Fraunhofer Institute for Physical Measurement Techniques IPM

Annual report 2022/2023

Measuring • Monitoring • Optimizing

Annual report 2022/2023

Measuring · Monitoring · Optimizing

Measurement technology will make a key contribution to the digitalization and industrialization of the building sector."

Prof. Dr. Karsten Buse, Director

Building sector
Key industry and field of innovation

Dear customers,
dear partners,

More than ten percent of Germany's gross domestic product is spent on building investments, and close to 40 percent of global CO_2 emissions are caused by the building and construction industry. Also, the consumption of raw materials is massive: In Germany alone, 5,000 kilograms of mineral materials per inhabitant and year are used in construction.

In view of the sheer extent of consumption, it's surprising to see that digitalization and industrialization are no more than isolated use cases in the construction industry. After all, comprehensive digitalization is the key to huge resource savings and the gateway to circular economy. Digitalization is a precondition for consistent industrialization in areas such as prefabrication in factories, automated loading and unloading of trucks, crane control on building sites and robot-supported mounting and developments. At a later stage, digitalization is also needed for recycling, in particular for automated shape and material recognition.

At Fraunhofer IPM, we have been intensifying our research for the building sector, a commitment that is reflected in our membership of the Fraunhofer Building Innovation Alliance and in my role as the Alliance's Deputy Spokesman. Here are some examples: Our optical systems – based on robots and drones – enable the 3D digitalization of building infrastructure across the entire lifespan. The systems are mostly automated but supported by humans. Our measurement technology is able to identify building components and materials, or monitor a building's condition, for example with respect to humidity or mold. Laser beams can help us predict loosening façade components, and carbon monoxide gas sensors can warn in the early stages of a fire.

The government has also recognized that innovation is indispensable to make sustainable and affordable building possible despite inflation and rising standards. In 2022, members of the state and the federal parliament visited our institute to learn about technologies for innovative construction. Fraunhofer IPM in turn makes active contributions to the political debate, for example through the Strategic Dialog on "Affordable living and innovative building" initiated by the federal government of Baden-Württemberg.

Innovations that benefit people directly – that's what motivates our team to excel again and again. This Annual Report contains compelling examples of how we achieve this goal in the construction industry as well as in other sectors. Let's take you on a journey into the wonderful world of measurement technology: Quality assurance of bipolar plates in fuel cells using ultra-fast digital holography, measurement of water depth in the sea using two-color scanners to support the shipping industry, distributed sensors to investigate the response of our forests to climate change, assessment of fertilization state of arable land by detecting laughing gas and efficient heat pumping without refrigerants that contribute to climate change through refining electrocalorics.

These are just some examples from more than 100 ongoing projects. Our monthly newsletter and our social media posts regularly inform about highlights from our daily research work. Let's keep in touch!

The best of success in everything that you do. We would be happy to continue working with you!

Yours,

Prof. Dr. Karsten Buse, Director

Fraunhofer Building
Innovation Alliance

Content

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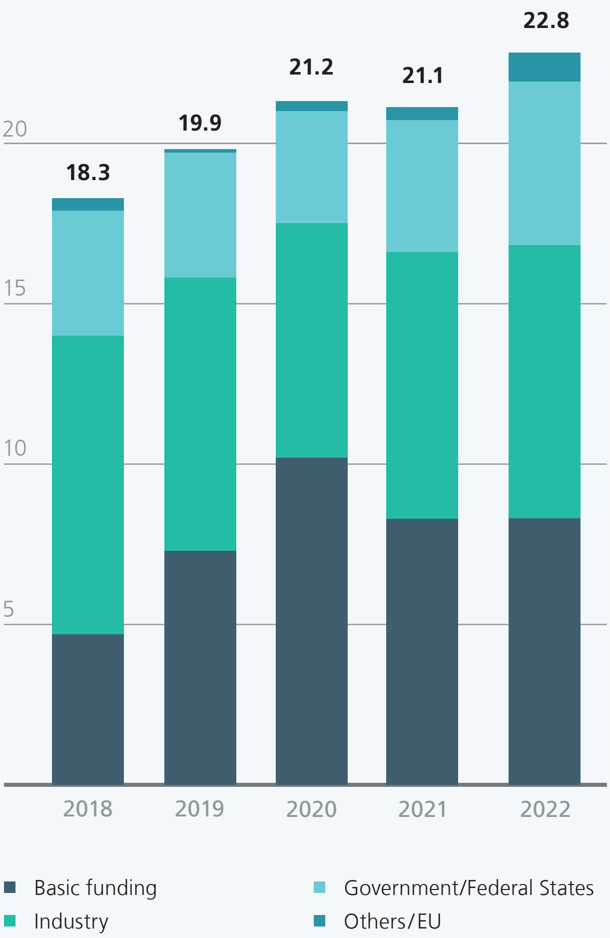
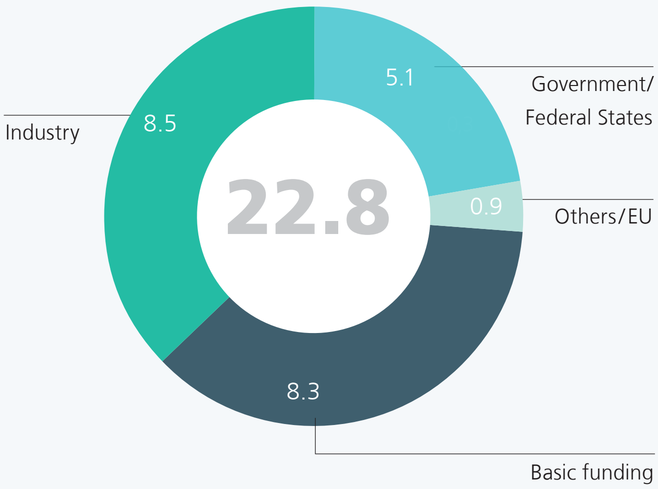
Figures Fraunhofer IPM

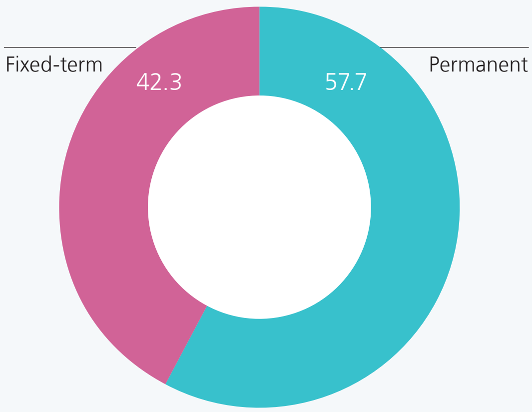
Development Operating budget in million euros



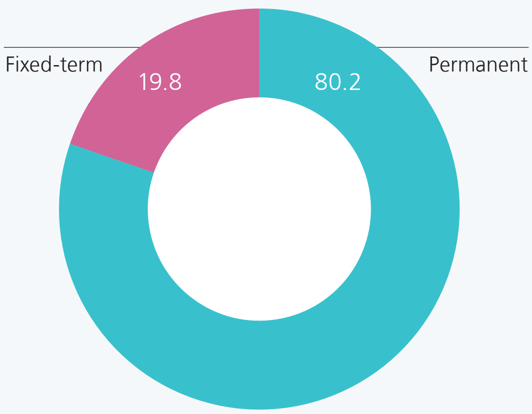
Operating budget 2022 in million euros



Staff under the terms of the Collective Agreement for the Public Service TVöD
Percentages of fixed-term/permanent contracts of employment 2022

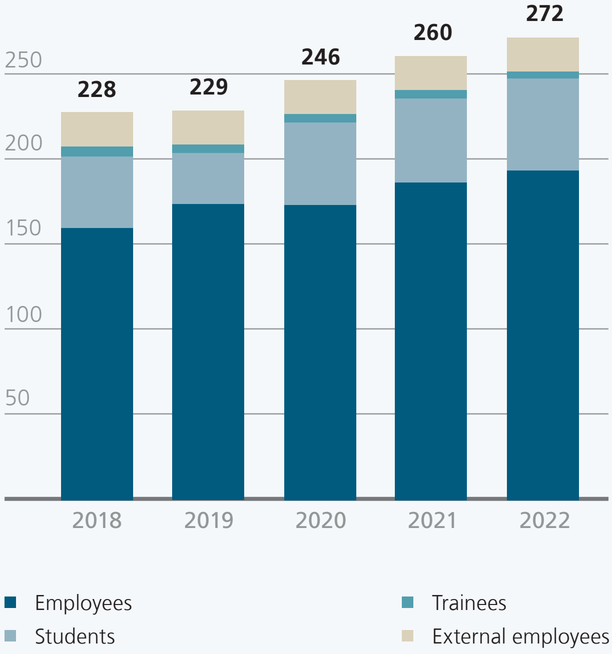


Scientific

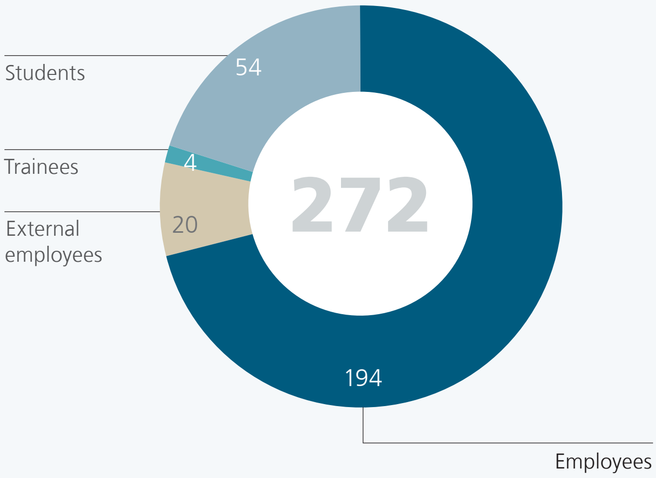


Non-scientific

Development Number of employees



Employees 2022



Organization

MANAGEMENT

Director
Prof. Dr. Karsten Buse

Deputy Director
Dr. Daniel Carl

EXECUTIVE ASSISTANTS AND PUBLIC RELATIONS

Head of Communications and Media
Holger Kock

Organizational Development
Dr. Heinrich Stülpnagel

ADMINISTRATION AND IT

Head of Administration
Wolfgang Oesterling

Administration
Sabine Gabele

Information and Communications Technology
Gerd Kühner

Human Resources
Manuel Mak

TECHNICAL SERVICES

Head of Technical Services
Clemens Faller

Mechanics and Construction
Thomas Hinrichs

Technical Equipment and Maintenance
Benjamin Schlegel

PRODUCTION CONTROL ▸ Page 24

Head of Department
Dr. Daniel Carl

Optical Surface Analytics
Dr. Alexander Blättermann

Inline Vision Systems
Dr. Tobias Schmid-Schirling

Geometrical Inline Measurement Systems
Dr. Alexander Bertz

OBJECT AND SHAPE DETECTION ▸ Page 36

Head of Department
Prof. Dr. Alexander Reiterer

Mobile Terrestrial Scanning
Dr. Philipp von Olshausen

Airborne and Underwater Scanning
Dr. Christoph Werner

Smart Data Processing and Visualization
Prof. Christoph Müller

GAS AND PROCESS TECHNOLOGY ▸ Page 46

Head of Department
Prof. Dr. Jürgen Wöllenstein

Nonlinear Optics and Quantum Sensing
PD Dr. Frank Kühnemann

Spectroscopy and Process Analytics
Dr. Raimund Brunner

Thermal Measurement Techniques and Systems
Dr. Katrin Schmitt

Integrated Sensor Systems
Prof. Dr. Jürgen Wöllenstein

THERMAL ENERGY CONVERTERS ▸ Page 58

Head of Department
Dr. Olaf Schäfer-Welsen

Caloric Systems
Dr. Kilian Bartholomé

Thermoelectric Systems
Dr. Olaf Schäfer-Welsen

Advisory Board Keeping us on track

Our highly qualified Advisory Board guides and supports us in shaping our strategic direction and future goals. After two virtual meetings, in 2022 the board met again for the first time on site in Freiburg.

Chairman

Dr. Lutz Aschke
Carl Mahr GmbH & Co. KG

Members

Sebastian Bannert
Robert Bosch GmbH

Hanna Böhme
Freiburg Economic Tourism and Trade Fair Agency (FWTM)

Stephanie Busse
DB Netz AG

Dr. Mathias Jonas
International Hydrographic Organization

Prof. Dr.-Ing. Katharina Klemt-Albert
RWTH Aachen University, Institute of Construction Management, Digital Engineering and Robotics in Construction

Dr. Fabian Lausen
Federal Ministry of Education and Research

Dr. Mirko Lehmann
Endress+Hauser Flowtec AG

Claus Mayer
Ministry of Economics, Labour and Housing in Baden-Württemberg

Prof. Dr. Andreas Nüchter
Julius-Maximilians-Universität Würzburg

Dr. Volker Nussbaumer
Volkswagen AG, Group Charging GmbH

Dr. Stefan Raible
ScioSense Germany GmbH

Prof. Dr. Michael Totzeck
Carl Zeiss AG

Prof. Dr. Ulrike Wallrabe
University of Freiburg, Department of Microsystems Engineering IMTEK

Investments 2022

We continued to invest in our technical infrastructure in 2022 to ensure we are best placed to support our customers with top-class research.

Tunable continuous-wave laser light source

We now have a tunable continuous-wave laser light source covering the wavelength ranges of 450–650 nm and 900–1,300 nm to assist us with our research on digital multi-wavelength holography. The C-WAVE allows measurements to be taken at any wavelength, enabling users to tailor the measuring range and precision to different areas of application and components at the touch of a button. Using this technology, we can explore new fields of application for digital holography, such as quality assurance in fuel cell manufacturing. Drawing on the C-WAVE's high wavelength stability and the ability to finely tune the wavelength, we are now able to take holographic measurements with a measuring range of 1 m for the first time.

Plasma activation system

Thanks to our new plasma activation system, we can now activate wafer surfaces and consequently perform efficient low-temperature wafer bonding without incurring any losses in bond strength. Low-temperature wafer bonding can be used to bond combinations of materials that do not tolerate significant rises in temperature. We primarily use the technology to bond lithium niobate wafers to SiO_2 wafers. Once bonded, the resulting wafer stacks provide the base material for manufacturing thin-film lithium niobate substrates.

Filament optical fiber processor

We use fiber-optic components as standard in our optical measurement systems. With our new filament fiber processor, we can now process and test optical fibers. The processor allows us to splice fiber connections by directly fusing individual fiber components together without the need for connectors. This makes fiber connections more robust and minimizes optical losses. Previously, we used fiber components with standard connectors and connected them using commercially available couplings. Our new processor also enables us to reshape optical fibers so that we can deliberately manipulate the dispersion of light in and around the fibers. This is helping us to expand our research and manufacturing capabilities in areas such as nonlinear optics and multispectral systems.

Magnetically shielded room (MSR)

We can now perform measurements free from the influence of external magnetic fields in our magnetically shielded room (MSR). This special environment is ideal for magnetic flow measurements, materials testing and the magnetic measurement of nanosatellites. The 30 m^2 MSR effectively shields against magnetic fields from the low-frequency (0.01 Hz) to the high-frequency (> 1 kHz) range.

Highly permeable materials "absorb" the magnetic fields present in the environment and conduct them through the room's walls, ensuring that the inside of the room is free from magnetic fields. The walls are regularly demagnetized to make sure that they retain the same shielding effect. Following demagnetization, the residual magnetic field in the center is < 20 nT.

We perform measurements free from the influence of external magnetic fields in a 30 m^2 room.

Deep learning server

Our high-performance server allows us to train artificial neural networks (ANN) much more quickly than before. ANN are used for the AI-based automated evaluation of our measurement data and help us to produce digital 3D models. The new server has given us a huge amount of processing power and features eight graphics cards (NVIDIA A100), each with 80 GB of memory, which enable us to perform parallel computing and to process much larger neural networks. The graphics cards have a memory bandwidth of over 2 terabytes per second.

Professorships Universities & Universities of applied sciences

Fraunhofer IPM maintains connections with the University of Freiburg in the form of three associated professorships and one lectureship. Through the close university connection, we can draw on the latest results from basic research in our project work. Since 2019, the institute has also been cooperating with the Furtwangen University of Applied Sciences as part of the Fraunhofer / University Cooperation Program.

UNIVERSITY OF FREIBURG

universität freiburg

Department of Microsystems Engineering – IMTEK

Laboratory for Optical Systems

Prof. Dr. Karsten Buse
PD Dr. Ingo Breunig
www.imtek.de/laboratories/optical-systems

IMTEK

Research foci

- Nonlinear optical materials
- Optical whispering gallery resonators
- Miniature solid-state lasers
- Optical frequency converters (optical parametric oscillators OPO)
- Frequency combs
- Fast tuning of laser frequencies
- Integrated optics

Laboratory for Gas Sensors

Prof. Dr. Jürgen Wöllenstein
Dr. Katrin Schmitt
www.imtek.de/laboratories/thin-film-gassensors

IMTEK

Research foci

- Micro structured gas sensors
- Micro structured IR emitters for the MIR spectral range
- Laser spectroscopy
- Compact optical gas measuring systems
- Photoacoustics
- Catalytic sensors for flammable gases
- Systems integration

Department of Sustainable Systems Engineering – INATECH

Chair for Monitoring of Large-Scale Structures

Prof. Dr. Alexander Reiterer
Annette Schmitt
www.inatech.de/alexander-reiterer

INATECH
INSTITUT FÜR NACHHALTIGE TECHNISCHE SYSTEME

Research foci

- Inspection and monitoring of objects and large structures
- Development and implementation of innovative sensor concepts based on laser scanners and cameras
- Data analysis and interpretation with a focus on linkages to influence parameters, causative forces and changes measured
- Development and implementation of complete system chains – from data acquisition to data evaluation

The Faculty of Engineering of the University of Freiburg is right next door.

FURTWANGEN UNIVERSITY

Faculty of Digital Media

Professorship of Computer Graphics

Prof. Christoph Müller

www.hs-furtwangen.de/en/
faculties/digital-media

Research foci

- Real-time 3D visualization for industrial and medical applications
- Interactive visualization solutions for measuring technology
- Photorealism in real-time computer graphics
- Software engineering in 3D computer graphics
- Synthetic training data for AI-based image classification

Interviews

Introducing
Two researchers who spread their wings and founded a start-up

"We want to be there for our customers."

