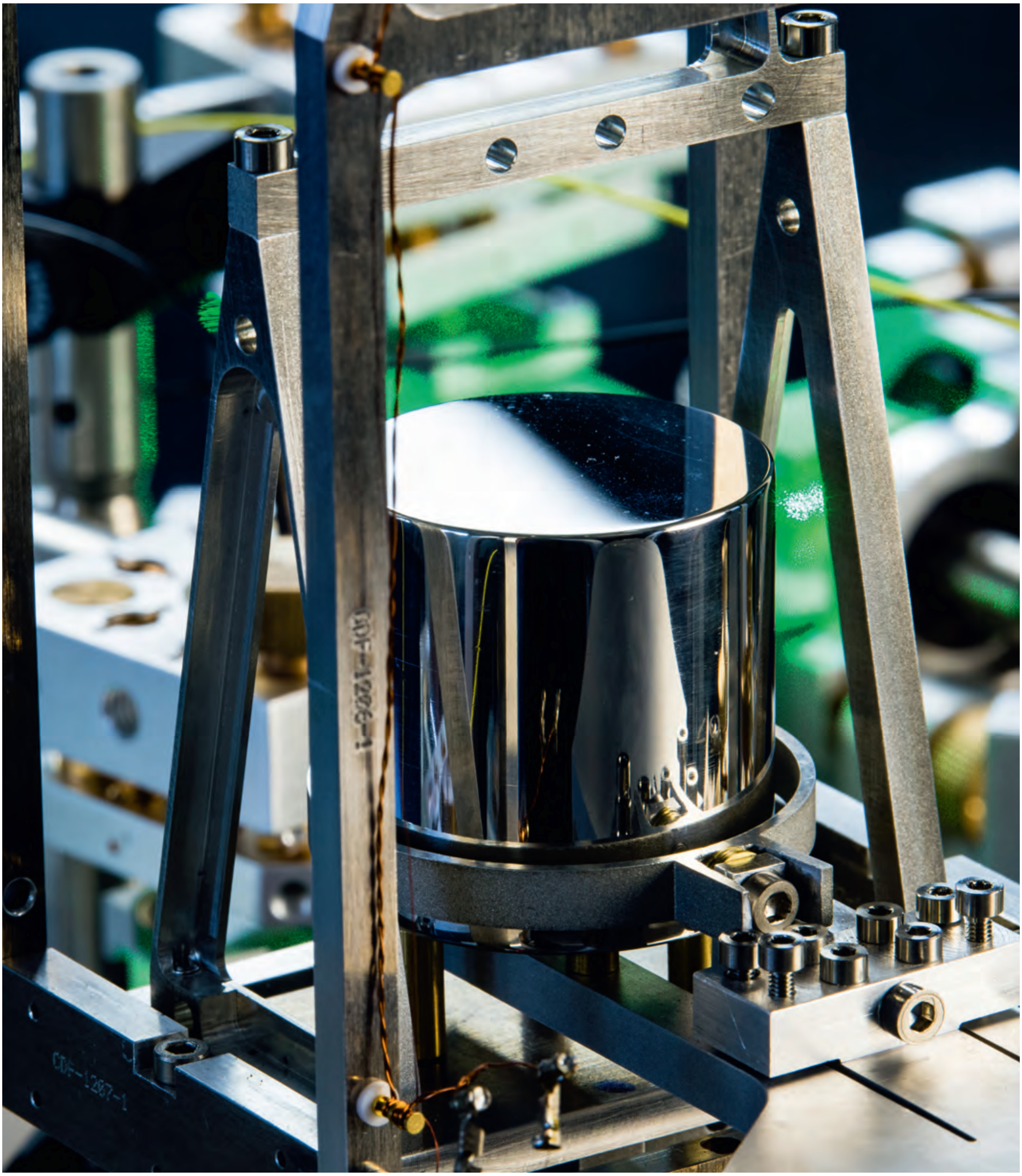



# RESEARCH REPORT 2017

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

# SOMMAIRE



THE LNE'S KIBBLE BALANCE
FORMERLY KNOWN AS THE WATT BALANCE.

# FOREWORD

**Thomas Grenon,**
Managing Director

On the eve of the 2018 General Conference on Weights and Measures (CGPM) in Versailles, LNE teams have this year gone to great lengths to enable the pending redefinitions in the International System of Units (SI). The remarkable results obtained in creating new standards for the kilogram, kelvin and ampere are the fruit of many years' work on the part of LNE engineers and researchers, and attest to their cutting-edge capabilities.

2018 will mark a turning point in international metrology and LNE fully intends to help shape the coming revolution.

The 50th anniversary of the atomic second was also an opportunity to highlight the outstanding achievements of LNE-SYRTE researchers in the field of time and frequency measurements, which have been key to realising the second and enabling its dissemination around the globe. We recognised these achievements in presenting the LNE Research Award to three LNE-SYRTE researchers for their significant contribution to these efforts.

In 2017, LNE stepped up its focus on a range of emerging fields that offer great potential, including smart grids and photovoltaics, while addressing issues of concern to society as a whole, such as air and water quality and public health issues linked to the packaging of consumer goods. These are just a few examples of the vast array of research projects undertaken by LNE and they perfectly illustrate two key components of our mission statement: to support groundbreaking innovations and to act in the best interests of citizens and consumers. ■

# LNE RESEARCH IN 2017:

25%
of the total
**LNE budget**

75
**research projects**

88
**articles**
published in
peer-reviewed journals

16
**PhD students**

200 **doctors and engineers**

A portfolio
of 13 **patents**

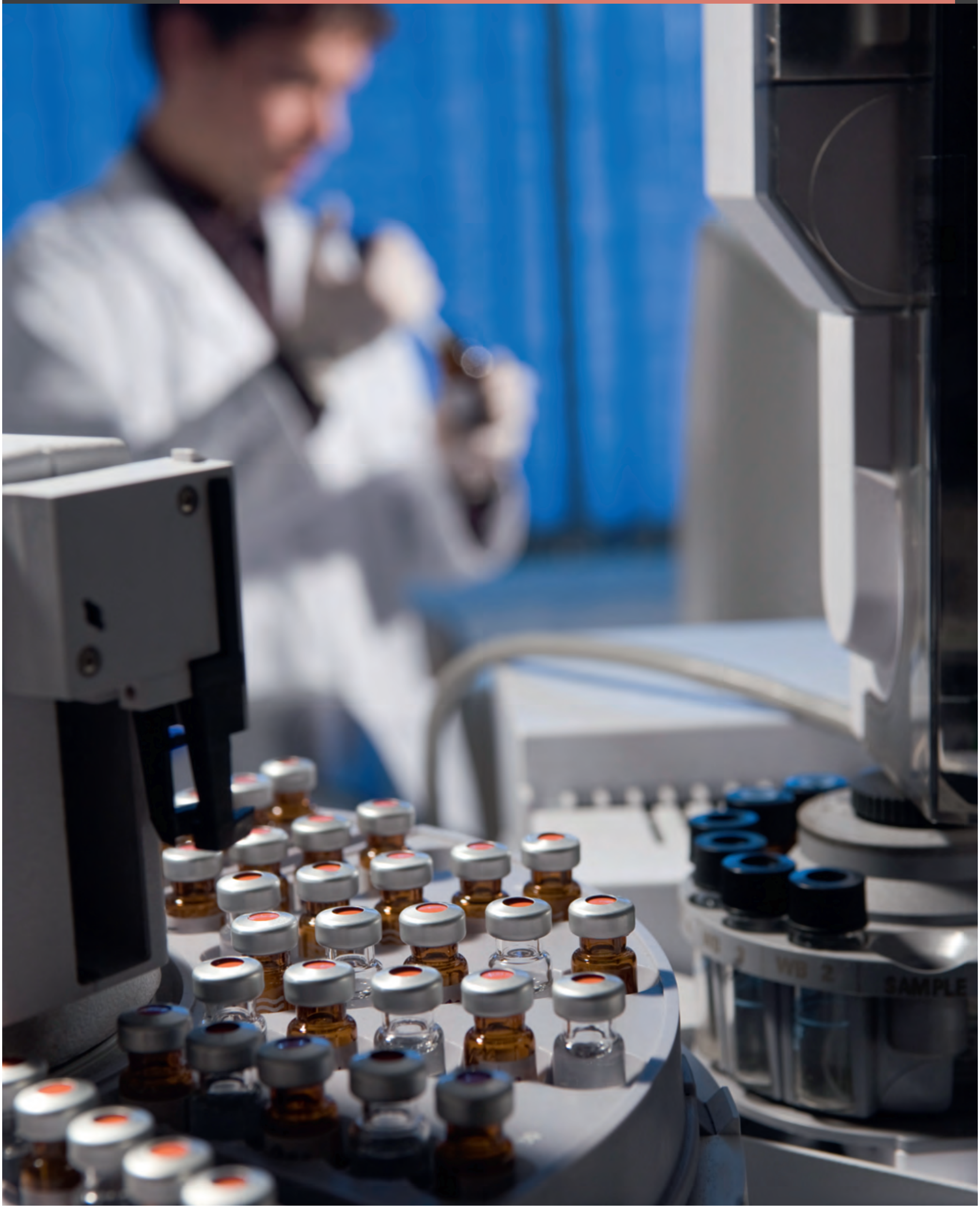
# FRENCH NATIONAL METROLOGY NETWORK RESEARCH IN 2017:

115
**research projects,**
including 60 joint research
projects (JRP)

