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Instrumentation & Vacuum Briefing

Quantum sensors
Miniaturized ultrahigh vacuum is essential for portability

International System of Units
Why SI is quirky by nature

Laser plasma acceleration
Portable muon source could peer inside huge objects

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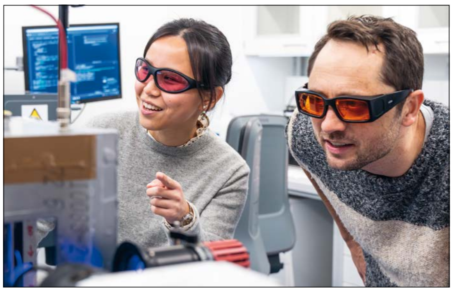

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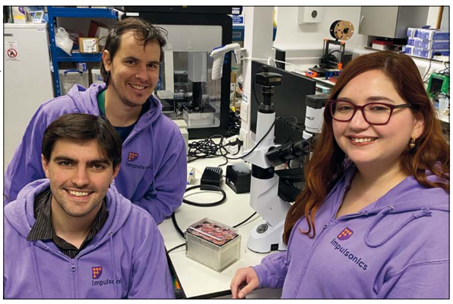

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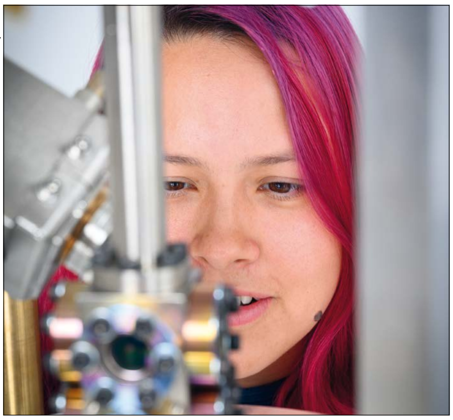
Aquark



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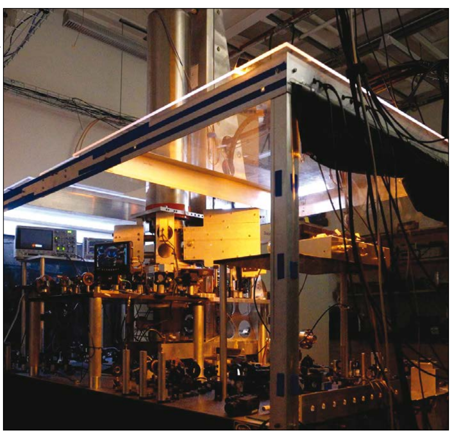


NIST-F4 caesium fountain clock helps provide the ultimate foundation for universal time, 20

Instrumentation advances move from lab innovation to real-world impact

Welcome to this *Physics World Instrumentation and Vacuum and Briefing*. It includes updates on R&D, interviews that explore technology commercialization, and a romp through the quirky world of SI units.

Physicists have developed some amazing quantum sensors but many of these technologies remain in the lab because of the challenges of miniaturizing key components. Ultrahigh vacuum (UHV) plays an important role in quantum sensors based on cold atoms, and Aquark's Florence Concepcion of UK-based Aquark talks about her mission to reduce the size and energy consumption of UHV systems (p5).

The ability to manipulate individual living cells plays an important role in biology and medicine. However, cells tend to stick together when grown *in vitro* and separating them often involves using harsh chemicals that can damage cells or modify their properties. Now, UK-based Impulsonics has developed a system that uses ultrasound to gently separate living cells. On page 37 the company's co-founder Luke Cox explains how the technology works and how it is being commercialized.

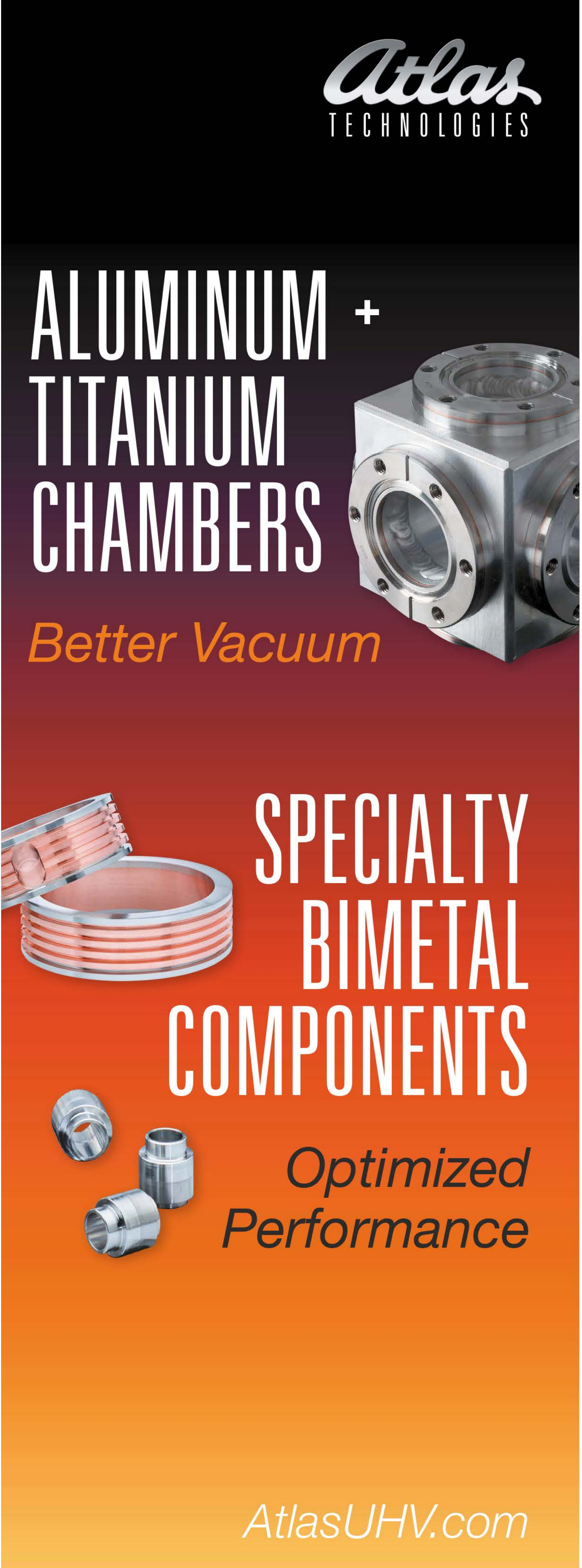
Another entrepreneur featured in this briefing is Brian Pogue, who is co-founder of DoseOptics. The US-based company has developed a system that detects the extremely faint Cherenkov light that is emitted when a radiotherapy beam strikes a patient's skin. This allows the radiotherapy to be monitored in real time, ensuring that the beam passes through the target tissue and avoids healthy areas of the body (p34).

Conventional particle accelerators tend to be large and expensive and this has limited their use in fields as varied as radiotherapy and particle physics. One way of making a compact accelerator is to use intense laser light to accelerate particles. On page 11, I describe how researchers in the US have created a compact, free electron laser that is driven by a laser plasma accelerator (LPA). Over on page 31 Isabelle Dumé explains how an LPA has been used to create a beam of muons.

Created in 1960, the International System of Units (SI) is the bedrock of metrology. Although SI and its predecessors have been honed and re-defined over the centuries, it still has some surprising quirks. In a feature article (p20), Ben Stein explores some of these oddities including how the candela was derived from the brightness of a candle made from whale fat and beeswax; and the ongoing debate about using the dimensionless radian as the SI derived unit for planar angle.

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

Hamish Johnston, online editor, *Physics World*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Miniaturizing ultrahigh vacuum to enable cold-atom quantum devices

Florence Concepcion is senior quantum engineer at Aquark Technologies. She joined the UK-based company in 2023 after doing a PhD at Imperial College London, focusing on a topic at the intersection of astrophysics and atomic physics. Her role at Aquark marked a career transition to vacuum technology. She spoke to *Physics World*'s Hamish Johnston about her work there to create portable quantum sensors

Concepcion and her colleagues at Aquark are developing miniaturized cold-atom quantum devices. Their goal is to create robust and portable quantum sensors. These include cold-atom clocks that can be used in real-world applications such as navigation – particularly in environments where satellite-positioning systems are not available.

Last year, Concepcion received an Innovate UK Future Leaders Fellowship from the UK government, which is worth £1.9 million over four years. She explains the importance of vacuum to Aquark's technologies and how she will use the fellowship money to develop miniature, robust and portable ultrahigh vacuum (UHV) chambers

What needs to be done to transform cold-atom quantum technologies from the laboratory bench to practical quantum devices?

The key is portability.

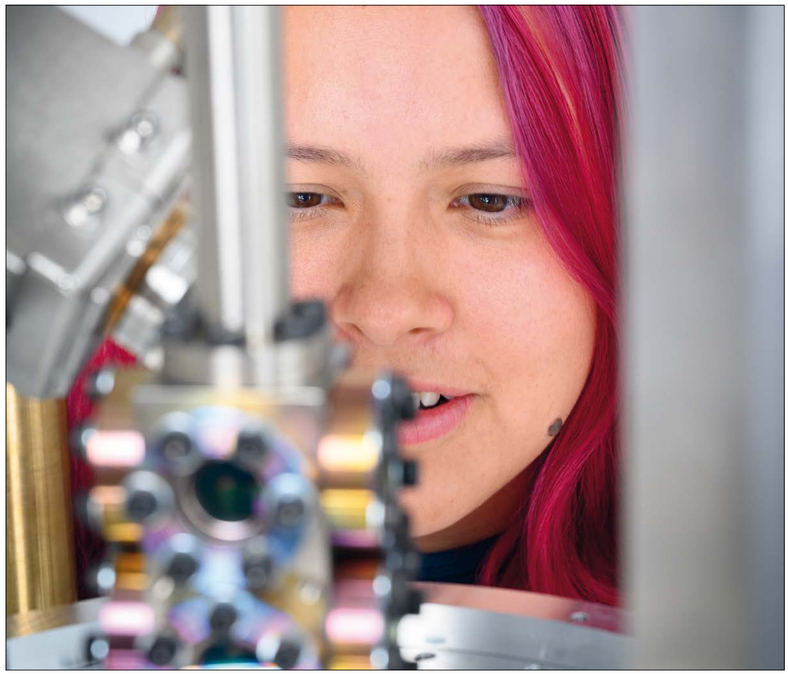
Cold-atom quantum experiments tend to be large and power hungry, so by reducing size, weight and power consumption, these technologies can transition to applications outside of the lab.

These systems operate under ultrahigh vacuum (UHV) conditions, but conventional UHV chambers are made of heavy, bulky materials such as stainless steel, titanium and glass. The miniaturization of these chambers is an important, necessary step to achieving portability, but a challenge.

Typically, UHV is maintained using an ion pump, which consumes energy and must run continuously throughout the lifetime of the cold-atom system. Ion pumps rely on strong magnetic fields, making them inconvenient for the quantum sensing of very weak magnetic fields – which is an important application.

Another huge factor is that creating and operating a conventional UHV system requires people with highly-specialized and scarce skills – there was no "UHV chamber building" module at my university! Moreover, these UHV chambers are typically custom-made one at a time, relying heavily on a number of complex build processes (where skills are also scarce). Construction can take hundreds of hours of preparation, increasing the cost per chamber.

Together, these challenges make it very difficult to create compact cold-atom quantum technologies, which can be operated outside of the laboratory. That is the challenge we face today.



Aquark

Florence Concepcion The Aquark physicist is miniaturizing UHV systems.

How will you use your Innovate UK Future Leaders Fellowship to overcome these challenges?

My goal is to create smaller, more robust and less expensive UHV chambers for Aquark's cold-atom systems. At the heart of this, my goal is the use of passive vacuum pumping, whereby a conventional ion pump is used to first evacuate a small, portable chamber. The chamber is then sealed and UHV is maintained passively using non-evaporable getters. These are "sticky" materials that are deposited on the inside surfaces of the chamber and absorb gas molecules. These coatings also reduce outgassing of molecules from the chamber material itself, furthering UHV lifetime.

As well as studying getters, I am also looking at how helium gas permeates into the chambers. The problem is that helium travels easily through many materials and will eventually destroy UHV – so by finding ways to reduce permeation we can improve the lifetime of our sensors.

And, of course, designing our chambers to minimize leaks is crucial. This involves the careful consideration of what materials we use to build our chambers and how the chambers are sealed. If you use the wrong materials, In this world-first trial, our cold-atom-based atomic clock functioned continuously for the entire duration of the voyage

you will never achieve the required vacuum, regardless of what else you do!

Importantly, I want to be able to create multiple UHV chambers at the same time, using microfabrication techniques. This will require less time and highly-specialized effort per chamber and therefore enable cheaper UHV chambers and lead to the commercialization of quantum sensors.

I will be considering all of these factors over the next few years in the design and development of manufacturable, miniaturized chambers that maintain UHV on timescales of several years.

Aquark has already taken quantum devices out of the lab using conventional UHV systems. Can you talk about some of those outings?

In 2025, the company partnered with the UK's Royal Navy to test our cold-atom-based atomic clock, AQlock, on board the vessel *HMS Pursuer*. In this world-first trial, our atomic clock functioned continuously for the entire duration of the voyage as the ship plied the waters of the Solent on the south coast of England – not far from our headquarters in Southampton.

The Navy is interested in precision timing because it is crucial for reliable navigation, the synchronization of systems, and communications. Today, the most accurate time signals are supplied by global navigation satellite systems (GNSSs) such as GPS. These signals are vulnerable and can be easily jammed or spoofed. And systems could even fail during intense solar storms. So, naval vessels benefit from having the best possible timekeepers onboard.

In 2025 Aquark also tested a cold-atom quantum technology on a rather famous vessel called Boaty McBoatface.

Yes, Boaty McBoatface is an autonomous underwater vehicle designed for seabed exploration. It operates at the UK's National Oceanography Centre (NOC) – which is here in Southampton. Our trial happened in one of their testing tanks.

Aquark is a member of NATO's Defence Innovation Accelerator for the North Atlantic (DIANA), which funds research into emerging and disruptive technologies. On Boaty McBoatface we successfully operated our Super-Molasses Trap (SMT), which holds and cools about one million rubidium atoms to near absolute zero temperature in UHV. The SMT can make very precise measurements of Earth's local gravity as well as detecting accelerations. DIANA is interested in how the sensing of gravity and other accelerations can be used for navigation when GNSS is vulnerable to jamming or in some cases, not available – such as in the polar regions and deep underwater.

Hamish Johnston is an online editor of *Physics World*

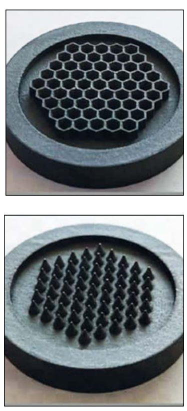
Research updates: Vacuum

Pockets and pillars capture molecules in vacuum pump

A passive vacuum pump that uses 3D-printed surfaces to better absorb gas molecules has been unveiled by researchers in the UK. It removes gas nearly four-times faster than a similar system with a flat surface. The pump could make it easier to design quantum sensors that require high-vacuum conditions (*Phys. Rev. Appl.* **25** 014047).

Cold atoms are at the heart of many quantum-sensing technologies. For example, atom interferometry is used to measure tiny deviations in local gravity – which can be used to map underground infrastructure.

Cold-atom systems must operate at high vacuum and most vacuum pumps are mechanical or electrical in nature. The size of these active pumps and the energy that they consume makes it difficult to operate sensors in remote or mobile scenarios. As a result, researchers who are designing quantum sensors are keen on reducing or even eliminating their reliance on active pumps.



Better getters These two 3D surfaces are much better than a flat surface when it comes to passive pumping.

One solution is the use of passive pumps, which have surfaces made from materials that absorb large numbers of gas molecules. Now, Lucia Hackermueller and colleagues at the University of Nottingham, Torr Scientific and Metamorphic Additive Manufacturing have created two new textured surfaces that accelerate passive pumping.

One of their surfaces is a hexagonal array of tapered pockets that resembles a honeycomb. The other surface is a hexagonal array of conical protrusions. They chose their designs after doing Monte Carlo computer simulations of how gas molecules behave near textured surfaces. When a molecule collides with a flat surface it will either be absorbed or bounce off the surface and escape. However, if the surface has 3D structures on it, a molecule may ricochet back and forth several times between structures before it escapes. Each collision increases the chance that the molecule will be absorbed by the surface. So, the researchers sought to optimize the number of bounces in their simulations.

They then used the 3D printing of a titanium alloy to create the two promising designs on hockey-puck sized flanges that could be installed in a conventional high-vacuum system. The final step in the fabrication process was to coat the surfaces with a nonevaporable getter, which is a material designed specifically to absorb gas molecules in a vacuum system.

The team found that their hexagonal-pocket design pumped gas 3.8 times faster than a flat surface – and the hexagonal-protrusion design achieved a performance that is nearly as good.

Team member Ben Hopton at the University of Nottingham says, "What's exciting about this work is that relatively simple surface engineering can have a surprisingly large effect.

Hamish Johnston

Adaptive optics technology boosts gravitational wave detectors

Future versions of the Laser Interferometer Gravitational Wave Observatory (LIGO) will be able to run at much higher laser powers thanks to a sophisticated new system that compensates for temperature changes in optical components. Known as FROSTI (for FROnt Surface Type Irradiator) and developed by physicists at the University of California Riverside, US, the system will enable next-generation machines to detect gravitational waves emitted when the universe was just 0.1% of its current age, before the first stars had even formed (*Optica* **12** 1569).