Our employees Simon Stemmler and Bastian Stahl founded bimeto GmbH in 2022. Stemmler had previously managed the Airborne and Underwater Scanning Group, while Stahl is completing his doctorate at Fraunhofer IPM on the topic of "The Automated Interpretation of 3D and Image Data for the Digital Recording of Urban Infrastructure."

You made the leap from researchers to company founders. How did that come about?
Simon: The idea first emerged during an advisory board meeting after I reported on a project on the digitalization of building pits. One of the meeting's participants, Steffen Auer, was very keen to find out more about the project because his company, which manufactures doors and gates, kept encountering problems on construction sites due to building shell dimensions being measured incorrectly. He asked me whether the technology could also be used to survey buildings. Today, Mr. Auer is one of our co-partners ...

What happened next?
Simon: We began by taking sample measurements. That worked so well that we all saw the technology's potential not only to take simple door measurements, but also to produce entire 2D CAD layout plans from 3D scans. From that moment, it took just one year for us to found the company.

Bastian, how did you come on board?
Bastian: When my Head of Department Alexander Reiterer asked me if I could envisage founding a company, I was a bit surprised. But I was quickly sure that I wanted to get involved. It was a good decision!

What risks did you have to weigh up?
Bastian: Instead of focusing on the risks, I mainly saw it as a huge opportunity. Plus, having the support of Fraunhofer and an industrial partner gave me an added sense of security. I'm also at the ideal stage of life to give something like this a go.

Simon: It was a similar story for me. I felt it was important to establish the company as a limited liability company (GmbH). As an employee of a GmbH, you're not personally liable. Many people who start up a company go down the route of being self-employed, but this means they incur all of the risk themselves. I wanted to avoid that at all costs. Once everything was arranged as I wanted it and the financing was in place, I could focus fully on the opportunities ahead of me. I was very excited by the thought of managing my own company with my own team.

How did you raise the financing?
Simon: The start-up capital came from a shareholder loan and a bank loan. We also came across an additional source of funding more or less by chance when we discovered that the Federal Ministry of Finance was offering a "federal research allowance" to companies looking for innovation funding. The allowance would retroactively cover up to 25 percent of our staff costs through turnover tax relief. We successfully applied for it in late 2022.

What was it like starting out and how has bimeto grown?
Simon: Our comfortable financial situation meant that we could take the plunge and begin acquiring customers straightaway – without first having to spend a lot of time applying for funding and raising cash. We now work closely with two industrial partners and managed to carry out some projects and generate a significant turnover in our first year. We also hired a software developer and architect, so we have a fantastic team behind us, which makes work a lot of fun.

How does it feel to suddenly be an employer?
Simon: We are both advocates of flat hierarchies. This is definitely the best way to work all the while we are such a small team. We currently manage a lot of the business ourselves, although it goes without saying that we outsource tasks like accounting and filing our taxes to our tax consultant, who was recommended by our shareholders. What I really needed

Simon Stemmler (left) and Bastian Stahl (right) have not regretted seizing the opportunity to found their own company. Together with their four-person team, they develop solutions for automated 3D building modeling.

to adjust to has been dealing with customers. This involves negotiating prices, which sometimes requires a certain level of assertion. It's completely new territory for me and I've had to step up my communication skills.

Bastian: It's been a similar learning curve for me, although I focus on project work so don't tend to negotiate contracts. I've been surprised by just how direct our customers can be at times. I've had to learn to grin and bear the occasional harshly worded emails that come my way. But we've also already received some very positive feedback. Our customers appreciate our personal approach if something goes wrong. They also like how our software is faster than other building digitalization solutions currently available, which gives us the scope to provide them with customized support.

What role do the two other managing directors play in the day-to-day running of the company?
Simon: They actually don't have much of an active role. But they make excellent sparring partners whenever we have any questions. It's also nice to know that there are other people to share the burden with because we have to make a lot of important decisions.

What past experiences have you drawn on?
Bastian: Before founding the company, I spoke with other founders from across Fraunhofer, which was a valuable experience. The Fraunhofer-Gesellschaft helped us to formulate the license agreement. After all, we use scientific insights that we have gained at Fraunhofer for our business.

Do you still work with Fraunhofer IPM?
Bastian: Yes. We recently commissioned them to do some development work for us – just like a normal customer, although we're not really like a normal customer, of course. We've known each other personally for so long that the communication is quick and easy. Plus, I'm still researching part time at the Institute until I complete my doctorate, after which I'll switch to working at bimeto full time. It's a win-win situation for both of us.

What does the future hold for bimeto?
Simon: In the medium term, our goal is to establish ourselves solely as a provider of software for the digitalization of buildings. This will require us to develop the software further and to build a support team. We want to grow organically and be in the black within the next five years. But after that, we'll see. As co-partners, we'll have a say in whether we eventually sell bimeto or remain independent.

bimeto GmbH

bimeto GmbH provides smart building modeling solutions. By applying automated 3D data interpretation methods, the company speeds up the process of using building surveying to create digital building models. bimeto's software makes construction planning much more efficient by automatically converting 3D point clouds into digital 2D CAD plans or 3D building models. bimeto GmbH is located in Freiburg and currently has four employees.

www.bimeto.de

Customer interview
Siemens Mobility GmbH

"We strive to give our customers what they want before they even know that they want it."

For a project commissioned by Siemens Mobility GmbH, Fraunhofer IPM together with another industrial partner developed a thermoelectrically cooled trolley for use in on-board kitchens on trains. We spoke to Andreas Häußler, Head of the Sanitary Modules and Galley Department at Siemens Mobility, to discover more about the cooling trolley's requirements and the challenges involved in designing it.

What are Siemens Mobility GmbH's main products? How do you make your money?
Andreas Häußler: Siemens Mobility is an independent member of the Siemens Group. We are based in Germany and provide transport solutions and related services around the world. Our core products are rolling stock, rail automation and electrification solutions, software, turnkey rail systems and services, such as railroad depots.

What is your position at Siemens Mobility?
I work in engineering. My small department of 20 people focuses exclusively on developing complete systems in two areas: galleys, which are the on-board kitchens, and sanitary modules. This may sound straightforward, but it's a surprisingly complex task. It's easy to understand how toilet facilities and on-board kitchens work, but fitting them optimally into a railroad car is another matter.

Andreas Häußler is Head of the Sanitary Modules and Galley Department at Siemens Mobility GmbH. His team is responsible for developing on-board kitchens (galleys) and sanitary modules for regional and long-distance trains.

What makes integrating a kitchen into a railroad car so challenging?
The complexity stems from the rail industry itself. Systems need to meet very specific requirements to gain approval. On-board kitchens and toilets are actually very straightforward products, but they still feature a few hidden elements. You could also perhaps say that we do things a bit differently than our competitors. We offer specially developed additional components that we've validated and, in some cases, even invented in our own labs. You won't necessarily find these extra elements elsewhere.

Who decides what innovations your company will develop and bring to the market?
We usually receive a list of overriding requirements from the sales team, but often these don't go into much detail. After all, customers tend to look at the bigger picture. For example, they might say that they want inexpensive, comfortable, hygienic trains. But the idea to develop a self-cooling trolley didn't come from a customer or the sales team. Our department likes to think up and develop innovations like this ourselves. And in this case, we successfully did so in partnership with Fraunhofer IPM. With new ideas like this, we strive to give our customers what they want before they even know that they want it. We thought to ourselves that surely there would be a demand for a cooling trolley. We developed the product together with Fraunhofer IPM as our external R&D partner so that we could benefit from the Institute's expertise in cooling technology.

"We try to fulfill our customer's wishes. Sometimes we even present the customer with innovations that they themselves haven't thought of yet, like, for example, the thermoelectrically cooled trolley," says Andreas Häußler.

Siemens Mobility GmbH

As a leader in intelligent transport solutions for more than 175 years, Siemens Mobility GmbH is constantly innovating its portfolio. Its core areas include rolling stock, rail automation and electrification, a comprehensive software portfolio, turnkey systems as well as related services. In fiscal year 2022, which ended on September 30, 2022, Siemens Mobility posted revenue of 9.7 billion euros and had around 38,200 employees worldwide.

Further information is available at: www.siemens.com/mobility

When designing the cooling trolley, did you have requirements that still demanded innovative solutions even given the current level of technology?
Of course. This was due to the need for it to be integrated into a railroad car. By definition, a cooling trolley needs an additional refrigeration system – and this takes up space and requires a source of energy. When installing an active refrigeration system in a trolley, you have two options: Firstly, you could keep the trolley's dimensions the same so that it still fits into the existing infrastructure. But to do this, you would have to reduce the useable space inside the trolley. Or secondly, instead of reducing the useable space, you could set about finding an innovative refrigeration system that is very compact and requires very little energy. And this is exactly what we decided to do. What's more, we also wanted to avoid using standard refrigerants. These three criteria – an innovative refrigerant, compact size and low energy demand – were vital when developing the cooling trolley. And, together, we managed to meet them all!

Finally, what does the future hold for rail travel?

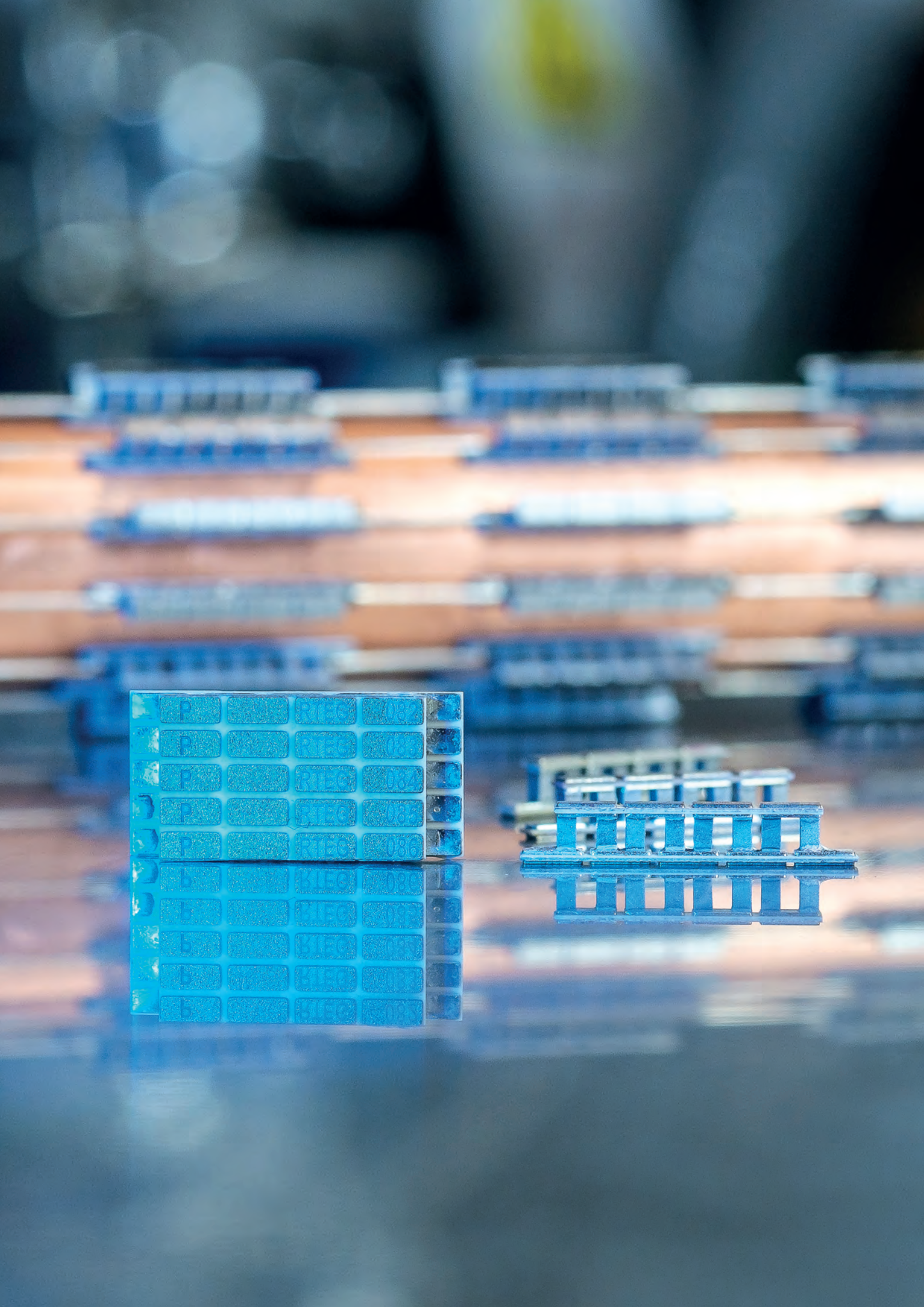
Due to climate change, it's essential that we stop using our cars so much. Despite faster connections, this means we'll be spending more time on trains in the future. We want to make train travel an enjoyable experience. This is the challenge we've set ourselves – and it will require us to continue developing both train technology and all the interior components.

Thank you very much for talking to us, Mr. Häußler!

Andreas Häußler: "The positive feedback from customers at the InnoTrans trade fair showed us that our cooling trolley is an innovation we can sell."

Business units

Working for our customers


P RTEG 082
P RTEG 084
P RTEG 086

Overview Production Control

Measuring as fast as manufactures produce is our contribution to efficient, controlled production.

Our Production Control business unit develops optical systems and imaging processes for inspecting surfaces and taking precision measurements of complex 3D structures on active production lines. The aim: To ensure processes are controlled and therefore more efficient. Our systems are so fast and so accurate that even the smallest defect or area of contamination can be detected on a high-speed production line and classified in real time. In fact, when combined with (marker-free) individual component tracking and tracing technologies, our optical sensors and measurement systems have the potential to make 100 percent reliable real-time production control a reality – in many cases for the very first time. This assigns them a role as enabling technology for the implementation of modern production strategies against the backdrop of the fourth industrial revolution.

A wide range of methods is used, including digital holography, infrared reflection spectroscopy and fluorescence methods, with fast, low-level image and data processing. They can also be customized to suit different customer use cases, including for forming technology in the automotive sector and for quality assurance in the production of medical devices and electronics.

Optical sensors and imaging processes

Customized systems

Data collection and interpretation in real time

Our groups and focus areas

Optical Surface Analytics

- Element analysis in complex multilayer systems
- Analysis of filmic coatings and contamination
- Detection and classification of particulate contamination

Inline Vision Systems

- Surface inspections and dimensional accuracy checks for semi-finished products and components
- Inspection of long products for surface defects and straightness
- Marker-free component identification in production and via mobile app

Geometric Inline Measurement Systems

- Precision surveying of functional surfaces on active production lines
- 3D surveying of workpieces directly on the machine tool
- Rapid dynamic deformation measurements

"Modern production lines need modern measurement and inspection systems. This is exactly where we come in."

Dr. Daniel Carl, Head of Department

Highlights Production Control

Projects · Innovations · Events

Joseph von Fraunhofer Prize

Fluorescence measurement technology: From rough estimates to a precise method

Lubricants, corrosion inhibitors, adhesives – components are exposed to a variety of substances during production. It is not unusual for some of these substances to remain on the component surface, which can negatively affect the downstream process. Unwanted residues can often be detected because of their fluorescence activity: Organic substances transform some short-wave, violet laser light into long-wave, visible light. The visible light can be detected with high sensitivity through spectral filtering, so that just a few milligrams per square meter become visible. According to the same principle, functional layers can be identified.

Over the years, Fraunhofer IPM has developed the rather imprecise fluorescence measurement technology into a high-precision, quantitative measuring method suitable for the 100 percent quality control inspection of components. Our colleagues Dr. Alexander Blättermann and Dr. Albrecht Brandenburg received the Joseph von Fraunhofer Prize 2022 in recognition of this development. The two scientists and their team have since expanded the technology to create a system family for industrial component inspection: The F-Scanner series systems fully inspect sheet metal of several meters' length as well as small electrical component for residual contamination, or control coatings during the production process. One single fluorescence scanner measures up to 40 million points per second, and quantitatively detects residual

Miniature F-Scanner: A robotic arm moves the measuring device across the component – a benefit for 3D components with complex shapes.

"The method allows us to detect the smallest impurities on surfaces, helping to increase the quality – and thus the safety – of adhesive joints in electronic control units."

Dr. Heiko Elsinger, Automotive Electronics, Robert Bosch GmbH

Prof. Neugebauer, president of the Fraunhofer-Gesellschaft, presenting the award to Dr. Albrecht Brandenburg (2nd from left) and Dr. Alexander Blättermann (right) at the annual meeting in Hamburg.

contamination from ten milligrams upwards. Many industrial companies around the world already use the high-precision inspection systems for in-line purity or coating inspections.

Video: The F-Scanner in production

SensoRein project

Fiber-based sensor for demand-based cleaning of closed food processing systems

When it comes to cleaning closed containers in the food processing industry, the general philosophy is often “the more, the better”. The amounts of cleaning agent, water, energy and the cleaning times are generous to ensure that the strict hygiene standards are adhered to. The fiber-based fluorescence sensor F-Fiber ensures that such cleaning processes are adapted to the actual degree of contamination. The sensor was developed as part of the SensoRein project.

F-Fiber consists of a fine optical fiber embedded in a stainless steel ferrule. The fiber tip is integrated directly into the food container wall where it is flushed by the tank or tube content. Over time, molecules are deposited. The organic deposit emits fluorescence when excited with UV light via the sensor fiber. The same fiber guides the emitted fluorescence back onto a detector and evaluates it. The strength of the fluorescence signal allows for conclusions to be drawn about the degree of fouling in the container, so that the cleaning process can be triggered, or the ongoing cleaning process can be adjusted.

Project SensoRein (Sensor-based monitoring of cleaning requirements and cleaning results in closed systems), funded by the Federal Ministry of Food and Agriculture (BMEL) and coordinated by the German Engineering Federation (VDMA)

Minimally invasive: A fine optical sensor tip detects organic deposits in closed food processing systems.

