T.3 : Indian involvement in the LHC construction and physics possibilities that lie ahead

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1. Introduction

To explore physics at the new energy frontiers, particle colliders are a better option - as compared to a beam hitting a fixed target - because they can give a higher centre of mass energy for the creation of new particles, although, one pays a price of producing fewer collisions. Circular machines offer the advantage that beams (circulating in opposite directions) can be first accumulated, and then ramped in energy before colliding them (at specific points), making the experiments *more productive* than is possible with linear machines. However, in the case of leptons, like electrons and positrons, while going over a curved path in a magnetic field (especially when strong superconducting magnets are used) the energy loss through synchrotron radiation (SR) becomes intolerably high. Thus, in the case of such leptons, when beam energy approaches several hundred GeV, linear accelerators are a better option. However, for hadrons, as even at ~ TeV level energy, loss due to SR is not important, circular machines are still viable. Tevatron, at Fermilab in USA, presently the highest energy particle collider operating with proton and antiproton beams each of ~1TeV energy, would lose its hegemony when LHC, the world's biggest particle accelerator, starts to produce collisions between proton beams. LHC has been set up in a 26.7 km circumference tunnel by the European Organization for Nuclear Research (CERN), Geneva. With this tunnel (earlier used by Large Electron–Positron (LEP) and superconducting magnets providing a maximum of 8.33 tesla magnetic field, LHC will be able to deliver highest energy proton-proton (p-p) collisions of 7 TeV energy each.

LHC is really a very large accelerator. It straddles the Swiss-French border about 100 m below the ground. When it starts colliding protons (and later lead nuclei), it will, hopefully, be able to answer some deep scientific questions using four detectors, namely, ATLAS (A Toroidal LHC ApparatuS), CMS (Compact Muon Solenoid), ALICE (A Large Ion Collider Experiment at CERN LHC), and LHCb (Large Hadron Collider beauty experiment) located around four different places where the ion beams will cross. (ATLAS and CMS are general purpose detectors, whereas LHCb is optimized to look for the production of bottom quarks, b, in the forward direction, and ALICE is mainly focussed on studying the Pb ion collisions.) At the LHC's designed luminosity of 10^{34} cm^{-2} sec^{-1}, (see Table 1 for the main design parameters) for a process with ~100 millibarn cross section, p-p collisions would create around a billion events per second. So, while this high event rate gives an unprecedented chance to discover new physics, complexities also arise due to a flood of data : the rare processes *one would be looking for with LHC* may be swamped by a sea of already known *orders of magnitude larger* processes. So one will have to devise a good and quick discriminating scheme to separate the known physical effects. Discriminating the rare events from large QCD background processes will be a tough challenge for the physicists before they can fully succeed in exploiting LHC to discover new physics.

Table 1. LHC's principal parameters for p-p operation.

Circumference	26.7 km
Beam energy at collision	7 TeV
Beam energy at injection	450 GeV
Dipole field at 7 TeV	8.33 T
Luminosity	10^{34}cm^{-2}s^{-1}
Beam current	0.56 A
Protons per bunch	1.1×10^{11}
Number of bunches	2808
Nominal bunch spacing	24.95 ns
Normalized emittance	3.75 µm
Total crossing angle	300 µrad
Energy loss per turn	6.7 keV
Critical synchrotron energy	44.1 eV
Radiated power per beam	3.8 kW
Stored energy per beam	350 MJ
Stored energy in magnets	11 GJ
Operating temperature	1.9 K

2. Indian contribution to the construction of the LHC accelerator

LHC comprises of two interleaved synchrotron rings, through which beams circulating in opposite directions (clockwise and counterclockwise) will move and cross at specified "collision points". Although the design of the machine was started a fairly long time back, it went through numerous iterations. A summary of the machine and the other features is available in a recent paper by L. Evans ("The large hadron collider", *New Journal of Physics 9, 335, 2007*). The main magnetic elements of LHC are its two-in-one superconducting dipoles and quadrupoles built out of Nb-Ti superconductor embedded in Cu matrix that operate at 1.9 K using super-fluid helium. Cryo-magnets include 1232 main dipoles and 392 arc quadrupoles. These are integrated with corrector magnets to take care of higher order poles. The proton beams will be injected at 450 GeV energy and then ramped up to a maximum design energy of 7 TeV each. India joined the LHC enterprise in 1996.