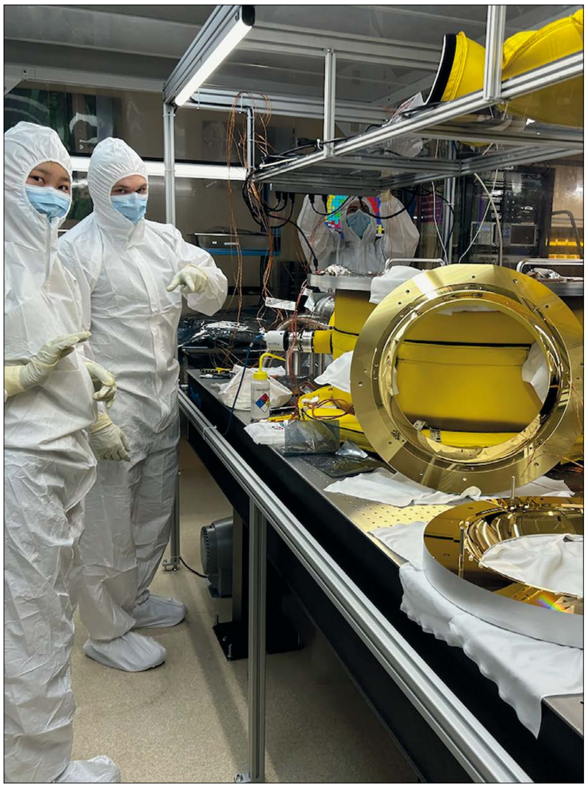
Gravitational waves are distortions in space-time that occur when massive astronomical objects accelerate and collide. When these distortions pass through the four-kilometre-long arms of the two LIGO detectors, they create a tiny difference in the (otherwise identical) distance that light travels between the centre of the observatory and the mirrors located at the end of each arm. The problem is that detecting and studying gravitational waves requires these differences in distance to be measured with an accuracy of 10^{-19} m, which is 1/10 000th the size of a proton.

Extending the frequency range

LIGO overcame this barrier 10 years ago when it detected the gravitational waves produced when two black holes located roughly 1.3 billion light-years from Earth merged. Since then, it and two smaller facilities, KAGRA and VIRGO, have observed many other gravitational waves at frequencies ranging from 30–2000 Hz.

Observing waves at lower and higher frequencies in the gravitational wave spectrum remains challenging, however. At lower frequencies (around 10–30 Hz), the problem stems from vibrational noise in the mirrors. Although these mirrors are hefty objects – each one measures 34 cm across, is 20 cm thick and has a mass of around 40 kg – the incredible precision required to detect gravitational waves at these frequencies means that even the minute amount of energy they absorb from the laser beam is enough to knock them out of whack.

At higher frequencies (150–2000 Hz), measurements are instead limited by quantum shot noise. This is caused by the random arrival time of photons at LIGO's output photodetectors and is a fundamental consequence of the fact that the laser field is quantized.


J Richardson

Clean scene
A behind-the-scenes glimpse of the researchers during the assembly and experimental testing of the FROSTI prototype.

A novel adaptive optics device

Jonathan Richardson, the physicist who led this latest study, explains that FROSTI is designed to reduce quantum shot noise by allowing the mirrors to cope with much higher levels of laser power. At its heart is a novel adaptive optics device that is designed to precisely reshape the surfaces of LIGO's main mirrors under laser powers exceeding 1 megawatt (MW), which is nearly five times the power used at LIGO today.

Though its name implies cooling, FROSTI actually uses heat to restore the mirror's surface to its original shape. It does this by projecting infrared radiation onto test masses in the interferometer to create a custom heat pattern that "smooths out" distortions and so allows for fine-tuned, higher-order corrections.

The single most challenging aspect of FROSTI's design, and one that Richardson says shaped its entire concept, is the requirement that it cannot introduce even more noise into the LIGO interferometer. "To meet this stringent requirement, we had to use the most intensity-stable radiation source available – that is, an internal blackbody emitter with a long thermal time constant," he tells *Physics World*. "Our task, from there, was to develop new non-imaging optics capable of reshaping the blackbody thermal radiation into a complex spatial profile, similar to one that could be created with a laser beam."

Richardson anticipates that FROSTI will be a critical component for future LIGO upgrades – upgrades that will themselves serve as blueprints for even more sensitive next-generation observatories like the proposed Cosmic Explorer in the US and the Einstein Telescope in Europe. "The current prototype has been tested on a 40 kg LIGO mirror, but the technology is scalable and will eventually be adapted to the 440 kg mirrors envisioned for Cosmic Explorer," he says.

Jan Harms, a physicist at Italy's Gran Sasso Science Institute who was not involved in this work, describes FROSTI as "an ingenious concept to apply higher-order corrections to the mirror profile." Though it still needs to pass the final test of being integrated into the actual LIGO detectors, Harms notes that "the results from the prototype are very promising".

Richardson and colleagues are continuing to develop extensions to their technology, building on the successful demonstration of their first prototype. "In the future, beyond the next upgrade of LIGO (A+), the FROSTI radiation will need to be shaped into an even more complex spatial profile to enable the highest levels of laser power (1.5 MW) ultimately targeted," explains Richardson. "We believe this can be achieved by nesting two or more FROSTI actuators together in a single composite, with each targeting a different radial zone of the test mass surfaces. This will allow us to generate extremely finely-matched optical wavefront corrections."

Isabelle Dumé

Spectroscopy

Randomly textured lithium niobate boosts snapshot spectrometer

A new integrated "snapshot spectroscopy" system developed in China can determine the spectral and spatial composition of light from an object with much better precision than other existing systems. The instrument uses randomly textured lithium niobate and its developers have used it for astronomical imaging and materials analysis – and they say that other applications are possible (*Nature* **646** 567).

Spectroscopy is crucial to analysis of all kinds of objects in science and engineering, from studying the radiation emitted by stars to identifying potential food contaminants. Conventional spectrometers – such as those used on telescopes – rely on diffractive optics to separate incoming light into its constituent wavelengths. This makes them inherently large, expensive and inefficient at rapid image acquisition as the light from each point source has to be spatially separated to resolve the wavelength components.

In recent years researchers have combined computational methods with advanced optical sensors to create computational spectrometers with the potential to rival conventional instruments. One such approach is hyperspectral snapshot imaging, which captures both spectral and spatial information in the same image. There are currently two main snapshot-imaging techniques available. Narrowband-filtered snapshot spectral imagers comprise a mosaic pattern of narrowband filters and acquire an image by taking repeated snapshots at different wavelengths. However, these trade spectral resolution with spatial resolution, as each extra band requires its own tile within the mosaic. A more complex alternative design – the broadband-modulated snapshot spectral imager – uses a single, broadband detector covered with a spatially varying element such as a metasurface that interacts with the light and imprints spectral encoding information onto each pixel. However, these are complex to manufacture and their spectral resolution is limited to the nanometre scale.

In the new work, researchers led by Lu Fang at Tsinghua University in Beijing unveil a spectroscopy technique that utilizes the nonlinear optical properties of lithium niobate to achieve sub-Ångström spectral resolution in a simply fabricated, integrated snapshot detector they call RAFAEL. A lithium niobate layer with random, sub-wavelength thickness variations is surrounded by distributed Bragg reflectors, forming optical cavities. These are integrated into a stack with a set of electrodes. Each cavity corresponds to a single pixel. Incident light enters from one side of a cavity, interacting with the lithium niobate repeatedly before exiting and being detected. Because lithium niobate is nonlinear, its response varies with the wavelength of the light.


iStock/koey

Spectral resolution Researchers in China have used uneven layers of lithium niobate to create a new type of snapshot spectrometer.

Random signal

The researchers then applied a bias voltage using the electrodes. The nonlinear optical response of lithium niobate means that this bias alters its response to light differently at different wavelengths. Moreover, the random variation of the lithium niobate's thickness around the surface means that the wavelength variation is spatially specific.

The researchers designed a machine learning algorithm and trained it to use this variation of applied bias voltage with resulting wavelength detected at each point to reconstruct the incident wavelengths on the detector at each point in space.

"The randomness is useful for making the equations independent," explains Fang; "We want to have uncorrelated equations so we can solve them."

The researchers showed that they could achieve 88 Hz snapshot spectroscopy on a grid of 2048 × 2048 pixels with a spectral resolution of 0.5 Å (0.05 nm) between wavelengths of 400–1000 nm. They demonstrated this by capturing the full atomic absorption spectra of up to 5600 stars in a single snapshot. This is a two to four orders of magnitude improvement in observational efficiency over world-class astronomical spectrometers. They also demonstrated other applications, including a materials analysis challenge involving the distinction of a real leaf from a fake one. The two looked identical at optical wavelengths, but, using its broader range of wavelengths, RAFAEL was able to distinguish between the two.

The researchers are now attempting to improve the device further: "I still think that sub-Ångström is not the ending – it's just the starting point," says Fu. "We want to push the limit of our resolution to the picometre." In addition, she says, they are working on further integration of the device – which requires no specialized lithography – for easier use in the field. "We've already put this technology on a drone platform," she reveals. The team is also working with astronomical observatories such as Gran Telescopio Canarias in La Palma, Spain.

Computational imaging expert David Brady of Duke University in North Carolina is impressed by the instrument. "It's a compact package with extremely high spectral resolution," he says; "Typically an optical instrument, like a CMOS sensor that's used here, is going to have between 10 000 and 100 000 photo-electrons per pixel. That's way too many photons for getting one measurement…I think you'll see that with spectral imaging as is done here, but also with temporal imaging. People are saying you don't need to go at 30 frames second, you can go at a million frames per second and push closer to the single photon limit, and then that would require you to do computation to figure out what it all means."

Tim Wogan

Laser-driven free electron laser runs for more than eight hours

A laser plasma accelerator (LPA) has been used to power a free electron laser (FEL) for more than eight hours, delivering stable pulses of coherent light. The system was created in the US by researchers at the company Tau Systems and Lawrence Berkeley National Laboratory. The team says that its achievement represents a major breakthrough in stability for LPA-driven FELs, which could someday make coherent UV and X-ray pulses more accessible to academia and industry. The new system is described in *Phys. Rev. Accel. Beams* **29** 041301.

An FEL creates bright pulses of coherent light – usually in the ultraviolet-to-X-ray portion of the electromagnetic spectrum. These pulses are used in a wide range of research including physics, chemistry, biology and materials science.

The pulses are created by sending bunches of high-energy electrons through a device called an undulator, which applies a transverse magnetic field that alternates in direction as the bunch propagates. As the electrons are accelerated back and forth by the field they emit light. Under the right conditions the emitted light interacts with the electron bunch in such a way that the coherence and brightness of the light increases as the electron bunch travels through the undulator.

FELs require a bright and stable source of high-energy electron bunches, so today's facilities are driven by large and expensive electron accelerators. The European X-ray Free Electron Laser, for example, is located at the end of a 3.4 km linear accelerator.

Surfing a plasma wave

High-energy electron bunches can also be created by firing high-intensity laser pulses at a plasma target. Electrons in the plasma are much lighter than the ions, so they are accelerated more by the intense electric field of the laser pulse. The result is a region of separated positive and negative charge that contains a large electric field. This region trails the laser pulse like the wake of a ship – and is called a wakefield. If electrons are injected into this wakefield, they are captured and accelerated to near the speed of light.

Robinson Kuntz/Berkeley Lab

Stabilizing influences
The BELLA Center's Hai-En Tsai (right) and Jeroen van Tilborg make adjustments in the Berkeley Lab Laser Accelerator (BELLA) Berkeley Lab.

The process is similar to how a surfer is propelled by an ocean wave.

While LPA-driven FELs would require expensive lasers, they would be smaller and cheaper than accelerator-driven facilities. Today, however, the electron pulses delivered by LPAs are not good enough to drive a FEL. Some shortcomings are related to fluctuations in the focal point of the laser and well as changes in the pulse energy and duration. These fluctuations can be caused by mechanical vibrations, temperature fluctuations and other environmental disturbances.

Founded in 2021, the Texas-based company Tau Systems is developing practical LPAs for a range of applications including FELs. Now, the company has joined forces with researchers at Berkeley Lab's BELLA Center to implement a set of laser-stabilization technologies on BELLA's Hundred Terawatt Undulator beamline.

The team implemented five active systems that worked together to stabilize the focal point of the powerful laser. Some of this was done using a "ghost" beam – a low-power copy of the driving beam – to observe subtle fluctuations that would not be apparent by monitoring the main beam.

High-quality bunches

As a result the system delivered bunches of 100 MeV electrons at a frequency of 1 Hz and at high stability for over 10 h. These bunches were then used to drive a self-amplified spontaneous emission (SASE) FEL based on a 4 m long undulator that is embedded within a vacuum chamber.

The LPA–FEL delivered violet (420 nm wavelength) pulses for more than 8 h without any human intervention. The FEL gain of the system was about 1000, which is the ratio of brightness of the emitted coherent FEL pulse to the brightness of light emitted by unamplified undulation.

This run is a significant improvement on the team's 2025 achievement of using a LPA–FEL setup to deliver pulses of similar quality for an hour.

"This is the moment the community has been working toward," says Stephen Milton of Tau Systems. "We have shown that an LPA-driven FEL is not just a proof-of-concept experiment. It is a platform capable of delivering the stability that real scientific and industrial users demand."

Finn Kohrell of the BELLA Center adds, "Maintaining FEL stability for a record eight hours represents a significant advancement in LPA-driven FELs and provides deeper insights both into achieving optimal FEL performance and into validating LPAs as high-brightness injectors, which is crucial for LPA application in future light source facilities".

During operation, the team gathered data about the stabilization process and mapped correlations between the parameters of the drive laser; the plasma source; the electron bunches; and the FEL's output pulses. The researchers are now using this information to improve their control systems and they say that these data indicate that further gains in stability and brightness are possible.

The next experimental step will involve increasing the FEL energy to their system's maximum value of 500 MeV.

"At this level, we can lower the undulator radiation wavelength to the 20–30 nm range, placing it in the hard ultraviolet or soft X-ray regime," explains Kohrell. "[This would be] a crucial step toward making the technology viable for real-world applications."
Hamish Johnston

Cavity-based X-ray laser delivers high-quality pulses

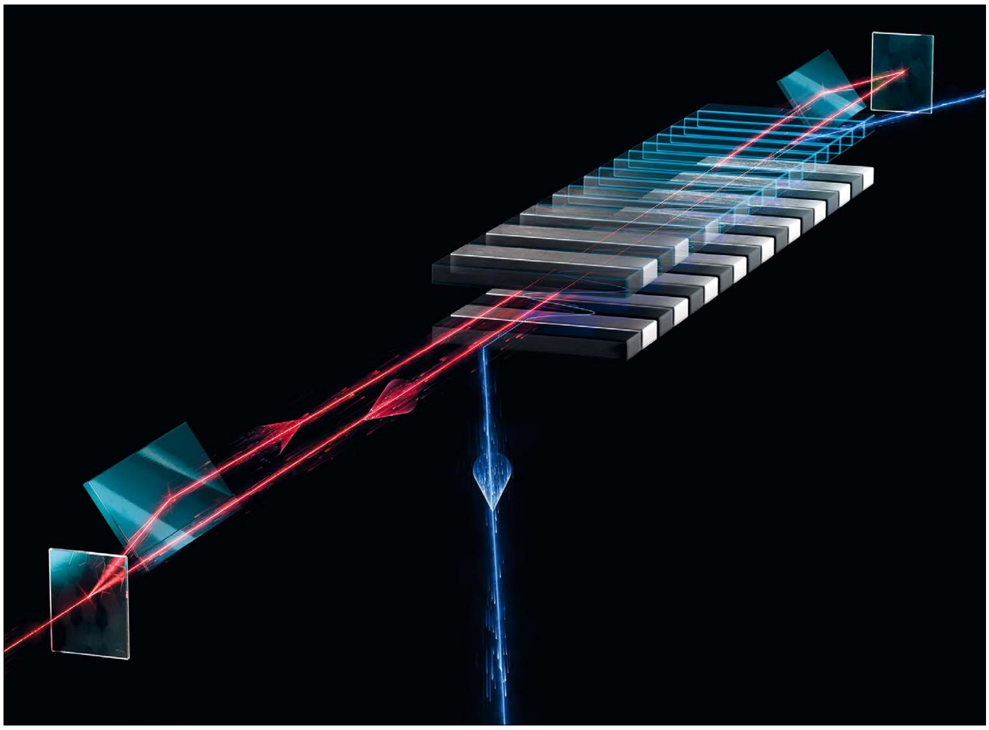
Physicists in Germany have created a new type of X-ray laser that uses a resonator cavity to improve the output of a conventional X-ray free electron laser (XFEL). Their proof-of-concept design delivers X-ray pulses that are more monochromatic and coherent than those from existing XFELs (*Nature* **650** 93).

In recent decades, XFELs have delivered pulses of monochromatic and coherent X-rays for a wide range of science including physics, chemistry, biology and materials science.

Despite their name, XFELs do not work like conventional lasers. In particular, there is no gain medium or resonator cavity. Instead, XFELs rely on the fact that when a free electron is accelerated, it will emit electromagnetic radiation. In an XFEL, pulses of high-energy electrons are sent through an undulator, which deflects the electrons back and forth. These wiggling electrons radiate X-rays at a specific energy. As the X-rays and electrons travel along the undulator, they interact in such a way that the emitted X-ray pulse has a high degree of coherence.

While these XFELs have proven very useful, they do not deliver radiation that is as monochromatic or as coherent as radiation from conventional lasers. One reason why conventional lasers perform better is that the radiation is reflected back and forth many times in a mirrored cavity that is tuned to resonate at a specific frequency – whereas XFEL radiation only makes one pass through an undulator.

