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Big-science supplement

The challenges in building the world's next-generation facilities


CATALOGO 2012

The challenges of “big science”

This special supplement to *Physics World* looks at the challenges facing the next-generation “big science” facilities – from how to get projects funded (p17) to the engineering and scientific issues that have to be met before construction can begin. Among the facilities in particle physics pushing existing technology to the limits are CERN’s Large Hadron Collider, where researchers are planning a major upgrade (p5), and the SuperB experiment, which is aiming to employ cutting-edge CMOS detector technology (p23) for materials science. There are challenges in store, too, for those designing the neutron-producing target at the European Spallation Source so that it can withstand the large heat gradients (p13). Superconducting magnet technology is the name of the game for the European X-ray Free Electron Laser in Germany (p19), as it is for the ITER fusion experiment in Cadarache, France, where it will be used to contain a high-temperature plasma (p9). Big science also means big lasers, which are set to play a key role in a German-based collaboration to accelerate protons (p27) as well as at the European Extremely Large Telescope (p30). Big science never looked bigger or better.

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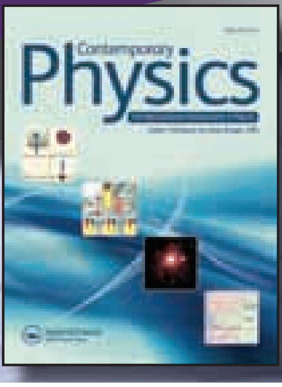
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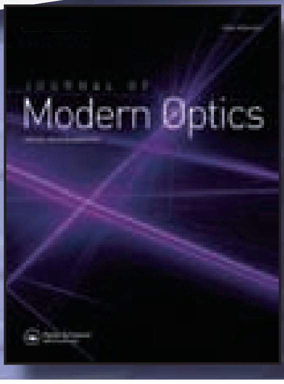
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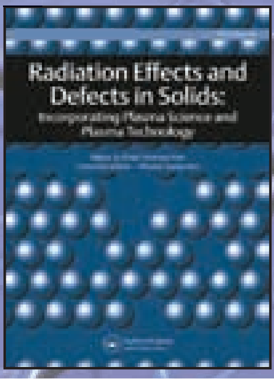
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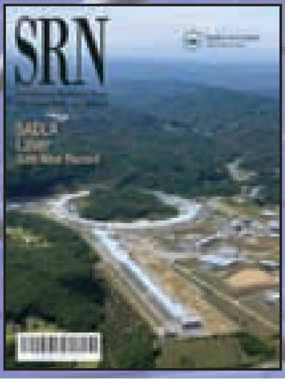
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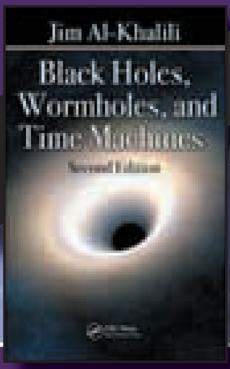
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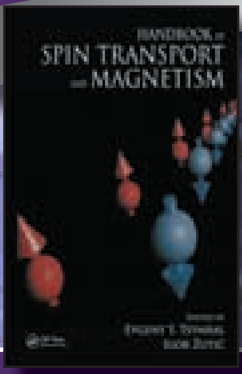
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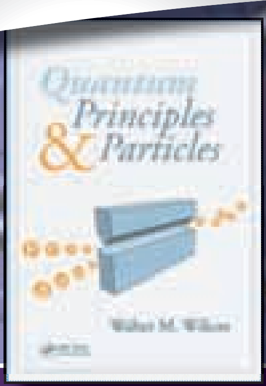
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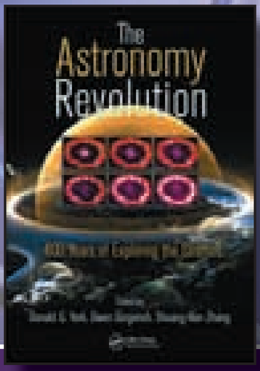
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Making CERN’s best even better

CERN’s Large Hadron Collider is finally up and running, but the lab is already planning an audacious upgrade using technology not yet invented, as Matthew Chalmers reports.

It is hard to imagine upgrading an instrument as big and complex as the SwFr 6.5bn (€10bn) Large Hadron Collider (LHC) at the CERN particle-physics lab near Geneva. The 27 km-circumference collider, which was switched on in September 2008 after 25 years of planning and construction, was built to drive 2808 bunches of protons – each containing about 100 billion protons – into one another 40 million times per second inside four detectors the size of large buildings. A tiny fraction of head-on collisions, physicists hope, will hold clues about nature’s fundamental structure, in particular what gave certain elementary particles their masses.

At full luminosity – a measure of the rate of particle collisions – of around 10^{34} cm^{-2} s^{-1}, the LHC beam will store enough energy to melt a tonne of copper as it circulates within a whisker of highly sensitive and expensive components. To protect the accelerator and its detectors from stray protons, the LHC is equipped with around 100 movable carbon or tungsten collimators each with a small slit through which the beam can pass. Yet long before the LHC fired its first protons, CERN was planning ways to produce even more intense collisions that will improve the chances of discovering rare, new particles or forces.

The upgrade to the LHC – dubbed the High Luminosity LHC (HL-LHC) – will pack a beam luminosity more than 10 times the LHC’s design goal: up to 5×10^{35} cm^{-2} s^{-1}. The HL-LHC will therefore need more sophisticated collimation to avoid unacceptable heat loads and require upgrades to the LHC’s injection system, which currently relies on CERN’s more elderly accelerators and proton transit lines, to ensure beam quality and stability.

More bang for your buck

Lucio Rossi, HL-LHC co-ordinator, says that the project is the main R&D focus for CERN over the next 10 years, the other being the Compact Linear Collider – one possible design for the next big particle-physics experiment after the LHC. “[HL-LHC] will be like turning up the lights in a darkened room from the point of view of the experiments,” he says. The realities of building, commissioning and operating the LHC have meant that its high-luminosity incarnation will not materialize until around 2022, however, with a price tag of around €1bn. Half of this money will go on upgrading the collider and half on refitting the LHC’s four detectors – ALICE, ATLAS, CMS and LHCb – so that they can cope with the HL-LHC’s harsh collision environment.

The LHC was designed to circulate two 7 TeV beams, generating 14 TeV collisions, but initially has been forced to operate at half this value after an unstable magnet interconnect evaporated during high-current tests just nine days after the LHC switched on in late 2008. Intervening in the LHC is no easy task because, when running, it is kept at a temperature of 1.9 K using 130 tonnes of liquid helium to ensure that the niobium–titanium cables that power its dipole magnets are below their superconducting transition temperature.


CERN

Testing a new type of quadrupole magnet that will be used in a future upgrade of the Large Hadron Collider at CERN.

It takes months to warm the whole machine to room temperature and then to cool it back down, and three long shutdowns are planned during the next decade. The first, in 2013–2014, will involve fixing around 1000 defective interconnects so that the magnets can operate closer to their target bending field (8.3 T), which allows them to carry 7 TeV protons, while all 10 000 joints will be fitted with a lateral restraint to ensure stability. Further improvements are anticipated in the second shutdown, likely to happen in 2017 or 2018, while the HL-LHC and associated improvements in the detectors will mainly take shape during the third long shutdown scheduled for 2021.

As well as almost doubling the number of protons in each bunch, the HL-LHC relies on improved electromagnetic “optics” to bring the beams of protons into collision in the LHC’s four detectors. Two key technologies are under development: high-field superconducting quadrupole magnets that squeeze the beam more tightly in the vertical and horizontal directions; and radio-frequency “crab” cavities that reduce the angle at which the bunches cross.

“The LHC luminosity upgrade is very demanding technologically, with the LHC already representing the apex of 30 years of work worldwide on superconducting magnets,” explains Rossi. “Existing quadrupole magnets go up to 8 T, and it has so far taken six years of solid work by many US teams to build the first 11.5 T prototype, but we need 13 T and an even larger aperture." The magnets are mostly being developed by researchers at Fermilab in the US in conjunction with staff at CERN. The crab cavities present an even bigger challenge because they have never been used to kick a beam of protons in the transverse direction, not least at a steady rate of 40 MHz. Much of the R&D for crab cavities, which must be compact and have acute phase accuracy, is taking place at the Cockcroft Institute of Accelerator Science and Technology in the UK, with a test cavity that may be installed at the LHC during 2017–2018.

