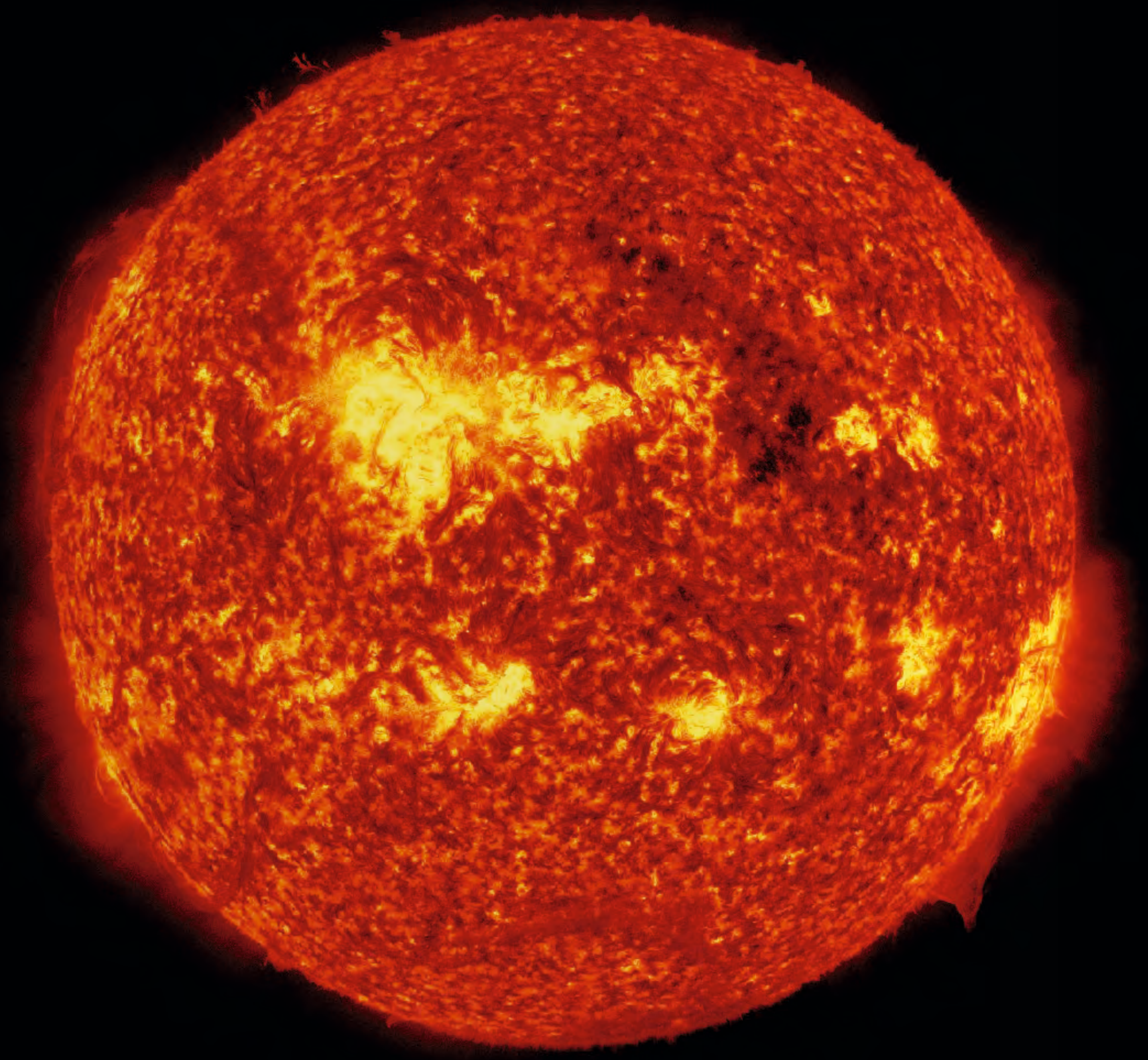
LASER COMMUNITY.

Of people and photons

A laser-sharp sense of smell

Tiny optical sensors for industry are acquiring new faculties—now they can touch, hear—and even smell.

#36



LASER COMMUNITY. *#36*

ISSUE Summer 2023 **PUBLISHER** TRUMPF SE + Co. KG, Johann-Maus-Strasse 2, 71254 Ditzingen, Germany; www.trumpf.com
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DISTRIBUTION Gabriel Pankow, Phone +49 7156 303-31559, gabriel.pankow@trumpf.com, www.trumpf.com/en_INT/newsroom/customer-magazines
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DESIGN AND PRODUCTION Die Magaziniker GmbH, Stuttgart, Germany; Gernot Walter (AD), Martin Reinhardt **TRANSLATION** Apostroph Group, Hamburg **REPRODUCTION** Reprotechnik Herzog, Stuttgart, Germany **PRINTED BY** W. Kohlhammer Druckerei GmbH + Co. KG, Stuttgart, Germany

Cover page: midjourney / Die Magaziniker; page 2: NASA

Gernot Walter

Dear readers,

Experts are familiar with the so-called fusion constant: this is the exact time it will take until nuclear fusion provides us with electricity. Scholars have agreed for half a century that this is about 50 years. But joking aside: since the end of last year, it has become clear that something substantial is now happening with this subject. After decades of research, scientists at the Lawrence Livermore National Laboratory in the USA have now achieved a breakthrough. They were able to ignite nuclear fusion with lasers and thus reproduce the principle of the sun on earth.

Before we achieve the operation of entire fusion power plants on an industrial scale, though, there is still a lot for us to do in laser technology. But if we succeed, it would be a giant step for mankind. *Starting on page 18*, you can read about how far the road to the “holy grail of energy generation” still is, and the consequences this development could have for laser technology in the interview with Prof. Constantin Häfner, Director of the Fraunhofer Institute for Laser Technology ILT. In any case, I wish all those working on the fusion power project of the century a lot of courage for new technical solutions.

A completely different technology has already achieved a breakthrough: electromobility. It has already found its way into the mass market, with the help of laser technology. TRUMPF was already involved as an equipment supplier in the first battery projects in China and South Korea. Today, manufacturers in Europe also benefit from this wealth of experience. This is shown by the example of Valmet Automotive in Finland. The company proves that profitable battery production is possible even in a country with high location costs. *Starting on page 6*, you can read about how Valmet Automotive makes up for the higher labor costs predominately by using bright minds, clever solutions and a lot of laser technology from TRUMPF.

In conclusion, please allow me to say a few personal words: Over the past 24 years at TRUMPF, I have experienced many highs and very few lows. Now I am saying goodbye, and entering a new phase of my life, which some people call retirement. In the next issue, my successor, Dr. Hagen Zimer, will greet you here. I wish him every success and vision in his new role—and I hope you, dear readers, enjoy reading this issue.

DR.-ING. CHRISTIAN SCHMITZ
Chief Executive Officer Laser Technology
Member of the Managing Board of TRUMPF SE + Co. KG
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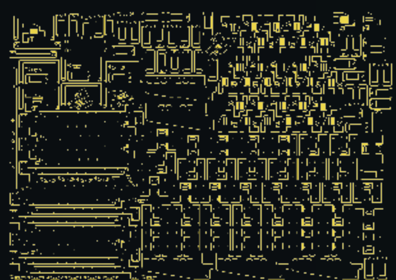
Sweet

As TRUMPF marks its centenary, Laser Community is celebrating sweet 17 years. Our inaugural issue from the year 2006 featured two big stories: offbeat design concepts for laser machines; and remote laser welding, today a standard process on thousands of production lines: **See #1.**

Stark

Matti Immonen's photos of the battery factory in Salo took our breath away: his use of light, composition, eye for detail—each image starker than the rest: "Fantastic Finland!" See **page 6.**



Fresh

The transparent pattern of nested parts covering the front and back page is emblematic of the TRUMPF story: worked from sheet metal (where things began), machined by laser (the high-tech breakthrough), processed by quantum computer (the next chapter). As fresh as ever! See pages **1 and 32.**