Although CERN and DAE laboratories had been jointly working in the field of high energy physics for many years, a formal cooperation agreement was signed only in 1991 by the then Director General, CERN, Carlo Rubbia and Chairman of Indian AEC, P. K. Iyengar. In 1996, this agreement gave the platform for DAE to accept CERN's invitation to participate in the construction and utilization of LHC, and a protocol was signed by C. H. Llewellyn Smith, the then Director General of CERN, and R. Chidambaram, the then Chairman of Indian AEC. It envisaged an "in kind" Indian contribution, towards the accelerator construction valued at 34 million Swiss Francs (i.e. US $ 25 million at 1994 prices). Later, an agreement signed in 2002 by the then Director General CERN, Luciano Maiani, and Chairman of Indian AEC, Anil Kakodkar, raised the limit on this contribution to 60 million Swiss Francs (CHF). As per terms of the protocol, it was agreed that half of the value of India's *in kind* contribution (valued at European costs) would be credited to an "Indian Fund", with the other half being treated as DAE's contribution towards the construction of the LHC accelerator. RRCAT has been the lead DAE laboratory for this collaboration and a Joint Committee, co-chaired by Director, RRCAT and In charge of LHC, has handled the task to identify specific items for Indian contribution. After identification of the delivery items, the two sides have been signing addenda to the protocol, spelling out the technical details of the item, time schedule, payment terms etc. This arrangement has worked well, and cumulative Indian contribution is about 43 million CHF. Over the last decade or so, a number of subsystems were identified for delivery, their prototypes were built in India, and qualified through series of tests conducted at CERN. During the prototype development of many of the components, it became necessary to make design changes not only to conform to the user requirements, but also to re-engineer them to bring down the production costs. After all the qualification tests were met, bulk quantities of the subsystems were manufactured by Indian industry and delivered to CERN under the overall supervision of RRCAT. Table 2 summarizes the major elements of our contribution and figures T.3.1 to T.3.5 show the photographs of some of these items delivered in bulk by India, mostly during the period from 2001 to 2007.

A brief description of important items listed in Table 2 is given below:

Table 2: Major Elements of Indian Contributions to LHC

Sr.	Details of Indian Contributions	Qty.
1	50000 litres Liquid Nitrogen tanks.	2
2	Superconducting corrector magnets i) Sextupole (MCS) ii) Decapole and Octupole	 1146 616
3	Precision Magnet Positioning System (PMPS) Jacks	7080
4	Heater Discharge Power Supplies	5500
5	Integration of HDPS units into racks	6200
6	Control units for circuit breakers of energy extraction system.	70
7	Local protection units (LPU)	1435
8	SC Dipole magnet tests / measurements, expert support	100 man years
9	Expert help for LHC Hardware, Commissioning of Cryogenics, man Power converters, Protection years systems, Controls	25 man Years
10	Data management software upgrade, Data analysis software/documentation projects	41 man years.
11	Development of JMT-II software	
12	Software development - slow control of Industrial Systems of LHC	
13	Design and calculations for vacuum system for beam dump line	
14	Analysis of cryo-line jumper and magnet Connections	

Items listed in this table were pursued with the help of different units of DAE with RRCAT acting as the nodal agency. RRCAT was involved in (1), (2), (3), (7), (8), (9), (10), (13) and (14); BARC was involved in (10), (11), (12); BARC and Electronics Corporation of India Ltd (ECIL) were associated with (4), (5), (6) and (7); BARC, VECC, IGCAR and RRCAT provided necessary skilled engineers and physicists for (8), and BARC and RRCAT provided experts for (9).