In addition to developing "radiation hard" electronics by making the semiconductor chips and associated hardware able to withstand higher radiation doses, CERN is considering moving power supplies near the detectors as far away from the beam as possible – ideally above ground, as opposed to their current location close to the detectors 100 m underground. The only way to carry the enormous 200 kA currents required is to use superconductors as well. But low-temperature superconductors, such as niobium alloys, are problematic for this application because the liquid helium required to cool them warms because of hydraulic pressure when suspended vertically. Instead, CERN may have to turn to high-temperature superconductors such as yttrium barium copper-oxide materials, which do not require liquid helium to get them into the superconducting state. "Longer high-temperature superconducting cables exist, but none carrying such high currents," says Rossi.

Detecting more events

The higher collision rate delivered by the HL-LHC demands major modifications to the ATLAS, CMS, ALICE and LCHb experiments, not least to deal with the increased radiation dose that they will suffer. At normal running, the two general-purpose ATLAS and CMS detectors are flooded with the debris from around 20 proton–proton collisions every time two bunches cross, which must be assessed in less than 25 ns (i.e. before the next bunch crossing) by a "trigger" to decide whether or not the collision is worth recording to disk. At the HL-LHC, however, this "event pile-up" will be more like 400 per bunch crossing, requiring much faster front-end electronics and data-acquisition systems.

The innermost layer of the LHC experiments – the semiconductor pixel detectors that track the collision debris just a few centimetres from the interaction region – will be replaced in all four experiments to cope with the onslaught. As well as being more radiation hard, the upgraded trackers will be more granular to reduce occupancy on pixels, for example by using better nanofabrication techniques to create smaller sensitive regions. Without this change, the vital task of picking out which particles are associated with a particular proton–proton collision (so-called vertex reconstruction or "vertexing") will be impossible.

"Ideally, you would have a zero-mass tracker so that the particles fly through it without losing energy, but that's not possible," says Craig Buttar of Glasgow University, who is a member of the UK ATLAS upgrade team. "Plus, you have all the services – the power cables, the optical signals for control and read-out, and the cooling system – to contend with."

CERN

The LHC uses more than 1200 dipole magnets to bend protons around its 27 km circumference.

Both ATLAS and CMS are considering using pressurized carbon dioxide in place of current flourocarbons to cool the upgraded inner detectors, for instance, because it takes up less space.

ATLAS researchers plan to add a new pixel layer to its existing tracker during the 2013–2014 shutdown to improve vertex reconstruction, and those working on CMS are planning similar intervention in 2017–2018. "For CMS, the new tracker is an enormous operation because we need to increase the number of channels by a factor of 10 without increasing the power," says Dave Newbold of Bristol University, who is software co-ordinator for the CMS upgrade. "Even without the luminosity upgrade, though, we would still have to maintain and improve our detectors. We might have spent 15 years building them, but they're never really finished."

The LHCb collaboration, which is devoted to the physics of B-mesons, is considering replacing its current particle-identification detector based on Cerenkov light, as well as a new tracker capable of better vertexing, although in general LHCb operates at a lower luminosity than ATLAS and CMS. Plans to upgrade the ALICE experiment, which is designed to study collisions between lead ions during dedicated LHC runs, are only indirectly linked to the HL-LHC because the detector has been optimized for a lead–lead luminosity of 10^{27} cm^{-2} s^{-1}.

Despite taking up two decades of R&D at the edge of what is technologically possible, the HL-LHC will not be the end of the story for CERN's flagship collider: it is the stepping stone to an even more powerful machine perhaps some time in the 2030s incorprorating new superconducting magnets with bending fields of 20 T that would allow a beam energy of 16.5 TeV per beam. The magnet technology does not yet exist, but in May 2010 CERN established a working group to explore the High Energy LHC (HE-LHC). With a likely price tag of several billion euros, HE-LHC will also require completely new accelerators to feed it, but the project's chances of success will depend on what the LHC and HL-LHC discover. "The HE-LHC will happen," says Rossi, "the question is when?"

Matthew Chalmers is a writer based in the UK.

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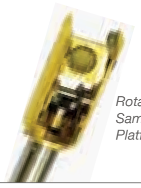

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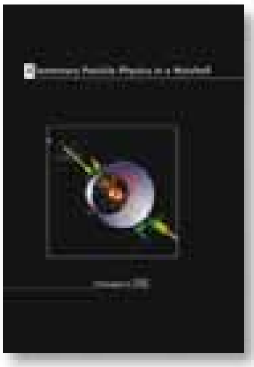

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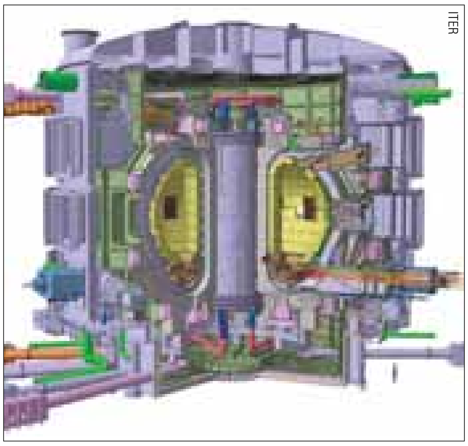
Magnet challenges for ITER

To control a plasma at a temperature of 150 million Kelvin, the ITER fusion reactor will need a magnet system like no other, as **Daniel Clery** explains.


ITER

ITER's magnet system will be able to store 50 GJ of energy.

Generating power with nuclear fusion – slamming together hydrogen isotopes until they fuse into helium – has proved much harder to achieve than its nuclear-fission counterpart. But now, after more than 60 years of research, physicists hope they are on the home straight with the €16bn ITER experiment – a huge tokamak now under construction in Cadarache, France. The fruit of a worldwide collaboration involving China, the European Union (EU), India, Japan, South Korea, Russia and the US, ITER is a colossal machine that, once complete in 2019, will weigh as much as an aircraft carrier.

Fusion researchers hope that ITER will be the first tokamak to generate more power than is needed to keep it going – some 500 MW from a 50 MW input. Most of that input heats the fusion fuel – a 50:50 mixture of the hydrogen isotopes deuterium and tritium – to millions of degrees and applies a magnetic straightjacket to hold it in place while it burns. The magnets required to provide that field – 13 T at its strongest point – are now being built in factories across the globe (see table) and are proving to be a huge engineering challenge. They have to endure huge mechanical forces, thousands of current pulses, intense neutron bombardment and a thermal gradient that soars from 4 K to 150 million K across just a few metres. "It's the scale, not the science, that brings issues," says Neil Mitchell, head of ITER's magnet division.

When ITER was being designed back in the late 1980s and early 1990s, it was obvious that the reactor would have to use superconducting magnets because conventional magnets would need gigawatts of power to contain a plasma at a temperature of millions of degrees. A few tokamaks with superconducting magnets had been built before, such as France's Tore Supra, which began operating in 1988 and stores around 700 MJ of energy in its superconducting magnets. But none have been as big as ITER, which will have magnets that will store a whopping 50 GJ. Indeed, some of the coils are so large that they cannot be transported by road and so will be wound on site at a purpose-built plant.

Magnets in a spin

A tokamak such as ITER has several sets of magnets that perform different roles in confining the superhot plasma within the reactor vessel. The central solenoid is a coil positioned in the central hole of the torus. It acts as the "primary" of a giant transformer with the plasma itself being the "secondary" coil. Driving a current through the central solenoid induces the plasma to flow round the torus, creating a current. This current generates another magnetic field that then "pinches" the plasma current towards the centre and so keeps it away from the walls.

This pinching field is reinforced by "poloidal field" coils – six horizontal, circular coils around the outer edges of the tokamak similar to bands around a barrel. Then there are 18 "toroidal field" coils – huge D-shaped windings that wrap around the plasma. These generate a field parallel to the plasma current that gives it a twist so that the plasma spirals as it moves. This helps to stabilize the plasma and keep it away from the walls. Finally, there are sets of lower-energy "correction" coils that help to shape the plasma.

Despite the challenges of scale, Mitchell says that the magnet technology for ITER is "rather conventional" because it will use well characterized superconducting materials such as niobium tin (Nb_3Sn) for the central solenoid and toroidal-field coils, and niobium titanium for the poloidal-field and correction coils. But making an ITER conductor is not just a matter of winding a few strands into a cable. Nb_3Sn is a brittle material that must endure enourmous mechanical forces and 60 000 thermal cycles. "It's very much a challenge," says Chris Rey, the central-solenoid systems manager at the US ITER Office at the Oak Ridge National Laboratory in

Magnet system	Number of coils	Stored energy (GJ)	Peak field (T)	Length of conductor (km)	Total weight (tonnes)	Countries where conductor was made	Countries where coils were made
Toroidal field	18	41	11.8	82.2	6540	China, EU, Japan, South Korea, Russia, US	EU, Japan
Central solenoid	6 modules	6.4	13	35.6	974	Japan	US
Poloidal field	6	4	6	61.4	2163	China, EU, Russia	EU, Russia
Correction coils	9 pairs	–	4.2	8.2	85	China	China

Tennessee. "It's expensive, so you can't make prototypes. You have to get it right straight out of the box."

