THE LARGE HADRON COLLIDER: A STATUS REPORT

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The status of LHC construction, machine and detectors, is reviewed, with particular emphasis on the expected physics and on the industrial production of machine components.

Summary

1. Introduction

The installation of a Large Hadron Collider in the LEP tunnel, was first considered at the beginning of the 80's and it was approved by the CERN Council in December 1996. The tunnel has a circumference of 27 km. The nominal beam energy was determined to be 7 TeV, corresponding to a nominal magnetic field in the cryogenic dipoles of 8.3 Tesla.[1]

From the outset, it was decided that the LHC should accelerate both protons and heavy ions. The LHC energy range and luminosity will allow it to aim at several physics goals:

i search for the Higgs boson in the whole mass region where it is predicted by the Standard Theory, from the LEP reach up to almost 1 TeV;

ii search for new particles, such as those associated with Supersymmetry, indicated as the remedy to the "unnaturalness" of the Standard Theory itself;

iii high precision study of CP-violation in B meson decays; and

iv study of the physical properties of the new phase of nuclear matter at high temperature (quark-gluon plasma) that supposedly is produced in relativistic heavy ion collisions.

In 1996, a cost was stated for the LHC proper (the hardware that goes in the LEP tunnel and the civil engineering works to adapt the tunnel and to build the experimental areas) assuming that all other expenses would be covered by the normal operational budget of the Laboratory.

During the years 2000 and 2001 the LHC programme underwent a full cost and schedule review, including the costs associated with the refurbishing of the injection line (which uses the existing PS and the SPS machines), the cost-to-completion of the four detectors, the cost of the computing infrastructure, as well as overall personnel costs and contingency. The result was approved by the Council in December 2002 to form the basis of the present CERN planning and is as follows.

- **Machine**: 4.8 BCHF. This includes:
  - materials and CERN personnel expenses for the whole LHC; and
  - 330 MCHF for residual contingency and for a reserve for the cost escalation of LHC contracts.
- **Detectors**: 1.2 BCHF, of which 20% is supported by the CERN budget.

The figures given above include special contributions that CERN has received from the Host States (Switzerland and France) and from several CERN non-Member States (US, Japan, Russia, Canada, India), the latter adding to about 0.75 BCHF. These contributions are mostly in-kind, with items provided by industry and by the main particle physics laboratories in these countries. The world-wide participation in the machine and detector construction makes the LHC the first really global particle physics project.

The construction of such a large machine is requiring an unprecedented effort from the Laboratory. The last approved Long Term Plan, which covers the period 2003-2010, indicates that around 80% of

CERN resources (personnel plus materials) are allocated to the LHC programme (directly $\approx 50\%$, indirectly $\approx 30\%$).

In this talk, I'd like to first review briefly the physics that can be expected from the LHC. For time reasons, I will restrict this to the High Energy frontier, namely the physics with ATLAS and CMS.

Then I will give you a tour of the civil engineering of the detector caverns, the industrial production and the installation of the LHC, machine and detectors. With the main contracts in place since last year, we are now assisting the very exciting ramping up of the industrial production, due to reach cruising speed during the next year.

After the difficult discussions we had with the CERN Council over the last two years, and a drastic reformulation of CERN internal strategies, the LHC financial set up is now considered to be on solid, if very tight, ground.

Given all these results, Management is in the position to confirm the LHC schedule already announced in March 2002, namely:

- completion of the LHC machine in the last quarter of 2006;
- first beams injected during the spring of 2007; and
- first collisions in mid 2007.

2. New Physics at High Energy

At the LHC scale of exchanged momenta, valence quarks in the proton have lost much of their importance. Gluons and the sea of quark-antiquark pairs dominate. Unlike at lower energy, proton-proton and proton-antiproton collisions are much alike at these energies. These features and the very high luminosity (target luminosity $10^{34}\text{cm}^{-2}\text{s}^{-1}$) will make the LHC a real factory for any conceivable particle, from Higgs bosons to B mesons ... to mini black holes, should they exist. Table 1 shows the yearly production of several kinds of particles, compared to the total statistics that will be collected at previous machines by 2007.

