physicsworld
2025/26

Instrumentation & Vacuum Briefing

Instrumentation drives the quantum revolution
Travis Humble on Oak Ridge's Quantum Science Center

Trapped protons take to the road
Mobile vacuum chamber could move antimatter

Non-invasive sensor probes brain pressure
Device could improve brain injury diagnoses

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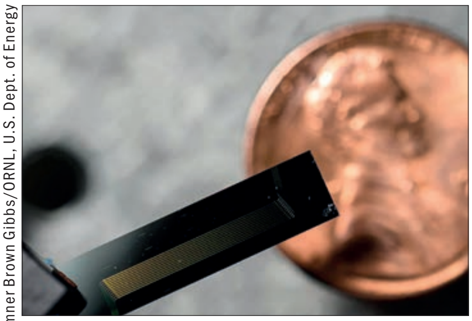
Instrumentation & Vacuum Briefing

Sumner Brown Gibbs/ORNL, U.S. Dept. of Energy

The powder diffractometer at the Spallation Neutron Source, which is one of the brightest sources of neutrons in the world p5



University of Rochester/J Adam Fenster

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Welcome

BASE/Julia Jäger

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Robert Prevedel *at Germany's EMBL*

Instrumentation for all

You can have just about anything delivered to your door these days – and that could soon include antimatter. Researchers at CERN's Baryon-Antibaryon Symmetry Experiment (BASE) experiment have shown that they can transport trapped protons across the lab's Meyrin campus (p27). This was done in a cryogenically-cooled vacuum chamber that was loaded onto a lorry. Although no antimatter was transported, the BASE team says that the system will soon be used to deliver antiprotons to labs outside of CERN – with the first recipient being Heinrich Heine University in Germany.

Today, antiprotons are created at accelerators, which tend to be large and expensive facilities. This means that most physicists cannot currently do experiments with these antiparticles in their own labs.

The same applies to access to the high-quality X-ray beams that are created at synchrotron facilities – which are also large and expensive accelerators. To address this problem, Ashley Bucsek and colleagues at the University of Michigan have developed a way to carry out 3D X-ray diffraction without the need for a synchrotron (p25). "My colleagues and I hope that the adaptation of this technology from the synchrotron to the laboratory scale will make it more accessible," she says.

Meanwhile in Japan, researchers have developed a new target design that could make particle accelerators more accessible (p9). The proposed proton accelerator is driven by a laser and it has the potential to be small enough to be installed in hospitals, where it could be used for particle therapy.

Elsewhere in this briefing, we hear from Travis Humble who is director of the Quantum Science Center at Oak Ridge National Laboratory in the US (p5). He explains how the centre ensures that Oak Ridge's formidable facilities and instruments are accessible to academic and industrial users to drive the development of new quantum technologies.

Instrumentation for the masses is also a key theme in our interview with Panicos Kyriacou, who is chief scientist at Crainio (p21). The UK-based start-up has developed a new optics-based sensor with the potential to revolutionize how brain injuries are diagnosed. He explains how Crainio's technology measures the pressure on the brain without having to drill a hole in the skull. As well as making diagnoses much less invasive, the technology could eventually be accessible in the field – for use in ambulances or even at sporting events such as rugby matches.

Hamish Johnston
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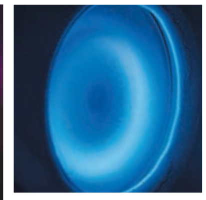
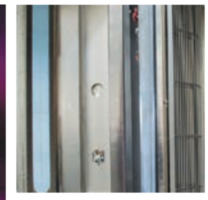
APPLICATIONS FOR GAS SENSING IN ANY VACUUM ENVIRONMENT FROM GENCOA

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Oak Ridge's Quantum Science Center takes a multidisciplinary approach


ORNL

Travis Humble is director of the Quantum Science Center at Oak Ridge National Laboratory (ORNL) in Tennessee, US – which is run by the US Department of Energy (DOE). The centre links the capabilities of ORNL with other US national labs, universities and companies. He speaks to Hamish Johnston about how the centre makes use of ORNL's powerful facilities and instruments to create new quantum technologies

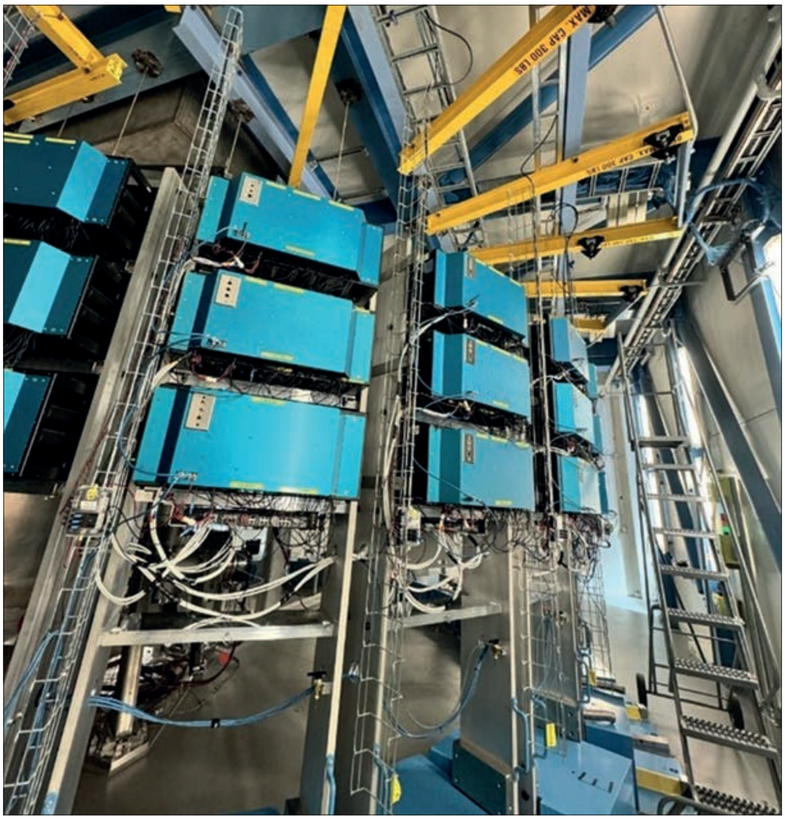
What is the mission of the Quantum Science Center?
The Quantum Science Center is one of five of the DoE's National Quantum Information Science Research Centers. The Quantum Science Center is a partnership led by Oak Ridge and it includes more than 20 other institutions including universities and companies.

ORNL and the other national laboratories play a crucial role in research and development within the United States. And partnerships play a crucial role in that activity. Some partnerships are with universities, especially individual investigators who require access to the powerful instruments that we develop and maintain. The labs are funded by the DOE, and users can apply to use the instruments or collaborate with our resident scientists to develop research ideas and follow through to publication. In addition to providing cutting edge facilities to the nation's scientists, national labs also play an important role in creating a scientific workforce that is educated in how to develop and use a range of scientific infrastructure and instrumentation. These personnel will ensure that scientific breakthroughs will continue to be made and that scientists will continue to have access to the best research facilities.

ORNL is home to several facilities for material characterization, including the Spallation Neutron Source (SNS). How is the lab using these facilities to develop new materials for quantum technologies?
ORNL has many unique facilities, including the SNS, which is a user facility of the DOE. It is one of the brightest sources of neutrons in the world, which makes it an incredibly powerful tool for characterizing novel materials.

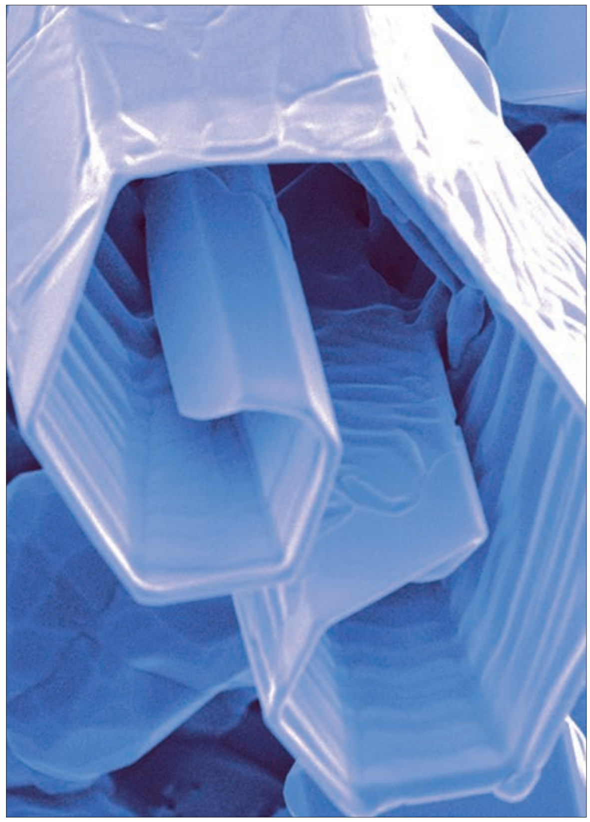
We are using the SNS to look at some remarkable materials that have useful quantum properties such as topological order and entanglement. These strongly correlated systems have useful electronic or magnetic properties. What makes them so interesting is that under the right conditions they have unique phases in which their electrons or spins are entangled quantum mechanically.

Travis Humble Focusing on the discovery, synthesis and characterization of new quantum materials at Oak Ridge National Laboratory.



Sumner Brown Gibbs/ORNL, U.S. Dept. of Energy

Power up The POWGEN powder diffractometer at the Spallation Neutron Source, which is one of the brightest sources of neutrons in the world.



ORNL

Zoom in A scanning electron microscope image of MnSi microcrystal grown using chemical vapour deposition at the Center for Nanophase Materials Sciences.

We probe these materials using a range of instruments on the SNS and infer whether or not the materials are entangled. This allows us to identify materials that will be useful for developing new quantum technologies.

What other instruments are used to develop new quantum materials at ORNL?

The SNS is certainly one of our biggest and boldest instruments that we have for characterizing these types of systems, but in no way is it the only one. ORNL is also home to the Center for Nanophase Materials Sciences (CNMS). This is one of the DOE's Office of Science Nanoscale Science Research Centers and it's a remarkable facility co-located with the SNS at ORNL. The CNMS enables the synthesis and characterization of new quantum materials with the ultimate goal of gaining control over their useful properties.

Can you give an example of that work?

We are very interested in a type of material called a spin liquid. It's a magnetic system where the quantum spins within the material can become entangled with each other and have correlations over very large distances – relative to the size of individual atoms. Using SNS we have detected a signature of entanglement in these materials. That material is ruthenium trichloride and it is one type of quantum magnet that we are studying at ORNL. The next step is to take materials that have been certified as quantum or entangled and translate them into new types of devices. This is what the CNMS excels and involves fabricating a quantum material into unique geometries; and connecting it to electrodes and other types of control systems that then provide a path to demonstrating novel physics and other types of unique behaviours.

In the case of quantum spin liquids, for example, we believe that they can be translated into a new qubit (quantum bit) technology that can store and process quantum information. We haven't got there yet, but the tools and capabilities that we have here at Oak Ridge are incredibly empowering for that type of technology development.

ORNL is also famous for its supercomputing capabilities and is home to Frontier, which is one of the world's most powerful supercomputers. How does the lab's high-performance computing expertise support the use of its instrumentation for the development of new quantum materials?

High-performance computing (HPC) has been a remarkable and disruptive tool because it allows us to explain and understand the physics of complex systems and how these systems can be controlled and ultimately exploited to create new technologies. One of the most remarkable developments in the last several years has been the application of HPC to machine learning and artificial intelligence.

This benefits material science, chemistry, biology, and the study of other complex physical systems, where modelling and simulation play a huge role in our scientific discovery process. And supercomputers are also used in the design and optimization of products that are based on those complex physical systems. In fact, many people would say that next to theory and experiment, computation is a third pillar of the R&D ecosystem.

Listen to our full podcast interview with Travis Humble.

ORNL

Appalachian spring The Spallation Neutron Source photographed earlier this year.

In my view HPC is just as powerful a research tool as the SNS or the CNMS when it comes to understanding and exploring these complex physical systems.

Why is it important to have the SNS, CNMS, Frontier and other facilities co-located at ORNL?

This integration allows our researchers to very quickly compare computer simulations to experimental data from neutron scattering and other experiments. This results in a very tight and coordinated cycle of development that ensures that we get to the best results the fastest way possible. This way of working also highlights the multidisciplinary nature of how we operate – something we call "team science".

