physicsworld
2025

Particle & Nuclear Briefing

Accelerator focus CERN outlines bold vision for particle physics

Burning issue The challenges of commercializing fusion

Keeping time Nuclear clock ticks closer

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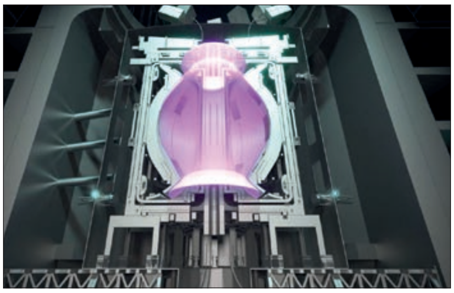

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"Sometimes nature will surprise us and we need to be ready for that."
Juan Pedro Ochoa-Ricoux *Particle physicist from the University of California Irvine (p43)*

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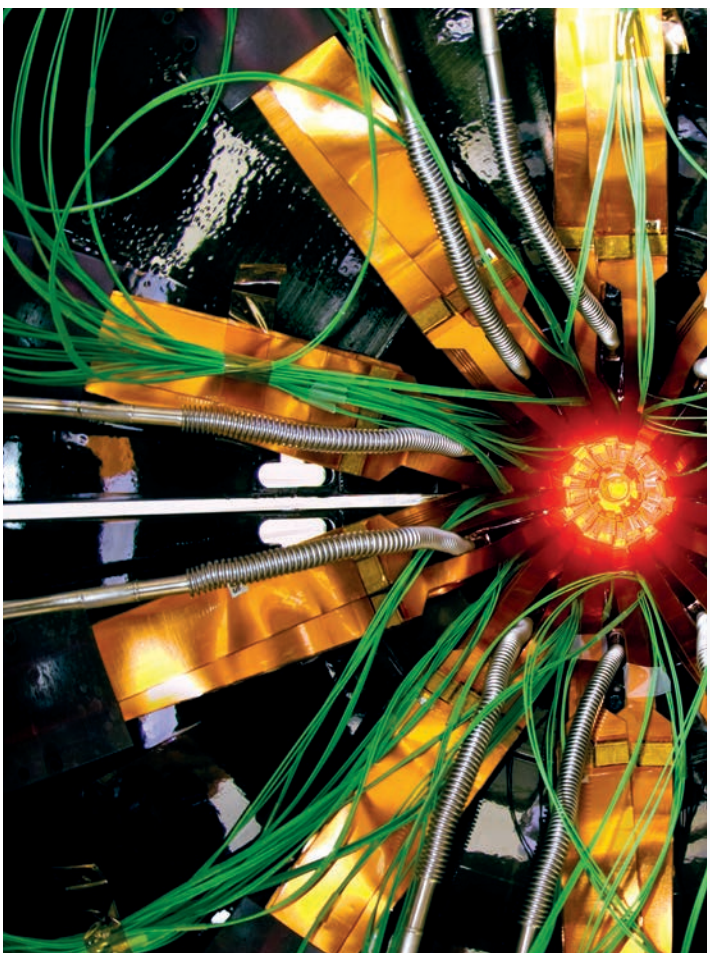
Particle & Nuclear Briefing

On the cover The Future Circular Collider would involve building a 91 km circumference machine at CERN. (Courtesy: © 2024-2025 CERN/PIXELRISE)



Welcome

CERN

"I am deeply committed to diversity and CERN is deeply committed to it in all its forms, and that will not change."
Mark Thomson, *who will take up the position as CERN director-general on 1 January 2026 (p19)*

"For fusion to become commercially viable with an acceptably low output of nuclear waste, several generations of power-plant-sized devices could be needed."
Guy Matthews *physicist who retired in 2022 after 40 years at the Culham Centre for Fusion Energyphysicist from the University of California Irvine (p39)*

A new era for particle physics

Welcome to this *Physics World Particle and Nuclear Briefing*, which includes news, features and opinion on the latest developments in particle and nuclear physics.

"There is only one CERN in the world." That is the view of incoming CERN director-general Mark Thomson, who is set to take over running the world's largest particle-physics lab on 1 January 2026. As the UK physicist replaces current incumbent Fabiola Gianotti, Thomson will have a full in-tray. More than 70 years since the founding of CERN and more than a decade following the discovery of the Higgs boson at the lab's Large Hadron Collider (LHC) in 2012 (p32), particle physics is at a crossroads with regard to what comes after the LHC. While the consensus is to build a "Higgs factory" to study the Higgs in unprecedented detail, there is disagreement over what kind of machine it should be – a large circular collider or a linear machine just a few kilometres long (p19).

Such planning for the future will form a large part of activities for Thomson with CERN having put its weight behind the Future Circular Collider that would be constructed near the LHC. This huge 91 km circumference electron-positron collider will cost some £12bn to build yet Thomson could find it a hard sell with some of the funding needing to come from outside CERN's 24 member states. Discussions on how to proceed will come to the fore in June when physicists meet to discuss plans to update the European Strategy for Particle Physics. The document – with the aim to develop a common vision for the future of particle physics in Europe – is expected to be complete in January 2026, just as Thomson takes up office, and will set the tone for particle physics in the continent for decades to come.

Apart from particle physics, fusion is another huge multinational, multimillion dollar endeavour and there is no bigger project than the ITER fusion tokamak currently under construction in Cadarache, France. The facility has been hit by cost hikes and delays for decades, and there was more bad news last year when ITER's council said the tokamak will now not fire up until 2035. "Full power" mode with deuterium and tritium won't happen until 2039 (p5).

When it comes to the next steps and delivering fusion power plants, there are more technical challenges in store. Guy Matthews, who retired in 2022 after 40 years at the Culham Centre for Fusion Energy, including 30 years on the Joint European Torus, says that the focus on public relations is masking the challenges of commercializing nuclear fusion (p39).

Yet that hasn't stopped the UK from aiming to build a prototype fusion plant, known as the Spherical Tokamak for Energy Production (STEP). Officials met in the UK late last year to discuss plans for STEP and the many challenges that lie ahead. "Fiendish", "technically tough", "difficult", "complicated", were a few of the choice words used to describe moving towards a fusion power plant. It put in stark relief that developments in fusion still have a long way to go.

We hope you enjoy the briefing and let us know your feedback on the issue by e-mailing physics.world@ioppublishing.org.

Michael Banks, News editor of *Physics World*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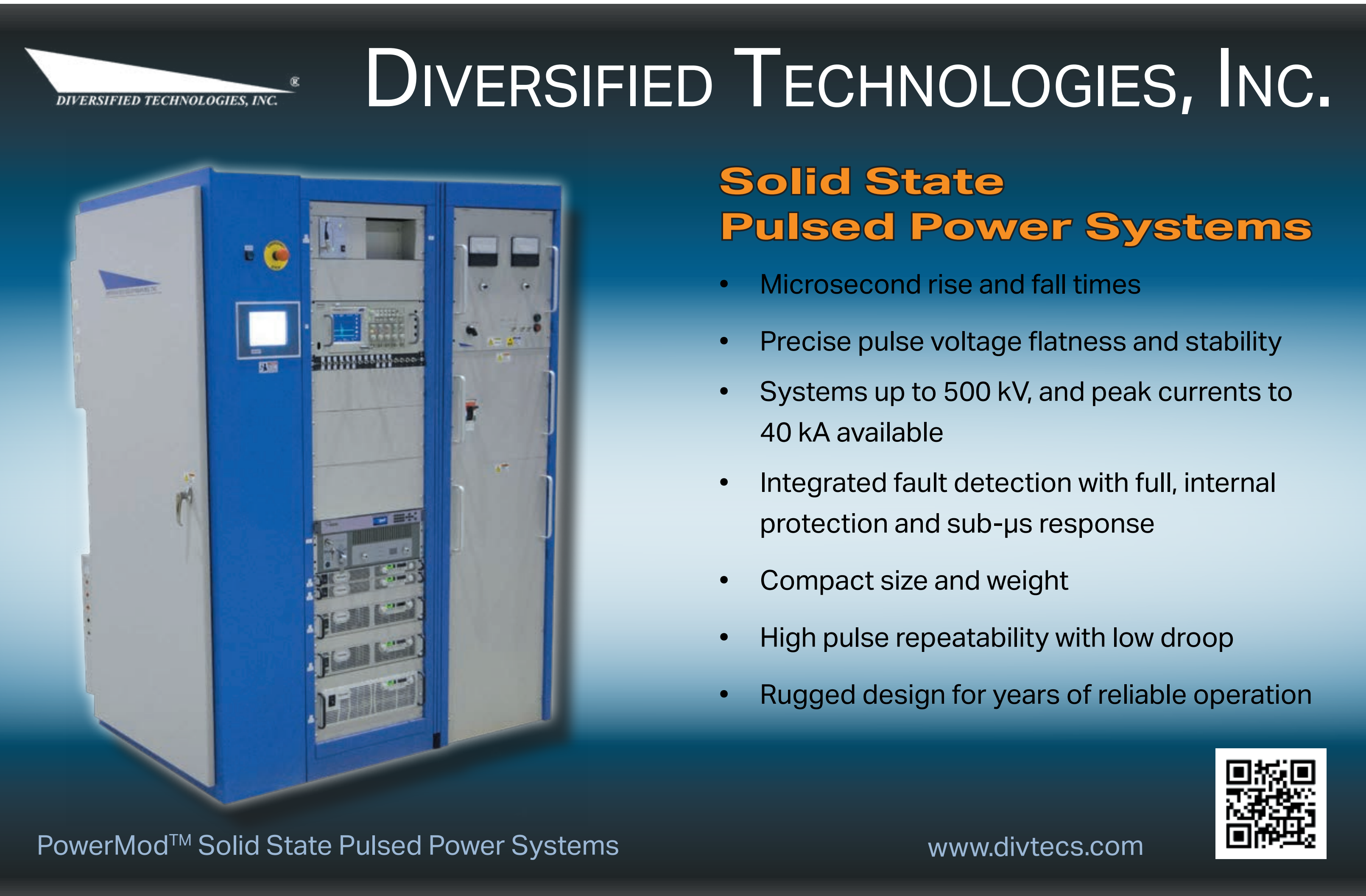
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ITER hit by new decade-long delay

The ITER fusion reactor will now cost €5bn more and not reach full operation with deuterium and tritium until 2039, as **Michael Banks** explains


ITER Organization/EJF Riche

Waiting game
The new "baseline" means that ITER will start operation in 2034 with a deuterium-only plasma but with more systems in place compared to the previous plan.

The ITER fusion reactor currently being built in France will not achieve first operation until 2034 – almost a decade later than previously planned and some 50 years after the project was first conceived in 1985. The decision by ITER management to take another 10 years constructing the machine means that the first experiments using "burning" fusion fuel – a mixture of deuterium and tritium (D–T) – will now have to wait until 2039. The new "baseline" was agreed as a "working reference" by ITER's governing council last year.

ITER is an experimental fusion reactor that is currently being built in Cadarache, France, about 70 km north-west of Marseille. Expected to cost tens of billions of euros, it is a collaboration between China, Europe, India, Japan, Korea, Russia and the US. Its main aim is to generate about 500 MW of fusion power over 400 seconds using a plasma heating of 50 MW, a power gain of 10. The reactor would also test a "steady state" operation under a power gain of five.

Yet since its conception in the 1980s, ITER has been beset with cost hikes and delays. In 2016 a baseline was presented in which the first deuterium plasma would happen in 2025. This first plasma, however, would have been a brief machine test before further assembly, such as adding a divertor heat-exhaust system and further shielding. "The first plasma [in 2025] was rather symbolic," claims ITER director-general Pietro Barabaschi, who took up the position in October 2022 following the death of former ITER boss Bernard Bigot. ITER would only have reached full plasma current in 2032, with the first D–T reaction waiting until 2035 after the installation of additional components.

A new 'baseline'

Barabaschi notes that since 2020 it was "clear" that the 2025 first plasma date was no longer achievable. ITER has cited several reasons, one of which was the COVID-19 pandemic, which led to supply-chain and quality-control delays. Manufacturing issues also emerged such as the discovery of cracks in the water pipes that cool the thermal shields. In early 2022 the French Nuclear Safety Authority briefly halted assembly due to concerns over radiological shielding. Officials then began working on a more realistic timeline for construction to allow for more testing of certain components such as the huge D-shaped toroidal-field coils that will be used to confine the plasma.

The plan now is to start operation in 2034 with a deuterium-only plasma but with more systems in place compared to the previous first plasma baseline of 2025. Research on the tokamak would be carried out for just over two years before the machine reaches full plasma current operation in 2036. The reactor would then be shut down for further assembly to prepare for D–T operation, which is now expected to begin in 2039. Barabaschi notes that the delay will cost an extra €5bn. "We are still addressing the issue of cost with the ITER council," adds Barabaschi, who did not want to be drawn on how much ITER will now cost overall due to the "complexity" of the way it is funded via "in-kind" contributions.

Sibylle Günter, scientific director of the Max Planck Institute for Plasma Physics in Garching, Germany, says that despite the news being of "no cause for celebration", ITER is still relevant and necessary. "We are not aware of any project that will analyse the challenges as comprehensively as ITER in the foreseeable future," she adds. "ITER has also already achieved ground-breaking engineering work up to this point, which will be important for all the fusion projects now under way and those still to come."

In the meantime, some changes have been made to ITER's design. The material used for the "first wall" that directly faces the plasma will switch from beryllium to tungsten. Barabaschi points out that tungsten is more relevant for a potential fusion demonstration plant, known as DEMO. Officials were also celebrating the news in late June that the 19 toroidal-field coils have been completed and delivered to the ITER site. Each coil – made of niobium-tin and niobium-titanium – is 17 m tall and 9 m across, and weighs about 360 tonnes. They will generate a magnetic field of 12 T and store 41 GJ of energy.

Michael Banks is news editor of *Physics World*

News

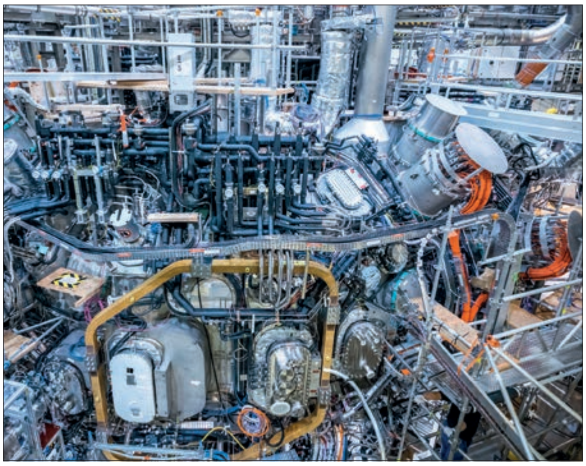
Fusion

US plasma physicists propose a 'flexible' stellarator facility

A group of 24 plasma physicists has called for the construction of a stellarator fusion facility in the US. The so-called Flexible Stellarator Physics Facility would test different approaches to stellarator confinement and whether some of the designs could be scaled up to a fusion plant (arXiv:2407.04039).

Tokamak and stellarator fusion devices both emerged in the early 1950s. They use magnetic confinement to manipulate plasmas but they differ in the containment vessels' geometries to confine the plasma. Tokamaks use toroidal and poloidal magnetic fields that are generated by magnets and the electric current that flows through the plasma, while stellarators apply a helical magnetic field, produced by external coils.

The ITER fusion reactor, currently being built in Cadarache, France, is the largest and most ambitious of the roughly 60 tokamak experiments worldwide. Yet there are only a handful of stellarators operational, the most notable being Germany's Wendelstein 7-X device, which switched on in 2015.



MPI for Plasma Physics/Jan Michael Hosan

Ring of steel Germany's Wendelstein 7-X device, which began operation in 2015, has achieved significant theoretical advances and experimental results.

The authors of the white paper write that delivering the "ambitious" US decadal strategy for commercial fusion energy, which was released in 2022, will require "a persuasive" stellarator programme in addition to supporting tokamak advances.

Felix Parra Diaz, who is the lead author of the white paper and head of theory at the Princeton Plasma Physics Laboratory, told *Physics World* that recent advances, especially at Wendelstein 7-X, are propelling the stellarator device as the best route to a fusion power plant. "Stellarators were widely considered to be difficult to build due to their complex magnets," says Parra Diaz. "We now think that it is possible to design stellarators with similar or even better confinement than tokamaks. We also believe that it is possible to construct these devices at a reasonable cost due to new magnet designs."

The white paper calls on the US to build a "flexible facility" that would test the validity of theoretical models that suggest where stellarator confinement can be improved and also where it fails. The design will focus on "scientific gaps" on the path to stellarator fusion. The authors of the white paper propose a two-stage approach to the new facility. The first stage would involve exploring a range of flexible magnetic configurations while the second would involve upgrading the heating and power systems to further investigate some of the promising configurations from the first stage.

Peter Gwynne
Boston, MA

Facilities

Milestones for US underground lab as it nears completion

A prototype argon detector belonging to the Deep Underground Neutrino Experiment (DUNE) in the US has recorded its first accelerator-produced neutrinos. The detector, located at Fermilab near Chicago, was installed in February 2024 in the path of a neutrino beamline. After what Fermilab physicist Louise Suter calls a "truly momentous milestone", the prototype device will now be used to study the interactions between antineutrinos and argon.

DUNE is part of the $1.5bn Long-Baseline Neutrino Facility (LBNF), which is designed to study the properties of neutrinos in unprecedented detail and examine the differences in behaviour between neutrinos and antineutrinos. Construction of LBNF/DUNE began in 2017 at the Sanford Underground Research Facility in South Dakota,

Dan Svoboda

Watchful eye Scientists at the Fermilab detector operations centre monitor the start-up of the DUNE prototype detector.

which lies some 1300 km west of Fermilab. When complete, DUNE will measure the neutrinos generated by Fermilab's accelerator complex.

Earlier this year excavation work was completed on the two huge underground spaces that will be home to DUNE. Lying 1.6 km below ground in a former gold mine, the spaces are some 150 m long and seven storeys tall and will house DUNE's four neutrino detector tanks, each filled with 17 000 tonnes of liquid argon. DUNE will also feature a near-detector complex at Fermilab that will be used to analyse the intense neutrino beam from just 600 m away.

The "2x2 prototype" detector, so-called because it has four modules arranged in a square, record particle tracks with liquid argon time-projection chambers to reconstruct a 3D picture of the neutrino interaction.

"It is fantastic to see this validation of the hard work put into designing, building and installing the detector," says Suter, who co-ordinated installation of the modules. It is hoped that the DUNE detectors will become operational by the end of 2028.

Michael Banks

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The FPGA Power Brick LV is an integrated fully scalable Machine and Motion Controller

The FPGA Power Brick LV is an integrated fully scalable Machine and Motion Controller combining the brains of the cutting edge Power PMAC processor, the unsurpassed custom-designed Digital Signal Processor Gate3 and the low voltage brawns of the latest high performance MOSFET-based drives technology into one compact 4 or 8-axis servo package drive.

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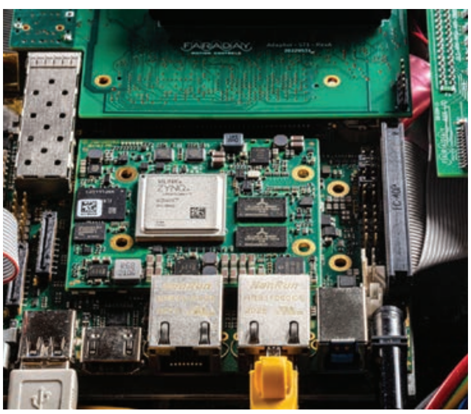
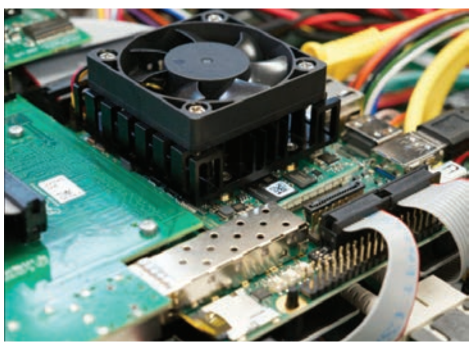


Inside the Power Brick LV

A Zynq Ultrascale+ MPSoC has been used to achieve multi-channel encoder processing for applications such as synchronizing data acquisitions with motion systems during continuous experiment scans. Individual or combinations of encoders can be used to generate multiple output triggers, and encoder position capture (of all types of encoders) can be based on those triggers.

