DFM
Danish National Metrology Institute

ANNUAL REPORT
2019

METROLOGY: THE SCIENCE OF MEASUREMENT

Metrology is the science of measurements and is the backbone of our high-tech society. Most aspects of daily life are influenced by metrology, and increasingly accurate and reliable measurements are essential to drive innovation and economic growth.

DFM PROFILE

DFM is appointed as the Danish National Metrology Institute and contributes to the integrity, efficiency and impartiality of the world metrology system. DFM is also responsible for coordinating the Danish metrology infrastructure. DFM is a fully owned subsidiary of DTU, the Technical University of Denmark.

DFM ACTIVITIES

DFM' s scientific research results in new knowledge, measurement techniques and standards, which support the needs of Danish industry and authorities for accurate measurements.

The services offered are high-level calibrations and reference materials traceable to national primary or reference standards, training courses related to metrology and consultancy services.

DFM has a special role in developing measurement capabilities needed by small and medium sized high-tech companies in order for them to evolve and prosper.

DFM works to ensure global confidence in Danish metrology services, which are critical for competing in the global marketplace.

DIVERSITY AND SUSTAINABILITY

Diversity, inclusion and a global outlook are important to DFM in order to expand its strongholds in research. It is DFMs view that diverse teams perform better than homogeneous teams.

DFM aims to ensure that metrology supports sustainability through new standards and regulations that guide the sustainable development of products, services and processes, via reliable and widely accepted measurements.

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WHY DO WE NEED METROLOGY?

Optical investigation of nanostructures on a plastic foil produced by Roll-to-Roll printing

Calibration of gauge blocks by mechanical comparison – an essential link in the traceability chain for length measurements

Imagine a society in which there are no common measurement standards. Consumers would not be able to trust that they paid the right amount for food, gas, electricity, petrol, water and other consumables. Manufacturers would not be able to trust that parts bought from several suppliers could actually be assembled, and we would not be able to monitor the change in pollution of our environment and evaluate their effects on global warming.

Metrology has played an important role in all civilisations. In the earliest civilisations, metrology was used to regulate trade by establishing local standards for weights and measures, but as the world trade expanded, the demand for international standards for weights and measures increased. In parallel, the technological revolution created a demand for other standards than just mass and length: The steam engines required standards for temperature and pressure, the electrical machines required measurement standard for voltage, current and resistance, and other technological inventions spurred the demand for further measurement standards.

Today we live in a global and high technology society. This demands a wide range of international measurement standards of high quality and a system to make sure that all measurements performed in society are traceable to those standards. DFM is part of an international network of national metrology institutes, which work closely together to ensure that the necessary measurement standards are available to the local society and that the measurements performed in different parts of the world are equivalent. These include measurements of physical and chemical quantities, measurements that industries rely on to foster innovation and to develop efficient manufacturing methods, measurements that secure fair trade, consumer protection, health and safety, law and order, and environment monitoring. Measurement are of increasing importance in connection with financial transactions, particularly to secure accurate time stamp of such transactions.

The situation is not static. New technologies continues to appear and the demand for addressing new fields, such as quantum technologies and life sciences, only increases. If the national metrology institutes were not able to meet these demands, the technological development would fade out. So not only do we need metrology in order to run a society, we also need to improve continuously our metrological capabilities!

MANAGEMENT REPORT 2019

Bjarne Fjeldsted, Chairman of the Board and Michael Kjær, CEO.

DFM's total revenue grew 15 % to 42,9 million DKK – the highest in DFM's history. The growth was driven by increased demand for DFM's commercial products and services. Total commercial sales grew 43 % compared to 2018, while the total pretax profit grew to 1,2 million DKK from 0,7 million DKK in 2018. The management considers both revenue and profit as very satisfactory.

An expansion of the DFM facility was completed in 2019. The expansion includes new laboratories for contact and non-contact thermometry as well new offices, meeting rooms and a new canteen. The expansion will improve our ability to provide Danish and international customers with state of the art metrology services, reference materials and products. In addition, it will assure that we offer the growing number of DFM employees a good working environment.

DFM strongly supports increased European collaboration between metrology institutes and therefore supports the ongoing efforts by EU and EURAMET to continue and increase funding for a new European metrology research program (EMPIR) for the period 2021 - 2027. DFM is pleased that the Ministry of Higher Education and Science have decided to continue and increase its support for Danish participation in the new program.

Overall research activities increased in 2019, especially within quantum metrology and nanometrology, ensuring that DFM will become a strong participant in the establishment of a new European metrology infrastructure. The increase was due to an increased contract with the Ministry as well as an increase in the number of externally funded research projects, both national and European. This growth resulted in an increase of seven new staff members, five of whom in the two activities mentioned above.

DFM will continue its efforts to further increase the impact of metrology in Danish industry based on our research, project and commercial activities. As a consequence, DFM will increase investments in new metrology equipment over the next years, providing the basic metrology infrastructure that industry will require in the future to maintain and increase their global competitiveness.

Bjarne Fjeldsted
Chairman of the Board

Michael Kjær
CEO

EXPOSING THE MOLE, COULOMETRY AT DFM

Degassing the cell

Ensuring traceability

Precise volume

To better meet the needs of Danish industry, DFM is introducing a new service in proton coulometry. This realization of amount of protons in hydrochloric acid is important in underpinning the realization of the pH scale in Denmark.

The SI unit for amount of substance, the mole, is known to anyone who has studied chemistry. The ability to measure it accurately is vital in all areas touched by chemistry, including but not limited to: environmental science, the pharmaceutical industry and the food and drinks industry.

To expand DFMs portfolio of measurands and standards, and to further our ability to support Danish industry; DFM now has a Coulometric Measurement System. This system is capable of the measurement of amount of substance with very low levels of uncertainty.

The coulometric technique is probably unfamiliar to most readers, but it can be thought of as analogous to another experimental technique that many people encounter during their education, the titration. Where a well-known solution is added dropwise (the titrant) to the solution under analysis (the analyte), in the presence of an indicator dye, until a colour change is observed. The change indicates the completion of the reaction being observed (the endpoint). In this example, there are several potential problems to obtaining a precise value of the amount of substance of the analyte: the size of the droplet is of a fixed relatively large size, precise knowledge of the titrant is needed and an accurate determination of the exact moment of colour change.

In order to improve upon this classic method, coulometric analysis uses charge to control the reaction of the measured substance, instead of the titrant. This permits a higher resolution than adding a solution dropwise; it also removes the need for a characterized titrant solution and any impurities such a solution may possess. The determination of the endpoint is no longer user dependent, instead highly sensitive electrochemical measurement probes are used to follow the reaction's progress. These improvements make the determination of the exact endpoint of the analysis much more precise and this gives capability to measure amount of substance of analytes with a relative measurement uncertainty of less than 0.03 %.

In 2019 DFM participated in its first international comparison on coulometry, the initial findings of this study are very positive, recommending that DFM has established its competence in this area. Thus, DFM is now pleased to be able to offer a new service for the measurement of the amount of protons in 0.1 M hydrochloric acid solutions.

DFM ASSISTS IN DEVELOPING THE COMPUTER OF THE FUTURE – THE QUANTUM COMPUTER

An imaging scatterometer based on a conventional microscope was deployed at the University of Copenhagen. The technique provides structural information of samples during the fabrication process.