This requires good coordination between all parties, you have to have clarity in your communication, and you have to have a very clear vision about the goals that you're trying to accomplish. This ensures that everyone has a common understanding of the mission of ORNL and the DOE.

How do you ensure that collaboration across different instruments and disciplines is done efficiently?

In my experience, the ability of team members to communicate efficiently, to understand each other's concepts and reasoning, and to translate back and forth across these disciplinary boundaries is probably one of the central and most important parts of this type of scientific development. This is crucial to ensuring that people using a common infrastructure gain powerful scientific results.

For example, when we talk about qubits in quantum science and technology, people working in different subdisciplines have slightly different definitions of that word. For computer scientists, a qubit is a logical representation of information that we manipulate through quantum algorithms. In contrast, material scientists think of a qubit as a two-level quantum system that is embedded in some electronic or magnetic degree of freedom. They will often see qubits as being independent of the logical and computational connections that are necessary to create quantum computers. Bridging such differences is an important aspect of multidisciplinary research and amplifies success at our facilities.

I would say that the facilities and the ecosystem that we've created within the laboratory support interchange and collaboration across disciplines. The instruments enable new fundamental discoveries and the science is then developed and translated into new technologies.

That is a multi-step process and can only succeed when you have a team of people working together on large-scale problems – and that team is always multidisciplinary.

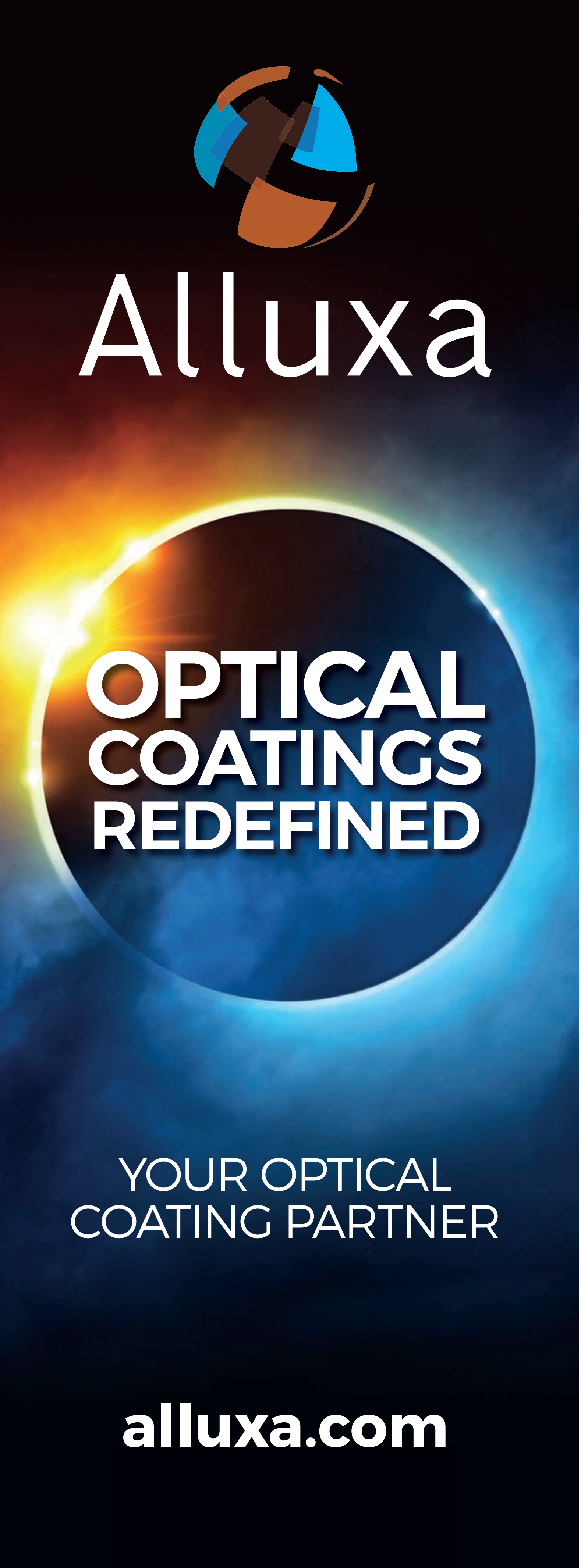
Can you talk about your partnerships with industry.

In the last decade quantum science and technology has emerged as a national priority in terms of science, industry and national security. This interest is driven by concerns for national security as well as the economic advantage – in terms of new products and services – that quantum brings. Innovation in the energy sector is an important example of how quantum has important implications for both security and the economy.

As a result, US national laboratories are partnering very closely with industry to provide access to instruments at the SNS, the CNMS and other facilities. At the same time, our researchers get access to technologies developed by industry – especially commercial quantum computing platforms.

I think that one of the most exciting things for us at ORNL today is gaining insights into these new quantum products and services and adapting this knowledge into our own scientific discovery workflows.

Hamish Johnston is an online editor of *Physics World*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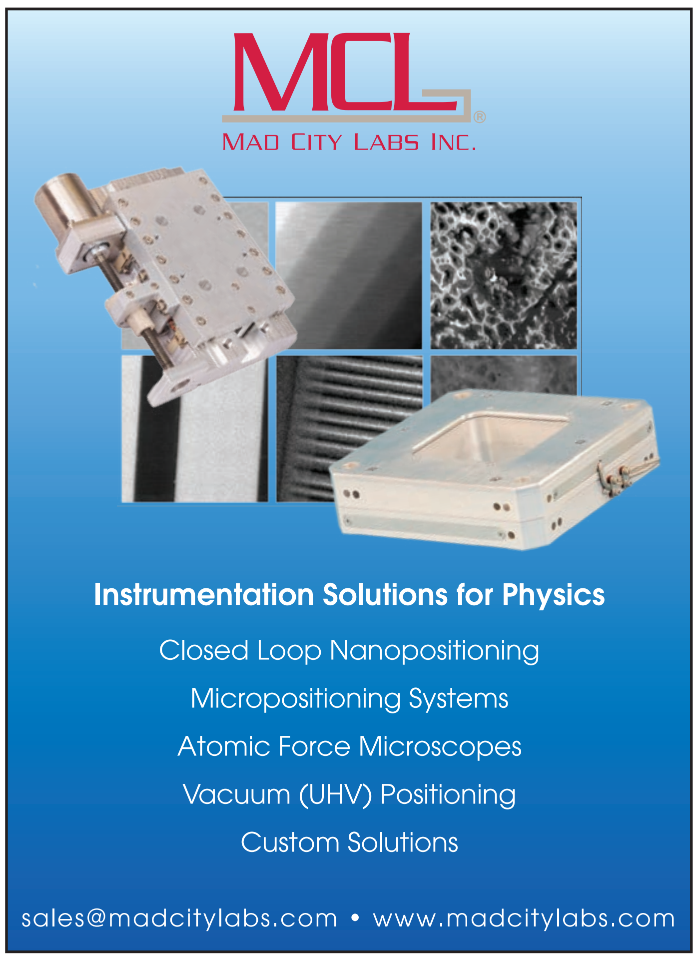
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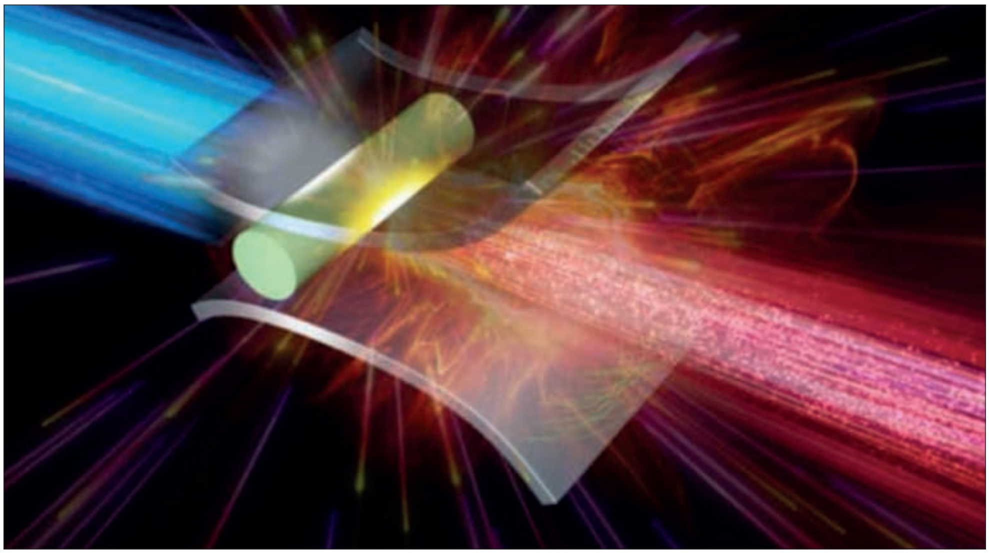
Micronozzle could give laser-driven particle accelerators a boost



Masakatsu Murakami

How it works A conceptual illustration of micronozzle acceleration. A solid hydrogen rod is embedded in an aluminium micronozzle, which channels and focuses plasma flow to optimize proton acceleration.

The proton energies achievable in laser accelerators could be tripled by using specially designed micronozzle targets, according to computer simulations done by physicists in Japan and India. In their design, the electric field generated in the micronozzle would be funnelled towards the outgoing protons, allowing the acceleration to proceed for much longer. The researchers believe that the work, described in *Scientific Reports* (**15** 19112), could be useful in nuclear fusion, hadron therapy and materials science.

Conventional accelerators use oscillating electric fields to drive charged particles to relativistic speeds. The Large Hadron Collider at CERN, for example, uses radio-frequency oscillations to achieve proton energies of nearly 7 TeV.

Conventional accelerators tend to be very large, which limits where they can be built. Laser acceleration, which involves using a high-energy laser pulse to accelerate charged particles, offers a way to create much more compact accelerators.

Laser acceleration is crucial to inertial confinement fusion, and high energy proton beams produced by laser accelerators are used in scientific laboratories for a variety of scientific applications including laboratory astrophysics.

The standard techniques for laser acceleration involve firing a laser pulse at a proton target surrounded by metal foil. Solid hydrogen only exists near absolute zero, so the proton target can be a hydrogen-rich compound such as a hydride or a polymer. The femtosecond laser pulse concentrates a huge amount of energy into a tiny area and this instantly turns the target into a plasma. The light's oscillating electromagnetic field drives electrons through the plasma, leaving behind the much heavier ions and creating a huge electric field that can accelerate protons.

Reviewing the design

In the new work, physicist Masakatsu Murakami and colleagues at the University of Osaka in Japan, together with researchers at the Indian Institute of Technology Hyderabad, used computer modelling to examine the effect of changing the shape of the metal surrounding the target from a simple planar foil to a two-headed nozzle, with the target placed at the narrowest point. During the first stage of the acceleration process, the wide head of the nozzle behaves like a lens, concentrating electric field from a wide area to produce an enhanced flow of hot electrons towards the centre. This electric current on the nozzle enhances ablation of protons from the hydrogen rod, kicking them forward into the vacuum.

Subsequently, the electrons keep moving through the "skirt" of the nozzle, creating a powerful electric field that, owing to the nozzle's shape, remains focused on the accelerating proton pulse as it travels away into the vacuum. "With the single H-rod and the single foil, the protons are accelerated only during the laser illumination," explains Murakami. "However, interestingly with the micronozzle target, the acceleration keeps going even after the laser pulse illumination…Most of the plasma expands in a small volume together with the protons – just like a rocket nozzle," he says. Whereas the standard proton energies achievable with a laser accelerator today are around 400 MeV, the researchers estimate that their micronozzle design could allow energies into the gigaelectronvolt regime without changing anything else.

Murakami, who has been studying nuclear fusion for 40 years, believes that "this method will be used for fast ignition of laser fusion". However, he says, its potential uses go far beyond this. Proton beam therapy – which generally uses protons with energies of 200–300 MeV for cancer treatment that delivers a higher dose of radiation to the tumour with less damage to healthy tissue: "Even higher energy is required to target cancers that are located in deeper parts of the body," he says. The technique could also be useful for materials science techniques such as proton radiography or for simulation of the physics of astrophysical objects such as neutron stars. "I'm planning to do proof of principle experiments in the near future," says Murakami.

