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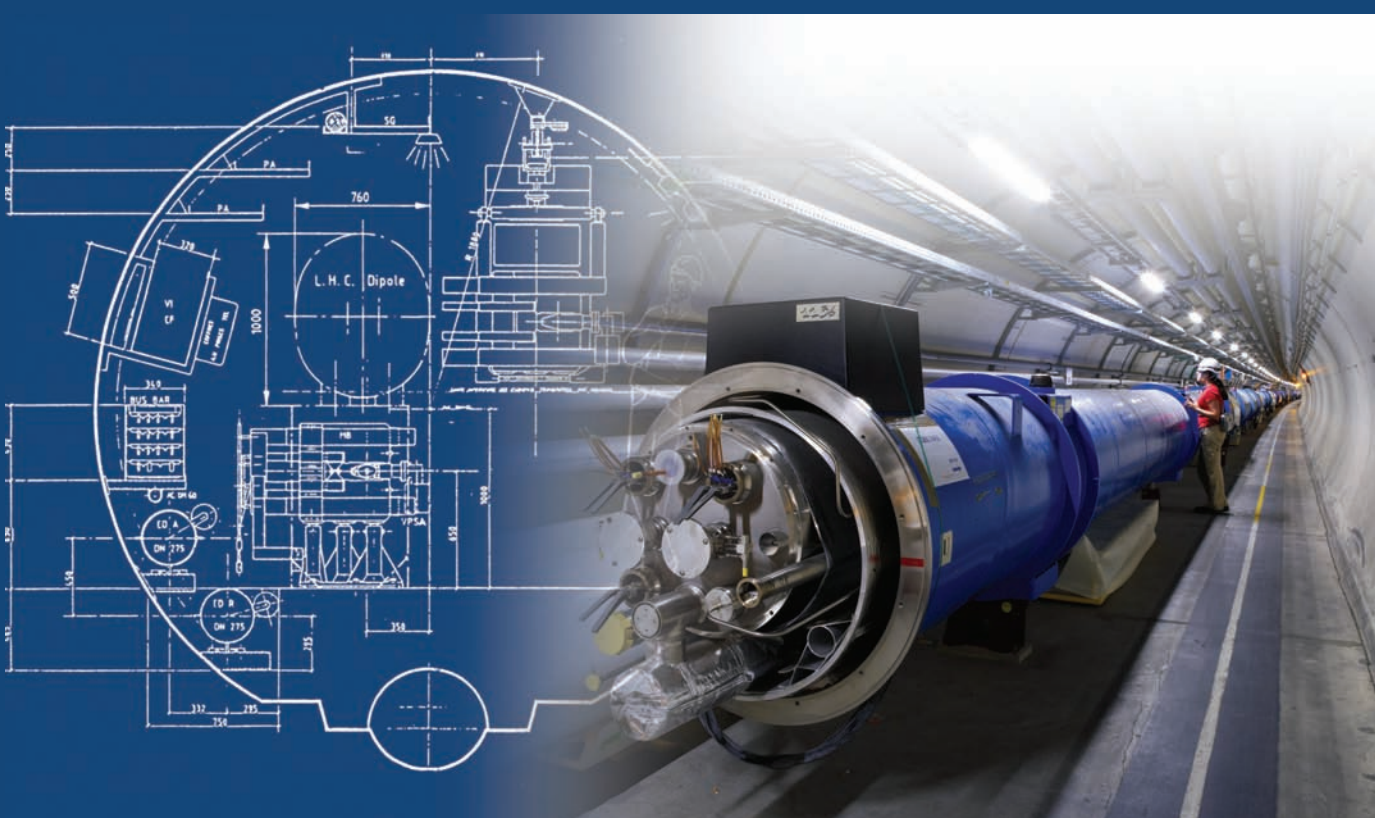
CERN COURIER

VOLUME 48 NUMBER 8 OCTOBER 2008



The LHC: from dream to reality

CERN

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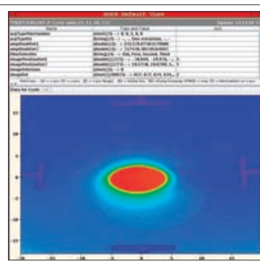

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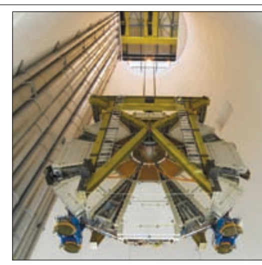

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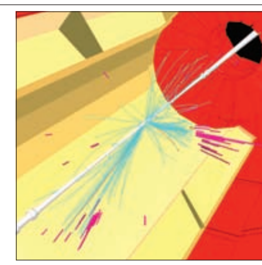

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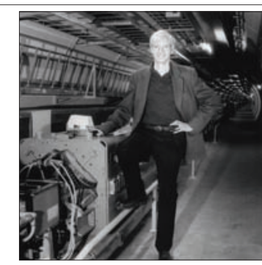

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Covering current developments in high-energy physics and related fields worldwide

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The LHC: from dream to reality

A momentous event

On 10 September the world watched as protons travelled around the ring of the Large Hadron Collider for the very first time – in both directions. Now, only a month later, we are able to celebrate another major event for CERN and the particle physics community world wide, with the official inauguration of the LHC on 21 October.

The start-up of the LHC marks the end of an eventful journey from the first ideas, through the long stages of planning and approval, construction and commissioning, to the start of operations. It began in 1984 with a debate on the possible objectives of a future accelerator, based on the state of our knowledge at that time. The CERN Council then approved the construction of the LHC in 1996, giving the go-ahead for the work that has now reached completion.

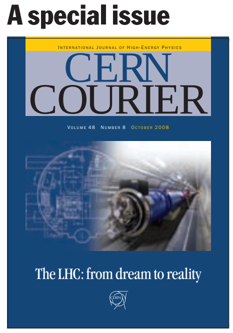
For the past 12 years, physicists, engineers and technicians from CERN and its associated institutes have been engaged in constructing the three pillars of the LHC: the accelerator (including the upgrade of the existing accelerator chain), the four experiments, and the computing infrastructure needed to store and analyse the data. An enormous amount of effort has gone into these three major endeavours and we are all about to reap the fruits of those labours.

As the current director-general of CERN I feel tremendous pride in the commitment and dedication shown by everyone at CERN, at its partner institutions in the Member States and non-Member States, and at the many contractors involved, in overcoming the various hurdles on the way to completing this unique endeavour.

What lies ahead is more important still, as the LHC is poised to generate new knowledge that we will share with the whole of mankind. For that is precisely why CERN was founded – to restore Europe to its place at the forefront of science and, in particular, at the forefront of physics.

Robert Aymar, director-general, CERN

A special issue



To mark the start-up and inauguration of CERN's Large Hadron Collider, this issue of *CERN Courier* takes on a different form. It looks back at the history of the project, from its beginnings at the Lausanne workshop in 1984 up to the recent first signs of beam, through words and pictures selected from the many articles that have appeared in the pages of the *Courier*, augmented by new articles to bring the story of this remarkable adventure up to date.

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Cover: An early idea for the LHC in the LEP tunnel (p9) together with a photo during installation. (Montage by Fabienne Marcastel, CERN.)

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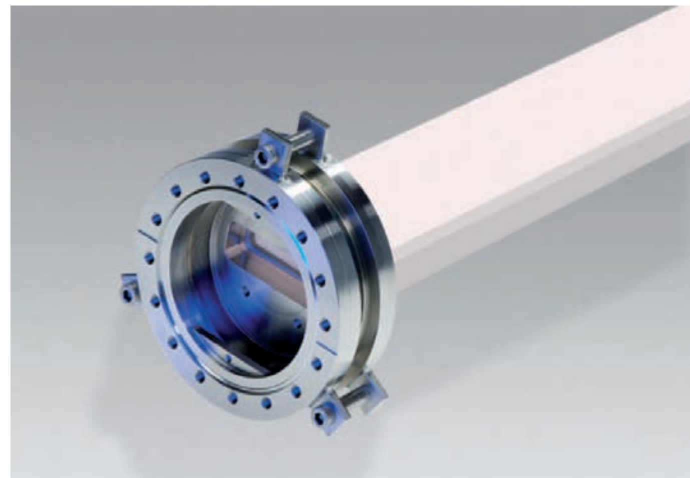
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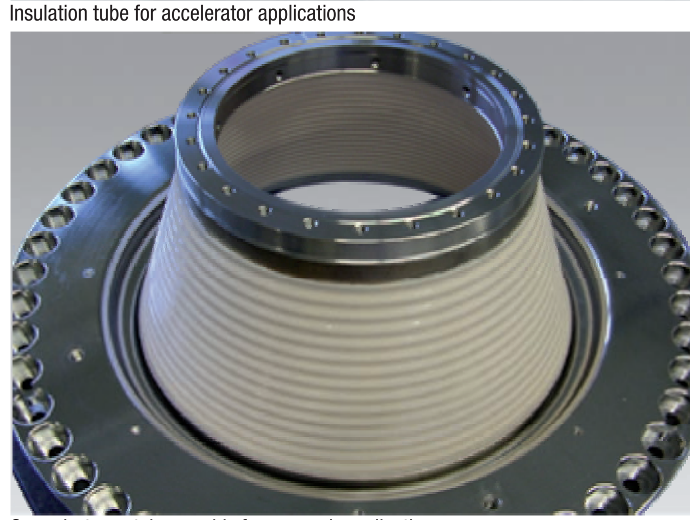
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LHC NEWS

The LHC sees its first circulating beam

At 10.28 am on 10 September, the first beam made the full 27 km journey around the LHC, travelling in a clockwise direction. Cheers and applause filled the CERN Control Centre (CCC) as two spots appeared on the screen, indicating that the beam had completed the full circle, from injection at Point 2 round to the same point. The emotion was echoed around CERN where staff and users had been watching events unfold via screens in the main auditorium and elsewhere, as well as in the control rooms of the LHC experiments. Also keenly watching the action were some 250 journalists attending the event, many in the Globe of Science and Innovation.

It had taken the operations team in the CCC, just less than an hour to allow the beam to progress carefully, through one sector at a time. Finally, the beam made three circuits before the team decided to take a well-earned pause before starting the procedures for the beam travelling in the opposite direction. Then in the afternoon, again taking about one hour for the complete journey sector-by-sector, the first beam travelled anticlockwise all the way from injection at Point 7, finally making a total of two circuits.

Present in the crowd in the CCC, were all the directors-general of CERN who had watched over the proposals, approval and construction of the LHC. Herwig Schopper (1981–1988) had overseen the construction of the LEP collider, with its 27 km tunnel that the LHC now occupies; Carlo Rubbia had been a tireless and inspirational advocate for the machine (1989–1993); Chris Llewellyn Smith (1994–1998) had conducted the hard negotiations that led to the project's approval in 1996; Luciano Maiani (1999–2003) was at the helm as major construction got under way; and Robert Aymar, the current director-general, has seen the project to its successful completion. The crowd also included Giorgi Brianti, the "father" of the machine with its unique twin-aperture, two-in-one magnet system.

Only very careful planning and preparatory work had made it possible for the Operations Team to be able to propose starting up the machine under the eyes of the world's media. Although common practice for the launch of space vehicles, for example, this was a "first" in the world of particle physics – and not without additional stress for the operators. From 9.00 am to 6.00 pm at CERN, regular live action from the CCC was broadcast by many TV channels. The journalists in the Globe were also able to attend a press conference in the afternoon, given by the current director-general, together with Llewellyn Smith, Rubbia, Schopper, Brianti, Evans, and Jos Engelen, CERN'S Chief Scientific Officer.

The sight of first beam marks the end of a long journey for the LHC project, from the first proposals in 1984 to the final hardware commissioning this past summer. It is also the first step in the process of bringing the LHC into operation. The next stage for the operations team will be to establish beams that circulate continuously, for hours at a time. The final step will be to commission the LHC's acceleration system to boost the energy to 5 TeV per beam – the target energy for 2008, which will be a world record energy and another "first" for CERN.

Delighted faces in the CERN Control Centre as beam makes its way around the LHC for the first time, standing left to right, Paul Collier, Operation Group Leader, Lyn Evans, LHC Project Leader, and Robert Aymar, director-general. It had taken only one hour to coax the beam around the 27 km ring.

Directors-general present and past, left to right: Robert Aymar, Luciano Maiani, Chris Llewellyn Smith, Carlo Rubbia and Herwig Schopper, who between them have seen the LHC dream become reality.

Efacec Solutions for CERN's LHC Electric Power Assets

Efacec congratulates CERN for the inauguration of the Large Hadron Collider, the most demanding and powerful accelerator ever built in the world.

CERN has been playing an important role for the scientific community with a huge impact on the daily life of every one of us. The World Wide Web and medicine therapy machines for cancer, among others, are good examples of its achievements.

Efacec is pleased to keep on teaming up with CERN in such a demanding and challenging venture, the LHC. In this scope, Efacec has been participating in the supply of Power Converters and Power Supply equipment, as well as providing Automation and Management SCADA solutions for CERN's electric power assets.

Overview

Efacec, the largest Portuguese company in the field of electric power network solutions, employs around 3,000 people. It has a turnover of approximately 600 million Euros. It is present in over 65 countries, in the following business areas:

- Energy Solutions (Transformers; High and Medium Voltage Switchgears; Energy Servicing)
- Engineering Solutions and Services (Engineering; Automation; Maintenance; Environment; Renewable Energies)
- Transport, Logistics and Aerospace

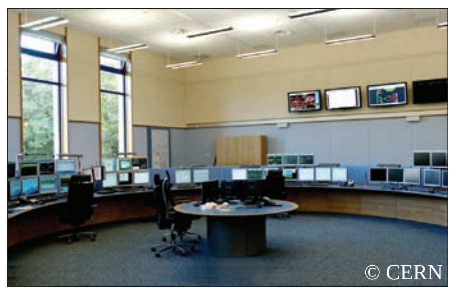
In addition to those business activities, Efacec is mostly concentrated in Portugal and in 6 international regions: Spain, United States of America, Latin America, Maghreb, Southern Africa and Central Europe.

Efacec relationship with CERN

Since the 80's Efacec has been working with CERN, namely manufacturing huge electronic boards for the LEP experiment, a relationship that was kept during the 90's, manufacturing several CERN designed electronic products.

In the 90's, CERN awarded the Network Control Centre and Substation Automation contracts to Efacec, providing SCADA/DMS and other IT systems for CERN's power network management, as well as Remote Terminal Units (RTU) for substation automation, integrating the already existing protection relay systems.

Efacec has been participating in the supply of Power Converters and Power Supply equipment, as well as providing Automation and Management SCADA solutions for CERN's electric power assets



Detail of CERN's Network Control Centre, featuring an Efacec's SCADA/DMS solution

As this is an evolving system, CERN remains focused on the legacy systems' migration to new technologies, granting the necessary implementations in order to keep a high standard level for the network operation and the management of other important LHC infrastructure assets. This way, Efacec and CERN continue to work together in the pursuit of this goal.

Already in the new millennium, Efacec produced and supplied more than 400 Four-Quadrant Power Converters, as well as more than 1,000 Quench Heater Discharge Power Supply equipments for the LHC superconductive magnets.

Efacec solutions for the electric power industry

Efacec has a worldwide presence, providing solutions for different needs of the electric power industry.

Nowadays, Efacec is building a new state of the art Power Transformers production facility in Effingham County, Georgia, USA. The facility will employ over 600 employees at build out.

Recently, Efacec inaugurated a new facility in Argentina for the production of components for Medium Voltage Equipment. This is the first production unit for its world network production set of facilities. In India, a joint-venture with an important local partner reinforces this network.

Besides these new international facilities, already in operation or expected to kick-off in a near future, Efacec has important production facilities in Portugal, Brazil, Mozambique, Angola, Malaysia and China. Other facilities for engineering and servicing, in Portugal and in other countries, contribute to strengthen its worldwide presence.

Its electronic production and engineering facilities have been working not only for CERN, but also for other customers, including the space industry, besides responding to the Efacec needs.

Concerning electric power network management and automation, Efacec has been working in this industry segment, playing an important role as a world class provider.

Our main engineering facilities in this segment are located in Portugal and Brazil. Recently, Efacec purchased an important company, ACS, based in Atlanta, USA, strengthening its overall capacity to respond to worldwide electric power automation and management demands. In this area, Efacec provides several solutions, such as:

- Power Network Control Centres, featuring SCADA/DMS/EMS
- Power Production Assets Management Control Centres, featuring SCADA for renewable sources penetration
- Integrated Substation Automation, including Protection
- Feeder Automation
- Distribution Automation
- Remote Terminal Units

Efacec also provides solutions for telecom infrastructures, an important backbone asset for the electric power industry.

Finally, one of its major skills is providing complete turnkey solutions, namely in the area of distribution and transmission substations, as well as power plants.

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Lausanne LHC workshop

In March 1984 a major workshop provided a chance to look to the next step beyond the construction and exploitation of LEP.

The installation of a hadron collider in the LEP tunnel, using superconducting magnets, has always been foreseen by ECFA and CERN as the natural long term extension of the CERN facilities beyond LEP. Indeed such considerations were kept in mind when the radius and size of the LEP tunnel were decided. The recent successes of the CERN proton–antiproton collider now give confidence that a hadron collider would be an ideal machine to explore physics in the few TeV range at the particle constituent (quarks and gluons) level. The present enthusiasm for the Superconducting Super Collider (SSC) in the US reflects the impressive potential of such machines.

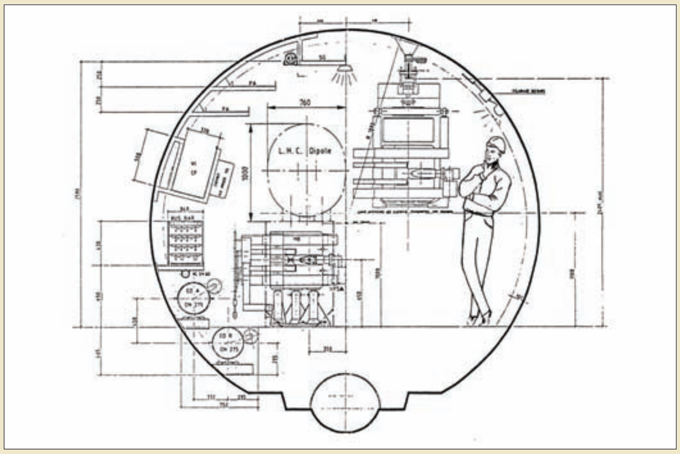
Although the installation of such a hadron collider in the LEP tunnel might appear still a long way off (LEP is scheduled for initial operation in 1988), it was still an opportune moment for ECFA, in collaboration with CERN, to organize a 'Workshop on the Feasibility of a Hadron Collider in the LEP Tunnel' from 21–27 March. The first four days of detailed work were held in Lausanne, at the kind invitation of the University, and were followed by two days of summary talks and discussion at CERN.

The workshop was initiated particularly by the then ECFA Chairman, John Mulvey, in keeping with ECFA's role in stimulating and coordinating plans for future particle-physics facilities in Europe. The workshop was timed to enable CERN to communicate present ideas on long-term prospects to an ICFA (International Committee for Future Accelerators) seminar held in Tokyo on 15–19 May and entitled 'Perspectives in High-Energy Physics'.

In his opening address at the workshop summary session, CERN director-general Herwig Schopper emphasized that CERN's top priorities remain the completion of LEP Phase I (to achieve electron-positron collisions up to 50 GeV per beam), followed by Phase II (taking the beam energies to around 100 GeV). Thus the Large Hadron Collider (LHC) means looking as far ahead as the middle of the next decade.

Nevertheless, LHC would have to use the infrastructure permitted by LEP. Present ECFA Chairman Jean Sacton emphasized what LEP and CERN would offer. Besides the LEP tunnel itself, the PS and SPS provide excellent proton (and antiproton) injectors. In particular, with the experience of the Intersecting Storage Rings (ISR) and the proton–antiproton Collider under its belt, CERN can claim unique experience and expertise with bunched-beam hadron colliders. The European particle-physics community is also well aware of the competition from the SSC in the US breathing down its neck.

Giorgio Brianti summed up the outcome of the LHC machine studies so far. After confirming that the LEP tunnel would indeed be suitable for such a machine, the next conclusion was that



Sketch of a cross-section of the 27 km circumference tunnel for the LEP. On the floor are the LEP magnets, with above, the space available for the LHC superconducting magnets.

construction moreover need not interfere significantly with LEP operation, given the foreseen LEP operating schedule. Four excavated colliding beam regions are still vacant, although this may not still be the case by the time of LEP Phase II.

To be competitive, the LHC has to push for the highest-possible energies given its fixed tunnel circumference. Thus the competitivity lives or dies with the development of high field superconducting magnets. The long gestation period of LHC fits in with the research and development required for 10 T magnets (probably niobium-tin), which would permit 10 TeV colliding beams. The keen interest in having such magnets extends into the thermonuclear fusion field, and development collaborations in the US, Japan and Europe look feasible.

There are two main options – either to build a single ring and have proton–antiproton colliding beams, as in the CERN SPS Super Proton Synchrotron and scheduled for Fermilab's Tevatron, or to build two rings and have colliding proton beams. Two considerations turned the thinking firmly towards the second option. The first is the advantage of the higher luminosity (up to $10^{33}/cm^2$ per s) of proton–proton collisions. The second is the complications in separating the multi-bunch proton and antiproton beams outside the collision regions, which would require cumbersome separators. These considerations outweigh the intrinsic economy of having protons and antiprotons circulating in the same ring. At the workshop, designs were presented of two-in-one magnets in single cryostats with the two proton-beam channels less than 20 cm apart.

At such high energies, there are aspects of machine operation which need special attention. For example – the enormous stored energy in the beams means that the beam-abort system would have to cope with 60 MJ, the vacuum chamber design has to take account of synchrotron radiation heating, the refrigeration system has to distribute liquid helium over tens of kilometres and be able ▷

to cope with several superconducting magnet quenches at a time. The growing experience at the Fermilab Tevatron, where the world's first superconducting synchrotron has come so impressively into operation, would provide important input into design decisions.

Preceding the workshop, studies of machine design, magnets and cryogenics had been (and continue to be) underway at CERN, with periodic meetings to review progress. This work was summarized at Lausanne, including a panel discussion on superconducting magnet design and technology.

On the experimental side, eight working groups had been set up: Jets (convener P Jenni), Electron and photon detection (P Bloch), Muon detection (W Bartel), Tracking chambers (A Wagner), Vertex detection (G Bellini), Triggering (J Garvey), Data acquisition (D Linglin) and Forward physics (G Matthiae). There was also a great deal of input from theorists, and the Lausanne theory talks were also attended by many experimentalists.

The reports of these working groups provided much valuable input, and several general conclusions emerged. The highest energy would be a valuable asset but there is no actual threshold known now. The key point is to have at least 10 TeV collision energy in order to have typically at least one TeV at the hadron constituent level. There is also a trade-off between energy and luminosity, a gain in luminosity for a loss in energy and vice versa. According to present wisdom, differences between proton–proton and proton–antiproton reactions would be in most cases too small to be detectable. Information from proton collisions should hence be adequate.

Production rates for hitherto unknown objects are 'expected' to decrease quickly with the mass of these objects, so that here high luminosity would be an advantage. Multi-bunched beams were envisaged with 3564 bunches per ring, giving 25 ns between bunches and an average of one interaction per bunch crossing. Much thought is going into particle detector performance and there is confidence that the high luminosities could be handled.

Another attractive possibility with both proton and electron rings in the same LEP tunnel is the provision of high-energy electron–proton collisions 'for free'.

No attempt was made at the workshop to arrive at even a tentative cost estimate for LHC in the LEP tunnel. The project has only been under consideration for a few months and a great deal of further study is needed. However, as Carlo Rubbia emphasized in his concluding remarks, the feasibility of the LHC has been demonstrated, a good physics case has been outlined and CERN is able to promise a great deal when future perspectives in high-energy physics are discussed.

● June 1984 pp185–187 (abridged).

Résumé

En mars 1984, un atelier tenu à Lausanne est l'occasion pour la communauté de la physique des particules de réfléchir à l'étape faisant suite à la construction et à l'exploitation du LEP. C'est là qu'on parle pour la première fois de construire un collisionneur de hadrons dans le tunnel du LEP.

Aachen: the case for LHC

A workshop held in October 1990 revealed great enthusiasm for a new hadron collider.

It was a workshop on a scale to match the ultimate goal. When some 500 physicists met in Aachen, Germany, in October to put the research case for the proposed Large Hadron Collider (LHC) at CERN, the turnout was among the biggest attendances of the year.

Organized by ECFA, the European Committee for Future Accelerators, the meeting, by its attendance and by the depth of its scientific content, clearly displayed the enthusiasm for LHC in the research community, and provided valuable additional impetus for the already-compelling idea of a proton collider using superconducting magnets in the 27 km tunnel built for LEP.

Introducing the plenary sessions at Aachen, CERN director-general Carlo Rubbia underlined the complementarity of a dual LEP–LHC complex with its electron and proton beams, providing a balanced two-pronged attack on the physics-research frontier while at the same time making the most of CERN's versatile beam-handling systems, both existing and potential. With CERN already serving a varied menu of particles, LHC physics would be well-endowed with beam options. As well as providing proton–proton collisions at about 8 TeV per beam, LHC could follow the tradition of CERN's other proton machines and handle heavy ions as well.

With basic (dimensional) arguments saying that reaction rates have to decrease with collision energy, then high luminosity (related to the collision rate) is a basic collider requirement which is expected to become even more important at higher energies. Thus a main aim of the LHC design is to attain the highest-possible luminosities.

The Aachen meeting mirrored on one hand the physics potential opened up by such a high-luminosity approach, and on the other the challenges for the detector systems which will have to handle bunches of 10^{11} protons crossing every 15 ns or so, resulting in billions of secondary particles each second. In addition to coping with this flood of data, the potentially delicate detector components will have to withstand long exposure to this harsh radiation environment.

The presentations at Aachen summarized the work of the hundreds of physicists in LHC working groups set up by ECFA earlier this year. Three groups looked at the physics potential of the three collision options (proton–proton, electron–proton, and ion–ion), while others studied detector aspects.

For proton–proton collision physics, Daniel Denegri of Saclay looked at the implications of the current Standard Model, while Felicitas Pauss of CERN attempted to look at the uncharted territory beyond. Putting the physics case for LHC proton–proton studies, Guido Altarelli of CERN was confident that new physics would turn up at the mass scales covered by this machine and provide a natural explanation for some of the apparently arbitrary numbers of today's Standard Model (the unification of the weak nuclear force and electromagnetism loosely tied to the quark–gluon field theory of strong nuclear forces). While no cracks have yet appeared in this structure, Altarelli thought that with LHC the betting would be against the Standard Model, and its continued survival would be a turnup for the book.

Major goals include the clarification of the electroweak symmetry breaking mechanism (Higgs Particle), where Altarelli remarked there was room for contributions from LEP a well as from the proton–proton sector. However with its proposed high luminosity of 10^{34}/cm^2 per s, LHC has the discovery potential to attack the main outstanding questions of particle physics. Subsequent talks outlined the additional potential opened up by LHC's electron–proton and ion–ion collision options.

Summarizing the work on the interaction regions where LHC experiments would be housed, Lars Leistam of CERN pointed ▷

1991: The right machine

Rubbia presents the LHC.

At the December meeting of CERN's Council, the Organization's Governing Body, the delegates from the 16 Member States unanimously agreed that the LHC proton–proton collider proposed for the 27 km LEP tunnel is the 'right machine for the advance of the subject and of the future of CERN'. Detailed information on costs, technical feasibility and prospective delivery schedules, and involvement of CERN Member States and other countries, together with an outline of the LHC experimental programme, its goals and its implications, including funding, will be provided before the end of 1993 so that Council can move towards an LHC decision. Following the vote, Council President Sir William Mitchell said "this is a historic occasion". "The LHC project now exists," he added.

The vote followed a special extended Council session on the LHC project on 19 December before extended delegations from CERN Member States and invited guests from other nations. They heard presentations from Scientific Policy Committee chairman Chris Llewellyn Smith on the physics potential for LHC, from ECFA Chairman J-E Augustin on the LHC user aspects, and from CERN director-general Carlo Rubbia on the LHC project and the future of CERN. This special meeting helped prepare the ground for Council's vote the following day.

● January/February 1992 pp23–24 (extract).

out that if construction work on big new underground caverns is to begin in 1993, then the plans for the experimental areas should be ready by the end of next year. Although ideas for individual experiments have not yet been tabled, the sessions on muon identification at least gave some idea of what an LHC detector might look like. Contenders included toroids, solenoids, and their variants, and an idea to convert the L3 setup currently used at LEP.

● December 1990 pp 3-5 (abridged).

Résumé

Un atelier tenu à Aix-la-Chapelle en octobre 1990 révèle le grand enthousiasme de la communauté de la physique des particules pour le LHC. Les interventions portent sur les résultats des groupes de travail ayant étudié le potentiel du collisionneur proposé du point de vue de la physique, ainsi que certains aspects des futurs détecteurs.

The Evian experiment meeting

Some 600 participants attended the meeting in March 1992, where ideas for LHC experiments first went public.

CERN director-general Carlo Rubbia (right) concludes the meeting with organizing committee chair Gunther Flügge.

As plans for the LHC proton collider to be built in CERN's 27 km LEP tunnel take shape, interest widens to bring in the experiments exploiting the big machine. The first public presentations of 'expressions of interest' for LHC experiments featured on 5–8 March at Evian-les-Bains on the shore of Lake Geneva, some 50 km from CERN, at the special 'Towards the LHC Experimental Programme' meeting.

This event followed soon after CERN Council's unanimous December 1991 vote that the LHC machine, to be installed in the existing 27 km LEP tunnel, is 'the right machine for the advance of the subject and for the future of CERN'. With detailed information on costs, feasibility and prospective delivery schedules to be drawn up before the end of next year, and now with plans for experiments under discussion, the preparations for LHC move into higher gear. The Evian meeting was a public forum for a full range of expressions of interest in LHC experiments, setting the stage for the submission of Letters of Intent later this year and cementing the proto-collaboration arrangements.

Participants at the meeting also heard the latest news on LHC machine studies, and the thinking on preparations for experimental areas and LHC physics potential. As well as its main objective of proton–proton collisions, LHC also opens up possibilities for ion–ion collisions, for fixed-target studies and eventually for electron–proton collisions as well. Most of these areas were covered at Evian.

LHC beams can in principle collide at eight points. Four of these coincide with the four big experiments at the LEP electron–positron collider. Of the remaining four points, one, deep under the Jura mountains, will have to be used for an LHC 'beam-cleaning' system to ensure high performance by reducing troublesome beam halo. Another will be reserved for the beam dump where the LHC protons will be absorbed once the circulating beams are no longer required. This leaves room for two big new LHC-collider detectors, plus the potential of the existing LEP experimental areas, using either adapted LEP experiments or new apparatus mounted in push–pull to alternate with LEP running.

At Evian, four major detectors for studying proton–proton collisions were being tabled, three of which are new, and one a development from an existing LEP experiment. The ASCOT (Apparatus with SuperCOnducting Toroids) general purpose detector is proposed by a team from CERN, the UK (Edinburgh and Rutherford Appleton Laboratory), Germany (Wuppertal and Munich MPI and University), France (Saclay) and Russia (Moscow, Dubna and Protvino). It is based on a 24 m long superconducting toroid instrumented with drift tubes for precision muon detection.

Inside the magnet, the emphasis is on electrons, with a lead/liquid argon electromagnetic calorimeter, and tracking through interleaved layers of scintillators and transition radiation detectors, with semiconductor pads close to the beam pipe. A 1.5 T superconducting solenoid in front of the electromagnetic calorimeter distinguishes electrons and positrons. Hadron calorimetry uses iron and liquid argon.

The EAGLE (Experiment for Accurate Gamma, Lepton and Energy measurements) collaboration proposes a comprehensive detector to cover a wide range of physics, and already involves physicists from 14 CERN member states, plus Canada, Russia, Australia, Brazil and Israel. EAGLE foresees a powerful inner-electron detector inside a 2 T central superconducting solenoid. The design features high-quality electromagnetic sampling calorimetry combined with fine-grained electron and photon preshower detection, a high-precision vertex detector for lower collision rates, hadron calorimetry and a conventional toroid muon spectrometer.

The Compact Muon Solenoid (CMS) LHC detector is designed to be compatible with the highest LHC collision rates, and is built around a 15 m long superconducting solenoid providing a 4 T field. The strong field gives relatively compact muon measurement. R and D work for the muon detectors is looking at resistive-plate chambers and parallel plate chambers for timing information and honeycomb-strip chambers and wall-less drift chambers for spatial information. The central tracker will use small cells, based on silicon (or gallium arsenide) strip detectors and microstrip gas chambers, to ensure good pattern recognition under the stringent LHC conditions. Also inside the coil is a high-resolution electromagnetic calorimeter and a hadron calorimeter. CMS involves a team from 12 CERN member states, plus Byelorussia, Bulgaria, Estonia, Georgia, Hungary, Russia and the US.

The L3 experiment at LEP was originally designed for use at both LEP and LHC, with a large experimental hall and magnet. Upgrade for LHC would involve improving the muon resolution, adding a fine-grain hadron calorimeter, increasing the magnetic field, and being able to lift the detector 120 cm from the LEP position to the LHC beams above. For the work, 39 institutes from the L3 LEP line-up have been joined by 20 more, mainly from China and the former Soviet bloc.

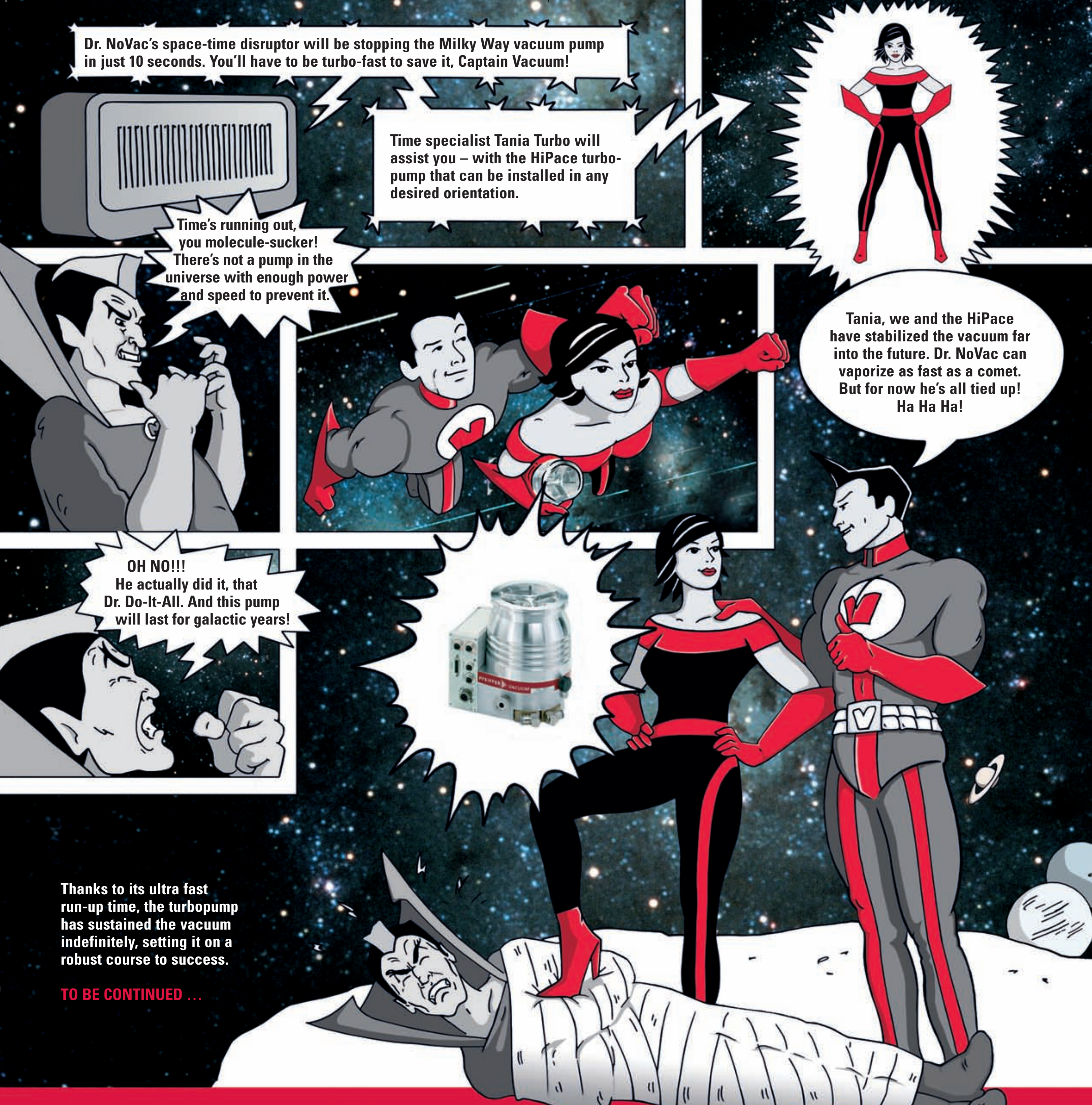
Supplementing the main proton–proton LHC programme are a range of other experiments, including fixed-target studies. Expressions of interest received so far include ideas for two neutrino experiments and three studies concentrating on CP violation in B-particle decays, one using a gas-jet target, one using extracted beams and one a colliding-beam setup.

Although not the spearhead of LHC physics, ion–ion collisions will still play a major role, continuing a CERN tradition in this field. For ion collisions, three teams are interested – one using CMS, another using the (suitably modified) Delphi experiment at LEP and a third using a new dedicated detector.

More than 600 members of the potential LHC user community met at Evian. Introducing the event, Organizing Committee chairman Gunter Flügge of Aachen traced the previous history of major international get-togethers and other milestones which have delineated LHC progress: from the 1984 Lausanne workshop where the LHC idea was launched, through the valuable 1987 recommendations of the CERN Long Range Planning Committee under the chairmanship of Carlo Rubbia, to the 1989 Barcelona meeting on Instrumentation Technology and the 1990 Aachen workshop to study the physics objectives. Wrapping up at Evian, CERN director-general Carlo Rubbia proposed an ongoing schedule for the selection of LHC experiments, with Letters of Intent to be submitted after the summer for selection at the end of the year. The selected experiments would then proceed with a full design report. Whatever the outcome of this selection, Evian will always be remembered as the stage where these ideas made their public debut.

● Compiled from April 1992 pp1–3 and May 1992 pp1–3.

Résumé
Les projets d'expériences du LHC sont rendus publics pour la première fois lors d'une réunion tenue à Évian en mars 1992, qui rassemble 600 participants. Parmi les projets présentés, il y a CMS, mais aussi ASCOT et EAGLE, élaborés par deux collaborations qui par la suite ont fusionné pour constituer ATLAS.