DFM and the University of Copenhagen have collaborated in a joint PhD project on characterization of nanowires with potential applications in quantum computing. The developed characterization technique will result in a better understanding of the nanowire fabrication process and ensure a time-efficient production and a high quality of the final nanowires.

A traditional computer uses logical bits for memory that have values of either 0 or 1. The quantum computer utilizes the laws of quantum physics and "quantum bits" (qubits) as memory. A qubit, compared to a traditional bit, can have both values simultaneously. This makes it possible to parallelize computations leading to much faster algorithms than for any traditional computer. Quantum computations with qubits have already been demonstrated, but hundreds of qubits are needed for more useful applications. However, scaling up the number of qubits is extremely challenging. This has resulted in a scientific race between the world's leading tech companies.

Danish universities have a long history in quantum physics research with the modern interpretation being pioneered at the Niels Bohr Institute. Currently scientists, engineers, and students collaborate to develop components based on new materials for the quantum computer. Nanowires is a promising candidate for quantum memory. Nanowires are, as the name suggests, wires on the nanoscale. The diameter of a wire is so small (typically 50-200 nm) that it enables manipulation of the quantum properties of single electrons in the wires, which can then be used as qubits.

The fabrication of nanowires at the University of Copenhagen is a complicated process with many different steps prone to errors. The standard method for characterization and quality control of nanowires is scanning electron microscopy. Since this technique is inherently slow and expensive, a common procedure is to only characterize the final wires and evaluate whether the final sample is up to standards. If not, an operator has to guess where in the process the error occurred. Since many of these fabrication steps are expensive and time consuming, the ability to stop the fabrication immediately after an error would be very valuable.

Scatterometry is an optical technique where the measured properties of light scattered off a sample (e.g. spectrum and angle) are used together with mathematical modeling to reconstruct the structure of the sample. A scatterometer developed at DFM was integrated into the production facilities at the university as part of a joint PhD project between the university and DFM. The scatterometer was successfully used to characterize the nanowire samples at four different process steps, and identifications of errors at individual process steps were demonstrated. The scatterometer enables efficient production of high quality of nanowires with future applications in quantum technology.

DFM – EDUCATING FUTURE METROLOGY PROFESSIONALS

Students from the EAAA course on quality and measurement techniques are visiting DFM. The students were challenged with practical exercises in the use of hydrometers and was on a tour at selected DFM laboratories.

Supported by training material developed at DFM, the Business Academy Aarhus (EAAA) newly opened a program for education to measurement technician, largely due to a request from Danish Industry.

In Denmark, formal courses in metrology has not been available for 20 years. The increasing demand for metrology professionals is now being addressed and in December 2019, the first 40 course participants proudly passed their first exam in metrology.

As part of the course, DFM welcomed these students to a day that included hand-on exercises and a tour of DFMs calibration facilities. This contributed to the students increased awareness of the national metrological infrastructure and the various players that need to interact to maintain a reliable measurement traceability chain. The event was also a good opportunity for DFM staff to meet the target audience of the developed teaching material.

Metrologi.dk is a project piloted by DFM in corporation with FORCE Technology. The aim is to broaden the availability of teaching material in Danish on metrology subjects. In 2019, new instructional materials were published resulting in more than 40 lecture notes, practical exercises, and videos are available on a new user-friendly designed website.

The partners in the project interacts with numerous technical education programs from high schools and business academies to universities in order to assist the teachers in the introduction of important metrology concepts at various levels of education.

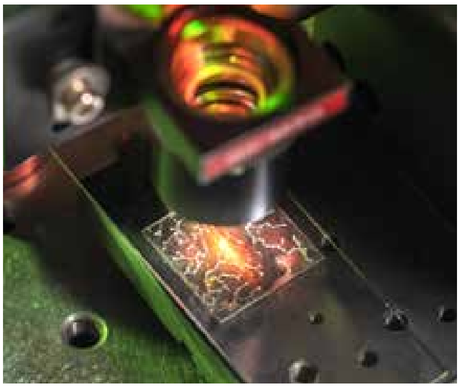
As an example, the curriculum of the first module of the course at EAAA *"Introductory Metrology"* was to a large extend based on learning material from **metrologi.dk** authored by DFM. DFM is continuously following the development of the metrology education program at EAAA and preparing suitable teaching material. In 2020 modules on "Temperature and Pressure" and "Mass, Flow and Density" will be introduced and plenty of interesting texts and practical exercises covering these subjects will be available at **metrologi.dk**.

"It has indeed been very important for the lecturers at Business Academy Aarhus to have the possibility to use updated material written by national experts in the field of Metrology for teaching purposes on the courses of Metrology autumn 2019 and spring 2020. Visits at DFM and Force Technology are also highly appreciated by lecturers from Business Academy Aarhus as an educational tool during teaching sessions."

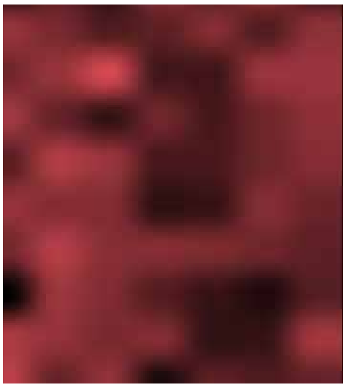
Rudi Brent, Educational Coordinator for Metrology courses, EAAA

The vivid discussions and high attendance at the **metrologi.dk** stakeholder meetings clearly indicate that the education to measurement technicians has a very high priority within Danish Industry. Participants represent small and large Danish enterprises using different levels of technology, as well as various educational institutions. More than 15 different organizations regularly participate at the meetings to discuss the present and future of metrology education.

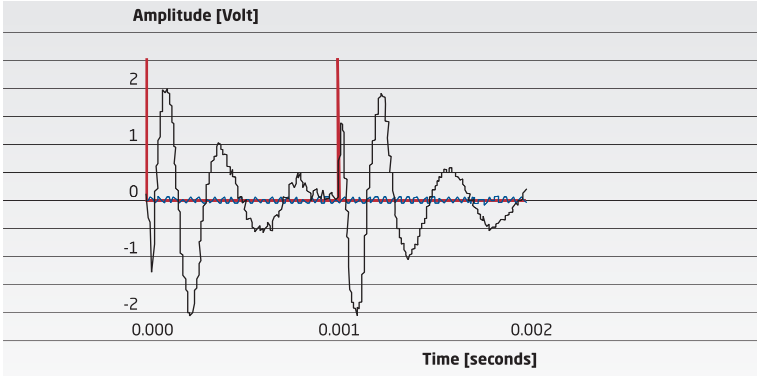
PHOTOACOUSTIC INFRARED MICROSCOPE FOR AUTOMATED HISTOPATHOLOGY



Experimental Setup for photoacoustic imaging



Photoacoustic imaging of pig liver tissue



Photoacoustic imaging signal when on molecular resonance (black). Off resonance (blue)

When performing operation for cancer, it is vital that the surgeon is able to locate and remove the cancerous tissue. DFM has investigated the use of photoacoustic imagining for cancer screening, as a useful real-time tool for identifying cancerous tissue.