Q-LIB project

Producing electrode foil for Li-ion batteries efficiently

From laptops to electric cars: Countless products contain lithium-ion batteries. These batteries store energy through chemically active substances, such as nickel-manganese-cobalt beads plus lithium. These active materials are applied to an electrode foil as a suspension and then dried into a thin layer with a thickness of about 100 µm. It is not uncommon for the components of the suspension to separate during the drying process, with the result that the binder content is too low in some places and the coating does not adhere.

For the Q-LIB project, Fraunhofer IPM, Fraunhofer ISIT and industrial partners have developed an optical measurement system to identify the element composition of the foil coating using laser-induced breakdown spectroscopy (LIBS) in the production process. The system performs a depth-resolved analysis of the correct mixing ratio and the homogenous distribution of the components within the entire coating, working at a feed rate of up to 20 m/min. This allows monitoring and controlling the coating process.

Project Q-LIB (Reducing costs and improving quality in lithium-ion battery electrode production through quantitative, optical inline measurement technology), funded by the Federal Ministry for Economic Affairs and Climate Action BMWK (funding reference 03ETE013A)

Track & Trace Fingerprint

Tracking and tracing without marking: From precision components to logs

Knowing where a component was produced and where it was integrated is immensely important, as it enables the industry to continuously improve production processes. Fraunhofer IPM's Track & Trace Fingerprint technology allows marker-free component tracking and tracing. Instead of markings, an object's surface microstructure is used for recognition. In 2022, the team advanced the development for a number of applications – and even managed to see the wood for the trees.

As a result of the ProIQ project, we succeeded in reliably identifying rotationally symmetrical components for the first time. The challenge is that the fingerprint area must be positioned precisely for identification to work, which is not the case when the rotational position is unknown. To solve this problem, the researchers refined the Track & Trace Fingerprint algorithm so that the component ID – the fingerprint – deduced from the image includes all possible rotational positions. This also works when the fingerprint is based on the lateral surface, as the example of a head shaft on a dental tool, which was just a few millimeters in size, proved. Another challenge was that the components are sanded and hardened, which changes the microstructure of the surface. The components could nevertheless be reliably identified. Based on

The LIBS measurement system, here in a laboratory at Fraunhofer ISIT, provides information about the chemical composition of electrode foil.

Even rotationally symmetrical microcomponents without end face, such as the head shaft of a dental instrument shown here, can be traced by means of the lateral surface using the Track & Trace Fingerprint technique.

the technology and in close collaboration with the professional dental products manufacturer DentsplySirona, approaches for a long-term process improvement were developed.

Working on a pilot production line at our industrial partner Bosch, the team achieved similarly impressive recognition rates: They had been tasked with reliably identifying an individual small component of a high-performance injector among thousands of components during the production process. The researchers managed to reliably identify 99.95 percent of the components in 30,000 random samples each made up of 100,000 anchors. The component in question was also rotationally symmetrical and created particular optical challenges on account of its polished, mirroring surface. The fast rate of production requiring an equally fast data processing speed, and also the restricted space and working distance inside the production facility presented further challenges.

The rate of production and the mirroring surfaces are not something that would come up in a completely different application for the Track & Trace Fingerprint technology: the identification of logs. In the future, logs are to be identified based on their uniquely structured cutting surface, making tracking and tracing from harvesting to the sawmill possible without the need for traditional numbering tags. Unlike industrial components, logs vary greatly in shape and diameter. This means that there is no standardized reference frame for the fingerprint area. The image window chosen for unique positioning is thus much larger and uses the center of the growth rings for orientation. Apart from the switch from microstructure to macrostructure, the system has to contend with adverse environmental conditions. Here, it is important that sawdust on the cutting surface, or fungus and algae growing on the log do not interfere with recognition. This is why the team uses the unchangeable, ring-shaped growth ring patterns and knots as recognition features, which can still be recognized once the wood has aged, been transported or subject to mechanical wear.

Project ProIQ (Adaptive, cross-process quality control cycles using photonic sensors for the identification and quality measurement of high-precision components), funded by the Federal Ministry of Education and Research and coordinated by the VDI Technologiezentrum

Project DiGeBaST (Digitalization of felled logs), funded by the Federal Ministry of Education and Research (Digital GreenTech program)

Optical quality control

Tunnel vision: Inspection of dimensional accuracy and surface of all types of large components while moving

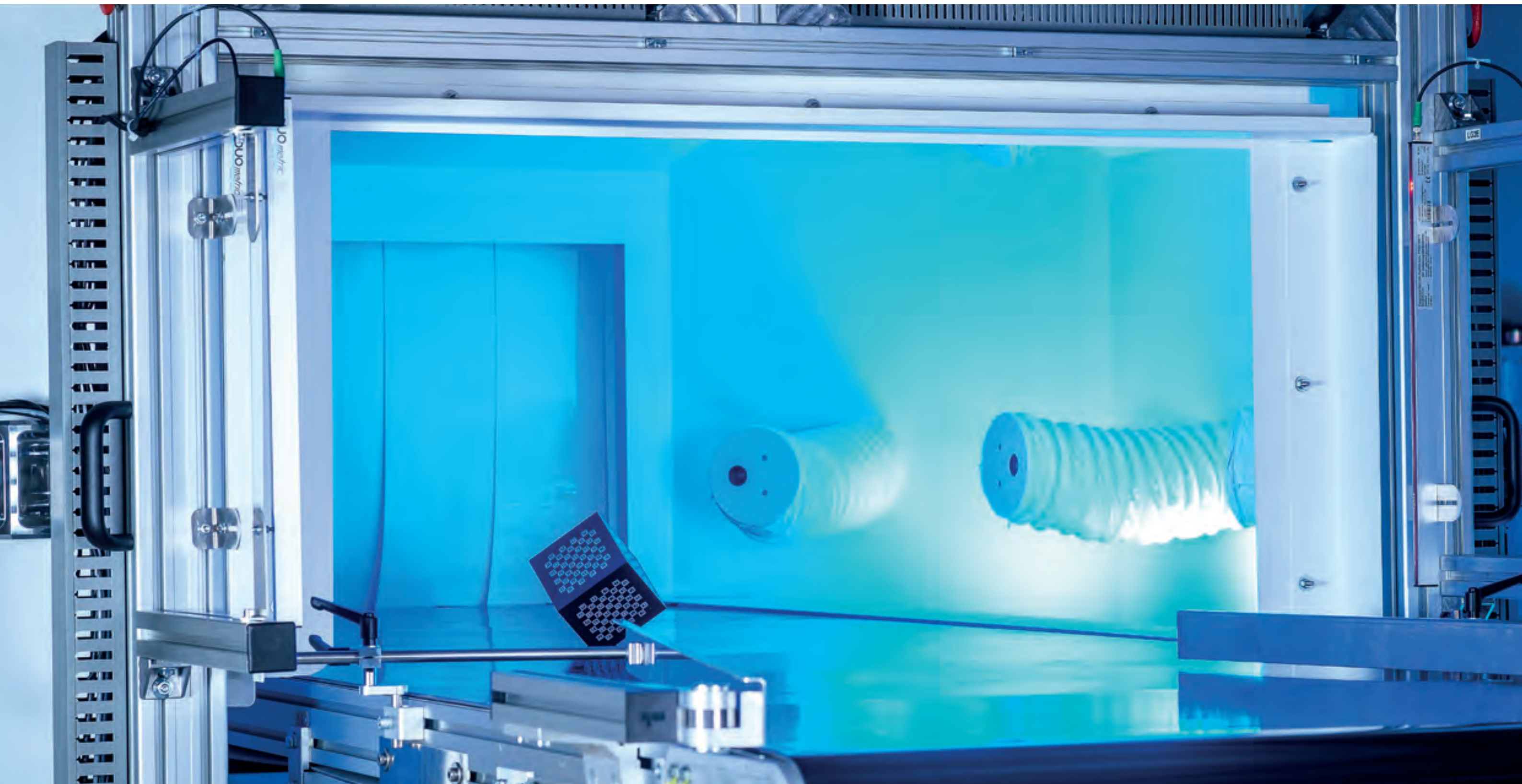
With its Inspect 360° system, Fraunhofer IPM has demonstrated how high-resolution cameras, diffuse flash lighting and real-time image processing can be used for the complete inspection of components without the need for additional handling. Inspect 360° inspects the geometry and surface of components up to 20 cm in diameter in free fall through a hollow sphere. The team was commissioned by an industrial company to develop an inspection tunnel based on this technology, which is suitable for the defect inspection of larger components up to 100 cm in diameter. As each camera can be focused individually, the system is able to test almost any type of component and to record the surface on almost any shape in any orientation in full focus.

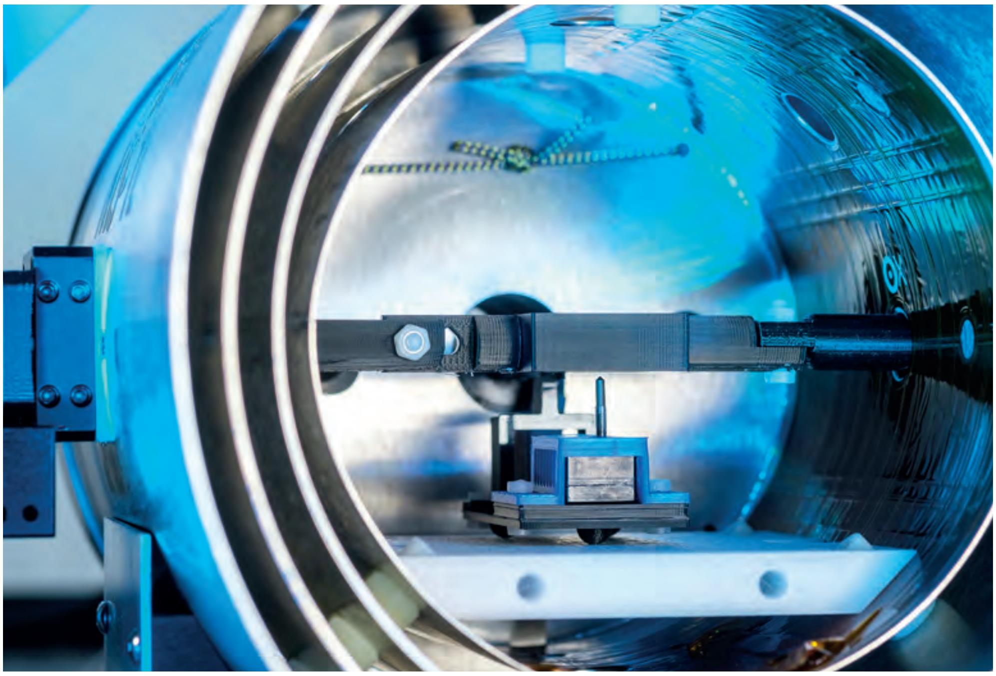
As the components are transported through a 50 cm high, one meter wide and five meters long inspection tunnel on a conveyor belt, they are exposed to homogenous lighting and recorded by 13 cameras several times and from several perspectives. The lighting technology used ensures that unwanted cast shadows or reflexes are avoided. The high-resolution images are processed in real time and evaluated by a service provider specializing in image processing. AI algorithms are used to detect and classify defects such as cracks, holes, grooves or contour errors on stainless steel components for the automotive industry with an accuracy in the tenth-of-a-millimeter range.

"We redesigned our freefall sphere into an inspection tunnel to enable us to inspect any type of component on a conveyor belt."

Dr. Tobias Schmid-Schirling, Group Manager

A conveyor belt takes the components through an inspection tunnel where they are optically inspected.





A flow conductor, mounted on an optically pumped magnetometer (OPM), enables high-resolution measurements of the local magnetization of materials in the range of a few pT/mm².

QMAG project

Quantum magnetometer for materials testing

Quantum sensors, such as optically pumped magnetometers (OPM), open up new possibilities in measurement technology. In a similar way to atomic clocks, they use atomic constants, meaning they do not need to be calibrated. Quantum mechanical principles such as entanglement improve the statistical measurement uncertainty compared with traditional approaches, so that the resulting sensors are robust, highly sensitive and have an extraordinary dynamic range.

Inside miniaturized, optically pumped magnetometers (OPM), a laser uses the Larmor precession to measure the magnetic field in 1 mm³ rubidium gas. This level of sensitivity is sufficient to detect damage due to material fatigue in a sample volume of just 0.1 mm³ based on its magnetization.

Fraunhofer IPM and Fraunhofer IWM work with additional partners on the development of novel, magnetic measurement systems for materials testing. The extreme sensitivity of OPMs – just one millionth of the Earth's magnetic field – enables the high-resolution, magnetic detection of damage in ferromagnetic materials, such as the stress concentration on imperfect welding connections in steel.

To enable industrial applications to benefit from this level of sensitivity, our team is working on new components such as flow conductors as "magnetic prisms" for controlling sensitivity and spatial resolution, suitable actuators, and a special shield against interfering magnetic fields from the surrounding area. Critical components can thus be tested to the strictest specifications in terms of functional safety at an early stage of production, even though the ambient conditions are anything but ideal for OPM in this context.

Project QMAG (Quantum magnetometry), funded by the Fraunhofer-Gesellschaft (lighthouse project) and the state of Baden-Württemberg

Optically pumped magnetometers permit highly sensitive detection of material damage.

> "A laser light where the color can be adjusted quickly, flexibly and precisely marks a paradigm shift in measurement technology for 3D sensors and analytics."
>
> *Prof. Dr. Karsten Buse, Director*

Partnership with the University of Freiburg

The latest measurement technology requires innovative light sources – and a strong partnership

Full-surface 3D measurements with micrometer-level precision in harsh manufacturing environments or even directly inside machinery – the tremendous hidden potential of digital holography has truly come to light in recent years. Measurement systems from Fraunhofer IPM that draw on this technology are being used more and more widely in industry. Wavelength-versatile light sources with long-term stability will play a crucial role in developing this measurement technology even further and in helping it to gain a greater foothold in the market. However, commercial laser system solutions that meet the requirements of digital holography are expensive.

Our Geometrical Inline Measurement Systems and Nonlinear Optics and Quantum Sensors research groups are working closely with the Laboratory for Optical Systems at the University of Freiburg to improve the situation. Together, the researchers are developing various types of laser sources specifically adapted to meet the needs of digital holography. For example, in the MIAME project (Micrometers to meters), they are developing a tunable light source that allows light to be detuned within nanoseconds using an electro-optical whispering gallery resonator – similar to how the tone of a vibrating guitar string changes when it is shortened as it vibrates. The groups' skills complement each other perfectly and range from expertise in fundamental physics to knowledge of what it takes to successfully commercialize the light source and how to use it in measurement technology.

3D image capturing and processing

82nd Heidelberg Image Processing Forum

Fraunhofer IPM hosted the event for the first time. Two of the seven presentations on "3D image capturing and processing" were given by employees from our Production Control business unit: Dr. Alexander Bertz presented on the topic of "Digital holography – imaging coordinate measurement technology of the future" and Dr. Tobias Schmid-Schirling spoke about "Inspecting the surface and geometry of components in free fall." Prof. Dr. Alexander Reiterer, Head of the Object and Shape Detection Department, reported on the topic of "Mobile data acquisition for large-scale infrastructure and AI-based data interpretation" (see page 43).

Prof. Dr. Karsten Buse welcomed guests to the Heidelberg Image Processing Forum.

Production Control | Trade fairs & Events

Control

International Trade Fair for Quality Assurance
May 03–06, 2022
Joint booth of the Fraunhofer-Gesellschaft, Fraunhofer Business Unit Vision

We were represented with the following topics: Surface inspection, mobile and marker-free tracking of components, inline inspection of surface cleanliness and coatings, and fluorescence laser scanners for checking surfaces in production.

drinktec

World's Leading Trade Fair for the Beverage and Liquid Food Industry
September 12–16, 2022
Joint booth of VDMA

The Optical Surface Analytics team presented the fiber-optic sensor F-Fiber for the qualification of Cleaning-in-Place (CIP) processes: F-Fiber measures organic contamination in food-containing vessels and tubes, thus creating the possibility to control CIP processes according to requirements.

parts2clean

Leading International Trade Fair for Industrial Parts and Surface Cleaning
October 11–13, 2022
Joint booth of the Fraunhofer-Gesellschaft, Fraunhofer Business Area Cleaning

The F-Scanner 1Dmini and the F-Scanner 2D for in-line cleanliness control were presented: The systems use imaging fluorescence analysis to quantitatively detect particulate or filmic contamination on component surfaces.

EuroBLECH

International Sheet Metal Working Technlogy Exhibition
October 25–28, 2022
Joint booth of the Fraunhofer-Gesellschaft

At the trade fair, Fraunhofer IPM displayed the F-Scanner 1D: The scanning fluorescence measurement system enables 100 percent inspection of surface cleanliness and coatings on three-dimensionally shaped components.

