



A Ball Artist in the Quantum Arena

Electrons don't have much in common with basketballs, apart from the fact that they are often portrayed as having the shape of a ball. Nevertheless, **Peter Hommelhoff** is as adept a player with one as he is with the other. In his experiments at the **Max Planck Institute of Quantum Optics** in Garching, where he heads a Max Planck research group, he has achieved a new level of control over these elementary particles.

TEXT **ALEXANDER STIRN**

Blocks, rebounds, jump shots – Peter Hommelhoff is a man who knows how to handle a ball. For years, the physicist spent weekend after weekend on the basketball court, defending his team's basket, stealing rebounds and pushing his way through the defense.

These days, this over-two-meter-tall man heads a research group at the Max Planck Institute of Quantum Optics in Garching. That doesn't mean he no longer enjoys the game – quite the contrary. Now, however, instead of basketballs, Hommelhoff's equipment is, in classical terms, 50 trillion times smaller: the 37-year-old is determined to manipulate the movement of electrons using laser light and microwaves.

Hommelhoff's court now is an optical table, packed full with lenses, mirrors and beam splitters. Water cools the systems, and nitrogen dispels the last of the dust particles. His shooting arm is a laser. His backboard and hoop are located in a vacuum chamber. Only his

tricks are still the same: Peter Hommelhoff tries to knock electrons free, accelerate them and force them into a curved trajectory, systematically rebounding them and sinking the particles right where he wants them.

PHYSICS SCORES WITH ITS LOGICAL LANGUAGE

More than 20 years have passed since the foundation was laid for Hommelhoff's career in sports and science. It was the summer of 1991. The student and his family had just moved from Bielefeld to Heidelberg. One of the first paths there led the 16-year-old to the basketball practice of the then German record holder USC Heidelberg. Before that, the lanky youth had only ever played with the large orange balls for fun – or to warm up for one of his many other sports, especially fencing. Now, however, in the city of the professionals, he wanted his training, too, to become more professional. "Still, I didn't

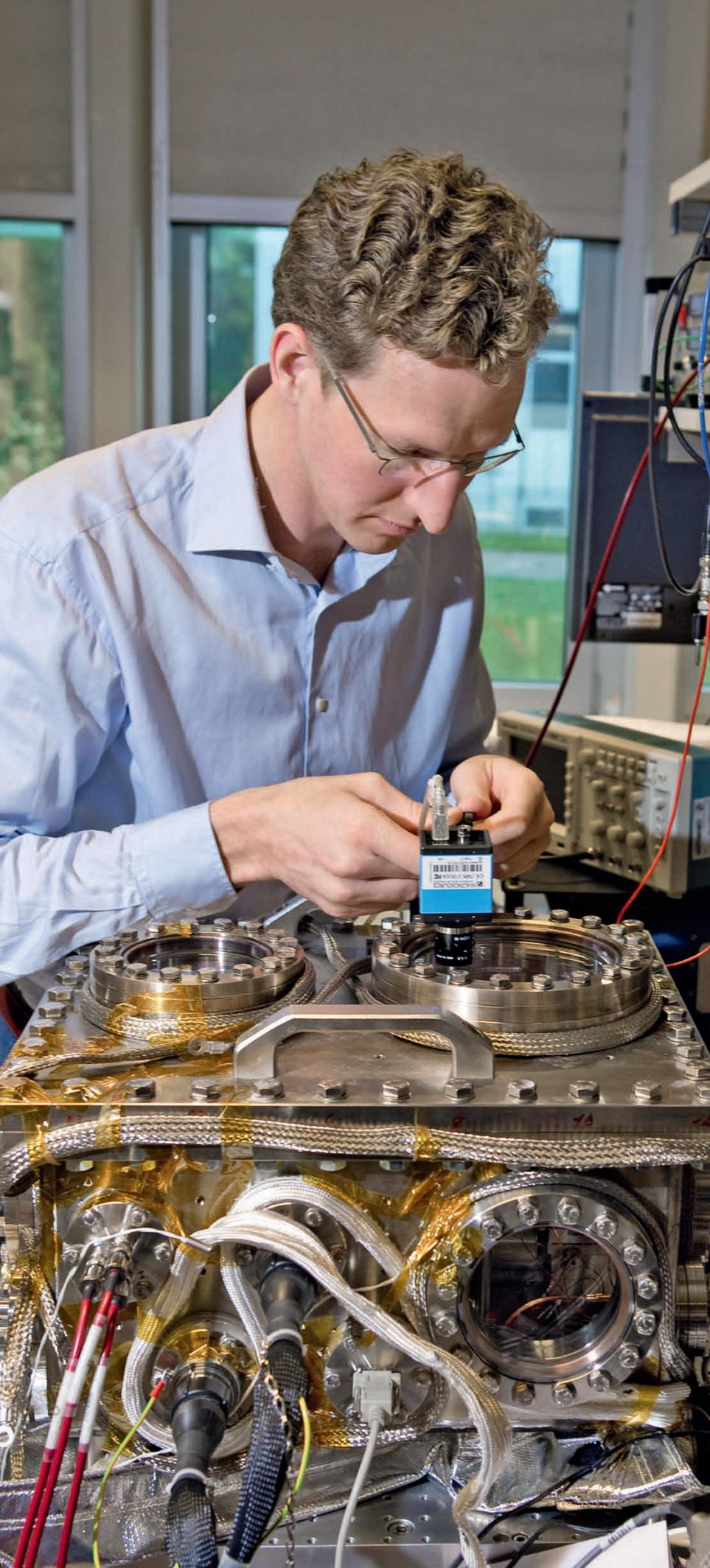
become a super-player – I guess I simply started too late for that," says Hommelhoff today, and grins.

