hoch³ FORSCHEN

SCIENCE QUARTERLY

Summer 2018

TECHNISCHE UNIVERSITÄT DARMSTADT

Imprint

Publisher
President of TU Darmstadt,
Karolinenplatz 5,
64289 Darmstadt,
Germany

Editor
Corporate Communication
Jörg Feuck (Editor-in-chief)
Ulrike Albrecht (Graphic Design)
Patrick Bal (Images)

Conceptual design
conclouso GmbH & Co. KG, Mainz,
Germany

Photography (title)
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Circulation
6.000

Next issue
15th of September 2018

Service for readers
presse@pvw.tu-darmstadt.de

Newsletter subscription
www.tu-darmstadt.de/newsletter

ISSN
2196-1506

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From atomic nuclei to stars

Physics professor Achim Schwenk and his team at the Institute for Nuclear Physics at the TU Darmstadt examine the forces at the heart of atomic nuclei. This helps to improve our understanding of astrophysical objects.

By Uta Neubauer

Neutron stars are objects at the extremes. Measuring about 20 km in diameter, they are just about as large as a city the size of Darmstadt, but their mass is remarkable: a scoop out of a neutron star the size of a sugar cube would weigh about a hundred million tonnes on earth. "Basically, they're densely packed atomic nuclei," explains Achim Schwenk, theoretical nuclear physicist and professor at the TU Darmstadt.

Atoms are the building blocks of all matter on earth, and the defining structure of elements. They consist of a tiny nucleus that contains neutrons and protons and a voluminous shell of electrons. The mass of the atom almost entirely comes from the nucleus; the shell weighs virtually nothing. Normal stars are also made up of atoms. When they explode at the end of their life span, depending on the star's mass, a compact neutron star can form. The negatively charged electrons are then pressed into the atomic nuclei during the star's supernova explosion, where they combine with the positively charged protons to make neutrons. What remains is soup of atomic nuclei, that consists of 95% neutrons.

"We are particularly interested in exotic nuclei with a large neutron excess."

Astronomers have now tracked around 2000 neutron stars. "They are so small that they can only be detected, for example, with radio telescopes by their electromagnetic radiation," explains Schwenk. So measuring neutron star radii is something of a challenge, which is where the theoretical nuclear physicists come in. Schwenk and his team are not astronomers, but their findings on the interactions among neutrons in atom nuclei can be transferred to the macrocosm. "We are particularly interested in exotic nuclei with a large excess of neutrons," he adds. And the forces that act there also keep neutron stars in shape.

The number of neutrons of a chemical element is – unlike its number of protons – variable. Carbon, for instance, can contain between two and 16 neutrons, although almost 99 percent of the carbon atoms that occur on Earth contain six neutrons. We know that iron has 30 and lead 40 variants with different numbers of neutrons. However, most of these so-called isotopes are unstable, and decay radioactively. Until ten years ago, physicists could only calculate the energy, and thus the stability, of nuclei if they contained a maximum of 12 particles. Calculations ended at carbon, which has six protons and six neutrons. But then new calculational methods coupled with improved computer power, plus an novel understanding of nuclear forces, gave this research field a big boost, explains Schwenk. Recently, an international collaboration that included theorists from Darmstadt managed for the first time to precisely calculate an atomic nucleus of 100 particles, tin-100, element 50 in the periodic table of a total of 118 chemical elements.

Unlike chemists, nuclear physicists are interested in the nuclear chart, which presents all the known isotopes graphically, rather than the periodic table. "Around 3000 isotopes have already been discovered," explains Schwenk. "There are about 20 new ones every year, and about 4000 are still unknown." In the region of extreme neutron-rich isotopes there are vast areas that haven't been explored in the nuclear chart. The problem: these unstable nuclei are only created under extreme conditions in the Universe or with tremendous efforts in the laboratory.

