Bottling the Big Bang - www.oloscience.com

The air of anticipation around CERN, the European Organisation for Nuclear Research near Geneva, is palpable. In a matter of weeks, the world's most powerful particle accelerator, the Large Hadron Collider (LHC), will start operating, hurling subatomic particles around its 27km circumference at almost the speed of light. Two months later, the two contra-rotating beams will be squeezed, focused and aimed at each other to collide with colossal force, creating conditions that existed millionths of a second after the Big Bang.

The physics goals of the LHC are mind-boggling. Discovering the Higgs boson, the particle that explains the origins of mass; explaining why the universe is made of matter not anti-matter; freeing the constituent parts of the particles that make up the nuclei of atoms; possibly making minute black holes which, in passing, would indicate that alternate dimensions exist. But in order to answer these questions, equally mind-blowing engineering has been brought into play, 100m below the ground in the tunnels and caverns that make up the LHC complex.

The project has several parts. There is the LHC itself, one of a series of particle accelerators at CERN and the final link in a chain that takes charged particles — protons or lead nuclei — from a standing start to 99.999999 per cent of the speed of light. Then there are the detectors that observe what happens when the particles collide.

There are four major detectors: ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid), which sit opposite each other on the LHC circuit, aim to observe every particle resulting from the collisions; ALICE (A Large Ion Collider Experiment) and LHCb are looking for specific phenomena. Associated with these are a raft of ancillary services, including control systems and an enormous computing effort to collate and study the data from the experiments.

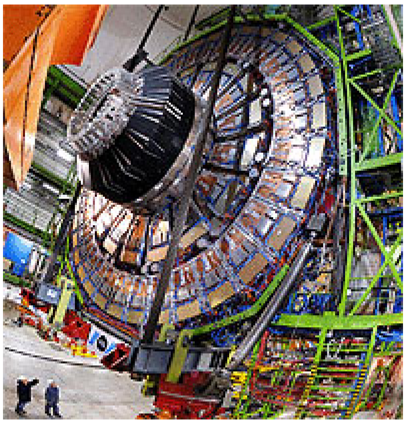
The scale of everything is stunning. Even before it starts, LHC is already producing superlatives. The largest magnets ever made. The biggest deployment of superconducting technology. The most powerful network of computers. The lowest temperatures. The highest speeds.

From the surface, it is hard to comprehend the size of CERN. Its headquarters are just outside Geneva and look much like any other university. But there is no indication of the whereabouts of the ring of the LHC, longer and deeper than London's Underground's Circle Line (and more circular) and crossing the Swiss-French border four times.

CMS, the most distant of the experiments from the headquarters, is a 20-minute drive into the mountains from ATLAS, which is the only one of the four detectors in Switzerland. ALICE's surface buildings sit incongruously next to a pretty village; LHCb is behind a supermarket near Geneva airport, just within France.

Visiting CERN is a jaw-dropping experience. ATLAS, the larger of the two general detectors, is half the size of Notre Dame cathedral, a glittering chunk of technology 44m long, 22m high and weighing 7,000 tonnes; it is like standing next to a cliff covered in gold mirror. CMS, 15m across and 22m long, is even heavier at 12,000 tonnes; it resembles a planet-busting superweapon from a science fiction film.

Compared with these monsters, the LHC itself seems relatively modest. Its tunnel was one of the few parts of the project not purpose-built; it housed the site's previous high-energy particle accelerator, the Large Electron-Positron collider (LEP), which operated from 1989 to 2000. Without the site's other accelerators, it would be useless.



An endcap of CMS is lowered down into its cavern

LHC works with protons most of the time, and these start off in a bottle of hydrogen. Stripping away the electrons produces the isolated protons, and 'bunches' of these, containing about 10^{11} particles, are injected by a linear accelerator into the first of CERN's circular accelerators or synchrotrons, the PS Booster, which accelerates them to 1.4GeV. They are then transferred to another accelerator, the Proton Synchrotron, which increases their energy to 25GeV; then on to the Super Proton Synchrotron (SPS), which accelerates them to 450GeV. The SPS has two branches to transfer bunches to the LHC, one to the clockwise circuit, one anticlockwise. LHC accelerates the protons to 7TeV, roughly equivalent to the kinetic energy of a flying mosquito, but far more concentrated.

Before LHC was built, all the accelerators had independent control systems but now, to aid co-ordination of the accelerators and their supporting power and cooling grids, all the systems are operated from a single, purpose-built control centre. It is a haven of blue-carpeted calm where cataclysmic forces are marshalled and focused. 'We can have 50 or 60 people in here and it still feels quiet,' said Paul Collier, one of the LHC engineers.

