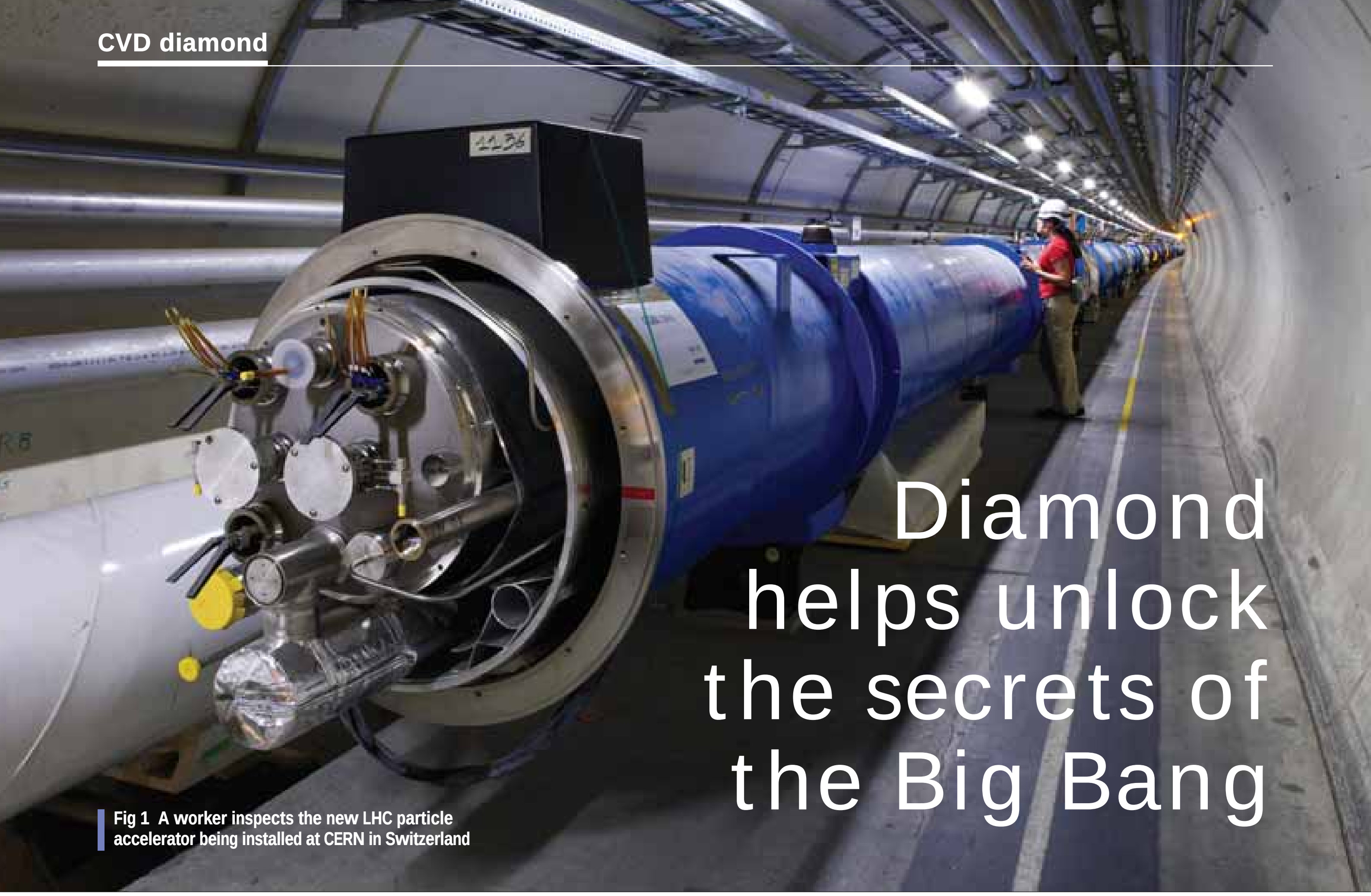


Diamond helps unlock the secrets of the Big Bang

Fig 1 A worker inspects the new LHC particle accelerator being installed at CERN in Switzerland

Next year will feature a milestone in the field of nuclear physics when a new particle accelerator comes onstream at CERN in Switzerland. Scientists will then have the capability to collide two beams of particles head-on at super-fast speeds – much greater than has ever been achieved previously – thus recreating the conditions in the Universe moments after the Big Bang. These beam collisions should create showers of new particles, and the hope is that one of them will be identified as the elusive Higgs boson (known as the "God particle" because of its importance to the accepted theory explaining how sub-atomic particles interact with each other). The solid-state tracking devices which will follow the paths of any particles created during the collisions will have to withstand high levels of radiation and cope with up to 40 million collisions a second. This report by **Elaine McClarence** describes the important role that diamond will play in the construction of the detectors.

