Life at the high-energy frontier

The Large Hadron Collider at CERN and its cathedral-sized detectors will change the course of particle physics forever. **Matthew Chalmers** visits the lab to capture the mood as the most ambitious scientific project ever undertaken prepares for switch-on

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Nick Chohan is looking forward to Christmas. For the last three years the amiable CERN physicist and his team have been working around the clock in a large metal hangar that straddles the Franco-Swiss border, carefully testing the 1232 superconducting magnets that will soon guide protons at almost the speed of light around the world's most powerful particle accelerator. This is no mean feat – it takes three people up to 12 hours just to connect one of the 15 m long, 35 tonne cylindrical dipoles to the test rig, and each one costs close to a nerve-wracking SwFr1m (over €600 000). But this month the last magnet is due to arrive at Chohan's lab, and by the end of the year all of them will have been cleared for installation underground.

Particle physicists are used to thinking big, of course. In their quest to understand how nature behaves at the most fundamental level, they have been building machines that smash particles together at ever higher energies for the best part of a century. But the Large Hadron Collider (LHC), currently being built at the European particle-physics laboratory CERN, near Geneva, is rewriting the rules of the game.

"Few people fully appreciated the scale and complexity of the LHC at the beginning," says CERN's chief scientific officer Jos Engelen. "It has surprised many of us, myself included." And with the 27 km-circumference machine scheduled to switch on next year after more than 20 years of preparation, the excitement among CERN physicists is palpable. Once the LHC reaches its full design performance, some time early in 2008, protons will smash into one another about one billion times per second at an energy of 14 TeV (14×10^{12} electronvolts), recreating conditions that existed shortly after the Big Bang and placing CERN at the forefront of high-energy physics for at least a decade.

A journey into the unknown

Nobody really knows what lies at the high-energy frontier, but the LHC is far from a stab in the dark. Since the 1970s our understanding of matter at the tiniest scales has been enshrined in the Standard Model of particle physics, which describes the world in terms of six quarks (which are bound in hadrons such as protons and neutrons) and six leptons (such as electrons) that interact via force-carrying particles called bosons. It is this theory, and its shortcomings, that points experimentalists to the energy regimes worth studying.

The Standard Model has been verified with impressive precision, its finest hour being the discovery of the W and Z bosons at CERN's Super Proton Synchrotron (SPS) in 1983. The appearance of these particles at precisely the collision energy that theorists expected

(about 0.1 TeV) proved that two of nature's four fundamental forces – the electromagnetic and the weak nuclear forces – are simply low-energy facets of a more general "electroweak" interaction. The problem is that this electroweak symmetry, which would have existed when the universe was much younger, requires quarks and leptons – and therefore all matter – to be massless.

One of the biggest challenges in particle physics is to find the missing piece of the Standard Model jigsaw that enables nature to break this symmetry and so give rise to the medley of particle masses we observe. The favoured candidate for this is the Higgs mechanism, which requires the existence of a new massive particle called the Higgs boson. As Engelen puts it: "Verifying electroweak symmetry breaking is the defining motivation for the LHC. If we see nothing at the TeV scale then there is something deeply wrong with our understanding of particle physics."

Another major goal of the LHC is to search for physics beyond the Standard Model, in particular for signs of supersymmetry or SUSY – an even more general symmetry of nature that treats matter and force particles as two sides of the same coin. SUSY would not just unify the electromagnetic and weak interactions, but would also bring the strong nuclear force and even gravity in a single framework. If it is real, there should be a host of weird new "sparticles" waiting to reveal themselves in the LHC collisions.

Boys and toys

Designing and building the LHC – for which the total cost is €6.3bn – is the responsibility of Lyn Evans. When asked to describe the extent to which the job is taking over his life as switch-on draws near, the 61-year-old Welshman looks as if he has not understood the question. "For the past 13 years the LHC has been my life," he exclaims, adding that he is relieved to see the bright blue accelerator finally take shape in its tunnel. Evans has nursed the LHC through numerous difficulties, notably problems with the cryogenic system

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CERN

In deep
Over half of the
superconducting
dipole magnets that
will make up the bulk
of the 27 km LHC are
already in place.