Dr. NoVac's space-time disruptor will be stopping the Milky Way vacuum pump in just 10 seconds. You'll have to be turbo-fast to save it, Captain Vacuum!
Time specialist Tania Turbo will assist you – with the HiPace turbopump that can be installed in any desired orientation.
Time's running out, you molecule-sucker! There's not a pump in the universe with enough power and speed to prevent it.
Tania, we and the HiPace have stabilized the vacuum far into the future. Dr. NoVac can vaporize as fast as a comet. But for now he's all tied up! Ha Ha Ha!
OH NO!!! He actually did it, that Dr. Do-It-All. And this pump will last for galactic years!
Thanks to its ultra fast run-up time, the turbopump has sustained the vacuum indefinitely, setting it on a robust course to success.
TO BE CONTINUED ...

The challenges of the LHC

The Large Hadron Collider project has had to overcome challenges at every stage. **Lyn Evans** focuses on the three phases of approval, construction and operation.

It is generally considered that the starting point for the Large Hadron Collider (LHC) was an ECFA meeting in Lausanne in March 1984,although many of us had begun work on the design of the machine in 1981. It took a very long time – 10 years – from this starting point for the project to be approved. During most of this time Giorgio Brianti led the LHC project study. However, we should not forget the enormous debt we owe to Carlo Rubbia in the second half of that decade for holding the community together behind the LHC against all the odds.

The first project approval came in December 1994, although under such severe financial constraints that we were obliged to make a proposal for building the machine in two stages. This would have been a terrible thing to do, but at that point we had no alternative. However, after a major crisis in 1996, when CERN had a rather severe budget cut, at least the constraints on borrowing were relaxed and a single-stage machine was approved (p24).

It is clear that building the LHC is a very challenging project. It is based on 1232 double-aperture superconducting dipole magnets – equivalent to 2664 single dipoles – which have to be capable of operating at up to 9 T. We were doing R&D on these magnets in parallel with constructing the machine and the experimental areas. This was not just a question of building a 1 m scale model with the very skilled people here at CERN, but of being able to build the magnets by mass production, in an industrial environment, at an acceptable price. This is something we believe we have achieved.

The machine also incorporates more than 500 "two-in-one" superconducting quadrupole magnets operating at more than 250 T/m. Here, our colleagues at Saclay have taken on a big role in designing and prototyping the quadrupoles very successfully. There are also more than 4000 superconducting corrector magnets of many types. Moreover, operating the machine will involve cooling 40 000 tonnes of material to 1.9 K, when helium becomes superfluid. An additional challenge has been to build the machine in an international collaboration. Although usual for detectors, this was a first for the accelerator community, and it has proved to be an enriching experience.

The production of the superconducting cable for the dipoles has driven the final schedule for the LHC, because we have to supply the cable to the magnet manufacturers. We could not risk starting magnet production too early when we were not sure that we could follow it with cable production. Figure 1 shows the ramp-up of cable production in 2002–2003.

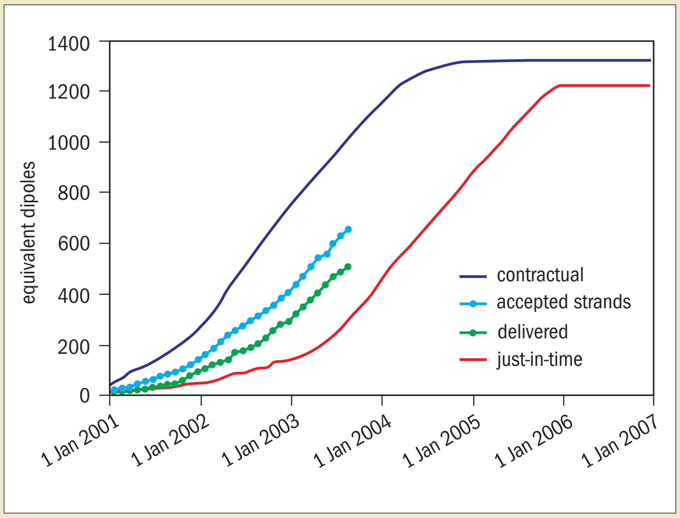


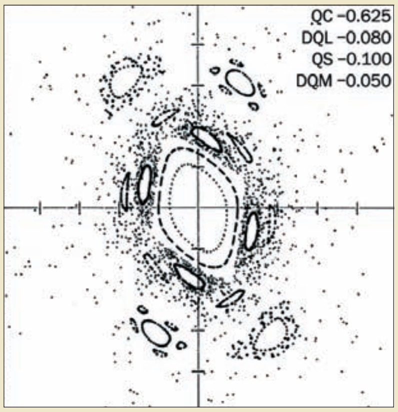
Fig. 1. The delivery of the superconducting cable for the LHC comfortably above the "just-in-time" line in 2003.

A computer-generated image of the Large Hadron Collider.

The next step is the series production of the dipoles, with installation in the tunnel starting in January 2004 and finishing in summer/autumn 2006. The "collared coils" – more than half the work on the dipoles – are now being made at the rate we need. These are assembled into the cold masses, which are delivered to CERN where they are installed in their cryostats, tested and stored.

At the same time the infrastructure of the tunnel is being prepared for the installation of the superconducting magnets. Sector 7-8, the first sector to be instrumented, now has its piping and cabling installed. The next step is the installation of the cryoline, to provide the liquid-helium refrigeration. We are now looking forward to as smooth a passage as possible from installation into commissioning.

The LHC is a very complicated machine, and its operation presents many challenges. The most fundamental concern is ▷



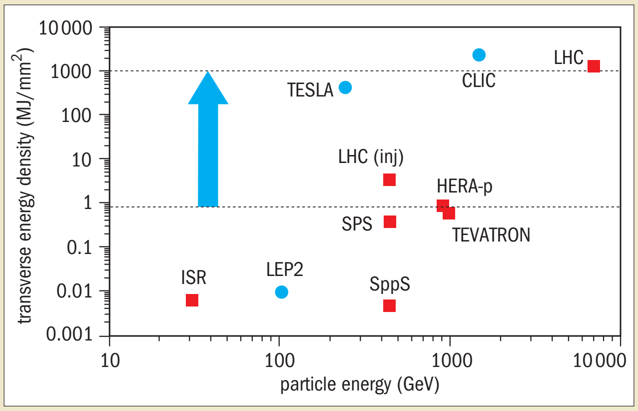


Fig. 2 (left). Simulation showing the chaotic effect of the beam–beam interaction on the position–velocity space of a particle in one of the beams. Fig. 3 (right). At less than 1% of nominal intensity the collimation system enters new territory. The collimators must survive under very punishing conditions.

the beam–beam interaction and collimation. In designing a particle accelerator, we try to make sure that the magnets have as little nonlinearity as possible: that is, they have pure dipole and quadrupole fields. We then introduce controlled non-linearities – sextupoles to control chromatic aberrations and octupoles to give beam stability (Landau damping). We want smooth, distributed non-linearity, not a "lumped" linearity at one point in the ring. So we take a great deal of care, but then we are stuck with what we absolutely do not want – the beam–beam interaction itself. When the beams are brought into collision, a particle in one beam sees the Coulomb field of the other beam, which is strongly non-linear and is lumped – in every revolution the particle sees the beam–beam interaction at the same place. This produces very important effects, which I shall describe.

First, however, I should mention that the conversion of the Super Proton Synchrotron (SPS) into a proton–antiproton collider was a vital step in understanding this phenomenon. Indeed, it is not generally known what a step into the unknown we took with the collider. In this machine the strength of the beam–beam interaction, which we call the beam–beam "tune shift", was very large, much larger than at the Intersecting Storage Rings (ISR). The collider was to operate in a domain where only electron–positron machines had worked, and these machines have the enormous advantage of strong synchrotron-radiation damping: particles that go through large amplitudes are "damped" into the core of the beam again. So we were going to operate a machine with no damping and a strong beam–beam effect. (Indeed, tests at SPEAR at lower and lower energies with reduced damping showed catastrophic effects, which when extrapolated indicated that the proton–antiproton collider could never work!)

Figure 2 shows the effects in a simulation of the transverse phase space (the position–velocity space) of a particle in a perfect machine, apart from the beam–beam interaction. Because of the strong nonlinearity of the beam–beam interaction, particle motion can become chaotic and unstable at large amplitude. This was a real worry at the proton–antiproton collider, which proved to be an absolutely essential prototype for defining the parameters of the LHC. We have designed the LHC to beat this effect by sitting in a very small corner of "tune space" with very precise control in order to stay away from high-order resonances, although the beam–beam interaction will always be a fundamental limit.

A second major challenge of operating the LHC concerns collimation, which is needed to remove halo particles from the beams to avoid their touching the superconducting magnets, and to control the background in the detectors. We also need collimation to protect against fault conditions – the stored energy in the nominal LHC beam is equivalent to 60 kg of TNT! If there is a fault the beam will be kicked out, and for that there is a 3 μs hole in the bunch spacing to allow the field in the kicker magnets to rise. If there is a misfiring particles will be lost as the kickers rise, and the collimators can melt, so they have to be very carefully designed.

Already, at less than 1% of its nominal intensity, the LHC will enter new territory in terms of stored energy. It is two orders of magnitude more in stored beam energy, but the beam-energy density is three orders of magnitude higher (figure 3) because as the beam is accelerated it becomes very small. To cope with this we have designed a very sophisticated collimation system. At injection the beam will be big, so we will open up the collimators to an aperture of about 12 mm, while in physics conditions the aperture of the beam will be 3 mm – the size of the Iberian Peninsula on a €1 coin. The beam will be physically close to the collimator material and the collimators themselves are up to 1.2 m long.

We are now on the final stretch of this very long project. Although there are three-and-a-half years to go, they will be very exciting years as we install the machine and the detectors. It is going to be a big challenge both to reach the design luminosity and for the detectors to swallow it. However, we have a competent and experienced team, and we have put into the design 30 years of accumulated knowledge from previous projects at CERN, through the ISR and proton–antiproton collider. We are now looking forward to the challenge of commissioning the LHC.

● January/February 2004 p27 (abridged).

Based on a talk given at a symposium at CERN, published in *Prestigious Discoveries at CERN. 1973 Neutral Currents. 1983 W & Z Bosons* (Springer 2003).

Résumé

Le Grand collisionneur de hadrons a dû surmonter des obstacles à chaque étape de sa réalisation. Dans cet article, Lyn Evans, chef du projet LHC, examine les trois phases du projet – approbation, construction et exploitation – et, en particulier, les nombreux défis que représente l'exploitation d'une machine aussi complexe.

Lyn Evans, *CERN.*

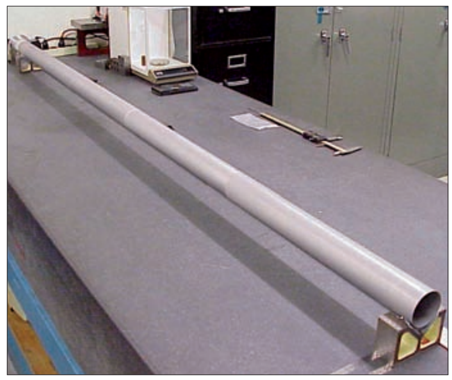
Beryllium beam pipes for ALICE, ATLAS and CMS

With the startup of the Large Hadron Collider (LHC), the ALICE, ATLAS and CMS experiments are also beginning. Brush Wellman Electrofusion Products (Fremont, California) played a crucial role in making all three of these projects a reality by supplying the beryllium beam pipes.

The ALICE beam pipe is 4820 mm long, the CMS beam pipe is 6240 mm long and the ATLAS beam pipe is an impressive 7300 mm long. Although Electrofusion has been building beryllium beam pipes since 1973, these LHC projects demanded a much higher level of precision and more advanced techniques from Electrofusion than ever before. Unlike beam pipes used in other projects, these are buried deep within the LHC, surrounded by layer upon layer of detectors, thermal systems, cabling and structural supports. The resulting limited future accessibility meant that CERN engineers needed to do everything possible to minimize the possibility of failure.

As an example, previous to the LHC project, the beryllium portions of the beam pipes were joined to aluminium and stainless steel sections using an atmosphere brazing technique. However, due to materials introduced during the typical beam pipe brazing process, the risk of contamination or leaks during operation concerned the engineers at CERN. Electrofusion was therefore encouraged to investigate alternative joining processes for the LHC beam pipes. In response to this request, Electrofusion developed processes for joining beryllium to beryllium and beryllium to aluminium using electron beam welding. Joining beryllium to stainless steel was achieved by vacuum furnace brazing.

Although these improved joining techniques minimized contamination and leakage concerns, they brought with them a new challenge: how to predict and compensate for the distortion of beam pipe sections during the newly developed joining processes. The mechanical tolerance specifications were extremely challenging so Electrofusion developed sophisticated tooling coupled with complex theoretical calculations to achieve the end result.


The ATLAS beam pipe, prior to final assembly.

The beam pipes for ALICE and CMS had stainless steel extensions and flanges and the beam pipe for ATLAS had aluminium extensions and flanges, so Electrofusion repeated the tooling design and calculations for the different types of joints. An iterative design process also played a part in developing this difficult joining technique. After some test runs with the electron beam welding process, it was determined that the electron beam welding equipment needed to be reconfigured and upgraded. Even then, the first few welds of the "live" beam pipe sections did not meet Electrofusion's exacting standards. Tooling had to be modified, power settings had to be adjusted and the sections had to be remachined and rewelded. Through all of this, Electrofusion was able to expand its fundamental knowledge base of beryllium fabrication and joining.

The tight mechanical tolerances posed special challenges with the beryllium sections. The individual beryllium beam pipe sections were approximately 1 m long and required a typical wall thickness of only 800 µm. Machining beryllium into simple shapes is difficult, so something this complex required extra attention. First, rods of solid beryllium were gun-drilled to produce the final inside diameters of the pipes (58–60 mm). To arrive at the final shape profile, the gun-drilled beryllium pipes were subsequently precision machined on the exterior surfaces. Using solid rods reduced the need for longitudinal weld seams and helped to meet the extremely demanding vacuum leakage specification of 2×10 E–10 Pa•m^3/sec.

The final installation of the beam pipes in the LHC required bake-out so part of the acceptance testing dictated that Electrofusion perform a qualification bake-out of each beam pipe prior to shipping. Electrofusion constructed a custom tube furnace to accommodate beam pipes up to 10 m long. The furnace needed uniform axial heating and accomplished this with sophisticated temperature monitoring and control.

As with all projects of this sophistication and magnitude, collaboration and communication between CERN and Electrofusion was essential. Gordon Simmons, the engineering manager at Electrofusion who oversaw the development of the three beam pipes, was in constant communication with CERN engineers throughout the fabrication period. Working together, they overcame manufacturing challenges and negotiated compromises to bridge the very demanding tolerance callouts specified by the project engineers and the limitations of precision manufacturing. They are looking forward to future modifications and improvements that will make LHC experiments even more productive.

In addition to beryllium beam pipes, Electrofusion has expertise in fabricating beryllium windows into a wide array of complex UHV chambers, flanges and custom frames. Electrofusion provides ultrahigh purity beryllium as well as very thin foils – as thin as 7.6 µm. Founded in 1966, Electrofusion Products became a subsidiary of Brush Wellman in 1990, gaining access to a broad spectrum of beryllium alloys and complementary metallurgical engineering resources.

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What next after LEP?

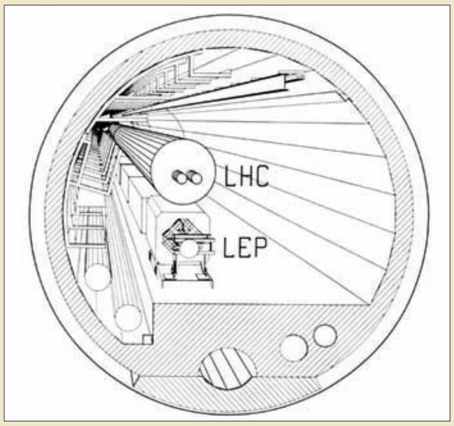
Work for the LEP electron–positron collider continues to drive ahead, however LEP is far from being the last word in CERN's long term plans. A clue was already in the LEP Design Study " ...by the adoption of a beam height of only 80 cm, there is enough room left (in the tunnel) for the installation of a second machine at a later stage...".

A workshop, organized by ECFA and CERN in March 1984, examined the feasibility of a hadron collider in the LEP tunnel (p9). There the idea emerged for a ring of superconducting magnets, installed above the LEP ring, to collide protons together (or protons with antiprotons) at as high an energy as possible. Since this meeting, considerably more work has been done to firm up ideas.

Using 10 Tesla dipole bending magnets, collision energies of 17 TeV (8500 GeV per beam) could be achieved with a respectable collision rate (luminosity 10^{33} cm^{-2} s^{-1}). A 'two-in-one' aperture solution for the superconducting magnets is recommended for economy and compactness.

It is the relative ease of colliding proton beams (as compared to the difficulties of first making and then handling antiprotons) which promise high collision rates and make the proton–proton option the preferred solution. Despite the need to provide a large number of bunches (a figure of 3564 has been quoted), the two proton rings in the LEP tunnel could be filled using CERN's existing 450 GeV SPS machine and its proton supply in only a few minutes. Of course new injection lines would have to be built.

● July/August 1986 pp5–4 (abridged).



The designers of the LEP electron–positron collider were far-sighted enough to leave enough room for a possible second machine.

Elsewhere

In Europe the news of the initial approval for the US Superconducting Supercollider was received enthusiastically as it showed that the future of high-energy physics is regarded as being of paramount importance at the highest levels. While the US plans gather momentum, the possibility of a hadron ring in the LEP tunnel at CERN is still attractive. Although restricted in energy by the 'modest' dimensions of the LEP tunnel compared to the SSC (27 km circumference against 84), the LHC scheme scores points for the magnificent beam injection systems already in place at CERN, a complete tunnel, and several collision options.

● March 1987 p2 (abridged).

Superconducting magnet success

Technical preparations for a possible proton–proton collider (LHC) in the LEP tunnel have made substantial progress with the successful testing of the first LHC superconducting high-field 1 m long model magnet. The single aperture niobium-titanium wound dipole was designed by R Perin and his LHC magnet study team, and manufactured by Ansaldo Componenti, Genova.

Operating at 2 K, it reached and passed its 8 Tesla nominal field without any quench, the first three quenches occurring at central fields of 8.55, 8.9 and 9 Tesla respectively. It then attained 9.1 Tesla without quenching and operated at this level for some time.

This is the first time a high field 'accelerator quality' superconducting dipole model has been designed and built as a joint venture between a scientific laboratory and industry. CERN provided most of the know-how and the superconductor, while manufacture was taken over by Ansaldo.

● June 1988 p13 (abridged).

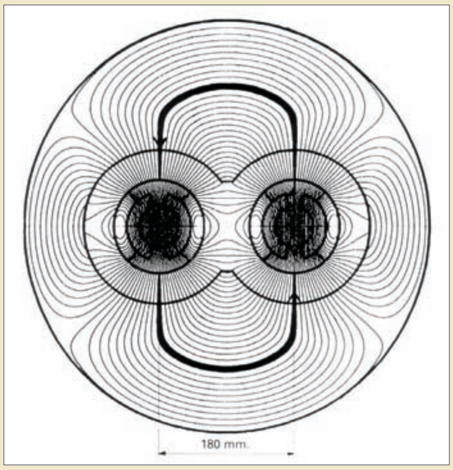
Magnets: beyond niobium-titantium

The superconducting proton ring being built for the HERA electron–proton collider at DESY has already demonstrated that niobium-titanium technology is mature, even on an industrial scale. The HERA-type design (coils around the beam-pipe, mechanical support collars and cold iron return) has gone on to become widely adopted, but reaches its natural limit for dipole construction using niobium-titanium near 10 Tesla.

This is now well understood and has been demonstrated with several test magnets developed in a collaboration between CERN and Italian supplier Ansaldo. A similar geometry was used with niobium-tin in a collaboration between CERN and Elin (Austria) which reached a record field for this kind of magnet of 9.45 Tesla in September 1989.

CERN's proposed LHC collider in the LEP tunnel envisages 10 T fields with a double aperture carrying the two beam pipes for the proton beams inside a single cryostat. Four contracts have been placed with European firms for the development of one-metre, double-aperture niobium-titanium magnets with a view to placing further orders for full-scale, 10 m prototype units. Using superfluid helium at 1.8 K instead of conventional 4.2 K cryogenics provides the necessary additional potential.

● Sept/October 1990 pp17–18 (extract).



A field map of the superconducting dipole design for the LHC proton collider for CERN's LEP tunnel, showing the 'two-in-one' design with the two beam pipes held in a single cryostat.

First ten-tesla twin

An important step in the development of the high-field superconducting magnets for CERN's proposed LHC proton collider came on 21 October when a 1 m long model of the proposed twin-dipole magnet produced a field of 10 Tesla in its two beam apertures at the design temperature of 1.8 K.

To save LHC space and cost, the separate magnetic channels for the twin proton beams were proposed for the same iron yoke, mounted in a single cryostat. Achieving 10 Tesla with this special design was a real challenge to the magnet designers, but the new results show that it can be met. The peak field seen by the superconductor was 10.2 T – a world record for accelerator magnets.

The magnet was designed and tested at CERN by the LHC magnet development team led by R Perin and D Leroy, and manufactured by Jeumont-Schneider in France using niobium-titanium superconducting cables, which were supplied by Alsthom-Intermagnetics.

Last year orders were placed for ten full-size (10 m-long) LHC dipoles from four suppliers – Ansaldo (Italy), Noell (Germany), a consortium of Elin (Austria) and Holec (Netherlands), and a French consortium formed by GEC Alsthom and Jeumont-Schneider. Some of these dipoles will be delivered next year for tests of an LHC half-cell.

● December 1991 p1 (abridged).

Magnet progress

The magnet designs and lattice configuration are evolving in the light of ongoing experience. The magnet configuration now foresees more evenly distributed correction coils, and longer bending magnets – three 13.6 m dipoles rather than four 10 m ones – per 50 m half-cell. This means that 'only' 1152 dipoles, rather than 1600, would be needed to fill the ring.

This new configuration gives an increased beam energy of 0.81 TeV per Tesla, rather than 0.77 as in the original 'Pink Book' design study, so that the required 7.7 TeV proton beams (15.4 TeV collision energy) can be guided using 9.5 Tesla fields instead of the 10 T originally foreseen.

A 10 m prototype has been put through its paces at the French Saclay Laboratory. This dipole has a full LHC configuration, with twin-beam apertures inside a single magnetic assembly, but to obtain an initial rapid result uses the same coils as the HERA superconducting proton ring, which have a bore of 75 mm instead of the 50 mm of the LHC design. Cooled to 4.4 K, these coils behave like those in HERA, but when taken down to the 1.9 K levels foreseen for LHC cryogenics, the current increases from 6600 to 9500 A, after only a few quenches. The field reached was 8.3 Tesla.

● May 1992 p5 (abridged).

The case for the LHC

CERN is now responding to the December 1991 request from its governing body, Council, to supply detailed information on the technical feasibility of the machine, its costs and its experimental programme.

The LHC idea for a proton collider in the LEP tunnel was first heard in public in March 1984 at a workshop at Lausanne (p9). The following year, CERN Council asked Carlo Rubbia to chair a Long Range Planning Committee to explore options for the future of the Laboratory. This committee evaluated the lepton and quark routes to 1 TeV collisions. The LHC option emerged as the Committee's priority recommendation.

LHC's high-field superconducting magnets appeared feasible on the timescale of a decade or so, and would anyway benefit from the effort mounted for the proton ring at DESY's HERA collider. To ensure that the LHC proposal fell on fertile ground, the Rubbia Committee proposed intensifying R&D, involving other laboratories and industry. The goals were high fields and 'twin aperture' designs. In parallel, a push began towards detectors to cope with the high collision rates. "It is time to get our hands dirty," urged Carlo Rubbia in 1987.

After valuable groundwork by ECFA, a major demonstration of LHC support came in October 1990 at the ECFA LHC Workshop in Aachen, Germany (p11). In 1991 a detailed technical report, the so-called Pink Book, was favourably received by a specially appointed LHC Review Committee of 15 leading experts from Europe, the USA and Japan. In December 1991 Council concluded 'the LHC is the right machine for the advance of the subject and of the future of CERN' (p11).The 1991 Pink Book design envisaged three collision regions. Early discussions on the experimental programme quickly established that the most probable configuration for high luminosity would instead have two collision regions.

This, combined with the realization that the electronics of several detectors would be integrating over more than one bunch crossing, questioned the reasoning behind the originally specified proton-bunch spacing of 15 ns. With the two beams converging on either side of each collision point producing beam–beam perturbations, Carlo Rubbia asked whether performance would not benefit from the reduced long-range beam–beam force with fewer, albeit more intense, bunches.

A new analysis of machine performance for only two high luminosity experiments confirmed that a longer gap between bunches could lead to higher luminosity per experiment. The final result is that with a 25 ns bunch spacing the beam-beam limited luminosity in each of two collision points can be expected to be around $2.5 \times 10^{34}\,cm^{-2}\,s^{-1}$.

● December 1993 pp6–10 (extract).

First test of quadruople at Saclay

The first cold mass of the "two in one" quadrupole for the LHC demonstration half-cell (one quadrupole and three dipoles) has been successfully tested at the French Saclay Laboratory. The magnet reached 15 060 A, its nominal intensity, during its second ramp; the first ramp had been stopped by transition in one of the quadrupoles at 14 437 A, 96% of its nominal current. The 15 060 A level was maintained for several hours.

The current was subsequently increased to 15 100 A without problems. The nominal gradient of 252 T/m is already 17% higher than the new LHC requirements (8.65 T). The resulting first magnetic measurements show that the magnets are very close to specifications. The 252 T/m gradient obtained in the 56 mm aperture is claimed to be a new world record.

This quadrupole has been designed in a CERN/CEA (Commissariat à l'Energie Atomique) collaboration (DSM/DAPN IA/STCM) at Saclay. The basic elements and the tooling have been manufactured by European industry, while winding, assembly and testing have been undertaken entirely at Saclay.

● December 1993 p10 (abridged).

SSC superconvulsion

After a baffling succession of seesaw decisions, which saw the mood swing from the depths of pessimism to supreme optimism and back, on 21 October a US House of Representatives Committee proposed $640 million for the 'orderly termination' of the superconducting supercollider (SSC) project in Ellis County, Texas.

By next July, the US Secretary of Energy is requested to produce a plan to 'maximize the value of the investment in the project and minimizing the loss to the US'.

● December 1993 pp1–2 (extract).

Pushing for LHC

LHC has been part of CERN's planning for 15 years. Even before the drawing-board stage, the farsighted John Adams noted in 1977 that the tunnel for a future large electron–positron (LEP) collider should also be big enough to accommodate another ring of magnets.

After a decade of workshops and reviews, LHC is ready for approval, affirms CERN's new director-general, Christopher Llewellyn Smith. "We need a decision soon to work towards physics in 2003."

This early approval is vital to sustain LHC momentum for the physicists and engineers and for industrial partners, and to ensure prudent planning and optimal use of resources. It is also vital for a new phase of negotiations with non-member states.

With the demise of the US Superconducting Supercollider (SSC) project, international interest from beyond the framework of CERN member states in CERN's research programme now gets an additional boost. To accommodate ex-SSC researchers in the LHC experimental programme and to capitalize on valuable SSC groundwork, the deadlines for submitting full technical proposals for LHC experiments have been deferred by several months. Initial discussions in December suggested that at least 500 more researchers could join the LHC programme. This potential influx includes sizable contingents from other nations (Japan, Russia, China, Canada, India, Korea) and the US.

● January/February 1994 pp2–3 (extract).

Dipole prototype success

In April 1994 the fist LHC dipole prototype was successfully powered for the first time.

In a crash programme, the first prototype superconducting dipole magnet for CERN's LHC proton–proton collider was successfully powered for the first time at CERN on 14 April, eventually sailing to 9 T, above the 8.65 T nominal LHC field, before quenching for the third time.

The next stage is to install the delicate measuring system for making comprehensive magnetic field maps in the 10 m long, 50 mm diameter twin-apertures of the magnet. This first valuable prototype will be trained to its maximum field, expected to be close to 10 T, only after completion of the magnetic-field measurements. Seven prototypes have been ordered from four different industrial consortia. All are expected to be complete before the end of the year. The first prototype was ordered by the Italian INFN and built by Ansaldo.

● June 1994 pp14–15 (extract).

Council pauses for thought

At the Council meeting on 24 June, 17 of the 19 member states agreed that the LHC proton collider should be CERN's next major machine.

A week of intense diplomatic activity which had high-level telephones ringing across Europe culminated in an imaginative and unexpected move on 24 June, when delegates adjourned the 100th session of CERN's governing body, Council, to be reconvened at a later date.

On the Council table was the vote for CERN's next major machine, now universally agreed as the world focus of particle-physics research for the start of the 21st century, the LHC proton–proton collider, to be built in CERN's 27 km LEP tunnel, and the largest and most complex scientific joint effort ever undertaken in Europe.

On 24 June, 17 of CERN's 19 member states voted to include the LHC in the ongoing basic programme of the Laboratory. However two of the major CERN contributors, Germany and the UK, while underlining their strong commitment to the LHC, could not approve the motion as tabled, insisting on prior preparatory work for the budget framework for the coming years, and for a special contribution to LHC construction of the two Host States (France and Switzerland) on whose territory CERN is built.

The worldwide participation in CERN's research programme already provides enormous intellectual input and added dynamism, as well as providing an effective vote of confidence in the organization. With LHC, this participation should increase. In December, Council recommended that this increased involvement should be 'on the understanding that usage on a significant scale must involve the provision of resources to suit both CERN and the non-member states concerned'.

Negotiations are underway with Canada, China, India, Israel, Japan, Russia and the US. Most of these countries sent delegates to the 100th Council session, where they convincingly underlined the case for the LHC and explained how the seeds for their national contributions had been sown.

● September 1994 pp8–10 (extract).

Best birthday present

In the final administrative hours of CERN's eventful 40th anniversary year came the unanimous approval on 16 December 1994 by CERN's governing body, Council, for the construction of the 14 TeV LHC collider in the 27 km LEP tunnel. After the decision had hung in the balance until the last possible moment, CERN received the best 40th birthday present it could have wished for – a unique machine which will provide a world focus for basic physics research.

To allow the LHC to be built within a tightly constrained budget, the new accelerator will be built in two stages – the first aiming to reach two thirds of the ultimate collision energy of 14 TeV (7 TeV per beam) and to start experiments in 2004. Collision energies of 9–10 TeV would open up a research programme with both proton and heavy ion beams. In this way the LHC would provide valuable 'front porch' physics before receiving its full complement of superconducting magnets to increase its energy to 14 TeV by 2008.

The December Council meeting decided on a comprehensive review of LHC progress before the end of 1997. If this reveals that sufficient additional LHC support is forthcoming from non-member states, then the project could revert to its original direct route to 14 TeV. At the Council meeting, observers from the US and Japan immediately welcomed the decision and indicated that negotiations towards new cooperation with CERN can begin. The unanimous vote emerging from the December meeting was contingent on member states' contributions to the CERN budget (SFr918 million for 1995) being frozen until 1997.

LHC's full 14 TeV energy requires 1232 superconducting dipole magnets to bend the beams, 1104 of them arranged in triplets (half-cells) around the ring. The intermediate two-thirds energy option would use a 'missing magnet' configuration, with only two bending magnets in each half-cell, the central position remaining as an empty cryostat. Installing only two-thirds of the big dipoles obviously makes for initial cost saving, but this would have to be offset against the effort in eventually replacing empty cryostats by the missing dipoles. In the missing-magnet scenario, the installed magnets have to be specially aligned (the beam still has to be steered round a full circle) and subsequently realigned for the full magnet complement.

Underlining the already advanced state of LHC development work, on 6–7 December a 35 m string of powerful LHC-prototype superconducting magnets ran for 24 hours at 8.36 Tesla, the magnetic field required to hold LHC's 7 TeV protons in orbit round the 27 km ring, and the highest ever used in an accelerator. This will be achieved by cryogenics working at superfluid helium temperature, 1.8 K.

The LHC design is under constant review to optimize cost and performance. The beam bending power has been increased by packing in more magnets, lengthening both the individual magnets and the modules into which they are fitted. The latest version has 23 cell modules to each machine octant, with each half-cell consisting of three 14.2 m dipoles, one 3 m quadrupole and accompanying corrector magnets.

● January/February 1995 pp1–4 (abridged).

The LHC string test gives encouraging results.

The LHC string test

The LHC string test assembled towards the end of last year continues to give encouraging results. In the 1995 tests, nominal current was achieved (corresponding to a field of 8.36 T) without a quench and when the current was further increased, the first quench occurred at 12 773 A, equivalent to a dipole field of 8.64 T.

In this initial phase, the test string uses two 10 m dipole prototypes and a 3 m quadrupole prototype, together with dummy corrector magnets, making a total length of 35 m. The 110 m support beam could eventually accommodate a full cell. It is mounted on a 1.4% slope, the steepest gradient in the LHC ring, and, as in the LHC itself, the magnets are installed in a single continuous cryostat.

Initial results have been so encouraging that during a scheduled interruption to upgrade the cryogenic plant a third dipole magnet will be added to the string, making it look almost like a full 50 m half-cell.

● September 1995 p4 (extract).

A refined design

Encouraging results from the 'string test' of cryogenic magnets for CERN's future LHC proton–proton collider are helping to refine the machine design. The system has been used to study the 1.9 K cryogenic system, the powering scheme and the vital quench protection system. The latter must safely dissipate 7.4 MJ of energy stored in each of the dipole magnets in the event of a superconducting-magnet quench.

The protection worked better than expected and the maximum pressures measured during a quench from full power never exceeded 10 bar even when all but one of the three installed relief valves were kept closed. As a result only one relief valve per half cell will be needed, which has revived the idea of a separate cryogenic service line in the tunnel.

A large number of helium supply lines must pass around the machine tunnel and to avoid the extra cost of a separate cryoline they were initially envisaged as integrated into the magnet cryostat. The fact that a linking valve box incorporating the quench relief valve would only be needed every 50 m and that the separate line would allow the increased pipe diameters needed for only four cryogenic installations, at points where the cryo-plants of LEPI I are already installed, swung the economic balance the other way. A separate cryoline design has now been adopted as it is both economic and will simplify installation.

● September 1995 p4 (extract).

Full steam for the LHC

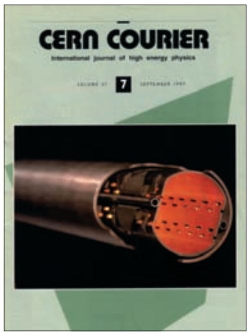
At its December 1996 meeting, CERN's governing body, Council took the important decision that the Laboratory's big project for the next millenium, the L HC proton collider, shall be completed in a single stage and planning shall proceed on the basis that the LHC will be commissioned in 2005.

When a green light for LHC had first been illuminated at the December 1994 Council meeting, the understanding was for a two-stage project, with an initial intermediate energy and the collider only attaining its design energy of some 7 TeV per beam in 2008 (p23). However at that time Council said that if sufficient interest and financial commitment were forthcoming from non-member states, the project might be completed in a single stage. Since then, non-member state interest and commitment for the LHC have grown.

However this impressive LHC blueprint for physics in the next millennium was approved against a sad background of budget reductions. After intense discussion, it was decided that while LHC funding would remain intact, CERN's overall budget, compared to that foreseen in 1994, would be reduced by an unprecedented 7.5% in 1997, with reductions increasing to 8.5% in 1998–2000, and to 9.3% thereafter.

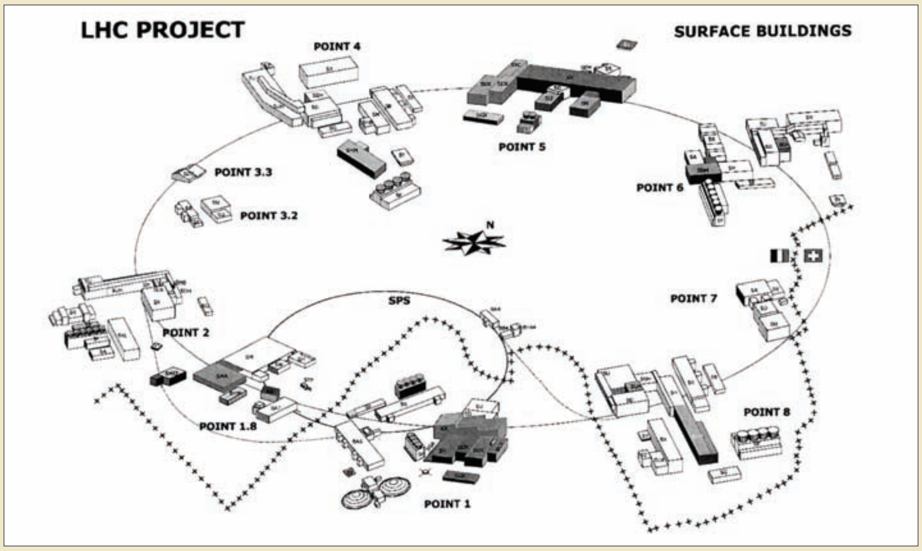
● January/February 1997 p1 (extract).

Screening the beams



CERN'S LHC proton collider will be equipped with 'beam screens' to shield the surrounding superconducting magnets from radiation emitted by the beams. However the slits allow residual gas molecules to pass through and become 'frozen' to the walls of the ultracold beam pipe.

● September 1997.



Civil engineering for LHC goes on above and below ground. New surface buildings for the LHC are here shown shaded, alongside the existing ones. Crosses mark the Franco-Swiss border.

● May 1998 p2.

French back LHC engineering

Progress on the LHC took another step forward recently when French prime minister Lionel Jospin signed the decree allowing LHC civil engineering work to commence on French territory. This important landmark comes after a long and painstaking study of the environmental impact of the project and follows approval of civil-engineering on Swiss territory earlier this year, where work is already underway.

LHC civil engineering contracts are being awarded in three separate packages. Excluded from these packages is one of the tunnels that will supply the LHC with protons from CERN's Super Proton Synchrotron accelerator. This tunnel is being built by Switzerland as part of its special host-state contribution to the LHC (p36).

● October 1998 p5 (abridged).

Multipoint progress

During 1998 two more 10 m collared coils were delivered by industry and assembled at CERN into complete magnets, and the first 15 m prototype dipole, built by industry under an agreement between CERN and the Italian INFN, was put through its paces. Orders for six prototype collared coils with the series-manufacture design have been issued, and the first has even arrived.

Prototype high-temperature superconducting current leads have been ordered and tested. Other cryogenic-related equipment reflects further the world involvement in the LHC. Power supplies for quench heaters are being developed by a collaboration working through the Indian Centre of Advanced Technology, Indore, while equipment to handle the extraction of the stored superconducting energy in the event of a quench is being designed and constructed by Russian industry and by IHEP, Serpukhov.