In May 2008, particle physics research enters a new phase of activity as the highest energy particle accelerator ever constructed begins operation. The Large Hadron Collider (LHC) at CERN in Switzerland (Figs 1, 2 and 3) has been built to answer some of the outstanding questions posed by theoretical physicists about the nature of the origins of the universe, including finding evidence of the Higgs boson, hypothesised to be the last missing fundamental particle as predicted by the standard model for particle physics *(see separate panel on page 17)*. Physicists hope that confirming the existence of this particle will explain how other elementary particles acquire mass, making a step towards a single unifying theory for the four fundamental forces of nature: electromagnetism, the strong nuclear force, the weak nuclear force and gravity.

The LHC will enable high-energy physicists to study the collision of particles at very high energies and the decay behaviour of the collision products (Fig 4). Creating new particles at high energies and high production rates is part of this work. Particle colliders such as the LHC accelerate particles to the very high energies necessary for the production of new particles. At the same time, there needs to be a large number of particles in the beam in order to get a high interaction rates and statistically significant numbers of very rare types of collision.

To give some idea of the undertaking, LHC is a proton-proton collider that will deliver up to 40 million collisions a second with collision energies of 14 TeV, about seven times greater than has ever been achieved before. This has posed tremendous technical challenges, both in monitoring the collisions and handling the colossal streams of data the experiments produce.

There are a number of areas where the use of synthetic diamond has been suggested for monitoring and detection applications, particularly where silicon detectors cannot be used over the long term. Some applications, especially those related to safety monitoring, will use diamond when the LHC begins operation in 2008; others are likely to adopt diamond as the collider moves towards higher collision energies and intensities where current detection technology cannot survive the harsh radiation environment for long periods.

Fig 2 Aerial view showing the 27 km circumference LHC tunnel

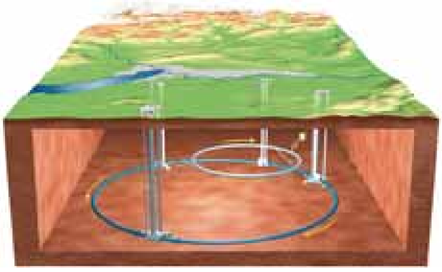


Fig 3 Schematic layout of the LHC

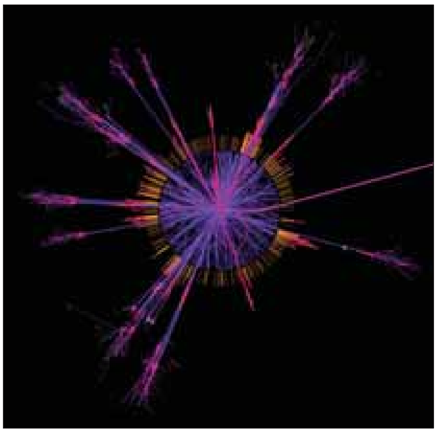


Fig 4 Simulation of the collision of two protons in the ATLAS experiment viewed along the beam pipe - the colours of the tracks emanating from the centre represent different particle types emerging from the collision

Diamond synthesised by chemical vapour deposition (CVD) possesses a number of properties that make it a suitable material for the fabrication of solid-state detectors: namely, that it is radiation hard, gives fast signals, displays very low leakage current in high radiation environments, has excellent thermal properties and can be made into discrete, free-standing detectors.

The Collider design

The LHC has two separate accelerator rings with magnetic fields of opposite polarity, built into a 3 m wide tunnel, that guide two proton beams in opposite directions, around a massive 27 km circuit built underground in a facility that straddles France and Switzerland near Geneva. The beams travel around the ring and cross at various points known as interaction regions. The protons are ‘bunched’ so that two bunches of protons travelling in opposite directions collide at each interaction region roughly every 25 ns. At four of these positions, large experimental halls house the LHC’s key experiments: ALICE (“A Large Ion Collider Experiment”), ATLAS (“A Torroidal LHC Apparatus”), CMS (“Compact Muon Solenoid”), LHCb (“LHC-beauty”), LHCf (“LHC-forward”), and TOTEM (“Total Cross Section, Elastic Scattering and Diffraction Dissociation”).

Of these experiments two have already been identified as having potential requirements for diamond; these are ATLAS and CMS, both general-purpose experiments for recording the proton-proton collisions at the LHC.