Heidelberg brought changes in terms of school, too. At home in Bielefeld, Hommelhoff would have taken advanced Latin and Greek without a second thought – two clear, well structured languages with logical grammar. In Baden, however, the Greek course was no longer quite so enjoyable, so he chose another subject with a language that is just as clearly structured and logical: physics.

He found the science interesting, even fascinating, but found other subjects to be intriguing, as well. Peter Hommelhoff had no idea what he ought to study. Luckily he had to do his military service after finishing his college entrance exams. Hommelhoff went into the navy, serving on the frigate "Emden" – despite being 2.03 meters tall. He worked as a navigator there, due to his aptitude for math and physics.

Near the end of his service, the private was forced to use his remaining vacation days. He flew to Mallorca for a

Today, Peter Hommelhoff is more likely to aim a laser at electrons than a ball at a basket.



week, where he spent his time cycling and thinking. Afterwards, Peter Hommelhoff was none the wiser. Nevertheless, he somehow decided to study physics. “Ultimately, I guess it was a conscious decision, but in any case, it was most certainly the right decision,” he says in retrospect.

THERE WERE NO DISTRACTIONS FROM STUDYING BEFORE GAMES

Peter Hommelhoff wanted to get out of small, lovely Heidelberg to study. He moved to Berlin. He was also moving up in terms of sports. OBC Wolmirstedt, a basketball club near Magdeburg, approached the physics student and offered him a spot in the regional league – the fourth highest German division at the time. Due to his height, Hommelhoff played center. He was something like a sweeper under the basket; he had to be assertive and demonstrate his physical strength. “Of course I would much rather have been dribbling and driving the ball forward,” says Hommelhoff. “But if you want to play, you do what the coach says.”

Every Friday, the student drove to Magdeburg, where he spent the night in an empty apartment that the club’s president had arranged for his son – just in case junior should one day study in Magdeburg. Saturday mornings, Hommelhoff studied for his courses, and afternoons, he played in the regional league in front of as many as 500 spectators. “I was always able to

Peter Hommelhoff positions a camera over a window in the vacuum chamber to observe the electrons that a laser catapults from a nanotip. A shiny metallic heating cable is wrapped around the chamber. The cables serve to control the experiment and supply electricity to, among other things, an electron spectrometer.

» Over lunch, the physicists speculated about what would happen if they were to fire a laser at Hommelhoff's extremely sharp electron sources. No sooner was the idea discussed than they had put it into action.