The beams run for most of their circuit through two separate pipes about 20cm across, which are under a high vacuum of 10^{-13} atm. At regular intervals, the beams pass through radiofrequency cavities, which pump power in to accelerate the particles, and a series of magnets that generate a field of 8.3T (for comparison, the Earth's magnetic field is about 40mT at the surface), steering the protons around their near-circular orbit.

The amount of current needed to maintain the field is huge, some 11,700A, so the magnets are superconducting; they are made from strands of a niobium/titanium alloy. When cooled to below 10K, this material conducts electricity with zero resistance. In the LHC magnets, the cables are cooled by liquid helium at 2.7K. At this temperature, helium is in a state known as a superfluid, which allows it to conduct a large amount of heat and therefore makes it an extremely efficient refrigerant.

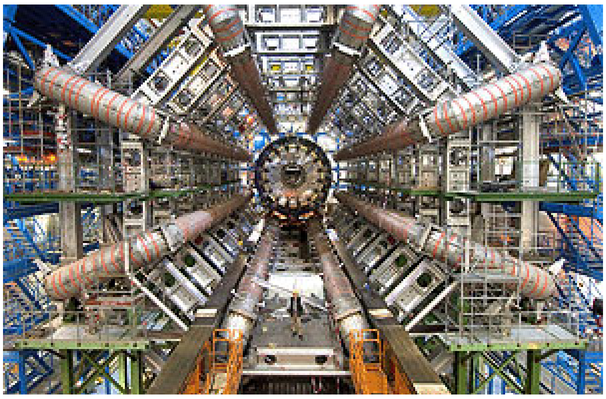
The superconductivity is essential to reduce the amount of electricity needed to run the magnets. 'Even so, we use about 30 per cent of the electricity demand of the Canton of Geneva,' said LHC physicist Mike Lamont.

The total power consumption of the LHC alone is 120MW, with CERN as a whole consuming 230MW. 'That's one of the advantages of being in both France and Switzerland. The Swiss Grid alone can't supply all the electricity we need; we actually get most of it from France. Even then, glitches in the power supply cause major problems — the system can take weeks to settle down properly after a glitch. We have a large amount of power conditioning to make sure the supply is smooth, but we can still have problems.'

There are several types of magnet used on the LHC. Most of them are dipoles, but immediately before the beams enter the caverns housing the detectors, they run through a more complex type of magnet called a quadrupole. These squeeze the diameter of the proton bunch down from about a millimetre to about 16μm and aim it so that it will collide with the beam travelling in the opposite direction from the other side of the detector. 'Despite the number of protons in a bunch, only about 20 per bunch will actually collide with another proton; the others will just fly through without noticing anything,' said Lamont.

Each bunch is about 7m apart, which means bunches will cross 30 million times every second; in other words, there will be 600 million particle collisions a second.

Like any high-energy synchrotron, the LHC will be dangerous when running. Beams of particles at near-light speed give off radiation similar to X-rays, so in operation, nobody will be allowed inside the LHC tunnel, or the detector caverns. 'I don't know how long it would take you to die,' said Lamont. 'But you'd die.'



The superconducting coils of the toroidal magnet system, striped in red, awaiting the arrival of the inner detectors and solenoid

The consequences of colliding two protons with energies of 7TeV are dramatic. The energy — much less than that produced by a handclap, but focused down to an almost imaginably small size — is enough to break the particles apart and recombine the fragments into a variety of different particles. Many of these can only exist in the hot, dense conditions immediately following the collision: conditions similar to those just after the Big Bang. It is the job of the detectors to see and categorise these particles, and they have a variety of ways to do it.

ATLAS and CMS, the two 'general-purpose' detectors on the LHC, are both designed to do the same physics: detect all the particles produced during collisions, and reconstruct the processes that made them. Two detectors are necessary, so that each can confirm the findings of the other, but there is a certain amount of rivalry between ATLAS and CMS that pervades CERN.

'We come from different schools of physics, and we have very different ideas, but both groups believe they have the right answer,' said Marzio Nessi, technical director at ATLAS. 'Whoever sees the Higgs boson, for example, first — they'll be the ones to get the Nobel Prize.'

All the detectors work in roughly the same way, and ATLAS, CMS and ALICE have similar designs. The detectors are barrel-shaped, with large magnets wrapped around the collision point. When charged particles fly out of the collision, the magnetic field makes them follow a curved trajectory — positive charges in one direction, negative in the other. Vast arrays of detectors, containing materials that ionise when charged particles pass through them, track the paths of the particles through the detector. Particles with high momentum will curve very little, low momentum ones will fly in tight spirals.

