DIFFER

ANNUAL REPORT
2017

WE ARE DIFFER. **SCIENCE FOR FUTURE ENERGY**

DIFFER

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Colophon

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Cover image	Visit of the external evaluation panel to DIFFER's new Artificial Leaf laboratory in August 2017. Left to right: DIFFER researchers Stefan Welzel, Mihalis Tsampas and Georgios Zafeiropoulos, and panel members Peter Styring and Heinz Frei

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Management team and head of HR

Henk Tamsma (head of HR) and MT members Wim Koppers, Marco de Baar and Richard van de Sanden

FROM THE DIRECTOR

It is a great pleasure to present the annual report 2017 of DIFFER, the Dutch Institute for Fundamental Energy Research. When you browse these pages, I hope you get the same sense of excitement as I do looking back on our institute's accomplishments.

In this second full year in our new institute building on the TU/e Science Park, DIFFER's researchers, technicians and support staff have many achievements to be proud of. The enormous pace in which our main experimental facility Magnum-PSI has grown into the world's premiere facility to test wall materials for future fusion reactors, is truly amazing. There was a lot of activity in the four permanent laboratories for solar fuels that were delivered this year. In addition, there were top notch scientific publications, three of our researchers won a highly competitive NWO personal grant, and we organized multiple events to set up international programs with partners from science and industry. I am sure the other highlights presented in this annual report offer something for everyone interested in fundamental research towards sustainable energy technologies.

During 2017, a great deal of effort went into preparing the external evaluation of the institute by an international expert panel in October. It was the ideal moment to reflect on the transition that the institute has gone through since being founded in 2012. Presenting the many achievements of our staff during this challenging period to our evaluation panel was a pleasure. In turn it is gratifying to receive the panel's glowing assessment of DIFFER's past achievements and their strong endorsement of our future plans. The NWO executive board has expressed their full support for DIFFER's new and expanded mission.

"I hope you get the same sense of excitement as I do looking back on our institute's accomplishments."

What will the future bring? In addition to providing valuable insights in Solar Fuels and Fusion Energy, we aim to apply our cross-cutting, multidisciplinary approach in an exploratory program on other technologies for sustainable energy storage and power generation. The newly set-up Ion Beam Facility and the tCenter for Computational Energy Research (with TU/e) bring together the expertise to study materials and processes in active energy devices on a variety of length and time scales. This will generate insights valuable for a wide array of energy technologies.

DIFFER's leading position in Dutch energy research is matched by our strong ties to (inter)national research collaborations and agendas. As NWO's premier strategic instrument on energy research, DIFFER will continue to connect the various disciplines and actors in energy research and build a cohesive community for fundamental energy research.

I am convinced that DIFFER is in an excellent position to make a substantial difference in energy research. The interviews with ambitious researchers in this report speak for themselves. I wish you pleasant reading.

Richard van de Sanden, director
Eindhoven, March 2018

ABOUT **DIFFER**

DIFFER is the Dutch Institute for Fundamental Energy Research, with the mission to perform leading fundamental research on materials, processes and systems for a global sustainable energy infrastructure, in close partnership with (inter)national academia and industry.

SCIENCE FOR FUTURE ENERGY

Climate change and rising energy demand require humankind to transform its current fossil-dominated infrastructure into a fully sustainable system by the end of the century. Scientific research plays a key role in developing the solutions to this grand societal challenge. As national institute for fundamental energy research, DIFFER seeks to build the interdisciplinary networks capable of solving the score of scientific questions involved. Our own research efforts are focused on two themes: Solar Fuels for renewable energy conversion and storage, and Fusion Energy as a clean, safe and inexhaustible power source.