Events in 2023

BAU
April 17–22, 2023

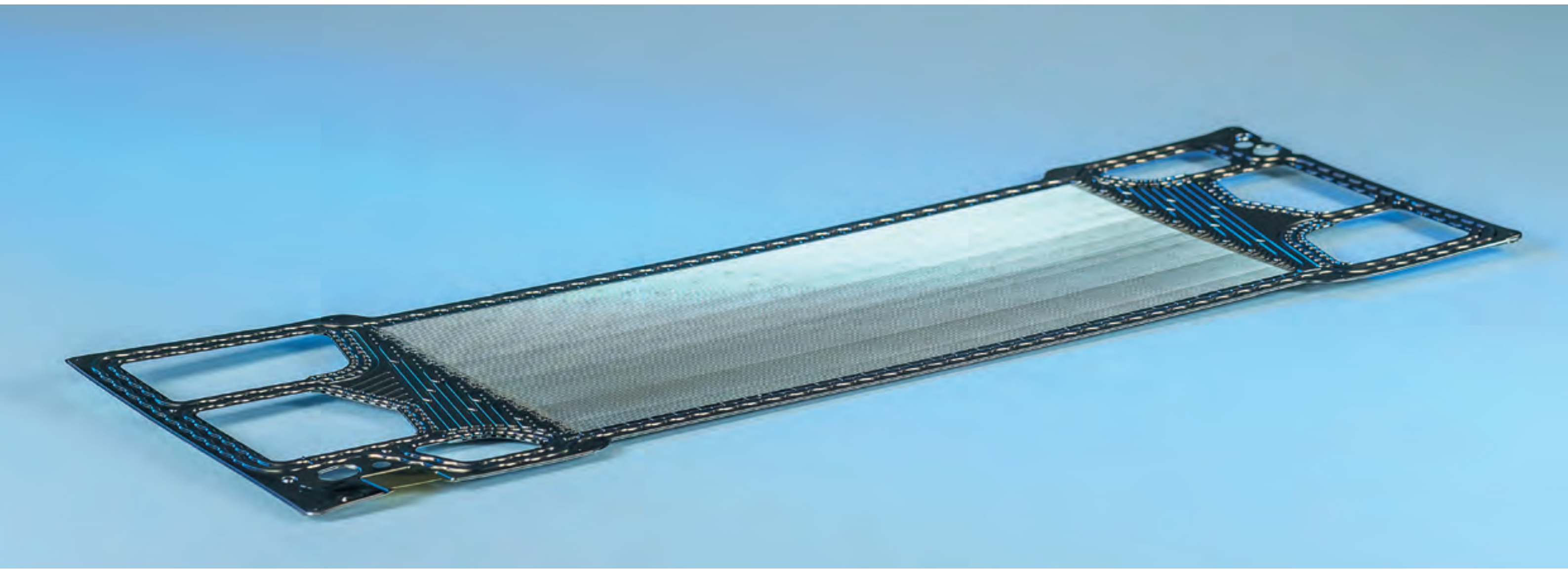
Control
May 09–12, 2023

parts2clean
September 26–28, 2023

Blechexpo
November 07–10, 2023

Focus Modern quality assurance

New approaches for the reliable high-tech series production of fuel cells



Depending on the type and size, modern fuel cell stacks contain roughly 300 to 600 bipolar plates stacked in alternation with membrane electrode assemblies. These thin plates measure approximately 400 by 200 millimeters as standard and typically contain tube structures manufactured using cold forming.

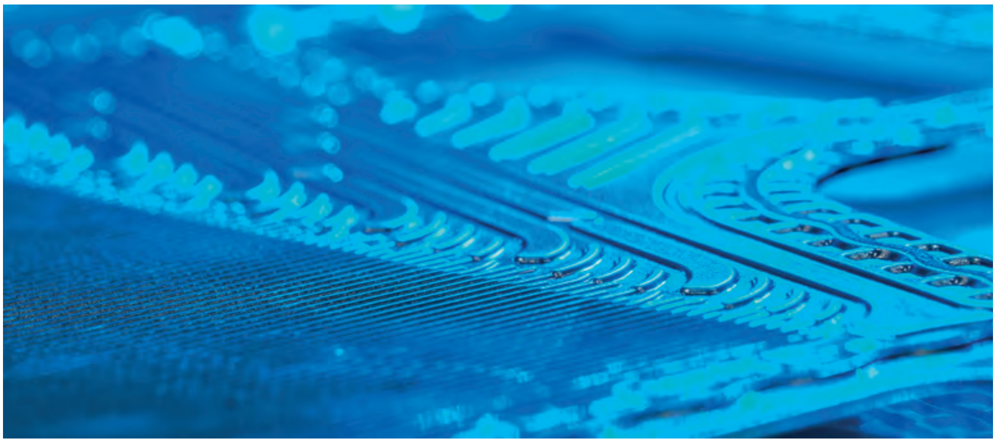
While the automotive industry almost exclusively uses battery technology to power standard electric vehicles, many experts see fuel cell technology as a promising alternative. Fuel cells convert the chemical energy stored in hydrogen into electricity. One advantage of using hydrogen as an energy source is that vehicles can be refueled just as quickly as with gasoline. Hydrogen also has a high energy density, meaning that the range per tankful is comparable to the distance drivers are accustomed to with gasoline or diesel engines. In light of this, why are electric vehicles currently so rarely powered by fuel cells?

Technological obstacles such as unresolved safety issues or a lack of gas station infrastructure may initially spring to mind as possible reasons. However, the way in which fuel cells are industrially manufactured actually presents a much greater obstacle and is currently problematic on three main fronts: significant process engineering challenges, the large amount of rejects and the lack of automation. These factors make fuel cells expensive and are preventing them from being widely used on the market.

Why is there such a lack of automation in fuel cell manufacturing?

Each individual fuel cell is a high-tech product in which every last little detail matters. Many different aspects therefore need to be comprehensively inspected during manufacturing. Due to the absence of inline quality control processes, manufacturing cycle times are currently so low that only a few fuel cells can be produced each day.

The term fuel cell generally refers to entire fuel cell stacks. These stacks are complex sandwich systems consisting of numerous stacked membrane electrode assemblies (MEA) in which chemical energy is converted into electrical



Metallic bipolar plates can be manufactured out of sheet metal or metal foil with thicknesses of less than 0.1 mm. Surface defects or deviations in dimensions frequently occur during the forming process. Previously, quality control was usually conducted downstream using costly and time-consuming spot tests.

energy. Bipolar plates are arranged between these assemblies to supply the reaction gases and drain the resulting water.

Depending on the type, modern fuel cell stacks contain around 300 to 600 bipolar plates measuring approximately 200 by 400 millimeters. The bipolar plates contain delicate tube structures manufactured using cold forming. This means that each stack contains sealing surfaces with a total length of roughly one kilometer. These surfaces must be sealed tightly enough to ensure that hydrogen cannot escape despite its small molecule size and low viscosity. Bipolar plates must also be highly efficient at conducting electricity as well as being extremely chemically, thermally and mechanically stable. All in all, this makes fuel cell systems immensely complex to manufacture and prone to faults.

Quality assurance fit for the future – precise, reliable and inline

The early detection of micro-defects that can occur when forming sheet metal is one of the most challenging quality assurance tasks during the series production of fuel cells. A team at Fraunhofer IPM is currently taking on this challenge with the help of extremely fast digital-holographic 3D sensors. In addition to inspecting the entire surface of formed products, these sensors can work with other sensors to detect tool wear and any shavings in the tool. The team is also experimenting with highly sensitive quantum magnetometers (optically pumped magnetometers – OPM) capable of detecting deeper cracks in the material. These magnetic field sensors are able to measure extremely subtle changes in the magnetic field. If these measurements are then able to provide precise information on the cracks, they would serve as the basis for a very exact, inline-capable method for inspecting the tightness of welded seams. The initial interim results are very promising.

Innovative quality assurance tasks are also required for the high-speed stacking of membrane electrode assemblies and bipolar plates. These processes are used to precisely inspect plate and membrane alignment and to avoid particulate impurities. Researchers at Fraunhofer IPM are working to perform both of these quality assurance tasks using rapid, highly specialized image processing systems.

Detailed, reliable and marker-free tracking and tracing

Without tracking and tracing, even the best quality assurance process would fall short of the mark. Products that have passed quality assurance testing during production need to be marked using a clear, long-lasting method. This is no trivial matter when it comes to membrane electrode assemblies and bipolar plates because markings cannot be applied to either of these parts. The solution is Track & Trace Fingerprint – a marker-free method developed by Fraunhofer IPM that can clearly identify the individual parts within a stack on the basis of their surface microstructures, even after many years have passed.

"We are developing a digital-holographic 3D sensor for the inline quality control of metallic bipolar plates."

Dr. Daniel Carl, Head of Department

Overview Object and Shape Detection

The automation of 3D data collection and processing is our contribution to the digitalization of our environment.

Our Object and Shape Detection business unit is focusing on the entire process chain for the automated mapping, referencing, interpretation and visualization of the geometry and position of infrastructural objects. We develop measurement systems, mainly laser scanners, and custom lighting and camera systems for mapping objects and shapes three-dimensionally with extreme speed and precision – mostly from moving platforms. Typical measuring ranges are between a few centimeters to hundreds of meters.

Measured data is evaluated in a fully automated process and interpreted by specially developed software. To this end, we employ techniques from the field of artificial intelligence (AI), such as deep learning. Data that is processed and visualized for specific applications provides a sound basis for planning, which is particularly important where infrastructure is concerned, for instance.

Fast, precise and robust sensors

Miniaturized measurement systems

Data interpretation software

Our groups and focus areas

Mobile Terrestrial Scanning

- Rail systems
- Road systems
- Systems for meteorological applications

Airborne and Underwater Scanning

- Systems for unmanned aerial vehicles
- Systems for underwater applications
- Systems based on low-cost and consumer products

Smart Data Processing and Visualization

- Real-time visualization of spatial data
- Creation of synthetic measurement data
- Flexible function libraries
- Platform-independent systems

"We use our expertise to make buildings more efficient to plan, construct and operate."

Prof. Dr. Alexander Reiterer, Head of Department

Highlights Object and Shape Detection

Projects · Innovations · Events

"Digitalization made in Germany works after all!"

Tim Höttges, CEO Deutsche Telekom

Fourth "T-Car" for Deutsche Telekom

Deutsche Telekom is working full steam on expanding its optical fiber network. The company continues to use Fraunhofer IPM high-end measurement technology for measuring the development areas and planning the network expansion. In the spring of 2022, the third T-Car equipped by us hit the road, followed by a fourth one in the fall of the same year. The magenta-colored vehicles are equipped with laser scanners, camera systems, GNSS antennas and high-performance computers for data processing, and supply 2D and 3D measurement data for entire roads.

The four T-Cars covered more than 60,000 kilometers in 2022. Some of these kilometers were driven by Telekom CEO Tim Höttges himself. "Seeing how data is turned into information is always exciting. This is where we need artificial intelligence," Höttges said in a video showing him test-driving a T-Car. AI-based algorithms semantically enrich the data and transfer them to digital planning maps. The maps contain geometrical measurements as well as information on the surface characteristics of the development area and typical objects, such as trees or street lamps. The maps can be used to automatically identify the ideal route for the optical fiber cables without the need to take measurements on site.

Facebook video:
"Tim is testing the T-Car"

Four T-Cars supply semantically enriched measurement data in the form of digital planning maps for the fast development of the Deutsche Telekom optical fiber network.

Collecting data while driving by: Garbage trucks or delivery vans, equipped with measurement technology, are set to supply 3D data of urban environments as a high-quality data basis to help with the development and efficient management of cities.

MuSiS project

The city as a digital twin

Garbage trucks, buses and delivery vans carrying low-cost, highly efficient measurement technology generate planning data for urban areas while driving around. This is the vision of the MuSiS research project and the reason why Fraunhofer IPM and incontext.technology GmbH have joined forces to develop a process for creating a digital twin of urban environments quickly and with deep granularity. To implement this idea, a compact, multi-purpose measuring box will record the environment using laser scanners, cameras and sound level meters. The robust multisensor system developed by a team at Fraunhofer IPM has a positioning unit to ensure that the measurement data are linked to location information. The data are anonymized before being recorded and preprocessed, reduced and processed by an artificial neural network while still on the vehicle. The idea is to make the measurement data available for various applications in real time. Project partner incontext.technology develops AI-based algorithms for the automatic use and semantic enrichment of the data streams, and creates data models for the digital twin.

Project MuSiS (Multimodal digital twin for a safe and sustainable city), funded by the federal state of Baden-Württemberg through the Ministry of Economic Affairs, Labor and Tourism's Invest BW program

3D-Path project

Automatic 3D route planning for XXL transportation

Will the long goods truck make it along the windy road? Will the heavy goods truck with excessive width be able to drive over the bridge? These are the kinds of questions that logistics companies have to consider when planning the routes of bulky or heavy goods transport vehicles. The basis for their plans are usually standard navigation maps with manual entries of specific information on critical points. As part of the 3D-Path project, Fraunhofer IPM is developing an automated process together with industrial partners to make route planning for XXL transports much simpler.

An optical infrastructure measurement system provides 3D data that are automatically connected with basic maps. The resulting enhanced maps contain all the information necessary for virtual 3D route planning for bulky and heavy goods transport. As part of the 3D-Path project, the team at Fraunhofer IPM is developing a semantic object recognition based on deep learning algorithms to identify typical obstacles such as trees, masts or curbs based on the measurement data. The data is set to be transmitted to a CAD or BIM-compatible format through a vectorization module, which is intended to automate what is today still a manual process of vectorizing 3D point clouds.

Project 3D-Path (Automated 3D route planning for overweight and oversized transportation), funded by the EU as part of the Eurostars program

AI enriches measuring images of road situations by adding semantic information. These data are integrated into navigation maps to facilitate route planning for bulky and heavy goods vehicles.

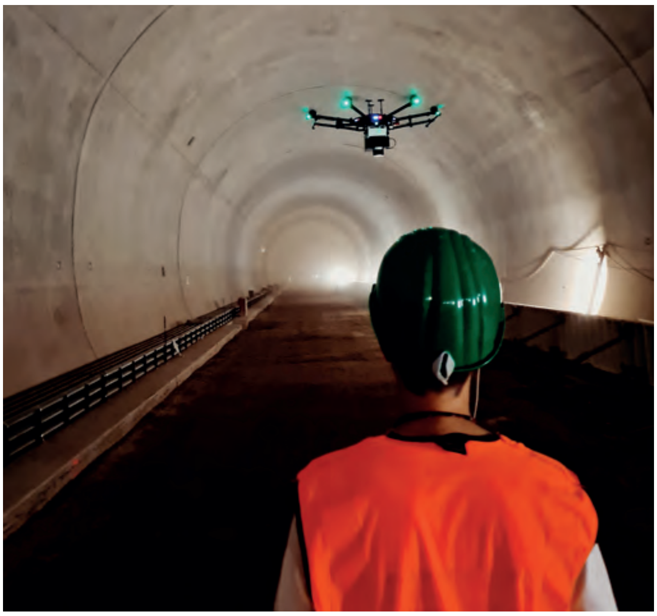
DoTIS project

Flying tunnel scanner: Less weight and faster than expected

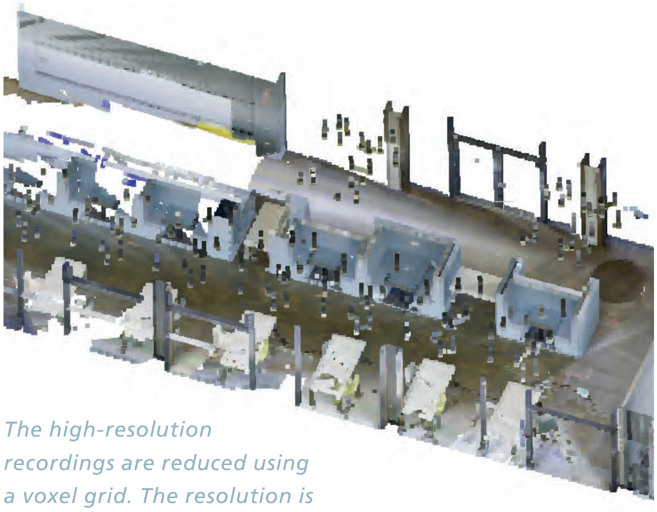
It's dark, the space is restricted, no chance of satellite reception – anyone wanting to inspect the condition of a tunnel construction will face a whole range of challenges. Precise measurements are still possible even under such difficult conditions, as our DoTIS project team was able to show. The team developed a laser scanner for drones that records tunnel geometry from the air, based on pulsed time-of-flight (TOF) distance measurements. The lightweight tunnel profiler (LTP) is smaller than a shoe box and only weighs 2.1 kilograms – which is even less than planned. The planned measurement speed was exceeded, too: With a scan rate of 120 Hz and a measurement rate of one million measurements per second, the scanner achieves a millimeter-range resolution.

The team developed completely new optics and a motor-mirror-unit for beam deflection, enabling shadow-free 360-degree measurements. The drone's trajectory – and thus the laser scanner's position – are determined with the help of a laser-based sensor. This approach can do without the usual satellite navigation data (GNSS). The 3D point cloud for the tunnel geometry is calculated on the basis of the time-synchronized distance and trajectory data.

Project DoTIS (Drone-based Tunnel Inspection System), funded by the Eurostars-2 program and Horizon 2020, the EU's research and innovation funding program



Lightweight and flying high: The laser scanner for tunnel inspections with its carbon fiber housing weighs little more than two kilograms.



The high-resolution recordings are reduced using a voxel grid. The resolution is still within the millimeter-range.

BIM – Building Information Modelling

The building as a digital twin

In the future, AI-based tools are to make surveying of existing buildings more efficient and planning process easier. What are the spatial dimensions? How many windows, doors, stairs, radiators and lamps does a building have? Digital building models are to provide the answers to these questions, making a physical inspection unnecessary. This type of digital twin is created with the help of an artificial neural network (ANN) that has learned to recognize and classify typical building objects from measurement data.

Our team is working on creating such an ANN as part of a feasibility study, using extensive training data in three steps. The work is painstaking: In a first step, a 3D laser scanner was placed around our institute in various places 1,600 times in order to record all rooms, corridors and stairs. Together with measured data from a building shell, a school and an apartment, this provides much more extensive training data for the ANN than any of the building data sets available in the market today. In a second step, all of the measurement data is annotated by assigning each object to one of 26 object classes. In a third and most important step, the semantically enriched data is then used by the team to train the ANN for automated interpretation of unknown building data.

The measured data from our institute building contains more than 23 billion 3D measuring points.

Ken Brodlie Prize for best paper

Indexing point clouds in real time

Data provided by LiDAR sensors is becoming more and more detailed. Recording just a short section of road can supply billions of 3D points. This vast volume of data is an unstructured point cloud, which has to be pre-processed and indexed to enable analysis or visualization. In their paper "Real-time Indexing of Point Cloud Data During LiDAR Capture", our colleague Bastian Stahl and three co-authors showed that this can be done in real time during data capture. The scientists developed a software which transmits the 3D data generated by the LiDAR system directly into a hierarchical data structure, a so-called octree. Using a synthetic data set, they achieved a throughput of up to 1.8 million data points per second. The real-time indexing also worked smoothly in the live test with a high-end laser scanner. The team's work was recognized by the Computer Graphics & Visual Computing journal with the Ken Brodlie Prize.