During a cancer operation the removed tissue is sent to a histopathologist, who by visual inspection decides if all cancer cells are removed. A fast response time and high certainty obviously is vital. Photoacoustic imaging can be performed without any form of tissue preparation and has the ability to characterize tissue, leveraging differences in the optical absorption of underlying tissue components, such as hemoglobin, lipids, melanin, collagen and water, which all are bio-markers for cancer. Hereby an automated screening tool can be constructed, which will allow for a much higher diagnostic certainties that allow only cancerous tissue to be removed.

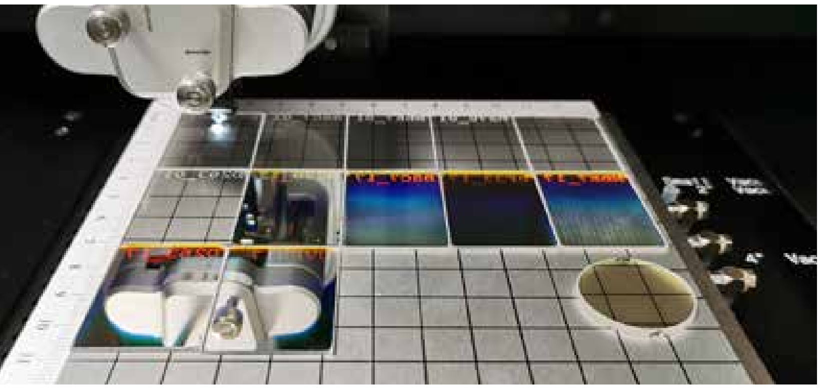
In photoacoustic imaging, a pulsed tunable laser beam is delivered into biological tissues, where it is partially absorbed based on the molecular composition of the tissue and converted into pressure heat waves. This leads to thermo-elastic expansion and the release of a wide-band ultrasound that can be detected by an ultrasound microphone. The strength of photoacoustic imaging is due to the ability to target different molecules using different wavelengths combined with the simple signal detection method. Thus, the image reconstruction of the probed region is also simple.

Two different approaches to the detection of acoustic waves have been investigated, the standard method of using an ultrasound microphone and an all-optical interferometric method.

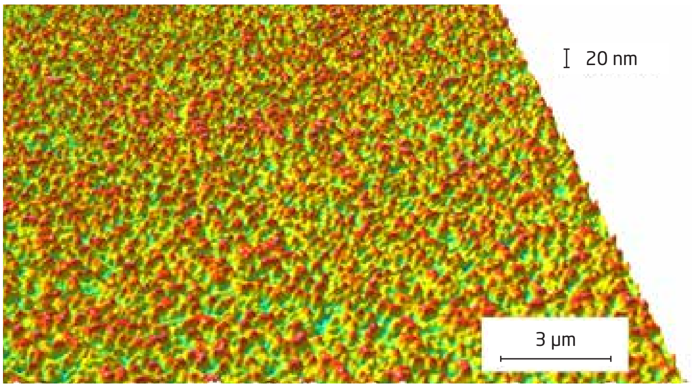
The first method was tested on a pig liver using a 1064 nm laser. The above image to the left shows the in-depth imaging capability to image the lobule of the liver. The images size is 1 mm x 1 mm and is obtained using 200 nJ/pulse. This demonstrates that the photoacoustic system has the sensitivity for detecting samples and even live tissue. The all-optical interferometric ultrasound method was conducted on a thin polystyrene sample illuminated with mid-infrared light. Measurements were conducted with 3.42 μm light resonant with C-H vibration and compared to off-resonant measurements at 3.65 μm. The amplitude of the ultrasound induced changes in the optical paths in the interferometer proportional to changes in the interference fringes. The signals can be obtained with very low pump powers down to 10 nJ/pulse. This is preferable in order to avoid damage of the tissue.

This work was partly funded by the EUROSTARS project PIRMAH (Photoacoustic Infrared Microscope for Automated Histopathology).

AUTOMATED ATOMIC FORCE MICROSCOPY FOR NANOSCALE IMAGING AND ROUGHNESS



Automated AFM measurement at work.



Surface with nanoscale roughness imaged by AFM.

Atomic Force Microscopy (AFM) provides high fidelity imaging at the nanoscale. However, its application in industry has been largely limited by its low throughput. DFM has established an automated routine for AFM batch measurement and data analysis, making it more accessible for the industry.

IMAGING AT THE NANOSCALE

Nanoscale imaging has become increasingly useful for industrial processes: polishing, surface hardening, thin film coating, and surface analysis of medical devices to name a few. Nanoscale images provide plenty of information for roughness analysis, defect identification, quality assurance, process control, etc. As an imaging tool, AFM has high resolution, high accuracy, and do not damage the sample. However, AFM imaging is relatively slow. One image typically takes minutes to finish. This has limited its application in industry, where typically a number of samples and sampling points need to be measured for the results to make sense.

THE SOLUTION TO LOW SPEED: AUTOMATION

You may have heard of the turtle and the rabbit race story. The turtle wins the race against the rabbit because it keeps running, while the rabbit is sleeping. The same principle can be used to improve AFM. A routine is established so that AFM measurement and data analysis can be performed unattended. The samples are placed on a custom-made sample stage, and measurement positions and parameters are defined in a script. As many as 50 images can be recorded in an overnight test.

The images are then batch processed in data analysis software for levelling, plotting, roughness analysis, particles analysis, etc., generating a measurement report. Once the procedure for a specific type of samples has been established, the whole test and reporting can be performed with minimal human intervention. The result is reduced cost and improved reproducibility.

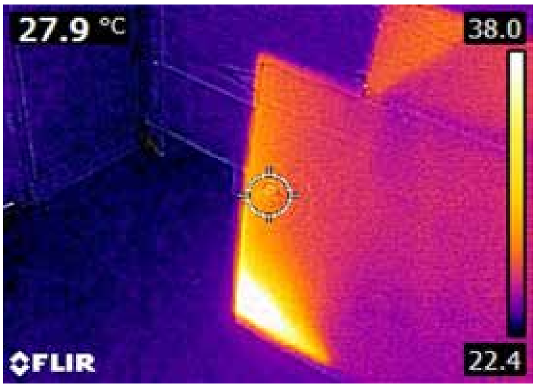
WORDS FROM THE CUSTOMER:

The automated AFM service has been adopted by Thermo Fisher Scientific – (Nunc A/S), a major bio plasticware manufacturer, and Delta Optical Thin Film A/S, a high-tech company specialized in optical filters.

"The automated AFM service and the experienced staff at DFM has helped us establish a link between specific nanoscale surface structures of high-quality glass substrates and some unwanted features of optical coatings. Multiple images per sample and several samples can be measured with short lead time, which fits in a tight manufacturing schedule. Combined with an affordable pricing per batch, we have become a repeat customer for DFM's automated AFM service."

