Bright lights – synthetic diamond plays its role in the new Diamond synchrotron

Diamond Light Source is a new synchrotron radiation facility that has recently come onstream in the UK. As part of this development, researchers are looking at the potential of synthetic diamond within the beamlines for applications that range from optics to diagnosis and monitoring. Various types of diamond material are already used within one of the first phase beamlines and researchers are looking to expand the role of diamond materials for both existing and future experimental stations. Report by **Elaine McClarence**.

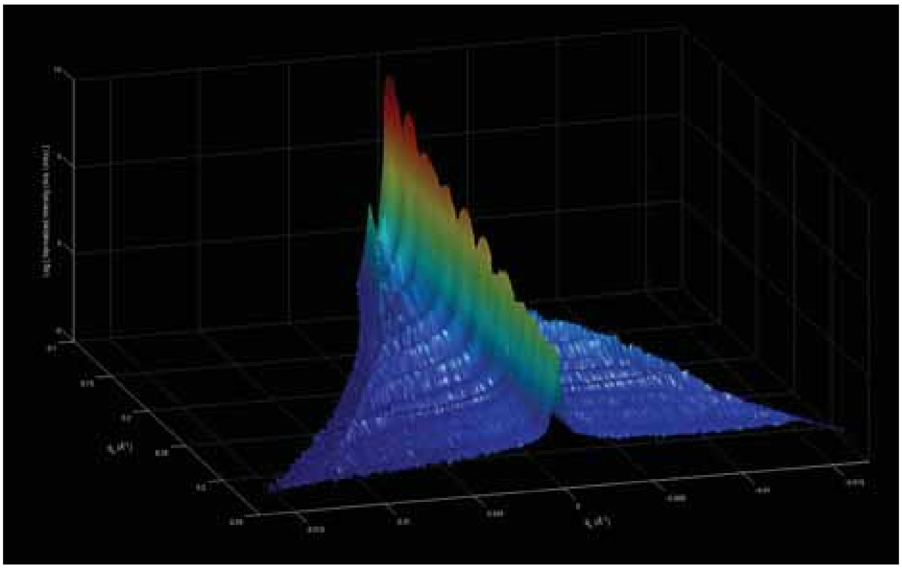

Fig 1 First results from the first users on the Materials and Magnetism beamline represented as a 3D graphic image

In 2007 the first phase of seven experimental stations at Diamond Light Source, the UK's new synchrotron radiation facility, became operational. Located south of Oxford, Diamond Light Source will provide academic and industrial researchers with a powerful tool for probing the structure of a wide range of materials. Between 2008 and 2012, the power, brilliance and potential of this important research facility will increase, as a second phase £120m investment programme adds significantly more experimental capacity in the form of 15 new beamlines and associated experimental stations.

What are synchrotrons?

Synchrotrons are important scientific research tools. In essence, they are rather like enormous super-microscopes capable of studying biological, chemical and material samples at very high resolution, down to the atomic and molecular level, by using synchrotron light. The ability to

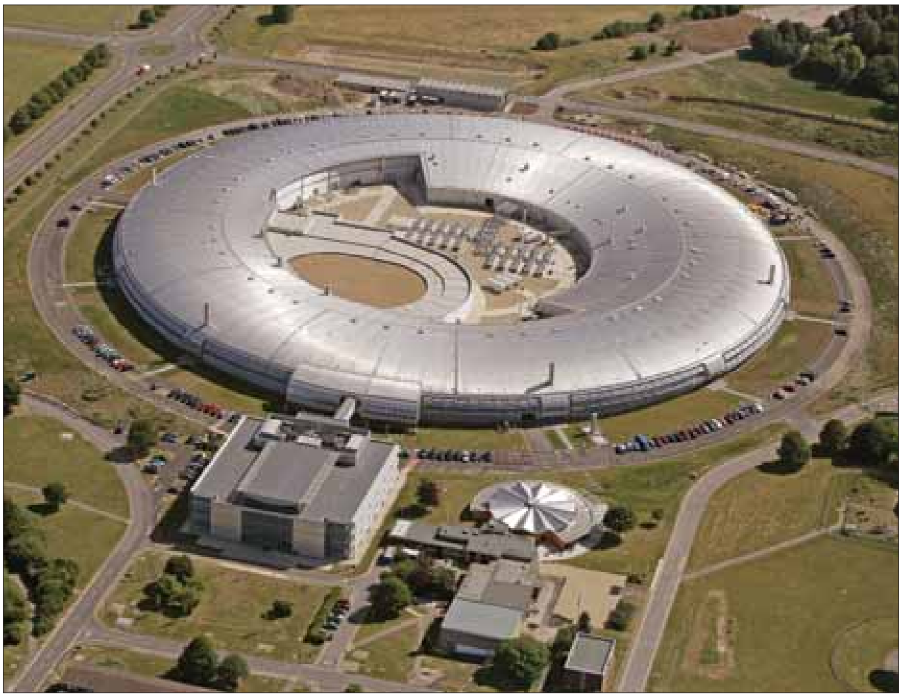

Fig 2 The Diamond Light Source is the latest generation of synchrotron and is the largest UK funded research facility built in the last 40 years