The LHC will be a very versatile machine indeed, with an expected lifetime spanning over two decades, possibly extended by a luminosity upgrade, which is just being considered these days.

2.1. *Searching for the Higgs Boson*

There is little doubt that the LHC and its planned detectors will be able to detect the Standard Theory Higgs boson over the whole mass range where it is predicted,[2] from around 114 GeV (the LEP limit) up to about 1 TeV, with a confidence limit above 5σ in one year at low luminosity ($3 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$), and well above in one year at the nominal luminosity (30 fb^{-1}). The lowest mass region is particularly difficult, which shows the usefulness of the magnificent job done by the accelerator physicists and by the LEP collaborations to extend the lower bounds as much as possible. Of particular importance in this region is the recently studied W or Z fusion channel:

$$qq \to qqH \to qq\tau^+\tau^- \tag{1}$$

with one of the quarks in the final state tagged as a forward jet.

The mass of the Higgs boson will be measured with very good precision, much the same as the W mass was measured at the Tevatron. At the end of the day, after ten years at nominal luminosity (i.e. an integrated luminosity of 300 fb^{-1}) one may be able to attain errors of the order of 10^{-3}, in most of the low mass range, to order of per cent, in the higher mass range.

2.2. *Higgs Boson Couplings*

The real signature of spontaneous symmetry breaking is, of course, that the values of the Higgs boson couplings to the various particles should be in the ratio of the corresponding masses. The absolute values of the couplings are hard to measure in a hadron collider, due to not well known production cross sections and total Higgs boson width. However, a lot of uncertainties disappear in the ratios and coupling constant ratios would give anyway decisive evidence that the observed particle is indeed the long sought Higgs boson. Precisions of 10-20% can be obtained for a number of important channels. Increasing the LHC luminosity by a factor 10 (as considered at present for the LHC upgrade) could reduce errors by a factor of 2 and give some access to the triple Higgs coupling.[3] It is here that a low energy electron-positron linear collider (LC) could make significant progress, measuring absolute couplings to a precision of a few percent.

Table 1. Expected event production rates in ATLAS or CMS for some (known and new) physics processes at the initial "low" luminosity of $\mathcal{L} = 10^{33}$ cm^{-2} s^{-1}.

Process	Events/s	Events per year	Total statistics collected at previuos machines by 2007
$W \to e\nu$	15	10^8	10^4 LEP/10^7 Tevatron
$Z \to e^+e^-$	1.5	10^7	10^7 LEP
$t\bar{t}$	1	10^7	10^4 Tevatron
$b\bar{b}$	10^6	10^{12} - 10^{13}	10^9 Belle/Babar ?
H, $m = 130$ GeV	0.02	10^5	?
Gluino pairs, $m = 1$ TeV	0.001	10^4	$- - -$
Black holes, $m > 3$ TeV ($M_D = 3$ TeV, $n = 4$)	10^{-4}	10^3	$- - -$

2.3. *The Standard Theory Becomes "Unnatural" above the TeV Region*

Scalar particle masses are not protected against becoming of the order of the largest mass of the theory, the cut-off, because of quantum corrections.[4] Only an unreasonable fine-tuning between the bare mass and its quantum corrections could make $M_H \ll M_{\text{Planck}}$ as required by observation. Presently three different solutions have been developed:

- the Higgs boson is not elementary but rather a fermion-antifermion state, bound by new strong forces at the TeV scale[5] (dubbed by the generic name Technicolor); this solution is strongly disfavoured by the LEP/Tevatron data;

- Supersymmetry in the TeV region.[6] In softly broken SUSY,[7] the Higgs mass is determined by the scale of SUSY breaking. Minimal SUSY models are compatible with LEP and Tevatron data; a (quasi) stable neutral lightest supersymmetric particle seems today the best candidate for the cosmological cold dark matter indicated by astronomical observations; and

- additional space dimensions with a very large radius,[8] where gravity is characterized by a mass which is itself of the order of TeV: in this case the Planck mass has no fundamental meaning and even unprotected masses are of the order of TeV.