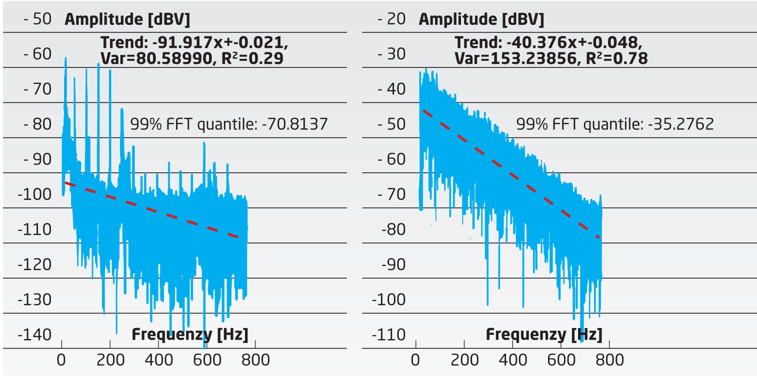
Thomas Nørskov Stoustrup, Development Engineer, Delta Optical Thin Film A/S

ADVANCED LASER BASED HEAT SENSOR FOR FIRE DETECTION



Forward looking infrared image of the heat flow on a 1 cm thin cardboard plate

The standalone sensor head



Detected features in frequency domain.

DFM has developed an innovative fire detection system based on advanced laser technology. The system can identify small temperature rises at a very early stage of a fire, providing an early and reliable detection, even in dusty areas, prone to fires, where current systems show limited performance or are unable to operate.

Most fire detection and prevention systems used today do not work well at harsh industrial sites or for large areas. Standard smoke detectors often give false alarms due to dust and pollutants in these environments and cannot detect the submicron particulate matter released during early stages of fire. Laser based fire detection systems can be very sensitive, however they often rely on changes of the optical power amplitude of the transmitted/reflected light, and are therefore not reliable for detection of fire through dust and steam. Sensors that detect radiation emitted by flames are prone to give rise to false alarms from radiation coming from sources such as sunlight, artificial light, welding or other non-dangerous sources.

DFM has developed a completely different optical approach to detect fires by measuring dynamic speckle patterns, which in principle is independent of the amplitude of the detected light field. These changing patterns are produced by interference when laser light hits a rough surface. When a fire is developing, the heat flow makes the laser beam jitter. This is observed when the laser beam is reflected back to the detector placed next to the laser source. The noise pattern of the dynamic speckle pattern is analyzed and broadband white noise above a certain threshold indicate fire while noise sources confined to a narrow range of wavelengths are ruled out as a mechanical vibrations.

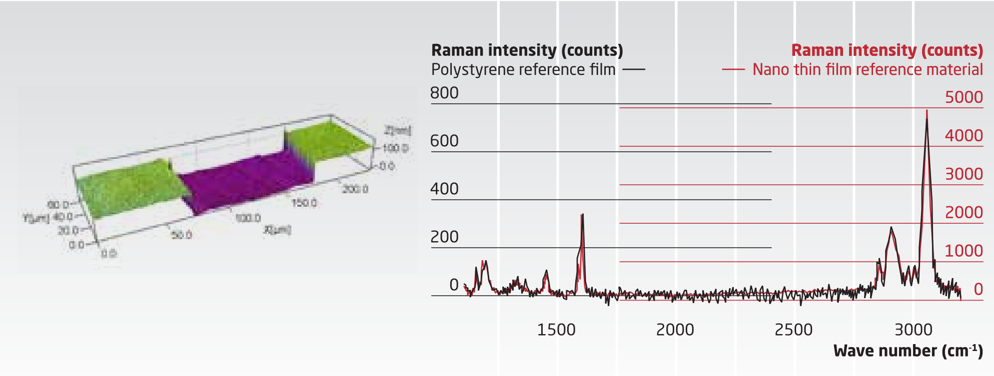
The fire detection system was validated at the Energnist I/S plant in Kolding, Denmark. Due to the extremely harsh, noisy and dusty environment, the plant normally has three to four false alarms per month. The new system detected fires with an accuracy of 91 percent.

The optical detector and the laser will be upgraded to a more powerful system with increased sensitivity and an expanded sensing range of more than 1 kilometer, making it useful for outdoor monitoring.

This work has been done in collaboration with the following companies: Elotec AS from Norway is a manufacturer and supplier of alarm and surveillance systems that was established in 1992, Dansk Brand- og sikringsteknisk Institut (DBI) and LAP Sikkerhed A/S.

This work was funded by the EUROSTARS project Firedetect.

IMPROVING QUALITY ASSURANCE OF NANOSCALE SPECTROSCOPIC IMAGING IN PHARMACEUTICAL MANUFACTURING



Topography image (left) and Raman spectroscopy (right) of the polymer nano thin film reference material.

Confocal microscopy for the measurement of film thickness

DFM addresses the need for new standard reference materials required for quality assurance of cutting-edge nanoscale infrared spectroscopic imaging instruments. A polymer based nano thin film standard reference material was developed and adopted by a Danish pharmaceutical manufacturer.

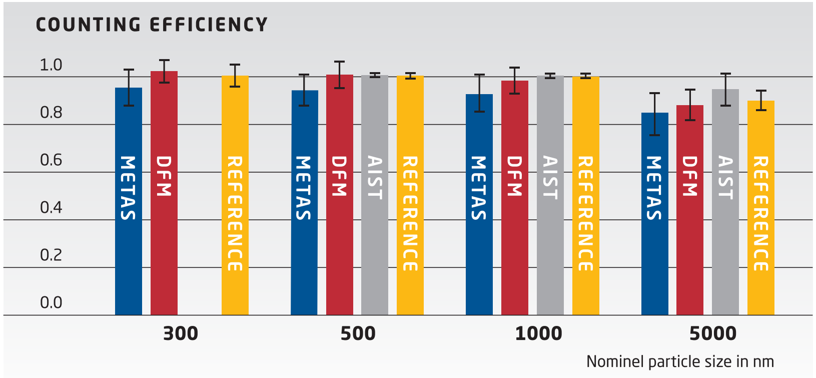
Infrared spectroscopy is a widely used technique for chemical identification in industrial development. A fundamental limitation of direct infrared spectroscopic microscopy is the low spatial resolution, about a few micrometers. Recently, this issue has been addressed by combining infrared spectroscopy with the high spatial resolving power of atomic force microscopy to achieve nanoscale infrared spectroscopic imaging with spatial resolution down to 10 nm. This provide new opportunities for industrial quality assurance, such as defect and contamination analysis, polymer composite mapping, micro-particle and nano-particle characterization.

For nanoscale infrared spectroscopic imaging to be applied in industry, calibration guidelines must be followed to ensure that the performance fulfill the standard. Conventional infrared spectrometers are calibrated against well-defined absorption spectra of reference materials. Reference materials for infrared spectrometers in the pharmaceutical industry are polystyrene films with thicknesses of tens of micrometers. This type of reference material is too rough for nanoscale infrared spectroscopic imaging.

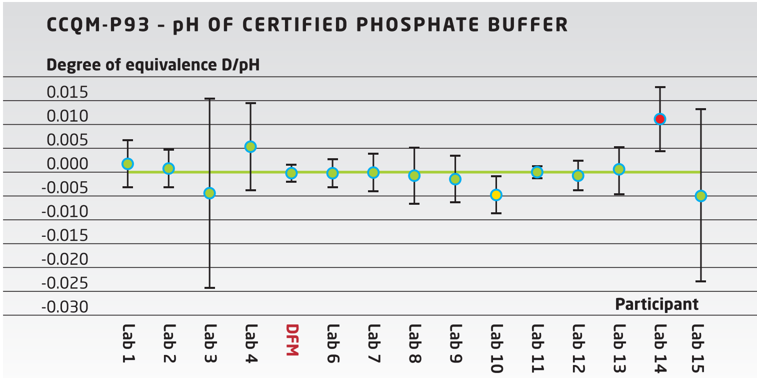
To address this issue, DFM has developed a polymer nano thin film on a highly smooth silicon substrate as a standard reference material for nanoscale infrared spectroscopic imaging. The thickness of the thin film, ca. 100 nm, is measured by confocal microscopy with traceability to the SI system of units via calibration against step height standards. The chemical composition of the polymer is confirmed by Raman spectroscopy to be identical to existing certified reference materials, thus it is suitable for wavelength and relative absorbance calibration of infrared spectroscopic imaging instruments.

