Indian contribution to the Large Hadron Collider under construction at CERN, Geneva

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India is participating in the construction of the Large Hadron Collider (LHC), which is the most ambitious particle accelerator being built by CERN. We describes the Indian contribution to the LHC, in terms of both hardware and software and also in terms of skilled manpower support made available for evaluation of some of the LHC sub-systems over the past few years.

The Large Hadron Collider (LHC) is the most ambitious project undertaken by the European Organization for Nuclear Research (CERN)[1], which is a premier international laboratory engaged in high energy physics research. The LHC was launched in 1996, with an anticipated completion time of about ten years. Its initial goal is to produce proton–proton collisions with a centre of mass energy of 14 TeV, to be followed by collisions between lead nuclei involving a centre of mass energy of 1150 TeV. These experiments are meant to search for the Higgs boson, investigate basic constituents of matter as well as origin of matter–antimatter asymmetry, study the quark–gluon plasma state of matter that prevailed at the beginning of universe, etc. Different experimental stations equipped with a wide array of detectors, and a host of laboratories around the world are involved in these efforts. All physics studies will be carried out via four 'collision points' equipped with large detector set-ups. These are CMS, ALICE, ATLAS and LHCb and will give scientists a peek into a totally unexplored micro-cosmic world. Indian scientists are taking part in the first two of these four detector set-ups. The coordination among scores of research laboratories spread all over the globe that are participating in these efforts is remarkable. This note covers the Indian contribution related to construction of the LHC only. We do not discuss any of the aspects which are connected with the physics, experimental stations or detector fabrication activities, which will be covered later in separate articles.

Background

Motivated by the desire to increase the pace of accelerator development in our country and to give a thrust to experimental high energy physics programme, the Department of Atomic Energy (DAE) and CERN signed an agreement of cooperation in 1991 for a ten-year period. In the early years of this agreement, the Centre for Advanced Technology (CAT), Indore successfully delivered a few subsystems for upgradation of LEP-200 project, thereby confirming viability of such an arrangement. The formal framework provided by this agreement was also tapped by the Indian High Energy Physics (HEP) community by participating in a frontier area of research involving the heavy (lead) ion collision programme being carried out at CERN. A number of DAE institutions and universities took part in these efforts and won recognition for Indian scientific efforts (at CERN), already known for TIFR scientists' contribution to the L3 detector installed there in the eighties. So, when CERN launched its most expensive (worth 2.5 billion Swiss francs) Large Hadron Collider (LHC) project, and was looking for competent partners who could take part in this programme, in terms of ideas, hardware and manpower, our past association came in handy. It was clear that such a mega science project would need support from Non CERN Member States (NMS), who have the required strength and India was naturally in contention because of its earlier links with CERN. Indeed, in a meeting of CERN and Indian scientists held at TIFR in 1994 to discuss participation of the Indian HEP community in LHC experiments, various ideas for mutual collaboration had been proposed. Thus the signing of a protocol in March 1996 between DAE and CERN and India's joining the LHC project and consenting to provide in-kind contribution in terms of hardware, skilled manpower and software to the tune of 25 million USD (equivalent to 34.4 million Swiss francs) was, in a way, a culmination of the earlier interactions. India joined Canada, Japan Russia and USA to participate in the construction of LHC as NMS with one difference, namely that half of the Indian (in-kind) contribution was to be used to create an 'India Fund' at CERN. The benefit of creating such a fund lay in that it could help cover expenses that would be required for the pursuit of the experimental programme. By 2001–2002, different components identified for Indian contributions to LHC had touched 34 million Swiss francs and large-scale fabrication of many such components was well on course, with the help of large industrial enterprises in the country. This convincingly established our credentials and ultimately resulted in (i) CERN extending the 1991 cooperation agreement with India for a further ten-year period; (ii) our in-kind contribution on the request of CERN being enhanced to 60.4 millions Swiss francs; and (iii) India being accorded the 'Observer' status[2] by CERN Governing Council with only Israel, Japan, the Russian Federation, Turkey, USA, EC and UNESCO being the other observers. Different elements of Indian contribution to the LHC project are described below.