FPGA Power Brick LV rear view

The Zynq Ultrascale+ MPSoC has two sections, a large FPGA connected to the encode hardware, and a dual- or quad-core ARM A53 running Linux. Data can be passed between the two and to/from the Ethernet port. The FPGA is entirely user-programmable. Open-source examples will be supplied, or users with suitable FPGA programming knowledge are free to customize all sections of the co-processor as required.



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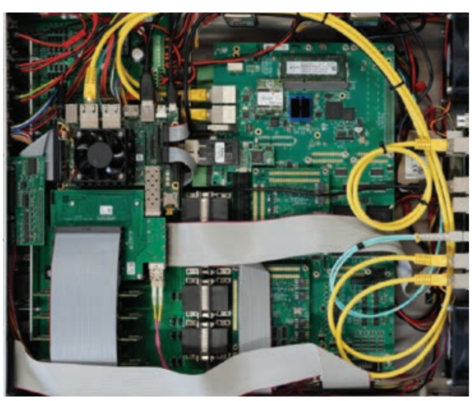

Inside the Power Brick LV

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News

UK outlines next STEPs towards fusion

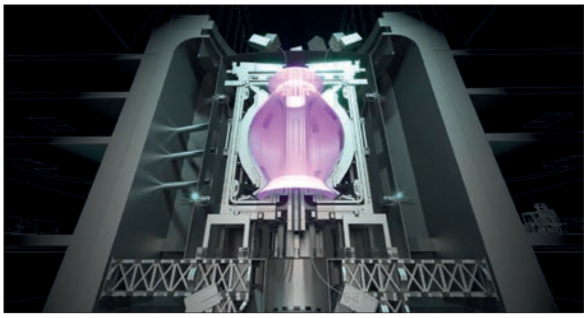
Engineers and physicists have met to discuss the challenges and opportunities of building a practical fusion power plant in the UK. **Michael Banks** listens in

"Fiendish", "technically tough", "difficult", "complicated". Those were just a few of the choice words used at an event in September 2024 in Oxfordshire, UK, to describe ambitious plans to build a prototype fusion power plant. Held at the UK Atomic Energy Authority (UKAEA) Culham campus, the meeting saw engineers and physicists discuss the challenges that lie ahead as well the opportunities of this fusion "moonshot".

The prototype fusion plant in question is known as the Spherical Tokamak for Energy Production (STEP), which was first announced by the UK government in 2019 when it unveiled a £220m package of funding for the project. STEP will be based on "spherical" tokamak technology currently being pioneered at the UK's Culham Centre for Fusion Energy (CCFE). In 2022 a site for STEP was chosen at the former coal-fired power station at West Burton in Nottinghamshire. Operations are expected to begin in the 2040s, with STEP aiming to prove the commercial viability of fusion by demonstrating net energy, fuel self-sufficiency and a viable route to plant maintenance.

A spherical tokamak is more compact than a traditional tokamak, such as the ITER experimental fusion reactor currently being built in France, which has been hit with cost hikes and delays in recent years. The compact nature of the spherical tokamak, which was first pioneered in the UK in the 1980s, is expected to minimize costs, maximize energy output and possibly make it easier to maintain when scaled up to a fully fledged fusion power plant.

The current leading spherical tokamaks worldwide are the Mega Amp Spherical Tokamak (MAST-U) at the CCFE and the National Spherical Torus Experiment at the Princeton Plasma Physics Laboratory (PPPL) in the US, which is nearing the completion of an upgrade. Despite much progress, however, those tokamaks are yet to demonstrate fusion conditions through the use of the hydrogen isotope tritium in the fuel, which is necessary to achieve a "burning" plasma. This goal has, though, already been achieved in traditional tokamaks such as the Joint European Torus, which turned off in 2023.


UKAEA

Ambitious timeline The Spherical Tokamak for Energy Production prototype fusion power plant faces many significant technical challenges before it can come online in the 2040s.

"STEP is a big extrapolation from today's machines," admitted STEP chief engineer Chris Waldon at the event. "It is complex and complicated but we are now beginning to converge on a single design [for STEP]".

The meeting at Culham was held to mark the publication of 15 papers on the technical progress made on STEP (*Philosophical Transactions A* **382** 20230416). Officials were keen to stress, however, that the papers were a snapshot of progress to date and that since then some aspects of the design have progressed.

One issue that crept up during the talks was the challenge of extrapolating every element of tokamak technology to STEP – a feat described by one panellist as being "so far off our graphs". While theory and modelling have come a long way in the last decade, even the best models will not be a substitute for the real thing.

While theory and modelling have come a long way in the last decade, even the best models will not be a substitute for the real thing

"Until we do STEP we won't know everything," says physicist Steve Cowley, director of the PPPL. Those challenges involve managing potential instabilities and disruptions in the plasma – which at worst could obliterate the wall of a reactor – as well as operating high-temperature superconducting magnets to confine the plasma that have yet to be tested under the intensity of fusion conditions.

Another significant challenge is self-breeding tritium via neutron capture in lithium, which would be done in a roughly one-metre thick "blanket" surrounding the reactor. This is far from straightforward and the STEP team is still researching what technology might prevail – whether to use a solid pebble bed or liquid lithium. While liquid lithium is good at producing tritium, for example, extracting the isotope to put back into the reactor is complex.

Howard Wilson, fusion pilot plant R&D lead at the Oak Ridge National Laboratory in the US, stressed that STEP will not be a commercial power plant, but merely demonstrate "a pathway towards commercialization". That is likely to come in several stages, the first being to generate 1 GW of power, which would result in 100 MW to the "grid" (the other 900 MW needed to power the systems). The second stage will be to test if that power production is sustainable via the self-breeding of tritium back into the reactor – what is known as a "closed fuel cycle".

Ian Chapman, chief executive of the UKAEA, outlined what he called the "fiendish" challenges that lie ahead for fusion, even if STEP demonstrates that it is possible to deliver energy to the grid in a sustainable way. "We need to produce a project that will deliver energy someone will buy," he said. That will be achieved in part via STEP's third objective, which is to nail down the maintenance requirements of a fusion power plant and their impact on reactor downtime. "We fail if there is not a cost-effective solution," added STEP engineering director Debbie Kempton.

STEP officials are now selecting industry partners to work alongside the UKAEA to work on the design. Indeed, STEP is as much about physically building a plant as it is creating a fusion industry. A breathless two-minute preevent promotional film – that loftily compared the development of fusion to the advent of the steam train and vaccines – was certainly given a much-needed reality check.

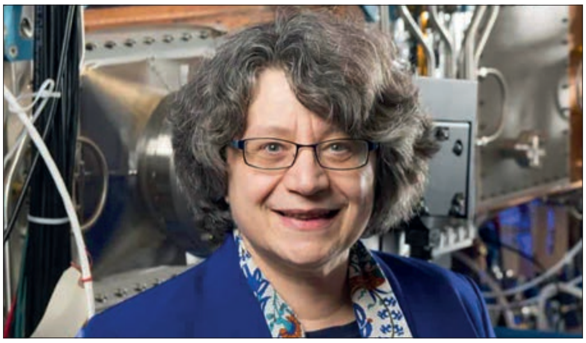
Michael Banks is news editor of *Physics World*

Fermilab boss Lia Merminga resigns

Lia Merminga has resigned as director of Fermilab – the US's premier particle-physics lab. She stepped down in January after a turbulent year that saw staff layoffs, a change in the lab's management contractor and accusations of a toxic atmosphere. Merminga is being replaced by Young-Kee Kim from the University of Chicago, who will serve as interim director until a permanent successor is found. Kim was previously Fermilab's deputy director between 2006 and 2013.

Tracy Marc, a spokesperson for Fermilab, says that the search for Merminga's successor has already begun, although without a specific schedule. "Input from Fermilab employees is highly valued and we expect to have Fermilab employee representatives as advisory members on the search committee, just as has been done in the past," Marc told *Physics World*. "The search committee will keep the Fermilab community informed about the progress of this search."

The departure of Merminga, who became Fermilab director in August 2022, was announced by Paul Alivisatos, president of the University of Chicago. The university jointly manages the lab with Universities Research Association (URA), a consortium of research universities, as well as the industrial firms Amentum Environment & Energy, Inc. and Longenecker & Associates.


Reidar Hahn, Fermilab

Stepping down Lia Merminga has quit as Fermilab director after a turbulent few years at the lab.

"Her dedication and passion for high-energy physics and Fermilab's mission have been deeply appreciated," Alivisatos said in a statement. "This leadership change will bring fresh perspectives and expertise to the Fermilab leadership team."

The reasons for Merminga's resignation are unclear but Fermilab has experienced a difficult last two years with questions raised about its internal management and external oversight. In August 2024, a group of anonymous self-styled whistleblowers published a 113-page "white paper" on the arXiv preprint server, asserting that the lab was "doomed without a management overhaul".

The document highlighted issues such as management cover ups of dangerous behaviour including guns being brought onto Fermilab's campus and a male employee's attack on a female colleague. In addition, key experiments such as the Deep Underground Neutrino Experiment suffered notable delays. Cost overruns also led to a "limited operations period" with most staff on leave in late August.

In October 2024, the US Department of Energy, which oversees Fermilab, announced a new organization – Fermi Forward Discovery Group – to manage the lab. Yet that decision came under scrutiny given it is dominated by the University of Chicago and URA, which had already been part of the management since 2007. Then a month later, almost 2.5% of Fermilab's employees were laid off, adding to portray an institution in crisis.

The whistleblowers, who told *Physics World* that they still stand by their analysis of the lab's issues, say that the layoffs "undermined Fermilab's scientific mission" and sidelined "some of its most accomplished" researchers at the lab. "Meanwhile, executive managers, insulated by high salaries and direct oversight responsibilities, remained unaffected," they allege.

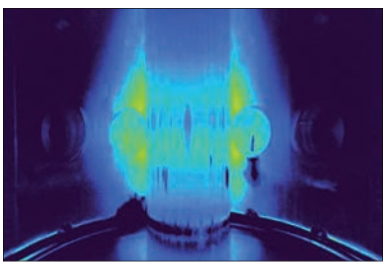
Peter Gwynne
Boston, MA

Fusion

SMART spherical tokamak reaches first plasma

A novel fusion device based at the University of Seville in Spain has achieved its first plasma. The SMall Aspect Ratio Tokamak (SMART) is a spherical tokamak that can operate with a "negative triangularity" – the first spherical tokamak specifically designed to do so. Work performed on the machine could be useful when designing compact power plants.

SMART has been constructed by the university's Plasma Science and Fusion Technology Laboratory. With a vessel dimension of 1.6 x 1.6 m, SMART has a 30 cm diameter solenoid wrapped around 12 toroidal field coils while eight poloidal field coils are used to shape the plasma. Triangularity refers to the shape of the plasma relative to the tokamak. The cross section of the plasma in a tokamak is typically shaped like a "D". When the straight part of the D faces the centre of the tokamak, it is said to have positive triangularity. When the curved part of the plasma faces the centre, however, the plasma has negative triangularity.


University of Seville

Hot stuff The first plasma at the SMall Aspect Ratio Tokamak at the University of Seville.

It is thought that negative triangularity configurations are better at suppressing plasma instabilities that expel particles and energy from the plasma, helping to prevent damage to the tokamak wall. Last year, researchers at the university began to prepare the tokamak's inner walls for a high-pressure plasma by heating argon gas with microwaves. When those tests were successful, engineers then worked toward producing the first plasma. "This is an important achievement as we are now entering the operational phase," notes SMART principal investigator Manuel García Muñoz.

Michael Banks

News

Fusion

China's EAST tokamak smashes fusion record

A fusion tokamak in China has broken its previous fusion record of maintaining a steady-state plasma. Scientists working on the Experimental Advanced Superconducting Tokamak (EAST) announced in late January that they have produced a steady-state high-confinement plasma for 1066 seconds, breaking EAST's previous 2023 record of 403 seconds.

EAST is an experimental superconducting tokamak fusion device located in Hefei, China. Operated by the Institute of Plasma Physics (ASIPP) at the Hefei Institute of Physical Science, it began operations in 2006. It is the first tokamak to contain a deuterium plasma using superconducting niobium-titanium toroidal and poloidal magnets.

EAST has recently undergone several upgrades, notably with new plasma diagnostic tools and a doubling in the power of the plasma heating system. EAST is also acting as a testbed for the ITER experimental fusion reactor that is currently being built in Cadarache, France.

The EAST tokamak is able to maintain a plasma in the so-called "H-mode". This is the high-confinement regime that modern tokamaks, including ITER, employ. It occurs when the plasma undergoes intense heating by a neutral beam and results in a sudden improvement of plasma confinement by a factor of two.

In 2017 scientists at EAST broke the 100 seconds barrier for a steady-state H-mode plasma and then in 2023 achieved 403 seconds, a world record at the time. EAST officials say they have now almost tripled that time, delivering H-mode operation for 1066 seconds.

ASIPP director Song Yuntao notes that the new record is "monumental" and represents a "critical step" toward realizing a functional fusion reactor. "A fusion device must achieve stable operation at high efficiency for thousands of seconds to enable the self-sustaining circulation of plasma," he says, "which is essential for the continuous power generation of future fusion plants."

Michael Banks

Hefei Institute of Physical Science

Record breaker The Experimental Advanced Superconducting Tokamak based in Hefei, China, has sustained a high-pressure plasma for over 1000 seconds.

Speed of sound taken in a 'quark soup'

A measurement of the speed of sound in a quark-gluon plasma at CERN's Large Hadron Collider could provide insights into neutron stars, as **Tim Wogan** reports

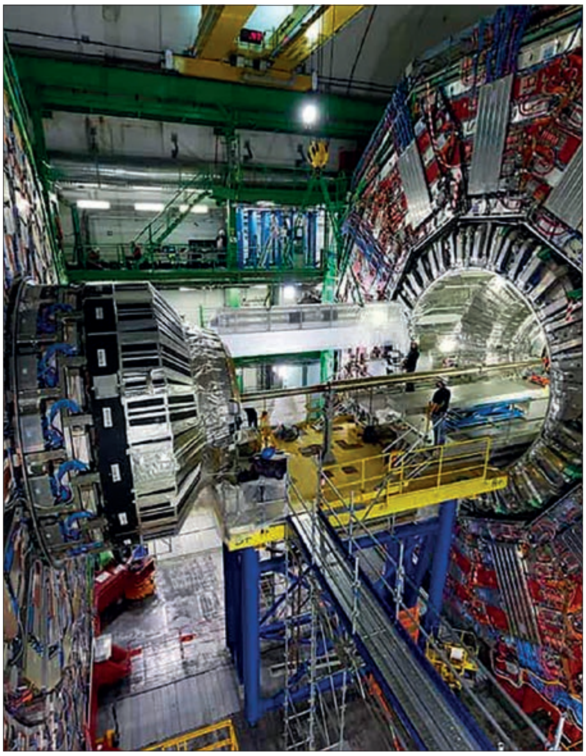
The speed of sound in a quark–gluon plasma has been measured by observing high-energy collisions between lead nuclei at CERN's Large Hadron Collider. The work, by the CMS Collaboration, provides a highly precise test of lattice quantum chromodynamics (QCD) and could potentially inform neutron-star physics (*Rep. Prog. Phys.* **87** 077801).

The strong interaction – which binds quarks together inside hadrons – is the strongest force in the universe. Unlike the other forces, which become weaker as particles become further apart, its strength grows with increasing separation. What is more, when quarks gain enough energy to move apart, the space between them is filled with quark–antiquark pairs, making the physics ever-more complex as energies rise.

In the interior of a proton or neutron, the quarks and gluons (the particles that mediate the strong interaction) are very close together and effectively neutralize one another's colour charge, leaving just a small perturbation that accounts for the residual strong interaction between protons and neutrons. At very high energies, however, the particles become deconfined, forming a hot, dense and yet almost viscosity-free fluid of quarks and gluons, all strongly interacting with one another. Calculations of this quark-gluon plasma are non-perturbative, and other techniques are needed. The standard approach is lattice QCD.

To check whether the predictions of lattice QCD are correct, the speed of sound is key. "The specific properties of quark–gluon plasma correspond to a specific value of how fast sound will propagate," says CMS member Wei Li of Rice University in Texas. He says indirect measurements have provided constraints in the past, but the value has never been measured directly.

In the new work, the CMS researchers collided heavy ions of lead instead of protons. The CMS detector monitored the particles emitted in the collisions using a two-stage detection system to determine what type of collisions had occurred and what particles had been produced in the collisions. "We pick the collisions that were almost exactly head-on," explains Li. "Those types of collisions are rare." The energy is deposited into the plasma, heating it and leading to the creation of particles. The researchers monitored the energies and momenta of the particles emitted from different collisions to reconstruct the energy density of the plasma immediately after each collision. "We look at the variations between the different groups of events," he explains. "The temperature of the plasma is tracked based on the energies of the particles that are coming out, because it's a thermal source that emits particles."


CERN

Sound finding
Heavy-ion collisions at the Compact Muon Solenoid detector at CERN have allowed researchers to measure the speed at which heat – and therefore energy density – flows through a quark-gluon plasma.

The specific properties of quark–gluon plasma correspond to a specific value of how fast sound will propagate

In this way, the researchers were able to measure the speed at which heat – and therefore energy density – flowed through the plasma. Under these extreme conditions, this is identical to the speed of sound i.e. the rate at which pressure travels. "In relativity, particle number is not conserved," says Li. "You can turn particles into energy and energy into particles. But energy is conserved, so we always talk about total energy density."

Stringent tests

The team's findings matched the predictions of lattice QCD and the researchers would now like to conduct even more stringent tests. "We have extracted the speed of sound at one specific temperature," says Li. "Whereas lattice QCD has predicted how the speed of sound goes with temperature as a continuous function. In principle, a more convincing case would be to measure at multiple temperatures and have them come out all agreeing with the lattice QCD prediction."

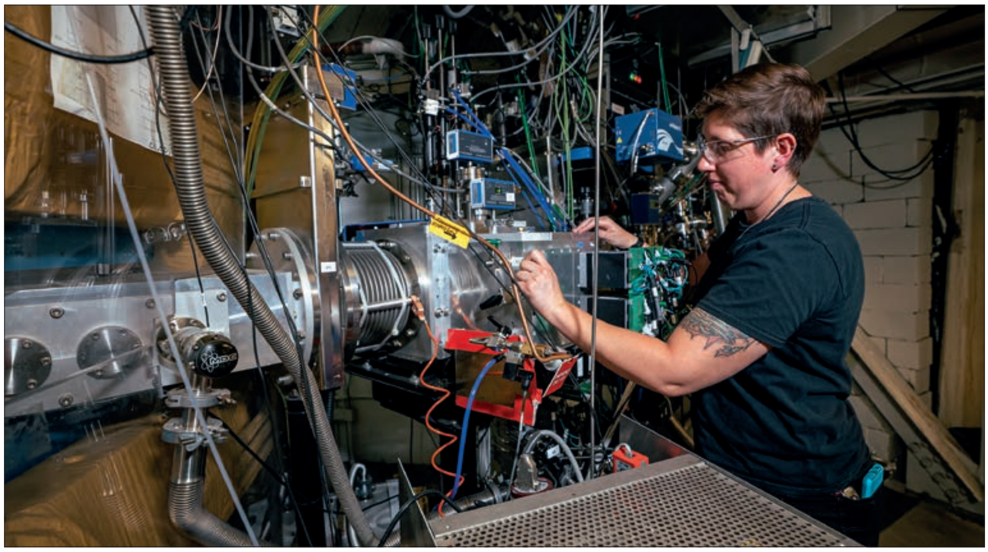
One remarkable prediction of lattice QCD is that the temperature of the quark–gluon plasma drops to its lowest possible value, the sound speed reaches a minimum before then increasing as the temperature drops further and the quarks become bound into hadrons. "It would be remarkable if we could observe that," he says.

Nuclear theorist Larry McLerran of the University of Washington in Seattle – who is not a CMS member – believes the most interesting aspect of the finding is not what it shows about the theory being tested but what it demonstrates about the techniques used to test it. "The issue of sound velocity is interesting," he says. "They have a way of calculating it – actually two ways of calculating it, one of which is kind of hand waving, but then it's backed up with detailed simulation – and it agrees with lattice gauge theory calculations." McLerran is also interested in the potential to study heavy-ion collisions at low energies, and hopes these might give clues about the cold, dense matter in neutron stars.

Research updates

Titanium used to create superheavy livermorium

A new technique at the Lawrence Berkeley National Laboratory brings an island of stability closer, as **Sam Jarman** reports



Marilyn Sargent/Berkeley Lab

Smashing result An international team led by Jacklyn Gates at Lawrence Berkeley National Laboratory have identified heavy atoms of element 116, livermorium.