Accelerator physicist Nicholas Dover of Imperial College London describes the work as "very interesting," adding, "This target that they propose is a very complex thing to make. It would be a big project for a target fabrication lab to generate something like this – it's not something we just cook up in our lab. Having these numerical optimizations is really helpful for us." He notes, however, that one reason accelerator physicists often use planar targets (essentially pieces of kitchen foil) is the need to replace them in every shot. In scientific applications, this may not matter, he says. Applications in fields like medicine, however, would probably require the development of mass production facilities to fabricate the targets economically.

Tim Wogan

Acoustics

Isolated pockets of audible sound are created using metasurfaces

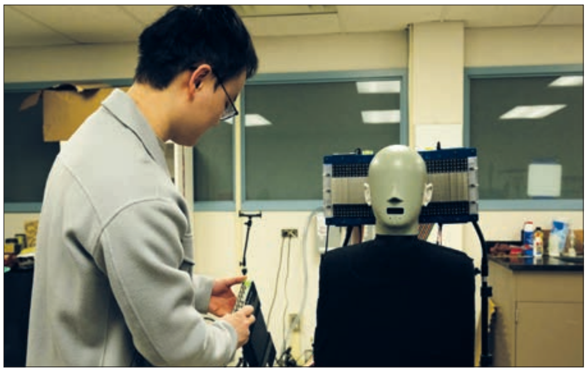
A ground-breaking method to create "audible enclaves" – localized zones where sound is perceptible while remaining completely unheard outside – has been unveiled in the US by researchers at Pennsylvania State University and Lawrence Livermore National Laboratory. The innovation could transform audio experiences in public spaces and improve secure communications (*PNAS* e2408975122).

"One of the biggest challenges in sound engineering is delivering audio to specific listeners without disturbing others," explains Penn State's Jiaxin Zhong. "Traditional speakers broadcast sound in all directions, and even directional sound technologies still generate audible sound along their entire path. We aimed to develop a method that allows sound to be generated only at a specific location, without any leakage along the way. This would enable applications such as private speech zones, immersive audio experiences, and spatially controlled sound environments."

To achieve precise audio targeting, the researchers used a phenomenon known as difference-frequency wave generation. This process involves emitting two ultrasonic beams – sound waves with frequencies beyond the range of human hearing – that intersect at a chosen point. At their intersection, these beams interact to produce a lower-frequency sound wave within the audible range. In their experiments, the team used ultrasonic waves at frequencies of 40 kHz and 39.5 kHz. When these waves converge, they generated an audible sound at 500 Hz, which falls within the typical human hearing range of approximately 20 Hz – 20 kHz.

To prevent obstacles like human bodies from blocking the sound beams, the researchers used self-bending beams that follow curved paths instead of travelling in straight lines. They did this by passing ultrasound waves through specially designed metasurfaces, which redirected the waves along controlled trajectories, allowing them to meet at a specific point where the sound is generated.

"Metasurfaces are engineered materials that manipulate wave behaviour in ways that natural materials cannot," said Zhong. "In our study, we use metasurfaces to precisely control the phase of ultrasonic waves, shaping them into self-bending beams. This is similar to how an optical lens bends light."


Poornima Tomy/Penn State

Good vibrations Penn State's Jia-Xin Zhong used a dummy with microphones in its ears to measure the presence or absence of sound along an ultrasonic trajectory.

The researchers began with computer simulations to model how ultrasonic waves would travel around obstacles, such as a human head, to determine the optimal design for the sound sources and metasurfaces. These simulations confirmed the feasibility of creating an audible enclave at the intersection of the curved beams. Subsequently, the team constructed a physical setup in a room-sized environment to validate their findings experimentally. The results closely matched their simulations, demonstrating the practical viability of their approach.

"Our method allows sound to be produced only in an intended area while remaining completely silent everywhere else," says Zhong. "By using acoustic metasurfaces, we direct ultrasound along curved paths, making it possible to 'place' sound behind objects without a direct line of sight. A person standing inside the enclave can hear the sound, but someone just a few centimetres away will hear almost nothing."

Initially, the team produced a steady 500 Hz sound within the enclave. By allowing the frequencies of the two ultrasonic sources to vary, they generated a broader range of audible sounds, covering the frequencies from 125 Hz – 4 kHz. This expanded range includes much of the human auditory spectrum, increasing the potential applications of the technique.

The ability to generate sound in a confined space without any audible leakage opens up many possible applications. Museums and exhibitions could provide visitors with personalized audio experiences without the need for headphones, allowing individuals to hear different information depending on their location. In cars, drivers could receive navigation instructions without disturbing passengers, who could simultaneously listen to music or other content. Virtual and augmented reality applications could benefit from more immersive soundscapes that do not require bulky headsets.

The technology could also enhance secure communications, creating localized zones where sensitive conversations remain private even in shared spaces. In noisy environments, future adaptations of this method might allow for targeted noise cancellation, reducing unwanted sound in specific areas while preserving important auditory information elsewhere.

Future challenges

While their results are promising, the researchers acknowledge several challenges that must be addressed before the technology can be widely implemented. One concern is the intensity of the ultrasonic beams required to generate audible sound at a practical volume. Currently, achieving sufficient sound levels necessitates ultrasonic intensities that may have unknown effects on human health.

Another challenge is ensuring high-quality sound reproduction. The relationship between the ultrasonic beam parameters and the resulting audible sound is complex, making it difficult to produce clear audio across a wide range of frequencies and volumes.

"We are currently working on improving sound quality and efficiency," Zhong said. "We are exploring deep learning and advanced nonlinear signal processing methods to optimize sound clarity. Another area of development is power efficiency – ensuring that the ultrasound-to-audio conversion is both effective and safe for practical use. In the long run, we hope to collaborate with industry partners to bring this technology to consumer electronics, automotive audio, and immersive media applications."

Andrey Feldman

Cryogenics

Quantum twisting microscope measures phasons in cryogenic graphene

By adapting their quantum twisting microscope to operate at cryogenic temperatures, researchers have made the first observations of a type of phonon that occurs in twisted bilayer graphene. These "phasons" could have implications for the electron dynamics in these materials (*Nature* **641** 345).

Graphene is a layer of carbon just one atom thick and it has range of fascinating and useful properties – as do bilayer and multilayer versions of graphene. Since 2018, condensed-matter physicists have been captivated by the intriguing electron behaviour in two layers of graphene that are rotated with respect to each other.

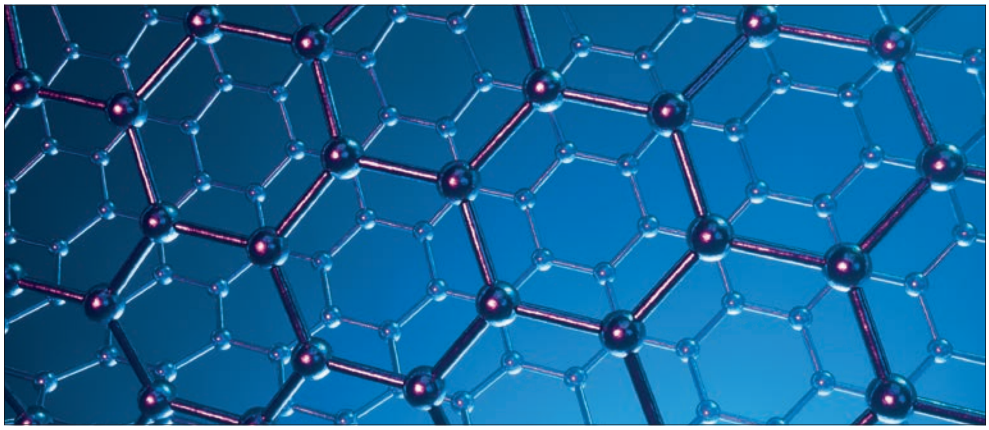
As the twist angle deviates from zero, the bilayer becomes a moiré superlattice. The emergence of this structure influences electronic properties of the material, which can transform from a semiconductor to a superconductor.

In 2023, researchers led by Shahal Ilani at the Weizmann Institute of Science in Israel developed a quantum twisting microscope to study these effects. Based on a scanning probe microscope with graphene on the substrate and folded over the tip such as to give it a flat end, the instrument allows precise control over the relative orientation between two graphene surfaces – in particular, the twist angle.

Now Ilani and an international team have operated the microscope at cryogenic temperatures for the first time. So far, their measurements support the current understanding of how electrons couple to phasons, which are specific modes of phonons (quantized lattice vibrations). Characterizing this coupling could help us understand "strange metals", whose electrical resistance increases at lower temperatures – which is the opposite of normal metals.

There are different types of phonons, such as acoustic phonons where atoms within the same unit cell oscillate in phase with each other, and optical phonons where they oscillate out of phase. Phasons are phonons involving lattice oscillations in one layer that are out of phase or antisymmetric with oscillations in the layer above.

"This is the one that turns out to be very important for how the electrons behave between the layers because even a small relative displacement between the two layers affects how the electrons go from one layer to the other," explains Weizmann's John Birkbeck as he describes the role of phasons in twisted bilayer graphene materials.



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Carbon layers Artist's impression of two layers of graphene prior to a twist being applied.

For most phonons the coupling to electrons is weaker the lower the energy of the phonon mode. However for twisted bilayer materials, theory suggests that phason coupling to electrons increases as the twist between the two layers approaches alignment due to the antisymmetric motion of the two layers and the heightened sensitivity of interlayer tunnelling to small relative displacements.

"There are not that many tools to see phonons, particularly in moiré systems" adds Birkbeck. This is where the quantum twisting microscope offers a unique perspective. Thanks to the atomically flat end of the tip, electrons can tunnel between the layer on the substrate and the layer on the tip whenever there is a matching state in terms of not just energy but also momentum too.

> There are not that many tools to see phonons, particularly in moiré systems

Where there is a momentum mismatch, tunnelling between tip and substrate is still possible by balancing the mismatch with the emission or absorption of a phonon. By operating at cryogenic temperatures, the researchers were able to get a measure of these momentum transactions and probe the electron–phonon coupling too.

"What was interesting from this work is not only that we could image the phonon dispersion, but also we can quantify it," says Birkbeck stressing the absolute nature of these quantified electron phonon coupling-strength measurements.

The measurements are the first observations of phasons in twisted bilayer graphene and reveal a strong increase in coupling as the layers approach alignment, as predicted by theory. However, the researchers were not able to study angles smaller than 6°. Below this angle the tunnelling resistance is so low that the contact resistance starts to warp readings, among other limiting factors.

A certain amount of technical adjustment was needed to operate the tool at cryogenic temperatures, not least "to navigate without eyes" because the team was not able to incorporate their usual optics with the cryogenic set up. The researchers hope that with further technical adjustments they will be able to use the quantum twisting microscope in cryogenic conditions at the magic angle of 1.1°, where superconductivity occurs.

Pablo Jarillo Herrero, who led the team at MIT in the US that first reported superconductivity in twisted bilayer graphene but was not involved in this research says it is an "interesting study" adding, "I'm looking forward to seeing more interesting results from low temperature QTM research!"

Hector Ochoa De Eguileor Romillo at Columbia University in the US, who proposed a role for phason–electron interactions in these materials in 2019, but was also not involved in this research describes it as "a beautiful experiment". He adds, "I think it is fair to say that this is the most exciting experimental technique of the last 15 years or so in condensed matter physics; new interesting data are surely coming."

Anna Demming

Fusion

Fusion industry meets in London to discuss the future of energy

"Fusion is now within reach" and represents "one of the economic opportunities of the century". Not the words of an optimistic fusion scientist but from Kerry McCarthy, parliamentary under-secretary of state at the UK's Department for Energy Security and Net Zero.

She was speaking in April at the inaugural Fusion Fest by Economist Impact. Held in London, the day-long event featured 400 attendees and more than 60 speakers from around the world.

McCarthy outlined several initiatives to keep the UK at the "forefront of fusion". That includes investing £20m into Starmaker One, a £100m endeavour announced in early April to kick-start UK investment fusion fund.

The usual cliché is that fusion energy is always being 20 years away, perhaps not helped by large international projects such as the ITER experimental fusion reactor that is currently being built in Cadarache, France, which has struggling with delays and cost hikes.

Yet many delegates at the meeting were optimistic that significant developments are within reach with private firms racing to demonstrate "breakeven" – generating more power out than needed to fuel the reaction. Some expect "a few" private firms to announce breakeven by 2030.

