EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 984

OPERATION FOR LHC CRYOMAGNET TESTS: CONCERNS, CHALLENGES & SUCCESSFUL COLLABORATION

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Abstract

The LHC construction phase is coming to a close, with installation work progressing rapidly and beam start-up foreseen by end 2007. For the testing of the 1706 LHC cryomagnets in cryogenic conditions and its successful completion by early 2007, considerable challenges had to be overcome since 2002 to assure certain semi-routine tests operation at CERN. In particular, the majority of staff for tests and measurement purposes was provided by India on a rotating, one-year-stay basis, as part of the CERN-India Collaboration for LHC. This was complemented by some CERN accelerator Operation staff. While only 95 dipoles were tested till 2003, the efforts and innovative ideas coming from the Operation team contributed significantly to the completion of tests of nearly all 1706 magnets by end-2006. These included the improvements and management of the tests work flow as well as the test rates. Amongst these, certain pivotal ideas to stream-line the tests methodology as proposed and implemented successfully by the Indian Associates deserve a special mention. An insight into this as well an overall view of the tests operation will be given, together with an indication of some of the operation-related results from the tests programme.

Presented at the Asian Particle Accelerator Conference (APAC 2007)
29 January - 2 February 2007, Indore, India

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Geneva, 22 February 2007

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INTRODUCTION

The Large Hadron Collider (LHC) consists of two interleaved synchrotron rings of 26.7 km circumference, to be installed in the tunnel used previously for the LEP machine [1]. Main elements of these rings are the two-in-one superconducting dipoles and quadrupoles operating in superfluid helium at a temperature of 1.9 K. Cryomagnets include 1232 dipoles (with correctors), 360 Short Straight Sections (SSS) integrated with quadrupoles and higher order poles which are needed for the different accelerator lattice functions and 114 Matching & Dispersion Suppressor region magnets integrated in Special SSS (IR-SSS).

Testing and qualification of the above magnets at cryogenic temperature is a prerequisite to their installation in the LHC tunnel. A superconducting magnet test facility equipped with 12 test benches and the necessary cryogenic infrastructure is operational at SM18 in CERN to perform the power tests and magnetic measurements for qualifying these magnets. Testing of the first series production magnets commenced in ~2001. Since early 2003, the test facility is being operated round the clock to meet the target to complete the testing of all the magnets required for the LHC by December 2006. The construction of all the 12 test benches was completed and the full usage started around June 2004.

The testing and qualification activities of a magnet is intended to verify its cryogenic, mechanical and electrical insulation integrity, qualify the performance of magnet protection systems, train the magnet up to the nominal field or higher so as to minimize training of magnets in the tunnel, characterize the intended magnetic field, accept the magnet based on its quench and training performance and generally, ensure that the magnet meets its design criteria. These may be categorized broadly within the five phases namely, to connect, cool down, cold tests, warm up and to disconnect respectively.

The workforce in the SM18 test facility consists of three teams, with the tests and measurement Operation Team as the major entity supported by the Cryogenics Team and the Magnet Connect/Disconnect Team (called ICS). The Operation Team consists mainly of associates from the Department of Atomic Energy (DAE), India, along with a number of regular CERN employees. The other two teams consist of contract employees from industrial consortia. A CERN team called Equipment Support looks after the improvements, exploitation and the troubleshooting of tests hardware and software on an on-call basis. A sub-team of ICS handles the movement of magnets within the test facility by means of a remotely controlled vehicle named ROCLA. All these teams work in mutual collaboration to complete the magnet tests within the specified time period.

In the massive effort of testing of all 1706 Cryo-magnets in cryogenic conditions within a stringent time frame, considerable challenges had to be overcome since the beginning to arrive at successful completion. This paper presents a brief account of some of the major hurdles encountered in the process and the innovative strategies and techniques that were developed to overcome them. Relevant statistics are presented to highlight the effectiveness of some of these strategies.