Beam Condition Monitors

The ATLAS experiment is designed as a general purpose detector and is larger and more complex than any of its predecessors, having a radius of 13 m, a length of 46 m and weighing 7,000 tonnes (Fig 5). One of its important goals is to find unequivocal evidence for the Higgs boson. In ATLAS, diamond will be used within the beam conditions monitor, BCM, which is essentially a safety system. The role of this system is to monitor beam operation conditions by distinguishing proton-proton collisions from background caused by up-stream interactions (Figs 6 - 9).

Sixteen 10 x 10 mm diamond sensors are installed in the ATLAS experiment and are the heart of the ATLAS Beam Conditions Monitor. They allow the continuous monitoring of particles produced both at

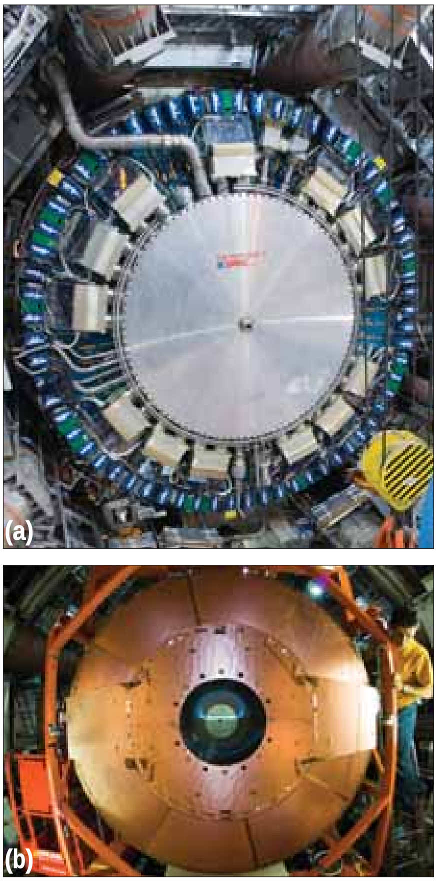


Fig 5 The first ATLAS inner detector with
(a) end-cap removed and
(b) fully inserted within the liquid argon cryostat

the time of the expected collisions of proton bunches and those from collisions occurring during the intervals between proton bunches. Since collisions between proton bunches occur every 25 ns, a very fast, radiation-tolerant sensor is required. The sensors are placed 1.8 m from the interaction point, and only 6 cm from the beam line, giving maximum exposure. Diamond provides the ideal solution allowing scientists to 'observe' signals from collisions within a few nanoseconds of the beam crossing leaving a further 10-15 ns 'open' during which time only particles that result from poorly tuned, or 'lost' protons, from the machine will be observed. By carefully monitoring the rate at which lost protons are detected, the alarm can be sounded if these losses mount dramatically - a potentially dangerous situation for the rest of the ATLAS experiment. For the CMS, similar beam conditions monitors are likely at several locations close to the beam pipe.

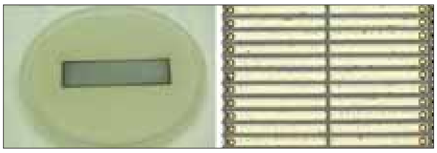


Fig 6 Diamond pixel module prototype:

left, a 2 x 6 cm diamond sensor in the wafer for photolithography;

right, the 400 micron x 50 micron pixel pads

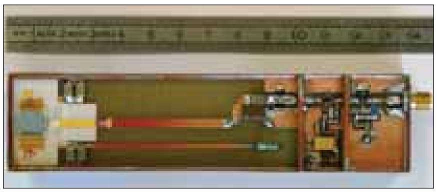


Fig 7 ATLAS BCM module with diamond sensors positioned at the left and readout amplifier at the other end of the box

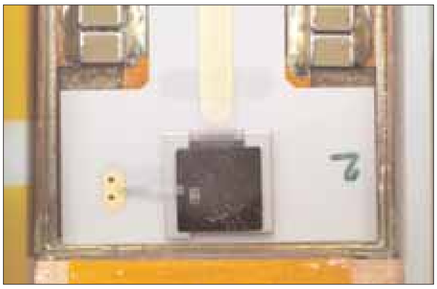


Fig 8 Close up of the diamond sensors – there is a pair of diamonds in each module, one on top of the other

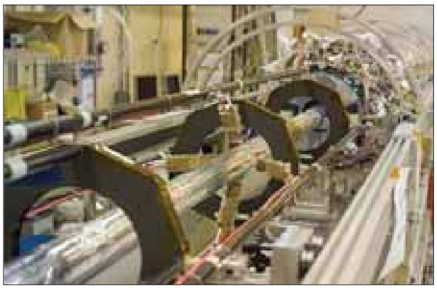


Fig 9 Two BCM stations comprising four BCM module boxes in a circular array around the beampipe

Although several of the LHC's other experiments have shown an interest in similar beam protection (or BCM) systems, only the ATLAS and CMS systems will actually be installed when the LHC is enters operation in 2008, with other installations expected during future upgrades.