generate synchrotron light was first noted in 1947 as an initially unwanted by-product of high energy physics research. The first synchrotron dedicated solely to academic research was the Synchrotron Radiation Source (SRS) built at the Daresbury Laboratory, Cheshire, in the UK, which was completed in 1981. Today there are more than 40 major synchrotron light sources globally; including the European Synchrotron Research Facility (ESRF) in Grenoble, France, the Advanced Photon Source in Michigan, USA, and Spring8 in Japan.

These machines deliver intense beams of electromagnetic radiation from X-rays through the ultraviolet and visible to the infrared to study a wide range of material samples that are related to broad academic and industrial research projects. The short wavelength radiation provides the ability to see small features, and the high brilliance enables rapid imaging of systems in motion. Synchrotrons are used in new drug developments, nanotechnology, novel materials for advanced engineering applications, electronic and optical devices. Activities that have involved synchrotron research have covered contributions to studying malarial parasites; optimising food manufacturing processes such as chocolate-making; understanding stresses in complex engineering structures to the development of anti-flu drugs.

About the Diamond Light Source

Diamond Light Source, which began construction in 2003, is the largest UK-funded research facility built in the last 40 years. It represents the third and most advanced generation of such facilities. The project has been funded by the UK government via the Science and Technologies Facilities Council (STFC) and the Wellcome Trust. The £260m first phase of the Diamond Light Source project became operational in January 2007 and comprised the construction of the buildings, the machine and the first seven beamlines and experimental stations. When complete, the facility will contain up to 40 such beamlines.

The Diamond Light Source uses electrons to generate synchrotron light in the form of X-rays, ultra-violet and infra-red beams. To give an idea of the intensity of the beams produced, the X-rays generated are 100 billion times brighter than a typical laboratory X-ray source. The starting point is to generate electrons using an electron gun. The stream of electrons so generated, are accelerated to a potential of 3 GeV pushing the electrons close to the speed of light. This is done in steps starting with a linear accelerator, moving through a smaller booster synchrotron before being injected into the large storage ring that is over 560 m in diameter. Once in the main storage ring, the electrons give off synchrotron radiation as they travel around guided by powerful magnets. At certain points around the storage ring, insertion devices – essentially arrays of specially configured magnets – are used to produce beams of infra-red, ultra-violet and X-ray synchrotron radiation of exceptional brilliance and quality.

These beams are then directed out to all the operational beamlines where individual experiments are performed. Each station is dedicated to a different type of experimental technique and, in each case, the appropriate type of radiation is selected from the range that the synchrotron generates.

Potential of diamond components in synchrotrons

The trend in modern X-ray sources such as synchrotrons is towards higher brilliance i.e. more photons of a given wavelength out of ever smaller sized optical sources, which leads to higher power densities of the order of hundreds

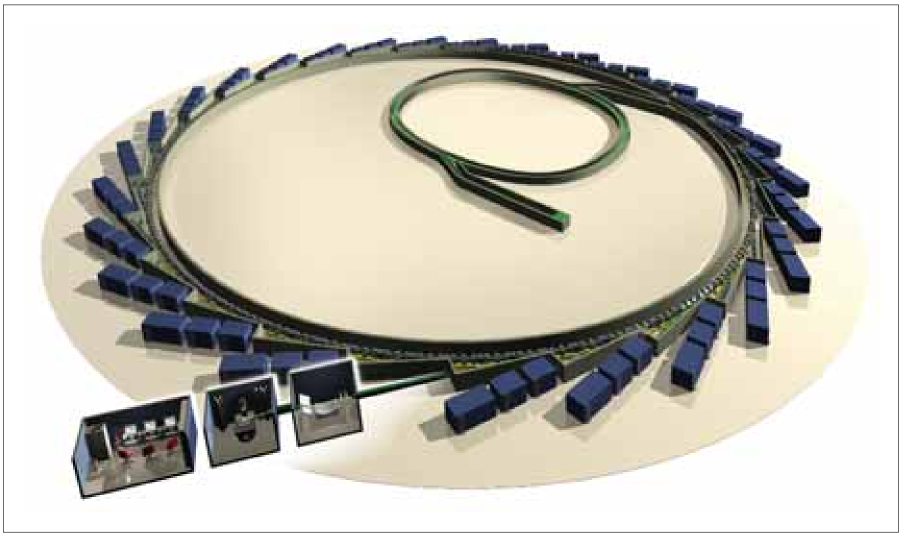

Fig 3 Individual experiments are performed at dedicated stations which uses different ranges of radiation