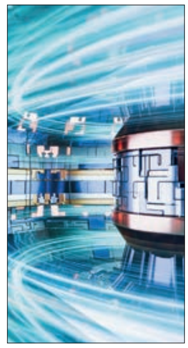
And these aren't small ventures. Commonwealth Fusion Systems, based in Massachusetts, US, for example, has 1300 people. Yet large international companies are, for the moment, only dipping their toe into the fusion pool.

While some $8bn has already been spent by private firms on fusion, many expect the funding floodgates to open once breakeven has been achieved in a private lab.

Most stated that a figure of about $50–60bn, however, would be needed to make fusion a real endeavour in terms of delivering power to the grid, something that could happen in the 2040s. But it was reiterated throughout the day that fusion must provide energy at a price that consumers would be willing to pay.

It is not only private firms that are making progress. Many will point out that ITER has laid much of the groundwork in terms of fostering a fusion "ecosystem" – a particular buzzword of the day – that was demonstrated, in part, by the significant attendance at the event.

And developments are not just being confined to magnetic fusion. Kim Budil, director of the Lawrence Livermore National Laboratory, which is home to the National Ignition Facility, noted that the machine had recently achieved a fusion gain for the eighth time.



iStock/koto_feja

Looking forwards
The inaugural Fusion Fest by Economist Impact featured more than 450 attendees from around the world.

In a recent shot, she said that the device had produced 7 MJ with about 2 MJ having been delivered to the small capsule target. This represents a gain of about 3.4 – much more than its previous record of 2.4.

NIF, which is based on inertial confinement fusion rather than magnetic confinement, is currently undergoing refurbishment and upgrades. It is hoped that this will increase the energy input to about 2.6 MJ but gains of between 10–15 will be demonstrated if the technique can go anywhere.

Despite the number of fusion firms ballooning from a handful in the early 2010s to some 30 today, the general feeling at the meeting was that only a few will likely go on to build power plants, with the remainder using fusion for other sectors.

The issue is that no-one knew what technology would likely succeed, so all to play for.

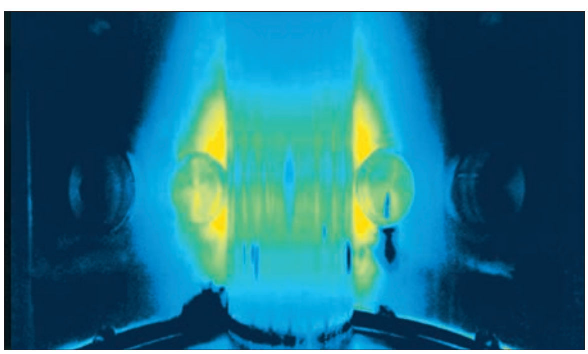
Michael Banks

SMART spherical tokamak produces its 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 fusion power plants based on spherical tokamak technology.

SMART has been constructed by the University of Seville's Plasma Science and Fusion Technology Laboratory. With a vessel dimension of 1.6 × 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.



University of Seville

Hot stuff
The first plasma at the SMall Aspect Ratio 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.

It is thought that negative triangularity configurations can better suppress plasma instabilities that expel particles and energy from the plasma, helping to prevent damage to the tokamak wall.

Last year, researchers at the University of Seville 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.

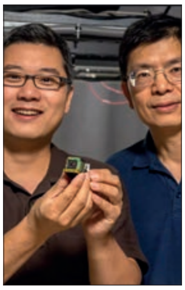
"This is an important achievement for the entire team as we are now entering the operational phase," notes SMART principal investigator Manuel García Muñoz. "The SMART approach is a potential game changer with attractive fusion performance and power handling for future compact fusion reactors. We have exciting times ahead."

Michael Banks

Metasurface-enhanced camera uses a neural network

US-based researchers have developed an inexpensive and ultrathin metasurface that, when paired with a neural network, enables a conventional camera to capture detailed hyperspectral and polarization data from a single snapshot (*Science Advances* DOI: 10.1126/sciadv.adp5192). This could lead to significant advances in medical diagnostics, environmental monitoring, remote sensing and consumer electronics.

Based at Pennsylvania State University, the team designed a large set of silicon-based meta-atoms with unique spectral and polarization responses. When spatially arranged within small "superpixels" these meta-atoms can encode both spectral and polarization information into distinct patterns that traditional cameras cannot detect. Machine learning algorithms were then used to recognize these patterns and map them back to their corresponding encoded information.


Kate Myers/Penn State

Camera transformation Penn State researchers Xingjie Ni and Zhiwen Liu. Ni holds a camera sensor integrated with a 3 × 3 mm metasurface, which turns a conventional imaging device into a hyperspectro-polarimetric camera.

"Our metasurface consists of numerous distinct meta-atoms, each designed to exhibit different transmission characteristics for various incoming spectra and polarization states," explains team member Xingjie Ni. "Essentially, the metasurface translates information that is normally invisible to the camera into a format it can detect. Each superpixel corresponds to one pixel in the final image, allowing us to obtain not only intensity information but also the spectrum and polarization data for each pixel."

Potential applications include development of miniaturized and portable hyperspectro-polarimetry imaging systems, which he believes could revolutionize the abilities of existing imaging systems. "For instance, we might develop a small add-on for smartphone cameras to enhance their capabilities, allowing users to capture rich spectral and polarization information that was previously inaccessible in such a compact form," he says.

According to Ni, traditional hyperspectral and polarimetric cameras, which often are bulky and expensive to produce, capture either spectral or polarization data, but not both simultaneously. Such systems are also limited in resolution, not easily integrated into compact devices, and typically require complex alignment and calibration.

In contrast, the team's metasurface encoder is ultracompact, lightweight and cost-effective. "By integrating it directly onto a conventional camera sensor, we eliminate the need for additional bulky components, reducing the overall size and complexity of the system," says Ni.

Ni also observes that the metasurface's ability to encode spectral and polarization information into intensity patterns enables simultaneous hyperspectral and polarization imaging without significant modifications to existing imaging systems. Moreover, the flexibility in designing the meta-atoms enables the team to achieve high-resolution and high-sensitivity detection of spectral and polarization variations.

"This level of customization and integration is difficult to attain with traditional optical systems. Our approach also reduces data redundancy and improves imaging speed, which is crucial for applications in dynamic, high-speed environments," he says.

Abigail Williams

Camera takes inspiration from cats' eyes

A novel camera inspired by cats' eyes could soon be employed in autonomous vehicles, drones and surveillance systems (*Science Advances* DOI: 10.1126/sciadv.adp2809).

The new device uses a vertically elongated slit, like the pupil of cats' eye, explains Minseok Kim of the Gwangju Institute of Science and Technology in Korea. This artificial pupil creates an asymmetric depth of focus when it dilates and contracts, allowing the camera to blur out backgrounds and focus sharply on objects. Another feature is a metal reflector that enables more efficient light absorption in low-light settings. This mimics the tapetum lucidum, a structure that reflects incident light back into the retina and gives cats' eyes their glow.

"The result is a camera that works well in both bright and low-light environments, allowing it to capture high-sensitivity images without the need for complex software post-processing," Kim says.

A important challenge was to simplify the intricate structure of the tapetum lucidum. Instead of replicating it exactly, they used a metal reflector placed beneath a hemispherical silicon photodiode array, which reduces excessive light and enhances photosensitivity. This design allows for clear focusing under bright light and improved sensitivity in dim conditions.

"Another challenge was to create a vertical pupil that could mimic the cat's ability to focus sharply on an object while blurring the background," says Kim. "We were able to construct the vertical aperture using a 3D printer, but our future work will focus on making this pupil dynamic so it can automatically adjust its size in response to changing light conditions."


Shutterstock/Kseniia Perminova

Almost purr-fect A new device shaped like the pupil of a cats' eye works well in both bright and low-light environments.

The research could improve technologies that rely on high-performance imaging in difficult lighting conditions, Kim says. The team expects the system to be useful in autonomous vehicles, where precise object detection is critical.

"It could also be applied to drones and surveillance systems that operate in various lighting environments, as well as in military applications where camouflage-breaking capabilities are essential," Kim adds. "The system could also find use in medical imaging, where the ability to capture high-sensitivity, real-time images without extensive software processing is crucial."

The researchers now plan to further optimize their camera's pixel density and its resolution to improve image quality. "We also aim to conduct more real-world tests," says Kim. "Lastly, we are looking into binocular object recognition systems so that the camera can handle more complex visual tasks."

Isabelle Dumé

Metrology

The evolution of the metre

This year marks the 150th anniversary of the metre. **Isabelle Dumé** joined the celebrations in Paris and discovered how a product of the French Revolution became a mainstay of worldwide scientific collaboration

Isabelle Dumé

A metrology revolution
In the 1790s, the Revolutionary government in France installed standard metre lengths made of marble in busy areas around Paris. This is one of the last remaining examples.

The 20th of May is World Metrology Day, and this year it was extra special because it was also the 150th anniversary of the treaty that established the metric system as the preferred international measurement standard. Known as the Metre Convention, the treaty was signed in 1875 in Paris, France by representatives of all 17 nations that belonged to the Bureau International des Poids et Mesures (BIPM) at the time, making it one of the first truly international agreements. Though nations might come and go, the hope was that this treaty would endure "for all times and all peoples".

To celebrate the treaty's first century and a half, the BIPM and the United Nations Educational, Scientific and Cultural Organization (UNESCO) held a joint symposium at the UNESCO headquarters in Paris. The event focused on the achievements of BIPM as well as the international scientific collaborations the Metre Convention enabled. It included talks from the Nobel prize-winning physicist William Phillips of the US National Institute of Standards and Technology (NIST) and the BIPM director Martin Milton, as well as panel discussions on the future of metrology featuring representatives of other national metrology institutes (NMIs) and metrology professionals from around the globe.

The history of metrology dates back to ancient times. As UNESCO's Hu Shaofeng noted in his opening remarks, the Egyptians recognized the importance of precision measurements as long ago as the 21st century BCE. Like other early schemes, the Egyptians' system of measurement used parts of the human body as references, with units such as the fathom (the length of a pair of outstretched arms) and the foot. This was far from ideal since, as Phillips pointed out in his keynote address, people come in various shapes and sizes. These variations led to a profusion of units. By some estimates, pre-revolutionary France had a whopping 250,000 different measures, with differences arising not only between towns but also between professions.

The French Revolutionaries were determined to put an end to this mess. In 1795, just six years after the Revolution, the law of 18 Geminal An III (according to the new calendar of the French Republic) created a preliminary version of the world's first metric system. The new system tied length and mass to natural standards (the metre was originally one-forty-millionth of the Paris meridian, while the kilogram is the mass of a cubic decimetre of water), and it became the standard for all of France in 1799. That same year, the system also became more practical, with units becoming linked, for the first time, to physical artefacts: a platinum metre and kilogram deposited in the French National Archives.

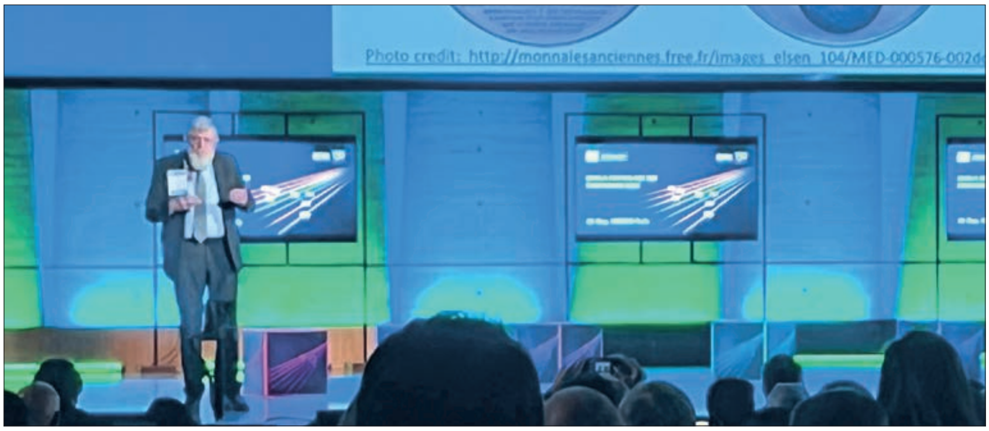
When the Metre Convention adopted this standard internationally 80 years later, it kick-started the construction of new length and mass standards. The new International Prototype of the Metre and International Prototype of the Kilogram were manufactured in 1879 and officially adopted as replacements for the Revolutionaries' metre and kilogram in 1889, though they continued to be calibrated against the old prototypes held in the National Archives.