The particles end up in calorimeters, which measure the energy of the particle by stopping it dead. There are two types — electromagnetic calorimeters (ECALs), which work on particles such as electrons and photons that do not interact much with matter; and hadronic calorimeters (HCALs), for particles such as protons and neutrons. Generally, these use materials that can convert the kinetic energy of the particles into light or an electric signal, that can be collected and analysed.

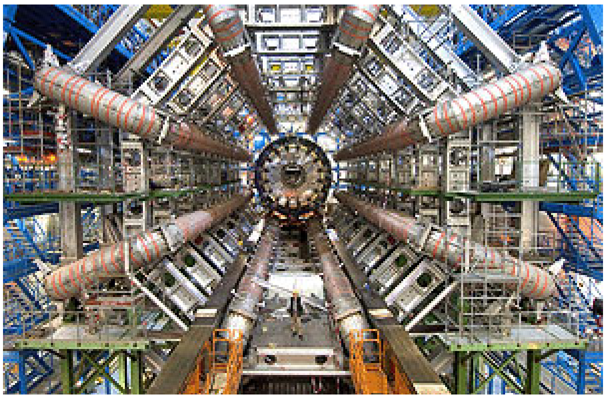
The only particles that can pass through both types of detector are muons, which are similar to electrons. It is vital to detect these, as they are produced when some of the particles that CERN is particularly looking for decay; for example, theory predicts that a Higgs boson will decay into four muons. All the LHC detectors therefore have specific systems for finding muons, which are often the most impressive and largest part of the system.

It is obvious from looking at ATLAS and CMS that their technologies are different. ATLAS is characterised by the arrangement of its magnetic fields. The inner parts of the mammoth detector are surrounded by a solenoid coil, which bends the paths of all particles apart from muons. This is surrounded by a toroidal field shaped like an exceptionally deep ring doughnut and generated by eight superconducting loops, which run the full length of the detector; the largest superconducting magnets ever constructed (although they will be overtaken by the magnets at ITER, the nuclear fusion reactor soon to take shape in southern France). Within this magnetic field are the systems to track and stop the muons. At either end of the barrel are 'big wheels', huge discs of muon detectors to stop the particles that fly forwards from the collision.

'There are 2,000 scientists working on this project, and every single one of them would die to see it completed,' said Nessi. 'They speak over 30 different languages and come from over 160 institutions, but we've found ways to communicate and work and bring these systems together. You just don't get that level of devotion on most engineering projects.'

Integrating the systems has been a particularly difficult task, he added: 'All these thousands of detectors need to be cooled, so they all have their little circuits to carry liquid helium or argon to them; and they are all linked to the data-gathering system via fibre-optics.'

CMS, meanwhile, has only a solenoid magnet surrounding the trackers, ECAL and HCAL systems, but it is the largest superconducting solenoid ever built, a 13m long, 6m diameter coil of niobium-titanium, producing a 4T magnetic field.



A technician slides the final rack of detectors into the support structure of the ALICE experiment

The ECAL of CMS is particularly unusual, containing 80,000 crystals of lead tungstate, denser than iron but transparent and made in China and Russia. When electrons and photons pass through these crystals, they produce a flash of light which can be amplified and analysed to determine the energy of the particles. The immense weight of the crystals is supported in a fibreglass construction structured like the inside of the human lung, with separate 'alveoli' or pockets for each crystal.

Building CMS was a particularly tricky task, said civil engineer John Osborne, because of its location. 'We're near the mountains, so we had to dig through 80m of glacial deposits before we got to solid rock to make the cavern,' he said. 'So while ATLAS was built entirely within its cavern, CMS was built on the surface while we did the excavation, tested there, then lowered into the cavern in slices.'

To dig the cavern, Osborne's team sunk a series of tubes through the water-saturated glacial deposits and filled them with a freezing mixture, cold enough to freeze the water surrounding the tubes and create a curtain of ice.

They then dug the 100m deep pit through which the CMS slices would be lowered, while the ice held back the water in the surrounding rock. Once the sides of the pit were lined with cement, the ice curtain was left to melt, and the team continued excavating horizontally to complete the cavern.

While ATLAS and CMS are general detectors, ALICE is specialised, looking at a different sort of collision. For most of its operational period (270 days a year), LHC will accelerate protons. But for the remaining time, its circuit will be filled by nuclei from lead atoms — more than 200 times heavier than a proton, and far more complex in structure, containing both protons and neutrons. Because their mass is greater, their momentum and therefore their collision energy is also higher, and they produce a much greater variety of particles.

