physicsworld
2026/27

Big Science Briefing

Sustainable outlook How big science is limiting its environmental impact

Clean potential Harnessing the prospect of commercial laser fusion

Hot stuff Plasma-wakefield particle acceleration takes off

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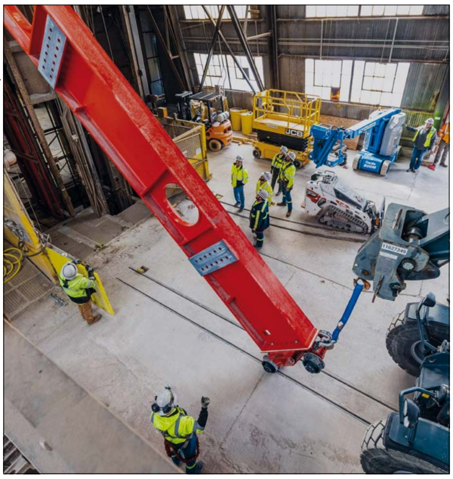

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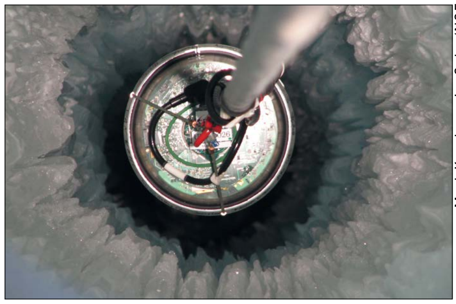
Big Science Briefing



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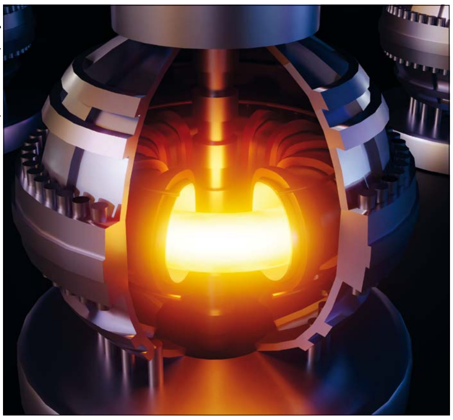

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Lawrence Livermore National Laboratory/Damien Jemison

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Physics World's Hamish Johnston talks to Ross Jenkinson of the UK's University of Manchester about the challenges and rewards of using quantum computers in particle physics – a field where classical super-computers can struggle to simulate simple systems.

Balancing big science's energy needs

Welcome to this *Physics World Big Science Briefing*, which includes news, features and opinion regarding the latest developments in large-scale facilities.

This summer in the Northern hemisphere has been a real scorcher. According to the Copernicus Climate Change Service, July was the joint second-warmest globally on record, with temperatures 1.47°C above the estimated pre-industrial average.

Western Europe has experienced its hottest ever June and July, with prolonged hot and dry conditions fuelling extreme wildfires across the region. With that weather set to become the norm rather than a one-off event, everyone will need to do their bit to curtail the impact of climate change and "big science" is no different. Indeed, sustainability will be a keyword at this year's Big Science Business Forum held in Maastricht from 27–30 October.

As we report in this briefing, one area making its technologies and facilities more sustainable is accelerator science (see p20). The aim is not only to cut the energy and resources that accelerators use, but also to understand – and, more importantly, minimize – their "whole-lifetime" environmental impact.

Longer term, researchers are also prioritizing disruptive accelerator concepts that could slash the size, cost and carbon footprint of next-generation facilities. One example is plasma-wakefield acceleration, which uses laser- or particle-beam-driven intense "plasma waves" as the accelerating medium, yielding electric fields up to 1000 times greater than in classical accelerators (see p18). Those ultra-high accelerating gradients promise a significant reduction in the size, cost and carbon footprint of next-generation accelerator facilities.

With the world's energy demands increasing, and our impact on the climate becoming ever clearer, the search is on for greener, cleaner energy production. That's why fusion energy has undergone something of a renaissance in recent years.

According to a report by the Fusion Industry Association on the state of the fusion industry, 71% of the 56 private fusion companies surveyed for the report expect the first fusion plant to deliver commercial electricity by the 2030s (see p5).

One of the companies with such ambitious aims is Focused Energy, a laser-fusion firm based in Germany and California, which is attempting to generate energy from the laser-driven fusion of hydrogen isotopes. In this issue, Debbie Callahan, chief strategy officer at Focused Energy, describes how they plan to have a pilot plant, dubbed LightHouse, operational by the end of the 2030s (see p13).

While many milestones need to be hit before we see fusion generating electricity for the grid, when it comes to meeting the demands of a changing climate, big science is continuing to play a key role.

Michael Banks, news editor, *Physics World*

Economic ‘Q’ metric proposed

New framework includes 10 parameters that can be used to evaluate the viability of a fusion power plant, as **Michael Banks** finds out

Researchers in the US have proposed a new metric to determine the economic viability of future fusion power plants. The measure is similar to one used by fusion researchers to ascertain the output of fusion reactions, which is known as the Q factor.

Nuclear fusion, which powers the stars, involves two light nuclei binding to form a heavier nucleus, releasing huge amounts of energy in the process. Harnessing fusion on Earth using the hydrogen isotopes deuterium and tritium could lead to an environmentally friendly and almost limitless energy source.

In the 1950s, the engineer and physicist John Lawson laid out what became known as the “Lawson criterion” for fusion. It describes the combinations of temperature, plasma density and energy confinement time that can produce net energy from the plasma due to fusion, regardless of its absolute power or volume.

Specifically it calculates a factor known as “plasma Q”, which is the ratio of fusion power produced to the external power required to sustain the plasma, with a Q = 1 meaning break-even.

When it comes to magnetic confinement, in which magnetic fields are used to contain a high-temperature plasma, the Joint European Torus based in Oxfordshire, UK, which ended experiments in 2024, achieved a Q of 0.67 in 1997.

The ITER experimental fusion reactor, which is currently being built in Cadarache, France, aims to have a Q of 10 when fully operational towards the end of the 2030s.

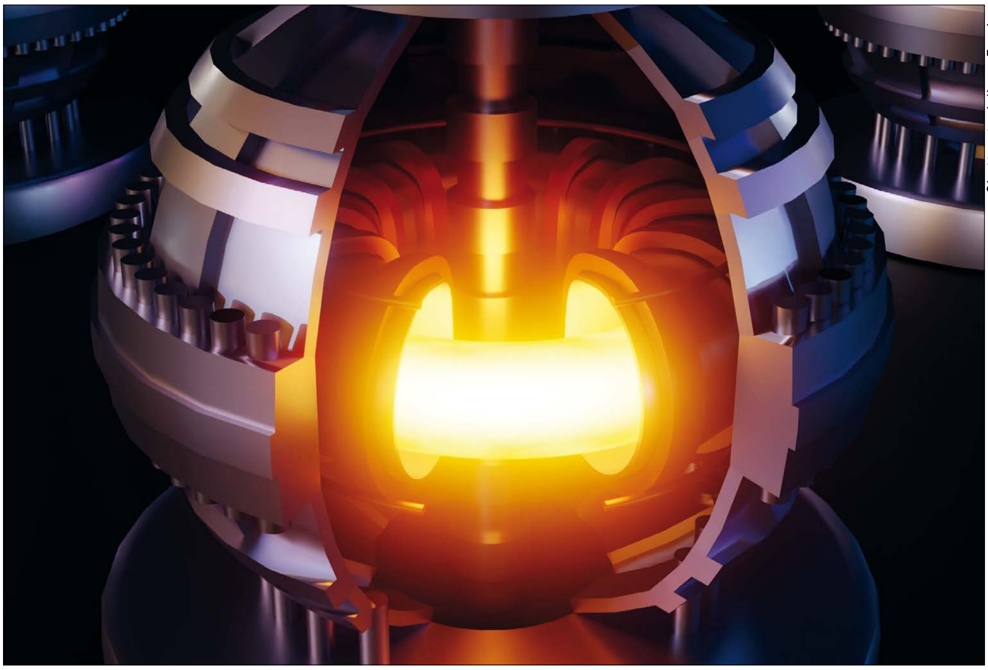
Developments in industry have also sped up in recent years and just last month the Fusion Industry Association released a report finding that private fusion companies raised almost $4.5bn in funding over the past year – a 70% increase over the previous year.

The report discovered that 71% of the 65 companies surveyed expect the first fusion plant to deliver commercial electricity by the 2030s. Others, however, remain unconvinced that fusion will soon be a viable energy source.

With that in mind, researchers are proposing a framework for understanding what is required to make fusion energy commercially viable in the marketplace.

While the costs of basic experiments can be easily documented, estimating the costs of a fusion reactor is somewhat more challenging.

“It’s challenging to reduce complex scientific and engineering requirements to economic consequences,” says economist Andrew Lo from the Massachusetts Institute of Technology (MIT), who co-authored the new study (*J. Fusion Energy* **45** 49). “But if we don’t do that, we’re not going to get the funding we need to achieve the impact we want.”



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Hot stuff
The “economic Q” is given as the ratio of capital gained to that expended by building and maintaining a nuclear fusion facility.

A new ‘Q’

The new framework includes 10 parameters that evaluate the economic viability of a fusion energy power plant. Some of these are scientific and physical, dealing with the energy consumed and produced in a given plant.

Other parameters are based on engineering and economics, such as the costs of plant construction, returns from invested capital, the efficiency of converting fusion power into an economic product as well as the durability of components used in the energy conversion. The “economic Q” is then given as the ratio of capital gained to that expended.

MIT nuclear engineer Dennis Whyte, who also co-authored the study, says that the framework is about what it takes to achieve a net-positive economic return with the economic Q needing to be greater than 1 for basic viability.

Whyte, who is also chief executive of the United Kingdom Atomic Energy Authority, adds that the parameters do not depend on the size of the reactor being built, so any inputs can be scaled to a given project or power output.

“When you’ve got a framework to evaluate it in a quantitative way, it tells you about the literal worth of making a particular design decision,” adds Whyte. “That seems to me at this moment of fusion development absolutely critical, and what we’ve been missing.”

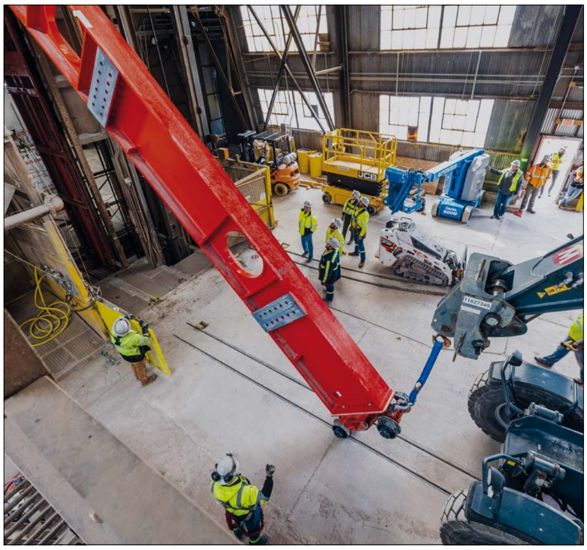
News

Steels lowered into the DUNE detector

A vast complex of steel beams for a next-generation neutrino detector has begun its descent underground in what officials have called a "pivotal phase" towards construction of the \$3.3bn Deep Underground Neutrino Experiment-Long-Baseline Neutrino Facility (DUNE-LBNF).

An event was held in May – attended by senior officials including CERN director-general Mark Thomson and Dario Gil, undersecretary for science at the US Department of Energy (DOE) – to commemorate the start of moving 4.5 million kilograms of steel beams underground that will be used to hold DUNE's detectors in place.

In February 2024, excavation work finished on two huge underground spaces for DUNE. Located 1.6 km underground at the Sanford Underground Research Facility in South Dakota and are some 150 m long and seven storeys tall, the spaces will be used to house DUNE's four neutrino detector tanks that are each filled with 17 000 tonnes of liquid argon and cooled to 88 K.



Matthew Kapust, SURF

Going underground Massive steel beams will be used to hold neutrino detectors in place.

When complete in 2031, DUNE-LBNF will study the properties of neutrinos in unprecedented detail, as well as the differences in behaviour between neutrinos and antineutrinos.

DUNE will measure the neutrinos that are generated by Fermilab's accelerator complex, which lies around 1300 km away just outside Chicago.

The cryostat materials, which have been contributed by the CERN, are now set to be moved underground and installed before further work commences.

"Today represents the start of a pivotal phase for DUNE, the development of the far detector structures in South Dakota," noted Fermilab director Norbert Holtkamp. "Our focus remains on safety, quality and schedule – in that order – to ensure we successfully deliver on behalf of the US Department of Energy, our nation and the world."

Michael Banks

Large Hadron Collider shuts down ahead of major upgrade

Officials at the CERN particle-physics lab near Geneva turned off the Large Hadron Collider (LHC) in June for the last time. Over the coming four years, the accelerator complex will be upgraded to prepare for the High-Luminosity LHC (HiLumi LHC) that is set to start operations in 2030.

Taking decades to plan and construct, the LHC began circulating its first proton beams in September 2008 garnering attention from the world's media. Yet days later the accelerator suffered an electrical fault that delayed first proton collisions for a year.

On 4 July 2012 the ATLAS and CMS collaborations announced the discovery of the Higgs boson, which led to the Nobel Prize in Physics for Peter Higgs and François Englert a year later.

In the past decade, the LHC has also discovered more than 85 hadrons, put limits on the discovery of new particles, examined the imbalance between matter and antimatter and explored the nature of the quark–gluon plasma.

The LHC will now make way for HiLumi LHC that will increase the collider's luminosity by a factor of up to ten. This will enable precision studies of the Higgs boson and enhance the potential to uncover phenomena beyond the Standard Model.

Smashing success Members of the CMS collaborations celebrate the end of run 3 at the Large Hadron Collider.

The shutdown will involve upgrading about 1.2 km of the 27 km ring by including 11–12 T superconducting magnets and superconducting "crab" cavities — that reduce the angle at which the bunches cross — to increase the number of collisions at the two detectors.

The ATLAS and CMS detectors will also be upgraded to cope with between 140 and 200 proton–proton collisions in every "bunch crossing", compared to around 60 during the last LHC run.

German accelerator physicist Oliver Brüning, who is director for accelerators and technology at CERN, says that the LHC has "exceeded every expectation".

"For nearly two decades, it has transformed our understanding of the universe and inspired generations of scientists, engineers and citizens around the world," adds Brüning. "We say goodbye to the LHC as we have known it, while preparing to welcome its successor: the HiLumi LHC, which will extend this scientific adventure far into the future."

Michael Banks

John Hill takes the helm at Brookhaven National Laboratory

John Hill has become director of the Brookhaven National Laboratory in Long Island, New York,. Hill will now oversee Brookhaven's 3000-strong team of scientists, engineers and technicians as well as manage the lab's annual $900m budget.

Brookhaven opened in 1947 as one of the first three US national labs, the others being Argonne and Oak Ridge. Brookhaven carries out a wide range of research in the physical, biomedical and environmental sciences and is home to seven Nobel-prize-winning discoveries.

Brookhaven operated the Relativistic Heavy Ion Collider (RHIC) until it shut down in February. RHIC collided heavy nuclei such as gold and copper to produce a quark-gluon plasma – a state of matter thought to have been present in the very early universe.

In 2020, Brookhaven was chosen to host the next-generation Electron-Ion Collider (EIC). Costing about $2bn, the EIC will smash together electrons and protons to probe the strong nuclear force and the role of gluons in nucleons and nuclei.

Kevin Coughlin/Brookhaven National Laboratory

Planning the future John Hill will oversee Brookhaven's $900m annual budget.

Building the EIC involves revamping the RHIC accelerator as well as adding an electron ring and other components with the first experiments starting the 2030s.

As well as RHIC and the EIC, Brookhaven is also home to other big-science projects including the National Synchrotron Light Source II, which opened in 2015 at a cost of $912m.

With a PhD in physics from the Massachusetts Institute of Technology, Hill joined Brookhaven as a postdoc in 1992 before leading the lab's X-ray scattering group from 2001 to 2013.

He then became deputy associate laboratory director for energy and photon sciences until becoming the lab's deputy director for science and technology from 2023 to 2025. In September 2025 he became interim director following the resignation of the theoretical physicist JoAnne Hewitt.

In the role, Hill will also become president of Brookhaven Science Associates – a partnership between Stony Brook University and the science and tech firm Battelle – that manage and operate Brookhaven on behalf of the US Department of Energy.

Hill notes that he is "very excited" to lead the lab in the coming years. "Brookhaven is entering a defining decade, and I'm honoured to take on this role at this time," he says. "The vision we have for our future is a powerful one, including delivering the nation's next particle collider and advancing science across a range of critical areas."

Michael Banks

Jessica Dempsey leads the Square Kilometre Array Observatory

Astronomer Jessica Dempsey has become director-general of the Square Kilometre Array Observatory (SKAO), which will be the world's largest and most sensitive radio telescope when it opens next year. Dempsey will now serve a five-year term as director-general and succeeds Philip Diamond, who held the role since 2012.

Three decades in the making, the SKAO is based in South Africa and Australia and consists of 197 dishes and 131 072 antennas to study how galaxies form, the nature of dark matter, and whether life exists on other planets.

The Australian side, known as SKA-Low, will focus on low-frequency observations, while South Africa's SKA-Mid will observe mid-range frequencies.

The headquarters of the organization is based in the UK at Jodrell Bank and SKAO has 13 full members, which includes China, Germany and India.

Dempsey studied both astrophysics and theatre and film science as an undergraduate at the University of New South Wales before becoming an actor in the late 1990s.

