5 kbit/s	12 PLCs	4 in IP 4+4 Alc.
Cryo-genics	154	12 WorldFIP	1 Mbit/s	12 PLCs	4 in IP 4+4 Alc.
Correct Convert.	108	6 WorldFIP	2.5 Mbit/s	2 VMEs	2 in IP 2+2 Alc.
Beam Instrum.	54 FE	4 WorldFIP	31,25 kbit/s	6 VMEs	2 in Surf. BA
TOTAL	54 FE 524 CC	30 WFIP 12 Profib.		32 PLCs 8 VMEs	

Table 2: Fieldbuses and Electronic Equipment Summary

An effort has been made to reduce to two the number of fieldbuses types: Profibus and WorldFIP. Industrial PLCs from SCHNEIDER and SIEMENS will be used extensively; VME and PCI standards remain the best choice for electronic applications where high speed and special functions are mandatory. Due to radiation effects PLCs, VME and PCI crates will be housed in alcoves and US areas.

3 SEQUENCE AND TIME FOR INSTALLATION

A first study of the sequence for installation of the general services followed by the equipment has been done. Once the tunnel is ready the main steps of the installation will be:



- The 18 kVolts and lighting will be re-established
- The Survey Group will trace on the floor the exact position of the support jacks for the cryostats.

- Modification and re-installation of cable trays.
- Power to the monorail, power lines and distribution boxes, grounding, leaky feeder and telephone.
- Tubing for He, Ni, compressed air, water.
- Laying of control cables and electronic boxes.
- Fibre optic pipes, derivation boxes, blowing of optical fibres for communications, terminations.
- Installation of QRL and cable tray N°4.
- QRL grounding, test and commissioning.
- Control cables for cryostats and grounding.
- Blowing of the fibres for beam instrumentation and termination with connectors.
- Progressive powering and testing of the cryostats.

A first estimation for the time required for execution of each activity described above has been given. The detailed sequence of the works and there exact duration have still to be compared and fully integrated into the general planning.

Concerning the availability of cables and considering the time needed for the technical specification, the market survey, the tendering, the negotiation of the contracts, possibly the manufacture of special cables and the delivery to CERN stores it becomes urgent to know for each system the type and quantities of cables to be ordered.

REFERENCES

[1] http://lhc-tewg.web.cern.ch/LHC-tewg/

SCENARIO OF THE LHC ALIGNMENT

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Abstract

The overall alignment strategy for the components of the continuous cryostat is described. The phases of alignment during the installation process (from transport to completion) as well as the interference with components and other activities are presented in detail. The time and time slots required within the other activities are specified. The recording of the results from the tests on STRING2 is discussed. Scope of EST/SU responsibilities will be clearly presented.

1 ALIGNMENT PHASES

2.1 Marking out on the floor

This is the first operation to be done once the dismantling of the LEP has been completed. This marking out is necessary for the installation of some services (cabling, transport, QRL…). It will take place with the lighting operational, a clean floor and no other activity taking place at the same time.

It will be done with a 3D total station from a geodetic network, measured previously. Contrary to previous accelerators, the beam line along the whole circumference of the LHC will NOT be marked. In the Arcs and DS, the center and direction of the jacks as well as the beginning of the half cell will be marked. In the LSS, the mean beam line, the entry and exit points coming from MAD as well as their suports will be materialised. The accuracy expected is ±3 mm r.m.s.

On String2, the instrument and methodology were validated, the accuracy (±1.5 mm max) was better than specified but not necessary.

2.2 Alignment of the jacks

This phase is indispensable because of the limited adjustment range of the jacks (±10 mm in xy , ±20 mm in Z) and the fact that the floor is not horizontal. The tolerance of this positioning is ±2 mm.

It will be done in the same conditions and using the same instruments as for the marking out phase. A special tool has to be developed to align the jack without acting on the screws which have to be adjusted into the middle of their adjustment range with a tolerance of ±1mm.

The process of fixing the jack to the floor shall not alter its positioning.

The theoretical data and the measured position of the jacks in 3D will be stored in an Oracle database. The height of the floor will be known and therefore grinding actions can be performed when necessary.

For String2, the LHC jacks (from the Indian collaboration) were used but were not within the mechanical specification. Therefore, the heads of the jacks located on the marks were in some cases far from their nominal position (up to 7mm). Instruments and methodology were validated.

2.3 Verification of the position of the cold mass according to the fiducials

The cryo-magnets will arrive in the tunnel, knowing the position the fiducials with respect to the cold mass axis from measurements made at the surface. There is a strong possibility that there is a movement of the cold mass with respect to its cryostat during its descent into the shaft and transportation to its final position. Up to now, this phenomena has been observed on all the cryo-dipoles for String2.

Therefore, a measurement to detect these movements has to be foreseen. This action will have to be done in the middle of the tunnel in front of the final position and using either a Laser tracker or mechanical sensors.

For the Short Straight Sections, no significant movement has been observed.

2.4 First alignment of the components

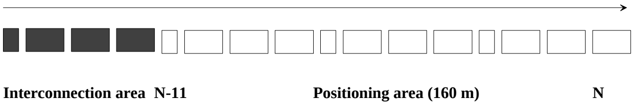

Figure 1: Survey area

The operation consists of two phases :

- An absolute positioning carried out relative to the geodetic network and using a 3D total station, during which the magnet N (Fig. 1) is aligned with an accuracy of ±0.5 mm r.m.s. in XYZ.
- A local "smoothing" on the last 11 magnets aligned in the previous phase. The measurements will be done with an optical level and offsets w.r.t. a stretched wire. During this phase the magnet N-11 (Fig. 1) is aligned relative to the other 10 with a accuracy of ±0.2 mm r.m.s in transversal and vertical direction, ±0.5mm in longitudinal and ±0.2 mrd in transversal inclination (roll). It can then be connected to its neighbour.

During these two phases, the magnets are not connected and there is to be no other activity in the area up to 160 m downstream of the connection working site. In this area at least eight cryostats (over the twelve) have to be present and no consecutive missing magnets are acceptable.

The components of String2 were found before their alignment to be within ±2mm in radial and longitudinal direction and ±10 mm in the vertical. This last value is not within the tolerance but the problem has been understood. The smoothing operation has not been done yet.

2.5 Smoothing of the components

The goal of this operation is to obtain an accuracy of ±0.15 mm r.m.s in the vertical and transversal direction over an area of 100m (at least). All the cryo-magnets are concerned by this operation, not only the quadrupoles as was the case for LEP. The magnets will have to be connected, under vacuum and at 80K.

The measurements will be made directly on the fiducials not referring to the geodetic network anymore but using the same instrument as for the previous phase. They will be carried out over a whole octant.

In order to ensure good quality offsets w.r.t a stretched wire , the wind has to be as light as possible.

2 ALIGNMENT MAINTENANCE

3.1 Realignment possibility

The cryo-magnet aligned at the beginning of the campaign will have to be realigned before the start of the LHC to compensate for the ground motions. The "smoothing" technique, as described in §2.5 will be used.

Moreover it is absolutely necessary that the realignment of a magnet should be possible when it is not connected or connected and under atmospheric pressure or under vacuum pressure or under cold conditions (80K)

3.2 Monitoring of the interconnections

As the LHC is installed in the LEP tunnel, it is already known that there are "unstable areas", for example the area around Point 8. The areas closed for civil engineering works will also be "unstable". Moreover, statistics predict that in the "stable" areas some interconnections will move significantly due only to Gaussian ground motion. A total of 31 interconnections will be affected by movements bigger than 1.2 mm.

To prevent the interconnections from breaking, they have to be monitored and the proposed system is called Rasnik (from NIKKEF university). The principle is that a mask illuminated by a light source is detected by a CCD camera after passing through a lens (Figure 2). If one of the three components moves w.r.t. the others, the displacement will be visible by the CCD camera (figure 2). The mask/light source and lens will be located on one cryostat, the CCD on the one adjacent.

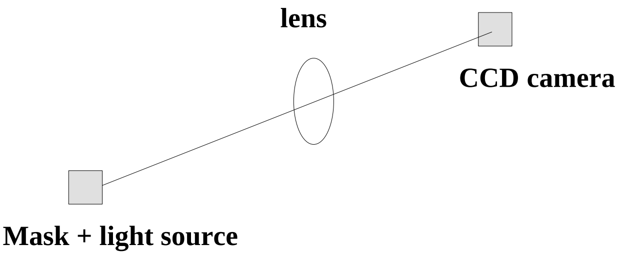

Figure 2: The Rasnik system

It still has to be decided where and how many such systems have to be installed in the LHC.

Such systems will be installed on each interconnection of String2.

3 RESPONSIBILITIES

The EST/SU group is responsible for the alignment of the jacks and the cryo-magnets but not for the installation of the jacks (transportation, drilling of holes and fixation). Good coordination will be needed for this operation especially because the manpower will be working under a result oriented contract.

The alignment of the QRL is the responsibility of the LHC/ACR group. The EST/SU group will provide the co-ordinates of the geodetic network and of the fiducials located on a jig used for the alignment of the jumper connection. The theoretical data will be stored in a database as well as the results of the alignment. As decided, EST/SU will do random checks in the field in order to verify the quality.

4 CONCLUSION

The scenario for the alignment of the cryo-magnets is ready and has been partially tested on String2 which was an easy example because it is located in an horizontal plane with no roll and there were no problems with the height of the floor. String2 was also a bad example because due to time constraints the area was overcrowded and no tests could be undertaken.

The problem of the coordination of the works, especially the installation of the jacks, in the tunnel has to be studied seriously.

Some serious tests have to be done in order to verify the opportunity of checking the position of the cold mass in the cryostat, once in the tunnel.

REFERENCES

LHC-G-ES-0006, LHC-G-ES-0008, LHC-G-ES-0009, J.P. Quesnel, March 2001

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RELIABILITY ORIENTED MECHANICAL QUALITY ASSURANCE OF THE LHC INTERCONNECTIONS

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Abstract

The present paper is dedicated to the Quality Assurance (QA) of the LHC interconnections. The interconnections belong to the systems which will be entirely assembled in the tunnel. They will compensate for the thermal contraction of the cryomagnets, thus accumulating a large amount of plastic deformation at cryogenic temperatures. All the main and the auxiliary bus-bars are joint inside the zones of interconnections by using specially developed techniques. Since the LHC interconnections form a very complex set of systems an unprecedently high reliability is required. The paper highlights the measures which will be implemented to reach the required reliability levels.

1 INTRODUCTION

Successful operation of the LHC over a scheduled period of 20 years depends very much on the reliability of all the structural components of the system. A poor reliability of a group of components may yield a sequence of failures that will make smooth operation of the accelerator impossible. Thus, an investment in the reliability oriented mechanical Quality Assurance may reduce considerably the number and the total cost of repairs and interventions associated with early and chance failures.

The lifetime of components is approximately characterised by the function of failure rate shown in Fig.1 and known as bathtub diagram (cf. [1]). This curve is typical of most manufactured structural components. The early failures occur during the burn-in period with a usually rather high failure rate (collapse of weak components). In the second period the failure rate stabilises at an approximately constant level or slowly evolves. Finally, the failure rate again increases due to wearout of components.

The early failures are controlled by the quality of the manufacturing processes (in the framework of the QAP), inspections and factory tests. The other categories - chance and wearout failures - are controlled by the appropriate design and the reliability oriented optimisation of the structural components.

Generally, the mechanical QA aims at minimising the early failures and reducing the failure rate (increasing the mean time between failures). Therefore, simultaneously, it aims at maximising the availability and the reliability (useful life) of the LHC. The following methods are applied in the framework of the mechanical QA:

- production screening
- automatic technologies
- control of implementation of procedures

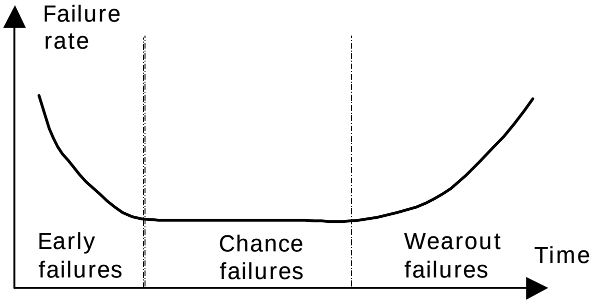


Figure 1: Bathtub diagram

2 TARGET AVAILABILITY OF THE LHC INTERCONNECTIONS

The target availability of the LHC interconnections has been specified on the basis of the assumption of maximum one short intervention (10.5 days) per 10 years of the LHC operation (10x200 days). This leads to the required availability of the LHC interconnections equal to 99.5%. This ambitious task can be reached by performing a consistent reliability oriented design, based on the following general steps:

- definition of the expected availability of the LHC interconnections,
- availability oriented optimum design – global approach,
- apportionment of the availability to the subsystems,
- allocation of structural components to different groups of failure risk,
- definition of the expected reliability with respect to every component,
- criticality analysis – selection of the critical components,
- reliability oriented optimum design of the components – local approach,
- testing the critical components and improving their reliability to reach the expected levels,
- final verification of compatibility of the constructed system with respect to the assumptions.

This approach has been developed with respect to the LHC interconnections (cf. [2]). The main objective is to minimise the risk of frequent failures of the critical components and the associated number of interventions. This is equivalent to searching for a maximum of smooth operation of the system within given time limits.

Since in the LHC interconnections (cf. [3]) there are 3 systems that might fail: mechanical compensation system (bellows expansion joints, cf. [4]), electrical connections of superconducting bus-bars (cf. [5], [6]) and the RF system (fixed and sliding RF contacts), it is assumed that the expected availability is apportioned to each of them on an equal basis. Thus, the expected availability amounts to 99.8% for either of them. Given the number of interconnections for the LHC Arc and DS zones the apportioned reliability for one interconnect (per system) is 99.9999%.

3 MECHANICAL QUALITY ASSURANCE – MAIN ASSUMPTIONS

Generally, the mechanical QA requirements apply to (cf. [7]):

- interfaces and components
- assembly technologies
- assembly procedures

Interfaces and components have to be checked both on the surface (activities in bldgs SMA18 & SMI2) and in the tunnel, when assembling the LHC interconnections. The items that must be controlled in the tunnel are shown in Fig.2. The assembly technologies and procedures are implemented in the prototype of the LHC standard cell - String 2 - and tuned before final installation of the LHC. The relevant control/inspection procedures are presently being developed and tested during the construction of the String 2.

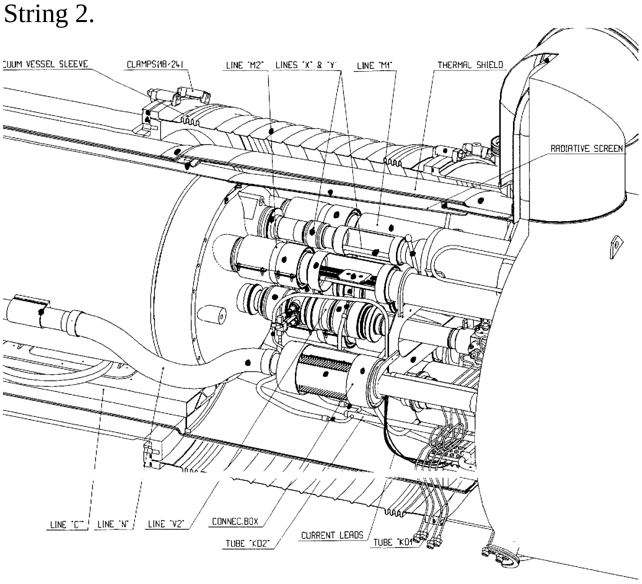


Figure 2: Control points in the LHC interconnections

The following assumptions are made with respect to the mechanical QA:

- wherever possible the control procedures should stay in the shadow of the assembly work,
- all the main control procedures should be tested and qualified in String 2 or in the LHC interconnections mock-up,
- the inspectors should be trained on the LHC interconnection training mock-up.

4 QUALITY CONTROL OF THE INTERFACES AND COMPONENTS

The cryomagnet extremities (cf. [8]) will have to be carefully checked prior to final installation in the tunnel. The control comprises a precise check on the surface (activities in bldgs SMA18 & SMI2), with the results enclosed to the cryomagnet traveller and a visual inspection in the tunnel according to a predefined check list. In both cases the following interfaces have to be verified:

- bellows expansion joints and protecting shells,
- main and spool piece bus-bars and spacers,
- electrical insulation,
- cooling channels interfaces,
- connection boxes,
- radiation and thermal shield interfaces,
- MLI blanket extremities,
- vacuum vessel flanges and seals.

The list of principal components of the LHC interconnections contains:

- bellows expansion joints and metal hoses,
- RF contact modules and cooling capillaries collectors,
- cryogenic plugs (aux. bus-bars),
- buswork spacers,
- components of the connection boxes,
- small sliding sleeves and stabilising plates,
- radiation screens and thermal shields,
- MLI blankets,
- vacuum vessel sleeves, seals and clamps.

The most critical components are the single ply bellows expansion joints for the beam vacuum interconnections (cf. [9]) and the muliply bellows for the cryogenic cooling channels. They are expected to satisfy very tough requirements in terms of reliability in the framework of the reliability apportionment. Therefore, the components of the mechanical compensation system are subjected to a very severe qualification program covering the following aspects:

- control of the material quality (cf. [10]):
    - chemical composition,
    - ferrite content,
    - stability at low temperature,
    - magnetic permeability,
    - fracture toughness,
    - tensile properties (yield strength, hardening),

- control of the structural stability under pressure/vacuum
    - local stability of convolutions,
    - overal stability of the expansion joints,
    - fatigue/stability coupling,
- control of the fatigue life via the accelerated life testing
    - evolution of the axial stiffness,
    - fatigue at 293K / 77K / 4.5K,
    - check of the reliability level,

Evolution of axial stiffness and analysis of reliability typical of the LHC bellows expansion joints (example: RF contact bellows) is shown in Fig.3.