Practical X-ray cavities, however, are difficult to create. This is because X-rays penetrate deep into materials, where they are usually absorbed – making reflection with conventional mirrors impossible.



European XFEL

How XFELO works A hard X-ray pulse (red) is reflected by a set of diamond mirrors and oscillates through arrays of silver magnets – undulators. On each roundtrip the pulse meets a new electron bunch (blue), which emits X-rays while passing through the undulators on a slalom course.

Crucial overlap

Now, researchers working at the European XFEL at DESY in Germany have created a proof-of-concept hybrid system that places an undulator within a mirrored resonator cavity. X-ray pulses that are created in the undulator are directed at a downstream mirror and reflected back to a mirror upstream of the undulator. The X-ray pulses are then reflected back downstream through the undulator. Crucially, a returning X-ray pulse overlaps with a subsequent electron pulse in the undulator, amplifying the X-ray pulse. As a result, the X-ray pulses circulating within the cavity quickly become more monochromatic and more coherent than pulses created by an undulator alone.

The team solved the mirror challenge by using diamond crystals that achieve the Bragg reflection of X-rays with a specific frequency. These are used at either end of the cavity in conjunction with Kirkpatrick–Baez mirrors, which help focus the reflected X-rays back into the cavity.

Some of the X-ray radiation circulating in the cavity is allowed to escape downstream, providing a beam of monochromatic and coherent X-ray pulses. They have called their system X-ray Free-Electron Laser Oscillator (XFELO). The cavity is about 66 m long.

Narrow frequency range

DESY accelerator scientist Patrick Rauer explains, "With every round trip, the noise in the X-ray pulse gets less and the concentrated light more defined". Rauer pioneered the design of the cavity in his PhD work and is now the DESY lead on its implementation. "It gets more stable and you start to see this single, clear frequency – this spike." Indeed, the frequency width of XFELO X-ray pulses is about 1% that of pulses that are created by the undulators alone

Ensuring the overlap of electron and X-pulses within the cavity was also a significant challenge. This required a high degree of stability within the accelerator that provides electron pulses to XFELO. "It took years to bring the accelerator to that state, which is now unique in the world of high-repetition-rate accelerators", explains Rauer.

Team member Harald Sinn says, "The successful demonstration shows that the resonator principle is practical to implement". Sinn is head of European XFEL's instrumentation department and he adds, "In comparison with methods used up to now, it delivers X-ray pulses with a very narrow wavelength as well as a much higher stability and coherence."

The team will now work towards improving the stability of XFELO so that in the future it can be used to do experiments by European XFEL's research community.

Hamish Johnston

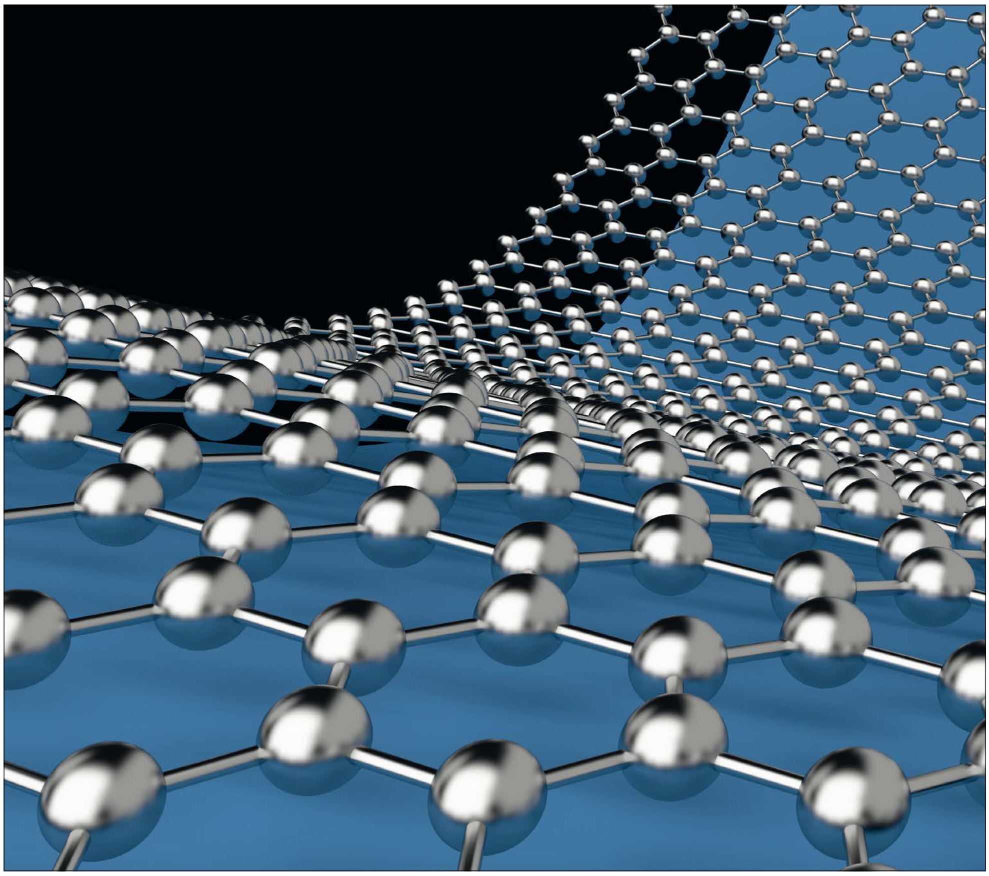
Microscopy

‘Nano-aquariums’ deliver atomic-resolution imaging

Graphene liquid cells have been used to study atoms dissolved in organic solvents at atomic-scale resolution. Through a combination of smarter material choices and machine learning techniques, a team led by Sarah Haigh at the University of Manchester showed how these graphene “nano-aquariums” can work with virtually any type of solvent – offering deeper insights into the atomic-scale properties of solids left behind when solvents dry out (*Science* **392** 77).

To understand the atomic interactions taking place at solid–liquid interfaces, researchers will often start by sandwiching liquid samples between pairs of transparent films. In most cases, they will then use transmission electron microscopy (TEM) to create atomic-scale images of these interactions. This involves irradiating the sample and films with a tightly focused electron beam.

“These windows need to be as thin as possible to get the best resolution,” explains Manchester’s Nick Clark. “Graphene is just about the thinnest window possible, and over the past decade or so it’s enabled atomic-resolution imaging of solid nanoparticles inside liquids.”



Shutterstock/Ambelrip

Graphene film The 2D material has given transmission electron microscopy a boost.

Uncontrollable evaporation

So far, however, these graphene liquid cells have proven difficult to work with. While sealing liquid samples inside these cells, the solution will often evaporate uncontrollably, creating significant variability in the sample’s concentration. In addition, most organic solvents are incompatible with the soft polymer membranes used to support the graphene films during the sealing process, limiting previous studies to mild aqueous solutions.

To address these challenges, Haigh’s team replaced the polymeric supports with stiff ceramic cantilevers. These offer similar levels of mechanical stability while being far more chemically inert. As a result, the cells can be sealed mechanically while fully immersed in liquid. This prevents the sample from drying out during sealing, while also making the process compatible with virtually any solvent.

The resulting graphene cells are remarkably stable, which allows the team to collect large numbers of images via repeated irradiation by the TEM electron beam.

“We combined this with neural-network based denoising to minimize the signal to noise ratio required to extract atomic coordinates, and a fully automated analysis workflow,” Clark adds. “This enabled us to collect enough atomic coordinates to draw representative conclusions.”

Individual gold atoms

With this combination of techniques, the team could resolve individual gold atoms and the graphene lattice beneath them, and examine how the behaviour of gold atoms at the graphene-liquid interface varied with their choice of organic solvent.

With their rapid TEM imaging, they could track over one million gold adatoms – single atoms which adsorb to a solid surface – and account for the dynamic, interconnected behaviours of structures formed from pairs, triplets, and larger clusters of adatoms.

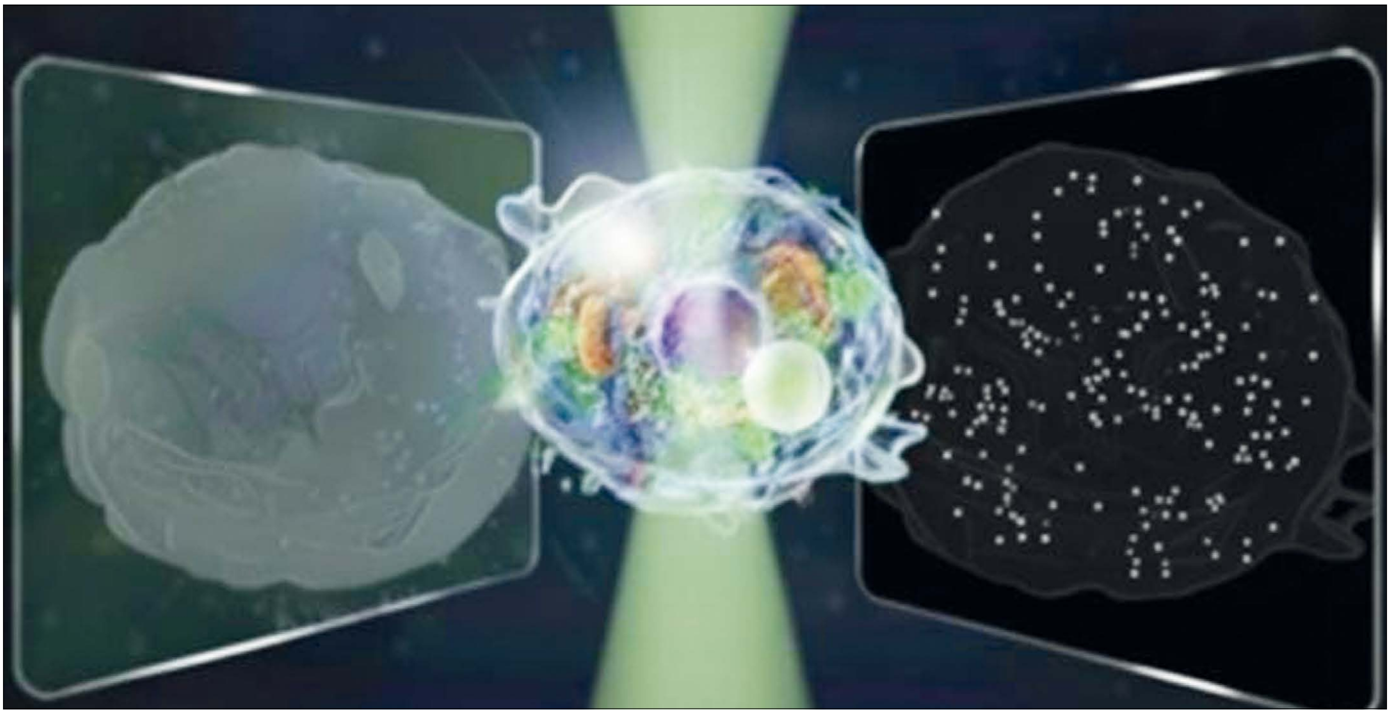
Chemists have long known that these behaviours are strongly connected to the catalytic properties of the solid material left behind when the solvent dries out. For the first time, however, this approach allowed Haigh’s team to explore in detail how these properties depend on the choice of solvent.

“We were able to decouple the actual liquid phase dispersion from the drying process, and showed how both must be controlled to generate isolated atoms on the final dried support – which we know gives the most active catalytic materials,” Clark explains.

Through further improvements to their technique, Haigh, Clark and their colleagues are confident it could drive advances across a range of real-world technologies. “We hope that our new characterization approach will allow us to help those working on catalysis, or batteries, or liquid filtration to understand what’s happening at the solid-liquid interfaces in their devices at atomic scale,” Clark says.

Sam Jarman

Microscope detects micro- and nanoscale structures simultaneously



Horie *et al* 2025

Double up
Conceptual illustration of the bidirectional quantitative scattering microscope, which detects both forward and backward scattered light from cells. This dual detection enables visualization of structures ranging from whole-cell morphology to nanoscale particles.

A new microscope that can simultaneously measure both forward- and backward-scattered light from a sample could allow researchers to image both micro- and nanoscale objects at the same time. The device could be used to observe structures as small as individual proteins, as well as the environment in which they move, say the researchers at the University of Tokyo who developed it (*Nature Communications* **16** 9712).

"Our technique could help us link cell structures with the motion of tiny particles inside and outside cells," explains Kohki Horie of the University of Tokyo's department of physics, who led this research effort. "Because it is label-free, it is gentler on cells and better for long observations. In the future, it could help quantify cell states, holding potential for drug testing and quality checks in the biotechnology and pharmaceutical industries."

Powerful combination

The new device combines two powerful imaging techniques routinely employed in biomedical applications: quantitative phase microscopy (QPM) and interferometric scattering (iSCAT).

QPM measures forward-scattered (FS) light – that is, light waves that travel in the same direction as before they were scattered. This technique is excellent at imaging structures in the Mie scattering region (larger than 100 nm, referred to as microscale in this study). This makes it ideal for visualizing complex structures such as biological cells. It falls short, however, when it comes to imaging structures in the Rayleigh scattering region (smaller than 100 nm, referred to as nanoscale in this study).

The second technique, iSCAT, detects backward-scattered (BS) light. This is light that's reflected back towards the direction from which it came and which predominantly contains Rayleigh scattering. As such, iSCAT exhibits high sensitivity for detecting nanoscale objects. Indeed, the technique has recently been used to image single proteins, intracellular vesicles and viruses. It cannot, however, image microscale structures because of its limited ability to detect in the Mie scattering region.

The team's new bidirectional quantitative scattering microscope (BiQSM) is able to detect both FS and BS light at the same time, thereby overcoming these previous limitations.

Separating the signals

The BiQSM system illuminates a sample through an objective lens from two opposite directions and detects both the FS and BS light using a single image sensor. The researchers use the spatial-frequency multiplexing method of off-axis digital holography to capture both images simultaneously. The biggest challenge, says Horie, was to cleanly separate the signals from FS and BS light in the images while keeping noise low and avoiding mixing between them.

Horie and colleagues, Keiichiro Toda, Takuma Nakamura and team leader Takuro Ideguchi, tested their technique by imaging live cells. They were able to visualize micron-sized cell structures, including the nucleus, nucleoli and lipid droplets, as well as nanoscale particles. They compared the FS and BS results using the scattering-field amplitude (SA), defined as the amplitude ratios between the scattered wave and the incident illumination wave. "SA characterizes the light scattered in both the forward and backward directions within a unified framework," says Horie, "so allowing for a direct comparison between FS and BS light images."

Spurred on by their findings the researchers say they now plan to study even smaller particles such as exosomes and viruses.

Isabelle Dumé

Acoustics

Physicists overcome 'acoustic collapse' to levitate objects with sound

Sound waves can make small objects hover in the air, but applying this acoustic levitation technique to an array of objects is difficult because the objects tend to clump together. Physicists at the Institute of Science and Technology Austria (ISTA) have now overcome this problem thanks to hybrid structures that emerge from the interplay between attractive acoustic forces and repulsive electrostatic ones (*PNAS* **122** e2516865122). By proving that it is possible to levitate many particles while keeping them separated, the finding could pave the way for advances in acoustic-levitation-assisted 3D printing, mid-air chemical synthesis and micro-robotics.

In acoustic levitation, particles ranging in size from tens of microns to millimetres are drawn up into the air and confined by an acoustic force. The origins of this force lie in the momentum that the applied acoustic field transfers to a particle as sound waves scatter off its surface. While the technique works well for single particles, multiple particles tend to aggregate into a single dense object in mid-air because the acoustic forces they scatter can, collectively, create an attractive interaction between them.


ISTA

No more clumping Sue Shi and Scott Waitukaitis in their lab at ISTA, where they developed a way to overcome "acoustic collapse" – a fundamental limitation of acoustic levitation – by adding electric charge to the levitated objects.

Keeping particles separated

Led by Scott Waitukaitis, the ISTA researchers found a way to avoid this so-called "acoustic collapse" by using a tuneable repulsive electrostatic force to counteract the attractive acoustic one. They began by levitating a single silver-coated poly(methyl methacrylate) (PMMA) microsphere 250–300 μm in diameter above a reflector plate coated with a transparent and conductive layer of indium tin oxide (ITO). They then imbued the particle with a precisely controlled amount of electrical charge by letting it rest on the ITO plate with the acoustic field off, but with a high-voltage DC potential applied between the plate and a transducer. This produces a capacitive build-up of charge on the particle, and the amount of charge can be estimated from Maxwell's solutions for two contacting conductive spheres (assuming, in the calculations, that the lower plate acts like a sphere with infinite radius).

The next step in the process is to switch on the acoustic field and, after just 10 ms, add the electric field to it. During the short period in which both fields are on, and provided the electric field is strong enough, either field is capable of launching the particle towards the centre of the levitation setup. The electric fields is then switched off. A few seconds later, the particle levitates stably in the trap, with a charge given, in principle, by Maxwell's approximations.

Mesmerizing dance of particles

This charging method works equally well for multiple particles, allowing the researchers to load particles into the trap with high efficiency and virtually any charge they want, limited only by the breakdown voltage of the surrounding air. Indeed, the physicists found they could tune the charge to levitate particles separately or collapse them into a single, dense object. They could even create hybrid states that mix separated and collapsed particles.

And that wasn't all. According to team member Sue Shi, a PhD student at ISTA and the lead author of the research, the most exciting moment came when they saw the compact parts of the hybrid structures spontaneously begin to rotate, while the expanded parts remained in one place while oscillating in response to the rotation. The result was "a visually mesmerizing dance," Shi says, adding that "this is the first time that such acoustically and electrostatically coupled interactions have been observed in an acoustically levitated system."