Making the conductor starts with individual strands – each less than a millimetre across – composed of a mixture of niobium and tin that is encased in a copper shell. Three strands are then wound together to make a "triplet", and 32 triplets are bunched together make a "petal". Six petals arranged around a central pipe make a cable, roughly 4 cm in diameter, with the pipe allowing the flow of liquid helium to cool the cable to superconducting temperatures. The final part of the process involves encasing the cable in a metal jacket with a roughly square cross-section so that when the conductor is wound into a coil, the windings fit snugly together and cannot move. Prior to the ITER project, around 15 tonnes of this sort of superconducting cable were manufactured per year; ITER requires 400 tonnes – or around 80 km of cable.

To form magnets, the conductors are wound into a metal conduit in the required shape. The largest niobium–tin magnets are the toroidal-field coils that will be arranged vertically around the tokamak. Each one is 14 m tall and weighs 360 tonnes – roughly the mass of a jumbo jet. Once wound, the coils are heated to 650 ºC for eight days so that the niobium and tin form the superconductor Nb_3Sn.

Testing times

Despite their size, the coils still demand exquisite precision to create a perfect field for plasma confinement. The conductor must be carefully wound into an exact position in the conduit and then held there with an error of only a few millimetres. That sort of manufacturing control is made more difficult by the way that the ITER project is run. Because the seven members of the ITER collaboration all want a share of the industrial contracts, they agreed to divide up the manufacturing between them and each delivers their components to Cadarache "in-kind" without money changing hands. But this means, for example, that making the conductors for the toroidal-field coils has been split between six different member states and, because some of them have contracted more than one company to do the work, a total of 10 firms are involved. "Their grasp of the technology isn't even," says Mitchell. "There's a lot of negotiation and it's producing a lot of delay. The amount of testing we're doing is five times what was originally expected."

That testing threw up a problem earlier this year when a sample of Nb_3Sn conductor made in Japan for the central solenoid failed in tests earlier than expected. The specification requires the conductor to survive 60 000 current pulses during the 20-year life of the reactor. However, this particular sample began to fail after only 6000 pulses. "The conductor absolutely works," says Rey, "it's the lifetime that's not understood." The ITER organization at Cadarache has set up a task force to look into the problem and it will report back later this year.

ITER insiders are playing down the significance of the failed test. It took place at the SULTAN facility at the Paul Scherrer Institute in Villigen, Switzerland, where straight sections of conductor a couple of metres long are subjected to high fields and currents. While this shows that the samples are working, according to Rey it "doesn't accurately represent the conditions in ITER". A second sample of the same conductor is now being tested and is reportedly performing much better. An ITER spokesperson says that if the second sample maintains its performance to the end of the test, the conductor is likely to be approved for production next year.


ITER

A purpose-built facility in Cadarache, France, will be used to wind some of ITER's coils on site because they will be too large to be transported by road.

Cost concerns

Another tough decision is whether or not to test the completed coils. In an ideal world, once wound, each magnet would be cooled to 4 K and have high current put through it to see if it worked as expected. Such an approach significantly reduces risk because when the reactor is built, most of the coils cannot be removed for repair or be replaced. But cold-testing such huge magnets – the largest has a diameter of 24 m – also hugely increases cost because it would require a purpose-built facility, much power and a lot of time. There are other risks too: testing one coil in the absence of all of the others might be easier but it would not then experience the full magnetic field of the entire magnet system, and so would have different stresses that could potentially bend it out of shape.

Each ITER member state that is making the magnets must decide for itself whether to do full cold tests on completed coils – and the consensus seems to be that it is not cost-effective. Rey says that the US is planning to test its coils – the six modules of the central solenoid – at a factory in Tallahassee, Florida, by cooling them to 80 K with liquid nitrogen. At that temperature the coil experiences 90% of the thermal stresses that it would encounter at 4 K. Once cool, researchers can test for helium leaks and do a voltage test that stresses the conductors' insulation. "Most large superconducting magnets fail on their insulation," Rey says. US ITER managers calculate that it would be cheaper to do the 80 K tests than to ship a faulty module back from France for modification.

But a lack of money will likely persuade project members not to carry out 4 K high-current tests. The US ITER project is still mulling it over – its budget is under severe strain in the current financial climate. The EU, too, is struggling to find its 45% share of the construction cost. In the end, we may not know for sure whether ITER's magnets work as planned until the day they are switched on at the end of the decade.

Daniel Clery is a science journalist based in Woodbridge, UK.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Neutron target station takes the heat

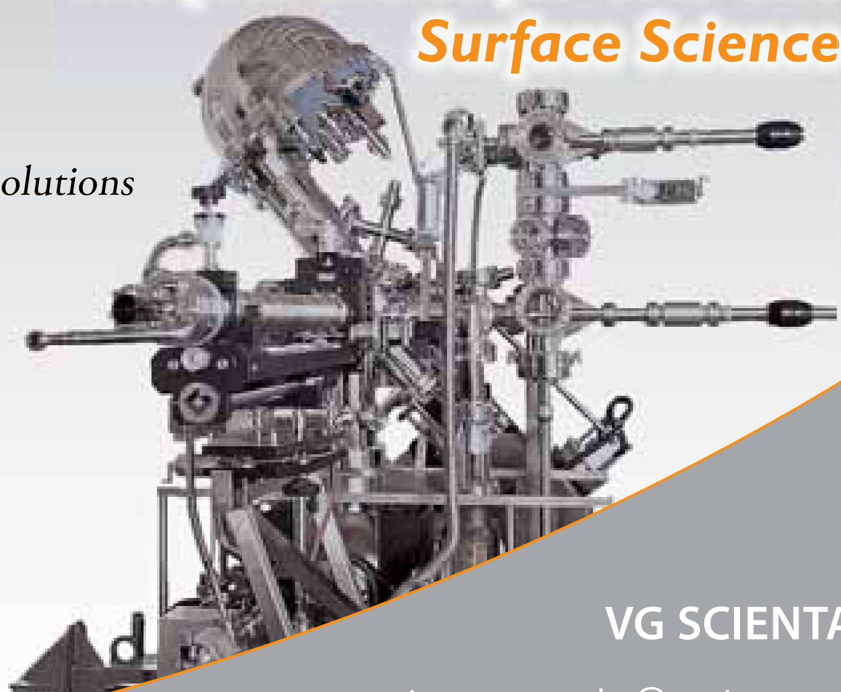
Handling 100 °C temperature changes that occur in less than 3 ms is a key task for those designing the European Spallation Source, as **Michael Banks** reports.

ESS

Designs for the European Spallation Source to be built in Lund, Sweden, are likely to contain a seven-tonne tungsten target that will generate an intense beam of neutrons.

When complete in 2019, the €1.48bn European Spallation Source (ESS) will be the most powerful source of neutrons in the world. With construction expected to start in 2013, and the facility fully open by 2025, the ESS will produce neutrons by accelerating protons in a linac to 2.5 GeV before smashing them into a seven-tonne target. The neutrons will then be cooled by a moderator and sent to 22 experimental stations to be used by researchers to probe the structure and physical properties of a wide range of solids, liquids and gases. The ESS will specialize in long wavelength, or "cold", neutrons that suit experiments on large-scale structures such as polymers and biological molecules.

But one big problem for those designing the ESS is that this process of "spallation" will deliver so much energy – the proton beam will have a power of 5 MW – that the temperature of the target will jump by more than 100 °C in just 2.8 ms. Indeed, as the target becomes radioactive it will produce a decay heat of 35 kW even when there is no proton beam. Researchers at the ESS are therefore designing a proton target that can not only generate copious amounts of neutrons,



but also be able to handle these extreme heat conditions.

A neutron-rich material makes for a good proton target and ESS bosses are currently investigating two different options – a lead bismuth eutectics (LBE) alloy or tungsten. LBE is solid at room temperature but at the ESS's operating conditions becomes liquid, which is similar to another possible target material – mercury. On the other hand, tungsten is solid up to 3000 °C and has a very high density of 19.25 $\mathrm{g\,cm^{-3}}$, giving it a high neutron yield. The material also has the advantage of longevity, with a life-span of three years or more, compared with six months for a lead–bismuth target.

As *Physics World* went to press, the ESS board was expected to decide which target to use, with tungsten the clear favourite having got the thumbs up from the ESS's science advisory board in July. Indeed, tungsten is also already used at other neutron-scattering facilities including ISIS in Oxfordshire, which has a solid tungsten target about the size of a house brick. "The material is really the best you can pay for," says Ferenc Mezei, head of the ESS's target division. "There are other materials, iridium for example, that have a higher density but they are much more expensive."