The BIPM itself was originally conceived as a means of reconciling France and Germany after the 1870–1871 Franco–Prussian War. At first, its primary roles were to care for the kilogram and metre prototypes and to calibrate the standards of its member states. In the opening decades of the 20th century, however, it extended its activities to cover other kinds of measurements, including those related to electricity, light and radiation. Then, from the 1960s onwards, it became increasingly interested in improving the definition of length, thanks to new interferometer technology that made it possible to measure distance at a precision rivalling that of the physical metre prototype.

It was around this time that the BIPM decided to replace its expanded metric system with a framework encompassing the entire field of metrology. This new framework consisted of six basic units – the metre, kilogram, second, ampere, degree Kelvin (later simply the kelvin), candela and mole – plus a set of "derived" units (the newton, hertz, joule and watt) built from the six basic ones. Thus was born the International System of Units, or SI after the French initials for Système International d'unités.

The next major step – a "brilliant choice", in Phillips' words – came in 1983, when the BIPM decided to redefine the metre in terms of the speed of light. In the future, the Bureau decreed that the metre would officially be the length travelled by light in vacuum during a time interval of 1/299,792,458 seconds.

This decision set the stage for defining the rest of the seven base units in terms of natural fundamental constants. The most recent unit to join the club was the kilogram, which was defined in terms of the Planck constant, h, in 2019. In fact, the only base unit currently not defined in terms of a fundamental constant is the second, which is instead determined by the transition between the two hyperfine levels of the ground state of caesium-133. The international metrology community is, however, working to remedy this, with meetings being held on the subject in Versailles this year.



Isabelle Dumé

Metre man William Phillips giving the keynote address at the Metre Convention's 150th anniversary symposium.

Measurement affects every aspect of our daily lives, and as the speakers at last week's celebrations repeatedly reminded the audience, a unified system of measurement has long acted as a means of building trust across international and disciplinary borders. The Metre Convention's survival for 150 years is proof that peaceful collaboration can triumph, and it has allowed humankind to advance in ways that would not have been possible without such unity. A lesson indeed for today's troubled world.

Isabelle Dumé is a regular contributor to *Physics World*

Tiny laser delivers high-quality light for metrology

A new solid-state laser can make a vast number of precise optical measurements each second, while sweeping across a broad range of optical wavelengths. Created by a team led by Qiang Lin at the University of Rochester in the US, the device can be fully integrated onto a single chip.

Optical metrology is a highly versatile technique that uses light to gather information about the physical properties of target objects. It involves illuminating a sample and measuring the results with great precision – using techniques such as interferometry and spectroscopy. In the 1960s, the introduction of lasers and the coherent light they emit boosted the technique to an unprecedented level of precision. This paved the way for advances ranging from optical clocks, to the detection of gravitational waves.

Yet despite the indispensable role they have played so far, lasers have also created a difficult challenge. To ensure the best possible precision, experimentalists much achieve very tight control over the wavelength, phase, polarization and other properties of the laser light. This is very difficult to do within the tiny solid-state laser diodes that are very useful in metrology.

Currently, the light from laser diodes is improved externally using optical modules. This added infrastructure is inherently bulky and it remains difficult to integrate the entire setup onto chip-scale components – which limits the development of small, fast lasers for metrology.

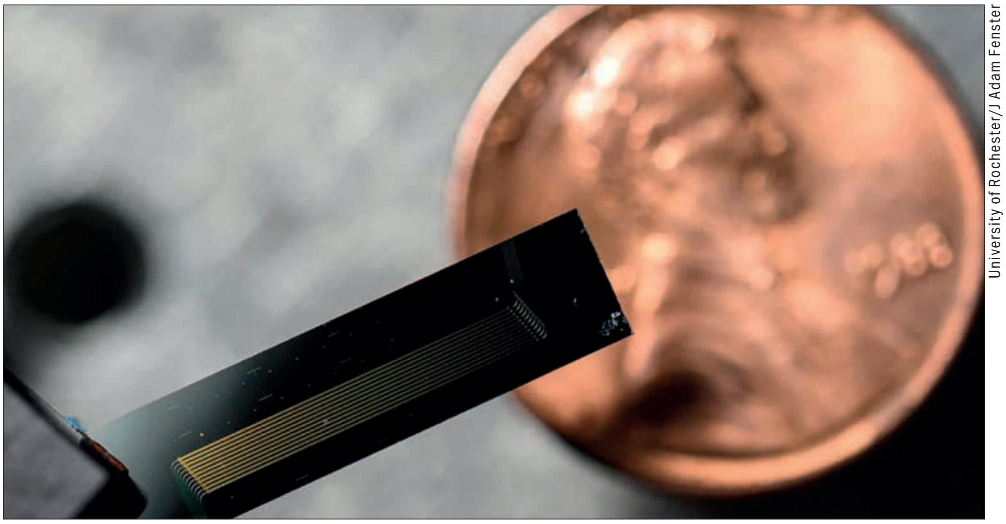
Two innovations

Lin and colleagues addressed this challenge by designing a new laser with two key components (*Light: Science & Applications* **14** 209). One is a laser cavity that comprises a thin film of lithium niobate. Thanks to the Pockels effect, this material's refractive index can vary depending on the strength of an applied electric field. This provides control over the wavelength of the light amplified by the cavity.

The other component is a distributed Bragg reflector (DBR), which is a structure containing periodic grooves that create alternating regions of refractive index. With the right spacing of these grooves, a DBR can strongly reflect light at a single, narrow linewidth, while scattering all other wavelengths. In previous studies, lasers were created by etching a DBR directly onto a lithium niobate film – but due to the material's optical properties, this resulted in a broad linewidth.

"Instead, we developed an 'extended DBR' structure, where the Bragg grating is defined in a silica cladding," explains team member Mingxiao Li at the University of California Santa Barbara. "This allowed for flexible control over the grating strength, via the thickness and etch depth of the cladding. It also leverages silica's superior etchability to achieve low scattering strength, which is essential for narrow linewidth operation."

Using a system of integrated electrodes, Lin's team can adjust the strength of the electric field they applied to the lithium niobate film. This allows them to rapidly tune the wavelengths amplified by the cavity via the Pockels effect. In addition, they used a specially designed waveguide to control the phase of light passing into the cavity. This design enabled them to tune their laser over a broad range of wavelengths, without needing external correction modules to achieve narrow linewidths.


University of Rochester/J Adam Fenster

Penny-sized The new chip-scale laser developed by Qiang Lin and colleagues can help make extremely fast and accurate measurements by very precisely and rapidly changing its wavelength.

Narrowband performance

Altogether, the laser demonstrated an outstanding performance on a single chip – producing a clean, single wavelength with very little noise. Most importantly, the light had a linewidth of just 167 Hz – the smallest range achieved to date for a single-chip lithium niobate laser. This exceptional performance enabled the laser to rapidly sweep across a bandwidth of over 10 GHz – equivalent to scanning quintillions of points per second.

"These capabilities translated directly into successful applications," Li describes. "The laser served as the core light source in a high-speed LIDAR system, measuring the velocity of a target 0.4 m away with better than 2 cm distance resolution. The system supports a velocity measurement as high as Earth's orbital velocity – around 7.91 km/s – at 1 m." Furthermore, Lin's team were able to lock their laser's frequency with a reference gas cell, integrated directly onto the same chip.

By eliminating the need for bulky control modules, the team's design could now pave the way for the full miniaturization of optical metrology – with immediate benefits for technologies including optical clocks, quantum computers, self-driving vehicles, and many others.

"Beyond these, the laser's core advantages – exceptional coherence, multifunctional control, and scalable fabrication – position it as a versatile platform for transformative advances in high-speed communications, ultra-precise frequency generation, and microwave photonics," Lin says.

Sam Jarman

Non-invasive pressure sensor could revolutionize diagnosis of brain injuries

Panicos Kyriacou is chief scientist at the UK-based start-up Crainio, which has developed an inexpensive light-based instrument that enables non-invasive measurement of intracranial pressure. He tells Tami Freeman that the sensor could improve the diagnoses of traumatic brain injury


Crainio

Traumatic brain injury (TBI), caused by a sudden impact to the head, is a leading cause of death and disability. After such an injury, the most important indicator of how severe the injury is intracranial pressure – the pressure inside the skull. But currently, the only way to assess this is by inserting a pressure sensor into the patient's brain. UK-based startup Crainio aims to change this by developing a non-invasive method to measure intracranial pressure using a simple optical probe attached to the patient's forehead.

Can you explain why diagnosing TBI is such an important clinical challenge?

Every three minutes in the UK, someone is admitted to hospital with a head injury, it's a very common problem. But when someone has a blow to the head, nobody knows how bad it is until they actually reach the hospital. TBI is something that, at the moment, cannot be assessed at the point of injury.

From the time of impact to the time that the patient receives an assessment by a neurosurgical expert is known as the golden hour. And nobody knows what's happening to the brain during this time – you don't know how best to manage the patient, whether they have a severe TBI with intracranial pressure rising in the head, or just a concussion or a medium TBI.

Once at the hospital, the neurosurgeons have to assess the patient's intracranial pressure, to determine whether it is above the threshold that classifies the injury as severe. And to do that, they have to drill a hole in the head – literally – and place an electrical probe into the brain. This really is one of the most invasive non-therapeutic procedures, and you obviously can't do this to every patient that comes with a blow in the head. It has its risks, there is a risk of haemorrhage or of infection.

Therefore, there's a need to develop technologies that can measure intracranial pressure more effectively, earlier and in a non-invasive manner. For many years, this was almost like a dream: "How can you access the brain and see if the pressure is rising in the brain, just by placing an optical sensor on the forehead?"

Panicos Kyriacou "At Crainio we want to create a technology that could be used widely, because there is a massive need, but also because it's affordable."

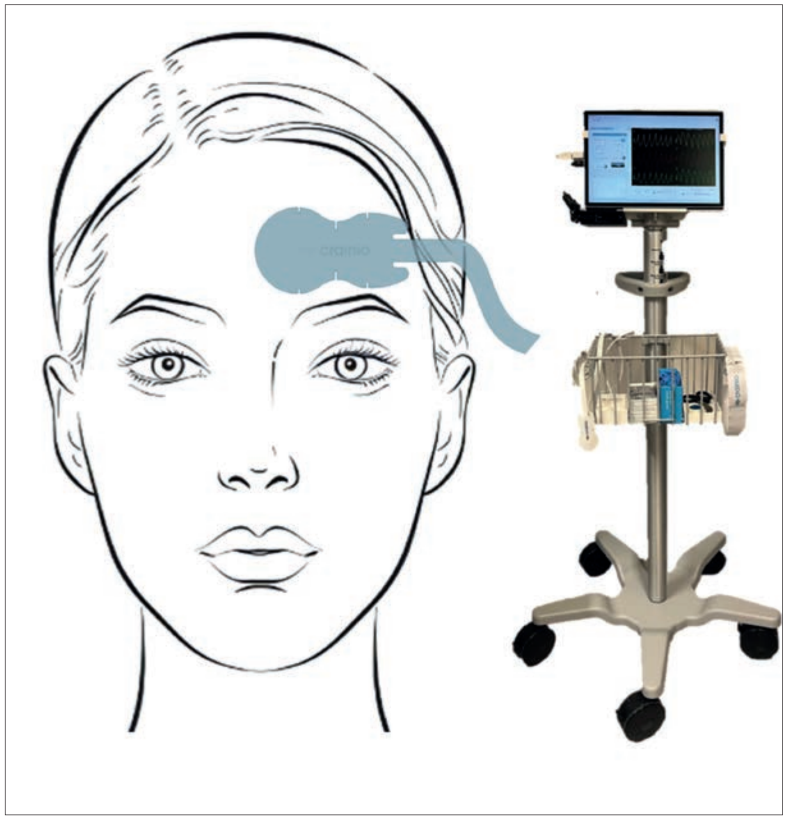
Crainio has now created such a non-invasive sensor; what led to this breakthrough?