Fusion Energy has the potential to provide concentrated, safe and clean energy from the process which powers the sun and stars. The international fusion reactor ITER aims to demonstrate the technical feasibility of fusion as an energy source. DIFFER is part of the EUROfusion consortium which supports the development of the ITER project. Our Fusion Energy research program addresses high priority topics in EUROfusion's European Fusion Roadmap. With our unique high flux plasma generator Magnum-PSI, we explore plasma surface interactions under the extreme conditions near the reactor wall, to validate solutions for the reactor walls of ITER and its successors. Our program on control in burning plasmas develops the understanding and tools to control the highly nonlinear plasma dynamics in ITER. Both research lines contribute to the understanding and control of the extreme conditions in the fusion environment, with the aim to develop robust solutions that ensure optimal fusion performance.

Solar Fuels tackle the efficient conversion of sustainable energy into chemical bonds. Our program on Solar Fuels addresses the global challenge of energy conversion and storage by converting (intermittent) sustainable energy into fuels. The research theme also develops insights applicable to the broader topic of electrification of the chemical industry, which is currently heavily reliant on fossil feedstock. DIFFER investigates both the indirect conversion of sustainable electricity into hydrocarbon fuels, and a direct 'artificial leaf' approach to convert solar energy into chemical bonds, using so-called photo-electrochemical cells. DIFFER's cross-disciplinary research naturally involves societal partners and adresses the synthesis and design of novel materials and processes to obtain scalable, efficient and cost-effective systems.

The evaluation panel visiting Magnum-PSI in October 2017

DIFFER evaluated by external expert panel

On 16 and 17 October 2017, an international expert panel headed by Prof. Dr. Sibylle Günter (IPP Garching) visited DIFFER for an external evaluation of past performance and a review of the institute's new strategy for 2017-2022. The evaluation panel considered DIFFER's research to have excellent relevance for society and rated its research activities as very good. The Fusion Energy program centered around Magnum-PSI was judged to be world-leading in its field, with similar prospects for the younger theme of Solar Fuels. The panel expressed excellent expectations for the future of the institute. In the new strategy, DIFFER has broadened its mission to allow for exploration of energy science beyond nuclear fusion and solar fuels, and continues to build a strong network for fundamental energy in the Netherlands.

Joint campus environmental license

DIFFER is located on the campus of Eindhoven University of Technology. To ensure safe and efficient operation, all knowledge institutes and high-tech companies on the campus have worked with the Eindhoven city council to come together under a single environmental license. The campus-wide license was issued on 7 September 2017 and will allow smooth and fast operation of existing and new research projects.

TU/e and DIFFER join forces in CCER

In 2017, DIFFER and Eindhoven University of Technology (TU/e) initiated the joint Centre for Computational Energy Research (CCER). The center brings together experts in high performance computing from both organisations to accelerate energy innovation. Prof. Dr. Ir. Frank Baaijens, rector magnificus of the TU/e and Prof. Dr. Wim van den Doel of the NWO Executive Board officially opened the CCER on 21 June 2017. The CCER already published its first scientific results and has set up a seminar series for specialists in computational (energy) research.

Right: address by CCER's director Vianney Koelman (TU/e and DIFFER) on the opening event of CCER on 21 June 2017.

PEOPLE HIGHLIGHTS

Jonathan Citrin (l) and Thomas Morgan (r)

Thomas Morgan to lead work package Liquid Metal Divertor

The EUROfusion consortium has appointed DIFFER group leader Dr. Thomas Morgan as leader of its new work package on liquid metal walls for the exhaust of future fusion power plants."In this design, a layer of liquid metal protects the underlying reactor wall against the harsh fusion environment, and this can be replenished as it is eroded", explains Morgan. EUROfusion work packages bring together experts from its 30 member organisations and over 100 Linked Third Parties (page 27) to tackle important issues on the road to fusion electricity.

Jonathan Citrin chairs ITPA Transport and Confinement Topical Group

The International Tokamak Physics Activity (ITPA) has appointed DIFFER group leader Dr. Jonathan Citrin as chair of its topical group on Transport and Confinement. The ITPA is an international framework organised by the ITER fusion project to coordinate high priority research activities. ITPA group members are chosen as representative top experts of their sub-fields. In the coming 3 years, Jonathan Citrin will lead the group's activities on addressing the open questions impacting ITER design and operation, in line with the evolving ITER Research Plan.