Opportunities in tracking detectors

Solid-state tracking devices are at the heart of general-purpose high energy physics experiments. Tracking detectors enable the paths of particles created in the interaction region to be followed both spatially and temporally as they move away from the interaction region. Detectors in high-energy collider experiments can be exposed to high radiation levels: in the LHC, detectors very close to the beam interaction region are expected to receive a fluence of more than 1015 particles/cm^2 over a lifetime of about ten years, an extremely high value and one which few detector materials are able to survive.

Diamond, as well as being 'radiation hard', also has electrical properties suitable for single particle detections of which charge carrier mobility and the charge carrier lifetime, are most important.

At end of the initial testing and proving period, the luminosity (rate of collisions) of the LHC is going to be increased by about a factor of ten. At this time silicon detectors in the innermost layers of the ATLAS tracking detector may be replaced with diamond sensors because silicon is not sufficiently radiation hard and would only survive for a few months at the higher luminosity. These tracking detectors are much more sophisticated than the BCM devices and are quite a bit larger. Essentially, the detectors are charged particle detectors. "We have made 18 x 62 mm prototypes of these tracking devices. Each sensor has some 46,000 individual readout elements and a particle's location is determined by which of these elements reports the particle's passage," explains Professor William Trischuk, a scientist at Toronto University, who is working on diamond applications for the ATLAS experiment.

The inner layer - called the "Pixel B-layer" ("Pixel" because the readout elements are pixels about 0.4 x 0.05 mm in size; and "B" for the kind of particle that such a precision tracking layer helps to detect) - has about 200 modules. Current thoughts are that each of these modules will be about 18 x 62 mm in size, though this may change in the future. "These would surround the interaction region, at about a radius 3.5 cm from the LHC beam, covering about 100 cm along the beam-line to catch collision products that are thrown out not only radially but also forward and backward from the interaction point," explains Prof Trischuk. It is likely that a decision will be made in 2009 on which sensor technology will be used to replace the current silicon based Pixel B-layer in 2012 or 2013. Similarly, such detectors would be appropriate for the CMS experiment.

Long development history

Diamond detectors have been part of an intense research programme within the scientific community to develop semiconductor based particle detectors that could survive the expected decade of operation for the LHC and maintain performance even after very large doses of radiation. The CERN RD42 group began a research programme in the early 1990s to look into diamond's potential. Because of progress in diamond synthesis by chemical vapour deposition, primarily carried out by Element Six Ltd, RD42 realised the potential to make suitable detectors.

The role of Element Six has been to develop the synthesis technology so that the diamond material produced could meet the needs of high-energy physics experiments. The work within Element Six has produced electronic grade material with properties optimised for use in the LHC. This has been achieved by reducing impurities and defects in the polycrystalline diamond coupled with developing manufacturing processes that deliver a product of consistent quality. Researchers at Element Six have put considerable effort into improving the electronic properties of the diamond for the detector application based on polycrystalline and single crystal CVD diamond.

The first diamond strip detector was tested by RD42 in 1993. The detector had a charge collection distance of about 50 µm and the spatial resolution attained was about 26 µm. By the turn of the millennium, the group had met its initial goal of producing

CVD diamond sensors whose signal was an appreciable fraction of that produced by a comparable thickness of silicon with a similar spatial resolution. From the viewpoint of signal generation, the larger band gap in diamond compared with silicon (~5.45 eV vs. ~11 eV) is a disadvantage in that it takes about four times as much energy to produce an electron-hole pair in diamond as in silicon. Development has now reached the stage where signal-to-noise levels approach half those in comparable silicon detectors. The real benefit with diamond detectors is that after the sensor material has received a lifetime dose (typically about 1015 particles/cm^2) diamond still delivers about half of its original signal-to-noise level, while silicon sensors are hard-pressed to deliver even 10% of their original signal-to-noise level. So there is a radiation dose beyond which diamond sensors actually produce larger signals than silicon sensors - and this could be most of the life of the LHC.

