LHC STATUS

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Abstract

The installation of the Large Hadron Collider at CERN is now approaching completion. Almost 1100 of the 1232 main bending magnets are installed and the whole ring will be installed by the end of March 2007. Emphasis is now moving from installation to commissioning, with the cool down of the first of the 8 sectors to liquid helium temperature well underway. In the other sectors, interconnect work is proceeding at a satisfactory pace and will be finished by the end of August. It is foreseen to inject the first beam into the LHC in November with the objective of having first collisions at the injection energy (450 GeV/c) in order to debug the machine and detectors before stopping for the annual winter shutdown. During this time, the detector installation will be finished and the machine will be pushed to full current ready for the first physics run at 7 TeV per beam in 2008.

MACHINE LAYOUT

The LHC is a two-ring superconducting proton-proton collider housed in the 27 km circumference tunnel originally constructed for the Large Electron-Positron collider (LEP), now decommissioned. It is designed to provide proton-proton collisions with unprecedented luminosity (10^{34} cm^{-2} s^{-1}) and a centre-of-mass energy of 14 TeV for the study of rare events such as the production of the Higgs boson if it exists. In order to reach the required energy in the existing tunnel, the dipoles must operate at high field (8.3 T) and therefore have to be cooled in superfluid helium at 1.9 K to increase the critical current of the NbTi conductor to the required value. In addition to p-p operation, the LHC will be able to collide heavy nuclei (Pb-Pb) with a centre-of-mass energy of 1150 TeV (2.76 TeV/U and 7 TeV per charge). By modifying the obsolete antiproton ring (LEAR) into an ion accumulator (LIER) in which electron cooling is applied, the luminosity can reach 10^{27} cm^{-2} s^{-1}.

The basic layout of the LHC is shown in Figure 1. The machine has eight arcs and straight sections approximately 528 m long. Four of the straight sections house the LHC detectors. The two high luminosity detectors, ATLAS and CMS, are located at diametrically opposite straight sections at Points 1 and 5 respectively. The two other detectors (ALICE and LHCb are located at Points 2 and 8, which also contain the injection systems for the two rings.

The other four straight sections contain machine utilities. Points 3 and 7 contain two collimation systems for capturing stray particles. Point 3 is designed to capture off-momentum particles whilst the collimation layout at Point 7 is designed to control the beam halo. Point 4 contains the Radio Frequency superconducting acceleration cavities operating at 400 MHz, twice the frequency of the LHC injector. Finally, Point 6 contains the beam abort systems for the two beams which will allow the beams to be extracted safely and deposited onto external dumps capable of absorbing the considerable stored energy (up to 350 MJ at top energy and intensity).

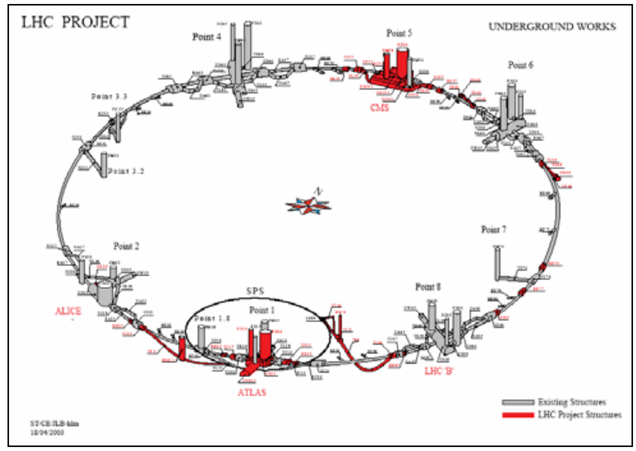

Figure 1: Machine layout.

INSTALLATION AND COMMISSIONING OF MAJOR SYSTEMS

Magnets

The full list of superconducting magnets and their function is shown in Table 1. All magnets have now been delivered. They range from the large 15 m long, 35 ton dipoles to the 11 cm long, 5 kg decapole-octupole correctors inside the dipole cold mass which correct for unwanted multipoles of the dipole field. Half of these correctors (616 units) and half of the sextupole correctors (MCS, 1232 units) were built in India under the supervision of RRCAT. All magnets were tested at 4.2 K at RRCAT before being shipped to the European manufacturers of the dipoles to be integrated into the cold masses.