Also being supplied from Russia, in this case the Budker Institute, Novosibirsk, are 360 warm dipoles and 180 quadrupoles for the two 2.5 km transfer lines feeding protons from the SPS to the LHC. The first magnets have arrived.

With the technical specification of the dipole cold masses complete, almost the last act of 1998 at CERN was to issue a call for tenders for the first phase of LHC dipole procurement.

● February 1999 p11 (abridged).

Boosting power for the LHC

For CERN's new LHC proton collider, superconducting magnets will not be the only superconducting technology in the 27 km ring. Early on, research and development work for LEP showed that cavities made of niobium-coated copper were more effective than those of the more expensive solid niobium. The LHC is set to use this technology from the outset.

The radiofrequency scenarios for LEP's electrons and positrons, and the LHC's protons, are very different, even though they both use a 27 km ring. Electrons, being very light particles, lose a lot of energy per turn by synchrotron radiation, which has to be replaced continually by the "accelerating" cavities. Most of LEP's radiofrequency power is transferred to the beam and then dissipated by synchrotron radiation.

Proton beams lose little energy in this way. The main role of the LHC cavities is to keep the many proton bunches tightly bunched to ensure high luminosity at the collision points and to deliver power to the beam during energy ramping. Matching these radiofrequency conditions using conventional copper cavities would lead to unacceptable displacement of the beam-crossing points.

Superconducting cavities with small losses and large stored energy are the best solution. This leads to a design using single-cell accelerating cavities with large beam tubes, similar to those considered for the new generation of electron–positron colliders.

A protoype cryomodule housing superconducting accelerating cavities for the LHC.

The LHC will use eight cavities per beam, each capable of delivering 2 MV (an accelerating field of 5 MV/m) at 400 MHz. The cavities will operate at 4.5 K (the LHC magnets will use superfluid helium at 1.8 K). For the LHC they will be grouped in fours in cryomodules, with two cryomodules per beam, and installed in a long, straight section of the machine where the interbeam distance will be increased from the normal 195 to 420 mm.

● June 1999 p7 (abridged).

Extreme cryogenics keeps the LHC cool

The LHC will be the largest cryogenic system of its kind in the world. It has to operate below 2K to achieve the strong magnetic fields required to hold protons in orbit in the confines of the 27 km tunnel.

Pre-series test cells for the LHC cryogenic distribution line (QRL) went on test at the laboratory at the beginning of June. Made by three European industrial groups, the test cells have been produced following a 1995 decision to separate the accelerator's cryogenic distribution system from the magnet cryostats (p23).

Helium at different temperatures and pressures will be supplied to the magnets via service modules joining the accelerator's cryogenic components to the QRL every 107 m within the accelerator's bending arcs, a distance that corresponds to a single LHC cell of six dipole and two quadrupole magnets. Elsewhere the interconnections will be at varying distances. Each of the three test cells currently being put through its paces at CERN is a section about 112 m long in which two service modules are joined by a pipe module made up of several straight pipe elements.

Owing to the huge scale of the LHC – some 25.6 km of cryogenic distribution line involving about 200 km of piping needing thousands of welds, around 3300 bellows and 1700 control valves at low temperature – a combination of precision stainless steel piping experience and cryogenics expertise is required from contractors.

The QRL is four times as long as any existing system and requires the lowest heat "inleak" ever demanded. Altogether this makes stringent quality control a key issue.

● September 2000 p10 (extract).

Main magnets hit production

The prototyping of the main dipole magnets for the LHC reached a conclusion last year with successful tests of the final prototypes, manufactured in a collaboration between CERN and industry. All dipoles delivered to CERN from now on will be installed in the new accelerator. Dipole prototyping began in 1990 when the machine's design called for 10 m magnets with a 50 mm aperture and a field of 8.6 T. The initial plan was for all of the prototyping to be carried out in industry, and work was soon under way in five companies.

By 1995, however, it had become apparent that a closer working partnership between CERN and industry was needed for the R&D phase. From then on, collared coils were produced in industry, while assembly and cryostating were carried out at CERN. By this time, two of the initial companies had withdrawn, leaving France's Alstom-Jeumont consortium, Germany's Noell and Italy's Ansaldo still in the running.

A redesign of the LHC lattice soon emerged: the dipole length was increased to 15 m to allow a greater operational margin with a field of 8.3 T and an aperture of 56 mm. Two full-scale prototype collared coils were ordered from each company and these were assembled into magnets at CERN during the course of 1999 and 2000. All worked satisfactorily, achieving the required field with little training. Lessons learnt from these final prototypes were quickly fed back to the three manufacturers, all of which are now producing a pre-series batch of 30 magnets each.

A short straight section, containing a prototype LHC main quadrupole, on its testbench at CERN.

A total of 392 short straight sections will house the LHC's main focusing quadrupoles, along with other beam-correcting magnets. The main quadrupoles have been designed and prototyped by France's CEA laboratory at Saclay, which will also be responsible for the technical follow-up in industry. Their integration into fully equipped, short straight sections has been taken care of by the neighbouring CNRS-IN2P3 laboratory at Orsay. The contribution of both laboratories is part of France's host-state contribution to the LHC project.

The German firm Accel has won the contract for producing the quadrupoles, and engineers from Saclay are currently transferring their tooling from France to the Accel plant near Cologne.

● June 2001 pp15–16 (extract).

CERN reacts to budget shortfall

Following the funding shortfall for the LHC that emerged in September 2001, the laboratory established five task-forces to examine ways of redeploying resources to the new accelerator. In parallel, the laboratory's governing body, Council, established an External Review Committee (ERC) under the chairmanship of Robert Aymar, director of the International Thermonuclear Experimental Reactor. The task-force recommendations were presented to Council in March, and form the basis of a medium-term plan that was submitted to Council for approval in June. Elements of the plan include a cutback in the ongoing research programme (with the Proton Synchrotron and Super Proton Synchrotron accelerators shutting down for all of 2005), redeployment of personnel to the LHC, new accounting and reporting measures and a reduction in accelerator R&D.

In its report, the ERC found that "the technical basis of the LHC accelerator is sound," and affirmed that the LHC is "the worldwide priority in high-energy physics". However, the ERC did find that the crisis that became apparent last year arose from "serious weaknesses... in cost awareness and control, as well as in contract management and financial reporting". The report makes various recommendations to improve financial procedures at CERN.

● September 2002 p5 (extract).

Lyn Evans (left) and Luciano Maiani at the breakthrough of a new transfer tunnel to the LHC on 15 May 2001.

● July/August 2001.

A complete LHC cell of six dipoles, straight sections, a prototype cryogenic distribution line and an electrical feedbox began tests in the full String 2 June 2002.

● October 2002 p5.

The first US-built magnet, came 6000 km by land and sea from the Brookhaven National Laboratory in New York to arrive at CERN in its container on 21 January 2003.

● March 2003 p5.

More than 80 dipole cold masses had arrived at CERN by late summer 2003. This one is being installed in the robotic "crab", designed to carry the magnets around the site.

● October 2003 p5.

Cryogenic unit keeps its cool

The cryogenic unit at Point 8 has reached its nominal temperature of 1.8 K.

The cryogenic system for the LHC reached a major milestone on 7 April by achieving operation of the unit at Point 8 at its nominal temperature of 1.8 K. The LHC and its superconducting magnets are designed to operate at this very low temperature, making the 27 km accelerator the coldest large-scale installation in the world. Although acceptance tests performed on the surface had already reached the required temperature in 2002, this is the first time that the nominal temperature has been achieved *in situ*.

The LHC cryogenics system is hugely complex, with 31 kt of material (compressor stations, cold boxes with expansion turbines and heat exchangers, and interconnecting lines) requiring 700 kl of liquid helium passing through 40 000 pipe junctions.

Although normal liquid helium at 4.5 K would be able to cool the magnets so that they became superconducting, the LHC will use superfluid helium at the lower temperature of 1.8 K. Superfluid helium has unusually efficient heat-transfer properties, allowing kilowatts of refrigeration to be transported over more than 1 km with a temperature drop of less than 0.1 K.

Eight cryogenic installations distributed around the LHC ring, with a total power exceeding 140 kW, will cool the helium in two stages, first to 4.5 K and then to the final 1.8 K. Four units built by the Japanese-Swiss consortium IHI-Linde have already been installed; the other four units, made by the French company Air Liquide, are currently being installed and will be tested in 2006.

● June 2005 p5 (extract).

On 7 March the first of the superconducting dipole magnets was lowered into the accelerator tunnel. The dipoles will be lowered 50 m below the surface via a special oval shaft and then taken through a transfer tunnel to their final destination for careful positioning in the LHC tunnel.

● April 2005 p5 (extract).

Further milestones

In the first week of September 2005, the last rolls of austenitic steel for the collars of the dipole magnets arrived at CERN from NSSC (Nippon Steel) in Japan. The collars are designed to contain most of the magnetic forces created in the eight layers of superconducting coil that provide the magnetic field.

The production of the collared coils is also well on track. On 8 August Babcock Noell Nuclear (BNN) delivered their last collared coil, completing their contract for one-third of the dipole magnet coils.

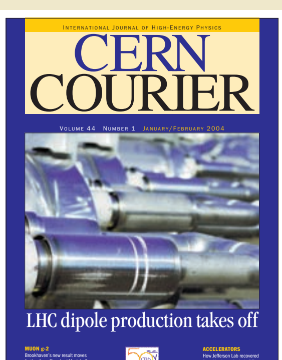
In mid-September 2005 the first 600 m of the cryogenic distribution line that will supply superfluid helium to the superconducting magnets passed initial testing at room and cryogenic temperatures. At the same time, the number of magnets installed in the tunnel passed the 100 mark, and several major contracts related to their construction have been successfully completed.

October saw the completion of the 60 km of vacuum pipes for the LHC beams by a single firm, DMV of Bergamo, Italy. These 16 m long pipes, made from austenitic steel, had to be continuously extruded and had to contain not a single weld in order to ensure perfect leak tightness between the vacuum inside and the superfluid helium outside.

● November 2005 p5 (extract).

The first 800 jacks for one sector of the LHC had arrived at CERN from India in autumn 2003. They are designed to adjust the positions of the 32 tonne magnets to 0.05 mm precision.

● December 2003 p8.



By December 2003 the industrial production of the superconducting dipoles was in full swing.

● Jan./Feb. 2004 pp30–32.

Repair of faulty elements in the cryogenic distribution line discovered in June 2004 got under way at CERN in November, allowing installation to proceed with help from other accelerator laboratories.

● January/February 2005 p5.

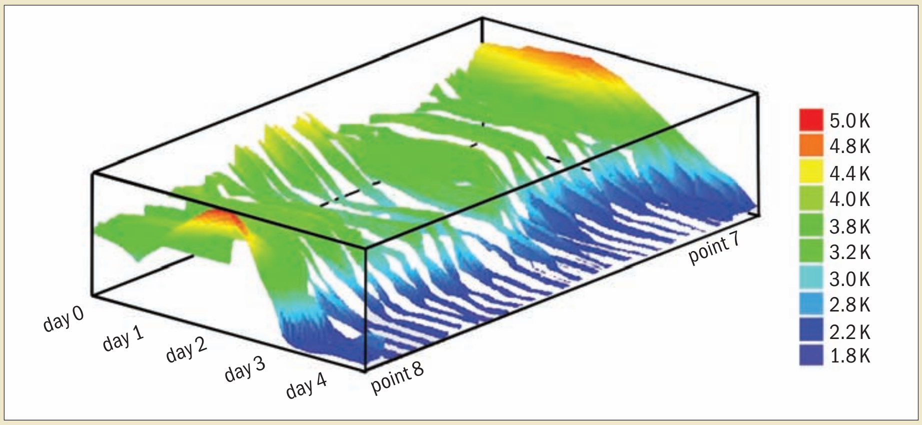
The first section of the cryogenic distribution line, corresponding to an eighth of the accelerator, has been tested at a temperature of 10 K since the end of November 2005.

● January/February 2006 p6.

An LHC sector reaches 1.9 K for the first time

The first sector of the LHC to be cooled reached its operating temperature of 1.9 K for the first time on 10 April. Although only an eighth of the LHC ring, this sector is already the world's largest superconducting installation. This achievement marks the end of more than two months of commissioning.

The 3.3 km sector comprises more than 200 dipole magnets and short straight sections, which contain quadrupole magnets, and has a total mass of 4700 tonnes. During the first stage, it was pre-cooled to 80 K just above the temperature of liquid nitrogen. At this temperature, the material reaches 90% of its final thermal contraction, representing a 3 mm shrinkage for each metre of the steel structures.



The magnet temperature profile along sector 7-8 during the final phase of the cool down.

On 5 March, the teams began work on the second stage, which involved cooling the sector to 4.5 K using the gigantic refrigeration plants (*CERN Courier* May 2004 p15). For the final stage, which began in mid-March, the 1.8 K refrigeration plants came into play. These use a sophisticated pumping system to bring down the heat-exchanger saturation pressure to cool the magnets and the 10 tonnes of helium that they contain to 1.9 K. To achieve a pressure of 15 millibars, the system uses a combination of hydrodynamic centrifugal compressors operating at low temperature and positive-displacement compressors operating at room temperature.

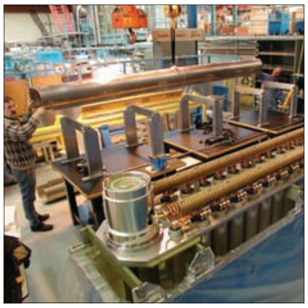
While the sector cooling progressed steadily, problems arose in a different sector when a quadrupole magnet, one of an "inner triplet" of three focusing magnets, failed a high-pressure test at Point 5 on 27 March. The goal is now to redesign and repair the inner triplet magnets; teams at CERN and Fermilab have identified potential repairs that could be carried out without removing undamaged triplet magnets from the tunnel.

● May 2007 p5 (abridged).

Plug-in faults

Teams detected a fault in one of the interconnections during the warm-up of sector 7-8, the first to have been cooled to 1.9 K. One of the "plug in" modules responsible for the continuity of the electrical circuit in each of the LHC's two vacuum chambers was damaged as the sector warmed up. X-ray studies revealed four more faulty modules in sector 7-8, but it was clear that a device that could check the space inside the beam pipes would be extremely useful. The solution is a ball 34 mm in diameter, which transmits at 40 MHz – the frequency of beam bunches in the LHC. A pumping system propels it through the vacuum pipe, and the beam-position monitors every 50 m pick up the signals.

● November 2007 p5 (extract).



Installation of pulse-forming networks for the LHC injection kickers, built and tested at TRIUMF (above) as part of the Canadian contribution to the LHC, began in May 2005.

● May 2006 p8.

Industrial production of the superconducting dipoles was set for completion in November 2006.

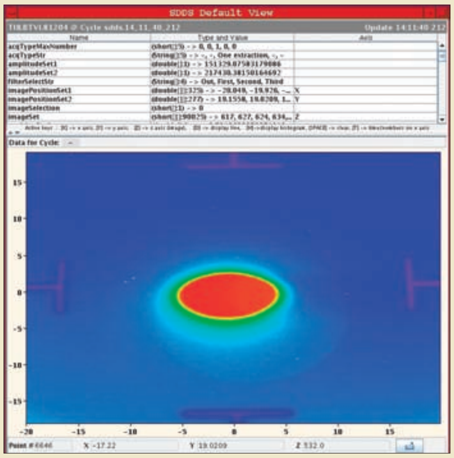
● October 2006 p28.

On 5 September 2006 the 1000th superconducting magnet system was installed in sector 3-4. During the same week, the final system for sector 8-1 was also installed.

● November 2006 p7.

The final superconducting magnet system, 15 m long and weighing 34 tonnes, made its descent into the accelerator tunnel on 26 April 2007.

● June 2007 p5.



A screen shot shows the successful passage of beam in the TI 8 transfer line.

Protons knock on the LHC's door

On 24 May, a proton beam arrived on the threshold of the LHC, passing down transfer line TI 8 to the LHC, which runs from the SPS towards the LHC, where it intersects just before point 8. The TI 8 line became operational in October 2004 (*CERN Courier* March 2005 p26).

Now a beam has passed along it for only the second time, on this occasion in preparation for the full LHC start-up. The beam was extracted from the SPS, sent down the 2.8 km transfer line and stopped just 15 m or so from the LHC tunnel.

● July/August 2008 p5.

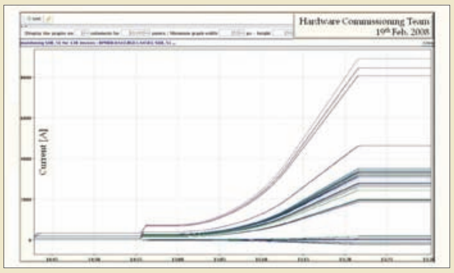
Making solid progress

Half of the LHC ring – between Point 5 and Point 1 – was below room temperature by the first week of April, with sectors 5-6 and 7-8 fully cooled. The next step for these sectors will be the electrical tests and powering up of the various circuits for the magnets. From late April onwards, every two weeks the LHC commissioning teams will have a new sector cooled to 1.9 K and ready for testing.

Sector 7-8 was the first to be cooled to 1.9 K in April 2007 and the quadrupole circuits in the sector were powered up to 6500 A during the summer. The valuable experience gained here allowed the hardware commissioning team to validate and improve its procedures and tools so that electrical tests on further sectors could be completed faster and more efficiently. Each sector has 200 circuits to test.

The next electrical tests were carried out on sector 4-5 from November 2007 to mid-February 2008. Once the temperature had been stabilized at 1.9 K by the beginning of December, the circuits were powered up to an initial 8.5 kA. The main dipole circuit was then gradually brought up to 10.2 kA during the last week of January 2008, with the main quadrupole circuits reaching 10.8 kA in February. At this current the magnets are capable of guiding a 6 TeV proton beam.

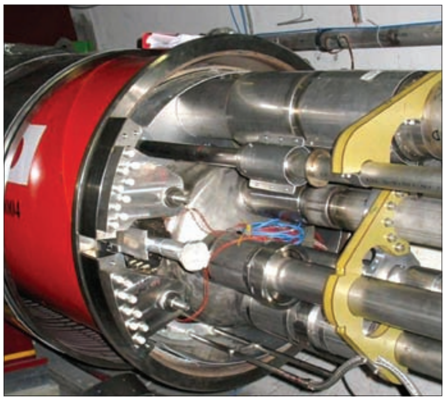
During this testing of sector 4-5, however, a number of magnet-training quenches occurred for both dipole and quadrupole circuits. Three dipoles in particular quenched at below 10.3 kA, despite having earlier been tested to the nominal LHC operating current of 11.8 kA. It appears that retraining of some magnets will be necessary, which is likely to take a few more weeks. CERN's management, with the agreement of all of the experiments and after having informed Council at the March session, decided to push for collisions at an energy of around 10 TeV as soon as possible this year, with full commissioning to 14 TeV expected to follow over the winter shutdown.



In electrical tests for sector 4-5 in February, 138 superconducting circuits ramped in unison to a current equivalent to a beam energy of 5.3 TeV.

Sector 5-6 will be the next to cross the 10 kA threshold; electrical tests here began in April. Sector 4-5, meanwhile, was warmed up again to allow mechanics to connect the inner triplet magnets, which were modified after a problem arose during pressure testing last year.

● May 2008 p5 (abridged).



On 13 July 2007, an inner triplet assembly of quadrupole magnets passed its pressure test in the tunnel after strengthening modifications.

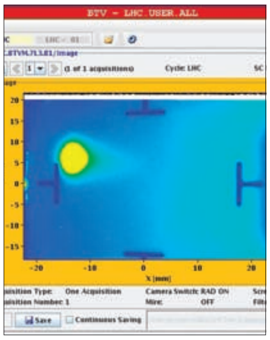
● September 2007 p5.

Director-general Robert Aymar sealed the last interconnect between the main magnets on 7 November 2007, at the end of two years of work involving 123 000 connections.

● December 2007 p7.

The LHC is on course to start up in 2008, with the machine components fully installed and commissioning well underway.

● Jan./Feb. 2008 p5.



Particles in the LHC! A bunch of protons arrives at point 3 on the very first attempt during synchronization tests on 8 August 2008.

● September 2008 p5.

Detail experts in high vacuum technology. No detail is too small

Oerlikon Leybold Vacuum has long-term experience in the development and production of vacuum components and is one of the largest vendors for turbomolecular pumps worldwide. These pumps are doing reliable service at almost all high-energy physics laboratories in the world. The experts at Leybold Vacuum help to shape vacuum solutions already in the development phases for new technologies.

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This new generation of TURBOVAC turbomolecular pumps with mechanical rotor suspension and compound stage excels through a new design in family character, an improved vacuum performance and a standardized accessories program.

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- TURBOVAC SL 80
- TURBOVAC SL 300
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Typical applications

The turbomolecular pumps from the TURBOVAC SL product family are designed to handle the most advanced and demanding applications and requirements in research and industry, including:

- Analytical instruments
- Leak detectors
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- Gas chromatography (GC-MS)
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The new market-launched TURBOVAC SL turbomolecular pumps product line.

- Coating technologies
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Features at a glance

- High flexibility in installation and communication
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- Small footprint
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Leybold Vacuum offers a broad product portfolio of components, accessories and services – all from a single source. Our vacuum engineering/design is superior to any other supplier for all kinds of vacuum systems. We support our customers: worldwide, with consulting and training at strategic centers of competence in Europe, USA and Asia. Leybold Vacuum offers Customer Care packages for global customers through our worldwide service net. In addition, customers rely on our experienced field service team. 24 hours, 7 days a week availability and an exchange program with back-up pool management ensure that our customers up-time and a reliable vacuum solution for their processes.

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- First launch of the MAGLEV pump in 1975
- First turbomolecular pump with integrated temperature management system (TMS) in 1989
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Going global: Japan helps LHC construction


Kaoru Yosano (left) and CERN's director-general Chris Llewellyn Smith paint one eye of a "daruma" talisman, marking commencement of Japanese collaboration in the LHC project.

As CERN's major project for the future, the LHC sets a new scale in world-wide scientific collaboration. As well as researchers and engineers from CERN's European Member States, preparations for the LHC now include scientists from several continents. Some 50% of the researchers involved in one way or another with preparations for the LHC experimental programme now come from countries that are not CERN Member States.

Underlining this enlarged international involvement is the recent decision by the Japanese Ministry of Education, Science and Culture to accord CERN a generous contribution of ¥5 bn (about Sfr65 m) to help finance the construction of the LHC. This money will be held in a special fund earmarked for construction of specific LHC components and related activities.

At the June Council session, Japan was unanimously elected as a CERN Observer State, giving them the right to attend Council meetings. Speaking at the Council meeting in his new capacity as Observer State spokesman, Kaoru Yosano, Japan's Minister of Education, Science and Culture, pointed to his country's wish to contribute to the LHC project at an early stage. He said that large scientific projects like the LHC "captivated the imagination of citizens".

● September 1995 p1 (extract).

CERN and Russia step up cooperation

The signing of a new protocol between CERN and Russia marks a considerable increase in joint collaboration and a further consolidation of ties dating back 30 years. As well as directly assisting construction of CERN's new LHC proton collider, the protocol, within the framework of the 1993 CERN–Russia Cooperation Agreement, and with Russia as a CERN Observer State, will provide valuable further stimulus for Russian high technology.

Covering Russian participation in LHC construction and the preparations for its research programme over a 10 year period, the protocol includes two separate in-kind contributions, each with net value to CERN of Sfr67 m, for LHC construction and for the LHC detectors. In addition, a generous contribution from the Joint Institute for Nuclear Research at Dubna, near Moscow, will be invested in LHC preparations.

This latest two-way development in CERN/Russian collaboration will be to the mutual advantage of both parties. It will boost the LHC effort en route to completion of the machine at its full design collision energy of 14 TeV. In addition, the increased scope and scale of this challenging work, together with its inherent complexity and sophistication, will provide impetus to Russian science and industry, and provide vital transfer of front-line technology and skills.

As well as the new protocol, additional contributions to LHC experiments could come through the International Science Technology Centre programme funded by the European Union, Japan, Russia and the US to promote the integration of former Soviet Union weapons scientists into fresh projects, and where six particle physics projects have already been approved.

● September 1996 p32–33 (extract).


Loading a 6 m dipole magnet prior to the 6000 km journey from Novosibirsk to CERN in 1999.

● September 1999 p11.

After the SSC

In the wake of the demise of the US Superconducting Supercollider (SSC) project (p21), which impoverished both US and world science, some rapid scene shifting is going on. The SSC may be dead, but the underlying physics quest lives on.

To nurture the natural enthusiasm to continue this physics, contacts have been developing at several levels. In December 1993, informal exploratory talks were held at CERN between spokesmen of the LHC experiments and their counterparts from the major SDC and GEM projects which were being readied for the SSC, and with CERN management. The object was the common interest in multi-TeV physics at the LHC, and, once this is in place, to exploit valuable R&D already accomplished and the high level of expertise achieved in the SSC framework. A substantial number of US physicists involved in SDC and GEM could be interested in joining LHC experiments, together with Japanese researchers involved in SDC. Many of the SDC Canadian contingent could also turn their sights towards Geneva.

● April 1994 pp1–2 (extract).

US and CERN sign historic LHC agreement

In a significant international agreement, signed in Washington, DC, on 8 December, US scientists will contribute a total of $531 m towards the 27 km LHC now under construction and its physics experiments. This is the first time that the US will contribute significantly for an accelerator to be built outside the US, and it is the first agreement between CERN and the US government. About 25% of the US experimental high-energy physics community are expected to do research at the LHC.

Under the agreement, the US will provide goods and services for the LHC, scheduled to come into operation in 2005. Specifically, the Department of Energy will provide components and materials, costed at $200 m, for use in the accelerator. Three of the department's national laboratories, Brookhaven, Berkeley and Fermilab, will use $110 m to design and produce systems for the accelerator's interaction regions where the detectors are located. The remaining $90 m will be used for procurements from US industrial firms, including niobium and niobium–titanium for European production of superconducting cable, and for some of the superconducting cable supply.

The US will also provide an in-kind contribution of components, costed at $331 m, to the massive ATLAS and CMS detectors, with $250 m from the Department of Energy and $81 m from the National Science Foundation. More than 550 US scientists from nearly 60 universities and six national laboratories in 25 states are collaborating on designing and fabricating these components.

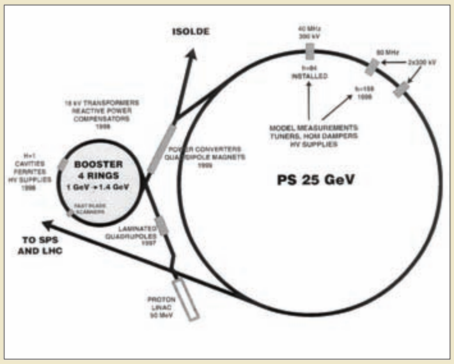
Further protocols were signed during the meetings of CERN's governing body, Council, at CERN at the end of December, when the US joined the growing ranks of CERN observer states.

● January/February 1998 p1 (extract).

Canada makes a TRIUMFant contribution

Since 1995 the TRIUMF Laboratory in Vancouver has been collaborating with CERN staff to provide a five-year $30-Canadian contribution to CERN's LHC collider complex. This is in addition to contributions to the LHC detectors, and has involved activities in a variety of areas, not only on the LHC itself, but also on the machines in the injector chain, especially in this initial phase. In particular, the Proton Synchrotron (PS) and its Booster require major modifications to deliver proton beams with much higher brightness, more strictly controlled emittance, and a different bunch spacing.

As most of the equipment required for the PS and Booster had to be installed during the 1997–1998 winter shutdown, last year was an especially challenging period for TRIUMF staff and for the many companies manufacturing the components. Happily, the commitments were all met, though not without special efforts and some use of air freight!



CERN's PS complex, showing the equipment (shaded blocks) contributed to the LHC injector train by Canada via TRIUMF.

The ALSTOM Canada assembly team beside the last of the 52 twin-aperture "warm" quadrupole magnets delivered to CERN in 2003. (Courtesy Yvon Langevin, ALSTOM Canada.)

● January/February 2004 p9.

Although the majority of the Canadian contributions have been directed to the PS complex, others have involved the SPS and LHC. For the LHC itself, Canada is contributing to the injection kickers, the cleaning-insertion quadrupoles, and the current calibration equipment. Besides all these hardware contributions, CERN and TRIUMF staff have been collaborating on a variety of beam dynamics studies.

● April 1998 p5 (extract).

India gains observer status

With the activities surrounding the LHC, CERN's community of scientific users has grown to comprise about half of the world's experimental particle physicists, with nearly a third coming from outside the CERN member states. India has been an active partner for many years, and in the December meeting, Council granted the country observer status.

In the past, India has contributed equipment and technical teams to LEP, the PS injector complex and fixed-target experiments. This effort was formalized in a cooperation agreement in 1991, extended in 2001 for a further decade. Then, in the framework of the 1996 protocol signed with the Indian Department of Atomic Energy, India is one of the first nonmember states to contribute significantly to the LHC: Indian scientists work on the ALICE and CMS collaborations, and Indian IT expertise is used in Grid computing projects.

● January/February 2003 p5 (extract).

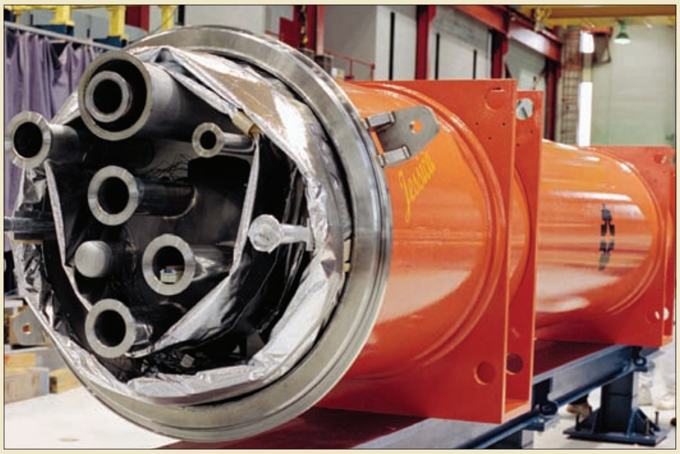

New
feedthroughs
MDC MFG INC

A machine for the world

Nations outside CERN's 20 member states have also made major contributions to the construction of the new collider.

The LHC has attracted significant contributions from several major nations outside the CERN member-state community, making it truly a world machine.

In addition to these important contributions from Canada, India, Japan, Russia and the US, CERN host-states France and Switzerland also contribute significant additional resources to the LHC above and beyond their natural involvement as part of the 20-nation European CERN community.



A prototype superconducting quadrupole magnet for the interaction regions at the LHC under assembly at Fermilab. Similar magnets are also being supplied by Japan.

Canada

The contribution to the LHC from Canada is valued at C$40 m, much of which is used for hardware to help to upgrade the injector chain, particularly the Booster and the PS synchrotron. This involvement goes back to 1995 and is coordinated by the Canadian TRIUMF laboratory.

Equipment includes ferrite rings, and the tuning and high-voltage power supplies for four new radiofrequency cavities for the Booster, which was upgraded from 1 to 1.4 GeV specifically for its new role in the LHC injector chain.

Canadian contributions also include most of the magnets and power supplies for the transfer line between the Booster and the PS, major equipment for the Booster main magnet power supply, and a reactive power compensator to reduce Booster-induced transients on CERN's electrical supply system.

A second wave of Canadian contribution is mainly for the LHC ring, including 52 twin-aperture quadrupole magnets for "beam cleaning" insertions, together with power supplies for kicker magnets, pulse-forming networks and switches. Canada will also develop beam-position-monitor electronics and carry out some beam optics studies.

The Budker Institute of Nuclear Physics in Novosibirsk supplied some 540 magnets for the transfer lines from the SPS to the LHC, as part of the Russian contribution.

India

The initial CERN–India cooperation agreement was signed in 1991 and is renewed every five years. The value of equipment covered is $25 m, of which half is transferred by CERN into a special fund to underwrite further joint ventures.

The main Indian hardware contribution is superconducting sextupole and decapole spool pieces amounting to half of the total LHC requirement for such corrector magnet equipment. In addition, India will supply LHC magnet support jacks and quench heater power supplies.

Circuit breakers are being supplied by Russia, but India remains responsible for the necessary electronics. In addition, India is carrying out several programming and documentation projects.

Japan

Japan's early entry into the LHC arena in 1995 provided a memorable boost for the project. Japanese contributions currently total approximately ¥13 850 m (some SFr160 m). Of this sum, some SFr25 m was earmarked for construction of the solenoid magnet for the ATLAS experiment.

The KEK national laboratory acts as a major coordinator for all of this work. Japan is the source of much of the basic material (steel and superconducting cable) for the LHC.

A further significant Japanese contribution to the LHC is the 16 quadrupoles used to squeeze the colliding beams and boost the interaction rate. Also on the list of equipment are compressors for cooling superfluid helium. ▷

As a special contribution, Switzerland is underwriting the construction cost of one of the tunnels through which protons will eventually be fed to the 27 km LHC ring.

Russia

The contribution of the Russian Federation to the LHC machine is valued at SFr100 m. One-third is channelled into a special fund for CERN–Russian collaboration.

The largest and most visible part of this contribution is the thousands of tonnes of magnets and equipment for the beamlines to link the SPS synchrotron to the LHC. The supply of this equipment from Novosibirsk will soon be complete. Novosibirsk is also supplying insertion magnets for the LHC ring.

The Protvino laboratory is responsible for 18 extraction magnets and the circuit breakers that will receive the electronics from India. The Joint Institute for Nuclear Research, Dubna, is contributing a damping system, and a number of other Russian research centres will furnish a range of items and equipment, including design work, radiation studies, survey targets, ceramic components, busbars and shielding.

USA

Work in the US for the LHC centres on interaction regions 1, 2, 5 and 8, together with some radiofrequency equipment for Point 4. The work is shared between the Brookhaven, Fermilab and Lawrence Berkeley National laboratories.

The impressive list of contributed hardware includes superconducting quadrupoles and their cryostats for beam intersections (Fermilab), superconducting dipoles for beam separation (Brookhaven) and cryogenic feed boxes (Berkeley).

The beam insertion hardware overlaps with that from Japan, and there has been excellent co-operation on LHC contributions between these two industrial giant nations.

Host nations

France and Switzerland, as CERN host nations, make special contributions to the LHC. For France, this includes 218 person-years of work, spread over four major technical agreements, covering the cold mass for LHC short straight sections (handled by the CEA Atomic Energy Commission), the short straight section cryostats and assembly (by the CNRS national research agency), calibration of 8000 thermometers for the LHC (by the Orsay laboratory), and design and series fabrication work for the superfluid helium refrigeration system (CEA).

Testing times

The first testing of series production LHC magnets began in 2001, with two test benches and a limited cryogenic infrastructure. The first sets of dipoles had to be thoroughly tested, with full magnetic and other measurements. This extensive testing, together with the limited operational experience and support tools, meant that some 20–30 days were required to test a magnet during 2001–2002, and only 21 magnets were tested in this period.

To increase throughput, the test facility began to operate round the clock early in 2003. With a final set-up of 12 test benches and a minimum of 4 people per shift, this required a minimum team of 24. The initial plan had been to outsource, but by early 2002 it was clear that this was no longer an option. It was at this time that the Department of Atomic Energy (DAE), India, offered technical human resources for SM18. A collaboration agreement between India and CERN had been in place since the 1990s, including a 10 man-year arrangement for tests and measurements during the magnet prototyping phase. This eventually allowed more than 90 qualified personnel from four different Indian establishments to participate in the magnet tests on a one-year rotational basis (a condition requested by India) starting around 2002.

● June 2007 pp19–22 (extract).

In addition to this national involvement, the local Rhone-Alpes regional government and the départements of Ain and Haute-Savoie also contribute.

Under the regional government plan, about 90 person-years of assistance will be supplied by young graduates of technical and engineering universities. Haute-Savoie contributes design work on the integration of microelectronics for the LHC cryogenic system.

In addition, the LAPP laboratory at Annecy is developing ultrasonic equipment to monitor superconducting dipole interconnections, and it is doing design work for the vacuum chambers of the major LHC experiments. Ain has contributed the land to build a major new construction and assembly hall next to the CERN site.

The Swiss contribution comes from the federal government and the canton of Geneva, and it covers the cost of a 2.5 km tunnel through which protons will be fed from the SPS to the LHC in the anticlockwise direction.

● September 2001 pp15–17 (abridged).

Résumé

Le LHC a bénéficié de contributions importantes d'États autres que les 20 États membres, en particulier, le Canada, les États-Unis, l'Inde, le Japon et la Russie. Les États hôtes, la France et la Suisse, ont également apporté des ressources supplémentaires, en sus de leur contribution en tant qu'États membres.

UK@CERN 2008

The successful Meet the Buyer event in September enabled CERN, and other Large Facilities to meet with UK industry representatives. UK Trade & Investment and the Science and Technology Facilities Council are pleased to announce a follow-up UK industry mission to CERN, ESRF and ILL.

16-20 November 2008

This event will take a select group of UK companies to see first hand the types of research and industrial opportunities available.
There will be one-to-one meetings between companies and procurement specialists and researchers, with a focus on opportunities arising in the next twelve months.
For further information please contact Sarah Webb (see below).

Further support for industry engagement is provided by the Knowledge Exchange team based at the STFC's Swindon Headquarters

Penny Woodman is heading up the Swindon KE team and is putting together a structured programme of visits for industry to meet with research groups. Her team will help you make introductions to other research areas and find industrial contacts through KITE Club events. (penny.woodman@stfc.ac.uk)

http://www.scitech.ac.uk/KE/Ind/KITE/KClub/Contents.aspx

Business opportunities management

Sarah Webb, Business Opportunities Manager, has also been scouring the length and breadth of the UK getting to know who has relevant manufacturing and R&D expertise in specific fields. She is always on the lookout for new companies to talk to and welcomes you to contact her. (sarah.webb@stfc.ac.uk)

A titan fit for the LHC

The ATLAS detector is built around a huge and unusual air-core toroid magnet.

In Greek mythology, Atlas was a Titan who had to hold up the heavens with his hands as a punishment for having taken part in a revolt against the Olympians. For LHC, the ATLAS detector will also have an onerous physics burden to bear, but this is seen as a golden opportunity rather than a punishment.

The major physics goal of CERN's LHC proton–proton collider is the quest for the long-awaited "Higgs" mechanism, which drives the spontaneous symmetry breaking of the electroweak Standard Model picture. The large ATLAS collaboration proposes a large general-purpose detector to exploit the full discovery potential of LHC's proton collisions. LHC will provide proton–proton collision luminosities at the awe inspiring level of $10^{34}\,cm^{-2}\,s^{-1}$, with initial running in at 10^{33}. The ATLAS philosophy is to handle as many signatures as possible at all luminosity levels, with the initial running providing more complex possibilities.