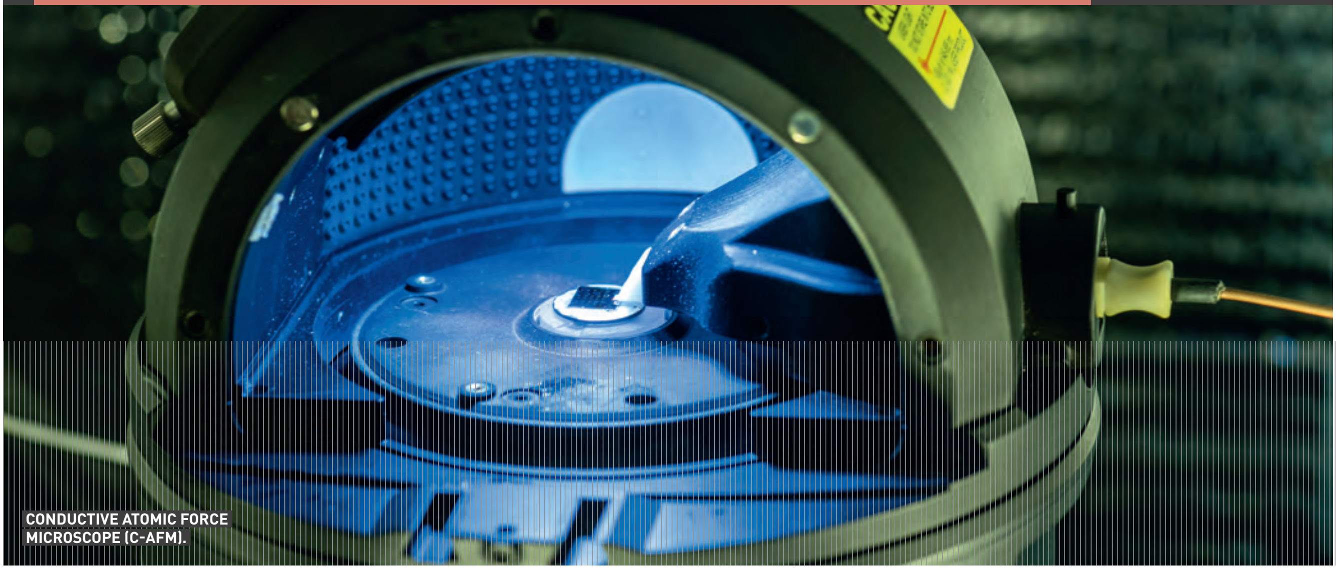
160
**articles**
published in
peer-reviewed journals

238
**papers delivered**

55
ongoing **theses**




# RESEARCH SERVING THE CITIZEN


CONDUCTIVE ATOMIC FORCE MICROSCOPE (C-AFM).

# SOLAR ENERGY AND PHOTOVOLTAICS

## SOLCELL: METROLOGY FOR MULTIJUNCTION SOLAR CELLS

Multi-junction solar cells hold the current record for conversion efficiency, at 46%. As part of the LNE-led SolCell project, a European consortium of laboratories and manufacturers has developed a vast characterisation and metrology program designed to boost and better harness the performance of these unparalleled cells. François Piquemal, project coordinator: "*One of the main benefits of SolCell is the development of a new LED-based solar simulator, which will avoid the need for balloon-based calibration.*"

LNE scientists have made significant progress in designing tunnel junctions used to connect new semiconductors, such as "narrow-gap" semiconductors, to expand the light spectrum that can be used by multi-junction cells. The physicist is delighted with the results, commenting: *"These efforts have led to a promising new cell."*

Meanwhile, several groups, including an LNE team, have shown the benefits of using scanning microwave microscopy to determine the dopant profiles of the different layers of semiconductor materials used to make cells on a nanometric scale. *"We have demonstrated how this technique can be used to measure a reference standard to better characterise the properties of materials," says the project coordinator, who emphasises the "extraordinary interaction between SolCell partners".* ■

## NEW METROLOGY FOR THE PHOTOVOLTAIC INDUSTRY

Different types of solar cell have very different characteristics, which can be more or less suited to the climate and weather found in different parts of the world. Today, the performance of a PV cell is stated only in terms of its maximum power rating, which is estimated at a perpendicular incidence and temperature of 25 °C, with an irradiance of 1000 watts per $m^2$. Hence the importance of fine-tuning current metrology benchmarks and coming up with new ones able to allow for this disparity. That is the goal of the European PhotoClass project, which involves nine partners, including LNE.

As part of the project, /LNE-LCM scientists have developed a new approach to better characterise the spectrum of sun simulators used to test the performance of PV cells. *"Many tests are carried out using artificial sources that can only partially simulate the sun's spectrum. These differences determine the corrections needed to eventually determine the power of a PV cell,"* explains Jimmy Dubard, LNE-LCM project manager. The researcher and his team measured the spectrum of pulses from flash lamps along with the related time dependence.

LNE-LCM specialists were also involved in measurements to characterise different modules based on temperature and irradiance. Their findings will help establish new standards that better reflect the different conditions in which PV cells are used around the world. ■

# A NEW REFERENCE STANDARD FOR RADIOTHERAPY

**LNE-LNHB researchers have devised a new reference standard for very narrow beam radiation to better determine the dosage given to a patient during radiotherapy.**

Some radiotherapy methods, such as intensity modulated radiotherapy (IMRT), require very narrow high-energy beams (< 1 cm²). However, it is often difficult to measure the exact dose delivered during this type of therapy, since the systems routinely available in hospitals are calibrated based on doses from beams that are 100 times wider. To reduce the resulting uncertainty, LNE-LNHB researchers have developed a new primary measurement standard with a subcentimetre cross section.

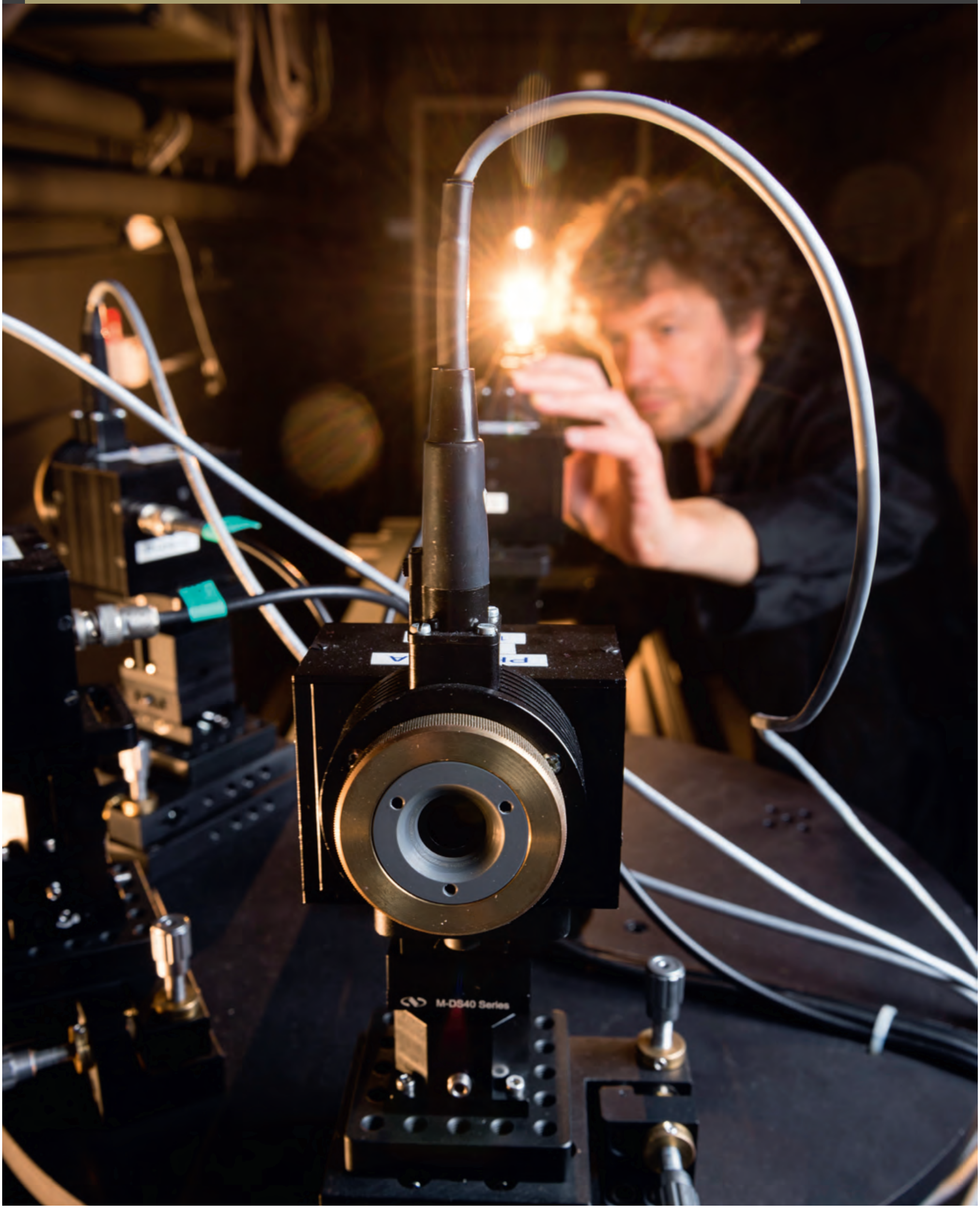
To be more precise, when the width of an X-ray beam is reduced, its energy spectrum changes, which affects dosage measurement. Yet the software used to calculate the dose delivered by the narrow beam is based on a wider benchmark beam and does not take this difference into account. Hence the importance of having a reference standard specific to narrow beams.

This kind of benchmark is generally established using a calorimeter: the standard dose, which reflects the dose absorbed at a given point by 10 cm of water, is calculated based on the resulting rise in temperature measured by the calorimeter at the centre of the beam. However, for beams with a cross section of less than 1 cm², this type of measurement is hampered by the fact that the size of the calorimeter cannot be reduced ad infinitum.