Large Hadron Collider

The LHC is a 'two-in-one' particle accelerator, being installed in the existing tunnel of about 27 km circumference that runs nearly 100 m underground, straddling the Swiss–French border. It is designed to carry two streams of particles running in opposite directions (through tubes embedded in twin-aperture magnets), which will intersect at four 'collision points'. The LHC uses advanced Nb–Ti superconducting (Sc) magnets which can operate at ~8.6 T field in superfluid helium at 1.9 K. Its high-tech hardware items are impressive: 1232 main dipoles, 400 quadrupoles, 6000 correctors, 6400 radiation-hard quench protection power supplies and detection electronics, 27 km long nested cryogen (1.8 to 20 K) distribution lines, eight 18 kW, 4.5 K LHe refrigerators and cold compressors, over 400 flexible cryogenic interconnects, high T_c current leads, 13 kA power converters, 32 modules of Sc RF cavities, 6800 alignment jacks, beam transfer lines of up to ~ 2.3 km length linking various segments of injector complex (two LINACs, Proton Synchrotron and SPS etc.), elaborate beam diagnostics and beam dumps (for extremely high energy particles). As of now the LHC is due for commissioning in 2007 when the proton–proton collision studies are expected to begin, but efforts on all the experimental stations are progressing in parallel.

Indian contributions

The in-kind contributions that DAE committed to CERN involve hardware, software as well as skilled manpower support. The hardware supply has opened a door for Indian industry to take up the challenge of delivering high-quality products for a cutting-edge international research project. CAT, Indore with a major programme in accelerators, is the nodal DAE agency which has the responsibility to carry out necessary R&D work to prototype and develop the components, so as to meet the given specifications before their large-scale production can be entrusted to industry. A Coordination Committee constituted by Secretary, DAE coordinates the collaboration with CERN. A joint India–CERN Committee oversees the implementation of this collaboration and the Government of India has provided the necessary budget to DAE for executing this work.

From the beginning of this collaboration, it was felt that India should make contributions in those domains which involve high technology and, as far as possible, in a cost-effective manner that is consistent with the policy of CERN to distribute a mix of all types of work–industrial, workmen-intensive, high-tech related, software and even conventional items – amongst CERN members and NMS. During the initial four-year period, based on a series of technical discussions between DAE and CERN, the following items of delivery by India were identified: (i) superconducting corrector magnets – sextupoles (MCS), decapoles (MCD) and octupoles (MCO); (ii) mechanical systems, namely precision magnet positioning system-jacks (PMPS-jacks); (iii) accelerator protection system – quench protection heater power supply (QPS), quench detection electronics (QDE) and control electronics for high current circuit breakers; (iv) vacuum system – vacuum system design for long beam transport lines for beam dumps; (v) cryogenics – large capacity liquid nitrogen tanks and test facility for testing of Sc magnets at 4.2 K; (vi) engineering studies – analysis of cryogenic distribution line interconnects and test and analysis for magnets along with necessary technical documentation; (vii) software – SCADA for industrial systems, database software, web interface and LHC machine control software; (viii) skilled manpower for test and evaluation of a variety of cryo-magnets at CERN.

The above-listed job elements are being pursued in different units of DAE. CAT is involved with (i), (ii), (iv), (v) and (vi) above; BARC and Electronics Corporation of India Ltd (ECIL) are associated with (iii) and (vii); and CAT, BARC, VECC and IGCAR are pooling necessary skilled engineers and physicists for (viii). Figure 1 shows LHC String-2 at CERN, where we have identified some of the major hardware contributions from India.

Technical details of specific items being contributed

Superconducting corrector magnets (MCS and MCDO)[3]

Dipoles and quadrupoles are the principal magnets of the LHC. Dipoles bend the charged particle beams in a circular path through the accelerator's 27-km ring, while quadrupoles focus them tightly. The main dipoles of LHC are equipped with sextupolar and decapolar (MCD) corrector magnets (MCS and MCD). Each decapole corrector also has an octupolar insert (MCO), and together are designated as MCDO. In all, 2464 MCS and 1232 MCDO assemblies are required for the LHC. (For logistic reasons CERN decided to procure these magnets from two different sources, one from India and the other from within Europe. Thus India's share of supply is half, i.e. 1232 MCS and 616 MCDO corrector magnets.) Each corrector magnet consists of an Sc coil assembly, glass fibre slit tube, steel lamination, aluminium shrinking cylinder for pre-compression of coils, end plates for connection, parallel resistor for magnet protection and a magnetic shield also acting as a support. The coils are wound from solid rectangular Sc wire of niobium–titanium in a copper matrix. The coils in each corrector are connected in series and the ends are connected to the leads for connection to the power supply. These connections are made by the ultrasonic weld technique, which results in low joint resistance. A number of prototypes of MCS, MCD and MCO were made and tested at CAT, at room temperature and at 4.2 K to finalize their engineering design, and special techniques were developed for production.