The ATLAS concept was first presented as a letter of intent to the LHC Committee in November 1992. Following initial presentations at the Evian meeting in March of that year, two ideas for general-purpose detectors, the ASCOT and EAGLE schemes, merged, with Friedrich Dydak (MPI Munich) and Peter Jenni (CERN) as ATLAS co-spokesmen.

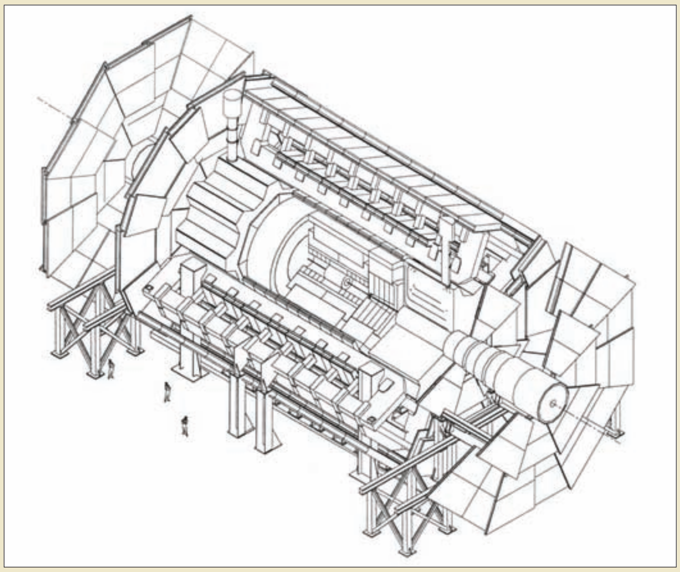
Since the initial letter of intent presentation, the ATLAS design has been optimized and developed, guided by physics performance studies and the LHC-oriented detector R&D programme. The overall detector concept is characterized by an inner superconducting solenoid (for inner tracking) and large superconducting air-core toroids outside the calorimetry. This solution avoids constraining the calorimetry while providing a high-resolution, large acceptance and robust detector.

The outer magnet will extend over a length of 26 m with an outer diameter of almost 20 m. The total weight of the detector is 7000 tonnes. Fitted with its endcap toroids, the outer magnet alone will weigh 1400 tonnes.

Designs on calorimetry

To achieve its basic aims, the ATLAS design has gone for very good electromagnetic calorimetry for electron and photon identification and measurements, complemented by complete (hermetic) jet and missing energy calorimetry; efficient tracking at high luminosity for lepton momentum measurements, for heavy quark tagging, and for good electron and photon identification, as well as heavy-flavour vertexing and reconstruction capability; precision muon-momentum measurements up to the highest luminosities and very low transverse-momentum triggering at lower luminosities. Other overall design aims include large angular coverage together with triggering and particle-momentum capabilities at low transverse momenta.

The inner detector is contained in a cylinder 6.8 m long (with a solenoid of length 5.3 m) and diameter 2.3 m, providing a magnetic field of 2 T. Design of the coil is being developed by the Japanese KEK Laboratory. Reflecting LHC's bold physics aims and the pace of detector R&D, this inner detector is packed with innovative tracking technology (compared with existing major detectors), including high-resolution pixel and strip detectors inside and straw tubes with transition radiation capability farther away from the beam pipe. Finest granularity will be provided by semiconductor pixel detectors immediately around the beam pipe, providing about a hundred million pixels. With this technology moving rapidly, the final solution will benefit from ongoing R&D work.



Cutaway view of the ATLAS detector. The outer toroidal magnet will extend over 26 m, with an outer diameter of almost 20 m. The total weight of the detector is 7000 tonnes.

Surrounding the tracking region will be highly granular electromagnetic-sampling calorimetry, probably based on liquid argon (however, studies on an alternative liquid-krypton scheme are still in progress), contained in an "accordion" absorber structure in a cylinder 7 m long and 4.5 m across, plus two endcaps. The inner solenoid coil is integrated into the vacuum vessel of the calorimeter cryogenics, reducing the amount of material that emerging particles have to cross.

Liquid argon is used for both electromagnetic and hadronic calorimetry in the endcaps of the calorimeter, the former arranged in a "Spanish fan" geometry to cover all azimuthal angles without cracks, the latter in a wheel-like structure using copper absorber. Integrated into the endcaps is the forward calorimetry based on an array of rods and tubes embedded in a tungsten absorber some 5 m from the interaction point.

The bulk of the hadronic calorimetry is provided by three large ▷

Tiles and accordions

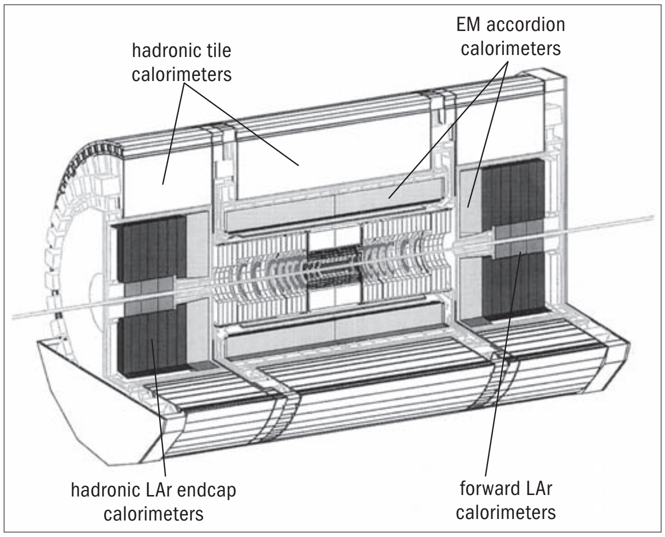
Design work and prototyping is well under way for the modules that will make up the ATLAS detector. One feature of the design stresses very good electromagnetic calorimetry for electron and photon identification and measurements, complemented by accurate measurements of hadronic jets and missing energy.

Arranged as a conventional central barrel with two endcaps, the inner part (including endcaps) uses the very-radiation-resistant liquid argon technique for electromagnetic measurements, contained in a 13 m long cylinder with outer radius 2.25 m, surrounded by less expensive iron-scintillator tiles sampling calorimetry for the hadronic part, extending to a radius of 4.25 m.

In the inner part of the endcaps, liquid argon is also used for the hadronic calorimeter. Special requirements are needed for the forward calorimeter around the beam pipe, about 5 m from the collision point. Fully integrated with the endcaps, liquid argon is again the sampling medium of choice.

For the electromagnetic liquid-argon part, the 1024 lead–stainless steel converters of the sampling calorimeter are arranged in a novel corrugated "accordion" structure, with plates following the direction of the emerging secondary particles.

The barrel hadronic calorimetry is provided by an active medium of 3 mm-thick scintillator tiles, interleaved with absorber in the form of 14 mm steel sheets, and fashioned as a large 2500-tonne cylinder to surround the liquid argon barrel and endcaps. Full-scale prototypes under test show promising energy resolution.



Schematic of the electromagnetic (EM) and hadronic calorimetry in ATLAS, showing the central barrel and endcaps.

● April 1997 pp5–6 (abridged).

barrels of a novel tile scintillator with plastic scintillator plates embedded in iron absorber and read out by wavelength-shifting fibres. The tiles, laid perpendicular to the beam direction, are staggered in depth to simplify construction and fibre routing. The total weight of the calorimetry system is 4000 tonnes (the entire UA1 detector that ran at CERN's proton–antiproton collider for a decade and was considered a big detector in its time, weighed 2000 tonnes).

The air-core toroid magnet, with its long barrel and inserted endcaps, generates a substantial field over a large volume but with a light and open structure that minimizes troublesome multiple scattering. The toroid route was chosen because this geometry features the magnetic field perpendicular to the particle, and avoids large volumes of iron flux return. The French Saclay Laboratory is responsible for the barrel and the British Rutherford Appleton Laboratory for the endcaps.

Interleaved with the main air-toroid magnet will be the muon chambers, the last outposts of ATLAS. These chambers, arranged in projective towers in the barrel region, are diametrically 22 m apart, with the central muon barrel extending 26 m and forward muon chambers 42 m apart, along the beam direction. Cathode-strip chambers will be used in the highest-rate environment close to the beam direction, supplemented farther out by "monitored" drift tubes – pressurized thin-wall tubes arranged in several layers.

Overall, ATLAS so far involves some 1500 scientists and engineers representing 140 institutions in 31 countries (including 17 CERN member states). The participation of non-member state groups is still subject to the satisfactory establishment of bilateral agreements between CERN and the appropriate funding agencies. However, their potential involvement in ATLAS is already woven deeply into the fabric of the collaboration.

For example, semiconductor strips for the inner detector could involve teams from institutes in Australia, Canada, the Czech Republic, Finland, Germany, Japan, Norway, Poland, Russia, Sweden, Switzerland, the UK and the US, while the scintillator tiles could involve Armenia, Brazil, the Czech Republic, France, Italy, Portugal, Romania, Russia, Spain, Sweden, CERN and the US.

In addition to the 7000 tonnes of ATLAS hardware, a major effort is also required for software and data acquisition. To handle ATLAS data, the first-level trigger, which identify unambiguously which event crossing is responsible for the event, operates at the full-bunch crossing rate of 40 MHz (one bunch every 25 ns). It takes about 2 μs for the first-level trigger information to take shape and be distributed. During level-1 trigger-processing time, all data is held in pipelines prior to output at 100 kHz for subsequent processing at level 2. During these 10 ms, the level-2 processors look at subsets of detector data before passing it on for final processing (at about 1 kHz) at level 3, where complete event reconstruction becomes possible. Trigger processors at all three levels will be programmable.

● June 1995 p9 (abridged).

Résumé

La collaboration ATLAS est née de deux projets de détecteur pour le LHC, ASCOT et EAGLE. Le concept général du ce détecteur s'est caractérisé depuis le début par un solénoïde interne supraconducteur et de grands toroïdes à air à l'extérieur du système de calorimétrie.

Thales, a long-standing partner to the international scientific community

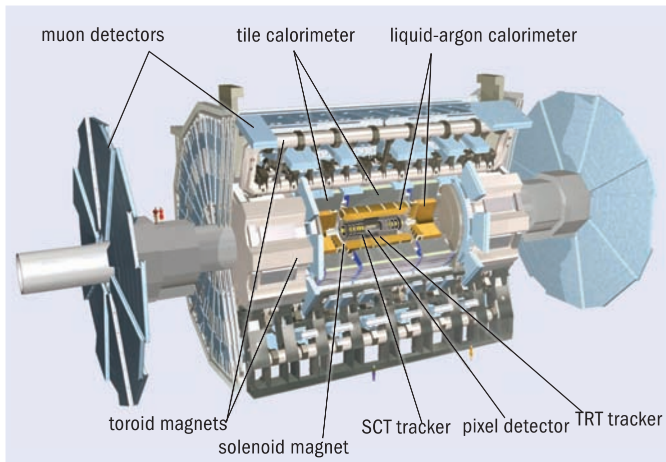
For more than fifty years, Thales has been building a long term relationship with the scientific community and has been involved in most of the major Particle Physics projects all around the world. Today we are proud to participate to the LHC program by providing the majority of the amplifier tubes for the whole injector chain (linacs and synchrotrons) and the main ring. Many different types of grid tubes, showing outstanding lifetimes in demanding operating conditions, are feeding the injection linacs, booster and proton synchrotrons with RF. In addition, Thales TH 2167 klystrons, enabling, in cw operation, 300 kW at 400 MHz, are installed on all the LHC super-conducting cavities. These klystrons, specifically developed for CERN conditions and delivered in accordance with the original scheduled planning, have been commissioned with CERN support and are now fully operational for the first proton collisions starting from September 08.

In parallel, Thales is already involved in the future upgrades of the LHC program. Taking benefit of more than 30 years of experience with several hundreds of thousands hours of operation on the former LEP ring, Thales high power UHF klystrons will be used on the Linac4 new injector, first step towards the future SLHC project. Thales grid tube solutions are also under investigation to upgrade RF systems for new experiments including future bunching systems and amplifiers for neutrino experiments. Finally, and in the frame of the Compact Linear Collider (CLIC) project (lepton collider using a two beams concept), Thales produces S-band klystrons and associated components that are intensively used on the CTF3 test stand.

With such exclusive klystron and grid tube positions, Thales will remain a key partner for the next 25 years of scientific experiments at CERN.

The making of a giant

Peter Jenni talks about the ATLAS experiment and expectations for future physics.



ATLAS is the well deserved name for the largest-volume detector ever constructed at a particle collider. It sits about 100 m underground in a cavern that could accommodate the Arc de Triomphe in Paris. A multipurpose detector, its physics goals range from the search for the Higgs boson and supersymmetric particles to the exploration of extra dimensions and other alternative scenarios.

The ATLAS collaboration was born in the autumn of 1992 from the merging of two existing groups, ASCOT and EAGLE, that had presented different expressions of interest at the meeting in Evian the previous March. By the end of 1994, the ATLAS collaboration had taken shape and submitted the technical proposal. "In summer 1995 the detector was pretty much the same as it is today with the exception of the inner detector, whose technical design report was presented later, in 1997," says Peter Jenni, (co-)spokesperson of the ATLAS collaboration since the beginning. "When, we submitted the technical proposal in December 1994, all the big decisions, such as which type of calorimeter or magnetic field to use, had already been taken."

So, after about 15 years in the making, not much has changed from the original design for ATLAS. There were only ever two main turning points. "Until 1997, the design of the precision chambers in the inner detector was not established," explains Jenni. "The collaboration was hesitating between using microstrip gas chambers and silicon strips in the outer layer. It finally decided to adopt the silicon solution. In 2002, the ATLAS detector underwent an internal financial audit and the resources review board accepted a completion plan with a reduced budget. As a result, the development of some parts of the detector had to be postponed. The impact of such financial cuts was particularly significant on the high-level trigger and data acquisition, but some features of the inner detector, the muon system, the electronics of the calorimeter and the shielding system had to be reviewed as well." Since then, not all these projects have been completed, and some of them never will be. "However," says Jenni, "this does not affect the main design or performance of the detector."

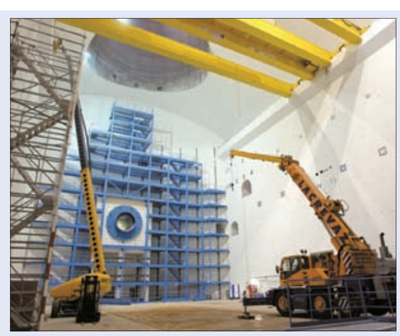
The detector was designed from the beginning to study a range of phenomena. "The initial design requirements of ATLAS were optimized for the search for the Higgs boson and supersymmetric particles," confirms Jenni. "The Higgs boson always featured strongly because, depending on the mass, the decays to deal

The coil winding for the central solenoid magnet was completed in Japan in 1999. The superconducting magnet provides a field of 2 T at the centre of ATLAS's tracking volume.

● December 1999 p5.

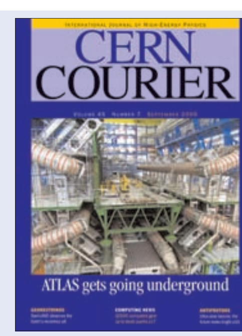
The prototype B-0 toroid coil arrived at CERN from the CEA laboratory in Saclay on 6 October 2000. At "only" 9 m in length this prototype is the largest toroid coil ever built.

● December 2000 p6.



The ATLAS cavern was handed over to CERN by the civil engineering contractors in a ceremony on 4 June 2003. This 12 storey access structure was one of the first items installed.

● November 2003 pp26–28.



As the toroid magnet took shape, on 21 June 2005 the barrel calorimeter (p40) saw the first cosmic-ray events in situ.

● September 2005 p7.

with experimentally are very different. Therefore it is an excellent benchmark for making sure you have built a detector with many capabilities."

If the ATLAS detector has not changed much since 1995, the physics panorama has. New particles have come onto the scene, as well as new scenarios that attempt to describe the first moments of the universe. "ATLAS will be able to study the signature of still-to-be discovered heavy objects decaying into electron pairs or muon pairs, such as the Z'," explains Jenni. "The superconducting toroid system allows us to measure muons with great precision, even with the highest luminosity, independently from the inner detector." Jenni also expects an excellent performance for studying signatures from particles coming from possible supersymmetry (SUSY). "Our detector has a particularly good hadronic calorimeter, which will allow us to measure accurately the missing energy associated with the possible existence of SUSY or extra dimensions. Moreover, if there is a graviton-like resonance from extra-dimension scenarios we will have to measure the angular distribution. In this case, toroids have the advantage that the field is optimal also in the forward direction." In Jenni's opinion: "The performance of detectors with high luminosity will make the difference in the race for discovery in the long run."

However, according to the most recent schedules, such high luminosity will not be available at the LHC until 2011 or 2012. In particular, the first protons will collide in the LHC at 5 TeV, rather than at 7 TeV. Instead of being disappointed, Jenni is pragmatic. "We will use the first two-month run to get to know and test the detector with known signatures, such as the W boson and the top quark – 10 TeV at low luminosity will already give us a lot of data to calibrate, as well as understand all the subdetectors and the chain of data preparation and analysis. Before any discovery can be claimed we first have to show that the known physics is reproduced and that the detector performs well."

After this first learning phase, the collaboration will be ready for 2009, when the accelerator will run at full energy and increasing luminosity. If the expected Higgs boson really exists, ATLAS will start to record its signatures. "An estimate for finding the Higgs is not before 2010, but this seems rather optimistic," says Jenni. "For SUSY or extra dimensions, the time needed to study the signatures depends on the different theoretical models. We could cast light on some of them before the Higgs can be confirmed".

When it comes to discoveries, an important aspect for the collaboration and for CERN will be how they will be disseminated. "The first thing we will take care of is to publish our results in a scientific review, not in the *New York Times*," declares Jenni. "Then will come the sharing of the excitement of the results with the public and this is a very important aspect. For an experiment like ATLAS, outreach is an important activity. I think that it is crucial to involve active scientists, although scientists do not necessarily know how to deal with it. We will all have to learn how to do it together with CERN."

ATLAS has been a pioneer in this field, with an attractive website that features video material, interactive games, press kits, regular news etc. "Inside ATLAS we have some communication plans to deal with the publication of the first results. There is already quite a lot of preparation of educational resources to be used to explain how things work. An EU co-funded project has recently received a first approval from the Commission," continues Jenni. "All this, however, seems rather theoretical for the moment. I feel that we will have to learn how to do things for real."

In the race for discovery at the LHC, ATLAS is not alone. The collaborations are competitors, but they are also allied because what one detector sees will have to be confirmed by the others. "Different detectors have made different choices, giving priority to different features (calorimetry, particle identification systems etc). Physics will tell us who made the right choice," confirms Jenni. "Having invested so much in this powerful multipurpose detector, it is clear that the ambition and duty of ATLAS is to exploit the LHC potential to the maximum".

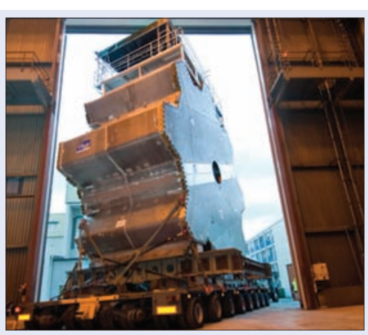
Résumé

ATLAS, le détecteur géant, a peu changé par rapport à la conception d'origine, à l'exception du choix du détecteur interne. Ses objectifs de physique vont de la recherche du boson de Higgs à l'exploration des dimensions supplémentaires de l'espace.

Peter Jenni *talked to* **Antonella Del Rosso**, *CERN.*

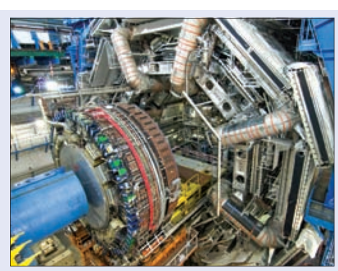
The final barrel for the ATLAS Semiconductor Tracker (SCT), was delivered in September 2005. Its integration into the full barrel assembly followed a few days later.

● November 2005 pp6–7.



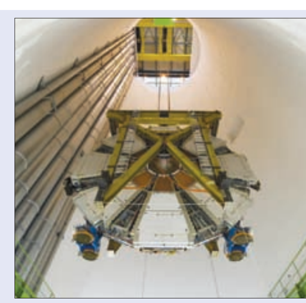
Moving at 1 km/hour on a special trailer the first of the endcap toroids leaves the assembly hall in February 2007 before being cold-tested at 80 K, prior to installation in the cavern.

● March 2007 p6.



Many of the final systems of the ATLAS detector (seen here with the endcap calorimeter system withdrawn) were tested with cosmic-ray data in June 2007 in the third "milestone week" of global commissioning.

● September 2007 pp23–25.



The final large piece of the ATLAS detector was lowered into the underground cavern on 29 February 2008. The "small" muon wheel safely made the 100 m journey in an hour and a half.

● April 2008 p5.

A study in compactness

A superconducting solenoid and precision calorimetry figured in the design for the CMS.

The milestone workshops on LHC experiments in Aachen in 1990 and at Evian in 1992 provided the first sketches of how LHC detectors might look. The concept of a compact general-purpose LHC experiment based on a solenoid to provide the magnetic field was first discussed at Aachen, and the formal expression of interest was aired at Evian. It was here that the Compact Muon Solenoid (CMS) name first became public.

Optimizing first the muon-detection system is a natural starting point for a high-luminosity (interaction rate) proton–proton collider experiment. The compact CMS design called for a strong magnetic field, of some 4 T, using a superconducting solenoid, originally about 14 m long and 6 m bore. (By LHC standards, this warrants the adjective "compact".)

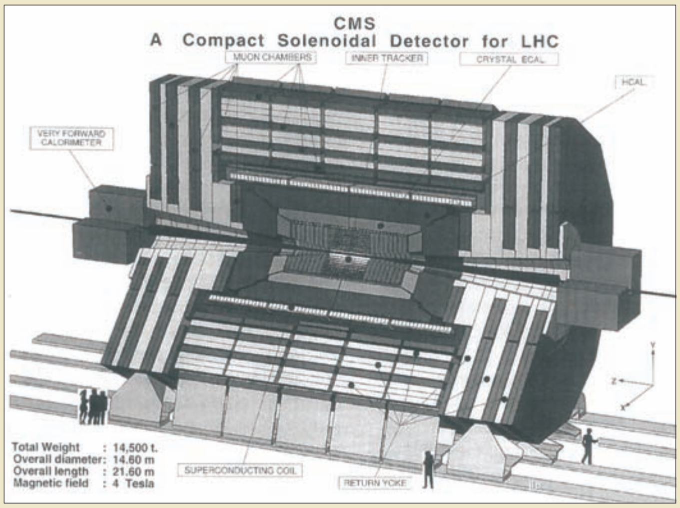
The main design goals of CMS are: 1) a very good muon system providing many possibilities for momentum measurement; 2) the best possible electromagnetic calorimeter consistent with the above; 3) high-quality central tracking to achieve both the above; and 4) an affordable detector.

Overall, CMS aims to detect cleanly the diverse signatures of new physics by identifying and precisely measuring muons, electrons and photons over a large energy range at very high collision rates, while also exploiting the lower luminosity initial running. As well as proton–proton collisions, CMS will also be able to look at the muons emerging from LHC heavy-ion beam collisions.

The Evian CMS conceptual design foresaw the full calorimetry inside the solenoid, with emphasis on precision electromagnetic calorimetry for picking up photons. (A light Higgs particle will probably be seen via its decay into photon pairs.) The muon system now foresaw four stations. Inner tracking would use silicon microstrips and microstrip gas chambers, with over 10^7 channels offering high track-finding efficiency. In the central CMS barrel, the tracking elements are mounted on spirals, providing space for cabling and cooling.

Following Evian, a letter of intent signed by 443 scientists from 62 institutes was presented to the then new LHC Experiments Committee. Two electromagnetic-calorimetry routes were proposed, a preferred one based on homogeneous media, and the other on a less expensive sampling solution using a lead/scintillator sandwich read out by wavelength-shifting fibres, named shashlik.

Due to limited resources in the collaboration at the time, the shashlik solution was adopted as baseline. However, R&D continued on cerium fluoride (CeF_3) and two other candidate media, lead-tungstate crystals ($PbWO_4$) and hafnium-fluoride glasses. The collaboration had doubled in size by the summer of 1994 and in September of that year lead tungstate was chosen after extensive beam tests of matrices of shashlik, cerium fluoride and tungstate towers. The radiation length of $PbWO_4$ is only 0.9 cm and the required volume (approximately 12.5 m^3) is only half that for



Full calorimetry inside a solenoid – the layout of CMS.

CeF_3, leading to a substantial reduction in cost. In addition, lead tungstate is a relatively easy crystal to grow from readily available raw materials and significant production capacity already exists.

Following the November 1993 decision to foreclose the SSC project, US physicists were looking for new possibilities and many knocked at the CMS door. A letter of intent submitted to the US Department of Energy in September 1994 covered a 270-strong US contingent in CMS, where the main responsibility would be for the endcap muon system and barrel hadronic calorimeter.

Meanwhile, interest continued to grow so that CMS now involves some 1250 scientists from 132 institutions in 28 countries. Some 600 scientists are from CERN member states, the remainder hail from further afield: some 300 from 37 institutes in the US, and 250 from research institutes in Russia and member states of the international Joint Institute for Nuclear Research, Dubna, near Moscow.

The choice of magnet was the starting point for the whole CMS design. Although the solenoid has been cut from 14 to 13 m in length, its radius (2.95 m) and magnetic field (4 T) remain unaltered. This long and high field solenoid removes the need for additional forward magnets for muon coverage, while accommodating easily the tracking and calorimetry.

The 12-sided structure, designed at CERN, is subdivided along the beam axis into five rings, each some 2.6 m long, with the central one supporting the inner superconducting coil. Endcaps complete the magnetic volume. The coil itself, designed at Saclay, is split into four sections, each 6.8 m in diameter, the maximum girth compatible with transport by road. The conductor is 40-strand niobium-titanium enclosed in an aluminium stabilizer. With 900 W of cooling power at 4.5 K and 3400 W at 60 K, cooldown will take 32 days. ▷

In order to deal with high track multiplicities in the inner tracking cavity, detectors with small cell sizes are needed. Solid-state and gas-microstrip detectors provide the required granularity and precision. Two layers of pixel detectors have been added to improve the measurement of the track-impact parameter and secondary vertices. The silicon-pixel and microstrip detectors will be kept at 0° to slow down damage by irradiation. High track finding efficiencies are achieved for isolated high transverse-momentum tracks. It is also fairly high for such tracks in jets. All high transverse-momentum tracks produced in the central region are reconstructed with high-momentum precision (5 per mil), a direct consequence of the high magnetic field. The responsibility for the inner tracker extends to institutes in Belgium, Finland, France, Germany, Greece, India, Italy, Switzerland, the UK, the US and CERN.

Centrally produced muons are identified and measured in four muon stations inserted in the magnet-return yoke. The chambers are judiciously arranged to maximize the geometric acceptance. Each muon station consists of 12 planes of aluminium drift tubes designed to give a muon vector in space, with 100 μm precision in position and better than 1 mrad in direction.

The four muon stations also include resistive-plate chamber-triggering planes that identify the bunch crossing and enable a cut on the muon transverse momentum at the first trigger level. The endcap muon system also consists of four muon stations. Each station consists of six planes of Cathode Strip Chambers. The final muon stations come after a substantial amount of absorber so that only muons can reach them. The large bending power is the key to very good momentum resolution even in the so-called "stand alone" mode, especially at high transverse momenta. The muon-system team includes scientists from Austria, China, Germany, Hungary, Italy, Poland and Spain with large contingents from the US and Dubna member states.

As the coil radius is large enough to install essentially all the calorimetry inside, a high-precision electromagnetic calorimeter can be envisaged. The lead-tungstate ($PbWO_4$) crystal calorimeter leads to a di-photon mass resolution twice as good as that anticipated from the shashlik. The electromagnetic calorimeter groups scientists with large experience of total absorption calorimeters from China, Dubna member states, France, Italy, Germany, Switzerland, the UK, the US and CERN.

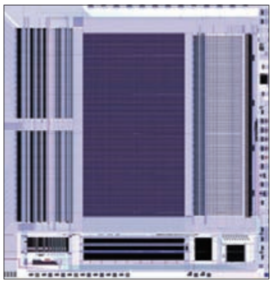
The hadron calorimeter, benefiting from US involvement, will use interleaved copper plates and plastic scintillator tiles read out by wavelength-shifting fibres. As well as the US, the CMS hadron calorimetry squad includes institutes from China, Hungary, India, Spain and Dubna Member States.

For LHC's design luminosity of $10^{34}\,cm^{-2}\,s^{-1}$, CMS will have to digest 20 highly complex collisions every 25 ns. This input rate of 10^9 interactions per second has to be reduced to just 100 for off-line analysis. This will be accomplished by a two-level trigger. The first-level trigger uses pipelined information from the muon detectors and the calorimeters to reach a decision after a fixed time period of 3 μs. The data from a maximum of 10^s interactions per second, from the muon detectors and the calorimeters only, is forwarded to an online processor farm. This "virtual" Level 2 uses the full granularity to reject almost 90% of the events. The entire data from the remaining events is then passed to the farm for further processing. The trigger- and data-acquisition systems are the responsibility of a team from Austria, Finland, France, Germany, Hungary, Italy, Portugal, Poland, Dubna Member States, Spain, Switzerland, the UK, the US and CERN. Software and computing, for monitoring and control as well as data handling and analysis, will take on a new dimension at the LHC.

● June 1995 pp5–8 (abridged).

CMS changes to silicon track

The collaboration for the CMS experiment will base its tracker entirely on silicon sensor technology using fine-feature-size electronics. The decision to go all-silicon follows unexpectedly rapid recent advances in read-out for microstrip detectors, in the fabrication of sensors on 6 inch diameter silicon wafers, and automated assembly techniques for an all-silicon detector. It is a significant departure from the CMS baseline-tracker proposal, which foresaw a central region of silicon devices surrounded by microstrip gas chambers (MSGCs).



The layout of the 7.2 × 8 mm APV25 read-out chip designed by the CMS experiment at CERN's LHC.

In the mid-1990s, MSGCs seemed to offer an economical alternative to silicon. In early implementations, however, their performance was found to deteriorate significantly with increased exposure to ionizing particles. Nevertheless, solutions to these teething problems seemed to be available and CMS chose MSGCs as their baseline proposal – on the condition that certain milestones were reached. These were successfully achieved, but silicon-related technology was advancing in parallel, reducing the cost advantage that MSGCs offered.

A decisive factor in reducing the tracker's price tag, by almost SFr6.5 million, was the development by CMS of a CMOS read-out chip using low-cost technology, originally aimed at increasing the compactness of computer chips. With a feature size of 0.25 μm compared with the 1 μm of conventional CMOS chips, the new APV25 chip is certainly compact. It is also extremely radiation-hard, with lower noise and power consumption than a conventional CMOS chip. The other decisive factor is that silicon detectors are already widely available from industry in large quantities and their price has been falling.

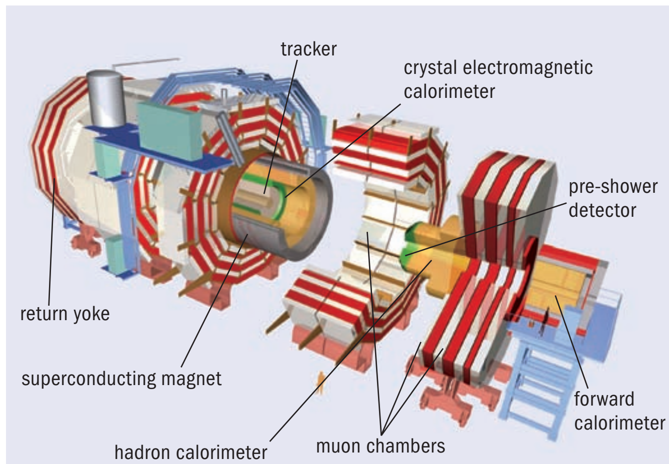
● May 2000 p5 (abridged).

Résumé

La conception du détecteur CMS (Compact Muon Solenoid) imposait un champ magnétique fort, de l'ordre de 4 T, créé par un solénoïde supraconducteur, qui devait initialement mesurer 14 m de long et avoir une ouverture de 6 m. L'ensemble de la calorimétrie devait se trouver à l'intérieur du solénoïde, priorité étant donnée aux mesures électromagnétiques de précision.

Building on innovation

Tejinder (Jim) Virdee describes concepts and technologies behind the CMS detector.



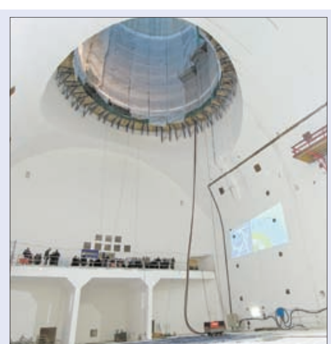
From the beginning, the CMS collaboration had taken a new approach with the plan to assemble the detector above ground in a spacious surface building while the civil engineering work on the underground cavern was underway. Alain Hervé, who had been Technical Coordinator for the L3 experiment at LEP before taking up the same position with CMS, strongly recommended constructing the detector in slices that would be lowered down the 100 m shaft into the cavern after extensive commissioning on the surface. This had never been done before for such a large-scale high-energy physics experiment, most experiments being constructed directly in the experimental area. This decision, and the requirement of the ease of maintenance, determined the overall structure of the detector, with slices that could be lowered one by one – 15 heavy pieces in all.

"It is very unusual to do this, but the surface building was made quite large, and we could work on several pieces at the same time because they could easily be moved back and forth. Also the underground civil-engineering work in the caverns would take time, so we started assembling the detector four to five years before the underground cavern was finished. The fully tested elements were lowered underground between November 2006 and January 2008. The experiment is commissioned and now ready for data-taking. The duration of the lowering operation and commissioning was essentially that foreseen 17 years ago," explains Jim Virdee, who has been with CMS since the very beginning and spokesperson since 2007. "I know a few future experiments are looking at this way of doing things," he adds, "so I think it might catch on. It gives a lot of flexibility, providing ease of maintenance and installation. Even late on we could work on various elements in parallel in the underground cavern."

The long process from the design phase to final construction encompassed some crucial changes in technology, which allowed savings in time, money and effort. Despite the unexpected challenges that arose, the collaboration remained flexible and creative in solving them. "We needed radiation-hard electronics in our tracker, electromagnetic calorimeter and hadron calorimeters, along with radiation-tolerant muon systems. We did a lot of R&D on this with industries that had produced radiation-hard electronics, usually for

The first ring for the barrel yoke of the CMS superconducting magnet under assembly in 1999 by the manufacturer Deggendorfer Werft und Eisenbau GmbH (DWE) in Germany.
● November 1999 p7.

Two modules of the CMS solenoid at the manufacturers, Ansaldo, in Italy. The lower module was the first travel to CERN from Genova, at the end of January 2004. (Courtesy INFN.)
● March 2004 p6.



On 1 February 2005, the cavern for the CMS detector at CERN was inaugurated in a ceremony attended by many guests, including representatives of the construction companies.
● March 2005 p5.

The first half of the barrel hadron calorimeter was tested in March 2006 using a radioactive source before insertion into the solenoid in early April. The second half was inserted a month later.
● July-August 2006 pp28–29.

space or military applications," recalls Virdee. The collaboration was ready to launch production of the front-end electronics of the inner tracker when the foundry that was going to produce the electronics moved, and somehow lost its ability to produce electronics with good radiation hardness. "So we were thrown back to the drawing board and had to develop a new way of obtaining radiation-hard electronics," says Virdee. "We essentially changed all of our on-detector electronics for the tracker and the electromagnetic calorimeter. This was a major issue that we were confronted with in the late 1990s and it's all worked out very well. A lot of people thought we had left it too late, and I was being advised that we were taking a risk, but it was a risk we had to take."

Another significant challenge concerned the production of 75 000 lead-tungstate crystals in Russia and China. These were chosen for their compactness, owing to their short radiation length, and high radiation hardness, but early tests revealed problems when using silicon photodiodes, with the scintillation light being drowned out by unwanted signals arising from charged particles at the end of the shower passing through the photodiodes. A solution was discovered using silicon-avalanche photodiodes, which could work in a magnetic field. Working with the crystal supplier in Russia also proved interesting. "The economic conditions in Russia have changed a lot since we started producing the crystals," says Virdee, "so much so that we had to place the last few orders in roubles, not in dollars any longer because the rouble was considered by the manufacturer to be a more stable and stronger currency!"

In 1999 the CMS collaboration made a major decision to change the design of their inner tracker. Originally, they had included both microstrip gas chambers (MSGCs) and silicon sensors after performing much R&D on various technological options. The cost-per-square-centimetre of silicon detectors in the early 1990s was high, so the plan was to use silicon detectors close to the interaction point and use MSGCs further away. "This technology required some development to make it suitable for use in the LHC, and essentially we succeeded in doing that," says Virdee. However, development of silicon detectors continued during the decade. Larger wafers were becoming available at a competitive cost and with improved performance. Furthermore, automation – employed in the electronics industry – allowed rapid and reliable production of the 17 000 silicon modules needed for the tracker.

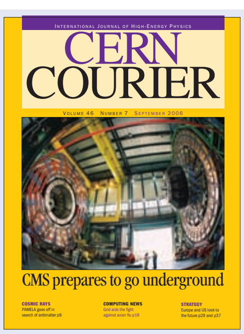
At the beginning of 1999, when it was clear that silicon had reached a competitive state with the MSGCs, the collaboration took the bold decision based on practical aspects to use only silicon. "We were pressed for time, and having two different technologies required us to have two different systems doing similar work. At the time we had not invested as much effort in the systems issues as we would have wished for," Virdee explains. "So one of the key issues that arose was: can we come up with a single design to simplify the work and save time? The basic issue was that the silicon detectors were of high quality, and were mass-produced by industry, so we could just buy them while high-rate production lines for MSGCs had still to be commissioned."

Once the LHC starts, the CMS physicists, some of whom have spent most of their working lives building the large and complex subdetectors, will have the long-awaited chance for discoveries. "However, before we do that we need to verify that the subdetectors perform as designed. Currently, we are doing that by running with cosmic rays. As far as we can tell the detector is working as expected and this is very encouraging. The moment of truth, however, will be when we record collision data," says Virdee. "This start-up is very exciting because we are making a big leap up in energy and entering a new regime. All indications are that there is something special about this energy range."