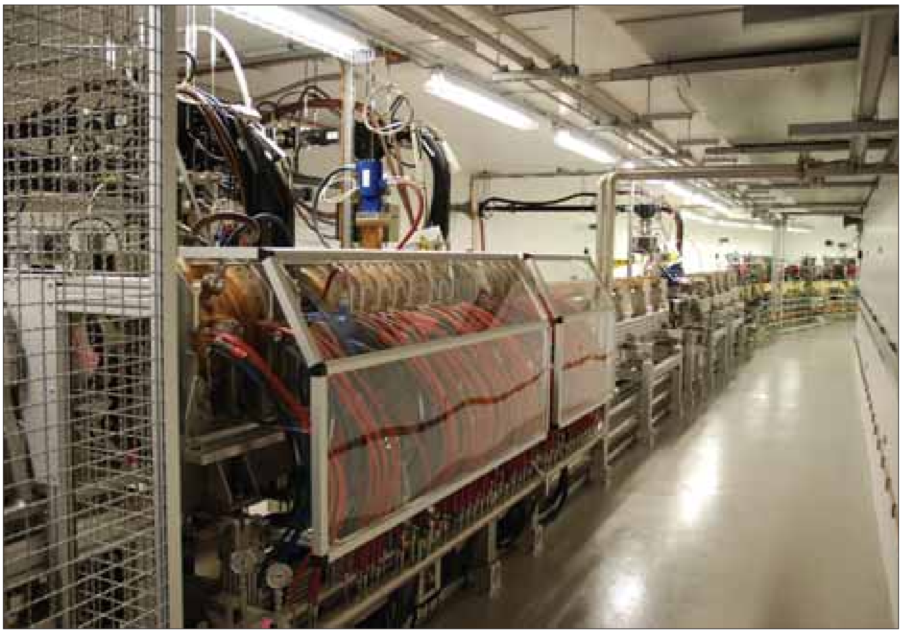

Fig 4 The linear accelerator is the first stage in generating synchrotron light and helps push a stream of electrons at velocities close to the speed of light

of watts per square millimetre at the beam optical elements. Such elements include filters, windows, phase plates, beams splitters and monochromators. Currently, silicon is used for such elements, but as power densities increase, diamond becomes more attractive as it has a lower absorption coefficient than silicon, a better thermal conductivity and a lower thermal expansion coefficient. The challenge has been to manufacture synthetic diamond with the surface and bulk characteristics that would allow its superior performance to be fully exploited.

Fig 5 Once the stream of electrons enter the large 560 m diameter storage ring, they begin to give off synchrotron radiation