2.1 Precision Motion Positioning System (PMPS) jacks

The various cryo-magnets need to be precisely positioned in the LHC tunnel to ensure proper beam trajectories of particles. The dipole magnet assemblies,

Fig. T.3.1: A test bed at an industry in Bangalore to qualify PMPS jacks

Fig.T.3.2: A consignment of PMPS jacks ready for shipment to CERN.

each weighing more than 32 tons, with a length of 15 m, need to be positioned with a precision of 50 microns all along the 27 km length. Jacks have to be capable of accommodating LHC tunnel slope of 1.4%. The main specifications of the jack are: (a) range of movement (i) in X–Y plane ± 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 N-m in nominal realignment operation. After a comprehensive design analysis and prototype development, production of jacks was taken up in two industries located in Indore and Bangalore, and taken through full range of qualification tests. A total of 7080 units were made and supplied to CERN under the supervision of RRCAT. Out of 7080, 280 had to meet even tighter tolerance on precision movement and were equipped with a motorized arrangement for remote operation of jacks. Fig.T.3.1 shows picture of the PMPS jack undergoing qualification tests at an industry in Bangalore and Fig.T.3.2 shows a consignment of jacks ready for shipment to CERN.

2.2 Superconducting corrector magnets (MCS and MCDO)

The main dipoles of LHC are equipped with sextupolar (MCS) and decapolar (MCD) superconducting corrector magnets. Each decapole corrector also has an octupolar insert (MCO), and together these are designated as MCDO. Each corrector magnet consists of a superconducting coil assembly, glass fibre slit tube, steel lamination, aluminum 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. After the development of corrector magnets was completed at RRCAT, these were mass manufactured in two industries in Bhopal and Bangalore. Each corrector magnet assembly was taken through warm and liquid helium tests. Fig.T.3.3 shows picture of finished MCS and MCDO assemblies ready for dispatch to CERN.

Fig.T.3.3: Crates of MCS and MCDO ready for dispatch to CERN

2.3 Heater Discharge Power Supplies (HDPS)

The LHC superconducting dipole and quadrupole magnets are powered with current up to 13 kA. All superconducting magnets require protection in case of quench (resistive transition) or other failures. 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 buildup above a certain threshold value across magnet coils), the protection system will power the quench heater strips using HDPS and distribute the energy evenly in the entire magnet. The HDPS were manufactured by ECIL under a team led by BARC engineers. Fig.T.3.4 shows a picture of a DAE team at CERN, along with HDPS and other electronic units integrated in racks, ready for being sent to LHC tunnel for installation.


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Fig.T.3.4: A DAE team at CERN along with HDPS unit and integrated assemblies of electronic units (in the racks on the left) ready for installation in LHC tunnel.

Fig.T.3.5: A batch of Local Protection Units made at ECIL ready for shipment.

2.4 Local Protection Units (LPU)

These electronic devices detect quench occurring in LHC superconducting magnet system and an LPU is made of local quench detector and the acquisition and monitoring controller put together in a 3U, 19″ crate. The local quench detector is attached to a LHC superconducting magnet and activates the respective protection systems in case a resistive transition occurs. The design of LPUs was done by an RRCAT team and these were mass manufactured by ECIL. Fig.T.3.5 shows a picture of the local protection units made by ECIL ready for dispatch to CERN.

2.5 Expert manpower for magnetic tests and measurements and for commissioning of LHC subsystems

The LHC cryo-dipoles, quadrupoles and corrector elements required testing as part of a QA plan at super fluid helium temperatures of 1.9 K, as well as at room temperature. These involved 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 was 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. Teams of Indian specialists worked at SM18 hall for around five years and performed complete tests and measurements on full series of magnets, that in all amounted to almost 100 man years! The positive experience with regard to magnet evaluation work, prompted CERN to seek and receive Indian help for commissioning some LHC subsystems. These included cryogenic systems as well as a variety of electronic hardware. The Indian scientists and engineers provided almost 25 man years of help for the LHC subsystem commissioning work.

A prominent aspect of our contribution is that the entire LHC, (that is the full 26.7 km length) will be resting on PMPS jacks supplied by India! The Indian industry did an excellent job in not only maintaining the quality, but also the time schedule. The electrical items were mostly mass produced by Electronics Corporation of India Ltd (ECIL) and met several tough challenges, like, circuit breakers have to disrupt flow of 13 kA current in a very short time. Besides ECIL, many other Indian industrial organizations were involved in the development of the products. However, all supplies were delivered under the overall direction and responsibility of RRCAT.