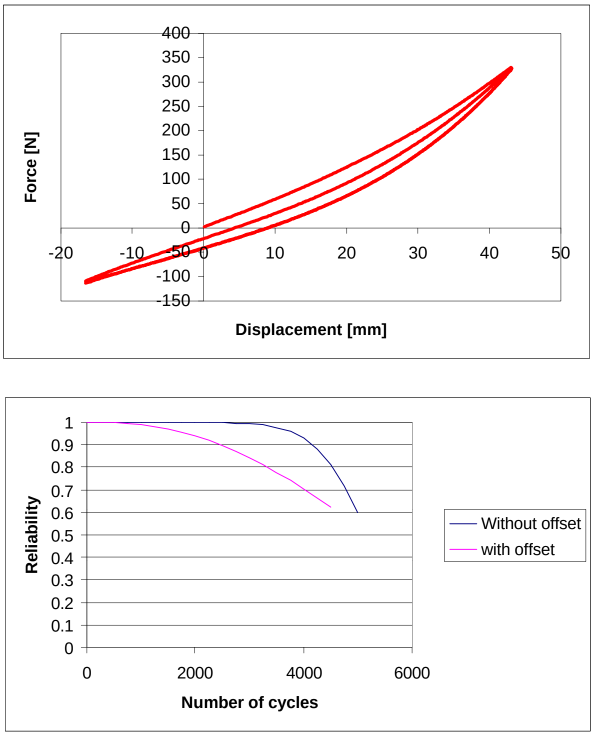


Figure 3: Control parameters defined for the LHC expansion joints

For the series production (around 20000 expansion joints) the following principles will be applied:

- the QAP as defined by CERN (cf. [7]) should be respected during the production of the LHC expansion joints,
- every unit delivered to CERN will be visually inspected,
- 1% of each delivery batch will be selected at random and tested to confirm the reliability level

Similar, however less severe procedure will be applied with respect to the vacuum vessel sleeves (qualification program for the preseries production, QAP for the series production and careful inspection of the supplied units). The components that are less critical from the point of view of the reliability of the LHC interconnections (like radiation screen and thermal shield) will be subjected mainly to a dimensional control and visual inspection.

5 QUALITY ASSURANCE OF THE ASSEMBLY TECHNOLOGIES

The following assembly technologies will be used when completing the LHC interconnections:

- soldering of main bus-bars,
- ultrasonic welding of the spool piece and auxiliary bus-bars,
- orbital welding of the vacuum and cryogenic channels.

In order to obtain a good reliability of the electrical and mechanical joints all the apllied technologies will be on-line controlled. Also, a principle of sampling will be applied. Upon completion of every N cells (N remains to be defined) the samples of all the above listed joints will be prepared (in parallel with the construction works) and tested. Sampling procedures shall not interfere with the assembly of the LHC interconnections.

5.1 Soldering of main bus-bars

The process of soldering will be monitored by using a closed loop control system. This is to yield the operation independent of the human factor and therefore more reliable. Every joint will be equipped with a thermocouple linked via a data acquisition system to a PC. The processor will control and stabilise (via the feedback system) the temperature of the joint between 223 and 230 ^{o}C during the soldering process (Fig.4).

5.2 US welding of the spool piece and auxiliary bus-bars

The process of ultrasonic welding (cf. [11]) will be controled on-line by using a PC linked directly to the welding machine. To this end two curves (driving-in and dissipated power) and a number of parameters will be monitored (Fig.5).

The following parameters will be controlled and stored during the welding operations:

- time span of the welding phase: $t_2 \ge t_{2\min}$,
- minimum power dissipated during the welding phase: $P_2(t) \ge P_{2\min}$,
- average power dissipated during the welding phase: $\frac{E_2}{t_2} = \frac{1}{t_2}\int_0^{t_2} P_2(t)dt \ge \widehat{P}_{2\min}$

The welding curves and the parameters will be registered and attached to the relevant interconnection traveller.

5.3 Orbital welding

The process of orbital welding was qualified with respect to all types of welds in the LHC interconnections (Qualification Reports: QMOS/T1149909 and QMOS/T1159909). An on-line control of the process by using a CCD camera as well as a visual inspection of every weld are envisaged. Also, in the justified cases a usage of the clam shells in order to test locally the helium leak tightness is planned.

6 CONTROL AND INSPECTION DURING THE ASSEMBLY PROCEDURES

The control and inspection activities (see Table 1) shall follow the predefined groups of operations in the context of assembly of the LHC interconnections (cf. [3]). The inspectors of three different profiles are required, as specified in Table 2. The profile 1 represents the general inspection activities dedicated to the configuration of the cryomagnet extremities in the tunnel (after surface-to-tunnel transport). The profile 2 represents the inspection of the mechanical parameters and technologies. The profile 3 corresponds to inspection of the electrical circuits and verification of all the electrical parameters.

Table 1: Inspection activities in the LHC interconnections

Inspection number	**Groups of operations in the LHC interconnections**	**Type of inspection**
1	configuration of the cryomagnet extremities (templates)	configuration, mechanical
2	closure of the beam-vacuum (V1, V2), main & spool piece bus-bars, line Y	mechanical, electrical
3	connections of the auxiliary bus-bars (line N)	mechanical, electrical
4	closure of the cryogenic lines, final check (M1, M2, M3, X, C', E, N, K1, K2)	mechanical
5	installation of the radiation screen & MLI	mechanical
6	installation of the thermal shield & MLI	mechanical
7	final closure, vacuum vessel sleeve	mechanical

The inspectors shall have a general knowledge of the LHC parameters (cf. [12]) and a good knowledge of the systems constituting the LHC interconnections. They will be trained on the LHC interconnection mock-up, before undertaking their responsabilities in the tunnel. The inspectors will proceed according to the relevant check lists. One traveller per interconnect will be issued. All the operations (parameters, data) and results of inspections (7 reports) will be stored in the traveller. All the nonconformity reports will also be enclosed to the travellers.

Table 2: Profiles of inspectors

Profile of inspector	**Definition of activities**
General	check of the cryomagnet extremities (visual + traveller), verification of tolerances (template), bus-bar extremities (conditioning), bellows expansion joints & protection shells identification of the nonconformities (cf. [13])
Mechanical	check of final dimensions and prestress of connected objects (bellows, bus-bars), visual check of materials, state of surface, insulation, MLI, verification of material certificates and the interconnection travellers, mechanical check of the welded and soldered joints, identification of the nonconformities
Electrical	check of the continuity of electrical circuits, check of polarities and electrical insulation (cf. [14]), verification of the corresponding travellers, identification of the nonconformities

7 CONCLUSIONS

- The control/inspection activities should not interfere with the assembly operations.
- The inspectors (general, mechanical, electrical) should be trained on a specially constructed LHC interconnection mock up prior to the assembly activities in the tunnel.
- The String 2 construction (phase 1 & 2) is used to test control/inspection procedures.
- One traveller per interconnect, containing the information about the components, technological operations, procedures, inspections and nonconformities will be prepared.

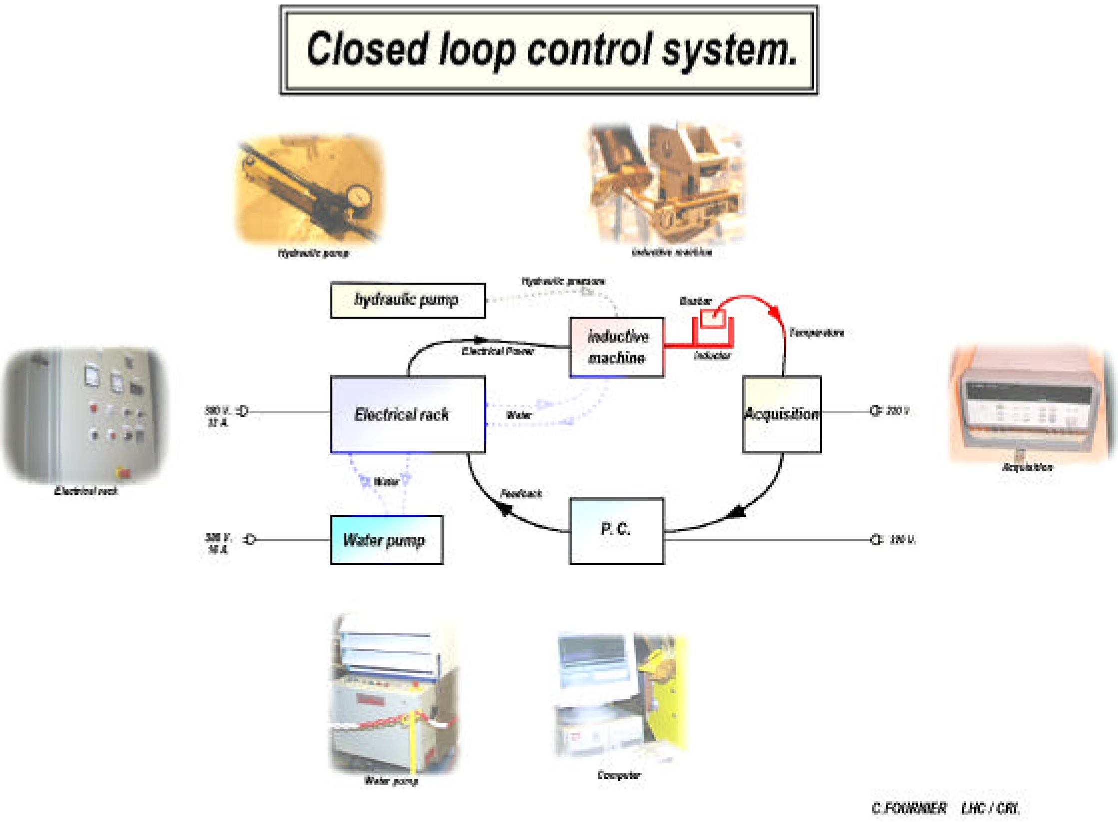
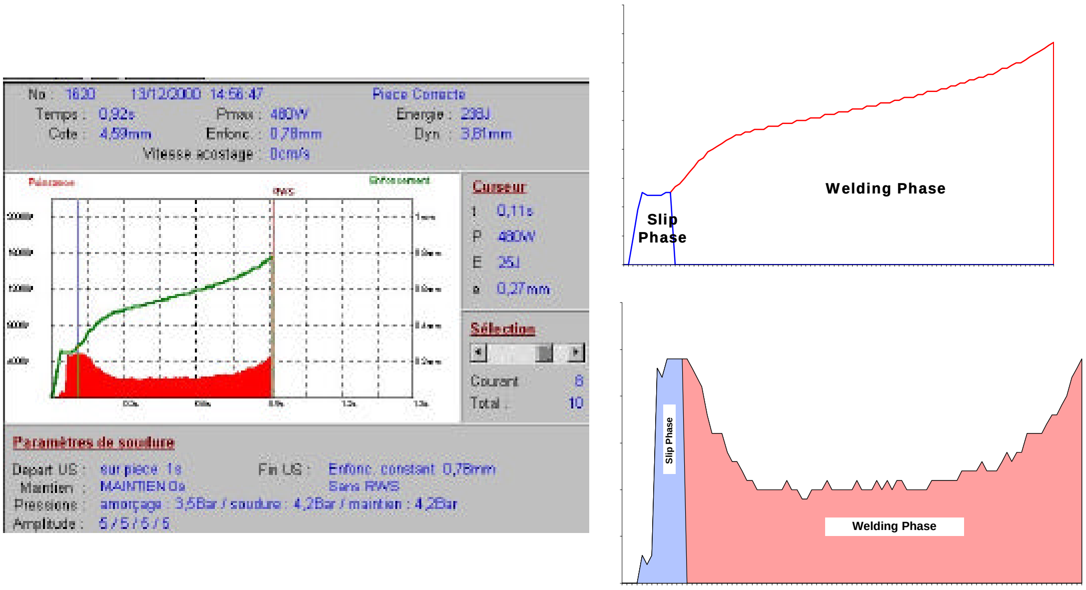


Fig.4 Closed loop control system used for the main bus-bar soldering


No : 1620 13/12/2000 14:56:47 Piece Correcte
Temps : 0,92s Pmax : 480W Energie : 238J
Cote : 4,59mm Enfonc. : 0,78mm Dyn : 3,81mm
Vitesse acostage : 0cm/s

Curseur
t 0,11s
P 480W
E 25J
e 0,27mm

Sélection
Courant 8
Total : 10

Paramètres de soudure
Depart US : sur piece 1s Fin US : Enfonc. constant 0,78mm
Maintien : MAINTIEN 0s Sans RWS
Pressions : amorçage : 3,5Bar / soudure : 4,2Bar / maintien : 4,2Bar
Amplitude : 5 / 5 / 5 / 5

Fig.5 Control parameters for the process of US welding (source CERN-LAPP collaboration)

ACKNOWLEDGEMENTS

The contribution of all my colleagues from the Section I2 of Group LHC/CRI is gratefully acknowledged.

REFERENCES

[1] I. Kovalenko, N.Y. Kuznetsov, Ph.A. Pegg, “Mathematical theory of reliability of time dependent systems with practical applications”, Wiley, Chichester, 1997.

[2] C. Garion, B. Skoczen, “Reliability oriented optimum design of the LHC interconnections – Part I: mechanical compensation system”, LHC Project Note 245, CERN, 2000.

[3] J.C. Brunet, A. Jacquemod, J.Ph. Tock, “LHC Arc interconnections between cryomagnets”, Engineering Specification, LHC-LI-ES-0004, CERN, 2000.

[4] B. Skoczen, “LHC mechanical compensation system – bellows expansion joints”, Engineering Specification, LHC-LI-ES-0002, CERN, 1998.

[5] J.Ph. Tock, “Main bus-bars interconnections between cryomagnets of the LHC Arcs”, Engineering Specification, LHC-LI-ES-0005, CERN, 1999.

[6] B. Skoczen, “Externally routed auxiliary bus-bars”, Functional Specification, LHC-DCC-ES-0002, CERN, 1999.

[7] P. Lienard, M. Mottier, “Manufacturing and inspection of equipment”, Quality Assurance Procedure, LHC-PM-QA-309, CERN, 1999.

[8] J.C. Brunet, “Arc cryomagnet extremities”, Interface Specification, LHC-LI-ES-0001, CERN, 1999.

[9] L. Gelebart, S. Marsh, B. Skoczen, “Qualification of nested bellows for the LHC beam vacuum interconnection”, LHC/CRI Technical Note, CERN, 1999.

[10] CERN Technical Specification (SPL-LS) N^o 525 (Ed.3 – 2/08/1999), “Sheets and tubing for special cryogenic applications, Stainless steel type X2CrNiMo17-12-2 (1.4404, AISI 316L)”.

[11] I. Monteiro, A. Chatelain, C. Girard, “Bilan technique du projet LHC 3 (Soudure Ultra-sons). Bilan de Septembre 1999”, LHC3-ME-BI-001-04, LAPP, Annecy, 1999.

[12] P. Cruikshank, P. Proudlock, G. Riddone, R. Saban, R. Schmidt, “General parameters for equipment installed in the LHC”, Engineering Specification, LHC-PM-ES-0002, CERN, 1999.

[13] M. Mottier, “Handling of nonconforming equipment”, Quality Assurance Procedure, LHC-PM-QA-310, CERN 1999.

[14] F. Rodriguez-Mateos, “Voltage withstand levels for electrical insulation tests on components and bus-bar cross-sections for the different LHC machine circuits”, Engineering Specification, LHC-PM-ES-0001, CERN, 1998.

[15] B. Skoczen, “On the global and local mechanical stability of the LHC”, LHC Project Note 224, CERN, 2000.

TEST OF THE INTERCONNECTIONS OF LINE N

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Abstract

A method to test the connections in the line-N before and after welding is proposed. The method is based on temporary screwed connections and automated test equipment. It is independent of the installation direction and would allow for missing magnets. The necessary hardware is described and the test procedure is illustrated.

1 INTRODUCTION

In the LHC most superconducting correction are connected up in families for simplicity and economical reasons. Because all correctors of a family share the same power supply, super-conducting bus bars connect the coils. Faulty connections affect, of course, the machine operation in an essential way. Moreover, it is almost impossible to localise a fault within a corrector family in superconducting condition. The repair of a fault will cost both, money and time. Therefore the installation procedure has to be as reliable as possible. A method of checking during the installation to detect faults, before the cryostat is closed, is required.

The scope of this paper is, however, restricted to the Short Straight Sections in the arcs. The dispersion suppressor, the matching section, and the insertion zones are expected to be relatively easy to test and not considered here. In this context only the 42 wires, carrying up to 600A, are considered. They run through the so-called Line N all along the arcs. However, to provide the proper Helium flow, these lines have to be plugged at every Short Straight Section (SSS). As a consequence all wires have to be welded at the plugs to the next stretch of wires (about 50m) going to the next plug. At each SSS up to 92 wires, including the connections to up to four magnets, have to be welded.

A similar, however simpler, procedure was used at HERA with extraordinary success.

2 GENERAL REMARKS

The cable used in the line N consists of three layers of wire. The layers contain of 8, 14 and 20 wires. The cable comes prefabricated in a length of about 55m. The downstream end (right, as seen from the tunnel inside) isfitted with the so-called plug. Here the wires are sorted according to their position in the layers. The cable is pulled through three dipoles and the Short Straight Section (SSS) at the time of installation in the tunnel.
Hence the upstream (left) end of the cable has to be cut to length and the wires have to be disentangled before the welding can start.

To open and re-weld a faulty connection requires cutting the wire pair. Obviously this can be repeated only a few times. Hence it is absolutely necessary to perform a test of the connections before and after welding the wires to their respective counterparts or the correction magnets. This requires some way of intermediate connection like screwing.

The connection to be tested must be accessible from both sides. During the installation, one side is still open (called downstream) and easily accessible. To limit the number of wires the wires in the line N are shared between different magnet families. One family is fed from one side, the other from the other side. Hence, in general, at a given SSS a given wire is not connected to the starting point of the installation. This proposal for the test requires that all wires are accessible at the next and at the previous interconnection (might be the start of the installation).

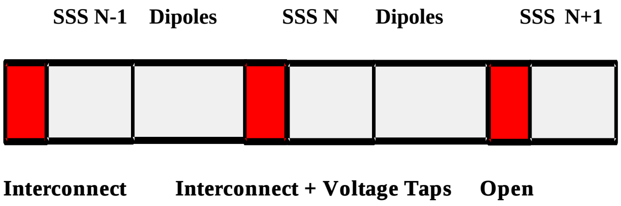

Figure 1. Required access points

To verify the polarity of inserted magnets the voltage taps have to be used. All magnets have one voltage tap connected to the so called port A. At the time of installation the polarity itself can not be tested, because only one voltage tap exists per magnet. One has to rely on a previous test, insuring that the voltage tap is attached to the so-called port A of the magnet in question.

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[*] The author wants to thank both CERN and DESY for the support for this work.

3 PROPOSAL FOR A TEST PROCEDURE

It is assumed that the following conditions are met:

- All wires are individually accessible before and after welding, simultaneously at 3 neighbouring SSS.
- The numbering of the wires in the cable is defined consistently, everywhere in the LHC. This has particular impact in those cases, where two magnets are added, using the same wire pair.

A temporary connection can be made before welding using templates as sketched in figure 2 to simplify the installation. The templates carry 2*21+2*4=50 slots.