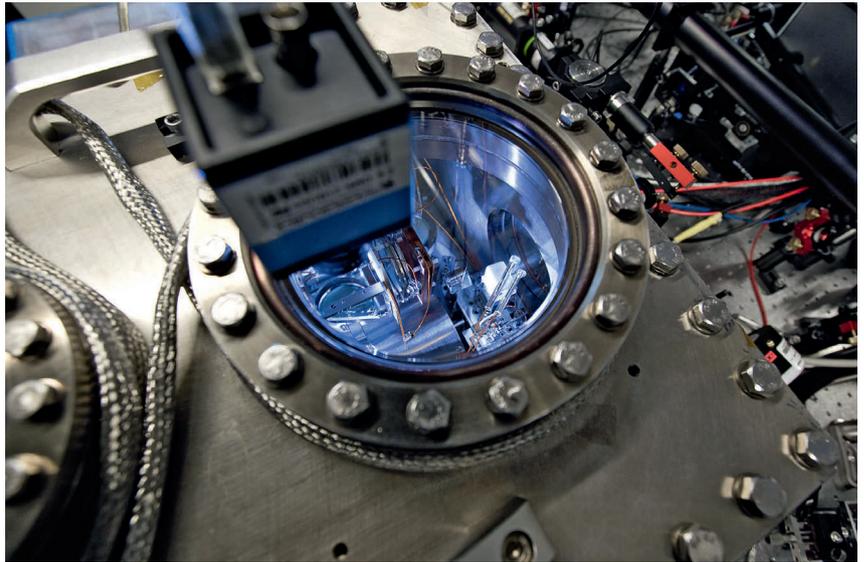
do my best studying before games, because there were no distractions there," he recalls.

But the idyll came to an end after his intermediate exams. Students at Berlin's universities went on strike, and Peter Hommelhoff wanted to leave – preferably to the US, basketball's promised land, as he says. However, a year abroad in a completely different academic system would conflict with the goal of finishing his studies as quickly as possible. Instead, Hommelhoff went to Zurich, to the Swiss Federal Institute of Technology (ETH).

There, the young German focused on particle physics. The collision of electrons and protons at high energies became the topic of his thesis. He played basketball on the ETH team and won the bronze medal in the Swiss university basketball championships in 1999. The gold medal went to – of all people – friends from the University of Zurich who always practiced with the ETH players.

What made a much stronger impression, though, was a lecture that a fellow student told Hommelhoff about shortly before his final exams: a German quantum optics researcher had announced his participation in the central physics colloquium of the two faculties in Zurich, where he would report on his work. His name: Theodor Hänsch. He was no stranger to Peter Hommelhoff, who had already previously noticed the professor's articles in physics journals.

Surprisingly few students found their way into the auditorium – among them Hommelhoff and his two friends: "At the very end, Hänsch looked over toward us three dolts and said something like: By the way, my group is looking for doctoral students."



A glimpse of one source of individual electrons. Through the porthole of the vacuum chamber, the tungsten tip is recognizable as a fine, bright line. The researchers use the camera mounted on top to register the spatial distribution of the electrons.