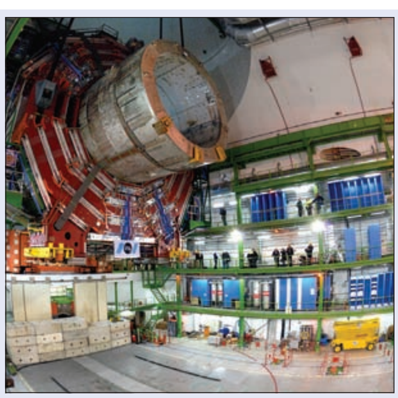
Résumé

La collaboration CMS a choisi une méthode de construction inédite : assembler le détecteur en surface avant de descendre les différentes sections dans la caverne. CMS a accompli d'autres prouesses techniques : la production de 75 000 cristaux de tungstate de plomb pour le calorimètre électromagnétique et l'utilisation du silicium pour la totalité du trajectographe.

Jim Virdee *talked to* **Carolyn Lee***, CERN.*

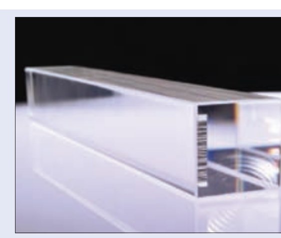


On 24 July 2006 the massive CMS magnet yoke was closed for tests of much of the detector while still on the surface, before the lowering began.
● September 2006 p7.



On 28 February 2007 the heaviest section of CMS, containing the complete solenoid, made the 100 m descent into the cavern, descending at a rate of about 10 m an hour.
● April 2007 p6.

The silicon strip tracking detector reached its final resting place in the CMS experiment on 13 December 2007. It is the largest detector of its kind ever constructed.
● January/February 2008 p6.



The final crystals for the electromagnetic calorimeter arrived at CERN from China and Russia in March 2008, completing a mammoth production process nearly 10 years after the delivery of the first production crystal in September 1998.
● June 2008 p6.

New kid on the block

ALICE was the third collaboration to submit a technical proposal for an experiment at the LHC, doing so on 15 December 1995 with the design for a dedicated heavy-ion detector.

In the children's story, Alice chased a white rabbit down a hole to find herself transported to a magical world. At the LHC, ALICE (A Large Ion Collider Experiment) will be pursuing new states of matter, and the wonderland to be found could be every bit as new and exciting. The LHC will continue CERN's tradition of diverse beams, being able to accelerate not only protons, but also high-energy beams of lead ions. It is this capability which ALICE is designed to exploit.

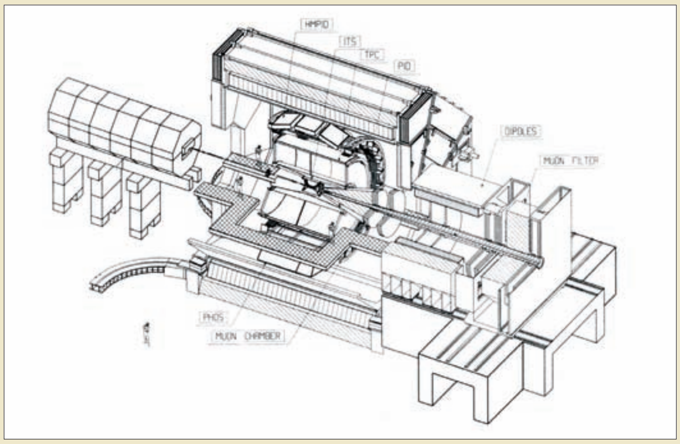
The idea of building a dedicated heavy-ion detector for the LHC was first aired at the historic Evian meeting in March 1992. From the ideas presented there, the ALICE collaboration was formed, and in 1993, a Letter of Intent was submitted. High-energy heavy-ion collisions provide a unique laboratory for the study of strongly interacting particles. Quantum chromodynamics (QCD) predicts that at sufficiently high energy densities there will be a phase transition from conventional hadronic matter, where quarks are locked inside nuclear particles, to a plasma of deconfined quarks and gluons. The reverse of this transition is believed to have taken place when the universe was just 10^{-5} s old, and may still play a role today in the hearts of collapsing neutron stars.

The feasibility of this kind of research was clearly demonstrated at CERN and Brookhaven with lighter ions in the 1980s. Today's programme at these laboratories has moved on to heavy ions, and is just reaching the energy threshold at which the phase transition is expected to occur. This physics reach will be extended at the RHIC heavy ion collider at Brookhaven, scheduled to come into operation in 1999. The LHC, with a centre-of-mass energy around 5.5 TeV/nucleon, will push the energy reach even further.

ALICE is bringing members of CERN's existing heavy-ion community together with a number of groups new to the field drawn from both nuclear and high-energy physics. By LHC standards, the detector is of moderate proportions, being based on the current magnet of LEP's L3 experiment. When LEP switches off, the L3 magnet will be left in place whilst ALICE is installed. LHC beams will pass through the magnet slightly off-centre, 30 cm higher than the current LEP beams.

On the trail of quark-gluon plasma

Because the physics of the quark-gluon plasma could be very different from that of ordinary matter, the ALICE detector has been designed to cover the full range of possible signatures, whilst being flexible enough to allow future upgrades guided by early results. The detector consists of two main parts, a central detector, embedded within the magnet, and a forward muon spectrometer included as an addendum to the Letter of Intent in 1995.



The two main components of the ALICE detector are clearly visible in this cutaway drawing. The central detector will be built inside the existing solenoid of the L3 experiment at the LEP electron-positron collider. The forward muon spectrometer, on the right, will measure the spectrum of heavy quark resonances.

The set-up is completed by zero-degree calorimeters located far downstream in the machine tunnel, to intercept particles emerging very close to the colliding beams.

One of the greatest challenges of heavy-ion physics is to pick out the individual tracks from the dense forest of emerging particles. ALICE's tracking system has been designed for safe and robust pattern recognition within a large volume solenoid producing a weak field. The L3 magnet with a field of 0.2 tesla is ideal for the purpose.

The Inner Tracking System, ITS, consists of six cylindrical layers of highly accurate position-sensitive detectors from radii of 3.9 cm to 45 cm extending to ±45°. Its functions are secondary vertex recognition, particle identification, tracking, and improving the overall momentum resolution. The different layers are optimized for efficient pattern recognition. Because of the high particle density in the innermost regions, the first four layers provide position information in two dimensions. The first two layers are silicon pixel detectors, and the second two are silicon drift detectors. The two outermost layers will be composed of double sided silicon micro-strip detectors. The complexity and importance of this device is reflected in the number of institutions responsible for its production: Bari, Catania, CERN, Heidelberg, Kharkov, Kiev, Nantes, NIKHEF, Padua, Rez, Rome, St Petersburg, Salerno, Strasbourg, Turin, Trieste and Utrecht.

Central tracking is completed by a Time Projection Chamber, ▷

TPC, being built by Bratislava, CERN, Cracow, Darmstadt, Frankfurt, and Lund. Proven technology has been chosen to guarantee reliable performance at extremely high multiplicity. The drawbacks of this technology are high data volumes and relatively low speed. The TPC occupies the radial region from 90 cm to 250 cm, and is designed to give a rate-of-energy-loss resolution of better than 7%. It will also serve to identify electrons with momenta up to 2.5 GeV/c.

Identification parade

Two different technologies are under study for the last subdetector to cover the full azimuthal angle, the particle identification system, PID. Pestov spark counters, single-gap gas filled parallel-plate devices, are being investigated by Darmstadt, Dubna, Marburg, Moscow-ITEP, Moscow-MePHI, and Novosibirsk, whilst parallel plate chambers, PPCs, are being developed by CERN, Moscow-ITEP, Moscow-MePHI, and Novosibirsk. The final design is expected to be complete by the end of 1998. The PPCs are less demanding to construct and operate, but the Pestov counters give a timing resolution of less than 50 ps, some four times better than PPCs.

A second particle identification device for higher momentum particles, the HMPID, is included in the design as a single arm device above the central PID. A ring-imaging Cerenkov (RICH) detector is the preferred option, being developed by Bari, CERN, Zagreb, and Moscow-INR. However, an organic scintillator approach being pursued by Catania, and Dubna has not yet been ruled out.

Below the central barrel region of the detector is another single-arm device, the photon spectrometer, PHOS, to measure prompt photons and neutral mesons. It is being prepared by Bergen, Heidelberg, Moscow-Kurchatov, Munster, Protvino, and Prague using scintillating lead tungstate crystals developed in the context of CERN's generic detector R&D effort.

Zero-degree calorimeters, ZDC, will be positioned 92 m from the interaction point to measure the energy carried away by non-interacting beam nucleons, a quantity directly related to the collision geometry. These are calorimeters of the spaghetti type, with quartz fibres as the active medium. Their construction is the responsibility of Turin. Another forward detector, the forward multiplicity detector, FMD, will be embedded within the solenoid with the purpose of providing fast trigger signals and multiplicity information outside the central acceptance of the detector. Innovative micro-channel plate detectors are under consideration by Moscow-Kurchatov and St Petersburg, with conventional silicon multipad detectors as a back-up.

The forward muon spectrometer, FMS, is a major addition to the original design as specified in the Letter of Intent. It was included to measure the complete spectrum of heavy-quark resonances, which are expected to provide a sensitive signal for the production of a quark-gluon plasma. The first section of the spectrometer is an absorber placed inside the solenoid about 1 m from the interaction point. This is followed by a large 3 tesla dipole magnet outside the solenoid containing 10 planes of tracking stations. A second absorber and two further tracking planes provide muon identification and triggering. Teams from CERN, Clermont-Ferrand, Gatchina, Moscow-Kurchatov, Moscow-INR, Nantes, and Orsay are working on a more detailed design for the FMS, which is expected later this year.

Triggering is the responsibility of Birmingham and Kosice. Proton–proton mode and ion–ion mode have different trigger requirements. In proton–proton mode, a minimum bias trigger is required, whilst for ion–ion collisions, the trigger's function is to select on collision centrality. A level zero trigger decision is made at around 1.2 microseconds based on centrality information from the FMD. At level-one (2 microseconds) this is supplemented by the ZDC. A dimuon trigger from the FMD also contributes to level-one. The final level-two trigger decision is made after further processing at 100 microseconds.

The architecture of the ALICE data acquisition system is determined by the relatively short heavy-ion runs foreseen for the LHC, roughly 10% of each year's running. The collaboration will have ten times as long to analyse the data as they have to collect them, and so a high bandwidth system is envisaged in order to collect as much data as possible in the time available. CPU-intensive operations such as event filtering and reconstruction will be performed offline. Data acquisition is the responsibility of Budapest, CERN, and Oslo.

● March 1996 pp9–12 (abridged).

Green light for ALICE

ALICE has received the green light to proceed towards final design and construction. ALICE is the natural continuation, at CERN of the SPS Heavy Ion programme, initiated in 1986, which has recently provided exciting new results in the quest for the quark-gluon plasma.

Up to fifty thousand charged particles are expected to be emitted in a lead–lead collision at the LHC of which about ten thousand will go through the ALICE central detector. That is why the central tracking in ALICE is based on the Time Projection Chamber (TPC) technique, which has already proven its value in registering tracks in a high multiplicity environment within the NA49 SPS experiment. The LHC collision rate in heavy ion mode is compatible with TPC drift times of around 100 microsec.

In the forward direction, within a 9 degree angle around the beam, ALICE will be equipped with a muon spectrometer, made of a sophisticated hadron absorber, a dipole magnet, five tracking stations (made of Cathode/pad Strip Chambers) and two trigger stations (made of Resistive Plate Chambers). Measurements on muon pairs are an essential part of the ALICE physics programme, since heavy dileptons probe the early stages of the produced medium.

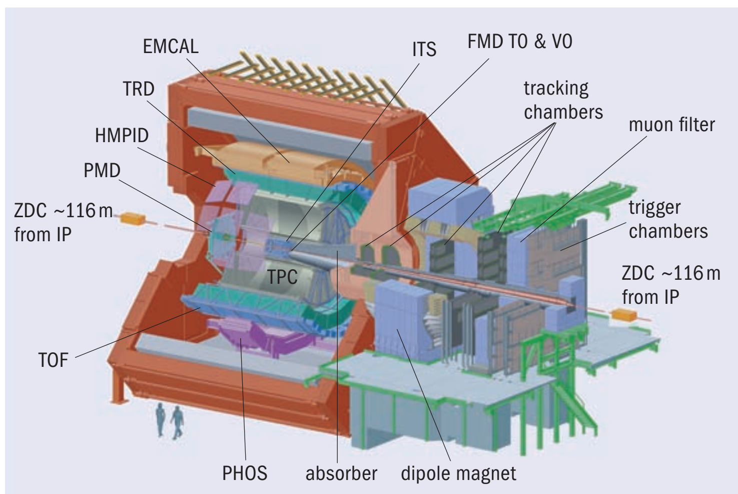
● April 1997 pp4–5 (extract).

Résumé

En décembre 1995, ALICE devient la troisième collaboration à soumettre une proposition technique pour le LHC. Contrairement aux deux détecteurs polyvalents, ALICE a été conçue pour exploiter les collisions d'ions plomb au LHC. L'expérience sera un laboratoire exceptionnel de l'étude des particules à interaction forte.

The heavy-ion challenge

Jürgen Schukraft discusses how the ALICE detector has evolved over two decades.



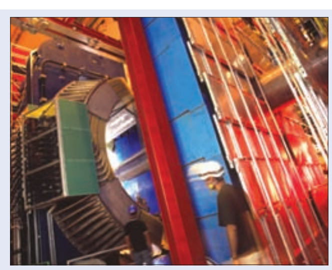
When the ideas for ALICE were first formed at the end of 1990, the heavy-ion programme was still in its infancy and very little was known about what physics to expect or what kind of detector would be required. Nevertheless, an expression of interest for a dedicated general-purpose heavy-ion detector was presented at Evian in 1992. "That's the first appearance of ALICE," recalls Jürgen Schukraft, who has been at the helm of the experiment since its inception in 1991. "We had to do enormous extrapolations because the LHC was a factor of 300 higher in centre-of-mass energy and a factor of 7 in beam mass compared with the light-ion programme, which started in 1986 at both the CERN SPS and the Brookhaven AGS. It was akin to planning for the International Linear Collider with a centre-of-mass energy of 1 TeV based on knowledge from Frascati's ADONE machine, one of the first electron-positron colliders running at 3 GeV."

Sixteen years later, the field of heavy ions is in a mature state. The ALICE collaboration has the benefit of results from the heavy-ion programmes at the SPS and at Brookhaven's RHIC, to use as guidance, allowing an infinitely better idea of what to look for, as well as the kind of detectors and the precision needed. Heavy ions will collide at the LHC with energy levels 28 times higher than at RHIC and 300 times higher than at the SPS, representing a huge jump in energy density. "The field of heavy ions has gone from the periphery into a central activity of contemporary nuclear physics," explains Schukraft. "The exciting thing about the LHC is that because of the huge jump in energy compared with RHIC, there are many open questions to be answered and lots of surprises to be expected. While we don't know the answers yet, today at least we know some of the questions."

ALICE will study the quark–gluon plasma (QGP), the first evidence of which was discovered at RHIC and the SPS, and will continue the investigations by confirming interpretations and testing predictions at the LHC. "Back in 1992, we were imagining what the quark–gluon plasma would look like and we expected it to behave like an ideal

The first 500 crystals for the ALICE experiment's photon spectrometer (PHOS) arrived at CERN in May 2002 after a journey via Moscow from the town of Apatity in the Russian arctic region. They are the first of 17 000 lead tungstate crystals that will make up the PHOS.
● October 2002 p6.

On 25 September 2003, the two coils for the ALICE dipole magnet arrived at point 2 of the LHC after a 1200 km journey from their manufacturer, Sigmaphi, in Vannes, France. Each coil is 5 m long, 6 m wide, more than 3 m high and weighs 20 tonnes.
● November 2003 p7.



In mid-July 2006, ALICE reached some important milestones with the installation of the trigger and tracking chambers of the muon spectrometer. These are the first detectors to be installed in their final position in the underground cavern at point 2.
● October 2006 p7.

Different elements for particle identification in ALICE began to arrive in the cavern later in 2006, beginning with the High Momentum Particle Identification Detector (HMPID) installed inside the solenoid magnet on 23 September.
● December 2006 p6.

gas, but what we found is that it behaves like a perfect fluid, so it is completely different," says Schukraft. "This was a very big surprise, because instead of being weakly interacting, or gas like, it is strongly interacting. It is the best fluid anyone has ever found in nature, much better than liquid helium, for example." He adds: "The discovery that QCD matter is more like a fluid, was made at RHIC. We now expect to see it flow at about the same strength at the LHC if our understanding is correct – because it can't get any better than 'ideal' – or we will be scratching our heads if it behaves differently."

Another question on the minds of the ALICE collaboration is whether there is not only QGP, but yet another unusual state of matter called colour glass condensate (CGC), which may form at high gluon densities in heavy nuclei. While QGP is hot and dense, CGC is cold and dense, and would exist in the initial state – before the nuclei collide – and then melt away. "We hope to discover new aspects of QCD in the strongly coupled regime, where the strong interaction is actually strong," says Schukraft. "One of the central concepts of the Standard Model is phase transition and spontaneous symmetry breaking. The QCD phase transition is the only one accessible to study by experiment and ALICE will measure its properties and parameters."

As the field of heavy ions has unfolded, the ALICE collaborators have been flexible in changing or adding to their detector. Over the course of time, 50% of new detector components have been added to the original Letter of Intent submitted in the spring of 1993, as a result of the new data from the SPS and RHIC. This includes the muon spectrometer (*CERN Courier* December 2007 p30), a transition-radiation detector and the electromagnetic-jet calorimeter, scheduled to be completed in 2011 (*CERN Courier* June 2008 p27). "Now we know better what we need for this new regime," explains Schukraft. In addition, some detectors had to be invented from scratch – such as the time-of-flight detector, which was impossible to build at the time the original design was made, and silicon pixel detectors, which were not around then (*CERN Courier* July/August 2008 p28).

ALICE is expecting to receive 1 PB of data for the one month per year of heavy-ion operation, at a rate of more than 1.25 GB/s, which presents a huge challenge. According to Schukraft, state-of-the-art technology in data-collection infrastructure during the 1990s worked at a rate of 10 MB/s. "Most people thought 1 GB/s would be a real challenge to reach and that we would have to find a way to reduce the data volume. There were many discussions on how to handle this huge amount of data, yet today within a factor of 2–3 it is quite common. However, 15 years ago one could not dream of handling such a large amount of data at such a rapid rate," he says. He expects that the heavy-ion data taking will start by the end of 2009 and soon after begin to show the first interesting results.

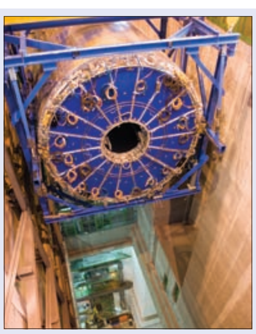
Although the collaboration's main interest is heavy-ion collisions, for most of the year ALICE will be running using proton–proton collisions, which is important for comparing measurements from the lead–lead collisions. The detectors are optimized for complete particle identification at angles close to 90°, detecting particles from extremely low to fairly high momentum. During the proton runs, ALICE collaborators will be tuning the Monte Carlo generators and evaluating the background and detector performance for QCD measurements, such as charm and beauty production at low transverse momentum.

"What we are doing at the LHC is very exciting," says Schukraft. "The LHC is really amazing in its ability to combine three different approaches in one machine: high-energy phenomena, producing new particles to be studied by ATLAS and CMS; indirect effects of virtual high-mass particles, studied in LHCb; and distributed energy that heats and melts matter, to be studied by ALICE. We look forward to studying lead–lead collisions at LHC energy scales."

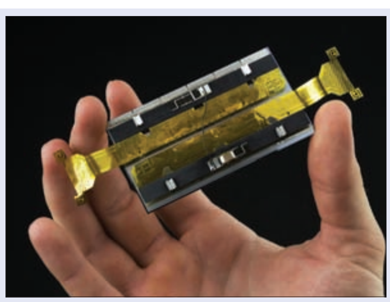
Résumé

Quand les premières idées concernant ALICE ont été lancées, la physique des ions lourds était encore balbutiante, et personne ne savait ce qu'on pouvait attendre du LHC. Les expériences ont depuis révélé les premiers signes du plasma quarks-gluons et la collaboration ALICE a adapté son détecteur pour l'exploration de ce nouvel état de la matière.

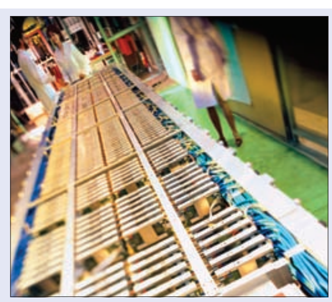
Jürgen Schukraft *talked to* **Carolyn Lee**, *CERN.*



In January 2007 the fragile 5 m diameter time projection chamber (TPC) weighing 8 tonnes was lowered into the cavern. (Courtesy A Saba for CERN.)
● *March 2007 p6.*



On 15 March 2007, the inner tracking system (ITS) was inserted into the TPC. The ITS consists of six layers of high-precision silicon detectors, with double-sided silicon strips (above) in the outer two layers, silicon drift detectors in the middle two layers and silicon pixels in the two inner layers.
● *June 2007 p6.*



At the end of April 2008, the time-of-flight (TOF) detector was completed and installed around the TPC, within the huge solenoid magnet and 3.7 m from the beam. Here a TOF supermodule is seen under assembly at CERN. (Courtesy A Saba for CERN.)
● *July/August 2008 p8.*

On 15 June the silicon pixel detector at the heart of ALICE saw the first signs of particles at the LHC during tests in a transfer line.
● *July/August 2008 pp29–31.*

ADVERTISING FEATURE

CECOM was founded in 1964 in Rome by Cesare Ceracchi. Its growth was due to the prestigious collaboration between several organizations and companies, e.g. CERN, INFN, ENEA, several universities in Italy, Elettronica Spa and Avio Spa. Excellence, precision, quality, flexibility and frontier technology have made CECOM a leader in mechanics and UHV applications.

Since the early 1980s CECOM has divided its work between the fields of scientific research and civil–military/aeronautics. These applications have characterized CECOM's skills: the stringent requirements of aeronautic applications, in terms of performance, reliability, lifetime and quality assurance have been joined to the flexibility required by the research applications (development of prototypes, UHV requirements, special tests), thus improving CECOM's knowledge and abilities.

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- INFN, ENEA, DIAMOND LIGHT SOURCE (beam stoppers, photon shutters, RF cavity, aluminium vacuum chamber, vacuum vessels and components).
- CELLS (bellows and vacuum chambers for the straight sections are in progress).
- CCRLC, CNR, DESY, ELETTRA.

CECOM will be one of the sponsors at CERN's LHC Opening Ceremony on October 21st.

A beauty of an experiment

The full technical proposal for the LHCb experiment was published in 1998.

With preparations for the ATLAS and CMS large general-purpose detectors for CERN's LHC collider now advancing, the initial cast for the LHC experimental programme is extended with the publication of a full technical proposal for the LHCb experiment. The aim of this experiment is to study in detail the physics of the Standard Model's third (and final) generation of particles, particularly the beauty, or "b" quark contained in B mesons. This third generation of quarks makes possible the mysterious mechanism of CP violation.

When component quarks mutate under the action of the weak force, subtle effects come into play. The first to be discovered was the violation of parity (left–right mirror symmetry) in standard nuclear beta decay. This parity violation is seen even with the up–down quark doublet that makes up protons and neutrons.

Searching for a more reliable mirror to reflect particle interactions, physicists proposed CP symmetry. As well as switching left and right, such a mirror also switches particles and antiparticles – the CP mirror image of a right-handed particle is a left-handed antiparticle. However, having six quarks (arranged pair-wise in three generations) opens up the possibility of violating CP symmetry as well. Such effects had been seen in 1964 with neutral kaons. But these kaon phenomena are only a tiny corner of the Standard Model's CP violation potential. Much larger effects should happen in the B sector. The race is now on to collect enough B particles to become the first to glimpse this additional CP violation.

While these will surely reveal more CP violation effects, the full picture will probably only emerge with the interaction rates and energy conditions of the LHC, which will considerably extend the B physics reach. As well as investigating all aspects of CP violation, LHCb would also consolidate our knowledge of particle reactions and explore fully all quark and lepton sectors of the Standard Model.

The LHCb experiment, which so far has attracted some 340 physicists from 40 research centres in 13 countries, aims to exploit the luminosity of 2×10^{32} per cm^2/s which should be available from the LHC from Day 1. For the other experiments, the LHC's collision luminosity will be cranked up to 10^{34}. LHCb expects to harvest about 10^{12} b quark–antiquark pairs each year. LHCb is a large single-arm spectrometer covering an angular range from 10 out to 300 mrad and will be housed in the 27 km LHC/LEP tunnel in the Intersection 8 cavern nearest Geneva airport, currently the site of the Delphi experiment at the LEP electron–positron collider.

At the heart of the detector is the vertex detector, studied by a CERN/Amsterdam/Glasgow/Heidelberg/Imperial College London/Kiev/Lausanne/Liverpool/MPI Heidelberg/NIKHEF Amsterdam/Rome 1 team. The vertex detector will record the decays of the B particles, which travel only about 10 mm before decaying. Each of the 17 planes of silicon (radius 6 cm) spaced over a metre consists of two discs to measure radial and polar ▷

Beauty at the LHC

The Standard Model of physics, with its picture of six quarks and leptons grouped in pairs into three generations, is coming under detailed scrutiny as physicists try to understand what makes it work so well. This demands precision probes of all quark channels, rare as well as familiar.

The LHC will be a prolific source of B particles containing the fifth (beauty, b) quark, either in beam–beam collisions or using one of the high energy proton beams in a fixed-target set-up. Obvious aims of the B-physics programme at the LHC are to investigate the mixing of neutral B mesons, the particle lifetimes and the spectroscopy of beauty baryons. However the main goal will be observing CP violation in the neutral B system (neutral mesons containing b with either d or s quarks).

CP violation – the subtle disregard of an otherwise perfect symmetry of a combined particle-antiparticle and left-right switch – has been known for 30 years and only seen in the decays of neutral kaons. Its origin is still a mystery but it is widely believed to be responsible for the universe's matter-antimatter asymmetry. The Big Bang initially produced equal amounts of matter and antimatter but the tiny CP-violation mechanism was enough to tilt the balance in favour of matter as we know it.

To complement the B physics capabilities of LHC's big detectors (ATLAS and CMS), one dedicated B physics experiment is planned for the initial phase of the LHC experimental programme. Three groups submitted Letters of Intent based on different experimental approaches:

- **colliding beams at the full LHC 14 TeV collision energy (the COBEX project)**
- **an internal gas jet target intercepting a circulating beam at the fixed target energy of 114 GeV (the GAJET project)**
- **a beam extracted from the beam halo by a bent crystal and a septum magnet for a fixed target experiment (the LHB project).**

Considering these ideas, the LHC Experiments Committee pointed out that when LHC comes on line, initial measurements of CP violation in the B meson system will have been made by several ongoing projects. The LHCb will therefore be a second-generation study. While identifying attractive features in all three Letters of Intent, the Committee was of the view that an experiment using the collider approach, handling the full production rate, is the most attractive.

The Committee, whose view was subsequently endorsed by the Research Board, encouraged all participants in the three Letters of Intent to join together to submit a fresh design for a collider-mode B experiment.

● September 1994 p10.

coordinates. The arrangement should provide a hit resolution between 6–18 microns and 40 microns for the impact parameter of high momentum tracks.

Downstream of the vertex detector, the tracking system reconstructs the trajectories of emerging particles. Using 11 stations spaced over about as many metres, this tracking uses a honeycomb of drift chambers on the outside (where the particle fluxes are lower), enclosing a finer granularity arrangement on the inside. Microstrip gas chambers with gaseous electron multiplication is the prime contender for this part of the detector, but silicon strips and micro-cathode strips are also being investigated. The inner tracker is being investigated by Heidelberg (University and MPI), PNPI St Petersburg and Santiago (Spain), and the outer by Dresden, Free University of Amsterdam, Freiburg, Humboldt Berlin, IHPE Beijing, NIKHEF Amsterdam and Utrecht.

LHCb's 1.1 tesla superconducting dipole spectrometer magnet (studied by CERN and PSI Villigen) would benefit from the infrastructure developed for the Delphi magnet at LEP. The magnet polarity is reversible to help the systematic study of CP violation effects.

Particle identification is carried out using the ring-imaging Cerenkov (RICH) technique, with the first RICH equipped with a 5 cm silica aerogel and 1 m C_4F_{10} gas radiators behind the vertex detector and the second station with 2 m of CF_4 gas radiator behind the tracker. Cerenkov photons would be picked up by a hybrid photodiode array, the subject of a vigorous ongoing R&D programme. The RICH study group consists of Cambridge, CERN, Genoa, Glasgow, Imperial College London, Milan and Oxford.

Following the second RICH is the electromagnetic calorimeter for identifying and measuring electrons using a 'shashlik' structure of scintillator and lead read out by wavelength-shifting fibres. It has three annular regions with different granularities to optimize readout. Identification of these electromagnetic particles is facilitated by a lead-scintillator preshower detector. Electromagnetic calorimetry is studied by a Bologna/Clermont Ferrand/INR Moscow/ITEP Moscow/Lebedev Moscow/Milan/Orsay/Rome I/Rome 2 team.

The hadron calorimeter (Bucharest/IHEP Moscow/Kharkov/Rome 1) is of scintillator tiles embedded in iron. Like the electromagnetic calorimeter upstream, it has three zones of granularity. Readout tests with a full-scale module prototype in a beam have already exceeded the expected performance of 50 photoelectrons per GeV. Downstream, shielded by the calorimetry, four layers of muon detector (Beijing/CERN/Hefei/Nanjing/PNPI/Shandong/Rio de Janeiro/Virginia) uses multigap resistive plate chambers and cathode pad chambers embedded in iron, with an additional plane of cathode pad chamber muon detectors mounted in front of the calorimeters. As well as muon identification, this provides important input for the triggering.

Data handling will use four levels of triggering (event selection), with initial (level 0) decisions based on a high transverse-momentum particle and using the calorimeter and muon systems. This reduces the 40 MHz input rate by a factor of 40. The next level trigger (level 1) is based on information from the vertex detector (to look for secondary vertices) and from tracking (essentially to confirm high transverse momentum) and reduces the data by a factor of 25 to an output rate of 40 kHz. Level 2, suppressing fake secondary decay vertices, achieves another further 8-fold compression. Level 3 reconstructs B decays to select specific decay channels, achieving another compression factor of 25 and data are written to tape at 200 Hz. Data handling and offline computing are being looked at by Bologna, Cambridge, CERN, Clermont Ferrand, Heidelberg, Lausanne, Lebedev, Marseille, NIKHEF, Orsay, Oxford, Rice and Virginia.

● May 1998 pp3–5 (abridged).

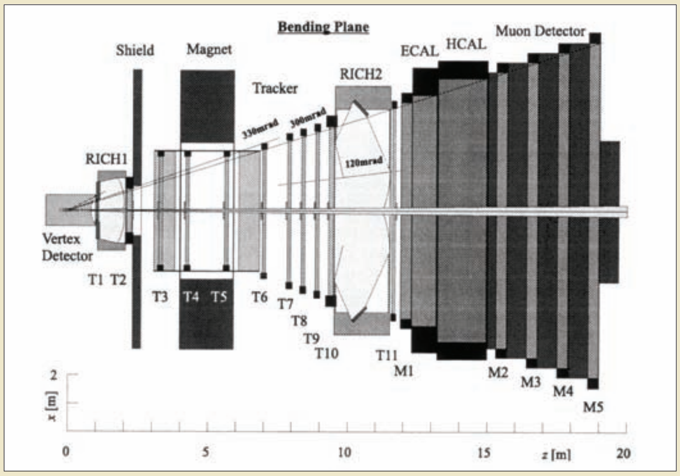

Diagram of the LHCb experiment which will investigate the physics of particles containing the fifth – beauty or 'b' – quark.

Birth of a collaboration

The stage being set for CERN's LHC proton-proton collider includes a place for an experiment – LHC-B – to study the physics of B particles. The Letter of Intent for this experiment has been reviewed by the appropriate committees, who recommend that the collaboration should now proceed to a vigorous research and development programme for the various detector components en route to a full technical proposal.

By the time the LHC is operational, the B meson system will have been extensively studied elsewhere – in the B factories being built at SLAC (Stanford) and at KEK, Japan, at Cornell's revamped CESR ring, at the HERA-B experiment at DESY, Hamburg, and at Fermilab's Tevatron. The LHC-B experiment will therefore be a second-generation study. While all three initially submitted approaches had different appealing features, the collider route, exploiting the full B production rate, was thought to be the most attractive for mature physics. CERN therefore encouraged all participants in the initial B-physics ideas to collaborate in a fresh design for a collider-mode experiment. The result is the LHC-B collaboration, which currently groups almost 200 researchers from 40 institutes in 15 countries, and is growing.

● April/May 1996 pp2–4 (extract).

Résumé

La collaboration LHCb a publié sa proposition technique complète en vue d'une expérience au LHC. L'objectif était d'étudier la troisième famille de quarks, tout particulièrement le quark b, et le phénomène de la violation de CP. Le détecteur devait être essentiellement un spectromètre à un seul bras.

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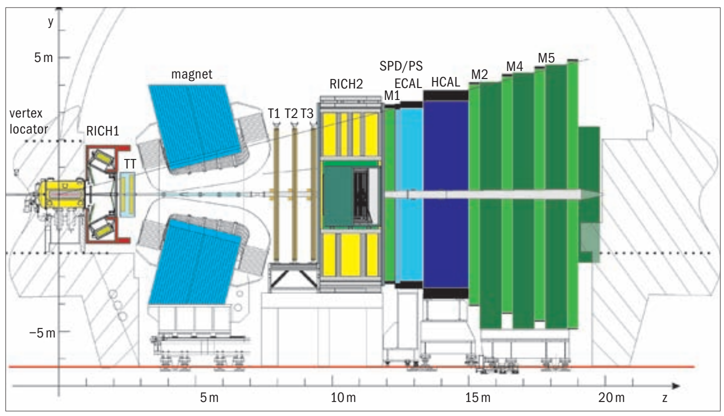
A question of asymmetry

Andrei Golutvin explains how quantum phenomena in B mesons may reveal new physics in LHCb.

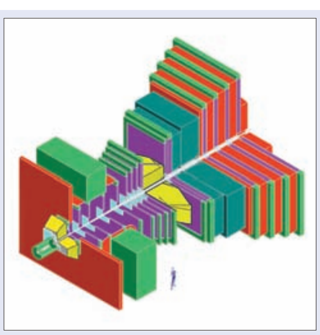


Unlike the general-purpose detectors, the geometry of the LHCb experiment does not cover the full solid angle, but is developed along the forward direction with respect to the collision point. For 20 m a series of detector planes collects information on the particles coming from the collision point. This design is optimized for the study of B mesons, which, given their relatively small mass compared with the high energy of the LHC collisions, fly mostly in the forward direction.

B mesons have received increasing attention from theorists and experimentalists alike over recent years because their behaviour seems linked to various quantum phenomena that could shed light on new physics. "Today's Standard Model of particle physics leaves many unanswered questions," says Andrei Golutvin, spokesperson of the LHCb collaboration. He has recently taken over this role from Tatsuya Nakada who was the first spokesperson and a founder of the experiment. "A lot of physicists expect new physics to be just around the corner and already accessible at the LHC," he continues. "General-purpose detectors like ATLAS and CMS will look for direct evidence of the existence of new particles. We have a different strategy. We focus on the study of B mesons, where some of their behaviour is very precisely predicted by the Standard Model. However small, a deviation from these predictions would indicate the existence of new phenomena."

In recent years, two experiments at B-factories – BaBar at SLAC and Belle at KEK – have shown that the B particles are a key element in the process of understanding CP violation – the subtle asymmetry between matter and antimatter within the Standard Model. However, this does not seem to be enough to generate the absence of antimatter in the universe. "We will study with an unprecedented precision how CP violation takes place in the B-system," explains Golutvin. "The yet undiscovered heavy particles could be a new source of CP violation that could affect the decays of B particles. The B_s mesons seem particularly interesting," he continues. "Their loop-dominated decays are potentially very sensitive to new particles that could 'enter' in the loop virtually and cause observable effects. For example, if we find that the decay rate of the B_s to a particular final state, such as two muons, is higher than predicted by the Standard Model, it could be an indication of a contribution coming from Higgs bosons or supersymmetric particles."

The LHC, with its high luminosity and high energy, will provide the LHCb collaboration with a particularly rich harvest of beauty particles, hundreds of times more than those made available by other

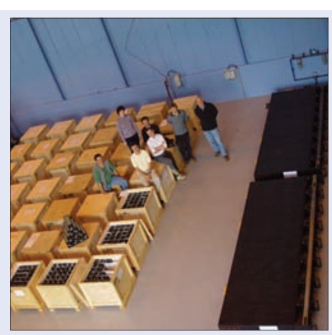


LHCb was formally approved in 1998. The diagram shows the LHCb experiment in its underground area, surrounding the LHC beam pipe.

● November 1998 p5.

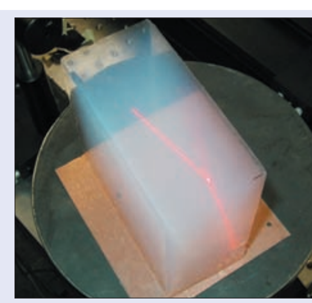
The preliminary CARIOCA chip was tested at CERN in September 2000. It was designed by the CERN-UFRJ group for use in the readout of the muon chambers.

● November 2000 p8.



The first 1200 modules of LHCb's ECAL (left) arrived at CERN from Russia in September 2002, together with the first two of 52 HCAL modules (right).

● November 2002 p8.



Early in 2003 a team in Novosibirsk reported successful production of high transparency aerogel for the LHCb RICH. (Courtesy INFN/LHCb Milano-Bicocca group.)

● *March 2003 p8.*

accelerators to previous experiments. "Both BaBar and Belle, as well as CDF and D0 at the Tevatron proton–antiproton collider, made big contributions to flavour physics, the physics of processes that involve the transformation of quark flavours," says Golutvin. "Now we know that the indirect contribution of new physics in CP violation is not big, certainly below the 10% level for the most of the decay modes. Thanks to the LHC performance, LHCb will be able to study very rare events and show possible new avenues to physics."

In its 15-year history, the LHCb detector underwent one major layout modification. The modification – known as the "LHCb light" option – reduced the amount of material in the layers the particles cross, thus reducing the background produced by the interaction of primary particles with the material of the detector. "We work out the momentum of charged particles by measuring the bending angle after the dipole magnets. The original idea was to have additional detectors to follow the trajectory of particles inside the magnet, which means of course a more complicated detector," Golutvin explains. "After an idea by Nakada and with the help of computer simulations, we understood that we could have very robust pattern recognition even without all those chambers." The results was that about six years ago the LHCb collaboration decided to simplify detector a little by having no chambers in the magnet. "This minimizes the amount of material along the trajectories of particles and also simplifies the operation of the detector," says Golutvin. "Besides that, there were a few other minor changes. For example, we decided to use a beryllium beam pipe also to minimize the background."