The research goes back to 2016, at the Research Centre for Biomedical Engineering at City, University of London (now City St George's, University of London), when the National Institute for Health Research (NIHR) gave us our first grant to investigate the feasibility of a non-invasive intracranial sensor based on light technologies. We developed a prototype, secured the intellectual property and conducted a feasibility study on TBI patients at the Royal London Hospital, the biggest trauma hospital in the UK.

It was back in 2021, before Crainio was established, that we first discovered that after we shone certain frequencies of light, like near-infrared, into the brain through the forehead, the optical signals coming back – known as the photoplethysmogram, or PPG – contained

The primary motivation of Crainio is to create solutions for healthcare, developing a technology that can help clinicians to diagnose traumatic brain injury effectively, faster, accurately and earlier

AUDIO Listen to our full podcast interview with Panicos Kyriacou



Crainio

Easy does it Crainio has found a non-invasive way to measure brain pressure, the sensor is just like a sticking plaster on the forehead and the backend is a small box containing all the electronics.

information about the physiology or the haemodynamics of the brain.

When the pressure in the brain rises, the brain swells up, but it cannot go anywhere because the skull is like concrete. Therefore, the arteries and vessels in the brain are compressed by that pressure. PPG measures changes in blood volume as it pulses through the arteries during the cardiac cycle. If you have a viscoelastic artery that is opening and closing, the volume of blood changes and this is captured by the PPG. Now, if you have an artery that is compromised, pushed down because of pressure in the brain, that viscoelastic property is impacted and that will impact the PPG.

Changes in the PPG signal due to changes arising from compression of the vessels in the brain, can give us information about the intracranial pressure. And we developed algorithms to interrogate this optical signal and machine learning models to estimate intracranial pressure.

How did the establishment of Crainio help to progress the sensor technology?

Following our research within the university, Crainio was set up in 2022. It brought together a team of experts in medical devices and optical sensors to lead the further development and commercialization of this device. And this small team worked tirelessly over the last few years to generate funding to progress the development of the optical sensor technology and bring it to a level that is ready for further clinical trials.

In 2023, Crainio was successful with an Innovate UK biomedical catalyst grant, which will enable the company to engage in a clinical feasibility study, optimize the probe technology and further develop the algorithms. The company was later awarded another NIHR grant to move into a validation study.

The interest in this project has been overwhelming. We've had a very positive feedback from the neurocritical care community. But we also see a lot of interest from communities where injury to the brain is significant, such as rugby associations, for example.

Could the device be used in the field, at the site of an accident?

While Crainio's primary focus is to deliver a technology for use in critical care, the system could also be used in ambulances, in helicopters, in transfer patients and beyond. The device is non-invasive, the sensor is just like a sticking plaster on the forehead and the backend is a small box containing all the electronics. In the past few years, working in a research environment, the technology was connected into a laptop computer. But we are now transferring everything into a graphical interface, with a monitor to be able to see the signals and the intracranial pressure values in a portable device.

Following preliminary tests on patients, Crainio is now starting a new clinical trial. What do you hope to achieve with the next measurements?

The first study, a feasibility study on the sensor technology, was done during the time when the project was within the university. The second round is led by Crainio using a more optimized probe. Learning from the technical challenges we had in the first study, we tried to mitigate them with a new probe design. We've also learned more about the challenges associated with the acquisition of signals, the type of patients, how long we should monitor.

We are now at the stage where Crainio has redeveloped the sensor and it looks amazing. The technology has received approval by MHRA, the UK regulator, for clinical studies and ethical approvals have been secured. This will be an opportunity to work with the new probe, which has more advanced electronics that enable more detailed acquisition of signals from TBI patients.

We are again partnering with the Royal London Hospital, as well as collaborators from the traumatic brain injury team at Cambridge and we're expecting to enter clinical trials soon. These are patients admitted into neurocritical trauma units and they all have an invasive intracranial pressure bolt. This will allow us to compare the physiological signal coming from our intracranial pressure sensor with the gold standard.

The signals will be analysed by Crainio's data science team, with machine learning algorithms used to look at changes in the PPG signal, extract morphological features and build models to develop the technology further. So we're enriching the study with a more advanced technology, and this should lead to more accurate machine learning models for correctly capturing dynamic changes in intracranial pressure.

This time around, we will also record more information from the patients. We will look at CT scans to see whether scalp density and thickness have an impact. We will also collect data from commercial medical monitors within neurocritical care to see the relation between intracranial pressure and other physiological data acquired in the patients. We aim to expand our knowledge of what happens when a patient's intracranial pressure rises – what happens to their blood pressures? What happens to other physiological measurements?

How far away is the system from being used as a standard clinical tool?

Crainio is very ambitious. We're hoping that within the next couple of years we will progress adequately in order to achieve CE marking and all meet the standards that are necessary to launch a medical device.

The primary motivation of Crainio is to create solutions for healthcare, developing a technology that can help clinicians to diagnose TBI effectively, faster, accurately and earlier. This can only yield better outcomes and improve patients' quality-of-life.

Of course, as a company we're interested in being successful commercially. But the ambition here is, first of all, to keep the cost affordable. We live in a world where medical technologies need to be affordable, not only for Western nations, but for nations that cannot afford state-of-the-art technologies. So this is another of Crainio's primary aims, to create a technology that could be used widely, because there is a massive need, but also because it's affordable.

Tami Freeman is an online editor of *Physics World*

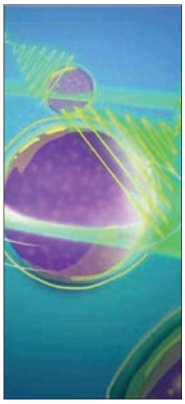
Microscopy

Brillouin microscopy is 1000 times faster

Researchers at the EMBL in Germany have dramatically reduced the time required to create images using Brillouin microscopy, making it possible to study the viscoelastic properties of biological samples far more quickly and with less damage than ever before. Their new technique can image samples with a field of view of roughly 10 000 pixels at a speed of 0.1 Hz – a 1000-fold improvement in speed and throughput compared to standard confocal techniques (*Nature Photonics* **19** 494).

Mechanical properties such as the elasticity and viscosity of biological cells are closely tied to their function. However, measuring these properties is not easy since most techniques are invasive and disrupt the systems being imaged.

In recent years, Brillouin microscopy has emerged as a non-destructive, label- and contact-free optical spectroscopy method for probing the viscoelastic properties of biological samples with high resolution in 3D. It relies on Brillouin scattering, which occurs when light interacts with the phonons (quantized vibrations) that are present in all matter. This interaction produces two additional peaks, known as Stokes and anti-Stokes Brillouin peaks, in the spectrum of the scattered light. The position of these peaks (the Brillouin shift) and their linewidth (the Brillouin width) are related to the elastic and viscous properties, respectively, of the sample.



Daniela Velasco/EMBL

Speed up
The new Brillouin microscopy approach allows entire light-sheets to interact with 3D biological samples recording data from many more points in parallel, reducing the number images required.

However, Brillouin microscopy analyses just one point in a sample at a time and the scattering signal from a single point is weak. This requires long light exposure times that can damage photosensitive components within biological cells.

EMBL researchers led by Robert Prevedel began exploring ways to speed up the rate at which Brillouin microscopy can acquire two- and three-dimensional images. In the early days of their project, they were only able to visualize one pixel at a time and it took several minutes, or even hours, to obtain 2D images of 50–250 square pixels.

In 2022, they expanded the field of view to include an entire spatial line, acquiring image data from more than 100 points in parallel. In their latest work they extended the technique to view roughly 10 000 pixels in parallel over the full plane of a sample. They then used the microscope to study mechanical changes in live zebrafish larvae.

"This advance enables much faster Brillouin imaging, and in terms of microscopy, allows us to perform 'light sheet' Brillouin imaging," says Prevedel. "In short, we are able to 'under-sample' the spectral output, which leads to around 1000 fewer individual measurements than normally needed."

Prevedel and colleagues hope their result will lead to more widespread use of Brillouin microscopy, particularly for photosensitive biological samples.

Isabelle Dumé

Laboratory-scale 3D X-ray diffraction can be used on campus

Trips to synchrotron facilities could become a thing of the past thanks to a new laboratory-scale 3D X-ray diffraction microscope designed by a team at the University of Michigan in the US. The device uses a liquid-metal-jet electrode to produce high-energy X-rays and can probe almost everything a traditional synchrotron can (*Nature Communications* 16 3964). It could give more researchers access to synchrotron-style capabilities.

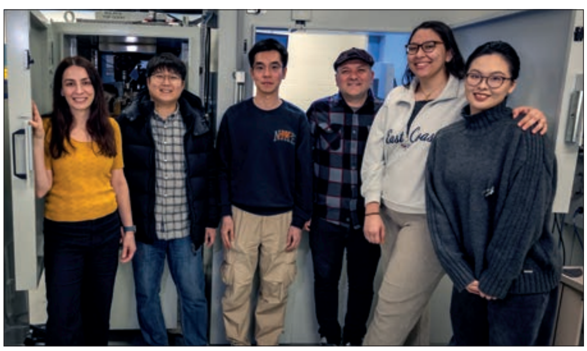
Synchrotrons are particle accelerators that produce bright, high-quality beams of electromagnetic radiation at wavelengths ranging from the infrared to soft X-rays.

One technique supported by synchrotrons is 3D X-ray diffraction (3DXRD) microscopy, which probes the mechanical behaviour of polycrystalline materials. A computer algorithm is used to construct a 3D image of a sample from a sequence of X-ray images taken at multiple angles.

Today, 3DXRD can only be performed at synchrotrons where scientists must apply for beamtime months or even years in advance. They receive a block of time lasting six days at the most to complete their experiments.

Previous attempts to make 3DXRD work in smaller laboratories have largely been unsuccessful. Efforts to produce X-rays using electrical anodes have foundered because these anodes are made of solid metal, which cannot withstand the high power of the electron beams needed to produce X-rays.

Now, Ashley Bucsek and colleagues have created a liquid-metal-jet anode that can absorb more power. The sample volume is illuminated by a monochromatic box or line-focused X-ray beam while diffraction patterns are serially recorded as the sample rotates full circle. "The technique is capable of measuring the volume, position, orientation and strain of thousands of polycrystalline grains simultaneously," Bucsek says.



Marcin Szczepanski, Michigan Engineering

Lab scale
Members of Ashley Bucsek's group use 3D X-ray diffraction to study polycrystalline materials on campus. Left to right: Ashley Bucsek, Sangwon Lee, Wenxi Li, Abdulhamit Sarac, Janice Moya and Yuefeng Jin.

When the team tested the device by imaging samples of titanium alloy samples, they found it was as accurate as synchrotron-based 3DXRD. "My colleagues and I hope that the adaptation of this technology from the synchrotron to the laboratory scale will make it more accessible," Bucsek says.

The device was developed with US-based instrumentation firm, PROTO Manufacturing.

The team will now do longer experiments. "Conducting such prolonged experiments at synchrotron user facilities would be difficult, if not impossible, due to the high demand," says Bucsek.

Isabelle Dumé

Optics

Laser enables long-range detection of radioactive material

Researchers in the US have demonstrated that they can remotely detect radioactive material from 10 m away using short-pulse CO_2 lasers – a distance over ten times farther than achieved via previous methods.

Conventional radiation detectors, such as Geiger counters, detect particles that are emitted by the radioactive material, typically limiting their operational range to the material's direct vicinity. The new method, developed by a research team headed up at the University of Maryland, instead leverages the ionization in the surrounding air, enabling detection from much greater distances (*Phys. Rev. Applied* **23** 034004).

The study may one day lead to remote sensing technologies that could be used in nuclear disaster response and nuclear security.

Radioactive materials emit particles – such as alpha, beta or gamma particles – that can ionize air molecules, creating free electrons and negative ions. These charged particles are typically present at very low concentrations, making them difficult to detect.

Now, Howard Milchberg and colleagues – also at Brookhaven National Laboratory, Los Alamos National Laboratory and Lawrence Livermore National Laboratory – demonstrated that CO_2 lasers could accelerate these charged particles, causing them to collide with neutral gas molecules, in turn creating further ionization. These additional free charges would then undergo the same laser-induced accelerations and collisions, leading to a cascade of charged particles.

This effect, known as "electron avalanche breakdown", can create microplasmas that scatter laser light. By measuring the profile of the backscattered light, researchers can detect the presence of radioactive material.

The team tested their technique using a 3.6 mCi polonium-210 alpha particle source at a standoff distance of 10 m, significantly longer than previous experiments that used different types of lasers and electromagnetic radiation sources.