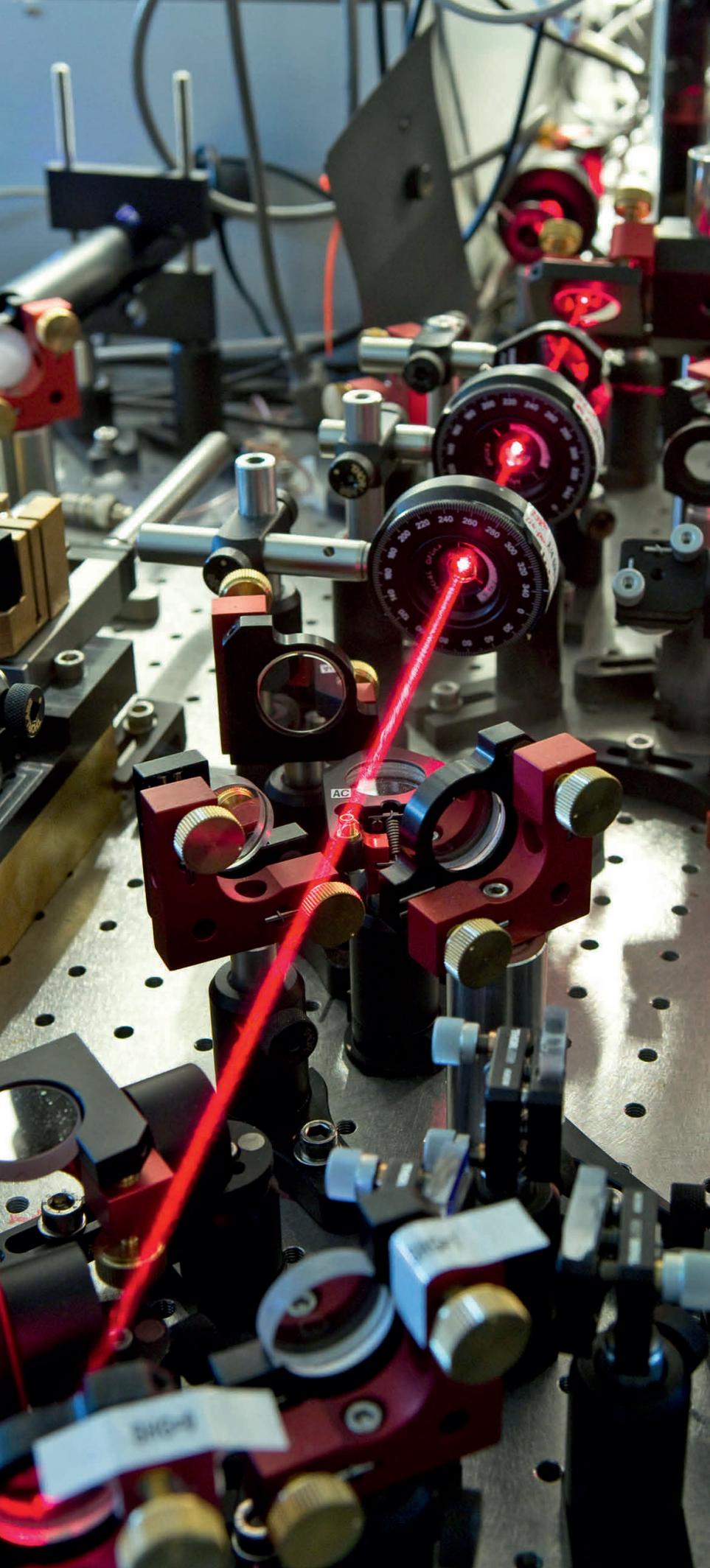
The two spoke briefly, Hänsch scribbled his e-mail address in Hommelhoff's little notebook, and a couple of weeks later, the newly graduated physicist began working in Munich – although he had never taken a single optics course during his studies, with the exception of one required lecture in quantum electronics. "I simply found Theodor Hänsch's lecture extremely interesting, and he really got me excited about the topic," Peter Hommelhoff recalls. The physicist turned down other Ph.D. offers, including one from Hamburg and one from Zurich. "It was the right decision," he says today. Quantum optics had Peter Hommelhoff firmly in its clutches.

As a scientist, he was moving onward and upward, but as a basketball player, he had to step back. He played – mostly for fun – in the second team

of München Baskets, a small club in Upper Bavaria. But Peter Hommelhoff was still dreaming of the US. In 2003, after completing his doctorate summa cum laude under Theodor Hänsch, he realized his dream. "It had to happen sooner or later," he says with a laugh.

THE GOAL: A WAVEGUIDE FOR SLOW ELECTRONS

Next stop: Stanford, California. Hommelhoff wasn't up to snuff for the university team there – where professional NBA stars are born – if only because, as a postgraduate student, he was now much too old. But even without a regular team, there was always a group ready to play a pick-up game. "For four years there, I played everything I enjoyed playing, and most certainly not just center," he says. >