It was clear from the beginning that to produce a large number of these magnets, special machines, tooling and assembly processes would be required. The Sc magnet team at CAT developed the coil-winding machine, the ultrasonic welding machine, the coil assembly and epoxy

Figure 1. LHC String-2 assembly with major components supplied by India.

curing fixtures, etc. It may be pointed out that, apart from electrical and mechanical qualifying checks, the magnets must pass stringent acceptance tests involving magnetic measurements at 300 and 4.2 K. For these tests and measurements, special gauges and instruments have been set-up at CAT. These include a magnetic measurement set-up for measurements of magnetic properties at room temperature and at liquid helium together with the required cryostats, contact resistance measurement system, power supplies and quench data acquisition system, etc. For series production of these magnets, qualified industries were identified and their manpower was trained before passing on the complete know-how. Production of the magnets in two industrial units is well on its way and about 1000 series magnets have already been supplied to CERN, after carrying out all the tests, including those at 4.2 K, at CAT.

Since the corrector magnets have a number of intricate parts, apart from internal quality assurance by the manufacturers, inspection is also done by CAT engineers with required expertise. Detailed quality assurance (QA) plan, methods for mechanical and electrical checks, qualification of coil-winding process, etc. were first worked out during the pre-series phase and implemented during series production of magnets. The most important qualification tests include: (i) magnetic performance at room temperature, which is done on specially built automatic warm magnetic measurement benches with harmonic search coils, (ii) quench training performance at 4.2 K (by powering up to short sample limit current), and (iii) contact resistance of Sc coil terminal joints. These tests are performed on all magnets at CAT (apart from the ones at the manufacturer's works as part of pre-dispatch inspection). Table 1 compares performance achieved on our corrector magnets *vis-à-vis* target values given by CERN. Figures 2 and 3 display some of the results of measurement on these magnets.

PMPS-jacks[4]

The dipoles and other cryo-magnets need to be precisely positioned in the tunnel to ensure proper beam trajectories of particles. The dipole magnet assemblies, each weighing more than 32 tons with a length of 15 m, need to be positioned with a precision of 50 μm all along the 27 km length. The tunnel of the LHC has a slope of 1.4% from the horizontal and the jacks have to be capable of accommodating this slope. There are varying forces on the cryo-magnets originating from the relative movement of the interconnections and cryogenic distribution lines. The development of precision-positioning devices for these magnets and maintaining such position over large periods of time are achieved using PMPS-jacks. They enable one person to move the magnet assembly and position it with a high setting resolution for a long time under the action of variable transverse forces. (The set position has to remain within 100 μm when the transverse force reaches a value of 0.5 ton, and within 1 mm under a very severe transverse load of 8 tons.) Each jack has a column (vertical guide cylinder and ram) held at the ends by two spherical thrust bearings. The column is moved laterally at the top by a backlash free device. An auxiliary hydraulic-jack placed in the cylindrical cavity under the ram is used to lift the load. A suitable layout and positioning of three jacks in a tripod configuration under the cryo-magnets yields the required degrees of freedom for alignment adjustments. Each jack has two degrees of controlled movement, one in the vertical direction and the other in a direction in the horizontal plane. The main specifications of the jack are: (a) range of movement (i) in *X–Y* phase ± 10 mm (in both directions simultaneously), and (ii) in *Z* direction ± 20 mm; (b) load capacity 32 MT, and (c) maximum operating torque for lateral movement to be less than 60 Nm in nominal realignment operation. A total of 6800 devices are being made by the Indian industry for supply to CERN under the responsibility of CAT.

The main challenge for the design of these jacks was minimizing the weight and cost of the jacks and low operating torque. The process of design included preparing engineering specifications by understanding the functional requirements, evolving possible concepts capable of meeting these specifications, doing a value analysis of each concept and selecting the best option, doing detailed engineering calculations, selecting the right materials, and developing proper manufacturing processes. Different production techniques (casting for body, forgings for guide cylinder, etc.) and surface treatments have been used to meet tribological and corrosion-prevention requirements. Three prototypes were made and tested under full-load conditions to validate the design. Testing was also carried out at CERN under actual dipole mass to verify functionality. Before launching the series production, prototype manufacture of 36 jacks was undertaken. The prototypes were tested in String-2 at CERN to validate the full design, manufacture and evaluation scheme (String-2 is a full-size model of an LHC cell having eight cryo-magnets with a to-