Gernot Walter, Matti Immonen, TRUMPF

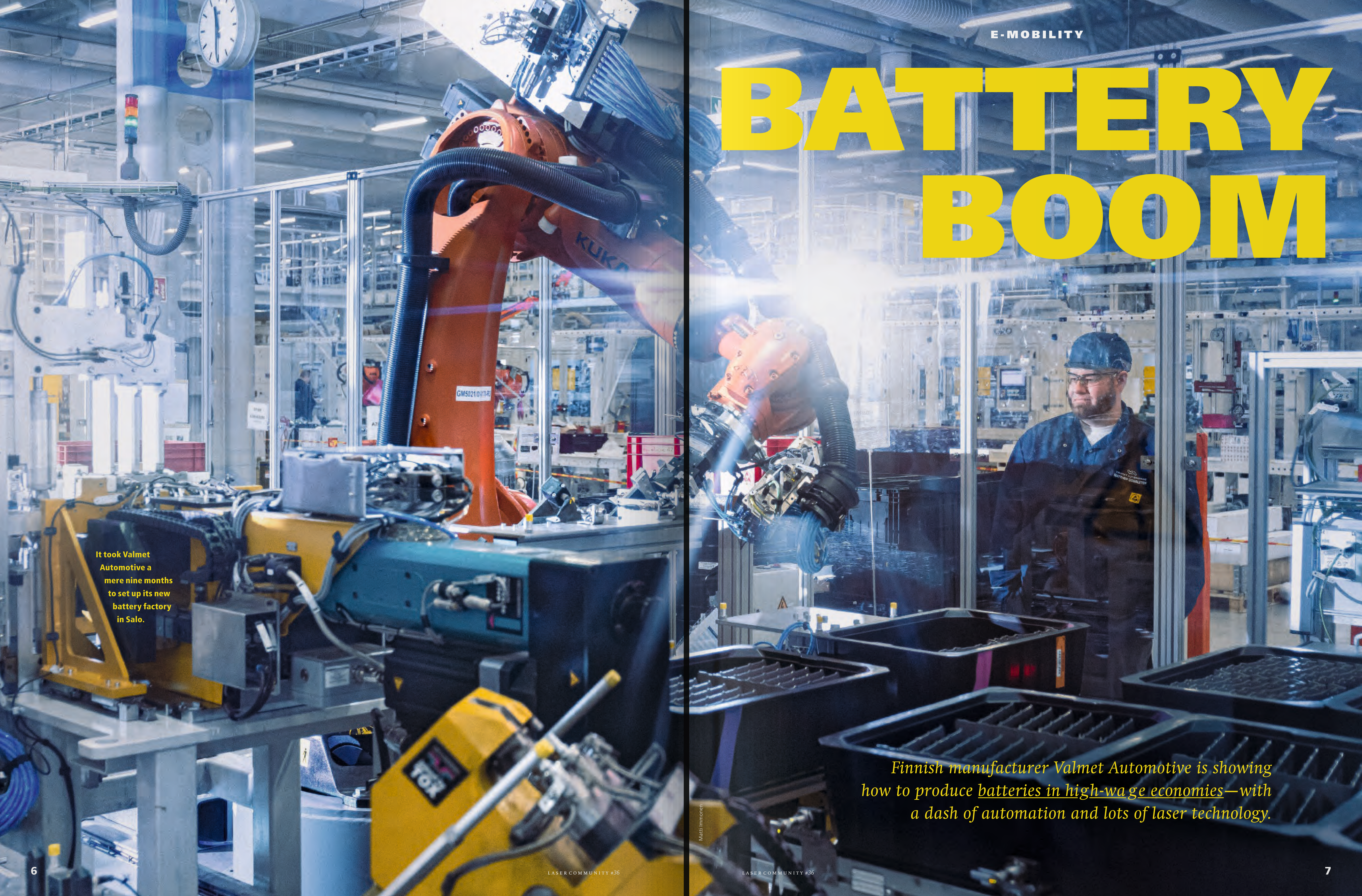
LASER COMMUNITY.

Mark Oliver, Matti Immonen

Dominik Asbach, Die Magazinisten, Philippe Keith

BATTERY BOOM

Finnish manufacturer Valmet Automotive is showing how to produce batteries in high-wage economies—with a dash of automation and lots of laser technology.



It took Valmet Automotive a mere nine months to set up its new battery factory in Salo.

Matti Immonen

“Here’s the deal: we need you to set up a fully operational battery factory in nine months. Here’s an empty building.” Matthew Congleton recalls his initial surprise: “That was some challenge!” Congleton, who hails from the U.S., is head of production at the Finnish vehicle contract manufacturer Valmet Automotive’s battery plant in Salo. His first move, back in February 2019, was to travel to Salo, a good hour’s drive west of Helsinki. In the empty production building, part of a former Nokia site, balls of dust skimmed across the bare floor. It was difficult to imagine that high-tech manufacture had ever taken place here. “It was all just very unused and very empty,” he says. “But if Nokia had once produced electronic components there, it couldn’t be so difficult for us to make batteries.” He got down to work right away.

SPEED IS OF THE ESSENCE The boom in e-mobility has unleashed a huge demand for EV components. “Anything we produce, automakers are buying it up,” says Congleton. In view of this explosive growth, Valmet Automotive resolved to set up its own battery production operation as quickly as possible. For the Finnish company, it would mark the first step from being a pure contract manufacturer to becoming an OEM by learning how to be successful in the battery manufacturing field. The capacity to produce battery packs in Europe eliminates a big risk for Europe’s automotive industry: it substantially shortens the supply chain. “During the pandemic, we saw how fragile supply chains can become—the same thing happened when a container ship got wedged in the Suez Canal,” says Congleton. “And we’re seeing it again with the war in Ukraine.” In his eyes, there never was a problem with setting up battery production in a high-wage economy such as Finland. “The standard of education is so high here. That’s important for the production of complex systems like a battery. For this, you need specialists. Besides, increased output and efficiency far outweigh the higher labor costs.”

Despite all the stress of getting such a project off the ground, the company’s experience in Salo shows that it can be done. While a team was busy in Germany looking at production line automation, work on the building in Salo got underway. “We were having to do a whole bunch of things in parallel,” Congleton recalls. “It was our first battery factory, and at a completely new location. We were hiring people to set up the production operation and, at the same time, acquire the requisite expertise in a totally new business area. Crazy times!” But, at the beginning of October 2019, right on schedule, Valmet Automotive began producing its first battery packs in Salo. Until today, the company produced more than one million packs using around 80 million laser welds. The initial workforce of 30 employees has now grown to 800.

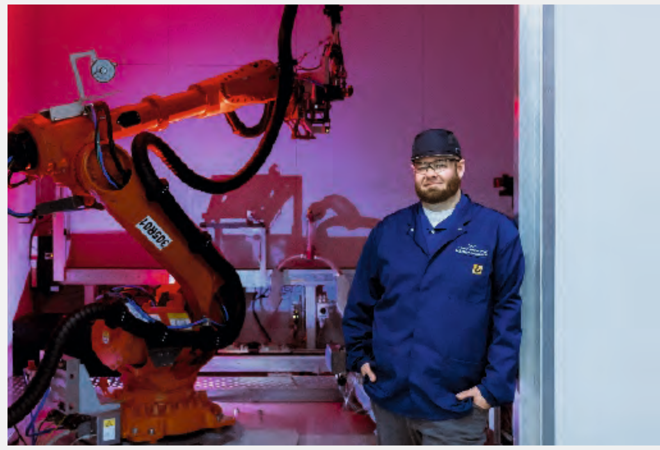
MAXIMUM FLEXIBILITY There’s a lot happening right now in the field of e-mobility. For Valmet Automotive, that’s a challenge but also an opportunity. In the absence of much standardization, there’s still a huge variety of systems and designs in circulation. “The industry’s young, and

Where Nokia once produced cell phones, Valmet Automotive now welds battery packs. This has also eased the recruitment of qualified employees.