During normal running of the LHC, one of the most beautiful and delicate subdetectors of LHCb, the VErtex LOcator (VELO), sits only 5 mm away from the beam. Its mission is to identify the vertices where the B mesons are produced and decayed. Given the number of particles that will be produced closed to the beam direction, the VELO will receive a great deal of radiation in a short time. "The current VELO will have to be replaced after 3 to 4 years of nominal operation," confirms Golutvin. "The work on the replacement VELO modules started in July this year and should be completed by April 2010. As for the rest of the detector, it is designed to withstand the radiation during the initial physics programme."

LHCb is designed to run at a luminosity of a few times $10^{32}\,cm^{-2}s^{-1}$, much smaller than the nominal LHC luminosity, $10^{34}\,cm^{-2}s^{-1}$. This will be achieved by focusing the beams less at the LHCb collision point. The collaboration is considering a possibility for a major upgrade to work at an order of magnitude higher luminosity, after the initial physics programme is completed in about 5 to 6 years from now.

As with the other experiments at the LHC, the LHCb collaborations will use the first run to understand and calibrate the various parts of the detector. After that, it will start physics analysis at the same time as ATLAS and CMS. So just what does the collaboration expect? "As expressed by many people, the following three possible situations would be very exciting for particle physics," says Golutvin. "The first one is that ATLAS and CMS see some new physics and we don't. This will be very exciting for them and may be not too much for us. Still, the physics community will have to explain why the new physics does not seem to affect the quantum loop, in order to understand the exact nature of the new physics. Then there is the second option: ATLAS and CMS don't see new physics while we see a clear deviation from the Standard Model. This might happen if the new particles are very heavy. We would see their virtual effect but they could not be directly produced at the LHC energies in the other experiments. Of course, the best case is if all the experiments see new physics effects and a coherent scenario can be built for this new physics."

Nature alone knows which of these scenarios will eventually occur, but it could be that new physics might emerge quickly in LHCb, so Golutvin and the LHCb collaboration remain very optimistic.

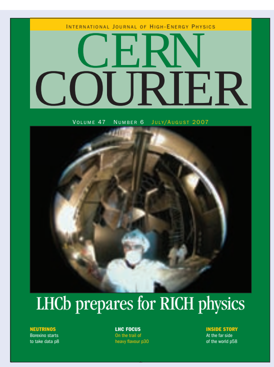
Résumé

Le LHC, avec sa luminosité et son énergie élevées, fournira à LHCb une abondance de mésons B, beaucoup plus que ce que peuvent produire d'autres installations. Le détecteur, avec sa géométrie à un seul bras, comprend le délicat sous-détecteur VELO qui servira à localiser le point de production et de désintégration des mésons B.

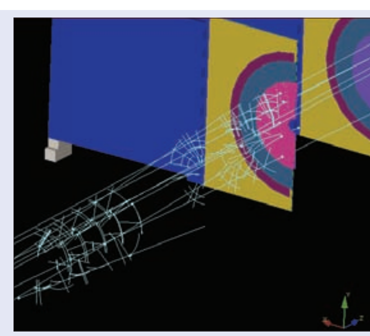
Andrei Golutvin *talked to* **Antonella Del Rosso**, *CERN.*

The first beryllium section of LHCb's beam vacuum chamber was installed at the end of August 2006. Here, a technician inserts the wakefield suppressor.
● *October 2006 p7.*

The last modules for the VELO arrived at CERN in early March 2007, from Liverpool University, where this subdetector was designed and constructed.
● *June 2007 p6.*



In 2007 commissioning the RICH detectors was in full swing in the LHC cavern, with RICH2 completely installed.
● *July/August 2007 p30.*



Particle tracks seen in the VELO and triggered by the calorimeter during synchronization tests at Point 8 in the LHC on 22 August 2008. About 25% of the VELO was switched on at the time.
● *October 2008 p61.*

CERN and PHOTONIS teamed up to develop a unique HPD

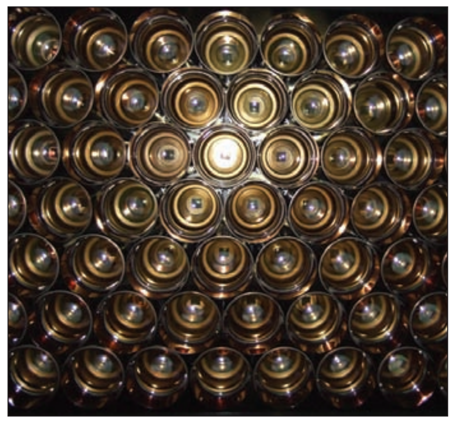
Today we talk with Thierry Gys, an applied physicist working at CERN since 1988. He studied physics engineering at the University of Brussels, Belgium.

Q: What was the exact need of CERN when you started working on the LHCb experiment?
A: The LHCb Ring Imaging Cherenkov (RICH) detectors required the detection, over a total surface of 3.3 m^2, of single photons within a wavelength range of 200–600 nm, with optimal quantum efficiency, minimal noise, and a speed compatible with the LHC collision frequency of 40 MHz. Commercially available photon detectors did not fulfill these requirements.

Q: What was the solution you developed together?
A: A hybrid photon detector (HPD) with 80% active area that encapsulates a silicon pixel detector array bump-bonded to a binary read-out chip. This results in high-speed and low-noise detection of single photons, but also requires this electronics to be compatible with the vacuum tube manufacturing process.

Q: Why PHOTONIS?
A: Because we knew PHOTONIS from the past and they had proven to be a reliable partner. Furthermore, PHOTONIS was willing to invest in the development of a new detector based on our specifications. With large companies it usually is very difficult to buy devices that are not available off-the-shelf but need to be developed. With PHOTONIS we found the right partner. CERN already worked with PHOTONIS: they delivered image intensifiers for the UA2 and CHORUS experiments in the late 80s and the early 90s.

Q: About the newly developed HPD: who developed what? / how does the solution work?
A: The HPD manufacturing is divided in two phases: the HPD anode, that consists of the flip-chip assembly packaged into a ceramic carrier, and the HPD manufacturing per se, that includes the anode coupling to the tube body, and the photocathode deposition process and the vacuum sealing. The anode design and manufacturing involved several CERN support groups and various industrial partners. The tube manufacturing was fully carried out within PHOTONIS. All this imposed a severe quality control at all steps, where LHCb-RICH groups played an essential role. The working principle is as follows: a Cherenkov photon is converted by the photo-cathode into a photo-electron. This latter is released in vacuum, and accelerated towards a silicon pixel target where it produces a rather small charge signal. The read-out chip transforms this signal into a binary information.



HPDs mounted in the LHCb-RICH detectors
Photograph courtesy of R. Plackett/ Imperial College London

The result of 10 years cooperation

Q: How long did it take to come from the first ideas until deliveries?
A: All in all it took more than 10 years. The concept and proof-of-principle were from 1994, the first full-scale prototypes were made available in 1998, the final prototypes in 2003, and the last production HPD's were delivered in 2007.

Q: Any problems experienced during production?
A: A few anode batches were not compatible with the HPD manufacturing process. The cause was not fully understood, and might have been related to effects of the chip wafer dicing. But PHOTONIS found a recipe to tackle this problem. PHOTONIS had also to change their supplier of quartz windows in the middle of the production phase. This caused some stress and a delay of a few months. To respect the original schedule, they successfully increased their capacity and so we made it. Both PHOTONIS and us were happy it finally worked out.

Q: And what is the status today?
A: In total, 550 HPDs have been delivered, and 484 HPDs are installed in the LHCb-RICH detectors. Unfortunately, we observe an unexpectedly high vacuum degradation in some of the HPDs. These had to be replaced by spares. The problem is under detailed investigation, and PHOTONIS is working on a solution that will lead to replacing some more of the degraded HPD's around Christmas this year.

Q: Did it help that you understand the Dutch language?
A: Yes, definitely. I found out by chance that the Dutch people of PHOTONIS called our HPD "jampot" which stands for "jam-jar". It was good fun to file a complaint about this nickname. As you probably know, the Dutch and Belgians like to tease each other a little!

Q: What are you hoping to find with these particular HPDs?
A: The LHCb experiment will investigate the slight differences between matter and antimatter by studying a type of particle called the "beauty quark" or "b-quark". In this context, the RICH detectors, and their HPDs, will help identifying the various particles involved in the b-quark decay processes.

Q: If you had to do the same project today, would you again choose PHOTONIS?
A: Probably yes, as long as an agreement is found about the new nicknames to come!

Q: What are your next challenges?
A: Take some holiday this year!

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TOTEM goes the distance

With detectors positioned at distances of 147 and 220 m from the CMS interaction point and others inside CMS, the TOTal Elastic and Diffractive Cross Section Measurement (TOTEM) experiment will measure the total interaction cross-section of protons at the LHC.

The data collected by the experiment will help to improve knowledge of the internal structure of the proton and the principles that determine the shape and form of protons as a function of their energy. Furthermore, TOTEM will allow precise measurements of the LHC luminosity and individual cross-sections used by the other LHC experiments. Specific to the TOTEM experiment are the "Roman pots". Veritable marvels of technology, these cylindrical vessels can be moved to within 1 mm of the beam centre. They contain detectors that will measure very forward protons, only a few microradians away from the beams, which arise from elastic scattering and diffractive processes.

Inelastic interactions between protons will be studied by gas electron multiplier (GEM) detectors installed in "telescopes", placed in the forward region of the CMS detector, where the charged-particle densities are estimated to be in the region of $10^6\,cm^{-2}s^{-1}$. Each of the telescopes contains 20 half-moon detectors arranged in 10 planes, with an inner radius matching the beam pipe. TOTEM will exploit the full decoupling of the charge-amplification and charge-collection regions, which allows freedom in the optimization of the readout structure, a unique property of GEM detectors (*CERN Courier* June 2006 p37).

The closer that the Roman pot detectors can get to the path of the beam, the more precise the results. For the LHC, the Roman pots will collect data from a distance of 800 μm from the beam. Several improvements in TOTEM's detectors will provide an unprecedented level of precision: the thin stainless-steel windows of less than 150 μm in thickness; the flatness of the windows (less than 30 μm); and the precision of the motor mechanism that moves the pots towards the beam. The pots used in the TOTEM experiment are manufactured by VakuumPraha in Prague, according to specification drawings produced at CERN.

In the final configuration, eight Roman pots will be placed in pairs at four locations at Point 5 on the LHC. There are two stations at each end of the CMS detector, positioned at distances of 147 m and 220 m from the collision point (interaction point 5). Although TOTEM and CMS are scientifically independent experiments, the Roman-pot technique will complement the results obtained by the CMS detector and by the other LHC experiments overall. The ATLAS experiment will also be using a pair of Roman pots based on the design developed by TOTEM, with slight adaptations to suit its own specific needs.

TOTEM has now installed all the Roman pots and has equipped a few of them with detectors. This will allow them to test the movement of the Roman pots with respect to the beams at the LHC start-up and to take some first data. Some detectors were also installed within CMS. After having gained experience this year, the remaining detectors will be installed during the winter shut-down to make the experiment fully operational for next year's runs.

● Based on an article in *CERN Bulletin* 2008 issue 37–38.

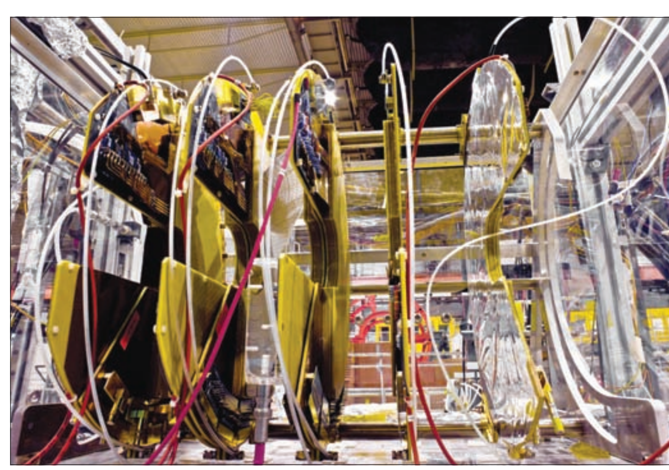
LHCf looks forward to high energies

Positioned 140 m from the ATLAS interaction point, the LHCf experiment will attempt to improve the models that describe the disintegration of ultra-high-energy cosmic rays as they enter the atmosphere. This will allow their energies to be determined more accurately and their composition to be analysed with greater precision. This information will help support the hypotheses on the mysterious origins of cosmic rays.

The LHCf detectors are placed along the beam pipe just beyond the experiment cavern, at the point where the pipe splits into two. This location allows them to detect the neutral particles (or their decay products) that are emitted in the forward region and are not bent off course by the magnetic fields of ATLAS and the LHC magnets.

While the old generation of accelerators allowed researchers to verify the cosmic-ray disintegration models up to energies in the region of 10^{15} eV – LHCf will test them at energies of up to 10^{19} eV. Even if this year's data is generated by lower-energy collisions, it will still be important as it will lie in the top-most region of data collected from previous experiments.

● Based on an article in *CERN Bulletin* 2008 issue 37–38.



Gas electron multiplier (GEM) chambers in TOTEM will detect inelastically scattered particles in the LHC collisions.

Roman pots for the LHC

The "Roman pot" technique has become a time-honoured particle-physics approach each time a new energy frontier is opened up, and CERN's LHC proton collider, which can attain collision energies of 14 TeV, will be no exception. While other detectors look for spectacular head-on collisions, where fragments fly out at wide angles to the direction of the colliding beam, with Roman pots the intention is to get as close as possible to the beams and to intercept particles that have been only slightly deflected.

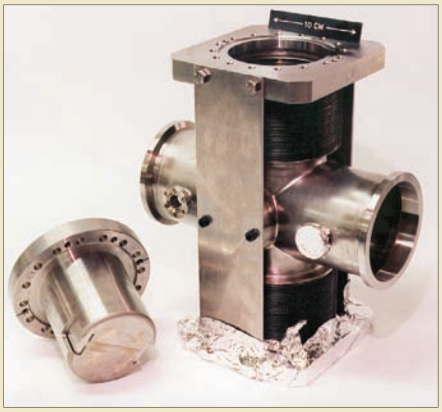
If two flocks of birds fly into each other, most of the birds usually miss a head-on collision. Likewise, when two counter-rotating beams of particles meet, most of the particles are only slightly deflected, if at all. Paradoxically, most of the particles in a collider do not collide. Of those particles that do, many of them just graze past each other, emerging very close to the particles that are sailing straight through.

These forward particles are also important for measuring the total collision rate (cross-section). In the same way as light diffracting around a small obstacle gives a bright spot in the centre of the geometric shadow, so the wave nature of particles gives a central spot of maximum "brightness".

To pick up these forward particles means having detectors that venture as near to the path of the colliding beams as possible, like avid spectators at a motor race leaning over the safety barrier. This is where Roman pots come in.

Why Roman? They were first used by a CERN/Rome group in the early 1970s to study the physics at CERN's Intersecting Storage Rings (ISR), the world's first high-energy proton–proton collider.

Why pots? The delicate detectors, able to localize the trajectory of subnuclear particles to within 0.1 mm, are housed in a cylindrical vessel. These "pots" are connected to the vacuum chamber of the collider by bellows, which are compressed as the pots are pushed towards the particles circulating inside the vacuum chamber.



In the "Roman pot" technique, the detectors are placed as close to the colliding beams as possible. The pots, which are mounted on either side of the horizontal beam pipe, move vertically in a bellows structure towards the path of the colliding particle beams. One of the pots housing the detectors is shown (left) removed from the bellows structure.

The physics debut of these Roman pots was a physics milestone. Experiments at lower energies had found that the proton interaction rate was shrinking, and physicists feared that the proton might shrink out of sight at higher energies. Using the Roman pots, the first experiments at the ISR were able to establish rapidly that the interaction rate of protons (total cross-section) in fact increases at the new energies probed by the ISR.

In their retracted position, the Roman pots do not obstruct the beam, thus leaving the full aperture of the vacuum chamber free for the fat beams encountered during the injection process. Once the collider reaches its coasting energy, the Roman pot is edged inwards until its rim is just 1 mm from the beam, without upsetting the stability of the circulating particles.

Each time a new energy regime is reached in a particle collider, Roman pots are one of the first detectors on the scene, gauging the cross-section at the new energy range. After the ISR, Roman pots have been used at CERN's proton–antiproton collider, Fermilab's Tevatron proton–antiproton collider and the HERA electron–proton collider at the DESY laboratory, Hamburg.

In the future, Roman pots will again have their day in the TOTEM experiment at CERN's LHC proton collider.

● April 1999 p8.

LHCf: a tiny new experiment joins the LHC

While most of the LHC experiments are on a grand scale, LHC forward (LHCf) is quite different. Unlike the massive detectors that are used by ATLAS or CMS, LHCf's largest detector is a mere 30 cm. Rather like the TOTEM detector (see *CERN Courier* April 1999 p9), this experiment focuses on forward physics at the LHC. The aim of LHCf is to compare data from the LHC with various shower models that are widely used to estimate the primary energy of ultra-high-energy cosmic rays.

The LHCf detectors will be placed on either side of the LHC, 140 m from the ATLAS interaction point. This location will allow the observation of particles at nearly zero degrees to the proton beam direction. The detectors comprise two towers of sampling calorimeters designed by Katsuaki Kasahara from the Shibaura Institute of Technology. Each is made of tungsten plates and plastic scintillators 3 mm thick for sampling.

Yasushi Muraki from Nagoya University leads the LHCf collaboration, with 22 members from 10 institutions and four countries. For many of the collaborators this is a reunion, as they had worked on the former Super Proton Synchrotron experiment UA7.

● November 2006 p8.

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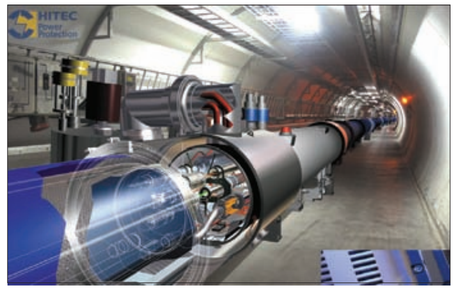

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Switching on to the Grid

The LHC will provide a testbed for a new concept in network-based information handling.

When CERN's LHC collider begins operation, it will be the most powerful machine of its type in the world, providing research facilities for thousands of researchers from all over the globe.

The computing capacity required for analysing the data generated by these big LHC experiments will be several orders of magnitude greater than that used by current experiments at CERN, itself already substantial. Satisfying this vast data-processing appetite will require the integrated use of computing facilities installed at several research centres across Europe, the US and Asia.

During the last two years the Models of Networked Analysis at Regional Centres for LHC Experiments (MONARC) project, supported by a number of institutes participating in the LHC programme, has been developing and evaluating models for LHC computing. MONARC has also developed tools for simulating the behaviour of such models when implemented in a wide-area distributed computing environment. This requirement arrived on the scene at the same time as a growing awareness that major new projects in science and technology need matching computer support and access to resources worldwide.

In the 1970s and 1980s the Internet grew up as a network of computer networks, each established to service specific communities and each with a heavy commitment to data processing.

In the late 1980s the World Wide Web was invented at CERN to enable particle physicists scattered all over the globe to access information and participate actively in their research projects directly from their home institutes. The amazing synergy of the Internet, the boom in personal computing and the growth of the Web grips the whole world in today's dot.com lifestyle.

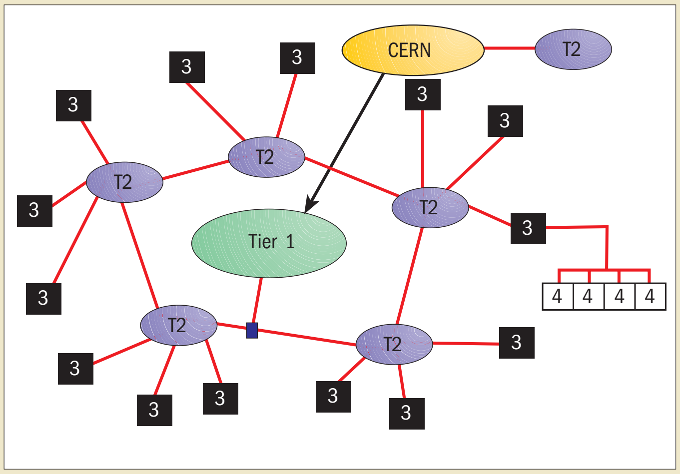
Internet, Web, what next?

However, the Web is not the end of the line. New thinking for the millennium, summarized in a milestone book entitled *The Grid* by Ian Foster of Argonne and Carl Kesselman of the Information Sciences Institute of the University of Southern California, aims to develop new software ("middleware") to handle computations spanning widely distributed computational and information resources - from supercomputers to individual PCs.

Just as a grid for electric power supply brings watts to the wall-plug in a way that is completely transparent to the end user, so the new data Grid will do the same for information.

Each of the major LHC experiments – ATLAS, CMS and ALICE – is estimated to require computer power equivalent to 40 000 of today's PCs. Adding LHCb to the equation gives a total equivalent of 140 000 PCs, and this is only for day 1 of the LHC.

Within about a year this demand will have grown by 30%. The demand for data storage is equally impressive, calling for some several thousand terabytes – more information than is contained in the combined telephone directories for the populations of millions of planets. With users across the globe, this represents a new challenge in distributed computing. For the LHC, each experiment will have its own central computer and data storage facilities at CERN, but these have to be integrated with regional computing centres accessed by the researchers from their home institutes.



A grid infrastructure for one country, with one Tier 1 centre, and several Tier 2 regional centres. Tier 3 centres are at university level, Tier 4 centres are inside research departments.

CERN serves as Grid testbed

As a milestone en route to this panorama, an interim solution is being developed, with a central facility at CERN complemented by five or six regional centres and several smaller ones, so that computing can ultimately be carried out on a cluster in the user's research department. To see whether this proposed model is on the right track, a testbed is to be implemented using realistic data.

Several nations have launched new Grid-oriented initiatives – in the US by NASA and the National Science Foundation, while in Europe particle physics provides a natural focus for work in, among others, the UK, France, Italy and Holland. Other areas of science, such as Earth observation and bioinformatics, are also on board. In Europe, European Commission funding is being sought to underwrite this major effort to propel computing into a new orbit.

● June 2000 pp17–18.

Résumé

La physique des particules a toujours poussé à leurs limites le calcul électronique et les techniques afférentes – comme en témoigne le World Wide Web, développé au CERN. Fidèle à cette tradition, la physique des particules au CERN constituera bientôt un banc d'essai crucial pour un système réticulaire de traitement de l'information encore plus puissant – la Grille.

The Grid gets EU funds

Plans for the next generation of network-based information-handling systems took a major step forward when the European Union's Fifth Framework Information Society Technologies programme concluded negotiations to fund the Data Grid research and development project. The project was submitted to the EU by a consortium of 21 bodies involved in a variety of sciences, from high-energy physics to Earth observation and biology, as well as computer sciences and industry. CERN is the leading and coordinating partner in the project.

Starting from this year, the Data Grid project will receive in excess of €9.8 million for three years to develop middleware (software) to deploy applications on widely distributed computing systems. In addition to receiving EU support, the enterprise is being substantially underwritten by funding agencies from a number of CERN's member states. Due to the large volume of data that it will produce, CERN's LHC collider will be an important component of the Data Grid.

As far as CERN is concerned, this programme of work will integrate well into the computing testbed activity that is already planned for the LHC. Indeed, the model for the distributed computing architecture that Data Grid will implement is largely based on the results of the MONARC (Models of Networked Analysis at Regional Centres for LHC experiments) project.

The work that the project will involve has been divided into numbered subsections, or "work packages" (WP). CERN's main contribution will be to three of these work packages: WP 2, dedicated to data management and data replication; WP 4, which will look at computing-fabric management; and WP 8, which will deal with high-energy physics applications. Most of the resources for WP 8 will come from the four major LHC experimental collaborations: ATLAS, CMS, ALICE and LHCb.

Other work will cover areas such as workload management (coordinated by the INFN in Italy), monitoring and mass storage (coordinated in the UK by the PPARC funding authority and the UK Rutherford Appleton Laboratory) and testbed and networking (coordinated in France by IN2P3 and the CNRS).

● March 2001 p5 (abridged).

The Gigabyte System Network

To mark the major international Telecom '99 exhibition in Geneva, CERN staged a demonstration of the world's fastest computer-networking standard, the Gigabyte System Network. This is a new networking standard developed by the High-Performance Networking Forum, which is a worldwide collaboration between industry and academia. Telecom '99 delegates came to CERN to see the new standard in action.

GSN is the first networking standard capable of handling the enormous data rates expected from the LHC experiments. It has a capacity of 800 Mbyte/s (that's getting on for a full-length feature film), making it attractive beyond the realms of scientific research. Internet service providers, for example, expect to require these data rates to supply high-quality multimedia across the Internet within a few years. Today, however, most home network users have to be content with 5 kbyte/s, or about a single frame. Even CERN, one of Europe's largest networking centres, currently has a total external capacity of only 22 Mbyte/s.

● November 1999 p10 (abridged).

Approval for Grid project for LHC computing

The first phase of the impressive Computing Grid project for CERN's LHC was approved at a special meeting of CERN's Council, its governing body, on 20 September.

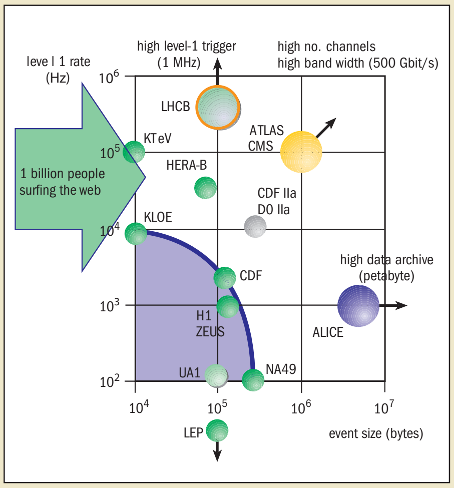
After LHC commissioning, the collider's four giant detectors will be accumulating more than 10 million Gbytes of particle-collision data each year (equivalent to the contents of about 20 million CD-ROMs). To handle this will require a thousand times the computing power available at CERN today.

Nearly 10 000 scientists, at hundreds of universities round the world, will group in virtual communities to analyse this LHC data. The strategy relies on the coordinated deployment of communications technologies at hundreds of institutes via an intricately interconnected worldwide grid of tens of thousands of computers and storage devices.

The LHC Computing Grid project will proceed in two phases. Phase 1, to be activated in 2002 and continuing in 2003 and 2004, will develop the prototype equipment and techniques necessary for the data-intensive scientific computing of the LHC era. In 2005, 2006 and 2007, Phase 2 of the project, which will build on the experience gained in the first phase, will construct the production version of the LHC Computing Grid.

Phase 1 will require an investment at CERN of SFr30 million (some €20 million) which will come from contributions from CERN's member states and major involvement of industrial sponsors. More than 50 positions for young professionals will be created. Significant investments are also being made by participants in the LHC programme, particularly in the US and Japan, as well as Europe.

● November 2001 p5 (abridged).



Particle-physics experiments lead the demand for more computing power. The LHC experiments will yield huge increases in data rate and/or event size.

● October 2001 p32 (extract).

The LHC Computing Grid gets started…

This summer the IT division at CERN was a hive of activity as dozens of young software engineers worked round the clock to launch the LHC Computing Grid (LCG) into its first phase of operations. Meanwhile, similar hectic preparations were going on at other major computing centres around the world.

The LCG project, which was launched last year, has a mission to integrate thousands of computers worldwide into a global computing resource. This technological *tour de force* will rely on novel Grid software, called middleware, and will also benefit from new hardware developments in the IT industry.

The challenge facing the LCG project can be summarized in terms of two large numbers. The LHC will produce more than 10 petabytes of data a year and require around 100 000 of today's PCs to analyse that data.

The LCG project has been rapidly gearing up for this challenge, with more than 50 computer scientists and engineers from partner centres around the world joining the effort over the past year. The first version of the LCG, called LCG-1, is now up and running on a restricted number of sites and with limited functionality.

● October 2003 p9 (abridged).

…while the EGEE gets ready

The success of the European Union (EU)-funded European Data Grid (EDG) project (p69) – a three-year effort led by CERN, which is due to finish in spring 2004 – has generated strong support for a follow-up project. The objective is to build a permanent European Grid infrastructure that can serve a broad spectrum of applications reliably and continuously. So CERN has established a pan-European consortium called Enabling Grids for E-science in Europe (EGEE) to build and operate such a production Grid infrastructure, providing round-the-clock Grid service to scientists throughout Europe.

A proposal for the project was submitted to the EU 6th Framework Programme in May 2003. This proposal, again led by CERN, involves some 70 partners, encompassing all major computer centres in Europe, as well as leading American and Russian centres.

The LHC Computing Grid will provide the springboard for EGEE and in turn benefit from Grid software engineering that is part of the EGEE project. However, the mission of EGEE is also to extend the potential benefits of a Grid infrastructure beyond high-energy physics.

● October 2003 p9 (abridged).

CERN's computer centre prepares for LHC

A major upgrade of CERN's computer centre has been underway for the past year to increase capacity for the facility's role as the heart of the LHC Computing Grid (LCG). Since services must be kept running round the clock during the upgrade, a rolling approach is needed. In a major migration last year many systems, including five StorageTek tape silos, were moved to the newly created machine room in the basement. This allowed an upgrade of the electrical distribution in half of the main machine room to be done during the autumn.

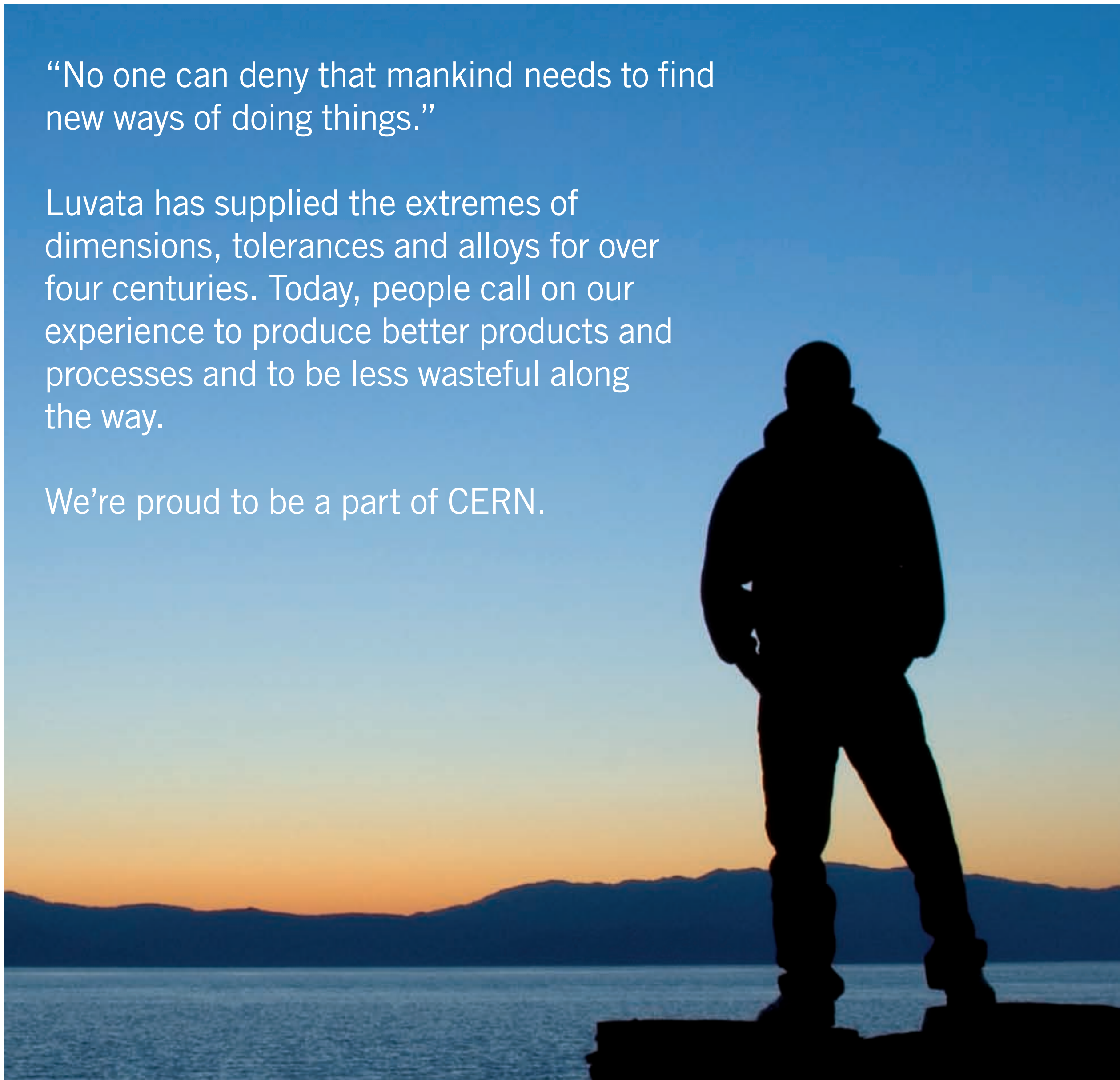
Since this upgrade, the centre can now cope with a demand of up to 1 MW in this area of the machine room, which is equivalent to about 5000 PCs. With all this power being turned into heat, adequate air-conditioning is a major concern and the first stages of a new underfloor cold-air distribution system have been installed to cope with increased demand. During the spring of 2004 equipment began to be moved over from the other half of the machine room, starting with the servers for CERN's administrative applications. These were moved to a dedicated area equipped with dual power supplies to ensure that these crucial services can be maintained even during an extended power cut – although full protection will only become available once a new substation is commissioned for the centre in early 2005.

The machine room of CERN's computer centre.

To manage all of the equipment moves, close control over the configuration of the different systems and high levels of automation are essential. These are taken care of by ELFms, CERN's Extremely Large Farm management system. Two ELFms components, quattor (a system administration toolkit for automated installation, configuration and management of clusters and farms running UNIX derivatives) and the Hardware Management System have a particularly important role. The quattor Configuration Database, developed as part of the European DataGrid project, now holds information about more than 95% of the systems in the computer centre – information ranging from the precise details of the software installed to the location of the system in the computer centre.

Using the ELFms Hardware Management System (developed with support from the UK's GridPP as part of the LCG project) and information from quattor, the computer centre operations manager can produce a list of systems to be moved and know that the right people will be contacted in the correct order to shut down and move systems, reinstall the operating system if required, and then restart them on schedule. With almost 1500 machines moved in four months the newly deployed software has been given a thorough workout and has performed according to expectations.

● September 2004 p5.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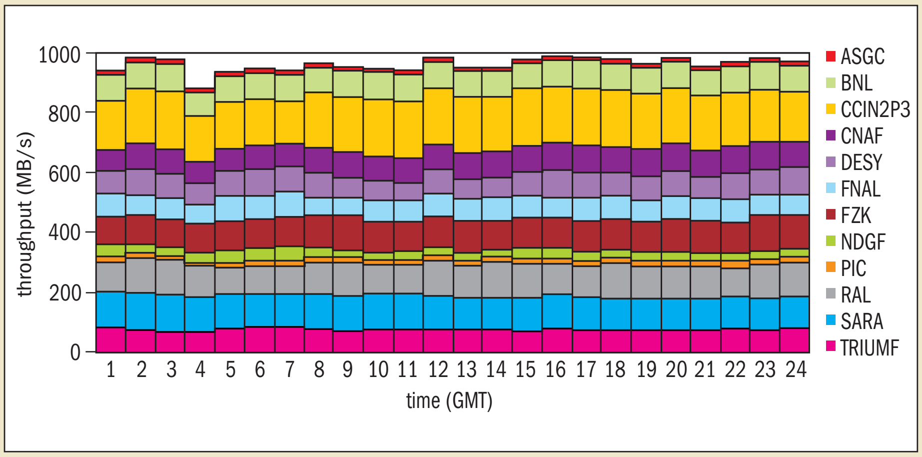
The LCG meets 1 GB/s challenge

On 15 February the Worldwide LHC Computing Grid collaboration (WLCG) officially announced the successful completion of a service challenge at the Computing for High-Energy and Nuclear Physics 2006 conference (CHEP '06) in Mumbai, India. The challenge involved sustaining a continuous flow of physics data on a worldwide Grid infrastructure at up to 1 GB/s. The maximum sustained data rates achieved correspond to transferring a DVD of scientific data from CERN every five seconds.

The data were transferred from CERN to 12 major computer centres worldwide. More than 20 other computing facilities were involved in successful tests of a global Grid service for real-time storage, distribution and analysis of the data. The completion of this service challenge is a key milestone on the way to establishing the necessary computing infrastructure for the LHC. The results represent a step forward from a previous service challenge in early 2005 that involved just seven centres in Europe and the US and achieved sustained rates of 600 MB/s.



Hourly average throughput from CERN demonstrating data rates up to 1 GB/s.

● April 2006 p15 (abridged).

Worldwide Grid awaits LHC start-up

In January, almost 300 members of the Worldwide LHC Computing Grid (WLCG) collaboration attended a week-long workshop at CERN to discuss the status of the infrastructure, as well as detailed plans and timescales to prepare for the start-up of the LHC. The week included experiment-specific sessions and a joint-operations workshop.

The WLCG was formed by resource providers – Grid projects, mainly EGEE in Europe and OSG in the US, and individual resource providers – to deal with the 15 PB of LHC data expected every year. The computing sites are arranged in a number of tiers, with CERN serving as the Tier-0 site, which will collect and distribute data to 12 Tier-1 sites (p67). Some 150 Tier-2 sites will help process the data.

All four large LHC experiments organized sessions to allow direct contact between site managers and experiments experts. The ALICE session concentrated on different tutorials regarding specific aspects of ALICE software such as monitoring, AliRoot and AliEn. Topics in the ATLAS session included data management, storage-resource management and the security model of the services deployed.

The CMS session covered file-transfer and integration plans as well as computing resources and storage classes. Discussions in the LHCb session included topics such as testing of the "glexec" middleware module by some sites, data security and data transfer between sites.

Three working groups have been set up to focus on improving service and site reliability, which are all coordinated. The Grid Monitoring Group will pull together monitoring data and provide views for the different stakeholders. The Site Management group will work to harmonize tools and best practices and will issue recommendations to improve site management. The System Analysis group will continue work done by ARDA to provide feedback from the applications point of view. Another area still under development is the interoperation between the EGEE and OSG infrastructures.

● For more information, videos and the presentations, see http://indico.cern.ch/conferenceDisplay.py?confId=3738.

● April 2007 p13 (abridged).

The high-energy frontier

The discoveries that are expected to come from the LHC should revolutionize our understanding of matter, forces and space.