The results of the artificial isotope synthesis are highly revealing for theoretical nuclear physicists like Schwenk: "We can use our colleagues' measurements to check that we have understood the interaction between neutrons correctly, and whether we

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Photo: Katrin Binner

Moving into the world of quarks and gluons: Professor Achim Schwenk.

can use them to predict matter in astrophysics." Only recently, an international consortium, which included the Darmstadt nuclear physicists, published a study on neutron-rich chrome isotopes. Their production succeeded with a particle accelerator from the large research facility CERN near Geneva. The experimenters fired a proton beam at a uranium target. The fission products included neutron-rich chrome isotopes, the mass of which could then be determined more precisely than ever before. Schwenk emphasises that the method is so precise that it could be used to extrapolate the weight of a paper clip on a jumbo jet. Einstein's formula $E=mc^2$ can then be applied to calculate from the mass m the energy E that binds the neutrons and protons in the core. The Darmstadt scientists had predicted this binding energy, which is closely related to the stability. A similar theoretical-experimental investigation into neutron-rich titanium isotopes was carried out by an international team in collaboration with Schwenk's team in February.

In response to the question of whether experiment and theory matched up, Schwenk replied: "This still depends one where we are in the nuclear chart, which is what makes it so exciting." It worked well with titanium. The isotopes examined here contained between 29 and 33 neutrons and 22 protons. Nuclei with this number of particles are almost spherical. With other elements, a deformation of the nucleus – for instance from the shape of a football to that of a rugby ball – has to be considered more strongly.

Furthermore, we do not yet understand nuclear forces well enough, adds Schwenk. "Our calculations have a theoretical uncertainty that is like the uncertainty in an experiment." There is another reason why the Darmstadt physicists won't be suffering from a lack of work in the foreseeable future: "So far, we've only talked about neutrons and protons. However, for the fundamental understanding of nuclear structure, we want to go down another level." In other words, into the world of quarks and gluons. Quarks are the elementary particles from which protons and neutrons are made. Gluons (based on the word "to glue") are what keeps them together into neutrons, protons, and other particles.

Not only in the vast expanse of the Universe, but in the world of the tiniest particles, there is still much to discover. With the theoretical physicists in Darmstadt, both are starting to come together.

The author is a science journalist with a doctorate in chemistry.

Award-winning nuclear physics

Achim Schwenk has been on the faculty at the TU Darmstadt since 2009. The European Research Council (ERC) awarded him an ERC Starting Grant in 2012, "The strong interaction at neutron-rich extremes", with a total award of 1.5 million euros.

Schwenk is also Max Planck Fellow at the Max Planck Institute for Nuclear Physics in Heidelberg since 2015 and spokesperson for the Collaborative Research Centre SFB 1245 "Nuclei: From fundamental interactions to structure and stars". In 13 SFB projects, scientists at the TU Darmstadt explore the interactions and phenomena in the interior of atomic nuclei and stars. Experiments at the S-DALINAC accelerator of the TU Darmstadt and at major international research facilities complement the theoretical investigations.

Schwenk and his colleagues eagerly await the completion of FAIR at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt. At FAIR, matter will be produced that only occurs in the Universe, including exotic neutron-rich nuclei.

Current publications:

Maxime Mougeot et al., Phys. Rev. Lett., June 2018, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.120.232501.

Erich Leistenschneider et al., Phys. Rev. Lett., February 2018, https://doi.org/10.1103/PhysRevLett.120.062503

Using Artificial Intelligence to fight hunger

A team under IT professor Kristian Kersting is using machine learning methods to improve conditions in feeding the world.


Photo: Katrin Binner

Professor Kristian Kersting (left) with his research associate Patrick Schramowski.

By Boris Hänßler

Almost 800 million people in the world are suffering from chronic malnutrition, and this figure looks set to grow in the future. According to a report issued by the United Nations, by 2050 there should be in the region of 9.7 billion people on the planet, some 2.2 billion more than there are today. The world nutrition organisation FAO estimates that global demand for food will have increased by 70 percent by then, as every single person is also expected to be eating more meat and dairy products. By the same token, more crop areas will be required for biological fuels, and the continuing climate change will cause more and more infertile ground. So how on earth, literally, are future generations going to feed themselves in the light of these changes?

Kristian Kersting, Professor of Machine Learning, and his team believe one possible solution lies in the use of Artificial Intelligence (AI) – the very technology that science fiction likes to portray as being the cause of the planet's destruction. In reality, it is almost impossible to imagine numerous areas such as banks, insurance companies and e-commerce without AI. Professor Kersting has recognised that machine learning, a special process in AI, could be used to help advance agriculture – as the base for what is known as precision farming, which could realise greater yields on growing areas of the same size or smaller.