Square Kilometre Array Observatory

Safe pair of hands Astronomer Jessica Dempsey will lead the Square Kilometre Array Observatory for the next five years.

Dempsey then did a PhD in astronomy at UNSW, graduating in 2007 before working at the James Clerk Maxwell Telescope at Mauna Kea Observatory in Hawaii, becoming operations manager in 2012 and then deputy director of the telescope in 2016.

In 2022 Dempsey was appointed director of the Netherlands Institute for Radio Astronomy and throughout her career has championed more equitable opportunity and experience for women and all underrepresented individuals in science, in 2023 becoming professor of ethics in astronomy at Radboud University.

Dempsey says it is "humbling" to lead the organization and is "passionately dedicated" to its success.

SKAO is currently preparing for the start of "science verification", in which astronomers will gain access to the first SKAO data. This is due to begin for the SKA-Low telescope in Australia in the second half of 2027.

"As someone who loves nothing more than building and running telescopes, there is not a better time to be asked to take up this role – we are just getting to the cool stuff," explains Dempsey.

Diamond, meanwhile, noted that the observatory is in "very good hands" with Dempsey's appointment.

"I have full faith in [Dempsey's] ability to lead this extraordinary organization through its next chapter ," adds Diamond.

Michael Banks

News

Vera C Rubin Observatory starts 10-year quest to map the cosmos

A major astronomy facility in the Andes has begun a 10-year survey of the Southern sky with the aim of creating the most comprehensive, cinematic record of the universe ever made.

Based in Cerro Pachón in the Andes, the Vera C Rubin Observatory is named in honour of the US astronomer and dark-matter pioneer Vera Rubin.

The observatory contains the Legacy Survey of Space and Time (LSST) – the largest camera ever built. Taking almost two decades to build, the 3200 megapixel instrument forms the heart of the observatory's 8.4 m Simonyi Survey Telescope.

The observatory is funded by the US National Science Foundation and the Department of Energy along with international partners including France and the UK.

Last year the observatory released its first images, featuring millions of galaxies and Milky Way stars and thousands of asteroids in exquisite detail. This was then followed by further commissioning work as well as an "operational readiness" review.

NSF–DOE Vera C Rubin Observatory/NOIRLab/SLAC/AURA

Southern sky The lupus constellation as seen by the Legacy Survey of Space and Time camera.

It will now take a ultrawide, ultra-high-definition picture of the southern night sky every 3–4 nights, replicating the process over a decade to produce almost 1000 full images of sky.

This will be used to plot the positions and measure the brightness of objects in the sky to help improve our understanding of dark matter and dark energy.

The survey will examine 20 billion galaxies as well as produce the most detailed star map of the Milky Way, imaging 17 billion stars and cataloguing some six million small objects within our solar system including asteroids.

When the LSST survey is complete, the final dataset will contain billions of objects with trillions of measurements, all accessible through regular data releases.

"It is amazing and humbling as we start the Legacy Survey of Space and Time, after more than two decades of incredible work by our dedicated team," says Vera C Rubin Observatory director Bob Blum. "Rubin Observatory is for everyone; the LSST will change how we do astronomy and astrophysics, allowing researchers anywhere to participate in cutting-edge science."
Michael Banks

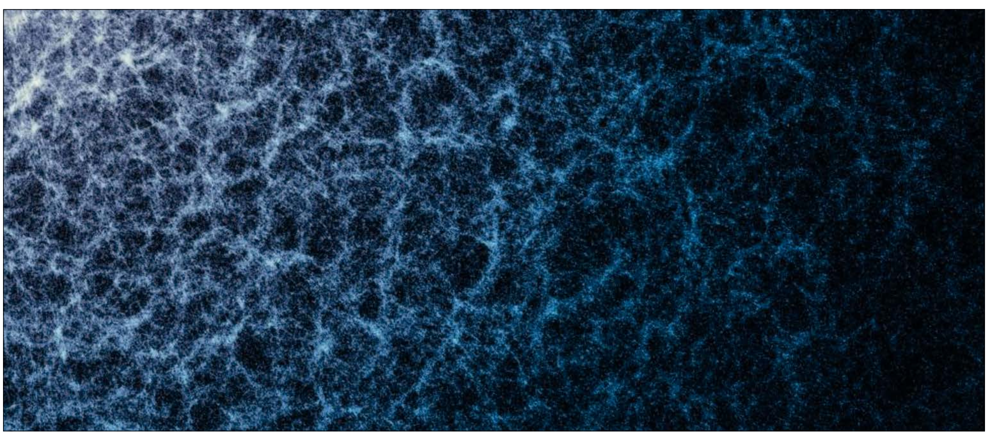
Dark energy survey unveils the largest 3D map of the universe

The Dark Energy Spectroscopic Instrument (DESI) has created the largest high-resolution 3D map of the universe. The work involved observing more than 47 million galaxies and quasars as well as 20 million stars over a five-year period. Researchers will now use the vast dataset to probe the nature of dark energy.

DESI, which began collecting data in 2021, is mounted on the Nicholas U Mayall 4-m Telescope at the Kitt Peak National Observatory in Arizona. It comprises 5000 robot-controlled optical fibres that send light to an array of spectrographs.

This allows DESI to make an extensive map of galaxies and quasars with the spectroscopic data providing a measure of how fast a galaxy is moving away from us, which is determined by a galaxy's redshift.

By comparing how galaxies clustered in the past with their distribution today, researchers can trace dark energy's influence. Work published in 2024 found hints that the acceleration of the expansion of the universe has not been constant.



DESI Collaboration and DESI Member Institutions/DOE/KPNO/NOIRLab/NSF/AURA/R Proctor. Image processing: M Zamani, SF NOIRLab

Dark enery guide The work involved mapping more than 47 million galaxies and quasars as well as 20 million stars over a five-year period.

DESI will now use the expanded dataset to further test whether the "cosmological constant" could be evolving over time with the results expected to be published next year.

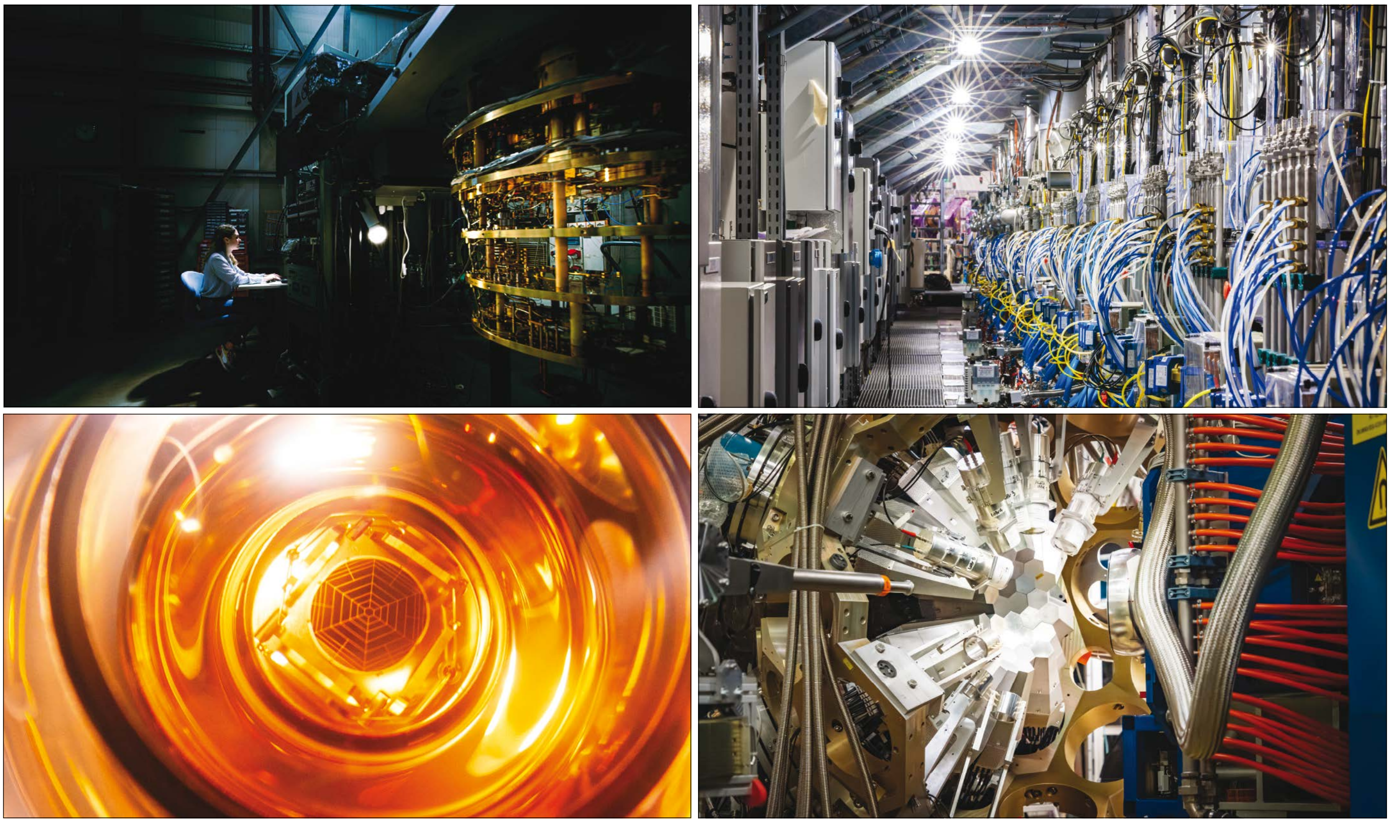
DESI director Michael Levi, who is based at the Lawrence Berkeley National Laboratory, says the survey has been "spectacularly successful and is "incredibly exciting".

"The instrument performed better than anticipated," he says, "We're going to celebrate completion of the original survey and then get started on the work of churning through the data, because we're all curious about what new surprises are waiting for us."

DESI will now continue observations into 2028 and further expand the map by about 20% to include parts of the sky that are more challenging to observe.
Michael Banks

Global Physics Photowalk winning entries revealed

Michael Banks examines the images from this year's competition that cast the world's premier particle-physics labs in a new light



Luminous labs (Clockwise from top left) A photograph of the Cryogenic Laboratory for Detectors; the linear accelerator of SPIRAL2; the Advanced Gamma Tracking Array photon detector coupled with PRISMA magnetic spectrometer; a photomultiplier from the KM3NeT/ORCA experiment.

Marco Donghia; Yannig Van De Wouwer/GANIL/CNRS; Matteo Monzali; Hugo Pardinilla/CPPM/CNRS

From an image of a detector hunting for signs of dark matter to a picture of a deep-sea neutrino telescope studying astrophysical phenomena, the winning entries for the 2025 Global Physics Photowalk were announced in March by the Interactions Collaboration – an international network of particle-physics institutions.

Some 16 labs around the world took part in the event, in which they opened up their labs for a day in 2025 to amateur and professional photographers. Each lab entered its top three images into the global competition and from those 48 images a panel of judges selected their top three photos, while the public also chose their top three favourite images via an online vote held in January.

Marco Donghia's photograph (top left) was awarded first place by the judges. It features a researcher sat in front of the Cryogenic Laboratory for Detectors, which is based at INFN National Laboratories of Frascati. The experiment aims to detect extremely weak and rare signal such as those produced by dark matter.

"Finding out I had won left me speechless," notes Donghia. "The cryostat I photographed is just a few fractions of a degree above absolute zero, yet this recognition filled me with such warmth and emotion that no cryogenic temperature could cool them down."

An image by Yannig Van De Wouwer (top right) of the back of the linear accelerator of SPIRAL2 at the Large Heavy Ion National Accelerator, GANIL, based in Caen, France, won first place in the public vote.

Second place in the judges' competition went to Matteo Monzali for his photo (bottom right) of the Advanced Gamma Tracking Array photon detector coupled with the PRISMA magnetic spectrometer. The experiment is based at the TANDEM-ALPI-PIAVE accelerator complex at INFN National Laboratories in Legnaro.

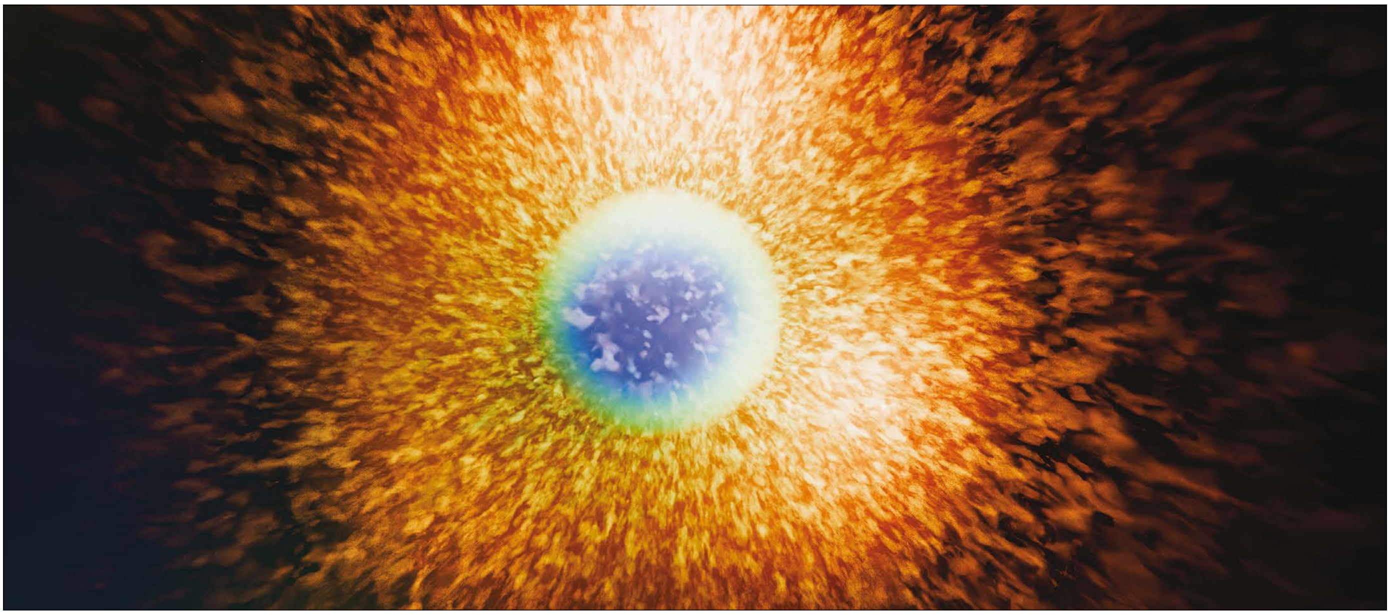
Third place in the judges' competition (bottom left) went to Hugo Pardinilla's spectacular close-up image of a photomultiplier from the KM3NeT/ORCA experiment, a neutrino telescope currently being installed in the Mediterranean Sea off the coast of Provence, France.

This is the fifth international photowalk following events held in 2010, 2012, 2015 and 2018.

● All 48 images submitted to the 2025 competition can be viewed at interactions.org/photowalk

Focusing on fusion

Harnessing the full potential of nuclear fusion could mean access to limitless amounts of clean energy. Among those working towards that goal is plasma physicist **Debbie Callahan**, chief strategy officer at Focused Energy. She talks to Hamish Johnston about the start-up's technology, her move from a national laboratory to industry, and career opportunities in the fusion sector



iStock/koto_feja

With the world's energy demands increasing, and our impact on the climate becoming ever clearer, the search is on for greener, cleaner energy production. That's why research into fusion energy is undergoing something of a renaissance.

Construction of the International Thermonuclear Experimental Reactor (ITER) in France – the world's largest fusion experiment – is currently under way, while there are numerous other large-scale facilities and academic research projects too. There has also been a rise in the number of smaller commercial companies joining the race.

One person at the forefront of fusion research is Debbie Callahan – a plasma physicist who spent 35 years working at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory in the US. She is now chief strategy officer at Focused Energy, a laser-fusion firm based in Germany and California, which is trying to generate energy from the laser-driven fusion of hydrogen isotopes.

Callahan talked to *Physics World*'s Hamish Johnston about working in the fusion sector, Focused Energy's research and technology, and the career opportunities available. The following is an edited extract of their conversation, which you can hear in full on the *Physics World Weekly* podcast of 22 January.

How does NIF's approach to fusion differ from that taken by magnetic confinement facilities such as ITER?

To get fusion to happen, you need three elements that we sometimes call the triple product. You need a certain amount of density in your plasma, you need temperature, and you need time. The product of those has to be over a certain value.

Magnetic fusion and inertial fusion are kind of the opposite of each other. In a magnetic fusion system like ITER, you have a low-density plasma, but you hold it for a long time. You do that by using magnetic fields that trap the plasma and keep it from escaping.

In inertial fusion – like at NIF – it's the opposite. You don't hold the plasma together at all, it's only held by its own inertia, and you have a very high density for a short time. In both cases, you can make fusion happen.

What is the current state of the art at NIF, in terms of how much energy you have to put in to achieve fusion versus how much you get out?

To date, the best shot at NIF – by which I mean an individual, high-energy laser bombardment of the target capsule – occurred during an experiment in April 2025, which had a target gain of about 4.1. That means that they got out 4.1 times the amount of energy that they put in. The incident laser energy for those shots is around two megajoules, so they got out about eight megajoules.

This is a tremendous accomplishment that's taken decades to get to. But to make inertial fusion energy successful and use it in a power plant, we need significantly higher gains of more like 50 to 100.

Can you explain Focused Energy's approach to fusion?

Focused Energy was founded in July 2021, and has offices in the US and Germany. Just a month later, we achieved fusion ignition, which is when the fusion fuel becomes hot enough for the reactions to sustain themselves through their own internal heating (it is not the same as gain).