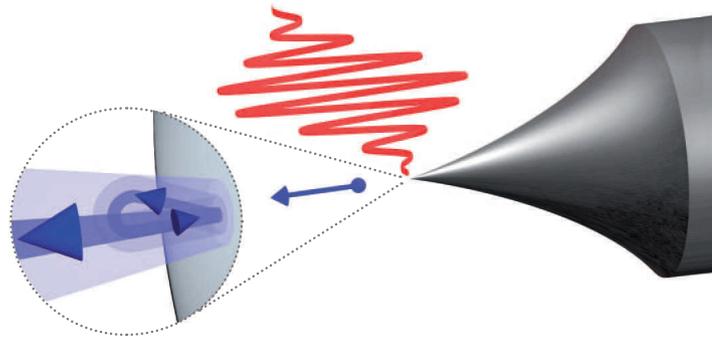
In his research, on the other hand, Hommelhoff stayed true to the tiny particles. He wanted to design a waveguide for slow electrons, but to do this, he first had to build a punctiform source for his elementary particles. Peter Hommelhoff experimented with extremely resistant tungsten wires, electrochemically etching them to make them sharp. This resulted in tips comprising just a couple dozen tungsten atoms. By coating them with palladium, they can even end in a single atom – an ideal electron dispenser.

FIRING A LASER AT AN EXTREMELY SHARP ELECTRON SOURCE

Four months later, Hommelhoff and his wires got company. An additional postdoctoral student moved into the lab and built his experiment at the other end of the four-meter-long optical table. He was experimenting with femto-second lasers, as they are called – light sources whose individual pulses are a few trillionths of a second long. Over lunch, the two physicists speculated what would likely happen if they were to fire such a laser at Hommelhoff's extremely sharp electron sources.

No sooner was the idea discussed than they had put it into action. "It immediately became interesting and, ultimately, opened up an entirely new field of research," recalls Peter Hommelhoff.

In laser light, the tips act much like a lightning rod, whose sharp, skyward-pointing piece of metal focuses the electric field lines, ensuring that the lightning hits precisely at that location. The tungsten tips likewise bundle a field: that of the laser light. They do



left page: Peter Hommelhoff and his team guide the red laser so precisely that they can determine when wave peaks and valleys of the pulses strike their sharp tip. In this way, they control the movement of the electrons.

above: Sketch of a tip experiment: The red laser pulse is directed precisely at the tungsten tip, where it knocks out an electron (blue arrow), which is first accelerated away from the tip by the oscillating electromagnetic field of the light, and then back to the tip before it is finally flung off.

below: Peter Hommelhoff and Michael Krüger calibrate the optical instruments of the laser assembly.

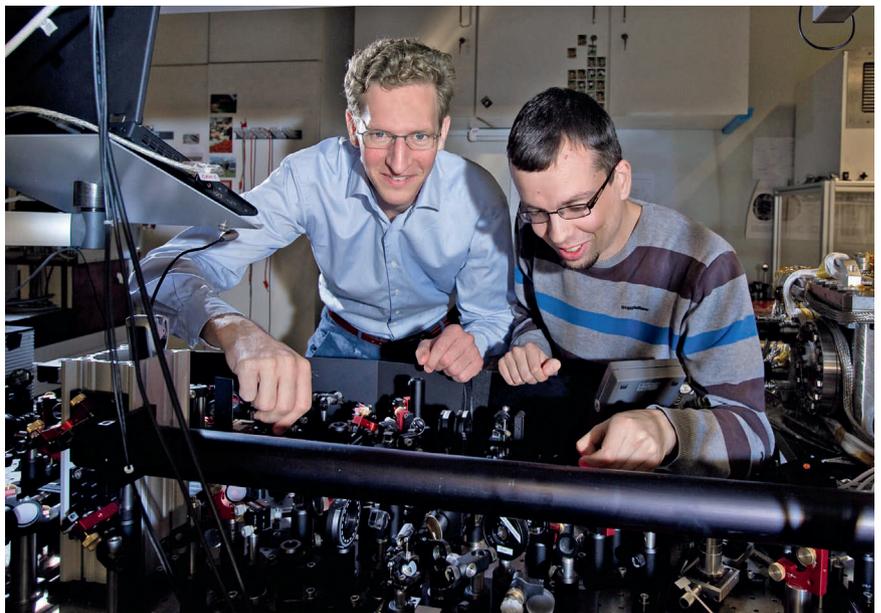
this so effectively that the laser can drive electrons out of the metal.