PhD theses 2017

In 2017, 3 DIFFER PhD candidates successfully defended their research theses at the Eindhoven University of Technology.

Three personal grants for top researchers

To offer talented scientists the opportunity to further expand their research, the Netherlands Organisation for Scientific Research (NWO) has set up the "Vernieuwingsimpuls" system of personal grants. These grants support top researchers in all stages of their scientific careers. Three DIFFER researchers obtained a personal grant from this scheme in 2017:

Dr. Andrea Baldi heads DIFFER's group on Nanomaterials for Energy Applications and was awarded an NWO mid-career Vidi grant to investigate how light enhances the catalytic performance of metallic nanoparticles. Understanding this effect could lead to applications in energy conversion, pollution mitigation and chemical synthesis.

Prof. Dr. Jaime Gómez Rivas, group leader at DIFFER and professor at Eindhoven University of Technology, won an NWO Vici grant for premier scientists in their fields. In a five year research line he will use his photonics expertise to create hybrid light-matter states in materials and enhance the charge transport. This holds great promise to improve optoelectronic devices, such as solar cells, LEDs, lasers and photodetectors.

Dr. Koen Hendriks will use the funding from his NWO early career Veni grant to start a post-doc in the joint DIFFER-TU/e research group on Storing Solar Energy. He will use his expertise as a chemical engineer to develop the promising concept of electricity storage in flow batteries, by working on a new class of organic molecules that can hold both positive and negative charge.

RESEARCH

THEME **FUSION ENERGY**

Theme leader:
Marco de Baar

Research groups: 6

Science staff:

permanent staff	10
post-docs	7
PhD students	20
research engineers	11

Peer reviewed publications	60
Open access	23
PhD theses	2
Invited talks	28

Grants and prizes:

KHMW Shell MSc thesis prize:
Oliver Linder
NEVAC best article prize 2017:
Stein van Eden
Enabling Research Grant:
Hennie van der Meiden
Enabling Research Grant:
Jonathan Citrin

Industrial collaborations:

NL ASML, HIT
EU Research Instruments

nationale wetenschaps agenda

The research in the Fusion Energy theme directly addresses the challenges posed in the Energy Transition route of the Dutch National Research Agenda (NWA).

The process of nuclear fusion powers the sun and has great potential as a concentrated, safe and clean energy source on earth. Fusion Energy research at DIFFER addresses two of fusion's grand challenges: developing tools to control the hot, turbulent fuel of charged particles (plasma) in a fusion reactor, and learning how wall materials for fusion reactors will interact with the extreme plasma conditions at the reactor exhaust.

The international fusion project ITER aims to demonstrate the technical feasibility of fusion energy. ITER is the first ever experiment where the power from the fusion reaction will be larger than the power of the reactor's heating and control systems; a fundamentally new regime for plasma physics stability and control. DIFFER develops techniques to sense, predict and control the instabilities in the hot, magnetized plasma. This is crucial to optimize the reactor performance.

At the ITER exhaust (or divertor), wall materials face extreme conditions in an environment similar to the surface of the sun. DIFFER's linear plasma device Magnum-PSI is the only laboratory facility in the world capable of exposing materials to exactly these extreme plasma surface interactions. Our researchers study the effect of wall materials and develop new concepts for reactor components.

European connection

The research at DIFFER addresses two high priority topics in the European Fusion Roadmap. As the Dutch partner in the European Horizon2020 research program EUROfusion, DIFFER is the linking pin between Dutch researchers and companies and the international fusion community (see page 27).

Magnum-PSI explores materials for future fusion reactors

DIFFER's main research facility Magnum-PSI is fully operational after the installation of a new superconducting magnet and has completed an exciting experimental campaign in 2017. Magnum-PSI is the only laboratory facility in the world that can explore how materials evolve under the same plasma conditions as at the exhaust of future fusion reactors such as ITER and its successors. The newly delivered 2.5 Tesla superconducting magnet supports hours-long discharges of dense plasma with particle flux densities of 10^{23} – 10^{25} $m^{-2}s^{-1}$ and power densities over 10 MW m^{-2}. This allows for detailed laboratory studies of how materials evolve over a sizeable part of their lifetime in a fusion reactor.