Matti Immonen

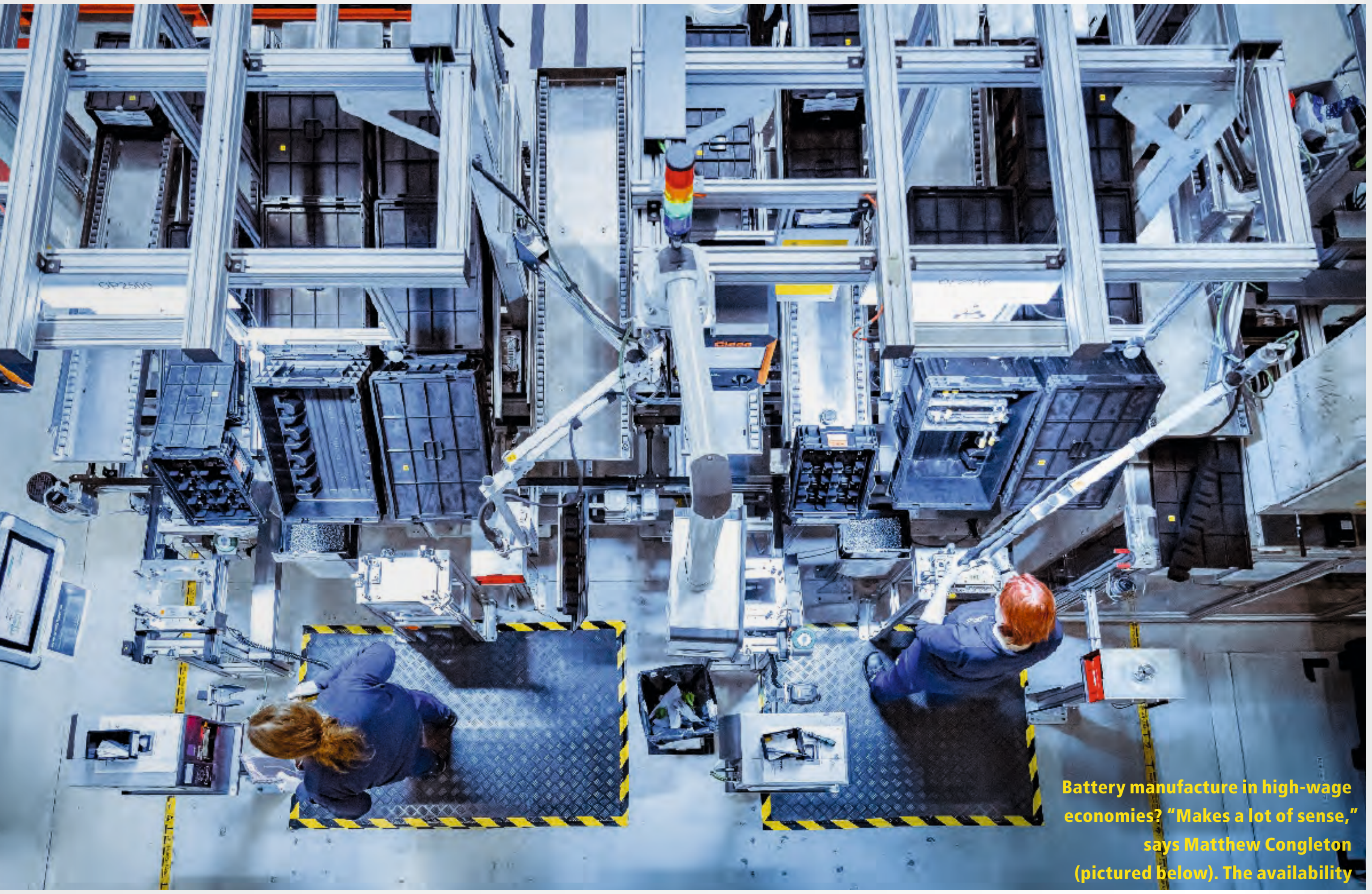
Matti Immonen

“The laser is unbeatable,” says production manager Matthew Congleton. It welds the battery cell tabs into tightly sealed packs without damaging the delicate components inside.



High automation over 180 meters. Manual operations are the exception on the production line in Salo.

“There’s little standardization in the manufacture of EV batteries. Valmet Automotive has therefore made its production lines very flexible.”



Battery manufacture in high-wage economies? "Makes a lot of sense," says Matthew Congleton (pictured below). The availability of specialized knowledge easily outweighs the higher costs.

a lot of the technology and quality standards are only just being developed," Congleton explains. The automakers themselves are still testing things out. Battery position, for example, has a key impact on weight distribution and therefore on vehicle handling. A variety of options are being explored, with some manufacturers opting to place the battery under the car, while others are looking to incorporate it in the chassis. For manufacturers like Valmet Automotive, that means remaining as flexible as possible. "We adapt each production line to a specific product," says Congleton. The level of automation varies, depending on how much product the customer needs and how fast. "It takes time to set up an automated line, but it will then give you a faster output. We can build either a highly automated, high-volume line or a lower-volume line with more manual input." In Salo, Valmet Automotive is currently welding battery packs for Mercedes-Benz and Volvo on a total of three production lines. In addition, individual components can also vary radically, with some battery systems weighing a mere twelve kilograms, while others top the 100-kilo mark.

What never changes, however, is the laser system used to weld the copper and aluminum battery cell tabs into finished battery packs. The seam must be smooth, strong and tight, so that the cells remain securely bonded even in the event of vibrations. "With a laser, you can do this even with very thin sheet metal," says Congleton. "Lasers are fast and produce a high-strength seam without heating up the material being welded. A strong seam prevents any damage to the delicate components within the battery pack, should the vehicle crash." The 180-meter production line for Mercedes-Benz battery packs features a total of two TruDisk lasers with 5 kilowatts of power each. The use of PFO scanner optics enables remote welding with fast throughput and precise results, which is ideal for this contract, where high volumes and therefore a high level of automation are required. There is very little manual intervention. Only the quality check at the end is performed by an employee. Another virtue of the laser process, Congleton explains, is its high repeatability. "Once you've got the welding parameters right, the process runs like clockwork. We haven't changed the parameters in three years."

Contact: Valmet Automotive, Matthew Congleton, Production Director in Salo, matthew.congleton@valmet-automotive.com

Matti Immonen

POWER

FAIR WIND FOR DEEP WELDS

At present, it is impossible to laser-weld the steel towers for wind turbines. This could well change following tests with the most powerful industrial solid-state laser in Europe.

Germany's Federal Institute for Materials Research and Testing (BAM) is currently exploring new ways of welding heavy-duty steel parts such as wind-turbine towers, components for railroad cars, marine hulls and nuclear-waste containers—all jobs with a welding depth of at least 20 millimeters. At present, MIG/MAG welding is used to join such parts. This works well enough—but there are two key drawbacks: the process is not especially precise, and it generates a lot of heat in the material being welded. By far the better option is to use a laser. But the laser welding of really thick parts requires power—a lot of power.

Since the beginning of the year, BAM has been testing Europe's most powerful solid-state laser for industrial purposes. This comes with a thumping 60 kilowatts of power. By way of a benchmark, automobile manufacturers require a mere four to six kilowatts to laser-weld car bodies. With such an increase in power, a laser could be used to weld to depths of 20 millimeters and more.

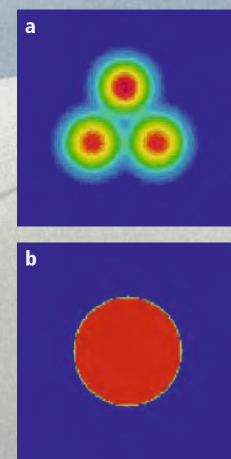
The mega laser currently being tested at BAM harnesses three TruDisk solid-state lasers in total, each with a power of 20 kilowatts. The light from these three lasers is first guided through a 100-micrometer-thick laser light cable before being bundled in a 300-micrometer cable. The optics then focus this beam to a spot of a mere 400 micrometers. What sounds very simple is, in fact, a bit like trying to force a melon through a garden hose. First of all, you need a high-quality beam. Secondly, the system must be able to cope with back-reflections, thereby ensuring that this enormous laser power can be wielded in a controlled manner. It therefore uses resistant disk lasers, special optics with parabolic mirrors instead of lenses, and a special LKX connector between the laser light cable and the optics.

Before the system is ready for industrial use, a number of issues still need resolving—for example, what to do about the large amount of melt produced during the welding process and how to securely weld wide joint gaps with such a small spot. The BAM team is running initial tests at 25 kilowatts before progressively ramping up to full power for really thick sheet metal.

Testing is now underway for the laser welding of heavy-duty parts such as wind-turbine towers.

AdobeStock / bernd schieber/EyeEm, Gernot Waller

Three into one: intensity distribution in cross section at the beginning (a) and end of the laser light cable (b).



LASER'S NEW SENSES

VCSEL is the new magic formula in the world of high-tech sensor design. These mini microchips with integrated laser diodes are used to create high-precision sensors for industry and the consumer electronics market. And now they can even smell, touch and hear.

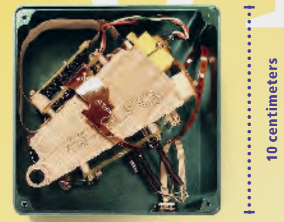
What's in the plume of smoke? The sensor in the funnel knows.