"The results are highly impressive," comments EunMi Choi from the Ulsan National Institute of Science and Technology in South Korea. Choi's team had used a gyrotron source to detect radioactive materials back in 2017.

Shutterstock/fewerton

Remote detection The ability to locate radioactive material at distances greater than the range of emitted particles could play an important role in nuclear disaster response and nuclear security.

"The researchers successfully demonstrated 10-m standoff detection of radioactive material, significantly surpassing the previous range of approximately 1 m," she says.

Milchberg and collaborators had previously used a mid-infrared laser in a similar experiment in 2019. Changing to a long-wavelength (9.2 μm) CO_2 laser brought significant advantages, he says.

"You can't use any laser to do this cascading breakdown process," Milchberg explains. The CO_2 laser's wavelength was able to enhance the avalanche process, while being low energy enough to not create its own ionization sources. "CO_2 is sort of the limit for long wavelengths on powerful lasers and it turns out CO_2 lasers are very, very efficient as well," he says. "So this is like a sweet spot."

The team also used a CMOS camera to capture visible-light emissions from the microplasmas. Milchberg says that this fluorescence around radioactive sources resembled balls of plasma, indicating the localized regions where electron avalanche breakdowns had occurred.

By counting these "plasma balls" and calibrating them against the backscattered laser signal, the researchers could link fluorescence intensity to the density of ionization in the air, and use that to determine the type of radiation source.

The CMOS imagers, however, had to be placed close to the measured radiation source, reducing their applicability to remote sensing. "Although fluorescence imaging is not practical for field deployment due to the need for close-range cameras, it provides a valuable calibration tool," Milchberg says.

The researchers believe their method can be extended to standoff distances exceeding 100 m. The primary limitation is the laser's focusing geometry, which would affect the regions in which it could trigger an avalanche breakdown. A longer focal length would require a larger laser aperture but could enable kilometre-scale detection.

Choi points out, however, that deploying a CO_2 laser may be difficult in real-world applications. "A CO_2 laser is a bulky system, making it challenging to deploy in a portable manner in the field," she says, adding that mounting the laser for long-range detection may be a solution.

Milchberg says that the next steps will be to continue developing a technique that can differentiate between different types of radioactive sources completely remotely. Choi agrees, noting that accurately quantifying both the amount and type of radioactive material continues to be a significant hurdle to realising remote sensing technologies in the field.

"There's also the question of environmental conditions," says Milchberg, explaining that it is critical to ensure that detection techniques are robust against the noise introduced by aerosols or air turbulence.

Jacklin Kwan

Protons take to the road at CERN


BASE/Julia Jäger

Lifted by crane The BASE-STEP autonomous Penning-trap system is moved to a lorry at CERN. Marcel Leonhardt (right), physicist at HHU, checks the status of the device and confinement of the protons on a tablet.

Physicists at CERN have completed a "test run" for taking antimatter out of the laboratory and transporting it across the site of the European particle-physics facility. Although the test was carried out with ordinary protons, the team that performed it says that antiprotons could soon get the same treatment. The goal, they add, is to study antimatter in places other than the labs that create it, as this would enable more precise measurements of the differences between matter and antimatter. It could even help solve one of the biggest mysteries in physics: why does our universe appear to be made up almost entirely of matter, with only tiny amounts of antimatter?

According to the Standard Model of particle physics, each of the matter particles we see around us – from baryons like protons to leptons such as electrons – should have a corresponding antiparticle that is identical in every way apart from its charge and magnetic properties (which are reversed). This might sound straightforward, but it leads to a peculiar prediction. Under the Standard Model, the Big Bang that formed our universe nearly 14 billion years ago should have generated equal amounts of antimatter and matter. But if that were the case, there shouldn't be any matter left, because whenever pairs of antimatter and matter particles collide, they annihilate each other in a burst of energy.

Physicists therefore suspect that there are other, more subtle differences between matter particles and their antimatter counterparts – differences that could explain why the former prevailed while the latter all but disappeared. By searching for these differences, they hope to shed more light on antimatter-matter asymmetry – and perhaps even reveal physics beyond the Standard Model.

> Antimatter needs to be carefully isolated from its environment to prevent it from annihilating with the walls of its container or ambient gas molecules

Extremely precise measurements

At CERN's Baryon-Antibaryon Symmetry Experiment (BASE) experiment, the search for matter-antimatter differences focuses on measuring the magnetic moment (or charge-to-mass ratio) of protons and antiprotons. These measurements need to be extremely precise, but this is difficult at CERN's "Antimatter Factory" (AMF), which manufactures the necessary low-energy antiprotons in profusion. This is because essential nearby equipment – including the Antiproton Decelerator and ELENA, which reduce the energy of incoming antiprotons from GeV to MeV – produces magnetic field fluctuations that blur the signal.

To carry out more precise measurements, the team therefore needs a way of transporting the antiprotons to other, better-shielded, laboratories. This is easier said than done, because antimatter needs to be carefully isolated from its environment to prevent it from annihilating with the walls of its container or with ambient gas molecules.

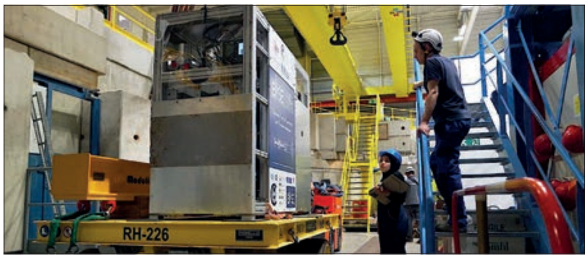
The BASE team's solution was to develop a device that can transport trapped antiprotons on a truck for substantial distances. It is this device, known as BASE-STEP (for Symmetry Tests in Experiments with Portable Antiprotons), that has now been field-tested for the first time. ▶

Vacuum

During the test, the team successfully transported a cloud of about 105 trapped protons out of the AMF and across CERN's Meyrin campus over a period of four hours. Although protons are not the same as antiprotons, BASE-STEP team leader Christian Smorra says they are just as sensitive to disturbances in their environment caused by, say, driving them around. "They are therefore ideal stand-ins for initial tests, because if we can transport protons, we should also be able to transport antiprotons," he says.

The BASE-STEP device is mounted on an aluminium frame and measures 1.95 m × 0.85 m × 1.65 m. At 850–900 kg, it is light enough to be transported using standard forklifts and cranes.

Like BASE, it traps particles in a Penning trap composed of gold-plated cylindrical electrode stacks made from oxygen-free copper. To further confine the protons and prevent them from colliding with the trap's walls, this trap is surrounded by a superconducting magnet bore operated at cryogenic temperatures. The second electrode stack is also kept at ultralow pressures, which Smorra says is low enough to keep antiparticles from annihilating with residual gas molecules. To transport antiprotons instead of protons, Smorra adds, they would just need to switch the polarity of the electrodes.



BASE/Maria Latacz

The next step BASE-STEP on a transfer trolley, watched over by BASE team members Fatma Abbass and Christian Smorra

The transportable trap system (*Nature* **641** 871) is designed to remain operational on the road. It uses a carbon-steel vacuum chamber to shield the particles from stray magnetic fields, and its frame can handle accelerations of up to 1 g (9.81 m/s^2) in all directions over and above the usual (vertical) force of gravity. This means it can travel up and down slopes with a gradient of up to 10%, or approximately 6°.

Once the BASE-STEP device is reconfigured to transport antiprotons, the first destination on the team's list is a new Penning-trap system currently being constructed at the Heinrich Heine University in Düsseldorf, Germany. Here, physicists hope to search for charge-parity-time (CPT) violations in protons and antiprotons with a precision at least 100 times higher than is possible at CERN's AMF.

"At BASE, we are currently performing measurements with a precision of 16 parts in a trillion," explains BASE spokesperson Stefan Ulmer, an experimental physicist at Heinrich Heine and a researcher at CERN and Japan's RIKEN laboratory. "These experiments are the most precise tests of matter/antimatter symmetry in the baryon sector to date, but to make these experiments better, we have no choice but to transport the particles out of CERN's antimatter factory," he tells *Physics World*.

Isabelle Dumé

Neutron Airy beams make their debut

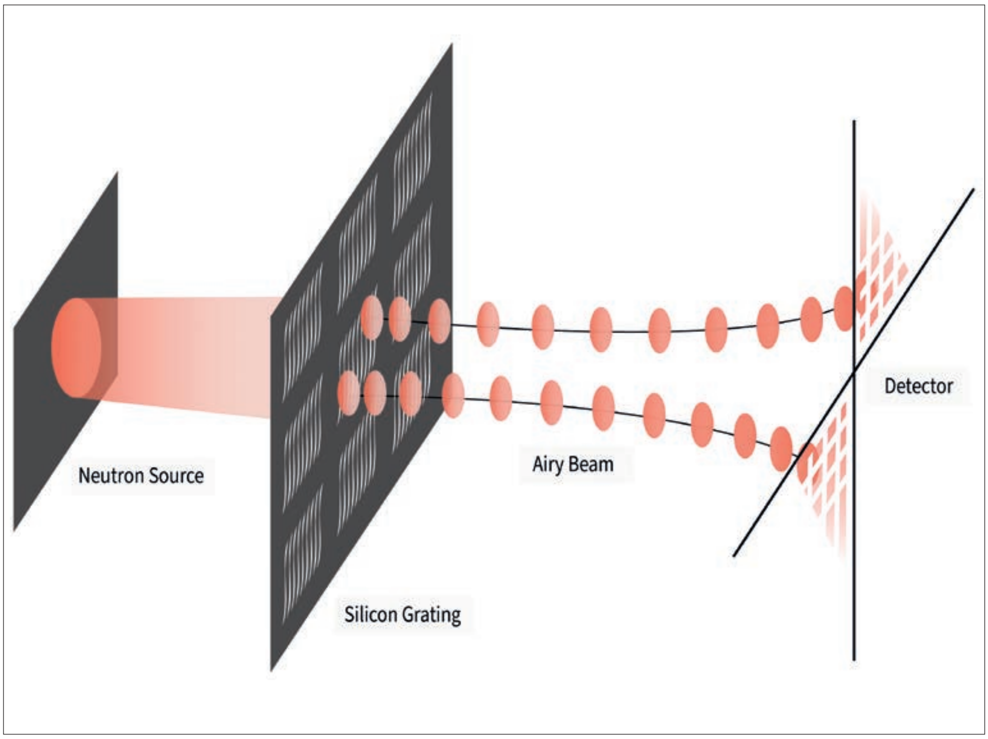
For the first time, physicists have made neutrons travel in a curved parabolic waveform known as an Airy beam. Such beams have already been made using photons and electrons and neutron Airy beams could be used in fundamental research and advanced imaging techniques (*Phys. Rev. Lett.* 134 153401).

In free space, beams of light propagate in straight lines. When they pass through an aperture, they diffract, becoming wider and less intense. Airy beams, however, are different. They have a property known as self-acceleration and do not spread out as they travel. Airy beams are also "self-healing", meaning that they reconstruct themselves after passing through a partial obstacle.

Scientists have been especially interested in Airy beams since 1979, when theoretical work by British physicist Michael Berry suggested several possible applications for them, says Dmitry Pushin, a physicist at the University of Waterloo in Canada. Researchers created the first Airy beams from light in 2007, followed by an electron Airy beam in 2013.

"Inspired by the unusual properties of these beams in optics and electron experiments, we wondered whether similar effects could be harnessed for neutrons," Pushin says.

Making such beams out of neutrons turned out to be challenging, because neutrons have no charge and cannot be shaped by electric fields. Also, lenses that focus neutron beams do not exist.



N Hanacek / NIST

Parabolic path An Airy beam of neutrons could be useful when investigating new drugs as well as in quantum computing.

A team led by Pushin and Dusan Sarenac of the University at Buffalo in the US overcame these difficulties using a holographic approach based on a custom-microfabricated silicon diffraction grating. The grating comprised an array of 6 250 000 micron-sized cubic phase patterns etched onto a silicon slab. "The grating modulates incoming neutrons into an Airy form and the resulting beam follows a curved trajectory, exhibiting the characteristics of a two-dimensional Airy profile at a neutron detector," Sarenac explains.

The technology was tested in the US at the NIST Center for Neutron Research and Oak Ridge National Laboratory; and at the Paul Scherrer Institute in Switzerland. Further studies are planned at the UK's ISIS Neutron and Muon Source to explore ways of combining neutron Airy beams with other structured neutron beams, such as helical waves and vortices. This could prove useful in studying chirality in drug development; materials science; spintronics; and quantum computing.