As well as having applications in areas such as materials science and micro-robotics, Shi says the technique developed in this work could be used to study non-reciprocal effects that lead to the particles rotating or oscillating. "This would pave the way for understanding more elusive and complex non-reciprocal forces and many-body interactions that likely influence the behaviours of our system," Shi tells *Physics World*.

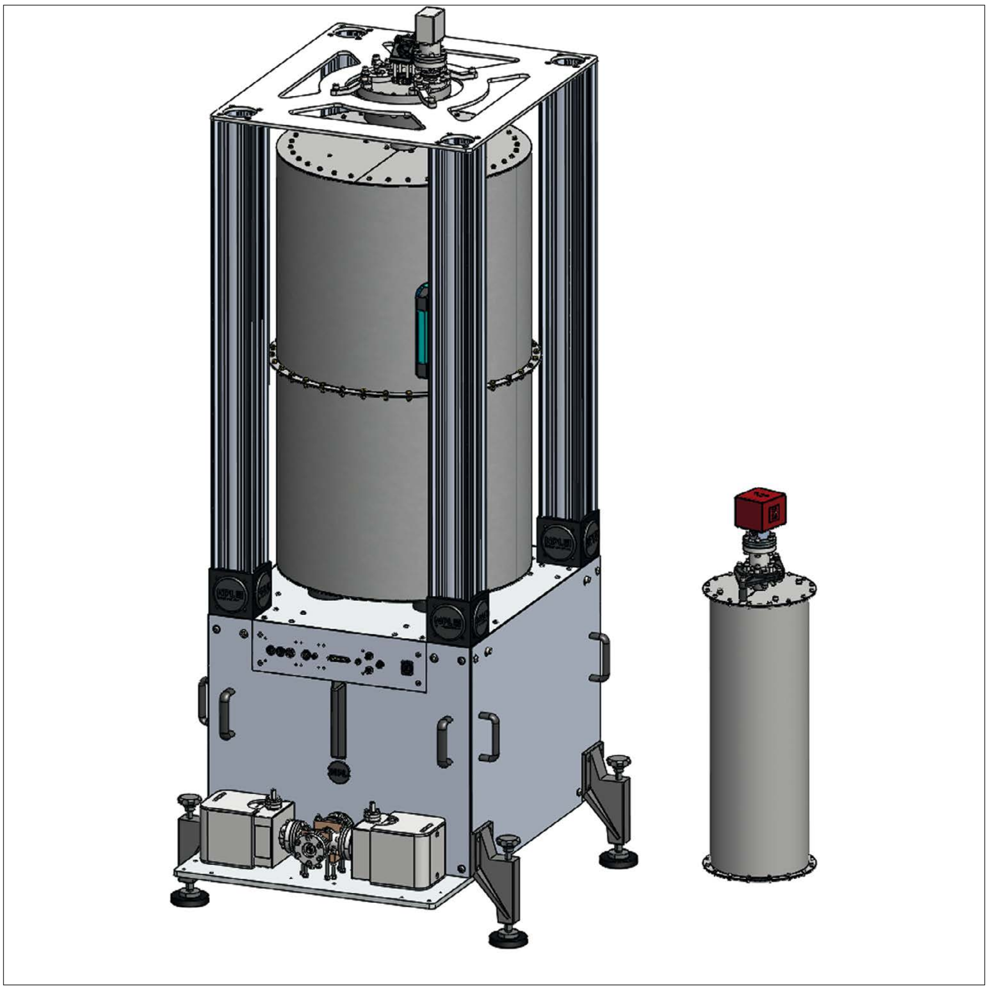
Isabelle Dumé

NPL unveils miniature atomic fountain clock

A miniature version of an atomic fountain clock has been unveiled by researchers at the UK's National Physical Laboratory (NPL). Their timekeeper occupies just 5% of the volume of a conventional atomic fountain clock while delivering a time signal with a stability that is on par with a full-sized system (*Applied Physics Letters* **128** 014002) . The team is now honing its design to create compact fountain clocks that could be used in portable systems and remote locations.

The ticking of an atomic clock is defined by the frequency of the electromagnetic radiation that is absorbed and emitted by a specific transition between atomic energy levels. Today, the second is defined using a transition in caesium atoms that involves microwave radiation. Caesium atoms are placed in a microwave cavity and a measurement-and-feedback mechanism is used to tune the frequency of the cavity radiation to the atomic transition – creating a source of microwaves with a very narrow frequency range centred at the clock frequency.

The first atomic clocks sent a fast-moving beam of atoms through a microwave cavity. The precision of such a beam clock is limited by the relatively short time that individual atoms spend in the cavity. Also, the speed of the atoms means that the measured frequency peak is shifted and broadened by the Doppler effect.



NPL

Smaller version Illustration of a conventional atomic fountain clock (left) next to NPL's miniature atomic fountain clock.

Launching atoms

These problems were addressed by the development of the fountain clock, in which the atoms are cooled (slowed down) by laser light, which also launches the atoms upwards. The atoms pass through a microwave cavity on the way up, and again as they fall back down. The atoms travel at much slower speeds than in a beam clock. The atoms spend much more time in the cavity and therefore the time signal from an atomic clock is much more precise than a beam clock. However, long times result in greater thermal spread of the atomic beam – which degrades clock performance. Trading-off measurement time with thermal spread means that the caesium fountain clocks that currently define the second have drops of about 30 cm.

Other components are also needed to operate fountain clocks – including a vacuum system and laser and microwave instrumentation. This pushes the height of a typical clock to about 2 m, and makes it a complex and expensive instrument that cannot be easily transported.

Now, Sam Walby and colleagues at NPL have shrunk the overall height of a rubidium-based fountain clock to 80 cm, while retaining the 30 cm drop. The result is an instrument that is 5% the volume of one of NPL's conventional caesium atomic fountain clocks. "That's taking it from barely being able to fit though a doorway, to something one could pick up and carry with one arm," says Walby.

Despite the miniaturization, the mini-fountain achieved a stability of one part in 10^{15} after several days of operation – which NPL says is comparable to full-sized clocks.

Walby tells *Physics World* that the NPL team achieved miniaturization by eliminating two conventional components from their clock design. One is a dedicated chamber used to measure the quantum states of the atoms. Instead, this measurement is make within the clock's cooling chamber. Also eliminated is a dedicated state-selection microwave cavity, which puts the atoms into the quantum state from which the clock transition occurs.

"The mini-fountain also does this [state] selection," explains Walby, "but instead of using a dedicated cavity, we use a coax-to-waveguide adapter that is directed into the cooling chamber, which creates a travelling wave of microwaves at the correct frequency."

The NPL team also reduced the amount of magnetic shielding used, which meant that the edge-effects of the magnetic field had to be more carefully considered. The optics system of the clock was greatly simplified and the use of commercial components mean that the clock is low maintenance and easy to operate – according to NPL.

Radical simplification

"By radically simplifying and shrinking the atomic fountain, we're making ultra-precise timing technology available beyond national labs," says Walby. "This opens new possibilities for resilient infrastructure and next-generation navigation."

According to Walby, one potential use of a miniature atomic fountain clock is as a holdover clock. These are devices that produce a very stable time signal when not synchronized with other atomic clocks. This is important for creating resilience in infrastructure that relies on precision timing – such as communications networks, global navigation satellite systems (GNSSs) and power grids. Synchronization is usually done using GNSS signals but these can be jammed or spoofed to disrupt timing systems.

Holdover clocks require time errors of just a few nanoseconds over a month, which the new NPL clock can deliver. The miniature atomic clock could also be used as a secondary frequency standard for the SI second.

The small size of the clock also lends itself to portable and even mobile applications, according to Walby: "The adaptation of the mini-fountain technology to mobile platforms will be subject of further developments".

However, the mini-clock is large when compared to more compact or chip-based clocks – which do not perform as well. Therefore, he believes that the technology is more likely to be implemented on ships or ground vehicles than aircraft. "At a minimum, it should be easily transportable compared to the current solutions of similar performance," he says.

"Highly innovative"

Atomic-clock expert Elizabeth Donley tells *Physics World*, "NPL has been highly innovative in recent years in standardizing fountain clock designs and even supplying caesium fountains to other national standards labs and organizations around the world for timekeeping purposes. This new compact rubidium fountain is a continuation of this work and can provide a smaller frequency standard with comparable performance to the larger fountains based on caesium."

Donley spent more than two decades developing atomic clocks at the US National Institute of Standards and Technology (NIST) and now works as a consultant in the field. She agrees that miniature fountain clocks would be useful for holding-over timing information when time signals are interrupted.

She adds, "Once the international community decides to redefine the second to be based on an optical transition, it won't matter if you use rubidium or caesium. So I see this work as more of a practical achievement than a ground-breaking one. Practical achievements are what drives progress most of the time."

Hamish Johnston

The SI: quirky by nature

iStock/dk photos

The International System of Units is the foundation of metrology, ensuring that all units across science are consistent. But in among the strict modern definitions based on universal constants, there are some unusual quirks, as **Ben Stein** explains

Ben Stein is the managing editor at the communications office of the US National Institute of Standards and Technology (NIST). This feature is an expanded version of a post that originally appeared on NIST's *Taking Measure* blog (www.nist.gov/blogs/taking-measure).

Even though it is the bedrock of modern measurements, the International System of Units (SI) is not set in stone. As science advances, the SI's stewards are committed to changing the system for the better, replacing definitions based on objects to ones reliant on unchanging universal constants of nature.

The most famous recent example came in 2019, when the kilogram was redefined in terms of the Planck constant, replacing the standard platinum-iridium mass stored for more than 100 years at the Bureau International des Poids et Mesures (BIPM) in France. The next base unit of measurement likely to be redefined is the second, with modern atomic (and potentially nuclear) clocks offering more precision than those based on the stalwart caesium atom, which has defined the unit of time since 1967.

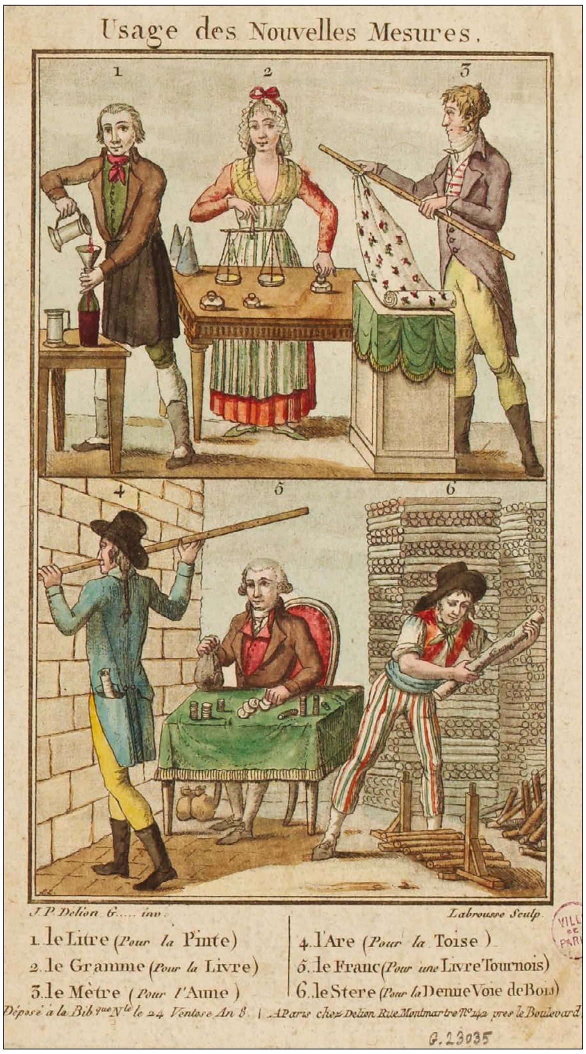
But as the SI continues to evolve, it has also retained its share of quirks, some that arose from the practical limitations of technology and others due to our human biology.

Not just a gram

Today's SI has seven fundamental base units of measurement (see box on p21), including metres for length, amperes for electric current and kelvins for thermodynamic temperature. So why is the base unit of mass not one gram (g) but a thousand grams (kg)?

The reason is quite simple: it was once hard to make objects that are exactly one gram. Kilograms – which are roughly two bags of flour – were much easier to make accurately and more useful in day-to-day trade.

In 1795 the French revolutionary government, working off the country's Commission on Weights and Measures, formally defined the gram as the mass of a one centime-



Revolutionary system *Usage des Nouvelles Mesures* (1800) by L Labrousse illustrates the 1795 decree of the French revolutionary government that a decimal measurement system would replace old measures.

tre cube of water at 4 °C. But that's about the size of five green peas and the weight of five raisins – it doesn't make for a very practical definition for commerce.

So they simultaneously commissioned the making of a standard that was 1000 times heavier. Following years of careful calculations by a scientific committee, a metallurgist named Étienne Lenoir crafted a solid platinum cylinder in 1799 that represented the original prototype kilogram. By 1875 the kilogram took hold internationally when 17 countries signed the Metre Convention – an international treaty establishing agreed-upon references for length and mass. The UK signed on in 1884, and nowadays there are 65 member states and 35 associate states and economies.

In 1889 "Le Grand K" – a new platinum and iridium prototype for the kilogram – was declared the official definition of the unit. Stored in an underground vault at BIPM, it served as the international standard of mass until as recently as 2019.

The new definition for the kilogram relies on a fixed Planck constant h. To measure this value as precisely as possible, metrologists used two techniques: X-ray crystal density (XRCD, also known as the Avogadro experiment), and the Kibble balance. The latter uses electromagnetic forces provided by a coil of wire immersed in a magnetic field to balance a mass. The equipment let metrologists obtain accurate values of current and voltage, from which the Planck constant could be derived. But as of 20 May 2019, when the constant was set in stone and the kilogram was redefined, the Kibble balance could be used to measure mass with high precision instead.

The base seven: how we measure our world

There are seven base units in the International System of Units (SI). Over the centuries since they were adopted globally, each has evolved from their original definition so they can be applied and measured more consistently and accurately. In 2019 the latest definitions of these units took effect. Not only are all seven base units defined by fundamental constants like the Planck constant, but the values of these constants are locked as exact numbers based on the best scientific measurements available at the time.

Unit for time: second
The second (s) was once simply reliant on the length of a day, but is currently defined by the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, $\Delta\nu_{Cs}$. In 2019 the frequency was fixed as an exact unchanging value. It is likely that the definition will be refined further using atomic or nuclear clocks.

Unit for length: metre
Historically, the metre (m) was 1/10 000 000 of the distance from Earth's equator to the North Pole. Today, it is the distance that light travels through a vacuum in 1/299 792 458 seconds, where the denominator is the exact value of the speed of light in vacuum, *c*.

Unit for mass: kilogram
The kilogram (kg) used to be defined by the mass of a platinum-iridium cylinder called the International Prototype Kilogram, or Le Grand K. It is now defined in terms of the Planck constant, *h*.

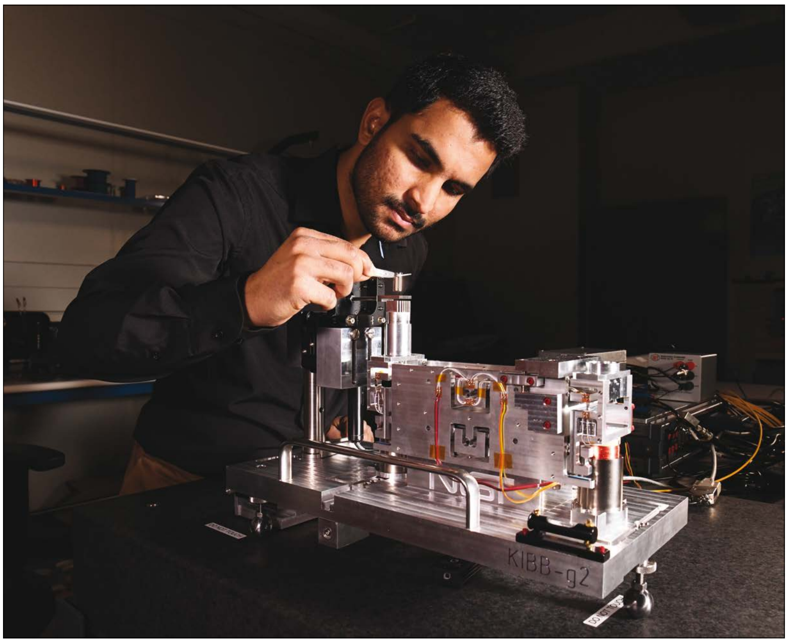
Unit for electric current: ampere
The ampere (A) was once defined by an imaginary and impossible experiment involving the force between two infinite parallel, current-carrying wires. It is now defined in terms of the elementary charge, *e*.

Unit for amount of substance: mole
The mole (mol) used to be defined by the number of atoms in 0.012 kg of carbon-12. To avoid it depending on the mass of a sample, it is now defined in terms of a specific number of atoms or molecules, the Avogadro constant, N_A.

Unit for thermodynamic temperature: kelvin
Previously, the kelvin (K) was defined by the thermodynamic triple point of water, but it is now tied to an exact value of the Boltzmann constant, k, which relates thermodynamic temperature to energy.

Unit for luminous intensity: candela
The candela (cd) was simply based on the light emitted by a burning candle. The current definition is reliant on a fixed numerical value for the luminous efficacy of monochromatic radiation of frequency 540 × 10^{12} Hz, K_{cd}.

J Lee/NIST



Kilogram Until 2019 the kilogram was defined by a platinum-iridium mass stored in France. The new definition of the kilogram is based on the Planck constant, and is reproduced using tabletop Kibble balances – such as this one being examined by NIST engineer Kumar Arumugam.