At a Glance: The Large Hadron Collider

- Switching on next year, the LHC will guide protons at almost the speed of light in opposite directions around a 27 km underground ring before smashing them into one another with an energy of 14 TeV at four separate points
- Although 14 TeV is no more than the energy of 14 mosquitoes in flight, it is concentrated in such a tiny volume that the resulting energy density is the highest ever produced in a laboratory
- The several thousand magnets required to guide and focus the proton beams are currently being connected in a tunnel that lies between 50 and 150 m beneath the Franco-Swiss border and that originally housed the Large Electron Positron collider
- The protons start out on the main CERN site in "Linac2" before being gradually ramped up in energy by the Proton Synchrotron and then Super Proton Synchrotron (SPS), from where they will be injected into the LHC
- The protons will then be electromagnetically whipped up to 7 TeV, whereupon hundreds of billions of them will circulate the ring 11 245 times every second
- Waiting to catch the debris to fly out from the proton collisions will be four exceptionally large detectors: ATLAS, just across the road from the main CERN site; LHCb and ALICE on either side; and CMS some 10 km away
- The future of high-energy particle physics rests heavily on what is and is not revealed in these detectors in the next few years

that delivers liquid helium to the superconducting magnets in order to keep them at a chilly 1.9° above absolute zero. But he is confident the machine is on track for a 2007 switch-on.

The main task now is to get all the magnets from Chohan's test facility safely connected up inside the LHC tunnel. In addition to the 1232 dipoles, which will bend the protons around the ring in opposite directions, there are also thousands of quadrupole, sextupole, octupole and numerous other corrector magnets that will allow the beams to be focused and manipulated. Since it is far too risky to deliver the magnets directly to each point around the ring, they instead make a short journey from the test lab by lorry to a special shaft at the main CERN site via a traffic-light system that Evans can control to minimize the chances of an accident occurring. More than half of the dipoles are in place and, with a 65-strong installation team working 24 hours a day, the job should be finished by the end of March.

Then the real fun begins, if you are an accelerator physicist that is. "The plan is to have beams circulating with an energy of 0.45 TeV each by the end of November next year, with a short data run just before Christmas," says Evans. "Then we'll tell the four experiments to switch off so that we can ramp the energy up and get into the record books." To do this, the LHC will need to produce a collision energy of 2 TeV (1 TeV per beam) in order to beat the current record held by the Tevatron proton-antiproton collider at Fermilab in the US. But in early 2008, after a short winter shutdown, the machine should be ramped to 14 TeV within a couple of months, leaving the Tevatron standing in the dust.

It is vital that you know what you are doing when playing around with such a high-energy beam. "The LHC is the first accelerator ever built that has the ability to self-destruct," says Steve Myers, who his head of accelerators and beams at CERN. "The stored energy of each beam is equivalent to 100 kg of TNT going off, which could put the machine out of action for months if the protons veer off course." He quickly adds, however, that the chances of that happening are extremely small thanks to the stringent safety measures that are in place. If things start to go really wrong, for instance, the beams will automatically be sent down two 600 m-long tangential tunnels into a huge graphite block surrounded by some 1000 tonnes of steel and concrete shielding.

"You wouldn't want to be having your lunch down there when the beam is dumped," jokes machine operator Roger Bailey, who adds on a more serious note that this area would then remain highly radioactive for many months. Bailey will be one of the people responsible, from the comfort of CERN's brand new €5m control room, for carefully "threading" the beams around the magnetic fields of the LHC when the first protons are injected from the SPS next year. The downside of such rigorous safety standards, he points out, is that they will make it much harder to tinker with the beam to optimize the performance of the LHC. And anyone who actually attempts the potentially fatal act of eating their sandwiches in the LHC tunnel once the machine switches on will first have to get through security doors at the surface employing the latest iris-recognition technology.