More power

There are some challenges to implanting a target given the heat created by the ESS's huge proton-beam power of 5 MW, which will be around 20 times greater than that at ISIS. One proposed solution is to make the target rotate once every three seconds so that only a certain part is hit by the proton beam at any one time.

One design for the ESS's target is to use a disc – 2.5 m in diameter and 13 cm high – made up of a solid inner hole and an outer ring. The beam will hit the disc edge-on, first encountering the outer layer, which is made up of around 10 000 small rods of tungsten each about 12 cm high and 1.5 cm in diameter. The beam then travels through the inner solid tungsten where it will lose energy so fast that it does not actually reach the centre of the disc. The advantage of using rods in the outer ring, rather than solid tungsten, is that in taking most of the proton beam, they distribute and reduce the stress of the whole target during its rapid rise and decrease in temperature.

The disc is made to rotate so that the 5 MW beam will be distributed such that a section of the disc sees – on average – about the same power density as that at ISIS. This allows that part of the target to cool down by 100 °C in around 3 s before it comes in contact with the beam again.

The sheer size of the target, and its activation, means that researchers cannot build a full prototype to test such high beam powers. However, in designing the ESS's target, researchers can take solace from the fact that the technology has been tested before, for example at ISIS's muon facility, which uses a small rotating graphite target to produce muons – heavier cousins of electrons.

"Rotating targets are around," says Mezei. "So we are confident that this kind of technology will work".

***Michael Banks is news editor of* Physics World.**

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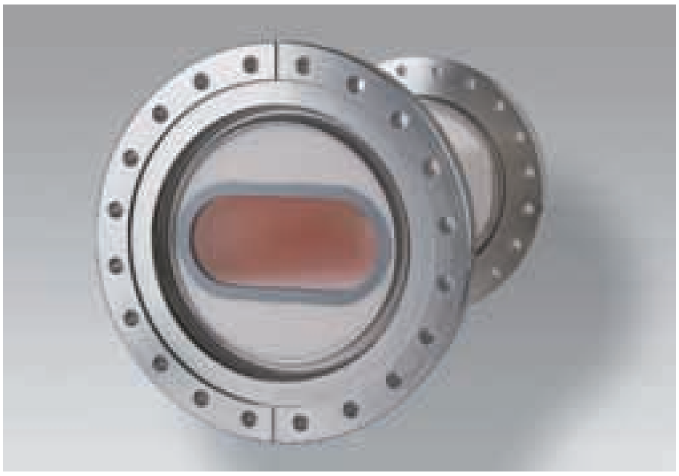
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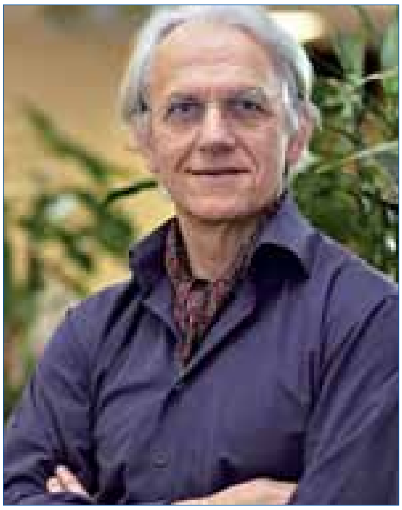
The road to reality

Taking a big facility from drawing board to reality is not easy, as Gérard Mourou, head of the Extreme Light Infrastructure project, tells Michael Banks.

What is the Extreme Light Infrastructure (ELI) project?
ELI is a project designed to create and utilize short pulses of light just 10 femtoseconds (10^{-15} s) long with energies of several kilojoules. This corresponds to a laser power of close to exawatts (10^{18} W) that will be so powerful that it can rip apart empty space itself.

How did you dream up the idea?
It started 10 years ago when I was working in the US at the University of Michigan. Together with my colleague Toshiki Tajima, then at the University of Texas at Austin and the Lawrence Livermore National Laboratory, we came up with the idea that, in principle, it would be possible to make an exawatt or even a zettawatt (10^{21} W) laser.



Gérard Mourou is the driving force behind the €1bn Extreme Light Infrastructure project.

What were your first steps to getting ELI on the European agenda?
In 2005 there was a call from the European Commission (EC) in Brussels for project ideas for the next European Strategy Forum on Research Infrastructures (ESFRI) roadmap. I wrote a short proposal for the facility – only a few pages long – based on my and Tajima's ideas. We then held a workshop in Paris, attended by top scientists, to write a scientific case. Immediately the committee – that included around 40 scientists from various disciples – liked this, so we were then included on the 2006 ESFRI roadmap.

Why was the committee so positive?
Before ELI, lasers could look at physics in the electronvolt (eV) regime, but with ELI we can go from eV to GeV energies, so we can open up new areas of study such as ultrarelativistic plasmas. ELI was also the new kid on the block, as many of the existing projects had been around for years, so that was also positive.

Did you also have the backing of fellow researchers?
Absolutely, that was one of the most important aspects. I knew a lot of people were going to be supporting the project in many countries. In laser physics we are lucky to have the LASERLAB-EUROPE – a network of European laser laboratories – so with their support the project got off the ground.

Was your work over after ELI made it onto the roadmap?
Not at all. In 2007 we started the ELI preparatory phase, which lasted three years. We had €6m to study the concept of ELI, which basically covers what you need to build the facility such as finance and scientific aspects.

What was hardest about this phase?
Most difficult was picking where it should be built, which was somewhat divisive.

How did the site choice develop?
The EC was pushing to have one large infrastructure based in Eastern Europe and it thought ELI would be ideal. Initially, we had five candidates – the Czech Republic, France, Hungary, Romania and the UK. Each country had to submit a report including information about the quality of schools, local infrastructure, hospitals, airports and so on. It was immediately clear, however, that while the UK and France had the skills and the infrastructure, they did not have the money.

In what way was the site choice divisive?
After the UK and France pulled out, we had a meeting to choose between the three remaining countries. There was a lot of political fighting, with countries taking different sides.

How was that resolved?
We decided it would be best to split the project in three, which originated from a new scientific case that was developed in 2008. At that time we thought we could cover four areas with ELI: ultrahigh-powered lasers, attosecond science, laser-based particle-beam production, and nuclear physics. By splitting up the facilty each country could get one each: Hungary got the attosecond centre, Romania nuclear physics and the Czech Republic electron-beam physics (see *Physics World* May 2010 pp12–13).

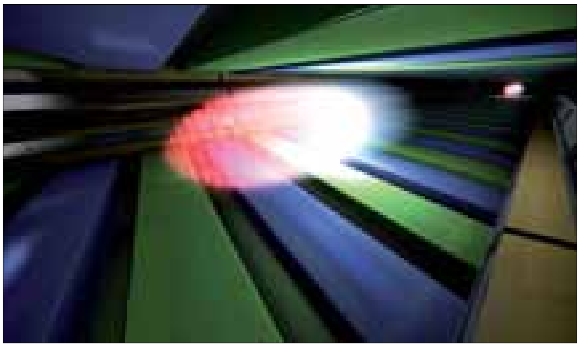
Was splitting up the facility a good idea?
I think so. No-one loses out now. Before, one country would have got everything. Now, instead of one €300m facility we have three centres – each costing €300m – so in effect we have a €1bn facility. The three countries are now working closely together.

And what are the next steps for ELI?
Now the preparatory phase is over it is up to the three countries to build the facilities and it is their responsibility to make it happen. There is also the location of the fourth centre to be decided, with a number of countries interested in hosting it, including Russia.

***Michael Banks is news editor of* Physics World.**

Freeze-framing the atomic world

Superconducting technology at the European X-ray Free Electron Laser promises the shortest, fastest and most intense pulses of X-rays ever generated, reports Matthew Chalmers.


European XFEL

The European X-ray Free Electron Laser will use superconducting accelerator technology to take X-ray snapshots lasting of the order of 10 fs.

Today's top-of-the-range digital cameras can freeze the macroscopic world for periods of less than a 10th of a millisecond. While that may seem fast, more sophisticated tools still are required to capture the action of the atomic and molecular world. The European X-ray Free Electron Laser (European XFEL) currently under construction in Hamburg, Germany, will take X-ray snapshots lasting about 10 fs – the timescale over which atoms rearrange during chemical reactions or the magnetization in a ferromagnet reverses – and do so at a rate of an astonishing 27 000 frames per second.

Conventional lasers can produce ultrashort pulses of coherent radiation at infrared, visible and ultraviolet wavelengths, but the European XFEL will do so for hard X-rays – offering atomic-scale resolution – and its pulses will pack an intensity one billion times higher than that of the best conventional X-ray radiation sources. Due to start operation in 2015, the €1.08bn project will allow users to map the atomic structure and dynamics of viruses, decipher the molecular composition of cells, film chemical reactions as they happen, and even study the extreme processes that occur deep inside planets.