The plug is on the left side of an interconnection, if one looks from the inside of the tunnel. The wires coming from the plug will be fixed to the template beforehand. The corresponding cable has to be inserted from the downstream (right) side. It runs through 3 dipoles and will be cut to length and unwound, wire by wire, in situ. The first wire, to come off the outer layer, must be wire #1. It will go into the slot on top at the right (downstream) side of the template. The second wire will go into the lower slot. The wires are distributed over the template according to the rules, described and implemented into a VB program in reference [1]. The wire positions are calculated following an algorithm. Using the temporary connection (see below) on the plug side of the newest installed cable and the knowledge about the required connections a computer can help to identify and place the wires on the template. Likewise a computer can always find the position of a given wire in a given connection box. The essential input to this program, the content of the wiring diagrams (LHCLSD1.0001 …LHCLSD8.005), has been prepared by the author and needs to be checked independently.

The wires are sticking through the slots, pointing towards the observer. The wire ends have to be prepared for welding; i.e. the insulation has to be taken off. Before actually welding two printed-circuit-boards with screw-terminals in 5.08mm spacing are screwed onto the prearranged wires. Suitable cables connect these boards with some electronics, to be discussed below. In addition a U shaped clip, sliding on the long edges of the template, can fix the position of the wires.

Once all wires have been distributed over the slots, the connections, as foreseen, will be tested. After an initial electrical test, to be described below, the attached printed circuit boards are temporarily removed. However, due to their stiffness and held by the clips, the wires stay together properly sorted and the welding procedure will hardly lead to wiring errors. After the welding the printed circuit boards are put in place again to repeat the verification.

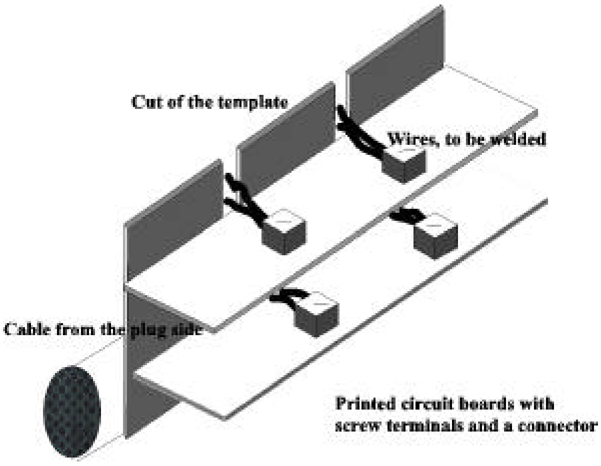

Figure 2. Sketch of the wiring template, looking sideways, along the cables, and under an oblique angle. Note the notches in the base templates and the additional printed circuit boards, to be removed after the test.

The required test set-up consists of three sets of two printed-circuit-boards, connected to the test electronics as indicated in figure 1 at the point under test and the two adjacent SSS. Cables connect computer controlled relay matrices with the templates at the point of test, at the previous point, and at the next SSS. In addition, a cable is connected to the voltage tap feed-through at the point of test.

The test proceeds from slot to slot at the point of test. It depends, of course, on the type of connection.

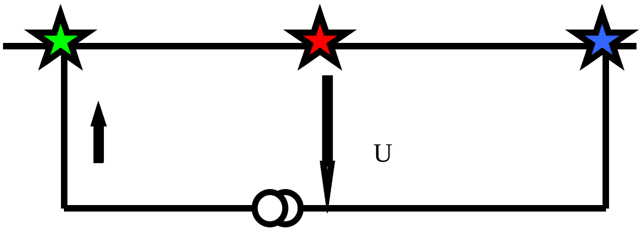

Figure 3 Test of a through-connection

A simple through-connection is tested by finding the numbers of the two wires in the slot in question and by finding the slots to the left and right to which the wires are leading. A current is drawn from upstream (left) to downstream (right). The voltage at the slot under test is measured with respect to the sink-point of the current source. The voltage of all other slots must be zero (small).

If a magnet is connected in series (fig. 4), two slots are to be tested simultaneously. Both slots have to be determined, as well as the wire number and the corresponding slots to the left and the right. One of the slots at the point of test is connected to a voltage tap; i.e. to port A.

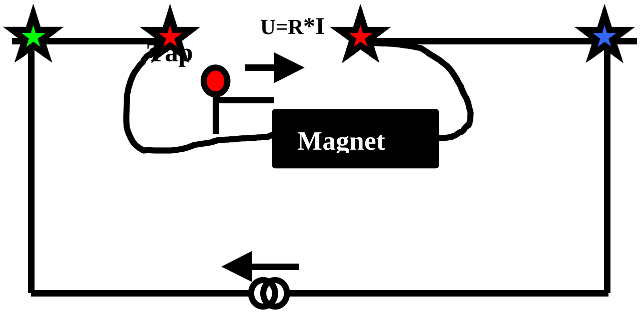

Figure 4. Test of a series connection

A current is drawn from the side, at which the port A is connected, to the opposite side. The voltage between the voltage tap and the slot connected to port B must be positive (polarity) and about equal the magnet-resistance * current.

In a similar fashion all types of connections can be tested. Figure 5 shows the case of two magnets added to the same wire pair.

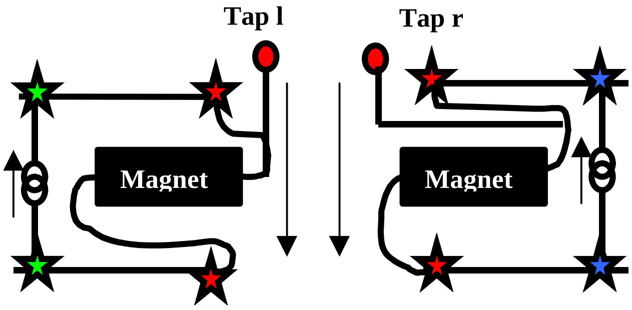

Figure 5. Test of a pair of magnets

4. REQUIREMENTS AND RESOURCES NEEDED

4.1. General

1. The magnet fabrication and several tests at the surface insure the proper polarity and the proper connection of the voltage tap to port A. (Notation of LHC-DC-ES-0001.00). This requires labelling the ends of the conductors, such that the labels will survive at least until the installation in the tunnel be finished. Preferentially, the labels should be identifiable throughout the lifetime of the LHC. A suitable scheme has to be agreed on soon.
2. The magnet test crew verifies the labelling (including the polarity) at room temperature. The magnet test crew also verifies the room temperature resistances of all devices in a given assembly, i.e. a dipole or quadrupole cryostat. This is an easy test that the proper type of corrector magnet is installed.
3. The installation crew insures the proper connection of the bus bars by either using the geometric properties of the cables or by using a tagging system of the cables, as the one in preparation by ICP.
4. An independent verifying crew checks each interconnection immediately after the installation crew has finished a particular half-cell, in particular the SSS interconnection.

The topics 3 and 4 are clearly interwoven. For example, the verifying computer will display the routing at the actual interconnection, to the benefit of both groups.

4.2. Preparation of the line N cable

1. The auxiliary bus bar cable is fanned out at the pressure plug side, it is attached to the template, mentioned and sketched above, and it is temporarily fixed (screw terminals) to the pulse sequence generator.
2. After pulling the auxiliary bus bar into the tube N, the installation crew prepares all connections for the welding. The bus bar is fanned out onto the template, already in place, with the help of the electronic marking system. The wires are connected temporarily using the screw clamps on the printed circuit boards. This procedure establishes all connections, including the test cables.
3. At the open end two printed circuit boards replace the temporary connections to the sequence generator. The layout of the boards ensures that the wires have the length as required for the final welding. The PC boards are connected to a computer controlled relay matrix. Similar relay matrixes are connected to the wires at the point of test and at the previously tested interconnect.
4. Before the welding, the verification crew checks all intended connections using the access from the open end, the voltage-taps available at this position, and the access from the last interconnection (or DFB).
5. If the test is passed successfully, the verification crew permits the welding. Otherwise the installation crew is informed and it repairs the fault.
6. The installation crew removes the printed circuit boards by undoing the screw connections. The template keeps the wires to be welded together in place.
7. The installation crew performs the welding.
8. The installation crew attaches again the printed circuit boards to the welded joints.
9. The verification crew repeats the tests of point 4.
10. After this test the installation crew removes the printed circuit boards at the previous interconnection

including the attached electronic equipment. It insulates the wires and secures them mechanically. The printed boards at the present interconnection are left in place.

11. Before and after closing the vessel at the previous interconnection, high voltage tests are the last steps. These tests may not be applied statically, because in this case the bus bars would be tested many times with the same voltage. A suitable high voltage pulse will be damped along the wire, because the wire – ground system is a quite poor transmission line. As some experience in testing is required, the verification crew should do this job. It signs off or traces the fault until the installation crew can repair the damage and the fault. The HV test could be performed outside normal working hours to minimise interference.
12. Both crews move on to the next interconnection.

4.3. Equipment at the point of test and the two adjacent interconnects

In addition to ordinary tools, each verifying crew will need the following resources:

- A computer (PC) with a screen, keyboard and mouse shall be securely fixed on a carriage with inflatable tires. The measurement stand must be compatible with the requirement that a magnet transport can pass by, whenever the test stand is not used.
- Three relay matrices
- A DVM (readable)
- A current source (programmable, DC, low frequency AC may be useful)
- A non-commercial high voltage pulse generator with high impedance.
- Several special sets of cables connecting the relay boxes with the printed circuit boards, the power converter in/outlets at the feed-box or the nearest voltage taps respectively. These things must be carefully checked in advance and carefully labelled.
- A low price oscilloscope (to localise an eventual high voltage breakdown)
- A hand-held DVM
- A current probe
- Electronic wire tagger [1]

5. SUMMARY

The proposed procedure makes it possible to test the routing at every interconnection be-fore and after the welding procedure. All inserted magnets are tested for polarity (assuming that the voltage tap is connected to Port A) and type. All connections are tested for crossover, open circuits and short circuits. The procedure requires access at the open end, the feed box (DFB) and the previously installed interconnection. The tests are as local as conceivable, minimising the work, the stress, and the requirements.

6. ACKNOWLEDGEMENT

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REFERENCES

[1] K. H. Mess, DESY, forthcoming LHC Project Note

ELECTRICAL QUALITY ASSURANCE DURING INSTALLATION OF CRYO-ASSEMBLIES IN THE LHC TUNNEL

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Abstract

An electrical quality assurance plan applying to the machine during the installation phase and which shall ensure proper functioning of the electrical circuits of the accelerator is presented. To begin with, the plan must make reference to the level of quality expected from the components and identify all previous tests to which these components have been submitted. The checks and tests done during the installation and interconnection of the machine elements as well as their sequence to assure the correct configuration and polarity are outlined. The tests of the interconnection of the line N are described in detail in a separate paper. The proposed way of proceeding and the interference with other activities are outlined. Specific safety issues are identified, in particular access restrictions during the tests. The recording of the results from the tests is discussed.

1 INTRODUCTION

It is required that an electrical quality assurance plan be defined for the LHC machine during the installation and interconnection phase. Its purpose is to ensure the safe and correct functioning of all electrical circuits of the machine during its commissioning and operation. Such a plan must be worked out in close collaboration with all parties intervening in the installation and must be strictly adhered to. The plan shall define all the checks and tests, which have to be done as well as the procedures required implementing these checks and tests. The team in charge of working out the plan will define the organisation and responsibilities for carrying it through and will issue an engineering specification to document it.

The present report will mainly focus on the work to be done on the so-called continuos cryostat, but is also fully applicable to the rest of the machine stand alone cryo-assemblies, located in the long straight sections.

2 QUALITY ASSURANCE PLAN

2.1 Aims

An important challenge during installation will be to ensure the correct interconnection of the superconducting bus bars powering the LHC cryo-magnets. Along the continuos cryostat, between each main magnet there are 6 main bus-bar interconnections (MB, MQF and MQD circuits) and 20 auxiliary bus-bar interconnections (spool piece correctors of the main dipoles), each type carrying respectively a current of up to 13 and 0.6 kA. In addition, at each main quadrupole, there are 42 interconnections of the auxiliary bus bar, so-called line N, powering the correctors in the multipolar-correctors in the MQ cold mass. Consequently, in the continuos cryostat, there are per machine sector 1200 main bus bar interconnections, 4000 auxiliary bus bar interconnections and 1932 line N interconnections, with in addition a number of 6 kA bus bar interconnections along the dispersion suppresser part.

Further, each cryo-magnet, will feature connectors with instrumentation wires incorporating voltage taps, quench heater connections and sensors and at each main quadrupole there will be connections to the leads leading to the closed orbit correctors.

The aim of the electrical quality assurance plan will be to identify all the checks and tests that have to be carried out in the tunnel during the installation of the entire machine, including insertions, to ensure later the safe an correct functioning of all electrical circuits. The main task will be the to specify the procedures and sequence for all these tests and checks. They will mainly apply to qualify and accept work carried out in the tunnel, but will also ensure that no transport or installation induced damage has occurred. The plan should also include procedures for in situ repairs or an exchange during the installation phase. It should also already address and define electrical tests and checks applicable in later stages, like sector testing, commissioning, operation and shutdowns.

2.2 Organisation and responsibilities

The job to specify the tests and checks, define the procedures, design and qualify the required tools, supervise the tunnel testing and analyse the data shall be entrusted to a CERN team, working in close collaboration with the installation teams concerned.

The execution of the electrical tests and checks in the tunnel shall be carried out by a qualified verifying crew, with one such crew being active at each installation site currently in progress. According to the present machine installation schedule, the first verifying crew will start in September 2003 along sector 7-8 with a further three crews going into operation by the end of 2003 or beginning 2004.

As in any quality assurance plan, it is good practice to separate the execution work from the checking functions. Therefore, the CERN team in charge of the plan as well as the verifying crews shall be independent from the installation team. It is proposed that such a team be formed within the ICP Group of the LHC Division.

3 QA PROCEDURES

Each procedure shall relate to a given ensemble of electrical components of a specific type of cryo-assembly. Their contents will be intimately related to the installation principles of the machine. They shall contain the following information:

- The type of cryo-assembly and equipment to which they apply.
- An inventory of all previous electrical checks and tests already done in the life of the corresponding type of cryo-assembly, and which qualifies them for tunnel installation. The procedures shall apply if all such prior tests have been passed as stipulated in the traveller.
- The definition of electrical tests and checks pertaining to the given procedure including: the method of execution, the pass or no-pass criteria, their sequence, their implementation by specific tooling, the data recording.
- The specification of the action to be taken depending on the outcome of the test. In case of non-conformity and depending on the type, a "light" corrective procedure will be proposed.

4 WHAT CHECKS AND TESTS?

As said above, all checks and tests to qualify that a given cryo-assembly can be lowered into the tunnel will have been done previously and documented in the corresponding traveller. Therefore, any checks and tests to be done in the tunnel shall be related primarily to installation work. However, it is proposed that some essential features be checked, once the cryo-assembly is in place. The types of tests foreseen are described below.

4.1 Magnet circuits (joints in interconnections)

The main issue here is the quality and correctness of the joints to be made at the interconnections. The intrinsic quality of the joint (electrical and mechanical) will be based on the monitoring of the manufacturing process parameters. The process will have been qualified and test joints will regularly be made and tested to check reproducibility. The checks that will be done before joining, on the bare joint and on the finally insulated joint are:

- Visual checks of joint preparation, of bare joint and insulated joint. Photos can be taken at each stage as back-up documentation for later analysis if needed, since a welded sleeve will cover the joints.
- Continuity and polarity test, to check the correctness of all circuits.
- Quality of the insulation, checking voltage withstand and when possible, the insulation resistance. The insulation check has to be done after the sleeve has been welded around the interconnection. The withstand voltages for the different magnet circuits are given in the engineering specification reference [1].

4.2 Voltage taps

The voltage taps will be checked for continuity and be used also for checking polarity.

4.3 Protection devices

The quench heater circuits shall be checked for continuity, insulation to ground, to magnet coils and between them). A checklist of other protection devices (diodes, parallel resistor) is to be made.

4.4 Transfer function

Such a measurement is to be done during installation and on the completed circuits, including total resistance and inductance. The following issues must be checked for this measurement: grounding, power converter interference, non-linear effect of the protection diodes in main magnet circuits.

5 PRECAUTIONS AND SCHEDULES

5.1 Precautions

- Condensation inside the cold mass must be avoided by all means. The cryo-magnets have to be filled with dry nitrogen before storage for lowering, and complete temperature thermalisation is needed before opening any of the interconnection lines.
- In the main magnet circuits, charging the coils even with a low current such as produced by a battery-operated tester, can produce a high voltage if the loop is opened abruptly and may damage the protection diodes. Therefore the protection snubber circuit, which suppresses such transients, must be in place before lowering the magnet.
- It will be mandatory to use only instruments specifically designed for these tests.
- **Electrical safety:** Access restrictions must be enforced while electrical tests are being carried out.

5.2 Schedules

- The electrical checks and tests will advance along the tunnel together with the installation site and will be closely interleaved with the interconnection work.
- Consequently, both activities must be carefully planned and co-ordinated to avoid bottlenecks.

6 LIST OF TESTS

The tests and checks will each be the subject of a detailed procedure, specifying when, how and with what instruments they are done. The first on the list given below, relate to tests done during installation, followed by those done once installation is completed and in case of repair or exchange of a cryo-assembly. For completeness, a further category of tests has been listed which apply to later stages like hardware commissioning, the sector test, machine commissioning and finally machine operation and shutdowns. For illustration, the procedures relating to the checking of the magnet circuits of the continuos cryostat are discussed in somewhat more detail below.

- Procedure 0: Electrical integrity of test of the cry-assembly once in place, but not yet connected.
- Procedure 1: Continuity, polarity and insulation checks of main bus bars (MB, QF, QD: 6 x 13 kA) and their voltage taps.
- Procedure 2: Continuity, polarity and insulation checks of auxiliary bus bars for spool pieces (MCS, MCD, MCO, 20 x 600 A) and their voltage taps.
- Procedure 3: Continuity, polarity and insulation checks of auxiliary bus bar of line N for correctors in SSS (MQT/S, MO, MS and MSS, 42 x 600 A) and their voltage taps.
- Procedure 4: Check closed orbit corrector circuit (local MCB)
- Procedure 5: Continuity, polarity, and insulation checks of bus bars in the insertion cryo-assemblies.
- Procedure 6: Check of quench protection devices of the cryo-magnets and related instrumentation.
- Procedure 7: Tests and measurements of each magnet circuit once installation is finished: electrical insulation, transfer function, resistance, inductance.
- Procedure 8: Tests and checks before/after a repair or exchange of a cryo-assembly in the tunnel.
- Procedure 9: Tests and checks for hardware commissioning (e.g. powering a magnet string with the corresponding power converter).
- Procedure 10: Tests and checks for sector test.
- Procedure 11: Tests and checks for machine commissioning.
- Procedure 12: Tests and checks applying for machine operation and shut-downs

6.1 Procedure 0:

The purpose is to check the electrical integrity of the cryo-assembly once in place but not yet connected:

- In principle no test should be needed. Any test in the tunnel at this stage is only to check that no transport damage has occurred.
- Therefore, in the absence of a damage report, a minimum test, which seems reasonable, is a simple low voltage test to ground using an instrument ensuring current limitation. No continuity test.
- In case of fault, define action.