Eyes on the ground

While the LHC steadily takes shape underground, a whole other world of activity is hotting up elsewhere around the CERN site. In fact, on the day *Physics World* arrived, Jim Virdee and his colleagues on the CMS experiment were about to throw a party. CMS is one of four enormous detectors that will be positioned around the LHC ring where the proton collisions will occur. Their task is to track and measure the hundreds and thousands of particles that will be produced when a quark from one proton strikes a quark from another proton travelling in the other direction, a tiny fraction of which may produce a Higgs or a SUSY particle in the process (see "Expedition to inner space" pp26-31).

With the CMS project comprising some 2000 physicists from 180 institutes in 34 countries, inviting the collaboration to an impromptu party is no easy task. "The big celebrations will come in due course," explains Virdee, who is deputy spokesperson for the experiment. "But later today a few of us are going to be

marking three recent milestones: closing the detector for the first time; testing the magnet at full strength; and taking cosmic-ray data." Witnessing the scale of the CMS detector, which is being built in a vast building in France about 10 km away from the main CERN site, it is easy to understand why its creators have something to shout about.

For example, the CMS magnet, which provides a bending field of 4 T in order to allow physicists to measure the momentum of particles, is quite simply the largest ever built. And as one cylindrical segment of the 12 500 tonne detector is slowly rolled back on its air-cushioned feet with a deafening screech, Virdee reels off the convoluted international history of the various pipes, wires and components that make up each concentric layer of the detector. About 80 m beneath the floor on which we are standing lies the huge cavern into which CMS will be lowered in pieces later this year. Here, things are much quieter, with nothing but the sound of tinny French radio echoing off the walls as a few technicians go about their business in the buckets of bright yellow cherry-pickers.

On the opposite side of the LHC ring, just off the main CERN site, the scene in the ATLAS cavern could not be more different. Unlike CMS, the 7000 tonne ATLAS experiment is being assembled directly underground. It already fills so much of the available volume in the cavern that the only way to get a sense of its scale is by watching the puppet-like figures in helmets and harnesses scramble over it from the gantries on the sides.

"It gives me a lot of pleasure to see the detector being built, and it is having a positive effect on the mood of the collaboration," says ATLAS spokesperson Peter Jenni. "But there is still much to do, and a large part of my job now is devoted to changing the mindset of the collaboration as we move from the construction phase through commissioning to eventual operation."

Flanking ATLAS are the two "smaller" LHC experiments LHCb and ALICE. Although these have more specific physics goals than CMS and ATLAS, they are by no means less important. LHCb, for example, will study the decay of B-mesons in order to tackle the problem of why matter and antimatter did not immediately annihilate with one another in the Big Bang to produce a universe comprising nothing but photons (see "Beautiful asymmetry" pp37–39). ALICE, meanwhile, will allow detailed studies of the strong nuclear force, which will test the non-electroweak sector of the Standard Model, quantum chromodynamics (see "A machine called ALICE" pp40–41).

It is the two general-purpose detectors CMS and ATLAS, however, that the world will be watching closest when the first proton beams are brought into collision next year. Hundreds of physics analyses in the form of complex computer programs are currently waiting to be let loose on the tens of thousands of gigabytes of data that will stream out of the detectors' several million read-out channels each day. Many of these will look for specific experimental signatures of a Higgs or SUSY decay, while others are destined to study even more exotic possibilities such as extra dimensions and mini black holes. In order to cope with this data deluge, the LHC requires a completely new computing infrastruc-

The LHC in their own words

"What is nice about CERN is that as a Masters or a PhD student you are listened to and treated as an equal. I feel I can knock on anyone's door and ask them a question."

Thijs Versloot

CERN summer student, LHCb

"The LHC is an interesting sociological experiment – you can see people in the collaborations jostling for power. I'd like to work on something less mainstream than the Higgs, to avoid being caught in a huge fight."

Anne-Sylvie Giolo

CERN fellow, CMS

"I like the idea that I am working on something so huge that it requires many people from lots of different countries. The downside of big collaborations is that there are lots of people competing to work on the sexiest measurements with only a few doing the necessary nitty-gritty stuff."