At NIF lasers are fired into a small cylinder of gold or depleted uranium and the energy is converted into X-rays, which then

Lawrence Livermore National Laboratory/Damien Jemison

Captured beams The target chamber of the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory.

Listen to our full interview with Debbie Callahan here.

Focused Energy

Fusion adopter Debbie Callahan worked at NIF for 35 years before becoming chief strategy officer at Focused Energy.

drive the capsule. It's what's called laser indirect drive. At Focused Energy, however, we're directly driving the capsule. The laser energy is put directly on the capsule, with no intermediate X-rays.

The advantage of this approach is that converting laser energy to X-rays is not very efficient. It makes it much harder to get the high target gains that we need. At Focused Energy, we believe that direct drive is the best option for fusion energy to get us to a gain of over 50.

So is boosting efficiency one of your key goals to make fusion practical at an industrial level?

Yes, exactly. You have to remember that NIF was funded for national security purposes, not for fusion energy. It wasn't designed to be a power plant – the goal was just to generate fusion energy for the first time.

In particular, the laser at NIF is less than 1% efficient but we believe that for fusion power generation, the laser needs to be about 10% efficient. So one of the big thrusts for our company is to develop more efficient lasers that are driven by diodes – called diode pump solid state lasers.

Can you tell us about Focused Energy's two technologies called LightHouse and Pearl Fuel?

LightHouse is our fusion pilot plant. When operational, it will be the first power plant to produce engineering gain greater than one, meaning it will produce more energy than it took to drive it. In other words, we'll be producing net electricity.

For NIF, in contrast, gain is the amount of energy out relative to the amount of laser energy in. But the laser is very inefficient, so the amount of electricity they had to put in to produce that eight megajoules of fusion energy is a lot.

Meanwhile, Pearl is the capsule the laser is aimed at in our direct drive system. It's filled with deuterium–tritium fuel derived from sea water and lithium.

How do you develop the capsule to absorb the laser energy and give as much of it to the fuel as possible?

The development of the capsule for a fusion power plant is quite complicated. First, we need it to be a perfect sphere so it compresses spherically. The materials also need to efficiently absorb the laser light so you can minimize the size of that laser.

You have to be able to cheaply and quickly mass produce these targets too. While NIF does 400 shots per year, we will need to do about 900 000 shots a day – about 10 per second. We'll also have to efficiently remove the exploded target material from the reactor chamber so that it can be cleared for the next shot.

It's a very complicated design that needs to bring together all the pieces of the power plant in a consistent way.

When you are designing these elements, what plays a bigger role – computer simulations or experiments?

Computer simulations play a large part in developing these designs. But one of the lessons that I learned from NIF was that, although the simulation codes are state of the art, you need very precise answers, and the codes are not quite good enough – experimental data play a huge role in optimizing the design. I expect the same will be true at Focused Energy.

A third factor that's developing is artificial intelligence (AI) and machine learning. In fact, at Livermore, a project working on AI contributed to achieving gain for the first time in December 2022. I only see AI's role in fusion getting bigger, especially once we are able to do higher repetition rate experiments, which will provide more training data.

What intellectual property (IP) does Focused Energy have in addition to that for the design of the Pearl target and the LightHouse plant?

We also have IP in the design of the lasers – they are not the same lasers as used at NIF. And I think there'll be a lot of IP around how we fabricate the targets. After all, it's pretty complicated to figure out how to build 900 000 targets a day at a reasonable cost.

We'll see a lot of IP coming out of this project in those areas, but there's also the act of putting it all together. How we integrate these things in order to make a successful plant is important.

What are the challenges of working with deuterium and tritium as materials for fusion?

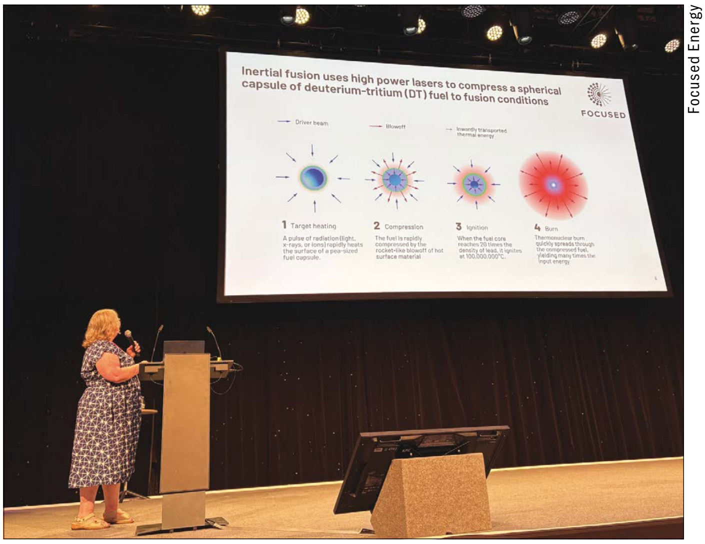
We chose deuterium and tritium because they are the easiest elements to fuse, and have been successfully demonstrated as fusion fuel by NIF.

Deuterium can be found naturally in sea water, but getting tritium – which is radioactive – is more complicated. We breed it from lithium. Our reactor designs have lithium in them, and the neutrons from the fusion reactions breed the tritium.

Focused Energy

Rejuvenating nuclear A rendering of Focused Energy's proposed fusion power plant at the Biblis fission power plant in Germany, which was shut down in 2011.

Focused Energy



Active collaboration Debbie Callahan presenting the work of Focused Energy at the IEEE Pulsed Power and Plasma Science Conference in Berlin in June 2025.

Making sure that we have enough tritium, and figuring out how to extract that material to use it for future shots, is a big task. We have to be able to breed enough tritium to keep the plant going.

To work on this, we have a collaboration funded by the US Department of Energy to work with Savannah River National Lab in South Carolina. They have a lot of expertise in designing these tritium-extraction systems.

How will you capture the heat from the deuterium–tritium fusion reaction?

We will use a conventional steam cycle to convert the heat into electricity. It's funny – we'll have this very hi-tech way of producing heat, but at the end of the day, we will use a traditional system to produce the electricity from that heat.

So what's the timeline on development?

Our plan is to have a pilot plant up by the end of the 2030s. It's a fairly aggressive timeline given the things that we have to do. But that's part of being a start-up – we have to take some risks and try to move quickly to achieve our goal.

To help that we have, in my view, a superpower – we have one foot in Europe and one foot in the US. There are a lot of opportunities between the two continents to partner with other companies, universities and governments. I think that makes us strong because we have access to some of the best talent from around the world.

How does working at Focused Energy compare with life as an academic at Lawrence Livermore?

There are a lot of similarities. My role now is to bring the knowledge and skills I learned at NIF to Focused Energy, so it's been a natural transition.

In fact, there was a lot of pressure working at NIF. We were trying to move very quickly, so it's actually very similar to working in a start-up like Focused Energy.

One big difference is the level of bureaucracy. Working for a government-funded lab meant there were lots of rules and paperwork, which takes up your time and you don't always see the value in it.

In contrast, working for a small start-up means we can move more quickly because we don't have as many of those kinds of constraints. Personally, I find that great because it leaves more time for the fun and interesting things – like trying to get fusion on the grid.

Are you still involved in academic research in any way?

As a firm, we are still out there collaborating with academics. Last year, for example, we gave four separate presentations at the American Physical Society Division of Plasma Physics meeting.

I feel very strongly about peer review. Of course, publishing isn't our number one priority, but we need feedback from others. We're trying to do something that no-one's done before, so it's important to have our colleagues give us feedback on what we're doing, point out mistakes we're making or things we're forgetting.

Working with universities and national labs in both Europe and the US is vital. Communicating with others in the field is important for us to get to where we want to go.

And of course, being an active part of the fusion community is good for recruitment too. We regularly give presentations at conferences that students attend. We meet those students and they learn about our work – and they might be future employees for our company.

What's your advice for early-career physicists keen on joining the fusion industry?

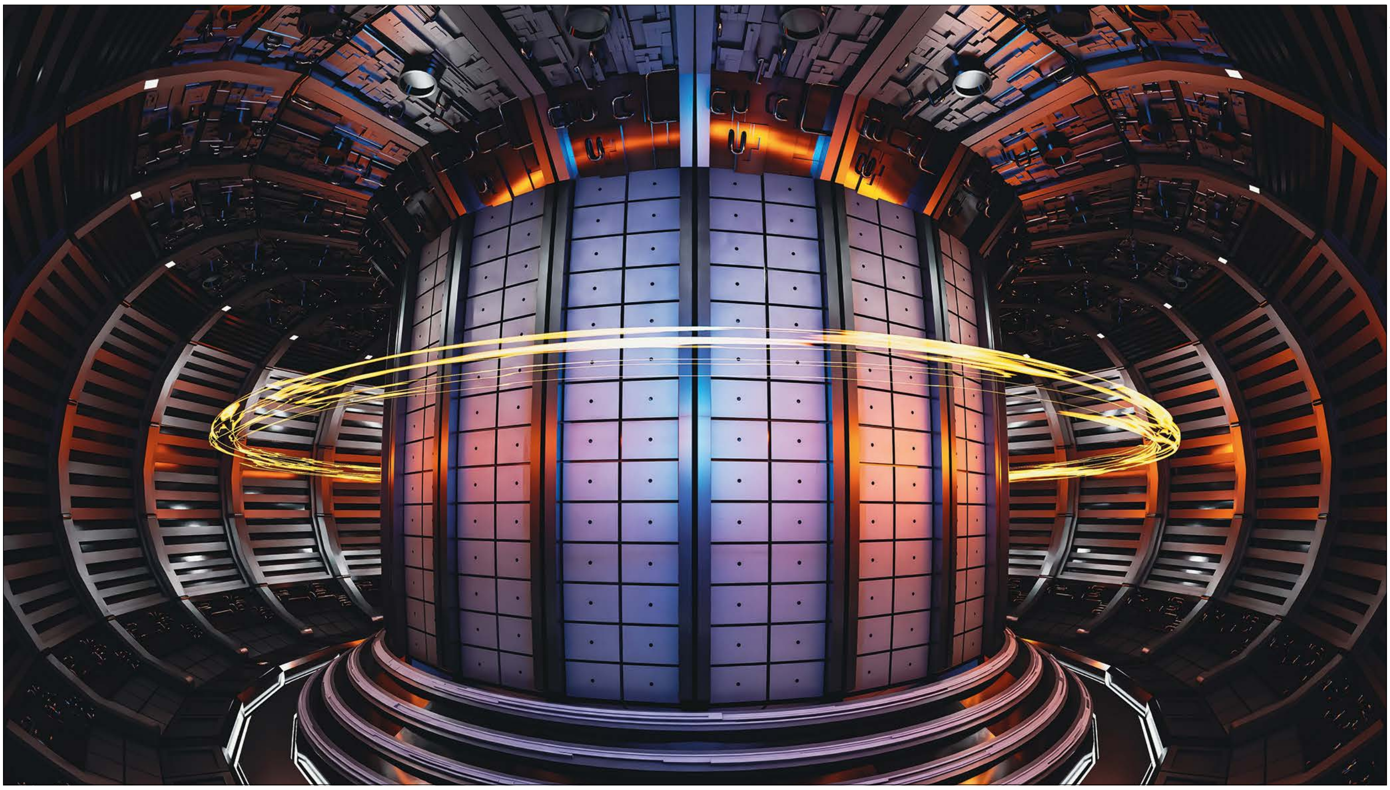
There are so many opportunities right now, especially compared to the start of my career when the work was mainly just at universities or national labs. Nowadays, there are a lot of companies in the sector. Not all of them will survive because there's only so much money, but there are still lots of opportunities. If you're interested in fusion energy, go for it.

The field is always developing. There's new stuff happening every day – and new problems. So if you like problem-solving, it's great, especially if you want to do something good for the world.

There are also opportunities for people who are not plasma physicists. At Focused Energy we have people across so many fields – those who work on lasers, others who work on reactor design, some developing the AI and machine learning, and those who work on target physics, like me.

To achieve fusion energy, we need physicists, engineers, mathematicians and computer scientists. We need researchers, technicians and operators. There's going to be tremendous growth in this sector.

Hamish Johnston is an online editor of *Physics World*



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Hiden Analytical has designed a quadrupole mass analyser that can resolve the isotopes of hydrogen and helium that are involved in nuclear fusion.

Mass spectrometry delivers fusion insights

A quadrupole mass analyser designed for fusion research combines radiation hardness with the ability to distinguish between the light atomic species involved in the nuclear reaction

Nuclear fusion promises to deliver an abundant, safe and sustainable source of energy, but replicating the reactions that power the Sun remains a scientific and engineering challenge. Experimental reactors, such as the ITER facility now being built in France, are designed to heat and confine a plasma containing deuterium and tritium to extreme temperatures, with the aim that the two hydrogen isotopes fuse together to form helium along with a neutron and a huge amount of energy. Crucial to success is understanding what is happening inside the reactor, allowing the plasma composition and properties to be adjusted in real time to initiate and sustain the reaction.

The extreme conditions inside the reactor preclude the use of direct probes, but a combination of external diagnostics can be used to monitor the plasma conditions and the progress of the reaction. To push the capabilities of these techniques, Chris Marcus and colleagues at Oak Ridge National Laboratory (ORNL) in the US have been developing a system that will exploit both mass spectrometry and optical spectroscopy to analyse the complex mixtures of light gases that are released from the tokamak while the reaction is taking place. "Each of these techniques provides complementary information that will help to isolate the hydrogen and helium isotopes we are interested in," he says.

Complementary diagnostics

As part of this project, Marcus has been working with Hiden Analytical in the UK to develop a mass spectrometer that offers unique capabilities for fusion research. A key part of the brief was to achieve a higher resolving power for hydrogen and helium isotopes than can be achieved with standard instruments. "Our main objective was to detect small concentrations of helium-4, the main product from the nuclear reaction," says Marcus. "But commercial instruments are unable to resolve helium-4 from deuterium when it is present at concentrations below about 10%."

The spectrometer developed by the Hiden team exploits a quadrupole design, which is favoured for its rapid scanning speeds, compact footprint, and the ability to provide real-time analysis of atoms and molecules over a broad mass range. These quadrupole sensors work by ionizing the gas species, and then sending the ions through four cylindrical rods impressed with a composite DC and radio-frequency voltage. The resulting electric field separates the ions according to their mass-to-charge ratio, isolating the species of interest and preventing any other ions from reaching the sensor. The ion current produced at the output can then be related to the relative abundance of each species in the gas mixture.

However, conventional quadrupole analysers can only distinguish between atoms and molecules with a difference in mass of 1 amu. That makes it difficult to isolate helium-4 from deuterium, the species of particular interest for fusion research, since their masses differ by just 0.026 amu. "Although large-rod mass spectrometers are able to separate helium and deuterium, they are not suitable for deploying close to the outlet of a fusion reactor," says Bob Mellor of Hiden Analytical. "We needed to develop a compact instrument that also delivers the extra resolving power."

Improving resolution

Fortunately, quadrupole devices offer stable operation in several different zones. Standard instruments exploit a region of stability that can be accessed at lower voltages, but the Hiden team designed a spectrometer that can operate in a different stability zone that can separate helium and deuterium, albeit at significantly higher voltages. "This zone, which we call Zone H, achieves the detection limits that Oak Ridge required, but still enabled the use of a small quadrupole sensor," says Mellor. The operational mode of the spectrometer can easily be switched between Zone H and the more usual Zone 1, which means that the instrument can also be used for conventional vacuum diagnostics.

Once a prototype instrument had demonstrated the feasibility of this solution, the next challenge for Hiden was to engineer a system that would be immune to the strong magnetic fields and high levels of radiation close to the tokamak. That posed a particular problem for the power and control electronics, since solid-state devices are prone to radiation damage and must be installed behind a radiation shield. As a result, the connecting cable between the power unit and the sensor can be up to 140 m long, which presents problems in connecting the RF voltage that is impressed on the quadrupole sensor rods.

A coaxial cable can be used, but simply connecting the RF voltage over long distances results in significant power loss in the generator. This means that the operating frequency of the sensor must be reduced to keep within the available power budget. "If you go much longer than 10 m, the frequency becomes so low that you don't have any useful resolving power," says Mellor.

The solution is to transmit RF power down the long coaxial cable to a set of intermediary electronics, or matching unit, that contains radiation-hard passive components and thermionic valves. "In the matching unit there is a power to-voltage

Hiden Analytical

The HAL 101X combines dual-zone operation with radiation-hard electronics.

convertor that generates the high-voltage RF to be impressed on the rods," explains Mellor. "Independent testing at a fusion facility has confirmed that this solution is immune to radiation, magnetic fields, and ground vibrations."

The resolving power of the mass spectrometer has also been evaluated at ORNL. "We have demonstrated that the quadrupole analyser can detect helium-4 at a concentration of 3% in a mixture containing 97% of deuterium," says Marcus. "It also provides a fast response time, providing an analysis in less than a second, which is another key requirement for fusion diagnostics.

Experimental validation

In the meantime, Hiden has developed a series of commercial instruments to make the technology available to other fusion developers, as well as for other applications that require similar levels of performance. Both the DLS-2 and DLS-2X offer switchable dual-zone operation, combining high resolving power for light species along with high-performance residual gas analysis for vacuum diagnostics. They are available in two possible configurations: one with a Zone H that achieves an ultrahigh mass resolution of 0.0065 amu for species with masses of up to 10 amu, and the other providing a separation of 0.02 amu over a mass range extending to 22.5 amu. While the resolving power and sensitivity are the same for both instruments, the DLS-2X also features remote electronic control for use in harsh environments.