NIST

Candela In the 1990s NIST used this silicon diode photodetector, which included a filter that spectrally matched the accepted human visual response, to realize the candela. This was the first use of a detector device to realize the candela for the US.

While the kilogram is still the official international unit of mass, researchers are using tabletop Kibble balances and other instruments to directly measure the gram in terms of the Planck constant. Improving our ability to measure the gram is useful for pharmaceutical manufacturers, who want to dispense drug doses accurately, and for the military and companies that need to make precision parts for electronics, aerospace and other critical applications.

But there is one place where the gram has long been a shining star: the classroom. As my NIST colleague Elizabeth Benham points out, educational companies make one-gram cubes that are one centimetre on each side, and one millilitre in volume. These "centimetre cubes" excel at showing the relationships between mass, length and volume. Students can build 10 by 10 layers (1000 cubes) to create a "supercube" that is a kilogram in mass and a litre in volume. So if you're sad about the gram not being a base unit, you can take solace in the fact that for school students, it is the mass measurement unit of choice.

The most human unit

In today's SI, the base units are defined by fundamental constants of nature, such as the Planck constant and the charge of the electron. As best as we can tell, these constants appear to be the same everywhere in the universe, so extraterrestrials would measure the same values for these constants as we do.

But there is one base unit that is very specific to humans: the candela, which means "candle" in Latin, Spanish and Italian. It stems from the UK parliament introducing a unit known as "candlepower" in 1860 so the country could achieve uniform street lighting. Initially, scientists defined the unit in terms of a single candle made from whale fat, with a bit of beeswax to improve the burn. Inevitably, this standard was abandoned because no two objects are exactly alike: one candle shines light at a slightly different rate than another.

By the middle of the 20th century, scientists tried to define the unit in terms of a more universal property – namely, blackbody radiation, the electromagnetic energy from an object that is a perfect absorber and emitter. In 1946 the International Committee for Weights and Measures in France proposed a "new candle" based on the intensity of radiation from platinum at its freezing point (2041.4 K). In 1948 the General Conference on Weights and Measures (CGPM) ratified this standard and named it the "candela". The new definition also specified that the candela was a measure of intensity as perceived by the human visual system.

This is a very practical addition because researchers can actually quantify human visual perception. In the early 20th century, scientists carefully measured how sensitive the eye is to visible light and established a "photopic curve" – average levels of human sensitivity to different colours. To cite a contemporary example, green laser pointers appear brighter to us than red laser pointers with the same power as a result of our human biology.

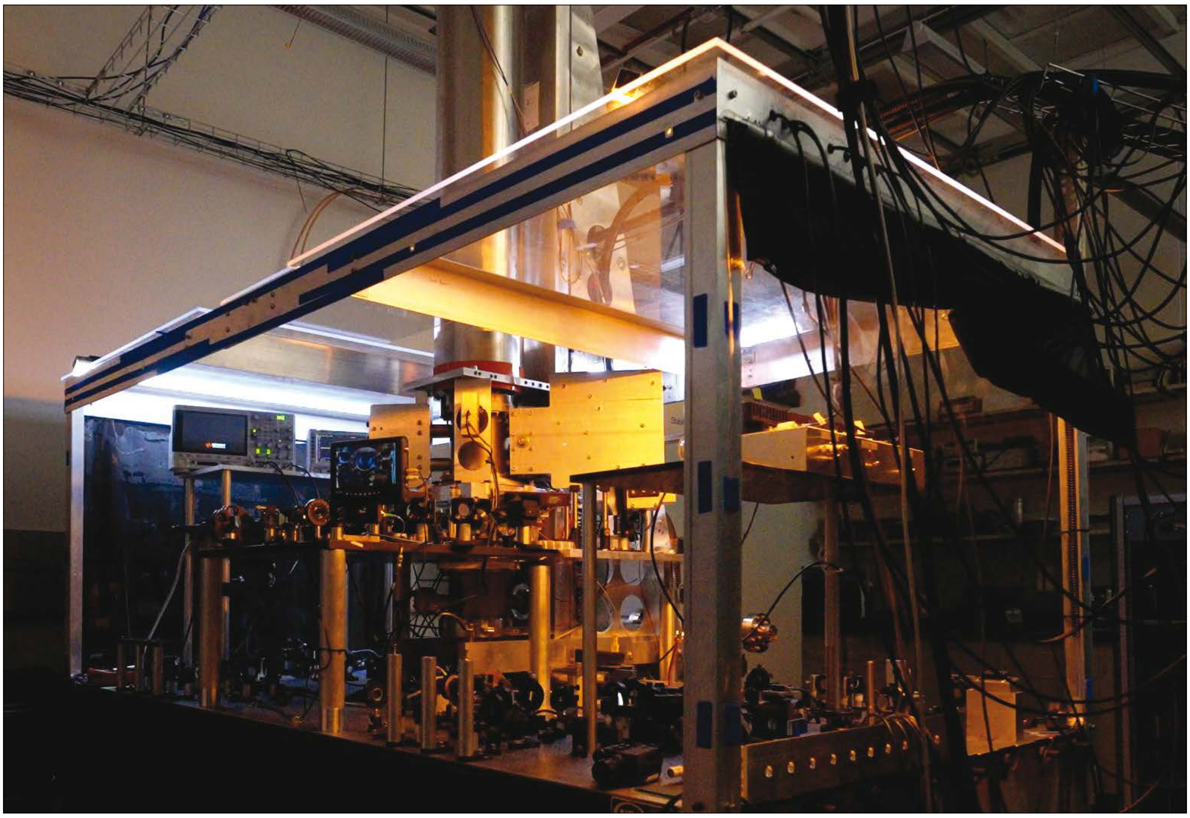
In 1979 the CGPM eliminated blackbodies from the definition. Even this fundamental concept was problematic, since no object can be a perfect blackbody. Instead, the group defined the candela directly in terms of a single colour of visible light, with a frequency of 540×10^{12} Hz.

This reference colour is a shade of yellow-green to which the human eye is most sensitive in a well-lit room, and from it, scientists use the photopic curve to determine the luminous intensity of other colours. Scientists think our eyes adapted to this chartreuse hue because it lines up with the peak spectral irradiance of sunlight that strikes the Earth's surface. Early humans' sensitivity to this colour could have helped them spot different types of vegetation when foraging, with yellow-green leaves indicating younger, more calorie-dense food, while greener leaves signify that a plant's nutrients have moved to other places such as the roots and stems.

In 2019 the candela was officially redefined yet again. It is now expressed by fixing the luminous efficacy of 540×10^{12} Hz light as a constant of 683 lumens per watt – a sort of conversion factor between the physical intensity of visible light and human perception of its intensity.

If extraterrestrials have plant-like food, they might be more sensitive to another colour in the spectrum based on the star (or stars) that shines over their home planets. For example, at least one scientist has speculated that plants in a red-dwarf star system might look black to us

R Eskalis/NIST



Second
NIST-F4, NIST's current primary frequency standard, is one of fewer than 20 caesium fountain clocks worldwide that provide the ultimate foundation for universal time.

because they might need to absorb as much light as possible from this cooler star. But a native creature may have evolved to see lower-frequency light, which would make the plant appear intensely infrared to them. If we ever make contact, measurement scientists from our planet will likely be very interested in knowing how aliens might define their own candela.

Time's unusual unit

As all physicists know, the SI centres on the number 10, whether measuring molecules at nanometre (nm or 10^{-9} m) scales or a nuclear power plant with a gigawatt (GW or 10^{9} W) of power.

Whereas older measurement systems often had complicated conversions involving different units – such as 16 ounces in a pound and 14 pounds in a stone – the metric system sticks with the same unit and helpfully adds prefixes to indicate quantities on the mindbogglingly wide scale of 10^{-30} to 10^{30}. In fact, the expansion of the prefixes from 48 to 60 orders of magnitude is another recent SI improvement (made in 2022) to accommodate the latest needs in computing and other scientific fields. We now have ronna (R) for 10^{27}, quetta (Q) for 10^{30}, ronto (r) for 10^{-27} and quecto (q) for 10^{-30}.

Despite all this, we count time a bit differently. We still express decimal fractions of a second the metric way – we call a thousandth of a second a millisecond, and a billionth of a second is a nanosecond – but on the scale of seconds and minutes, timekeeping becomes a base-60 system. When we reach 60 seconds, it becomes one minute, and then 60 minutes equal one hour, and we call 24 hours a day. Minutes, hours and days are not official SI units, but they are accepted for use within the metric system.

Humans have good reasons to use base-10 system – scientists believe that our affinity for base-10 has to do with the number of fingers we have for counting. However, the origin of our base-60 system is more complicated.

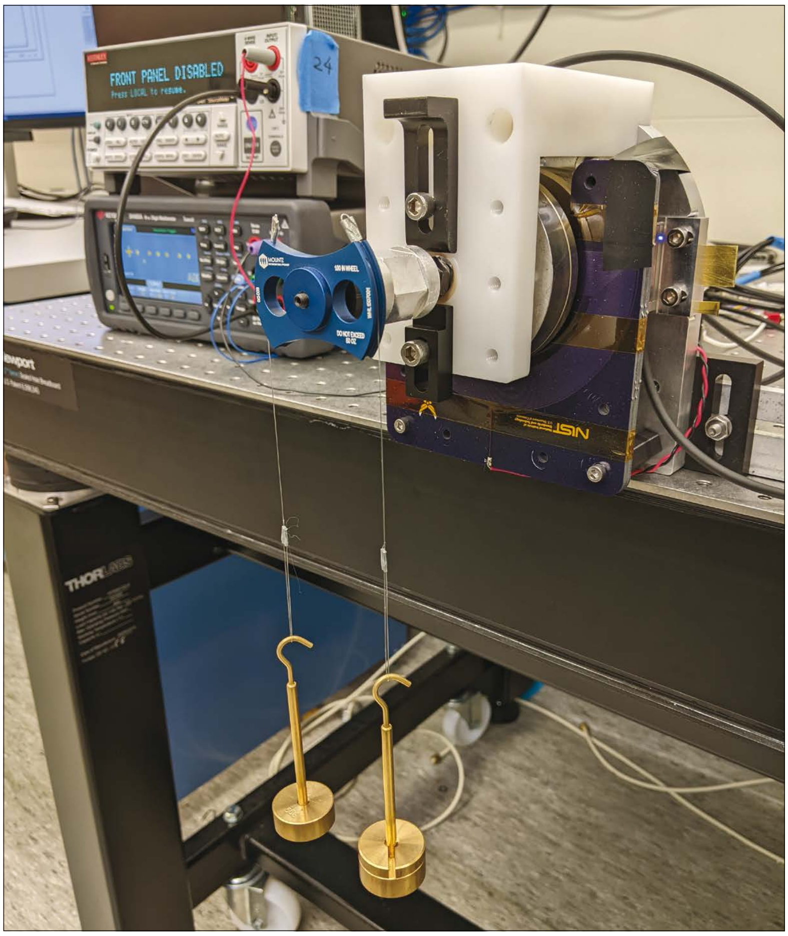
People living in one of the earliest civilizations, the Sumerians, first developed base-60 around 3000 BCE. While the reasons they chose 60 are unknown, scientists speculate that 60 is a convenient number for arithmetic – it is evenly divisible by many numbers, including 1 through 6, 10, 12, 15, 20 and 30. And going back to human fingers, we can count to 60 pretty easily by using our knuckles. Knuckles split each finger (excluding the thumb) into three parts, so four fingers add up to 12 parts. If you use the thumb and fingers of your other hand to count by 12s, the total is 60.

Starting around 2000 BCE, the Babylonians used base-60 for astronomical observations, splitting the sky into that many sectors. In medieval times, the Persian scholar Al-Bīrūnī used this system in his writings to split the hour into 60 minutes, and the minute into 60 seconds. By the time of the Renaissance, clocks and watches began to display this base-60 logic. To this day, even our smart watches continue to use the ancient Babylonian system.

But why didn't minutes and hours get updated into a base-10 system like the other scales? It wasn't for lack of trying. In 1793 the revolutionary French government passed a decimal time system. It split the day into 10 decimal hours, an hour into 100 decimal minutes, and a minute into 100 decimal seconds. The French public swiftly rejected this new system, so the idea was suspended just 17 months later. It was a hassle to use new decimal clocks, let alone try to sync their timekeeping devices to the rest of Europe.

No unit of rotation

The SI is very straight-edged, with the metre as our base unit for length. However, there is no base unit for geometrical angles. In our round world and curved universe, NIST



Radian
The Electronic NIST Torque Realizer (ENTR) being compared against the present standard torque calibration processes to verify performance.

why isn't there a base unit devoted to rotation?

It's more than a philosophical question. An SI without a base unit for angles creates real-world issues. For example, measurements of an object's torque (such as when you twist a screwdriver) have the same units as work (like when lifting a weight straight up from the ground). The units for both are "Newton metres". So if you see a measurement in Newton metres, you may not know if it's a measure of torque or work.

Go back to the French revolution and it turns out we were en route to a very metric definition of angle. The grade, later known as the gradian, was proposed as the angular unit of measurement. A circle would be divided into 400 grads, with 100 grads representing a right angle. On the Earth's surface (very slightly curved from our ant-like vantage point) a hundredth of a grad would represent 1 km of arc length along the Earth's surface.

But the grade eventually became overshadowed by the radian, a concept that was introduced by British mathematician Roger Cotes, a colleague of Isaac Newton. (A similar unit was proposed in the 1400s by Persian mathematician Al-Kashi.) Because its angular measurements were expressed in terms of π, proportional to the actual circumference of a circle, the radian was considered a more mathematically useful unit. Look no further than calculus: with sine and cosine as a function of x in radians (instead of degrees) it's a piece of cake (or pie?) to take derivatives and integrals, without having to worry about ugly conversion factors such as $\pi/180$ when working with degrees. Similarly, approximating trigonometric functions by expanding them into Taylor series is easy when you work in radians.

The SI's more "quirky" features remind us that it is not a perfectly logical or consistent system

While mathematically convenient, the radian can also be metrologically terrifying. The radian, as defined, is a dimensionless unit: the arc length (in metres) divided by the length of the radius (also in metres), cancels out the metres. So it's "just a number" as some might say.

To remedy this, the National Institute of Standards and Technology (NIST)'s Peter Mohr and Bill Phillips (building upon suggestions from others) proposed in 2015 that the radian become a base unit of measurement.

Elevating the radian to a base unit would bake in the idea of a dimension along the arc of a circle. By expressing an angle in terms of radians as a base unit, you'd be specifying not only the amount of the angle but also that the dimension is circular.

This would solve the real-world problem that we mentioned earlier. Torque could now be defined in terms of Newton metres per radian. With this new definition, you'd be able to show torque as the amount of energy per rotation of an object, perhaps a more physically accurate concept than what we had before. And more generally, making the radian a unit would allow the SI to more fundamentally communicate concepts such as rotation and the angle at which an object is oriented.

But a radian base unit also has major problems, creating dimensional headaches of its own. If you were measuring the power of a rotating system, you would need a new dimensional constant (1/radians) to convert "rotational power" into linear power. Another complication is that the widely used "h-bar" in quantum mechanics, $h/2\pi$, would become expressed in units of J·s/radians, which would require changes in quantum mechanics textbooks and software that performs quantum mechanics calculations.

For these and other reasons, an international metrology group exploring this issue decided in 2024 to keep the radian a dimensionless "quantity with the unit one" but also added special notes for the latest version of the official SI brochure. It now says that radians should be "written explicitly where appropriate" to clarify a measurement, an improvement that would finally help to distinguish torque from linear work.

The SI's more "quirky" features remind us that it is not a perfectly logical or consistent system. If we someday communicate with intelligent extraterrestrials, and learn about their measurement systems, will their otherworldly metrology contain as many oddities? While this is an answer we are not likely to learn during our lifetimes, one thing is for sure: the SI reflects our history and identity as humans, down to our chartreuse-sensitive eyes and our base-60 hands. ■

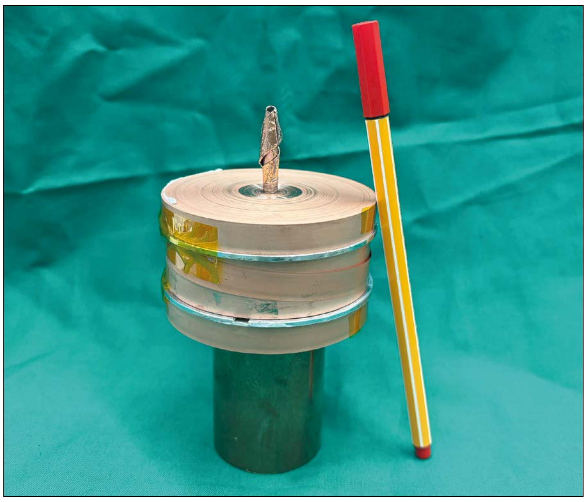
Magnets

Miniature magnets break field strength record

Physicists at ETH Zurich in Switzerland have produced magnetic fields as high as 40 T in a superconducting coil that has a bore diameter of just 3.1 mm. Until now, creating such intense fields required large and expensive facilities and tens of megawatts of power. The new miniaturized structure requires a few thousand times less power than larger magnets and it could help bring ultrastrong benchtop magnets closer to reality (*Sci. Adv.* **12** eadz5826).

"All previous 40 T class magnets have been metres in size, weigh more than six tons, and require about 20 MW of power to operate," says Alexander Barnes, who led the research effort. "Our miniature magnet can also generate a 40 T magnetic field, but it is small enough to fit in the palm of your hand and requires a few watts or less to operate."