Jamie Boyd

CERN fellow, ATLAS

"It's fantastic to finally see the detector come together and know it has been made possible by the efforts of so many people around the world. It energizes you and builds morale."

Jim Virdee

Deputy spokesperson, CMS

"The unprecedented scale of the LHC experiments has meant that I've had to pick up management skills on the job. Sitting back and thinking about the physics is more of a hobby these days."

Peter Jenni

Spokesperson, ATLAS

"I am lucky that my career has coincided with a machine like the LHC. Having worked on all of CERN's major colliders, I should be retiring just after it has reached its design performance."

Steve Myers

CERN head, accelerators and beams

"There is nothing about my job that I do not like. For me it's all about strategy. No matter what you are working on you need to have a vision, and to realize that vision you need to find and implement a strategy."

Robert Aymar

CERN director general

In control

CERN's ergonomically designed control room allows all of the lab's accelerators to be operated from under one roof. Currently unmanned, the area in the top right of the image is where the LHC will be switched on next year.

ture – known as the Grid – which is proving a major challenge in itself (see “Gearing up for the Grid” pp33–34).

The rush to analyse the LHC data will also make and break hundreds of scientific careers. While having two independent detectors based on very different technologies is vital to any claim of discovery, the competition between CMS and ATLAS to have their name associated with it could place CERN's unique open environment under unbearable strain. Indeed, the hunt for the Higgs at the LHC has parallels with the feisty race between the UA1 and UA2 experiments at the SPS to find the W boson two decades ago. When Nobel prizes are at stake, physicists can be pretty cut-throat.

“It is natural that people identify with their experiment, and I think that pushes all of us to do a better job,” says Jenni. “Of course, both collaborations will do their best to be first, and it is clear that there are some personal ambitions, but in the end the credit will – and should – go to CERN. There will certainly not be just a single person associated with a discovery like the Higgs,” he says. But some of those who are closer to the actual analysis teams are less idealistic. “Forget the rivalry between ATLAS and CMS”, one CERN physicist told *Physics World*, “there will be enough trouble within the collaborations themselves, especially once data start to arrive.”

This is not something that has passed the CERN management by. Head of communications James Gillies is currently working on a strategy with which to deal with a possible Higgs discovery. “The last thing we want to have to do is issue an ‘anti-press-release’ that says CERN hasn’t found the Higgs after all,” he says. Although there are clear scientific procedures in place to deal with the first signs of the Higgs or other particles, Gillies is concerned that a particular institute or even individual might make premature claims of discovery.

The trouble is that it could take years after the first signs of a new particle to amass enough data for CERN to make a definitive “five sigma” announcement.

Living the dream

The way the LHC is perceived in the public domain is absolutely crucial, not just for CERN but for the future of particle physics. Indeed, you could argue that the LHC is the biggest gamble that physicists have ever taken. “The LHC is an absolute necessity if we are to take the field further,” says CERN's director general Robert Aymar. “If nothing new turns up below a [quark–quark] collision energy of 1 TeV, this would be very bad for particle physics, and for humanity.” As Engelen, who is also deputy director general of the lab, puts it: “Seeing nothing at all is what would make the theorists really speechless!”

Almost everybody agrees, however, that the most probable outcome is also the best for particle physics: that something, whatever it is, will turn up. This would make it more likely that the next big collider project currently under consideration – the International Linear Collider, which would enable precision measurements to be made of, say, the Higgs boson – will get the green light (see “Beyond the Higgs” pp42–43). As Aymar points out: “Politicians are not going to back a machine that costs twice as much as the LHC without some hard evidence to go on.”

But such thoughts are far from everyone's mind at CERN right now. From senior management to summer students returning to their home institutes, the mood at the lab is one of quiet confidence and raw excitement. “The decision to go ahead and build the LHC was taken in 1996,” recalls Aymar. “But if we had to take that decision tomorrow, the outcome would be exactly the same. Without this machine, we might as well dream.”

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