The principal goal of the experimental programme at the LHC is to make the first direct exploration of a completely new region of energies and distances, to the tera-electron-volt scale and beyond. The main objectives include the search for the Higgs boson and whatever new physics may accompany it, such as supersymmetry or extra dimensions, and also – perhaps above all – to find something that the theorists have not predicted.

The Standard Model of particles and forces summarizes our present knowledge of particle physics. It extends and generalizes the quantum theory of electromagnetism to include the weak nuclear forces responsible for radioactivity in a single unified framework; it also provides an equally successful analogous theory of the strong nuclear forces.

The conceptual basis for the Standard Model was confirmed by the discovery at CERN of the predicted weak neutral-current form of radioactivity and, subsequently, of the quantum particles responsible for the weak and strong forces, at CERN and DESY respectively. Detailed calculations of the properties of these particles, confirmed in particular by experiments at the LEP collider, have since enabled us to establish the complete structure of the Standard Model; data taken at LEP agreed with the calculations at the *per mille* level.

These successes raise deeper problems, however. The Standard Model does not explain the origin of mass, nor why some particles are very heavy while others have no mass at all; it does not explain why there are so many different types of matter particles in the universe; and it does not offer a unified description of all the fundamental forces. Indeed, the deepest problem in fundamental physics may be how to extend the successes of quantum physics to the force of gravity. It is the search for solutions to these problems that define the current objectives of particle physics – and the programme for the LHC.

Higgs, hierarchy and extra dimensions

Understanding the origin of mass will unlock some of the basic mysteries of the universe: the mass of the electron determines the sizes of atoms, while radioactivity is weak because the W boson weighs as much as a medium-sized nucleus. Within the Standard Model the key to mass lies with an essential ingredient that has not yet been observed, the Higgs boson; without it the calculations would yield incomprehensible infinite results. The agreement of the data with the calculations implies not only that the Higgs boson (or something equivalent) must exist, but also suggests that its mass should be well within the reach of the LHC.

Experiments at LEP at one time found a hint for the existence of the Higgs boson, but these searches proved unsuccessful and told us only that it must weigh at least 114 GeV (*CERN Courier* November 2005 p23). At the LHC, the ATLAS and CMS experiments will be looking for the Higgs boson in several ways. The particle is predicted to be unstable, decaying for example to photons, bottom quarks, tau leptons, W or Z bosons (figure 1). It may well be necessary to combine several different decay modes to uncover a convincing signal, but the LHC experiments should be able to find the Higgs boson even if it weighs as much as 1 TeV.

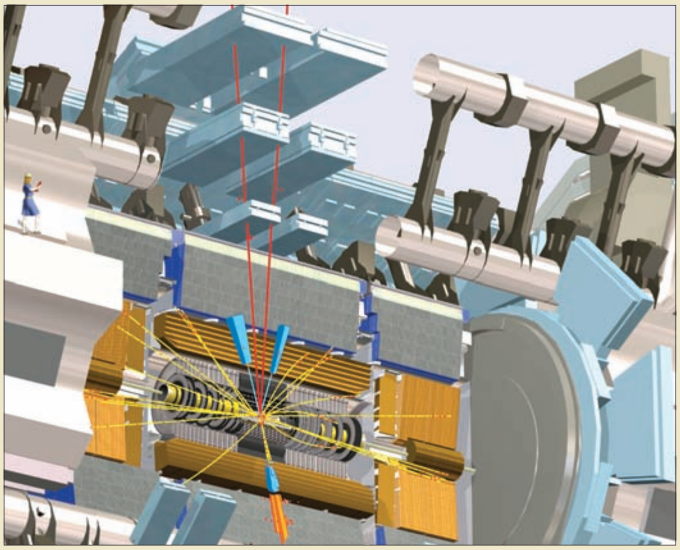


Fig. 1. Simulation in the ATLAS detector where a Higgs boson decays to two Z bosons. One of these decays to two muons (the red tracks going to the top) while the other decays to an electron–positron pair, depositing energy in the electromagnetic calorimeter in the opposite direction.

While resolving the Higgs question will set the seal on the Standard Model, there are plenty of reasons to expect other, related new physics, within reach of experiments at the LHC. In particular, the elementary Higgs boson of the Standard Model seems unlikely to exist in isolation. Specifically, difficulties arise in calculating quantum corrections to the mass of the Higgs boson. Not only are these corrections infinite in the Standard Model, but, if the usual procedure is adopted of controlling them by cutting the theory off at some high energy or short distance, the net result depends on the square of the cut-off scale. This implies that, if the Standard Model is embedded in some more complete theory that kicks in at high energy, the mass of the Higgs boson would be very sensitive to the details of this high-energy theory. This would make it difficult to understand why the Higgs boson has a (relatively) low mass and, by extension, why the scale of the weak interactions is so much smaller than that of grand unification, say, or quantum gravity.

This is known as the "hierarchy problem". One could try to resolve it simply by postulating that the underlying parameters of the ▷

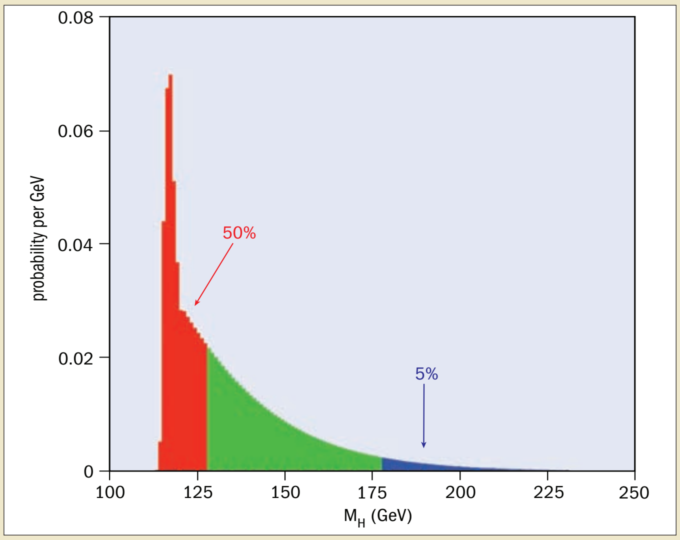


Fig. 2. A graph showing the probability distribution for the mass of the Higgs boson in the Standard Model found by combining direct search information from LEP with an analysis of precision electroweak data (Erler 2007).

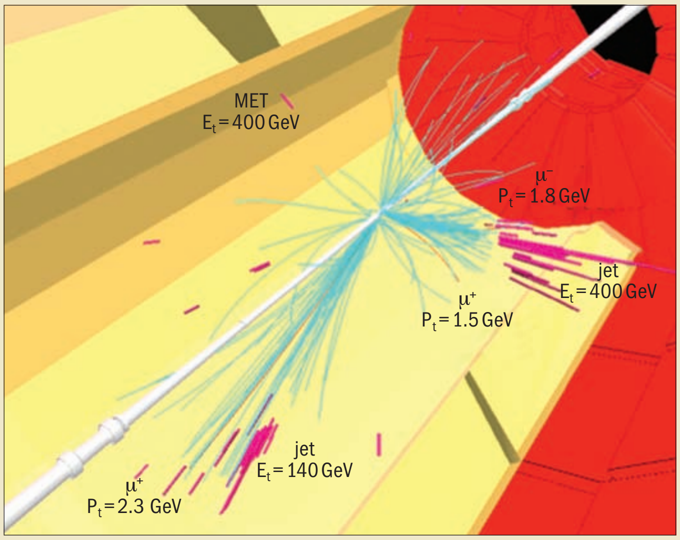


Fig. 3. Simulation of a supersymmetric event in the CMS detector in which a pair of gluinos decay into muons and quark jets and dark-matter particles that carry away a large amount of "missing" invisible energy (MET).

theory are tuned very finely, so that the net value of the Higgs boson mass after adding in the quantum corrections is small, owing to some suitable cancellation. However, it would be more satisfactory either to abolish the extreme sensitivity to the quantum corrections, or to cancel them in some systematic manner.

One way to achieve this would be if the Higgs boson is composite and so has a finite size, which would cut the quantum corrections off at a relatively low energy scale. In this case, the LHC might uncover a cornucopia of other new composite particles with masses around this cut-off scale, near 1 TeV.

The alternative, more elegant, and in my opinion more plausible, solution is to cancel the quantum corrections systematically, which is where supersymmetry could come in. Supersymmetry would pair up fermions, such as the quarks and leptons, with bosons, such as the photon, gluon, W and Z, or even the Higgs boson itself. In a supersymmetric theory, the quantum corrections due to the pairs of virtual fermions and bosons cancel each other systematically, and a low-mass Higgs boson no longer appears unnatural. Indeed, supersymmetry predicts a mass for the Higgs boson probably below 130 GeV, in line with the global fit to precision electroweak data.

The fermions and bosons of the Standard Model, however, do not pair up with each other in a neat supersymmetric manner. The theory, therefore, requires that a supersymmetric partner, or sparticle, as yet unseen, accompanies each of the Standard Model particles. Thus, this scenario predicts a "scornucopia" of new particles that should weigh less than about 1 TeV and could be produced by the LHC (figure 3).

Another attraction of supersymmetry is that it facilitates the unification of the fundamental forces. Extrapolating the strengths of the strong, weak and electromagnetic interactions measured at low energies does not give a common value at any energy, in the absence of supersymmetry. However, there would be a common value, at an energy around 10^{16} GeV, in the presence of supersymmetry. Moreover, supersymmetry provides a natural candidate, in the form of the lightest supersymmetric particle (LSP), for the cold dark matter required by astrophysicists and cosmologists to explain the amount of matter in the universe and the formation of structures within it, such as galaxies. In this case, the LSP should have neither strong nor electromagnetic interactions, since otherwise it would bind to conventional matter and be detectable. Data from LEP and direct searches have already excluded sneutrinos as LSPs. Nowadays, the "scandidates" most considered are the lightest neutralino and (to a lesser extent) the gravitino.

Assuming that the LSP is the lightest neutralino, the parameter space of the constrained minimal supersymmetric extension of the Standard Model (CMSSM) is restricted by the need to avoid the stau being the LSP, by the measurements of $b \rightarrow s\gamma$ decay that agree with the Standard Model, by the range of cold dark-matter density allowed by astrophysical observations, and by the measurement of the anomalous magnetic moment of the muon (g_μ–2). These requirements are consistent with relatively large masses for the lightest and next-to-lightest visible supersymmetric particles, as figure 4 indicates. The figure also shows that the LHC can detect most of the models that provide cosmological dark matter (though this is not guaranteed), whereas the astrophysical dark matter itself may be detectable directly for only a smaller fraction of models.

Within the overall range allowed by the experimental constraints, are there any hints at what the supersymmetric mass scale might be? The high precision measurements of m_W tend to favour a relatively small mass scale for sparticles. On the other hand, the rate for $b \rightarrow s\gamma$ shows no evidence for light sparticles, and the experimental upper limit on $B_s \rightarrow \mu^+\mu^-$ begins to exclude very small masses. The strongest indication for new low-energy physics, for which supersymmetry is just one possibility, is offered by g_μ–2. Putting this together with the other precision observables gives a preference for light sparticles.

Other proposals for additional new physics postulate the existence of new dimensions of space, which might also help to deal with the hierarchy problem. Clearly, space is three-dimensional ▷

40-30

The 40-30 company partners with CERN to build the world's most powerful particle accelerator

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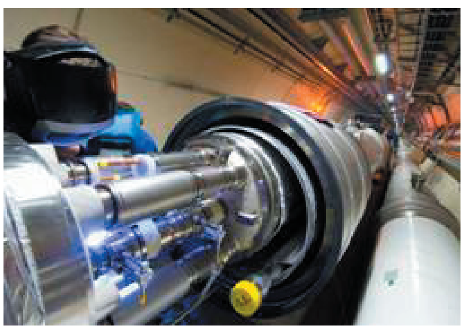

40-30's assignment is to partake in the LHC's assembly and to control both the leak tightness of all components making up the system, including the cryo cooled superconducting magnets connections. Since 2005, 40-30 personnel have taken part in building the main LHC ring, controlling the 1,800 magnets' helium and vacuum leak tightness (the lines have an average length of 15 metres each weighing over 27 metric tonnes), we are also involved in helium leak checking all connecting flanges as the line is assembled . 40-30 participated in the cleaning and installation for the LHC's straight line sections and has been conducting overhaul and maintenance of the pumping system responsible for the creation of vacuum.

In addition 40-30 is responsible for certain component maintenance, leak detectors, mass spectrometers, pumps and associated valves used within the CERN vacuum circuit. In order to provide this service 40-30 have fifty employees that has been involved over the past five years who use bicycles to move between station points, These personnel have already amassed in excess of 100,000 km within the CERN tunnel.

This construction by CERN is the world's most powerful particle accelerator that has required more than 500 companies over the past 10 years at a cost of around €3bn.

On 10 September, the EU organisation for nuclear research in Geneva launches the biggest experiment of the history, funded by 20 EU member states - including the UK - to replicate conditions of the big bang.

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The role of physics in innovation

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Physics drives modernisation and progress across the global economy, and physics-based businesses bring the knowledge of the research base into the commercial world. Without physics research and technologies there would be no modern communications, no MP3 players and no GPS technology. Everyday devices such as mobile phones are only able to exist because of physics research. Every pixel of the screen of a mobile phone contains a transparent transistor; seemingly esoteric research into how sound waves travel across the surfaces of crystals produced the technologies that allow mobile phones to be made small enough to fit in your pocket. The ability to communicate and transfer information on the move has enabled new solutions to problems and allowed a whole new way of working to emerge, greatly increasing flexibility and speed of response.

Innovations across every sector of the economy are made possible as a direct result of knowledge produced by physics and physicists. For this to continue, we must maintain a strong research base in physics and strong physics-based businesses. And, most importantly, we must work to secure a strong supply of physics-trained workers. It is not possible to predict the future, but however it turns out, physics and physicists will be essential.

The Institute of Physics works with businesses, universities, governments and funding bodies to promote awareness of the excitement of physics and support innovation and scientific research. Through our outreach programmes, such as the award-winning Lab in a Lorry, we bring engaging and exciting physics to school children and the public at large, sparking interest and increasing awareness. We operate more than 50 subject groups and divisions which bring together specialists from many disciplines though meetings and conferences aimed at pushing the limits of scientific research. The Institute is also a world leader in physics publishing, producing an extensive range of journals covering all aspects of the discipline, many supported by specialist websites.

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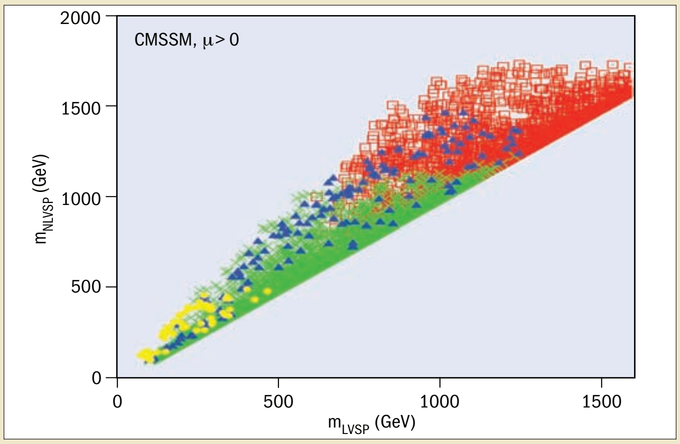


Fig. 4. Masses of the lightest visible supersymmetric particle (LVSP) and the next-to-lightest visible supersymmetric particle (NLVSP) found in a sampling of parameters (red) of a constrained minimal supersymmetric extension of the Standard Model, including those that produce a suitable amount of dark matter (blue), most of which are detectable at the LHC (green), but perhaps not directly as astrophysical dark matter (yellow).

on the distance scales that we know so far, but the suggestion is that there might be additional dimensions curled up so small as to be invisible. This idea, which dates back to the work of Theodor Kaluza and Oskar Klein in the 1920s, has gained currency in recent years with the realization that string theory predicts the existence of extra dimensions and that some of these might be large enough to have consequences observable at the LHC (*CERN Courier* July/August 2003 p21). One possibility that has emerged is that gravity might become strong when these extra dimensions appear, possibly at energies close to 1 TeV. In this case, some variants of string theory predict that microscopic black holes might be produced in the LHC collisions. These would decay rapidly via Hawking radiation, but measurements of this radiation would offer a unique window onto the mysteries of quantum gravity.

If the extra dimensions are curled up on a sufficiently large scale, ATLAS and CMS might be able to see Kaluza–Klein excitations of Standard Model particles, or even the graviton. Indeed, the spectroscopy of some extra-dimensional theories might be as rich as that of supersymmetry while, in some theories, the lightest Kaluza–Klein particle might be stable, rather like the LSP in supersymmetric models.

Back to the beginning

By colliding particles at very high energies we can recreate the conditions that existed a fraction of a second after the Big Bang, which allows us to probe the origins of matter. Experiments at LEP revealed that there are just three "families" of elementary particles: one that makes up normal stable matter, and two heavier unstable families that were revealed in cosmic rays and accelerator experiments. The Standard Model does not explain why there are three and only three families, but it may be that their existence in the early universe was necessary for matter to emerge from the Big Bang, with little or no antimatter.

Andrei Sakharov was the first to point out that particle physics could explain the origin of matter in the universe by the fact that matter and antimatter have slightly different properties, as discovered in the decays of K and B mesons, which contain strange and bottom quarks, members of the heavier families (*CERN Courier* June 1999 p22 and October 1999 p24). These differences are manifest in the phenomenon of CP violation. Present data are in good agreement with the amount of CP violation allowed by the Standard Model, but this would be insufficient to generate the matter seen in the universe.

The Standard Model accounts for CP violation within the context of the Cabibbo–Kobayashi–Maskawa (CKM) matrix, which links the interactions between quarks of different type (or flavour). Experiments at the B-factories at KEK and SLAC have established that the CKM mechanism is dominant, so the question is no longer whether this is "right". The task is rather to look for additional sources of CP violation that must surely exist, to create the cosmological matter–antimatter asymmetry via baryogenesis in the early universe. If the LHC does observe any new physics, such as the Higgs boson and/or supersymmetry, it will become urgent to understand its flavour and CP properties.

The LHCb experiment will be dedicated to probing the differences between matter and antimatter, notably looking for discrepancies with the Standard Model. The experiment has unique capabilities for probing the decays of mesons containing both bottom and strange quarks. It will be able to measure subtle CP-violating effects in B_s decays, and will also improve measurements of all the angles of the unitarity triangle, which expresses the amount of CP violation in the Standard Model. The LHC will also provide high sensitivity to rare B decays, to which the ATLAS and CMS experiments will contribute, in particular, and which may open another window on CP violation beyond the CKM model.

In addition to the studies of proton–proton collisions, heavy-ion collisions at the LHC will provide a window onto the state of matter that would have existed in the early universe at times before quarks and gluons "condensed" into hadrons, and ultimately the protons and neutrons of the primordial elements. When heavy ions collide at high energies they form for an instant a "fireball" of hot, dense matter. Studies, in particular by the ALICE experiment, may resolve some of the puzzles posed by the data already obtained at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven. These data indicate that there is very rapid thermalization in the collisions, after which a fluid with very low ▷

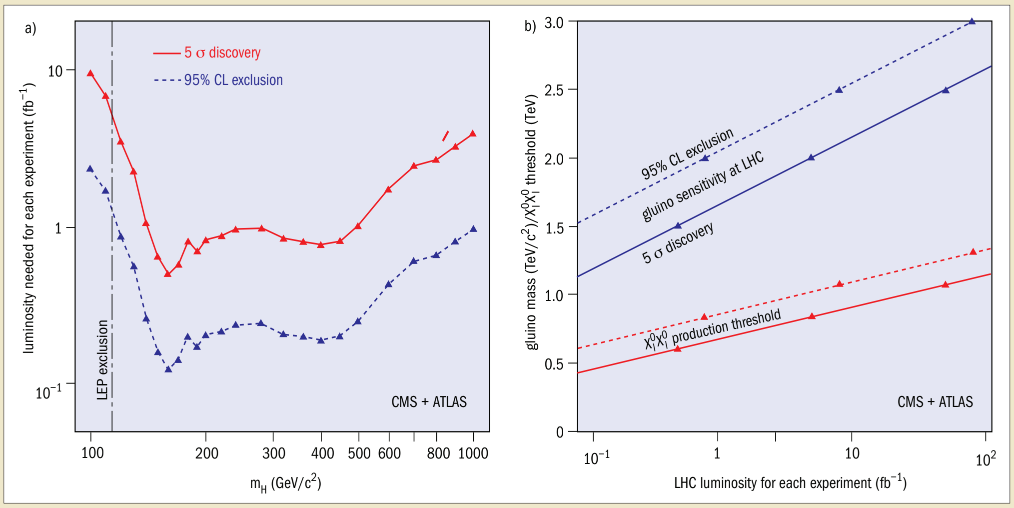


Fig. 5. a) The prospects for discovering a Standard Model Higgs boson in the initial running of the LHC, as a function of the mass of the Higgs. The plot combines the capabilities of the ATLAS and CMS experiments. b) The reach for gluino detection at the LHC and the corresponding threshold for the production of pairs of the lightest neutralinos (χ_1^0) at linear colliders, as functions of the LHC intensity for each experiment (Blaising et al. 2006).

viscosity and large transport coefficients seems to be produced. One of the surprises is that the medium produced at RHIC seems to be strongly interacting . The final state exhibits jet quenching and the semblance of cones of energy deposition akin to Machian shock waves or Cherenkov radiation patterns, indicative of very fast particles moving through a medium faster than sound or light (*CERN Courier* March 2007 p35).

Experiments at the LHC will enter a new range of temperatures and pressures, thought to be far into the quark–gluon plasma regime, which should test the various ideas developed to explain results from RHIC. The experiments will probably not see a real phase transition between the hadronic and quark–gluon descriptions; it is more likely to be a cross-over that may not have a distinctive experimental signature at high energies. However, it may well be possible to see quark–gluon matter in its weakly interacting high temperature phase. The larger kinematic range should also enable ideas about jet quenching and radiation cones to be tested.

First expectations

The first step for the experimenters will be to understand the minimum-bias events and compare measurements of jets with the predictions of QCD. The next Standard Model processes to be measured and understood will be those producing the W- and Z-vector bosons, followed by top-quark physics. Each of these steps will allow the experimental teams to understand and calibrate their detectors, and only after these steps will the search for the Higgs boson start in earnest. The Higgs will not jump out in the same way as did the W and Z bosons, or even the top quark, and the search for it will demand an excellent understanding of the detectors. Around the time that Higgs searches get underway, the first searches for supersymmetry or other new physics beyond the Standard Model will also start.

In practice, the teams will look for generic signatures of new physics that could be due to several different scenarios. For example, missing-energy events could be due to supersymmetry, extra dimensions, black holes or the radiation of gravitons into extra dimensions. The challenge will then be to distinguish between the different scenarios. For example, in the case of distinguishing between supersymmetry and universal extra dimensions, the spectra of higher excitations would be different in the two scenarios, the different spins of particles in cascade decays would yield distinctive spin correlations, and the spectra and asymmetries of, for instance, dileptons, would be distinguishable.

What is the discovery potential of this initial period of LHC running? Figure 5a shows that a Standard Model Higgs boson could be discovered with 5 σ significance with 5 fb^{-1} of integrated and well-understood luminosity, whereas 1 fb^{-1} would already suffice to exclude a Standard Model Higgs boson at the 95% confidence level over a large range of possible masses. However, as mentioned above, this Higgs signal would receive contributions from many different decay signatures, so the search for the Higgs boson will require researchers to understand the detectors very well to find each of these signatures with good efficiency and low background. Therefore, announcement of the Higgs discovery may not come the day after the accelerator produces the required integrated luminosity!

Paradoxically, some new physics scenarios such as supersymmetry may be easier to spot, if their mass scale is not too high. For example, figure 5b shows that 0.1 fb^{-1} of luminosity should be enough to detect the gluino at the 5 σ level if its mass is less than 1.2 TeV, and to exclude its existence below 1.5 TeV at the 95% confidence level. This amount of integrated luminosity could be gathered with an ideal month's running at 1% of the design instantaneous luminosity.

We do not know which, if any, of the theories that I have mentioned nature has chosen, but one thing is sure: once the LHC starts delivering data, our hazy view of this new energy scale will begin to clear dramatically.

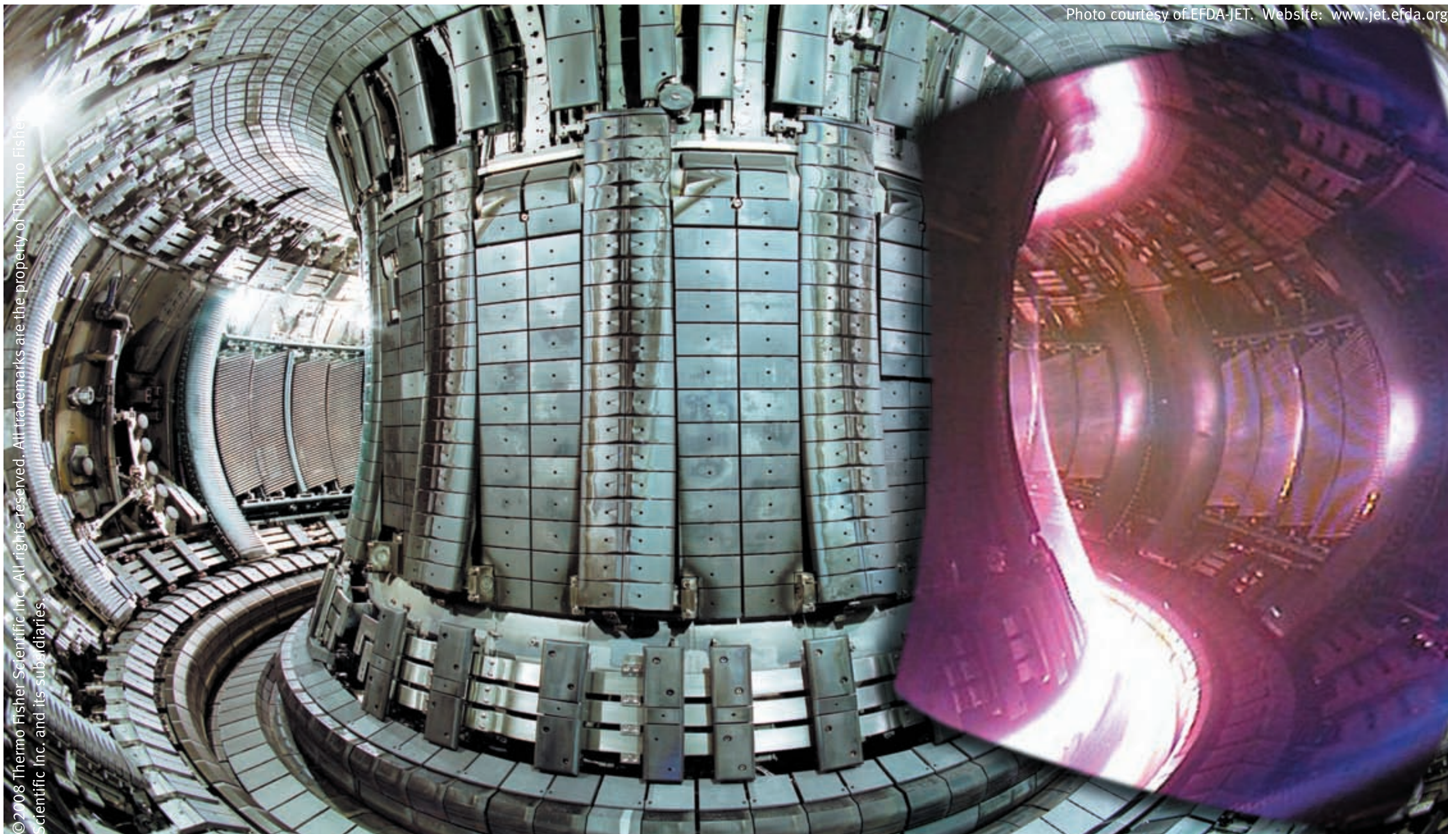
● May 2007 p29.

Based on the concluding talk at Physics at the LHC, Cracow, 3–8 July 2006 (http://arxiv.org/abs/hep-ph/0611237).

Résumé

De par son niveau d'énergie sans précédent et son énorme taux de collisions, le LHC sera un microscope capable de sonder la matière à des échelles plus petites que jamais auparavant. John Ellis explique comment le LHC devrait révolutionner notre compréhension de la matière, des forces et de l'espace.

John Ellis, *CERN.*



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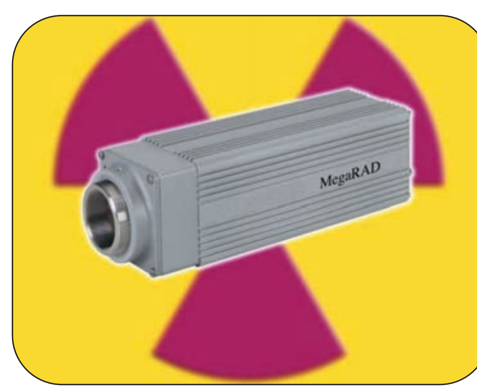

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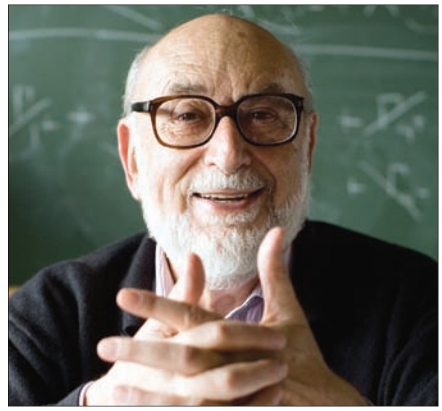
Robert Brout. (Courtesy F Englert.)



François Englert . (Courtesy F Englert.)

Peter Higgs in the CERN Control Centre.

A mechanism for mass

James Gillies met Robert Brout, François Englert and Peter Higgs to find out more about their seminal work on spontaneous symmetry breaking in elementary particle physics.

There's a famous photograph of a young Nepalese climber standing on top of Everest in 1953. It's the only picture there is, but Tenzing Norgay was not alone. Edmund Hillary, who declined to be photographed, accompanied him to the top. Who got there first? For a while, the two climbers refused to be drawn, saying that what matters is the achievement. And so it is with a mechanism developed in the 1960s to account for the difference between long and short-range interactions in physics.

In the early 1960s, particle physics had a problem. Long-range interactions, such as electromagnetism and gravity, could be explained by the theories of the day, but the short-range weak interaction, whose influence is limited to the scale of the atomic nucleus, could not. The idea that the carriers of the weak force must be heavy, while the carriers of long-range forces would be massless could account for the difference. Conceptually it made sense, but theoretically it couldn't be done: where would the heavy carriers get their mass? There was no way to reconcile massive and massless force carriers in the same theoretical framework.

Inspired by the new theory of superconductivity put forward in the late 1950s by John Bardeen, Leon Cooper and John Schreiffer, theorist Yoichiro Nambu paved the way to a solution by postulating the idea that a broken symmetry could generate mass (*CERN Courier* January/February 2008 p17). In doing so he in turn inspired three young physicists in Europe to take the next step.

A modest beginning

I met one of those physicists, Peter Higgs, in autumn 2007 in his apartment on the top floor of a walk-up block in Edinburgh new town with views over a leafy square. A slice from an LHC magnet greets visitors to the apartment, where the style is 1970s chic. Copies of *Physics World* and *Scientific American* are piled high on the coffee table, topped off with a copy of the satirical paper *Private Eye*. Bound copies of *The Gramophone* line the shelves, and the living room's prominent feature is a chair, optimally placed to make best use of the audiophile Leak hi-fi system.

A few months later, I met Robert Brout and François Englert in a spartanly furnished office, of the kind frequently occupied by professors emeriti, at the Université Libre de Bruxelles. Do we speak English or French was my first question. "Robert will be happier with English," came the reply. I hadn't realised that Brout was a naturalized Belgian, and that the two had first worked together in 1959 when he'd hired Englert to join him in his work at Cornell University in statistical mechanics.

As is so often the way with good ideas, the concept of the generation of particle mass through symmetry breaking was developed in more than one place at around the same time, two of those places being Brussels and Edinburgh. It was a modest beginning for a scientific revolution: just two short pages published on 31 August 1964 by Brout and Englert, and little more than a page from Higgs on 15 September. But those two papers were set to influence profoundly the development of particle physics right to this day.

All three scientists are careful to attribute credit to their forerunners, Nambu most strongly. Hints of other influences come from the fact that Higgs has been known to call spontaneous symmetry breaking in particle physics the relativistic Anderson mechanism, a reference to the Nobel prize-winning physicist Philip Anderson who published on the subject in 1963; and in lectures at Imperial College London students are told about the Kibble–Higgs mechanism, in a reference to a later paper published by Gerald Guralnik, Carl Hagen and Tom Kibble.

Brout's inspiration goes back much further, to another place that symmetry is broken spontaneously in nature with macroscopic effects. "Ferromagnetism was a puzzle in 1900," he told me, and ▷

was solved by French physicist Pierre Weiss in 1907. Essentially, symmetry is broken by the Brout–Englert–Higgs (BEH) mechanism because the ground state of the vacuum is asymmetric, rather like the alignment of the electrons' magnetic moments in a ferromagnetic material. In the case of the BEH mechanism, however, it's structure in the vacuum itself that gives rise to particle masses. In the words of CERN's Alvaro de Rújula: "The vacuum is not empty, there is a difference between vacuum and emptiness."

The thing that fills the vacuum is a scalar field commonly known as the Higgs field. Some particles interact strongly with this field, others don't, and it is the strength of the interaction with the field that determines the masses of certain particles. In other words, the carriers of the weak interaction, the W and Z particles, are sensitive to the structure of empty space. This is how the BEH mechanism can accommodate short and long-range interactions in a single theory. The long-awaited confirmation of the mechanism is expected in the form of excitations of the field appearing as scalar bosons (Higgs particles).

Esoteric as this may seem, there are potential astronomical implications, since what particle physicists call the Higgs field, cosmologists call the cosmological constant, or dark energy. A substance that appears to make up some 70% of the universe's matter and energy, dark energy made itself apparent as recently as 2003 in observations of the farthest reaches of the universe.

Renormalization

Despite the emergence of the BEH mechanism, particle physics still had a problem in the mid-1960s, because the underlying theory was literally not normal. It predicted abnormal results, such as probabilities of more than 100% for given outcomes. It needed to be renormalized, and that would take the best part of a decade. Brout and Englert toyed with the idea in 1966, but a rigorous renormalization had to wait until 1971, when Gerardus 't Hooft, a student of Martinus Veltman at Utrecht University, published the first of a series of papers by student and supervisor that would rigorously prove the renormalizability of the theory. They were rewarded with a trip to Stockholm in 1999 to collect the Nobel Prize in Physics.

If Brout, Englert and Higgs had provided a cornerstone of the Standard Model, 't Hooft and Veltman gave it its foundations. From then, theoretical and experimental progress was rapid, and accompanied by a rich harvest of Nobel Prizes. In 1973, a team at CERN led by André Lagarrigue found the first evidence for heavy carriers of the weak interaction. In 1979, Sheldon Glashow, Steven Weinberg and Abdus Salam received the Nobel Prize for Physics for their work on unifying the electromagnetic and weak interactions, the theory in which the BEH mechanism plays its crucial role. Then in 1984, Carlo Rubbia and Simon van der Meer received the Nobel Prize for their decisive contributions to the programme that discovered the carriers of the weak force, the W and Z particles, at CERN in 1982–1983.

"The experimental discovery of the W and Z particles confirmed both the validity of the electroweak model," explained François Englert "and of the BEH mechanism." There remained, however, a missing ingredient. A machine was needed that could shake the scalar boson of the BEH mechanism out of its hiding place in the vacuum of space. That machine is the LHC. Many scientists would, and indeed have, bet on the discovery of the particle, but however elegant and enticing the work of Brout, Englert and Higgs, no-one can be sure it is right until the scalar boson has been seen. Nature might have chosen to endow particles with mass in a different way, so until the particle is found, the BEH mechanism remains no more than speculation. Whatever the case, the LHC will give us the answer.

There are many stories as to how the BEH mechanism and its associated particle came to be named after Higgs. The one Higgs told me involves a meeting that he had with fellow theorist Ben Lee at a conference in 1967, at which they discussed Higgs's work. Then along came renormalization, making field theory fashionable, and another conference. "The conference at which my name was attached to pretty well everything connected with spontaneous symmetry breaking in particle physics was in '72," explained Higgs. It was a conference at which Lee delivered the summary talk.

Brout, Englert and Higgs have rarely met, but they have much in common. All came to a field, unfashionable with particle theorists at the time, from different areas of science. "Sometimes you do things in a domain in which you are not an expert and it plays a big role," explained Englert. "We had no reason to dismiss field theory because people didn't use it." The three also agree on many things – their inspiration for one. "What was interesting me back in the early 1960s was the work of Nambu, who was proposing field theories of elementary particles in which symmetries were broken spontaneously in analogy to the way that it happens in a superconductor," said Higgs. Englert said it slightly differently: "We were very impressed by the fact that Nambu transcribed superconductivity in terms of field theory," he said. "That's a beautiful paper."

The three are in agreement about the results that the LHC might bring. "The most uninteresting result would be if we find nothing other than that which we're most expecting," said Englert. According to Higgs: "The most uninteresting result would be if they found the Higgs boson and nothing much else." "If the Standard Model works, then we're in trouble," said Brout. "We'll have to rely on human intelligence to go further," said Englert completing the thought. And the most interesting direction for physics? Gravity, they all concur. "Any crumbs that fall off it would have major effects on the world of elementary particles," said Brout, "in my heart, gravity is the secret to everything."

Physicists and mountaineers have much in common. They are on the whole fiercely competitive, yet collaborative at the same time, and they can be magnanimous to an extraordinary degree. "I was delighted to discover that we are sharing the prize," Higgs said on being informed that the European Physical Society had awarded him a prestigious prize in 1997. "I get a lot of publicity for this work, but [Brout and Englert] were clearly ahead of me."

So who did get there first? At Everest, it turns out to have been Hillary who put his foot on the summit first. In physics Brout and Englert were first to publish, but that's not what matters. In physics, as in mountaineering, it's the achievement that counts.

Résumé

En 1964, Robert Brout et François Englert publiaient un court article sur la génération de la masse des particules par la rupture de symétrie. Un article encore plus court était publié indépendamment par Peter Higgs sur le même sujet deux semaines plus tard. Dans un séries d'entretiens avec James Gillies, les trois physiciens évoquent leurs travaux.