Since light is a wave that oscillates up and down with a high frequency, the particles that are released are treated much like a leaf at sea: first they are lifted up and expedited away from the tip, but the next half-wave drives the electrons back again. They sink and plonk down on the metal. "It's almost as if one were throwing a ball against the wall," says Peter Hommelhoff.

Like a rubber ball, the particles bounce off the tungsten tip and are hit by the laser light again. Its wave has since turned down once more, so the particles are accelerated again and now fly off for good. "This allows us to use the laser to control the emission of electrons – and to do so on an extremely fast time scale," says the Max Planck researcher.

In Hommelhoff's lab, the light required for this is produced by a titanium-sapphire laser. Its waves, which are emitted in the near infrared, oscillate up and down around 350 trillion times per second. That means every wave is about three femtoseconds long, or just three quadrillionths of a second. In addition, the laser is pulsed – that is, it is always turned on for only almost seven quadrillionths of a second and then stops again for a short time. Thus, about two light waves fit in each pulse.

This has consequences for the game with the electrons: depending when the



laser is turned on, the maximum of the light wave may lie exactly in the middle of the pulse. Then there is hardly any room for additional waves. However, it can also happen that two wave peaks are distributed at the beginning and the end of the pulse. In the first case, all electrons are knocked out at the same time, while in the second case, the physicist can observe electron pairs that are released in quick succession.

Actually, "observe" is an exaggeration: the processes are so quick and take place in such a small space that there

isn't a microscope in the world with which they can be observed directly. Instead, Hommelhoff registers the energy distribution of the released electrons that land on a detector.

ON THE WAY TO THE WORLD'S FASTEST SWITCH

This reveals interesting phenomena. In their very own quantum world, elementary particles don't just behave like tiny basketballs, they also have the characteristics of a wave. As soon as two

electrons are knocked free, their waves can overlap and partially cancel each other out. The detector displays a stripe pattern that physicists call interference. In his experiments, Hommelhoff even managed to systematically change the appearance of this interference pattern – by specifying exactly where the individual light waves occur within the larger laser pulse.

This fine-tuning became possible due to a device known as a frequency comb. Theodor Hänsch, Hommelhoff's doctoral adviser, developed it and received the Physics Nobel Prize for it in 2005. "The frequency comb is very powerful technology, and we expect to see additional revolutionary applications," says Peter Hommelhoff. After all, it shouldn't be restricted to interference patterns on detectors. Among oth-

er things, the physicist is currently working on making electrons fly from a tungsten tip to another electrode using systematically manipulated laser pulses. If he succeeds, it would be possible to switch an electrical current on and off with light alone. It would be the world's fastest switch.

HOW CAN ELECTRON MOVEMENT BE MANIPULATED?

Hommelhoff's away game in California took four years, and then his home town called. The physicist applied to lead a Max Planck research group, got the job, and once again had to choose – this time between Berlin and Munich: the Fritz Haber Institute or the Max Planck Institute of Quantum Optics? "The folks in Berlin had a lot to offer," recalls Peter

Hommelhoff. They got points for a lab in a villa in Dahlem, for a new air conditioning system, which is crucial for his experiments, for parquet floors – and for the prospect of becoming quite a star in a few years as the only quantum optics researcher at the institute. In Garching, in contrast, he risked being outshone by a newly minted Nobel laureate in the field of quantum optics, and by renowned research groups who were also doing research in this field.

Nevertheless, Peter Hommelhoff chose the Max Planck Institute of Quantum Optics. "I wanted the certainty of an institute where there were already many lasers and a lot of know-how available," he says today.

But the certainty is illusory. Hommelhoff had to start from scratch in Garching, too. The time needed to set up his new lab dragged on. It took one and a half years just to get the air conditioning up and running. A high-precision laser can't be operated without clean air with a constant temperature. But the AC company that was specially hired for the project failed to get the job done. "It was an absolute nightmare," says Peter Hommelhoff.