Apart from contributing to LHC accelerator, India has also contributed to the two detectors, namely, CMS and ALICE. TIFR has spearheaded Indian contribution to CMS, whereas VECC and SINP have handled the tasks for ALICE. In addition, these institutions have set up "Regional Tier 2 Centres" at Mumbai and Kolkata so that the Indian scientists will be able to take part in the analysis of the LHC data. India has also made contribution to the GRID computing. Indian contribution to LHC grid software development is worth ~50 man years and this partnership with CERN in the GRID activity will continue till end of 2010. Our contribution to LHC has been well appreciated (*CERN Bulletin* Issue 24 / June 13, 2005). India has an "Observer State" status at CERN which has been extended to only a few other countries, such as, USA, Japan, Russian Federation etc.

3. Physics that will emerge from LHC

The main aim of physicists is to understand the Universe on the basis of a few fundamental physical laws. For the macro-world, they use laws of mechanics, electrodynamics (as embodied in Maxwell's equations), statistical mechanics, relativity and so on; but when atomic or subatomic entities are involved, quantum mechanics is included. High energy physicists, the main users of LHC, focus attention on a still smaller micro-world! For them nature's building blocks are leptons (like electrons and neutrinos) and quarks, and their antimatter partners, as well as the bosons that mediate basic interactions, such as photons, weak bosons (W, Z^0), gluons etc. These ingredients of "standard model" (SM) of particle physics have very successfully helped in understanding many natural phenomena. Despite SM's impressive successes, many questions still remain: How do particles acquire mass, what causes the small differences in the properties of matter and antimatter, whether the basic forces in nature unify etc. There is also a basic puzzle of cosmology linked to the nature of dark matter and dark energy that are believed to form over 95% of the Universe! LHC is expected to help resolve some of these questions and mysteries. However, one must not think that as soon as the p-p collisions start, LHC will instantly deliver new physics results! Rather, a lot of work, in several stages, would be needed, as discussed below.

3.1 Tasks towards getting the detectors going

The real "eyes" to help establish the physics results with LHC are the big detectors so painstakingly put together by large international collaborative teams, and huge amount of spadework has been done to build them. Major elements of ATLAS and CMS are things like, tracker detectors, calorimeters, muon detectors and, of course, the read out electronics and data system. A whole set of design requirements had to be met, like fast, radiation-tolerant electronics, high granularity of detectors, so as to be able to handle huge particle fluxes and to reduce the influence of overlapping events, good charged-particle momentum resolution and reconstruction efficiency in the tracking system etc. For the innermost detector parts, main issues are the high count rates, radiation resistance and coping with ageing effects. ATLAS and CMS trackers have been designed to be able to withstand a radiation dose of 0.5 to 1 MGy for innermost pixel layers and up to 0.1 MGy for farther away layers from interaction point, after ten years of operation. When LHC is turned on, the first task for scientists would be to go over their systems, (and if required, debug detector and data system) then check that the collisions are occurring at the designated points, and that the detectors pass through the calibration tests. Only after completing these steps towards energy calibration etc, physicists will be able to start their real challenging research work.

3.2 First likely physics measurements using the LHC

After going through calibration tests on the detector system and establishing their capabilities -particularly of fast, radiation-tolerant electronics and confirming the required granularity in the inner detectors - scientists would move a step closer to their goal. With the detectors and data system as well as computing and network in place, and working efficiently, the physics community will have to tackle the new challenge posed in terms of interpreting the data from LHC and the potential rewards will be there in the form of physics discoveries!