In 2017, Magnum-PSI explored a wide variety of topics in collaboration with many international research groups. Our important external partner EUROfusion facilitates access for the European PSI community. Experiments covered pressing issues in plasma surface interactions that are relevant for the ITER design and for future reactors, such as the study of fuel retention in ITER's candidate wall material tungsten during very long plasma exposures; studies on the physics of plasma detachment, a critical operation mode to protect the plasma facing components; and a prototype liquid lithium divertor target which could solve many of the issues with present day fusion reactors wall materials.

The connection to DIFFER's Ion Beam Facility (IBF) provides a completely new diagnostic for Magnum-PSI. With the beamline to Magnum-PSI's Target Exchange and Analysis Chamber, the team can probe, locally, material composition and obtain elemental depth profiles, for instance to investigate fuel retention. IBF's successful commissioning in 2017 offers many exciting research possibilities for the coming years.

New life for Nano-PSI

The versatile and flexible Nano-PSI experiment exposes materials to relatively low temperature and low density plasmas. It is primarily used to study plasma enhanced modification of surfaces, for example of nano- and micro-structuring of electrodes for efficient water splitting (see page 18) or carbon capture materials. Nano-PSI has recently received an important upgrade which enables the use of hydrogen plasma in combination with a heated or a water-cooled target. This widens the applicability of the device to other research fields, for example, liquid tin experiments (an important liquid metal plasma-facing material) and research on diagnostics (ion beam detectors in a harsh environment). Another recent topic is the study of blister formation and hydrogen retention in extreme ultraviolet (EUV) mirrors which is of prime importance for next-generation lithography machines.

Deuterium plasma in Nano-PSI

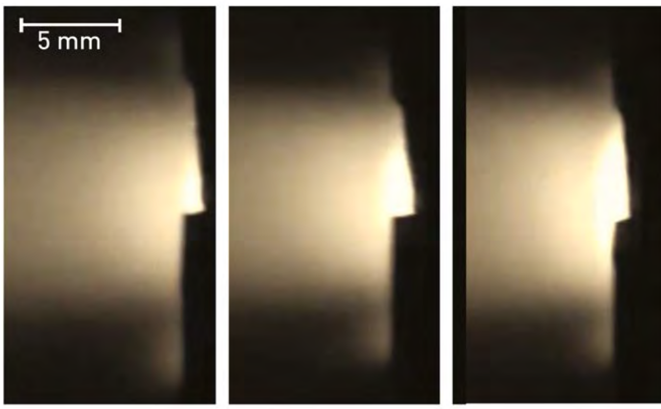
THE KNOWLEDGE TRADE

INTERVIEW - Renato Perillo

"I find it fascinating to see how people's backgrounds influence their approach to problems and the world in general", says PhD candidate Renato Perillo. Soft-spoken and people-focused, this Italian chemist investigates how puffs of nitrogen gas can help protect a reactor wall against the intense fusion conditions it faces. Deeper understanding will point out how to optimize the process. "From the chemistry side, I can determine the most important reactions between excited hydrogen and nitrogen" - he waves a page with dozens of reaction equations - "then run simulations and experiments in our facility Magnum-PSI."

As a plasma chemist in a physics-oriented field, Renato has a keen eye for others' perspectives. "I had a lot of physics to learn to understand fusion! But I can also share approaches from chemistry with my group members. Trading points of view helps everyone."
Is this why he guest authored for the Fusion in Europe magazine?