CONCERNS & HURDLES

Like any facility of unique requirements, SM18 had also its own characteristic issues, ranging from personnel logistics to infrastructure limitations. Following is a brief account of some of the major issues and challenges that had to be addressed in the routine operation of the facility.

Personnel Logistics Issues: In early 2002, for technical and organizational reasons, the outsourcing of the tests operation was no more an option. Moreover, due to various factors, only 7 non-experienced CERN staff members from accelerator operation could be assigned to run the SM18 test facility. However, for an anticipated round the clock operation of the facility with 12 test benches, a minimum of 4 persons per shift was necessary, thereby demanding minimum staff strength of 24. It was

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* On behalf of all the past & present members of SM18 Operation Team

at this time that DAE, India, offered technical human resources for SM18 operation. India already had a collaboration agreement with CERN since the nineties for the LHC, including a 10 man-year arrangement for tests & measurements during the magnet prototyping phase. Consequently, over 90 qualified personnel from 4 different Indian establishments have participated in magnet testing on a one-year rotational basis. The technical acumen and success of the early batches of Indian Associates lent credence and confidence that the tests activity could be successfully carried out in this manner. The strict, one year rotation was a condition desired by India, leading to the necessity of a large number of persons participating in the programme.

The Indian technical engineers, being not directly related to operation or CERN type of work, had to get familiar with the magnet tests activity before being productive. This essentially necessitated a continuous mentoring program, hence, limiting the number of 'trained staff' at any time. Preparing the work shift schedule with the limited experienced personnel & keep within the CERN rules and regulations was a major hurdle. Arranging proper facilities for the Indian associates to make them 'feel at home' in a foreign land was also an equally challenging task.

Novelty Aspects: Considering that the LHC cryomagnets were unique, they were tested with a research & development mindset by magnet and equipment specialists during the initial phases of SM18 operation. Partially automated test systems (for one magnet at a time) which existed then were considered adequate for usage by the experts. When the Indian and accelerator operation staff took over the running of the facility, the system appeared to be more or less a 'black box' where, not many details of the test systems and test sequences were provided. Testing of the SSS magnets was a challenging task until the end of 2004 while all necessary information got collected and collated; similarly, testing of the special SSS magnets was a grey area even till beginning of 2006; the special SSS magnets have a large variety of structures, types, temperature regimes and their complexity made the collection of all the relevant information required for tests an extremely complex task. Even the role and responsibilities of the Operation Team had to be properly defined during the early phases.

Magnet Qualifying Criteria: During the early phases, each dipole was trained to reach its ultimate field (about 8% above the one required for the LHC), which was a major time consuming activity. Extensive magnetic, special measurements and thermal cycles were carried out in majority of the magnets. Qualification of 'poorly performing' magnets was another laborious task, whereby the magnet was removed from the test bench, fitted with anticryostats and quench location instruments and brought for re-testing at a later date.

Co-ordination of Teams: Language was the biggest obstacle in proper co-ordination of activities of different teams involved in magnet testing. Indian associates who are not conversant with French often found it difficult to verbally communicate with other teams which were exclusively French speaking.

Nature of Industrial Contracts of Other Teams: The nature of consortium contracts was also a hurdle. It had been observed that many times, the work slowed down during the weekends because the contractual working hours of the ICS/ROCLA team got exhausted for the week; magnets were not moved, connected or disconnected. Likewise, lack of suitable technical support in case of malfunctioning of certain systems during outside normal hours was also a factor which affected the overall performance.

Infrastructure Limitations: The test facility in SM18 is organized in 6 clusters of two test benches each, total 12 benches. However, for space and costs reasons, each cluster has a common power converter, one set of data acquisition system and one set of quench heater power supplies, shared by both benches. This means that at any given time, these resources can only be utilized by one of the two benches in a cluster.