Isabelle Dumé

Neutrons differentiate between real and fake antique coins

The scattering of relatively slow moving neutrons from materials provides a wide range of structural information. However, materials that contain large amounts of hydrogen-1 nuclei (protons) can be difficult to study because hydrogen is very good at scattering neutrons in random directions – creating a noisy background signal.

However, there are some special cases where this incoherent scattering of hydrogen can be useful – measuring the water content of samples, for example.

Now, researchers in the US and South Korea have used a neutron beam to differentiate between genuine antique coins and fakes (*Scientific Reports* **15** 14848). The technique relies on the fact that the genuine coins have suffered corrosion that has resulted in the inclusion of hydrogen-bearing compounds.

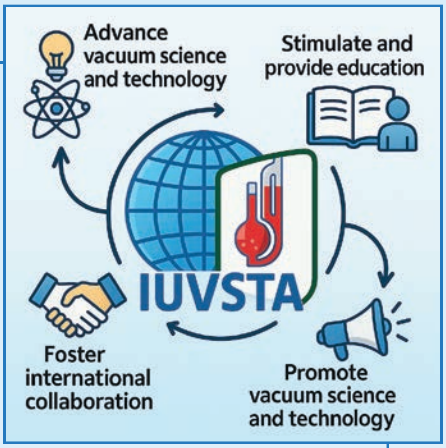
Led by Youngju Kim and Daniel Hussey at NIST in Colorado, the team fired a parallel beam of neutrons through individual coins (see figure on p31). The particles travel with ease through a coin's original metal, but tend to be scattered by the hydrogen-rich corrosion inclusions. This creates a 2D pattern of high and low intensity regions on a neutron-sensitive screen. The coin is rotated and a series of images taken. Computed tomography is then used to create a 3D image showing the corroded regions of a coin.

The ability to verify the age of coins is of interest to historians and economists

The team used this neutron tomography technique to examine an authentic 19th century coin that was recovered from a shipwreck, and a replica coin. Although both coins ▶

IUVSTA serves to advance Vacuum Science and Technology enabling nanotechnology, surface engineering, quantum science, semiconductor chips and more; Stimulates and provides education through Workshops, Technical Training Courses, Schools, Short Courses and Webinars; Promotes vacuum technology through scholarships and awards aimed at both early-career and established vacuum scientists from multiple disciplines; and fosters international collaborations with organization of 35 different countries of the world.

A Message from the President of IUVSTA
“Vacuum, the Enabling Technology for a Better Life!”



As the incoming President for the world’s vacuum societies union, IUVSTA, I’m excited to share my vision for how vacuum science and technology can be both an engine for our world’s innovation economy and build a more robust and resilient society at time where we are collectively facing challenges never seen before.

IUVSTA (International Union for Vacuum Science, Technique and Applications) represents over 100,000 scientists, engineers and technicians comprising 35 members nations. The members of the union do work that is important and critical to emerging technologies including quantum science, advanced computing, semiconductors, biotechnology and advanced manufacturing. IUVSTA’s role is to connect and communicate with the member countries, and to organize a number of scientific conferences, including the International Vacuum Congress (IVC-23, Sydney Australia Sept 15-19th, 2025), and to coordinate the organization and funding of Workshops, Technical Training Courses, Schools, and Short Courses and Webinars.

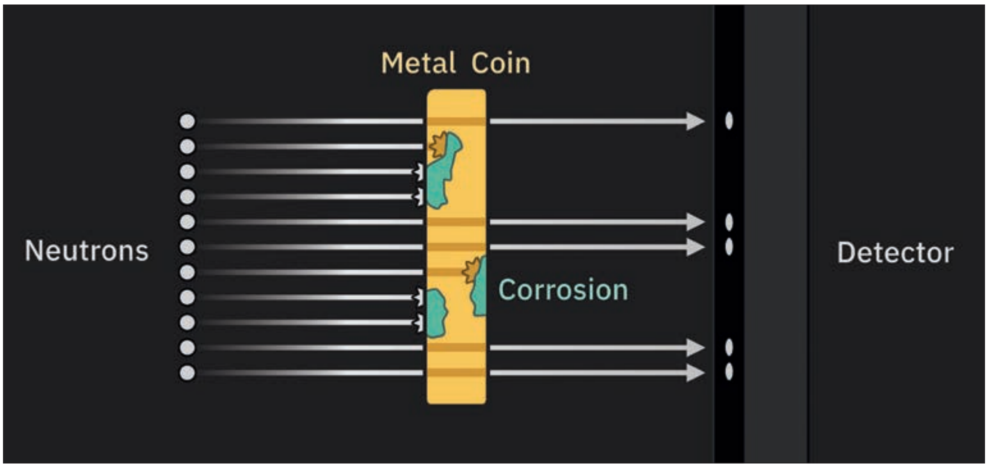
The Union funds and runs awards aimed at both early-career and senior scientists. These IUVSTA awards include the IUVSTA Prize for Science, the IUVSTA Prize for Technology, the IUVSTA Medard W. Welch International Scholarship, the IUVSTA EBARA Award, and IUVSTA Elsevier Student Travel Awards. One of the major goals that I will be working on over the next three years is public outreach to make the connections between the science done by our IUVSTA Divisions of Applied Surface Science, Biointerfaces, Electronic Materials & Processing, Nanometer Structures, Plasma Science & Technologies, Surface Engineering, Surface Science, Thin Film, Vacuum Science and Technology, and the IUVSTA Working Group on Sustainability and its impact on the everyday life for the citizens of the world. These impacts show up in many ways, everything from faster smaller, lighter computer chips to artificial intelligence systems, to self-driving cars, to a more energy efficient and resilient systems needed to address more aggressive weather patterns.

I look forward to working with you!”

Dr. Jay Hendricks, IUVSTA President 2025-2028.
Jay works at National Institute of Standards and Technology (NIST), in Gaithersburg, Maryland, USA, is the Deputy Program Manager for the “NIST on a Chip” Program and has worked at NIST 29 years.

had surface corrosion, the corrosion extended much deeper into the bulk of the authentic coin than it did in the replica.

The researchers used a separate technique called neutron grating interferometry to characterize the pores in the surfaces of the coins. Pores are common on the surface of coins that have been buried or submerged. Authentic antique coins are often found buried or submerged, whereas replica coins will be buried or submerged to make them look more authentic.



S Kelley/NIST

Finding fakes Illustration of how neutrons can pass easily through the metallic regions of an old coin, but are blocked by hydrogen-bearing compounds formed by corrosion

Neutron grating interferometry looks at the small-angle scattering of neutrons from a sample and focuses on structures that range in size from about 1 nm to 1 µm.

The team found that the authentic coin had many more tiny pores than the replica coin, which was dominated by much larger (millimetre scale) pores.

This is expected because when a coin is buried or submerged, chemical reactions cause metals to leach out of its surface, creating millimetre-sized pores. As time progresses, however, further chemical reactions cause corrosion by-products to fill in the pores. The result is that the pores in the older authentic coin are smaller than the pores in the newer replica coin.

The team now plans to expand its study to include more Korean coins and other metallic artefacts. The techniques could also be used to pinpoint corrosion damage in antique coins, allowing these areas to be protected using coatings.

As well as being important to coin collectors and dealers, the ability to verify the age of coins is of interest to historians and economists – who use the presence of coins in their research.
Hamish Johnston

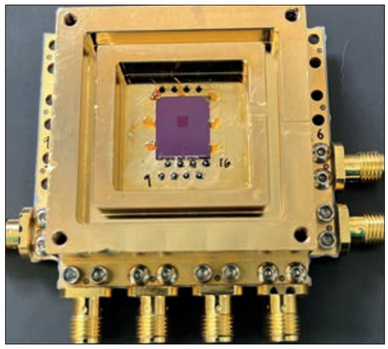
Particle and nuclear

Superconducting microwires detect high-energy particles

Arrays of superconducting wires have been used to detect beams of high-energy charged particles. Much thinner wires are already used to detect single photons, but this latest incarnation uses thicker wires that can absorb the large amounts of energy carried by fast-moving charged particles. The new detector was created by an international team led by Cristián Peña at Fermilab (*Journal of Instrumentation* 20 P03001).

In a single-photon detector, an array of superconducting nanowires is operated below the critical temperature for superconductivity – with current flowing freely through the nanowires. When a nanowire absorbs a photon it creates a hotspot that temporarily destroys superconductivity and boosts the electrical resistance. This creates a voltage spike across the nanowire, allowing the location and time of the photon detection to be determined.

A similar hotspot is created when a superconducting wire is impacted by a high-energy charged particle. However, unlike photons, charged particles do not deposit all of their energy at a single point in a wire. Instead, the energy can be spread out along a track, which becomes longer as particle energy increases. Also, at the relativistic energies reached at particle accelerators, the nanowires used in single-photon detectors are too thin to collect the energy required to trigger a particle detection.



New detector This SMSPD was created by a team led by researchers at Fermilab.

Cristián Peña/Fermilab

Peña's team addressed these challenges using advances in superconductor fabrication. On a thin film of tungsten silicide, they deposited an 8×8, 2 mm^2 array of micron-thick superconducting wires.

To test their superconducting microwire single-photon detector (SMSPD), they used it to detect high-energy particle beams generated at the Fermilab Test Beam Facility in the US.

"Our study shows for the first time that SMSPDs are sensitive to protons, electrons, and pions," Peña explains.

The team now aims to develop a deeper understanding of the detection process. "That will allow us to begin optimizing and engineering the properties of the superconducting material and sensor geometry to boost the detection efficiency, the position and timing precision, as well as optimize for the operating temperature of the sensor," Peña says.

Sam Jarman

Smartphone sensors and antihydrogen could put relativity to the test

Researchers in the AEgIS collaboration at CERN have designed a vacuum-based experiment that could soon boost our understanding of how antimatter falls under gravity. Created by a team led by Francesco Guatieri at the Technical University of Munich, the scheme uses modified smartphone camera sensors to improve the spatial resolution of measurements of antimatter annihilations (*Science Advances* DOI: 10.1126/sciadv.ads1176).

This could be used in rigorous tests of the weak equivalence principle (WEP), which is a key concept of the general theory of relativity. It suggests that within a gravitational field, all objects should be accelerated at the same rate, regardless of whether they are matter or antimatter. Therefore, if matter and antimatter fall at different rates in freefall, it would reveal serious problems with the WEP.

In 2023 ALPHA-g at CERN observed how antimatter responds to gravity. They found that it falls down, with the possibility that antimatter's gravitational response is weaker than matter's. There are several experiments that are seeking to improve on this observation.

AEgIS' approach is to create a horizontal beam of cold antihydrogen atoms and observe how the atoms fall under gravity. This is measured by a moiré deflectometer in which a beam passes through two grids of horizontal slits before striking a position-sensitive detector. As the beam falls under gravity between the grids, the effect is similar to a slight horizontal misalignment of the grids. This creates a moiré pattern on the detector. By detecting a difference in the measured pattern and that predicted by WEP, the AEgIS collaboration could reveal a discrepancy with general relativity.

Guatieri explains that "For AEgIS to work, we need a detector with incredibly high spatial resolution. Previously, photographic plates were the only option, but they lacked real-time capabilities."

AEgIS physicists are developing a new vertexing detector that observes the secondary particles produced when the antimatter annihilates on contact with the detector. Tracing the trajectories of these particles back to their vertex gives the precise location of the annihilation.

Caught on camera AEgIS' vertex detector integrates 60 light sensors taken from mobile phones.

Andreas Heddergott/TUM

The detector incorporates an array of modified mobile-phone cameras. "Mobile camera sensors have pixels smaller than 1 micron," Guatieri says. "We had to strip away the first layers of the sensors, which are made to deal with the advanced integrated electronics of mobile phones. This required high-level electronic design and micro-engineering."

The team measured the positions of antiproton annihilations to within just 0.62 micron: making their detector some 35 times more precise than previous designs.

With some further improvements, the AEgIS team is confident that their vertexing detector will support rigorous tests of the WEP. AEgIS team member Ruggero Caravita of Italy's University of Trento adds, "This game-changing technology could also find broader applications in experiments where high position resolution is crucial, or to develop high-resolution trackers".

Sam Jarman