An international team of physicists has used a beam of titanium-50 to create the element livermorium. This is the first time that nuclei heavier than calcium-48 have been used to synthesize a superheavy element. Led by Jacklyn Gates at Lawrence Berkeley National Laboratory (LBNL) in California, the team hopes its approach could pave the way for the discovery of entirely new elements (arXiv:2407.16079).

Superheavy elements are found at the bottom right of the periodic table and have atomic numbers greater than 103. Creating and studying these huge elements pushes our experimental and theoretical capabilities and provides new insights into the forces that hold nuclei together. Techniques for synthesizing these elements have vastly improved over the decades, and usually involve the irradiation of actinide targets (elements with atomic numbers of 89–102) with beams of transition metal ions.

Earlier this century, superheavy elements were created by bombarding actinides with beams of calcium-48. "Using this technique, scientists managed to create elements up to oganesson, with an atomic number of 118," says Gates. Calcium-48 is especially suited for this task because of its highly stable configuration of protons and neutrons, which allows it to fuse effectively with target nuclei. Despite these achievements, the discovery of new superheavy elements has stalled. "To create elements beyond oganesson, we would need to use targets made from einsteinium or fermium," Gates explains. "Unfortunately, these elements are short-lived and difficult to produce in large enough quantities for experiments."

To try to move forward, physicists have explored alternative approaches. Instead of using heavier and less stable actinide targets, researchers considered how lighter, more stable actinide targets such as plutonium (atomic number 94) would interact with beams of heavier transition metal isotopes. Several theoretical studies have proposed that new superheavy elements could be produced using specific isotopes of transition metals such as titanium, vanadium and chromium. These studies largely agreed that titanium-50 has the highest reaction cross-section with actinide elements, giving it the best chance of producing elements heavier than oganesson. However, there is significant uncertainty surrounding the nuclear mechanisms involved in these reactions, which have hindered experimental efforts so far.

"Based on theoretical predictions, we expected the production rate of superheavy elements to decrease when beams beyond calcium-48 were used to bombard actinide targets," Gates explains. "However, we were unsure about the extent of this decrease and what it would mean for producing elements beyond oganesson." To address this uncertainty, Gates' team implemented a reaction that has been explored in several theoretical studies – by firing a titanium-50 beam at a target of plutonium-244. Based on the nuclear mechanisms involved, this reaction has been predicted to produce the superheavy element livermorium, which has an atomic number of 116.

To create the titanium-50 beam, the researchers used LBNL's VENUS ion source. This uses a superconducting magnet to contain a plasma of highly ionized titanium-50. They then accelerated the ions using LBNL's 88-Inch Cyclotron facility. After the reaction, the Berkeley Gas-filled Separator isolated livermorium nuclei from other reaction products. This allowed the team to measure the chain of products created as the nuclei decayed.

> The team hopes its approach could pave the way for the discovery of entirely new elements

Altogether, the team detected two decay paths that could be attributed to livermorium-290. This is especially significant because the isotope is thought to lie tantalizingly close to an "island of stability" in the chart of the nuclides. This comprises a group of superheavy nuclei that physicists predict are highly resistant to decay through spontaneous fission. This gives these nuclei vastly longer half-lives compared with lighter isotopes of the same elements.

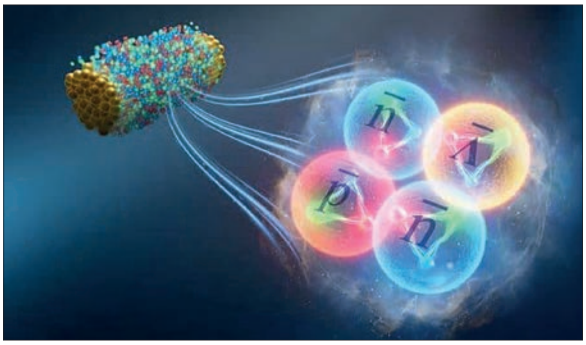
If the island is reached, it could be a crucial stepping stone for synthesizing new elements beyond oganesson. For now, Gates' team is hopeful its result could pave the way for new experiments and they plan to use their titanium-50 beam to bombard a heavier target of californium-249. If these experiments see similar levels of success, they could be a crucial next step toward discovering even heavier superheavy elements.

Research updates

Nuclear physics

Exotic antinucleus antihyperhydrogen-4 formed in heavy-ion collisions

An antihyperhydrogen-4 nucleus – the heaviest antinucleus ever produced – has been observed in heavy-ion collisions by the STAR Collaboration at Brookhaven National Laboratory in the US. The antihypernucleus contains a strange quark, making it a heavier cousin of antihydrogen-4. Physicists hope that studying such antimatter particles could shed light on why there is much more matter than antimatter in the visible universe (*Nature* 632 *1026*).



Institute of Modern Physics, China

Weighty matters An antihyperhydrogen-4 – an antimatter hypernucleus made of an antiproton, two antineutrons, and an antilambda particle – has been created by colliding gold nuclei.

While antimatter is created by nuclear processes, it is swiftly annihilated on contact with matter. The Standard Model says that matter and antimatter should be identical after charge, parity and time are reversed. Therefore, finding even tiny asymmetries in how matter and antimatter behave could provide important information about new physics.

One way forward is to create quark–gluon plasma in the laboratory and study particle–antiparticle creation. Quark–gluon plasma is made by smashing together heavy ions such as lead or gold. A variety of exotic particles and antiparticles emerge from these collisions. Many of them decay almost immediately, but their decay products can be detected and compared with theoretical predictions.

Quark–gluon plasmas can include hypernuclei, which are nuclei containing one or more hyperons that are thought to have been present in the high-energy conditions of the early universe. Hyperons are baryons containing one or more strange quarks, making hyperons the heavier cousins of protons and neutrons. In 2010, the STAR collaboration unveiled the first evidence of an antihypernucleus – an antihypertriton, which is the antimatter version of an exotic counterpart to tritium in which one of the down quarks in one of the neutrons is replaced by a strange quark.

Now, STAR physicists have found evidence of antihyperhydrogen-4 (antihypertriton with an extra anti-neutron). Antihyperhydrogen-4 decays almost immediately by the emission of a pion, producing antihelium-4. The researchers hope further work may provide some insight into the violation of charge–parity symmetry.

Tim Wogan

Research updates

Nuclear clock ticks closer

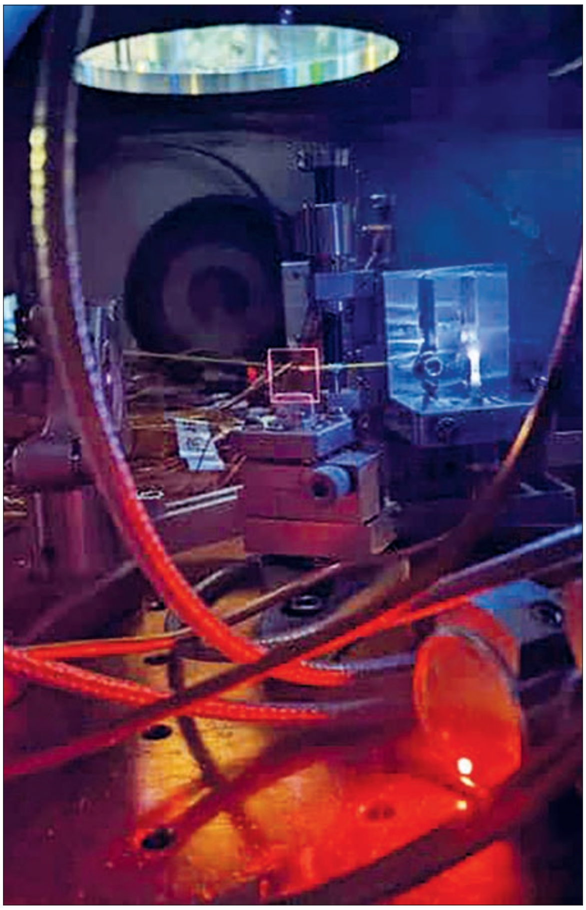
A new device might not only be the best time-keeper ever, but could also revolutionize fundamental physics, as **Isabelle Dumé** reports

An international team of researchers have successfully built all the elements necessary for a fully functioning nuclear clock. The scientists say that they hope to use their technology to make portable solid-state nuclear clocks that can be deployed outside the laboratory. They also want to investigate how the clock transitions shift depending on temperature and different crystal environments (*Nature* **633** 63).

Today's most accurate clocks rely on optically trapped ensembles of atoms or ions, such as strontium or ytterbium. They measure time by locking laser light into resonance with the frequencies of specific electronic transitions. The oscillations of the laser then behave like (very high-frequency) pendulum swings. Such clocks can be stable to within one part in 10^{20}, which means after nearly 14 billion years (or the age of the universe), they will be out by just 10 ms. As well as accurately keeping time, atomic clocks can be used to study fundamental physics phenomena.

Nuclear clocks should be even more accurate than their atomic counterparts since they work by probing nuclear energy levels rather than electronic energy levels. They are also less sensitive to external electromagnetic fluctuations that could affect clock accuracy. A nucleus measures between 10^{-14} and 10^{-15} m across, while an atom is 10^{-10} m. Shifts between nuclear energy levels are thus higher in energy and would be resonant with a higher-frequency laser. This translates into more wave cycles per second – and can be thought of as a greater number of pendulum swings per second.

Such a nuclear transition probes fundamental particles and interactions differently to existing atomic clocks. Comparing a nuclear clock with a precise atomic clock could therefore help to unearth new discoveries related to very tiny temporal variations, such as those in the values of the fundamental constants of nature. Any detected changes could point to physics beyond the Standard Model.



Chuankun Zhang/JILA

It's about time
Scientists have fabricated all of the components needed to create a nuclear clock made from thorium-229.

Mind the gap

The problem is that the high-frequency lasers needed to excite the nuclear transitions in most elements are not easy to come by. To excite nuclear transitions, most atomic nuclei need to be hit by high-energy X-rays. In the late 1970s, however, physicists identified thorium-229 as having the smallest energy gap of all atoms and found that it could thus be excited by lower-energy, ultraviolet light. In 2003, Ekkehard Peik and Christian Tamm at Germany's National Metrology Institute, proposed that this transition could be used to make a nuclear clock. But, it was only in 2016 that this transition was directly observed for the first time.

In the new study, an international team led by Jun Ye at JILA, a joint institute of NIST and the University of Colorado Boulder, have fabricated all of the components needed to create a nuclear clock made from thorium-229. This includes a coherent laser for resolving different nuclear states; a "high concentration" thorium-229 sample embedded in a solid-state calcium fluoride host crystal; and a "frequency comb" referenced to an established atomic standard for precisely measuring the frequency of the transitions.

Measuring light

A frequency comb is a special type of laser that acts like a measuring stick for light. It works using laser light that comprises up to 10^6 equidistant, phase-stable frequencies (which look like the teeth of a comb) to measure other unknown frequencies with high precision and absolute traceability when compared with a radiofrequency standard. The researchers used a frequency comb operating in the infrared part of the spectrum, which they upconverted (through a cavity-enhanced high harmonic generation process) to produce a vacuum-ultraviolet frequency comb whose frequency is linked to the infrared comb. They then used one line in the comb laser to drive the thorium nuclear transition.

The team also succeeded in directly comparing the ultraviolet frequency to the optical frequency employed in one of today's best atomic clocks made from strontium-87. This last feat will be the starting point for future nuclear–atomic clock comparisons for fundamental physics studies. "We'll be able to precisely test if some fundamental constants like the fine structure alpha are constant or slowly varying over time," says Chuankun Zhang, a graduate student in Ye's group.

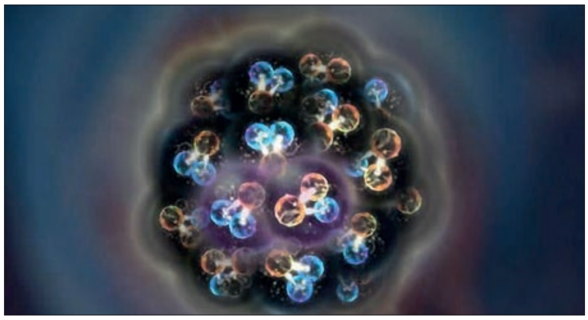
Research updates

Theoretical physics

Two distinct descriptions of nuclei unified

An international team of physicists has unified two distinct descriptions of atomic nuclei, taking a major step forward in our understanding of nuclear structure and strong interactions. For the first time, the particle-physics perspective – where nuclei are seen as made up of quarks and gluons – has been combined with the traditional nuclear physics view that treats nuclei as collections of interacting nucleons (*Phys. Rev. Lett.* 133 152502).

To investigate the inner structure of atomic nuclei, physicists use parton distribution functions (PDFs), which describe how the momentum and energy of quarks and gluons are distributed within protons, neutrons, or entire nuclei. PDFs are typically obtained from high-energy experiments at particle accelerators, where nucleons or nuclei collide at close to the speed of light. By analysing the behaviour of the particles produced in these collisions, physicists can gain essential insights into their properties, revealing the complex dynamics of the strong interaction. However, traditional nuclear physics often focuses on the interactions between protons and neutrons in the nucleus, without delving into the quark and gluon structure of nucleons. Until now, these two approaches – one based on fundamental particles and the other on nuclear dynamics — remained separate.


Institute of Nuclear Physics Polish Academy of Sciences

Coming together A new description of nuclei combines the quark–gluon model of particle physics with the proton–neutron description of nuclear physics.

The team has now developed a unified framework that integrates both the partonic structure of nucleons and the interactions between nucleons in atomic nuclei. This approach is particularly useful for studying short-range correlated (SRC) nucleon pairs, whose interactions are crucial to understanding the structure of nuclei but are hard to describe using conventional theoretical models. By combining particle and nuclear physics descriptions, the researchers were able to derive PDFs for SRC pairs, providing a detailed understanding of how quarks and gluons behave within these pairs.

"This framework allows us to make direct relations between the quark–gluon and the proton–neutron description of nuclei," says co-author Fredrick Olness at Southern Methodist University in the US. "Thus, for the first time, we can begin to relate the general properties of nuclei such as 'magic number' nuclei – those with a specific number of protons or neutrons that make them particularly stable – or 'mirror nuclei' with equal numbers of protons and neutrons to the characteristics of the quarks and gluons inside the nuclei."

The researchers applied their model to experimental data from scattering experiments involving 19 different nuclei, ranging from helium-3 to lead-208. By comparing their predictions with experimental data, they were able to refine their model and confirm its accuracy. These findings, the team members say, not only validate their approach but also open up new avenues for research.

Andrey Feldman

Nuclear physics

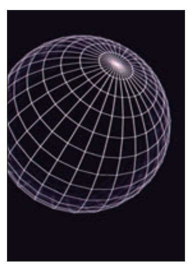
Nuclear shape transitions visualized for the first time

Xenon nuclei change shape as they collide, transforming from soft, oval-shaped particles to rigid, spherical ones. This finding, which is based on simulations of experiments at CERN's Large Hadron Collider (LHC), provides a first look at how the shapes of atomic nuclei respond to extreme conditions. While the technique is still at the theoretical stage, the researchers say that ultra-relativistic nuclear collisions at the LHC could allow for the first experimental observations of these so-called nuclear shape phase transitions (*Phys. Rev. Lett.* 133 192301).

Like electrons, nucleons exist in different energy levels, or shells. To minimize the energy of the system, these shells take different shapes, with possibilities including pear, spherical, oval or peanut-shell-like formations. These shapes affect many properties of the atomic nucleus as well as nuclear processes such as the strong interactions between protons and neutrons.

In the new work, a team led by You Zhou at the Niels Bohr Institute in Denmark and Huichao Song at Peking University studied xenon-129. This isotope has 54 protons and 75 neutrons and is considered a relatively large atom, making its nuclear shape easier, in principle, to study than that of smaller atoms. Usually, the nucleus of xenon-129 is oval-shaped (a γ-soft rotor). However, low-energy nuclear theory predicts that it can transition to a spherical, prolate or oblate shape under certain conditions.

To test the viability of such experiments, the researchers simulated accelerating atoms to near


You Zhou, NBI

Shape shifter The nucleus of the xenon atom can assume different shapes depending on the balance of internal forces at play.

relativistic speeds, equivalent to the energies involved at the LHC. At these energies, when nuclei collide with each other, their constituent protons and neutrons break down into smaller particles. These smaller particles are mainly quarks and gluons, and together they form a quark–gluon plasma, which is a liquid with virtually no viscosity.

Zhou, Song and colleagues modelled the properties of this "almost perfect" liquid using an advanced hydrodynamic model they developed called IBBE-VISHNU. According to these analyses, the Xe nuclei go from being soft and oval-shaped to rigid and spherical as they collide. Zhou adds that future experiments could validate the nuclear shape phase transitions they have observed in their simulations.

Isabelle Dumé

Research updates

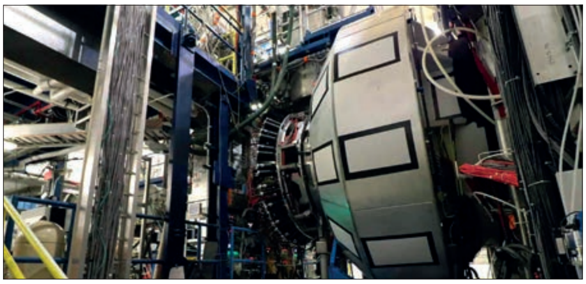
Nuclear physics

Inner workings of the neutron revealed

Researchers at the Jefferson Lab in the US have measured generalized parton distributions to reveal details about the internal structure of the neutron. An international collaboration used the CEBAF Large Acceptance Spectrometer (CLAS12) to study the scattering of high-energy electrons from a deuterium target to study how the neutron's constituent quarks contribute to its momentum and spin (*Phys. Rev. Lett.* 133 211903).

The theory of the strong force, called quantum chromodynamics (QCD), describes the interaction between quarks via the exchange of gluons. But it's so complex that it can't be used to compute the properties of bound states, such as neutrons and protons. To get around this, researchers use experimentally measurable functions called generalized parton distributions, which help connect the properties of the nucleons such as their spin to the dynamics of quarks and gluons.

The model assumes that a nucleon contains point-like constituents that represent the quarks and gluons of QCD. By measuring the distributions of these partons, physicists can examine correlations between a quark's longitudinal momentum — how much of the nucleon's total momentum it carries — and its transverse position within the nucleon. By analysing these relationships for varying momentum values, it is possible to create a tomographic-like scan of the nucleon's internal structure.


Jefferson Lab

In a spin
The Central Neutron Detector, which is part of CLAS12 at Jefferson Lab, has been used to measure details about the internal structure of neutrons.

Each type of quark is associated with its own set of generalized parton distributions, and the overarching aim of the experimental effort is to determine distributions for both protons and neutrons.

While these distributions are vital for understanding the strong interactions within both protons and neutrons, our understanding of protons is significantly more advanced. To address the deficiency regarding neutrons, the CLAS12 collaboration utilized the Central Neutron Detector to detect neutrons ejected from a deuterium target by high-energy electrons for the first time. By combining neutron detection with the simultaneous measurement of scattered electrons and energetic photons produced during the interactions, the team gathered comprehensive data on particle momenta. This was used to calculate the generalized parton distributions of quarks inside neutrons.

The CLAS12 team used electron beams with spins aligned both parallel and antiparallel to their momentum. This configuration resulted in slightly different interactions with the target, enabling the team to investigate subtle features of the generalized parton distributions related to angular momentum. By analysing these details, they successfully disentangled the contributions of up and down quarks to the angular momentum of the neutron.

Andrey Feldman

Particle physics

Antimatter partner of hyperhelium-4 spotted at CERN

Researchers in the ALICE collaboration at CERN have found the first evidence for antihyperhelium-4 – an antimatter hypernucleus that is a heavier version of antihelium-4. The antihyperhelium-4 was created by smashing lead nuclei together at CERN's Large Hadron Collider (LHC) (arXiv: 2410.17769, submitted to *Physical Review Letters*).

Hypernuclei are rare, short-lived atomic nuclei made up of protons, neutrons, and at least one hyperon, which is any baryon containing one or more strange quarks, but no charm, bottom, or top quarks. Hypernuclei and their antimatter counterparts can be formed within a quark–gluon plasma (QGP), which is created when heavy ions such as lead collide at high energies. A QGP is an extreme state of matter that also existed in the first millionth of a second following the Big Bang.


CERN/ J Ditzel with AI-assistance

Heavy stuff
Antihyperhelium-4 – a bound state of two antiprotons, an antineutron and an antilambda – has been created in lead–lead collisions at CERN.