The cryogenic infrastructure has limited resources which cannot feed to the simultaneous demand from all the 12 benches. This puts forth a limit on the number of magnets at superconducting temperatures concurrently, the number of training quenches allowed within a specified time period as well as a precise number of magnets using the cryogenic cool-down or warm-up resources [2]. Water resources (to cool down the power converters and other auxiliary systems) are also limited. These constraints necessitate the operation team to optimize all the work by following a complex set of rules and by exercising judicious judgment.

Sometimes due to some imposed factors, the shared resources are blocked. For example, when some special tests were conducted on a magnet, exceptional priority was assigned to this bench, which affected operation on many other benches due to the interlinking of various resources.

The synchronous, cog-wheeling approach foreseen initially [3] was never applied in routine operation because of varying performance of magnets; rather, the 'asynchronous' approach managed by the operation team yielded the desired magnet test rates, aided by the fine trimming of the magnetic and quench performance programmes [4].

EARLY PERFORMANCE

Magnet tests work began in ~2001 with two benches and a limited cryogenic infrastructure. The work environment that existed till late 2002 was not favourable for a time limited and challenging activity like this. Tests were conducted mainly with laboratory type of systems and mobile racks which were not suitable for round the clock operation. The first sets of dipoles consisting of 30 samples from each of the three suppliers (called the pre-series magnets) were required to be tested elaborately with full magnetic measurements and many other extensive tests. In the early phases of testing till end-

2003, due to the lack of readiness of all test benches and cryogenic feed boxes, adequate information, supporting tools and operational experience, only 95 dipoles (including pre-series ones) could be tested [5]. Fig. 1 shows the time required for testing the dipoles during the early stages of 2001-2. With such a low testing rate it would have been impossible to meet the target. Hence, it was imperative to formulate proper throughput strategies and to develop supporting tools for enhancing the throughput; this necessitated an ambitious figure of 16-18 magnet tests per week, higher than anticipated, in order to complete the tests of all magnets by December 2006. This also entailed an extensive study [6] resulting in the application of a selective and reduced magnetic measurement effort.

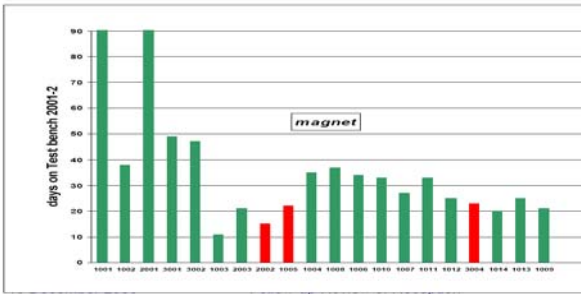


Figure 1: Bench Occupancy during 2001-02.

OPERATIONAL STRATEGIES & TOOLS

In the attempt to overcome the inherent hurdles and to attain maximum throughput, some effective management principles had to be addressed, necessary supporting tools developed, and certain level of operator empowerment had to be efficiently implemented, based on several innovative ideas and techniques. Feedback based on operational experience was given due importance in framing the strategies. Furthermore, the web based network backbone of CERN and computer facilities have been widely used for developing the supporting tools.

Most important innovations and strategies which essentially helped in achieving a high throughput included the introduction of a template based tests approach, web-based tools for tests management, magnet training rules & criteria for 24-hr operator decision taking and empowerment, general and cryogenic priorities handling by the shift crew, thermal cycle criteria and so forth. Some of these relevant points are discussed here in brief.

For the final, smooth operation of the facility with 12 benches, it was necessary to ensure a minimum staff strength of 24 at any time, comprising at least 15 experienced staff; however, the staff strength had to be appropriately adjusted according to the expected departures, arrivals and experience as and when required. This aspect was even further exemplified by the projected work load while the full 12 benches were still under construction on a cluster by cluster basis in 2003-4. To ensure all this, the number of Indian associates inducted into the project at any given time had to be carefully defined and planned, considering the strict one year rotation as well as input of the additional CERN staff during 2005 due to the year long accelerator shutdown. Fig. 2 gives a histogram of the total staff strength during the peak period 2005-6, and depicts the intricacies of manpower management. The staff strength was projected to drop steadily after December 2006, the scheduled deadline for the completion of all tests. Mentoring of newly inducted associates was designed to be an ‘on the job’ and a continuous process, increasing the number of personnel per shift during the process to ensure that the throughput was not affected.