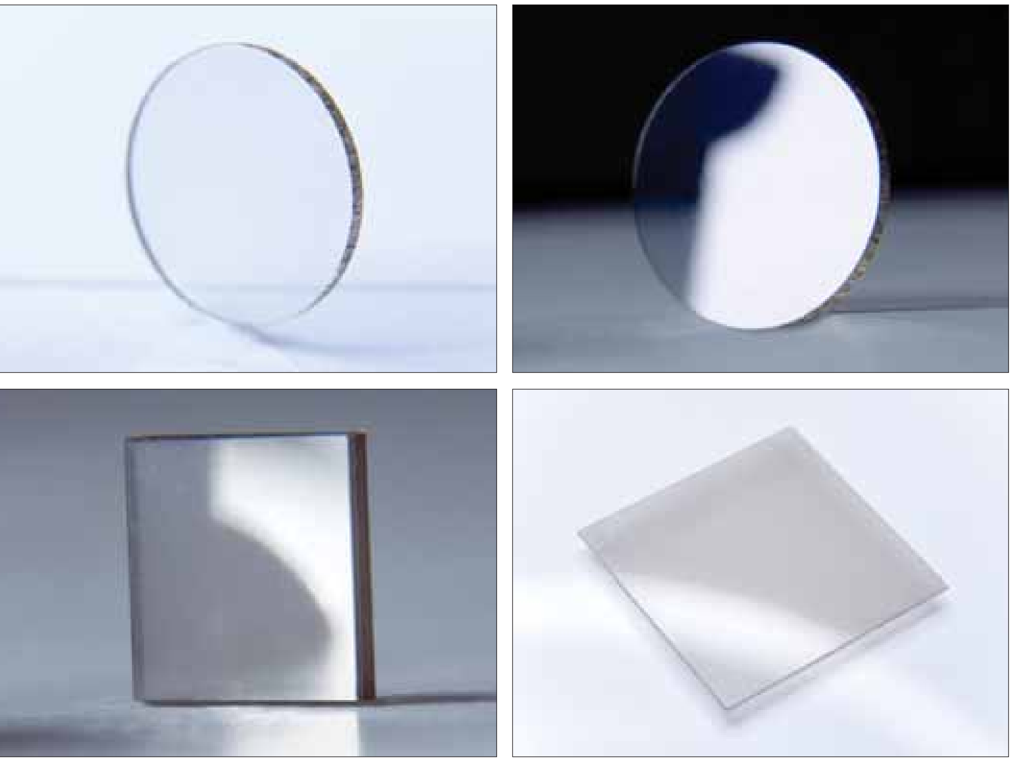

Fig 6 Element Six has developed a range of synthetic diamond products with consistent characteristics that are suitable for optical applications

Extreme Conditions beamline

Of the current beamlines at Diamond Light Source, the Extreme Conditions beamline (I15) uses diamond material in the widest range of applications. I15 is reserved for the study of materials at high temperatures and under extreme pressures. Diamond is used or its potential is being explored in three types of application on I15: X-ray windows made from polycrystalline chemical vapour deposition (CVD) diamond; anvils for high pressure cells made from high quality natural diamonds; and as a CVD diamond X-ray detector for monitoring the beam position. CVD diamond forms an ideal window for high energy X-rays above 20 keV, it can transmit the high energy X-rays with very little attenuation, but it absorbs and dissipates the unwanted low energy radiation to water cooling, and protects the ultrahigh vacuum of the insertion devices and storage ring from any contamination. Large CVD diamond windows made by Element Six are specially bonded into metal flanges at UKAEA, Culham by its Special Projects Group.

Professor Andrew Jephcoat, I15's Principle Beamline Scientist and a visiting professor at Oxford University's Department of Earth Sciences, explains the role of diamond in generating high pressures as part of the I15 beamline. His research interest is the study of the core of the Earth and other planetary interiors.

"To generate the conditions of planetary interiors, we need specially polished natural diamond anvils with their tips shaped to dimensions less than 0.1 mm. Literally squeezing together two anvils can generate millions of atmospheres pressure, and, at Diamond Light Source, we combine this with infrared heating lasers and X-ray synchrotron radiation to determine the structural changes occurring in solid and liquid matter under conditions prevailing deep in the Earth (1,000 km deep and more) as well as in the outer layers of the giant gaseous planets." Exposing materials to high pressure and high temperature can result in remarkable property changes such as high temperature superconductivity. "It is the mechanisms of such changes that Diamond Light Source beamline I15 will explore and this can help in the search for technologically relevant materials for future everyday applications," he adds.

Two kinds of diamond detectors are also currently being considered at the Diamond Light Source, initially for I15.

Dr Nicola Tartoni, part of the detectors team explains, "The first one is a CVD diamond window 34 mm in diameter and 0.9 mm thick. It is planned to be installed in the optics hutch of the beamline where it is being tested as an X-ray white beam position monitor diagnostic. This diamond window is placed in the vacuum pipe, where it is struck by the white X-ray beam, and is brazed to a copper holder to remove the heat. The window should emit electrons into a vacuum and four electrodes collect these electrons. From the ratios of the currents detected by a four channel transimpedance amplifier, it should be possible to detect the beam position."

The second type of detector currently under development is an X-ray beam intensity monitor. This detector uses a single crystal CVD diamond plate as a photoconductor. Initial tests by Dr Tartoni at the SRS in Daresbury have demonstrated that diamond can perform well in terms of the linearity as a function of beam intensity and stability. "My plan is to carry on with this activity as I would like to check their linearity and stability with a beam much more intense than that of SRS, such as the X-ray beam produced by the insertion devices at Diamond Light Source," Dr Tartoni explained.

Materials & Magnetism beamline (I16)

This beamline is used to probe the electronic and magnetic properties of materials at the atomic level. Various grades of CVD diamond are employed here for attenuation and diagnostic purposes. Professor Steve Collins, I16's Principal Beam Scientist, notes, "Mechanical Grade CVD diamond is just used to attenuate the X-ray beam when we want less of it. That means 100 W or more of power on a 0.2-2 mm thick material in an area of less than 1 mm^2, so we use diamond for its thermal properties." Transparent (optical grade) CVD used in a similar way but also gives off light so that the X-ray beam's path can be monitored.