Just a few hundred picoseconds after being formed in collisions, antihypernuclei will decay via the weak force – creating two or more distinctive decay products that can be detected. The first antihypernucleus to be observed was a form of antihyperhydrogen called antihypertriton, which contains an antiproton, an antineutron and an antilambda hyperon. It was discovered in 2010 by the STAR Collaboration, who smashed together gold nuclei at Brookhaven National Laboratory's Relativistic Heavy Ion Collider. Then in 2024, the STAR Collaboration reported the first observations of the decay products of antihyperhydrogen-4, which contains one more antineutron than antihypertriton.

Now, ALICE physicists have analysed data taken at the LHC in 2018 – where lead ions were collided at 5 TeV. They identified the same signature of antihyperhydrogen-4 detected by the STAR Collaboration but also found evidence for antihyperhelium-4. It contains two antiprotons, an antineutron and an antilambda baryon (containing three antiquarks – up, down and strange). It decays almost instantly into an antihelium-3 nucleus, an antiproton, and a charged pion, which is a meson comprising a quark–antiquark pair.

While the observation has a statistical significance of 3.5σ – below the 5σ level that is generally accepted as a discovery – it is in line with the Standard Model of particle physics. The detection therefore helps constrain theories beyond the Standard Model that try to explain why the universe contains much more matter than antimatter.

Sam Jarman

Research updates

Nuclear physics

Nuclear shapes seen in high-energy collisions

Scientists in the STAR collaboration have unveiled a pioneering method for investigating the shapes of atomic nuclei by colliding them at near light-speed in particle accelerators. Their innovative approach offers unprecedented insight into nuclear structure and could deepen our understanding of strong nuclear forces and their role in the composition of neutron stars and the evolution of the early universe (*Nature* **635** 67).

Understanding the properties of nuclei is daunting, largely due to the complexities of quantum chromodynamics (QCD), the fundamental theory governing the strong interaction. Calculations in QCD are notoriously difficult at low relative velocities, typical for nucleons within nuclei. One way to study nuclear shapes is to excite a nucleus to a higher energy state, often by colliding it with a fixed target. By measuring how long it takes the nucleus to return to its ground state, researchers can gather information about its shape. However, this relaxation process takes far longer than typical nuclear interactions, thus providing only an averaged image of the nucleus without any finer details.

Another method is to bombard nuclei with high-energy electrons, analysing the scattering data to infer structural details. However, this technique only reveals localized properties of the nucleus, falling short when capturing the overall shape, which depends on the coordinated movement of nucleons across the entire nucleus.

The approach taken by the STAR collaboration – consisting of hundreds of scientists and engineers from the US and elsewhere – circumvents these limitations by smashing nuclei together at extremely high energies and analysing the collision products. Since these high-energy collisions are much faster than typical nuclear processes, the new method promises to deliver a more detailed snapshot of nuclear shape.

When two nuclei collide at near-light speeds, they annihilate, turning into an expanding ball of plasma made of quarks and gluons. This plasma lasts only about 10^{-23} s before forming thousands of new composite particles, which are then caught by detectors. By studying the speeds and angles at which these particles are ejected, scientists can infer the shape of the colliding nuclei.

Chunjian Zhang/Fudan University and Jiangyong Jia/Stony Brook University

Collision point The STAR collaboration have created a new technique to study nuclear shapes by smashing nuclei together at extremely high energies.

"You cannot image the same nuclei again and again because you destroy them in the collision," explains Jiangyong Jia from Stony Brook University. "But by looking at the whole collection of images from many different collisions, scientists can reconstruct the subtle properties of the 3D structure of the smashed nuclei."

To verify the reliability of this method the STAR researchers compared their findings with those obtained through established techniques on nuclei with well-known shapes finding that the collisions aligned remarkably well with established results. The researchers now want to analyse nuclei whose shapes are not as well understood.

Andrey Feldman

Setting a trajectory for particle physics

Mark Thomson, who will take over from Fabiola Gianotti as director-general of CERN next year, talks to Michael Banks about his plans in the hot seat and the challenges ahead for high-energy physics


CERN

Looking ahead Mark Thomson will take up the position as CERN director-general on 1 January 2026.

How did you get interested in particle physics?

I completed a DPhil at the University of Oxford in 1991 studying cosmic rays and neutrinos. In 1992 I moved to University College London as a research fellow. That was the first time I went to CERN and two years later I began working on the Large Electron-Positron Collider, which was the predecessor of the Large Hadron Collider. I was fortunate enough to work on some of the really big measurements of the W and Z bosons and electroweak unification, so it was a great time in my life. In 2000 I worked at the University of Cambridge where I set up a neutrino group. It was then that I began working at Fermilab – the US's premier particle-physics lab.

So you flipped from collider physics to neutrino physics?

Over the past 20 years, I have oscillated between them and sometimes have done both in parallel. Probably the biggest step forward was in 2013 when I became spokesperson for the Deep Underground Neutrino Experiment – a really fascinating, challenging and ambitious project. In 2018 I was appointed executive chair of the Science and Technology Facilities Council (STFC) – one of the main UK funding agencies. The STFC funds particle physics and astronomy in the UK and maintains relationships with organizations such as CERN and the Square Kilometre Array Observatory, as well as operating some of the UK's biggest national infrastructures such as the Rutherford Appleton Laboratory and the Daresbury Laboratory.

What did that role involve?

It covered strategic funding of particle physics and astronomy in the UK and also involved running a large scientific organization with about 2800 scientific, technical and engineering staff. It was very good preparation for the role as CERN director-general.

AUDIO

In a conversation with *Physics World*'s Michael Banks, Mark Thomson shares his vision of the future of the world's preeminent particle physics lab.

I'm 100% behind CERN being an inclusive organization

What attracted you to become CERN director-general?

CERN is such an important part of the global particle-physics landscape. But I don't think there was ever a moment where I just thought "Oh, I must do this." I've spent six years on the CERN Council, so I know the organization well. I realized I had all of the tools to do the job – a combination of the science, knowing the organization and then my experience in previous roles. CERN has been a large part of my life for many years, so it's a fantastic opportunity for me.

What were your first thoughts when you heard you had got the role?

It was quite a surreal moment. My first thoughts were "Well, OK, that's fun" – it didn't really sink in until the evening. I'm obviously very happy and it was fantastic news, but it was almost a feeling of "What happens now?".

What happens now as CERN director-general designate?

There will be a little bit of shadowing, but you can't shadow someone for the whole year, that doesn't make very much sense. So what I really have to do is understand the organization, how it works from the inside and, of course, get to know the fantastic CERN staff, which I've already started doing. A lot of my time at the moment is meeting people and understanding how things work.

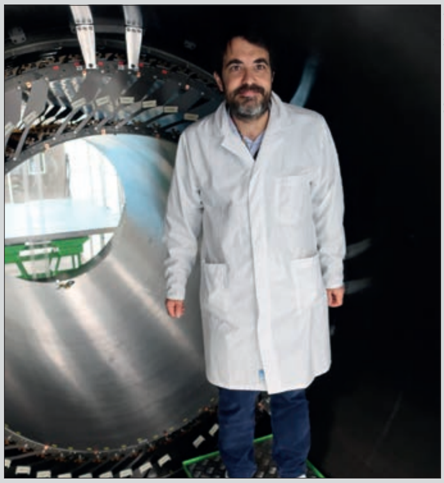
Online editor Margaret Harris chats about her recent trip to CERN, where she caught up with physicists working on some of the lab's most exciting experiments.

High energy, meet High Lumi

While CERN's leaders discuss proposals for new particle colliders (see main text), rank-and-file scientists at Europe's flagship particle-physics lab are gearing up to improve the machine they already have. The Large Hadron Collider (LHC) is now nearly 17 years old, and between 2026 and 2030 it will receive its final major upgrade, which is designed keep it churning out scientific data until the early 2040s.

Unlike a previous big upgrade, which raised the LHC's maximum collision energy from 7 TeV to 14 TeV, this one will increase its luminosity – the collision rate divided by the probability that a collision will take place (the cross section). The goal of the High Luminosity LHC (known informally as "High Lumi") is to boost collision rates at the LHC's two biggest particle detectors, CMS and ATLAS.

Doing this will require a multi-pronged approach, with more powerful focusing magnets, better collimators, improved beam optics and upgraded power lines all playing a role. One of the most eye-catching modifications involves changing the geometry of the LHC's beams at the points where they cross. These beams are not continuous streams of protons. Instead, they are made up of bunches that contain around 100 billion protons each. In the LHC's current form, these bunches cross at an angle, and collisions can only occur in the area where they overlap. Increasing this area by flattening the crossing angle is thus a conceptually simple way of


Margaret Harris

On track Physicist Karolos Potamianos from the University of Warwick and the University of Oxford with the carbon-fibre barrel that will house a new Inner Tracker for the high-luminosity upgrade at the Large Hadron Collider.

increasing the number of collisions per crossing.

To achieve this in practice, teams are constructing superconducting radio-frequency cavities that can push bunches of protons sideways, like a crab walks. These so-called "crab" cavities have been installed in other particle accelerators, but never in a high-energy hadron collider like the LHC. The High Lumi upgrade includes 16 such cavities, several of which have already arrived at CERN for testing.

Another focus of the upgrade is the detectors themselves. For example, the innermost part of the ATLAS detector, which is the first to "see" the decay products of particle collisions and therefore receives high amounts of radiation, will be removed and replaced with a new Inner Tracker (ITk). The ITk's design calls for hundreds of strip-like silicon-based sensors to be slotted into a carbon-fibre barrel. When *Physics World* visited in late January, this barrel was sitting on a platform in the ATLAS integration hall, watched over somewhat anxiously by members of the ITk team. Once the ITk is assembled, the team will experience further anxious moments as the 6 m long, 2 m high barrel and its intricate innards are lowered into place through a hole in the ceiling of the 100 m-deep ATLAS chamber.

As for the science of the High-Lumi era, CERN's current director-general, Fabiola Gianotti, told *Physics World* that one key focus will be studying how the Higgs boson interacts with itself. This interaction, she explains, is a portal to events that took place in the early universe, when the Higgs field became established and initially massless elementary particles interacted with it to become the massive electrons and quarks we know today. "I cannot promise we will discover new particles or new forces – I have no idea because it is in the hands of nature," Gianotti says. "But for sure we will make progress, progress in understanding how the laws of nature work at the most fundamental level."

Margaret Harris, Geneva

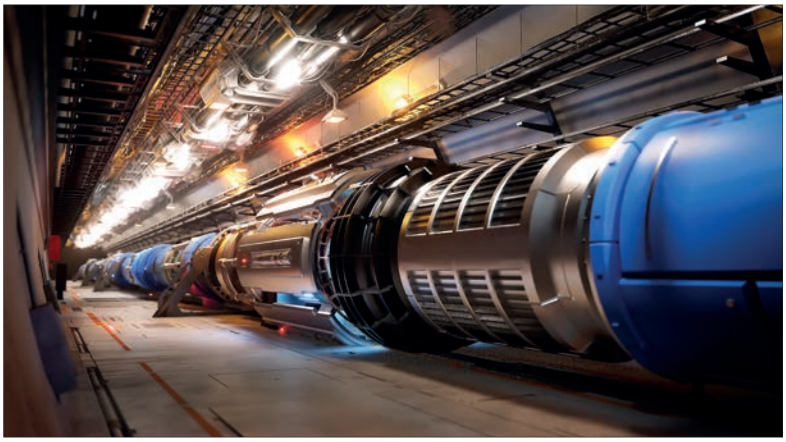
Might you do things differently?
I don't think I will do anything too radical. I will have a look at where we can make things work better. But my priority for now is putting in place the team that will work with me from January. That's quite a big chunk of work.

What do you think your leadership style will be?
I like to put around me a strong leadership team and then delegate and trust the leadership team to deliver. I'm there to set the strategic direction but also to empower them to deliver. That means I can take an outward focus and engage with the member states to promote CERN. I think my leadership style is to put in place a culture where the staff can thrive and operate in a very open and transparent way. That's very important to me because it builds trust both within the organization and with CERN's partners. The final thing is that I'm 100% behind CERN being an inclusive organization.

So diversity is an important aspect for you?
I am deeply committed to diversity and CERN is deeply committed to it in all its forms, and that will not change. This is a common value across Europe: our member states absolutely see diversity as being critical, and it means a lot to our scientific communities as well. From a scientific point of view, if we're not supporting diversity, we're losing people who are no different from others who come from more privileged backgrounds. Also, diversity at CERN has a special meaning: it means all the normal protected characteristics, but also national diversity. CERN is a community of 24 member states and quite a few associate member states, and ensuring nations are represented is incredibly important. It's the way you do the best science, ultimately, and it's the right thing to do.

The LHC is undergoing a £1bn upgrade towards a High Luminosity-LHC (HL-LHC), what will that entail?
The HL-LHC is a big step up in terms of capability and the goal will be to increase the luminosity of the machine (see box below). We are also upgrading the detectors to make them even more precise. The HL-LHC will run from about 2030 to the early 2040s. So by the end of LHC operations, we would have only taken about 10% of the overall data set once you add what the HL-LHC is expected to produce.

Beyond the HL-LHC, you will also be involved in planning what comes next. What are the options?
We have a decision to make on what comes after the HL-LHC in the mid-2040s. It seems a long way off but these projects need a 20-year lead-in. I think the consensus among the scientific community for a number of years has been that the next



Circular view The Future Circular Collider would involve building a 91 km circumference machine at CERN.

machine must explore the Higgs boson. The motivation for a Higgs factory is incredibly strong.

Yet there has not been much consensus whether that should be a linear or circular machine?

My personal view is that a circular collider is the way forward. One option is the Future Circular Collider (FCC) – a 91 km circumference collider that would be built at CERN.

What benefits would the FCC have?

We know how to build circular colliders and it gives you significantly more capability than a linear machine by producing more Higgs bosons. It is also a piece of research infrastructure that will be there for many years beyond the electron–positron collider. The other aspect is that at some point in the future, we are going to want a high-energy hadron collider to explore the unknown.

But it won't come cheap, with estimates being about £12–15bn for the electron–positron version, dubbed FCC-ee?

While the price tag for the FCC-ee is significant, that is spread over 24 member states for 15 years and contributions can also come from elsewhere. I'm not saying it's going to be easy to actually secure that jigsaw puzzle of resources, because money will need to come from outside Europe as well.

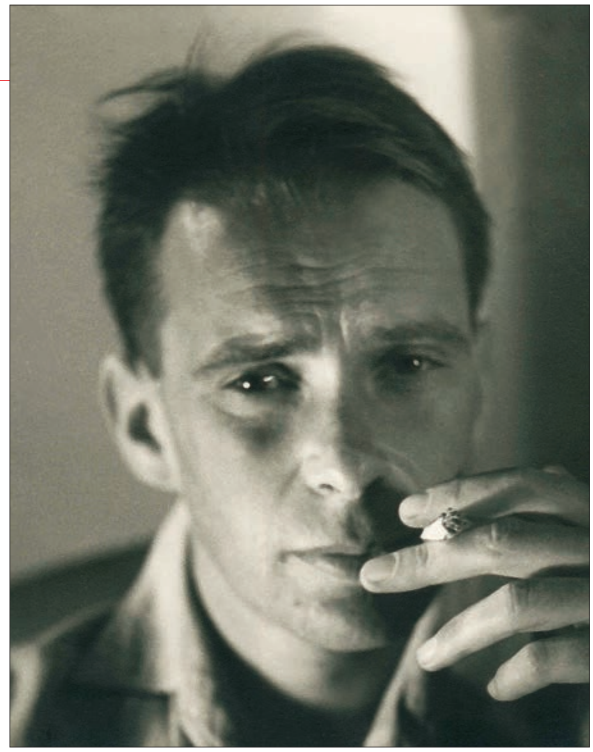
What would happen to the FCC if China builds the Circular Electron Positron Collider (CEPC), as it hopes to do by the 2030s?

I think that will be part of the European Strategy for Particle Physics, which will happen throughout this year, to think about the ifs and buts. Of course, nothing has really been decided in China. It's a big project and it might not go ahead. It's quite easy to put down aggressive timescales on paper but actually delivering them is always harder. The big advantage of CERN is that we have the scientific and engineering heritage in building colliders and operating them. There is only one CERN in the world.

Michael Banks is news editor of *Physics World*

From death rays to antimatter

Bruno Touschek was an Austrian-born theoretical physicist who proposed what became the world's first circular particle collider. But as **Giulia Pancheri** describes, few colleagues were aware of a dark past, which saw him work on a "death-ray" device for the Nazi military



Man of many talents Bruno Touschek pictured in 1955, a decade after escaping death in Germany. By this time he was a successful theorist who had already proposed building the world's first electron–positron collider.

Giulia Pancheri is a retired particle physicist at the INFN Frascati National Laboratory in Italy and author of *Bruno Touschek's Extraordinary Journey: From Death Rays to Antimatter* (Springer 2022)

One sunny day in May 1966, I entered the grounds of the Frascati National Laboratory near Rome for the first time. I had just graduated with a degree in physics from the University of Rome and had a fellowship to work in Frascati's theoretical-physics group. It was led by Bruno Touschek, who six years earlier had famously proposed building a new kind of particle accelerator that was to become a prototype for many future devices around the world.

His idea did not involve smashing particles into fixed targets or colliding electrons with each other. Instead, Touschek wanted to show you could store enough antimatter in the form of positrons and collide them head-on with electrons in a circular device, with the resulting annihilation revealing new secrets of the particle world. His dream became reality in 1963 when the Anello di Accumulazione (AdA), or "storage ring", came online.

AdA was such an extraordinary accomplishment that similar electron–positron colliders were soon built elsewhere too. Now, in 1966, Touschek was overseeing construction of ADONE – an even more powerful and beautiful machine – that would collide electrons and positrons with a centre-of-mass energy higher than any other accelerator in the world. I can still remember the emotion I felt when Touschek took me to a large hall, in a round building across the Via Enrico Fermi, where an enormous crane was putting ADONE's first magnets into position.

I was to spend the next year working in Touschek's research group but neither I – nor most of his colleagues at the University of Rome – were aware of his dark and dramatic past. To most students, the Austrian-born Touschek was best known for the wonderfully clear lectures he gave on statistical mechanics, which he delivered carefully and precisely, using delightful turns of phrase and in a beautiful, neat script.

For me and many others, Touschek was a genius. Totally confident in his abilities as a physicist, he wasn't arrogant but didn't suffer fools gladly and liked his students to be smart and hard working. There was an aura about him that he richly deserved, having brought the AdA storage ring to fruition. The true story about Touschek's turbulent early life only emerged years later, following his death in 1978.

I was shocked when I heard the news. It soon emerged that Touschek's death, at the age of 57, had been caused by liver failure brought on by many years of excessive drinking. His addiction issues were well known to those around him, but it was not something that any of us really questioned. The reasons for them had only started to surface in the months before his death as Touschek began to open up about his early life to his friend and mentor, the physicist Edoardo Amaldi.

A remarkable life

In the years that followed, much more was to come to light from his friends and colleagues, who spoke out in various articles, books, lectures and video documentaries. But the fullest story of his remarkable life only emerged in 2009 after the historian Luisa Bonolis and I came across a cache of letters that Touschek had written to his father (see "Bruno Touschek's family letters" box).

The shocking truth was that despite being Jewish, Touschek had been made to work for the Nazis during the Second World War. Commandeered to help build a scientific device that could emit military-grade "death-rays", his was an incredible story that is described in detail in my book *Bruno Touschek's Extraordinary Journey* (Springer 2022). Touschek, who was later imprisoned and sent to a concentration camp, displayed immense courage under the worst of circumstances. Despite those traumas, he was to make vital fundamental contributions to particle physics, which he carried out with determination and vision.

Tragic times

Born on 3 February 1921 in Vienna, Touschek was the only son of the Jewish artist Camilla Weltmann and Franz Xaver Touschek – a Catholic officer in the Austrian army who had fought in Italy during the First World War. It was to be a childhood marred by tragedy. His mother died from the after-effects of "Spanish flu" when he was nine and then, in 1934, his maternal uncle killed himself following Hitler's rise to power.

Life worsened when Austria was annexed by Nazi Germany in early 1938. Touschek was a pupil at the prestigious Piaristengymnasium school and was due to take his final exams the following year. Although his mother had converted to Catholicism to marry Bruno's father, Touschek was regarded as a Jew and forbidden from sitting the exams with his fellow students. He had to switch to the Schottengymnasium – a private, Catholic school – where he passed his exams in February 1939.