First collisions with a centre-of-mass energy of 14 TeV are likely to commence in 2009. Once the luminosity of 10^{32} $cm^{-2}s^{-1}$ is reached, LHC can start producing data pertaining to *W* and *Z* bosons, *t* quarks, high-transverse-momentum jets etc., and surpass the results so far delivered by any other accelerator. We may not only see a better test in the form of checking measured production rates of W, Z and t, but also a more precise mass measurement of top quark, reducing the current uncertainty of over 1.4 GeV (in a mass of 172.6 GeV) to possibly ~0.5 GeV. (The rest mass energy values for *W, Z* and top quark are 80.4, 91.2 and 172.6 GeV respectively.) We could expect better cross-section measurements for known processes for production of various particles. The pursuit of the prized trophy out of LHC, viz. the Higgs boson would be next!

3.3 Search for Higgs

The basic equations underlying SM would make all elementary particles mass-less. In reality, only photon and gluon, carriers of electromagnetic and strong nuclear interactions, are mass-less. All other elementary particles have masses showing that underlying symmetry of SM must be broken so that some particles acquire masses. There are two ways to break this symmetry. One way is to keep intact the symmetry of underlying equations (with mass-less photon and the massive *W* and *Z* bosons appearing in the same way) and look for an asymmetric solution, wherein symmetry is presumed to be already broken in the lowest-energy state, the so-called vacuum. This 'spontaneous' symmetry breaking is ascribed to a field that permeates all space, taking a specific value that can be calculated from the underlying equations. This idea, first proposed by Peter Higgs, leaves some particles, like, photon, to stay mass-less, but gives mass to others in proportion to their coupling to this vacuum field (Fig.T.3.6), and also implies the existence of particle(s) associated with Higgs field. (We return to this point below.) A second way to break the SM's symmetry is to postulate that, while underlying equations are symmetric, their solution is subject to certain boundary conditions that break the symmetry. The boundary conditions are introduced by visualizing, extra very small dimensions of space with edges where the symmetry may be broken. In this picture, there is no Higgs boson - something contrary to existing data, which actually favours the existence of a relatively light Higgs boson. Hopefully, LHC will experimentally resolve the matter.

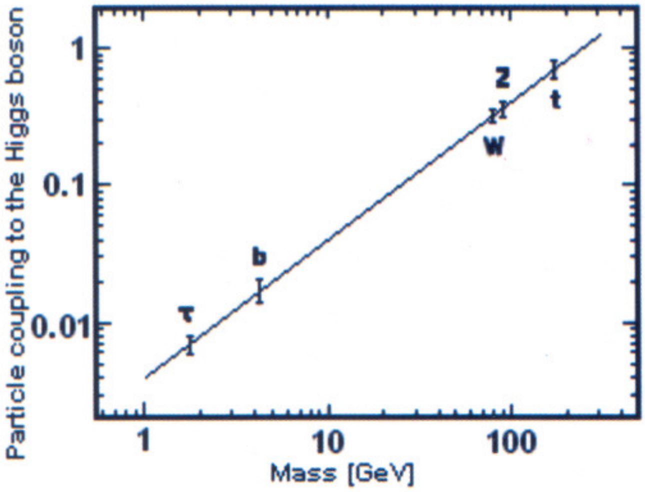

Fig.T.3.6: Prospects of LHC to determine Higgs coupling constants to SM particles as a function of their masses.

Akin to photon being the 'quantum' associated with electromagnetic field, the Higgs boson(s) is the particle(s) associated with this vacuum field, and LHC would look for it. At the time LEP was shut down, there were hints of its existence, but these claims could not be verified, and one could only surmise that any Higgs boson must have a mass of at least 114 GeV. However, the search for it has been continuing, and recent measurements with D0 detector at Tevatron saw at a significant level above the background (by a factor of about 20) simultaneous production of *two* Z bosons, which, with the earlier data from CDF detector appear to rule out a Higgs boson of mass up to ~170 GeV. These experiments show that search for the Higgs using rare decay channels is possible!