The LHC will be able to shed decisive light on these alternatives.

2.4. *Searching for SUSY*

As for particle content, MSSM features:

- two Higgs doublets, with five physical scalar bosons, three neutral: h, H, A and two charged ones: $H^{\pm}$; and

- the SUSY partners of known particles:
  - spin 0: scalar quarks, scalar leptons; and
  - spin 1/2: gluinos, gauginos, Higgsino.

The decay chains of the SUSY partners are likely to contain several neutral, invisible particles, giving rise to spectacular missing energy signal.

The simplest case is that of the Minimal Supersymmetric Standard Models (MSSM) of the restricted mSUGRA type, characterized by two mass parameters: m_0, $m_{1/2}$, and one sign, μ. The allowed region in parameter space is restricted by:[9]

- the non-observation of SUSY signals at LEP and Tevatron; and

- the values of the cosmological observables reflecting cold dark mass distribution.

If the lightest supersymmetric particle provides the cosmological dark mass and its parameters are in the typical region (i.e. no large conspiracies between different contributions) SUSY can be discovered very quickly at the LHC. At full luminosity, LHC can discover squarks and gluinos up to about 3 TeV.[10] Masses can also be determined, in several instances with good precision (few to several percent) by the observation of end points in the mass distribution of different particle combinations (dileptons, jets, etc.).

2.5. *MSSM Benchmarking of Colliders*

The masses of the SUSY partners can take large values when special cancellations between different parameters take place. In some cases, they could even escape detection at the LHC. This has been studied in Ref. 9. A number of points in parameter space have been chosen and for each of them the authors have computed the number of SUSY particles that will be observed at the LHC and other colliders. In line with the previous considerations, the LHC will see squarks and gluinos in most cases, in some cases also sleptons. However there are some “nasty” cases where SUSY particles will be out of reach and only a Standard Theory Higgs boson will be seen.

The situation with a “low energy” electron-positron collider of 0.5 TeV has also been considered. In generic cases, sleptons will be seen much more efficiently than with the LHC, as had to be expected, but the bad cases remain. Indeed a real resolution of the issue requires collider energies as high as 3 or 5 TeV, such as may be attainable with the double beam acceleration method (CLIC).

2.6. *Extra Dimensions at mm Scale?*

The quest for a unified theory of General Relativity and Quantum Mechanics has led to a revival of the old idea, introduced by Kaluza and Klein in the thirties, that space time must have extra space dimensions, besides the familiar 3 space + 1 time dimensions. Kaluza and Klein assumed that the extra dimensions are compact, with radius R, so that particles could not feel the extra space dimensions until their quantum wavelength was smaller than R. Recent ideas,[8] combine Kaluza Klein extra dimensions with a new notion, namely that matter and gauge fields can be confined to a lower dimensional manifold (a D-brane), while gravity extends instead to all space. This opens up the revolutionary idea that R may be very large, on the particle physics scale, and we would not detect the extra dimensions simply because the particles we are made of are dynamically confined to a D-brane with 3+1 dimensions. The gravitational potential in the full $4+\delta$ space-time (δ is the number of extra dimensions) is characterized by a constant M_D, with dimension of a mass. M_D is related to M_{Planck} according to:

$$R = \frac{1}{M_D}\left(\frac{M_{Planck}}{M_D}\right)^{\frac{2}{\delta}}. \qquad (2)$$

The upshot is that indeed M_D could be of the order of, say, 1 TeV (therefore no naturalness or hierarchy problem).