Shining light

X-ray free-electron lasers (FELs) are the latest leap in light-source technology, often referred to as "fourth generation" sources. Synchrotron radiation consists of photons emitted by charged particles on a curved trajectory. In the 1950s researchers started to shine it onto samples to see deeper into their structure, and these "first generation" light sources produced such interesting results that they were superseded by dedicated "second generation" facilities in the 1970s. By the 1990s a number of "third generation" sources became operational that use very long periodic magnets called "undulators" to create much brighter beams.

FELs were first demonstrated in 1977 and there are around 20 currently in operation worldwide, mostly producing radiation at infrared wavelengths. X-ray FELs, which began to emerge in around 2000, produce shorter wavelength, more coherent pulses that are billions of times brighter than the best third-generation light sources. X-ray FELs are much more demanding technologically because X-rays are almost impossible to reflect so there is no mirrored cavity with which to amplify the light. In fact, the European XFEL is not technically a laser at all, as it also does not rely on the quantum process of stimulated emission that allows lasers to produce coherent light. Instead, lasing is achieved by accelerating a bunch of electrons to high energies in a 1.7 km linear accelerator and then channelling them through undulators.

As the electrons weave along the alternating magnetic field of the undulator at near the speed of light, they emit synchrotron radiation, which in turn interacts with the electrons so as to order them into discs spaced one wavelength apart. Discs emit photons of the same phase, so the result of this "self-amplified stimulated emission" (SASE) process is extremely coherent, short and intense X-ray flashes that can be tuned to different wavelengths by simply varying the energy of the electrons and the strength of the undulator magnets. The European XFEL beam will drive three undulators – two being 105 m long and another at 165 m – from which two beams (with possible room for a third) will be extracted, offering users six individual experiment stations where the light can be manipulated to suit specific research needs.

Moving electrons in a FLASH

In 2000 a test facility at the DESY lab in Hamburg demonstrated the laser-like output of X-rays at a wavelength of around 100 nm and by 2005 the facility had been hooked up to experimental halls to constitute the Free-electron LASer in Hamburg (FLASH), with a regular user programme. FLASH, which achieved a wavelength of 4.45 nm in 2010, was the stepping stone to the European facility for harder X-rays with wavelengths of 1 nm and less. Initiated in 2004 by the German government, the European XFEL follows other successful European "big science" models such as CERN in Geneva and the European Synchrotron Radiation Facility in Grenoble.

The European XFEL will have the edge over the world's two existing X-ray FEL facilities – the Linac Coherent Light Source (LCLS) in Stanford, US, and the SPring-8 Angstrom Compact free-electron Laser (SACLA) in Japan – in terms of beam brilliance and pulse rate. That is mostly thanks to innovative linear-accelerator technology developed at DESY and tested at FLASH in 2009. Rather than using conventional room-temperature microwave cavities to accelerate electrons, which suffer from power loss caused by to resistance effects, European XFEL will use superconducting niobium cavities that allow an oscillating microwave to transfer almost all of its electrical power to the particles. The cavities, which have to be cooled to a temperature of 1.9 K by liquid helium, can therefore be safely operated for longer periods, creating many electron bunches stacked close together.

The European XFEL will insert electron bunches with a frequency of 4.5 MHz into the cavities (i.e. one every 220 ns), where they will then be accelerated by radio-frequency (RF) electric fields. The superconducting cavities can be operated at high power for 600 ms, meaning that the European XFEL can fire 27 000 pulses per second – 100 times more than is possible at the LCLS, for example. Two companies – Research Instruments in Germany and Zanon in Italy – are producing the 800 superconducting cavities required by the linac. "There's constructive rivalry between us and the European XFEL because each of us wants to be the one making the breakthroughs," says John Galayda, director of construction at the LCLS.

Beating expectations

Thanks to experience gained by researchers at the LCLS, the European XFEL team has recently learned that its technology will perform even better than was envisaged. "The design of the European XFEL was conservative, and with the start of the LCLS there was a chance to test models of the SASE process that showed that pulses with wavelengths as short as 0.5 nm and durations less than 10 fs are possible," says DESY's Massimo Altarelli, managing director of the European XFEL.

Indeed, the biggest technological challenge of the project is to design and build detectors, optics and diagnostic systems that can handle significant bursts of power – some 10 kW cm^{-2} – at intervals of 220 ns. The X-ray mirrors, which are around 80 cm long, have subtle parabolic shapes and are inclined at low angles to the beam to aid reflection. They also have to be machined to a precision of a nanometre, and positioned within a micrometre in order to maintain beam coherence over the considerable distances – around 100 m – between the accelerator and the experiment halls. These components also need to maintain their stability while being subjected to the high heat loads. Silicon-substrate mirrors coated with materials such as amorphous carbon are a front-running technology as the low atomic number of the materials reduces X-ray absorption and thus the heat they produce. "A massive R&D project is under way to address these issues," adds Altarelli.

Despite the exciting potential of the new facility, in which Germany and Russia hold a 60% and 25% stake, respectively, Altarelli thinks some European countries are underestimating the European XFEL's importance and could contribute more. "It takes a lot of time, effort and wheeling and dealing to reach political consensus," he says. "But in the end it will be worth it to have in Europe the fastest, most powerful light source ever constructed."

Matthew Chalmers is a writer based in the UK.

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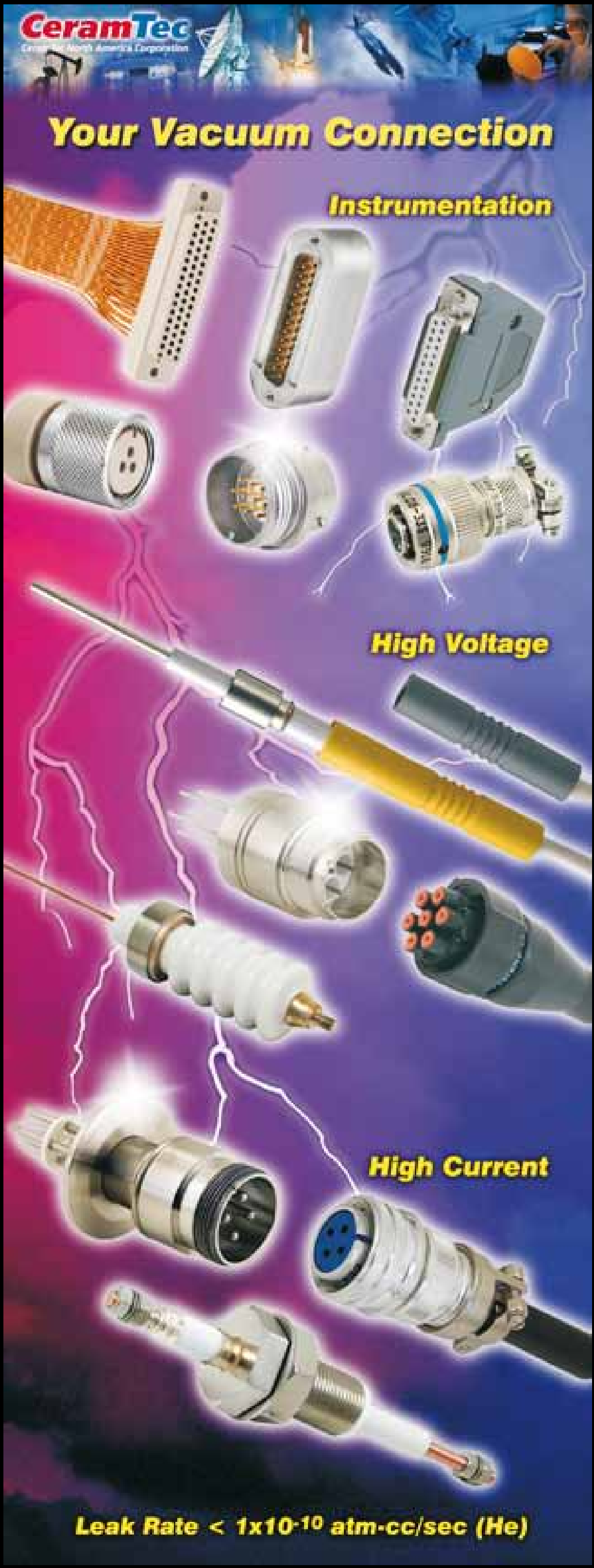

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Designing rapid-photography systems for particle detection

Physicists working on the SuperB experiment in Italy are developing an ultrafast camera to image the tracks of exotic particles. Edwin Cartlidge discusses the challenges that they face.