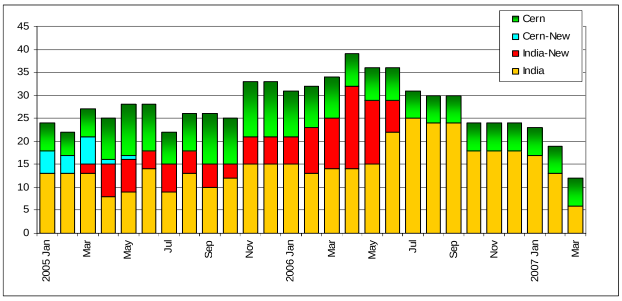


Figure 2: Variation of Operation Staff Strength 2005-6

Contributions of the Operation Team

On the initiative of the Operation Team, a number of new features to aid the magnet tests had been brought in since mid-2003; the whole process of operation for magnet tests underwent a renaissance from crude manual data logging to a more efficient, sophisticated and highly automated tests management system.

A “To-Do-List” was created, which described the minimum set of tests to be performed on a magnet [7]. The tests were sequentially numbered & prefixed with the nature of tests i.e., “Preparatory test” (PREP) or “Power test” (PT). The “To Do List” approach weaned away the R&D culture in magnet tests and evaluation to a very stable and clear cut approach that could be handled by the Operation Team. Operation methods necessary for conducting each test in the “To-Do-List” were systematically prepared and reviewed to avoid the human errors in magnet testing to the maximum possible extent.

The Magnet Tests Report templates were designed in a manner for ease of use, with operational notes /checklists appended wherever necessary. The flow of tests in the template obeyed the “To-Do-List” to ensure that the tests were carried out systematically, efficiently and in a fail safe, sequential manner.

A new operation web-site was developed where all important documentation like operation methods, manuals, presentations, various template files, troubleshooting procedures, shift-plan & so forth could be obtained with minimum effort. This site immensely helped in easing the training of fresh staff as well as in managing the daily operation activities. The Indian Associates were the exclusive contributors to these very significant & essential documentation production and continual mentoring activities.

A web-based system using HTML & ASP codes called the SM18 Test Management System (SMTMS) was developed with all the data relevant to magnet tests stored in this system [8]. Based on the “To-Do-List”, the web-based retrieval from SMTMS permits the automatic generation of the test sequences and reports such as the CDPT (CryoDipole Power Tests, which contains the training history), MAPS (Magnet Appraisal and Performance Sheet, which is a single page tabulation of the goodness of the magnet) and so forth. This enabled a fast, reliable, and error-free generation of crucial data pertaining to the magnet tests. With SMTMS, it is also possible to keep track of times taken for the various phases in magnet tests; all persons directly concerned could keep track of the tests progress from varied geographical locations in CERN & outside [9].

An electronic log-book was implemented using the CERN network backbone in providing web-based applications. Apart from ensuring easy access and usage by all SM18 operation or support personnel, this helped in categorizing and recording the different faults that occurred during the course of magnet testing.

To ensure smooth interaction between the various teams during the different stages of preparation before testing as well as at the end of the tests, a web based tool in the form of an Electronic-Workflow manifest called the e-traveller was created [8],[10]. The interface of this tool with mobile phones alerts and informs relevant teams (via short message service in appropriate languages) about the need for their services on a particular magnet. This helped the Indian associates to overcome the difficulties in verbal communication with the other teams but maintained the work rhythm as well as keeping an automatic record of the tests phases.