Table 1. Test results of pre-series MCS-MCDO magnets

Specification Magnetic field errors	Required	Achieved MCS	MCO	MCD
Variation in main field	< ± 1%	+ 0.77 to –0.53%	+ 0.43 to –0.57%	+ 0.74 to –0.51%
and other multipoles	< 1–1.5% of main field at 17 mm radius	< 1%	< 1.5%	< 1%
Magnetic axis offset (w.r.t. fixed reference dowels)				
x/*y*	< ± 0.10 mm (*x*/*y*)	+ 0.06 to –0.09 mm	+ 0.08 to –0.05 mm	+ 0.07 to –0.05 mm
Twist angle: MCS	< ± 1.5 mrad	+ 0.92 to –0.74 mrad		
MCO	< ± 2.5 mrad		+ 2.0 to –1.0 mrad	
MCD	< ± 2.0 mrad			+ 2.0 to –1.5 mrad

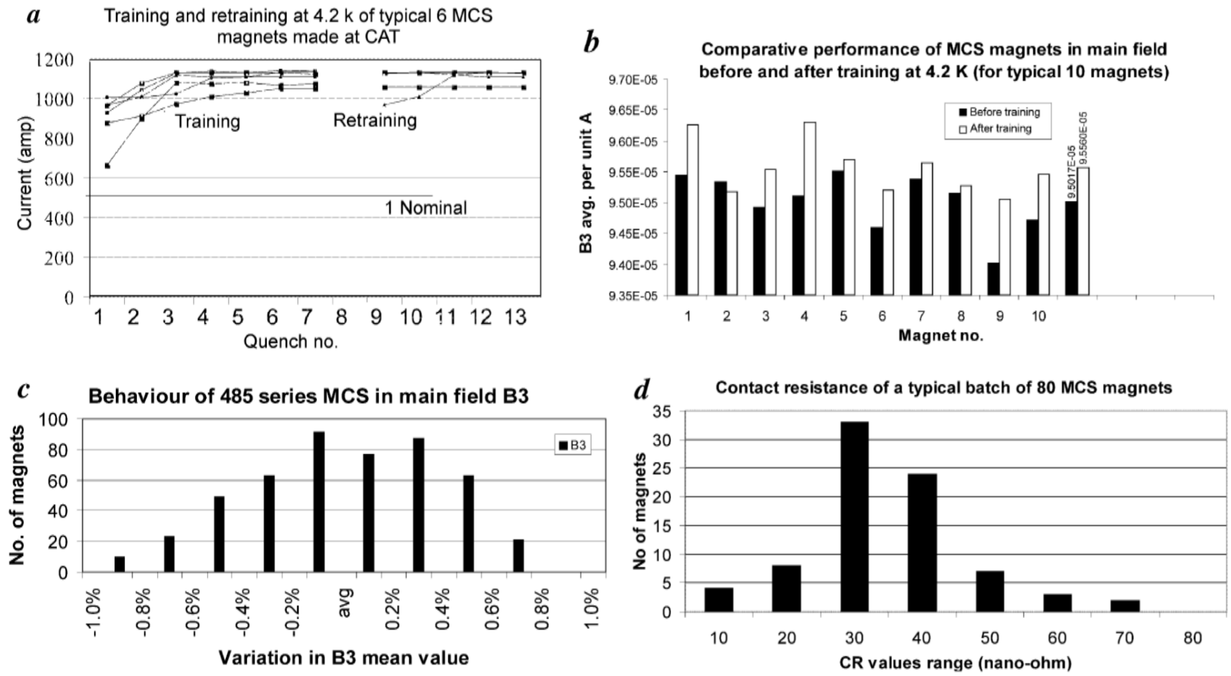

Figure 2. ***a***, Training history showing increasing current values at which sextupole corrector magnet quenches vs quench number. ***b***, ***c***, Quench characteristics variation in the main fields in the sextupole (B3). ***d***, Contact resistance for these corrector magnets.