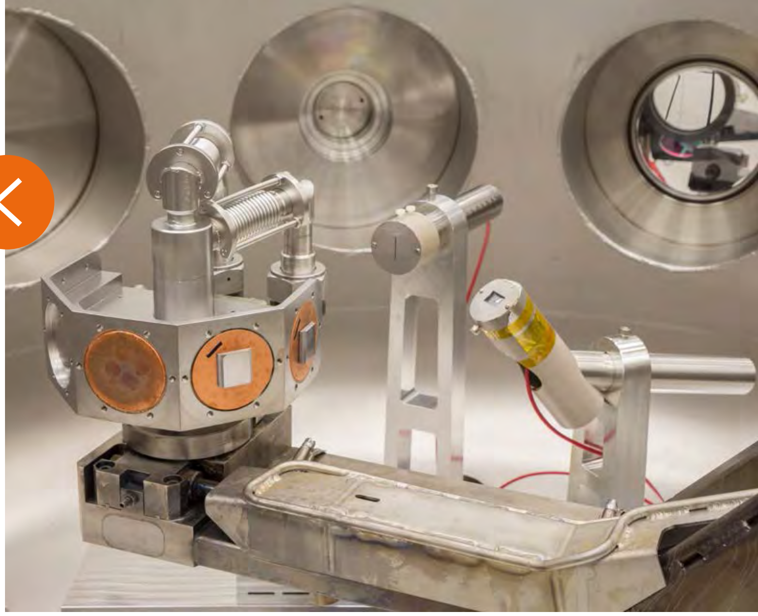
"Definitely! It is so important for scientists to show our work to a wide public. The kids of today will need to handle the energy issues of tomorrow - we need to make them curious, show what is possible, and get them involved."



Time-series of light emission by neutral tin particles during a vapour shielding cycle.

First NRA measurements with DIFFER Ion Beam

DIFFER currently houses the only operational ion beam facility for material analysis in the Netherlands. The facility, powered by a 3.5 MV in-line Singletron ion beam accelerator built by HVE, supports both DIFFER's research themes of Fusion Energy and Solar Fuels. The ion beam line is connected to two different facilities where ion beam analysis (IBA) is performed; the Target Exchange and Analysis Chamber (TEAC) of Magnum-PSI and the Ion Beam Analysis System (IBAS) – a conventional station for routine IBA measurements.



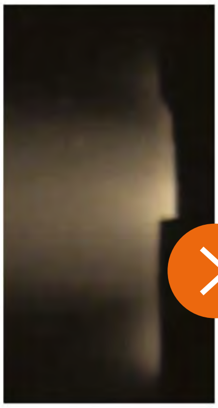
IBA detectors in the Magnum-PSI target exchange and analysis chamber, with target holder on the left.

The TEAC came online in 2017 and one of its first experiments involved a comparative measurement of the quantity and outgassing rate of deuterium – a hydrogen isotope – inside the surface layers of tungsten samples via both Nuclear Reaction Analysis (NRA) and Laser Induced Breakdown Spectroscopy (LIBS). The DIFFER ion beam facility is the first in the world where such studies are performed, and its results are highly relevant for the development of ITER.

Metal vapor to protect fusion reactor walls

PhD student Stein van Eden with a Magnum-PSI target holder

A nuclear fusion reactor houses an extremely harsh environment which pushes materials to their ultimate limits and beyond in sustaining the energetic plasma. Tackling this engineering challenge would make for a great leap forward to developing commercial fusion energy. Liquid metals are promising candidates to solve the wall problem because they may turn out to be more resilient to damage compared to solid materials. PhD student Stein van Eden and colleagues have experimentally demonstrated for the first time that strong evaporation of a liquid metal wall can greatly reduce the hazardous plasma heat flux in a self-regulated fashion. The evaporated particles act as a shield to protect the underlying liquid surface. By converting the power of the plasma into light rays and gas particles, both which are spread over a wide area, the vapor reduces the local heat flux on the reactor wall.