Today, four years later, everything is working. The research group now has ten members, and the conditions, according to Hommelhoff, are "brilliant." Additional experiments have been added to those to knock the electrons free, including the waveguide, the idea for which originally set the whole ball in motion back in Stanford.

The experiments are always about systematically manipulating the movement of electrons. Nevertheless, Hommelhoff still doesn't want to see that as the dominating question behind his work. "In basic research, it is unrealistic to set a goal and then try to achieve it at all costs," he says. Rather, the physicist advocates research driven by curiosity – without, however, allowing it to become arbitrary: "Instead of one big question, let us rather be guided by success and failure, follow paths that look interesting, turn off to go down others, and

Playing field for physicists: Jakob Hammer (left) tests the assembly for nanolenses in a vacuum chamber, Johannes Hoffrogge (center) operates the waveguide for electrons, and John Breuer (right) attempts to detect laser-accelerated electrons. In the background: Robert Davies.

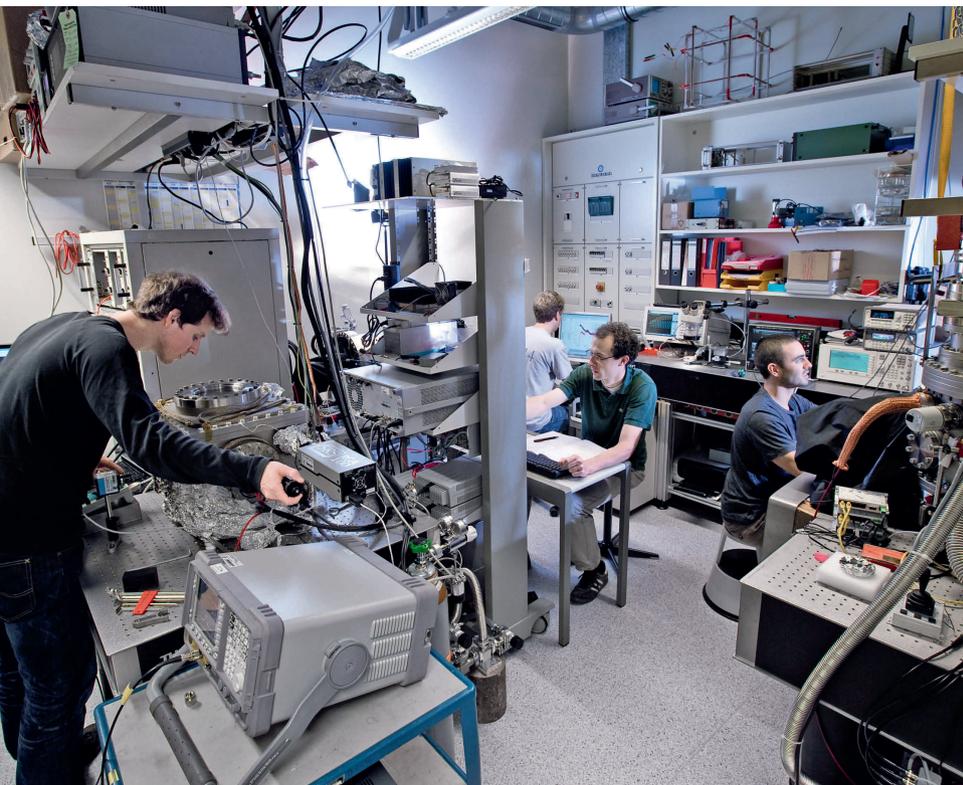
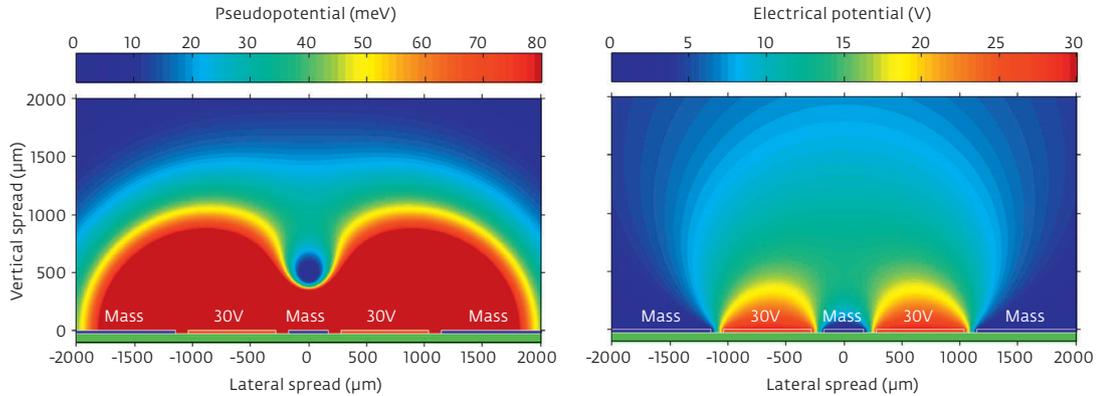