In order to attain a high throughput, it was necessary to reduce the number of training quenches per magnet, both from the point of view of limited cryogenic resources as well as the time involved. During 2003, the Operation team had observed that the majority of the magnets cross their nominal field (8.33T or 11850A) in the second ramp (see Fig. 3), whereas not much additional information on the ‘goodness’ of the magnet was available from the third & higher quenches [11]. Based on this, a new training rule named the ‘Two-Quench Rule’ was accepted by the magnet experts [4], under which it was recommended to do only two training quenches in each magnet provided it crossed the nominal field with a small margin. Later on, this rule was complemented by the so called ‘Three-Quench Rule’, under which a magnet is accepted if it crosses a field of 8.6T (12250A) in the third quench even if it had not passed the preceding rule. This strategy drastically reduced the overall cold tests time, thereby resulted in a high throughput. Likewise, the introduction of a Rapid On Bench Thermal Cycle (ROBTC) for magnets with poor performance in the first run was another major step towards reducing the overall magnet test time. These new rules, along with a 24-hr decision taking by the operator on the goodness of the magnet by analyzing the results and using the MAPS, helped in achieving a higher throughput. ROBTC and MAPS are discussed in detail elsewhere [12], [13]. The criteria for arriving at precise MAPS formulation were based on clear-cut rules and magnet specifications as well reviews, e.g. [14].

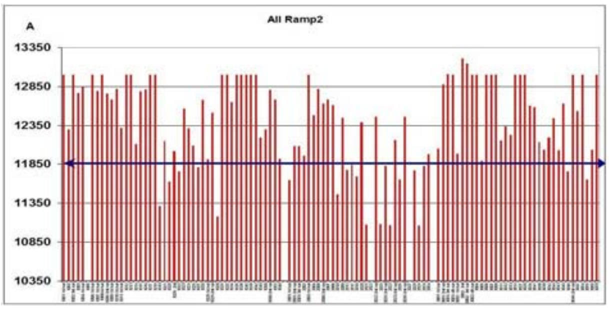


Figure 3: 2nd ramp performance of all dipoles till Dec 03 (each bar corresponds to 2nd ramp current reached)

RESULTS

Fig. 4 depicts the cumulative number of magnet tests, including repeats, since 2002. While the throughput was low till end-2003, it picked up sharply after the introduction of throughput strategies and tools. The plateau regions at the end of each year are due to the annual cryogenic infrastructure shutdown of typically seven weeks.

Fig. 5 gives further details of the magnets tested each year. It segregates the number of dipoles, arc SSS and IR-SSS tested each year, along with the cumulative number of magnets tested in that year. Starting with the meagre 21 magnets tested in 2001-2 and 76 in 2003, 456 magnets were tested in 2004. This count went up to an all time high of 703 magnet tests during 2005. During 2006, 648 magnet tests have been carried out; while this may appear low compared to 2005, it is a remarkable achievement taking into account the fact that the majority of the Special SSS magnets were also tested during 2006. Testing of the Special SSS magnets has been a time consuming activity in logistics & magnet training; each of the 114 magnets needs a special, dedicated to-do-list. Often, each magnet was trained until it reached the ultimate field and elaborate magnetic measurements were also required. [15]. Average repeat rates for the dipole, arc SSS and Special SSS magnets have been around 9%, 12.5% and 12.8% respectively, not counting the repaired

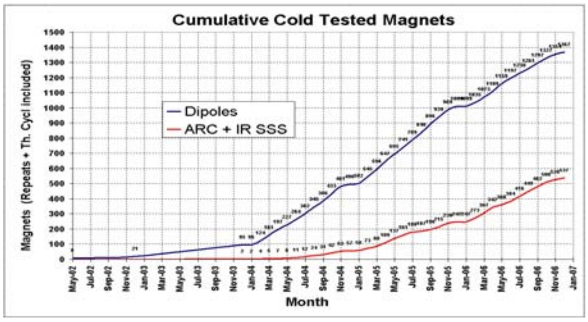
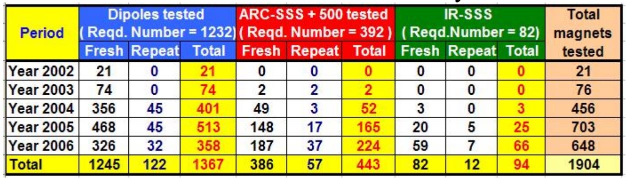