By the standards of traditional photography, the ability of modern digital cameras to take as many as 10 pictures a second in "burst mode" represents an impressive achievement. But for the €600m SuperB particle collider, which is set to open by 2016, this is extraordinarily slow. By colliding electrons with positrons to study the decay of particles containing bottom or charm quarks as well as tau leptons, the experiment should help explain why the universe seems to consist almost entirely of matter (as opposed to antimatter). The facility will also provide an indirect way of hunting for new fundamental particles, so to do all this it will need to take as many as two million images per second.

Physicists have already successfully built and operated two similar experiments, known as "B-factories", over the past decade: BaBar, fed by the PEP-II collider at the SLAC National Accelerator Laboratory in California; and Belle (which is still running) at the KEK-B collider in Tsukuba, Japan. But these facilities, while finding some evidence for matter–antimatter asymmetry, were not able to generate enough collisions to provide significant statistical evidence for the existence of new particles. SuperB, however, will have a luminosity – a measure of the rate of particle collisions – of around 10^{36} cm^{-2} s^{-1}, which is about 100 times higher than those of the US and Japanese experiments. It is this far higher luminosity that demands such rapid imaging.

Joining the dots

SuperB is the flagship project in a new infrastructure programme set up by Italy's science ministry and is being developed by a collaboration of scientists from Italy and countries across Europe as well as the US and Canada. To be located on the campus of the University of Tor Vergata just outside Rome, it will use two rings – each 1200 m in circumference and located a few metres below ground – to collide electrons with positrons inside a single detector about the size of a two-storey house. The detector will be used to calculate the energies and reconstruct the paths of the slew of particles produced in the collisions and will employ a variety of instruments including a high-speed camera, or "vertex tracker", which will consist of pieces of silicon placed around the collision point in concentric cylinders.

Many of the parts to be used in the SuperB ring will come from SLAC's decommissioned PEP-II accelerator and much of the detector will be made up of components from BaBar, but new technology is needed to make the big jump in luminosity. In particular, Pantaleo Raimondi and colleagues at the laboratory of the Italian National Institute of Nuclear Physics (INFN) at Frascati, a few kilometres from Tor Vergata, have developed a new kind of magnet that acts to increase the volume of intersection between the colliding beams to raise the luminosity without increasing the experiment's electrical power consumption. Simply using electron and positron beams that are 100 times as intense as those at PEP-II would have sent the electricity bill rising from €20m to €2bn a year.


SLAC National Accelerator Laboratory

Much of the detector used at the SuperB facility will be made up of components from BaBar – a particle detector at the SLAC National Accelerator Laboratory in California.

Another challenge for SuperB is to introduce a measurable difference in the length of the tracks of B-mesons and anti-B-mesons – this difference being the signature of matter–antimatter asymmetry – that in turn requires the two beams' energies to be offset from one another. But as Francesco Forti of the University of Pisa and the INFN (one of the two co-ordinators of the project's detector collaboration) explains, the new collision scheme reduces the amount by which the energy of the two beams can be offset from one another compared with the earlier B-factories. With this difference reduced, and with the greatly increased collision rate, the trackers must have a greater spatial and temporal resolution.

The kind of sensors used in BaBar's vertex trackers consist of a strip of silicon several centimetres long and a few tens of micrometres wide that becomes ionized when struck by charged particles from the collisions. This ionization releases a charge that travels along the silicon to a separate amplifier, which boosts the signal and converts it into a digital form (a "1", indicating a hit). By collecting the signals from all of the sensors that a particle hits, together with information about each sensor's spatial coordinates and the time it was struck, it is possible to "join the dots" and plot the trajectories of the charged particles produced in a collision.

By arranging these strips in a grid, so that they cross one another at right angles, the instantaneous position of particles can therefore be pinned down to square regions having sides a few tens of micrometres long. But using these strips to achieve SuperB's desired temporal resolution will, however, be much more difficult, given the far higher rate of collisions taking place. In the time that it takes the liberated charge to travel the length of a strip and register a signal, multiple particles could have struck the strip, making it hard to correlate collision products with strips and leading to blurred images.

"Using the BaBar detector for SuperB would be like a photographer choosing a very slow shutter speed to take a picture of a flowing stream," says Adrian Bevan, a particle physicist at Queen Mary University in London. "Whereas to the naked eye the stream would be crystal clear, in the photograph it becomes white because the individual snapshots are overlaid. That would also be the case for SuperB – all of the clarity would be lost."

The promise of CMOS

Faster imaging could instead be provided by so-called hybrid pixel sensors. These sensors are patterned into pixels of around 50 × 50 μm and consist of two layers – one layer sensing the particles and the other amplifying the signal – separated by tiny electrical connections. Unfortunately, the sensors are several hundred microns thick, which means that they can significantly alter the course of these particles via Coulomb scattering. In addition, the presence of an amplifier inside each sensor means that these devices generate more heat than the strips. Cooling them requires further equipment inside the detector, which in turn produces even more particle scattering.

A potentially more attractive alternative is to use sensors made from complementary metal-oxide semiconductors (CMOS). Like the hybrid sensors, these would consist of 50 × 50 μm pixels, but each pixel would be a single structure incorporating both the sensing and the amplifying functions. This would render them far quicker than strip detectors – registering the presence or absence of charge every 500 ns and so taking as many as two million pictures per second. And being just 10–15 μm thick, they would also be much slimmer than hybrid sensors and so would scatter particles far less and therefore should produce sharper images. In addition, because CMOS is a commercial technology – used in computer processors and increasingly as sensors inside digital cameras – vertex sensors made from it could be manufactured cheaply in standard foundries: 1 m^2 of such sensors could cost just €230 000, compared with the €1.7m for the same area of the more specialized strip detectors.

Unlike rival technologies, however, CMOS sensors have yet to be tested fully inside a particle-physics experiment, and it is not yet known precisely how well they will withstand the harsh radiation environment of the SuperB detector. Bevan says that there is probably not enough time to develop and install CMOS devices in the five outer layers of the vertex tracker (layers that were also present in BaBar) but is hopeful that they can be used to make an additional layer that is closer to the collision point and that is crucial for higher-resolution imaging. The sensors in this layer, he explains, could easily be replaced and so might initially be made from strip or hybrid sensors but then substituted by CMOS sensors after a year or two, by which time the collider should have ramped up to peak performance.


STFC Rutherford Appleton Laboratory

CMOS sensors offer quicker and more portable detection than conventional methods.

Bevan points out that, like hybrid pixels, CMOS sensors will also require significant cooling, using water or other fluids to remove dissipated heat in order to keep the sensors at about room temperature. But he says that if he and his colleagues can work out how to keep these devices cool inside SuperB, then, he explains, "we will be in an excellent position to apply that knowledge in less-extreme situations". Sensors capable of taking millions of pictures per second are not necessarily needed in applications outside particle physics, he adds, but by designing and building a system for SuperB we will learn how to make faster imaging devices more generally.

Bevan is part of a UK collaboration developing the CMOS sensors that includes physicists from the Rutherford Appleton Laboratory, Queen Mary University of London, Bristol University, Birmingham University and the Daresbury Laboratory, and which is working together with researchers from Pisa University. The collaboration is also investigating how the sensors cope under a range of different temperatures and magnetic fields to establish the suitability of these devices for applications beyond particle physics. One such area is astronomy, for the imaging of transient phenomena such as pulsars, gamma-ray bursts or active galactic nuclei. Another is medical imaging, with the increased speed of the CMOS sensors compared with more traditional CCD devices potentially allowing diagnoses using lower radiation doses of, for example, X-rays.

Edwin Cartlidge is a science journalist based in Rome, Italy.

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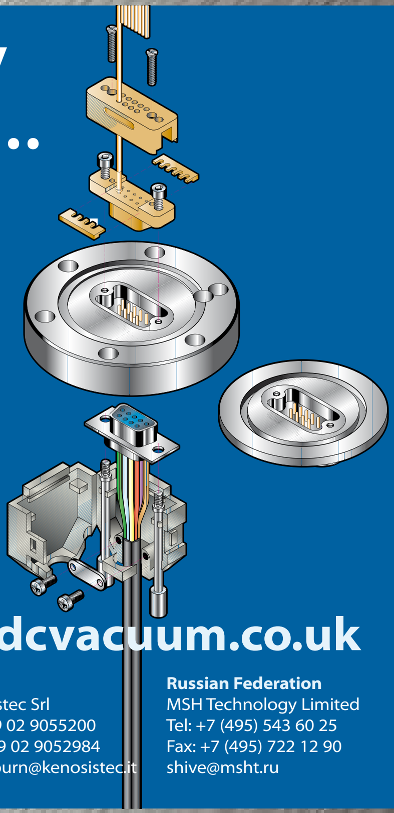

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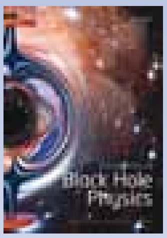

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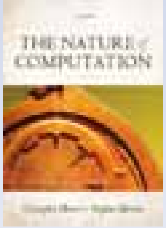

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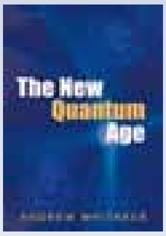

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Making LIGHT work of ion beams

Physicist Markus Roth from the Technische Universität Darmstadt is leading a collaboration dubbed LIGHT to tackle the challenges of transforming laser-based particle acceleration into a viable technology with applications in cancer therapy. Joe McEntee finds out how.

