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Focus on: Big science

Welcome to this focus issue of *Physics World*, which looks at some of the technical challenges facing those building or upgrading the world's top "big science" facilities. There is none bigger than CERN's Large Hadron Collider (LHC), where the hunt for more new particles beyond the Higgs boson will restart in earnest in 2015 following an 18-month repair and upgrade programme at the facility (p15). But particle physicists are already thinking about what could come after the LHC and have drawn up bold plans for an 80–100 km proton–proton collider (p19). There are even plans for a collider based on lasers, with an international team looking at creating an array of "fibre lasers" to be used as a future "Higgs factory" (p7). Yet big science is not just limited to the ground; as Jean-Jacques Dordain, director-general of the European Space Agency, explains, the agency is planning a suite of missions in the coming decade that will keep scientists busy for the years to come (p23). I hope you find this focus issue stimulating; please do let us have your comments by e-mailing pwld@iop.org.

Michael Banks, Contributing Editor

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Can the ICAN do it?

With particle colliders getting bigger and ever more expensive, could particle acceleration that uses fibre lasers offer a cheaper solution? **Daniel Clery** reports

Researchers at the Large Hadron Collider (LHC) may have finally found the Higgs boson but this has not stopped scientists designing new accelerators to hunt for physics beyond the Standard Model. Next up is likely to be the 31 km International Linear Collider (ILC) at a cost that may reach around $25bn, although physicists are even drawing up plans for other LHC successor machines built in tunnels up to 100 km long (see p19). However, the cost of building and powering these machines is likely to be high – and might even be unaffordable.

That is why one group of European laser laboratories is aiming to boost particles with light by building a laser like no other. This laser would produce pulses with power measured in petawatts (10^{15} W) thousands of times a second and with up to 30% efficiency. Their secret is to build this device from tens of thousands of fibre lasers – a common component in the telecommunications industry – and coherently combine the beams into one "superbeam". Although originally designed for high-energy physics, such a laser could be used as a high-powered X-ray source to make medical isotopes for cancer treatment or even for nuclear-waste disposal. "It heralds a revolution in laser-plasma-based acceleration," says Alexander Pukhov of Moscow State University.

Physicists have known for decades that it is possible to accelerate particles with high-powered laser pulses but it is only in recent years that they have started to take the idea seriously. In 2009 the International Committee for Future Accelerators (ICFA) and the International Committee on Ultra-High Intensity Lasers (ICUIL) set up a joint task force to investigate the technique. Its report, published in 2011, outlined a design for a linear electron–positron collider driven by lasers and capable of producing collisions with energies up to 10 TeV. Such a machine – with 10 times the energy of the ILC – would be only a couple of kilometres long at a fraction of the cost and power consumption of the LHC.


University of Southampton

Aiming high A 6-m fibre drawing tower at the University of Southampton's Optoelectronics Research Centre is used to create the components that are required in a fibre laser.

However, there was only one problem: the lasers necessary to drive such an accelerator do not currently exist, and it was this need that sparked the creation of the International Coherent Amplification Network (ICAN).

Taking notice of laser acceleration

The ability to accelerate particles with light relies mainly on two techniques. The first, called wakefield acceleration, was developed in the late 1970s by John Dawson and Toshiki Tajima at the University of California, Los Angeles. They found that if a short, high-powered laser pulse is fired into a plasma, then the transverse electric field of the photons pushes the lightweight electrons of the plasma out of the way, leaving a bubble of positively charged ions in the pulse's wake. Behind this positive bubble the electrons rush back in, creating a negative charge, and behind that a more positive charge as the electrons repel themselves again. The result is a plasma wave trailing in the pulse's wake that has, in effect, converted the transverse electric field of the laser pulse into a longitudinal electric field. This field can accelerate electrons quickly – either those from the plasma or the bunches fired into it. The field can have a strength up to 100 billion volts per metre (GV/m), three orders of magnitude more than the fields produced by the microwave cavities of a conventional accelerator (10–50 MV/m).

> There is one type of laser that can easily and cheaply produce high-repetition pulses with high efficiency: the fibre laser

The problem back then was creating the required ultra-short, ultra-high-power laser pulses because the high powers damaged the laser amplifiers. Gérard Mourou and his colleague Donna Strickland, then at the University of Rochester in New York, devised the second key technique – chirped-pulse amplification (CPA) – in the mid-1980s. This takes an ultra-short but moderately powered pulse, lengthens it in time using pairs of diffraction gratings and then boosts its energy with laser amplifiers. The boosted pulse is then shortened again using another pair of gratings to produce a pulse that now has a power in the petawatt range.

Researchers continued to refine these techniques until, in 2006, a team at the Lawrence Berkeley National Laboratory in California, using CPA-boosted laser pulses, managed to produce a high-quality beam of electrons with an energy of 1 GeV from a tube of plasma just 3.3 cm long. This made accelerator physicists sit up and take notice – and prompted the creation of the ICFA–ICUIL task force. But while its report could foresee a laser-driven accelerator, current lasers fall down when it comes to repetition rate.