There are two ways we can put this idea to a test. First, at distances of order of R, gravitational forces should show deviations from the Newton $1/r^2$ law. Present results do exclude this down perhaps to a micron, which is still roughly compatible with the idea. Second, in high energy collisions, at exchanged momenta $\gg 1/R$, gravitons and excited gravitons would be radiated with large cross sections (and leave the apparatus undetected), causing deviations from the expected, QCD or QED cross sections. The idea has been put to test already at LEP. One can obtain larger limits on M_D at the LHC,[11] from the observation of the reaction:

$$q + q \to \text{gluon} + (\text{unobserved particles}). \qquad (3)$$

Related to the same idea of a strong gravity in $4+\delta$ dimensions is the possibility of producing mini black holes in LHC collisions. Tiny black holes of $M_{BH} \approx 1$ TeV can be produced if partons pass at a distance smaller than their Schwartschild radius, which would also be of the order of 1 TeV^{-1}. One expects large partonic cross sections. For $M_D = 3$ TeV and $\delta = 4$, one finds $\sigma(pp \to BH) \approx 100$ fb, leading to 1000 (very spectacular) events in 1 year at low luminosity.

In conclusion:

- the LHC will give a definite answer to the Higgs boson problem and will explore the TeV region with very good efficiency;
- a sub TeV Linear Collider is needed for precision Higgs boson physics particularly in the case of a light Higgs boson;
- the LC would be also useful to distinguish SM from Minimal Supersymmetric SM; and

- multi-TeV capability is needed to really understand Supersymmetry ... or to identify other alternatives.

Pursuing accelerator R&D on Multi-TeV accelerators, CLIC and the Very Large Hadron Collider/Eloisatron is vital for the future of particle physics.

3. LHC Construction

Decisive progress has been made during the last 12 months, in all sectors of the LHC project. Old concerns have been overcome, for example those due to the insolvencies of some crucial companies, new concerns are appearing but no potential show stopper is in sight. With the help of some pictures, I will give you a guided tour through the LHC work: civil engineering, production of machine hardware components and the new activity, started this year, namely LHC installation in the tunnel.

3.1. *Civil Engineering*

The preparation of the experimental caverns and related structures is reaching its final phase, with more than 80% of the work completed.

The ATLAS cavern was inaugurated on June 4, 2003 and handed over to the experimental collaboration. The situation in July is shown in Fig. 1, with the 13 floor metallic structure by now installed on both sides.

The CMS cavern is completely excavated. Both the main and service shafts have revealed some cracks and water leaks, due presumably to movements of the rock produced by the excavation of the main cavern below. The repair may entail some extra cost and some delay in CMS installation, which are at present under evaluation.

Figure 1. ATLAS cavern: inside.

3.2. *Machine Components*

With all main contracts assigned, the real problem is the follow-up of the industrial production, to make sure that companies respect the promised schedule. The situation is made more delicate by the fact that CERN, in many cases, has the double role of supplier and end customer (e.g. supplying the superconducting cables to the dipole cold mass assemblers). Adequate stocks must be built up at CERN, any delay in the intermediate steps will entail additional costs. The crux of the matter is: vendors lie!

To monitor the progress in production, we have introduced the *LHC Dashboard*. For the main LHC components (superconducting cables, dipole assembly, etc.) the Dashboard shows:

- the contractual evolution, as defined in February 2002 when the present LHC schedule was agreed;
- the number of delivered components vs. time; and
- the "just in time delivery curve".

The LHC Dashboard can be accessed from the LHC project home page[12] and is updated every month. The site has been very frequently visited in the last year and we hope it contributes to increase the transparency of the process.

3.2.1. *Superconducting cables*

Cable production was quite a concern in 2002, due to the difficult start up of the production in some companies and to the breaking of the cabling machine in Brugg. The situation is considerably better now, with a reasonable production rate. As of August 31, about 42% of the inner cable billets and 51% of the outer cable billets have been manufactured and approved. This is enough to build magnets for slightly more than 3 octants (462 dipoles).

Figure 2. Cryostatted dipoles stored at CERN.