Photo: Denise Vernillo



A channel for electrons that leads out of the image plane is created in the intense blue spot of the pseudopotential (left). It is produced by an alternating electric field (right), depicted here as a snapshot.

then sometimes follow a detour and come back to the original problem.”

The latest experiment of the group in Garching, for example, involves using lasers to accelerate electrons. To date, electrical fields are used for this, for instance in a synchrotron ring or a free-electron laser, which produce a very intense, brilliant light with accelerated electrons. Using light to cause acceleration isn't actually possible: like the leaf on the billowing sea, the charged particles, too, are merely tossed about by the alternating field of a light wave.

Hommelhoff and his team hope to change this using a clever trick: The physicists procured a discarded electron microscope and sent its beam across a glass plate at a short distance above it. In the glass, they had previously etched tiny grooves running vertical to the direction of the electrons' flight, and measuring just a few hundred nanometers – one nanometer is one millionth of a millimeter – wide and deep.

TECHNOLOGY FOR IMPROVED ELECTRON ACCELERATORS

While the electrons dart across the plate, the researchers send laser light through their glass construct from below. Since the speed of light in glass is somewhat less than in a vacuum, the wave is disrupted above the grooved plate: an electron making its way across

the plate is initially accelerated over the gap in the grating. Over the next groove, however, it isn't slowed down again, but rather likewise accelerated by the delayed wave front. In this way, it continuously gains energy. “We essentially adjust the spacing and the width of the grooves to the speed of the electrons and the laser wavelength so that the electron always sees only the accelerating component of the field,” says Peter Hommelhoff.

It should, theoretically, be possible to achieve, already in the first configuration, the same performance as in a conventional particle accelerator. Later,

so they hope, this technology should make much smaller and more efficient accelerators possible. The experiment is already set to go in the institute in Garching, but the first targeted shots have yet to be fired.

“To achieve an effect, the electrons have to pass over the glass at a distance of one hundred nanometers. That is very demanding,” says Peter Hommelhoff. Demanding, but doable. The 37-year-old has hardly managed to play any basketball recently – but to play in the quantum arena, he still has to have a good aim and a very special knack for handling a ball. ◀

GLOSSARY

Frequency comb: An optical instrument whose core consists of a femtosecond laser that emits light in extremely short, regular pulses. According to a relationship discovered by French mathematician and physicist Joseph Fourier, the regular sequence of the pulses is reflected in the frequency spectrum of the light. It is, namely, no longer continuous, but rather, like the teeth of a comb, exhibits very sharp lines with fixed spacing. Theodor W. Hänsch found a way to precisely determine the position of a frequency line of the comb and thus the position of all lines, creating an extremely precise measuring instrument for optical frequencies.

Quantum optics: Deals with the interaction of light and matter, focusing on their quantum properties. Among these is wave-particle dualism, according to which light is considered to be not only a wave but also a particle (photon). The particle properties are noticeable, for instance, when electrons are knocked out of a fine metal tip. However, when they are subsequently accelerated back to the tip and then away again, they take on the wave characteristics of light.

Waveguide: A medium in which waves, especially electromagnetic waves, systematically propagate in one direction. A waveguide for electrons differs from an electrical conductor such as a metal wire in that the electrons in it are guided through a vacuum using electrical fields, and display their wave properties. Physicists have not yet succeeded in observing the latter.