NOSE 01

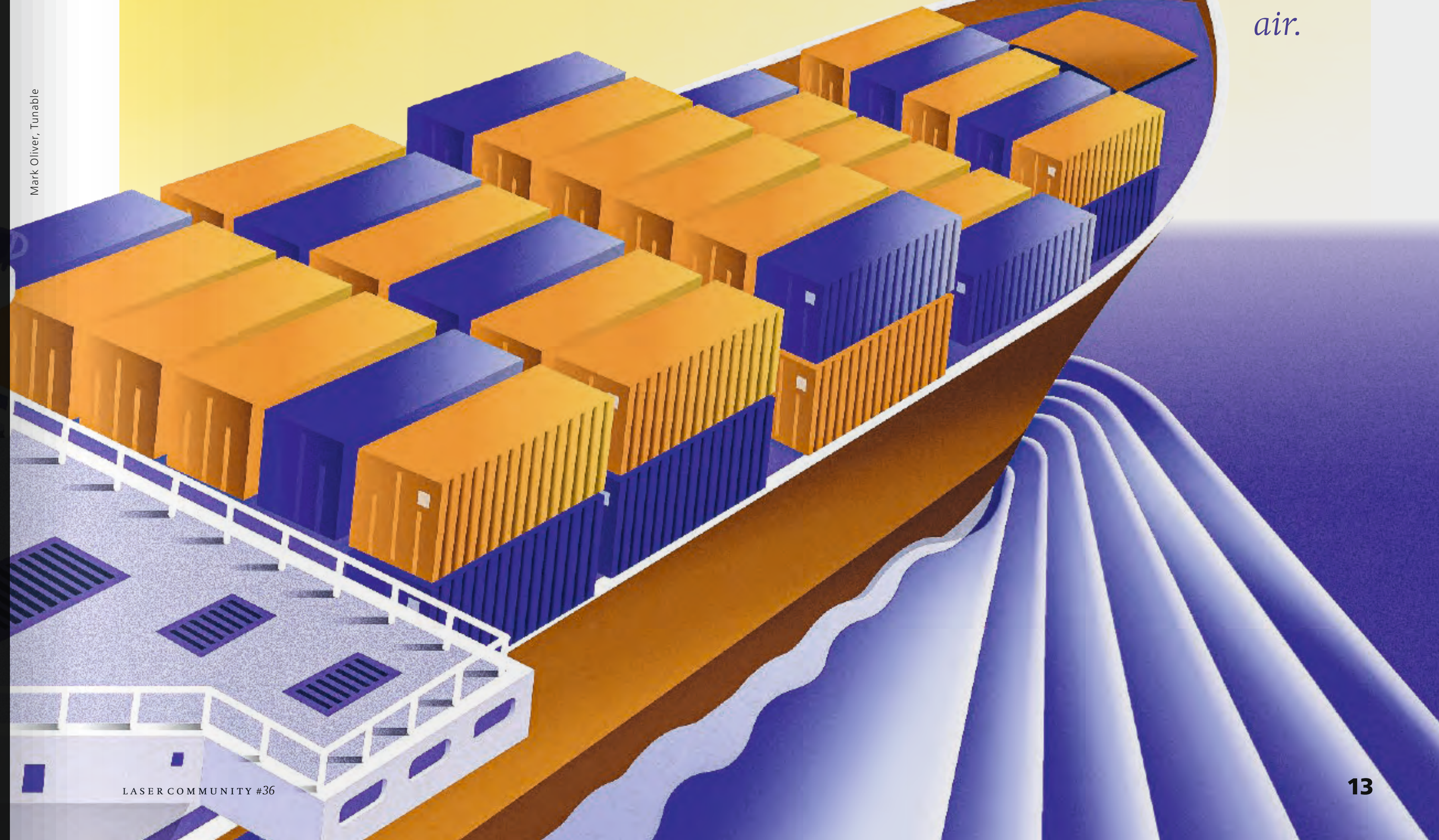
Out of the funnel of a container vessel streams a thick plume of smoke. But just how harmful are these emissions? In such an environment, chemical sensors soon run into problems: they get dirty, they don't like the vibrations and the heat, and after a while they begin to deliver false readings. And they also have to be regularly replenished with chemical reagents. The first ever optical gas sensor from Norwegian start-up Tunable is unacquainted with such difficulties. Installed inside the funnel, it delivers a steady stream of high-precision digital data. And it is maintenance-free.

Each gas molecule has a specific signature in the infrared spectrum and is therefore detectable by spectroscopy. This optical method is used by astronomers to determine the chemical composition of faraway exoplanets. Tunable, by contrast, works on a microscopic scale. Depending on the version, their sensor can detect up to ten or more different gases in the ambient air and determine their concentration. The model in the ship's funnel is trimmed to detect CO_2, nitrogen oxides, hydrocarbons such as methane and others. In a piece of great timing, the European Union has brought in legislation requiring the accurate monitoring of marine emissions as of 2024. Right now, Tunable's optical sensor is the only instrument capable of reliably delivering this information.

Eager to capitalize on this great start, Tunable is now looking at other applications where it's handy to know the precise composition of the ambient air. One of the key features of the Tunable sensor is that it detects not only the presence of specific gases but also changes in their spectral fingerprint of the gas mixture. It can therefore be used, for example, to determine the ripeness of a container load of tomatoes or other fruit. Once in port, it is then clear how quickly the produce must be shipped to the supermarket. This smooths the logistics process and reduces food waste. Tunable sensors also play a vital role in the shipping of liquefied natural gas, where they monitor LNG tanks and also analyze the composition of the gas and thereby determine its calorific value. Similarly, they are installed on LNG pipelines, where they additionally can sniff out even the smallest of leaks. □



The first ever optical gas sensor detects and identifies gas molecules and also determines their concentration in the air.



Mark Oliver, Tunable

02 FINGER

A laser-based particulate matter sensor scans the ambient air for tiny particles, raising the alarm when critical levels are reached.

Particulate matter is a serious health hazard. If particles with a diameter of less than 10 micrometers are inhaled, they can pass directly from the lungs into the bloodstream and remain in the body forever. The smaller they are, the more of a danger they pose. Bosch Sensortec has therefore developed a miniaturized optical sensor to detect particulate matter. It is capable of detecting particles of less than 2.5 micrometers in diameter and determining their precise concentration. Road traffic and exhaust emissions are well-known sources of particulate matter. Yet PM levels are often much higher indoors, where frying food, burning candles or wood-burning stoves can also pose a risk.

The sensor comprises a number of mini lasers. These scan the ambient air for particles and determine their size. Installed behind glass, the sensor has no direct contact with the ambient air and therefore never requires cleaning. For the same reason, it functions without a fan and is therefore completely noiseless. This tiny finger-like sensor is so small it can be fitted behind the display of a smartwatch and warn the wearer when PM levels become dangerously high. The technology is also suitable for smart-home applications. A PM sensor in the cooktop hood, for example, will automatically switch the extractor fan to full power should emissions from frying food become critically high. Similarly, when hidden away in a room thermostat, it will notify the ventilation system whenever a blast of fresh air is required. □

Is the air clean? A laser sensor in a smartwatch will tell you when PM levels are critical.

Mark Oliver, Bosch Sensortec

03 EAR

Robot problems? The optical microphone detects suspicious noises before any damage occurs.

In an age of Zoom meetings and cell phone clips of live music shared on WhatsApp, everyone knows that most mini mikes are not up to the job: the sound is often fuzzy with alarming crackles and beeps. Now, however, Norwegian start-up sensiBel is revolutionizing the mini microphone. Rather than measuring sound electrically, the mike uses a tiny laser beam to perform this optically. The result is a crystal-clear sound, faithfully capturing even the faintest of noises and performing as well as large studio microphones. In the future, smartphone videos by TikTok users will therefore be enhanced with hi-fi audio—as will teleconference calls, where everyone will understand what's being said and be able to conduct a normal conversation via the conference phone.

Meanwhile, there are many other applications for these mini sound wonders. The beauty of optical technology is that—unlike human hearing—it can pick up the faintest of sounds even in really loud environments. Installed in industrial equipment, for example, such mikes are capable of detecting a suspicious noise emanating from production machinery. With the help of smart programming, they can also be taught to recognize what a specific noise means and then advise on maintenance procedures before damage occurs. Obviously, this kind of acoustic monitoring is also suitable for cars, airplanes and many other systems, including critical infrastructure such as power plants or airports. Is that a suspicious drone hovering just behind low cloud cover? Although invisible to a camera, it would be immediately captured by an optical sound sensor installed on the ground. □

The idea of light as an audio medium is not as off-beat as you might think. Despite their minuscule size, optical microphones capture even the faintest of sounds with crystalline clarity.

Mark Oliver, SensiBel

AN OPTICAL REVOLUTION IN MINIATURE

Thanks to VCSEL technology, high-tech sensors have been radically downsized. Enterprising start-ups are now rushing to cash in.

VCSEL stands for vertical-cavity surface-emitting laser. The size of a breadcrumb, these microchips with integrated laser diodes require minimal power input and have a unit price—thanks to mass production—of just a few euros. Equally important, they provide high-performance data capture and data evaluation. Installed behind a smartphone display, for example, they supply the invisible and nonhazardous laser beam used in facial-recognition technology. With the help of multiple mini lasers, VCSELs capture highly granular data, which is then converted into an electrical signal by an integrated microchip.