Figure 4: Cumulative Cold Tested Magnets

and renamed magnets. In addition, ~3% of the dipoles and ~6% of the SSS had to be repaired or rejected after the cold tests. The latter type of issues, observed early in the project, confirmed the need to systematically test all the LHC magnets under cryogenic conditions.

Magnetic measurements were performed on 18.36% of dipoles, 13.32% of arc SSS's and 30.85% of Special SSS's. Often, exceptional tests were performed by the magnet experts on the Special SSS's, needing a considerable amount of time and data analysis.



Period	Dipoles tested (Reqd. Number = 1232)			ARC-SSS + 500 tested (Reqd. Number = 392)			IR-SSS (Reqd.Number = 82)			Total magnets tested
	Fresh	Repeat	Total	Fresh	Repeat	Total	Fresh	Repeat	Total	
Year 2002	21	0	21	0	0	0	0	0	0	21
Year 2003	74	0	74	2	2	2	0	0	0	76
Year 2004	356	45	401	49	3	52	3	0	3	456
Year 2005	468	45	513	148	17	165	20	5	25	703
Year 2006	326	32	358	187	37	224	59	7	66	648
Total	1245	122	1367	386	57	443	82	12	94	1904

Figure 5: Magnets Tested in each Year

CONCLUDING REMARKS

To complete the tests of all LHC Cryomagnets well in time before LHC beam running in 2007, several innovative ideas, strategies, tools and techniques were introduced and implemented by the Operation Team. The results and statistics of magnet tests underline the significance of them in the successful completion of the tests. While many challenges were met and overcome in operation, delays in magnet delivery issues particularly since mid-2006 remained beyond the control of the Operation Team. Nevertheless, it is expected that all magnet tests for the LHC would be completed by February 2007. The LHC magnet tests operation has also been a singular and very successful example of a large scale collaborative effort in terms of human resources; over 90 persons from India have spent one year each at CERN since 2001 and hence, it remains a unique example in international collaboration of that scale in the particle accelerator domain.

ACKNOWLEDGEMENTS

Acknowledgements are due to all the past & present members of the SM18 Operation Team from DAE-India & AB-Dept, CERN to bring the tests programme to a successful and timely completion. A.Laddha, M.Beachai, M.Gandhi, S.Malhotra, U.Bhunia, D.Perupayikkad, M.Mascarenhas, S.Sethumadhavan, M.Patil, K.Nair, J.Mishra, A.Kasbekar, Naushad Ali, A.Pagare, K.Palanisami, B.S.Rao, S.Kane, J.Gore, D.Roy, J.John, S.R.Shimjith from DAE-India and G-H Hemelsoet, E.Veyrunes, K.Priestnall, J.Mazars from CERN AB-Dept contributed significantly to this success. Similarly, the 24-hr operation cryogenic and ICS consortia teams, AT-Dept equipment & mechanical support teams and AB-Dept power on-call teams are acknowledged for their active cooperation. J-P Lamboy, L.Herblin, J. Axensalva, G.D'Angelo, and R.Mompo deserve a particular mention for their help to the Operation Team and dedication to the tests needs.

The direct and indirect support of L. Evans, P. Lebrun & L. Walckiers in helping to overcome the challenges for setting-up and running the SM18 tests facility operation is acknowledged.

The author is thankful to S. Bahuguna, S.R. Shimjith and S. Padmakumar, BARC-DAE, India for their assistance in preparing this paper.

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