Scientific publication: "Real-time Indexing of Point Cloud Data During LiDAR Capture"

ACQUA-3D project

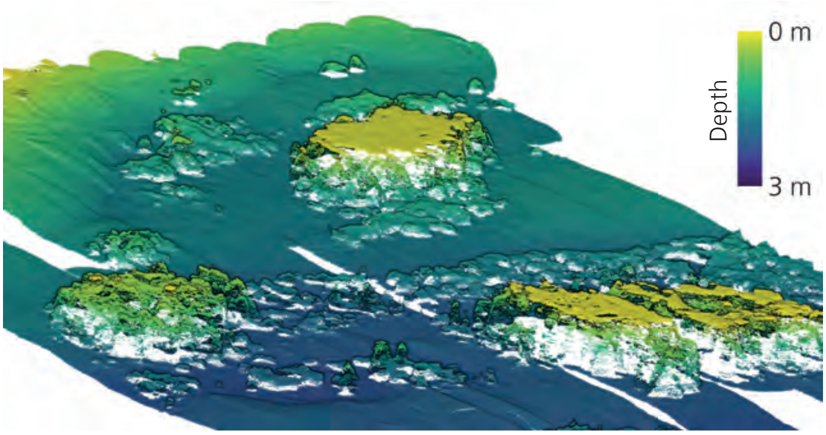
Compact topographic surveying system for shallow bodies of water

The condition of the bottom of water bodies in coastal and riparian areas gives an indication of flood risks and can be an early indicator of changes in the environment. Laser-based bathymetry systems measure the underwater topography of shallow bodies of water from the air, using the time-of-flight measurement of pulsed lasers. Since November 2022, we have been working with the University of Stuttgart and application partners EOMAP GmbH and Geo Group GmbH on developing a particularly small and light bathymetric measurement system for use on UAVs (Unmanned Aerial Vehicles), particularly for measuring shallow bodies of water.

The entire system with a projected total weight of less than 3 kilograms consists of a LiDAR module and a multispectral camera. The length of the two laser's light waves is suitable for identifying both the water's surface and the bottom of the water. 50 scans per second will generate 100,000 measuring points, producing a detailed image of the bottom of the water. Using a specially developed evaluation algorithm, a terrain model can be automatically generated from the measurement data, including the semantic classification of terrain and vegetation (see pages 44–45 to find out more).

Project ACQUA-3D, funded by the German Research Foundation and the Fraunhofer-Gesellschaft (trilateral transfer project)

Terrain model with semantic classification of terrain and vegetation



Sample measurement at a quarry pond: The laser bathymetric system provides a high-resolution point cloud, making details – such as vegetation – clearly visible even in up to three meters of depth.

The ECOSENSE DFG Collaborative Research Centre

LiDAR system for monitoring forest ecosystems

How is climate change affecting forest ecosystems? This is the question being investigated by the University of Freiburg and the Karlsruhe Institute of Technology (KIT) in the ECOSENSE DFG (German Research Foundation) Collaborative Research Centre (CRC). The aim of the research initiative, which was launched in May 2022, is to develop an autonomous, intelligent sensor network to improve the modeling of changes in forest ecosystems. Fraunhofer IPM is involved in the CRC through two of its professorships – one at the Department of Sustainable Systems Engineering (INATECH) and one at the Department of Microsystems Engineering (IMTEK).

As part of the CRC, our team is working closely with INATECH to develop a drone-borne LiDAR system for measuring chlorophyll fluorescence (ChlF). ChlF provides insights into the photosynthetic activities of plants to indicate how environmental changes are affecting vegetation. The LiDAR system will feature a novel evaluation chain and a special laser deflector to enable chlorophyll fluorescence to be determined across a wide area. The measurement data will be used to create detailed spatio-temporal 4D fluorescence maps of forests with resolutions all the way down to the level of individual leaves. In the Gas and Process Technology business unit, we are developing sensor technology for measuring gas flows at ground level as part of the CRC (see pages 56–57 to find out more).

The ECOSENSE Collaborative Research Centre (CRC 1537) is funded by the German Research Foundation.

4. MoLaS Technology Workshop

Great interest even after two years break due to the pandemic

The pandemic had forced us to postpone our Mobile Laser Technology Workshop two years in a row. In December 2022 at last we were able to welcome more than 90 participants to the workshop, which was held at our new site for the first time. The enforced break clearly did not lead to decreased interest – since 2014, the MoLaS Technology Workshop had become a recurring date for the mobile mapping community.

The presentations covered a wide range of topics, from multispectral laser scanning for humidity detection and SLAM- (simultaneous localization and mapping) based indoor scanning to new strategies for the interpretation of 3D point clouds. Terje Noevig of Blickfeld GmbH and Alexander Braun of Düsseldorf University of Applied Sciences gave keynote lectures on strategies for the mass production of cost-effective LiDAR systems for applications such as autonomous driving.

The international MoLaS Technology Workshop takes place every two years, and the next event is scheduled for November 27–28, 2024.

www.molas.fraunhofer.de

At last: having face-to-face discussions for the first time in four years. At the workshop, Valentin Vierhub-Lorenz presented his research findings on multispectral laser scanning.

Object and Shape Detection | Trade Fairs & Events

82nd Heidelberg Image Processing Forum

November 08, 2022

Fraunhofer IPM hosted the event on "3D image capturing and processing for the first time. Prof. Dr. Alexander Reiterer, Head of the Object and Shape Detection Department, reported on the topic of "Mobile data acquisition for large-scale infrastructure and AI-based data interpretation". Other presentations were given by employees from the Production Control Department (see p. 32)

Oceanology International

March 12–17, 2022

The main topic at the trade fair was the laser-based survey of large underwater structures and the topographic survey of coastal waters. In this context, we presented the Underwater LiDAR System ULi and the Airborne Bathymetric Laser Scanner ABS.

SMM

The leading international maritime trade fair
September 06–09, 2022

We presented our systems for underwater measurement ULi und ABS.

InnoTrans

International trade fair for transport technology
September 20–23, 2022
Joint booth of the Fraunhofer-Gesellschaft, Fraunhofer Transport Alliance

The focus was on tunnel inspection and vegetation control. We presented the Tunnel Inspection System TIS and the Weed Detection System WDS as live demonstrators.

INTERGEO

October 18–22, 2022

At the trade fair for geodesy, we demonstrated how to evaluate mobile mapping data as efficiently as possible. Our AI-based software for data evaluation 3D-AI was presented as a live demonstrator.

denkmal

Europe's Leading Trade Fair for Conservation, Restoration and Old Building Renovation
October 24–26, 2022

At the fair, we showcased our technologies for the 3D capture of buildings and automated data interpretation.

Events in 2023

BAU
April 17–22, 2023

INTERGEO
October 10–12, 2023

Focus Underwater laser scanning

3D surveying of underwater infrastructure and bathymetric measurements for deeper insights

Climate change is causing our coastlines to change rapidly. Laser-based systems are making it easier to perform topographic mapping.

Using measurement technology to discover what lies beneath the water's surface can be difficult. At present, underwater structures are generally inspected by divers. Visual inspections like this are performed with the help of image and video recordings, but lack objectivity and are time-consuming, not to mention dangerous. Other optical methods, such as laser triangulation and photogrammetry, have a limited working range and are sensitive to turbid water. The bathymetric surveying of shallow bodies of water – especially in coastal areas and waterways – is just as complex and laborious. To date, there is no standard, automated process for measuring both the topography of the surrounding land and the topography of the water's floor because these areas are often inaccessible to sonar systems. This means that manual surveying using a GNSS pole is often the only option remaining. However, the resolution attainable using this method is limited and the measurement process is very time-consuming and expensive.

LiDAR (light detection and ranging) technology using pulsed lasers offers many advantages when performing underwater 3D measurements and bathymetric measurements. LiDAR systems provide more precise and detailed measurements than, for example, camera or sonar systems and enable direct, true 3D data to be captured – even across relatively large distances. Water nevertheless poses a number of fundamental challenges, which is why optical systems are currently hardly ever used for underwater measurements. Water attenuates light significantly; furthermore, turbid matter in water cause light to disperse and dazzle the sensors. Over the past few years, researchers at Fraunhofer IPM have successfully overcome these challenges. The team has so far developed two systems – the Underwater LiDAR System ULi and the Airborne Bathymetric System ABS.

Measuring structures down to the millimeter – at depths of up to 300 meters

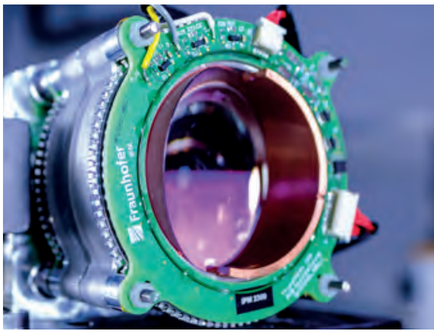
The underwater laser scanner ULi measures 3D structures in the water and can be operated statically or by being moved by a underwater ROV (remotely operated vehicle) or boat. This allows damage to underwater infrastructure like dams, wind turbine foundations, pipelines and data cables to be identified in good time. The system can also detect biofouling, which sometimes accumulates in layers several centimeters thick on ship hulls, pushing up fuel consumption.

ULi can dive to depths of up to 300 meters, capturing objects with precision in the millimeter range across distances of several tens of meters. The following applies: the clearer the water, the better the measurement results. The measurement distance is around twice the range of vision and structures much smaller than a centimeter can be resolved. The system provides measurements that are up to ten times more precise than sonar systems and creates a precise 3D model of the object being scanned. ULi captures underwater infrastructure using the pulsed time-of-flight method with a laser light with a wavelength of 532 nm and a sampling frequency of up to 100,000 measuring points per second. The measurement beam is deflected using two rotating Risley prisms, allowing the scanner to capture the entire field of view without the sensor needing to be moved.

Ultra-lightweight LiDAR scanner efficiently takes measurements from the air

Laser-based systems are efficient at generating bathymetric maps of bodies of water with a relatively high resolution. However, the few laser bathymetry systems already available are large and weigh up to 200 kilograms. The ABS with a weight of just around 3 kilogram is just the size of a shoe box and can be mounted on standard drones. Its low weight means that users do not need to go through the complex and expensive process of applying for flight permits. The LiDAR scanner measures the topography of the water's floor and surrounding areas using the multiwavelength principle, which involves deploying two laser beams with different wavelengths. The advantage: By using two perfectly superimposed pulsed lasers, the undesirable effect of light refraction is corrected, which makes the water appear optically less deep than it actually is. The measurements are therefore much more precise than those taken with just one laser beam. The infrared measurement beam (1,064 nm) does not penetrate the water, allowing it to provide information on the water's surface. It can also be used to detect vegetation, especially in coastal areas. It does this by taking measurements at up to twice the Secchi depth – i.e. two times the visual depth of the water – with a precision of up to 10 cm.

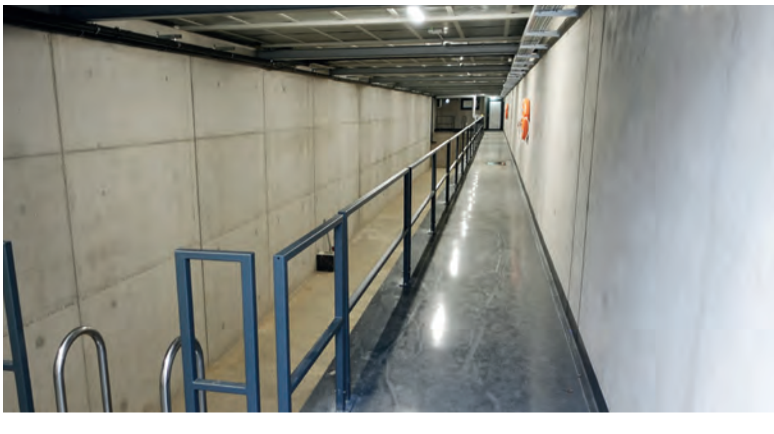
Signal processing presents a particular challenge when taking laser measurements in water. The reflected light contains different echoes from the water's surface, from particles in the water and from the water's floor. To separate this echo sequence in order to extract information on the topography being investigated, a full waveform analysis of the measurement data must be performed. Even the smallest of echoes can be extracted and precisely recorded using specially developed algorithms. The integration of GNSS data allows the flight trajectory to be determined and combined with the LiDAR data to generate a complete georeferenced 3D model.



A look inside: The ULi underwater laser scanner can dive to depths of up to 300 meters.

"LiDAR systems provide more precise measurements than camera or sonar equipment and produce 3D models."

Dr. Christoph Werner, Group Manager



Water basin for test measurements

We have been testing our LiDAR systems in a water basin on our premises since 2022. Measuring 40 meters long, 3 meters wide and 2 meters deep, the basin is long enough to perform test measurements. The scanners can be moved above the water's surface on a mobile platform and can also be submerged in the water. Filtration equipment is used to add or extract specific quantities of turbid matter. The basin is the only research facility of this size.

Overview Gas and Process Technology

Developing tailored measurement systems and methods is our contribution to modern gas and process monitoring.

Within our Gas and Process Technology business unit, we develop and produce measurement and control systems to fit our clients' briefs. Short measurement times, extreme accuracy and high levels of reliability are the hallmarks of our systems – no matter how extreme the conditions.

Our areas of expertise include laser spectroscopy methods, custom light sources and detectors, and energy-efficient sensor systems and quantum sensor technology. And we cover a wide range of applications, ranging from exhaust gas analysis and food transit monitoring to sensors and systems used to measure minuscule temperature differences.

Miniaturized sensors and systems

Spectroscopy methods

Quantum sensor methods

Our groups and focus areas

Integrated Sensor Systems

- Gas-sensitive materials
- Micro-optic infrared components
- Miniaturized gas sensor systems

Thermal Measurement Techniques and Systems

- Customized microstructures
- Thermal measurement systems
- Simulation of physical processes

Spectroscopy and Process Analytics

- Spectroscopy analytics
- Optical systems
- Evaluation methods

Nonlinear Optics and Quantum Sensing

- Nonlinear optics
- New spectroscopic measurement techniques
- Quantum sensor technology

> "We research the gas and process measurement technology of the future. In doing so, one of our aims is to build a secure hydrogen economy."

Prof. Dr. Jürgen Wöllenstein, Head of Department

Highlights Gas and Process Technology

Projects · Innovations · Events

More than a whiff of a clue: The photothermal gas analyzer analyzes trace gas concentrations in breath in real time and can detect signs of a disease.

ISLAS project

Photothermal breath gas diagnostics

With every breath, humans release volatile organic compounds, nitrogen oxide, methane and ammonia that could be used to detect signs of certain diseases. Despite this, breath gas diagnostics have not yet become established in everyday clinical practice. This is due to the lack of affordable, easy-to-use measuring devices that could take the place of current sampling methods. There is a particular demand for highly sensitive sensors that can work with small sample quantities to measure the relevant substances despite their complex gas composition.

In the ISLAS project, Fraunhofer IPM joined forces with Fraunhofer IAF to develop a photothermal breath gas analyzer that can measure trace gas concentrations sensitively and in real time. In photothermal spectroscopy, a separate probe laser is used to detect substances by their heat signature. The method patented by Fraunhofer IPM detects concentration values down to the single-figure ppb (parts per billion) range within just one second. A sample quantity of just a few microliters of breath gas is sufficient. Optical readouts also enable various types of interference caused by the gas matrix to be bypassed. The system is able to identify concentration trends within a single breath, providing important additional diagnostic information.

Project ISLAS (Intra-cavity laser spectroscopy for the highly sensitive determination of trace gases), funded by the Fraunhofer-Gesellschaft (preliminary research project)

Milk on the surface of an ATR sensor. In the future, sensors like this should eliminate the need for time-consuming laboratory measurements.

BREATH project

Fluorescence-based sensor for monitoring the oxygen content in respiratory air

When the oxygen saturation in the blood drops, action is warranted: Extremely low oxygen levels can cause lasting damage, and ultimately kill. This is why intensive and emergency medicine relies on continuously monitoring oxygen saturation. Usually, simple pulse oximeters are used that measure the oxygen in the blood via a small clip that is placed on the finger. This kind of measurement via the skin is neither very reliable nor accurate. More accurate values can only be obtained by measuring the arterial blood, which entails a relatively cumbersome and invasive procedure.

Through the BREATH project, Fraunhofer IPM is developing a non-invasive sensor to measure the blood oxygen level directly and in real time. This is achieved by measuring the O_2 concentration in the breath gas using the principle of fluorescence quenching, which allows conclusions to be drawn about the blood oxygen saturation. "Quenching" means that the emissivity of a fluorophore layer weakens upon contact with the target gas in line with the gas concentration. The team has developed a fluorophore for the determination of the oxygen concentration, which was integrated into a demonstrator system. Initial measurements showed promising results. The next goal will be to develop a miniaturized sensor system which is connected to an oxygen mask and a ventilator tube directly via standard connectors, and can be produced at low cost.

Project BREATH, funded by the Fraunhofer-Gesellschaft (SME project)

MIRIMAUS project

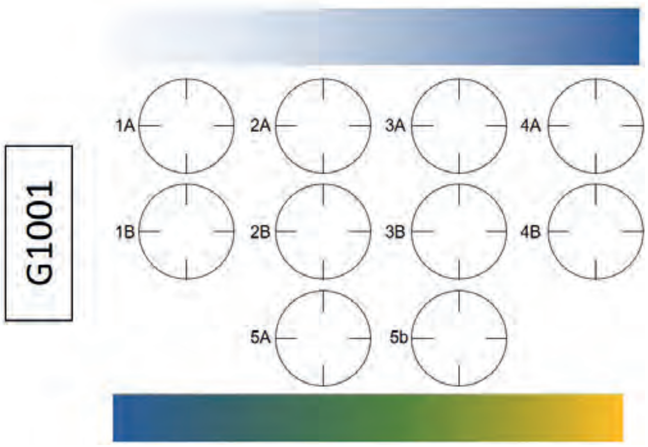
Quality control of unpasteurized milk using ATR spectroscopy and ultrasound waves

Not all milk is the same. In fact, the composition of this natural product varies from farm to farm. Fat and protein content play an important role during the processing of unpasteurized milk and also determine how much dairy farmers are paid. These parameters are measured by taking samples for evaluation in specialist labs.