## A CALORIMETER TO CALCULATE THE DOSE ACROSS THE ENTIRE BEAM AREA

LNE-LNHB physicists got around the problem by adopting a fresh approach, which involved designing an even bigger calorimeter... Instead of measuring the dose delivered by the beam at a central point, it measures the integral dose across an area that is wider than the direct beam. Rising to the challenge meant dealing with conflicting requirements related to the size of the calorimeter: on the one hand, they needed a detection area large enough to incorporate most of the beam (including diffuse radiation along the edges); on the other, they needed a calorimeter small enough to accurately measure an average rise in temperature. This led to a system able to gauge the dosimetry of a beam between 1 cm and 0.75 cm in diameter, compared with the 2 cm possible with the previous method.

Physicists at radiotherapy facilities will continue to calibrate their beams for a radiation area of 100 cm², which is the standard used for off-the-shelf software. However, they can also ask LNE-LNHB to calibrate their integral dose detector to compare the dose predicted by their software to that measured by the detector. The service is not yet available but the new calorimeter is ready to be used for beams in the new medical accelerator. ■




# RESEARCH SERVING THE INDUSTRY

# LIGHT-EMITTING DIODES: BESPOKE METROLOGY

**As LEDs continue to replace incandescents and halogens, the MESaIL project aims to offset the current lack of a metrological chain to characterise them.**

As we look for more sustainable solutions in a world where lighting represents 19% of electricity consumption, light-emitting diodes (LEDs) are set to become the dominant lighting technology based on their improved energy efficiency. The Metrology for Efficient and Safe Innovative Lighting (MESaIL) initiative—involving LNE and 13 other European partners—ended in 2017. The project was designed to develop a new metrological traceability chain for these different types of lighting, assess their lifespan and review issues related to safety and comfort.

Dominique Renoux, project manager for LNE: *"Today's reference standards are for halogens and incandescents, hence the need to offer a new approach."* MeSalL produced two new reference standards: an electric standard for energy-use metrics, and an optical standard for luminous-flux metrics. LNE researchers were instrumental in realising the latter.

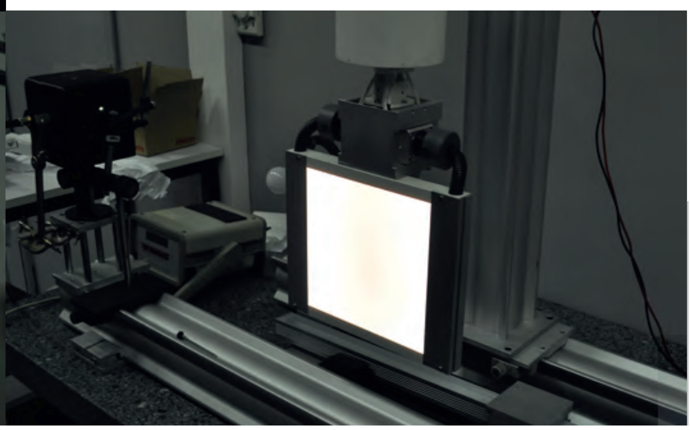
The French team created 15 devices to simulate different types of lamp—globe, tube and panel—using a source designed by the project's German partners.

The solution gives manufacturers a means of calibrating their measuring systems, as the project manager explains: *"This standard makes it possible to measure the spectrum, intensity distribution, variation over time and geometric distribution of a source. These quantities are important in determining parameters such as luminous flux and colour temperature, which feature in bulb specifications."*

## SIMULATING DIFFERENT TYPES OF LED

LNE specialists drew on different resources to study the accelerated ageing of recent technologies like Chip-on-Flex (COF), LED strips and organic LEDs, and set up a new testbench to measure variation over time (modulation) for these lighting systems. They devoted significant efforts based on subjective experiences to studying this last aspect and its impact on user perception. The team looked at how source frequency can affect attention when reading, for example. Previous findings had suggested that higher frequencies lead to less user discomfort as a result of the human eye's ability to filter light intensity. However, these latest results appear to show the opposite is true. According to Dominique Renoux: *"We still need to fine-tune our statistical analysis but the findings of our Swedish counterparts seem to dovetail with our own."* The proposed hypothesis suggests that greater sensitivity to higher frequencies could be due to the saccades involved in visual tasks. Watch this space! ■

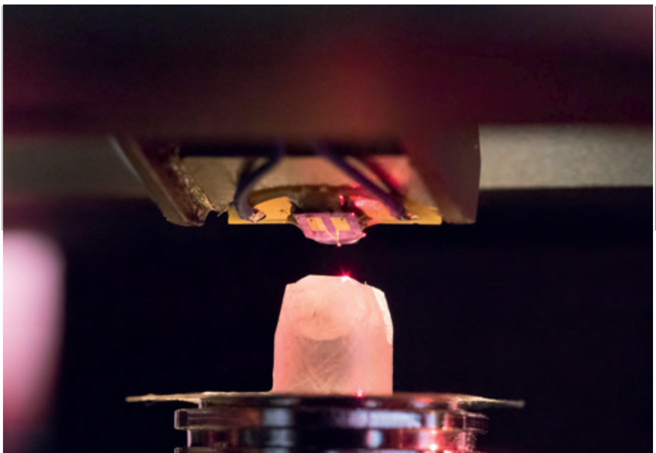
« TODAY'S REFERENCE STANDARDS ARE FOR HALOGENS AND INCANDESCENTS, HENCE THE NEED TO OFFER A NEW APPROACH FOR LEDS.» - Dominique Renoux



LNE CREATED DIFFERENT LIGHT SOURCES USING A PTB MULTI-LED BENCHMARK.

# THERMAL PROPERTIES OF MATERIALS

## NANOSCALE THERMAL MEASUREMENTS

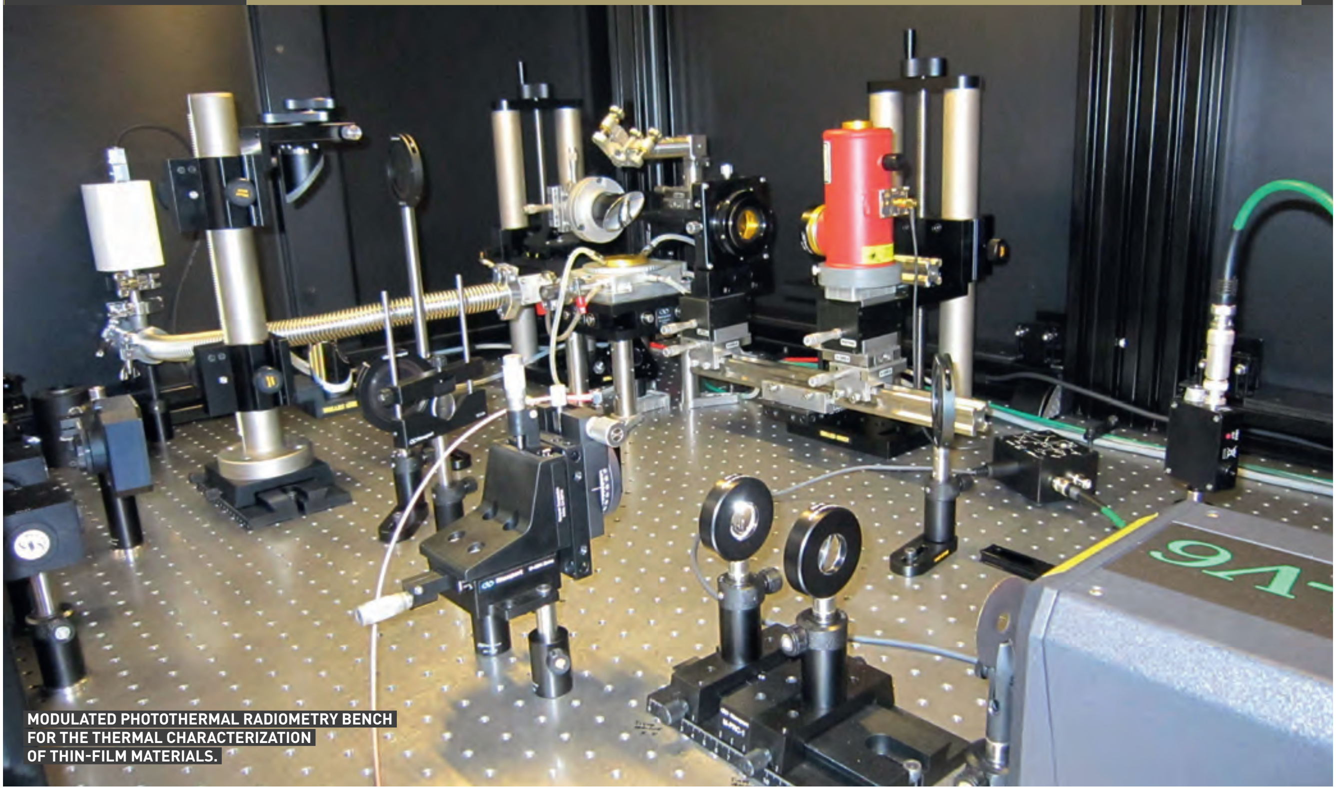

RESISTIVE TIP OF A SCANNING THERMAL MICROSCOPE ABOVE A SAMPLE OF POLYMETHYL METHACRYLATE (PMMA).

**A new approach using an atomic force microscope could enable quantitative measurements of thermal conductivity accurate to tens of nanometres.**

Many protocols routinely used to determine the properties of materials falter when it comes to nanometre-scale measurements. The same goes for those used to determine the thermal properties of materials, which limits the ability to characterise and conceive materials and devices on the scale of a few atoms. To overcome the problem, LNE researchers joined a number of European labs on the QuantiHeat project to study a new solution to measure thermal conductivity with the utmost precision.
The spatial resolution of the methods typically used for quantitative measurements, based on optical techniques, is limited to 500 nanometres. To increase that resolution, an alternative method known as scanning thermal microscopy (SThM) uses an atomic force microscope (AFM) equipped with a thermo-resistive filament to effectively map the thermal conduction properties of materials down to a few dozen nanometres. However, the results are only qualitative.