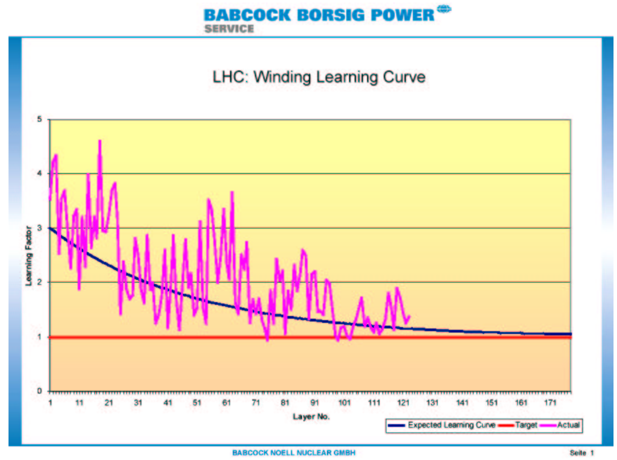

Figure 3. Nöll Nuclear: the learning curve for the winding of the LHC main dipoles coils.

3.2.2. *Cryogenic dipole assembly I*

The next crucial item is the assembly of the cryogenic dipoles by three European companies. The ramping up of the slope in the production of collared coils is impressive: 23 collared coils were received and approved in July, i.e. one per working day. This is not far from the expected cruising rate of 35 collared coils/month. The present bottleneck is in the cold testing of the full (cryostatted) magnet. Delays in the delivery to CERN of the cold feed boxes made it so that until summer we had available only 4 test stations, of the 12 foreseen. In July two more cold feed boxes had been commissioned and two new ones had arrived. We plan to reach the 12 units by the end of the year, which should enable us to eliminate the backlog. In the meanwhile, cryostatted dipoles are being stored at CERN, Fig. 2.

Responding to various rumours for the contrary, I want to state explicitly that all dipoles will be cold tested before installation in the tunnel, in particular to make sure that short circuits are not created by spurious metallic fragments in the coils, under the enormous electromagnetic forces that develop when cold dipoles are fully powered at 12000 A.

3.2.3. *Cryogenic dipole assembly II*

The companies that make the cold mass assembly had to ramp up in available space, tooling and personnel over the last year. They did it, remarkably well. Recruitment of young, enthusiastic people has taken place in all three companies and technology

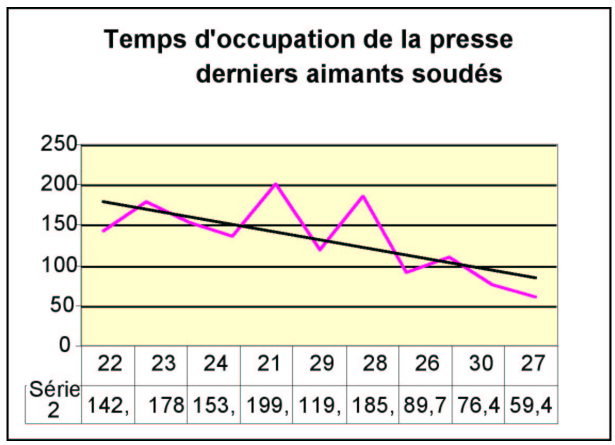

Figure 4. ALSTOM: the learning curve for the welding of the LHC main dipole cold mass.

transfer from CERN can be considered complete. Figure 3 shows the learning curve for coil winding at Nöll Nuclear. Upper (less efficient) peaks correspond to new recruits, lower (more efficient) peaks to senior people. The learning curve is approaching the expected asymptotic value, on which unit prices have been based in the contract! A similar learning curve applies to the very delicate soldering process of the two half shells that close the cold mass, as shown in Fig. 4 for Alstom. The theoretical 50 hours time is now being approached.