The new DFM standard reference material has been applied in a company to verify the performance of their newly acquired nanoscale infrared spectrometer. Such practice is required in order to be compliant with the European Pharmacopoeia regulations on instruments for the quality control of pharmaceutical production. DFM continues to leverage its expertise in nanoscale and advanced spectroscopy measurements, as to rapidly respond to the needs of Danish high tech industry.

PARTICIPATION IN INTERNATIONAL MEASUREMENT COMPARISONS



DFMs performance (red) in good agreement with reference (yellow)



The certified value of the DFM phosphate buffer shows a high degree of equivalence (D) with the reference values established in this comparison, taking into account the expanded uncertainty indicated by error bars

DFM regularly participates in measurement comparisons at the highest scientific level with other national metrology institutes. Two such comparisons were completed in 2019. The calibration, measurement, and certified reference material production capabilities of DFM linked to two calibration services have proven to operate with an internationally competitive performance.

Following the establishment of new calibration and measurement facilities at the highest scientific level, it is important to demonstrate that these facilities provide measurement results at an internationally acceptable level. This is demonstrated by conducting international comparisons, which can be executed in different ways.

PARTICLE COUNTERS

Even though optical particle counters have been successfully applied for the past three decades in various industries, such as semi-conductors and pharmaceuticals, an international comparison of calibration capabilities was still missing.

The three national measurement institutes DFM, METAS (Switzerland) and AIST (Japan) initiated and finalized a comparison with the aim of confirming their claimed calibration performances. Each participating institute provided one particle counter, which was circulated between the participants. Each participant measured the counting efficiency of each particle counter when counting particles of selected nominal diameters. The results of the comparison show a good agreement between the calibrations performed by all three partners. In the figure to the left, the results for one instrument are shown.

pH CERTIFIED PHOSPHATE BUFFER REFERENCE MATERIAL

The first international measurement comparison on production of pH buffer certified reference material (CRM) organized by the Consultative Committee for Amount of Substance, CCQM-P93, was concluded in 2019. It demonstrated not only the excellent ability of DFM to measure pH using the Harned cell (primary) method, but also DFM's ability to produce CRMs, including proper packaging and shipping of such. The study demonstrated that shipping of a DFM primary buffer does not affect the pH value of the buffer. Further, it was demonstrated for the first time that the DFM buffer is stable for at least 3 months, if properly stored.

The comparison involved 15 National Metrology Institutes, each of which produced a phosphate buffer CRM, assigned a pH reference value (and an associated uncertainty) to the CRM and then shipped the buffer with a certificate to the pilot laboratory. The pilot laboratory compared the buffers, and based on the comparison data and the certified values, a reference value for each certified buffer was established. DFM acted as Supporting Laboratory and aided in calculations of the reference values. Ideally, the difference D between the certified pH value and reference pH value should be zero within the expanded uncertainty 2u(D) of the difference. As shown in the figure above to the right, this was the case for 13 participants, including DFM, out of 15 participants.

PARTICIPATION IN COMMITTEES AND WORKING GROUPS UNDER THE METRE CONVENTION AND EURAMET

- EMPIR Committee
- EURAMET General Assembly
- EURAMET Technical Committee for Mass (TC-M)
- EURAMET Technical Committee for Electricity and Magnetism (TC-EM)
- EURAMET Technical Committee for Length (TC-L)
- EURAMET Technical Committee for Photometry and Radiometry (TC-PR)
- EURAMET Technical Committee for Acoustics, Ultrasound and Vibration (TC-AUV)
- EURAMET Technical Committee for Time and Frequency (TC-TF)
- EURAMET Technical Committee for Interdisciplinary Metrology (TC-IM)
- EURAMET Technical Committee for Quality (TC-Q)
- EURAMET Technical Committee for Metrology in Chemistry (TC-MC)
- EURAMET TC-MC Sub Committee for Electrochemistry
- BIPM Director's ad hoc Advisory Group on Uncertainty
- Joint Committee for Guides in Metrology – Working Group 1, Guide to the Expression of Uncertainty in Measurement (JCGM-WG1)
- Consultative Committee for Length – Working Group on Dimensional Nanometrology (CCL-WG-N)
- Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology – Working Group on Electrochemical Analysis (CCQM-EAWG)
- CCM Task Group on the Phases for the Dissemination of the kilogram following redefinition (CCM-TGPfD-kg)
- Consultative Committee for Amount of Substance (CCQM)
- Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV)
- Consultative Committee for Mass and Related Quantities (CCM)
- Consultative Committee for Acoustics, Ultrasound and Vibration – Working Group for Key Comparisons (CCAUV-KCWG)
- Consultative Committee for Ultrasound and Vibration – Working Group on Strategic Planning (CCAUV-SPWG)
- NMI Directors' Meeting
- Consultative Committee for Mass and Related Quantities – Working Group on Mass (CCM-WGM)

PARTICIPATION IN NATIONAL AND INTERNATIONAL PROJECTS

- Leading Edge Roughness Wind Turbine Blades (LER), EUPD
- Photo-Acoustic Sensor for Oil Detection in Compressed Air (PASOCA), IF/Eurostars
- Metrology for Additively Manufactured Medical Implants (MetAMMI), SIU/EMPIR
- Metrology for Modern Hearing Assessment and Protecting Public Health from Emerging Noise Sources (Ears II), SIU/EMPIR
- Underwater Acoustic Calibration Standards for Frequencies Below 1 kHz (UNAC-LOW), SIU/EMPIR
- Traceable Three-Dimensional Nanometrology (3DNano), SIU/EMPIR
- Continuous Pesticide Sensing in the Environment (CoPS), IF/Eurostars
- Photoacoustic Infrared Microscope for Automated Histopathology (PIRMAH), IF/Eurostars
- Corrosion detection on offshore platforms by drones (OFFSHORE), the European Regional Development Fund "EU's Regional Fond"
- Traceable in-line Optical Measurement of Nano and Micro Roughness (OptoRough), IF/Eurostars
- Quantum Measurement Enhanced Gravitational Wave Detection (Q-GWD), IF/Eureka Turbo
- Advanced Surface Treatments for Superior Plastic Injection Moulds (SuperMoulds), IF
- Aerosol Metrology for Atmospheric Science and Air Quality (Aeromet), SIU/EMPIR
- Metrology for Stable Isotope Reference Standards (SIRS), SIU/EMPIR
- Metrology for nitrogen dioxide (MetNO2), SIU/EMPIR
- Realization of a Unified pH scale (UnipHied), SIU/EMPIR