### 20% UNCERTAINTY ON A NANOMETRIC SCALE

To boost performance, LNE specialists began by improving the method of measuring thermal conductivity using SThM. The conventional approach to determining the position of the SThM tip uses a laser that can itself interfere with thermal measurements. *"We replaced it by continuously monitoring the resistive signal from the tip, which varies according to its distance from the surface of the sample,"* explains Bruno Hay, project manager for LNE. The researchers also took things a step further by publishing the new procedure in a public document in the format of a standard.
The next step was to calibrate the device. LNE scientists accurately determined the macroscopic thermal properties of a set of materials that could be used as reference measurement standards, using an SI-related absolute method. Another lab involved in the project then analysed the way in which these properties vary when the scale at which they are studied is gradually reduced. This provided a means of comparing measurements obtained using the new method. The LNE team eventually proved that their method enables measurements with a maximum uncertainty of 20% for thermal conductivity below 10 W $m^{-1}$ $K^{-1}$, even though, as the project manager admits: *"The calibration stage was harder than expected due to surface conditions and issues related to oxidation of the reference materials."* Yet there is no denying the results: *"We've paved the way in an area of metrology that was previously untouched!"*
The new approach could initially be used in microelectronics, where component miniaturisation encounters problems related to heat dissipation. It will now be possible to tackle these problems on a much smaller scale!



MODULATED PHOTOTHERMAL RADIOMETRY BENCH FOR THE THERMAL CHARACTERIZATION OF THIN-FILM MATERIALS.

# UNLOCKING THE THERMAL PROPERTIES OF THIN-FILM MATERIALS

**A new testbench based on photo-thermal radiometry can determine the thermal properties of micrometric and sub-micrometric films.**

Computer memories, solar panels and LEDs are just some of the technologies that require the use of extremely thin layers of materials, for which it is vital to determine thermal properties according to temperature and thickness if they are to be used effectively. Unfortunately, conventional techniques tend to falter at such scales, which is why the LNE Materials team developed a new system able to determine the thermal conductivity of materials with a thickness of just a hundred nanometres at temperatures ranging from room temperature to 1000 °C.

The new approach uses photo-thermal radiometry to determine the thermal properties of a material, by studying its response to laser-induced excitation. In practice, the method involves measuring the phase difference between the excitation signal and the sample response. Thermal conductivity is then calculated by comparing the experimentally-determined response to heat transfer models.

However, things get complicated when dealing with a thin film on top of a substrate. You need to be sure you are measuring the properties of the top layer alone and not those of the film and substrate combined. How? By varying the frequency of the excitation signal: the higher the frequency, the less the excitation penetrates the material. The thermal properties of the thin film can thus be calculated once the thermal properties of the substrate are known.

## FROM 100 NANOMETRES TO 500 MICROMETRES

The EU ThinErgy project provided a testbench to determine the thermal conductivity of phase-change materials: when subjected to an increase in temperature, their molecular structure undergoes a transition from an amorphous state to a crystalline state, which means they could be used to create a new type of memory.

According to Nolwenn Fleurence, project manager for LNE: *"We have yet to accurately determine our range of uncertainty. Research is ongoing to that effect. However, we have obtained results consistent with those established in today's literature for a temperature range between room temperature and 500 °C. We have also developed specific protocols to calibrate temperature and frequency."*

Researchers are now working to expand the project to determine the thermal diffusivity of a thin film, which represents the rate at which heat spreads through the medium. The difficulty lies in dealing with the very high acquisition frequency needed to reconstruct the signal given the fleeting nature of the sample response. As a result, the scientists plan to draw on "heterodyne" methods to introduce a slight delay between the excitation and acquisition frequencies. Nolwenn Fleurence: *"We can then reconstruct the signal to establish the complete sample response."* Initial applications could include PV cells and coatings for low-emissivity glass. ■

# IMPROVED ACCURACY FOR TOMORROW'S SMART GRIDS

**Doped optical fibres will eventually provide a more accurate reference standard to measure the current in smart grids.**

Smart grids will continue to grow in complexity as they adapt to factors such as the intermittent nature of renewables, the different types of power-generation infrastructure and the feed-in potential of consumers. Hence the need for more precise measurements across a wider range of electrical frequencies, including high-current circuits. LNE researchers have made significant progress toward creating a benchmark sensor to accurately calibrate commercially available instruments.

Their work was part of an EU project for a type of fibre-optic sensor based on the Faraday effect. These sensors can indirectly measure an electric current by calculating the change in the polarisation of light in an optical fibre in the magnetic field created by the current. Daniela Istrate, project manager for LNE: *"These sensors are not in contact with the electrical system and are extremely well suited to high voltages and currents. However, they have a relative uncertainty of $10^{-3}$. We need to gain an order of magnitude to ensure traceability."*

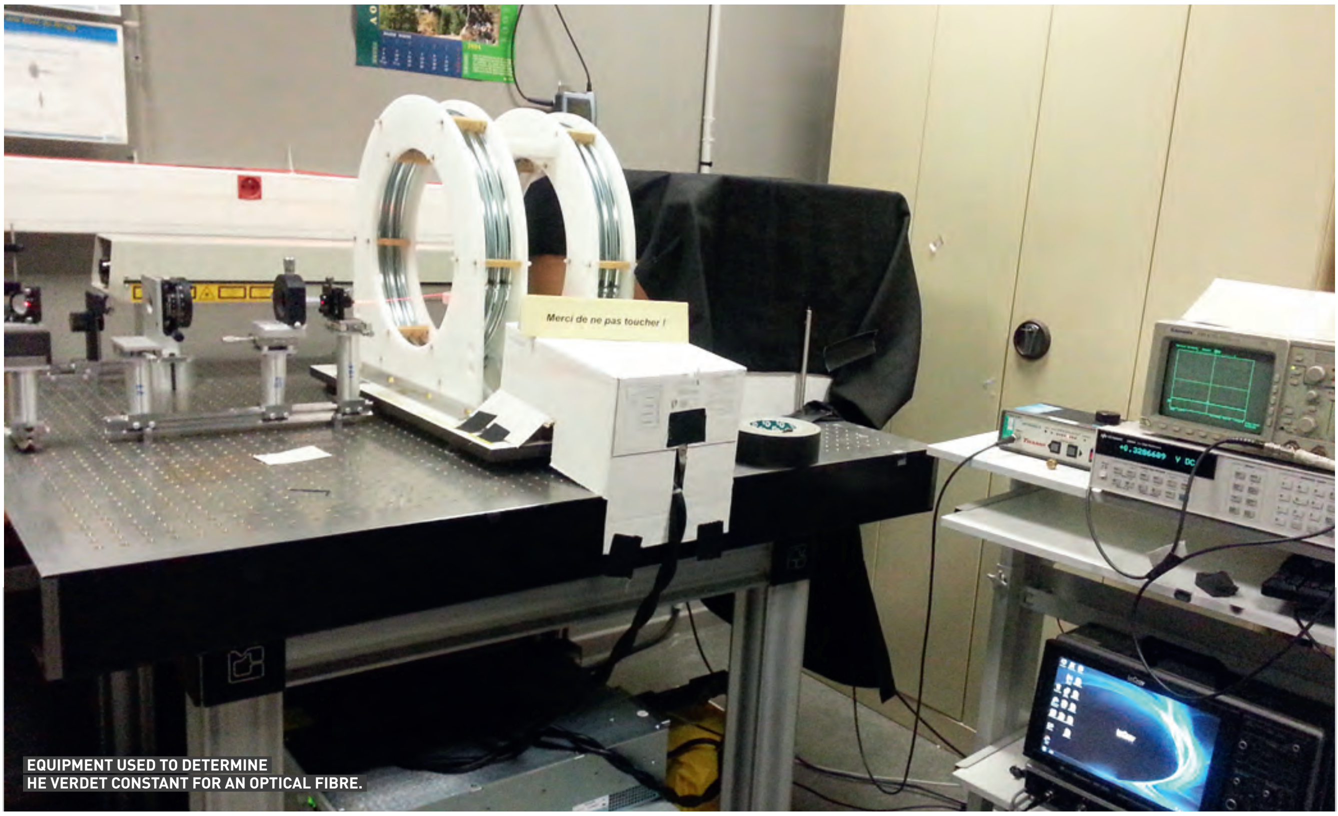
To do that, metrologists had to virtually start from scratch. The Faraday effect is even greater at shorter wavelengths. Commercially available optical fibres are designed to carry beams of light at wavelengths that are too long in terms of the target sensitivity. As a result, the project began by designing new rare-earth doped optical fibres in partnership with a manufacturer and academics.