Can you tell me more about your collaboration?

Laser Ion Generation, Handling and Transport (LIGHT) is a multidisciplinary research collaboration based in Germany aiming to test potential applications of laser-based particle acceleration. We have six partners – the GSI heavy-ion lab in Darmstadt, the technical universities at Darmstadt and Dresden, Helmholtz centres in Dresden-Rossendorf and Jena, and the Goethe University in Frankfurt. They each bring expertise spanning big lasers, plasma physics, conventional accelerator technology and high-field magnets.

Markus Roth is head of the Laser Ion Generation, Handling and Transport collaboration that is exploring the potential of laser-based particle acceleration.

How do you accelerate particles using laser light?

The LIGHT team uses GSI's petawatt (1×10^{15} W) PHELIX laser to focus ultrahigh-power laser light onto a thin foil target. This causes massive ionization in the target and expels a large number of relativistic electrons, which leaves the target with a strong positive charge. This creates a transient electric field in which any protons present are then accelerated to high energies.

What has been the LIGHT collaboration's most recent breakthrough?

This summer we managed to use the PHELIX laser to generate 10 MeV protons from a foil target. What is significant is not the energy of the protons – we achieved 50 MeV and much higher particle numbers a year ago – but the fact that the target chamber has, for the first time, been connected to a conventional ion accelerator. We have now used a focusing ion–optical system to take those laser-accelerated ions and inject them into an existing ion-accelerator beamline here at GSI. This is a big deal because whatever you want to do with laser-accelerated ion beams, sooner or later you will have to manipulate them using more or less conventional ion–optical systems.

One year into an initial three-year programme with LIGHT, what are the current research priorities?

Clearly we want to be able to capture and control the laser-driven ion beam. Injection and transport over a few metres is important, as is a fundamental understanding of the effects of space charge, beam loading (the feedback of electromagnetic fields on the accelerator at high particle densities) and the interaction of laser-driven ion beams with magnetic fields. Over the next 12 months, we want to inject a laser-driven ion beam into a conventional accelerator beamline and use a radio-frequency cavity to create a monoenergetic beam of high brightness. Control of particle energy is crucial in a lot of the applications we foresee for laser-driven ion beams. In the case of medical applications – proton therapy of deep-lying cancerous tumours, for example – you need an ion beam with very precisely controlled energy spread (less than 1%) to be able to adjust the depth of the radiation dose that gets deposited inside the patient.

When might such laser-driven ion beams be ready for early-stage clinical studies?

As a scientist familiar with medical applications – specifically the development of carbon-ion therapy here at GSI over the past two decades – I believe that we are looking at somewhere between 10 to 20 years. For therapeutic applications, we will need to demonstrate energies of greater than 250 MeV for protons and 400 MeV per nucleon for heavier ions such as carbon. But there are plenty of other challenges too. High-repetition-rate systems, 24/7 stability as in conventional medical accelerators and improved targetry are all going to be essential. It is worth noting that we have established my univeristy's target laboratory and that we intend to spin that activity out as a start-up within the next 18 months. We also collaborate with Scitech, a spin-out from the Rutherford Appleton Laboratory in the UK, on target materials and design.

Are you doing basic science as well?

By the end of next year, we plan to have tested the entire laser-fed beamline and to perform the first experiments with a recompressed ion beam that will yield ultrahigh beam powers (hundreds of gigawatts) for materials research at the extremes. We are talking laboratory astrophysics and laboratory geophysics here. By heating tiny volumes of a sample to high temperatures in just a few picoseconds, it is possible

GSI

Researchers inserting a target assembly into the PHELIX laser beamline at the GSI lab in Darmstadt. Earlier this year, the LIGHT team connected the laser-ion-acceleration target chamber to an existing ion-accelerator beamline at the lab.

to create an exciting new state called warm, dense matter. A case in point: we recently published results in *Physical Review Letters* demonstrating the transformation of carbon into the liquid state using a laser-driven ion beam. The high peak current and ultrashort pulse duration (1 ps) of the ion beam enable us to heat carbon to about 5000 K and observe the transformation of the lattice into a kind of liquid. Essentially, what we are trying to do is create extreme conditions in the laboratory that replicate what is going on in the core of giant planets such as Uranus. In terms of fundamental science, that is interesting because we have no idea right now how equations of state evolve under such conditions.

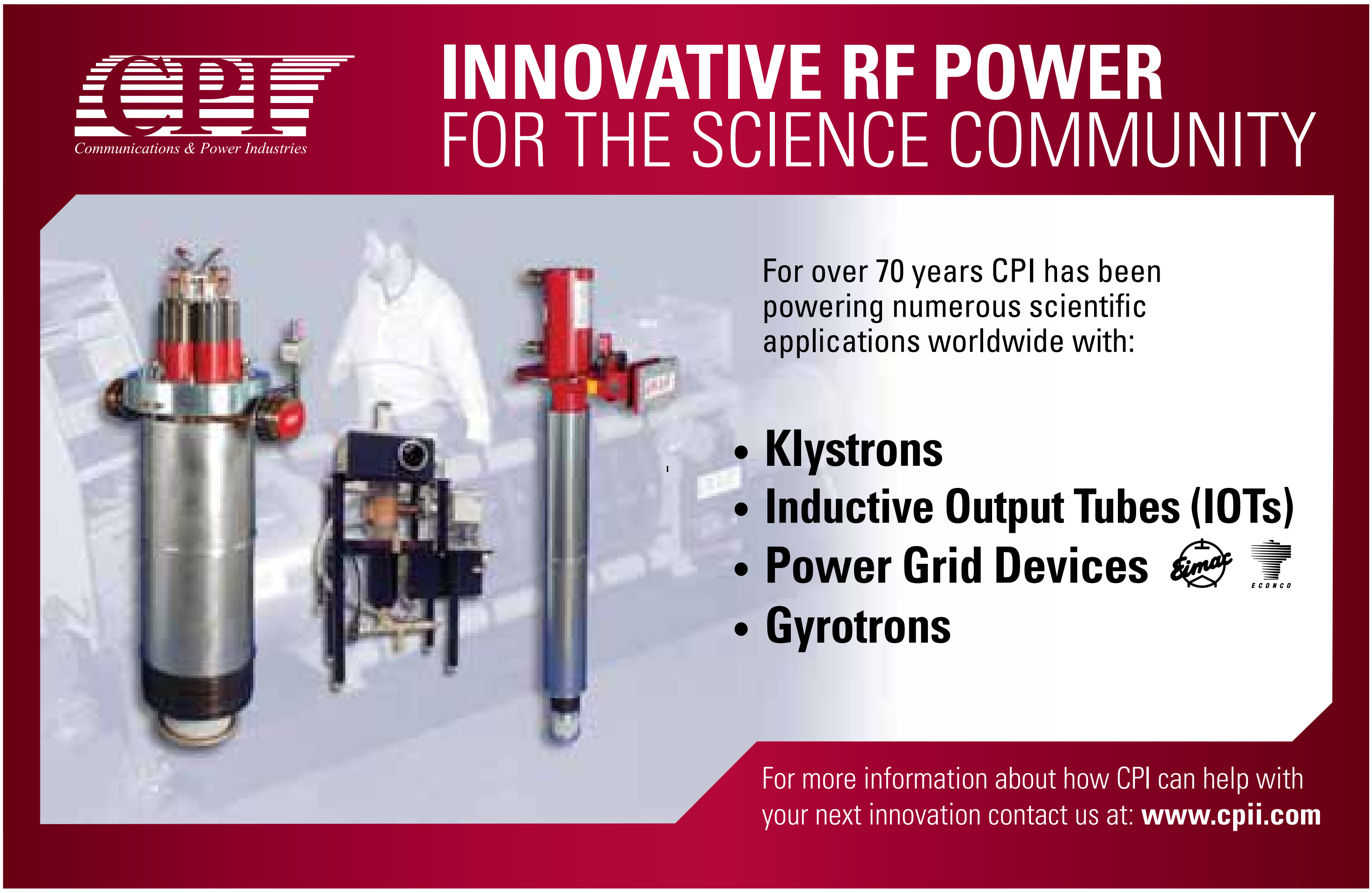
What about other, more down-to-earth, possibilities?