Such a device could be extremely useful for scientists who use strong magnets in their research, he adds. "Rather than having to travel to the few locations in the world that have the resources and space to house a strong magnetic field, with this technology scientists in the future could have access to these magnets in their own laboratory."



A Barnes

Small but mighty The new miniature magnets can produce magnetic fields as high as 40 T using a few thousand times less power than larger magnets and could help bring ultrastrong benchtop magnets closer to reality.

Making the magnet tiny

Barnes and his colleagues, who are nuclear magnetic resonance (NMR) spectroscopists, came up with the idea for their new magnet by asking themselves a simple question: "what do we need to put inside it in our experiments?" The answer was: only the sample and an NMR detection coil.

"So, instead of making magnets expensive and big enough to house all different kinds of equipment, we decided to make the magnet tiny – and just big enough to be able to fit inside it what we need to fit inside it," says Barnes. In this way, any bulky components can be placed outside the magnet and only the essential elements within the high-field region inside it.

"Think about the right-hand rule and the Biot-Savart law we all learn in first year physics," he explains. "This law tells us the more electrons moving in a circle, the higher the magnetic field. And the more electrons moving in a circle in a smaller volume close to the sample also means a higher magnetic field. This is all we did – we tried to maximize the electrons moving in a circle near our sample."

Superconducting tapes

Strong magnets are needed in a host of research and technology areas, from magnetic resonance imaging (MRI) and particle accelerators to NMR spectroscopy. Magnetic fields greater than 40 T can be produced using high-temperature superconducting (HTS) tapes. These structures can also be wound together to increase their already very high critical current even further, something that allows the resulting coils to reach higher magnetic fields. A famous example, Barnes reminds us, is the world-record 45.5 T steady-state magnet, which uses a HTS coil as an insert within a resistive background magnet. The problem, however, is that these high-field hybrid magnets are huge and require a lot of power.

Barnes' team says it might now have overcome this issue with its two compact HTS magnets wound with a conducting tape coated with the superconducting ceramic REBCO. The first magnet, composed of two pancake coils, produces a magnetic field of 38 T and the second, composed of four (quad) pancake coils, a field of 42 T. The researchers say they used a specialized winding technique combined with soldering to make sure there was a jointless connection between the pancake coils at a winding diameter of 3.5 mm.

The strong magnetic fields of the coils stem from the high current-carrying ability of REBCO and the extremely small magnet bore diameter of 3.1 mm. "These magnets reach current densities of 2257 and 1880 $\mathrm{A\,mm^{-2}}$ at peak currents of 1246 and 1038 A, respectively," says Barnes, "and despite the much higher current density, they consume a few thousand times less power and require a coil volume over 1000 times smaller than that of the 45.5 T hybrid magnet."

"Amazing" materials

He says he imagines a "bright future" where there are hundreds and thousands of benchtop magnets capable of 50 T and more, all over the world in academia and industry. These magnets can be used for NMR and electron paramagnetic resonance (EPR) spectroscopy, but also quantum computers and other applications. For instance, the ETH Zurich team is working on a project that uses these magnets to build miniature gyrotrons, which are microwave generators. "We have plans to use such devices for spectroscopy, but also for nuclear fusion heating and even vaporizing holes deep in the Earth to extract geothermal energy," Barnes tells *Physics World*.

It will not all be plain sailing, however, say the researchers. One of the main challenges in this work is to avoid damaging the REBCO-coated tapes. These tapes are "amazing" materials, says Barnes. They are a single crystal of rare-earth barium copper oxide and are more than 100 m long, but the problem is that they are subject to mechanical strain. If this strain exceeds a certain, critical threshold, then the superconducting layer can crack, leading to reduced current-carrying capacity as the structure's resistance increases.

The researchers say they are now busy working on increasing the magnetic fields – they are targeting 50 T soon – and performing NMR inside their existing coils. "ResonX, the commercial partner on this study, is also actively commercializing these magnets," reveals Barnes.

Isabelle Dumé

Giant barocaloric cooling effect for new route to refrigeration

A new cooling technique based on the principles of dissolution barocaloric cooling could provide an environmentally friendly alternative to existing refrigeration methods. With a cooling capacity of 67 J/g and an efficiency of nearly 77%, the method developed by researchers from the Institute of Metal Research of the Chinese Academy of Sciences can reduce the temperature of a sample by 27 K in just 20 seconds – far more than is possible with standard barocaloric materials (*Nature* **649** 1180).

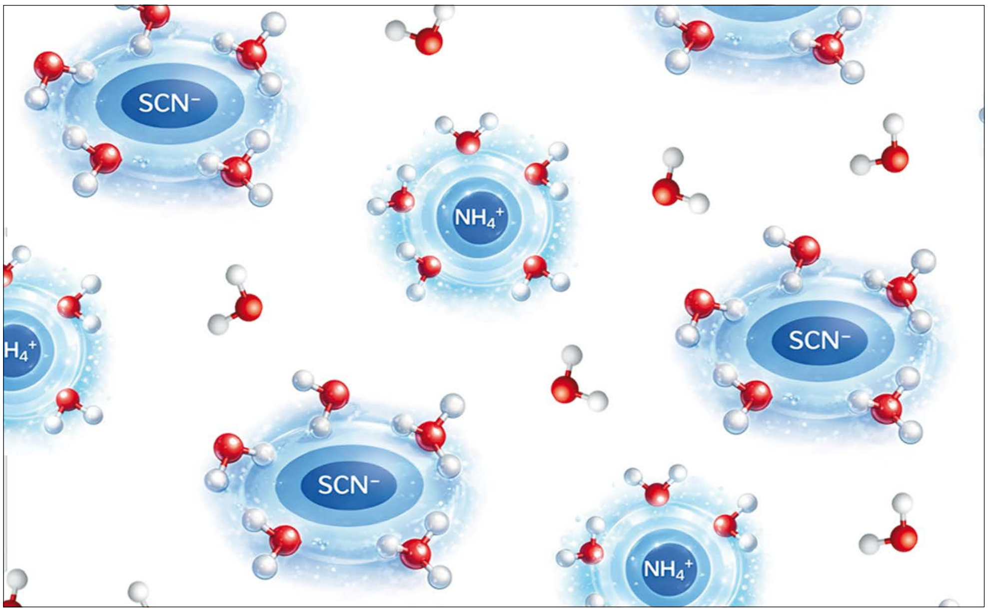
Traditional refrigeration relies on vapour-compression cooling. This technology has been around since the 19th century, and it relies on a fluid changing phase. Typically, an expansion valve allows a liquid refrigerant to evaporate into a gas, absorbing heat from its surroundings as it does so. A compressor then forces the refrigerant back into the liquid state, releasing the heat.

While this process is effective, it consumes a lot of electricity, and there is not much room for improvement. After more than a century of improvements, the vapour-compression cycle is fast approaching the maximum efficiency set by the Carnot limit. The refrigerants are also often toxic, contributing to environmental damage.

In recent years, researchers have been exploring caloric cooling as a possible alternative. Caloric cooling works by controlling the entropy, or disorder, within a material using magnetic or electric fields, mechanical forces or applied pressure. The last option, known as barocaloric cooling, is in some ways the most promising. However, most of the known barocaloric materials are solids, which suffer from poor heat transfer efficiency and limited cooling capacity. Transferring heat in and out of such materials is therefore slow.

A liquid system

The new technique overcomes this limitation thanks to a fundamental thermodynamic process called endothermic dissolution. The principle of endothermic dissolution is that when a salt dissolves in a solvent, some of the bonds in the solvent break. Breaking those bonds takes energy, and so the solvent cools down – sometimes dramatically.



B Li

Chilling effect Dissolving ammonium thiocyanate in water is a highly endothermic process, and it makes up part of the barocaloric cycle demonstrated in this experiment.

In the new work, researchers led by metallurgist and materials scientist Bing Li discovered a way to reverse this process by applying pressure. They began by dissolving a salt, ammonium thiocyanate (NH_4SCN), in water. When they applied pressure to the resulting solution, the salt precipitated out (an exothermic process) in line with Le Chatelier's principle, which states that when a system in chemical equilibrium is disturbed, it will adjust itself to a new equilibrium by counteracting as far as possible the effect of the change.

When they then released the pressure, the salt re-dissolved almost immediately. This highly endothermic process absorbs a massive amount of heat, causing the temperature of the solution to drop by nearly 27 K at room temperature, and by up to 54 K at higher temperatures.

A chaotropic salt

Li and colleagues did not choose NH_4SCN by chance. The material is a chaotropic agent, meaning that it disrupts hydrogen bonding, and it is highly soluble in water, which helps to maximize the amount present in the solution during that part of the cooling cycle. It also has a large enthalpy of solution, meaning that its temperature drops dramatically when it dissolves. Finally, and most importantly, it is highly sensitive to applied pressures in the range of hundreds of megapascals, which is within the capacity of conventional hydraulic systems.

Li says that he and his colleagues' approach could encourage other researchers to find similar techniques that likewise do not rely on phase transitions. As for applications, he notes that because aqueous NH_4SCN barocaloric cooling works well at high temperatures, it could be suited to the demanding thermal management requirements of AI data centres. Other possibilities include air conditioning in domestic and industrial vehicles and buildings.

There are, however, some issues that need to be resolved before such cooling systems find their way onto the market. NH_4SCN and similar salts are corrosive, which could damage refrigerator components. The high pressures required in the current system could also prove damaging over the long run, Li adds.

To address these and other drawbacks, the researchers now plan to study other such near-saturated solutions at the atomic level, with a particular focus on how they respond to pressure. "Such fundamental studies are vital if we are to optimize the performance of these fluids as refrigerants," Li tells *Physics World*.

Isabelle Dumé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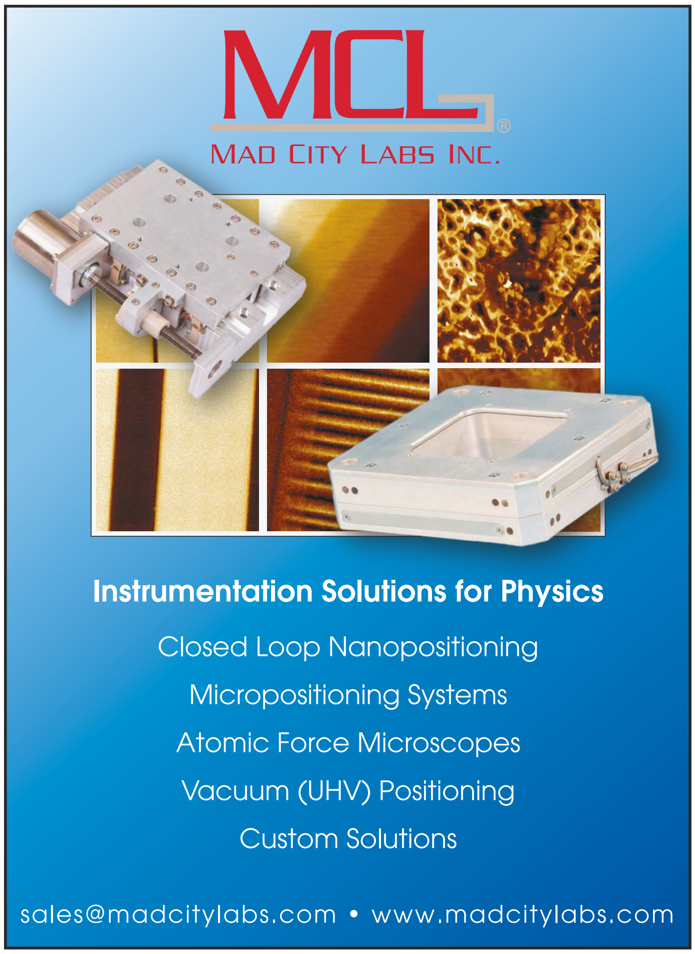
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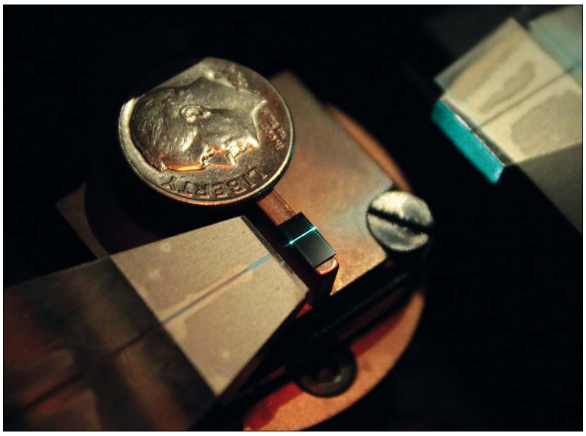
Tantala 3D integrated circuits deliver a rainbow of laser light

By harnessing the unique properties of tantala (tantalum pentoxide), a team of US-based researchers has created a photonic integrated circuit that can be tuned to deliver laser light across a broad spectrum of visible and infrared wavelengths. The work was done by researchers at the National Institute of Standards and Technology (NIST) and colleagues at Octave Photonics (*Nature* **652** 899).

From consumer electronics to atom-based metrology systems, many modern technologies depend on sources that deliver light at specific wavelengths. However, delivering high-quality narrow-band light is difficult – especially at visible wavelengths. As a result many of these technologies cannot be miniaturized to create low-cost, portable devices. Instead they must be implemented in bulky tabletop setups that are operated in expensive laboratory settings.

"Photonics technology offers routes to miniaturize components like laser sources and switches to the chip scale – devices smaller than a grain of rice," explains study leader Grant Brodnik. "Different photonic materials have different strengths and limitations, and there is currently no single material ecosystem that can accommodate all the diverse demands of photonics."


R Jacobson/NIST

True blue
This integrated photonic chip has been tuned to convert infrared laser light to blue laser light.

Mismatched materials

One promising solution involves integrating multiple advanced materials into the same device, harnessing combinations of their photonic properties to engineer capabilities that would not be possible with any single material. The key challenge is that many photonic materials have mismatched thermal, mechanical, and chemical properties, making them broadly incompatible with one another. So far, this has prevented researchers from seamlessly combining multiple materials into chip-scale devices.

To address this challenge, Brodnik's team looked to the unique properties of tantala. A key feature of the material is that it can transform laser light at one frequency into laser light within a broad spectrum of light at visible and infrared wavelengths.

Tantala can be deposited onto other materials at room temperature, before being annealed at relatively modest temperatures of around 500 °C. In comparison, more conventional materials such as silicon nitride require annealing temperatures approaching 1200 °C.

Once deposited, tantala benefits from low internal mechanical stress, at around 38 MPa compared with around 800 MPa for silicon nitride. Together, these properties make it compatible with a broad range of underlying substrates and structures without damaging devices during fabrication.

In this latest work, Brodnik and colleagues deposited tantala directly onto a patterned thin-film substrate of lithium niobate – which itself an advanced photonic material. The result is a monolithically integrated, 3D photonic platform.

Sprinkling tantala

"We essentially sprinkle tantala directly on top of existing photonic circuitry," Brodnik explains. "Then, we can make new photonics circuits on top, link other circuits below, or even operate together with the underlayer material and devices for new functionality."

The team then showed that their combined platform is capable of a range of useful capabilities. "We demonstrated various photonic functions that involve generating new, custom-colour light sources from single-colour input lasers," Brodnik says. "We also made frequency combs and supercontinuum, which are important tools for things like optical communications, precision metrology, and sensing applications."

Several of these devices relied on the tantala and lithium niobate layers working in tandem. For instance, they used tantala to generate intense laser pulses, before passing light into the lithium niobate layer for further non-linear processing. This allowed them to precisely measure the frequency of the laser light.

The work points to a new and broadly applicable route to the 3D integration of photonic materials, which could make it far easier to link advanced photonic functions across existing platforms.

In turn, this could open new pathways towards the scalable, affordable fabrication of complex photonic circuits, applicable in real-world devices. "New configurations offer opportunities to realise entirely new photonic designs that will drive lab experiments to field-deployable systems," Brodnik says.

Sam Jarman

Chip-integrated nanoantenna harvests light from diamond defects

When diamond defects emit light, how much of that light can be captured and used for quantum technology applications? According to researchers at the Hebrew University of Jerusalem, Israel and Humboldt Universität of Berlin, Germany, the answer is "nearly all of it". Their technique, which relies on positioning a nanoscale diamond at an optimal location within a chip-integrated nanoantenna, could lead to improvements in quantum communication and quantum sensing (*APL Quantum* **2** 036106).

Nitrogen–vacancy (NV) centres are point defects that occur when one carbon atom in diamond's lattice structure is replaced by a nitrogen atom next to an empty lattice site (a vacancy). Together, this nitrogen atom and its adjacent vacancy behave like a nega-

Optics and photonics

tively charged entity with an intrinsic quantum spin.

When excited with laser light, an electron in an NV centre can be promoted into an excited state. As the electron decays back to the ground state, it emits light. The exact absorption-and-emission process is complicated by the fact that both the ground state and the excited state of the NV centre have three sublevels (spin triplet states). However, by exciting an individual NV centre repeatedly and collecting the photons it emits, it is possible to determine the spin state of the centre.

The problem, explains Boaz Lubotzky, who co-led this research together with his colleague Ronen Rapaport, is that NV centres radiate over a wide range of angles. Hence, without an efficient collection interface, much of the light they emit is lost. Standard optics capture around 80% of the light

Lubotzky and colleagues say they have now solved this problem thanks to a hybrid nanostructure made from a PMMA dielectric layer above a silver grating. This grating is arranged in a precise bullseye pattern that accurately guides light in a well-defined direction thanks to constructive interference. Using a nanometre-accurate positioning technique, the researchers placed the nanodiamond containing the NV centres exactly at the optimal location for light collection: right at the centre of the bullseye.


Boaz Lubotzky

Guided light Illustration showing photon emission from a nanodiamond and light directed by a bullseye antenna.