6.2 Procedure 1

Continuity, polarity and insulation checks of main bus bars after the joints of one interconnection region have been made (applies to 1200 joints per machine sector).

- The continuity should be guaranteed by the process control of the soldering and the polarity by the geometrical positioning of the bus bars themselves (the so-called spider arrangement together with the mechanical rigidity will exclude a cross over of the conductors).
- The insulation between circuits and between circuits and ground needs to be checked after the joint insulation has been applied, the resin is cured and the sleeve is welded. The timing of this test must be carefully planned with the rest of the installation activity, since access to the equipment must be restricted.
- In order to avoid repetitive dielectric stressing of the circuit, it is planned to apply a reduced level of electric charge (i.e. a short pulse) which will decay along the string of magnets. A test with the full dc voltage applied will be done at the completion of the sector.

6.3 Procedure 2

Continuity, polarity and insulation checks of auxiliary bus bars for corrector spools (about 4000 joints per sector in continuos cryostat):

- The continuity, polarity and insulation check has to be done. A procedure similar to that proposed for line N could be applied.
- Also here, a procedure should be developed that avoids repetitive dielectric stressing of the circuits when checking the electrical insulation after each joint is made.

6.4 Procedure 3

Continuity, polarity and insulation checks of auxiliary bus bar of line N (about 2000 joints per sector in continuos cryostat).

- The method proposed for checking the bus-bar of the line N is presented in [2]

7 SUMMARY

The aims of the electrical quality assurance plan during installation of the cryo-assemblies in the machine are discussed. It is proposed that this plan covers also the commissioning and operation phases.

A team will be organised to specify the tests, define procedures, design and qualify the instruments, supervise tunnel testing and analyse the data. This will be documented by an engineering specification. A verifying crew independent from the installation team will carry out the actual electrical testing in the tunnel. Up to four verifying crews will be working during the LHC installation period.

REFERENCES

[1] F. Rodriguez-Mateos, “Voltage withstand levels for electrical insulation tests”, LHC-PM-ES-0001, CERN Engineering Specification, May 1999.
[2] K.H. Mess, “Test of the interconnections of line N”, These proceedings, Villars, March 2001.

VACUUM QA

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Abstract

The level of quality (cleanliness, leak tightness, etc.) expected for the components to be assembled is defined. The techniques and methods used to assure and verify the leak tightness of assembled components are explained. The sequence of tests, the time taken and the interference with other activities are explained.

1 INTRODUCTION

Quality assurance (QA) is necessary to ensure that the design, manufacture, installation, commissioning and operation of the vacuum systems[2] fulfils all requirements. This paper deals specifically with the QA issues for the installation of the Arc cryomagnets, but is also applicable to other zones of the LHC. Emphasis is placed on the pre-requisites to begin the work, the mobile vacuum equipment and the possible leak testing sequences.

2 BEFORE INSTALLATION BEGINS

The vacuum quality of the components and assemblies must be confirmed before any items are lowered to the LHC tunnel. The final checks will include inspection of the Manufacturing Test File (MTF) to confirm cleanliness and leak tightness, together with a visual inspection. All items must be marked with an equipment naming code and positioning code [1].

The cleaning and leak testing of LHC components and subassemblies are, by default, executed in industry as part of the supply contracts. Any exceptions must be agreed with LHC/VAC. The factory vacuum tests must be approved by LHC/VAC before delivery to CERN can be authorised.

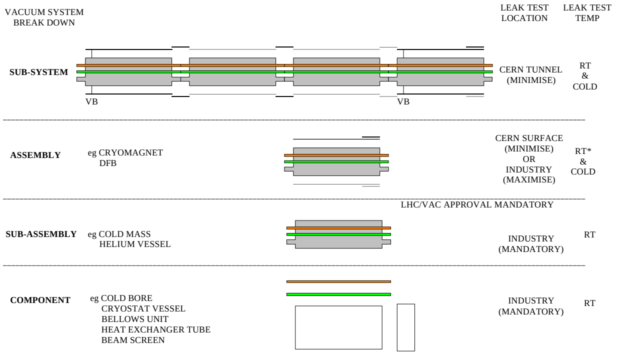

Figure 1: Leak testing strategy

3 IN THE TUNNEL

3.1 Assumptions

The infrastructure pre-requisites for cryomagnet installation are listed below:

- All floor drilling complete
    - vacuum cleaning during drilling
    - general cleaning afterwards
- Electrical network available
- Controls network available
- Data archiving operational
- Compressed air on
- Dry nitrogen on
- Ventilation on
- GSM network available
- LHC/VAC storage area under ground (UA) & surface (SD) at each Point.

The QRL pre-requisites for cryomagnet installation are listed below:

- Installation, leak & pressure test complete
- Cold commissioning complete
- Repairs complete
- End caps of helium tubes at jumpers have been cut (LHC/CRI)
- Open helium tubes at jumpers have protection covers
- QRL is isolated from cryoplant at QUI and pumping/pressure connections are installed
- Helium tubes without valves (XB & CC') have leak tight covers (see leak test ‘Scenario 3’)
- QRL cryogenic valves can be locally operated

The LHC Vacuum Group is responsible for, and organises, all leak testing activities in the LHC tunnel in collaboration with LHC/ACR and LHC/CRI Groups. Concerning pressure testing of the helium enclosures, TIS Division is additionally involved. The role of each party for the pressure test needs clarification.

3.2 Vacuum equipment

The vacuum instrumentation[3] permanently installed on the magnet cryostats has been designed to respect the tunnel “stay-clear” requirements. All mobile vacuum equipment fulfils the same criteria, and has been designed to fit underneath the cryomagnets during its use and storage. Space has been reserved under the SSS between the support jacks, together with a length of 900 mm under the down stream extremity of the MB•C cryodipole between the support jack and the interconnect sliding sleeve[4]. In addition, space must be made available in the UA zones for storage of mobile vacuum equipment during the Sector installation.

3.3 Leak testing techniques

Leak testing techniques using the helium mass spectrometer leak detector are shown in Figure 2.

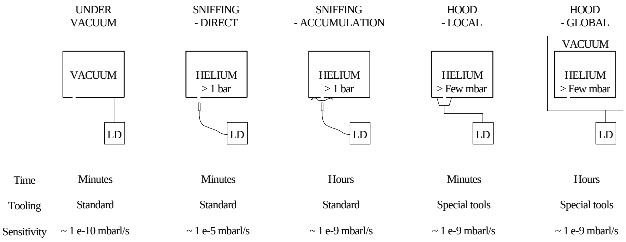

Figure 2: Leak testing techniques with tracer gas

Table 1 shows the number of in-situ welds per 214 m vacuum sector and the leak testing methods that can be applied. More than half of the welds are on the cold mass circuit (L, M, N), which cannot be tested using the traditional 'under vacuum' technique due to helium contamination.

	In-situ welds per 214 m insulation vacuum sector of LHC arc											
	Cryomagnet interconnects						Jumper interconnects					
	M,N 136	E 32	C',K 72	X 30	W (48)	V 64	LD 6	CC' 2	KD 4	XB 4	CY 2	Z 4
Leak test method												
Under vacuum		I	I ?	I ?	F	F						F
Sniffing - direct												
Sniffing - _accumulation	I, R	I, R	I, R	I, R			I, R	I, R	I, R	I, R	I, R	
Hood - local _(clamshell)	I, R	I, R	I, R	I, R			I, R	I, R	I, R	I, R	I, R	
Hood - global	F	F	F	F			F	F	F	F	F	

I- Intermediate leak test, F – Final leak test, R – Repair leak test

Table 1: In-situ welds and leak testing methods

A simplified layout of the helium and vacuum circuits of the QRL and cryomagnets is shown in Figure 3. There are no cryogenic valves at the XB and CC' jumper connections, therefore the lines C', K and X cannot be isolated from the QRL circuits. The 'under vacuum' technique would necessitate the evacuation of QRL headers B and C. Whether a sufficiently low helium residual can be achieved in this evacuated system requires confirmation.

Clamshell leak testing tools have been developed to perform leak testing on the in-situ welds on helium circuits using the 'hood-local' technique. The helium circuit to be tested is evacuated to < 1 mbar and the clamshell tool installed. A residual helium signal is measured before venting the helium circuit with helium gas.

The 'hood-global' technique can be used extensively to leak test the helium circuits once the insulation vacuum has been established.

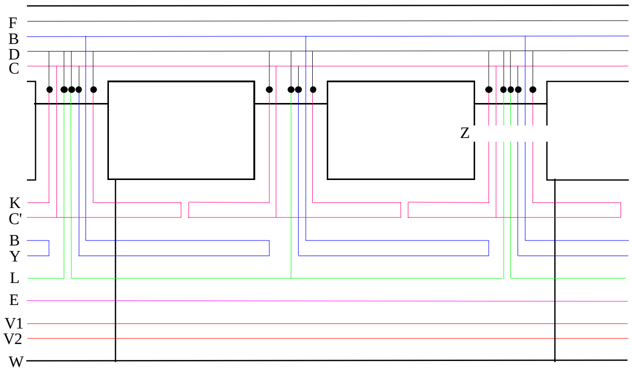

Figure 3 : Simplified layout of vacuum and helium circuits

3.4 Leak testing sequence

In order to establish a clear installation schedule for the LHC, a baseline scenario must be adopted for the leak testing sequence to be applied to the LHC Arcs. However, the leak testing sequence may evolve as a result of new inputs and experience gained before installation begins, and inputs during installation. Several such inputs are listed:

- On-going String 2 assembly
- QRL installation in Sector 7-8
- Overall LHC installation schedule
- Safety issues

The safety pressure test is the final step to verify adequate leak tightness of the helium circuits before the cryomagnets are cooled down. Helium can be supplied from the QUI, via the QRL circuits, to the cryomagnets. The Arc can be leak and pressure tested before the Sector installation is complete if the following conditions are fulfilled in the DS and LSS regions:

- The jumper test caps have not been cut

or

- Temporary covers are installed on the XB and CC' lines & the cryogenic valves are maintained closed,

or

- Temporary covers are installed on all jumper lines.

The following leak test sequences have been elaborated as a result of experience gained on String 1ref, String 2 and the QRL Test Cells, together with inputs from meetings between LHC/VAC, LHC/CRI, LHC/ACR and TIS [5].

3.4.1 *Scenario 1*

The leak test sequence ‘Scenario 1’ is shown in Table 2. The new welds of the two beam vacuum envelopes can be tested at regular intervals using the under vacuum technique.

Leak Test Scenario 1	Time/vac sector	Comments
Weld all interconnects of arc		
Leak test V1 & V2 after each 214 m	2 man days x 12	Volume gets big!
Close W bellows – with MLI		
1st pumping of insulation vacuum sector	3 days	
Leak test RT envelope of vac sector	2 man days x 12	
Complete Arc (Sector?)		
Leak & pressure test He circuits of arc	2 man days x 12	Many LD’s, TOF n/a
Open W bellows of leaking interconnects		Many repairs?
Repair defects on He circuits (clamshells)		
Close W bellows – with MLI		
Re-pump insulation vacuum sector	1 day	
Leak test RT envelope	1 man day x ?	
Repeat pressure test?		

Table 2 : Leak test sequence ‘Scenario 1’

Each magnet interconnect is closed, including thermal shields, multi-layer insulation (MLI) and sliding W bellows, once the assembly and welding activities are complete. The insulation vacuum can be established over a 214 m length between vacuum barriers. If there are no significant leaks on the helium circuits, which may give high or fluctuating helium signals in the insulation vacuum enclosure, the 214 m vacuum vessel envelope can be leak tested using the under vacuum technique.

Once the Arc is complete, the helium circuits can be leak tested using the hood-global technique. The circuits are collectively evacuated to < 1 mbar and then individually or collectively vented to helium via the QRL. The pressure can then be increased in each circuit to the test pressure. Both remote and manual operation of the QRL cryo-valves will be necessary during these activities. Any unacceptable leak(s) must be longitudinally localised within the 214 m vacuum sectors. With the radiative insulation, thermal shields and MLI installed at the magnet interconnects, leak location using time-of-flight (TOF) techniques may not be applicable; experiments will be conducted on String 2. After the necessary repairs are complete, the pressure test must be repeated.

The pumping and pressurisation of the QRL circuits at the QUI needs further study. In particular the technical, economical and safety issues associated with the handling of several hundred cubic metres of helium and nitrogen gas.

3.4.2 *Scenario 2*

The leak test sequence ‘Scenario 2’ is shown in Table 3. In order to apply the TOF technique, the thermal shields and MLI are not immediately installed. The leak and pressure testing of the helium circuits are then conducted as ‘Scenario 1’.

After the necessary repairs, all the W bellows must be reopened to install the radiative insulation, thermal shields and MLI, followed by a leak test of the W bellows seals. If a vacuum sector has no helium leaks, the reopening activities can be made in the shadow of repair activities on other vacuum sectors.

Leak Test Scenario 2	Time/vac sector	Comments
Weld all interconnects		
Leak test V1 & V2 after each 214 m	2 man days x12	Volume gets big!
Close W bellows – without MLI		TOF applicable
1st pumping of insulation vacuum sector	3 days	
Leak test RT envelope of vac sector	2 man day x 12	
Complete Arc (Sector?)		
Leak & pressure test He circuits of arc	2 man days x 12	Many LD’s
Open all W bellows		
Repair defects on He circuits (clamshells)		Many repairs?
Close all W bellows – with MLI		
Re-pump insulation vacuum sector	1 day	
Leak test RT envelope	2 man days x 12	
Repeat pressure test?		

Table 3 : Leak test sequence ‘Scenario 2’

3.4.3 *Scenario 3*

The leak test sequence ‘Scenario 3’ is shown in Table 4 and Figure 4, and is the leak testing sequence preferred by LHC/VAC. In addition to the activities of Scenario 2, the helium circuits can be leak tested prior to the completion of the Arc.

Leak Test Scenario 3	Time/vac sector	Comments
Weld interconnects of vac sector + 1 cell		
Leak test V1 & V2 after each 214 m	2 man days x12	Volume gets big!
Close W bellows – without MLI		TOF applicable
1st pumping of insulation vacuum sector	3 days	
Leak test RT envelope of vac sector	2 man day x 12	
Leak test He circuits of vac sector	1 man day x 12	Covers on BX, CC’
Open W bellows of leaking interconnects		
Repair defects on He circuits (clamshells)		
Close W bellows – without MLI		
Re-pump insulation vacuum sector	1 day	
Leak test RT envelope	2 man days x ?	
Complete Arc (Sector?)		
Leak & pressure test He circuits of arc		Many LD’s
Open all W bellows		
Repair defects on He circuits (clamshells)		No repairs?
Close all W bellows – with MLI		
Re-pump insulation vacuum sector	1 day	
Leak test RT envelope	2 man days x 12	
Repeat pressure test?		

Table 4 : Leak test sequence ‘Scenario 3’

If the helium circuits are welded 54 m upstream and 107 m downstream of a completed insulation vacuum sector, and temporary leak tight covers are installed on the XB and CC' lines of un-welded QRL jumper interconnects, the helium circuits can be evacuated and vented to helium. The hood global method can be used to detect any leaks in the vacuum sector. If required, repairs can be made in the shadow of continuing installation activities on the Arc. The pressure test can be executed when the Arc is complete. Alternatively the temporary covers at the jumper interconnects could be designed to withstand the test pressure, giving the possibility to make the pressure tests earlier.

Space constraints at the QRL/SSS jumper interconnects hinder the installation of temporary covers. The baseline designs of both QRL and SSS are fixed. Further studies are required to integrate temporary covers.

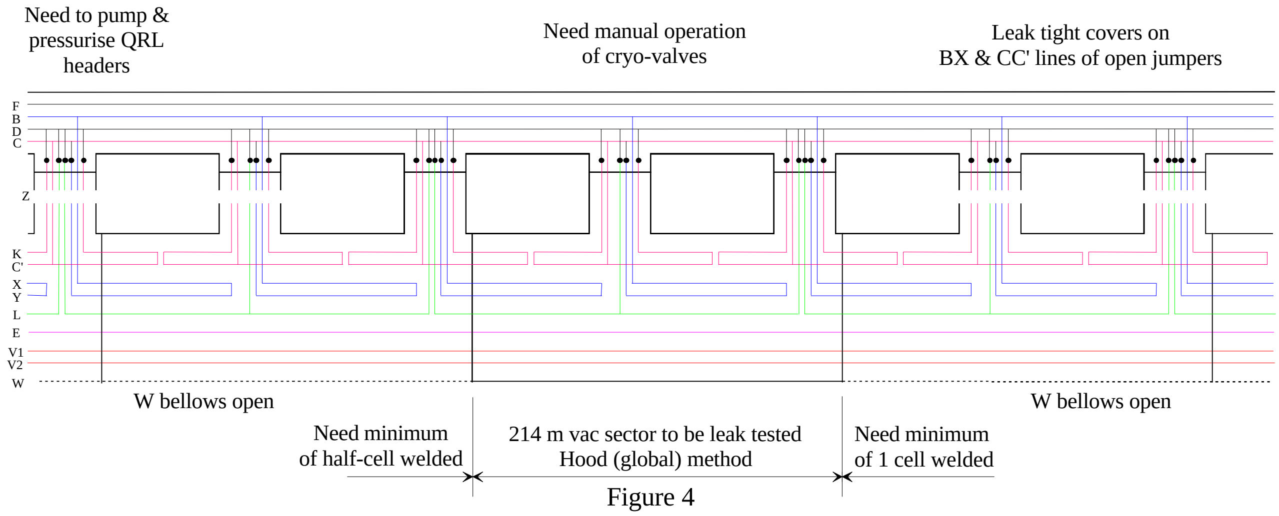

Figure 4

3.4.4 *Scenario 4*

Figure 5 shows an additional option to make leak testing of the helium circuits prior to connection with the QRL. Temporary covers and pumping/pressure connections are required on the SSS helium circuits at the SSS/QRL jumper interconnects. Following a local pressure test of all the helium circuits, the C', K and X circuits can be leak tested using the under vacuum method. The temporary connections will not allow closure of the Z bellows at the jumper connection without a redesign of the jumper connection layout, therefore the cold mass helium circuit can only be leak tested, using the global hood technique, after connection with the QRL. If the installation is proceeding from right to left, the cold mass circuits within an evacuated insulation vacuum sector can be pumped/ pressurised via the un-welded jumper interconnect to the left of the vacuum sector under test.