A THOUSAND APPLICATIONS Start-ups like Tunable and sensiBel have come up with novel applications for this powerful but inexpensive technology. Besides possessing the vision and know-how to devise and design such sensors, these companies are also expert in programming the algorithms that make them tick. It is this that converts a jumble of raw data into precise and meaningful measurements. If there's a common thread linking all the companies currently exploring the possibilities of VCSEL tech, then it's the following: once a new sensor concept has been developed and the algorithms written, a bunch of other applications suddenly emerges, none of which was really on anyone's radar before. That's how the optical microphone for high-fidelity recordings also gave rise to a new maintenance sensor for industrial machinery. sensiBel is currently transferring the optical technology from the micro to concepts for detecting movements, for example for an acceleration sensor. And Tunable is turning its gas sensor for ship funnels into a weapon in the fight against food waste. ■

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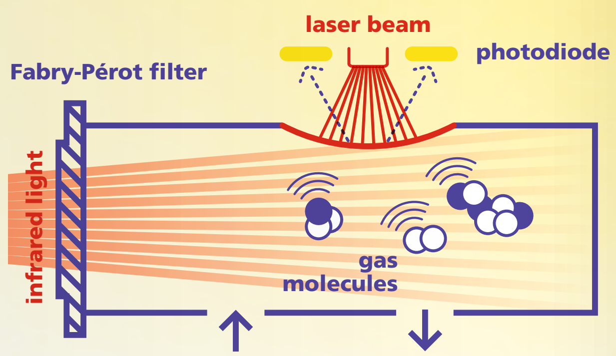
SMELL

Kristian Hovet, CEO of Tunable, Oslo, Norway

01

SINTEF is a Norwegian research institute oriented toward industrial applications. Their Oslo-based nano- and microtechnology center is a world leader in the field of optical sensors and has spawned multiple deep-tech start-ups with original product ideas. This was the route taken by Thor Bakke, now CTO at Tunable. Back in 2015, he set about developing an optical sensor capable of determining the composition and concentration of specific gases in ambient air. As Kristian Hovet, CEO of Tunable, explains: "At the heart of our system is an MEMS—a tiny filter that acts as a Fabry-Pérot interferometer." This Fabry-Pérot filter serves to tune the wavelength of light as it passes through, thereby enabling the sensor to scan the air for specific gas molecules. "It's like turning the FM dial on an old radio and surfing through the stations." Added to the system is a further feature: an optical microphone. As the gas molecules are scanned, this generates sound waves. By using an optical microphone to capture these sound waves, not only is the resulting measurement more accurate but, as Hovet explains, "it also means we can make the gas sensor much smaller, which in turn opens up a whole new range of potential applications." The start-up, which advertises with the slogan a "sense of smell, artificially perfected," brought its new product to market in 2022.



How it works: Ambient air is fed into a cavity that is irradiated with infrared light. A small Fabry-Pérot filter scaled for use in an MEMS serves to modify the precise wavelength of this light. Specific gas molecules absorb infrared at specific wavelengths. This causes them to heat up momentarily, resulting in a change in pressure, which in turn produces sound waves. These sound waves are picked up by a membrane in an optical microphone, which then converts these oscillations into a readable signal. On this basis, the system is then able to determine which gases are present in the air sample and at what concentration.

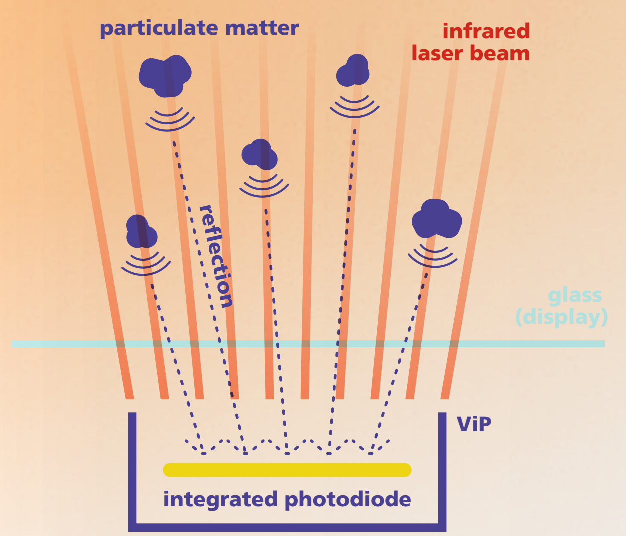
TRUMPF, private, Gernot Walter

TOUCH

Peter Ostertag, director of optics at Bosch Sensortec, Reutlingen, Germany

02

It's some ten years since alarm bells began ringing over the health hazards of particulate matter. Back in 2014, a development team had a clever idea. "Mean values, calculated from readings at strategically located measuring stations, are less relevant to my health than the quality of the ambient air I'm actually breathing at any one moment," he explains. "So, we set about developing a PM sensor that could be incorporated in wearable technology such as smartwatches." To this end, they teamed up with TRUMPF Photonic Components, which went on to provide the VCSEL for the sensor concept. Engineers quickly discovered that if the laser diodes were arranged in a particular way, the VCSEL would be able to scan the ambient air without the need for some form of integrated motoric solution. "That was the breakthrough," says Ostertag. "Our PM sensor is 450 times smaller than rival products—but just as sensitive." Preparations for mass production are now being ramped up, with the product launch scheduled for spring 2024. Potential applications include not only smartwatches but also smarthome devices to monitor indoor air.



How it works: A VCSEL with integrated photodiode (ViP) shines an infrared laser beam through glass—e.g., the display screen of an electronic device. When the beam hits particulate matter suspended in the ambient air, photodiodes capture the reflected light and measure this by means of the technique known as self-mixing interferometry. An algorithm then calculates the size of the particles and their concentration in the air.

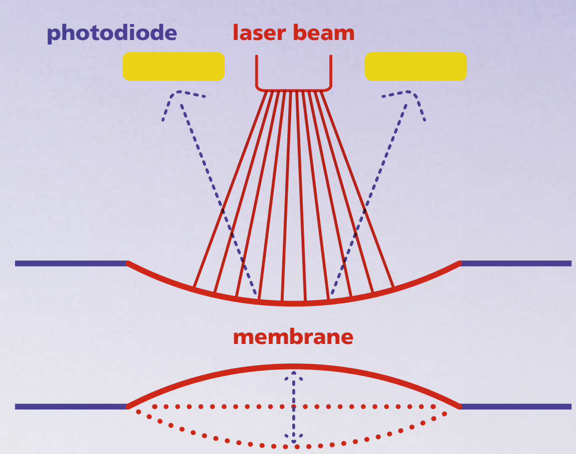
Private, SensiBel, Gernot Walter

HEAR

Sverre Dale Moen, CEO of sensiBel, Oslo, Norway

03

Like Tunable, sensiBel is a spin-off from the prolific Norwegian research institute SINTEF. Back in 2017, the start-up set about reinventing the microphone. Sverre Dale Moen joined the company later and is now CEO. "For over 100 years, the technology behind the microphone remained essentially the same," he explains. "But our optical MEMS has introduced an entirely new way of measuring sound." In the past, microphone performance diminished with decreasing size. "But that's no longer the case. With optical technology, the size of the mike is almost completely irrelevant to audio quality. An optical microphone measuring a few millimeters produces studio-quality recordings with great dynamic range and virtually no self-noise." It can pick up the faintest sounds and nuances, even in very noisy environments such as airports or manufacturing facilities. "And because of its size, it can also be used to create, for example, compact microphone arrays for 360-degree sound detection." The new optical mike from sensiBel is currently being released on the market.



How it works: Sound waves hit a tiny silicone membrane, causing it to oscillate. An infrared laser beam is shone onto the membrane, using diffraction. The reflected light is picked up by photodiodes, which thereby measure the distance to the membrane, as this varies with each oscillation. This ensures that even the smallest oscillations are registered—virtually without any self-noise from the microphone itself. A microchip converts the optical signals into digital audio output.

“High-tech lasers will become a mass-produced item”

Professor Constantin Häfner is looking forward to toasting bread with a laser.

Dominik Asbach

Constantin Häfner is head of the Fraunhofer Institute for Laser Technology ILT. Below, he explains that the future of laser technology may well be linked to nuclear fusion.

Professor Häfner, looking 10 or 20 years into the future of laser technology, what do you see?
I see a laser toaster.

Really?
I’m being serious.

Explain what you mean.
Today, lasers are ubiquitous. They’re in industry, in data transfer, at the supermarket checkout, in car headlights and practically everywhere else besides. In manufacturing, for example, lasers are increasingly replacing environmentally harmful, wet chemical processes such as those used to etch patterns on embossing rollers. And there’s one type of laser that is particularly suitable for these kinds of sustainable processes: the ultrashort pulse (USP) laser.

What’s so special about the USP laser?
The USP laser could be used in many other areas than is currently the case. It’s extremely precise, for example, yet we still only use it for relatively few applications. Now, why is that? The USP laser has reached an interesting juncture. In theory, USP lasers should be capable of achieving ever-greater levels of average power—I’m talking here about the multikilowatt class—and they should be able to do this reliably. But we’re not quite there yet, since the associated development and manufacturing costs are still so high that it wouldn’t be worthwhile in view of the current size of the market segment. However, the introduction of regulatory measures will soon bring market changes here, requiring the use of more-sustainable production methods that conserve resources. And USP lasers can make a lot of manufacturing processes more eco-friendly.

What else can you do with powerful USP lasers?
Secondary sources are another promising application. This is when laser beams are used to generate other useful beams such as X-ray and particle beams. This technique is already used for EUV lithography in microchip production. And there are plenty of other ideas as to where secondary sources might be used. But what we’re really looking for is the next killer application—something alongside EUV, for instance, which will further open up the market. Maybe this will come in the field of medicine—in the diagnosis and treatment of cancer, for example. Or maybe from a completely unexpected quarter. We just don’t know yet.

> "It's about *scaling up production* to achieve economies of scale never before seen with laser technology."

Will that impact laser technology as a whole?
Not especially. Something else will change laser technology—and this will transform it completely.