There are a number of exciting opportunities taking shape. One possibility being considered is the use of an intense laser-accelerated proton beam as the basis of a fast ignition scheme in inertial-confinement fusion – in other words, to trigger the thermonuclear burn wave that ignites the fuel. There is also interest from the nuclear industry, where laser-driven ion beams and diagnostic techniques such as X-ray diffraction could be combined to evaluate the lattice damage and annealing of materials used in nuclear reactors. Another avenue under investigation is the use of laser-driven ion beams to produce radioisotopes for medical imaging – potentially a more compact and economical option than existing cyclotron or synchrotron technologies.

So the future's bright for LIGHT?

Yes, things appear well set. GSI has been an accelerator facility for more than 35 years and now it is really stepping into this regime to figure out what special parameters you can achieve with laser-accelerated ion beams, and also what is required in terms of the enabling technologies for practical applications.

Joe McEntee is group editor at IOP Publishing.



Seeing through the atmosphere with the world’s biggest eye

The European Extremely Large Telescope will correct distorted light from the Earth’s atmosphere across its whole field of view. Michael Banks reports.

A telescope that can take only blurred images is of little use to astronomers. But ground-based instruments have to deal constantly with this problem as the light from distant objects in the universe becomes distorted as it passes through the Earth’s atmosphere. An answer to this is “adaptive optics” that can correct for atmospheric distortions of light from distant objects. But astronomers designing the €1bn European Extremely Large Telescope (E-ELT) – an optical and infrared telescope to be built in Cerro Armazones in Chile by the European Southern Observatory (ESO) – are taking adaptive optics to a new level. The telescope will not only have the most advanced adaptive-optics system ever, but also be the first to implement fully a new technique: one that can correct for distortions over the complete field of view.

Researchers test the adaptive-optics mirror for the Large Binocular Telescope based in Arizona.

Eye in the sky

The E-ELT will be used to study exoplanets, supermassive black holes and the nature of the first objects to form in the universe. It will consist of five mirrors, with the primary mirror being a massive 39.3 m in diameter and built from 798 hexagonal segments each 1.45 m wide. The telescope will gather 100 000 000 times more light than the human eye and more light than all of the existing 8–10 m-class telescopes in the world, including ESO’s own Very Large Telescope, which is also in Chile.

Adaptive-optics techniques were first invented in the 1950s but only implemented in the 1990s thanks to advances in computational power. When the light from a single source passes through the Earth’s atmosphere, it become distorted by local inhomogeneities in the refractive index of the atmosphere. Such inhomogeneities are produced by variations in density and temperature generated by atmospheric turbulence. These phase distortions then translate into a blurred image, known as the “seeing disc”, in the focal plane of the telescope. At good observing sites, the seeing discs are typically in the range 0.5–1.0 arcsecond – or 1/3600 of a degree.

One method to counteract the effect, which will be employed on the E-ELT, is to create an “artificial star” by firing a laser 90 km into the upper atmosphere. The laser light, with a wavelength of 589 nm, is tuned to excite the “D2 line” of atmospheric sodium to release light. By measuring the differences in the arriving wavefronts produced by this “artificial star” compared with what would be expected without atmospheric interference, the adaptive-optics system can apply the exact opposite phase pattern to a deformable mirror in the optical path, and thus generate a perfectly flat wavefront. “Without adaptive optics there is no point building the E-ELT,” says Colin Cunningham of the UK Astronomy Technology Centre and director of the UK’s E-ELT programme.

The more the better

Adaptive-optics mirrors are usually made up of a slender membrane of glass just a few millimetres thick with actuators on the back that deform the mirror slightly to correct for the deformed wavefront. Almost all current telescopes have an adaptive-optics deformable mirror feeding individual science instruments. By contrast, the adaptive-optics mirror on the E-ELT will be central to the telescope. Some 2.5 m in diameter and containing a record 6400 actuators that can deform the mirror by up to 160 μm, the mirror will attempt to correct for atmospheric interference 1000 times per second. “It is difficult to increase the number of actuators, as the more you have, the more challenging it becomes to have fast enough real-time control systems,” says physicist Richard Myers of Durham University, an expert on adaptive optics who is involved in the E-ELT’s EAGLE instrument.

One technical challenge that the E-ELT designers will hope to overcome is to produce a way of correcting for the whole field of view – equal to 5–10 arcminutes. Current telescopes, by contrast, shine a single laser beam that only corrects the turbulence near the line of sight of the guide star. The E-ELT will do this via the EAGLE instrument, which will fire eight laser beams simultaneously to produce a “tomographic” image of the atmospheric turbulence that could correct the images of up to 20 galaxies simultaneously.

However, one issue is how well this untested method of imaging can be done with numerous lasers. Researchers on the 4.2 m William Hershel Telescope (WHT), which is based in La Palma, Spain, will be testing the principle of this technique later this year by using nearby bright stars and lasers. “Scaling this up to the E-ELT will not be an easy thing to do,” says Myers. “But experiments on the WHT will address several aspects of this.”

Michael Banks is news editor of **Physics World.**

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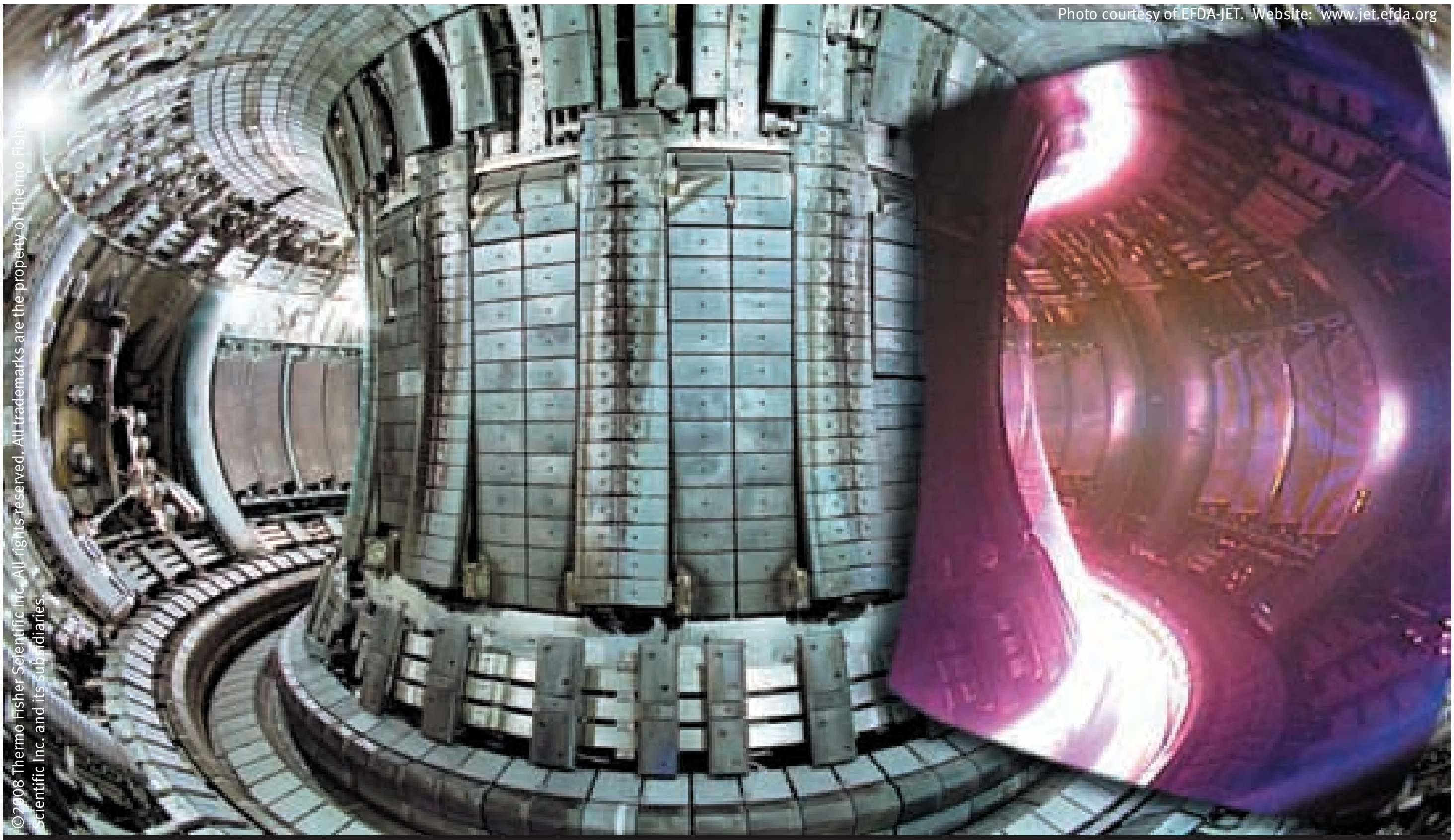

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