The ALICE physicists hope that the hot, dense conditions at the collision point will melt the protons and neutrons into their component parts, charged particles called quarks, and gluons, which carry the force that holds the quarks together. Physicists believe that in the microseconds after the Big Bang, a plasma of quarks and gluons existed which then coalesced into normal matter. Quarks are not found alone in nature, but nobody knows why. Moreover, protons and neutrons contain three quarks, but the mass of three quarks is only 1 per cent of the mass of either particle, and gluons have no mass. There is a theory that the mechanism that forces the particles together may give rise to the rest of the mass, and ALICE might be able to confirm this.

ALICE also contains a solenoid, but it is not superconducting. Instead, it is made of iron — it contains as much iron as the Eiffel Tower — and is second-hand; it was used on the LEP experiment in the same cavern. Its 77 tonnes of detectors are slid into the barrel of the magnet into a stainless steel support structure on trolleys, which allows them to be removed easily for maintenance during the LHC's winter shutdown (electricity is prohibitively expensive around Geneva in the winter).

This, says Diego Perrini, who is responsible for ALICE's support structures, illustrates an important difference between the detectors and the LHC itself. 'We can run ALICE with missing detectors; it just means we won't get any data from that particular sector,' he said. 'But all the LHC systems have to be functional for anything to work.'

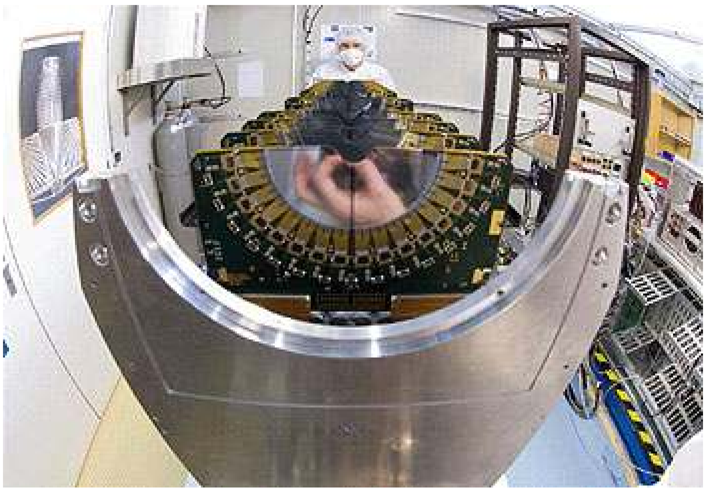
The exception to the barrel design is LHCb, which is looking for specific objects known as B-particles. These contain a type of subatomic particle called a b-quark (also known as a bottom quark or a beauty quark), which is not stable under normal conditions. Studying them will help understand why the universe is made of matter, not antimatter.

B-particles are only scattered in a shallow angle from the main beam, so LHCb's detectors are arrayed around and in front of the collision point like a series of walls.

LHCb contains some of the most specialised detectors in CERN, because it needs to locate the position of the particle collisions with more precision than any of the other experiments.

'B-particles are very unstable and decay only a millimetre away from the collision that produced them,' said Richard Jacobsson, an LHCb physicist. 'LHCb has to be able to confirm whether it is detecting particles that come from the collision, or from a 'secondary vertex' a short distance away, which would indicate the presence of a B-particle.'

It does this with a detector called the VELO (VErtex LOcator), which is the closest detector to a collision point anywhere in CERN, just 5mm away from the intersecting beams, which have energy similar to a high-speed train.



Half of the VELO array for the LHCb detector, which locates the position of

collisions precisely

The VELO consists of 42 semicircular modules that sit on either side of the collision point and close in to study the collision. Made from silicon that produces an electrical signal when struck by a particle, they were built in the UK, at the University of Liverpool.

Much of the engineering at CERN is in fact done by physicists, Jacobssen said. 'It puts us in an interesting position, because nobody has done anything like this before,' he said.

A large sheet of expanded polystyrene taped to one of the scintillation counters on LHCb testifies to the tricky nature of the work.

'Somebody put three holes in the casing,' said Jacobsson. 'We're not sure how.' Then there was a loud clang and a shout of 'Desolé!' 'I think that might be a fourth,' said Jacobsson.

Back on ATLAS, Nessi believes that typical engineering skills could be the key to the whole project.

”We've all had to learn to work in cross-disciplinary ways; we've learned new jobs, new skills, and worked with an array of people we couldn't have imagined. And the ones who are best at the collaborations? They're the ones who will make the big discoveries. The ones who’ll win”

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