With Europe heading towards war, Touschek now decided to go to Rome, where his maternal aunt Ada lived. There he attended a course on mathematical physics at the University of Rome, which was the first sign of his growing interest in theoretical physics. But Touschek's time in the Italian capital was spent with "more enthusiasm than profit", as Amaldi later wrote in a 1981 CERN report, *The Bruno Touschek legacy*.

Discouraged from continuing to study in Italy by the antisemitic racial laws enforced by Mussolini, Touschek instead applied to do chemistry at the University of Manchester in the UK. The reason for switching subjects isn't clear but Touschek was probably drawn by the fact that Chaim Weizmann – later Israel's first president – had been a lecturer in Manchester's chemistry department. The city also had a strong Jewish community, which must have offered the prospect of a safe haven.

But for reasons that remain unknown, Touschek did not – or could not – take up his offer of a place in Britain. Instead, in September 1939, just as war was breaking out, he began studying physics back home at the University of Vienna, where he excelled in its famous school of theoretical physics. His professors there included Hans Thirring, best known for developing the "Lense–Thirring" frame-dragging effect of general relativity.

Touschek was aware of the dangers of staying in Vienna but, with the war now on, his options were limited. Despite his mixed Jewish/Catholic background, the Nazi authorities deemed Touschek to be a "first-class" [i.e. fully] non-Aryan and, at the end of his first year, he was suspended from the university. In January 1941 he was expelled entirely. Touschek's chances of continuing to live and study in Vienna were disappearing fast.

To the heart of Germany

But Touschek then found protection and encouragement from the eminent German physicist Arnold Sommerfeld. Based at the University of Munich, Sommerfeld, then 72, was still an influential figure in the German physics community despite having been ostracized by the Nazi government for not complying with anti-Semitic policies. He had also refused to adhere to the notion of *Deutsche Physik*, such as denouncing relativity (which was deemed "un-German").

Touschek had got in contact with Sommerfeld after writing to him to point out some errors he'd spotted in one of his books. The ensuing correspondence saw Touschek travel to Munich in November 1941 with Paul Urban, a physicist from Vienna who was giving a seminar there and who'd mentored Touschek following his suspension and then expulsion from the university. Won over by Touschek's courage and determination, Sommerfeld crafted a plan for him to move to the University of Hamburg.

One of his former students would help Touschek continue his studies, with financial support from another

Bruno Touschek's family letters

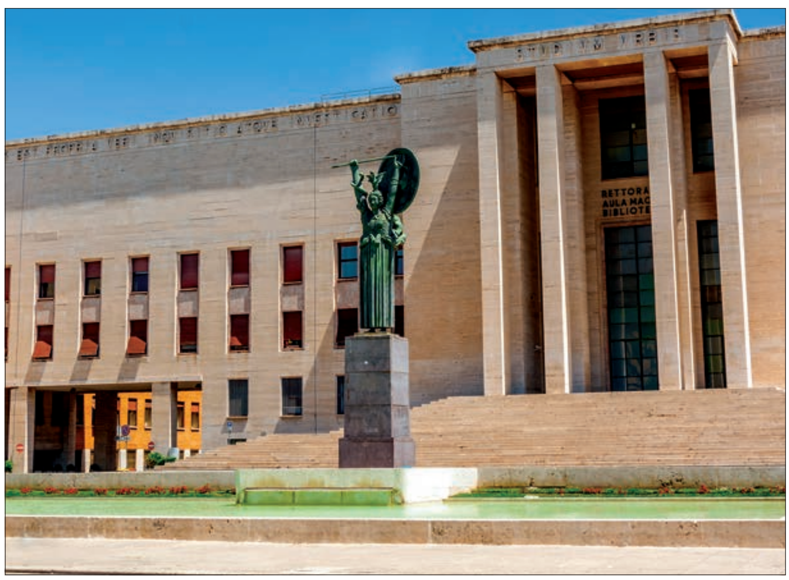
In the spring of 2009, the science historian Luisa Bonolis and I visited Bruno Touschek's widow, Elspeth Yonge, who lived in a small villa perched in the hills outside Rome. Bonolis knew from an earlier visit that Touschek had written many letters to his father and asked if we could see them. Yonge came back with a large cardboard box. Amongst various photographs and yellowed newspaper cuttings, was a folder of thin typewritten letters.

The letters, which are currently in the possession of the Touschek family, are written in German and had been carefully dated and collected by Bruno's father. Passed back to Bruno after his father's death in 1971, these letters describe Bruno's years in Germany in gripping detail, including his role in the betatron "death-ray" project, his imprisonment and escape from death in 1945.

Not yet published in full, the letters formed the basis of my book *Bruno Touschek's Extraordinary Journey: From Death Rays to Antimatter* (2022 Springer) and the contents of this *Physics World* article. Bonolis, who is currently based at the Max Planck Institute for the History of Science in Berlin, Germany, has also written a paper with a full list of references to many of the articles, books, videos and lectures about Touschek's life (arxiv:2111.00625).

Touschek family

Dramatic times Touschek's drawing of a bombed building from a letter to his father in 1943.



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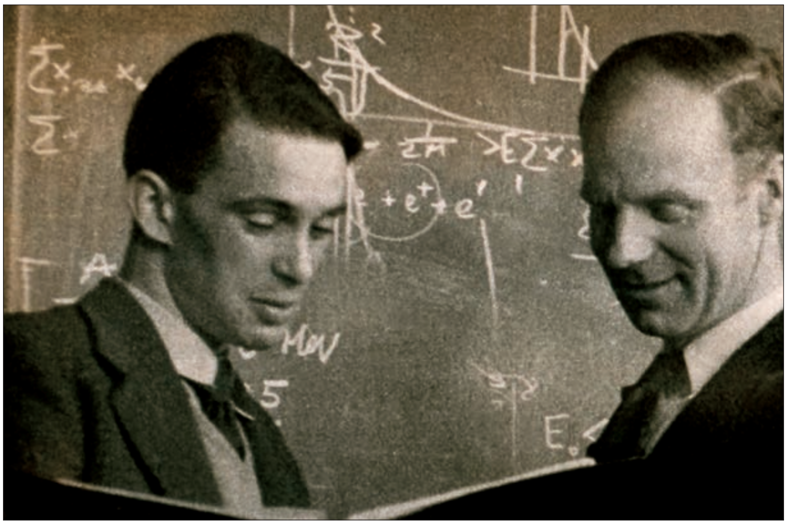
Wisdom and warfare Touschek's initial interest in theoretical physics was formed at the University of Rome, where he studied with Europe heading towards conflict in 1939.

Touschek family



Peaceful progress After the Second World War Touschek (left) moved to the UK, gaining his PhD from the University of Glasgow in 1949, where he extended his now growing knowledge of particle accelerators. He is seen here with Samuel Curran, a colleague from the newly established synchrotron group at Glasgow.

A Srivastava, INFN

Grounds for optimism Bruno Touschek proposed and successfully built AdA at the Frascati National Laboratory near Rome, where the original device is now on display to visitors.

ex-student, who now ran an electronics firm in the city. Moving to Germany might seem bizarre, but Hamburg was not as dangerous as Vienna, where his precarious status as a *Mischlinge* (mixed-race person) was well known. In any case, Austria was now effectively part of Germany and emigration – even to Italy – was not an option. Touschek simply hoped he could carry on with his physics, unnoticed.

Crucially for Touschek, there were scientists in Germany trying to protect their Jewish colleagues by hiring them for jobs in firms that were building equipment or devices for the Nazi military. Those scientists could claim that their Jewish friends' activities were indispensable to the success of the war effort. Such a ruse would keep Jewish scientists away from the attention of the Gestapo and prevent them from being sent to concentration camps.

That at least was the hope. As it turns out, the Gestapo was fully aware of the employment of Jewish scientists. The Nazi authorities tolerated the practice, knowing that as soon as the projects were completed, those scientists would be arrested and dispensed with. Unaware at the time of those dangers, Touschek packed his bags and headed for Germany.

Berlin and the betatron

After visiting Sommerfeld in Munich and receiving his "blessings" for the journey, Touschek arrived in Hamburg on 1 March 1942. Immediately he contacted the company and scientific colleagues Sommerfeld had recommended, before looking for somewhere to live. Money was tight and his studies progressed, albeit slowly. Touschek was then distraught to learn that his grandmother had been taken to the Theresienstadt concentration camp where she died.

Depressed, and with Hamburg and other cities starting to be fire bombed by Allied forces, in November 1942 Touschek was on the move once again, this time to Berlin. Closer than ever to the dark heart of the Nazi regime, he got a job with Löwe Opta, an electronics firms with links to the military. At Löwe, Touschek came to hear of a project to build a 15 MeV betatron – a machine that could accelerate electrons to high energies.

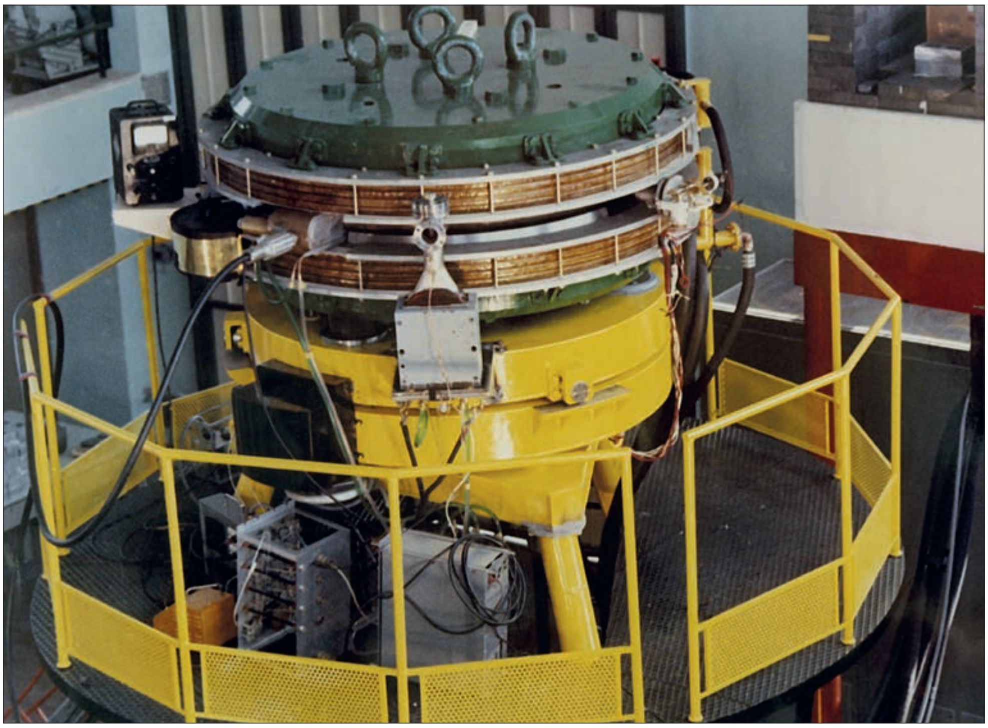
It was being commissioned by the Reich Ministry of Aviation, which had sought the help of the Norwegian physicist Rolf Widerøe, who in 1928 had invented the principle by which such accelerators operate. The Nazis hoped the device would be powerful enough to create "death-rays" – beams of electromagnetic radiation that could strike down enemy aircraft in military operations.

Devices to produce death-rays had first been proposed in the 1920s by several scientists – supposedly including even Guglielmo Marconi and Nikola Tesla – and betatrons had later been suggested as a possible source. In 1941 the US physicist Donald Kerst built the first betatron as a research tool at the University of Illinois – and Widerøe wanted his betatron to be as good, if not better. In their hearts, though, every member of Widerøe's betatron project knew it was unlikely that a betatron could ever really be put to military use.

Touschek formally joined Widerøe's team at the end of 1943, where his knowledge of theoretical physics made him a vital member of the project. Aware that he was under surveillance by the Gestapo, Touschek wrote to his father to say he had signed his own "death contract". In early 1944 he was summoned to the all-powerful Todt Organization, which senior Nazi engineer Fritz Todt had set up to build Germany's concentrations camps and provide industry with forced labour.

Luckily, his colleagues successfully appealed his call-up to the organization, insisting that Touschek was indispensable to the betatron. Despite further summons following – the last being in November 1944, when he was asked to appear with "blankets and warm underwear" – in each case Touschek managed to remain on the project. In one case his colleagues even appealed directly to General Erhard Milch, a close associate of armaments minister Albert Speer.

INFN-LNF



Collision course Left: Touschek in 1966 with Italo Federico Quercia, director of the Frascati National Laboratory, overseeing the construction of the ADONE electron–positron collider. ADONE was a higher energy evolution of the AdA collider (pictured right), which Touschek had spearheaded and was to become a prototype for many future devices around the world.

A march towards death

The betatron was completed at the end of 1944. But as 1945 dawned, it started to become obvious that Germany was going to lose the war. Orders came for the country to save important infrastructure and facilities from the advancing Allied armies. The betatron – a prized device – could still be of use and a plan was hatched to move it from the factory in Hamburg where it had been built to Wrist, a small village about 30 km north of the city.

Touschek and Widerøe completed the task on 15 March 1945. The following day, Touschek returned to Hamburg, arriving at his flat at midnight. At 7 a.m. the next morning, he was awoken by the Gestapo, who took Touschek away to the infamous Fuhlsbüttel prison, where he was kept for four weeks, initially in such miserable conditions that he thought of suicide.

Colleagues from the betatron project came and briefly managed to improve Touschek's situation, even bringing him some of his physics books. He was promised that a release would come soon. It did not. Instead on 15 April 1945, all 200 Fuhlsbüttel prisoners – Touschek among them – were ordered to march to the Kiel concentration camp, roughly 100 km north of Hamburg.

Unwell and weighed down by the physics books that he was carrying with him, Touschek fainted and collapsed on the road near Langenhorn on the outskirts of Hamburg. An SS officer accompanying the prisoners fired at Touschek, shooting him twice as he fell in a trench at the roadside. Blood pouring from his head, the officer and other prisoners continued their march, leaving Touschek for dead.

His wounds fortunately proved superficial. Touschek regained consciousness and was taken to hospital and then another prison, from which a betatron colleague had him released at the end of April 1945. Touschek would later tell his close friends this remarkable tale, which Amaldi also described in a letter from Widerøe who had visited him in prison. Lengthy descriptions appear as well in two letters Touschek wrote to his father in June and October 1945 (see *Eur. Phys. J. H* **36** 1 for English translations).

Touschek never properly explained why he was arrested, offering different explanations to different people in the years that followed. In my view, he simply would not – or could not – account for his involvement with a classified project financed by the Minister of Aviation of the Reich. His work for the Nazi regime was not something that Touschek could ever easily come to terms with or forget.

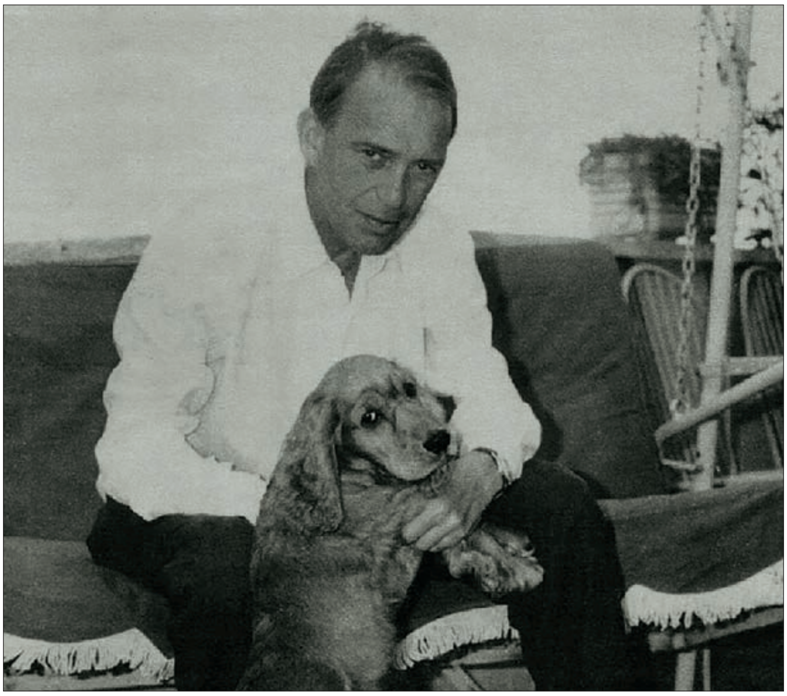
Göttingen, Glasgow and Rome

After the war, the Allies permitted German science to restart under the guidance of Werner Heisenberg at the University of Göttingen, provided it was directed only for peaceful purposes. But with the Manhattan atomic-bomb project making particle accelerators a useful source of nuclear isotopes, Touschek's experience with Widerøe's betatron caught the eye of the British, who occupied the Hamburg region. Recognising his mix of theoretical and practical know-how, a plan was drawn up to bring him to the UK.

Aware that Touschek's formal education was lacking, he was first allowed to obtain his diploma (master's) in physics at Göttingen, where he did a thesis on the theory of the betatron. In 1947, after a further six months in Heisenberg's research group, Touschek moved to the University of Glasgow, where he did a PhD supervised by John Gunn, with Rudolph Peierls as external advisor. He then spent a further three years there as a Nuffield lecturer.

An SS officer accompanying the prisoners fired at Touschek, shooting him twice as he fell in a trench at the roadside

Touschek family



Down time
Touschek relaxing at his home in Rome in 1970 with his cocker spaniel Lola.

Touschek's five years in Glasgow were fruitful both scientifically and personally. He extended his knowledge of particle accelerators by following the construction of the Glasgow 350 MeV synchrotron and advising UK groups in Birmingham and elsewhere who were building their own devices. On the theoretical physics side, he came to know Max Born, who had found refuge at the University of Edinburgh after leaving Germany in 1933.

Touschek collaborated with him on the second edition of Born's famous *Atomic Physics* book and discussed various physics problems with him, sometimes even explaining Heisenberg's newest papers. In this period Touschek began to work on the so-called "infrared catastrophe". Involving low-frequency photons emitted by accelerated charged particles, it was a phenomenon that was later to be relevant to all high-energy particle accelerators.

His credentials as a physicist now firmly established, in 1952 Touschek accepted a job offer from Amaldi as a researcher at the University of Rome. Returning to the city he had visited many times before the war – and where his aunt Ada had built a villa in the Frascati hills – Touschek found a vibrant intellectual atmosphere in the university's physics institute. It played host to numerous distinguished international visitors including the Nobel laureates Patrick Blackett and Wolfgang Pauli.

With the war now firmly in the past, numerous national and international physics projects were starting up. One was CERN, the European particle-accelerator centre near Geneva, which Amaldi strongly supported and served as its first director-general. Rome was also home to two significant, new Italian projects – the Institute for Nuclear Physics (INFN) and the Frascati lab – both of which were to play an important role in Touschek's future.

Particle accelerators were fast becoming a fundamental research tool and were being used to discover a whole "zoo" of new particles. Touschek became interested in their symmetry properties and started studying neutrinos, proposing chiral symmetry transformations. At Rome, he worked closely with Wolfgang Pauli, who was trying to prove the charge–parity–time (CPT) theorem, according to which particle states don't change if the particles become their anti-particles, if spatial co-ordinates are reflected or time is reversed.

Touschek's visionary thinking soon inspired other large physics labs to build similar electron–positron colliders

Touschek's understanding of CPT led him to realize that electron–positron colliders, which accelerate matter and anti-matter along the same orbit but in opposite directions, would be vital for the future of physics. Convinced by the CPT theorem that electrons and positrons could be smashed into – and annihilate – each other, in 1960 he started leading a team of Frascati scientists to build a prototype. This was AdA, which began operations in February 1961.

To prove its feasibility as a research device, the 1.3 m-diameter device was transported to the Orsay lab near Paris where the first electron–positron collisions were observed by a team of French and Italian researchers in late 1963. Key to AdA's success was the exceptional cadre of young theoretical physicists at Rome and the technical and scientific staff both in Frascati and Orsay. Although it never led to annihilation or produced novel particles, AdA was a testbed for a new breed of machines.