"However, in our project we first want to understand what physiological processes occur in plants when they experience stress," says Kersting, who is also a part of the Centre for Cognitive Science at the TU Darmstadt. "Stress occurs, for instance, when plants don't get enough water or are infected by pathogens." So in fact, the idea of using AI to analyse these problems isn't actually that far-fetched: it has already been used in agriculture for many years to obtain lots of data in greenhouses and fields – and the more data

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is available, the better machine learning often works. The more details the software has on the physiological processes of a plant during the entire growth cycle, the more readily the software is able to find recurring patterns in it that are responsible for stress.

But then again, it's not quite that easy to apply AI technology to agriculture. "Too much data can also be a problem," says Kersting. "You can have a terabyte in no time, which makes the calculations too time-consuming. So we need algorithms that use only a part of the data for learning with no difference in precision." Plant physiologists fear that otherwise, certain signals that are important for understanding stress in plants could be missed. Which is why Kersting believes it is even more important that the matter be approached in an interdisciplinary manner. He has found two perfect partners for his project, which is being supported by the Federal Ministry for Agriculture and Food: the Institute of Crop Science and Resource Conservation (INRES) of the University of Bonn, and the Aachen company Lemnatec, which makes conveyor belt systems for greenhouses and is greatly interested in using them for automatic plant analyses.

"Ultimately, what we want is a worthwhile partnership between human and artificial intelligence in order to overcome the growing problems of feeding the world."

Working together, the team has managed to find a solution that fulfils every requirement. They installed a hyperspectral camera that records a broad wave spectrum, providing deep insights into the plants. Kersting's team also had another clever idea for the evaluation of this data: they adopted a highly advanced learning method from language processing that is already widely used for commercial purposes. Examples include digital assistants and Internet searches. Google News also uses machine learning such as deep learning: from the tens of thousands of new articles that appear every day, AI selects the ones that are most relevant and organises them by subject. This is achieved with the aid of probability models, in which all the words in a text are allocated to a specific topic. The software learns from the word allocation how to organise the articles by topic.

Kersting's trick was to treat the hyperspectral images from the camera like the words in an article. To be precise, the software organises specific image samples to a "topic", such as a particular stress state experienced by a plant. Kersting's team is currently working on making the software learn to optimise itself so it finds patterns that represent susceptibilities, and thus stress, particularly quickly. "A healthy point can be identified, for instance, by the chlorophyll content in the plant's growth process," explains Kersting. "If, however, an ageing or dehydration process occurs, then the measured spectrum changes significantly. The benefit of machine learning is that is can recognise these signs much sooner than a human expert – the software learns to look out for more subtleties." Kersting has been able to banish the plant experts' concern that it could overlook something important. His team has checked current publications on stress processes in plants, and was able to reproduce results that are known to use from literature.

Later on, the idea is to combine cameras and conveyors in a greenhouses so that the system can monitor the processes of every single plant. "With this real-time analysis, it can inform the plant experts if, for instance, it found something new last night that is worth having a look at," says Kersting. "The expert can then confirm or refute this, which also teaches the machine." By this means, the system should not only learn to identify known processes more quickly, but also, for instance, to identify unknown pathogens independently in future. Machine learning is an important tool in breeding new resistant plants and also for using pesticides more quickly in acute cases, enabling the agricultural industry to save more plants and at the same time place less stress on the environment. Professors Kersting and his researchers have already been able to confirm that their analyses work in the field as well as in the laboratory.

It should also be possible to transfer the process to a range of plant species. Kersting: "Although cell structures differ, the physiological characteristics are presumably similar, so the technique could easily also learn the patterns of other plant species." Furthermore, in future the researchers plan to combine data from their sensor technology with data for gene expressions, which would be another important step for agriculture in researching resilient and high-yielding plants. "Ultimately, what we want is a worthwhile partnership between human and artificial intelligence in order to overcome the growing problems of feeding the world," summarises Professor Kersting.

The author is a technology journalist.

Publications

Matheus Thomas Kuska, Anna Brugger, Stefan Thomas, Mirwaes Wahabzada, Kristian Kersting, Erich-Christian Oerke, Ulrike Steiner, Anne-Katrin Mahlein (2017):
Spectral patterns reveal early resistance reactions of barley against Blumeria graminis f. sp. hordei.
Phytopathology 107(11):1388-1398.