Since 2022, Fraunhofer IPM has been working with industrial partners as part of the MIRIMAUS project to develop a low-cost sensor for measuring the fat, protein and lactose content of milk on site, for example when it is delivered to dairies. To achieve this, an attenuated total reflection (ATR) sensor for the spectroscopic analysis of the milk components is to be combined with an ultrasonic transducer. The high-energy ultrasound waves homogenize the milk, allowing a representative sample volume to be obtained. At the same time, the ultrasound is used to keep the surface of the ATR crystal clean and to prevent unwanted deposits (fouling). The project is also investigating whether standing ultrasound waves can be used to selectively enrich the milk components to improve the signal. The team at Fraunhofer IPM is responsible for designing and optimizing the measurement system.

Project MIRIMAUS (Mid-Infrared Inline Milk Analysis through UltraSound), funded by the Federal Ministry of Education and Research as part of the Eurostars program (Eurostars E!115483)

Not all milk is the same: In the future, a low-cost sensor should be able to measure important quality parameters of unpasteurized milk on site.



This is what the sensor label could look like: Gas-sensitive dyes will be applied to the areas marked by the circles. These dyes will have varying sensitivity levels to H_2O and CO_2.

The "Saving Grains" project

Color-changing sensors against post-harvest losses

Wheat, pulses and oilseeds – up to a quarter of the produce harvested in the southern hemisphere end up rotting. This is because storage conditions are so bad. The situation could be improved if producers used hermetically sealed grain sacks. However, these sacks are not well accepted because they prevent traders from being able to check the goods. What if the quality of the stored goods could be checked without opening the grain sacks? Commissioned by the Humboldt-Universität zu Berlin, we are working on a sensor design to make this possible.

Gas-sensitive disposable labels on the inside of transparent grain sacks are designed to monitor the carbon dioxide (CO_2) and humidity content inside the hermetically sealed sacks. CO_2 is produced through the metabolism of insects, and humidity can point to an ongoing fermentation process. Detecting these parameters therefore allows conclusions to be made about the quality of the grain. Our team is developing a colorimetric sensor which sets off a visible, reversible color change once a certain gas or humidity concentration has been exceeded. This is achieved with gas-sensitive dyes that are processed to form a printable paste, a specially developed coating process and dedicated label materials. Response behavior, cross-sensitivity and long-term stability of the color-changing sensors are characterized through extensive tests.

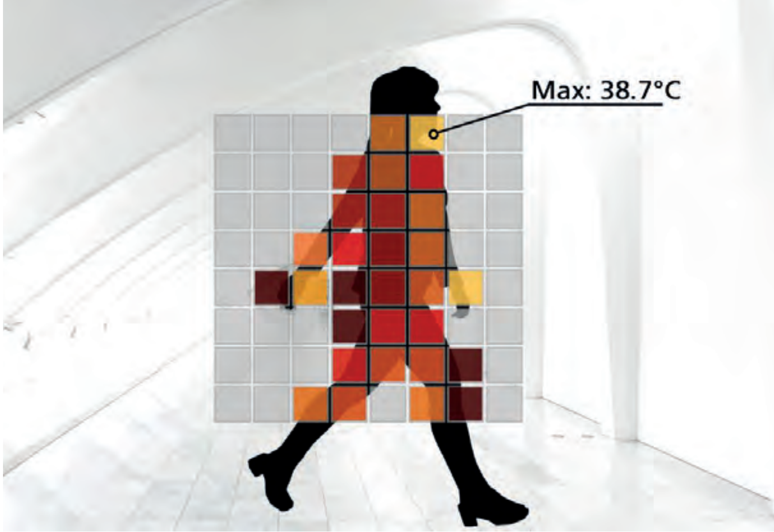
Mocca+ project

Measuring the purity of compressed air

Compressed air is a widely used and indispensable tool. It is subject to strict hygiene requirements in medicine and in the food and pharmaceutical industries, where it is used, among other things, to produce PET bottles, to help fill and clean medical devices, and in artificial ventilation. In these settings, compressed air must be demonstrably free from harmful substances. Contaminated intake air or technical defects in the compressed air system may lead to gaseous toxic substances – such as exhaust gas or petroleum components – entering the compressed air. It is therefore essential that compressed air is constantly monitored for harmful oil vapors and aerosols of BTEX compounds (benzene, toluene, ethyl benzene, xylene) and other carcinogenic substances.

In the Mocca+ project, Fraunhofer IPM is working with CS Instruments GmbH & Co. KG to develop a photoacoustic sensor for testing the purity of compressed air. The aim is for the sensor to pick up traces of toxic substances in the ppb (parts per billion) range in industrial environments. To achieve this, the researchers will ensure that the sensor can specifically detect traces of oil vapor as an early indicator of the potential presence of BTEX components. This would then trigger the predictive maintenance of the filtration equipment. By combining this technology with the direct sensitive measurement of BTEX in the ultraviolet spectrum, threshold monitoring will be possible with a high degree of measurement certainty.

Project Mocca+ (Monitoring of BTEX compounds in compressed air supported by predictive analysis), funded by the Ministry of Economic Affairs, Labor and Tourism of the federal state of Baden-Württemberg (Climate-Neutral Production Using Industrie 4.0 Solutions Innovation Competition)



Conventional infrared sensors are too imprecise to detect body temperature from a distance. Novel thermopiles are set to change that.

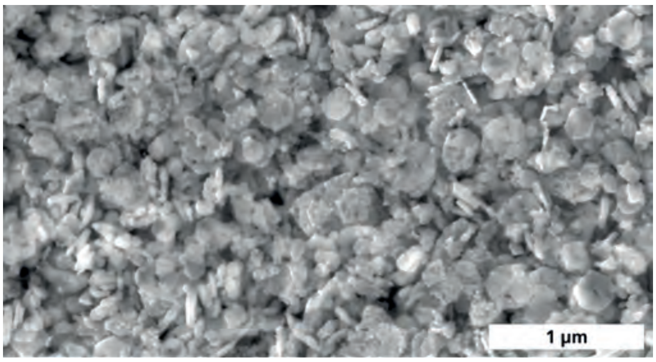
MEscal project

Effective catalyst for detecting methane

If flammable gases like methane or propane start escaping from gas stations, pipelines or gas heaters, the situation will quickly become dangerous. This is why millions of catalytic sensors (pellistors) monitor gas infrastructures for leaks to keep them safe and prevent gas losses. Modern pellistors work at temperatures of around 450 °C so they need a lot of energy. As part of the MEscal project, Fraunhofer IPM worked together with industrial partners to develop a particularly energy-efficient catalytic sensor for detecting methane. Thanks to the sensor's lower working temperature, it does not require complex contamination and explosion protection.

The key innovation developed at Fraunhofer IPM was a novel, highly effective catalytic material that triggers the oxidation of methane at temperatures of below 400 °C and contains fewer precious metals than conventional catalytic materials. The team designed the catalyst as a printable ink for coating MEMS-based sensor substrates. Coated low-power sensors of this kind have been found to be able to detect methane concentrations at up to five percent of the lower explosion limit (LEL).

Project MEscal (MEMS-based catalytical sensors for flammable gases), funded by the EU as part of the Eurostars-2 program (Eurostars E! 113779)



The metal-oxide-based methane catalyst – shown here as a SEM image – is applied to the sensor substrate as an ink.

TAPIR project

High-sensitivity infrared detectors – a new generation of thermopiles

Whenever a light turns on as if by magic when you enter a room, thermopiles are usually at play. These sensors can detect heat radiated from the body. In motion sensors, thermopiles measure temperature-dependent voltages that are generated at the junction point between two thermoelectric materials, provided that the temperature at this point is different to the ambient temperature.

As part of the TAPIR research project, Fraunhofer IPM is developing novel thermopiles that are much more sensitive than the infrared detectors currently available. To this end, the team is using a material system based on bismuth telluride (Bi_2Te_3) for the first time. Due to its high thermoelectric figure of merit, Bi_2Te_3 is vastly superior to the silicon and aluminum used in thermopiles as standard. The miniaturized IR detectors with 8 by 8 thermopile elements on a polymer substrate are intended to be used, for example, for the contactless remote detection of people with a high temperature, which would prove beneficial not only during a pandemic. Another potential use is in technical equipment, where the high-sensitivity infrared detectors could identify hot spots to warn of overheating.

Project TAPIR (Thermopile arrays on polymer substrates for infrared imaging detection), funded by the Fraunhofer-Gesellschaft as part of the internal program for rapid SME-oriented in-house research projects

TransHyDE project

Acoustic hydrogen leak detector

When using hydrogen (H_2), the strictest safety standards must be observed. The reliable detection of leaks in pipelines or containers is key for the safe operation of hydrogen-transmitting systems, particularly because H_2 makes material brittle, increasing the risk of leaks.

As part of the joint project TransHyDE_FP2, Fraunhofer IPM is developing intrinsically safe sensor technologies for hydrogen leak detection. To do so, the researchers make use of acoustic measurement technology based on the principle of phase delay and resonance frequency shifts: The propagation of sound in air changes in the presence of hydrogen. The sound velocity of gas mixtures depends on factors such as molar mass and the adiabatic exponent of the gases that make up the mixture. As hydrogen has very different properties from the gases that make up air, H_2 can easily be detected by measuring sound velocity.

When selecting the components for the detector, the team also kept an eye on the costs because to monitor the entire hydrogen infrastructure, a large number of leak sensors will be needed. Initial laboratory tests with demonstrator systems have been very successful. Even very low concentration of hydrogen – far below the explosion limit – were detected. In a next step, the researchers are investigating how fluctuating ambient conditions, such as humidity and temperature, as well as cross-sensitivity with other gases, such as CO_2, can affect the measurement and how their effects can be either minimized or offset by smart data interpretation.

Project TransHyDE (TransHyDE_FP2 safe infrastructure), hydrogen lighthouse project funded by the Federal Ministry of Education and Research (BMBF)

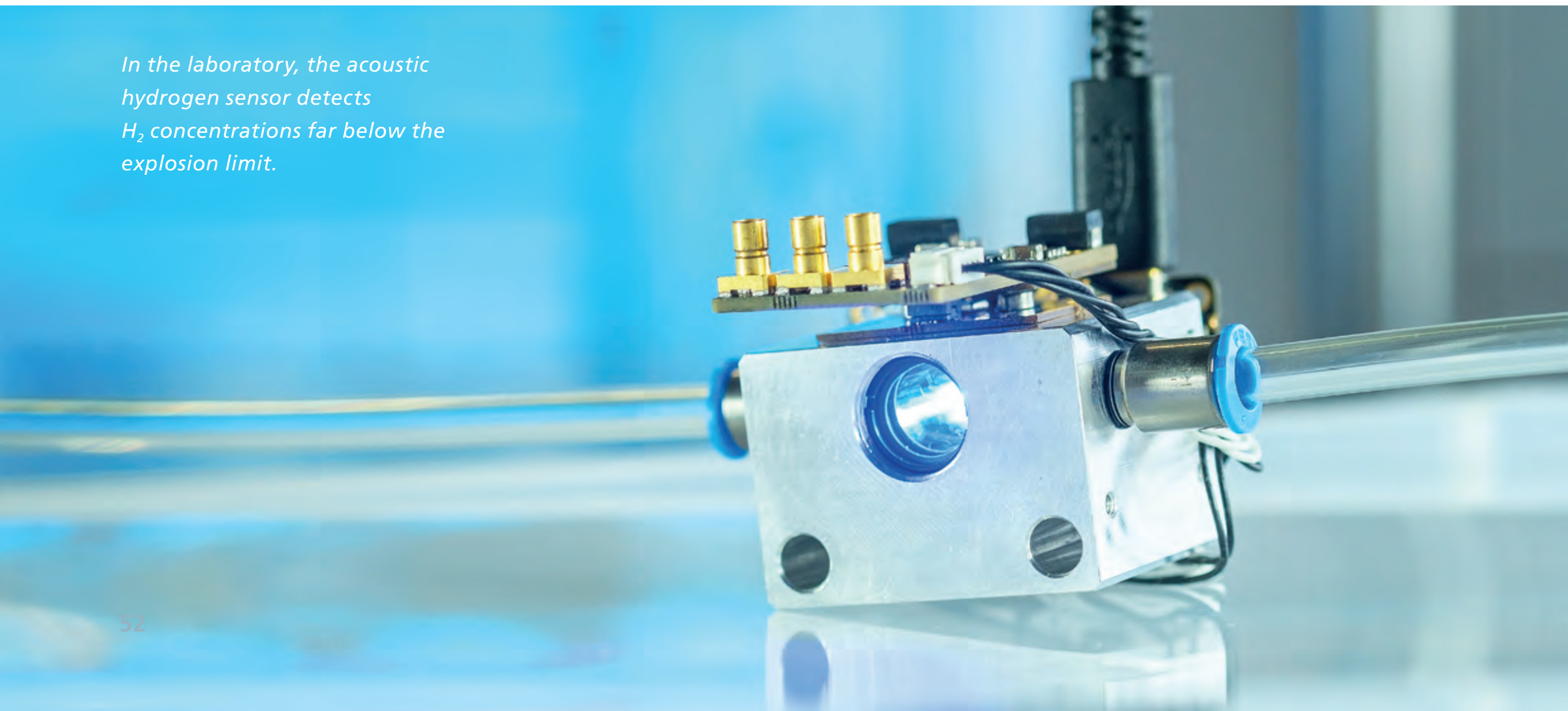
WALD project

H_2 sensor to detect pipeline leaks

In the future, "green" hydrogen (H_2) will mainly be produced in regions with a lot of renewable energy. Pipelines are the most economical solution for transporting the gas over long distances to where it is needed. To ensure these pipelines are safe, they must be regularly monitored for leaks. As part of the WALD project, Fraunhofer IPM has been working with research and industry partners to develop a cost-effective, hand-held sensor for the selective detection of H_2 in the range of between ppm (parts per million) to 100 volume percent. The sensor is set to detect even the smallest leaks, preventing explosive gas mixtures from forming.

The sensor combines two measurement principles that are used for different detection ranges to ensure high measurement certainty, selectivity and a wide dynamic range. Using thermal simulations, the Fraunhofer IPM team developed the ideal geometry for a heating structure – one of the sensor's core elements. A dedicated screen printing process was developed to deposit the structure onto a substrate. Initial laboratory measurements showed that the sensor detects H_2 at the lower explosion limit. As the project continues, the team will be working on developing the electronic elements, the housing and even the complete system integration.

Project WALD (WAsserstoffLeckDetektion, hydrogen leak detection), funded by the Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg as part of its hydrogen roadmap

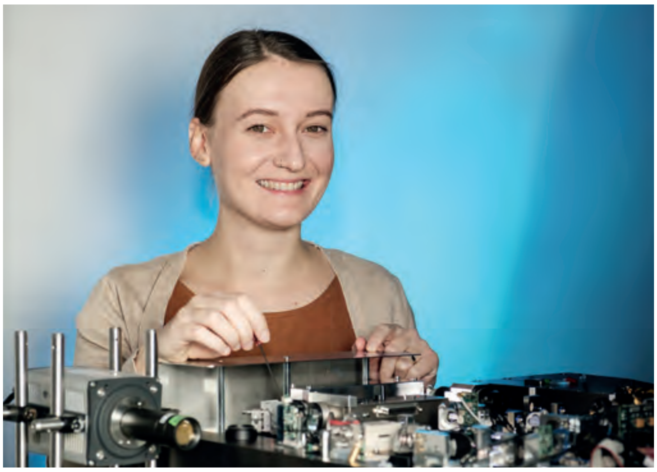


In the laboratory, the acoustic hydrogen sensor detects H_2 concentrations far below the explosion limit.

"

We are able to achieve surprisingly accurate spectroscopic results using extremely small quantities of light. This opens up some exciting fields of application."

Dr. Chiara Lindner



HySABi project

H_2 sensors for vehicles with fuel cell drives

While battery-powered electric vehicles will dominate the passenger car market of the future, utility vehicle manufacturers also see emission-free fuel cells as an alternative to combustion engines. Fuel cells power electric motors by converting hydrogen (H_2) into electrical energy. When powered by green hydrogen, fuel cell electric vehicles are environmentally friendly and emission-free.

However, hydrogen and oxygen can be an explosive combination. For vehicles to meet the automotive industry's strict safety standards, reliable sensors are needed to monitor the concentration of hydrogen in the fuel cell. As part of the HySABi project, Fraunhofer IPM is working with industrial partners to develop a novel H_2 sensor system for use in vehicle exhaust gas systems. The sensor combines two complementary measurement principles that provide sound and reliable measurements. The miniaturized sensor consumes little energy and can be operated at a low temperature to ensure that the gas mixture is not ignited by the sensor itself. The team has performed thermal simulations and taken sample measurements in preparation for creating an initial demonstrator, which will be tested in the lab and in vehicles up until the end of the project in spring 2024.

Project HySABi (Miniaturized H_2 sensor system to ensure acceptance of fuel cell drive systems), funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK); Project management Jülich (PtJ)

Award for outstanding doctoral thesis

Chiara Lindner wins "Quantum Futur Award"

To make quantum technology applicable, young scientists' approaches are needed. The Federal Ministry of Education and Research (BMBF) has recognized this and has been awarding the "Quantum Futur Award" for outstanding scientific work in the area of quantum technologies since 2018. In 2022, our colleague Dr. Chiara Lindner won 1st place in the doctoral theses category in recognition of her work in the area of quantum sensor technology ("Nonlinear interferometers based on spontaneous parametric down-conversion for Fourier-transform mid-infrared spectroscopy").

The submissions were assessed by a panel of judges from the worlds of politics, science and industry. At the award ceremony in November 2022 in Berlin, 10 finalists had the opportunity to give a short presentation of their topics. Chiara Lindner also impressed the online audience with her presentation and won 2nd place of the audience award. For her doctoral thesis, she designed a quantum optical equivalent to the FTIR spectrometer that can be used for high-resolution, sensitive gas spectrometry, amongst other purposes.

Research Fab Microelectronics Germany

Light sources for quantum computing

In order to consolidate and expand the existing microelectronic research and development in Germany regarding quantum and neuromorphic computing, the Research Fab Microelectronics Germany FMD launched the "Module Quantum and Neuromorphic Computing" (QNC). The FMD was established for the production of micro- and nanosystems with the Fraunhofer-Gesellschaft is a key partner. Fraunhofer IPM is to contribute its skills in the area of simulation, manufacturing and characterization of integrated optical lithium niobate waveguides for ion trap quantum computing. The German Federal Ministry of Education and Research is funding the equipment and structural setup required for the project.