Power demands

There are many lasers around the world that can produce petawatt pulses but they typically produce about one pulse per second. To generate enough beam luminosity for particle physics, the lasers will need to produce thousands – or even millions – of

Lasers

pulses per second and at high efficiency if they are to avoid huge power demands. "This is what you have to shoot for overall: high peak power plus average power and efficiency," says Roy Aleksan of France's Alternative Energies and Atomic Energy Commission (CEA).

There is one type of laser that can easily and cheaply produce high-repetition pulses with high efficiency: the fibre laser. This is essentially an optical fibre with its core doped with an element such as ytterbium to turn it into a lasing medium. When the fibre is pumped with light from another source, such as a laser diode, the light bounces around inside the fibre from the cladding to the core, efficiently stimulating more emission until a high-quality beam comes out of the end.

What fibre lasers do not have is high power, but Mourou, now at the Ecole Polytechnique near Paris, proposed combining the output of many fibre lasers to get the desired beam. This process uses short pulses from a seed laser that would first be stretched out with gratings, as with CPA. These would then be split into many separate beams and passed through fibre lasers to boost their energy. The boosted pulses are recombined into a single beam and then shortened again to achieve high power. Much of this can be done with off-the-shelf telecoms technology but the unproved part is recombining large numbers of beams. If any beams are out of phase with the rest, then they will destructively interfere and so reduce the beam power.

ICAN is the brainchild of Mourou, who formed it with colleagues from the University of Southampton, the Fraunhofer Institute in Jena and CERN. With €500 000 from the European Union (EU) and support from their own institutions, the ICAN researchers spent 18 months figuring out how to recombine the multitude of fibre-laser beams. They came up with a demonstrator system in which 64 fibres are attached to an 8 × 8 grid so that the beams emerge in parallel and are slightly overlapping. A camera looks at the emerging beams and analyses – from interference patterns in the overlapping regions – whether each beam is in phase with its four nearest neighbours. A feedback loop then tweaks the phase of each individual fibre laser to nudge errant phases back into line. "The big bottleneck was phasing. We've proved that we have the means to measure and correct phase," says Mourou.

ICAN team member David Payne of the University of Southampton says that the specification for a wakefield accelerator can be met by coherently combining many fibre lasers into an immensely powerful single beam of light. While this demonstrator proved the principle, a laser for high-energy particle acceleration would require much greater beam power and that, the ICAN team estimates, would require something like 30 000 fibre lasers.

To prove the whole system, ICAN is now seeking €3m from the EU's Horizon 2020 research programme for a design study followed by €50m for a full-scale demonstration laser. If that works, then it is up to the particle-physics community to take up the baton. A 10 TeV accelerator, as envisaged in the ICFA–ICUIL report, would need at least 200 such lasers: half to boost the electrons and half to boost the positrons. Each laser would fire its pulses into a 1 m plasma tube and each tube would give the particle beam a 10 GeV energy boost.

The scale of such a machine and the amount of untested technology involved means that construction will not be starting any time soon. But at a two-day symposium held to mark the end of the first phase of the ICAN project at CERN in June, it was clear that there are many other applications for which such a laser could be handy. Speaker after speaker stood up to explain how the sort of laser that ICAN is working on could benefit their field. Applications include probing the quantum vacuum for lightweight dark-matter and dark-energy candidates; producing radioisotopes for medical uses; accelerating protons for cancer therapy; or to make spallation neutrons for nuclear-waste transmutation in an accelerator-driven nuclear reactor.

Fermilab

Bold ambition Physicists at Fermilab are proposing to build a laser-based "Higgs factory" that could collide 63 GeV gamma-ray photons to create some 1000 Higgs particles per year.

A Higgs factory

One possible use that the ICAN team is keen to pursue in the short term, because a TeV accelerator is such a distant project, is a "Higgs factory". CERN's LHC only produces Higgs bosons in small numbers, and physicists will need to make many more to study it in detail. One of the Higgs' decay modes is to split into two gamma rays. So, by reversing that process, physicists believe that they can produce quantities of Higgs by colliding gamma rays together. Researchers at the Fermi National Accelerator Laboratory in Illinois had already come up with a plan for such a machine, called the Higgs Factory in the Tevatron Tunnel (HFiTT), but what they lacked was a high-powered, high-repetition-rate laser. "The required laser technology is becoming available through ICAN," says Mayda Velasco of Northwestern University.

HFiTT would require building a new conventional accelerator in the tunnel of the retired Tevatron collider to produce two counter-rotating beams of electrons with the relatively low energy of 80 GeV. The electron beams would be collided with photons from ICAN-style lasers to produce backscattered 63 GeV gamma-ray photons. These would then be collided to produce an estimated 10 000 Higgs bosons per year.

But before any of that can happen, the ICAN team must still show it can build a full-scale prototype laser – and that depends on winning funding from Horizon 2020. Competition for cash is, however, expected to be tough. Just 48 infrastructure projects will be supported in Horizon 2020 and priority will be given to mature projects, the European Commission's Maria Douka told the CERN meeting. But the team hopes that once it shows that ICAN can really be done, then people will flock to it. "They need to develop an accelerator," says Aleksan. "That will give them much stronger momentum. Then people can say, this is something we can use."