Mirwaes Wahabzada, Anne-Katrin Mahlein, Christian Bauckhage, Ulrike Steiner, Erich-Christian Oerke, Kristian Kersting (2016):
Plant phenotyping using probabilistic topic models: uncovering the hyperspectral language of plants. Scientific Reports (Nature) 6.

Water for everyone

Solving problems in an interdisciplinary and humanitarian manner: TU Darmstadt and the German Aerospace Centre are developing a sustainable system for supplying water to slum areas that is based on satellite data.

By Jutta Witte

The first charts that Professor Peter Pelz, Lea Rausch and John Friesen project onto the wall speak for themselves: satellite data of the Indian city of Mumbai show the rapid growth of the megacity in form of small dots that are further condensing from slide to slide. The population of 5.9 million in 1971 has now grown to 12.5 million, and according to current estimates, 55 percent of the people live in slums. In most developing countries in Asia, South America and Africa, these „informal settlement“ are firm fixtures in the city, but almost impossible to document in precise figures.

The three scientists from the Institute for Fluid Systems (FST) is working with computer scientists from the TU Darmstadt and geographers from the German Aerospace Centre (DLR) to research slums and how they develop in megacities. They want to optimise water supplies to these „urban poor“ and support the targeted development of infrastructures in slums. „In doing so, we want to contribute towards achieving the development goals that the United Nations have set for 2030,“ explains Professor Pelz, who is the head of the FST. The dynamic with which megacities and their slums are developing is a tremendous stress on their infrastructures. In particular, the lack of clean water supply causes a multitude of problems – diseases, high infant mortality and a lack of time for education and work, because the procurement of water binds a lot of capacities.

“Algorithms plan infrastructures, that’s a new approach.”

In order to break this vicious circle the scientists are working on a supply system that is scalable and adapted to the specific local conditions. “We don’t need a fine-grained, but a broad-based model,” explains Friesen. The focus is therefore on the search for general patterns that apply to every megacity. Satellite data from the DLR provides the basis for this. “With regard to global poverty in cities, there are still major gaps in our knowledge,” reports DLR scientist Dr. Hannes Taubenböck. “Much is based on estimates.” Using remote sensing data, the team was able to determine the typical morphologies of slums. A highly dense and visibly unplanned development as well as small, low houses make these areas clearly distinguishable from formally planned areas on satellite images..

Because they discovered this typical “binary structure”, the DLR scientists are able to establish the proportion of poor people in cities far more precisely than is possible from, for instance, a census. “We came up with significantly higher figures than the official bodies,” says Taubenböck. A look at the structures of Dharavi slum in Mumbai quickly reveals the reality. On an area where 7000 people live in Darmstadt, there are 42000 residental units. The estimated population is somewhere between 500,000 and one million people.

Based on the DLR data, the research partners have now also investigated the size of slums. The examples of Cape Town, Rio de Janeiro, Mumbai and Manila confirm that although slums can vary greatly, they are all roughly the same size. Regardless of the city, country and continent or geographic, political and economic boundary conditions, most have an area equivalent to at least a half and a maximum of five football fields. “If slums are of a uniform size globally, we can develop a transferable, robust and efficient system that determines the optimum infrastructure for supplying water to every slum,” emphasises Peter Pelz.

The foundations for this system are provided by the classified satellite data of the DLR and a cost model into which flow factors such as the prognoses on slum growth established from data mining. This cost model is translated into a mathematical optimization model. Algorithms then calculate the supply system; not by searching for a global solution in a smart way. Due to the high complexity, people are no longer able to do that. “Algorithms become the planners of infrastructures,” explain Rausch, Pelz and Friesen. “It’s an entirely new approach,” confirms DLR expert Michael Wurm. People only define the constrains for the calculations. These are cost or later also buisness models, as well as already existing infrastructures.

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Their eyes on sustainable development goals: Professor Peter Pelz (right) and his research associate John Friesen.