One of the milestones for the RD42 collaboration was passed in 2002 when one of the key properties of diamond for use as a high energy particle detector, charge collection distance, reached 270 µm. The optimisation of the charge collection distance was achieved by careful control of the growth process and through the development of proper material removal procedures. Material removal from the substrate side, where the density of grain boundaries is higher due to the typical columnar growth of the diamond micro-crystals, can be quite effective in enhancing the charge collection distance. Today the charge collection distance exceeds 300 µm.

Despite this progress, the sensor choices for initial LHC running are currently based on silicon devices. It was always stated that the ATLAS Pixel B-layer would only survive for the first few years of LHC running and would need to be replaced long before the full lifetime (of the order of 10 years) of the experiment so giving the opportunity for diamond to play a greater role in the future.

Making particle detectors from diamond material has become routine and the advantages are largely proven. The current challenge is industrialising the patterning of sensitive elements such as 0.05 x 0.4 mm pixels on the surface of large diamond plates in a clean and reliable way and then connecting the readout electronics to these sensors - once again in an industrial process. For silicon sensors, the advances in VLSI interconnection and packaging can be exploited, but these technologies usually require some adaptation to function with diamond. "We are in the process of transferring many of these processes to diamond material but there is a much smaller market for such devices and hence a much narrower field of industrial partners who are willing to devote the resources necessary to perfect the patterning and packaging necessary to make diamond detector modules," points out Prof Trischuk.

Higgs boson and dark energy

In the 1970s, the theory known as the Standard Model was considered a triumph of theoretical physics, incorporating all that was then known about the interactions of sub-atomic particles.

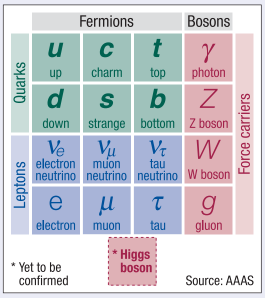
Today it is regarded as incomplete, since it cannot explain the best known of the so-called four fundamental forces: gravity; and it describes only ordinary matter, which makes up but a small part of the total Universe.

Physicists have observed 16 particles (12 matter particles and 4 force carrier particles) that make up all matter under the Standard Model of fundamental particles and interactions. But they would have no mass if considered alone. The Higgs boson explains why these particles have mass, which they acquire through interactions with an all-pervading field, called the Higgs field, which is carried by the Higgs boson (first proposed by University of Edinburgh physicist Peter Higgs and colleagues in the late 1960s).

The Higgs boson's importance to the Standard Model has led some to dub it the "God particle".

When the LHC is turned on in 2008, physicists will scour the 'crash wreckage' resulting from the particle collisions for signs of the Higgs boson. As such, the scientists working on ATLAS will to some extent be competing with those on CMS, with both teams aiming to be first to find the Higgs.

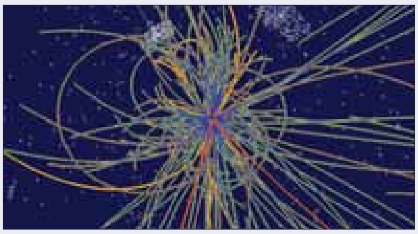
Some physicists even think that finding the Higgs boson could shed light on another great mystery in physics: dark energy. In 1998, two teams studying supernovae showed that this dark energy is accelerating the expansion of the Universe. Subsequent work revealed that dark energy may make up about 70% of the Universe, but the best theories could not explain it.



* Yet to be confirmed

Source: AAAS

The standard model



Simulation of a detection of the Higgs boson in the CMS experiment

The theory is that all of space is filled with the Higgs field. Unlike the gravitational field, which is strong around the Sun and the centre of the galaxy, the Higgs field would have essentially the same value everywhere. This would give dark energy, in the sense that dark energy is energy density in empty space a long way away from any matter. Finding the Higgs boson, therefore, would corroborate the whole theory that there's a Higgs field sitting throughout the Universe providing dark energy.

Such a breakthrough would reinvigorate physics' biggest endeavour: a grand theory to describe all physical phenomena in nature. On the other hand, the LHC might even reveal something completely unexpected about the workings of our Universe. And that, say physicists, might be even more satisfying.

Conclusion

Diamond has already had a significant impact on the Beam Conditions Monitoring field - including installations at several other accelerator complexes around the world such as BaBar, the high energy physics experiment located at the Stanford Linear Acceleration Centre, near Stanford University in California, and Belle at the National High Energy Physics Laboratory of Japan. With current work in progress, it seems likely that diamond will play a far greater role in helping uncover the greatest mysteries - how the universe works. ◆

Acknowledgements

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Figs 1-5 courtesy of CERN

Figs 6-9 courtesy Professor William Trischuk.

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