In ion trap quantum computing, qubits are held, manipulated, and read out using laser beams inside a mechanism known as an ion trap. Up until now, this is a task performed by expensive laboratory lasers, which are to be replaced by cost-effective, integrated optical light sources such as lithium niobate waveguides in the future. Fraunhofer IPM is receiving funding for procuring and commissioning a focused ion beam system for the optimization of existing waveguide manufacturing processes.

"FMD-QNC" (Research Fab Microelectronics Germany – Module Quantum and Neuromorphic Computing), funded by the Federal Ministry of Education and Research (BMBF)

modulequc
quantum & neuromorphic computing

For the first time

Industry workshop on quantum magnetometry

Quantum-based methods expand the range of magnetic field measurement technology and open up new options for industrial measurement technology. During an industry workshop in December 2022, experts from research and industry offered an overview of the state-of-the-art of quantum magnetometry. 35 participants discussed technological trends and the potential for industrial applications.

The focus of the workshop was on optically pumped magnetometers (OPM), which are one of Fraunhofer IPM's main research topics and one of the most important quantum-based magnetometry processes next to nitrogen vacancy centers (NV, center in diamond). OPM can be used for the extremely sensitive detection of magnetic fields. Their measurement accuracy is only limited by the laws of quantum physics. OPM allow the contact-free measurement of magnetic sources inside objects through the material. "We will continue to research OPM thoroughly," says workshop organizer Dr. Peter Koss. "We will meet again in about two years to assess the progress we have made by then in terms of making the research applicable."

IWQ

Optically pumped magnetometers are a new benchmark for detecting magnetic fields.

Dr. Peter Koss conducts research in the field of optically pumped magnetometers and organized the workshop.

Gas and Process Technology | Trade Fairs & Events

LASER World of PHOTONICS

World’s Leading Trade Fair with Congress for Photonics Components, Systems and Applications
April 26–29, 2022

At the fair, we were represented with the topics “Tailored wavelengths by nonlinear frequency conversion” as well as with laser-based photothermal gas analysis. At the World of QUANTUM congress, we presented a quantum Fourier transform spectrometer for infrared spectroscopy and the technology of quantum magnetometry. In addition, we were represented with our topics at the Fraunhofer joint booth via the Light & Surfaces group.

Sensor+Test

The Measurement Fair
May 10–12, 2022

We presented our innovations for measuring gases, liquids and solids as well as functional materials for gas sensing, thermoelectrics and optics.

ACHEMA

World Forum for the Process Industries
August 22–26, 2022

Fraunhofer IPM presented laser spectroscopic methods for gas analysis, energy-efficient gas sensors, technologies for particle measurement, and thermal sensors and systems.

FUTURAS IN RES – The Quantum Breakthrough

September 28–29, 2022
Prof. Dr. Karsten Buse, Director of Fraunhofer IPM, co-chaired the workshop; Dr. Frank Kühnemann gave a keynote speech.

Events in 2023

10. Gassensor-Workshop
March 16, 2023

Sensor+Test
May 09–11, 2023

LASER World of PHOTONICS
June 27–30, 2023

Focus Reduction of greenhouse gases

Nitrous oxide sensor technology for optimized, climate-friendly nitrogen fertilization to boost agricultural efficiency

Mobile nitrous oxide sensor: The sample is taken at ground level using a bell jar; the actual measurement system is concealed in a case.

How can a nitrous oxide sensor make agriculture more efficient? And how are suboptimal nitrogen fertilization practices contributing to global climate change? Answering these questions requires an understanding of what nitrogen fertilizing has to do with nitrous oxide formation in the soil and the occurrence of nitrous oxide in the atmosphere.

Few people are aware that nitrous oxide (N_2O), which is also known as laughing gas, is a highly significant greenhouse gas just like carbon dioxide (CO_2) and methane (CH_4). Only trace amounts of N_2O are found in the atmosphere – however, the gas is around 300 times more harmful to the climate than CO_2 and thus still makes a considerable contribution to the anthropogenic greenhouse effect. But what does nitrogen fertilization have to do with nitrous oxide? In simple terms, nitrous oxide predominantly enters the atmosphere in two ways: through nitrogen fertilizers and intensive livestock farming; it is released when microorganisms break down nitrogen-containing compounds. According to data from the German Environment Agency, agriculture is responsible for some 80 percent of nitrous oxide emissions in Germany. The remaining 20 percent largely come from the chemical industry since nitrous oxide is released into the atmosphere during the production of both fertilizers and plastics.

More needs-based fertilization means fewer nitrous oxide emissions

Nitrogen fertilizers used in agriculture are therefore one of the main sources of atmospheric nitrous oxide. To reduce the proportion of this gas in the air, the use of fertilizers in agriculture must be minimized without depleting the soil's nutrient content and thereby decreasing its agricultural quality. The

Using an innovative measurement concept that employs interband cascade lasers (ICL) as the light source, nitrous oxide can be measured in the mid-infrared range unimpeded by cross-sensitivity with other gases. The entire process is extremely quick and can be performed out in the field.

precise regulation of fertilizer use requires a better understanding of how gas is emitted from soil.

The content and distribution of nutrients in soil are important indicators for fertilizing soil efficiently and in an environmentally friendly and legally compliant manner. Researchers at Fraunhofer IPM recently started using a spectroscopic gas sensor to precisely determine the degradation of nitrogen-containing compounds by microorganisms in soil. The sensitive measurement system works quickly and at ground level to detect the amount of nitrous oxide that diffuses from arable land in cases of overfertilization – and can pinpoint the exact location of the gas. In the future, this data will be used to determine the optimum amount of fertilizer needed for individual fields. The aim is to minimize nitrous oxide emissions by reliably estimating the amount of fertilizer that will be required the next time the field is fertilized.

Mobile nitrous oxide sensor for fast, precise ground-level measurements

The team developed the nitrous oxide sensor as part of Fraunhofer's Cognitive Agriculture lighthouse project. Due to the extremely high sensitivity requirements, the researchers determined that a very compact and above all high-resolution laser spectroscopy sensor was the only technology up to the task. In the case of ground-level nitrous oxide, relevant increases in concentration are in the range of just a few ppb per minute (ppb, parts per billion). Consequently, the researchers decided to use an innovative measurement concept employing interband cascade lasers (ICL) as the light source. These are able to clearly measure nitrous oxide in the mid-infrared range, unimpeded by cross-sensitivity with other gases, achieving a drastic decrease in measurement time while simultaneously reducing power consumption. This compact, battery-operated measurement system allows quasi-mobile, real-time measurements of nitrous oxide to be taken for the first time – and can even be integrated into driverless agricultural vehicles. The Cognitive Agriculture project was successfully completed in late 2022. It involved seven Fraunhofer institutes in addition to Fraunhofer IPM.

Collaborative Research Centre ECOSENSE: Gas sensors for forest ecosystems

Since late 2022, Fraunhofer IPM has been working with the University of Freiburg as part of the Collaborative Research Centre ECOSENSE to research the negative impact of climate change on forest ecosystems. As carbon reservoirs, these ecosystems are important regulators of the climate system. In this project, the team at Fraunhofer IPM is firstly aiming to use miniaturized sensors to measure CO_2 flows in order to gain a better understanding of how they affect forest ecosystems. Secondly, the team is using a complex spectroscopic measurement technique to investigate the isotopic signature of CO_2 in the air. This signature allows conclusions to be drawn about the source of CO_2 in the atmosphere.

> "Nitrous oxide is around 300 times more harmful to the climate than carbon dioxide."
>
> *Prof. Dr. Jürgen Wöllenstein, Head of Department*

Overview Thermal Energy Converters

Pumping and converting heat highly efficiently is our contribution to the cooling technology of the future.

The Thermal Energy Converters business unit researches technology for pumping, converting, transferring and controlling heat. We develop, design and assemble efficient thermal energy conversion systems, including caloric heat pumps and cooling systems based on magnetocaloric, electrocaloric or elastocaloric materials. Our custom-built thermoelectric modules and systems for efficient thermal mangement and the use of waste heat are tailored to each individual application.

Moreover, we are conducting research on novel designs for efficient heat transfer based on heat pipes and heat pipe-based thermal switches for regulating heat flows.

Custom-built thermoelectric systems

Cooling with caloric systems

Heat transfer via heat pipe

Our groups and focus areas

Thermoelectric Systems

- Development of custom-built thermoelectric modules and systems
- Innovative Peltier cooling and thermal management
- Conversion of waste heat into electricity in the milliwatt to kilowatt range
- Structural, thermal and electrical analytics of components and materials

Caloric Systems

- Heating and cooling without harmful refrigerants
- Development of magnetocaloric, elastocaloric and electrocaloric systems
- Development and characterization of heat pipes for thermal management

"We develop innovative technologies to make refrigeration and heat pumps more efficient."

Dr. Olaf Schäfer-Welsen, Head of Department

Highlights Thermal Energy Converters

Projects • Innovations • Events

Peltier systems

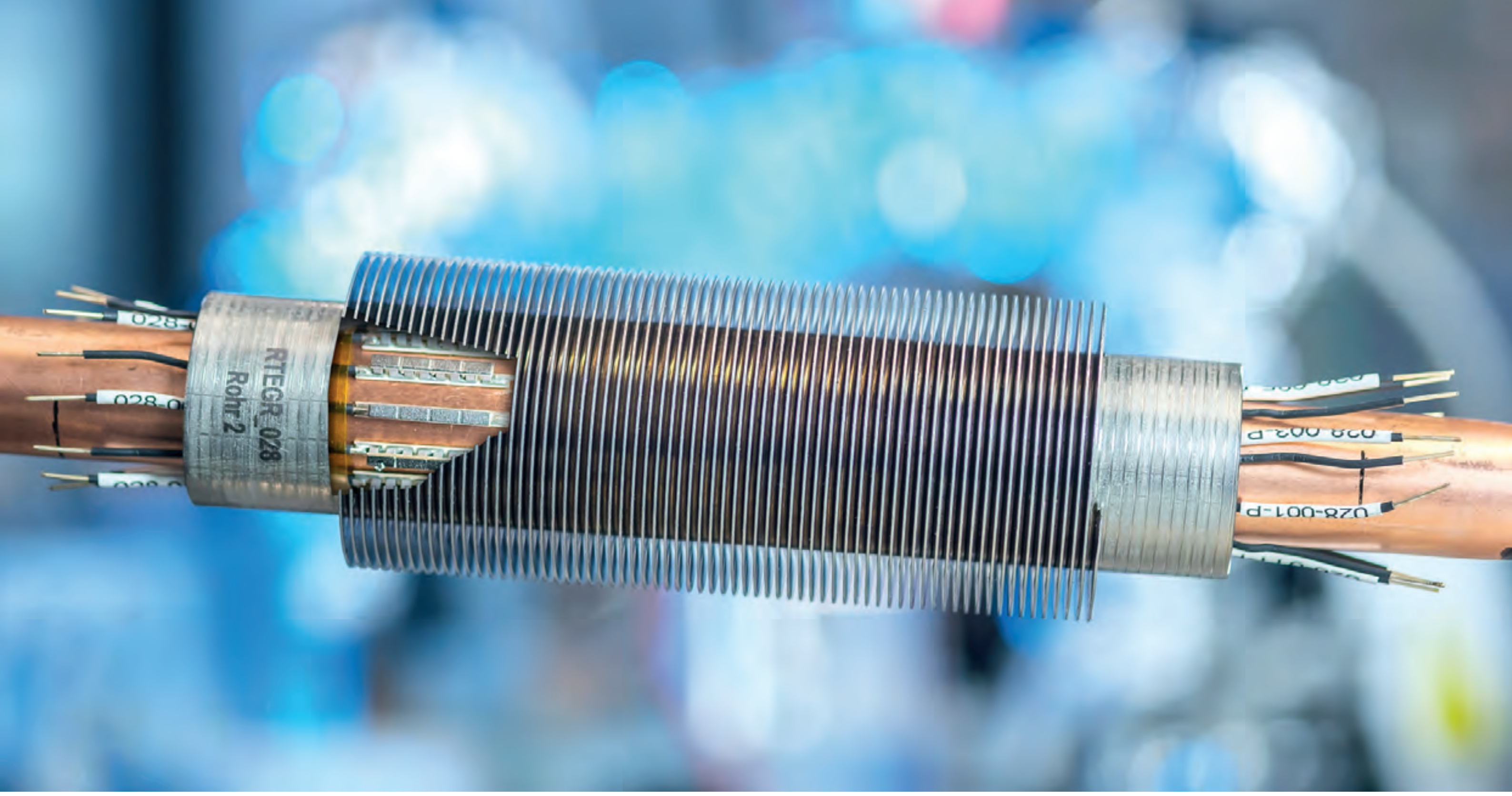
Mobile cooling trolley for railroad operators

Keeping food and beverages cool is a challenging endeavor for railroad operators offering on-board catering services. The items are transported to the train on trolleys with no active refrigeration system before being pushed into a cold storage room. When trains are delayed, the uninsulated trolleys may even end up standing on the platform for so long that the food has to be thrown away.

Together with our industrial partners Siemens Mobility and Zech + Waibel, Fraunhofer IPM has developed a thermoelectrically cooled Gastronorm (GN) trolley that uses 85 percent less energy than conventional compressor-based cold storage room solutions. At a temperature difference of 10 K between the external environment and the inside of the trolley, an overall coefficient of performance (COP) of up to 1.6 can be reached. The scientists achieved this impressive figure by carefully choosing and adjusting the heat sink, fans, Peltier modules and insulation. The energy-efficient trolley's cooling system has a battery runtime of up to 12 hours, meaning its contents are kept cool even during long wait times on the platform. When the doors are opened, the electrical output increases gradually until the Peltier modules generate up to 200 W of cooling power. The team presented the mobile cooling trolley for the first time at the InnoTrans trade fair in Berlin in 2022 (turn to our customer interview on pages 20–21 to find out more about our partnership with Siemens Mobility).

"The mobile cooling trolley will help pave the way for new on-board catering concepts for railroad passengers."

Andreas Häußler, Siemens Mobility



Making a square round: Thermoelectric modules perfectly adapted to the geometry of pipes are able to convert waste heat into electricity or to act as Peltier coolers to control the temperature of media flowing in pipes (photo montage).

RoteP project

All around the pipe – rethinking thermoelectric modules

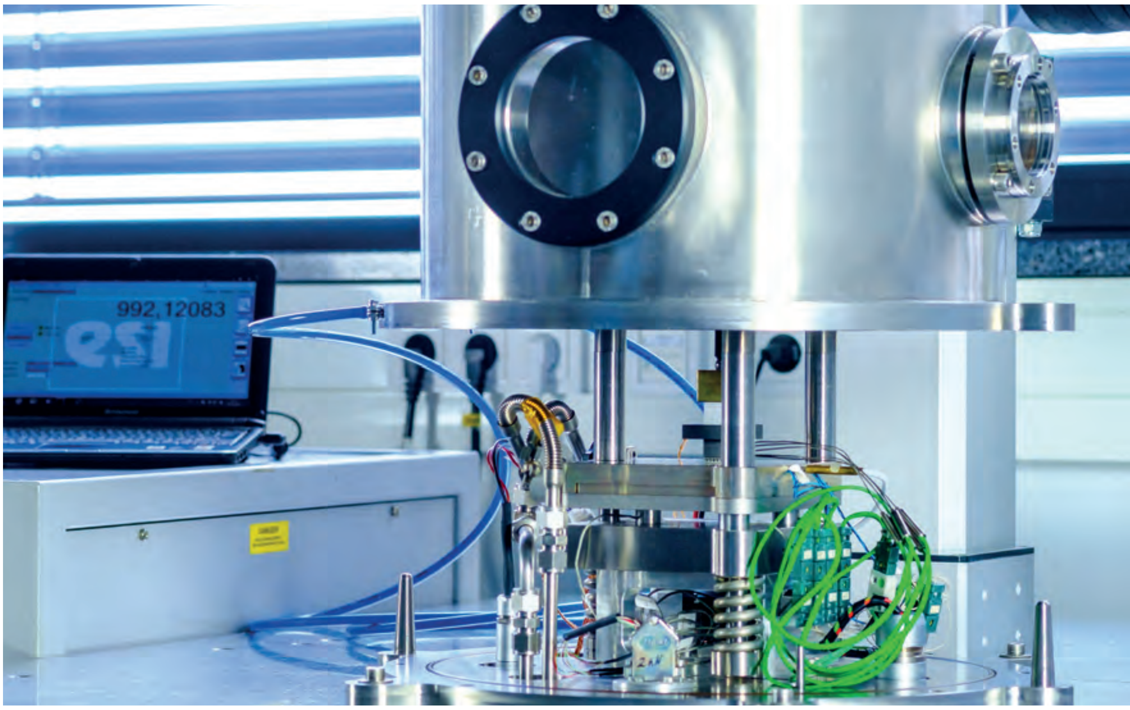
Thermoelectric modules (TEMs) are extremely versatile and can be used for both waste heat recovery and cooling. Traditionally, these modules are flat and square or rectangular in shape. In contrast, the heat-carrying fluids or fluids that need their temperature to be controlled generally flow through round pipes. This difference in shape is disadvantageous structurally and in terms of costs because it requires expensive, flat, high-maintenance heat exchangers to be used, on which the TEMS are pressed to form a solid structure. To improve the situation, our team has designed round TEMs that can be installed directly around pipes. This firstly involved developing a low-cost assembly method based on commercially available cuboidal thermoelectric structural elements.

The compact RO-TEG thermoelectric generator converts waste heat into electricity, while thermal resistance can be flexibly adjusted to external heat transfer resistances. Prospective investment costs range below one euro per watt of producible electrical power.

RO-TEG is ideal for converting waste heat into electricity in settings such as foundries, hardening plants, forges and industrial combustion and drying plants. In stand-alone furnaces, e.g. wood-burning stoves, the electricity generated can be used to operate a self-powered control system, to power a fine dust separator or to connect the furnace to a smart home network. When used as a Peltier cooler (RO-Pelt), the technology is able to precisely, quickly and locally control the temperature of media flowing in pipes. This technology has the same benefits as RO-TEG, which include a compact, low-cost design, small thermal transfer resistances due to being directly connected to the pipe and the ability to be flexibly adjusted.