## RARE-EARTH DOPED OPTICAL FIBRES

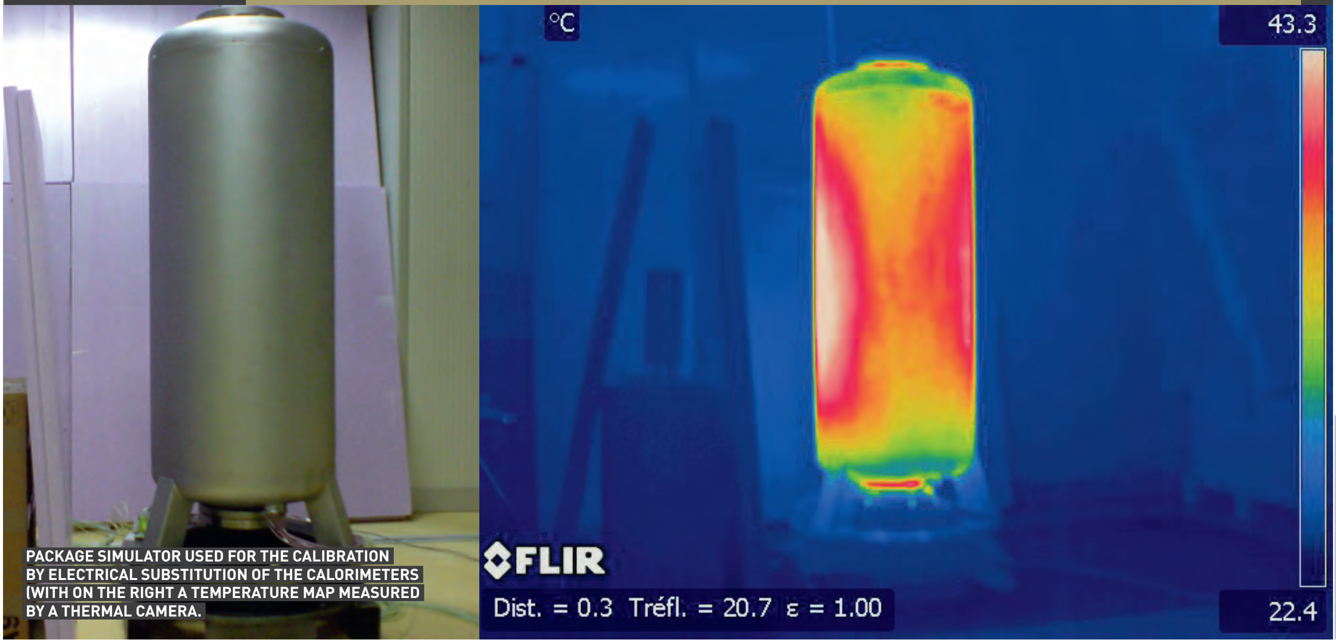
LNE scientists then created a testbench to determine parameters for the Faraday effect in these fibres. They also developed specific testbench software. Measurements conducted on five fibres were used to select the most suitable candidate for the current sensor. However, the temperature-induced variation in the Faraday effect was greater than expected, based on the values found in the available literature, and will require further analysis.

Daniela Istrate comments: *"Our findings bode well for the future and suggest it will be possible to create a reference sensor able to achieve a relative uncertainty of $10^{-4}$ up to 10 kiloamperes for a frequency range between zero and one megahertz."*

The project also provided a blueprint for the sensor build and a prototype is now being made. This should eventually ensure current measurement traceability with a level of precision needed for tomorrow's smart grids. ■




EQUIPMENT USED TO DETERMINE HE VERDET CONSTANT FOR AN OPTICAL FIBRE.




PACKAGE SIMULATOR USED FOR THE CALIBRATION BY ELECTRICAL SUBSTITUTION OF THE CALORIMETERS (WITH ON THE RIGHT A TEMPERATURE MAP MEASURED BY A THERMAL CAMERA.

# A CALORIMETER TO MEASURE THE AMOUNT OF HEAT GIVEN OFF BY PACKAGED RADIOACTIVE WASTE

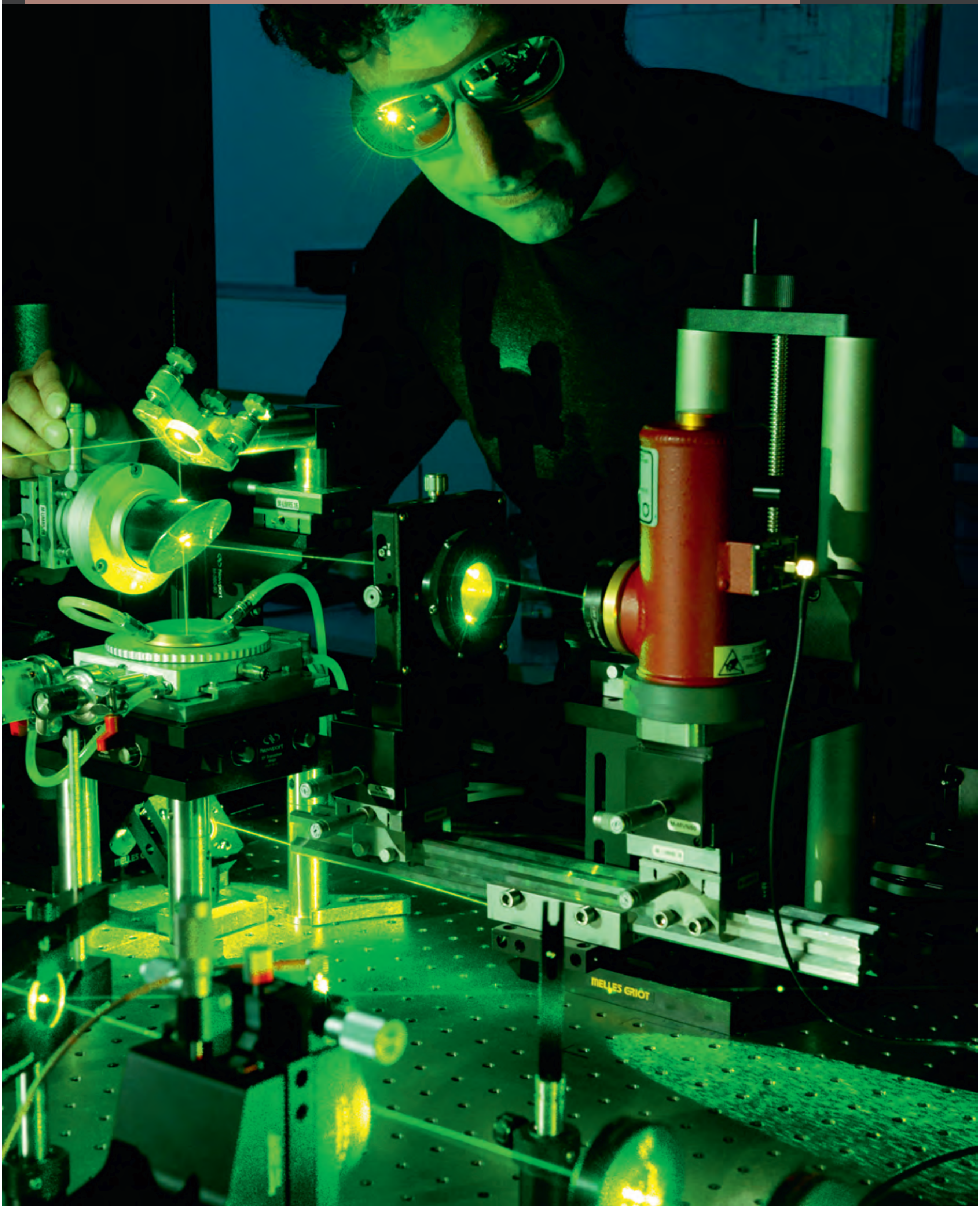
**Two prototype calorimeters were developed for Cigeo, a deep geological disposal facility for radioactive waste in France, to measure the amount of heat given off by waste "packages".**

The heat given off by packaged radioactive waste destined for deep geological storage (as part of the Cigeo project) needs to be checked and measured to ensure compliance with storage requirements. Measuring this thermal output requires specific metrology. To provide the necessary resources, LNE partnered with the French radioactive waste management agency (Andra) to develop two solutions for high-capacity calorimeters.

According to Bruno Hay, project manager for LNE: *"The project uses standard calorimeter metrics. However, there are also three considerations in terms of thermal metrology specific to the nuclear environment."* The first is size. At the start of the project, the largest calorimeters on the market were only suitable for volumes of a few dozen litres, yet radioactive waste packages contain between 175 litres and 2 m$^3$. Second, measurements have to cover a wide range of thermal outputs, typically ranging from a few watts to several hundred watts, with a maximum uncertainty of around 5%. Third, the radioactive environment requires instruments that can withstand radiation.

LNE researchers developed two prototype calorimeters to overcome these challenges. The first is based on the principle of an airflow calorimeter. The heat released by a package placed in a chamber is determined by measuring the temperature difference in the air flowing into and out of the chamber. The second proposed solution involves a flux calorimeter, for which a 1:5 prototype has already been made. This system involves placing the package in two concentric chambers and then determining thermal output by measuring the temperature difference between the two chambers. In both cases, the calorimeters were calibrated using package simulators with built-in heating resistors. Modelling solutions also helped predict how the flux calorimeter would behave at full size.

Bruno Hay comments: *"The uncertainties in our measurements are between 1% and 7%."* The team of specialists have also stressed that the flux calorimeter is easier to use for taking measurements. With airflow calorimeters, the flow of air passing through the chamber has to be adapted to the range of package heat dissipation, which requires continual recalibration. Whichever method is chosen, LNE has delivered two viable solutions! ■



# RESEARCH SERVING THE SCIENCE

# CHANGES TO THE INTERNATIONAL SYSTEM OF UNITS

**Maguelonne Chambon,**
Director of Research in Science and Technology

***In 2018, four SI units are set to be redefined. As a result, 2017 marked a turning point for LNE and laboratories in the French National Metrology Network (RNMF).***
The 2018 General Conference on Weights and Measures (CGPM) is set to adopt a new definition for four of the seven SI base units, including the kilogram, kelvin, ampere and mole. To meet a growing need for greater precision, the goal is to give the units more universal scope by basing them on fundamental physical constants, just as the metre was redefined in relation to the speed of light in 1983.
In practice, redefining the kilogram and kelvin means linking them to an exact numerical value of Planck's constant ($h$) and the Boltzmann constant ($k$). Researchers at LNE and RNMF laboratories made huge strides this year in delivering values for these two constants with unprecedented precision.

***Was this the culmination of long-term research?***
Yes. LNE first began work to measure h back in 2001. We are very proud to be one of the three teams to have measured the constant using the watt balance experiment, with minimum uncertainty, while our competitors benefited from 30 or 40 years' experience. As for the value of k, our teams set a world record in achieving a measurement with the lowest-ever level of uncertainty using a highly innovative approach that was not without its risks. We owe these successes to our highly skilled, highly motivated teams, led by scientists of the highest calibre.