For standard optics with a numerical aperture (NA) of about 0.5, the team found that the system captures around 80% of the light emitted from the NV centres. When NA > 0.7, this value exceeds 90%, while for NA > 0.8, Lubotzky says it approaches unity.

"The device provides a chip-based, room-temperature interface that makes NV emission far more directional, so a larger fraction of photons can be captured by standard lenses or coupled into fibres and photonic chips," he tells *Physics World*. "Collecting more photons translates into faster measurements, higher sensitivity and lower power, thereby turning NV centres into compact precision sensors and also into brighter, easier-to-use single-photon sources for secure quantum communication."

The researchers say their next priority is to transition their prototype into a plug-and-play, room-temperature module – one that is fully packaged and directly coupled to fibres or photonic chips – with wafer-level deterministic placement for arrays. "In parallel, we will be leveraging the enhanced collection for NV-based magnetometry, aiming for faster, lower-power measurements with improved readout fidelity," says Lubotzky. "This is important because it will allow us to avoid repeated averaging and enable fast, reliable operation in quantum sensors and processors."

Isabelle Dumé

Portable source could produce high-energy muon beams

Laser plasma acceleration (LPA) may be used to generate multi-gigaelectronvolt muon beams, according to physicists at the Lawrence Berkeley National Laboratory (LBNL) in the US (*Physical Review Accelerators and Beams* **28** 103401). Their work might help in the development of ultracompact muon sources for applications such as muon tomography – which images the interior of large objects that are inaccessible to X-ray radiography.

Muons are charged subatomic particles that are produced in large quantities when cosmic rays collide with atoms 15–20 km high up in the atmosphere. Muons have the same properties as electrons but are around 200 times heavier. This means they can travel much further through solid structures than electrons. This property is exploited in muon tomography, which analyses how muons penetrate objects and then exploits this information to produce 3D images.

The technique is similar to X-ray tomography used in medical imaging, with the cosmic-ray radiation taking the place of artificially generated X-rays and muon trackers the place of X-ray detectors. Indeed, depending on their energy, muons can traverse metres of rock or other materials, making them ideal for imaging thick and large structures. As a result, the technique has been used to peer inside nuclear reactors, pyramids and volcanoes.

As many as 10 000 muons from cosmic rays reach each square metre of the Earth's surface every minute. These naturally produced particles have unpredictable properties, however, and they also only come from the vertical direction. This fixed directionality means that can take months to accumulate enough data for tomography.

Another option is to use the large numbers of low-energy muons that can be produced in proton accelerator facilities by smashing a proton beam onto a fixed carbon target. However, these accelerators are large and expensive facilities, limiting their use in muon tomography.

A new compact source

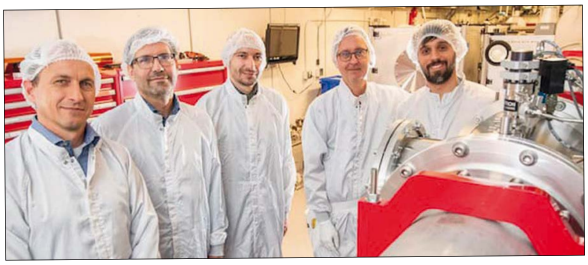
Physicists led by Davide Terzani have now developed a new compact muon source based on LPA-generated electron beams. Such a source, if optimized, could be deployed in the field and could even produce muon beams in specific directions.

In LPA, an ultra-intense, ultra-short, and tightly focused laser pulse propagates into an "under-dense" gas. The pulse's extremely high electric field ionizes the gas atoms, freeing the electrons from the nuclei, so generating a plasma. The ponderomotive force, or radiation pressure, of the intense laser pulse displaces these electrons and creates an electrostatic wave that produces accelerating fields orders of magnitude higher than what is possible in the traditional radio-frequency cavities used in conventional accelerators.

LPAs have all the advantages of an ultra-compact electron accelerator that allows for muon production in a small-size facility such as BeLLA, where Terzani and his colleagues work. Indeed, in their experiment, they succeeded in generating a 10 GeV electron beam in a 30 cm gas target for the first time.

The researchers collided this beam with a dense target, such as tungsten. This slows the beam down so that it emits Bremsstrahlung, or braking radiation, which interacts with the material, producing secondary products that include lepton–antilepton pairs, such as electron–positron and muon–antimuon pairs. Behind the converter target, there is also a short-lived burst of muons that propagates roughly along the same axis as the incoming electron beam. A thick concrete shielding then filters most of the secondary products, letting the majority of muons pass through it.

Crucially, Terzani and colleagues were able to separate the muon signal from the large background radiation – something that can be difficult to do because of the inherent inefficiency of the muon production process. This allowed them to identify two different muon populations coming from the accelerator. These were a collimated, forward directed population, generated by pair production; and a low-energy, isotropic, population generated by meson decay.



Robinson Kuntz/Berkeley Lab

Meet the team The BeLLA researchers are (from the left) Jeroen van Tilborg, Carl Schroeder, Stanimir Kisyov, Anthony Gonsalves, and Davide Terzani.

Many applications

Muons can be used in a range of fields, from imaging to fundamental particle physics. As mentioned, muons from cosmic rays are currently used to inspect large and thick objects not accessible to regular X-ray radiography – a recent example of this is the discovery of a hidden chamber in Khufu's Pyramid. They can also be used to image the core of a burning blast furnace or nuclear waste storage facilities.

While the new LPA-based technique cannot yet produce muon fluxes suitable for particle physics experiments – to replace a muon injector, for example – it could offer the accelerator community a convenient way to test and develop essential elements towards making a future muon collider.

The experiment in this study focused on detecting the passage of muons, unequivocally proving their signature. The researchers conclude that they now have a much better understanding of the source of these muons. Unfortunately, the original programme that funded this research has ended, so future studies are limited at the moment. Not to be disheartened, the researchers say they strongly believe in the potential of LPA-generated muons and are working on resuming some of their experiments. For example, they aim to measure the flux and the spectrum of the resulting muon beam using completely different detection techniques based on ultra-fast particle trackers, for example.

The LBNL team also wants to explore different applications, such as imaging deep ore deposits – something that will be quite challenging because it poses strict limitations on the minimum muon energy required to penetrate soil. Therefore, they are looking into how to increase the muon energy of their source.

Isabelle Dumé

Due to government shutdown restrictions currently in place =in the US, the researchers who headed up this study have not been able to comment on their work.

Thyracont's vacuum measurement instruments enable innovation across industries

From semiconductor fabrication to pharmaceuticals, quantum technologies, and materials research, Thyracont's vacuum instruments are at the heart of some of the world's most advanced vacuum systems. So let's have a look at how the Germany-based company's vacuum technology is being used in a wide range of applications

High-precision vacuum measurement Thyracont's instruments are used in industrial and laboratory applications.

Life sciences: reliable conditions for pharmaceutical freeze drying

Freeze drying (lyophilization) plays an important role in the manufacture of pharmaceuticals extending shelf life by removing water via sublimation under vacuum conditions. Because these processes run over long cycles, stable and contamination-resistant vacuum measurement is essential.

Thyracont's VCP transducer is designed for such applications. Its platinum-rhodium filament provides high resistance against corrosion and contamination, supports sterilization and reliable operation under thermal stress. Operating in the fine vacuum range (1000 to 5×10^{-4} mbar), it ensures stable process control in freeze-drying systems.

"Long-term stability and resistance against corrosive process media are decisive factors in freeze-drying processes. The VCP was specifically engineered to maintain reliable performance even withstanding steam sterilizations." Explains Frank P Salzberger, CEO of Thyracont.

High-tech and research: enabling analytical precision

Many of the cutting-edge instruments used in analytics and R&D operate under vacuum – including those used for mass spectrometry and materials testing. In applications such as beverage gas analysis, the VSP63MV Pirani transducer enables precise monitoring in the 1000 to 10^{-4} mbar range, supporting zero adjustment of the mass spectrometer, which is essential for the reliable detection of trace contaminants at very low concentrations.

The analysis of the thermomechanical properties of materials is necessary for the development of cryogenic technologies including those used in quantum technologies. This involves cooling materials and devices to very low temperatures and measuring how their physical properties change. Thyracont vacuum gauges such as the VSP63DL and VSM77D cover fine and high vacuum ranges down to ultra-high vacuum conditions, enabling stable thermomechanical characterization of materials at extreme temperatures.

Semiconductor and coating processes: stability in complex systems

In semiconductor manufacturing, wafer bonding requires tightly controlled vacuum conditions to ensure contamination-free and uniform layer formation. During initial evacuation, Thyracont's VSC43MA4 is used to monitor roughing and bypass pumping stages.

In subsequent high-vacuum stages, Smartline VSM transducers provide reliable measurement from atmospheric pressure to ultra-high vacuum, combining Pirani and cold cathode technologies with optimized range switching for stable operation.

"In semiconductor wafer bonding, it is essential to maintain stable measurement across the full pressure range – from roughing to ultra-high vacuum. Our Smartline VSM series ensures exactly this seamless transition," says Salzberger.

In optical coating applications, this approach ensures continuous monitoring while protecting sensitive sensor components.

Industrial vacuum processes: distillation and thermal treatment

Short-path distillation relies on precise vacuum control (typically 1×10^{-3} to 1 mbar)

Thyracont Vacuum Instruments GmbH

Smartline VSM transducers These provide reliable monitoring from atmospheric pressure to ultra-high vacuum.

Long-term stability and resistance against corrosive process media are decisive factors in freeze-drying processes

to enable gentle separation of heat-sensitive substances such as fragrances. A thin film is formed inside the chamber, and evaporation occurs at reduced temperatures, preserving delicate compounds.

Stable pressure control is essential to ensure consistent product quality. Devices such as the VD64P and VD850 support monitoring and control functions including switching outputs, leak detection, and integrated data logging for process documentation.

Peter Gerlesberger, development manager at Thyracont explains, "Reliable leak testing ensures that vacuum chambers and systems meet the required process conditions. With the VD850 users can quickly and reliably determine the magnitude of the leak rate".

Vacuum furnaces face similar requirements under high-temperature and contamination conditions. The VD850, as well as VSH transducers (Pirani/hot cathode), enable reliable pressure measurement across furnace inlet and outlet zones.

Packaging applications: quality control in food safety

Vacuum packaging plays a crucial role in in the food industry, extending shelf life and reducing food waste. Ensuring consistent

Thyracont Vacuum Instruments GmbH

VD850 digital compact vacuum meters These are equipped with a data logger and USB-C interface.

vacuum levels is critical for product safety and quality.

Testing is performed by replacing the food with a vacuum gauge and monitoring the pressure after sealing. The compact VD810 can be temporarily integrated directly into packaging, thereby simulating real-world process conditions.

The built-in piezo-ceramic sensor measures absolute and relative pressure in a rough vacuum and records pressure curves with timestamps. The recorded measurement data can be downloaded via USB or, optionally, via Bluetooth LE and used for process analysis and quality documentation.

The common thread

Across industries, from life sciences to semiconductor manufacturing, Thyracont vacuum measurement technology enables precise, stable, and reliable process control under demanding conditions. By combining robust sensor design with wide measurement ranges and intelligent system integration, these instruments contribute to the performance and quality of modern industrial and research applications.

THYRACONT
Vacuum Instruments

thyracont-vacuum.com/en

Cherenkov light reveals radiotherapy dose

Brian Pogue is professor of biomedical engineering at Dartmouth College in the US and co-founder of several start-ups developing optics-based systems for medicine. These include DoseOptics, which has developed a system to visualize Cherenkov light emission in order to monitor radiation therapy. In conversation with *Physics World*'s Tami Freeman, Pogue explains how the technology works and how it could improve treatment by providing a real-time map of the radiation dose a patient receives

What is Cherenkov light?
Small amounts of Cherenkov light are produced when ionizing radiation passes through any material. Many people will know it as the blue glow that surrounds spent nuclear fuel that is stored in water. Throughout much of popular science culture, this glow is often used to illustrate the presence of radiation.

Why is DoseOptics interested in Cherenkov light?
The light is very useful because it provides a direct measurement of the radiation dose received by any material. This includes human tissue that is involved in radiotherapy, so it can reveal exactly where a therapy beam enters a patient. However, the light is so dim that it can only be seen by the human eye in total darkness. Indeed, patients who receive radiotherapy to the head will often say that they can see the blue light when their eyes are closed.

If it's so dim, how do you detect it?
About 10 years ago we realized that we could detect and image the Cherenkov light if we synchronized our optical detectors to the radiotherapy accelerator pulses. This process is called time gating, whereby we only acquire an image when we know the Cherenkov light will be produced. This greatly reduces the background noise in the signal that we measure.

The light intensity is directly proportional to the radiation dose received by the patient. The result is a unique dosimetry technology for radiation therapy.


Brian Pogue

Brian Pogue The medical physicist has shown how Cherenkov light can be used to guide radiotherapy.

How did you spin out DoseOptics?
Working with several colleagues at Dartmouth and through our start-up company, we were very lucky to get a series of pilot grants from the US National Institutes of Health (NIH). The DoseOptics team spent the next few years perfecting our first product, which is called BeamSite. It's a camera system with a built-in intensifier that makes it very sensitive to Cherenkov light. Several cameras are used to monitor the location of the radiotherapy beam on the surface of the patient. Crucially, it works even when the room lights are on in the radiotherapy suite – so it is able to distinguish tiny Cherenkov signals within a huge background of ambient light.

> The radiotherapy team can monitor the treatment in real time – addressing potential problems with beam alignment as they occur

As well as time gating, we also do a massive amount of image processing and signal processing on the back end of the cameras, which are very sophisticated. This is done using field programmable gate arrays (FPGAs) – which are essentially tiny embedded-system computers.

Our cameras lock onto the signal and reject 99.99% of the background light, creating images of the Cherenkov light coming from the patient at 30 frames per second. This video is displayed on the therapy console so the radiotherapy team can monitor the treatment in real time – addressing potential problems with beam alignment as they occur.

The imaging stream allows the team to very simply and intuitively see the treatment as it unfolds in real time

Is BeamSite in routine clinical use?

Yes. We started out with early adopter academic medical centres, but BeamSite is now in widespread deployment. It is distributed by a British company called Vision RT and they market it as DoseRT. As of 2025 it is available worldwide and it is being used for everyday radiotherapy in more than 40 cancer-therapy clinics. We now have a consortium of users, who share stories and tips on how to use the technology effectively to make their therapy as safe as possible.

What is next for Cherenkov imaging?

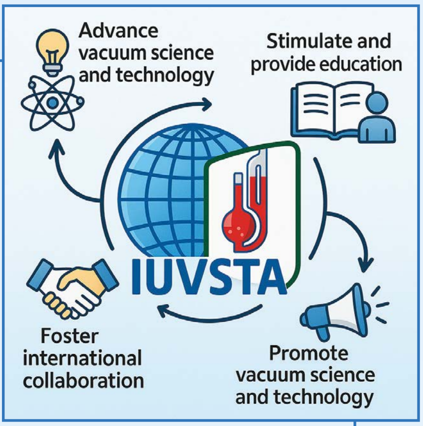
We are working on several things at Dartmouth including a study of contralateral breast dose. This is unwanted radiation received by the opposite breast during radiotherapy and it is caused by a misalignment of the beam. Dealing with this issue is important because breast cancer is the most common disease treated by radiation therapy but only the diseased breast should be treated with radiation.

We are exploring how Cherenkov light can be used to identify when contralateral breast dose occurs – and then develop techniques to minimize its occurrence.

Again, the benefit of Cherenkov light is that it reveals something that had previously been invisible. This imaging stream allows the team to very simply and intuitively see the treatment as it unfolds in real time. An important benefit of this is safety. If radiotherapy safety tools are complicated, there's potential for human error, which is especially true in busy radiotherapy centres. The simplicity of being able to see the treatment from the perspective of the therapy team will be the lasting power of this technology.

Tami Freeman is an online editor of *Physics World*

IUVSTA is an international union that serves to advance Vacuum Science and Technology enabling nanotechnology, surface engineering, quantum science, semiconductor chips and more; the union stimulates and provides education through Workshops, Technical Training Courses, Schools, Short Courses and Webinars; the union 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

I am particularly pleased to announce a strong program of upcoming international activities across our community, including the 110th IUVSTA Workshop on Advanced Plasma Diagnostics, the 24th IUVSTA Vacuum School, ECOSS-39, VASSCAA-13, FCSE 2027, EVC-18/JVC 20 and IVC-24. These events bring together scientists, engineers, students, and industrial partners from around the world and exemplify the collaborative spirit that has always been a hallmark of IUVSTA. I encourage all members to participate, contribute their expertise, and help strengthen the global network that drives innovation across our disciplines. Links to these events can be found at IUVSTA.org (QR code 1).

Supporting the next generation of scientists remains a central priority. The IUVSTA Executive Council approved the formation of an Early Career Researchers (ECR) Working Group at our April meeting in San Diego. This initiative aims to provide young scientists with an active voice within the Union and to encourage the development of innovative ideas and activities driven by emerging leaders in our field. By becoming an active member of IUVSTA, you will gain access to an incredible network of fellow scientists, mentors, and professionals from across the globe. Collaborate with leading experts, exchanging ideas at international conferences, and building connections that will last a lifetime. Please fill out an application found at this link (QR Code 2).

One of IUVSTA's most important investments in the future of our field is the **Medard W. Welch International Scholarship**. This annual scholarship supports outstanding early-career researchers pursuing research in vacuum science, vacuum technology, and their applications by enabling them to undertake research stays of three months to one year at laboratories outside their home countries. With a value of USD 15,000, the program promotes scientific excellence, international collaboration, and the development of the next generation of researchers. I encourage eligible young scientists from all IUVSTA member societies to consider applying and to take advantage of this unique opportunity to broaden their scientific horizons and strengthen global research connections. Application deadline is 15 September 2026 (QR Code 3).