Figure 2 shows the history of the main dipoles from production to installation. Delivery of all 1232 dipoles (excluding spares) is now complete (top curve). On arrival, the dipoles are inserted into their cryostats and connected to one of the cryogenic test stands (Figure 3), where they are cooled to their operating temperature of 1.8 K. Cold tests include electrical quality assurance and a training campaign where the dipoles are taken above their operational field of 8.3 T. A random sample of about 20 % is used for magnetic measurements in order to check that the correlation between warm measurements at the factories (all dipoles are measured warm) and cold measurements remains good. The cold testing of all magnets has been an enormous effort with the test stations running 24 hours per day, 7 days per week for over 3 years with only one short shutdown per year for maintenance. This would not have been possible without the contribution of highly qualified personnel from India. Nearly 100 Indian scientists and engineers from 4 different establishments have contributed on a one-year rotational basis.

Table 1: List of superconducting magnets and their function.

Type	Number	Function
MB	1232	Main dipoles
MQ	392	Arc quadrupoles
MBX/MBR	16	Separation and recombination dipoles
MSCB	376	Combined chromaticity and closed orbit correctors
MCS	2464	Sextupole correctors for persistent currents at injection
MCDO	1232	Octupole/decapole correctors for persistent currents at injection
MO	336	Landau damping octupoles
MQT/MQTL	248	Tuning quadrupoles
MCB	190	Orbit correction dipoles
MQM	86	Dispersion suppressor and matching section quadrupoles
MQY	24	Enlarged-aperture quadrupoles in insertions
MQX	32	Low-beta insertion quadrupoles

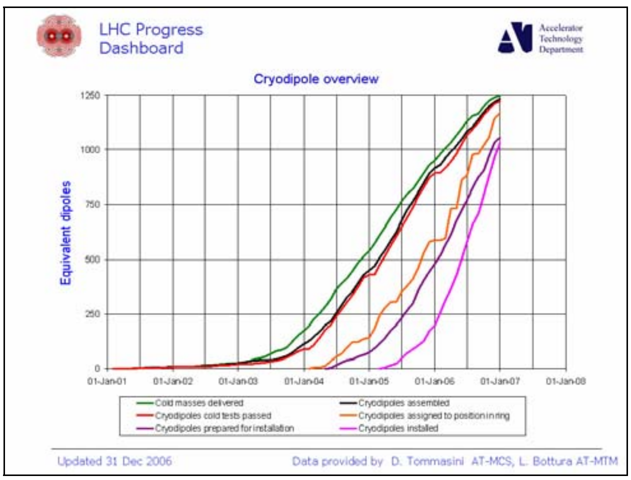

Figure 2: Cryodipole overview.

Once the cold tests are completed, each dipole is assigned a slot in the machine by the Magnet Evaluation Board depending on a number of criteria, one of the most important being the available aperture. The magnets are then prepared for the tunnel (fifth curve), and finally installed (last curve). They are all installed through a single large shaft (Figure 4) and are transported underground to their final location (Figure 5) which can be as much as 15 km from their point of dispatch. They are then transferred from the transport vehicle to their final position (Figure 6). The jacks for aligning the magnets were all made in India. At the time of writing, 1100 of the 1232 dipoles are installed and the whole installation will be finished by the end of March 2007.

The logistics chain for the main quadrupoles is similar to that of the dipoles. The quadrupoles are delivered as Short Straight Sections (SSS) with correctors (MSCB and MO or MQT) produced by other manufacturers already integrated. The SSS are inserted into their cryostats at CERN, which is a much more complicated process than for the dipoles because the SSS are the main interface between the magnets and the cryogenic system. Finally they are individually cold tested before tunnel preparation and installation. Figure 7 shows a similar set of curves as for the dipole. It can be seen that installation will also be complete by March.

Figure 3: Cryogenic test stands.

Figure 4: Lowering of a dipole.

Figure 5: Underground transport.

Figure 6: Magnet transfer.

In addition to the regular arc SSS, there are about 100 special SSS in the matching regions and dispersion suppressors which are integrated into cold masses at CERN from bare quadrupoles and correctors built in industry. Production of all special cold masses is finished. All 32 low-beta quadrupoles (MQX) have been delivered from the USA and Japan.

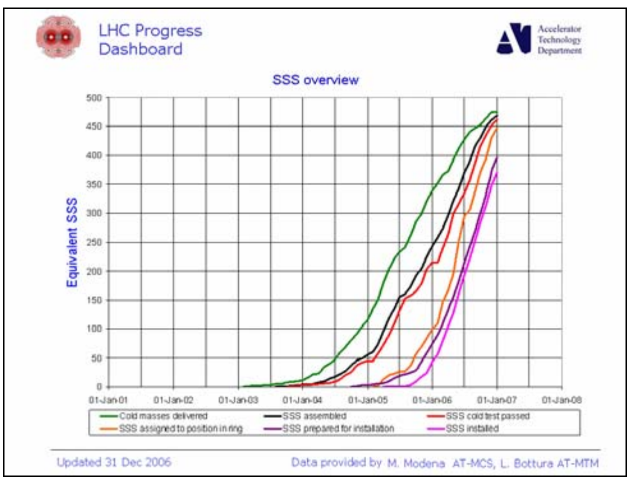

Figure 7: SSS overview.