*Oscillatory vapour shielding of liquid metal walls in nuclear fusion devices, Nature Communications **8**, 192 (2017)*

A SOURCE OF INSPIRATION

INTERVIEW - Mozhgan Laki

PhD candidate Mozhgan Laki in DIFFER's Extreme Materials programme with M2i finds inspiration in many places. Creative writing; the excitement of learning new things, even during an exam or physics olympiad; the magical present of a circuit board when she was seven years old. And, days before this interview, SpaceX's spectacular rocket launch of a Tesla electric car into space. Asked how inspiration informs her research: "Of course the science of spaceflight is very different than the scales and processes in my own work. But the excitement is the same. It was an amazing thing to see and to think about how a team came together for that project."

"I chose this project for the focus on spectroscopy, my specialty. We are building a Collective Thomson Spectrometer to monitor the ions in a welding arc. How does gas composition determine welding performance? How do impurities from the target influence the plasma? It is very motivating to know that our partner M2i is eager to learn from our work. The common goal makes for a great team. Which is necessary to tackle scientific challenges. You cannot launch that rocket on your own."

Calculating turbulence 1 million times faster

A grand challenge in fusion physics is to fully understand turbulent processes in tokamak fusion experiments and optimize the plasma performance and fusion power. Direct simulations of such turbulence are possible with nonlinear codes, but these computations are too complex for routine predictions of experiments. Models of reduced complexity can bridge the gap.

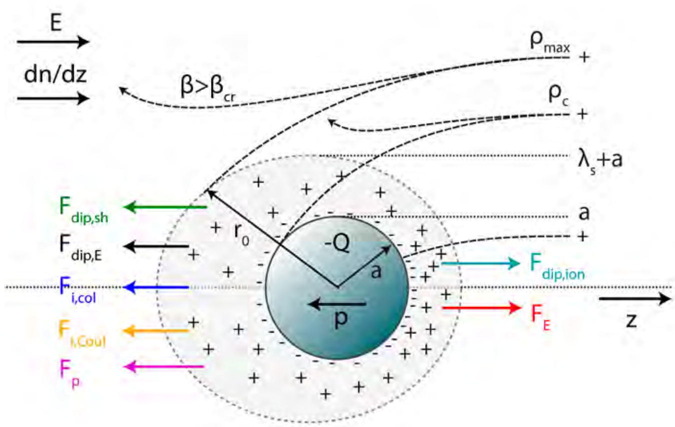
Jonathan Citrin and his DIFFER Integrated Modelling and Transport group, in close collaboration with researchers at CEA Cadarache, have made significant progress in the development of the "QuaLiKiz" reduced turbulence model. This computes turbulence 1 million times faster than nonlinear simulations. Through coupling to tokamak simulation suites, the model is now validated by a wide range of experiments. This significantly widens the scope for fundamental understanding of how tokamak plasmas self-organize, and how scenarios can be optimized for improved performance in both present-day machines and when extrapolating to ITER.

Dust particle dynamics near the reactor wall

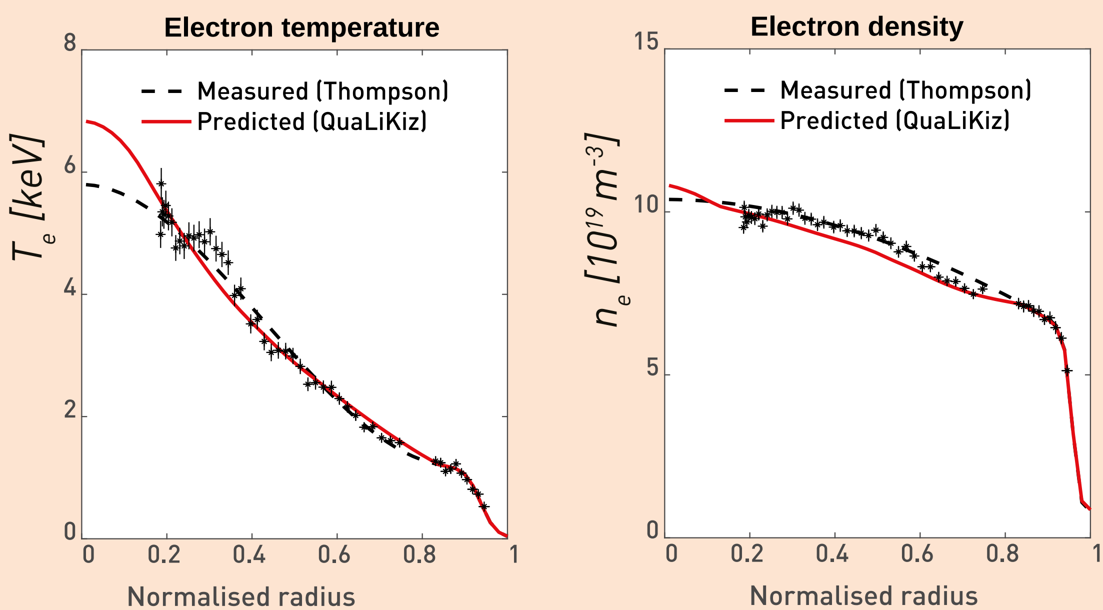
Dust particles in fusion devices are a significant impurity source and can result in severe power losses. Hence, it is essential to understand their transport behavior, which is governed by multiple forces such as Coulomb interaction, pressure and ion collection. These forces are usually described with certain approximations such as assuming a homogeneous plasma and particles so small that they fit inside the screening Debye length of the plasma.