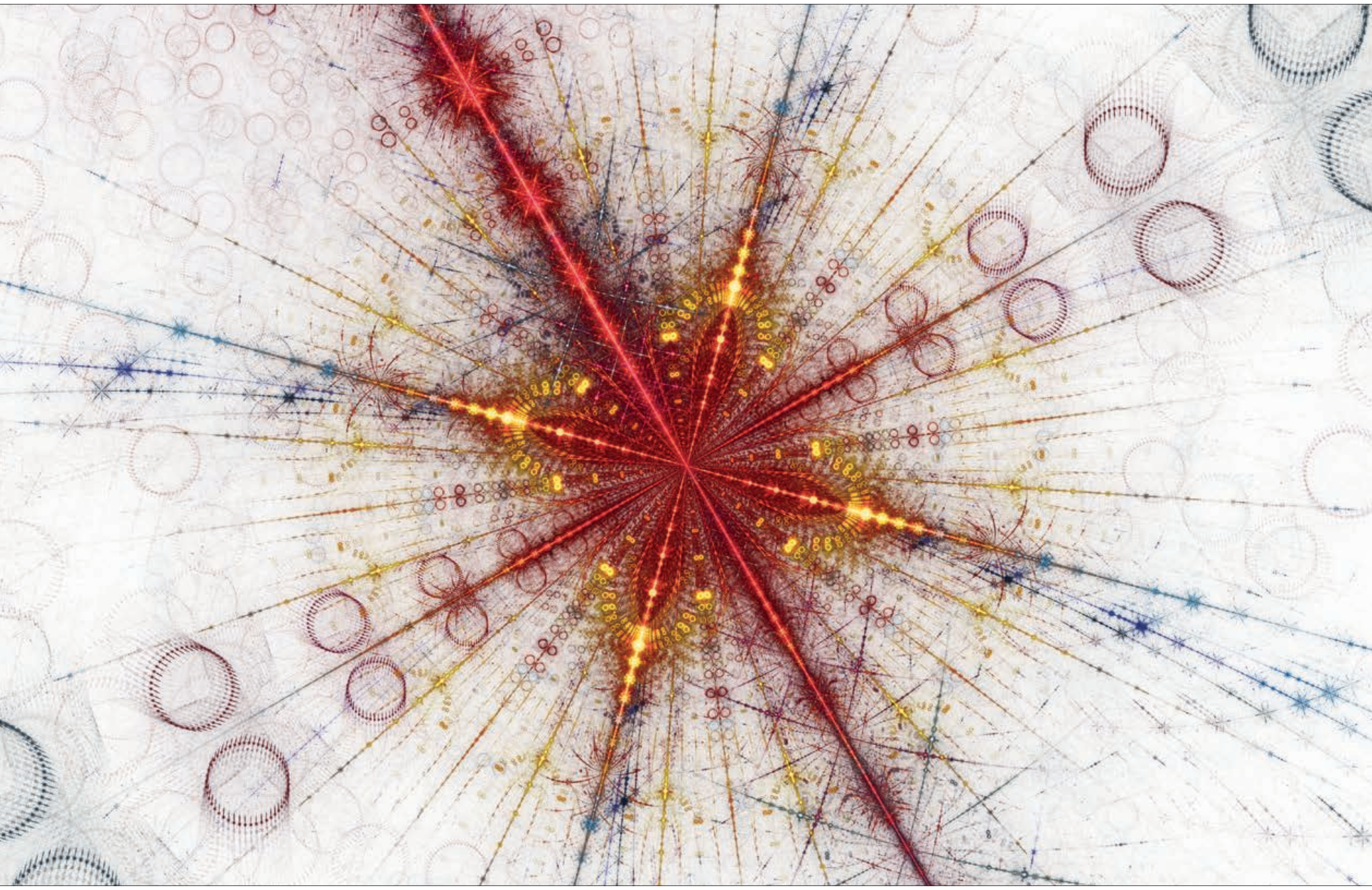
Lasting legacy

Touschek's visionary thinking soon inspired other large physics labs in France, the Soviet Union and the US to build similar electron–positron colliders, opening the door to the discovery of new particles. AdA thus laid the foundations to the Standard Model of particle physics and changed the face of physics itself. Touschek was able to see some of these great events, such as multihadron production at ADONE and the discovery of charm quarks.

In 1977 he spent a year's sabbatical at CERN, where the Super Proton–Antiproton Collider and the Large Electron–Positron collider (LEP) were going to be built. Not a fan of big international enterprises, which Touschek felt were becoming too bureaucratic and complex, he nevertheless enjoyed keen discussions with Carlo Rubbia about stochastic cooling – a technique to create a stock of antiprotons that could be annihilated with protons to discover the carriers of the weak force.

However, in February 1978 Touschek's health started rapidly declining. After a number of hospitalizations, he asked CERN's then director-general, Léon Van Hove, for a car to drive him to Innsbruck in Austria. The country of his birth, it was a place he had loved all his life. Touschek, who died on 25 May 1978, never got to witness the renaissance of particle physics – the experimental discovery of the W and Z bosons, the top quark and the Higgs boson – in the years and decades that followed.

But his legacy as a visionary scientist, who showed wisdom, stamina and perseverance – despite all the odds – lives on.



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Planning the future of high-energy physics

Tulika Bose, **Philip Burrows** and **Tara Shears** talk to Michael Banks about the discovery of the Higgs boson in 2012 and how the next big particle collider will deepen our understanding of its properties

More than a decade following the discovery of the Higgs boson at the CERN particle-physics lab near Geneva in 2012, high-energy physics stands at a crossroads. While the Large Hadron Collider (LHC) is currently undergoing a major £1.1bn upgrade towards a High-Luminosity LHC (HL-LHC), the question facing particle physicists is what machine should be built next – and where – if we are to study the Higgs boson in unprecedented detail in the hope of revealing new physics.

Several designs exist, one of which is a huge 91 km circumference collider at CERN known as the Future Circular Collider (FCC). But new technologies are also offering tantalising alternatives to such large machines, notably a muon collider. As CERN celebrates its 70th anniversary this year, Michael Banks talks to Tulika Bose from the University of Wisconsin–Madison, Philip Burrows from the University of Oxford and Tara Shears from the University of Liverpool about the latest research on the Higgs boson, what the HL-LHC might discover and the range of proposals for the next big particle collider.

What have we learnt about the Higgs boson since it was discovered in 2012?

Tulika Bose (TB): The question we have been working towards in the past decade is whether it is a "Standard Model" Higgs boson or a sister, or a cousin or a brother of that Higgs. We've been working really hard to pin it down by measuring its properties. All we can say at this point is that it looks like the Higgs that was predicted by the Standard Model. However, there are so many questions we still don't know. Does it decay into something more exotic? How does


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Super LHC The High-Luminosity Large Hadron Collider, to be completed by the end of the decade at a cost of £1.1bn, will result in a factor of 10 increase in luminosity over the original LHC.

it interact with all of the other particles in the Standard Model? While we've understood some of these interactions, there are still many more particle interactions with the Higgs that we don't quite understand. Then of course, there is a big open question about how the Higgs interacts with itself. Does it, and if so, what is its interaction strength? These are some of the exciting questions that we are currently trying to answer at the LHC.

So the Standard Model of particle physics is alive and well?

TB: The fact that we haven't seen anything exotic that has not been predicted yet tells us that we need to be looking at a different energy scale. That's one possibility – we just need to go much higher energies. The other alternative is that we've been looking in the standard places. Maybe there are particles that we haven't yet been able to detect that couple incredibly lightly to the Higgs.

Has it been disappointing that the LHC hasn't discovered particles beyond the Higgs?

Tara Shears (TS): Not at all. The Higgs alone is such a huge step forward in completing our picture and understanding of the Standard Model, providing, of course, it is a Standard Model Higgs. And there's so much more that we've learned aside from the Higgs, such as understanding the behaviour of other particles such as differences between matter and antimatter charm quarks.

How will the HL-LHC take our understanding of the Higgs forward?

TS: One way to understand more about the Higgs is to amass enormous amounts of data to look for very rare processes and this is where the HL-LHC is really going to come into its own. It is going to allow us to extend those investigations beyond the particles we've been able to study so far making our first observations of how the Higgs interacts with lighter particles such as the muon and how the Higgs interacts with itself. We hope to see that with the HL-LHC.

What is involved with the £1.1bn HL-LHC upgrade?

Philip Burrows (PB): The LHC accelerator is 27 km long and about 90% of it is not going to be affected. One of the most critical aspects of the upgrade is to replace the magnets in the final focus systems of the two large experiments, ATLAS and CMS. These magnets will take the incoming beams and then focus them down to very small sizes of the order of 10 microns in cross section. This upgrade includes the installation of brand new state-of-the-art niobium-tin (Nb_3Sn) superconducting focusing magnets.

What is the current status of the project?

PB: The schedule involves shutting down the LHC for roughly three to four years to install the high-luminosity upgrade, which will then turn on towards the end of the decade. The current CERN schedule has the HL-LHC running until the end of 2041. So there's another 10 years plus of running this upgraded collider and who knows what exciting discoveries are going to be made.

TS: One thing to think about concerning the cost is that the timescale of use is huge and so it is an investment for a considerable part of the future in terms of scientific exploitation. It's also an investment in terms of potential spin-out technology.

In what way will the HL-LHC be better than the LHC?

PB: The measure of the performance of the accelerator is conventionally given in terms of luminosity and it's defined as the number of particles that cross at these collision points per square centimetre per second. That number is roughly 10^{34} with the LHC. With the high-luminosity upgrade, however, we are talking about making roughly an order of magnitude increase in the total data sample that will be collected over the next decade or so. So in other words, we've only got 10% or so of the total data sample so far in the bag. After the upgrade, there'll be another factor of 10 data that will be collected and that is a completely new ball game in terms of the statistical accuracy of the measurements that can be made and the sensitivity and reach for new physics

Looking beyond the HL-LHC, particle physicists seem to agree that the next particle collider should be a Higgs factory – but what would that involve?

TB: Even at the end of the HL-LHC, there will be certain things we won't be able to do at the LHC and that's for several reasons. One is that the LHC is a proton–proton machine and when you're colliding protons, you end up with a rather messy environment in comparison to the clean collisions between electrons and positrons and this allows you to make certain measurements which will not be possible at the LHC.

What sort of measurements could you do with a Higgs factory?

TS: One is to find out how much the Higgs couples to the electron. There's no way we will ever find that out with the HL-LHC, it's just too rare a process to measure, but with a Higgs factory, it becomes a possibility. And this is important not because it's stamp collecting, but because understanding why the mass of the electron, which the Higgs boson is responsible for, has that particular value is of huge importance to our understanding of the size of atoms, which underpins chemistry and materials science.

PB: Although we often call this future machine a Higgs factory, it has far more uses beyond making Higgs bosons. If you were to run it at higher energies, for example, you could make pairs of top quarks and anti-top quarks. And we desperately want to understand the top quark, given it is the heaviest fundamental particle that we are aware of – it's roughly 180 times heavier than a proton. You could also run the Higgs factory at lower energies and carry out more precision measurements of the Z and W bosons. So it's really more than a Higgs factory. Some people say it's the "Higgs and the electroweak boson factory" but that doesn't quite roll off the tongue in the same way.

While it seems there's a consensus on a Higgs factory, there doesn't appear to be one regarding building a linear or circular machine?

PB: There are two main designs on the table today – circular and linear. The motivation for linear colliders is due to the problem of sending electrons and positrons round in a circle – they radiate photons. So as you go to higher energies in a circular collider, electrons and positrons radiate that energy away in the form of synchrotron radiation. It was felt back in the late-1990s that it was the end of the road for circular electron–positron colliders because of the limitations of synchrotron radiation. But the discovery of the Higgs boson at 125 GeV was lighter than some had predicted. This meant that an electron–positron collider would only need a centre of mass energy of about 250 GeV. Circular electron–positron colliders then came back in vogue.

TS: The drawback with a linear collider is that the beams are not recirculated in the same way as they are in a circular collider. Instead, you have "shots", so it's difficult to reach the same volume of data in a linear collider. Yet it turns out that both of these solutions are really competitive with each other and that's why they are still both on the table.

PB: Yes, while a circular machine may have two, or even four, main detectors in the ring, at a linear machine the beam can be sent to only one detector at a given time. So having two detectors means you have to share the luminosity, so each would get notionally half of the data. But to take an automobile analogy, it's kind of like arguing about the merits of a Rolls-Royce versus a Bentley. Both linear and circular are absolutely superb, amazing options and some have got bells and whistles over here and others have got bells and whistles over there, but you're really arguing about the fine details.

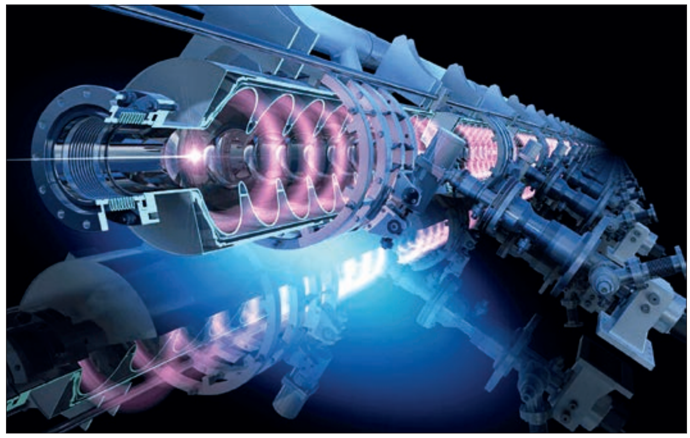
CERN seems to have put its weight behind the Future Circular Collider (FCC) – a huge 91 km circumference circular collider that would cost £12bn. What's the thinking behind that?

TS: The cost is about one-and-a-half times that of the Channel Tunnel so it is really substantial infrastructure. But bear in mind it is for a facility that's going to be used for the remainder of the century, for future physics, so you have to keep that longevity in mind when talking about the costs.

TB: I think the circular collider has become popular because it's seen as a stepping stone towards a proton–proton machine operating at 100 TeV that would use the same infrastructure and the same large tunnel and begin operation after the Higgs factory element in the 2070s. That would allow us to really pin down the Higgs interaction with itself and it would also be the ultimate discovery machine, allowing us to discover particles at the 30–40 TeV scale, for example.

What kind of technologies will be needed for this potential proton machine?

PB: The big issue is the magnets, because you have to build very strong bending magnets to keep the protons going round on their 91 km circumference trajectory. The magnets at the LHC are 8 T but some think the magnets you would need for the proton version of the FCC would be 16–20 T. And that is really pushing the boundaries of magnet technology. Today, nobody really knows how to build such magnets. There's a huge R&D effort going on around the world and people are constantly making progress. But that is the big technological uncertainty. Yet if we follow the model of an electron–positron collider first, followed by a proton–proton machine, then we will have several decades in which to master the magnet technology.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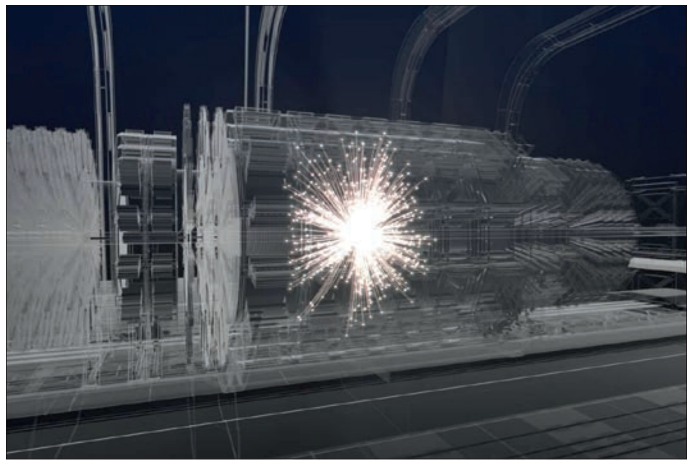
Balancing act A linear collider has the benefit that particles accelerated in it don't lose energy due to synchrotron radiation, potentially making it cheaper to build. To collect the same number of Higgs bosons at the nominal energy of 250 GeV the linear machine would probably have to be run for longer than the circular one.


CERN

Let's go round again The Future Circular Collider would involve constructing a huge 91 km-circumference ring near the existing LHC that would collide electrons with positrons to study the Higgs in unprecedented detail.

With regard to novel technology, the influential US Particle Physics Project Prioritization Panel, known as "P5", called for more research into a muon collider, calling it "our muon shot". What would that involve?

TB: Yes, I sat on the P5 panel that published a report late last year that recommended a course of action for US particle physics for the coming 20 years. One of those recommendations involves carrying out more research and development into a muon collider. As we already discussed, an electron–positron collider in a circular configuration suffers from a lot of synchrotron radiation. The question is if we can instead use a fundamental elementary particle that is more massive than the electron. In that case a muon collider could offer the best of both worlds, the advantages of an electron machine in terms of clean collisions but also reach-



Tulika Bose; Philip Burrows; McCoy Wynne

Expert panel (from left) Tulika Bose, Philip Burrows and Tara Shears.

ing larger energies like a proton machine. However, the challenge is that the muon is very unstable and decays quickly. This means you are going to have to create, focus and collide them before they decay. A lot of R&D is needed in the coming decades but perhaps a decision could be taken on whether to go ahead by the 2050s.

And potentially, if built, it would need a tunnel of similar size to the existing LHC?

TB: Yes. The nice thing about the muon collider is that you don't need a massive 90 km tunnel so it could actually fit on the existing Fermilab campus. Perhaps we need to think about this project in a global way because this has to be a big global collaborative effort. But whatever happens it is exciting times ahead.

● Tulika Bose, Philip Burrows and Tara Shears were speaking on a Physics World Live panel discussion about the future of particle physics held on 26 September 2024. This Q&A is an edited version of the event. You can watch a recording of this as well as our other 2024 events online at physicsworld.com/p/physics-world-live

Michael Banks is news editor of *Physics World*

CERN at 70: the inside story

CERN's former head of communications **James Gillies** reveals how his team handled unprecedented global interest in the world's most powerful collider, which ranged from fears of killer black holes to visits from celebrities

James Gillies was head of CERN's communications team from 2003 to 2016

"Read this," said my boss as he dropped a book on my desk sometime in the middle of the year 2000. As a dutiful staff writer at CERN, I ploughed my way through the chunky novel, which was about someone stealing a quarter of a gram of antimatter from CERN to blow up the Vatican. It seemed a preposterous story but my gut told me it might put the lab in a bad light. So when the book's sales failed to take off, all of us in CERN's communications group breathed a sigh of relief.

Little did I know that Dan Brown's *Angels & Demons* would set the tone for much of my subsequent career. Soon after I finished the book, my boss left CERN and I became head of communications. I was now in charge of managing public relations for the Geneva-based lab and ensuring that CERN's activities and functions were understood across the world.

I was to remain in the role for 13 eventful years that saw *Angels & Demons* return with a vengeance; killer black holes maraud the tabloids; apparently superluminal neutrinos have the brakes applied; and the start-up, breakdown and restart of the Large Hadron Collider (LHC). Oh, and the small business of a major discovery and the award of the Nobel Prize for Physics to François Englert and Peter Higgs in 2013.

Fear, black holes and social media

Back in 2000 the Large Electron-Positron collider, which had been CERN's flagship facility since 1989, was reaching the end of its life. Fermilab was gearing up to give its mighty Tevatron one more crack at discovering the Higgs boson, and social media was just over the horizon. Communications teams everywhere struggled to work out how to adapt to this new-fangled phenomenon, which was giving a new platform to an old emotion.

Fear of the new is as old as humanity, so it's not surprising that some people were nervous about big machines like the Tevatron, the Relativistic Heavy Ion Collider and the LHC. One individual had long been claiming that such devices would create "strangelets", mini black holes and other supposedly dangerous phenomena that, they said, would engulf the world. Before the web, and certainly before social media, theirs was a voice in the wilderness. But social media gave them a platform and the tabloid media could not resist.

For the CERN comms team, it became almost a full-time job pointing out that the LHC was a minnow compared to the energies generated by the cosmos. All we were doing was bringing natural phenomena into the laboratory where they could be easily studied, as I wrote in *Physics World* at the time. Perhaps the Nobel-prize-winning physicist Sam Ting was right to switch his efforts from the terrestrial cacophony to the quiet of space, where his Alpha Magnetic Spectrometer on the International Space Station observes the colossal energies of the universe at first hand.

Despite our best efforts, the black-hole myth steadily grew. At CERN open days, we arranged public discussions on the subject for those who did not know quite what to make of it. Most people seemed to realize that it was no more than a myth. The British tabloid newspaper the *Sun*, for example, playfully reminded readers to cancel their subscriptions before LHC switch-on day.

But some still took it seriously. There were lawsuits, death threats and calls for CERN to be shut down. There were reports of schools being closed on start-up

Listen to James Gillies on the *Physics World Stories* podcast to hear more.