Another important step toward the future is the approval of a Corporate Affiliates Group. The objective of this initiative is to strengthen collaboration between academia and industry, creating new opportunities for engagement while preserving the scientific independence and governance structure of the Union.

Looking ahead, IUVSTA is focused on strengthening its role as a catalyst for global collaboration. The Union's strategic objectives emphasize scientific excellence, international cooperation, support for early-career researchers, and stronger connections with industry. These goals can only be achieved through the active participation of our member societies and the dedication of volunteers who contribute their expertise and time to the advancement of vacuum science and its applications.

1. iuvsta.org

2. Welch award application

3. Early career researcher application

Dr. Jay Hendricks, IUVSTA President 2025-2028. Jay works at the National Institute of Standards and Technology (NIST), in Gaithersburg, Maryland, USA, as the Deputy Program Manager for the "NIST on a Chip" Program. **www.nist.gov/people/jay-h-hendricks**.

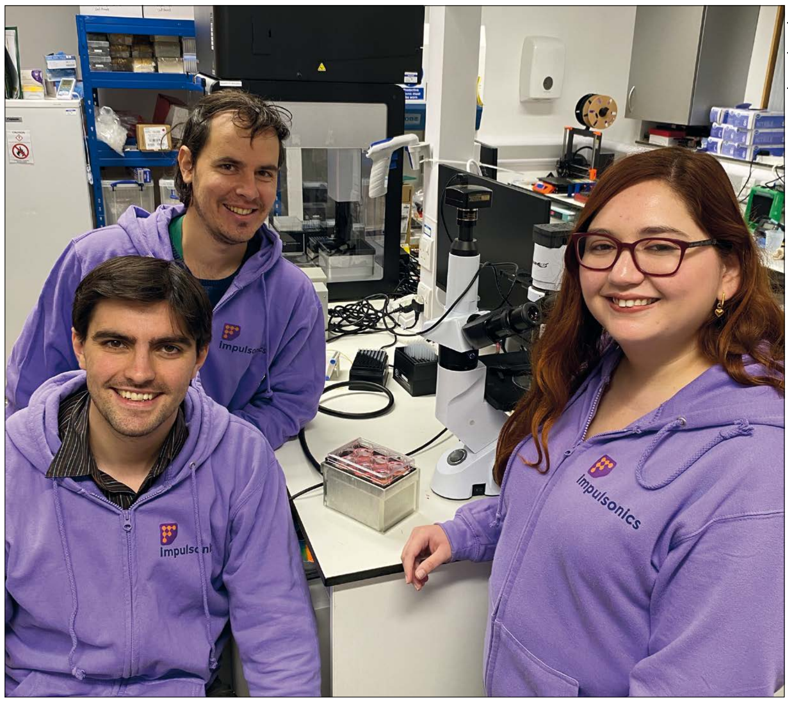
Ultrasound system solves the 'unsticking problem' in biomedical research

Ultrasound is used in a growing number of applications in science, medicine and industry. Impulsonics was founded in 2023 to commercialize ultrasound technologies developed at the UK's University of Bristol. The company uses ultrasound to solve the unsticking problem in biotechnology, as its co-founder and CEO **Luke Cox** explains to *Physics World*'s Hamish Johnston

Can you describe the unsticking problem?
When biological cells grow and multiply inside the body, most of them stick together naturally to form organs and other structures. Cells really don't like to be on their own, so this also happens when cells are grown in petri dishes. As well as sticking to themselves, cells grown *in vitro* will often stick to the surfaces of containers. All of this stickiness makes it difficult to grow and manipulate cells for a wide range of biomedical applications including drug discovery and regenerative medicine.

How are biological cells unstuck today?
The current approach has been around for about a century and involves chemicals like trypsin that "melt" the bonds that are responsible for the stickiness. The loosened cells are then centrifuged to remove the unsticking chemicals and more cell-friendly chemicals are added. This is a very complicated process that can be difficult and expensive to automate.

Another important down side of this process is that the chemicals used for unsticking can permanently alter the surface of some cells. Many drugs interact with the surface of cells, and these changes can affect the outcome of *in vitro* drug testing and also affect processes used in regenerative medicine.



Impulsonics

Teamwork From left to right: Luke Cox, Adam Price and Ximena Vasto in the Impulsonics lab.

How can ultrasound help?
At Impulsonics we carefully control the ultrasound applied to a sample of cells, creating regions of high and low pressure. This exerts gentle forces on the cells, which pulls them apart. This is combined with a mild chemical treatment that makes the cells a little less sticky but without melting the bonds.

Using sound and vibrations is not a new idea. Some existing processes use shaker plates and experienced scientists have the knack of separating cells by tapping their fingers on a vessel or tapping it on a table. However, there is a lot of variability of outcome in these techniques and our ultrasound method makes the process more controlled and consistent.

How do you create regions of high and low pressure?
Our system has and array of over 100 ultrasound speakers located below the petri dish. We have individual control of the output of each speaker and this allows us to create patterns of high- and low-amplitude sound in a dish. I like to think of it as "surround sound for cells" – it's a similar principle to what happens in a cinema, but we use many more speakers.

We know the cells are healthy and happy during the unsticking process and don't appear to be altered

Are you confident that the ultrasound is not damaging or altering the cells?
Yes, the frequency and amplitude regime that we operate in is very safe for living cells. We have tested that extensively. We know the cells are healthy and happy during the unsticking process and don't appear to be altered.

How is Impulsonics commercializing its technology?
The product that we are currently developing is designed to sit inside existing automated systems for producing and processing living cells. These systems are essentially liquid-handling robots that use pipettes to move cells from one plate to another. We provide the means to unstick cells and once that is done, the cells are processed as usual.

Impulsonics

Surround sound Impulsonics' system uses an array of more than 100 ultrasound speakers to shape the sound that unsticks biological cells.

Beyond biotechnology, our technology could be used to align tiny objects for the high-precision engineering of composite structures

Our longer term plan is to put our ultrasound technology at the core of our own benchtop system that integrates liquid handling. This product will appeal to the large number of smaller labs that cannot afford large automated systems, and currently process cells manually.

This will be a "walk up" instrument that you put your petri dish in and push a button. Then you can go away, have a coffee and come back when the process is complete.

What are some of Impulsonics other plans for the future?

Much of our focus will be on biotechnology, but not exclusively on applications related to unsticking. We are investigating the use of ultrasound technology to replace centrifugation in certain applications. Another possible use of our technology is the processing of larger biological structures called organoids, which are made of millions of cells. Organoids can be as large as a millimetre across and are currently difficult to manipulate.

Beyond biotechnology, our technology could be used to align tiny objects for the high-precision engineering of composite structures – possibly in combination with 3D printing. A technology that's related to ours are acoustic tweezers, which use ultrasound to levitate objects and these have broader scientific and industrial applications.

Hamish Johnston is an online editor of *Physics World*

Earthquake-sensing network detects space debris

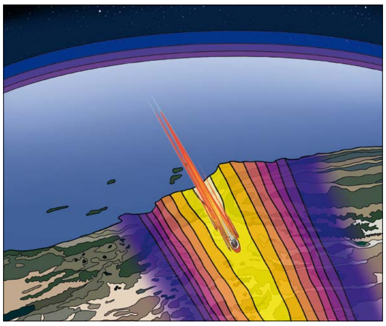
When chunks of space debris make their fiery descent through the Earth's atmosphere, they leave a trail of shock waves in their wake. Geophysicists have now found a way to exploit this phenomenon, using open-source seismic data from a network of earthquake sensors to monitor the waves produced by China's Shenzhou-15 module as it fell to Earth in April 2024 (*Science* **6783** 412). The method is valuable, they say, because it makes it possible to follow debris – which can be hazardous to humans and animals – in near-real time as they travel towards the surface.

"We're at the situation today where more and more spacecraft are re-entering the Earth's atmosphere on a daily basis," says team member Benjamin Fernando, a postdoctoral researcher at Johns Hopkins University in the US. "The problem is that we don't necessarily know what happens to the fragments this space debris produces – whether they all break up in the atmosphere or if some of them reach the ground."

Network of earthquake sensors

As the Shenzhou-15 module re-entered the atmosphere, it began to disintegrate, producing debris that travelled at supersonic speeds (between Mach 25–30) over the US cities of Santa Barbara, California and Las Vegas, Nevada. The resulting sonic booms produced vibrations strong enough to be picked up by a network of 125 seismic stations spread over Nevada and Southern California.

Fernando and his colleague Constantinos Charalambous at Imperial College London in the UK used freely available data from these stations to measure the arrival times of the largest sonic boom signals. Based on these data, they produced a contour map of the path the debris took and the direction in which it propagated. They also determined the altitude of the module as it travelled by using ratios of the speed of sound to the apparent speed of the incident wavefront its supersonic flight generated as it passed over the seismic stations. Finally, they used a best-fit seismic inversion model to estimate where remnants of the module may have landed and the speed at which they travelled over the ground.



S Economon and B Fernando

Mapping it out Geophysicists at John Hopkins University created a contour map of the path taken by space debris using freely available data from a network of seismic stations, which measured the arrival times of the largest sonic boom signals.

The analyses revealed that the module travelled roughly 20–30 kilometres south of the trajectory that US Space Command had predicted based on measurements of the module's orbit alone. The seismic data also showed that the module gradually disintegrated into smaller pieces rather than undergoing a single explosive disassembly.

Advantages of accurate tracking

To obtain an estimate of the object's trajectory within seconds or minutes, the researchers had to simplify their calculations by ignoring the effects of wind and temperature variations in the lower troposphere (the lowest layer of the Earth's atmosphere). This simplification also did away with the need to simulate the path of wave signals through the atmosphere, which was essential for previous techniques that relied on radar data to follow objects decaying in low Earth orbit. These older techniques, Fernando adds, produced predictions of the objects' landing sites that could, in the worst cases, be out by thousands of kilometres.

The availability of accurate, near-real time debris tracking could be particularly helpful in cases where the debris is potentially harmful. As an example, Fernando cites an incident in 1996, when debris from the Russian Mars 96 spacecraft fell out of orbit. "People thought it burned up and [that] its radioactive power source landed intact in the ocean," he says. "They tried to track it at the time, but its location was never confirmed. More recently, a group of scientists found artificial plutonium in a glacier in Chile that they believe is evidence the power source burst open during the descent and contaminated the area."

Though Fernando emphasizes that it's rare for debris to contain radioactive material, he argues "we'd benefit from having additional tracking tools" when it does.

Automated algorithms

Fernando had previously used seismometers to track natural meteoroids, comets and asteroids on both Earth and Mars. In the latter case, he used data from InSight, a NASA Mars mission equipped with a seismometer.

"The meteoroids hitting the Red Planet were a really good seismic source for us," he explains. "We detected the sonic booms from them breaking up and, occasionally, would actually detect the impact of them hitting the ground. We realized that we could actually apply those same techniques to studying space debris on Earth.

"This is an excellent example of a technique that we really perfected the expertise for a planetary science kind of pure science application. And then we were able to apply it to a really relevant, challenging problem here on Earth," he tells *Physics World*.

The scientists say that in the longer term, they hope to develop an algorithm that automatically reconstructs the trajectory of an object. "At the moment, we're having to find the sonic boons and analyse the data 'by hand'," Fernando says. "That's obviously very slow, even though we're getting better."

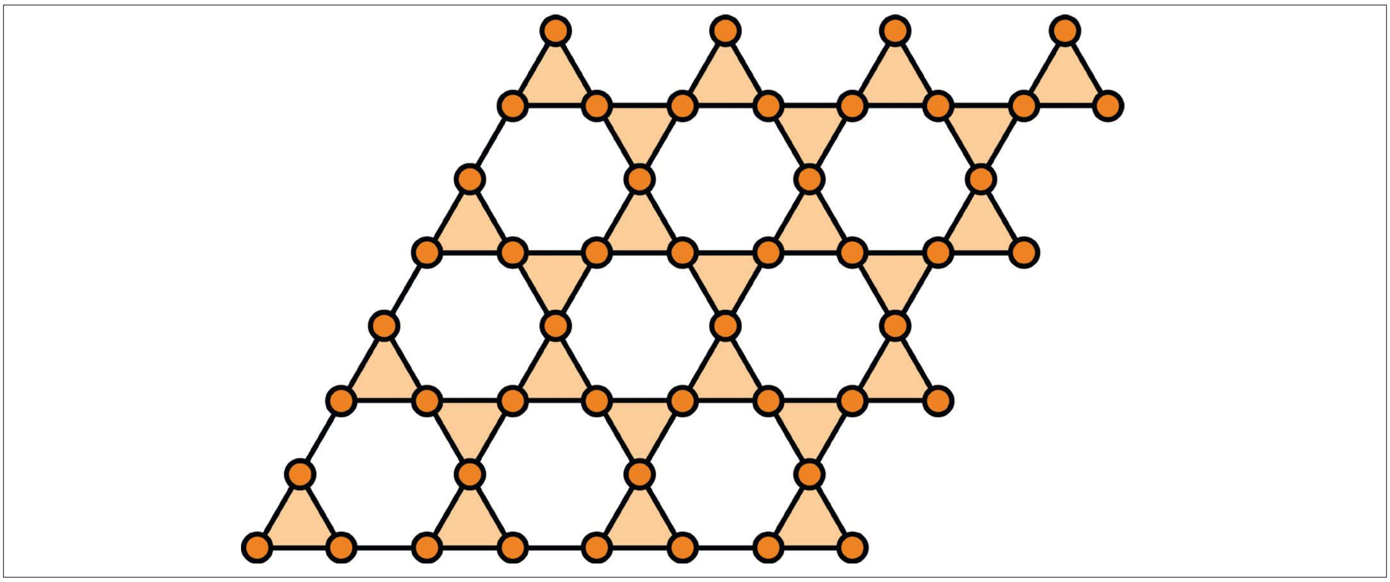
A better solution, Fernando continues, would be to develop a machine learning tool that can find sonic booms in the data when a re-entry is expected, and then use those data to reconstruct the trajectory of an object. They are currently applying for funding to explore this option in a follow-up study.

Beyond that, there's also the question of what to do with the data once they have it. "Who would we send the data to?" Fernando asks rhetorically. "Who needs to know about these events? If there's a plane crash, hurricane, or similar, there are already good international frameworks in place for dealing with these events. It's not clear to me, however, that such a framework for dealing with space debris has caught up with reality – either in terms of regulations or the response when such an event does happen."

Isabelle Dumé

Cryogenics

New sensor uses topological material to detect helium leaks



Kagome lattice
A new helium detector has be created using this 2D configuration.

A new sensor detects helium leaks by monitoring how sound waves propagate through a topological material – no chemical reactions required. Developed by acoustic scientists at Nanjing University, China, the innovative, physics-based device is compact, stable, accurate and capable of operating at very low temperatures (*Applied Physics Letters* **127** 243503).

Helium is employed in a wide range of fields, including aerospace, semiconductor manufacturing and medical applications as well as physics research. Because it is odourless, colourless, and inert, it is essentially invisible to traditional leak-detection equipment such as adsorption-based sensors. Specialist helium detectors are available, but they are bulky, expensive and highly sensitive to operating conditions.

2D acoustic topological material

The new device created by Li Fan and colleagues at Nanjing consists of nine cylinders arranged in three sub-triangles with tubes in between the cylinders. The corners of the sub-triangles touch and the tubes allow air to enter the device. The resulting 2D system has a so-called "kagome" structure and is an example of a topological material – that is, one that contains special, topologically protected, states that remain stable even if the bulk structure contains minor imperfections or defects. In this system, the protected states are the corners.

To test their set-up, the researchers placed speakers under the corners that send sound waves into the structure and make the gas within it vibrate at a certain frequency (the resonance frequency). When they replaced the air in the device with helium, the sound waves travelled faster, changing the vibration frequency. Measuring this shift in frequency enabled the researchers to calculate the concentration of helium in the device.

Many advantages

Fan explains that the device works because the interface/corner states are impacted by the properties of the gas within it. This mechanism has many advantages over traditional gas sensors. First, it does not rely on chemical reactions, making it ideal for detecting inert gases like helium. Second, the sensor is not affected by external conditions and can therefore work at extremely low temperatures – something that is challenging for conventional sensors that contain sensitive materials. Third, its sensitivity to the presence of helium does not change, meaning it does not need to be recalibrated during operation. Finally, it detects frequency changes quickly and rapidly returns to its baseline once helium levels decrease.

As well as detecting helium, Fan says the device can also pinpoint the direction a gas leak is coming from. This is because when helium begins to fill the device, the corner closest to the source of the gas is impacted first. Each corner thus acts as an independent sensing point, giving the device a spatial sensing capability that most traditional detectors lack.

Other gases could be detected

Detecting helium leaks is important in fields such as semiconductor manufacturing, where the gas is used for cooling, and in medical imaging systems that operate at liquid helium temperatures. "We think our work opens an avenue for inert gas detection using a simple device and is an example of a practical application for two-dimensional acoustic topological materials," says Fan.

While the new sensor was fabricated to detect helium, the same mechanism could also be employed to detect other gases such as hydrogen, he adds.

Spurred on by these promising preliminary results, the researchers plan to extend their fabrication technique to create 3D acoustic topological structures. "These could be used to orientate the corner points so that helium can be detected in 3D space," says Fan. "Ultimately, we are trying to integrate our system into a portable structure that can be deployed in real-world environments without complex supporting equipment.," he tells *Physics World*.

Isabelle Dumé