After LHC starts running, its two detectors, ATLAS and CMS, will search for the Higgs boson in different ways, basically identifying its creation through its decay into other particles: photons, bottom quarks, tau leptons, *W* or *Z* bosons. If the mass of Higgs boson (m_H) is low (less than 180 GeV), the dominant decay mode into hadrons may be difficult to isolate, because of QCD background. Above 130 GeV, Higgs decaying into *ZZ* (one Z being virtual when m_H is below the *ZZ* threshold), with its four-lepton final state, will be the most interesting mode. If m_H is above ~600 GeV, *WW* or *ZZ* would decay into jets or into states involving neutrinos resulting in missing transverse energy since neutrinos would go undetected. For m_H~1 TeV, tagging the 'forward' jets, from the *WW* or *ZZ* fusion production mechanism would be necessary. The two-photon decay channel will be important, as will be others that include *ttH*, *WH*, *ZH* for which a lepton arising from the decay of the accompanying particle will have to be used for triggering and background rejection. It may be essential to combine many different decay modes to produce a convincing signal. Even if m_H~1 TeV, LHC should be able to find it.

3.4 Physics studies with LHC beyond the Higgs search

Besides Higgs search, LHC will explore other new physics at TeV energy scale. The first in this arena is the super-symmetry, a theory that pairs up fermions and bosons and postulates that, for each fermion, there exists a bosonic super-symmetric partner, and conversely, each boson has a fermionic super-partner. Fermions, include leptons and quarks (the constituents of usual matter) and bosons, include photon, gluons, *W*, *Z* and possibly the Higgs itself. For the electron, the partner is the 'selectron', for 'gluon' it is the 'gluino'. Although it is unclear at what energies super-symmetry would manifest itself in nature, there are suggestions that the rest energy of some super-symmetric particles could be ~1 TeV and cosmologists consider the lightest super-symmetric particle (LSP) an ideal candidate for the dark matter. In due course, we may find LHC being used to look for signatures of super-symmetry and who knows there may be a fertile territory of discoveries ahead! At some point in time scientists could also use LHC to look for signatures of curled-up extra dimensions demanded by string theory.

LHC will, hopefully, also address the question of additional difference in the properties of matter and antimatter that will help explain the excess amount of matter in the Universe. Indeed, LHCb with its unique capability to probe the decay of mesons containing both bottom and strange quarks, the constituents of the *B* and *K* mesons, will help address this issue. ATLAS and CMS experiments will also explore the matter and antimatter difference, and, in particular, search for rare decays of mesons containing bottom quarks. Looking beyond the first run, physicists engaged in studying the Quark Gluon Plasma (QGP) plasma state of matter will eagerly look forward to the Pb-Pb collisions experiments (possibly some time in 2010). Hopefully, this will greatly advance the QGP studies started at Relativistic Heavy Ion Collider (RHIC).

3.5 The road after the LHC

With LHC, high energy physics will certainly enter an exciting phase. However, the discovery of as yet unknown physics, say, in the form of new particles, like Higgs, would still not be the end of the story! Being a collider of hadrons (that are composite objects), LHC will be limited in its capacity to carry out precision measurements. So, high energy physicists feel that an electron-positron collider should be built as a follow-up on the LHC. The target energy of such a e^+-e^- collider is still a matter of discussion, although considerable effort has been devoted to the study of a superconducting RF technology based International Linear Collider (ILC) with a CM energy of about 500 GeV in phase-1 (and about 1 TeV energy as upgrade in the phase-2). RRCAT is also engaged in the ILC related R&D in partnership with overseas labs. In parallel, CERN is working on an alternate option, viz. CLIC (Compact Linear Collider) with a potential energy reach of between 3 to 5 TeV. The novel idea of CLIC collider is to use a high current drive electron beam to produce 12 GHz RF power, which will be then be utilized to accelerate colliding electron and the positron beams. To test the proof of principle of CLIC, CERN has been developing CLIC Test Facilities for over a decade and is currently engaged in building CTF-3, where India is also a partner. The high energy physics community is also exploring other avenues that include building muon colliders, and CERN and Fermilab are studying this option. Muons, being about 200 times heavier than electrons, can be accelerated to much higher energies in circular machines, without the energy losses due to synchrotron radiation, and may even compete with linear e^+e colliders. While at present ILC is getting the maximum attention, it is difficult to say when it will get flagged off as a project. A prudent decision about the next machine would be to wait till LHC has operated for a few years. Hopefully, it will then become clear as to what machine option and parameters will best serve the physics goals for the next decades.