***Will the SI overhaul also provide new reference measurement standards to realise these new definitions?***
Absolutely, and this is something to which LNE contributed in 2017 by realising the first quantum standard for the ampere, embodying the new definition due to be adopted in 2018. The system is based on the quantum Hall effect and the Josephson effect, in which our teams draw on 30 years' experience. This is an accomplishment built on solid foundations and sound ideas, which enabled a realisation of the ampere when the previous definition was impracticable.

***What's next?***
With units now set to have a much more theoretical definition, the next step will entail a major campaign to share information with end users, especially manufacturers. That is the role of LNE and RNMF laboratories, and it is a priority for our team. For the kilogram, there are plans to conduct calibration campaigns in line with the new system. For the kelvin, our teams are working to assign values to different fixed points and provide methods for interpolation between them. For the ampere, we have already begun work to transition from lab experiments to practical applications. Important efforts are also underway to redefine the second in the next few years.

***Can we expect these changes to revolutionise metrology?***
From a conceptual standpoint, yes, no doubt. That said, these new unit definitions will be adopted gradually, in step with needs and in line with the current system. Revamping the International System of Units will have implications for extreme measurements (e.g. on nanometric scales, for long distances and at very high temperatures) and will open up new fields of expertise with regard to climate, biology and healthcare. ■

# USING PLANCK'S CONSTANT TO PROVIDE A MORE UNIVERSAL DEFINITION OF THE KILOGRAM

## UNPRECEDENTED PRECISION IN MEASURING PLANCK'S CONSTANT IS PAVING THE WAY FOR A NON-PHYSICAL DEFINITION OF THE UNIT OF MASS

The General Conference on Weights and Measures (CGPM) is set to redefine the SI base unit for mass in 2018. This new definition will no longer be embodied by a physical object but will instead be linked to Planck's constant (*h*), which is central to quantum mechanics. In 2017, scientists from LNE, CNAM and the Paris Observatory teamed up with other laboratories around the world to measure this fundamental constant with unprecedented precision. This laid the groundwork for a new, non-physical definition of the kilogram.

« LNE IS ONE OF THREE LABORATORIES TO HAVE ASSIGNED A VALUE TO *h* USING A KIBBLE BALANCE WITH A LEVEL OF UNCERTAINTY THAT MATCHES BIMP CRITERIA FOR THE REDEFINITION OF THE KILOGRAM.»
- Matthieu Thomas

Since 1889, the kilogram has been defined as the weight of a platinum-iridium cylinder known as "Le Grand K" (International Prototype of the Kilogram – IPK), which sits in a vault at the International Bureau of Weights and Measures (BIPM) in Sèvres, on the outskirts of Paris. In the past century and a half, the mass of this artefact has in fact changed by around 50 micrograms compared with that of its replicas. Aside from the problem of creating an unreliable standard for weight measurement, this drift also impacts other units, such as the newton, joule and watt, whose definitions are linked to that of the kilogram. Not to mention the fact that basing any global standard for weighing things on a single object is not without problems. Hence the idea of redefining the kilogram in relation to Planck's constant, which is both intangible and universal. The constant is the product of energy multiplied by time, with the energy linked to mass by Einstein's equation $E=mc^2$. ■

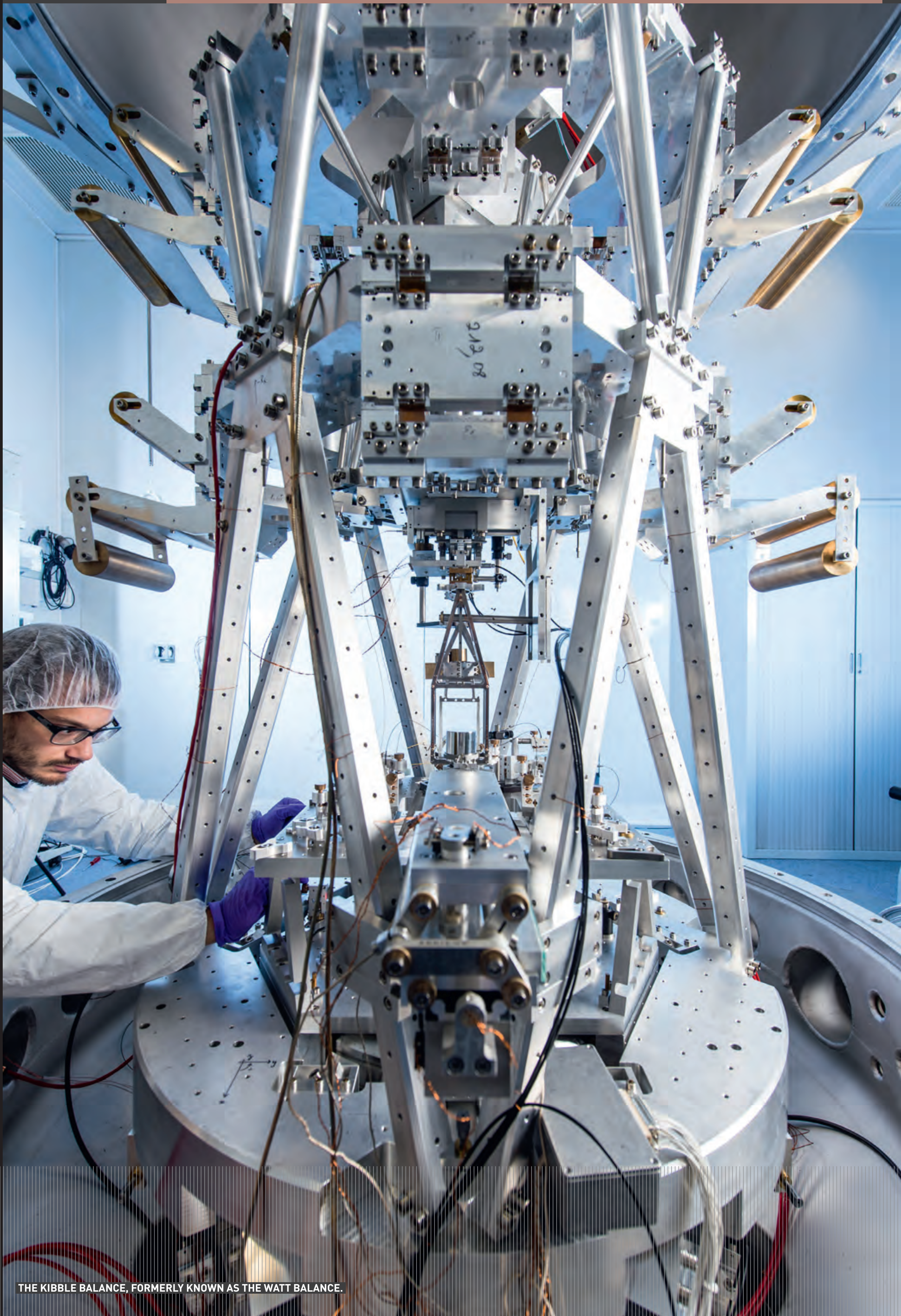
## A BALANCE TO CALCULATE PLANCK'S CONSTANT

Researchers calculated Planck's constant using a Kibble balance, which works as follows: a mass is suspended from one arm of the balance while the other holds a wire coil inside a magnetic field. A two-step process is then used to establish a relationship between the mass and the coil force and current. Planck's constant can be calculated by measuring the current and voltage and applying the Josephson and quantum Hall effects.

In 2016, several laboratories involved in redefining the kilogram carefully compared their mass standard to the BIPM benchmark, which was a vital first step towards accurately measuring Planck's constant. LNE took measurements over 30 consecutive days between February and March 2017 to produce a value for h with a relative uncertainty of $5.7\ 10^{-8}$.

According to Matthieu Thomas, *"Along with the Canadian and US teams, LNE is one of three laboratories to have assigned a value to h using a Kibble balance with a level of uncertainty compliant with BIPM guidelines for the redefinition of the kilogram."* It will therefore be among a select group responsible for officially determining the value of Planck's constant in 2018.

Once the new definition of the kilogram is in place, LNE's Kibble balance and its counterparts around the world can be used to calibrate any mass without the need for a physical object, by working back from the measurement used to calculate *h*. "Le Grand K" can then be put in a museum and the kilogram safely based on a truly universal standard. ■



THE KIBBLE BALANCE, FORMERLY KNOWN AS THE WATT BALANCE.

# CALCULATING THE BOLTZMANN CONSTANT WITH UNPRECEDENTED PRECISION

## USING AN ACOUSTIC THERMOMETER, LNE-CNAM SCIENTISTS HAVE PIONEERED A NEW DEFINITION OF THE KELVIN BASED ON A FUNDAMENTAL PHYSICAL CONSTANT

The SI base unit for temperature, the kelvin, will be redefined in 2018. Rather than being based on a physical object, as it is today, it will be directly linked to one of the fundamentals of physics known as the Boltzmann constant (*k*). As a prerequisite to this minor revolution in the world of metrology, the value of k will first need to be calculated with the smallest possible degree of uncertainty. LNE-CNAM researchers rose to that particular challenge this year by measuring the Boltzmann constant with unprecedented precision.
Since 1968, the kelvin has been defined as a fraction equal to 1/273.16 the temperature of the triple point of water, at which water exists in equilibrium in all three phases: solid, liquid and gas. This corresponds to 0.01 °C, or 273.16 K. However, the definition depends on the quality of the water used (impurities, isotopic composition, etc.), which has naturally varied over the years. In addition, because it is linked to a specific temperature, it is poorly suited to extreme cold and heat (below 20 K or above 1300 K).
To get around the problem, scientists had to look beyond the macroscopic characteristics of a given medium (in this case water) to find a universal definition. Hence the recommendation from the General Conference on Weights and Measures (CGPM) to base the kelvin on the microscopic definition of temperature, i.e. a measurement of the thermal agitation of atoms in a medium, irrespective of the chemical nature of its constituent parts, with thermal agitation linked to temperature via the Boltzmann constant. ■

ACOUSTIC THERMOMETER.