Meanwhile, the HAL 101X includes all the features that were developed for the gas analyser system being developed and tested at ORNL. That includes dual-zone operation and radiation-hard electronics, as well as an additional analysis mode in Zone 1 – called Threshold Ionization Mass Spectrometry (TIMS) – that can help to distinguish between species with similar mass-to-charge ratios when they are present in sufficiently high concentrations.

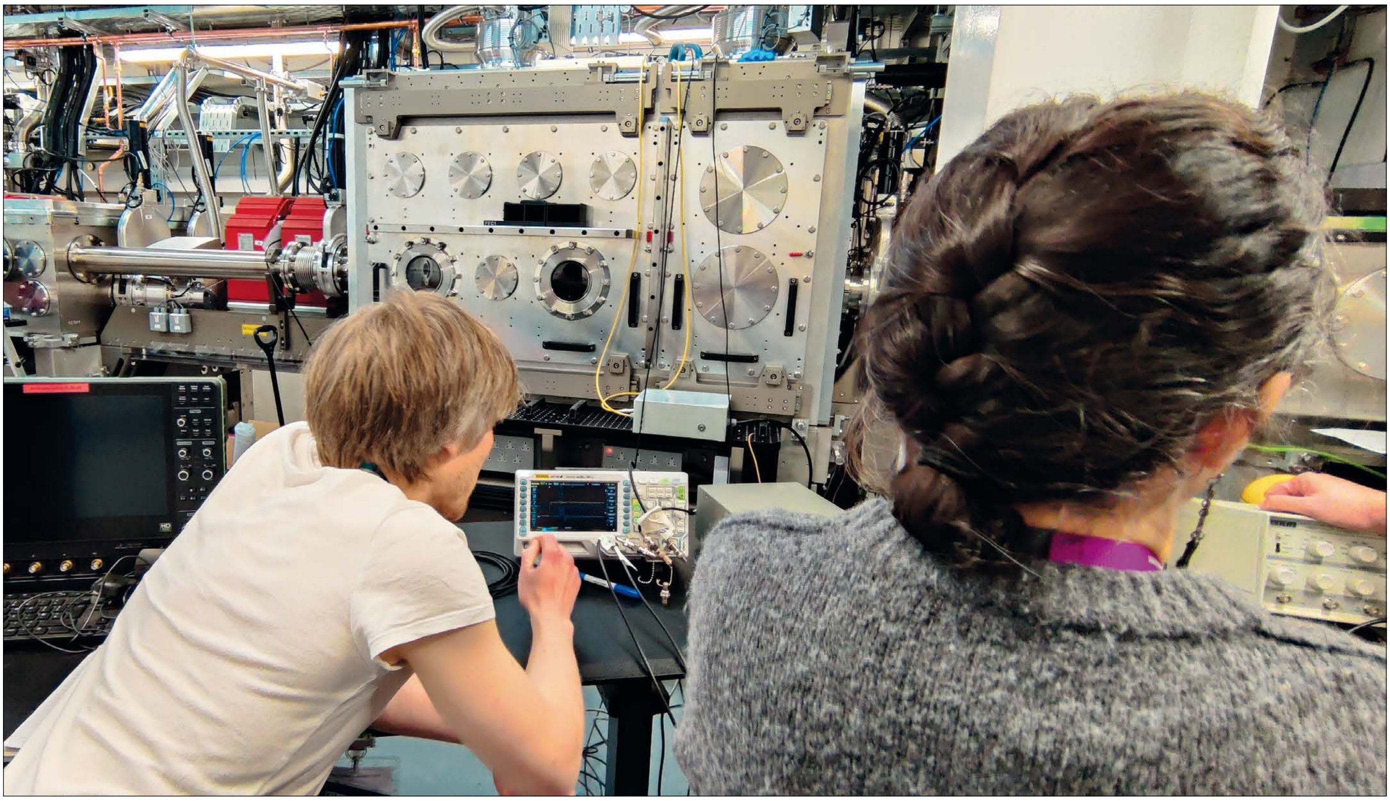
The Hiden team is now working with Marcus to investigate the capabilities of the HAL 101X to distinguish between other light gases that are important for fusion research. "We have established that we can isolate neon, which can be used as a catalyst for the fusion reaction," says Mellor. "The usual difficulty with neon is that its mass-to-charge ratio is overlapped by argon ions, but Zone H can be used to separate neon-20 from doubly charged argon." More challenging will be to resolve tritium from hydrogen deuteride, which are separated by just 0.006 amu. "It may be possible by using the TIMS method in Zone 1, or by further increasing the applied DC and RF voltages to achieve a higher mass resolution in Zone H," says Marcus.

While those investigations continue, Marcus is continuing to evaluate the HAL 101X on a diagnostic test stand at ORNL. "The next steps for the mass analyser will be to advance it into the production phase for the full diagnostic suite," says Marcus. "That will yield a complete system that has been validated for operational use."

Analysis

HALHF goes all in on plasma acceleration

The HALHF collaboration is developing a disruptive platform technology that could slash the size, cost and carbon footprint of future large-scale particle-accelerator facilities. **Joe McEntee** checks out progress



Tom Pacey, STFC ASTeC

Plasma promise HALHF@CLARA scientists set up the high-voltage discharge system used to generate a plasma for first PWFA and strong-focusing experiments at the UK's CLARA test facility.

Big science is all about big-money bets. What's more, payback on those research investments – sometimes running to billions of euros in capital spend – will usually only be realized decades down the line. With the stakes so high, funding agencies and governments are understandably keen to shorten the odds in their favour and ensure every bet's a winner.

Take the long-running debate within the international particle-physics community regarding a "next energy frontier" particle collider. The end-game: to build on the fundamental physics discoveries made by CERN's Large Hadron Collider (LHC) and the anticipated breakthroughs resulting from its imminent upgrade – the High-Luminosity LHC – which is due to enter operation in 2030.

The collective conversation here is a case study in consensus meets divergence. On the one hand, there's general agreement that any post-LHC big-science facility should be an electron–positron "Higgs factory", in which electrons and positrons are smashed together at high energies to deepen our understanding of the Higgs boson. Discovered in 2012, the Higgs boson is the newest addition to the family of elementary particles that make up the Standard Model of particle physics.

"It's widely accepted that an electron–positron Higgs factory, with its 'exceptionally clean' experimental conditions, will reveal the new physics that we know must exist beyond the Standard Model," explains Richard D'Arcy, associate professor of particle-accelerator physics in the John Adams Institute at the University of Oxford, UK.

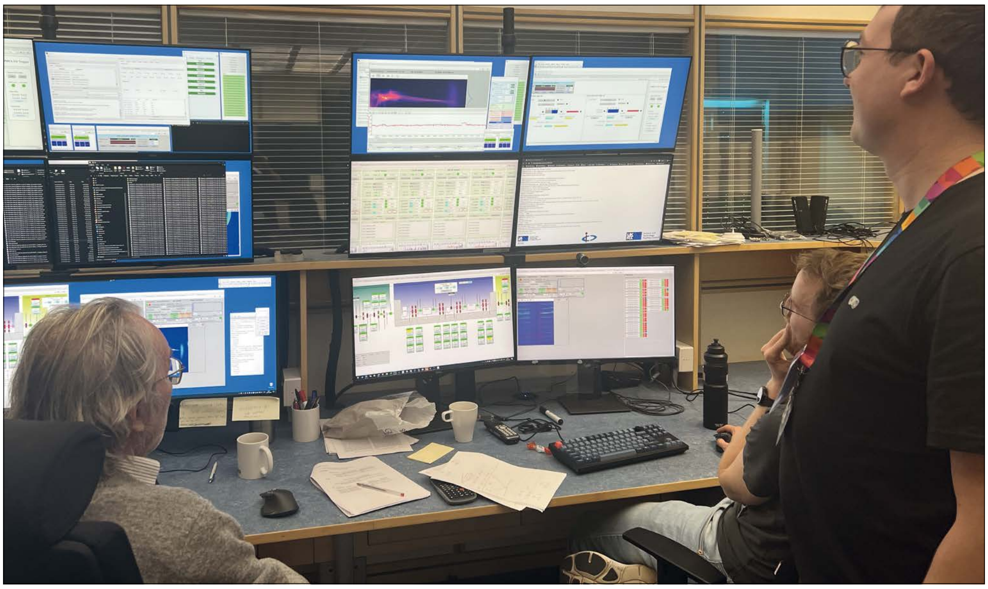
Collision course

In contrast, there are several mature and competing concepts for the implementation and operation of such a Higgs factory. Chief among them: the International Linear Collider (ILC) and the Compact Linear Collider (CLIC); also the Circular Electron–Positron Collider (CEPC) and the Future Circular Collider (FCC-ee).

All these proposals exploit existing accelerator technologies based on superconducting and/or normal-conducting RF cavities (metallic chambers in which charged particles injected into an electromagnetic field receive an electrical impulse to accelerate them).

However, each blueprint comes with downsides, whether that's prohibitive construction costs, sprawling land use and facility footprint, or eye-watering operational costs and energy budgets (or a combination thereof).

Opportunity knocks, it seems, for disruptive accelerator innovation that could unlock the door to a cut-price Higgs factory. One candidate technology that has seen significant advances over the past decade is plasma-



Stewart Bogert

Worcester College, Oxford

Richard D'Arcy "We have established a solid platform on which to build the next level of HALHF@CLARA experiments."

Performance metrics Scientists in the CLARA main control room just after optimizing the plasma acceleration process to generate particle-beam-driven GV/m electric fields for the first time in the UK.

wakefield acceleration (PWFA), which exploits laser- or particle-beam-driven intense "plasma waves" as the accelerating medium, yielding electric fields up to three orders of magnitude greater than in classical accelerators. Those ultra-high accelerating gradients, in turn, promise a significant reduction in the size, cost and carbon footprint of next-generation accelerator facilities.

New thinking, new physics

The Hybrid Asymmetric Linear Higgs Factory (HALHF) project is one of several international initiatives seeking to turn the game-changing potential of PWFA into a mainstream platform technology for future particle accelerators. HALHF researchers, for their part, are developing a linear-collider concept based on proven RF cavities and novel PWFA modules – a hybrid acceleration scheme that, they hope, will leverage the benefits of both.

Their concept is now taking form. Earlier in the spring, the HALHF project notched up a significant experimental milestone with the introduction of PWFA infrastructure into a test facility called CLARA (Compact Linear Accelerator for Research and Applications) at STFC Daresbury Laboratory in the UK. For context, CLARA hosts one of the world's brightest medium-energy electron beams and is designed specifically to support the development of next-generation accelerator technologies.

Initial HALHF@CLARA experiments were carried out over a five-week period by a team of scientists from the universities of Oxford, Oslo and Manchester working with colleagues from the German accelerator laboratory DESY and Daresbury's Accelerator Science and Technology Centre (ASTeC). Along the way, the researchers successfully integrated PWFA modules into CLARA and subsequently used them to drive plasma wakes with >GV/m gradients and then focus CLARA electron beams with >100 T/m fields.

"These results are foundational for future HALHF@CLARA experiments," claims D'Arcy, who also leads the PWFA group at Oxford and is one of the principal investigators on the HALHF project. "They are also impressive in their own right, representing the first time beam-driven plasma acceleration has taken place in the UK."

During this Phase 0 experimental run at CLARA, the HALHF team prioritized three key performance metrics: very high field strengths (orders of magnitude higher than what is possible with traditional accelerator technology); maintaining beam quality as the electrons pass through those very high field gradients; and, finally, minimizing (or even reducing) the energy spread of the electron bunches (which also maintains beam quality and ensures the PWFA set-up remains super-compact).

"By ticking off those three boxes," says D'Arcy, "we have established a solid platform on which to build the next level of experiments. That's when things will start to get really exciting."

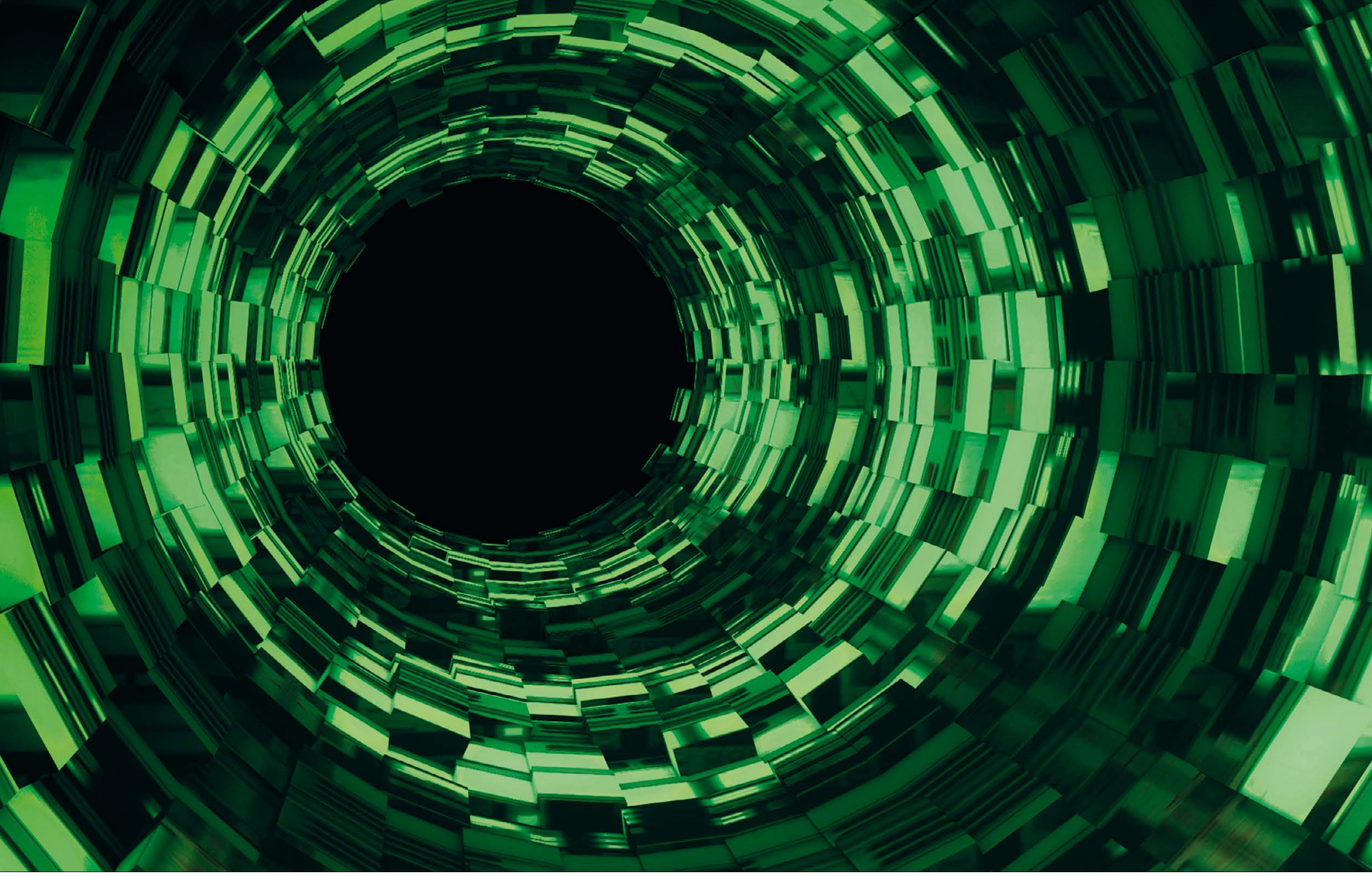
Progressions of power

Follow-on experimental runs, which are scheduled to get under way at CLARA later this year, will inevitably begin to tackle two outstanding challenges in plasma acceleration: pushing on to very high energies (which require the staging of PWFA modules in series) and attaining competitive luminosity (by operating the plasma modules thousands of times per second). "CLARA offers a unique opportunity to make substantial advances in both areas owing to its novel architecture and modular environment," D'Arcy adds.

In the meantime, the HALHF collaboration has submitted its contribution to the European Particle Physics Strategy Update 2026 – part of a concerted push to raise the profile of the research community working on plasma acceleration. The priorities for that community are clear: to increase resources and funding, coordinate development activity on an international level, and take the next steps to further the PWFA concept towards practical and at-scale realization.

"We want to show particle physicists that PWFA isn't some flash in the pan," concludes D'Arcy. "This is an enabling technology that really has legs."

Joe McEntee is a consultant editor based in South Gloucestershire, UK



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Big science seeks big wins from sustainability efforts

Particle accelerators have traditionally been designed to maximize their scientific impact, but now they need to be environmentally friendly too. **Joe McEntee** examines initiatives pursuing a more sustainable roadmap for big science

Joe McEntee is a consultant editor based in South Gloucestershire, UK

For particle physicists, bigger has always been better. The first working cyclotron, which was built by Ernest Lawrence in California in 1931, was little more than 35 cm in circumference and accelerated protons to 80 keV. Compare that with CERN's Large Hadron Collider (LHC), which is more than 27 km long and has been creating protons with energies of 7 TeV per beam – some eight orders of magnitude higher.

Only recently, though, have the burgeoning energy requirements of ever-larger accelerator facilities become a cause for concern. It was not until 2020 that CERN published its first-ever environmental report, which outlined to the public how the lab was reducing its energy consumption. Thanks to innovations in cryogenics, for example, CERN reported that the "data per joule" doubled between the LHC's first and second experimental runs.

All good and well. Yet while their core mission of fundamental scientific discovery remains paramount, it's clear that – if nothing changes – the environmental impact of new and upgraded accelerator complexes will track in tandem with the size, energy footprint and resource consumption of these large-scale research facilities.

The numbers are eye-watering. Particle-accelerator research centres currently consume hundreds of gigawatt-hours (GWh) of electricity per year – roughly the energy budget of a mid-sized European city. CERN's unique array of accelerators, detectors, computers and technical infrastructure, for example, together account for about 95% of the lab's total electricity use of 1290 GWh in 2024, with the LHC alone soaking up 695 GWh.