CERN/Maximilien Brice

Eyes of the world James Gillies led the CERN comms team when around 1000 media professionals representing some 350 outlets arrived at CERN in September 2008 to see the first proton beams enter and travel round the Large Hadron Collider.

day so that children could be with their parents if the world really did end. Worse still, in 2005 the BBC made a drama documentary *End Day*, seemingly inspired by Martin Rees's book *Our Final Century*. The film played out a number of calamitous scenarios for humankind, culminating with humanity taking on Pascal's wager and losing. I have read the book. That is not what Rees was saying.

We were now faced with another worry. Brown's follow-up book, *The Da Vinci Code*, had become a blockbuster and it was clear that *Angels & Demons*, after its slow start, would follow suit. I therefore found myself in a somewhat surreal meeting with CERN's then director-general (DG) Robert Aymar mulling over how CERN should respond. I suggested that the book's success was a great opportunity for us to talk about the real physics of antimatter, which is anyway far more interesting than the novel.

To my relief, Aymar agreed – and in 2005 visitors to CERN's website were greeted with a picture of our top-secret space plane that the DG uses to hop around the world in minutes. Or does he? Anyone clicking on the picture would discover that CERN doesn't actually have a space plane, but we do make antimatter. We could even make a quarter of a gram of it, given 250 million years.

More importantly, we hoped that visitors to the website would learn that the really interesting thing about antimatter is that nature seems to favour matter and we still don't know why. They'd also discover that antimatter plays an important role in medicine, in the form of positron-emission tomography (PET) scanners, and that CERN has long played an important part in their development.

Thanks to our playful, interactive approach, many people did click through. In fact, CERN's web traffic jumped by a factor of 10 almost overnight. The lab was on its way to becoming a household name and, in time, a synonym for excellence. In 2005, however, that was yet to come. We still had several years of black-hole myth-busting ahead.

Angels & Demons: when Hollywood came to CERN

CERN

Hello Hollywood Set partly at CERN, the movie *Angels & Demons* starred Tom Hanks (second from left), who toured the ATLAS detector in February 2009.

CERN

Movie magic *Angels & Demons* was previewed to the entertainment press at CERN in February 2009. Lead actors Tom Hanks (left) and Ayelet Zurer (centre) attended, while director Ron Howard (right) spoke to the press.

Dan Brown's 2000 mystery thriller *Angels & Demons* is a race against the clock to stop antimatter stolen from CERN from blowing up the Vatican. Despite initial slow sales, the book eventually proved so successful that it was turned into a 2009 movie of the same name, directed by Ron Howard. He visited CERN more than once and I was impressed by his wish to avoid the book's shaky science.

In the movie version, which stars Tom Hanks and Ayelet Zurer, CERN is confined to the pre-opening title sequence, with the ATLAS cavern reconstructed in CGI. Howard's team even gave me a watermarked script and asked for feedback on the science. Howard also made a short film about CERN for the movie's Blu-ray release. Ahead of that event, we found ourselves fielding calls from Howard's office at all times of day and night about the science.

The movie was officially launched at CERN to the entertainment press, with Howard, Hanks and Zurer in attendance, who all gushed what an amazing place the lab is. Handled by Sony Pictures, the event proved much more tightly controlled than typical CERN gatherings, with Sony closely vetting which science journalists we'd invited. My colleague Rolf Landua and I ended up having dinner with Hanks, Zurer and Howard – something I could never have imagined happening when the *Angels & Demons* book first came out.

Collider countdown

A couple of years later, an unexpected ally appeared in the form of Hollywood, which came knocking to ask if we'd be comfortable working with them on a film version of *Angels & Demons*. Again, the DG agreed and in 2009 the film appeared, starring Tom Hanks, along with Ayelet Zurer as a brilliant female physicist who saves the day. Fortunately, much of the book's dodgy science and misrepresentation of CERN didn't make it onto the screen (see box above).

Of course, the angels, the demons and the black holes were all a distraction from CERN's main thrust – launching the LHC. By 2008 Fermilab's Tevatron was well into its second run, but the elusive Higgs boson remained undiscovered. The mass range available for it was increasingly constrained and particle physicists knew that if the Tevatron didn't find it, the LHC would (assuming the Higgs existed). The stakes were high, and a date was set to thread the first beams around the LHC. First Beam Day would be 10 September 2008.

Any big new particle accelerator is its own prototype. Switching such a machine on is best done in peace and quiet, away from the media glare. But CERN's new standing on the world's stage, coupled with the still-present black-hole myth, dictated otherwise. Media outlets started contacting us – not to ask if they could come for the switch-on, but to tell us they would be there. Outside the CERN fence if necessary.

Another surreal conversation with the DG ensued. Media were coming, I told him, whether we liked it or not. Lots of them. We could either make plans to invite them in and allow them to follow the attempts to get beams around the LHC, or we could have them outside the lab reporting that CERN was starting the doomsday machine in secrecy behind the fence.

The DG agreed that it might be better to let them in, and so we did. Around 1000 media professionals representing some 350 outlets descended on the lab. Among them was a team from BBC Radio 4. Some months earlier, a producer called Sasha Feachem had rung CERN to say she'd been trying to persuade her boss, Mark Damazer, to do a full day's outside broadcast from CERN, and would I come to London to convince him.

I tried, and in an oak-panelled room at Broadcasting House, failed completely to do so. But Damazer did accept an invitation to visit CERN. After hitting it off with the DG, Radio 4's Big Bang Day was approved and an up-and-coming science presenter by the name of Brian Cox was chosen to anchor the BBC's coverage. It was the first time a media team had ever broadcast wall-to-wall from a science lab and I don't think Radio 4 has done anything like it since.

Journalists were accredited. A media centre was set up. Late-coming reporters were found places in the CERN main auditorium where they could watch a live feed from the control room, along with the physicists. We even installed openable windows in the conference room overlooking the control room so that TV crews could get clean shots of the action below.

A time was set early that September morning for the

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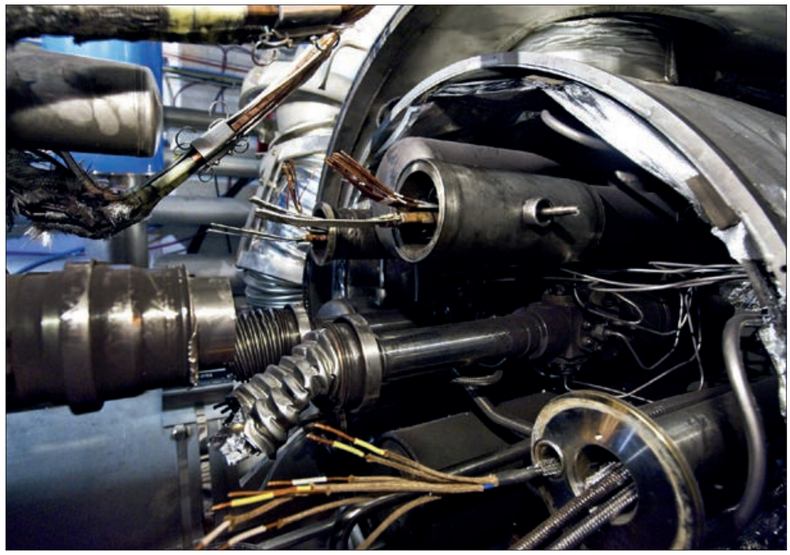
Comms boss James Gillies, shown here in 2013, ran CERN's media relations with the world from 2003 to 2016.

CERN/Maximilien Brice



What happened here? CERN had a job on its hands in 2008 explaining to the world how a damaged superconducting interconnect led to the Large Hadron Collider breaking down just nine days after the first beams had entered the machine.

first attempt at beam injection into the LHC, and the journalists were all in place. Then there was a glitch, and the timing was put back a couple of hours. Project leader Lyn Evans had agreed to give a countdown, and when the conditions for injection were back, he began. A dot appeared on a screen indicating that a proton beam had been injected.

After an agonising wait, a second dot appeared, indicating that the beam had gone round the 27 km-long machine once. There were tears and laughter, and the journalists who were parked in the auditorium with the physicists later said they'd had the best seats in the house. They were able to witness the magnitude of that moment alongside those whose lives it was about to change.

It was an exhausting but brilliant day. On my way home, I ran into Evans as he was driving out of the lab. He rolled down his window and said: "Just another day at the office, eh James!" Everyone was on top of the world. Media coverage was massive and positive, with many of those present telling us how refreshing it was to take part in something so clearly genuine in a world where much is hidden.

From joy to disaster

The joy proved short lived. The LHC has something like 10 000 high-current superconducting interconnects. One was not perfect, so it had a bit of resistance, which led to an electrical arc that released helium into the cryostat with enough force to knock several magnets off their stands. Nine days after switch-on, CERN suddenly had a huge and unexpected repair job on its hands.

The Higgs boson was still nowhere in sight. The Tevatron was still running and the painstaking task began of working out what had gone wrong at the LHC. CERN not only had to repair the damaged section, but also understand why it had happened and ensure it wouldn't happen again. Other potentially imperfect interconnects had to be identified and remade. The machine also had to be equipped with systems that would release pressure should helium gas build up inside the cryostat.

My mantra throughout this period was that CERN had to be honest, open, trustworthy and timely in all communications – an approach that, I think, paid dividends. The media were kind to us, capturing the pioneering nature of our research and admiring the culture of an organization that sought not to attribute blame, but to learn and move on.

When beams were back in the LHC in November 2009, they cheered us on. By the end of the year, the first data had been recorded. LHC running began in earnest in 2010, and with the world clearly still in place, the black-hole myth gave way to excitement about a potential major discovery. The Tevatron collided its last beams in September 2010, leaving the field clear for the LHC.

As time progressed, hints of something began to appear in the data, and by 2012 there was a palpable sense of expectation. A Higgs Update Seminar was arranged at CERN for 4 July – the last day possible for the spokespeople of the LHC's ATLAS and CMS experiments to be at CERN before heading to Melbourne for the 2012 International Conference on High-Energy Physics, which is always a highlight in particle physicists' calendars.

Gerry Guralnik and Carl Hagan – early pioneers of spontaneous symmetry breaking – asked whether they could attend the CERN seminar, so we thought we'd better invite Peter Higgs and François Englert too. (Robert Brout, who had been co-author on Englert's 1964 paper in *Physical Review Letters* (**13** 321) predicting what we now called the Brout–Englert–Higgs mechanism, had died in 2011.) Right up to the last minute, we didn't know if we'd be making a discovery announcement, or just saying "Watch this space." One person, however, did decide that he'd be able to say, "I think we have it."

As DG since 2009, Rolf-Dieter Heuer had seen the results of both experiments, and was convinced that even if neither could announce the discovery individually, the combined data were sufficient. On the evening of 3 July 2012, as I left my office, which was next to the CERN main auditorium, I had to step over people laying out sleeping bags in the corridor to guarantee their places in the room the next day.

As it turned out, both experiments had strong enough

CERN

One famous day The discovery of the Higgs boson, announced on 4 July 2012, was the highlight of James Gillies' career as CERN's comms chief. Fabiola Gianotti (foreground, wearing red top) leads the applause in the packed CERN auditorium.

Sculpture donated by the artist. Photo courtesy: CERN/Benoit Jeannet

Different worlds Visits are vital for CERN, which has hosted everyone from pupils and politicians to pop stars and artists – including Antony Gormley, whose metal sculpture *Feeling Material XXXIV* hangs in the lab's main building.

measurements to make a positive statement on the day, though the language was still cautious. The physicists talked simply about "the discovery of a new particle with features consistent with those of the Higgs boson predicted by the Standard Model of particle physics". Higgs and Englert heard the news seated side by side, Higgs famously wiping a tear from his eye and saying that it was remarkable that the discovery had been made in his lifetime.

The media were present in force, and everyone wanted to talk to the theorists. It's a sign of the kind of person Higgs was that he told them they'd have plenty of opportunity to talk to him later, but that today was a day to celebrate the experimentalists.

Nature versus nature

The Higgs discovery was undoubtedly the highlight of my career in communications at CERN, but the Higgs boson is just one aspect of CERN's research programme. I could tell you about the incredible precision achieved by the LHCb experiment, seeking deviations from the Standard Model in very rare decays. I could talk about the discovery of a range of composite particles predicted by theory. Or about the insights brought by a mind-boggling range of research at low energies, from antimatter to climate change.

Then there is CERN's neutrino programme. It's now focused on the US long baseline project, but it brought its own headaches to the communications team when muon neutrinos from CERN's Super Proton Synchrotron appeared to be arriving at the Gran Sasso Laboratory in Italy faster than the speed of light.

"Have you checked all the cables?" said one of our directors to the scientists involved, in a meeting in the DG's office. "Of course," they insisted. As it turned out, there had been a false reading – not strictly speaking from a poorly chosen cable, but a faulty fibre-optic connection. The laws of physics were safe. Unfortunately, this was not before a seminar was held in the CERN Main Auditorium in September 2011.

Had they held the seminar at Gran Sasso, I'm sure they'd have got less coverage. Our approach was to say: "This is how science works – you get a measurement that you don't understand, and you put yourself up to scrutiny from your peers." It led to a memorable editorial in *Nature* (**484** 287) entitled "No shame", which concluded that "Scientists are not afraid to question the big ideas. They are not afraid to open themselves to public scrutiny. And they should not be afraid to be wrong."

That remark in *Nature* was a positive outcome for CERN from a potentially embarrassing episode, but nature of another kind caught us off guard, not once but twice, when animals brought low the world's mightiest machine. First, breadcrumbs and feathers led us to believe that a bird had had a lucky escape when it tripped an electrical substation. Later, a pine marten, which also caused a power outage after gnawing through a live cable, was not so lucky. It has now joined the gallery of animals that have met unusual ends in the Rotterdam Museum of Natural History.

There were also visitors. Endless visitors, from school children to politicians and from pop stars to artists. On a return visit of my own to Antony Gormley's London studio after having given him a tour of CERN, he spontaneously presented me with one of his pieces. *Feeling Material XXXIV* – a metal sculpture that's part of a series giving an impression of the artist's body – now hangs proudly in CERN's main building

There was an incredible moment at one of the TEDxCERN events we organized when Will.i.am joined two local children's choirs for a rendition of his song "Reach for the Stars". And there were many visits from the late landscape architect Charles Jencks and Lily Jencks who produced a marvellously intelligent design for a new visitor centre in the form of a cosmic Ouroboros – like a snake biting its own tail, it appeared like two mirror-image question marks forming a circle. One of my only regrets is that we were unable to fund its construction.

For a physicist-turned-science-communicator such as myself, there was no better place to be than at my desk through the opening years of the 21st century. CERN is a unique and remarkable institution that shows what humanity is capable of when differences are cast aside, and we focus on what we have in common. To paraphrase Charles Jencks, to whom I'm leaving the last word, CERN is perhaps the last bastion of the enlightenment.

Damage control

When Fermilab found that tritium had accidentally leaked from one of its experiments, staff immediately drew up a plan to allay concerns. **Robert P Crease** explains why things worked out

iStock/Paper Trident

Dangerous liaisons Fears whipped up by social media present new challenges to labs seeking to handle affairs affecting their local and scientific communities.

Small leaks of radioactive material can be the death knell for large scientific facilities. It's happened twice already. Following releases of non-hazardous amounts of tritium, the Brookhaven National Laboratory (BNL) was forced to shut its High Flux Beam Reactor (HFBR) in 1997, while the Lawrence Berkeley National Laboratory (LBNL) had to close its National Tritium Labeling Facility in 2001.

Fortunately, things don't always turn out badly. Consider the Fermi National Accelerator Laboratory (Fermilab) near Chicago, which has for many decades been America's premier high-energy physics research facility. In 2005, an experiment there also leaked tritium, but the way the lab handled the situation meant that nothing had to close. Thanks to a grant from the National Science Foundation, I've been trying to find out why such successes happen.

Running on grace

Fermilab, which opened in 1971, has had a hugely successful history. But its relationship with the local community got off to a shaky start. In 1967, to acquire land for the lab, the State of Illinois used a US legal manoeuvre called "eminent domain" to displace homeowners, angering neighbours. More trouble came in 1988, when the US Department of Energy (DOE) considered Fermilab as a possible site for the 87 km circumference Superconducting Supercollider (SSC), which would require acquiring more land.

Some locals formed a protest group called CATCH (Citizens Against The Collider Here). It was an aggressive organization whose members accused Illinois officials of being "secretive, arrogant and insensitive", and of wanting to saddle the area with radiation, traffic and lower property values. While Illinois officials were making the bid to host the SSC, the lab was the focus of protests. The controversy ended when the DOE chose to site the machine in Waxahachie, Texas. (The SSC was cancelled in 1993, incomplete.)

Brookhaven's closure of the HFBR in 1997 was a wake-up call for US labs, including Fermilab itself. Aware that the reactor had been shut by a cocktail of politics, activism and media scare stories, the DOE organized a "Lessons learned" conference in Gaithersburg, Maryland, a year later. When Jackson came to the podium her first slide read simply: "Brookhaven's experience: There but for the grace of God…"

Then, in 2005, Fermilab discovered that one of its own experiments leaked tritium.

Tritium tale

All accelerators produce tritium in particle collisions at target areas or beam dumps. Much dissipates in air, though some replaces ordinary hydrogen atoms to make tritiated water, which is hard to control. Geographically, Fermilab is fortunate, being located over almost impermeable clay. Compacted and thick, the clay's a nuisance for gardeners and construction crews but a godsend to Fermilab, for bathtub-like structures built in it easily contain the tritium.

The target area of one experimental site – Neutrinos at the Main Injector (NuMI) – was dug in bedrock beneath the clay. Then, during routine environmental monitoring in November 2005, Fermilab staff found a (barely) measurable amount of tritium in a creek that flowed offsite. Tritium from NuMI was mixing with unexpectedly high amounts of water vapour seeping through the bedrock, creating tritiated water that went into a sump. This was being pumped out and making its way into surface water.

Aware of the local anger, Fermilab decided to revamp its public relations. In 1989, it replaced its Office of Public Information with a "Department of Public Affairs" reporting to the lab director. Judy Jackson, who became the department's head, sought professional consultants, and organized a diverse group of community members with different backgrounds, including a CATCH founder, to examine Fermilab's community engagement practices.

Jackson's department drew up a plan that would see letters delivered by hand to community members from lab director Pier Oddone, who would also pen an article in the Friday 9 December edition of the daily online newspaper *Fermilab Today*. The idea was that employees, neighbours, the media, local officials and groups would all be informed simultaneously, so that everybody would first hear the news from Fermilab rather than other sources.

Disaster struck when a sudden snowstorm threatened to delay the letters from reaching recipients. But the lab sent staff out anyway, knowing that local residents simply had to hear of the plan before that issue of *Fermilab Today*. When published, it appeared as normal, with a story about a "Toys for Tots" Christmas collection, a list of lab events and the cafeteria menu (including roasted-veggie panini).

Oddone's "Director's corner" column was in its usual spot on the right, but attentive readers would have noticed that it had appeared a few days early (it normally came out on a Tuesday). As well as mentioning the letter that had been hand-delivered to the community,

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Oddone said that there had been "a small tritium release" as a result of "normal accelerator operations", but that it was "well within federal drinking water standards".

His column provided a link to a web page for more information and Jackson's phone number in her department. That web page also listed Jackson's office phone number, and said it would link to any subsequent media coverage of the episode. Oddone's message seemed to be appropriate publicity about a finding that was not a health or environment hazard; it was a communication essentially saying: "Here's something that's happening at Fermilab."

For years Jackson marvelled at how smoothly everything turned out. Politicians were supportive, the media fair and community members were largely appreciative of the extent to which Fermilab had gone to keep them informed. "Don't try this at home," she'd tell people, meaning don't try to muddle through without having a plan drawn up with the help of a consultant. "If you do it wrong, it's worse than not doing it at all."

The critical point

Fermilab's successful navigation of the unexpected tritium emission cannot be traced to any one factor. But two lessons stand out from the 10 or so other episodes I've found around that time when major research instruments leaked tritium. One is the importance of having a strong community group that wasn't just a token effort but a serious exercise that involved local activists. The group discouraged activist sharpshooting and political posturing, thereby allowing genuine dialogue about issues of concern.

A second lesson is what I call "quantum of response", by which I mean that the size of one's response must be appropriate to the threat rather than over- or underplaying it. Back in the late 1990s, the DOE had responded to the Brookhaven leak with dramatic measures – press conferences were held, statements issued and, incredibly, the lab's contractor was fired. Instead of reassuring community members, those actions terrified many.