## USING AN ACOUSTIC THERMOMETER TO DETERMINE THE BOLTZMANN CONSTANT

To fix the value of the Boltzmann constant, lab scientists developed a new approach using an acoustic thermometer shaped like a sphere to measure the speed of sound in a gas within a virtually spherical chamber at a temperature matching the triple point of water. This was directly related to the 1968 definition of the kelvin. In practice, however, the sensitive experiment took a decade of development to adapt to complex considerations such as thermometry, gas purity, acoustic and electromagnetic phenomena, modelling of disturbances and more. As Laurent Pitre comments, *"When we started out, the mathematical tools needed to analyse findings weren't even available."*

Their efforts paid off in 2017, when they eventually calculated the Boltzmann constant with record precision and a relative uncertainty of $0.57 \times 10^{-6}$, which was a threefold improvement on the previous standard. This accuracy means the calculations of physicists at the French laboratory will contribute up to 55% of the value of *k*, which will now be used to revamp the SI units. Once the kelvin has been redefined, temperatures can reliably be measured with an uncertainty of below one part per million over the course of a century. This applies to all measurements from absolute zero to several thousand degrees Celsius. French researchers at LNE-CNAM were at the forefront of this revolution. ■

# THE AMPERE ENTERS THE QUANTUM ERA

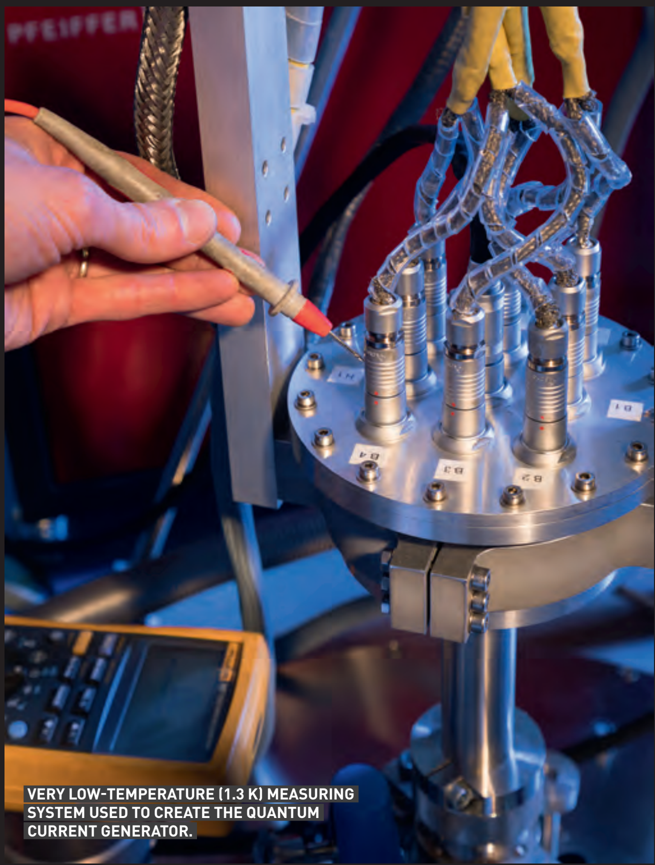
« OUR STANDARD IS THE FIRST EXAMPLE OF A SOLUTION COMBINING TWO QUANTUM STANDARDS. IT IS ACCURATE TO WITHIN $10^{-8}$ AND EMBODIES THE FUTURE DEFINITION OF THE AMPERE.» - Wilfrid Poirier

## A NEW SOLUTION HAS ENABLED AN ELECTRIC CURRENT STANDARD TO REDEFINE THE AMPERE AND ENABLE UNPARALLELED PRECISION

Since 1948, the ampere, the SI base unit for electric current, has been defined based on the electromagnetic force between two wires carrying a current one metre apart. However, this definition is hard to realise. It is also quite far removed from the fundamental nature of a current, i.e. the flow of electrical charges per second. Hence the idea of redefining the ampere based on the elementary charge (*e*), which led LNE researchers to create a standard embodying the new definition with a record relative uncertainty of $10^{-8}$.
In practice, the standard for electric current is obtained from two other standards, for voltage and resistance. Their units — the volt and the ohm— can be realised with an uncertainty of $10^{-9}$ using two quantum effects (the Josephson and quantum Hall effects), which depend only on *e* and Planck's constant. The ampere is then realised by applying Ohm's law, which describes the relationship between voltage, current and resistance. In concrete terms, the law is applied to physical devices that, even when calibrated using quantum standards, are subject to continuous or incremental change over time. Ampere-related uncertainty is typically $10^{-6}$.
To improve on this, LNE scientists developed a quantum circuit to apply Ohm's law directly to quantum standards for voltage and resistance. In practice, they had to find a way to get around the problem of parasitic resistance in the electrical connections between the two standards, which was causing errors in the quantum standard for current. They based their solution on the properties of the quantum Hall effect, which allow for additional connections between the two standards, in which the flow of current grows weaker, the more connections are added. As a result, the parasitic potential affecting the connections drops to become negligible and the current can be perfectly quantised. ■

## A CURRENT PROPORTIONAL TO THE ELEMENTARY CHARGE

A super-sensitive, ultra-accurate amplifier then combines the currents to provide a reference quantum current. This gives a current that can be exploited using feedback between an external source locked on a reference current. Wilfrid Poirier, senior research scientist, comments: *"Our standard is the first example of a solution combining two quantum standards. It is accurate to within $10^{-8}$ and embodies the future definition of the ampere since, by using the quantum Hall and Josephson effects, it can provide a current proportional to the elementary charge."*
The device remains quite intimidating, given the need for no fewer than three cryogenic systems to cool the quantum voltage and resistance standards and the amplifier to a temperature close to absolute zero. However, as the researcher explains: *"We have shown that it is possible to obtain the quantum Hall effect in graphene within a weaker magnetic field and at a more manageable temperature than in the kind of gallium arsenide samples used today. Eventually, we will need only one cryostat to implement the standard."* The new solution is nonetheless ready to use in redefining SI units in 2018. ■



VERY LOW-TEMPERATURE (1.3 K) MEASURING SYSTEM USED TO CREATE THE QUANTUM CURRENT GENERATOR.

# OPTICAL CLOCKS: RAMPING UP RELIABILITY

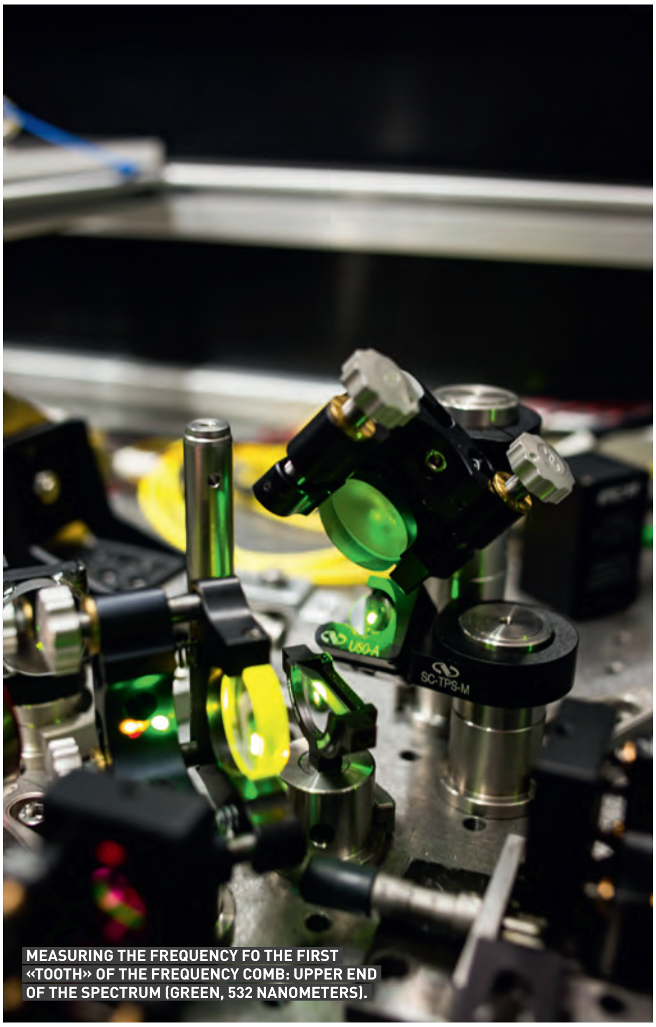
**The SAMIROF chain of measurements is now fully operational and paves the way for extremely precise comparisons between the next generation of atomic clocks.**

In the next 10 years, optical atomic clocks are set to replace their caesium counterparts to provide a more accurate definition of the second. These new clocks use a resonance frequency that is much higher than the microwave radiation used in caesium clocks and are intrinsically much more accurate. LNE-SYRTE has been developing the SAMIROF project since 2011 to ensure the routine reliability of these clocks. The project reached maturity this year.
SAMIROF aims to enable a long-term comparison between signals from six SYRTE atomic clocks. More specifically, it compares the signals from the three optical clocks with one another or with those of the lab's caesium clocks.
The principle is well established and involves using short pulses from a femtosecond laser. According to Rodolphe Le Targat, LNE-SYRTE: *"These pulses present a frequency spectrum like a comb with teeth that are very close together and very evenly spaced. They can measure the extremely high frequency of an optical clock just as a finely graduated ruler can measure distances to a very high degree of accuracy."*
All that remained was to use the new approach for long-term comparisons as part of a key campaign to stabilise the chain of measurements, including high-end automation and computerisation. *"With SAMIROF, we are now able to draw comparisons spanning several weeks without the need for human input, whereas previously they spanned only a few hours and required someone to make continual adjustments. SAMIROF also includes a fibre-optic connection between our clocks and those at other laboratories in France and elsewhere in Europe, with a view to highlighting any systematic errors specific to a particular research team."*

«THROUGH SAMIROF, WE ARE NOW ABLE TO DRAW COMPARISONS SPANNING SEVERAL WEEKS WITHOUT THE NEED FOR HUMAN INPUT, WHEREAS PREVIOUSLY THEY SPANNED ONLY A FEW HOURS AND REQUIRED SOMEONE TO MAKE CONTINUAL ADJUSTMENTS» - Rodolphe Le Targat

## TARGETING THE FUNDAMENTALS OF PHYSICS

SAMIROF also stretches beyond the challenge of measuring time to test the fundamentals of physics. In tracking any drift in frequency between extremely accurate clocks, it enables a study of any change in certain constants, for which some theories predict a variation over time. Similarly, a global network of optical clocks might help us pinpoint that mysterious dark matter that is thought to make up 85% of the universe, but which continues to elude physicists. SAMIROF is also key to operating the PHARAO space clock. In the next two years, PHARAO will be compared to a series of terrestrial clocks and will be used to conduct tests of general relativity from the international space station.
This could lead to a revolutionary new approach to measuring time and perhaps even the fundamental concepts of physics related to it. ■



MEASURING THE FREQUENCY FO THE FIRST «TOOTH» OF THE FREQUENCY COMB: UPPER END OF THE SPECTRUM (GREEN, 532 NANOMETERS).