What if bigger isn't better?

It's not a good look given the climate crisis – and only made worse with oil and gas prices soaring after the effective closure of the Strait of Hormuz. Fortunately, the accelerator-science community is ramping up efforts to make its core technologies and facilities more sustain-

Tunnel vision Accelerator scientists and engineers are boosting efforts to reduce the energy and resources that large-scale accelerator facilities consume, while ensuring their "whole-lifetime" environmental impact is understood and minimized.

> We hope that the guidelines will help accelerator facilities make informed decisions that balance scientific progress with environmental responsibility
>
> Hannah Wakeling, University of Oxford

able. The aim is not only to cut the energy and resources that accelerators use, but also to understand – and, more importantly, minimize – their "whole-lifetime" environmental impact.

In fact, with CERN bringing the upgraded High Luminosity LHC online by 2030, mulling over a 91 km circumference Future Circular Collider, and China eyeing up a 100 km collider of its own, now is a good time to embed environmental impact-reduction techniques into accelerator designs from the start.

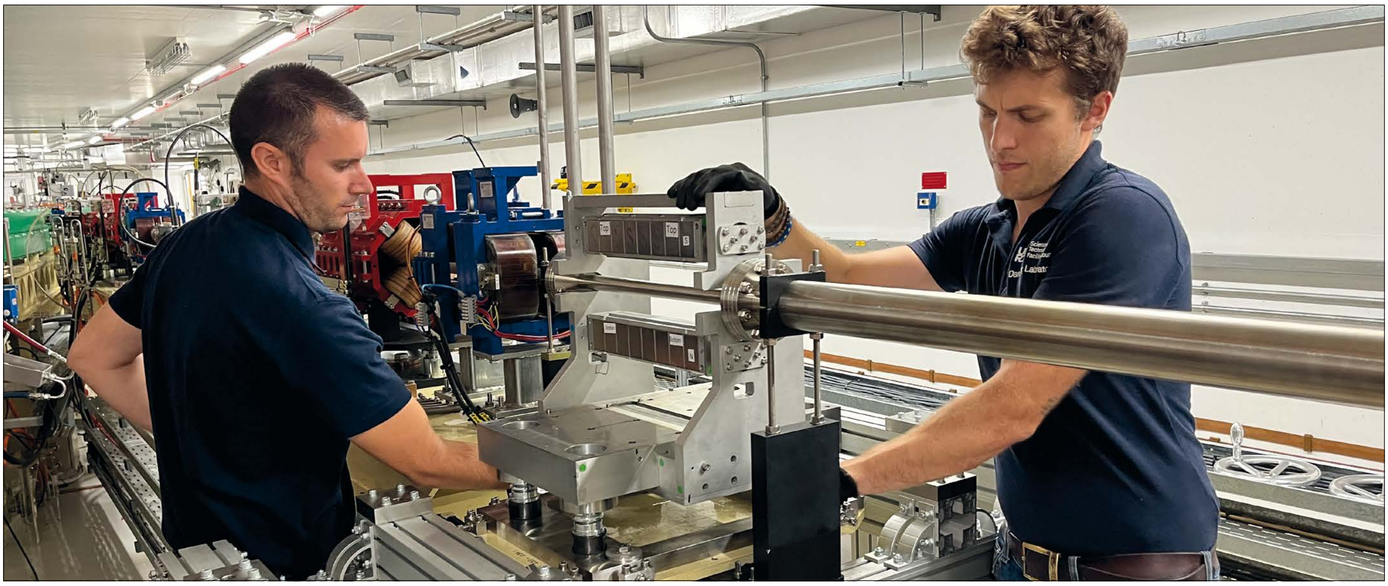
That, at least, is the hope of a group of accelerator scientists and sustainability experts from the UK, Switzerland and Germany, who in June published a "living document" that puts environmental sustainability front-and-centre in the planning, construction, operation and decommissioning of large-scale accelerator facilities (*EPJ Research Infrastructures* **10** 12).

"We're seeing a surge in interest from colleagues across the accelerator community, all of them eager to incorporate environmental sustainability into their work and to share lessons learned," says Hannah Wakeling, lead author of the report. An accelerator physicist in the John Adams Institute at the University of Oxford, UK, Wakeling's own research involves measuring the carbon footprint of particle accelerators, their use of raw materials and even their wider impact on biodiversity.

Trouble is, measuring and improving the environmental sustainability of accelerator facilities is not easy. Labs often don't have enough funding, staff or time for such initiatives. Sustainability recommendations are either too generic or cannot be applied to accelerator science and technology. There's also uncertainty about how to incorporate environmental sustainability into day-to-day operations.

Inspired by various initiatives in big science (see the box "Sustainable acceleration"), Wakeling and colleagues' open-access resource has 110 practical sustainability recommendations for anyone building, planning or running accelerator facilities. It includes advice on procuring resources responsibly and reducing environmental impact through, for example, tunnelling, shielding, component design, waste management and green computing. There are also recommendations on skills, knowledge transfer and culture change, the latter being what the authors think will have most impact.

"Looking at accelerator programmes through the lens



Science and Technology Facilities Council

Permanent waves The UK's Zero Power Tuneable Optics (ZEPTO) project is developing tuneable permanent magnets for accelerator facilities as an energy-efficient alternative to resistive electromagnets. Here engineers are installing a ZEPTO magnet on the booster-to-storage-ring transfer line at the Diamond Light Source synchrotron facility in Oxfordshire.

Sustainable acceleration

The following sustainability initiatives are a useful starting point for scientists and engineers who want to evaluate and lower the environmental impact of accelerator projects at an institutional, project or individual level.

- **Sustainable HECAP+** is a group of researchers in high-energy physics, cosmology, astroparticle physics and beyond who are promoting environmentally sustainable practices in areas such as computing, energy, mobility, research infrastructure, resources and waste.
- The **ICFA Panel on Sustainable Accelerators and Colliders** is promoting "energy-efficient and sustainable accelerator concepts, technologies and strategies…and the use of accelerators for the development of carbon-neutral energy sources".
- **Flexibility in RIs for global CArbon Neutrality (FlexRICAN)** is a pan-European academic-industry consortium evaluating how research facilities can enhance energy flexibility for the European electrical grid and contribute to local heating networks through waste heat recovery.
- **Europe-America-Japan Accelerator Development Exchange Programme (EAJADE)** has a work package of sustainable technologies for accelerator facilities including high-efficiency superconducting RF cavities and RF amplifiers.
- **ErUM Data Hub** is a German initiative helping 20 000 scientists exploring "the universe and matter" to make data management, software and digital tools more environmentally sustainable.

> Large-scale research infrastructures are a public good but they are inflexible and found wanting when it comes to environmental sustainability
>
> Giovanni De Carne, director of KIT's Institute for Technical Physics

of sustainability gives us an opportunity to do things differently," notes Wakeling. "We hope that the updated version of our high-level guidelines [v1.0 was published in 2025] will help accelerator facilities make informed decisions that balance scientific progress with environmental responsibility."

Towards accelerator 2.0

In general, the biggest opportunity to make accelerators more sustainable is when they are still being designed and conceived. "At these crucial stages," says Wakeling, "environmental impact assessments should be employed to highlight the areas of highest potential for impact reductions and more sustainable designs."

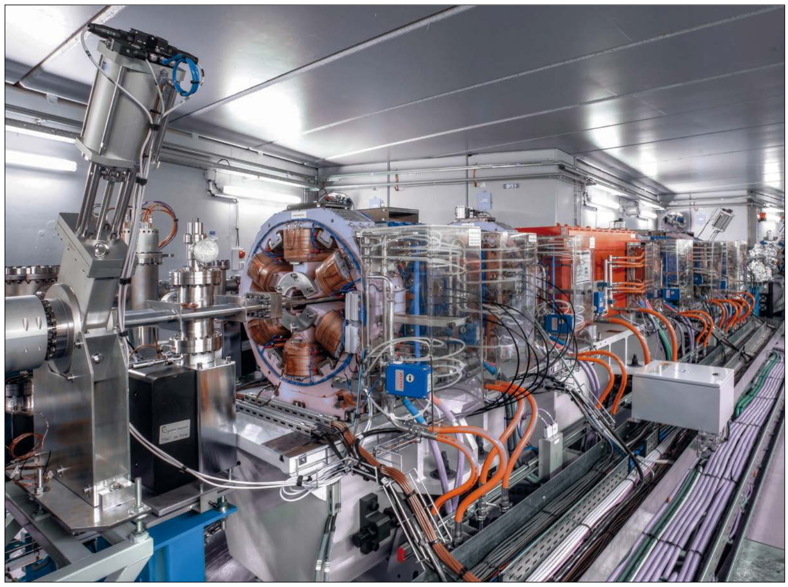
What's more, argues Wakeling, any decision to build or upgrade an accelerator shouldn't depend just on its cost or scientific output but on how environmentally sustainable it will be too. That, in turn, means prioritizing R&D funding for enabling technologies that can make the most difference and co-ordinating efforts between large-scale facilities to avoid scientific duplication and to minimize the consumption of resources.

One relevant effort is a pan-European consortium called Research Facility 2.0 (RF 2.0), which is aiming to develop accelerator facilities that can run entirely on renewable energy – in effect, almost independently of the public power grid. A three-year, €5.6m initiative funded by the European Union's Horizon programme

Nikolaos Sapountzoglu/CERN

They've got the power RF 2.0 engineers from CERN and industry partner Zaphiro have installed 24 phasor measurement units to monitor disturbances in the Large Hadron Collider's power network, including the BE1 400 kV switchyard (above), the main energy gateway to CERN. The demonstrator project aims to enhance the network's resilience and energy-efficiency.

ALBA



Accelerated development RF 2.0 partners have been exploring the long-term environmental and operational benefits of using permanent magnets (rather than electromagnets) in accelerator systems, including a demonstrator project in the storage ring of Spain's ALBA synchrotron light source. Here the actual electromagnets are shown along with the electrical and cooling connections that won't be needed with a permanent magnet solution.

and the Swiss State Secretariat for Education, Research and Innovation, RF 2.0 includes major accelerator labs like CERN, DESY and HZB (both in Germany), ALBA (Spain) and MAX IV (Sweden) plus the Karlsruhe Institute of Technology (KIT) and four high-tech SMEs.

"We are addressing a couple of fundamental problems," says RF 2.0 head Giovanni De Carne, who is director of KIT's Institute for Technical Physics. One issue is purely economic: a particle accelerator consumes a lot of electrical energy and therefore accounts for a recurring chunk of operating expenditure. In "run" years, for example, electricity costs typically equate to 5–10% of CERN's annual budget.

"The second problem is practical, but also philosophical," De Carne adds. "Large-scale research infrastructures are a public good – driving scientific and societal impact – but they are inflexible and found wanting when it comes to environmental sustainability, consuming large amounts of raw materials during construction and regular operations."

RF 2.0's goal is therefore to analyse the many ways accelerators use energy – from components and systems to experiments and engineering – and to develop and test novel platform technologies in real-world settings. One notable RF 2.0 demonstrator project, for example, led to a redesign of permanent magnets that steer and focus beams at the MAX IV synchrotron, reducing energy use and heat losses by up to 40%.

Another involved retrofitting solid-state amplifiers with energy-efficient "active parameterization" controllers to enhance particle acceleration at the ALBA synchrotron; it yielded 18% energy savings in one year versus prior technologies. A parallel R&D track has also led to sustainable high-performance computing initiatives such as a summer energy-saving programme at DESY's data centre, reducing the power draw during the hottest parts of the day.

Meanwhile at CERN, an RF 2.0 team has installed 24 phasor measurement units (PMUs) at the lab. These smart grid devices, which record the magnitude and timing of voltage/current fluctuations, are able to monitor harmonics, voltage sags and grid disturbances within the LHC's power network.

By recording phenomena that would otherwise go unnoticed with traditional metering systems, the PMUs help engineers to implement counter-measures to make the accelerator grid more robust. In the first year of operation, the devices recorded 135 voltage sags and rapid voltage-change events, with 18 of these adversely impacting operation of the accelerator complex – mainly affecting magnets and radio-frequency (RF) acceleration schemes.

"RF 2.0 cannot work in one single direction – a multidisciplinary approach is key," says De Carne. "We are bringing together physicists, engineers and technologists who, under normal circumstances, rarely talk to each other. The project provides a forum for them to connect and share insights on common problems but from their own unique perspective. It's been a real game-changer."

The RF 2.0 programme finishes at the end of 2026, after which De Carne hopes to secure follow-on EU funding for RF 2.0 to merge with another pan-European project called Innovate for Sustainable Accelerator Systems (iSAS). The two projects look like a neat fit, with iSAS consisting of 11 academic labs and six companies seeking to make superconducting RF cavities – a workhorse accelerator technology – more energy-efficient.

Disruptive thinking, sustainable outcomes

Along another coordinate, there's also top-down pressure for a more sustainable approach to future accelerators from the European Strategy Group for Particle Physics (ESG), which guides the future of the field in

John Adams Institute

KIT

Innovate and accelerate Hannah Wakeling (left) from the University of Oxford is one physicist seeking to make accelerator programmes more sustainable. Giovanni De Carne (right), director of the Institute for Technical Physics at KIT in Germany, runs the European RF 2.0 programme, which aims to develop accelerator facilities that can run entirely on renewable energy.

Another sustainability pathway is the use of AI and machine learning to optimize the efficiency of accelerator experiments

Europe. "Energy consumption and emissions must be minimized when realizing and operating facilities and projects," is the ESG's unequivocal message in the 2026 update to its third strategy paper. "The design of new particle physics infrastructures should be as sustainable as possible, balancing important sustainability aspects with cost and physics performance."

The ESG argues that R&D funding should be allocated to platform technologies with the most potential to yield energy savings. These include systems that convert grid power to RF more efficiently for particle acceleration, with some studies suggesting it could be possible to quadruple the efficiency with which RF systems convert electrical power into radiant power. Other promising technologies include thin-film superconducting RF cavities operating at higher cryogenic temperatures (around 4.2 K or higher versus 2 K for bulk niobium cavities).

Also important are novel permanent and high-temperature superconducting magnets that minimize heat losses. "Comparing the carbon footprints of electromagnet and permanent-magnet quadrupoles," says Wakeling in Oxford, "the higher manufacturing impact of a permanent magnet can, in certain cases, be offset by its lower operational impact in as little as one year. Worth noting as well that this conclusion only considers carbon and doesn't compare other environmental impacts."

Another sustainability pathway is the use of AI and machine-learning to optimize the efficiency of accelerator experiments – for example, by focusing on intersecting parameters tuned to improve equipment reliability, lifetime and resource consumption. In parallel, AI could cut the huge computational needs of particle physics by requiring fewer "events" to be stored and lowering computing time.

Longer term, researchers are prioritizing disruptive accelerator concepts that could slash the size, cost and carbon footprint of next-generation facilities. One example is the energy-recovery linac, in which superconducting RF cavities decelerate a "used" particle beam and recycle the kinetic energy to accelerate new particles to higher energies. Another is plasma-wakefield acceleration, which uses laser- or particle-beam-driven intense "plasma waves" as the accelerating medium, yielding electric fields up to 1000 times greater than in classical accelerators.

The best of all worlds

Notwithstanding all this technology innovation, so many factors influence accelerator design that the "best" decision in terms of its environmental benefits can't always be made. "In the end," says Wakeling, "this is all a balancing act: we want accelerator facilities to be cutting-edge in terms of their scientific output, but we also want them to be cutting-edge when it comes to environmental sustainability."

As for next steps, Wakeling and co-authors now plan to assess the anticipated impact of their 110 recommendations – whether high, medium or low – and the potential difficulty of putting them into practice (by referencing technology-readiness level, for example). Work is also underway to incorporate more quantitative analyses, including target figures for selected recommendations based on case studies from the accelerator community.

Equally, when assessing an accelerator's emissions over its whole life-cycle, Wakeling thinks there is much to learn from the space-science community, which has developed the Open-source Rocket and Constellation Lifecycle Emissions (ORACLE) GitHub repository. This initiative seeks to cut the carbon footprint of the space industry – especially large constellations of satellites – by allowing researchers to share code and data.

"We applaud efforts like ORACLE and wish to encourage and promote similar programmes within fields applicable to accelerator science," says Wakeling. But it's clear that significant research is still required to tackle the complex environmental challenges in accelerator science, with Wakeling and colleagues aiming to update their living document as new information and technologies become available.

"We invite contributions from colleagues within the accelerator community," Wakeling concludes, "to ensure this resource remains relevant, comprehensive and impactful."

Neutrino maestro

Mary Bishai is an experimental neutrino physicist at Brookhaven National Laboratory in the US and has collaborated on many leading particle-physics projects

Born and raised in Egypt, Mary Bishai studied physics at the University of Colorado, Boulder, US, before doing a master's and PhD, also in physics, at Purdue University. After a postdoc at Fermilab, she joined Brookhaven National Laboratory in 2004, where she is now a distinguished scientist.

Bishai served as co-spokesperson for the Deep Underground Neutrino Experiment (DUNE) from 2023 to 2025 and, over the years, has collaborated on many other leading particle-physics projects, including MicroBooNE, the Daya Bay neutrino experiment, the Main Injector Neutrino Oscillation Search, the CDF experiment at Fermilab, and the CLEO experiment at Cornell University. In 2026 she was elected fellow of the American Association for the Advancement of Science.

Jessica Rotkiewicz/Brookhaven National Laboratory

What skills do you use every day in your job?