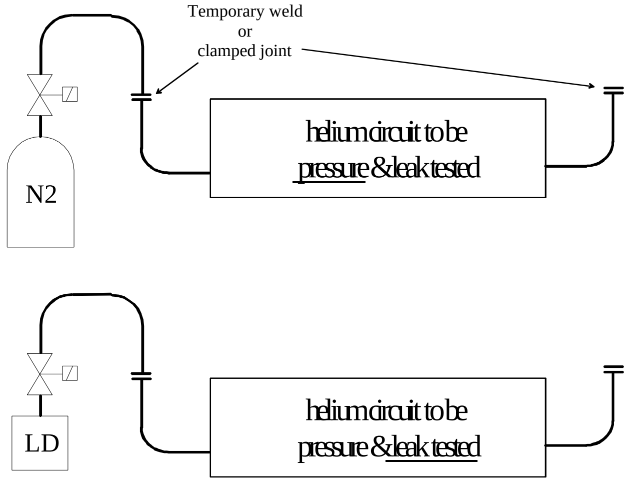

Figure 5 : Leak test sequence 'Scenario 4'

As the magnet interconnect welds are locally pressure tested, the thermal shields and MLI can be installed once the leak tests on the vacuum sector are complete. Again, further studies are required to integrate temporary covers and connections at the jumper interconnects.

4 CONCLUSIONS

Items to be installed in the tunnel must pass all vacuum requirements at the surface before lowering. The in-tunnel leak testing techniques are known and the tools exist. The mobile vacuum equipment has been designed to fit under the cryostat and the space has been reserved. Several leak testing sequences have been elaborated. The LHC Vacuum Group propose that Scenario 3 is adopted as the baseline leak testing sequence, however the solution of temporary covers on the BX and CC lines needs to be studied. Pressure testing of the Arc can be made independently of the Sector installation if required. Responsibilities for the pressure testing activities need to be defined.

5 ACKNOWLEDGEMENTS

The mobile vacuum equipment has been designed and manufactured by members of the LHC/VAC/AR Section, in collaboration with LHC/VAC/IN. The leak testing activities on the QRL Test Cells and String 2 performed by P. Coly, W. Maan, P. Thirion and P. Trabujo have provided experience with the leak testing tools and techniques. Thanks to the initiatives of J.Ph. Tock and B. Skoczen, together with the participation of W. Maan, R. Trant, L. Tavian, and R. Vuillermet, several ad hoc meetings on LHC leak and pressure testing have provided valuable inputs.

REFERENCES

[1] R. Saban, "Equipment naming conventions", Quality Assurance Definition LHC-PM-QA_204.00 rev 1.0.
[2] P. Cruikshank, "From String 2 to the Sector Test: Vacuum", Proceeding of LHC Workshop Chamonix XI, February 2001.
[3] J. Casas-Cubillos et al., "Instrumentation and wires for the machine and QRL in the arcs and dispersion suppressors", Engineering Specification LHC-CI-ES_0001 rev 1.0
[4] Minutes of TEWG #5, 10th August 1999.
[5] J.Ph. Tock, "Pressure Tests", Design Review of the LHC Arc Interconnects, April 2000

HANDLING NON-CONFORMITIES IN THE TUNNEL

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Abstract

The discovery of a non-conformity during the preparation or the installation of an LHC component will either result in the complete refusal of the component, the repair in-situ of the defective component or the decision to use it as-is. The procedure to handle this type of event will be described and the associated documentation will be presented.

1 THE CAREER OF A CONTINUOUS CRYOSTAT COMPONENT

Throughout this paper, the most common components of the continuous cryostat in the arc, like a dipole are considered. These components are industry made on a relatively large scale and come in a limited number of different types. Non conformities discovered on less common components, like electrical feed boxes, which are tailor made for a particular position in the LHC tunnel, could require special care.

All the continuous cryostat components include parts or sub-components that are manufactured in industry. In the case of the dipoles, the final assembly into a cryomagnet takes place on the CERN site. Before this operation however, the sub-components undergo reception tests that ensure the integrity of the part delivered by industry. Following its assembly, the cryomagnet undergoes tests and measurements at cold. These are aimed at qualifying it for installation in the tunnel.

It is worthwhile mentioning that the mechanical interfaces for these tests are significantly different from those required for installation in the tunnel. On the successful completion of the tests, the cryomagnet interfaces are reconfigured for installation in the tunnel and the cryomagnet is stored before transport.

1.1 Clearance for Installation

Before the cryomagnet is lowered in the collider tunnel, utmost care must be taken to ensure that no defect, which could compromise the installation of the component or the operation of the collider, is present.

The configuration of mechanical interfaces, the quality of the welds, the leak tightness, the electrical integrity of the active parts, of the cabling as well as of all the associated instrumentation must be verified before clearance for installation is granted.

This operation could be in the form of a sequence of additional tests or a careful and final inspection of the Manufacturing and Test Folder (MTF).

Like all the other operations carried-out during the manufacturing and subsequent tests, this operation should be documented in the MTF.

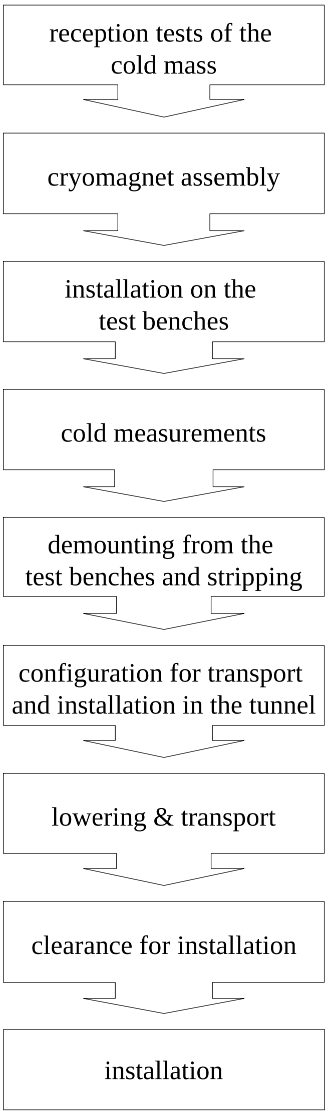

Figure 1 : The career of a continuous cryostat component

1.2 The late discovery of a non-conformity

The cost of cancelling the effect of a non-conformity by replacement or repair grows exponentially as its deeper integration in assemblies proceeds. While the cost of taking the decision of not installing a faulty corrector is limited to its cost, its replacement in a first level sub-component is ten times more expensive.

If the non-conformity is discovered after the cold tests of an already assembled cold mass, the cost increases ten fold.

The time required for the warm-up and the cool-down of five cells to replace a defective continuous cryostat component is today evaluated to 35 days. It comes as no surprise that when the non-conformity is discovered to be jeopardising the normal operation of the collider the cost increase is more than tenfold.

1.3 The non conformity detected at installation

Because of cost of the late discovery of a non-conformity, the clearance for installation must ensure that the component which is taken underground is fit for installation. If this test is carefully designed and diligently executed, the non-conformities detected at installation time will only be those which are created during transport or during installation.

2 QUALITY THROUGH PROCEDURES

All the operations, which are carried-out during the assembly or the tests of the components, must be documented in detail in the form of procedures. These should have been qualified in advance through engineering specifications. They must be diligently carried-out and only by certified personnel.

The settings of the tools (welding machines, voltage sources, ohm meters, etc.) used during the operations will be given in the procedures and will be recorded in reports while the work is being carried-out. Qualified inspectors should verify these reports early enough to reduce the cost of any corrective action. The quality of the end product of the operation should be periodically verified on samples that are analyzed in depth.

3 DETECTING NON-CONFORMITIES

The non-conformities encountered during the installation of the components for String 2 are a good first approximation of what could be experienced when installing LHC. They are taken as examples and related to the life cycle, or career, of a component to identify where they would have been detected if the test scenario was applied.

All the non-conformities were resolved with ad-hoc solutions which ranged from use-as-is to repair. No component was refused for installation. It is however important to point out that the Project Engineers for the components were either part of the team or could be easily consulted. When installing the collider in the tunnel, the situation will be very different. In fact, the assembly teams will certainly not include Project Engineers, expert advice will be more difficult to get hold of and time will be limited.

3.1 The mechanical non-conformities

The first two non-conformities, namely the *ovalisation of beam tube in dipole N1* and *the length of the cold-bore in SSS4* would have been detected either when the components were delivered to CERN or before clearance for installation was given depending on the when they were generated.

The *incompatibility between QRL jumper and SSS3 type* was known early in advance and could be best described as a "non-conformity by design"! In fact, the choice of installing a Type B short straight section (SSS) was made with the aim of testing the feasibility and the quality of the plugs although for the actual configuration the plugs had to be bypassed.

These *bus bar plugs were finally found to be leaking*. This non-conformity was detected only during the preliminary leak tests. Had the test scenario been applied, it would have been detected during the reception tests carried-out when the components were delivered to CERN.

The *position of the spool piece corrector bus-bars in SSSs* change when traversing the cold mass. This means that the inverse transformation must be done in the interconnects. Had the test scenario been applied, it should have been detected during the reception tests carried-out when the components were delivered to CERN.

3.2 The electrical non-conformities

A *short to ground in one of the orbit correctors of SSS4* was detected during the tests for clearance for installation which was actually done after the SSS had been positioned and interconnected to the neighbouring dipole. This damage resulted from the scaffolding erected around the interconnect. In the tunnel, this would have been discovered after the magnet had been fully interconnected.

Damage to orbit corrector current leads in SSS3 was observed before the cryomagnet was installed. The protection of the leads and their interface with the cold mass was redesigned as a result of this.

The *short to ground in a sextupole spool-piece in dipole A2* had already been detected when the dipole was cold tested. The non-conformity was therefore known but confirmed during the tests for clearance for installation. The circuit was modified in the interconnects to by-pass this particular sextupole spool-piece.

3.2 The non-conformities related to instrumentation

A *pressure sensor in SSS3* was known to be broken following the cold tests. Considering the requirements for thermo-hydraulic experiments a replacement sensor and a special instrumentation feed-through were installed.

During the clearance for installation tests, a number of *voltage taps for bus-bars were found to be missing in SSS3*. Had the test scenario been applied, this non-conformity too would have been detected during the reception tests carried-out when the components were delivered to CERN.

4 THE OPERATIONS IN THE TUNNEL

4.1 Preparation of the tunnel

Before the installation of a sector can start the proper installation of the infrastructure, the QRL and jacks must be verified, the non-conformities recorded and their impact evaluated.

4.2 Transport

After the continuous cryostat component is lowered in the tunnel and transported to its destination, it is positioned on the jacks. It is then inspected to ensure that no damage to cables, instrumentation wires, or to components resulting in visible deformations, was caused during the transport. The cryomagnet is then pre-aligned.

4.3 Magnet Interconnects

The operations on the interconnects are first performed in the innermost tubes advancing towards the periphery. The cold bores with their RF contacts are first assembled, the main bus-bars are soldered and the auxiliary bus-bars are welded. These operations are verified by checking the settings of the tools (soldering oven, ultrasonic welding machine). The tubes on the helium vessel are then welded. Again the settings are checked against values given in the welding procedure.

4.4 Junction with QRL

Every 106.9 m a short straight section is connected to the cryogenic line via a jumper connection. The tubes are welded and the settings are checked against values given in the welding procedure.

4.5 Line N

When all the components of a half cell are installed, the bus-bar cable is inserted over the full length of the half-cell. The connections of the wires in the cable to the lattice corrector leads is made following the procedure described in [1].

5 HANDLING NON-CONFORMITIES AT INSTALLATION TIME

The installation and the assembly of the sectors will be carried-out by personnel on an industrial contract with little or no knowledge of the design of the components and their function.

In order to allow the installation teams to efficiently react to a non-conformity, a *catalogue* of the most severe non-conformities must be established after a careful failure mode effect analysis. Each entry must be accompanied by precise instructions or a corrective procedure which must be applied when the non-conformity is detected. Such an event must be diligently logged in the MTF and reported.

A *panel of experts*, made up of project engineers responsible for the components, will prepare and update the catalogue. Furthermore, regular *SOS meetings* must be organised to treat and add the non-conformities missing in the catalogue. These meetings will also be an efficient means of disseminating information across installation fronts.

The assignment of a *budget* for each type of non-conformity in a given sector must also be foreseen. As an example consider the maximum tolerable number of faulty orbit or lattice correctors of a given type and on a given beam.

It is worthwhile mentioning that, while a replacement for some type components will be relatively easy to find (e.g. there are only two types of dipoles in a given sector), for others like the short straight sections it will not. In fact, for some of them only a few identical pieces will be manufactured.

6 ORGANISATION OF THE INSTALLATION

An *underground work co-ordinator* must be assigned to every sector of LHC. They will have the overall responsibility for the sector and will keep a record of the environmental non-conformities (e.g. those detected before installation started). They will participate to the SOS meetings organised by the panel of experts and act as a liaison between CERN and the installation teams. Because the knowledge of how CERN works is paramount for his activity, it is essential that the underground work co-ordinators are CERN staff members.

The proposed installation strategy shows [2] that up to four installation fronts will be active simultaneously installing different sectors of LHC. Experience with the installation of String 2 has shown that these multi-disciplinary teams must be led by an *installation chief* who is present in the tunnel full-time and participates to installation/assembly work.

Finally, an *inspection team* controlling the quality of the installation must cover all sectors.

The SOS meetings must be organised by a core of experts and attended by the group of underground work co-ordinators and members of the inspection teams.

REFERENCES

[1] K-H.Mess, Test Procedures during Installation Overall LHC installation sequence of the Electrical Interconnections in the 600 A Power Circuits of the N-line, this workshop.

[2] P.Bonnal, Overall LHC installation sequence, this workshop.

WHAT DO THE EXPERIMENTS EXPECT FROM THE MACHINE?

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Abstract

Starting from the physics motivation and the basic parameters of the LHC collider this paper discusses the specific requirements and expectations of each experiment. How these requirements have been taken into account in the design of some examples of equipment and layouts will be examined and some implications for the assembly, installation and commissioning phases of the collider mentioned.

1 INTRODUCTION

In order to understand what are the requirements of the experiments and therefore what they will expect from the machine, it is helpful to recall the physics which the LHC is expected to reveal. The two largest experiments, ATLAS and CMS are both general purpose facilities which will be capable of studying almost all the numerous aspects of 14 TeV physics. Protons are composite particles with a three quark elementary particle structure which means that hadron colliders reveal a wider range of physics at high energy than electron-positron colliders. However, the priority aim of both ATLAS and CMS is to discover the Higgs boson and explain the particle mass scale. These two experiments have been designed around the expected Higgs signal and the general environment. The first simple fact to note is that at full design luminosity the standard model predicts a thousand or less Higgs decays to 4 muons. Thus the experiments have to be able to identify these events among the total of 10^{16} minimum bias events. Between these two extremes there is a wealth of physics some of which will be within reach of lower luminosities, but even Z and W production is only at the level of 1 event in 10^6. The complexity of a 14 TeV collision must also be taken into account and finally adds up to the "LHC experimental challenge"[1]. The first and obvious expectation (requirement) of ATLAS and CMS is clearly a high average luminosity and very reliable operation so that sufficient rare events occur to give them a chance of finding them in sufficient numbers to establish a discovery. It should be noted that in this sense there is an equivalence between energy and luminosity and a small reduction in total energy can be compensated by an increased luminosity. Add to this, information about machine generated backgrounds and the general requirements of ATLAS and CMS can be established. There are, however, a total of five experiments in the currently approved LHC programme and the others are more specialised to investigate particular physics and hence have additional expectations.

2 LUMINOSITY & BACKGROUNDS IN ATLAS & CMS

2.1 Luminosity

The design luminosity of 10^{34} $cm^{-2}s^{-1}$ for a total of 10^7 seconds corresponds to an integrated luminosity of 100 fb^{-1} which should yield of the order of 1000 Higgs events This has to be compared with the latest milestone schedule which foresees a pilot run of 4 weeks early in 2006 followed by a 3 month stop to complete the installation of detectors and then a colliding beam run of. 7 months which it is hoped will yield 10 fb^{-1}, or 100 Higgs events, which should be sufficient to claim a Higgs discovery. But the safety margins are not high and the schedule is undoubtedly aggressive from the machine point of view.

2.2 Background

A typical 7 TeV + 7 TeV proton collision produces ≈ 100 secondaries with the energy flow very much in the forward directions, in fact there are some 800 W along each outgoing beam. At slightly larger angle the secondaries traverse the beampipe through the experiment and in doing so shower and produce enormous numbers of lower energy particles which create spurious hits in the large surface detectors. Nearly 200 watts will be absorbed by the TAS absorber which is essential to prevent these collision secondaries from quenching Q1, but then becomes a prime background source. ATLAS & CMS have foreseen massive shielding (up to 2 m radius of iron) to reduce background counts in the muon chambers by up to six orders of magnitude. As a result radiation levels in the caverns are low (1 Gy/yr) and both ATLAS and CMS will be rather insensitive to machine induced background such as upstream beam losses. With reasonable assumptions, effectively a beam lifetime of around 100 hours, the muon rates which are the only particles which will penetrate this shielding from the machine side are estimated to be below 10 muons $cm^{-2}s^{-1}$ which is acceptable. Less positive is the fact that this forward shielding is an integral part of the radiological shielding for people and the environment. It makes access to detectors very difficult and completing the experimental detectors in short machine stops impossible. This is the reason for the three month shutdown after the "pilot run".

3 SPECIAL REQUIREMENTS OF OTHER EXPERIMENTS

3.1 Totem

The last experiment to be approved, TOTEM is the smallest, but is not unimportant. It will be installed at Point 5 with CMS and will measure elastic and inelastic scattering to deduce the total cross-section - a basic measurement which ATLAS will also make. The machine requirements are very special as the elastic scattered particles are only deflected by a few micro-radian and hence very small divergence beams (beta*=1000 m) will be needed and the detectors will have to be placed very close to the beams in "Roman Pots" in the warm straight sections. To avoid multiple crossings dedicated runs with < 90 bunches will be needed and this together with the high beta* results in $L \approx 10^{28}$ $cm^{-2}.s^{-1}$. With a few successful runs of this type TOTEM will determine the total cross-section to ≈ 1 % and calibrate "luminosity monitors" but the difficulty will then be to extrapolate by six orders of magnitude in order to be able to measure the machine luminosity in the 10^{34} $cm^{-2}.s^{-1}$ region.