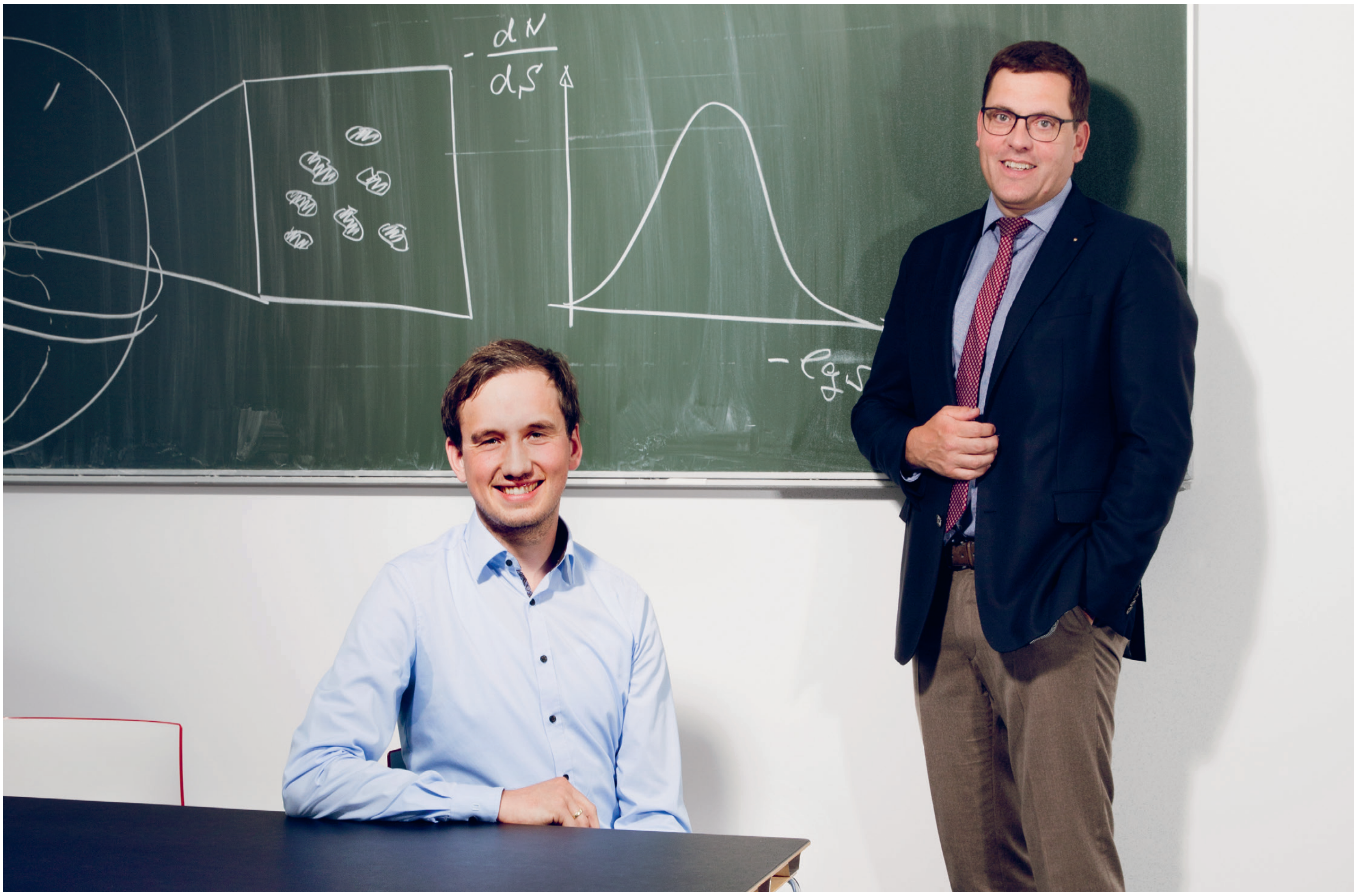

Photo: Katrin Binner

At the end a graphic is available visualizing the calculated network design with waterworks, various types of water tank, pipes or vehicles for water transportation. The scientists have already applied this method of "discrete optimisation" using a number of slums in Dhaka as examples. At the moment it still takes several hours for the calculations for smaller areas with about 20 slums. Clustering the slum data should reduce the number of variables in future, which would accelerate the process as metropolitan regions like Dhaka have far more than a thousand slums.