I enjoy brainstorming. If I am having a mental block or get stuck in a technical or personal interaction issue, I walk down the hall to chat with a colleague about their work – even if it isn't related to my own problem. This serves two purposes. First, it helps ameliorate the feelings of loneliness and frustration to discuss your challenges with others. Second, a surefire cure for any mental block is to divert your attention to a different topic. Another essential skill is to try to play devil's advocate with myself and colleagues. My team finds this infuriating sometimes, but it's vital – you need to be your toughest critic.

What do you like best and least about your job?

For a self-professed nerd like me, doing big science is heaven. I get to geek out on a broad set of technical and scientific challenges and work with lots of really cool experts from a variety of disciplines. Recently, for example, as part of DUNE, I've been looking at designs for the infrastructure that houses the Long Baseline Neutrino Facility. Located at Fermilab near Chicago, it will send the world's most powerful beam of neutrinos to a detector in an underground lab 1300 km away in South Dakota.

In any given week, I might find myself discussing the mechanical engineering of detectors or learning about the civil engineering required for large-scale facilities. I might be discovering fascinating details about the hydrogeology of the Fermilab site, exploring the design of focusing magnets, or studying the results of simulations of high-energy particle interactions in materials.

I could also find myself in a meeting of the artificial intelligence (AI) expert team, learning new AI approaches, such as improving the search for neutrinos from supernovae using our detectors. Wandering the hallways, I might bump into a colleague from Brookhaven's chemistry division and get chatting about new detector materials. I also work with theorists on new ideas for physics at DUNE.

I trained as an experimental particle physicist, but I'm happiest trying to connect the dots between physics goals and technical and engineering disciplines, coming up with multidisciplinary design solutions to realize these massive science projects. Best of all is when I ask a question in an area I'm not an expert in – say civil engineering – and someone replies: "Hmm, we hadn't thought about that."

I'm happiest trying to connect the dots between physics goals and technical and engineering disciplines, coming up with multidisciplinary design solutions to realize these massive science projects

My least favourite part of the job is that it can be very challenging to deal with large international collaborations of scientists and engineers over the very long time scales of large-scale projects. You need a lot of emotional resilience, stamina and patience to keep going for the decades it takes to get these large-scale projects to fruition. Burn out and despondency are downsides; keeping yourself and your team going is very difficult.

What do you know today, that you wish you knew when you were starting out in your career?

Always be honest to the science. If it looks like something you put a lot of effort into is a dead end, drop it; don't wait until someone tells you to stop. There will be a lot of dead ends before you find the right direction. When an approach fails, it means you have a new intellectual challenge – and that's the fun part. Don't be afraid to challenge established dogma and groupthink, even if it means difficult discussions with your colleagues no matter how senior. And most importantly, don't keep pushing when you are burning out. It's okay to step back and slow down for a while.

Research updates

IceCube examines neutrino energy spectrum

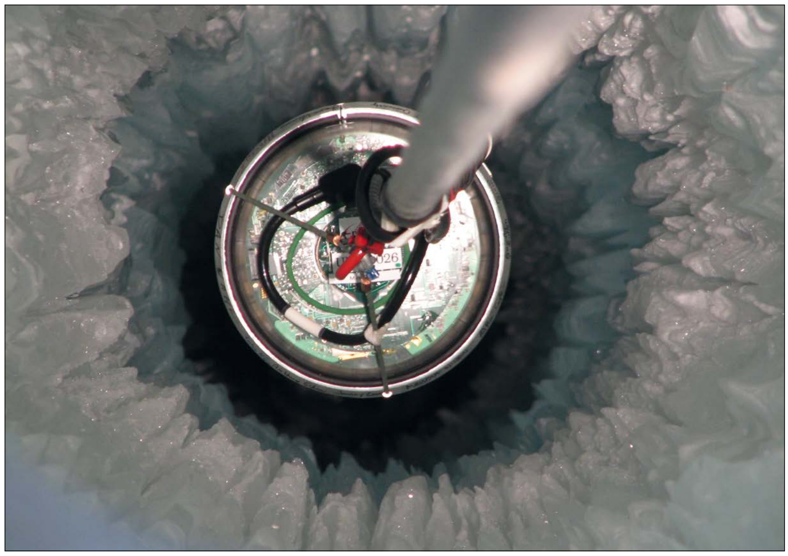
A new analysis of data from the IceCube Neutrino Observatory suggests that the energy spectrum of cosmic neutrinos is more complex than was previously thought. Whereas a previous study found that the energies of these ubiquitous, nearly massless particles follow a simple power law distribution, the latest analysis reveals a knee-like bend in the spectrum at around 30 TeV. The discovery could help astrophysicists better understand where cosmic neutrinos come from and what objects and processes in the universe are producing them.

Neutrinos are subatomic particles that are around a million times less massive than electrons. They are known to come in (at least) three different "flavours" – electron, muon and tau – but they have no electrical charge, and they interact with matter only rarely, via the weak nuclear force and gravity. This means they can travel vast distances through the universe without being deflected by magnetic fields or absorbed by interstellar material along the way.

Astrophysicists think cosmic neutrinos are produced in collisions between high-energy cosmic rays and other particles. Since cosmic rays are accelerated by a range of astrophysical sources – including gamma-ray bursts, active galactic nuclei powered by supermassive black holes, and other extreme cosmic processes – the neutrino spectrum is a way of gleaning information about where these sources are and how they work.

The catch is that because neutrinos interact so weakly, they must be studied using detectors with a very large volume. For this reason, neutrino scientists often use natural structures such as deep water or expanses of ice to support their detectors. These locations also have the advantage of being shielded from muons, cosmic rays and other sources of background noise.

Neutrino hunter New analyses by the IceCube observatory could help scientists understand where neutrinos form and what is producing them.


Mark Krasberg, IceCube/NSF

Caught in the tracks

The 5000 optical sensors that make up the IceCube observatory are suspended within a cubic kilometre of Antarctic ice. They are designed to detect the telltale flashes of visible and ultraviolet light that occur whenever a neutrino interacts with a molecule of ice. During these rare detection events, the neutrino either leaves behind an elongated track or produces a "cascade" in which its energy is contained in a small, spherical volume inside the ice.

IceCube's detectors have been operating since 2010 and the earliest data they produced suggested that the energies of the detected neutrinos followed a single falling power law distribution. Researchers were initially pleased with this result because it agreed with simple models that related cosmic neutrinos to cosmic rays, says Aswathi Balagopal V, a postdoctoral researcher at the University of Wisconsin, US, and a member of the IceCube collaboration. These models suggested that cosmic ray acceleration takes place exclusively in so-called shock environments where collision events produce neutrinos.

In the new work, Balagopal V and colleagues performed two different, independent, analyses on more than 10 years' worth of neutrino observations in the 1 TeV to 10 PeV range. The first analysis involved measuring a sample of neutrino cascades and a sample of neutrino tracks in the detector. The team then combined the results of both sets of measurements to characterize the neutrino spectrum (*Phys. Rev. D* **113** 062002).

The second analysis used a new event sample consisting of neutrinos with "interaction vertices" inside the detector (*Phys. Rev. Lett.* **136** 121002). "This sample therefore contains neutrinos of all flavours," explains Balagopal V, "and we performed a fit to the energy spectrum using these events."

Both analyses arrived at the same conclusion, rejecting a single power law distribution with a confidence of more than 4σ (the usual maximum confidence being 5σ). The best fit for the data was instead a broken power law, with the spectrum of neutrino energies falling more steeply at higher energies than at energies below around 30 TeV, Balagopal V told *Physics World*.

"This implies that there are fewer lower energy neutrinos when compared to what one would obtain with a simple extrapolation of the prediction from higher energies," she says. "This changing shape of the spectrum can indicate several things: either a changing population of cosmic neutrino sources; or a change in their production mechanism." If cosmic neutrinos come from more than one kind of astrophysical source, she adds, then each type may be accelerating cosmic rays in a different way.

A final option is that some theories suggest that interactions with dark matter can also produce such a spectral feature. "With these measurements, we have opened up the possibility of discoveries in any of these directions," Balagopal V says. "With more detailed analyses, we could identify if there are additional features in the energy spectrum and we are already analysing new IceCube data to this end."

Isabelle Dumé

'Forbidden range' of black hole masses emerges

Predictions that black holes cannot form within a certain "forbidden zone" of stellar masses have gained support thanks to a new analysis of gravitational waves detected by the LIGO–Virgo–KAGRA network of observatories. The analysis, which was conducted by researchers at Australia's Monash University adds weight to the theory that stars between 50 and 130 times more massive than our Sun end their lives in a type of supernova that was predicted in the 1960s but has never been directly observed (*Nature* **652** 874).

Most massive stars collapse at the end of their lives to form black holes. Theories of stellar evolution, however, suggest that stars in a middling-to-higher range of masses will instead explode as so-called "pair-instability" supernovas. These events are so powerful that they completely destroy the star, leaving nothing – not even a black hole – in its wake.

If this explanation is correct, there should be a gap in the observed range of black hole masses. Finding evidence of such a gap is not easy, but in recent years, researchers have developed a way of searching for it using observations of gravitational waves – the tiny ripples in space-time produced when super-heavy objects like black holes collide.

Identifying a mass gap

In the new work, researchers led by Hui Tong analysed data from LIGO–Virgo–KAGRA's fourth Gravitational-Wave Transient Catalog (GWTC-4), which contains information on the distribution of masses within binary black hole systems. Based on these data, the team report that there is indeed a gap in the masses of the smaller of the two black holes in the binary. None of these so-called secondary black holes had masses between 44 and 116 times the mass of the Sun

The masses of the primary (that is, larger mass) black holes in the binaries showed no such gap. However, the Monash researchers argue that their findings nevertheless support the "forbidden zone" theory. They point out that the mass range they identified is very similar to the range over which primary black holes in a binary start to spin more rapidly. According to Tong, this shift could mean that these black holes formed via a different mechanism. For example, they may have formed from merging black holes rather than directly from collapsing stars.

Carl Knox, OzGrav – Swinburne University of Technology

Champagne supernova Scientists suspect that stars in the "forbidden range" may form a long-predicted type of supernova.

If confirmed, Tong says this hypothesis could change our understanding of how massive stars evolve and how black holes are born. "We are essentially using something invisible, black holes, as a record of some of the brightest explosions in the universe," he says. "Instead of observing the explosion directly, we infer its effect from what is left behind in the black hole population. In doing so, we can connect the properties of these remnants to what happened inside the star at the moment of explosion."

Detecting an absence

Although pair-instability supernovae were predicted six decades ago, Tong says that traditional light-based (electromagnetic) telescopes struggle to detect them because they are rare, distant and leave little direct trace that can be uniquely identified. In this respect, he says that gravitational-wave astronomy could be game-changing: "The detection of gravitational waves allows us to 'hear' the violent collisions of the most compact objects in the universe and directly measure the properties of black holes across cosmic time."

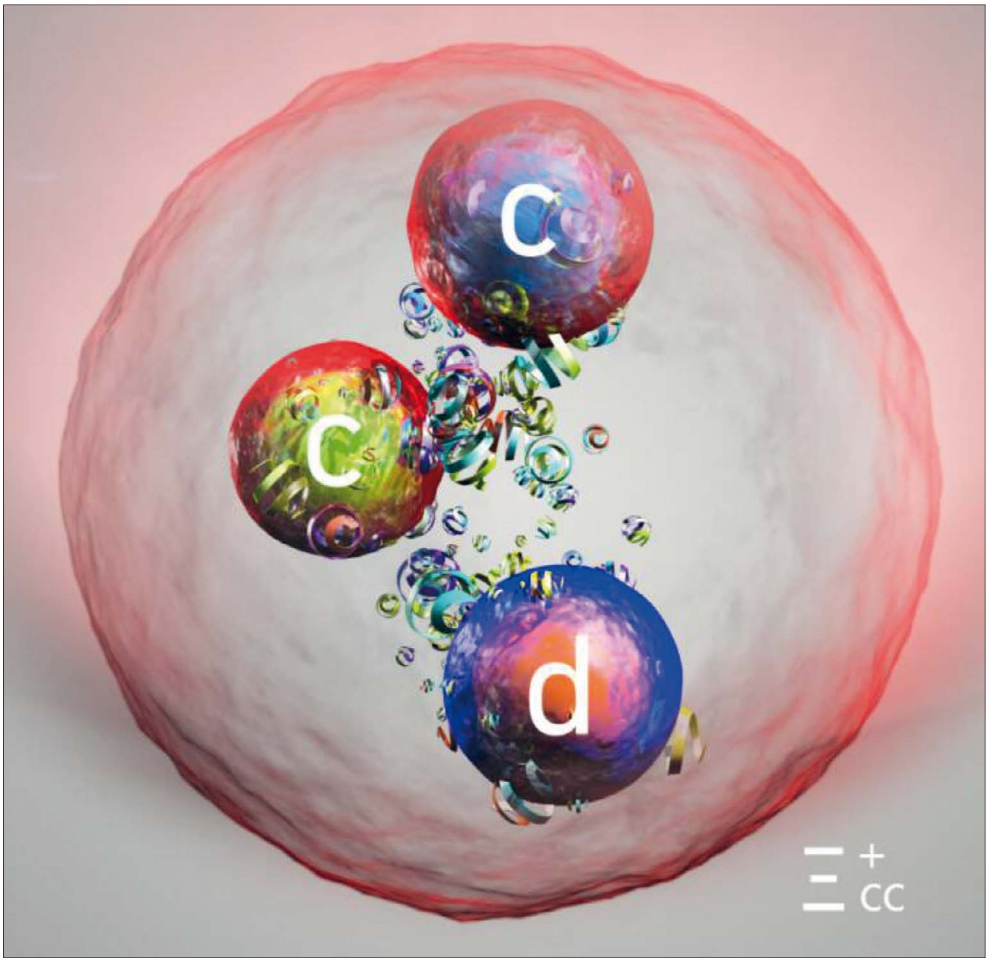
Even with this new tool, though, the work was not without difficulties. One of the biggest challenges, Tong recalls, was figuring out whether patterns observed in the black hole masses were real. "A large part of our work therefore involved testing different assumptions in our models and checking whether the results still held," he says. "That process takes time, but it's essential for building confidence that we're truly uncovering how black holes form and evolve."

Tong hopes that future gravitational-wave observations will steadily increase the number of detected black hole mergers, allowing researchers to build a much clearer picture of black hole mass distribution. "In the near term, current detectors such as LIGO will continue to improve this picture by finding more events and reducing uncertainties, helping us confirm how robust the features really are," he explains. "Then, next generation gravitational wave observatories planned for the 2030s will be transformative. With their much greater sensitivity, they will be able to detect black hole mergers from across a large fraction of the observable universe, potentially observing tens of thousands of merging black holes per year."

Turning gravitational wave astronomy from a field with hundreds of detections into one with an almost continuous stream of black hole signals would bring enormous advantages, Tong adds. "It would allow us to see far more distant and fainter systems, including black holes formed when the universe was only a few billion years old (compared to its current age of about 13.8 billion years), during its early and more active stages of star formation and trace how stars evolve over the history of the cosmos."

Isabelle Dumé

Heavier cousin of the proton discovered at the LHC



CERN

Doubly charmed The particle Ξ_{cc}^{+}, which has been discovered by the LHCb experiment at CERN, contains two charm quarks and a down quark.

Researchers at the Large Hadron Collider (LHC) have discovered a new particle: Ξ_{cc}^{+}, ("Xi cc plus"), which is a heavier cousin of the proton. The particle's fleeting existence had made it invisible for decades, but the upgraded LHCb detector captured it in just one year of data, opening a new window into the forces that hold quarks together.

Quarks are the fundamental building blocks of protons and neutrons, which in turn combine to form atomic nuclei. Protons themselves are made from two up quarks and one down quark, held together by the strong force. This is described by a sophisticated theory known as quantum chromodynamics (QCD). The Ξ_{cc}^{+} is unusual because it replaces the two up quarks with heavier charm quarks, keeping just one down quark.

"Up and down quarks are labels we give to distinguish the different types of quark," Tim Gershon of the University of Warwick, told *Physics World*. "In the Ξ_{cc}^{+}, both up quarks are replaced by the heavier charm quark. Since the charm and up quarks differ only by their mass – in particular having the same charge – this provides an ideal way to test QCD," explains Gershon who is spokesperson-elect for LHCb.

This quark content change makes the Ξ_{cc}^{+} roughly four times heavier than a proton. Its extremely short lifetime, less than a trillionth of a second, is why previous experiments could not detect it, despite the particle being produced frequently in LHC collisions.

More to come

"The key development that made the observation possible was the upgrade of the LHCb detector," Gershon says. "We could observe the Ξ_{cc}^{+} in one year of data-taking, while we had not been able to do so in a decade of data collected with the original LHCb detector."

The Ξ_{cc}^{+} appears briefly in proton–proton collisions before decaying into three lighter particles: a Λ_c^{+} baryon, a K^- meson, and a π^+ meson. These decay further into five final particles, including a proton, two K^- mesons, and two π^+ mesons. By reconstructing the trajectories of these particles, researchers saw a sharp signal corresponding to the existence of the Ξ_{cc}^{+} particle.

This observation also settles a longstanding question. Over twenty years ago, the SELEX experiment at Fermilab in the US reported hints of the particle. However, the signal could not be confirmed. The LHCb measurement provides a clear, unambiguous detection.

"Studies of particles containing two heavy quarks are very interesting for tests of the QCD binding mechanisms, and this observation provides important new data in that direction," Gershon says.