- Light-matter interplay for optical metrology beyond the classical spatial resolution limits (BeCOMe), SIU/EMPIR
- High Accuracy High Flow Optical Aerosol Spectrometer for improved Cleanroom Quality Assurance (HILAS), IF/Eurostars
- Gas leak detection on remote offshore platforms by drones (THERMODRONE). European Regional Development Fund
- Bacteria sensor for in-situ detection and identification of anti-microbial resistant bacteria (Bacsens), IF/Eurostars
- New quantities for the measurement of appearance (BxDiff), SIU/EMPIR
- In-line Monitoring and Control of Roll-to-Roll Replication Processes (R2RMon), IF/Eurostars
- Compact and cost-effective MIR-DIAL for improved industrial and urban pollution measurement (MIRDIAL), IF/GlobalStars
- Traceable Reference for low Uncertainty Evaluation of Photocatalytic Activity in Coatings (TRUEPAC), IF/Eurostars
- Ultra-violet supercontinuum sources and pulsed lasers for the semiconductor industry (UV-SUPER) IF/Grand Solutions

DFM SPECIAL REPORTS

- **M. Geisler, S. Alkærsig Jensen, Kai Dirscherl**
  Absolute work function measurements using kelvin probe force microscopy

CALIBRATION CERTIFICATES AND MEASUREMENT REPORTS

DC Electricity	3
Electrochemistry	455
Mass	33
Length	35
Optical Radiometry	47
Nano Structures	21
Acoustics	63
Particle Metrology	42
Thermometry	935
Pressure	11
Total	**1645**

PUBLICATIONS IN REFEREED JOURNALS

- **C. Thirstrup, L. Deleebeeck, A.M.N. Lima**
  Ion-specific quantitative measurement scheme using transit-time surface plasmon resonance
  Measurement Science and Technology **30,** 105102, 2019
- **J. Flemming, I. Kongstad, K. Dirscherl, G.V. Chakravarthy, R. Ambat**
  High Frequency Pulse Anodising of Recycled 5006 Aluminium Alloy for Optimised Decorative Appearance
  Surface and Coatings Technology **368,** 42-50, 2019
- **L. Lamard, D. Balslev-Harder, A. Peremans, J. C. Petersen, M. Lassen**
  Versatile photoacoustic spectrometer based on a mid-infrared pulsed optical parametric oscillator
  Applied Optics **58,** 250-256, 2019
- **H. Kerdoncuff, M. Lassen, J. C. Petersen**
  Continuous-wave coherent Raman spectroscopy for improving the accuracy of Raman shifts
  Optics Letters **44,** 5057-5060, 2019
- **S. Seitz, P.T. Jakobsen, M. Mariassy**
  Metrological advances in reference measurement procedures for electrolytic conductivity
  Metrologia **56,** 034003, 2019

- **C. N. Christensen, Y. Zainchkovskyy, S. Barrera-Figueroa, A. Torras-Rosell, G. Marinelli, K. Sommerlund-Thorsen, J. Kleven, K. Kleven, E. Voll, J. Petersen, and M. Lassen**
  Simple and robust speckle detection method for fire and heat detection in harsh environments
  Applied Optics **58,** 7760-7765, 2019
- **S. Duraipandian, J.C. Petersen, M. Lassen**
  Authenticity and Concentration Analysis of Extra Virgin Olive Oil Using Spontaneous Raman Spectroscopy and Multivariate Data Analysis
  Applied Sciences **9,** 2433, 2019
- **L. Vaut, G. Zeng, G. Tosello, A. Boisen**
  Sacrificial Polymer Substrates in Photopolymerization-Based Micro 3D Printing for Fabrication and Release of Complex Micro Components
  Advanced Materials Technologies **4,** 1900378, 2019
- **L. Casemiro Oliveira, A. Marcus Nogueira Lima, C. Thirstrup, H. Franz Neff**
  Surface Plasmon Resonance Sensors – A Materials Guide to Design, Characterization, Optimization, and Usage
  Springer Series in Surface Sciences, Vol. **70,** 2nd edition, Springer International Publishing 2019, ISBN 978-3-030-17485-9
- **N. Feltin, S. Ducourtieux, L. Crouzier, A. Delvallee, K. Dirscherl, G. Zeng**
  Scanning Probe Microscopy (SPM), Chapter 2.1.3: Characterization of Nanoparticles – Measurement Processes for Nanoparticles,
  ISBN: 978-0-12-814182-3

CONTRIBUTION AT CONFERENCES

- **S. A. Jensen, P. E. Hansen, D. M. Rosub, A. Hertwig**
  Rough cigs surface analyzed with Rayleigh-Rice theory
  10th Workshop Ellipsometry (WSE10), Chemnitz, Germany
- **J. C. Petersen, D. Balslev-Harder, N. Pelevic, A. Brusch, S. Persijn, M. Lassen**
  Flow immune photoacoustic sensor for real-time and fast sampling of trace gases
  SPIE OPTO photonics west 2019, San Francisco, USA
- **I. Prokhorov, T. Benoy, V. Ebert, G. Li, H. Meijer, J. Mohn, J. Petersen, D. Balslev-Harder, T. Poikonen, F. Steur, O. Werhahn**
  Metrological characterisation of optical isotope analysers for carbon dioxide in the framework of EMPIR SIRS project
  The General Assembly 2019 of the European Geosciences Union (EGU-2019), Wien, Østrig
- **K. Gurzawska, S. Suliman, M. Anna, J. Folkert, N. Rana, A. F. Wistrand, K. Dirscherl, B. Jørgensen, P. Ulvskov, K. Mustafa**
  GreenBone – plant-derived modified scaffolds with anti-inflammatory properties
  Oral Health Research Congress (CED-IADR/NOF 2019), Madrid, Spain
- **S. Barrera-Figueroa**
  Extending the traceability of acoustic measurements to infra- and ultrasound frequencies
  Dresden Metrology Summit
- **S. Barrera-Figueroa**
  Making pressure calibration easier – strategies for calibration of measurement microphones
  48th International Congress and Exhibition on Noise Control Engineering (Internoise 2019), Madrid, Spain
- **M. Enge, C. Hof, S. Barrera-Figueroa**
  Establishing new types of LS2P microphones as reference standards
  48th International Congress and Exhibition on Noise Control Engineering (Internoise 2019), Madrid, Spain
- **V. Cutanda-Henríquez, P. Møller-Juhl, S. Barrera-Figueroa**
  Modelling of measurement condenser microphones at low frequencies: numerical issues
  48th International Congress and Exhibition on Noise Control Engineering (Internoise 2019), Madrid, Spain