What's that?
I'm thinking about the billion-dollar energy market—and about the holy grail of energy production: nuclear fusion. In fall 2022, news came through that Lawrence Livermore National Laboratory in California had made a breakthrough in nuclear fusion. More precisely, it was the National Ignition Facility (NIF), which for the first time ever had succeeded in igniting a plasma by means of a laser. In other words, the NIF was able to trigger nuclear fusion, thereby releasing more energy than had been previously absorbed from the laser beam—all in all, about three times as much. I myself worked at the NIF from 2006 to 2019. Among other projects, my team and I worked on next-generation lasers of the type that will be needed to operate a nuclear fusion power plant.

What does this breakthrough mean for nuclear fusion?
It means that a fusion power plant just became a realistic goal. The experiment shows that the physics works: the plasma ignites and releases more energy than was absorbed. The task now is to develop the actual technology required to build a plant. That's why we need industry and engineers to drive forward this vision and turn it into reality. This is also the context in which I look at laser technology: it needs to ride the momentum generated by nuclear fusion. If laser-driven nuclear fusion is to become commercially viable, we will need to achieve economies of scale in laser technology. This means that laser tech will have to become substantially more efficient, more robust, more powerful and, above all, more economical.

How much more economical?
To give you some idea of the magnitude involved, for a future laser-powered nuclear fusion plant to be commercially viable, it will have to cost no more than six to eight billion U.S. dollars—that's at a power rating of around one gigawatt. Of that sum, between one or two billion dollars would be earmarked for the beamlines. At today's market prices, the diode lasers used to pump the beamlines would alone cost around 50 billion. And such a project would require around double the present global annual output of pulsed diode lasers. That all needs to become around 50 times cheaper. But it can be done: it's all about scaling up production to achieve economies of scale—to a degree we already know from the semiconductor industry.

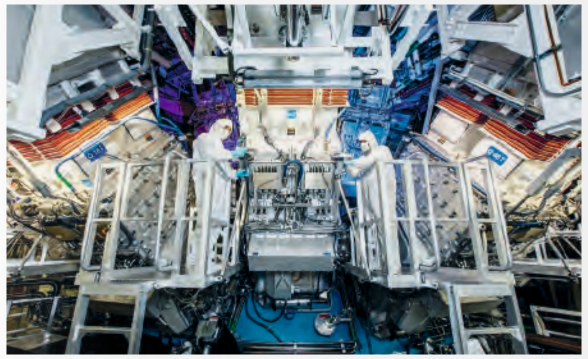
Sounds like a bold plan. How can it be done?
Sure, it's a bold idea, but nuclear fusion is a project that is of global importance. It could provide a clean and inexhaustible source of energy, and that should be attractive to national economies and private investors alike. Here, at Fraunhofer ILT, we're currently working with industry to advance laser technology and make it more affordable. This will enable the cost-effective production of, for example, laser drivers. To achieve this, we need the kind of innovations that will make, for example, the assembly of diode lasers much more economical. This means automation: for separating laser bars, for packaging, and for attaching lenses—to name but a few areas. The aim is for a production output with an almost 100 percent yield. And once we have that, even high-class diode laser systems will become incredibly cheap. The blueprint here is the production of LEDs, which were once high-tech but now, thanks to economies of scale, are an everyday item. If the global community really is prepared to commit itself to nuclear fusion—and I assume it is—then, at some point over the next 10 to 15 years, we'll have assembled all the requisite technology. Then we'll be able to build the first demonstrator, and this can be connected to the grid by mid-century. Market rollout will follow, along with the attendant economies of scale. And then, when there are globally, let's say, somewhere between five and ten fusion plants joining the grid each year, we'll need to be producing lasers with a combined power of around 700 megawatts annually. That's really going to shake up the laser and photonics market.

What does this mean for laser processing as a whole?
It means that the age of the laser is only just beginning. In the coming years, we're going to see a fast and furious cycle of innovation throwing up all sorts of developments and advances that will then be used in every other kind of laser application. At the same time, the welcome drop in price will revolutionize laser technology. High-tech lasers will then be mass-produced and therefore become an everyday item—just like the Swiss Army knife. This will lead to more and more lasers being used in all sorts of areas where today this would still be inconceivable and simply uneconomical.

For example, in a laser toaster!
Exactly! ■

Profile: Professor Constantin Häfner has headed the Fraunhofer Institute for Laser Technology ILT since 2019. He also teaches laser technology at RWTH Aachen University. Before joining Fraunhofer ILT, Häfner spent over ten years as director of the Advanced Photon Technologies Program at Lawrence Livermore National Laboratory, California.

> "Nuclear fusion will *transform* laser technology *completely*."



National Ignition Facility/Jason Laurea, Dominik Asbach

NUCLEAR FUSION

Nuclear fusion is what provides the sun with energy. Now, researchers are attempting to replicate this process on earth. Using high pressures and temperatures of around 100 million degrees Celsius, they hope to fuse hydrogen nuclei. This releases more energy than is required to trigger the reaction. There are two approaches:

1. Fusion by means of powerful magnetic fields, as used by the International Thermonuclear Experimental Reactor (ITER) in France.
2. Laser-driven nuclear fusion: a large number of powerful lasers fire at a minuscule target—tiny capsules of heavy hydrogen—and thereby trigger nuclear fusion. This was first successfully performed in late 2022 by a team at California's Lawrence Livermore National Laboratory (left).

STOP THE GRAIN WEEVIL!

Insects find their way into even the most secure of food stores. Once there, they feed on the crop, introduce bacteria and multiply rapidly. In the battle to combat grain weevils and other pests, researchers have come up with a smart laser-based defense system.

Gernot Walter / Die Magaziniker

The grain weevil

[*Sitophilus granarius*] has been ravaging harvests ever since crops were first cultivated. It has kept pace with the spread of agriculture and today is endemic in all temperate regions of the world.

The Indian meal moth

[*Plodia interpunctella*] uses food stocks as a breeding ground. Its larvae devour and contaminate all kinds of dry goods, including dried fruit, cereals and coffee beans.

GUNNAR BÖTTGER from the Fraunhofer Institute for Reliability and Microintegration IZM in Berlin is working on an insect laser—a joint research project led by the Julius Kühn Institute (JKI) in Berlin and with the participation of Brandenburg University of Technology (BTU) in Cottbus.

Gernot Walter / Privat

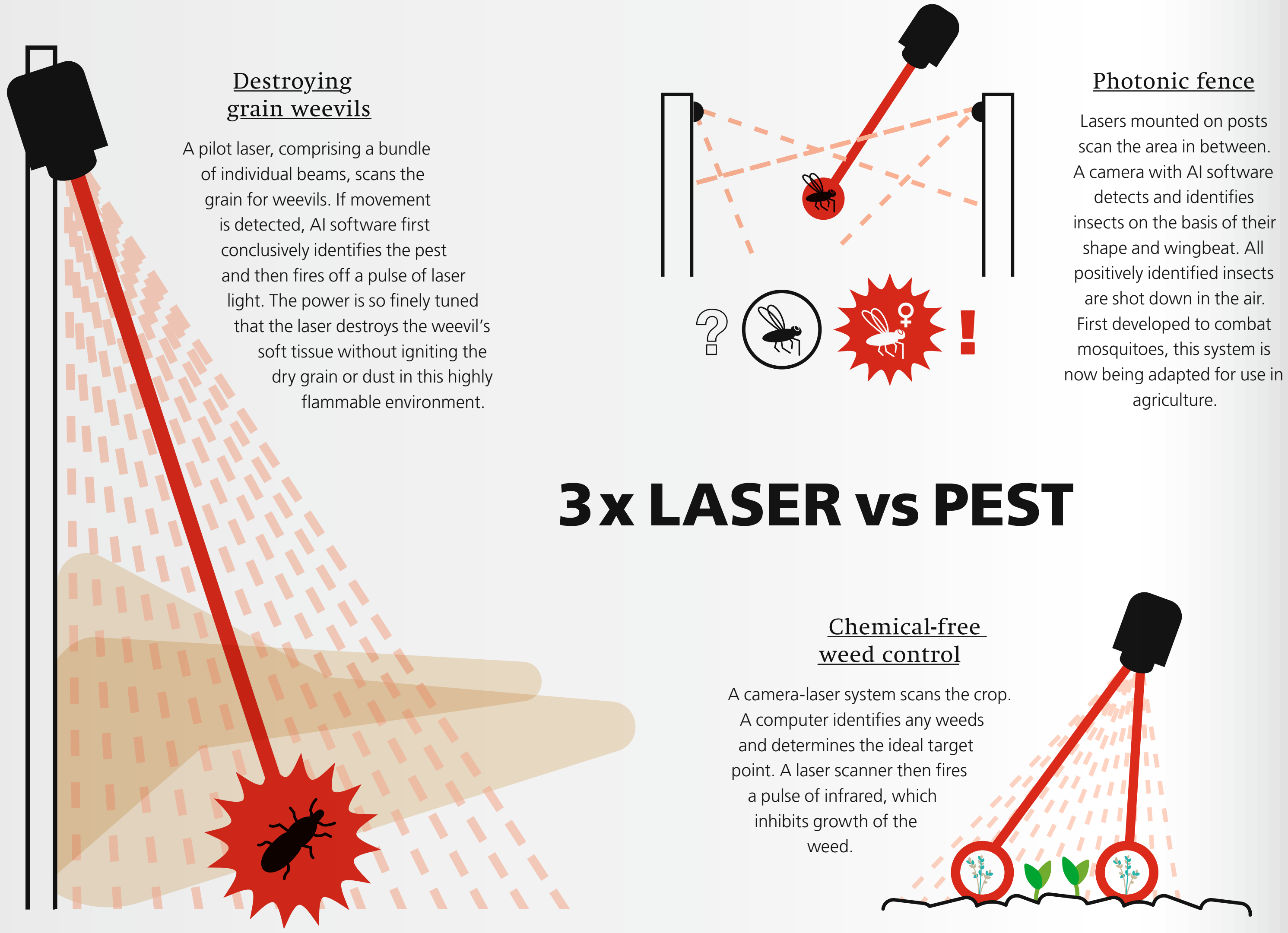
Fly, crawl or creep—insects will always find their way into agricultural warehouses and food-processing operations. And once there, they discover such an abundance of nutrition that they multiply rapidly. Immediate action is therefore vital. If not, the stored food can spoil, thereby increasing the proportion of the crop that is lost following harvest. According to the Food and Agriculture Organization of the United Nations (FAO), around four percent of European grain production is currently lost in this way—around 12 million metric tons a year.