3.2 LHCb

Another specialised experiment is LHCb - a single arm spectrometer for B-physics which will try and exploit the fact that B-type events will have secondary vertices. The challenge of LHCb is to trigger on secondary vertices only a few millimetres away from the primary vertex. This will certainly only be possible with one collision per bunch crossing implying a luminosity of $L \leq 2 \times 10^{32}$ $cm^{-2}.s^{-1}$ which will be obtained with a beta* ≈ 25 m.

LHCb will be installed at Point 8 in the existing cavern and in order to do this the single arm spectrometer with small angle acceptance will be built downstream of a displaced collision point. One of the key detectors of LHCb, the secondary vertex locator (VELO) is the subject of another paper at this meeting [2]. The small angle acceptance suggests that LHCb will be sensitive to machine background, certainly beam halo and beam-gas collisions in the long column of upstream residual gas, and maybe secondaries from other collision points. All this in addition to the secondary particle background described for ATLAS and CMS, but without any possibility of inserting shielding between the detectors and the beampipe.

It should also be noted that LHCb uses a warm dipole which will be ramped with the LHC beam energy, requiring three special magnets to provide local orbit compensation. Running with both polarities will be a standard request.

3.3 ALICE

ALICE is an experiment which has been designed to study heavy (Pb) ion collisions where the dominating feature is 8000 secondaries / unit of rapidity. To do this ALICE has chosen a TPC (similar to that of ALEPH). A TPC can handle many thousands of simultaneous particles but only at very low event rates. Hence ALICE luminosity requests will be: $L(\text{Pb-Pb}) = 10^{27}$ $cm^{-2}.s^{-1}$ and $L(\text{p-p}) \leq 10^{30}$ $cm^{-2}.s^{-1}$ The only way to provide the latter during normal high intensity proton runs will be to use halo-halo collisions with beam centres at least 4 sigma apart. A few dedicated runs will be insufficient to allow ALICE to collect adequate comparison data. With such a low signal, but a similar background to LHCb, ALICE will be sensitive to backgrounds during p-p running, in particular beam-gas at the collision point and the upstream straight section. It should be noted that both ALICE and LHCb will be able to measure this type of background as they always have non-colliding bunches on both beams, in the beam-dump gap.

A unique feature of ALICE are the ZDC's (zero degree calorimeters) placed in front of magnet D2 on both sides of the collision region, for the detection of neutrons and single protons during ion running. The acceptance of these calorimeters will be a strong function of local collision parameters since they are observing secondary particles of small angle passing through the inner triplets. Because of this a vertical crossing angle will be required and possibly special collision point displacements. At the present time they are watching closely the design of the injection absorber (TDI), which although withdrawn after injection will have RF screens in their acceptance.

4 CONCLUSION

The initial experimental programme of the LHC is already quite diverse, as expected for a hadron collider. The experiments have a number of "expectations", many of which can be summed up by; "adequate luminosity, high reliability and low backgrounds". However, it is clear that with five approved experiments there will be difficult compromises to make and priorities will need to be fixed. After initial commissioning there will be special requests for particular running conditions and operating the LHC will remain "interesting" for a very long time. In particular because once the primary aims have been achieved there are many other physics topics to be investigated. There will certainly be requests for running at low energy (1 TeV on 1 TeV) to make comparisons with Tevatron data and ALICE already has an extensive programme of lighter ion runs and even proton-ion and deuteron-ion running after the first few years. Totally new experiments can never be excluded.

REFERENCES

[1] J. Virdee, “Inaugural Lecture”, CMS web pages http://cmsinfo.cern.ch/Welcome.html/CMSdocuments/JimInaugural/JimInaugural_index.html

[2] M. Ferro-Luzzi, “LHCb and its vertex tank”, LHC days 2001, paper 5.3

THE ATLAS EXPERIMENT

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Abstract

The general purpose particle physics experiment ATLAS is part of the LHC project. The main parameters of ATLAS are presented, then the status of the experimental area is addressed, as well as the status of the development and manufacture of the main components of the experiment (particle detectors and magnets). The interfaces with the LHC machine and the LHC division are stressed. Finally, the installation key dates are indicated.

1 ATLAS MAIN PARAMETERS AND GOALS

ATLAS, the largest of the five LHC experiments, will be installed at Point 1 of the future LHC collider, very close to the Meyrin Site of CERN.

The overall dimensions of the experiment, represented in Fig.1, are 45 m long and 25 m in diameter. Its total mass is about 8000 tonnes.

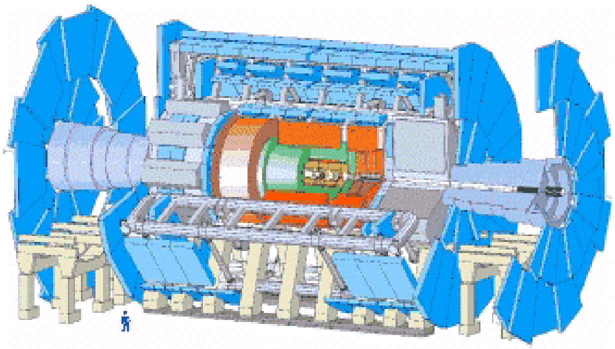

Figure 1: The ATLAS experiment

The experiment is divided into six main systems:

- the inner tracker, measuring the momentum of each charged particle
- the calorimeter, measuring the energy carried by the particles
- the muon spectrometer, identifying and measuring muons
- the magnet system, bending charged particles for momentum measurement
- the shielding, reducing the background in the detectors
- the support structures, providing accurate and stable location for the detectors.

The main ATLAS specificity is its huge air core super-conducting toroidal magnet, housing the largest muon spectrometer ever built.

The physics goals of ATLAS include B-physics, measurement of W mass, measurement of top quark mass, Higgs boson discovery, measurement of Higgs boson mass, discovery of supersymetric particles, squarks and gluinos.

2 STATUS OF THE CONSTRUCTION

2.1 Experimental area

The surface experimental area comprises six new buildings erected at LHC Point 1. These will house infrastructure equipment (cryogenics, cooling and ventilation, gas storage) and will provide access to underground areas. Three buildings have already been delivered, another one is completed but not yet delivered, and the remaining two will be erected in 2002.

The underground experimental area comprises two major caverns and various smaller dimension link tunnels. The service cavern USA15, the vault of which is being concrete formed, will be delivered in August 2001, while the experimental cavern UX15 delivery is expected early 2003.

2.2 Detectors and magnets

The manufacture of ATLAS is progressing in industry and research laboratories scattered around the world, before converging to CERN for integration tests, and later assembly into the experiment. The magnets are also being constructed in industry. A functional test module of a barrel toroid magnet coil, shown in Fig.2, is currently being tested at CERN.

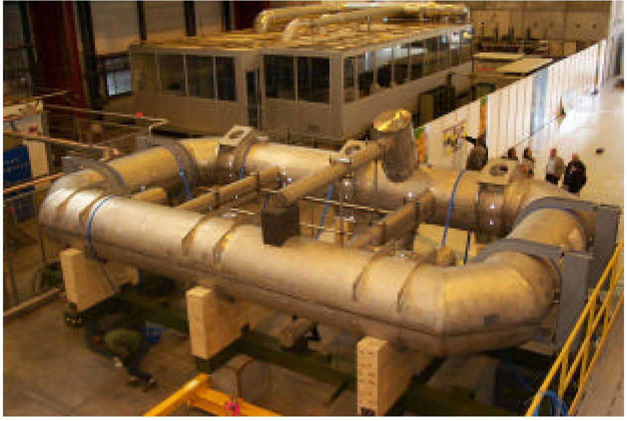

Figure 2: The B_0 toroid magnet test coil at CERN

The studies of the major support structures for detectors and magnets are finished and industrial contracts are being awarded. Main shielding elements are ending the final design phase.

3 INTERFACES WITH LHC

3.1 Experimental beam vacuum system

The main interface with the LHC machine is, without a doubt, the beam pipe that traverses the experiment. The geometry and materials used for the beam pipe are the result of long studies and discussions, in order to match the requirements of both the machine and the experiment.

The beam pipe of the ATLAS experiment is segmented into seven sections, of various geometry and materials, interconnected by bellows to compensate for possible misalignments.

The main requirements of the experiment are:

- the volume used should stay minimal so as to maximise the space for detectors
- the amount of material involved should stay minimal, so as to keep multiple scattering and background as low as possible
- thermal and electromagnetic compatibility have to be ensured.

To satisfy these requirements, exotic solutions have sometimes to be found: the ATLAS central beam pipe is a 29 mm inner radius, 7 m long, 0.8mm thick double wall each, beryllium tube!

Special developments have also taken place, mainly in CERN LHC/VAC group, to propose mass minimised aluminium flanges and mass minimised ion pumps.

Validation of these concepts, as well as study on vibration damping, are being performed, using a specially developed 42 m long test stand.

The CERN EST/SM group also contributes to special developments, in particular in the domain of distributed pumping techniques: NEG (Non Evaporable Getter) pumps are being developed to be used in the beam pipe, sputtered on stainless steel, aluminium or beryllium.

3.2 Cryogenics equipment

The CERN LHC/ECR group contributes to the design and procurement of the cryogenic equipment for the detector. In the case of ATLAS, the 25 superconducting magnets need large quantities of liquid helium, while the calorimeters use more than 50 tonnes of liquid argon underground.

3.3 The TAS collimator and its shielding TX1S

The last machine element on either side of the ATLAS experiment is the TAS collimator. It is a cylindrical block of copper, aiming at protecting the LHC cryomagnets from high rapidity secondaries generated by collisions at the interaction point. It is also used to protect the experiment from possible beam losses that would damage the costly detectors.

The TAS collimator will be the most radioactive element in LHC. It therefore has to be shielded, in order not to perturb muon chamber efficiency, and to limit the radiation rate to a level at which human maintenance in the experimental cavern is allowed.

This shielding is made of 1000 tonnes of steel and cast iron, supported cantilevered from the cavern wall. It also acts as support for the TAS collimator (see Fig. 3).

Special techniques had to be developed in order to survey and align the TAS: its location tolerance is 300µm with respect to the LHC beam.

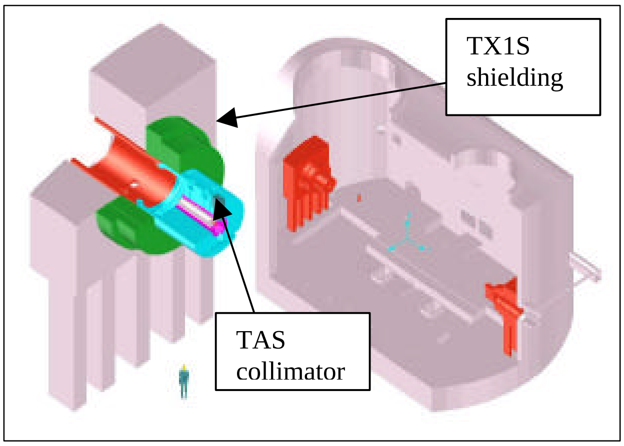

Figure 3: TAS collimator supported from TX1S shielding

4 ATLAS INSTALLATION KEY DATES

Various difficulties in the civil engineering works at Point 1 have lead to a 7 month delay in the delivery of the experimental cavern. The start of installation of the ATLAS experiment, planned to span over three years has therefore to be delayed by the same time frame.

An agreement was found recently between the representatives of the LHC accelerator, of the LHC experiments and CERN for a new target date for the first LHC beam. The ATLAS installation key dates are the following:

- Experimental cavern delivery: Feb 2003
- Start of barrel toroid magnet installation: Nov 2003
- Barrel calorimeter installation: Mar 2004
- End-cap calorimeters installation: Aug 2004
- Solenoidal field mapping: Aug 2004
- End-cap toroid magnets lowering: May 2005
- Beam pipe closure: Oct 2005
- Global commissioning: Nov 2005 – Jan 2006
- LHC First beam: 01 Feb 2006

It is important to note that the time span left for the global commissioning of the detector is only three months. This is considered as very ambitious for such a quantity of peak technologies, integrated for the first time.

THE LHCB VERTEX LOCATOR: INTEGRATION WITH LHC

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On behalf of the LHCb collaboration

LHCb is a single-arm spectrometer with a forward angular coverage from ~ 12 mrad to 300 (250) mrad in the (non-)bending plane. The choice of the detector geometry is motivated by the fact that at high energies both the b- and $\bar{b}$-hadrons are predominantly produced in the same forward cone, a feature exploited in the flavour tag. A modification to the LHC optics, displacing the interaction point by 11.25 m from the center, has permitted maximum use to be made of the existing IP8 cavern. LHCb comprises a vertex detector, a tracking system (partially inside a dipole magnet), aerogel and gas RICH counters, an electromagnetic calorimeter with preshower detector, a hadron calorimeter and a muon detector. All detector subsystems are assembled in two halves, which can be separated horizontally for assembly and maintenance, as well as to provide access to the beam pipe which spans throughout the LHCb detector.

The LHCb vertex locator (VELO) represents a major challenge in that it must provide identification and reconstruction of production and decay vertices of b-hadrons, both offline and for the Level-1 trigger. These vertices are located at distances of a few millimeters from the IP and must be reconstructed with micrometer precision. The choice was made to use a microstrip silicon tracker (r-ϕ geometry) positioned at a distance of 8 mm from the beam axis, which corresponds to a full aperture smaller than that required by LHC during injection (54 mm). As a consequence, the tracker must be retractable to leave the required clearance during injection. In order to obtain the aimed performance of the VELO, the silicon strip detectors are operated in a secondary vacuum, separated from the primary (LHC) vacuum by a thin-walled aluminium encapsulation. This allows for positioning the sensitive areas closer to the beam and reducing the amount of material traversed by particles. To obtain maximum coverage, the detector planes of the two opposite halves are staggered by a few mm to allow for a small overlap. This feature also allows for precise relative alignment of the two halves and for a stereo angle in the ϕ detectors without loss of acceptance. As a result, the aluminium encapsulation must be formed in a complex shape, with corrugations of varying depth, to minimize multiple scattering while taking into account RF coupling to the beams. Further, the design must consider dynamic vacuum phenomena in the vicinity of the beams and the severe radiation environment.

Fig. 1 shows a three-dimensional view of the current mechanical design of the VELO. The vacuum system consists of three communicating sections, namely the primary vacuum vessel, the LHCb beam pipe and the silicon detector housings. The LHCb beam pipe is segmented into three tapered metallic pipes (Al, Al-Be alloy and stainless steel are being considered) coated with low activation temperature NEGs. At its upstream side the pipe ends with a curved Ø0.76 m and 2 mm thick Al window. The primary vacuum vessel is a Ø1 m stainless steel tank of about 1.8 m length which will be evacuated by two powerful ion-getter pumps. It contains the Si detector housings (secondary vacuum vessels) and the supporting frames. Access to the silicon detectors has been decoupled from access to the primary vacuum. In this way, and by applying the ultrapure neon venting procedure which preserves the NEGs, it will be possible to first bake out the vacuum system to a temperature of ~ 150ºC and subsequently install the silicon detectors inside the vacuum. The main function of the Si detector housings is to protect the primary vacuum from excessive outgas rates and to reduce RF coupling between the LHC beams and the VELO. In the current design, the walls of the housing which fall within the LHCb acceptance are made of 0.5 mm Al, except for the sides facing the beams which are made of 0.25 mm Al. These vessels are evacuated by two turbomolecular pump stations. After installation, the detector support frame is decoupled from the vacuum flange and attached to the remote-controllable positioning system (all motors, gearboxes, belts and bearings are located outside the vacuum and coupled to the in-vacuo parts via bellows). The detector housings and supporting frames are decoupled from the primary vacuum vessel by using large rectangular stainless steel membranes, which allow for moving the detector halves by the required amount in the two transverse directions. Two kinds of valves are used to protect the thin separation foil in case of a pressure increase on either side of the foil. Pressure switches are used as a trigger to open electrically activated valves whenever the differential pressure between primary and secondary vacua rises above ~ 1 mbar. If the differential pressure exceeds ~ 5 mbar, a gravity-controlled valve opens under the direct effect of the pressure and independent of any external supply. The cooling of the detector modules is achieved by using a mixed-phase CO_2 cooling system. From the main supply line the liquid is expanded into a number of stainless steel capillaries (inner/outer diameter of 0.9/1.1 mm, one line per Si module) via flow restrictions. The capillaries and flow restrictions are vacuum-brazed to a manifold. The total amount of CO_2 in the system is relatively small, of the order of 5 kg, which corresponds to approximately 2.5 m^3 at STP. The amount in the tubing located inside the secondary vacuum is less than 100 g. The temperature of the coolant in the capillaries is set by controlling the pressure on the return line (typically 15 bar). In this way, a temperature in the range of -25° to +10° can be maintained with a total cooling capacity of about 2.5 kW (~ 50 W per cooling capillary). The constraints and requirements mentioned above make of the LHCb VELO a complex and challenging project. Several issues need to be addressed (a few of which were mentioned here) before arriving at a design which fulfils all these requirements. We take this opportunity to acknowledge the invaluable help and support of the LHC-VAC and SL-AP groups. More details on the LHCb vertex locator can be found on the VELO www sites[1].