- **P. Møller-Juhl, V. Cutanda-Henríquez, S. Barrera-Figueroa**
  On The Modelling Of Cavities At Low Frequencies With The BEM
  48th International Congress and Exhibition on Noise Control Engineering (Internoise 2019), Madrid, Spain
- **S. A. Verburg, E. Fernández-Grande, S. Barrera-Figueroa**
  Acousto-optic sensing of the sound field in a lightly damped room
  48th International Congress and Exhibition on Noise Control Engineering (Internoise 2019), Madrid, Spain
- **H. Kerdoncuff, M. Lassen, J. C. Petersen**
  Accurate and traceable determination of Raman shifts in reference materials by continuous-wave stimulated Raman spectroscopy
  CLEO/Europe-EQEC, Munich, Germany
- **G. Zeng**
  Applications of Atomic Force Microscopy in bacteria and biofilm research
  7th Bioimaging Workshop, Copenhagen, Denmark
- **G. Zeng, J. Garnæs**
  Investigation of surface roughness of AM parts
  BAM workshop on Additive Manufacturing, Berlin, Germany
- **Ivo Pietro Degiovanni, Marco Gramegna, Sébastien Bize, Hansjörg Scherer, Christopher Chunnilall, Stefan Kück, Franck Pereira Dos Santos, Tobias Lindstrom, Felicien Schopfer and Mikael Lassen**
  The EURAMET European Metrology Network for Quantum Technologies
  Single-Photon Workshop 2019 (21/10-25/10-2019)
- **H. Kerdoncuff, J. C. Petersen and M. Lassen**
  Sub-shot noise coherent Raman Spectroscopy for bio-optical applications
  FT-IR Spectroscopy in Microbiological and Medical Diagnostics
- **L. J. Wacker, H. Kerdoncuff**
  Drone based detection of corrosion
  The European Corrosion Congress (EuroCorr 2019), Sevilla, Spain
- **I. Prokhorov, G. Li, O. Werhahn, V. Ebert, F. Steur, H. Meijer, F. Rolle, M. Sega, J. Petersen, D. Balslev-Harder, T. Poikonen, J. Mohn**
  Headline Characterisation of optical isotope analysers for carbon dioxide in the framework of EMPIR project SIRS
  The 20th WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases, and Related Measurement Techniques (GGMT-2019), Jeju, Korea
- **R. B. Andrade, H. Kerdoncuff, K. Berg-Sørensen, M. Lassen, T. Gehring, U. L. Andersen**
  Squeezing-enhanced cw-stimulated Raman spectroscopy
  Biological and pharmaceutical applications of CRS microscopy, Odense, Denmark
- **R. B. Andrade, H. Kerdoncuff, K. Berg-Sørensen, M. Lassen, T. Gehring, U. L. Andersen**
  Squeezing-enhanced cw-Stimulated Raman spectroscopy
  International conference on quantum Metrology and Sensing, Paris, France
- **R. B. Andrade, H. Kerdoncuff, K. Berg-Sørensen, M. Lassen, T. Gehring, U. L. Andersen**
  Quantum enhancement of stimulated Raman spectroscopy
  Quantum-life workshop - Novo Nordisk Fonden, Hellerup, Denmark

INCOME STATEMENT AND BALANCE SHEET

INCOME STATEMENT (1000 DKK)	2019	2018
Commercial revenue	10 187	7 099
Project revenue	6 502	7 312
Government funding	26 399	22 738
Total revenue	**43 088**	**37 149**
Travel and out-of-pocket expenses	13 183	10 330
Total out-of-pocket expenses	**13 183**	**10 330**
Gross profit	**29 906**	**26 819**
Staff costs	24 690	22 322
Total costs	**24 690**	**22 322**
Operating profit before depreciation and impairment losses	**5 216**	**4 497**
Depreciation and impairment losses on property, plant and equipment	3 909	3 796
Operating profit before financial income and expenses	**1 307**	**701**
Financial income	63	24
Financial expenses	75	55
Profit before tax	**1 169**	**670**
Tax on profit for the year	253	144
Profit for the year	**916**	**525**
Profit for the year to be carried forward		

BALANCE SHEET AT 31 DECEMBER (1000 DKK)

ASSETS	2019	2018
Deposits	1 006	502
Total investments	**1 006**	**502**
Equipment	7 011	8 206
Leasehold improvements	15 979	15 455
Total property, plant and equipment	**22 990**	**23 660**
Total non-current assets	**23 996**	**24 162**
Contract work in progress	**5 075**	**6 077**
Trade receivables	3 461	1 372
Prepayments	73	45
Other receivables	169	156
Total receivables	**3 135**	**1 573**
Cash at bank and in hand	**10 636**	**10 243**
Total current assets	**19 414**	**17 893**
Total assets	**43 410**	**42 055**

EQUITY AND LIABILITIES		2018
Share capital	1 000	1 000
Retained earnings	18 095	17 179
Total equity	**19 095**	**18 179**
Prepayments from customers and of funding	13 426	12 927
Trade payables	1 515	1 705
Other payables	9 374	9 244
Total current liabilities	**24 315**	**23 876**
Total equity and liabilities	**43 410**	**42 055**

KEY FIGURES

KEY FIGURES IN MILLION DKK	2015	2016	2017	2018	2019
Net sales	27.2	31.5	35	37.1	43.1
Gross balance	23.7	35.4	41.1	42.1	42.3
Profit or loss for the financial year [1])	0.4	0.4	0.5	0.1	0.9
Net capital	16.9	17.2	17.7	18.2	19.1
Commercial sale	5.3	4.6	4.0	7.1	10.2
- to small enterprises (less than 50 employees)	0.4	0.6	0.5	0.9	1.0
- to medium size enterprises (50-250 employees)	0.8	0.9	0.9	1.5	1.9
- to large enterprises (more than 250 employees)	1.3	1.1	0.9	2	2.5
- to Danish public institutions	0.4	0.5	0.2	0.3	0.3
- to foreign enterprises and institutions	2.4	1.5	1.5	2.4	4.3
Foreign net sales	7.1	3.8	3.3	4.3	7.7
RESEARCH AND DEVELOPMENT					
Number of collaborative projects	23	29	29	23	24
- thereof innovation consortia	2	2	2	1	0
- thereof international projects	17	21	27	20	20
R&D activities (million DKK)	23.2	26.9	30.6	29.6	32.8
- thereof self-funded	2.1	1.8	3.0	2.6	2.8
R&D work (man-year)	17.5	17.3	17.6	19.7	21.1
NUMBER OF CUSTOMERS					
Danish private enterprises	25	59	57	146	168
- thereof small enterprises (less than 50 employees)	11	29	3	67	59
- thereof medium size enterprises (50-250 employees)	6	10	7	32	51
- thereof large enterprises (more than 250 employees)	8	20	17	47	43
Danish public institutions	5	10	3	20	15
Foreign enterprises and institutions	19	20	33	44	52
Total customer base	49	89	90	210	220
NUMBER OF STAFF CATEGORIZED BY EDUCATION (MAN-YEAR)					
Dr & PhD	18	20	25	26	27
MSc	4	2	3	1	1
Other technical staff	2	2	2	2	3
Administrative staff	3	4	4	4	5
Average number of staff	27	27	34	33	36
NUMBER OF PUBLICATIONS					
Refereed publications	23	19	21	19	10
PhD and Master theses	0	3	0	0	1
Other reports	14	15	7	2	0
Conference papers	15	18	17	17	24
Calibration certificates and measurement reports	521	582	717	1 543	1 645
Press cuttings	28	15	11	35	4
EDUCATION					
DFM courses (number of days)	2	3	3	4	2
DFM courses (number of participants)	22	18	21	28	21
Supervision/teaching at universities (number of students/courses)	3	3	6	3	4
Co-supervision of master thesis students (number of theses)	4	3	0	0	1
Contribution to teaching at universities (number of days)	4	3	6	3	4
Committee work (number of committees)	29	29	29	29	28
- thereof international committee work	23	23	25	25	24
EFFICIENCY					
Turnover per employee (1000 DKK)	994	1 066	1 129	1 126	1 147
Profit per employee (1000 DKK)	15	14	16	17	24
Commercial turnover per DKK of governmental funding	0.4	0.2	0.2	0.3	0.4
R&D turnover per DKK of governmental funding	1.5	1.3	1.4	1.4	1.3

1) Excluding extraordinary items

DANISH METROLOGY INSTITUTES

According to the CIPM Mutual Recognition Arrangement, a country can have one national metrology institute (NMI) and a number of designated institutes (DI). In Denmark, these metrology institutes are appointed by the Danish Safety Technology Authority (www.sik.dk). In the list below, each appointed metrology institute is identified by the acronym used in the BIPM database for Calibration and Measurement Capabilities. The fields covered by the appointments are indicated in the table on the next page.