At present, fumigation is used to combat the pests—but only once an infestation has been detected. Although this process liquidates the insects, it can only be used sparingly. If treatment has to be repeated, this can leave residues on the grain, which can then pose a risk to consumer health and to the environment. Researchers are therefore seeking ways to tackle the weevils and other insects without the use of chemicals. In an idea that might well have been inspired by science fiction, they have come up with a laser system that shoots down the very first wave of an infestation, killing the insects in an eco-friendly way. Behind the project stands the combined expertise of three German research institutes, which have developed a prototype insect laser over the course of several years. The researchers are initially targeting two of the most notorious bugs—one that crawls, and one that flies: the grain weevil, which ravages grain stores; and the Indian meal moth, which infests food-processing plants.

PERISH IN 500 MILLISECONDS Exploiting the fact that grain weevils initially move on the surface of the grain rather than within it, the laser system uses artificial intelligence (AI) in order to localize, identify, aim and then fire. As soon as a weevil appears in the camera's field of vision—whether on the grain itself or on the wall of the grain store—AI software developed by BTU Cottbus compares the image with a database. Once the culprit has been conclusively identified, the laser system swings into action. First of all, a scanner directs a fine red pilot beam to the relevant coordinates, thereby marking the target. Half a second later, a shot from the laser has dispatched the insect—500 milliseconds from detection to destruction.

By now, the system is able to detect grain weevils and Indian meal moths with an accuracy of over 90 percent. Yet a lot of work was required before the image-processing technology was able to reliably identify targets in what can be huge warehouses. Detecting a weevil only a few millimeters in length among millions of grains of wheat is a task akin to hunting for a needle in a haystack. The AI software was therefore subjected to extensive training with a mixture of photos and short video clips of the insects.

TURNING ON THE HEAT Researchers from Fraunhofer IZM also faced a tough task: the laser system had to be capable of destroying the insects but without damaging the foodstuffs, packaging materials or any part of the warehouse. In addition, there is the risk of fire: on no account should the laser accidentally ignite dry grain or packaging materials, or trigger a dust



explosion. In the absence of any research findings that might have helped establish useful parameters, the team carried out its own tests to determine the optimal wavelength and laser-beam intensity for the job in hand.

In the end, they opted for a commercial fiber-coupled diode laser operating at 808 nanometers (nm) and to a maximum of 10 watts. Smaller than a pack of cigarettes and easy to integrate, a semiconductor laser of such a wavelength is also very cheap to produce. In tests, it functioned best at a power of 8.44 watts, which was just enough to singe the wings of Indian meal moths and slightly color the outer shell of grain weevils. The Fraunhofer IZM researchers also tried out a self-built module comprising a fiber-coupled diode laser operating at a wavelength of 1,470 nm. This is also the wavelength used by manufacturers of medical equipment. It efficiently introduces energy into aqueous matter—e.g., body cells filled with plasma—or the soft tissue within an insect, which the laser then heats at an energy of two watts without any damage to the shell. Neither of the two laser modules generated temperatures liable to pose a fire hazard in a grain store. Metal parabolic mirrors were used to guide and shape the beam, since glass optics can only focus one tuned wavelength at a time.

CONCLUSION A combination of laser technology, automated image recognition and artificial intelligence now offers the agricultural industry a means of protecting stored crops and foodstuffs in an environmentally friendly manner. This paves the way for the development and commercialization of further applications in the newly emerging field of agrophotonics—laser-assisted agriculture. Until then, however, no pests need fear the red dot of a laser. ■

Gernot Walter

Experiments by Anton Zeilinger have paved the way for practical uses of entangled quanta.

Jacqueline Godany

FROM THEORY TO PRACTICE!

Anton Zeilinger has helped engineers develop concrete applications for quantum physics.

Anton Zeilinger is no ordinary physicist. His interests extend way beyond his actual subject field. On YouTube, for example, he features in countless discussions and debates on fundamental, philosophical questions of the kind: What is chance? Does everything in the natural world have a cause? If not, what might this mean? And what would be the logical consequences for science if not everything were logical? For the Austrian physicist, such questions are by no means a hobby. Instead, they emerge organically from the elaborate experiments that have helped found his reputation.

The 78-year-old has devoted his professional life to bringing quantum physics into the everyday world. He has developed ingenious ways of using lasers to entangle quantum particles. Entangled quanta instantaneously exchange information about their respective states. In effect, they act as if they were one single particle—yet can be any distance apart. In his quest to discover everyday uses for quantum entanglement, Zeilinger has staged some groundbreaking experiments. For example, he and his team were the first to send a quantum-encrypted wire transfer via fiber optic cable. And they were also able to swap quantum-based information between the islands of Tenerife and La Palma—via the air. Thanks to Zeilinger's research, quantum mechanics now has real-life engineering applications.

Around the world, developers are using his work to create concrete products—including high-precision industrial quantum sensors and the world's first quantum computers. Anton Zeilinger was awarded the 2022 Nobel Prize in Physics, together with quantum researchers Alain Aspect and John F. Clauser. ■

Demand for laser-based automation has never been higher. JTA projects are often highly classified.

LASER CONFIDENTIAL

JT Automation takes on some of the most challenging jobs that industry has to offer, with many of their custom systems destined and designed for top-secret manufacturing contracts. Thanks to a combination of American ingenuity and German laser tech, the company is growing rapidly.

Philippe Keith

I'm sorry, my lips are sealed!" he says with a broad grin. "But what I can reveal," adds Scott Boynton from JT Automation (JTA), "is that it fills me with pride to know that a product made by our equipment is being used by millions of people every day. Maybe you're one of them!" He is referring to a company from the cosmetics industry—and probably the most secretive laser project JTA has been involved in so far. "The company was so worried about competitors gaining access to this new technology that they had most of the equipment developed and built in Asia, where it's being used, but they entrusted us with the really crucial process," explains Boynton, cofounder of automation specialist JTA. "A lot of the projects we do are highly confidential," explains Ryan Lombardini, president of JTA. "So much so," Boynton adds, "that we're not even allowed to talk about our first major contract, from the aviation industry, which gave us our big breakthrough. All I can say is that we developed around 30 systems in three different designs for an aviation company, and we are now producing them. We've had to hire around ten new people to take on this job, which is worth nearly 20 million U.S. dollars. It's been a massive boost for us." This, in turn, has given JTA the funds to bankroll a new and larger location. In the coming months, the company will move from East Granby, Connecticut, to Windsor, the next town along, expanding its development and production footprint by more than sixfold. "That will enable us to restructure the company and make it much more efficient."

THREE BRAINS—ONE PHILOSOPHY Boynton is one of the company founders. Since hiring at Joining Technologies (JT) right after graduation, he has worked his way up the corporate ladder, eventually establishing JT Automation in 2016, together with JT management board members. JTA was founded in response to the ever-growing demand for laser-processing equipment tailored to specific customer requirements—and, in particular, the need for automated systems. After an initial spell as president, Boynton, who feels more at home in the creative world of product development, handed over to Lombardini, a homegrown talent who joined the firm on an internship in 2016. "Back then, we were still a small start-up with just a handful of people," he explains. "Today, our headcount is over 30, and we're always looking for new workers." Another key piece in the jigsaw is Jay Drew, vice president of sales and marketing. His job is to sound out customers and find out what they want. "We develop a lot of systems from scratch, which means we can freely adapt them to the needs of the customer," Drew explains.