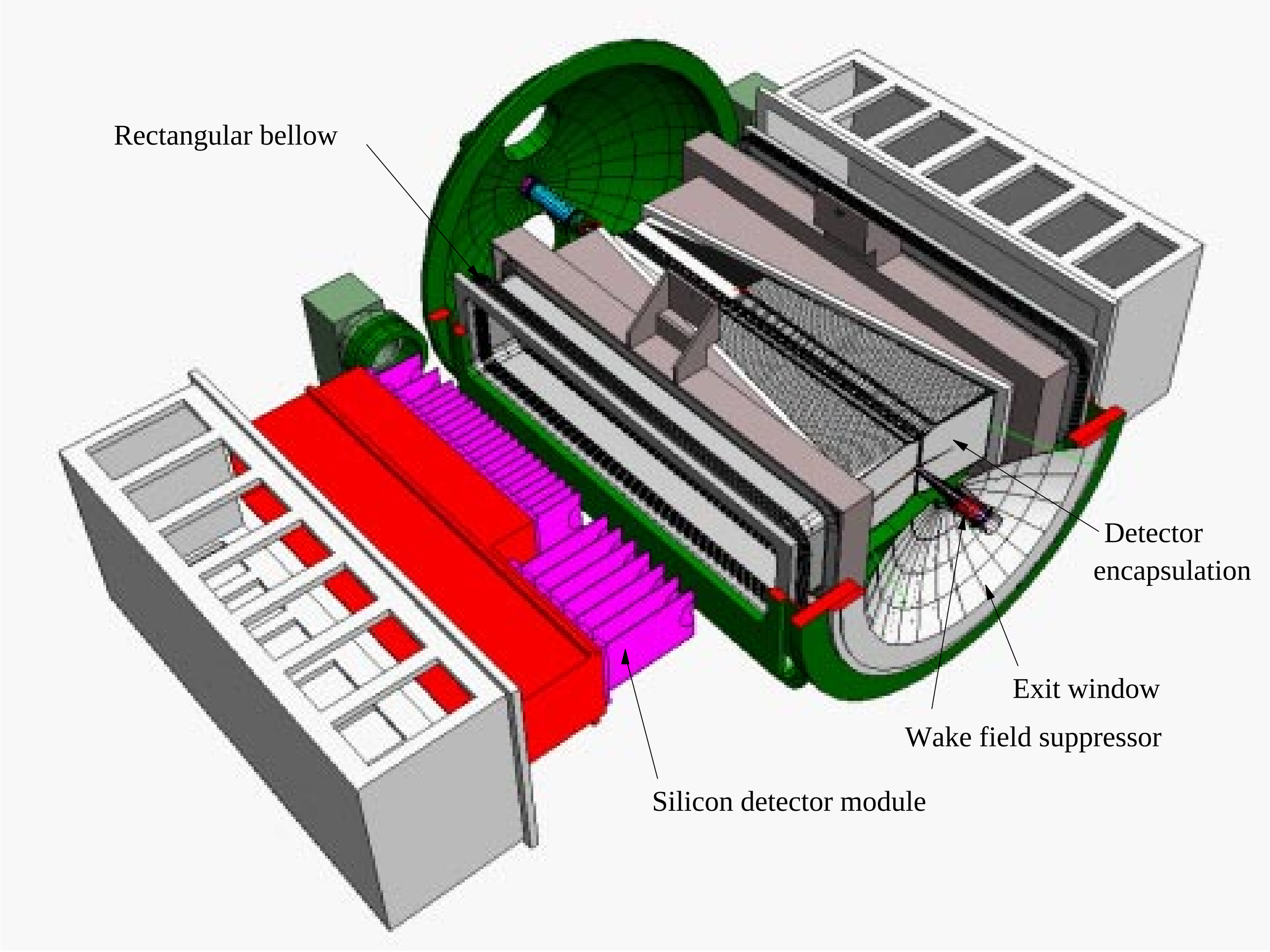

Figure 1 Three dimensional view of the VELO showing the primary vacuum vessel, detector encapsulations, silicon detector modules, wake field suppressors and exit foil.

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[1] Official LHCb VELO web site:
http://lhcb-vd.web.cern.ch/lhcb-vd/Default.htm.
NIKHEF web site:
http://www.nikhef.nl/pub/experiments/bfys/lhcb/vertex/vertexweb.html.

INJECTION SYSTEMS

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Abstract

The LHC injection systems consist of horizontally deflecting steel septum magnets followed by vertically deflecting kickers. A mobile beam stopper is placed downstream of the kickers for setting up with single bunches and to protect the superconducting machine elements during normal injection in case of a malfunctioning of the kickers. Adequate beam instrumentation and trajectory correction are needed for injection tuning. After an overview the status of the major components is given, together with their fabrication and installation schedule. Special integration issues and open points are addressed. A concept for the temporary warm line between the injection point and IP8 is presented, intended to replace this part of the LHC during the sector test.

1 OVERVIEW

Two new transfer lines, TI 2 and TI 8, are under construction to transport beams from SPS to LHC. TI 2 leads to an injection point (kicker centre) approximately 154 m left of IP2 where beam will be injected into LHC ring 1. TI 8 brings the beam to a point at the same distance right of IP8 (note that this IP is displaced by 11.22 m) where it will be injected into ring 2. An overview of TI 2, TI 8 and their injection systems has been given in [1]. Comprehensive status information and further details are accessible from the home page of the LTI Project [2]. According to the present draft planning [3] the first of these lines, TI 8, including its injection should be installed by 04/2004, to provide beam to the LHC during the following sector test.

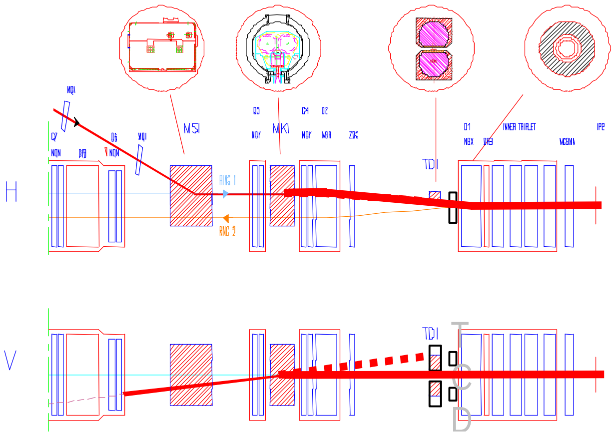

Figure 1: Schematic view of the injection near IP2.

A schematic view of the IP2 injection zone is given in Figure 1 (note that both injections are kept geometrically (mirror-)symmetric, except slight differences in the deflections due to differing optics and orbit bumps). Beam arriving through the transfer line will be horizontally deflected by 12 [mrad] by a series of 5 Lambertson type steel septum magnets (MSI). The vertical deflection onto the nominal orbit (by around 0.85 [mrad]) is achieved by a series of 4 kicker modules (MKI). To be able to set up the injection and to protect the LHC in case of kicker failures a mobile beam stopper (TDI) is placed at 90° phase advance downstream. To further protect the separation dipole D1 this stopper is complemented by a mobile shielding (TCDD). Appropriate beam instrumentation has been foreseen to permit to tune the injection to the required precision [1]. Various constraints put high demands on the proper vacuum integration in this whole area. The main ingredients will be discussed in more detail below.

2 SEPTUM MAGNETS

The 5 steel septum magnets for injection (MSI) are each 4 m long, and placed with an inter-magnet distance of 0.45 [m], resulting in an overall length of the MSI ensemble of 21.8 [m]. A schematic cross section of an MSI, showing also the flux lines, is given in Figure 2. Two different types will be used: MSIA with a septum thickness of 6 [mm] and MSIB with 15.5 [mm]. Seen in beam direction 3 MSIB are followed by 2 MSIA. The LHC beams circulate in shielded vacuum chambers inside two holes of 64 [mm] diameter. The gap height is 25 [mm].

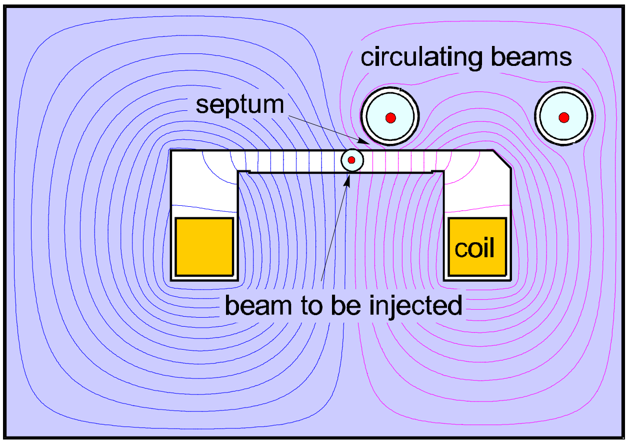

Figure 2: Cross section of an MSI magnet.

The Technical Specification of the magnets is contained in [4]. Results from calculations on the expected field quality can be found in [5], results on calculations concerning the efficiency of the magnetic shielding for the circulating beams are given in [6].

The magnets are presently being built at the Institute for High Energy Physics (IHEP), Protvino, in the framework of the participation of the Russian Federation in the LHC Project. One MSIB pre-series magnet has been built in 2000; its magnetic measurement programme is currently underway. The results are so far in pretty good agreement with the expected performance [7]. It is estimated that all required MSI magnets will be delivered by the beginning of 2002.

Design work is going on for their vacuum integration which must take into account a large number of requirements and constraints. First of all have the given beam holes to accommodate mechanically sufficiently stable vacuum chambers. The required beam aperture must be guaranteed taking various tolerances into account. Appropriate magnetic shielding needs to be foreseen in order not to influence the circulating beams. Impedance considerations demand a sufficiently thick highly conductive layer to be seen by the beams. The vacua in the main rings ($<10^{-10}$ Torr) and the injection lines ($\sim 10^{-8}$ Torr) are quite different, requiring sufficient pumping capacity. Finally need the chambers to be bakeable in situ to reduce outgassing during operation.

The present reference design, of which the feasibility needs still to be confirmed, departs from chambers mounted concentrically in the beam holes to ease alignment. In this design the chamber consists of a 1.4 [mm] thick μ-metal tube, inside plated with 0.6 mm copper. The nominal inner diameter stands at 52.2 [mm]. Kapton supported foil resistances are foreseen for in situ heating, wrapped into a 3 [mm] thermal and electrical insulation. The layout of the interconnects including the pumping ports is still in an early stage.

3 KICKERS

A schematic view of an LHC injection kicker [8] is given in Figure 3. A resonant charging power supply (RCPS) charges rapidly a pulse forming LC network (PFN). When the trigger arrives a thyratron based main switch is closed and the then generated pulse propagates through a set of coaxial cables into a travelling wave magnet. After passing through the magnet the energy is dumped into a termination resistor. The pulse length is defined by the time when the dump switch is closed. The impedance of all elements carrying the pulse current is matched (at 5 [Ω]) to avoid reflections.

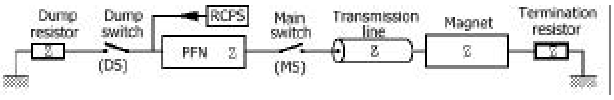

Figure 3: Schematic view of an injection kicker.

Per injection there are 4 magnets of 2.65 [m] magnetic length each with a nominal kick strength of 0.325 [Tm]. Each magnet has its own PFN, but two PFNs are charged simultaneously from one RCPS. The rise time (0.5 % - 99.5 %) is 0.9 [μs], the fall time 3.0 [μs]. The flat top duration can vary up to 7.8 [μs] to be able to accommodate various possible injection schemes. The flat top ripple is ± 0.5 %. The charging voltage is 54 [kV], the pulse current is 5.4 [kA]. A cross section of the magnet is shown in Figure 4.

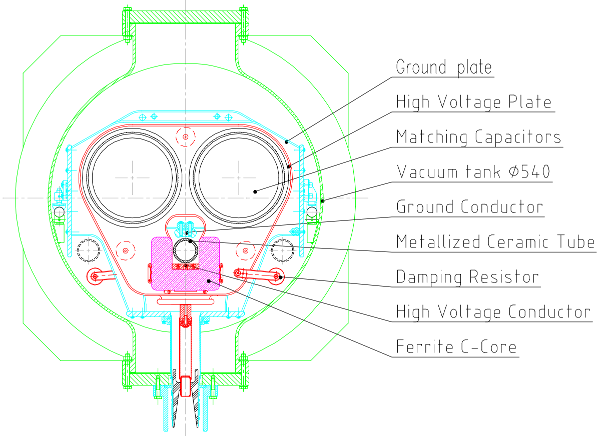

Figure 4: Kicker magnet cross section.

The beam to be injected passes through a ceramic vacuum chamber with metallic stripes inside for beam impedance reasons, and an inner diameter of 38 [mm]. The other beam passes in a tube through the same vacuum tank.

The RCPS, the necessary electronics and the PFNs will be housed in the galleries adjacent to the kickers. The transmission lines will be fed through the holes used for the LEP waveguides.

The vacuum tanks are being recuperated from the LEP separators. All major series components with the exception of the magnets and the electronics are fabricated at TRIUMF, Vancouver. The RCPS have already been built; their tests should be finished soon. Delivery is scheduled for 05/2001. The first series PFN has been built and the full series construction is expected to be accomplished by mid 2001. For the switches some more tests have to be made on the prototypes at CERN before the series production is launched. This should be finished by 05/2002. The series switches will be tested to-gether with the PFNs and shipped to CERN by 02/2003.

Concerning the magnets all pieces have now been received to assemble the prototype, after heat and surface treatment. Problems in industry with the welding of the high voltage and ground plates have meanwhile been overcome, but have produced a delay of about 1 year with respect to the initial planning. The prototype should be assembled and tested by 10/2001, the series production be finished by 12/2002 and all modules be ready by 10/2003. If this planning could not be maintained the function of the injection kickers could of course be simulated, for the sector test, by a small bending magnet.

4 PROTECTION DEVICES

A cross section of the present design of the injection beam stopper (TDI) is given in Figure 5. It consists of 2 absorber cores (one for the beam to be injected, one for the circulating beam) with approximately 8 [cm] diameter each, presenting to the beam a sequence of 2.85 [m] graphite, followed by 0.6 [m] Al and 0.6 [m] Cu. The absorber is shrink-wrapped in an Al frame which is suspended from a steel beam which, in turn, is moved by 2 motors (per beam). The whole assembly is housed in a recuperated, and slightly modified, LEP separator tank. To screen off the beam specially shaped, approximately 2 [mm] thick Cu sheets are used. For the injection the absorbers will be placed at about ± 8.5 σ from the nominal orbit. Afterwards the absorbers will be sufficiently retracted in order not to become a beam obstacle and, in the case of the injection near IP2, to give way to the particles heading for the ALICE Zero Degree Calorimeter [9]. The TDI is placed at 15 [m] upstream of D1.

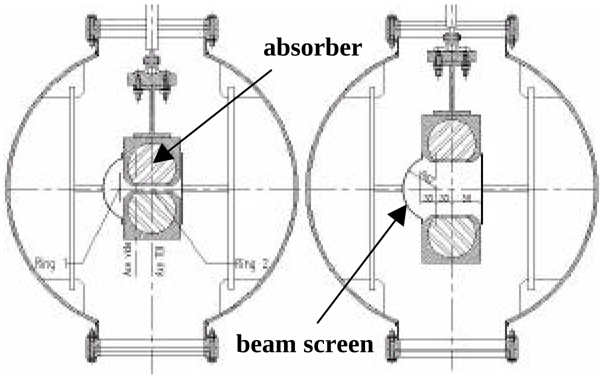

Figure 5: Cross section of the TDI (left: during in-jection, right: during acceleration and physics).

To protect the superconducting D1 magnet further, mainly against particles scattered off from the TDI, a supplementary shield (called TCDD), consisting of 2 hollow half cylinders made of Cu, with a length of 1 [m] and placed 3 [m] upstream of D1, is foreseen. Further information on possible kicker failures and the performance of the protection devices is given in [10].

After finalising the TDI design in close contact with the vacuum, accelerator physics and experiments representatives in 04/2001 it is intended to build one TDI with graphite core to be used in IP8. It is supposed to be finished by mid 2002. In parallel the feasibility of using different core materials, e.g. BN_3, will be studied. The experience to be gained during the sector test will help to decide whether ultimately a 2nd generation TDI needs to be built.

5 BEAM INSTRUMENTATION

Appropriate beam instrumentation in the injection area is needed to fine tune the injection to achieve the demanded precision and to monitor their performance.

The present layout features profile monitors (BTV) up- and downstream of both the MSI and MKI and upstream of the TDI. These will contain two screens, one luminescent Al_2O_3 screen, to be used up to intensities of a few times the pilot pulse, and one based on the OTR (Optical Transition Radiation) technique, for higher intensities. A beam current transformer (BCT) towards the end of the injection transfer line is used for intensity measurements. All matching quadrupoles of the transfer line will be complemented by beam position monitors (BPM) with readout in one plane. Double-plane monitors are placed in the main ring downstream of Q5, upstream of Q6, as well as downstream of Q2 and Q1. For improvement of the injection steering and to better monitor the positioning of the TDI with respect to the beam it is proposed [11] to place additional BPMs downstream of D2 and upstream of D1. Finally, beam loss monitors (BLM) are foreseen at several strategic locations, e.g. the MSI, the MKI, the TDI and the TCDD.

The performance parameters and the locations are largely defined (appropriate space has been reserved). However, apart from the main ring and the transfer line BPMs, there is still along way to go for the detailed design and the vacuum integration.

6 PLANNING

The present draft planning [3] foresees that TI 8, including the injection systems, be installed by 04/2004, in time for the sector test. For the commissioning of the line it is currently foreseen to proceed in 3 distinct phases: i) to test the SPS extraction and TT40 during 2003; ii) to test TI 8 up to the beam dump TED87765 once TI 8 is in place, i.e. around 03/2004 (the injection system wouldn't have to be in place yet); iii) the injection elements once those are fully set up, i.e. as from 04/2004 (with the MKI still switched off, leaving the beam up to the TDI), as laid down in [12].

This staggering would permit potential problems to be disentangled of each other and to build upon working pieces when commissioning the subsequent parts. It would also allow to use the allocated beam time to its best once the sector is ready to receive beam, since these tests could be carried out under optimum conditions as far as the beam delivery is concerned. Clearly such tests must be safety- and time-wise carefully coordinated in order to not compromise any remaining installation work.

The injection system near IP2 will be set up when this zone of the LHC is installed, i.e. around end 2005 [3].

It should be noted that the final bending magnets in TI 2 and TI 8, upstream of the MSI, must be installed prior to the installation of the cryostats since access will later be severely hampered.

7 PROVISIONS FOR THE SECTOR TEST

7.1 Temporary warm injection line

It has recently been decided [13] to replace the about 147 m long part of the LHC between the MKI and IP8, for the sector test, with a temporary warm line. Studies for possible solutions are departing from the following assumptions: i) the injection elements (MSI, MKI, TDI, TCDD) shall be definitively installed, to minimise installation work and to gain experience during the sector test; ii) the basic geometry (D1, D2) shall be reproduced using small bending magnets; iii) the focussing elements shall be placed such that the injection optics is largely reproduced (in particular the phase advance between the MKI and the TDI, for maximum efficiency of the TDI); and iv) power supplies shall be installed in the adjacent gallery (UA87). The necessary material can be largely taken from the stock foreseen for TI 2, to be recuperated again when the sector test is finished. Additional constraints come e.g. from the fact that by that time the LHCb support structure will still be missing where the final elements and vacuum chambers could be placed on. A first solution has been elaborated in collaboration with SL/AP [14], but still needs some refinement.

It should be decided whether the part of the vacuum system between D1 and D2 will at least be the definitive one. Concerning worries of a possible activation of the TDI during the sector test it should be noted that the TDI should normally only receive single low intensity pulses. Activation in view of the later final installation work in this sector should not be a big issue.

7.2 Temporary beam dump

A temporary facility to stop the beam at the end of the arc has to be foreseen for the sector test. Its precise placement has to be defined. To choose a dump with the appropriate performance it needs to be specified how much integrated and how much instantaneous intensity it has to absorb and how far induced activity should be contained in the dump.