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THE 12 SUBJECT FIELDS OF METROLOGY

Fundamental metrology in Denmark follows the EURAMET division into 12 subject fields, while the subfields reflect a Danish subdivision of metrological activities.

SUBJECT FIELD	CONTACT PERSON	SUBFIELDS	METROLOGY INSTITUTE
MASS AND RELATED QUANTITIES	Lars Nielsen, DFM	Mass measurement	DFM
	ln@dfm.dk	Force and Pressure	FORCE
		Volume and Density	FORCE
ELECTRICITY AND MAGNETISM	Carsten Thirstrup, DFM	DC electricity	DFM
	cth@dfm.dk	AC electricity	TRESCAL
		HF electricity	TRESCAL
LENGTH	Jan Hald, DFM	Basic length measurements	DFM
	jha@dfm.dk	Dimensional metrology	DFM & DTI
		Micro/Nano	DFM
TIME AND FREQUENCY	Jan Hald, DFM	Time measurement	
	jha@dfm.dk	Frequency	
THERMOMETRY	Jan Nielsen, DTI	Temperature measurement by contact	DTI
	jnn@teknologisk.dk	Non-contact temperature measurement	DFM
		Humidity	FORCE
		Moisture in materials	DTI
IONISING RADIATION	Arne Miller, DTU	Absorbed radiation dose – Industrial products	DTU
	armi@dtu.dk	Absorbed radiation dose – Medical products	
		Radiation protection	
		Radioactivity	
PHOTOMETRY AND RADIOMETRY	Anders Brusch, DFM	Optical radiometry	DFM
	ab@dfm.dk	Photometry	
		Colorimetry	
		Optical fibres	
FLOW	Jesper Busk, FORCE	Gaseous flow (volume)	FORCE
	jrb@force.dk	Water flow (volume, mass and energy)	DTI
		Flow of liquids other than water	FORCE
		Anemometry	DTI
ACOUSTICS, ULTRASOUND AND VIBRATION	Salvador Barrera-Figueroa, DFM	Acoustical measurements in gases	DFM & BKSV-DPLA
	sbf@dfm.dk	Acoustical measurements in solids	BKSV-DPLA
		Acoustical measurements in liquids	
METROLOGY IN CHEMISTRY	Lisa Carol DeLeebeeck	Electrochemistry	DFM
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		Products and materials	
		Food chemistry	
		Pharmaceutical chemistry	
		Microbiology	
		Environmental chemistry	
INTERDISCIPLINARY METROLOGY	David Balslev-Harder	No subdivisions	
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QUALITY	Kai Dirscherl, DFM	No subdivisions	
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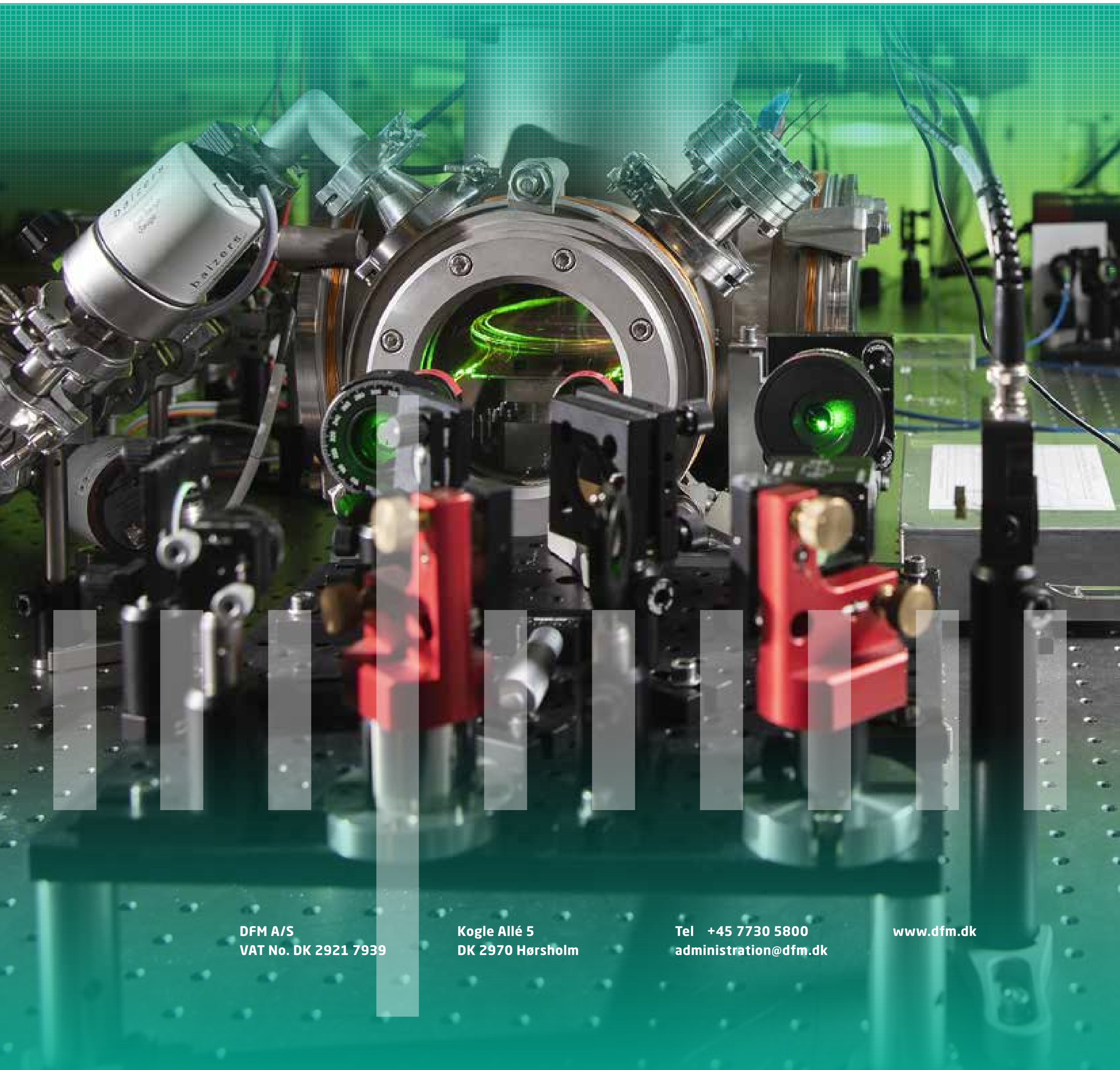

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