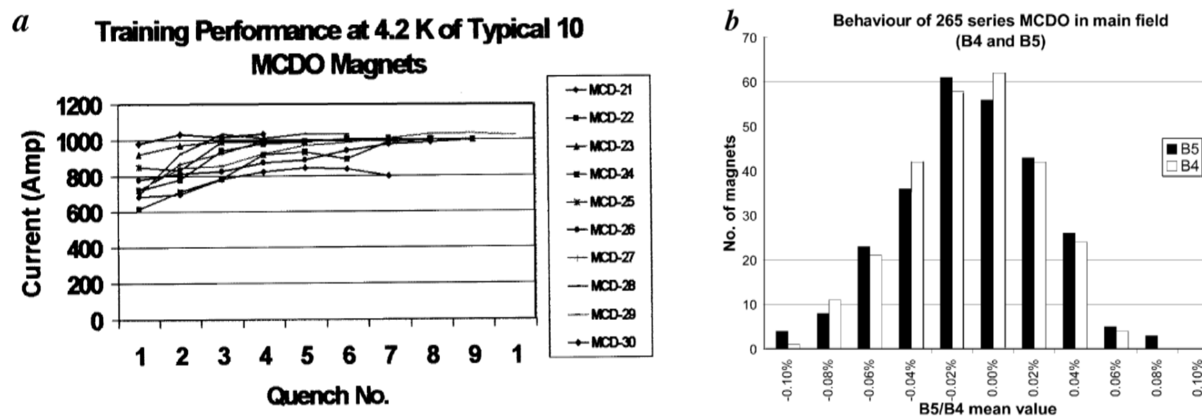

Figure 3. Quench characteristics of MCDO along with variations in the main field.

tal length of 120 m). The performance of the jacks under String-2 was found to be extremely good and fulfilled all the demands of CERN engineers. Extensive work was done on optimization of the design for achieving minimum weight of the jacks, accommodation in limited space available in the LHC tunnel, and tailoring the manufacture to suit Indian conditions, considering that a large number of jacks have to be made in limited time with minimum overall cost. The jacks have to remain operational for 20 years without maintenance. Stringent international standards have been followed to ensure quality and safety of the product. Safety testing at 1.5 times the load in vertical and transverse directions (equivalent to 48 tons of vertical load and 12 tons of transverse load) has been carried out. A multinational third-party inspection agency (M/s SGS India Limited) has been involved to ensure close supervision and quality assurance during manufacture. Nearly 3500 jacks have been shipped to CERN by now, after successful manufacture and testing at Indo-German Tool Room, Indore and Avasarala Automation Limited, Bangalore. All 6800 PMPS-jacks will be supplied by the middle of 2005. Figure 4 shows some of these jacks.

Quench protection heater power supply

The LHC Sc dipole and quadrupole magnets will be powered with current up to 13 kA. All Sc magnets require protec-

a

b

Figure 4 *a*. A series jack just before shipment after manufacturing and testing. ***b***, Two jacks under transverse load test.

tion in case of quench (resistive transition) or other failures, which may disturb accelerator operation or damage the equipment. The main dipole is equipped with quench heater strips on magnet coils and cold bypass diodes. When the quench is detected (via a floating-bridge detection of voltage build-up above a certain threshold value across magnet coils), the protection will power the quench heater strips and distribute the energy evenly in the entire magnet. Protection power supply provides a voltage of 900 V across the heater strips, providing a peak current of 85 A and uses the thyristor-triggered discharge of aluminum electrolytic capacitors for this purpose. The time constant of the circuit is about 75 ms. Since these units are kept directly under the magnets in a high radiation zone, the capacitors and thyristors have to cope with radiation-induced changes. Besides the power part, QPS units require an interface to the acquisition and monitoring system. India is contributing 5500 out of about 6200 units of QPS that are required for LHC, with the remaining coming from a European supplier. Initially four prototypes to qualify the design were built at BARC and then a pre-series of 60 units were built by ECIL. These are now being further modified to industrial standards for large-scale economic production. Rigorous component-qualification criteria, endurance tests and detailed QA plan are specified for industrial production of a large number of robust and reliable units.

Quench detection electronics

These electronic devices are meant to detect quench occurring on the LHC superconducting magnet system. Each unit consists of two devices, namely the local quench detector and the acquisition and monitoring controller put together in a 3U, 19″ crate. The local quench detector is attached to an LHC superconducting magnet and activates the respective protection systems in case a resistive transition occurs. The function is mainly based on analogue electronics. The acquisition and monitoring controller collects data from the local quench detector (and some other devices) and provides a field-bus link. The function is based on a single-chip data-acquisition system in combination with a field-bus coupler. India is contributing 1435 QDE units.