Finally, one should not forget the very large number of conventional magnets for the LHC and the injection lines manufactured at BINP, IHEP and TRIUMF. For the two beam lines TI2 and TI8, from the SPS to the LHC and for the LHC ring itself, BINP has manufactured 729 magnets of various types. For the injection and dump regions, IHEP has built 60 septum magnets and for the two cleaning insertions, TRIUMF has supervised the construction of 52 two-in-one quadrupoles in Canadian industry.

After installation, the magnets must be interconnected (Figure 8). This is a complex sequence of operations starting with the interconnection of the main and auxiliary busbars followed by an electrical quality assurance. The various lines are then closed with orbital welding machines followed by leak tests. After closure of the external envelope, there is a final pressure and leak test and an electrical quality assurance of the whole octant including the tunnel feed boxes. The last activities before cool down can commence is the "flushing" of the cold masses and cryogenic lines with high pressure helium gas to remove any foreign particles that could interfere with the cryogenic plants.

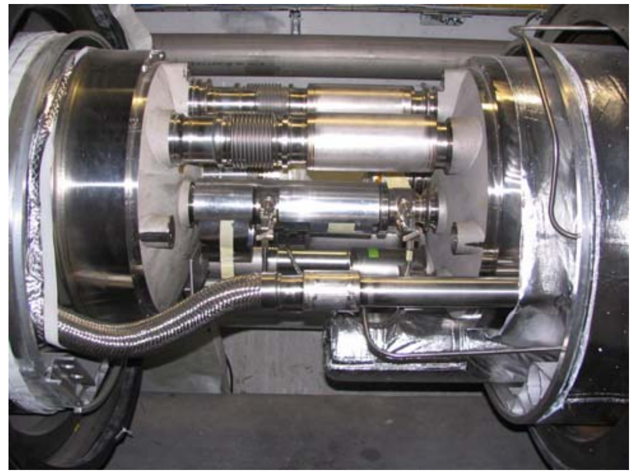

Figure 8: Dipole-dipole interconnect.

At the time of writing, one sector is completely finished and is being cooled down and interconnect work is proceeding in five other sectors in parallel (Figure 9).

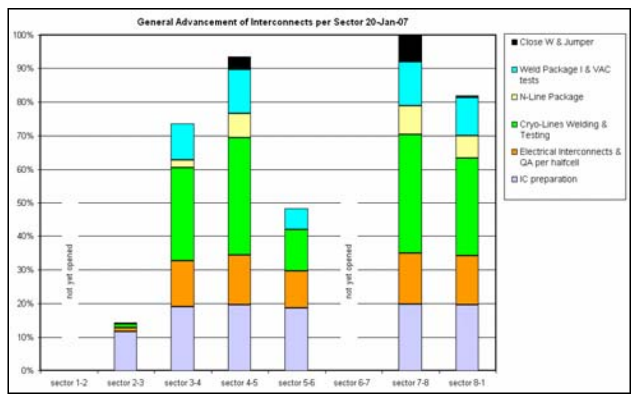

Figure 9: Interconnects status.

Cryogenics

Figure 10 shows a synoptic of the enormous cryogenic system required to cool the LHC. The gas storage, warm compressors and refrigerators are located at the surface. The cold compressors needed to produce the 15 mbar pressure required to reduce the temperature of the helium to 1.9 K are located in underground caverns together with valve boxes which allow a redistribution of cooling capacity between the octants. Finally the tunnel cryogenic distribution line (25 km of complex pipe work) distributes helium around the ring. This distribution line was completed in October 2006, liberating the whole of the tunnel for magnet installation. Commissioning of the whole cryogenic system is now nearing completion and the first octant is being cooled down.