Project RoteP, funded by the Fraunhofer-Gesellschaft (Discover project)

Modules with a round design can be flexibly adjusted.



Newly built measuring station for Peltier modules, where we characterize modules of different sizes and designs.

Measuring laboratory for Peltier modules

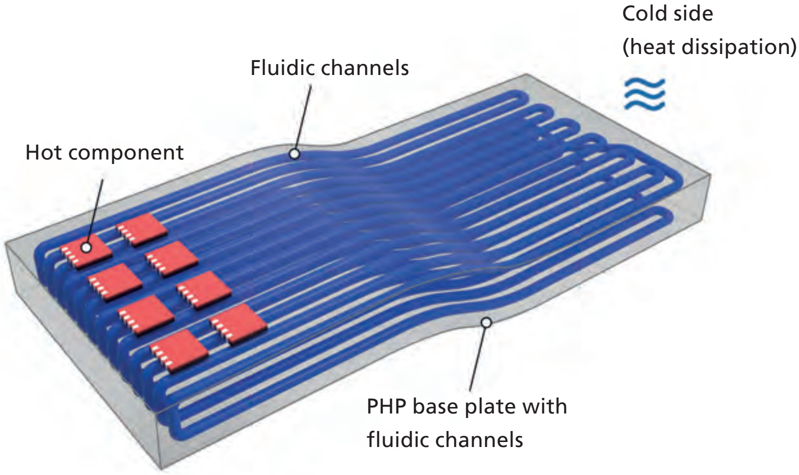
Peltier modules have been used as heat pumps for decades – to keep temperatures cool in niche products like wine coolers or to control the temperature during processes such as the duplication of DNA sections. Peltier coolers must meet strict requirements in terms of reliability, especially in the areas of biotechnology and medical technology. We use our newly developed module measuring station to characterize Peltier modules and determine all their essential characteristics. We measure the modules in terms of various parameters, including their thermoelectric and thermal performance as well as their temperature-dependent internal resistance. This data can be used to create data sheet curves typical of Peltier modules, such as temperature-dependent and current-dependent cooling power, COP and waste heat curves.

The measuring station can accommodate modules of different sizes and designs. The heat flows are measured against the electric current applied and the temperature difference. This involves clamping the modules together with two heat flow meters between heat exchangers and pressing them in place by applying a predetermined amount of pressure. An infrared camera can optionally be used to monitor the temperature distribution in the outermost pairs of legs in the direction of the Z-axis. Different atmospheres – from vacuum to overpressure with various gases – can be generated in the measuring chamber to simulate a range of usage scenarios. Long-term tests can also be performed, where temperature, pressure and power ramps are applied in accordance with a defined test protocol in order to identify and evaluate any failure mechanisms.

3D-printed pulsating heat pipes for efficient heat dissipation

Flat, compact and very efficient, pulsating heat pipes (PHP) have several advantages over conventional heat pipes and are even capable of dissipating large amounts of heat when they are just 2–3 mm thick. A new production method jointly developed by Fraunhofer IPM and Fraunhofer IWU will make PHPs even more efficient to manufacture in the future. The research team used additive manufacturing (3D printing) to produce PHPs from stainless steel with multilayer channel structures for the first time. The 3D printing process even enables the PHPs to be integrated together with their heat sink into load-bearing components or housings, saving space and allowing them to be used between materials without any unwanted thermal resistances.

Another advantage of 3D printing is that multilayer fluid channel structures are much less complex to manufacture. These structures are needed to ensure that heat can be efficiently dissipated from components with high thermal power densities of up to several 100 W/cm². 3D printing does away with the need for complex and expensive manufacturing steps, such as the milling of fluid channels and vacuum brazing. Besides stainless steel, lightweight aluminum alloys can also be used. The team has assembled the 3D-printed PHP as demonstrators and characterized them. The results were impressive, with the printed PHPs having been found to efficiently dissipate heat from hot components.



Pulsating heat pipes (PHP) with a multilayer fluid channel structure are very efficient at dissipating heat in electronic components. They can now be manufactured using 3D printing.

Thermal Energy Converters | Trade Fairs & Events

InnoCool-Workshop

April 07, 2022

Final event of the workshop series on the topic of caloric refrigeration and air conditioning technology

Progetto Fuoco

Trade fair for biomass heating systems
May 04–07, 2022

We presented an innovative electrical separator for the reduction of emissions in combustion plants.

InnoTrans

International trade fair for transport technology
September 20–23, 2022

We introduced the "Mobile Cooling Trolley", a thermoelectrically cooled gastronomic norm trolley for use on board of trains.

Chillventa

The world's leading exhibition for refrigeration technology
October 11–13, 2022

At our joint booth with Fraunhofer ISE, we were represented with the topic of caloric cooling systems and heat pumps.

electronica

World’s leading trade fair and conference for electronics
November 15–18, 2022

At electronica, we demonstrated solutions for thermal management based on heat pipes and Peltier elements, as well as techniques for materials analysis using 3D computed tomography.

Focus Electrocaloric heat pumps

Making heat pumps more efficient using a material-based technology featuring caloric systems instead of compressors

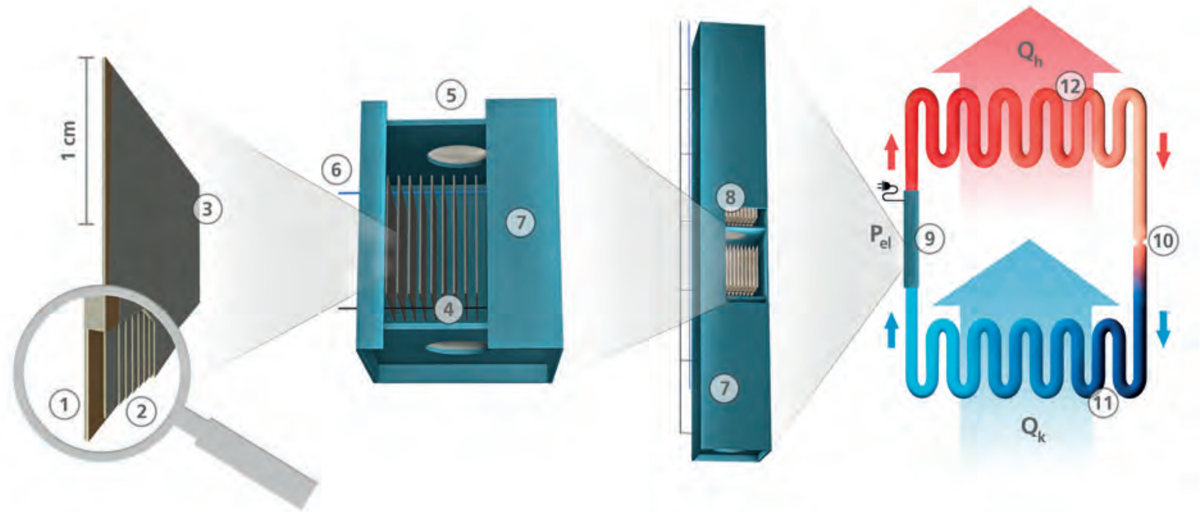
Electrocaloric components: Ceramic multilayer components were integrated into a heat pipe to enable especially efficient heat dissipation.

Ever since Carl von Linde registered his patent for a refrigeration machine in 1873, compression has been the name of the game in refrigeration technology. Refrigerators, air conditioners and heat pumps for heating buildings still operate on the principle of compression to this very day. However, for several years now, various research groups have been investigating caloric cooling systems as an alternative to compressors. And significant progress has been made in this area in recent years, including at Fraunhofer IPM. In general, compressors only achieve 40 to 50 percent of the Carnot limit, in other words, the absolute limit of efficiency. In caloric heat pumps, the theoretically achievable coefficient of performance is much higher. Another disadvantage of compressors is that they mostly still use flammable or environmentally harmful refrigerants.

No expensive materials or wear and tear

Fraunhofer IPM has been researching caloric systems for more than seven years. The researchers have already achieved resounding success in the development of magnetocaloric and elastocaloric heat pumps and have published their findings in renowned specialist journals. In the meantime, research in the area of electrocaloric heat pumps is now also gaining momentum. In the Fraunhofer lighthouse project ElKaWe, for which we are the project coordinator, we have been developing the technology in cooperation with five other Fraunhofer institutes since 2019. Electrocalorics (EC) is the least researched of all the caloric technologies even though it has a number of specific advantages over the alternative caloric approaches. For example, electrocaloric systems do not require expensive materials or complex mechanics so are beneficial in terms of costs, size and long-term stability.

As in all caloric systems, the heat in EC systems is pumped using caloric materials, in this case ceramics and polymers. These materials heat up when an electric field is applied and cool down as soon as the field is removed. The heat generated when the electric field is



Design of an electrocaloric (EC) heat pump: The EC components consist of the EC materials (1) including electrodes (2) and coating (3). Several of these components (4) as well as the check valves (5) and the electrical supply line (6) are integrated into a gas-tight housing (7) and assembled to form an EC segment. Several such EC segments (8) are connected in series to make up the EC system (9) and, together with a throttle (10), the evaporator (11) and the condenser (12), they constitute an EC heat pump.

applied is dissipated via a heat sink, causing the material to cool down to its initial temperature. As soon as the field is removed, the material can absorb thermal energy from a heat source. This effect is highly reversible and can be used to establish an electrocaloric cycle, making it suitable to serve as the basis for highly energy-efficient cooling systems and heat pumps.

High cycle frequency to ensure rapid heat transfer for high power densities

Despite their technological advantages, electrocaloric systems will only be able to enjoy market success if they can also compete in terms of costs. To achieve this, the systems will require high power densities. In other words, they must be able to pump as much heat as possible with as little EC material as possible. The cycle frequency determines how much heat systems of this kind can pump. And, in turn, this frequency depends on how quickly the heat can be dissipated from the caloric material. A patented heat transfer concept developed at Fraunhofer IPM works in accordance with the heat pipe principle by evaporating and condensing a liquid. This allows heat to be transferred up to one hundred times more quickly than with conventional heat dissipation concepts based, for instance, on the active pumping of liquids. The concept has already been tested on electrocaloric systems developed at the Institute, where it has reached cycle frequencies of up to 10 Hz.

Choice of material and system design are pivotal

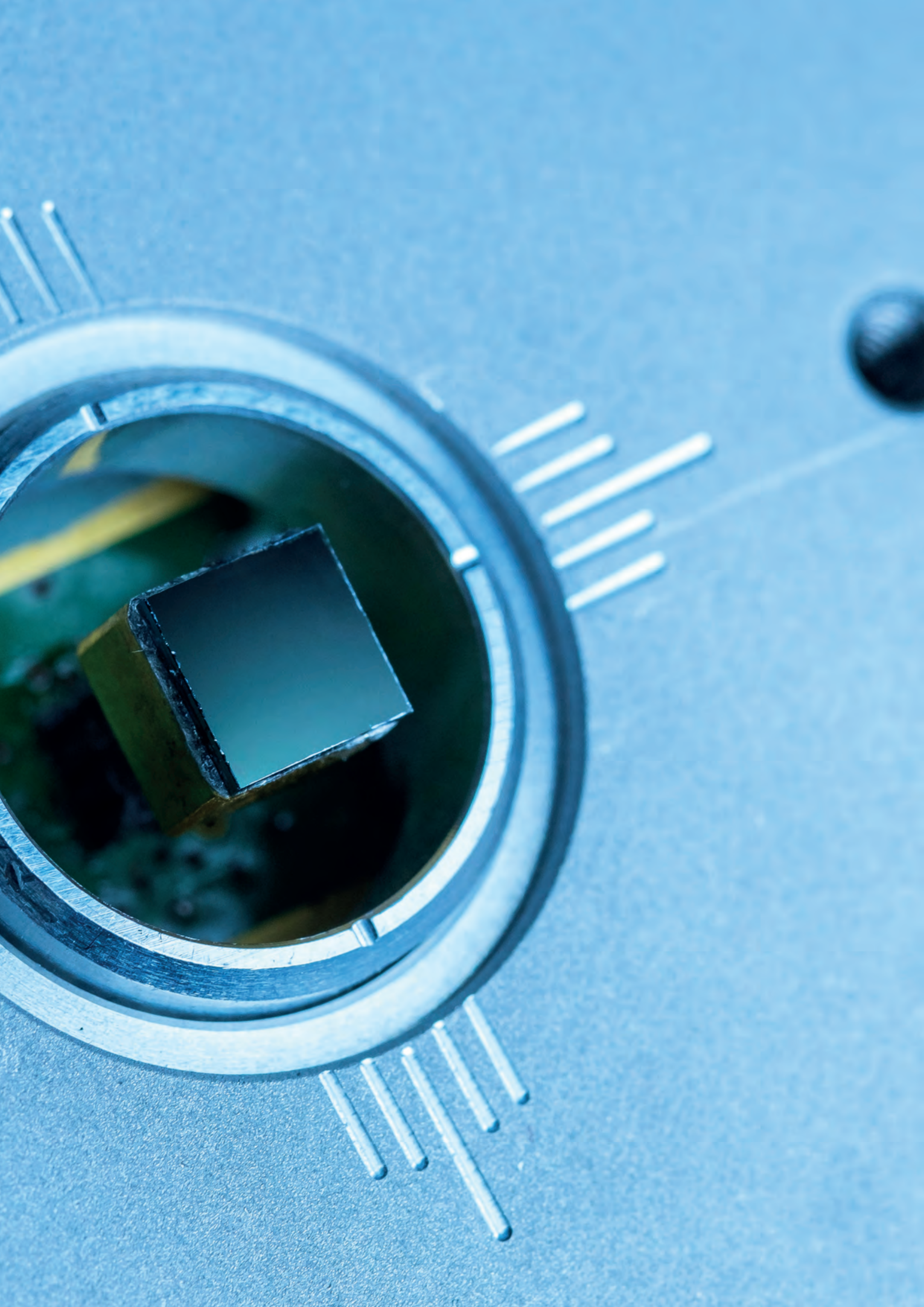
For EC heat pumps to be widely used in the future, two aspects need to be optimized in particular: the quality of the EC material and the system design, which must be perfectly tailored to the material. As part of the ElKaWe project, the research partners are working on developing EC functional materials with a high figure of merit together with the related manufacturing processes. The research project is also focusing on developing the electronics, coating the components and reliability testing. Fraunhofer IPM is responsible for designing, building and characterizing the system, all the while focusing on the need for optimized heat transfer. To date, the team has achieved a power density of 1.8 W per gram of electrocaloric material used in its laboratory setup, which is more than an order of magnitude greater than that of known comparable systems.

ElKaWe project website

"Efficient heating and cooling without moving parts is only possible with electrocalorics!"

Dr. Kilian Bartholomé, Group Manager

Index Fraunhofer IPM



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Large-scale projects 2022 Funded by the public sector

Ten research projects with a financial volume of more than one million euros each for Fraunhofer IPM have been worked on by our scientists over the year 2022.

HOLOMOTION Dynamic holographic measurement technique for mapping freeform metal surfaces / Sub-project: Researching a method for performing interferometric measurements in motion – dynamic holography
Duration: February 1, 2017 – March 31, 2023
Funding: BMBF; project sponsor: VDI Technologiezentrum GmbH

MultiVIS University cooperation with Furtwangen University (HFU)
Duration: July 1, 2018 – December 31, 2023
Funding: Fraunhofer-Gesellschaft (cooperation program with Universities of Applied Sciences (UAS)

ISLAS Intracavity laser spectroscopy for ultra-sensitive detection of trace gases
Duration: March 1, 2019 – June 30, 2022
Funding: Fraunhofer-Gesellschaft (MAVO)

QMag Development of two complementary quantum magnetometers for measuring minuscule magnetic fields with high resolution and sensitivity at room temperature
Duration: March 21, 2019 – December 31, 2023
Funding: Fraunhofer-Gesellschaft (Lighthouse project)

LaserBeat Impact hammer test using light – non-contact full inspection of tunnels on the basis of laser-induced structure-borne sound
Duration: April 1, 2019 – December 31, 2023
Funding: Fraunhofer-Gesellschaft (WISA)

ElKaWe Electrocaloric heat pumps
Duration: October 1, 2019 – September 30, 2023
Funding: Fraunhofer-Gesellschaft (Lighthouse project)

HochPerForm Ultra-compact fast actuator technology based on shape-memory alloys
Duration: March 1, 2020 – February 28, 2023
Funding: Fraunhofer-Gesellschaft (PREPARE)

MIAME Micrometer to meter: Laser light for 3D measurements on the meter scale with accuracies in the sub-micrometer range
Duration: April 1, 2020 – March 31, 2023
Funding: Fraunhofer-Gesellschaft (PREPARE)

QTWP QT waveguide plus: Labor upgrade for LNOI technology and waveguide characterization
Duration: September 1, 2021 – August 31, 2023
Funding: BMBF; project sponsor: VDI Technologiezentrum GmbH

FMD-QNC Research Fab Microelectronics Germany (FMD) – Module Quantum and Neuromorphic Computing (FMD-QNC)
Duration: November 1, 2022 – December 31, 2025

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www.light-and-surfaces.fraunhofer.de/en

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- Arbeitskreis Prozessanalytik der GDCh und DECHEMA
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- Competence Center for Applied Security Technology e. V. (CAST)
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- microTEC Südwest e. V.
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- VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik (GMA)
- VDSI – Verband für Sicherheit, Gesundheit und Umweltschutz bei der Arbeit e. V.

International

- ETS – European Thermoelectric Society
- ITS – International Thermoelectric Society
- Optica (formerly OSA)

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Imprint

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Design
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Print
STROHM DRUCK e. K., 78652 Deißlingen
This report was printed on FSC® classified
recycling paper.

ISSN 2570-1908

Picture acknowledgements
pp. 7/8: Oliver Kern Fotografie
p. 20: Fotostudio Ute Klein
p. 26: Piotr Banczerowski
p. 27 Top: Uwe Böhm

All other pictures and graphics: Fraunhofer IPM

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