It is reassuring that the quality of the magnets we are receiving is quite good. Figure 5 gives the histogram of the quenches to reach the nominal 8.3 Tesla field, for the 50 cold tested dipoles: 80% get

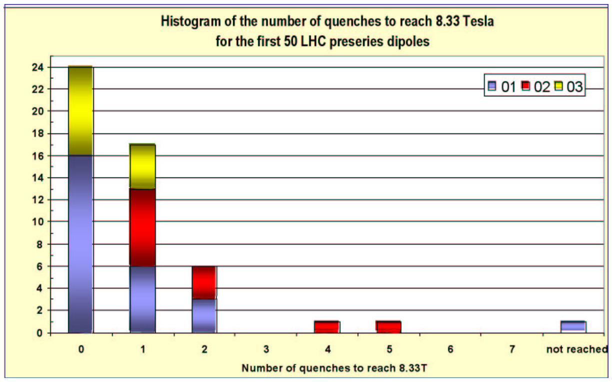

Figure 5. Histogram of the number of quenches to reach the nominal LHC field (8.3 Tesla) for the first 50 dipoles.

to the nominal field with not more than one quench, 50% of them showing no quench at all. One dipole out of 50 did not reach the nominal field because of a construction fault. We seem to have a robust and reliable design.

3.2.4. *Quadrupole subcomponents*

The corrector magnet supply for the Short Straight Section quadrupoles is still a problem, due to a failure of a subcontractor to comply with the agreed schedule. To compensate for the delay, the contract for the assembly of SSS quadrupoles has been extended for (up to) one more year, with no effect on the overall planning but some extra cost.

3.3. *Installation*

The LHC tunnel is being prepared to receive the LHC components. Sector 7-8, where the LHC-b cavern (previously DELPHI) is located, was ready on schedule. Installation of the cryogenic line started on June 21, with a six week delay, which we hope to recuperate. Information on the general installation progress can be found by clicking on *General Coordination* (also updated monthly) in the LHC Dashboard. To conclude:

- the insolvency cases occurred in 2002 have been dealt with without impacting the overall project schedule (but with some increase in the cost to completion);
- superconducting cable production has about reached its nominal rate;
- cryogenic-dipole production is ramping up in all 3 firms;
- installation is proceeding with some initial delay; and
- the LHC Dashboard web address, with component production and master schedule, is given in Ref. 12.

The present concerns are:

- extra costs in civil engineering;
- cracks at CMS shafts;
- production of corrector magnets for the SSS quadrupoles; and
- late production of cold feed boxes, delaying dipole cold testing at CERN.

4. LHC Detectors

Unlike the LHC machine, the construction of detector parts has been going on in a diffused way, in the large network of the collaborating institutions. The advancements made in civil engineering over the last two years have made it possible to start the assembly of the detectors at CERN and, in some case, their integration with the machine. This is, of course, a formidable challenge that is putting extreme strain on the Laboratory infrastructure and manpower and is requiring special coordination and monitoring tools. The result, however, is that CERN is now starting to be populated by gigantic, sophisticated, “toys” being assembled in different places.

Naturally, concerns abound, but it is encouraging to see, also here, that old concerns have mostly been overcome and progress is taking place.

The schedule remains very tight. The extra costs-to-completion of ATLAS, CMS and, to a lesser extent, ALICE, which have been declared in 2001, are at present covered by the Funding Agencies only up to some 70-80%. This will make it necessary to stage and de-scope the detectors, at least in the first go, leading to painful and risky choices. The more technical concerns have been summarized by R. Cashmore at the June CERN Council:

- ATLAS
  -Barrel Toroid Schedule;

-TRT schedule; and
-production of DMILL electronics by ATMEL.

- CMS
  -ECAL production; and
  -silicon tracker module mass production.

- ALICE
  -TPC production.

All in all, the collaborations are confident that they will provide properly working detectors at the start up of the machine.