The demand for robotic and automated systems has never been higher. For a start, many products are becoming more and more complex, which demands absolute precision in the manufacturing process. Secondly, skilled labor is in short supply and therefore at a premium. Robotics and automation can help stop this gap and relieve the existing workforce. "Customer orders vary a lot," says Drew. "Often, they are looking for something new, which we will then plan and develop from scratch. But sometimes they just want a specific TRUMPF workstation or a specific laser with extra features." Boynton illustrates this with reference to two of his favorite pieces of equipment: "When we're asked to customize a TRUMPF system or add new functionality, our preference is for the TruLaser Cell 7040 or the TruLaser Station 7000. Both enable us to produce a great solution at a far lower cost and lead time than it would take to deliver a fully customized system."

CULTURE ENCOURAGING INGENUITY JTA continues to grow at a rapid pace. As Lombardini explains: "Our workforce has really stepped up to the plate. Lots of our engineers and technicians have taken on new tasks, stepping into management and leadership roles, venturing into new territory. It's not just our financial growth that has given us stability." Drew also points to the corporate culture at JTA: "We hire people because they're good at what they do. We don't need to tell them how to do their job."

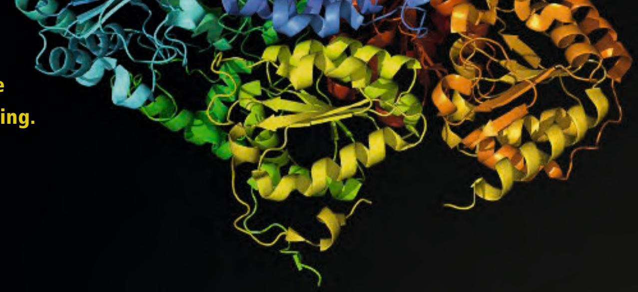
A project for the medical equipment industry illustrates the kind of ingenuity that this company can provide. Advances in medical science mean that the instruments used in minimally invasive surgery are becoming smaller and smaller. This regularly pushes manufacturing to its very limits. For example, a global manufacturer of medical equipment was looking to reduce the costs of producing a delicate, hand-built assembly. It therefore turned to its existing supplier base. The challenge was to devise a system to automatically load and weld workpieces measuring less than 0.5 millimeters. A hot tip took the company to JTA. "The customer needed someone capable of combining laser ablation, cutting and welding with precision automation and inspection so as to create a system that can produce hundreds of assemblies per hour, compared with the dozen or so possible with the existing manual process," Boynton recalls. "Obviously, it was a big challenge, but we saw a way that others didn't." Following two years or more of research and development, JTA delivered the system. The company has since ordered more of the same system in order to expand capacity. "It's a real pleasure to watch it at work—not only because of its extreme precision but also because of its micromechanical complexity," he adds. "But most important of all, mass production means that hundreds of thousands of people now have access to a life-changing process that our system is helping to produce." ■

Scott Boynton, Jeremy Drew and Ryan Lombardini (left to right) have a secret: let the workforce do their thing!

AHEAD

LASER-BASED ACCELERATORS WILL HELP US DEVELOP NEW DRUGS

Sabine Brock from DESY (Deutsches Elektronen-Synchrotron) is driving the development of laser-based particle accelerators. A key aim is to expedite the discovery of new active ingredients.



Soon a reality: observing the complex process of protein folding.

European XFEL / Heiner Müller-Elsner

Sabine Brock, what exactly is a laser-driven plasma accelerator?
It's basically a particle accelerator in a highly compact format. In the future, we will be able to use plasma-based particle accelerators to generate extremely brilliant X-ray light as well as beams from electrons, protons and neutrons. To do that today, you need an accelerator with vacuum pipes sometimes several kilometers in length. The accelerator tunnel for the European XFEL at DESY is over three kilometers long. This new technology accelerates particles within a laser-driven plasma over a distance of just a few centimeters. In time, this will enable the development of lab-scale systems that will be useful for medical and industrial applications. The technology works. It's now just a question of getting it ready for market as quickly as possible.

Won't these small beam generators then make classic particle accelerators like those at DESY redundant?
No, I don't see any danger of that. Laser-driven, plasma-based systems will be ideal for specialist applications, optimized for the specific job in hand. Our large-scale research facilities, on the other hand, are like a Swiss Army knife—suitable for a whole range of tasks in research and development.

What kind of applications do you have in mind for these small accelerators?
Basically, there's a whole range of ideas—using them in materials testing, for example, or in battery development and in quality control for the semiconductor industry. Right now, our innovation platform is focusing on the development of active ingredients for new drugs. That's an area where we urgently need to speed things up.

Why is this so urgent?
Demographic trends in the developed world leave us with little choice: an aging population means an increase in cardiovascular diseases and cancer. Besides, the pandemic underlined the importance of being able to develop new active ingredients for medicinal drugs as quickly as possible. At present, it takes, on average, 12 years from initial discovery to market release. That's far too long. What's more, only around one in ten thousand potential active ingredients actually makes it to the drug stage.

How can laser accelerators help?
They will enable us to observe protein chains as they react and fold and then to analyze this process with AI. Protein folding is a very complex process that plays a crucial role in how medicinal drugs work. At present, we have no way of predicting this or reconstructing it in specific cases. Laser accelerators will enable us to build extremely compact and intense X-ray sources, which we can then use, for example, to precisely track the path a drug takes through the human body, right down to the molecular level. It will be almost like having a video of this process. Our goal is to simplify and accelerate the studies required for drug approval.

You've set up the new HI-ACTS innovation platform in order to bring together science and industry, research and engineering. The aim is to get laser accelerator technology up and running. Why is this so important?
We need to develop robust, commercially viable laser-plasma accelerators, and we need to do this as quickly as possible, without taking any detours. In concrete terms, this means establishing sound industry standards right from the very start. We need to be thinking about the interfaces required for operation—rather than doing this at a later stage—and even conducting certification processes in parallel. And we need to remember that it's unlikely that all future users will have a degree in physics. In other words, any systems should be designed with easy operability in mind. And that's where industry can really help us scientists. ■

HI-ACTS The Helmholtz Innovation Platform for Accelerator-Based Technologies & Solutions (HI-ACTS) brings together science and industry. Its purpose is to develop laser-driven particle accelerators for commercial use. This platform is coordinated by DESY: www.hi-acts.de

INNOVATION PARTNERS The HI-ACTS platform brings together university hospitals, Helmholtz Association research centers and Fraunhofer institutes with industrial companies such as TRUMPF, Beiersdorf, Siemens Healthineers and Olympus.

DESY The Deutsches Elektronen-Synchrotron (DESY) in Hamburg is one of the world's leading centers for the development, construction and operation of particle accelerators. It provides facilities not only for fundamental scientific research but also for applied research—including recent work by TRUMPF to investigate the laser welding of copper.

Czech Republic

OVERVIEW OF THE ECONOMY

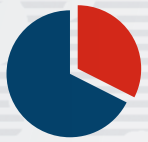
The Czech Republic has been a **center of industry** since the 19th century. The transition to a market economy in 1989 was swift.

Key industries are **automotive manufacturing** (e.g. Škoda in Pilsen), electronics and mechanical engineering.

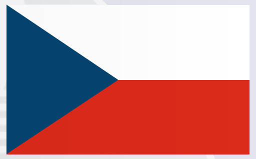
Export **trade** is strongly focused on the EU.

WELCOME TO LASER LAND CZECH REPUBLIC!

Industry as a proportion of GDP



31%



26,849 USD

Nominal GDP per capita

10.5 m inhabitants

LAND OF LASER

The Czech Republic was already **a center for glassmaking and gemstone cutting** over three hundred years ago. Both are at the roots of the optics industry.

Today, around 30,000 people work in the country's **photonics industry**, spread across five major companies and around 25 SMEs and start-ups. Key products and services include high-end optics, complex lenses and crystal growing.

The Czech Republic has a **strong research scene** with top universities and institutes: TOPTEC in Turnov, the HiLASE Centre in Dolní Břežany, near Prague, and the nearby ELI Beamlines Facility, which hosts the world's most intense lasers.

ELI Beamlines, pyty / AdobeStock, Gernot Walter

WHERE'S THE LASER?

In a carefree snack — thanks to precisely monitored blood-sugar levels. "Which finger should I prick today?" A troublesome decision for many diabetes sufferers. But thanks to the Danish company RSP Systems, it is now possible to measure blood-sugar levels without spilling any blood. Using tiny laser diodes—known as VCSELs—a ray of light is projected onto the surface of the skin. This light is then reflected back at a characteristic wavelength by glucose molecules in the interstitial fluid, which surrounds body cells. By means of a patented method, this reflection is analyzed and the blood-sugar level calculated to the millimole, all within a matter of seconds. Current devices are about the size of a landline phone, but future models will be as small as a wristwatch, giving diabetes sufferers even more freedom. As a result, more and more diabetics are now saying goodbye to the needle.

unsplash | luke wang

TRUMPF

LASERCOMMUNITY.37 *will appear in autumn 2023.*
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