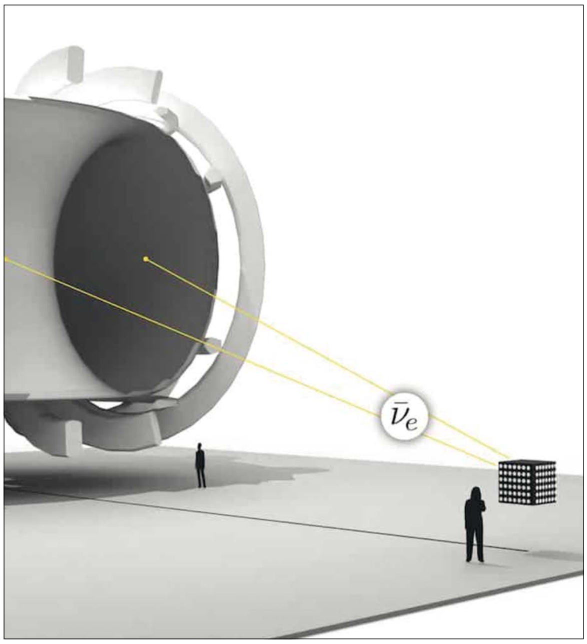
The discovery relied on upgrades to the LHCb detector. A silicon pixel system called the Vertex Locator tracks particle paths with incredible precision, while a Ring Imaging Cherenkov system identifies particle types based on the light they emit. These improvements allow the detector to collect much larger amounts of data than before, making rare particle discoveries possible.

The discovery of the Ξ_{cc}^{+} is just the beginning. Physicists now aim to measure its properties in detail, including its lifetime and additional decay channels. Beyond this, they hope to find even heavier cousins, where one or both charm quarks are replaced by a beauty quark – called Ξ_{bc} and Ξ_{bb} respectively.

"These may be out of reach with the current LHCb detector – although we will try our best." Gershon says. "But we do expect to be able to observe them with a future upgrade called LHCb Upgrade II. Unfortunately, the UK funding for this upgrade has recently been put in doubt due to decisions made at the UKRI funding agency. This latest result reiterates the uniqueness of LHCb – no other experiment can make these measurements – and the importance of finding a solution to be able to fund LHCb Upgrade II."

Andrey Feldman

Neutrinos could tackle spread of nuclear weapons



A Glaser

Telltale pattern Monitoring antineutrino emissions from a fusion reactor could enable scientists and authorities to determine whether the reactor is being used to generate fissile material.

Telltale patterns of antineutrino emissions could reveal whether fusion reactors have been reconfigured to produce material for nuclear weapons, say physicists in the US. Although commercial fusion power plants are still some years away, members of the team at Virginia Tech and Princeton University argue that it is nevertheless useful to develop robust ways of monitoring their output now, to ensure the technology is not misused (*Phys. Rev. Applied* **25** 064004).

"Neutrinos cannot be shielded, their signatures cannot be spoofed and they can be detected from a distance, either onsite or offsite, allowing for nonintrusive monitoring of reactor operation," says team member Patrick Huber, a physicist at Virginia Tech's Center for Neutrino Physics. Better still, the team's calculations show that existing antineutrino detectors such as Virginia Tech's mobile MiniCHANDLER are sensitive enough to spot these signatures.

Most fusion technologies rely on the deuterium-tritium (DT) fusion process, which occurs when a deuterium nucleus (a proton bound to a neutron) and a tritium nucleus (one proton and two neutrons) fuse to produce helium-4, a free neutron and large amounts of energy. Because fissile materials are not directly involved in this reaction, the nuclear proliferation risk of fusion reactors is widely regarded as being much lower than that of fission power plants.

That said, if neutrons released in the DT process were combined with small amounts of material such as uranium-238 or thorium-232 in the "blanket" that surrounds the DT fuel in the fusion reactor, it would, in principle, be possible to use the reactor to produce plutonium-239 or uranium-233. Both materials are used in nuclear weapons, and a gigawatt-scale fusion reactor operating in this mode could produce tens of kilograms per week – enough for several first-generation bombs.

Nuclear fingerprints

Crucially, though, this clandestine production would not necessarily go unnoticed. Whenever radioisotopes in the blanket absorb neutrons during the fusion process, they give off a distinctive pattern of antineutrinos. And according to the Princeton-Virginia Tech team's simulations, the current generation of antineutrino detectors is already capable of distinguishing this pattern from the one produced during normal reactor operations.

In the current study, the researchers focused on the plutonium antineutrino signal. Using a Monte Carlo particle transport code called MCNP6, they modelled the output of a simplified toroidal fusion reactor with an outer radius of 6.2 m and an inner radius of 2.0 m. This reference reactor would operate at a typical power density, and Huber explains that it would produce a total of 1500 MW of power through plasma fusion via the DT reaction. The team also analysed two designs for the "blanket": one featuring a molten salt (LiF-BeF_2 or FLiBe) and one that relied on dual-coolant lead-lithium (DCLL).

Next, the two Princeton members of the team, Alexander Glaser and Robert James Goldston, defined and evaluated a reference fissile material production scenario. As part of this, they estimated both the plutonium production rate and the energy release that occurs as some of the covertly introduced nuclear material undergoes fission. Huber explains that this evaluation provided the first part of the antineutrino background signal.

Glaser and Goldston then analysed the neutron activation and antineutrino signatures driven by neutrons emanating from the fusion plasma. These provided the second part of the background. Finally, the team used these signatures to assess the detectability of covert fissile material production against the combined background from neutron activation and cosmogenic antineutrinos.

Based on these simulations, the team concluded that a detector like MiniCHANDLER could pick up on the production of a few kg of plutonium over 30 days – a result that Huber says should be applicable to any fusion power system that relies on DT fusion. Importantly, he points out that unlike some alternatives, antineutrino-based monitoring does not require inspectors to have access to reactor buildings and could allow plants to be monitored around the clock.

Practical advantages

The idea of using antineutrinos to detect illicit nuclear material production is not new. It dates back to the 1970s, and the two Princeton team members have previously worked on nuclear monitoring and verification for a variety of nuclear reactors and nuclear fuel-cycle facilities (including some in Iran). Given the rapid development of fusion energy systems, Huber told *Physics World* it was "a natural next step" to consider non-intrusive, antineutrino-based monitoring options for them, too. He adds that the group has been studying possible safeguards for fusion reactors since the early 2010s and was part of an IAEA consultancy on the topic in 2013.

As well as optimizing the design of detector systems, Huber says he and his colleagues are also interested in studying thorium as an alternative "fertile" material. "Even though the fission signature would be weaker compared with the uranium reference case analysed in this study, the results we have reported on already suggest that such an effort is well justified," he says.

Isabelle Dumé

Nanopositioning, customization and control: opening new frontiers in optical computing

SmarAct, a German specialist in high-precision positioning, automation and metrology systems, is developing enabling technologies to translate the theoretical potential of all-optical computing into scalable real-world applications

German technology start-up Akhetonics is reimagining the future of high-performance computing (HPC), deploying its proprietary know-how in photonic-design automation and photonic integrated circuits (PICs) to realize the first all-optical digital computation devices. The end-game: an all-optical digital processor – what Akhetonics calls its reasoning processing unit (RPU) – that will fundamentally transform the way that data is processed, transmitted and stored at every level of the HPC stack.

While the anticipated upsides of photonic computing are compelling – think bandwidth scaling, energy-efficiency and reduced latency – the translation of Akhetonics' R&D effort and early-stage PIC designs into at-scale implementation is still in its infancy. What's evident even now, though, is that the start-up's progress is being accelerated by collaboration, interdisciplinary expertise and innovation spanning photonic system design and precision-motion and control technologies.

Akhetonics

Photonics reimagined SmarAct and Akhetonics worked together to build a versatile optical test set-up to characterize next-generation photonic integrated circuits (PICs). SmarAct's nanopositioning systems form the precision-motion core of the test workstation, while the positional reproducibility allows Akhetonics to map the full optical chip and evaluate large grids of test components rapidly and reliably.

Collaboration, co-development, customization

A case study in this regard is Akhetonics' partnership with SmarAct, a German manufacturer and developer of specialist products for nano- and picometre-precise positioning, metrology and automated assembly. Both companies are shaping the future of photonics, albeit along complementary tracks: Akhetonics with its vision of a full-stack photonic computing architecture; SmarAct with a portfolio of enabling technologies that's helping to make next-generation optical computing a practical proposition.

The two vendors began working together after an initial meeting four years ago at the European Conference on Optical Communication (ECOC 22) in Basel, Switzerland. Top of the Akhetonics shopping list: a versatile optical test system to characterize its advanced PICs.

"There are off-the-shelf PIC characterization systems on the market, but they all impose constraints on our design options," explains Leonardo Del Bino, co-founder and chief technology officer (CTO) at Akhetonics. "Instead, we teamed up with SmarAct to co-develop a compact and modular test architecture built to our exacting specifications. The resulting set-up gives us the flexibility to evaluate and optimize all sorts of innovative PIC designs."

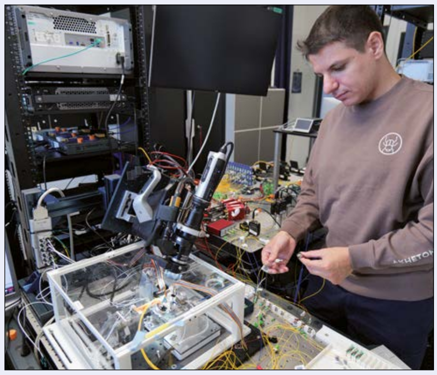
At the heart of the Akhetonics optical testing workstation sit two discrete nanopositioning subsystems: an XY-Rz chip platform (itself comprising three nanopositioning stages offering horizontal translation along the X and Y axes and rotation limited to the Z axis) and a Z-Rx-Ry "pivot" for an optical probe (where translation occurs only along the Z axis, with simultaneous angular rotation around the X and Y axes). The test set-up (which also incorporates a digital microscope for PIC inspection and alignment) can be used without restriction in every degree of freedom, with the two subsystems working in tandem to ensure precise multi-axis positioning for optical coupling and electro-optic characterization tasks.

On a more granular level, each nanopositioning subsystem is based on SmarAct positioners equipped with integrated optical encoders (SmarAct's METIRIO® sensors with a resolution of 1 nm) along all six axes of motion. The first subsystem provides three degrees of freedom for lateral alignment (with 49 mm travel in both X and Y, 360° rotation around Rz and a unidirectional positional repeatability of ±40 nm per linear axis). The second subsystem provides vertical and angular alignment (with 31 mm travel in Z, ±5° tilt around Ry, ±45° rotation around Rz and a unidirectional

SCoPE in brief

The SmarAct Control and Process Environment (SCoPE) is a modular and extensible software application platform that combines visual process modelling, Python scripting and hardware integration. SCoPE enables customers to develop, control and run automated processes in a unified environment that offers…

- **Process modelling and automation**: visual drag-and-drop process editor enables intuitive creation, control and execution of automation workflows. Live process display gives users direct feedback during execution.
- **Python scripting backend**: integrated Python scripting allows developers to extend workflows with custom logic, algorithms and third-party devices to create advanced automation scenarios. Package and dependency management are built-in.


Akhetonics

Reciprocal benefits The custom test system is the result of an ongoing collaboration between the engineering team at Akhetonics and the product development team at SmarAct.

- **Device control and hardware integration**: native support for SmarAct hardware such as positioning systems, controllers, grippers and interferometers through specialized plug-ins.
- **Custom user interfaces**: flexible Qt widget integration makes it possible to build tailored graphical user interfaces for specific applications.
- **Data visualization and imaging**: configurable plotting widgets, real-time data visualization, process messaging and an integrated image processing pipeline support instant process feedback and image-based automation tasks.
- **Plug-in architecture**: the modular plug-in system enables SmarAct and third parties to extend SCoPE with additional functions, algorithms, hardware integrations or communication interfaces.

positional repeatability of ±40 nm for the linear Z axis).

To evaluate new PIC designs, Akhetonics' optical test routines focus primarily on measuring and minimizing insertion losses between input/output fibres and on-chip planar waveguides. Typical measurements include wavelength- and polarization-dependent coupling losses (for example, when a fibre array couples laser light into a series of on-chip grating couplers or when light is coupled from a planar waveguide back into an optical fibre). The subsequent integration of electrical probes into the test system (using two separate XYZ probe towers) supports electro-optic characterization of key on-chip building blocks like optical modulators and photodetectors.

"The requirements for the electro-optical testing are nothing crazy," says Del Bino. On-chip electrical contacts are in the ballpark of 100 µm x 100 µm, so Akhetonics engineers need positional and alignment precision an order-of-magnitude better than that for their electrical probes. "On-chip optical testing is a different story," he adds. "A fibre-waveguide mismatch of 1 µm means significant coupling losses, so we need positional accuracy and repeatability of tens of nm or less."

The rewards of reciprocity

Operationally, the custom test system is the result of ongoing collaboration between the engineering team at Akhetonics and the product development team at SmarAct. After firming up performance requirements, the two vendors iterated back-and-forth with 3D CAD drawings before converging on a final agreed system design.

"We supplied the nanopositioning stages


Akhetonics

Versatility is the key Leonardo Del Bino, Akhetonics' CTO.


SmarAct

Line-of-sight Max Trippel, SmarAct's business development manager for photonic applications.

that form the precision-motion core of the workstation," explains Max Trippel, SmarAct's business development manager for photonic applications. Akhetonics then integrated these modules into its own test environment, including the fibre and fibre-array-unit holders; the required optical and electrical measurement equipment; and the software routines for photonic characterization. "This approach gives Akhetonics the flexibility to build exactly the test workflow it needs, while relying on a stable and repeatable positioning platform," Trippel adds.

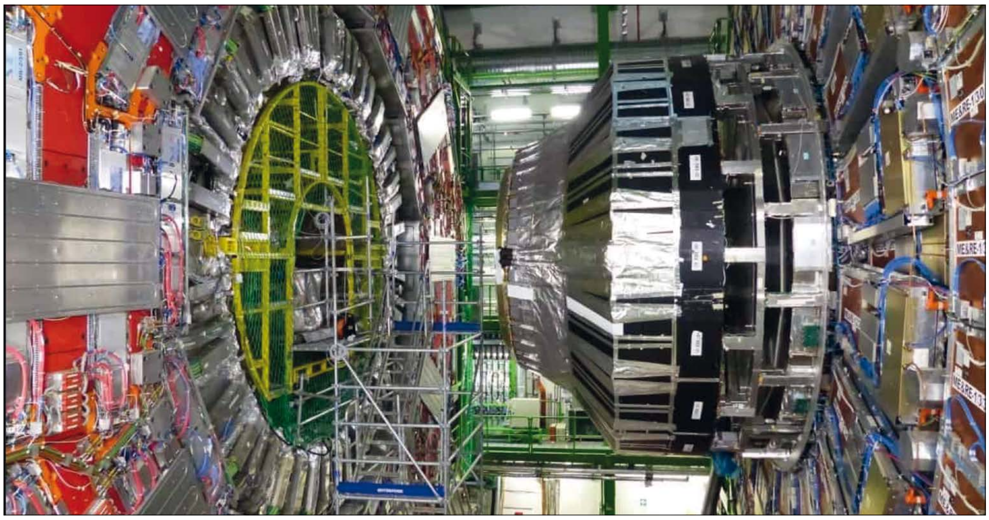
Crucially, the SmarAct software "ecosystem" and Python interface make it easy to integrate the nanopositioning stages within Akhetonics' PIC test routines. That software application platform, known as the SmarAct Control and Process Environment (SCoPE), also creates opportunities for continuous process improvement and product innovation (for example, the ability to develop custom routines for fast calibration and alignment on all axes).

In this way, SCoPE will be a natural fit as Akhetonics transitions its PIC testing programme from an R&D setting through small-batch production runs and, ultimately, to volume manufacturing capability (see "SCoPE in brief", above). "Our goal with SCoPE is to provide customers with easy access for system development, whether that's for the testing or assembly of photonic components," says Trippel. "SCoPE is a living platform and we're constantly integrating novel functionalities and application-specific plug-ins as well as features to facilitate control of third-party devices."

Strategically, the SmarAct-Akhetonics partnership is shaping up as a win-win for the long term, with the latter's growth trajectory and evolving platform technologies feeding into SmarAct's product development roadmap. "Our customers' success is our success," Trippel concludes. "Working in this way with Akhetonics and its peers means we have line-of-sight on 'what's next' in photonic computing. Watch this space: the last word has not been spoken."

Research updates

Tiny droplets of primordial soup appear in oxygen collisions



Matin Durrani

Cosmic conditions Oxygen collisions at CERN's Large Hadron Collider could have created a quark–gluon plasma.

Colliding oxygen nuclei could briefly recreate one of the most extreme states of matter in the universe – according to evidence gathered by physicists working on the CMS Collaboration at the Large Hadron Collider at CERN. Their analysis suggests that when smashed together, even relatively small atomic nuclei can produce a tiny droplet of quark–gluon plasma (QGP). This is a superhot "soup" of elementary particles that is believed to have filled the universe just after the Big Bang (*Phys. Rev. Lett.* **136** 162301).

Under normal conditions, quarks – the particles that make up protons and neutrons – are tightly bound together by gluons, which carry the strong nuclear force. But at extremely high temperatures, matter changes into a radically different form in which quarks and gluons move freely in a dense fluid-like state called a QGP.

Scientists believe the entire universe existed in this form for a tiny fraction of a second after the Big Bang. To recreate it here on Earth, physicists smash atomic nuclei together at nearly the speed of light.

One of the main ways researchers study this strange state of matter is by observing the fast-moving particle sprays created during the collision. In the absence of a QGP these energetic particles would travel outward freely. But if they pass through QGP, they lose energy, somewhat like a bullet slowing down in water. Physicists call this effect jet quenching.

"Jet quenching is one of the main tools we use to study the QGP," explains Jiangyong Jia of Stony Brook University in the US, who was not involved in the CMS study. "When a high-energy collision produces a QGP droplet, energetic quarks and gluons created in the same collision have to travel through it, and they lose energy along the way."