5. LHC Computing

The enormous flux of information coming out of LHC collisions and the need to transfer all these data to a world-wide network of institutions make the LHC the ideal testing ground of a new idea, developed at the end on the 90's, the GRID.[13]

By this, we mean an infrastructure, based on the existing high band telecommunication network, with imbedded nodes (Tiers) which can store the data and the applications and send them to a diffused population of users. The name GRID, in fact, is coined after the Power GRID, whereby a user draws energy just by plugging in his electrical appliance, but he neither owns the source of the energy, nor even knows where the energy is coming from.

Over the last years, a wealth of projects to develop the GRID has started, in Europe and in the US. CERN has promoted the EU funded Data GRID project.

In 2001, CERN launched a specific project for LHC computing, the LHC Computing GRID (LCG), which is now deploying a prototype service.

Data GRID has been followed by a wider scope project, with large European participation, called Enabling GRID for E-science in Europe (EGEE) and aimed at expanding GRID applications to other sciences and industry. EGEE is funded within the 6th Framework Programme by 32 MEuro over two years, an important sign of interest from the side of the European Community. LCG will use the middleware produced by the EGEE project and by the analogous US projects (Globus, Condor, PPDG and GriPhyN).

6. Conclusions: Where Are We?

In September 2001, a mid-project analysis of the whole LHC programme showed a sizable extra cost to completion, above the cost stipulated in 1996. I can summarize the subsequent steps taken to remedy the situation as follows.

- **Sept. 2001**
  - An extra cost-to-completion of the LHC programme was declared, of about 800 MCHF (machine, detectors, computing, missing extra contributions with respect to the 1996 plan).

- **Dec. 2001**
  - The main remaining contracts were adjudicated (cold mass assembly, cryogenic line).

- **March 2002**
  - LHC commissioning was rescheduled to April 2007, to comply with the industrial production rate of the main components (e.g. cables).

- **June 2002**
  - Following internal reviews and the recommendations by an External Review Committee, Management proposed a "balanced package" of measures, *to absorb the extra cost in a constant CERN budget*. In round figures, the package was as follows:
  - 400 MCHF from programme reduction, focusing of personnel on LHC, savings, extra external resources (e.g. for computing);
  - 100 MCHF from rescheduling the LHC to 2007; and
  - 300 MCHF, full repayment of the LHC reported, from 2008 to 2010.

- **Dec. 2002**
  - The Management's Long Term Plan for the years 2003-2010 was approved by the Council.
  - A long term loan (300 MEuros) was obtained by the European Investment Bank, to cover the LHC cash-flow peak.

Thus, in December 2002 we could conclude that the LHC was back on track, with a sound, if very tight, financial plan, including the means to overcome the cash-flow we shall face in the coming years.

Today the progress of the LHC is gauged by *new, specific control tools* in addition to the classical peer committee reviews:

- **Machine**:
  - Earned Value Management for the materials budget;
  - Cost & Schedule Annual Review; and
  - LHC Dashboard to report monthly on production and installation progress.

- **Detectors**:
  - regular integration reviews; and
  - periodic machine-detector meetings.

In addition:

- the LHC cost has remained stable over the last year;

- the production of machine and detector components, installation and integration are approaching the cruising speed; and

- several old concerns have been overcome; new concerns appear, but no show stopper.

In conclusion, I can say that CERN has profited from the cost-to-completion crisis in 2001 to enforce real changes: we have a much a leaner programme, but have also succeeded in making CERN into a well-focused Laboratory, an indispensable condition to carry forward such a large project under tight constraints.

Drawing from the results I have just presented, and with fewer reservations than last year, CERN Management can confirm the following LHC schedule:

- completion of the LHC machine in the last quarter of 2006;

- first beams injected during spring 2007; and

- first collisions in mid 2007.

Thinking about LHC upgrades has started!

Acknowledgements

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DISCUSSION

Robert Zwaska (University of Texas, Austin): What are the status and prospects for LHCb?

Luciano Maiani: No particular comments, LHCb is proceeding well and all indications are that it will be ready by April 2007.