Acknowledgement

I wish to thank a large number of colleagues at RRCAT and other DAE units, as well as those at many industrial organizations, who have contributed in numerous ways towards the success of this programme.

Message from Director, RRCAT to the staff after the beams were circulated in LHC

Dear Colleagues,

Over the last few days media has given a lot of positive coverage to the RRCAT's role in the DAE-CERN Collaboration for LHC construction. Happily the start of beam circulation in LHC went of very smoothly, which is a matter of deep satisfaction for us as we had contributed a fair amount of hardware for the machine, were partners in the tests on various subsystems and also took part in the machine commissioning. As the press release below shows CERN has also given prominence to our involvement. I wish to take this opportunity to thank every staff member of RRCAT for the praise that we have earned and hope that we will continue to strive to do our best in all our future endeavours.

With regards,
V.C.Sahni
September12, 2008

Press release by CERN, *Geneva, 10 September 2008* : **First beam in the LHC-accelerating science**

The first beam in the Large Hadron Collider at CERN was successfully steered around the full 27 kilometres of the world's most powerful particle accelerator at 10:28 this morning. This historic event marks a key moment in the transition from over two decades of preparation to a new era of scientific discovery.

"It's a fantastic moment," said LHC project leader Lyn Evans, "we can now look forward to a new era of understanding about the origins and evolution of the universe".

Starting up a major new particle accelerator takes much more than flipping a switch. Thousands of individual elements have to work in harmony, timings have to be synchronized to under a billionth of a second, and beams finer than a human hair have to be brought into head-on collision. Today's success puts a tick next to the first of those steps, and over the next few weeks, as the LHC's operators gain experience and confidence with the new machine, the machine's acceleration systems will be brought into play, and the beams will be brought into collision to allow the research programme to begin.

Once colliding beams have been established, there will be a period of measurement and calibration for the LHC's four major experiments, and new results could start to appear in around a year. Experiments at the LHC will allow physicists to complete a journey that started with Newton's description of gravity. Gravity acts on mass, but so far science is unable to explain the mechanism that generates mass. Experiments at the LHC will provide the answer. LHC experiments will also try to probe the mysterious dark matter of the universe; visible matter seems to account for just 5% of what must exist, while about a quarter is believed to be dark matter. They will investigate the reason for nature's preference for matter over antimatter, and they will probe matter as it existed at the very beginning of time.

"The LHC is a discovery machine", said CERN Director General Robert Aymar, "its research programme has the potential to change our view of the Universe profoundly, continuing a tradition of human curiosity that is as old as mankind itself".

Tributes have been coming in from laboratories around the world that have contributed to today's success.

"The completion of the LHC marks the start of a revolution in particle physics", said Pier Oddone, Director of the US Fermilab. "We commend CERN and its member countries for creating the foundation for many nations to come together in this magnificent enterprise. We appreciate the support that DOE and NSF have provided throughout the LHC's construction. We in the US are proud to have contributed to the accelerator and detectors at the LHC, together with thousands of colleagues around the world with whom we share this quest".

"I congratulate you on the start-up of the Large Hadron Collider", said Atsuto Suzuki, Director of Japan's KEK laboratory, "This is a historical moment."

"It has been a fascinating and rewarding experience for us", said Vinod C. Sahni, Director of India's Raja Ramanna Centre for Advanced Technology, "I extend our best wishes to CERN for a productive run with the LHC machine in the years to come".

"As some might say: One short trip for a proton, but one giant leap for mankind! TRIUMF, and indeed all of Canada, is delighted to bear witness to this amazing feat", said Nigel S. Lockyer, Director of Canada's TRIUMF laboratory. "Everyone has been involved but CERN is to be especially congratulated for bringing the world together to embark on such an incredible adventure".

In a visit to CERN shortly before the LHC's start-up United Nations Secretary General, Ban Ki-moon said: "I am very honored to visit CERN, an invaluable scientific institution and a shining example what international community can achieve through joint efforts and contribution. I convey my deepest admiration to all the scientists and wish them all the success for their research for peaceful development of scientific progress".