Control electronics for circuit breakers of energy extraction system

For rapid de-energization in case of quench, many magnet chains in the LHC will be equipped with an external energy extraction system having circuit breakers and energy-absorbing resistors. Each of the eight sectors of LHC is powered independently. Thus 154 dipole magnets and 47 quadrupole magnets are powered by a single source. About 1.33 GJ of stored energy in the dipole magnets of each sector will be extracted into two symmetrically placed dumps. Four 4.5 kA DC circuit breakers will carry the current fed from a current-equalizing bus-way. Each breaker electronics controller cabinet controls the operation (no-volt coil for slow opening, and current impulse for fast release open and close). Eight control modules were built at ECIL under the guidance of BARC, and tested with actual mechanical circuit breakers produced by Russian collaboration to verify the design. Seventy such units are to be produced for full protection system of LHC.

Vacuum system for beam dump line

Two beam dumps are designed to dump the proton beams circulating in opposite directions. These two lines are located in the two underground tunnels tangential to the LHC ring. The beam which is blown by ‘diluter’ magnets is led through a vacuum envelope of increasing cross section to the dump located at 631 m from diluter magnets downstream of beam extraction kickers. The vacuum system is designed as maintenance-free all-metal-line system, evacuated by mobile turbo-pump units and sustained by sputter-ion pumps. Pressure distribution and pump-down in long line and flexible interconnect and supports have been studied. The vacuum ranges from UHV (near the ring) to almost rough (near the dump). The line layout in the tunnel is critical in some areas and *in situ* welded construction will be necessary. Engineering studies, detailed drawings, and specifications for fabrication are nearing completion at CAT.

Liquid nitrogen storage tanks

A large quantity of liquid nitrogen is required for the LHC complex (initial cool-down of LHe circuits, etc.). Large-capacity 50,000 l storage tanks are required at various cryo-distribution points around the ring. Two such tanks, about 3.4 m diameter and 10.6 m tall, double-walled, vacuum and perlite insulated, 50,000 l capacity, operating at 3 bars pressure with liquid withdrawal rate of 2 kg/s were built by the industry in India and supplied to CERN. These tanks have performed well at CERN for the last three years, with less than 100 l/day evaporation rate, much below the specified value.

Flexibility analysis of cryo-line jumper and magnet connections

Nested pipe cryogenic distribution lines run all around the ring in the LHC. A large number of service modules in these lines feed liquid helium and nitrogen to the Sc magnets via a flexible 'jumper connection'. Finite element (FE) analysis of reaction forces and moments on the magnet by the jumpers was performed at CAT to check the possible unacceptable displacements and instabilities. Further, FE modelling of the complete jumper, short straight section (SSS) cold mass and interconnects has been completed and experimental verification using actual dipole, SSS and interconnect jumpers is under way.

Software development

Software packages in the area of database (GEODE and JMT) and data analysis on Web-interfaces were developed at BARC and CAT respectively. The major work in this area was done in SCADA for industrial system control (vacuum, cryogenics, powering, magnet protection and interlocks) for the LHC String-2 test. Supervision software has been developed by BARC using PCVue32. The main LHC machine control software will be initiated in the coming years.

Magnet tests and measurements

The LHC will have a large number of cryo-dipoles, quadrupoles and corrector elements. All these magnets need to be tested and characterized as part of a QA plan at superfluid helium temperatures of 1.9 K, as well as at room temperature (warm) at dedicated test stations. These involve cryogenic tests, power tests, quench behaviour analysis, protection test, precise magnetic measurements at injection and high fields, and warm measurements. The SM18 Hall at CERN has been the home for conducting all such evaluations, where several test stations were installed for dipoles (MB test-station based on twin rotating units and long shaft), quadrupoles (SSS test-station using automated scanner and LTD with single harmonic coil and single stretched wire system) and two benches for warm measurements. In addition, a bench with a standard magnet had been set up for calibration of the long shaft. A team of operators and central control room supervisors work at SM18 Hall, under direct charge of specialists, and perform complete tests and measurements on full series produced magnets. Standard analysis of raw data to quantify the field errors and deviations from the reference design values are used to monitor the magnets produced by industry and finally to create a database of field quality and quench behaviour, which will be useful for the machine operation. Cryogenics, powering, protection and coil signal processing are performed through a local SUN Ultra-2 workstation using special software, in conjunction with a cluster of workstations in the central control room. A typical test-campaign for every cold mass dipole lasts for well over 100 h (round the clock). So far about fifty engineers and physicists from CAT, BARC, VECC and IGCAR have assisted this campaign at CERN and another 50 man-years of further support for this activity will be provided in the coming three years.

1. http://public.web.cern.ch/public/.
2. http://cerncourier.com/main/article/43/1/1/1.
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