It's insane to fire a contractor that had been successful for half a century because of something that posed no threat to health or the environment. All it did was suggest that something far worse was happening that the DOE wasn't talking about. One Brookhaven activist called the leak a "canary" presaging the lab's admission of more environmental catastrophes.

The Fermilab lesson is two decades old now. The onset of social media since then makes it easy to form and consolidate terrified people by promoting and amplifying inflammatory messages, which will be harder to address. Moreover, tritium leaks are only one kind of episode that can spark community concerns at research laboratories.

Sometimes accelerator beams have gone awry, or experimental stations have malfunctioned in a way that releases radiation. Activists have accused accelerators at Brookhaven and CERN of possibly creating strangelets or black holes that might destroy the world. Fermilab's current woes stemming from its recent Performance Evaluation and Measurement Plan may raise yet another set of community relations issues.

Whatever the calamity, a lab's response should not be improvised but based on a carefully worked-out plan. In the 21st century, "God's grace" may be a weak force. Studying previous episodes, and seeking lessons to be learned from them, is a stronger one.

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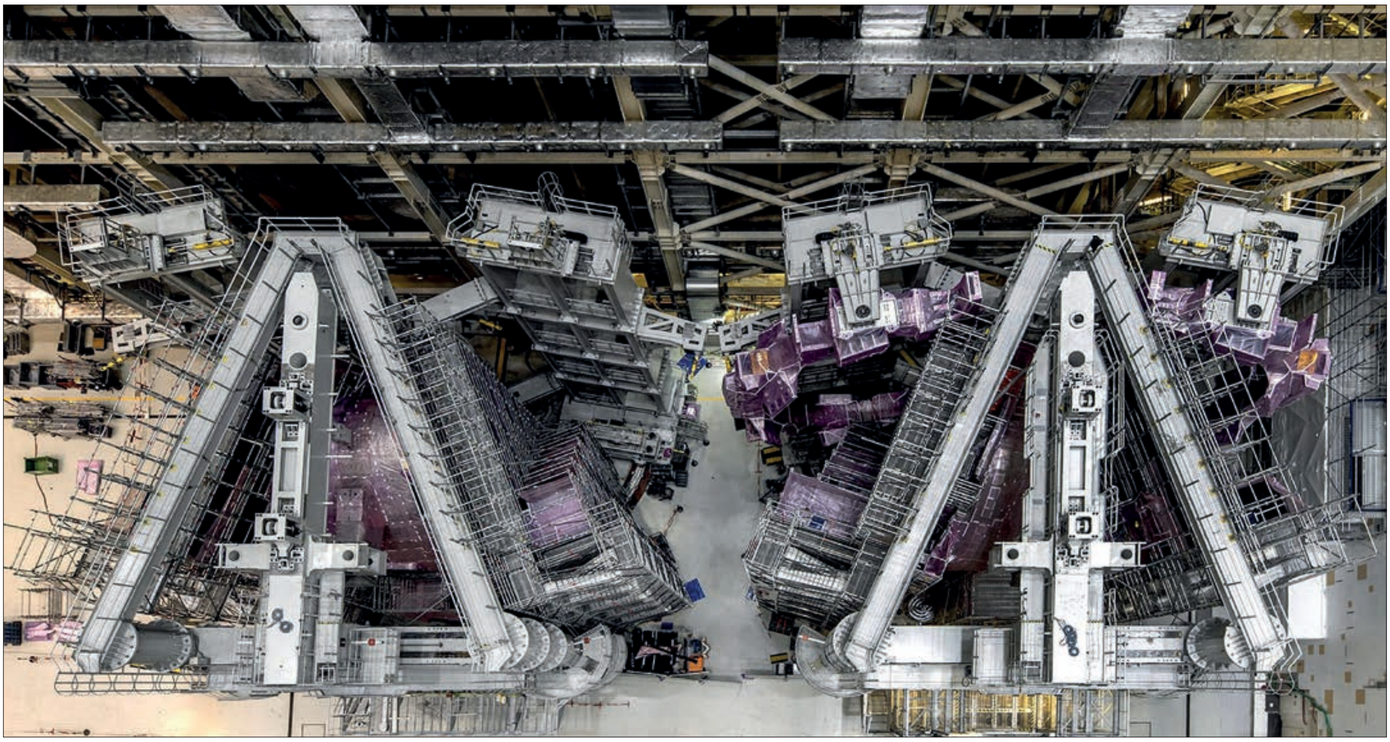
Fusion's burning challenge

Guy Matthews says that the focus on public relations is masking the challenges of commercializing nuclear fusion


ITER Organization

The long road ahead ITER, currently being built in France, illustrates the inherent complexity of fusion and the difficulty in delivering large nuclear projects.

"For a successful technology, reality must take precedence over public relations, for nature cannot be fooled." So stated the Nobel laureate Richard Feynman during a commission hearing into NASA's *Challenger* space shuttle disaster in 1986, which killed all seven astronauts onboard.

Those famous words have since been applied to many technologies, but they are becoming especially apt to nuclear fusion where public relations currently appears to have the upper hand. Fusion has recently been successful in attracting public and private investment and, with help from the private sector, it is claimed that fusion power can be delivered in time to tackle climate change in the coming decades.

Yet this rosy picture hides the complexity of the novel nuclear technology and plasma physics involved. As John Evans – a physicist who has worked at the Atomic Energy Research Establishment in Harwell, UK – recently highlighted in *Physics World*, there is a lack of proven solutions for the fusion fuel cycle, which involves breeding and reprocessing unprecedented quantities of radioactive tritium with extremely low emissions.

Unfortunately, this is just the tip of the iceberg. Another stubborn roadblock lies in instabilities in the plasma itself – for example, so-called Edge Localised Modes (ELMs), which originate in the outer regions of tokamak plasmas and are akin to solar flares. If not strongly suppressed they could vaporize areas of the tokamak wall, causing fusion reactions to fizzle out. ELMs can also trigger larger plasma instabilities, known as disruptions, that can rapidly dump the entire plasma energy and apply huge electromagnetic forces that could be catastrophic for the walls of a fusion power plant.

In a fusion power plant, the total thermal energy stored in the plasma needs to be about 50 times greater than that achieved in the world's largest machine, the Joint European Torus (JET). JET operated at the Culham Centre for Fusion Energy in Oxfordshire, UK, until it was shut down in late 2023. I was responsible for upgrading JET's wall to tungsten/beryllium and subsequently chaired the wall protection expert group.

JET was an extremely impressive device, and just before it ceased operation it set a new world record for controlled fusion energy production of 69 MJ. While this was a scientific and technical tour de force, in absolute terms the fusion energy created and plasma duration achieved at JET were minuscule. A power plant with a sustained fusion power of 1 GW would produce 86 million MJ of fusion energy every day. Furthermore, large ELMs and disruptions were a routine feature of JET's operation and occasionally caused local melting. Such behaviour would render a power plant inoperable, yet these instabilities remain to be reliably tamed.

Complex issues

Fusion is complex – solutions to one problem often exacerbate other problems. Furthermore, many of the physics and technology features that are essential for fusion power plants and require substantial development and testing in a fusion environment were not present in JET. One example being the technology to drive the plasma current sustainably using microwaves. The purpose of the international ITER project, which is currently

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being built in Cadarache, France, is to address such issues.

ITER, which is modelled on JET, is a "low duty cycle" physics and engineering experiment. Delays and cost increases are the norm for large nuclear projects and ITER is no exception. It is now expected to start scientific operation in 2034, but the first experiments using "burning" fusion fuel – a mixture of deuterium and tritium (D–T) – is only set to begin in 2039. ITER, which is equipped with many plasma diagnostics that would not be feasible in a power plant, will carry out an extensive research programme that includes testing tritium-breeding technologies on a small scale, ELM suppression using resonant magnetic perturbation coils and plasma-disruption mitigation systems.

Yet the challenges ahead cannot be understated. For fusion to become commercially viable with an acceptably low output of nuclear waste, several generations of power-plant-sized devices could be needed following any successful first demonstration of substantial fusion-energy production. Indeed, EUROfusion's Research Roadmap, which the UK co-authored when it was still part of ITER, sees fusion as only making a significant contribution to global energy production in the course of the 22nd century. This may be politically unpalatable, but it is a realistic conclusion.

The challenges ahead cannot be understated. For fusion to become commercially viable with an acceptably low output of nuclear waste, several generations of power-plant-sized devices could be needed

The current UK strategy is to construct a fusion power plant – the Spherical Tokamak for Energy Production (STEP) – at West Burton, Nottinghamshire, by 2040 without awaiting results from intermediate experiments such as ITER. This strategy would appear to be a consequence of post-Brexit politics. However, it looks unrealistic scientifically, technically and economically. The total thermal energy of the STEP plasma needs to be about 5000 times greater than has so far been achieved in the UK's MAST-U spherical tokamak experiment. This will entail an extreme, and unprecedented, extrapolation in physics and technology. Furthermore, the compact STEP geometry means that during plasma disruptions its walls would be exposed to far higher energy loads than ITER, where the wall protection systems are already approaching physical limits.

I expect that the complexity inherent in fusion will continue to provide its advocates, both in the public and private sphere, with ample means to obscure both the severity of the many issues that lie ahead and the timescales required. Returning to Feynman's remarks, sooner or later reality will catch up with the public relations narrative that currently surrounds fusion. Nature cannot be fooled.

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Review

Going wild for uranium

Margaret Harris reviews *Chain Reactions: A Hopeful History of Uranium* by Lucy Jane Santos

Oak Ridge Associated Universities Museum of Radiation and Radioactivity

Radioactive fun! This 1955 children's board game was inspired by the US government's drive to encourage the domestic discovery and mining of uranium.

Chain Reactions: A Hopeful History of Uranium
Lucy Jane Santos
2024 Icon Books
288pp £20hb

The uranium craze that hit America in the 1950s was surely one of history's strangest fads. Jars of make-up lined with uranium ore were sold as "Revigorette" and advertised as infusing "beautifying radioactivity [into] every face cream". A cosmetics firm applied radioactive soil to volunteers' skin and used Geiger counters to check whether its soap could wash it away. Most astonishing of all, a uranium mine in the US state of Montana developed a sideline as a health spa, inviting visitors to inhale "a constant supply of radon gas" for the then-substantial sum of $10.

The story of this craze, and much else besides, is entertainingly told in Lucy Jane Santos' new book *Chain Reactions: A Hopeful History of Uranium*. Santos is an expert in the history of 20th-century leisure, health and beauty rather than physics, but she is nevertheless well-acquainted with radioactive materials. Her previous book, *Half Lives*, focused on radium, which had an equally jaw-dropping consumer heyday earlier in the 20th century.

The shift to uranium gives Santos the license to explore several new topics. For physicists, the most interesting of these is nuclear power. Before we get there, though, we must first pass through uranium's story from prehistoric times up to the end of the Second World War. From the uranium-bearing silver mines of medieval Jachymóv, Czechia, to the uranium enrichment facilities founded in Oak Ridge, Tennessee as part of the Manhattan Project, Santos tells this story in a breezy, anecdote-driven style. The fact that many of her chosen anecdotes also appear in other books on the histories of quantum mechanics, nuclear power or atomic weapons is hardly her fault. This is well-trodden territory for historians and publishers alike, and there are only so many quirky stories to go around.

The most novel factor that Santos brings to this crowded party is her regular references to people whose role in uranium's history is often neglected. This includes not only female scientists like Lise Meitner (co-discoverer of nuclear fission) and Leona Woods (maker of the boron trifluoride counter used in the first nuclear-reactor experiment), but also the "Calutron Girls", who put in 10-hour shifts six days a week at the Oak Ridge plant and were not allowed to know that they were enriching uranium for the first atomic bomb. Other "hidden figures" include the Allied prisoners who worked the Jachymóv mines for the Nazis; the political "undesirables" who replaced them after the Soviets took over; and the African labourers who, though legally free, experienced harsh conditions while mining uranium ore at Shinkolobwe (now in the Democratic Republic of the Congo) for the Belgians and, later, the Americans.

Most welcome of all, though, are the book's references to the roles of Indigenous peoples. When Robert Oppenheimer's Manhattan Project needed a facility for transmuting uranium into plutonium, Santos notes that members of the Wanapum Nation in eastern Washington state were given "a mere 90 days to pack up and abandon their homes…mostly with little compensation". The 167 residents of Bikini island in the Pacific were even less fortunate, being "temporarily" relocated before the US Army tested an atomic bomb on their piece of paradise. Santos quotes the American comedian Bob Hope – nobody's idea of a woke radical – in summing up the result of this callous act: "As soon as the war ended, we located the one spot on Earth that hadn't been touched by war and blew it to hell."

These injustices, together with the radiation-linked illnesses experienced by the (chiefly Native American) residents of the Trinity and Nevada test sites, are not the focus of *Chain Reactions*. It could hardly be "a hopeful history" if they were. But while mentioning them is a low bar, it's a low bar that the three-hour-long Oscar-winning biopic *Oppenheimer* didn't manage to clear. If Santos can do it in a book not even 300 pages long, no-one else has any excuse.

Chain Reactions is not a science-

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The most novel factor that Santos brings to this crowded party is her regular references to people whose role in uranium's history is often neglected

focused book, and in places it feels a little thin. For example, while Santos correctly notes that the "gun" design of the first uranium bomb wouldn't work for a plutonium weapon, she doesn't say why. Later, she states that "making a nuclear reactor safe enough and small enough for use in a car proved impossible", but she leaves out the scientific and engineering reasons for this. The book's most eyebrow-raising scientific statement, though, is that "nuclear is one of the safest forms of electricity produced – only beaten by solar". This claim is neither explained nor footnoted, and it left me wondering, firstly, what "safest" means in this context, and secondly what makes wind, geothermal and tidal electricity less "safe" than nuclear or solar?

Despite this, there is much to enjoy in Santos' breezy and – yes – hopeful history. Although she is blunt when discussing the risks of nuclear energy, she also points out that when countries stop using it, they mostly replace nuclear power plants with fossil-fuel ones. This, she argues, is little short of disastrous. Quite apart from the climate impact, ash from coal-fired power plants carries radiation from uranium and thorium into the environment "at a much larger rate than any from a nuclear power plant". Thus, while the 2011 meltdown of Japan's Fukushima reactors killed no-one directly, Japan and Germany's subsequent phase-out of nuclear power contributed to an estimated 28,000 deaths from air pollution. Might a revival of nuclear power be better? Santos certainly thinks so, and she concludes her book with a slogan that will have many physicists nodding along: "Nuclear power? Yes please."

Margaret Harris is an online editor of *Physics World*

'Sometimes nature will surprise us'

Particle physicist **Juan Pedro Ochoa-Ricoux** talks to **Katherine Skipper** about how the next generation of neutrino experiments will test the boundaries of the Standard Model

JUNO/ Yuexiang Liu

Breaking new ground Particle physicist Juan Pedro Ochoa-Ricoux during the construction of the Jiangmen Underground Neutrino Observatory (JUNO).

It was a once-in-a-lifetime moment during a meeting in 2011 when Juan Pedro Ochoa-Ricoux realized that new physics was emerging in front of his eyes. He was a postdoc at the Lawrence Berkeley National Laboratory in the US, working on the Daya Bay Reactor Neutrino Experiment in China. The team was looking at their first results when they realized that some of their antineutrinos were missing.

Ochoa-Ricoux has been searching for the secrets of neutrinos since he began his master's degree at the California Institute of Technology (Caltech) in the US in 2003. He then completed his PhD, also at Caltech, in 2009, and is now a professor at the University of California Irvine, where neutrinos are still the focus of his research.

The neutrino's non-zero mass directly conflicts with the Standard Model of particle physics, which is exciting news for particle physicists like Ochoa-Ricoux. "We actually like it when the theory doesn't match the experiment," he jokes, adding that his motivation for studying these elusive particles is for the new physics they could reveal. "We need to know how to extend [the Standard Model] and neutrinos are one area where we know it has to be extended."

Because they rarely interact with matter, neutrinos are notoriously hard to study. Electron antineutrinos are however produced in measurable quantities by nuclear reactors and this is what Daya Bay was measuring. The experiment consisted of eight detectors measuring the electron antineutrino flux at different distances from six nuclear reactors. As the antineutrinos disperse, the detectors further away are expected to measure a smaller signal than those close by.

However, when Ochoa-Ricoux and his team analysed their results, they found "a deficit in the far location that could not only be explained by the fact that those detectors were farther away". Neutrinos come in three types, or "flavours", and it seemed that some of the electron antineutrinos produced in the power plants were changing into tau and muon antineutrinos, meaning the detector didn't pick them up.

This transformation of neutrino type, also known as "oscillation", occurs for both neutrinos and antineutrinos. It was first observed in 1998, with the discovery leading to the award of the 2015 Nobel Prize for Physics. However, physicists are still not sure if antineutrinos and neutrinos oscillate in the same way. If they don't, that could explain why there is more matter than antimatter in the universe.

The mathematics of neutrino oscillation is complex. Among many parameters, physicists define an angle called θ_{13}, which plays a role in determining the probability of certain flavour oscillations. For differences in oscillation probabilities between neutrinos and antineutrinos to be possible, this quantity must be non-zero. When Ochoa-Ricoux was working on the Main Injector Neutrino Oscillation Search (MINOS) at Fermilab in the US for his PhD, he had found tantalizing but inconclusive evidence that θ_{13} is different from zero.

Careers

On the one hand you analyse the data, but before you can do that, you actually have to build the apparatus

JUNO/ Yuexiang Liu

Science at work Juan Pedro Ochoa-Ricoux at the Jiangmen Underground Neutrino Observatory (JUNO) during its construction. Ochoa-Ricoux stands in front of the detector, a 35.4 m diameter sphere filled with 20 kilotons of liquid scintillator that will study neutrinos from nuclear reactors.

The memorable meeting Ochoa-Ricoux recalled at the start of this article was, however, the first moment he realized "Oh, this is real". Their antineutrino deficit data eventually proved that the angle is about nine degrees. This discovery set the stage for Ochoa-Ricoux's career, which, a little like the oscillating neutrino, he describes as a "mixture of everything".

The asymmetry between antimatter and matter is one of the biggest mysteries in physics and in the next four years, two experiments – HyperKamiokande in Japan and the Deep Underground Neutrino Experiment (DUNE) in the US – will start looking for evidence of matter–antimatter asymmetry in neutrino oscillation (Ochoa-Ricoux is a member of DUNE). "Had θ_{13} been zero" he says, "my job and my life would have been very very different".

All hands on deck

Ochoa-Ricoux wasn't just analysing the results from Daya Bay, he was also assembling and testing the experiment. This was sometimes frustrating work – he remembers having to painstakingly remeasure detector components because they wouldn't fit inside the machine. But he emphasizes that this was an important part of the Daya Bay discovery. "On the one hand you analyse the data, but before you can do that, you actually have to build the apparatus," he says.

While Ochoa-Ricoux now spends much less time climbing inside detector equipment, he is actively involved in designing the next generation of neutrino experiments. As well as DUNE, he works on Daya Bay's successor, the Jiangmen Underground Neutrino Observatory (JUNO) in China, a nuclear reactor experiment that is projected to start taking data at the end of the year.

The first neutrino oscillation measurement was made in 1998 by the Japanese researcher Takaaki Kajita, who would later share the 2015 Nobel Prize for Physics for his work. However, the experiment where Kajita made this observation, called SuperKamiokande, was originally designed to search for proton decay.

Ochoa-Ricoux thinks that DUNE and JUNO need to be open to finding something equally unexpected. JUNO's main aim is to determine which neutrino mass is the heaviest by measuring oscillating antineutrinos from nuclear power plants. It will also detect neutrinos coming from the Sun or the atmosphere, and Ochoa-Ricoux thinks this flexibility is vital.

"Sometimes nature will surprise us and we need to be ready for that," he says, "I think we need to design our experiments in such a way that we can be sensitive to those surprises."

Experiments like DUNE and JUNO could change our understanding of the universe, but there is no guarantee that neutrinos hold the key to mysteries like matter–antimatter asymmetry. There's therefore pressure to deliver results, but Ochoa-Ricoux is excited that the field is taking leaps into the unknown.

He also argues that as well as advancing fundamental science, these projects could lead to new technologies. Medical imaging devices like MRI and PET scanners are offshoots of particle physics and he believes that "When you understand your world better, sometimes it's impossible to predict what applications will come."

However, at the heart of Ochoa-Ricoux's mindset is the same fascination with the mysteries of the universe that motivated him to pursue neutrino physics as a student. For him, projects like JUNO and DUNE can justify themselves on those grounds alone. "We're humans. We need to understand the world we live in. I think that's highly valuable."

Katherine Skipper is a features editor at *Physics World*