Meanwhile, the researchers at TU Darmstadt are also exploring the question of how slum actually arise. Using the Turing mechanism – a model by the British mathematician Alan Turing explaining the emergence of spontaneous structures – they found certain migration patterns. It revealed, amongst other things, that slums always develop when the population density becomes so large that the people of a specific group, in this case the poor, start to "diffuse" from an area. This confirms the experts' conviction that even basic mathematical methods can be used to explain social phenomena. Their aim is now to include other disciplines that address the subject of "Water for all". "This could be the nucleus for future collaborative research," emphasises Peter Pelz.

The author is a science journalist with a doctorate in history.

Cooperation:

The project „Structures and infrastructures in megacities" was launched early in 2017. Along with the Institute for Fluid Systems and the Knowledge Engineering Group of the TU Darmstadt, the team „Town and society" of the Earth Observation Center of the German Aerospace Center is also involved. The project is funded by the KSB-Stiftung.

Publications:

Habitat International: The similar size of slums.
https://doi.org/10.1016/j.habitatint.2018.02.002

Remote Sensing: A Holistic Concept to Design Optimal Water Supply Infrastructures for Informal Settlements Using Remote Sensing Data.
www.mdpi.com/2072-4292/10/2/216/

Further information online:

www.fst.tu-darmstadt.de/
www.dlr.de/eoc/desktopdefault.aspx/ tabid-5414/9543_read-18621/

An elevator for fish

The EU Water Framework Directive states that from 2027, rivers must be continuously passable to fish, from the mouth to the source. Professor Boris Lehmann is facilitating this passage in a very special way at the Weir Baldeney (Ruhr): in future, fish will be taking the elevator to the upper water.

By Claudia Staub

Often the upriver routes taken by fish are obstructed. „They can be made passable by the use of fish lift systems," explains Boris Lehmann, Professor of Hydraulic Engineering at the TU Darmstadt. Fish lifts are widely used including on the Ruhr, which contains many dams.

The starting situation at Lake Baldeney is a little tricky, though. The system consists of three weir fields, a lock, a disused pumping station and a power station with two turbines. The difference in height between the upper and lower water is 8.75 metres, and there is no room along the shores for a conventional fish lift. „Finally, an interdisciplinary group of experts brought in a fish lift to be installed in the former pumping station," said Lehmann. The problem: there are no standard solutions for these kinds of systems. Furthermore, the licensing authority has issued special rules for constructions that need to be built in a special way. For instance, it has to be proved in advance that the fish will be able to access and use the lift.

In order to provide this evidence, Boris Lehmann's team – initially still working at the Karlsruhe Institute for Technology (KIT) – designed an ethohydraulic investigation concept. Ecological and biological issues are linked with engineering calculations in order to achieve the optimum results. But how is it possible to know in advance which route the fish really will take? „The river flow is the most important criterion for the orientation of the fish," explains Lehmann.

Flow conditions can easily be simulated on a computer using hydrodynamic-numerical models. In particular, the team looked at all the relevant outflow and operating conditions of the barrage, especially when the power station's turbines were in operation. The simulations were calibrated using a wide range of data, measurements and observations made on site. The calculated flow conditions were then used to estimate the migratory corridors of the fish.

The findings of all the preliminary investigations culminated in a large-scale model of the fish lift that was constructed in the test channel of the hydraulic engineering laboratory at the KIT. Two lifts were positioned beside each other in order to ensure that the barrage could be swum through at all times, as required by the authority. While one lift is in operation, the fish can be guided into and collected in the other.

Their swimming in and out is initiated by the calculated guiding current that can be halted by means of regulating elements. Trials with fish resulted in extremely good functionality of the system – and the evidence of function was provided. „When the lift goes into operation," says Lehmann, „then during the spawning season thousands of fish can be transported into the upper water of the Ruhr."

The author is an editor in the Corporate Communications department of the TU Darmstadt.

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Project and partners

An ethohydraulic investigation concept was carried out for the Ruhr weir on Lake Baldeney by the Department of Hydraulic Engineering at the TU Darmstadt in order to provide proof of functionality of a fish lift system. The project partners are the Institute for Water and Water Body Development at the KIT, the company Hydroenergie Roth, the Office for Environmental Planning, Water Body Management and Fishing, and LFV Hydroakustik GmbH.

Photo: Katrin Binner

Professor Boris Lehmann and his team at the hydro-engineering laboratory of the TU Darmstadt. Its core competencies include the research, planning and optimisation of complex hydro-engineering installations.