The beamline also uses a very high quality single crystal CVD diamond 6 x 7 x 0.4 mm, which is used as an X-ray quarter-wave phase retarder. As Professor Collins explains, "If you take a very high quality single crystal and go very close to the conditions for Bragg diffraction, a small difference in refractive index appears between the light (X-rays) polarised parallel and perpendicular to the diffraction plane. We have a naturally linearly polarised beam, polarised in the horizontal plane. If we make such a device and orient it at 45° then the beam splits into two equal parts – a parallel and a perpendicular component." The different refractive indices mean that one of the two orthogonally polarised beams travels slightly faster than the other. With the appropriate diamond thickness they emerge with a 90° phase difference and re-combine to give a circularly polarised X-ray beam. This can then be used to study, for example, magnetism in magnetic materials. "We use diamond because it is the lightest (lowest atomic number and therefore least absorbing) material that can be grown as a high-quality single crystal," says Professor Collins.

Future beamlines with diamond

The small-molecule single-crystal diffraction high intensity beamline, I19, will be available for its first users in October 2008. Synthetic diamond wafers of varying thicknesses (0.2, 0.4, 0.6 mm etc) will act as either attenuators or fluorescent screens for monitoring the beam position. Element Six Ltd also supplied these. A set of diamond-anvil cells for occasional high-pressure studies on the beamline is also planned.

The optics to get the beam from the insertion device in the synchrotron (an undulator magnet which is the X-ray source) to the sample are extremely complex. The major optical components are the monochromator, composed of two large single crystals of silicon which select a single X-ray wavelength, and a pair of mirrors which focus the resulting monochromatic beam in the vertical and horizontal onto the sample. "The alignment of these elements is extremely difficult and we have high-precision actuators to move the optical elements into the correct orientations and positions. There are dozens of these items and they must all be positioned exactly right for an optimal beam on the sample. This, as you'd expect, is very difficult and we need to 'see' the beam at almost every point along the length of the beamline to ensure that we're steering the beam correctly down its very tightly defined path. Hence, we have a series of diagnostic units," says Dr. David Allan, Principal Beamline Scientist on I19. These are composed of a fluorescent CVD diamond screen, which can be flipped in and out of the beam as required, and a video camera which allows the position of the beam to be monitored. "We see a bright spot on the screen from the otherwise invisible X-rays.

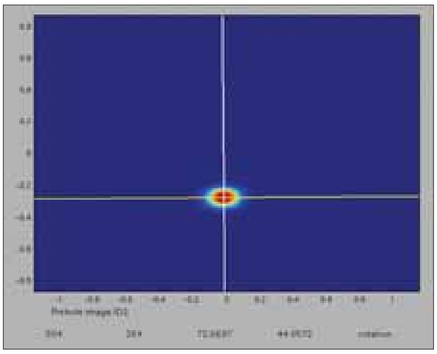

Fig 7 Image of stored electron beam produced from the emitted X-rays from one of Diamond's bending magnets and imaged using a pinhole camera

We need diamond as the heat-loads can be appreciable," Dr. Allen explains.

Attenuators are used to protect the optics during early alignment by simply absorbing a fraction of the incoming beam. They can also be useful to prevent saturation of the detectors if the beamline encounters a particularly strongly scattering sample. The attenuators look exactly the same as the diagnostic units, and, in some instances, the diagnostics units share this role.

Wider application

Beyond Diamond Light Source, synthetic diamond has found increasing use in synchrotrons since they were first used at the ESRF as a monochromator in 1992. They are also used similarly at two other large synchrotrons, the Advanced Photon Source in the US and Spring8 in Japan. ESRF also pioneered the use of diamond for transmission phase plates to modify the polarisation state of X-ray light and has an active research programme to develop diamond optical components for the next generation of light sources.

Synchrotron research is now a flourishing branch of science with broad industrial interest. As researchers continue to push towards higher brilliance; this may lead to higher power densities, which may be measured in hundreds of watts per square millimetre at the beam optical elements. In practice, diamond is the only material that can meet the extreme requirements of the brightest light ever produced on Earth. ◆

Acknowledgment

Figs 1-5 and 7 are courtesy of **Diamond Light Source Ltd**.

Contacts

Diamond Light Source: www.diamond.ac.uk
Element Six Ltd: www.e6.com