Cooldown begins with 2 weeks of flushing followed by an electrical quality assurance (ELQA) test. In this first cooldown, it has taken 2 weeks to go from ambient to

80 K (Figure 11) after which a second ELQA is done. From 80 K to 4.2 then to 1.9 K takes 1 week.

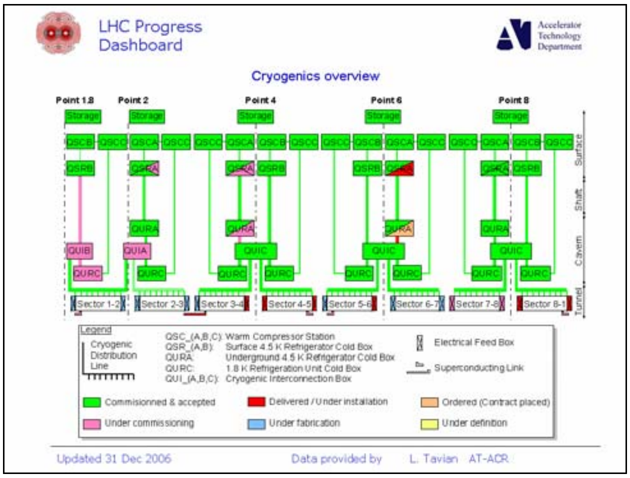

Figure 10: Cryogenic system.

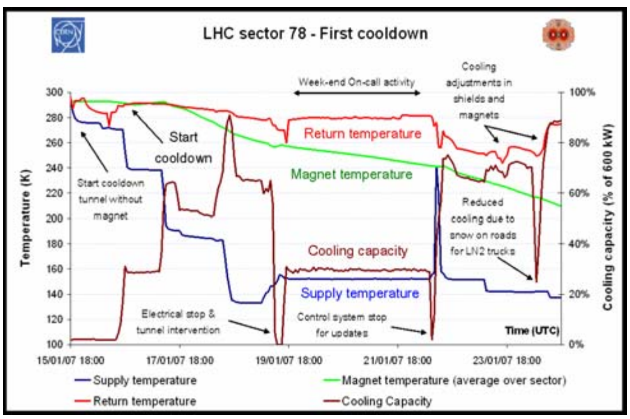

Figure 11: Cooldown.

Radio frequency and transverse feedback

The RF system is located at Point 4. Two independent sets of cavities operating at 400 MHz (twice the frequency of the LHC injector) allow independent control of the two beams. The superconducting cavities are made from copper on which a thin film of a few microns of niobium is sputtered onto the internal surface. Each RF system must provide a maximum voltage of 16 MV. For each beam there are 8 single cell cavities, each providing 2 MV with a conservative gradient of 5.5 MV/m. In fact the cavities have all been conditioned up to 8 MV/m, giving a good safety margin. Each cavity is driven by an individual RF system comprising a 300 kW klystron, coupler, circulator and load (Figure 12). All cavities are now installed (Figure 13) at Point 4 and are being connected to the RF and cryogenic systems.

The LHC transverse feedback system is also located at Point 4. It combines three principal functions: it damps transverse injection errors, prevents transverse dipole mode instabilities and can excite transverse oscillations for beam measurements and cleaning the abort gap. There are four independent systems, one per plane and per ring. The kickers, power amplifiers and supports were provided as a contribution from JINR, Dubna. The system is designed to provide useful gain up to 20 MHz. All kickers are now installed and are being commissioned.

Figure 12: Two 300 kW klystrons with circulators and loads.

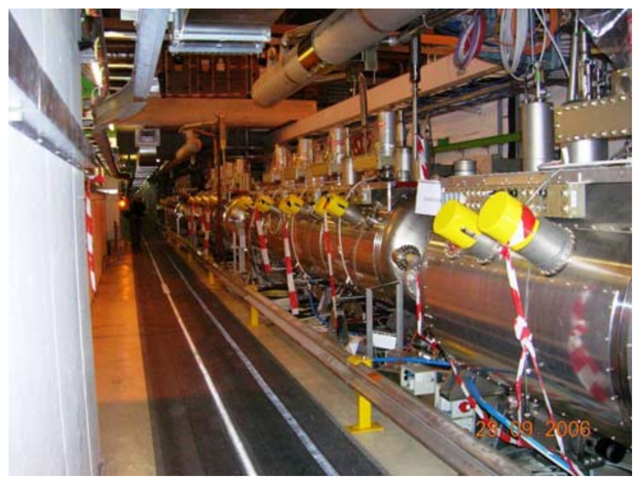

Figure 13: RF cavities at Point 4.