# TIME AND FREQUENCY:
## LNE-SYRTE RESEARCHERS JOCELYNE GUÉNA, DANIELE ROVERA AND MICHEL ABGRALL RECEIVE THE LNE RESEARCH AWARD

**You received the LNE Research Award this year for your work on time and frequency. What does that involve?**

**Jocelyne Guéna:** We aim to develop and use primary frequency standards for the definition of the second. Based on data from our clocks and those at other laboratories around the world, the International Bureau of Weights and Measures (BIPM) calculates International Atomic Time (TAI) once a month. Once adjusted to allow for any variation caused by the Earth's rotation, TAI is used to define Coordinated Universal Time (UTC). Due to the accuracy and availability of our instruments, our standards provide 40 % of primary calibration worldwide.

**What is the principle of these time and frequency standards?**

**Michel Abgrall:** The definition of the second is tied to the frequency of the transition between two hyperfine ground states of caesium atoms, which provides the absolute reference. The principle involves exciting this atomic transition using a macroscopic oscillator such as a maser, which generates a frequency close to the reference, despite lacking some precision and stability. The further the exciting frequency moves away from the atomic standard, the less reliable the transition rate becomes. Accurately measuring the latter therefore provides a precise measurement of the oscillator frequency deviation, which can then be recalibrated to provide an output signal at an exact frequency.

**How has your team excelled in this particular field?**

**Daniele Rovera:** The accuracy of current measurements relies on the use of an "atomic fountain" that uses caesium atoms cooled to a temperature close to absolute zero. Since they were first introduced in the mid-1990s, our laboratory has pioneered their development along with that of all related equipment. We designed the first prototypes and our atomic fountains now represent the cutting edge of this technology worldwide.

**Jocelyne Guéna:** Until recently, we were the only laboratory to have several fountains, allowing us to consistently provide an ultra-stable frequency standard, which explains the significance of our contribution to the realisation of universal time. The use of our fountains over the past few years has enabled the realisation of UTC, known as UTC(OP), which is accurate to within a few nanoseconds of the UTC calculated by BIPM. Since 2012, we have achieved the same level of performance as the US laboratory tasked with defining time for the GPS system, despite having far fewer resources, which is something we are really proud of.

**Didn't you also develop a portable atomic fountain for in situ calibration?**

**Daniele Rovera:** Yes, we've used the portable fountain lots of times to meet the needs of our European partners. It is the only one of its kind in the world. It was used to characterise and calibrate the PHARAO cold-atom space clock at the French space agency in Toulouse.

**You also developed a rubidium atomic fountain. How does the element compare to caesium?**

**Jocelyne Guéna:** This unique fountain works with both cold caesium atoms and rubidium atoms. Although it isn't more accurate than its caesium counterpart, it can be used to test systematic errors inherent in using another type of atomic transition. Most importantly, it can be used to carry out fundamental physics tests through caesium/rubidium comparison. In 2011, we began talks through international bodies to define new procedures that now enable integration of an alternative to the caesium transition to define international atomic time.

**Is this also a step towards the use of optical clocks instead of fountain clocks?**

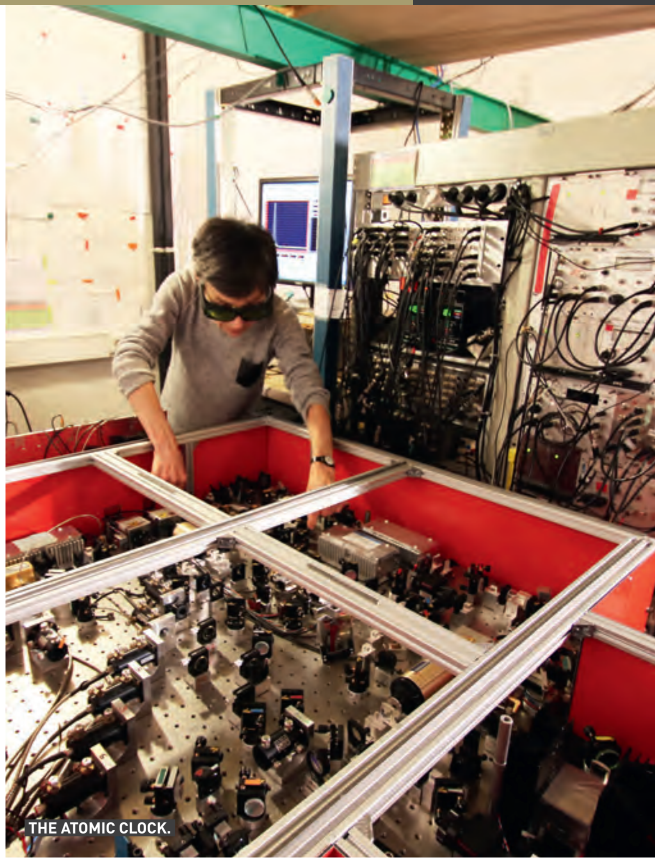
**Michel Abgrall:** Yes. The principles adopted with the rubidium fountain in developing these procedures will help with the future integration of optical clocks in defining the SI second. They operate at a higher frequency than fountain clocks and are already more accurate. However, they have yet to attain the required level of reliability.

**Daniele Rovera:** Fountain clocks, which use microwaves, have reached their limits. That is why our laboratory —drawing on its experience spanning the entire chain for time and frequency standards— is actively involved in developing the first generation of optical clocks, which will set the new standard a decade from now.

**There were three winners of the LNE Research Award this year. How do you complement one another?**

**Michel Abgrall:** Jocelyne is an international expert in atomic fountains, their workings and applications, especially in fundamental physics. Daniele is the man behind the algorithms used to manage UTC(OP) based on fountain data. As for me, I coordinate all the systems used to realise and distribute national time standards.

**Jocelyne Guéna:** Michel and I overlap to some extent on fountains, but he is also a bit of a "jack of all trades" with expertise that includes time scales. Daniele benefits from a long-term view of time and frequency metrology and is an expert in everything to do with comparing our performance with that of other laboratories around the world using GPS-type satellite links.


THE ATOMIC CLOCK.

### What does the LNE Research Award mean to you?

**Jocelyne Guéna:** It's a truly unexpected distinction! We shoulder a huge responsibility in providing a service that needs to be as accurate and reliable as possible. This is also a long-term undertaking that requires unwavering attention to detail, and which produces long-term results, which is something reflected in the many publications that are based on our standards. I really didn't expect such an award.

**Michel Abgrall:** I was really surprised to receive an award for ensuring the best possible primary standards and time scales. I am even more honoured to receive a prize that has in the past been given to the likes of André Clairon and Philippe Laurent, who are in a way our mentors here at the lab.

**Daniele Rovera:** I'm really happy to receive this joint award. It reflects the utmost trust we have in one another when it comes to our work, which is one of the keys to our success! ■


THOMAS GRENON DANIELE ROVERA MICHEL ABGRALL JOCELYNE GUÉNA

# THE FRENCH NATIONAL METROLOGY NETWORK (RNMF)

## NATIONAL METROLOGY LABORATORIES

### LNE-LCM/LNE-CNAM

LNE-LCM/LNE-CNAM is a joint metrology facility comprising researchers from LNE and the Conservatoire National des Arts et Métiers. It covers an array of measurements, including lengths, optical radiation, temperature and thermal quantities, mass and related quantities (pressure, force, torque, acoustics, accelerometery and viscosity).

### The LNE Scientific and Industrial Metrology Department

LNE oversees fields including electricity, magnetism, chemical metrology, mathematics and statistics in addition to the activities handled by LCM.

### LNE-LNHB/CEA

Laboratoire National Henri Becquerel at the French Alternative Energies and Atomic Energy Commission handles realisation of standards in the field of ionising radiation, such as dosimetry and radioactivity.

### LNE-SYRTE/OP

Laboratoire des Systèmes de Référence Temps-Espace at the Paris Observatory handles realisation of time and frequency standards.

## LNE PARTNER LABORATORIES

### LNE-ENSAM

Ecole Nationale Supérieure d'Arts et Métiers de Paris specialises in dynamic pressure.

### LNE-IRSN

Institut de Radioprotection et de Sûreté Nucléaire works in neutron dosimetry.

### LNE-CETIAT

Centre Technique des Industries Aérauliques et Thermiques covers hygrometry, liquid-water flow measurement and anemometry.

### LNE-LFTB

Laboratoire Temps Fréquences de Besançon works in time-frequency analysis with a focus on spectral density measurements and time/frequency stability.

### LNE-LADG

Laboratoire Associé de Débitmétrie Gazeuse specialises in flow measurement for gases.

### LNE-TRAPIL

Laboratoire de la Société Trapil works with flow measurement for liquid hydrocarbons.

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