8 SUMMARY

For injection during the sector test the present baseline planning is to have the definitive injection and protection devices, together with appropriate beam instrumentation installed and tested by 04/2004. A temporary warm line made up from equipment foreseen for later installation in TI 2 will replace the part of the LHC between the MKI and IP8. The performance specification for the temporary beam dump at the end of the arc needs to be drawn up.

The progress in a number of components needs to be monitored closely: i) the MKI magnets; the MSI magnets, their vacuum system and alignment; iii) the TDI and TCDD design and iv) the design and vacuum integration of the beam instrumentation. More work must also go into the specification of the access and interlock conditions and the application software.

Whereas from a pure hardware point of view, i.e. equipment building and vacuum integration, things look quite feasible (despite by far not yet achieved), the years 2002 and even more 2003 seem very critical in terms of logistics, planning, manpower resources, accessibility and constraints from operation.

ACKNOWLEDGEMENTS

The realisation of the LHC transfer lines and injection systems is the collaborative effort of many people from various CERN divisions. Their contributions and the constructive working spirit are gratefully acknowledged.

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REFERENCES

[1] A. Hilaire, V. Mertens, E. Weisse, “Beam Transfer to and Injection into LHC”, Proc. EPAC’98, Stockholm, June 1998, and CERN/LHC Project Report 208.
[2] http://proj-lti.web.cern.ch/proj-lti/.
[3] P. Bonnal, private communication.
[4] CERN SL-Spec 98-31 MS (http://sl.web.cern.ch/SL/msgroup/DFsection/lhc/98-31.pdf).
[5] M. Gyr, “Expected Magnetic Field Quality of the LHC Septum Magnets Used For Injection (MSI) and For Extraction to the Beam Dump (MSD)”, CERN/LHC Project Note 129/Rev. (1998).
[6] M. Gyr, “Estimated Residual Magnetic Field Acting on the Circulating Beam in the LHC Septum Magnets MSI and MSD - Shielding Efficiency”, CERN/LHC Project Note 212 (2000).
[7] M. Sassowsky, private communication.
[8] L. Ducimetière et al., “Design of the Injection Kicker Magnet System for CERN’s 14 TeV Proton Collider LHC”, Proc. IEEE Pulsed Power Conference, Albuquerque, USA (1995) and CERN-SL-95-80 (BT).
[9] ALICE Technical Design Report of the Zero Degree Calorimeter (ZDC), CERN/LHCC 99-5 (1999).
[10] O. Brüning et al., “Impact of and Protection Against Failures of the LHC Injection Kickers”, Proc. PAC’99, New York, and CERN/LHC Project Report 291.
[11] J. B. Jeanneret, “Collimation Schemes and Injection Protection Devices in LHC”, Proc. LHC Workshop Chamonix XI, 2001 and CERN-SL-2001-003 (DI).
[12] V. Mertens, “Preparing the Sector Test: Extraction, Transfer and Injection”, Proc. LHC Workshop Chamonix XI, 2001 and CERN-SL-2001-003 (DI).
[13] L. Evans, memorandum DG/DI/LE/jf/2001-37, dated 14. 2. 2001.
[14] A. Verdier, private communication.

CONSTRAINTS FROM INDUCED RADIOACTIVITY IN THE DESIGN OF THE LHC

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Abstract

This note summarizes the Legal, Operational, and Internal limits applied to radiation exposure of personnel at CERN and suggests a suitable Design Limit of 5 mSv/y. The effects of recent French legislation on CERN practices are mentioned. Current information on dose rates from induced activity in the LHC are given.

1 ANNUAL DOSE LIMITS

1.1 Legal limits

The fundamental limitation is that the dose received during any consecutive 12-month period must not exceed 20 mSv. However special restrictions apply to women of child-bearing age. If it is possible that a dose of more than 1 mSv per month can be exceeded, the group leader or the head of the contracting firm must inform women to that effect. Once a pregnancy is diagnosed, the woman is no longer authorized to work regularly in a Controlled Area, and is subject to a dose limit of 1 mSv during the rest of the pregnancy.

These dose limits also apply to contractors' personnel. In addition there is a limit which is proportional to the time spent on the site of the Organization. This limit is set at 1 mSv per week, averaged over the time spent at CERN, but must not exceed 20 mSv over 12 consecutive months, taking into account doses received elsewhere.

1.2 Operational limits

One can never actually measure the dose to a person: one can only measure the dose recorded on a personal dosimeter carried by that person. An operational limit is applied to the doses recorded by personal dosimeters. Any person whose annual dose could exceed 1 mSv must carry a personal dosimeter such as a film-badge. The issue period for these dosimeters is generally 2 months.

Regular checks are made on the doses recorded by the films. If a personal dosimeter unexpectedly exceeds 1 mSv in a given issue period, or in case of doubt over the reading of a dosimeter, RP Group has to carry out an investigation to determine the exposure conditions for the person concerned. RP Surveyors must be aware of and advise on all work where the dose is likely to exceed 1 mSv. For all these cases, the Personal Dosimetry Service of RP Group will compare the readings of film badges with those of operational dosimeters. In any case, all work in areas where the dose-rate exceeds 100 Sv/h, *i.e.* in a "Limited-Stay" Controlled Area or a High Radiation Area (2 mSv/h), must be authorized by the Divisional Radiation Safety Officer.

1.3 Reference Levels

With the aim of keeping exposures at CERN at the ALARA level[1], an annual reference dose of 15 mSv has been introduced. Any personal exposure leading to a dose of more than 15 mSv in a year must be justified during a review to be conducted jointly by the Division concerned and RP Group. Only the head of the Division can authorize exposures above this reference level. The person responsible for contractors' staff should arrange their work in such a way that an effective dose of 15 mSv per year is not exceeded.

1.4 Design Limits

It is unreasonable in the present design phase to assume that all persons performing maintenance work can be "allowed" to receive 15 mSv in one year. It is impossible to plan maintenance operations at the LHC from this distance in time with an accuracy sufficient to avoid exceeding this reference value. Estimates of dose rates can also be inaccurate to a factor of two or so, either way. It is more reasonable to plan maintenance operations with a Design Limit for the Annual Dose of 5 mSv.

2 DESIGN CONSTRAINTS

2.1 From INB

In Chapter VI, section 1.4 of the Installations Nucléaires de Base Rapport Préliminaire we have written:

> ... but for the design and construction of accelerator components which will become active, the following dose rate reference values have proved to be very useful:
>
> 1. **100 Sv/h:** In regions where the dose rates are below this value, persons may work on the radioactive components without special precautions. Above this value all work must be planned, especially with respect to its duration.
> 2. **2 mSv/h:** Above this value the intervention time in the zone must be severely limited and all work must be supervised by RP Group. Workers from firms outside CERN who only have a temporary contract with the firm are not allowed to work in these zones. When dose rates exceed this value, remote handling of the components concerned should be seriously envisaged.

---

[1] As Low As Reasonably Achievable

3. **20 mSv/h:** In regions where dose rates are above this value, no work is allowed since dose limits would be too easily exceeded. Remote handling of objects is essential.

The first limit comes from the maximum instantaneous dose rate allowed in a Simple Controlled Radiation Area at CERN. Above this the area must be classified as a Limited Stay Area where work in the area requires the authorization of the Radiation Safety Officer and control of dose accumulation by a Radiation Protection Technician together with the wearing of additional dosimeters.

The second limit comes from another area classification change, to that of a High Radiation Area, where special precautions are needed to prevent the excessive accumulation of dose.

Above the third limit, the annual design dose would be received in less than 15 minutes, and so real maintenance work involving human intervention is impracticable.

There is now an additional restriction mentioned in Point 2 above coming from a recent change in French legislation [1]. This means that any person working for a French firm in a High Radiation Area must have a long-term contract with that firm; it does not strictly apply to CERN staff with short-term contracts or non-French firms, but it would be better to treat any situation as if they were included.

2.2 From New French Legislation

Another change in French legislation [2] means that all persons entering what the French call Controlled Radiation Areas (which at present correspond to CERN's Limited Stay Areas) will have to carry an active "operational dosimeter" in addition to their passive dosimeter (film badge). At present only persons actually working (not just visiting) a "Limited-Stay" Controlled Area have to carry pen dosimeters or electronic dosimeters (in line with French Legislation). This year the annual limit in France will be aligned to the EC directive (and Swiss Legislation) and the new lower bound for a French Controlled Area will become 6 mSv per year. This means that to avoid letting CERN's "Simple" Controlled Areas (Experimental Areas *etc.*) fall into the French classification of Controlled Radiation Areas where we would have to distribute operational dosimeters – we must change their upper limit to 6 mSv per year instead of 15 mSv. So the limit for Job Authorization by the RSO and the necessity to carry operational dosimeters will also change.

The LHC Access and Interlock Working Group (AIWG) consider that LHC should plan an operational dosimeter system for all accesses to all machine areas (including experimental areas) during machine-off periods. The specification for the Access Control System of the LHC will require that an operational dosimeter, already linked to the person requiring access, must be present and checked on entry and exit from machine areas. This will have to be in service from day-one.

3 RADIATION LEVELS AT LHC

All details of radiation levels the have been predicted to date have been summarized at a meeting of the LHC Technical Co-ordination Committee, meeting 99-09 held on 29 October 1999. The following web address leads to the transparencies presented.

http://lhc.web.cern.ch/lhc/tcc/tcc.htm

4 CONCLUDING REMARKS

In contrast to the situation in an electron machine, if equipment dies because of radiation damage in a proton accelerator then someone will be irradiated while replacing or repairing it. All equipment installed in the beam tunnel will become radioactive according to INB regulations. The most radioactive regions of the LHC machine are

1. The TAS collimators in the ATLAS and CMS interfaces.
2. The low-beta regions at Points 1 and 5.
3. The TAN neutral absorbers at Points 1 and 5.
4. The momentum and betatron scraping regions at Points 3 and 7.
5. The dispersion suppressors at Points 1 and 5.
6. The beam-dump caverns.

5 REFERENCES

[1] Arrêté du 12 mai 1998 modifiant l'arrêté du 8 octobre 1990 modifié fixant la liste des travaux pour lesquels il ne peut être fait appel aux salariés sous contrat de travail à durée déterminée ou aux salariés des entreprises de travail temporaire. Journal Officiel Numéro 118 du 23 Mai 1998

[2] Arrêté du 23 mars 1999 précisant les règles de la dosimétrie externe des travailleurs affectés à des travaux sous rayonnements.... Journal Officiel Numéro 99 du 28 Avril 1999

INTEGRATION OF THE LHC/RF SYSTEMS

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The radiofrequency systems of LHC are located at point 4. There are basically three systems: the 400 MHz superconducting cavities, the 200 MHz capture cavities and the transverse damper. The whole installation is symmetric about IP4. The RF cavities are located in regions of zero dispersion, and the transverse damper is positioned just in front of Q5, where the ß functions are large.

The 400 MHz system is based on 8 superconducting cavities per beam and powered using one 300 kW klystron per cavity. A total of 16 klystrons are therefore required with 8 in UA43 and 8 in UA47. These will be connected to the cavities using half-height waveguides. This will require 8 new holes to be drilled between RA43/47. Each hole will serve two waveguides. The total static and dynamic heat load of the 16 cavities is 1000 W at 4.2 K. The accelerating voltage per cavity is 2 MV which corresponds to an accelerating of 5.3 MV/m. The total installed RF power per beam is 2400 kW.

The 200 MHz system will be used to capture the beam after the transfer from the SPS to the LHC. There are 4 normal-conducting copper cavities per beam, each delivering an accelerating voltage of 0.75 MV. The cavities are powered by four 240 kW CW RF power plants per beam, located in UA43 and UA47. Each power plant consists of four 60 kW tetrode amplifiers recuperated from the SPS. The total installed RF power per beam is 960 k W.

The transverse damper system has 6 kickers per beam and per plane, each kicker being 1.5 m long, working at up to 7.5 kV in a bandwidth from 3 kHz to 20 MHz. The two 30 kW tetrodes required per kicker will be installed below each kicker. The total installed RF power per beam is 720 kW.

The 200 MHz and the damper system will use existing holes (diameter 900 mm) to pass from UA43/47 to the machine tunnel. On the left side of the IP4 the cryo-line will have to be moved up to a height of 2 m so as not to interfere with the 400 MHz and the 200 MHz cavities (Figure 1). On the right side however, there is no interference and the cryo-line can remain at a height of 850 mm above the floor. There is, nevertheless, difficult access to the tuner of the cavity, which needs regular maintenance. In view of the critical clearness of the RF cavities to the cryo-line a precise knowledge of the tunnel dimensions is required and a 3D integration study is necessary.

The installation of the klystrons for the 400 MHz system will be delicate, as there is little clearance. It is planned to transport the klystrons horizontally and to use a dedicated crane to lift them into position. A mock-up of a part of the tunnel is being built in order to study these installations.

Major concerns are the power losses escaping into air and water that will have to be dealt with. It is proposed to install several ventilation units in UA43/47 and to use the general ventilation for the klystrons.

A maximum electrical power of 18.6 MW will be required for all RF systems.

The vacuum equipment of all the RF systems has to be finalized.

Because of the scarcity of space in the underground areas much of the RF equipment has to be in the surface building SR4. Two thirds of SR4 have been reserved for RF equipment. The five 4 MW power converters from LEP will stay for the 400 MHz system. The power converters for the 200 MHz and damper systems will be

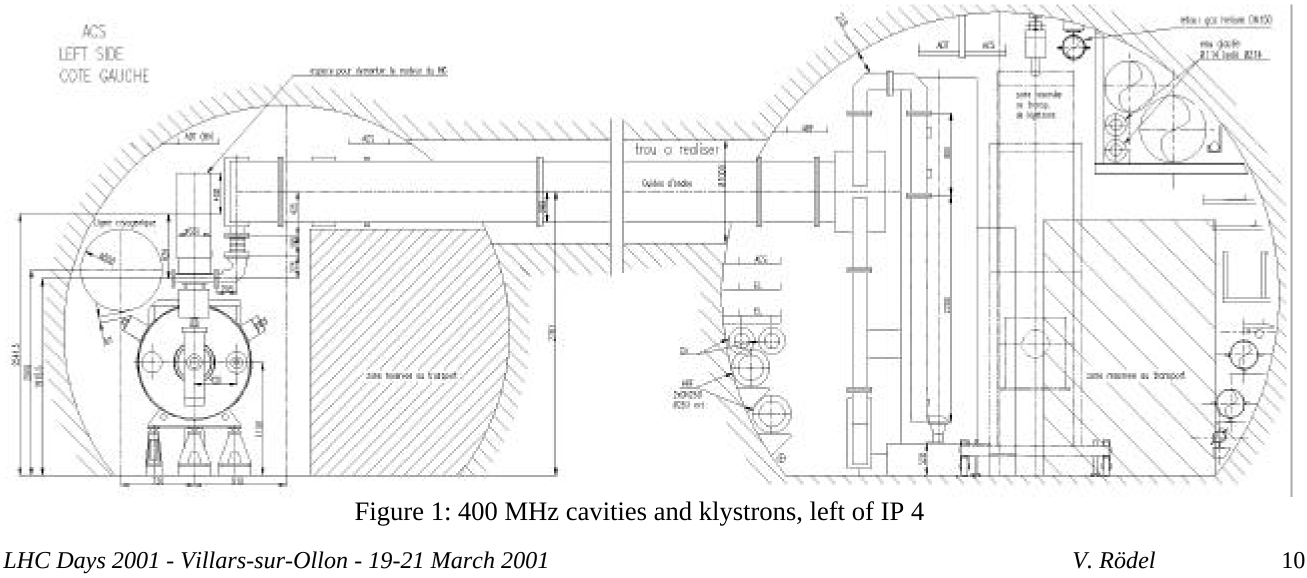

Figure 1: 400 MHz cavities and klystrons, left of IP 4

added. The building will also house a Faraday cage for the beam control equipment. There will be about 700 cables of different kinds between the underground areas and the surface building SR4.

It is planned to drill the 8 new holes (diameter 1m) for the 400 MHz system at the beginning of 2003. After installation of the cryo-line and all the services, the installation of the RF system in RA43/UA43 will take place from June to December 2004 and in RA47/UA47 in January to September 2005. A total of about 80 tons of RF equipment has to be transported from an intermediate storage area in SR4 to the underground areas. During the time of installation the transport passages in UA43/47 and RA43/47 will be partially blocked. Therefore careful planning of transport is necessary for this period.

Commissioning and RF tests, lasting 3 months, are foreseen right after installation. They will start with check-outs at low power levels. Prerequisites are communication, cooling and ventilation, electricity (220V, 380V), controls and access to RA43/UA43 and RA47/UA47. The checks will be on cables, interlocks, power converters, grid power supplies, RF amplifiers, RF couplers, RF instrumentation, cavity tuning, RF feedback systems, cryogenic and vacuum equipment, etc.

For commissioning with RF, the power converters will be switched on and their interlocks and crowbars checked. The RF zones have to be closed at locations still to be defined and the radiation monitors (X-rays) have to be operational. However access must be possible to UA43/UA47 during these procedures. Cooling down the superconducting cavities takes about two days and their conditioning about one week. Conditioning the 200 MHz cavities takes about 3 days.

For operation with beam, the RF beam control system has to be commissioned. This involves the setting up of feedback, phase, radial and synchronization loops for injection and capture. The beam dump interlock has to be tested.

A failure of a cavity during a run will result in the loss of the beam. If a 200 MHz cavity has failed, the cavity can be damped using the damping loops and the other 3 cavities could run at higher power level to compensate for the failed cavity. A new run with beam seems possible without removing the faulty cavity from the machine. This is different in the case of a failure of the superconducting cavity. It does not have a damping loop. One could envisage a detuning of the cavity in order to reduce the beam-induced voltage. Nevertheless, the cavity voltage will then be out of control and the bunches will likely become unstable. Changing a superconducting module is estimated to take about 7 days. The downtime due to a klystron is half a day at most. Changing a 200 MHz cavity will take (including conditioning) 3 days.

CONCLUSIONS

The RF systems (400 MHz, 200 MHz, transverse dampers) are now defined and many of the major components are being constructed or have been ordered. Their positions in the machine and those of the klystrons and tetrode power plants have been optimized from the point of view of RF and beam optics parameters. However, the underground areas UA43 and U47 are particularly crowded which requires precise 3-dimensional integrations. An important item is the ventilation system. The main problem in the machine tunnel is the integration with the cryo-line. Clearances are tight and precise dimensions of the actual tunnels are needed.

Note: After this presentation at the workshop, in view of the integration problems of the RF systems, the project leader proposed to install the ACS cavities and their klystrons in UX45. This would ease many integration problems, in particular with cryogenics, ventilation, transport and cabling. A study of such a layout has started.

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