The Power converters

Each of the eight LHC sectors contains one electrical circuit connecting all main bending magnets in series. The main quadrupoles are powered in each sector in two electrical circuits (horizontally focusing (QF) and defocusing (QD)). The power converters for each of these circuits are located in underground galleries, previously used for the LEP klystrons, located close to the even insertion regions. The stored energy in these circuits amounts to 1.2 GJ for the main dipole and 20 MJ for each of the main quadrupole circuits. For the main dipole circuit, an energy extraction system consisting of a high current switch in parallel with an extraction resistor (3*225 mΩ, 220 MJ built at the Institute of High Energy Physics (IHEP) at Protvino) is placed on either side of the arc cryostat. For the quadrupoles only one system is sufficient.

As well as the main dipole and quadrupole circuits, there are many other high current supplies feeding quadrupoles in the inner triplets and matching sections also located in the underground galleries (968 power converters in total) as well as the low current converters (600 A) for closed orbit correction (752 in total) distributed around the machine in racks underneath the main dipoles.

All 968 high current converters have been delivered and installed as well as 80 % of the orbit corrector supplies. The high current supplies are connected to the tunnel feed boxes with water-cooled cables. First commissioning of the supplies is done with these cables in short circuit in the feed box end so that the supplies see the resistive load of the cables but not the inductive load of the magnets. After all supplies are individually tested in this way, the whole group of supplies (about 50) in a cavern is tested at full current for 24 hours (Figure 14) in order to validate controls, water and air cooling and any problems of overheating due to, for example, bad routing of cable runs. About 60 % of the high power converters have already been tested in this way, and have allowed a number of problems to be resolved before the supplies are connected to their superconducting loads.

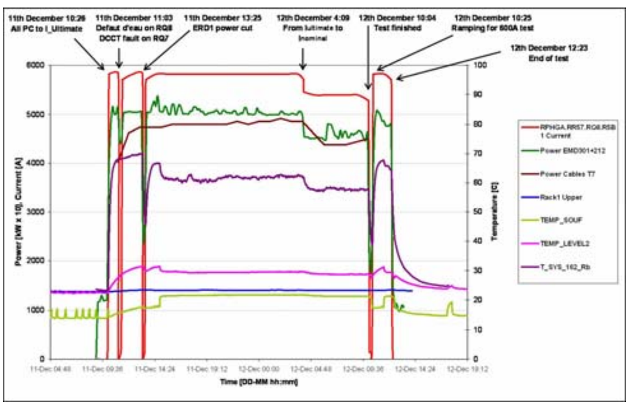

Figure 14: 24-hour run.

There are more than 40 current feed boxes of many different sizes. The largest feed the currents to the main dipoles and quadrupoles as well as retaining the vacuum forces at each end of the arc (Figure 15). The boxes are machined at IHEP and assembled into modules at CERN. A total of 1070 current leads operating between 600 A and 13 kA incorporating a section with high-temperature superconductor are needed. Most of these current leads have been built at the Budker Institute of Nuclear Physics (BINP) in Novosibirsk. Production and installation of these boxes is now proceeding smoothly at the rate required to meet the global installation schedule.

The main magnets are actively protected with quench heaters. If a quench is detected in a magnet, the quench heaters are fired and the power supply is switched off. The quench heater power supplies (a total of 5500 capacitive discharge supplies) have been built in India and assembled at CERN by Indian technicians.

Figure 15: Current feed boxes.

Other systems

Lack of space does not allow the other systems needed to operate the LHC to be treated in any detail. These include injection and extraction systems, collimators, beam instrumentation, vacuum, controls and machine protection. Except for the collimators, which are slightly delayed, installation is proceeding according to schedule. A minimum set of collimators has been defined for the 2007 run. The rest will be installed in the winter shutdown.

CONCLUSIONS

All major hardware procurement for the LHC Project is now complete. Installation of equipment in the tunnel is proceeding smoothly and commissioning of major sub-systems is starting. The first LHC sector (7-8) is complete and cooldown to 1.9 K is proceeding normally.

The schedule is too tight to allow full commissioning of all eight sectors up to the nominal design current corresponding to 7 TeV operation before the 2007-8 winter shutdown. It has therefore been decided that only the first two or three sectors will be fully commissioned in 2007. The remaining sectors will be able to operate safely at their injection level and will allow beams at 450 GeV to circulate in both rings. The RF system will then be activated to capture the beams, hopefully with a good enough lifetime to allow the beams to be brought into collision, providing first events in the detectors. This will be invaluable for early debugging of both the machine and detectors and will give a flying start to a high energy physics run in 2008 once all sectors have been commissioned to nominal current during the shutdown.

ACKNOWLEDGEMENTS

Many people, both inside and outside CERN have been dedicated to this Project. On behalf of my CERN colleagues, and in view of the location of this Conference, I would like to thank our Indian colleagues for their contribution of the highest quality.