James Gillies, *CERN.*

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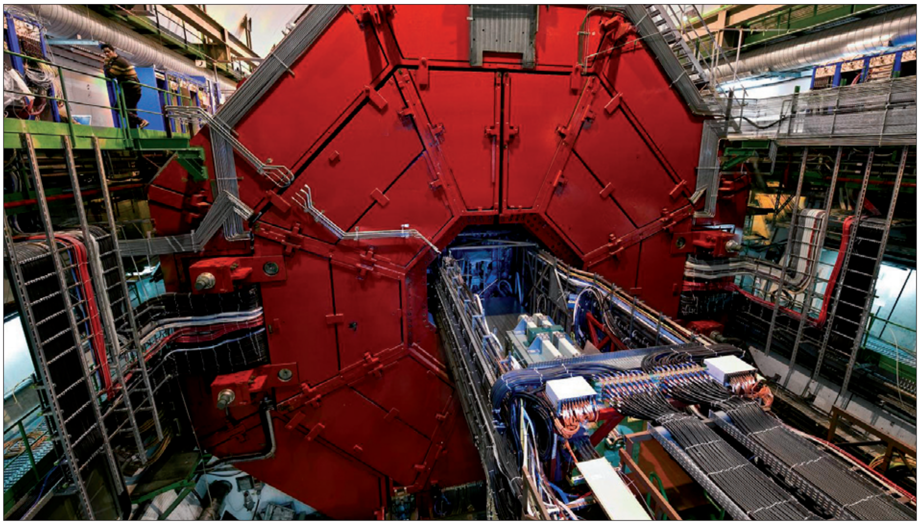

Figure 1. View of the ALICE detector with its magnet doors closed (courtesy of CERN).

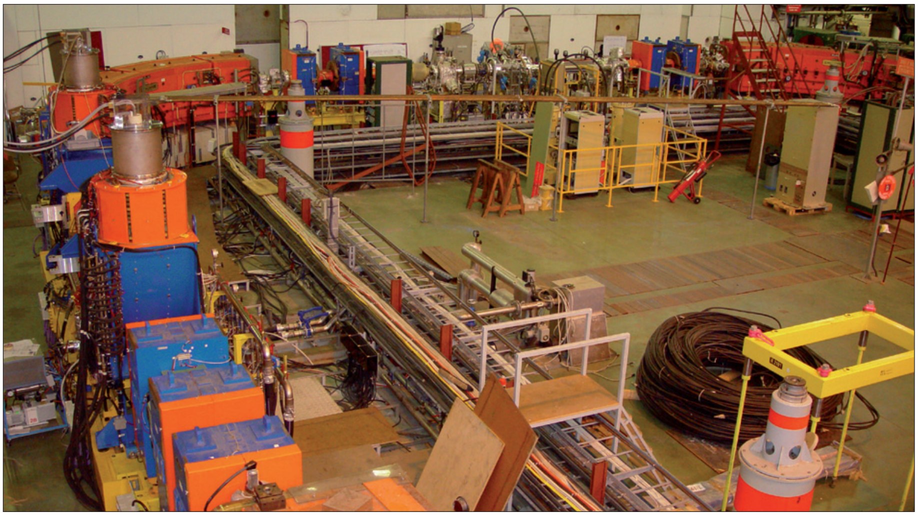

Figure 2. View of the Low Energy Ion Ring with its electron cooler on the left (courtesy of CERN).

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VIEWPOINT

Will the LHC surprise us?

Chris Llewellyn Smith, director-general of CERN at the time the LHC was approved, looks back at the physics case for building the machine and forward to the results it should bring.

I hope so. Having failed to find any completely unexpected new physics for more than 30 years, we clearly need nature's help to progress, and the case is good.

The last really big surprise in particle physics was the discovery of the third charged lepton (the tau) in 1975. There have of course been many extremely important discoveries since then, and our understanding of particle physics has advanced enormously. But the only real surprises have been how well the Standard Model has worked, the accuracy with which experiments have been able to check its predictions, and the failure to find its missing ingredient (the mechanism that gives particles their masses: Higgs?), or any other physics beyond the Standard Model, apart from the major discovery of neutrino masses (which, however, was not a huge surprise as no principle required zero mass).

On 14 April 1994 the first prototype dipole for the LHC was successfully powered, reaching 8.67 T (p22). Here Chris Llewellyn Smith (centre), then director-general, watches progress together with, left to right, Louis Walkiers, Romeo Perin, Jean-Pierre Goubert, Giorgio Brianti and Lyn Evans.

By the time of the major LEP summer study in 1978 the Standard Model was accepted by many, but by no means all, theorists and gaining supporters among experimenters. It was thought that "the [CERN] proton–antiproton collider [which had just been launched] should discover the Z, but apart from measuring its mass (with considerable errors) it will not allow us to investigate its properties in detail (it may also discover the W but this looks more difficult)". It was argued that LEP1 would be needed to study the Z in detail (or, if it did not exist, discover what else damps the rising weak cross section at LEP energies, where the phenomenological low energy theory had to be wrong), and measure the number of neutrinos into which it can decay; LEP2 would be needed to study the W, and find the Higgs boson (or whatever else generates masses) if it had not been found at LEP1. The surprises (at least for theorists like me) were how easy it was to detect the W (which was discovered in 1983, shortly before the Z) and the accuracy of the LEP results, which led to the exciting discovery that the strengths of the electromagnetic and strong forces converge at high energies, supporting the idea that they are different manifestations of a single "grand unified" force.

At the 1978 LEP summer study the importance of insisting on a relatively long tunnel in order not to compromise the energy of a later proton accelerator or LHC was discussed, and this argument was used when LEP was approved in 1981. The first serious discussion of LHC physics took place in 1984. It was obvious that the time had come to launch R&D on LHC magnets but "less clear whether it is sensible to discuss [LHC] physics...without more complete results from the SPS collider, let alone data from LEP, SLC and HERA...crystal gazing is unusually hazardous following recent tantalizing hints of new discoveries from UA1 and UA2". These hints, which turned out to be spurious (along with other hints of non-standard physics, from Fermilab neutrino experiments, LEP, and other experiments), remind us of the difficulty of exploring the frontier: we should not be surprised if there are false dawns at the LHC.

In 1984 it was stressed that the physics of mass generation was almost certain to be discovered at the LHC, if the question had not been settled at LEP, and that there are good reasons for expecting physics beyond the Standard Model in the LHC energy range – perhaps supersymmetry, which was discussed in some detail (it was only mentioned briefly at the 1978 summer study, although in the event a huge effort went into unsuccessful searches for supersymmetry at LEP). The case for the LHC was developed in more detail during the 1980s, but its essence has not changed.

The formal proposal to build the LHC presented to the CERN Council in 1993 was introduced with the statement that it will "provide an unparalleled 'reach' in the search for new fundamental particles and interactions between them, and is expected to lead to new, unique insights into the structure of matter and the nature of the universe". The LHC will take us a factor of 10 further in energy (at the level of the proton's constituents) or equivalently to a tenth of the distance scale that has been explored so far. This alone is enough to whet scientific appetites. But pulses are really set racing by the knowledge that the LHC has a good chance of finding what generates masses (a single elementary Higgs field? Multiple or composite Higgs fields?...?) and may cast light on other mysteries, including: why the mass of the W is so small compared to the scale of the proposed grand unification of electroweak and strong interactions, the magnitude of the asymmetry between matter and anti-matter in the universe, the number of quarks and leptons, and the origin of the dark matter and dark energy that pervade the universe.

What do I expect? I am fairly confident that Higgs, in some form, will show up. If the LHC finds the standard Higgs boson and nothing else I would be extremely disappointed as we would learn essentially nothing. (The biggest surprise would be to find nothing, which would take us nowhere, while making the case for going to much higher energies compelling but probably impossible to sell.) I think there is a reasonable probability that supersymmetry will be found, and I hope this happens: the most convincing arguments are that it is the only possible symmetry allowed by quantum field theory (the mathematical language of particle physics) that has not been found (why would nature utilise all possibilities but one?); "local" supersymmetry (and all the other "continuous" symmetries are local) requires the existence of gravity; and the idea of connecting matter (fermions) with force carriers (bosons) is very appealing, although against this must be set the extravagant proliferation of particles (none found, yet?) that this implies. I am somewhat less impressed by the fact that supersymmetry would stabilize the mass of the W, which is one of the arguments that could put supersymmetry in reach of the LHC.

Chris Llewellyn Smith in 1994 with LEP, in the tunnel now occupied by the LHC.

Thanks to the dedication of the CERN staff the LHC is now starting, and thanks to the community of users around the world, the experiments are ready to take data. It is a fantastic project. I am confident that it will work superbly. I am almost certain that it will make important discoveries, and I hope they will include surprises.

Chris Llewellyn Smith was director-general of CERN 1994–1998. During his mandate the LHC was approved and LEP was upgraded. The quotes in the text are from his theoretical summary talks at CERN following the 1978 LEP Summer Study (CERN 1979–2001) and the 1984 LHC Workshop (CERN 1984–2010), and the Executive Summary (CERN/SPC/679; CC/2016) of the formal proposal to construct the LHC which he presented to the CERN Council in December 1993 (p21).

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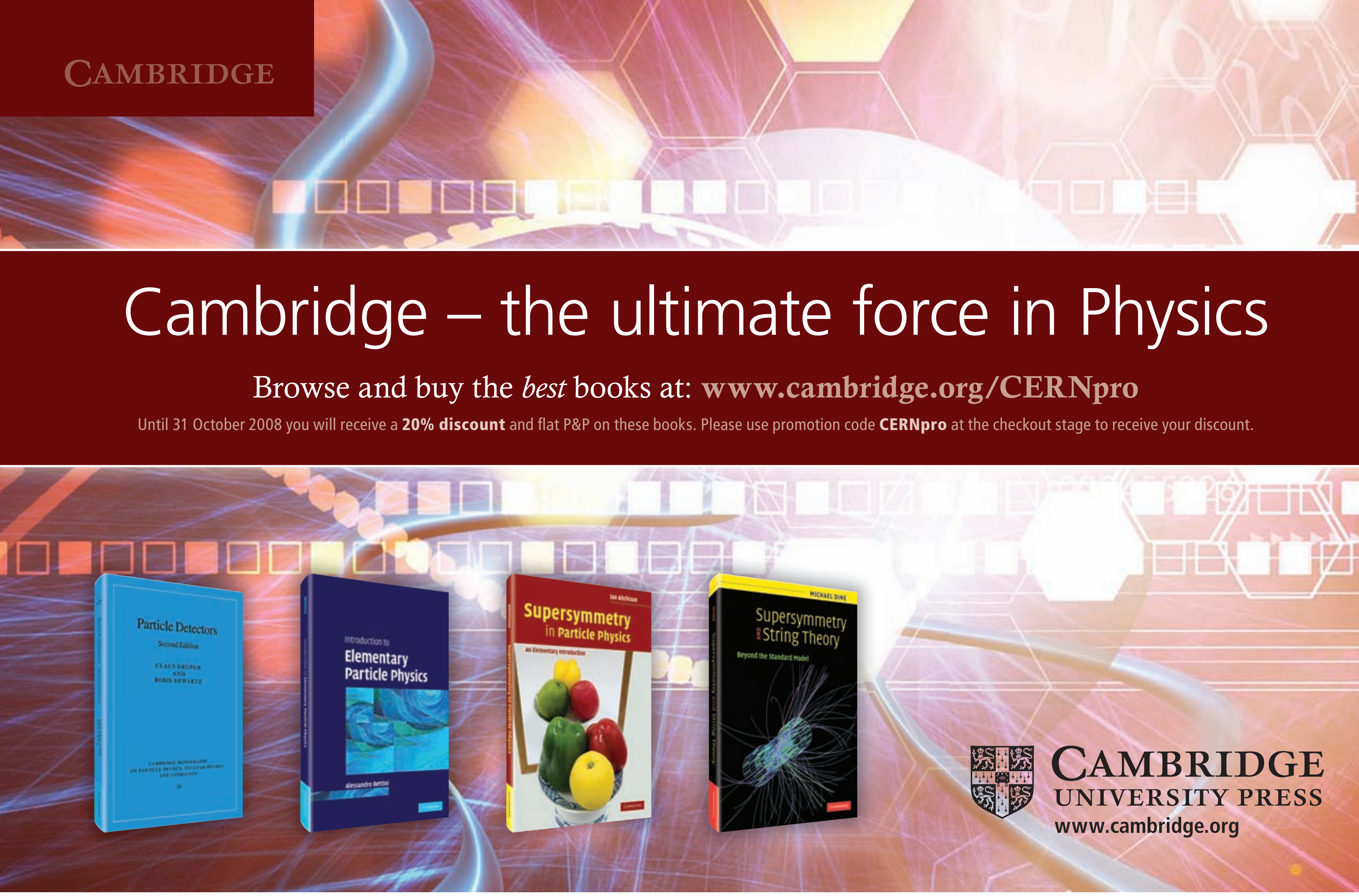
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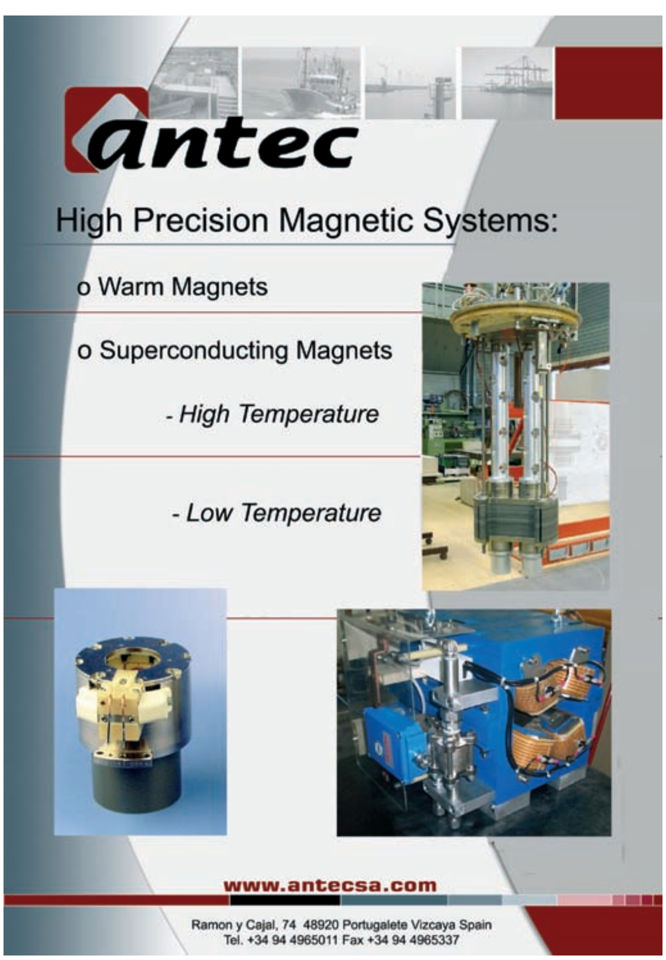
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BESSY

HUMBOLDT-UNIVERSITÄT ZU BERLIN

The Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung (BESSY) and the Humboldt-Universität zu Berlin (HU Berlin) invite applications for a joint appointment as

Head of the Institute "Accelerator Physics"

at BESSY / HZB and

Full Professor (W3) for Accelerator Physics

at the Faculty of Mathematics and Natural Sciences I - Department of Physics of the HU Berlin.

By January 1, 2009, BESSY will merge with the Hahn-Meitner Institut Berlin to form the Helmholtz-Zentrum Berlin für Materialien und Energie (HZB). The new center will have about 1000 employees on two campusses in Berlin-Wannsee and Berlin-Adlershof. Main research areas are in materials sciences and in solar energy research. An essential part of the mission of the HZB is the development and operation of large scale user facilities for research with synchrotron radiation and neutrons - presently the 3rd generation synchrotron facility BESSY II and the research reactor BER II - and the participation in the research areas ‚Structure of Matter' and ‚Energy' of the Helmholtz-Association with special emphasis on magnetic materials, functional materials and solar energy conversion. Additionally HZB operates an accelerator for proton therapy of ocular melanomas.

The appointee is responsible for heading the institute “Accelerator Physics” which corresponds to the present accelerator physics department at BESSY. Within the HZB, this institute will have the central task to develop and operate the BESSY II storage ring source and to carry out a research program on future accelerator based photon sources. The candidate is expected to have an established international reputation in the field of accelerator physics. He/she will actively participate in the educational programmes at the Humboldt-University and have the potential to attract external funding for a creative research program. Participation in joint research projects is strongly encouraged.

The position will be available as of April 1st 2009. Both BESSY and HU Berlin are equal opportunity employers. The goal is to enhance the percentage of women in the areas where they are underrepresented. Women, therefore, are particularly encouraged to apply. Applications of disabled persons will be preferred in cases of equal qualifications. The legal requirements according to § 100 BerlHG must be satisfied. **Deadline for application: Oct. 21st, 2008**

Applications should be addressed to Prof. Dr. W. Eberhardt, BESSY, Albert Einstein Str. 15, 12489 Berlin. For further information Prof. Eberhardt can be contacted by e-mail (eberhardt@bessy.de)

Applicants are kindly asked to send their application materials both in written form as well as electronically via http://www2.physik.hu-berlin.de/ssl/bessy

Wilson Fellowship in Experimental Physics

The Wilson Fellowship program at Fermilab seeks applications from Ph.D. physicists of exceptional talent with at least two years of postdoctoral work. The fellowships are awarded on a competitive basis and support physicists early in their careers by providing unique opportunities for self-directed research in experimental physics. Fellows will work on the Fermilab particle physics experiment of their choice. The Fermilab experimental program includes collider physics at both the Tevatron and the LHC, studies of neutrino and astroparticle physics, as well as R&D for future colliders and high intensity beams.

The Wilson Fellowships are tenure track positions with an annual salary fully competitive with university assistant professorships. The appointment is for an initial term of three years and can be renewed for an additional two years upon the completion of a successful review after the first two years.

Each candidate should submit a research statement describing a proposed research program, a curriculum vitae, and should arrange to have four letters of reference sent to the address below. Application materials and letters of reference should be received by October 31, 2008.

Materials, letters, and requests for information should be sent to:

Wilson Fellows Committee
Fermi National Accelerator Laboratory
MS 122, Attention: Cathryn Laue
P.O. Box 500, Batavia, IL 60510-0500
or Email: wilson_fellowship@fnal.gov

Additional information is available at:
http://www.fnal.gov/pub/forphysicists/fellowships/robert_wilson/

Fermilab

Fermilab is an Equal Opportunity Employer – M/F/D/V

HIC for FAIR

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

The Johann Wolfgang Goethe-University Frankfurt, Faculty of Physics invites applications to fill the following positions. These professorships are based in the Helmholtz International Center for the Facility for Antiproton and Ion Research (HIC for FAIR) funded through the Hessian state excellence initiative "LOEWE".

Full Professorship (W3) for Lattice Gauge Theory

An internationally renowned person representing the field of theoretical physics in its full breadth is sought. The applicants should especially engage in teaching theoretical physics and computational science in the bachelor and master programs of the department and support the teaching offered by the Helmholtz Graduate School for Hadron and Ion Research (HGS-HIRe).

The applicants are experts in the field of lattice gauge theory. Because of the connection to FAIR expertise in the treatment of quantum chromodynamics at finite temperatures and density and/or the description of exotic hadronic states is especially desired.

Full Professorship (W3) for Theoretical Astrophysics

An internationally renowned person representing the field of theoretical astrophysics in its full breadth is sought. The applicants should especially engage in teaching astronomy/astrophysics in the bachelor and master programs of the department and support the teaching offered by the Helmholtz Graduate School for Hadron and Ion Research (HGS-HIRe).

The applicants are expected to work in one or several of the following fields: stellar evolution, supernova dynamics, nucleosynthesis, physics of compact stellar objects, dynamics of neutron star collisions, exotic matter and phase transitions in the universe.

The applicants for both professorships should complement and extend the research profile of the physics department and strengthen it through the acquisition of third-party support. The willingness to collaborate in an interdisciplinary way with the researchers at "HIC for FAIR" and the physics department as well as skilled participation in teaching are expected.

The designated salary for the position is based on "W" on the German university scale or equivalent. Goethe-University stresses a family-friendly concept of workloads. Part-time engagement is possible. Reintegration into the job after parental leave is supported.
The Goethe University is committed to a pluralistic campus community through affirmative action and equal opportunity. For details see: www.uni-frankfurt.de/aktuelles/ausschreibung/professuren/index.html.

Applications accompanied by the usual information including a description of teaching experience as well as a concept for future teaching should be sent via e-mail **within 4 weeks** to the **Goethe-University, Dean of the Faculty of Physics, Max-von-Laue-Str. 1, D-60438 Frankfurt, Germany, dekanat@physik.uni-frankfurt.de,** with a copy to the **Scientific Director HIC for FAIR, Prof. Dr. C. Greiner, Institut für Theoretische Physik, Max-von-Laue-Str. 1, D-60438 Frankfurt, Germany, carsten.greiner@th.physik.uni-frankfurt.de.**

www.uni-frankfurt.de

Accelerators | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

DESY

PARTICLE PHYSICS.

DESY has openings for:

Several Fellowships

DESY

DESY is one of the world's leading accelerator centres for investigating the structure of matter. DESY develops, builds and operates large accelerator facilities for photon science and particle physics.

The project / the position

Fellows in experimental particle physics are invited to participate in DESY's particle physics research:

- Analysis of HERA data
- Participation in the LHC Experiments ATLAS and CMS
- Preparations of the International Linear Collider ILC (accelerator and experiments)

DESY Fellowships are awarded for a duration of 2 years with the possibility of prolongation by one additional year

Requirements

- A Ph.D. completed within the last 4 years
- Application including a resume and the usual documents (curriculum vitae, list of publications and copies of university degree)
- Three letters of reference shall be arranged to be sent to the DESY Human Resources Department

Salary and benefits are commensurate with those of public service organisations in Germany. Handicapped persons will be given preference to other equally qualified applicants. DESY operates flexible work schemes. DESY is an equal opportunity, affirmative action employer and encourages applications from women. There is an English-speaking Kindergarten on the DESY site.

Please send your application quoting the reference code, also by E-Mail to:
Deutsches Elektronen-Synchrotron DESY
Human Resources Department | Reference code: 80/2008
Notkestraße 85 | 22607 Hamburg | Germany
Phone: +49 40 8998-3392 | E-Mail: personal.abteilung@desy.de
Deadline for applications: 15 October 2008
www.desy.de

The Helmholtz Association is Germany's largest scientific organisation.
www.helmholtz.de

HELMHOLTZ | ASSOCIATION

The Indiana University Cyclotron Facility (IUCF) is a multidisciplinary institution supporting research in Accelerator Physics, Condensed Matter and Materials Physics, Medical Physics and Nuclear Physics and Chemistry. IUCF is also developing two major new research facilities – The LENS Neutron Source and the ALPHA electron storage ring. LENS is a pulsed neutron source supporting the study of large scale structures and neutron radiation effects testing. ALPHA will consist of a 60 MeV long pulse LINAC and electron storage ring to support accelerator physics research, radiation effects testing and the development of an Inverse Compton Scattering X-ray source. Several positions are now available to support these research and development activities at IUCF.

Postdoctoral Position in Accelerator Physics (1) – to participate in the design, construction and commissioning of the LINAC and Storage Ring. The successful candidate will have a PhD in Accelerator Physics, Nuclear Physics or Electrical Engineering. Experience with electron LINACS, vacuum systems, and controls is highly desirable.

Postdoctoral Position in Accelerator Physics (2) – to participate in the development of optical diagnostics for electron beams based on laser wires and Inverse Compton Scattering. The successful candidate will have a PhD in Accelerator Physics, Nuclear Physics, Condensed Matter Physics or Optics. Experience with lasers and optical systems is essential.

Staff Position in Accelerator Physics – to support the development of a high intensity electron linear accelerator and storage ring facility. The successful candidate will have a PhD in accelerator physics or related field and a minimum of five years experience in an accelerator laboratory environment. The candidate will have a demonstrated ability to lead a team of scientists, engineers and technicians to design, deploy and commission a synchrotron and must have a working knowledge of accelerator operations, accelerator controls, and beam diagnostics. Experience in electron accelerators is a strong asset. Applicants for this position should apply online at **http://www.indiana.edu/~uhrs/jobs/index.html.**

Interested postdoctoral applicants should send a CV and a statement of research interests, along with 3 names for reference to: **Dianne Dupree, IUCF, 2401 Milo B. Sampson Lane, Bloomington, IN 47408**, or to **didupree@indiana.edu**.

Indiana University is an Affirmative Action, Equal Opportunity Employer committed to excellence through diversity. The University actively encourages applications of women, minorities, and persons with disabilities. Applications will be reviewed until a suitable candidate is identified.

Baylor University PHYSICS

The Department of Physics, Baylor University, invites applications for two tenure-track faculty positions at the level of Assistant Professor beginning in August 2009.

The Department is seeking to hire one candidate in experimental high energy physics. Exceptional candidates in other research areas will be considered for the second tenure-track position. Current areas of departmental research include elementary particle physics, astrophysics, dusty plasma physics, condensed matter physics, surface physics, nonlinear dynamics, semiconductor physics, experimental atomic and molecular physics, and theoretical early universe cosmology and string/M theory. Applicants should submit (1) a cover letter, (2) a curriculum vitae including a list of refereed papers published and submitted, (3) a statement of current research interests and pursuits, (4) a statement on teaching interests and philosophy, and (5) a list of three references. Applicants should arrange to have three letters of recommendation sent directly to **Chair, Search Committee, Department of Physics, Baylor University, One Bear Place #97316, Waco, Texas, 76798-7316, USA** or e-mailed to **physicsjob@baylor.edu**. Salary is commensurate with experience and qualifications. To ensure full consideration for the position, applications should be completed by November 1, 2008. Applications will be accepted until the position is filled.

Baylor, the world's largest Baptist university, holds a Carnegie classification as a "high-research" institution. Baylor's mission is to educate men and women for worldwide leadership and service by integrating academic excellence and Christian commitment within a caring community. Baylor is actively recruiting new faculty with a strong commitment to the classroom and an equally strong commitment to discovering new knowledge as Baylor aspires to become a top tier research university while reaffirming and deepening its distinctive Christian mission as described in Baylor 2012 (**http://www.baylor.edu/vision/**).

Baylor is a Baptist university affiliated with the Baptist General Convention of Texas. As an AA/EEO employer, Baylor encourages minorities, women, veterans, & persons with disabilities to apply.

UCL

University College London High Energy Physics

The heart of physics in the heart of London

With strong involvement in ATLAS, as well as collider and neutrino experiments worldwide, plus particle phenomenology, we are an outstanding place to study for postgraduate degrees in particle physics. A limited number of places on Masters and PhD courses are available each year.

See **http://www.hep.ucl.ac.uk/postgrad/** for more details.

With over 27,000 staff and students, UCL is ranked third in Europe and 22nd worldwide*

*ref: Institute of Higher Education, Shanghai Jiao Tong University, 2008

TWO TENURE TRACK FACULTY POSITIONS

Experimental and Theoretical High Energy Physics

Florida State University

The Florida State University Physics Department is seeking applicants for two tenure track Assistant Professor positions starting in Fall 2009.

One position is in theoretical high energy physics, where current group interests include calculations of higher order QCD effects in collider physics, heavy quark phenomenology, determinations of parton distribution functions, and lattice field theory. We are seeking candidates with a strong background in theoretical high energy physics and experience in collider phenomenology. Interest and experience in areas of astroparticle physics, while not required, would also be welcomed.

The second position is in experimental high energy physics to work on the CMS experiment. The successful applicant will take an immediate leadership role in one or more projects within the collaboration and initiate a substantial physics research program.

Applicants should send a letter of interest, a curriculum vitae with a list of publications, a research plan, and arrange for at least three letters of recommendation to be sent to: **Physics Department, Florida State University, Tallahassee, Florida 32306-4350**. Please address applications for the theory position to Prof. Laura Reina and those for the experimental position to Prof. Harrison Prosper.

Review of applications will begin October 15, 2008 and continue until the position is filled.

Florida State University has a diverse student body and is committed to a faculty that reflects this. Florida State University is an Equal Opportunity/Affirmative Action Employer, and it especially encourages applications from women and members of minority groups.

NSLS-II

The National Synchrotron Light Source II - Brookhaven National Laboratory

The National Synchrotron Light Source II (NSLS-II) is a major US science facility to be located at Brookhaven National Laboratory on Long Island, within easy reach of New York City. It will produce photons over a wide energy range, from infra-red to hard x-rays, used for diverse, leading-edge, scientific research including energy technologies, environmental science and new materials in extreme environments, as well as biological sciences and drug discovery. The construction is expected to commence at the start of 2009 with a budget in excess of $900M.

www.bnl.gov/nsls2

Brookhaven National Laboratory invites applications from scientists, engineers, and professionals with leading expertise who are interested in playing a significant role in the design, construction, and scientific utilizations of NSLS-II.

Recruitment efforts are currently underway in the following areas:

- Accelerator Physics
- Scientific programs (Nanoprobe, Coherent Soft X-ray, & Powder Diffraction)
- Mechanical Engineering & Design
- High Power RF Systems
- Control System Applications
- Information Technology
- Diagnostics & Instrumentation
- Construction Inspectors
- X-Ray Optics & Nanopositioning

Brookhaven National Laboratory is an equal opportunity employer committed to work force diversity.

Please see http://www.bnl.gov/nsls2/jobs.asp for a current listing of open positions and to apply on-line using the BNL Candidate Gateway.

Office of Science
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

EOE

ESRF
The European Light Source

European Sychrotron Radiation Facility

The European Synchrotron Radiation Facility (ESRF) is Europe's most powerful light source. It offers you an exciting opportunity to work with international teams using synchrotron light in Grenoble, in the heart of the French Alps.

We are seeking to recruit the:

Head of the Instrumentation Services and Development Division

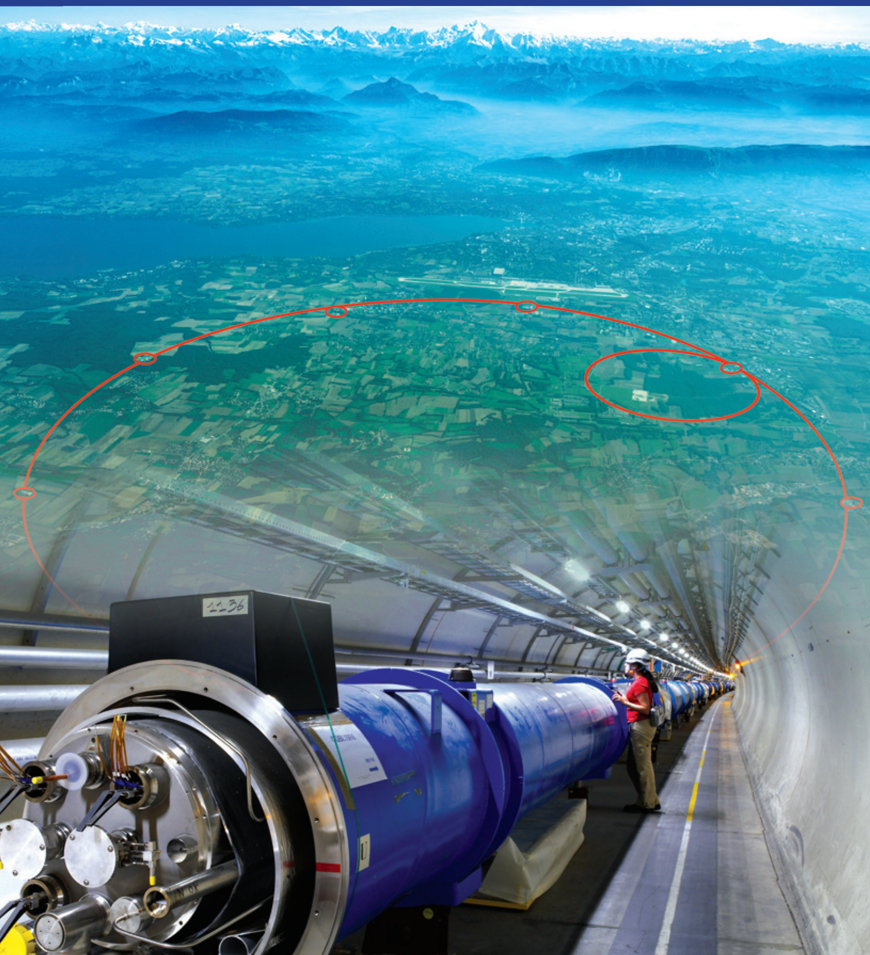
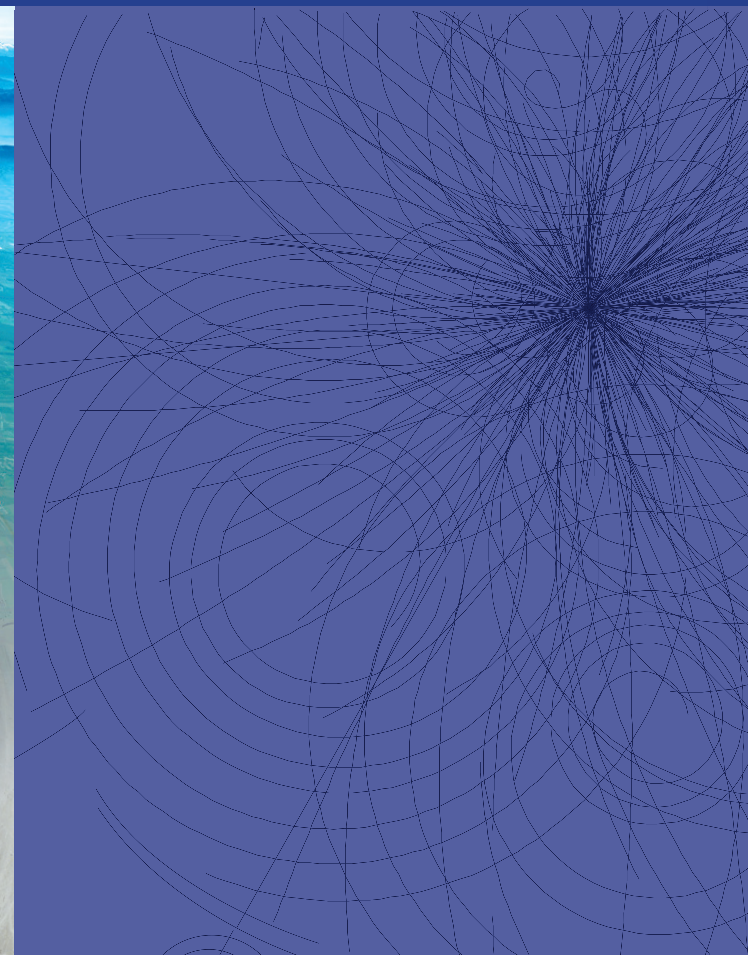
The new Instrumentation Services and Development Division (ISDD, 130 staff) will be responsible for the design, construction and support of instrumentation at the ESRF. Ensuring the optimal performance of the division, you will:

- Manage the heads of the different groups, including Electronics and Detectors, Mechanical Engineering, Scientific Software, Beamline Instruments, Software Support, Sample Environment Support and Chemistry
- Implement our new project management structure
- Follow the progress of major projects
- Manage the Division's budget
- Represent the ISDD on the Board of ESRF Directors and liaise with other appropriate units and groups of the ESRF
- Promote the ESRF at conferences and workshops

This senior position offers exciting opportunities for personal development and for involvement in resolving technical challenges.

For further information please consult: http://www.esrf.fr/Jobs/Directorate/8001

Interested candidates may send a fax (+33 (0)4 76 88 24 60) or e-mail (recruitm@esrf.fr) with their address, to receive an application form, which can also be printed from the web. Deadline for applications: 15 October 2008

Research Positions
LIGO Laboratory

California Institute of Technology (Caltech)
Massachusetts Institute of Technology (MIT)

The Laser Interferometer Gravitational-Wave Observatory (LIGO) has as its goal the development of gravitational wave astronomy. The LIGO Laboratory is managed by Caltech and MIT, and is sponsored by the National Science Foundation. It has built and now operates facilities equipped with laser interferometric detectors at Hanford, Washington and Livingston, Louisiana. The detectors have achieved design sensitivity and a data set spanning more than a year of coincidence operation has been collected. Analysis is ongoing, with extensive participation by the LIGO Scientific Collaboration (LSC). Further observation will be interleaved with incremental improvement of the instruments over the coming years, with a major upgrade (Advanced LIGO) underway in parallel. In addition, a vigorous R&D program supports the development of enhancements to the detectors as well as future capabilities.

The LIGO Laboratory expects to have positions at Caltech, MIT and at the two observatory sites. Scientists will be involved in the operation of LIGO itself, analysis of data, both for diagnostic purposes and astrophysics searches, as well as the R&D program for future detector improvements. Expertise related to astrophysics, modeling, data analysis, electronics, laser optics, vibration isolation and control systems is useful. Most importantly, candidates should be broadly trained physicists, willing to learn new experimental and analytical techniques, and ready to share in the excitement of building, operating and observing with a gravitational-wave observatory. In general, appointments will be at the post-doctoral level with one-year initial appointments with the possibility of renewal for up to two subsequent years. In some cases, appointments with an initial term of three years or of an indefinite term may be considered. Appointment is contingent upon completion of all requirements for a Ph.D.

Applications for positions at any LIGO Laboratory site (Caltech, MIT, Hanford, or Livingston) should be sent to HR@ligo.caltech.edu (Electronic Portable Document Format (PDF) submittals are preferred), OR mailed to either:

Dr. Jay Marx
c/o Cindy Akutagawa
Caltech
1200 E. California Blvd
LIGO 18-34
Pasadena, CA 91125

OR

Dr. David Shoemaker
MIT
185 Albany St
LIGO NW22-295
Cambridge, MA 02139

Applications should include curriculum vitae, list of publications and the names, addresses, email addresses and telephone numbers of three or more references. Applicants should request that three or more letters of recommendations be sent directly to HR@ligo.caltech.edu (Electronic Portable Document Format (PDF) submittals are preferred) or mailed to Dr. Marx or Dr. Shoemaker. Consideration of applications will begin December 1, 2008 and will continue until all positions have been filled.

Caltech and MIT are Affirmative Action/Equal Opportunity Employers
Women, Minorities, Veterans, and Disabled Persons are encouraged to apply
More information about LIGO available at www.ligo.caltech.edu

Those of us at the
University of Virginia
in the
Department of Physics
and the
Institute for Nuclear and Particle Physics
wish to congratulate CERN
on the startup of the
LHC

When UVa was founded nearly 200 years ago by Thomas Jefferson, one of the eight original professorships was in natural philosophy and focused on the physics of the day. At UVa today, there is a large community of physicists, many working on subatomic physics. We are proud that our research program includes a substantial investment in CMS, an involvement we look forward to maintaining for many years to come.

Visit us at www.phys.virginia.edu

University of Virginia
Department of Physics
Institute of Nuclear and Particle Physics