For many years, this energy-loss effect had only been clearly observed in collisions involving very heavy nuclei such as lead or gold. Lower mass systems, including collisions between protons and heavier nuclei, showed hints of unusual behaviour but no convincing evidence that particle jets were being slowed down.

The new CMS study examined collisions between oxygen nuclei, which are much smaller than lead nuclei. Oxygen contains just 16 protons and neutrons, compared with 208 in lead. This allowed researchers to investigate how small a droplet of QGP can become while still affecting energetic particles passing through it.

The collisions were performed in 2025 at an energy of about 5 TeV – the highest energy ever for oxygen ions. The CMS Collaboration measured how many high-energy particles emerged from the collisions. This was compared to simpler proton–proton collisions, which are not expected to result in jet quenching.

The physicists found a clear reduction in the number of energetic particles produced. At some energies, the suppression reached about 30%, far beyond what could be explained by random statistical fluctuations. The pattern looked remarkably similar to what researchers had previously observed in much larger lead–ion collisions, although the effect was weaker overall.

"Oxygen-16 has only 16 nucleons compared to 208 in lead, but it appears to produce a medium that absorbs jet energy in a qualitatively similar way to much heavier systems," Jia explains. "The shape of the suppression curve in oxygen–oxygen collisions resembles what is seen in lead–lead, which suggests the underlying physics is the same."

The team compared its measurements with several theoretical models. Models that included energy loss caused by QGP generally matched the data better than models without it. Still, some uncertainty remains. Part of the observed effect may come not from a QGP itself, but from differences in how quarks and gluons are distributed inside oxygen nuclei before the collision even occurs.

"The main limitation right now is the nuclear parton distribution functions," Jia says. These describe how quarks and gluons are arranged inside atomic nuclei. According to Jia, uncertainties in these distributions "can account for roughly half of the observed suppression on their own".

Future experiments involving proton–oxygen collisions are expected to help clarify the picture. The findings may also reshape how physicists think about the minimum size needed to create QGP.

"It shows that QGP formation is not limited to heavy nuclei," Jia says. "It can occur in collisions of nuclei as light as oxygen."

Researchers now hope to compare oxygen with other light nuclei such as neon to understand how the properties of QGP change as the colliding systems become larger or smaller. The work could eventually help physicists build a more complete picture of how ordinary matter behaved in the universe's earliest moments – and how the strong nuclear force operates under the most extreme conditions known in nature.

Andrey Feldman

Atom-like system bound by the strong force detected

Signs of an exotic atom-like system made up of a neutral meson bound to an atomic nucleus via the strong interaction have emerged in experimental data from two international collaborations (*Phys. Rev. Lett.* **136** 142501). If confirmed, this hitherto unobserved system could shed light on the origins of hadron masses and provide new insights into the fundamental symmetries of quantum chromodynamics in nuclear matter.

The strong interaction is one of the four fundamental forces of nature, alongside gravity, electromagnetism and the weak interaction. It is responsible for binding quarks into hadrons, which are three-quark particles such as protons and neutrons, and for holding protons and neutrons together within atomic nuclei.

Electrically neutral mesons – short-lived particles made up of a quark and an antiquark – are likewise subject to the strong interaction, which can bind them to atomic nuclei in a way that is conceptually similar to an electron bound to a nucleus by the electromagnetic force.

Studying these meson-based nuclear systems is important because it helps us better understand the properties of the strong interaction, says study co-leader Yoshiki Tanaka of RIKEN in Japan. The eta prime meson, η', is particularly interesting, Tanaka adds, because its relatively large mass cannot be explained by a simple quark model. "This U(1) problem, as it known, was raised as long ago as the 1970s by the physicist Steven Weinberg," he notes.

Rare events

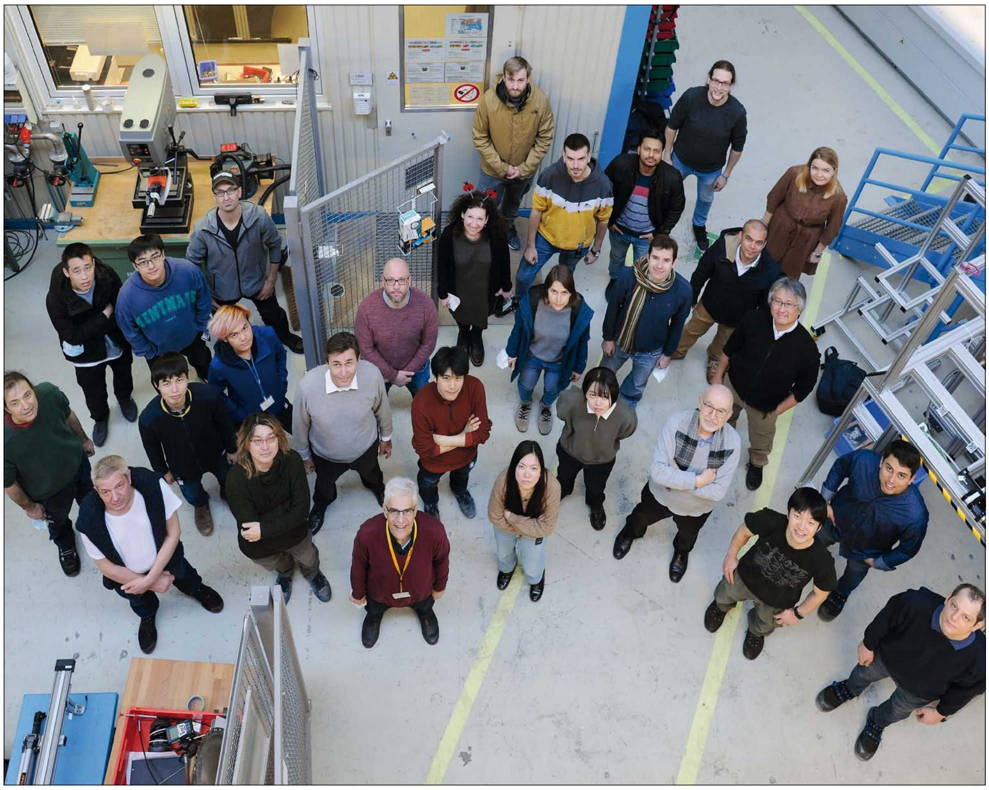
Modern theories attribute the η' meson's large mass to the presence of chiral symmetry breaking in quantum chromodynamics, which is the fundamental theory of the strong force. These theories predict that this mass should be reduced in a nuclear system, and this is what Tanaka and colleagues set out to test.

"Spectroscopy studies of η'-mesic nuclei provide direct experimental access to the η'-meson mass in nuclei and offer a unique opportunity to investigate the underlying mechanisms of how the mass of hadrons comes about," he explains.

In the team's study, a beam of protons strikes a ^{12}C atomic nucleus at near-relativistic speeds and removes a neutron from it. This neutron, together with a proton, forms a deuteron that propagates away in a forward direction, leaving behind a nucleus of ^{11}C in a highly energetic state. It is this excess energy that gives rise to an η'-meson.

In rare cases, the researchers explain, the meson then binds to the ^{11}C nucleus, forming an η'-mesic nuclear system. But because these events are so rare, they are hard to find. "One of the major challenges we encountered in the work was the very large amount of background events we registered during our measurements," Tanaka recalls. "These were about 100 to 1000 times higher than the signal events."

The researchers overcame this problem by developing a new experiment that allows them to efficiently select signal events associated with the formation of η'-mesic nuclei by "tagging" the particles they decay into. This enabled them to measure not only the forward-travelling deuteron, but also the decay products of the short-lived η'-mesic nuclear state.


G Otto, GSI/FAIR

Strong signs Observations of a nucleus paired with a neutral meson could provide new insights into the theory of quantum chromodynamics.

The researchers say that their results indicate that the η'-meson mass drops by about 60 MeV in nuclear matter. "This result qualitatively supports the theoretical scenario [that attributes] the origin of the η'-meson mass to chiral symmetry breaking together with the dynamics of gluons (massless particles that mediate the strong nuclear force) in general," Tanaka says.

Members of the team, which also includes researchers from the η-PRiME Collaboration and the Super Fragment Separator Experiment Collaboration, together with physicists from Justus Liebig University Giessen in Germany with their working groups GSI/FAIR, say they are now planning follow-up experiments to confirm that they have indeed observed η'-mesic nuclei. "We also aim to increase the significance to the 5σ level, which is required to firmly establish the discovery on new quantum states in particle and nuclear physics," Tanaka says.

Isabelle Dumé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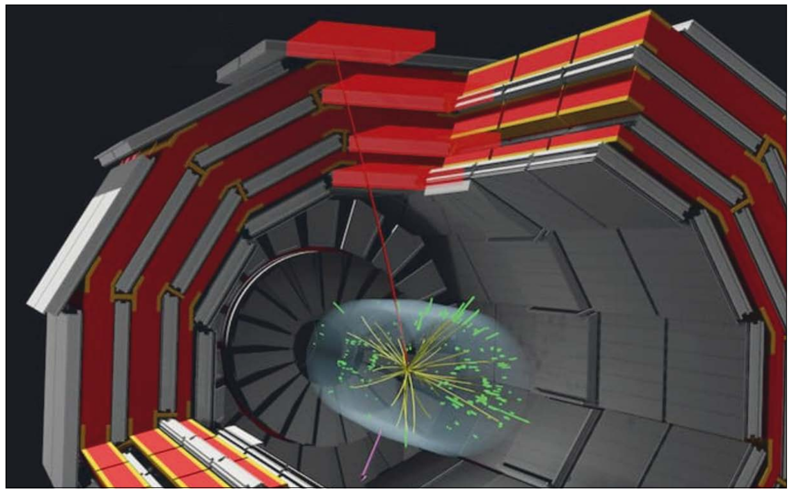
CERN makes most precise W boson mass measurement



C Paus

Particle fever
The new result of the W boson's mass agrees with the Standard Model of particle physics

Physicists have determined the mass of the W boson with the highest precision yet by analysing more than a billion proton collision events at CERN's Large Hadron Collider (LHC). The new result confirms a prediction from the Standard Model of particle physics while refuting a comparably precise measurement made by Fermilab's CDF Collaboration in 2022. This is significant because the older measurement, which used data from the defunct Tevatron collider, differed from the Standard Model's predictions by seven standard deviations, suggesting that the W boson might be far heavier than the model allows (*Nature* **652** 321).

The W boson is one of two elementary particles that acts as a carrier for the weak force (the other is the Z boson). As one of the four fundamental forces in nature, the weak force is what allows protons to change into neutrons (and vice versa), making it the driving factor behind radioactive decay and nuclear fusion. Precise measurements of the W and Z boson basses are therefore important for understanding these processes as well as for testing the Standard Model.

While physicists have measured the mass of the Z boson to an extremely high precision of 22 ppm (or 2.0 MeV), measuring the mass of the W boson with the same exactitude has proven more difficult. The main hurdle is that the W boson cannot easily be detected in colliders such as the LHC because it decays almost instantly. Scientists can look for its decay products instead, but that, too, is awkward. In one important channel, for example, it decays into a neutrino and a muon – and neutrinos are even more elusive than W bosons.

A fading mystery

In the new work, CERN's Compact Muon Solenoid (CMS) Collaboration studied more than a billion proton collision events produced at the LHC in 2016. Amongst these, they identified 100 million as producing a W boson that decayed into a neutrino and a muon.

By analysing these events and simulating all the possible scenarios that could produce them, they measured the mass of the W boson to be 80360.2 ± 9.9 MeV. This is significantly less than the CDF Collaboration's measurement, but it agrees with other previous experiments. Importantly, it also lies within the range the Standard Model predicts, leaving the CDF result – the most precise measurement before this one – looking like an outlier.

"If you take the CDF measurement at face value, you would say there must be new physics beyond the Standard Model," says Christoph Paus, a physicist at the Massachusetts Institute of Technology (MIT) in the US and one of the lead investigators of the CMS Collaboration. "And of course, that was the big mystery."

Now that the new, even more precise measurement agrees well with predicted values for the W boson mass, that mystery is fading, Paus tells *Physics World*.

Some physicists may find this disappointing. However, study lead author Kenneth Long, who was a senior postdoc in MIT's Laboratory for Nuclear Science at the time and has since moved to a research position in Lyon, France, says the new result is "just a huge relief to be honest" and "a strong confirmation that we can trust the Standard Model".

Precision measurement

To obtain their result, the CMS researchers needed to measure the momentum of the muon and use it to infer the W boson's mass. This is possible for two reasons. The first is that in the W's rest frame, its decay energy is shared roughly equally between its two daughter particles (the muon and the neutrino). The second is that muons are charged leptons, and the strong magnetic field inside the CMS detector makes them travel in a path whose curvature is a function of their momentum.

"The momentum is different to the mass, of course, but is strongly correlated with it," explains Paus. "The challenge is therefore to track the path of the muon and every possible interaction it could have with other particles and its surroundings to estimate a value for its initial momentum."

The CMS experiment had long planned on doing such a measurement, but it took a while to set up. Now that the measurement is complete, Paus, whose MIT group joined the W boson mass analysis effort in earnest at the end of 2020, describes it as an important starting point for the collaboration. He explains that the result proves it's possible to measure the W boson in what he calls a "high pile-up environment", meaning one where many proton–proton collisions overlap in a single recording, without using the Z boson mass as a calibration as was previously done in analyses at hadron colliders. "It has put the CMS experiment finally on the map for an electroweak precision measurement of this kind," he says.

The CMS researchers are now collaborating with experimentalist colleagues at CERN's ATLAS and LHCb detectors, as well as their theorist partners, in hopes of setting a new standard in electroweak precision physics.
Isabelle Dumé

Research updates

New record for matter-antimatter symmetry test


Jay SuhCredit

Fine result CERN's ALPHA collaboration has pinned down the ground-state hyperfine splitting of antihydrogen within four parts per million.

A new measurement of the ground-state hyperfine splitting in antihydrogen shows that it is identical to that of normal hydrogen to within four parts per million – two orders of magnitude more precise than previous experiments. Although the measurement by CERN's ALPHA collaboration did not reveal any asymmetries between matter and antimatter, the result is nevertheless a milestone in the search for reasons why the universe appears to be made up almost entirely of matter, with only minute amounts of antimatter (*Nature* **654** 52).

According to the Standard Model of particle physics, all matter particles have a corresponding antimatter particle that is identical to them in every way apart from their charge and magnetic properties, which are reversed. If this model is correct, then the Big Bang that formed our universe nearly 14 billion years ago should have generated equal amounts of antimatter and matter. But in that case, neither we nor almost everything else we observe should exist, because pairs of antimatter and matter particles annihilate each other whenever they collide.

"This apparent lack of antimatter in the universe remains one of the biggest mysteries in modern physics and suggests there is something about antimatter and matter that we do not understand," says Timothy Friesen of the University of Calgary, Canada, one of the lead authors of the paper on the new measurement.

In pursuit of precision

To look for subtle asymmetries that might explain why matter triumphed and antimatter all but disappeared, ALPHA is performing precise measurements on the simplest antimatter atom: antihydrogen, which consists of an antiproton bound to an antielectron, or positron.

These measurements take place at the CERN Antiproton Decelerator Facility using the ALPHA-2 antihydrogen apparatus, which is designed to prevent antihydrogen from coming into contact with normal matter. It does this by confining the antimatter within a cylindrical Penning–Malmberg trap under an extremely high vacuum and surrounded by strong superconducting magnets. These magnets suspend the antimatter in the trap so that it does not touch the walls of the container it is held in, preventing it from annihilating before measurements can take place.

In the latest work, the ALPHA collaboration focused on a parameter known as hyperfine splitting. This splitting occurs because magnetic interactions between the spins of the antiproton and positron cause the positronic ground state in antihydrogen to split into four sublevels, which the researchers label $|a\rangle$, $|b\rangle$, $|c\rangle$ and $|d\rangle$.

In hydrogen, the magnitude of this hyperfine splitting has been measured extremely precisely – we know its value to within a few parts per trillion – and it is particularly sensitive to the structure of the proton. Measuring this splitting in antihydrogen with the same precision would therefore be an excellent way of searching for differences between matter and antimatter. Previously, however, the most sensitive measurements only managed a precision of 400 parts per million (ppm).

Further improvements

To push beyond this level, the ALPHA researchers applied pulses of microwaves at frequencies between 28 GHz and 31 GHz to induce the positron spin flip transitions $|c\rangle \rightarrow |\mathrm{b}\rangle$ and $|d\rangle \rightarrow |a\rangle$ between the hyperfine levels of ground-state (2S and 1S) antihydrogen atoms. By measuring the frequencies at which these transitions occurred, they could then calculate the hyperfine splitting energy.

"At a magnetic field of 1 Tesla, we measured the hyperfine splitting for antihydrogen to a precision of 4 ppm – a result that has allowed for one of the best comparisons of matter-antimatter symmetry in antihydrogen ever," Friesen says.

While the new measurement is precise enough to push experiments into a regime that is sensitive to the structure of the antiproton, Friesen notes that it is still five orders of magnitude less precise than comparable measurements in ordinary hydrogen. "The comparisons at this level of precision with matter hydrogen are identical, and our current models of physics therefore still hold," he says.

The team does have some ideas for further improvements. "To push the measurement to improved precisions we are aiming to induce antiproton spin flip transitions, since these can be less sensitive to magnetic field inhomogeneities, which are our biggest systematic uncertainty," Friesen explains. "This, combined with laser cooling the antihydrogen samples to reduce the width of our spectroscopic line-shapes, could help improve the precision by at least another factor of 100."

Isabelle Dumé