In the journal Physics of Plasmas, PhD student Damien Aussems (joint DIFFER-TU/e program on Extreme Materials) investigated what happens when these assumptions break down. Aussems considered complex conditions, such as a rapidly varying plasma density near a reactor wall, or dust grains that grow beyond the Debye screening. By modifying the analytical expressions for the particle forces and deriving forces that are not included in the common computer codes for dust transport, he could finally explain experimental results in which particles that grow above a certain size are directed to the reactor wall.

An analytical force balance model for dust particles with size up to several Debye lengths, Physics of Plasmas ***24****, 113702 (2017)*



Force balance on a dust particle larger than the Debye length in an anisotropic plasma



Successful validation of the reduced core turbulence model QuaLiKiz on JET baseline discharge #87412

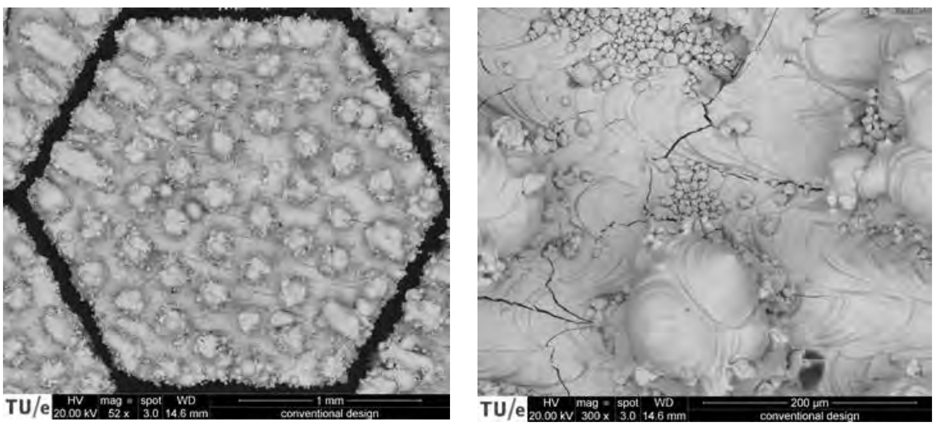
Tractable flux-driven temperature, density, and rotation profile evolution with the quasilinear gyrokinetic transport model QuaLiKiz, Plasma Physics and Controlled Fusion, ***59****, 124005 (2017)*

Peter Rindt at work at a 'glove-box'

3D-printing and liquid metals

The exhaust of future commercial fusion plants must safely withstand heat loads exceeding that of ITER, and face a much greater neutron load that degrades the strength of used materials below usable levels. This is a potential showstopper for future fusion reactors. However, a novel approach developed exclusively at DIFFER and TU/e combines liquid metals and 3D-printing of tungsten, to cope with both the heat and neutron load simultaneously.

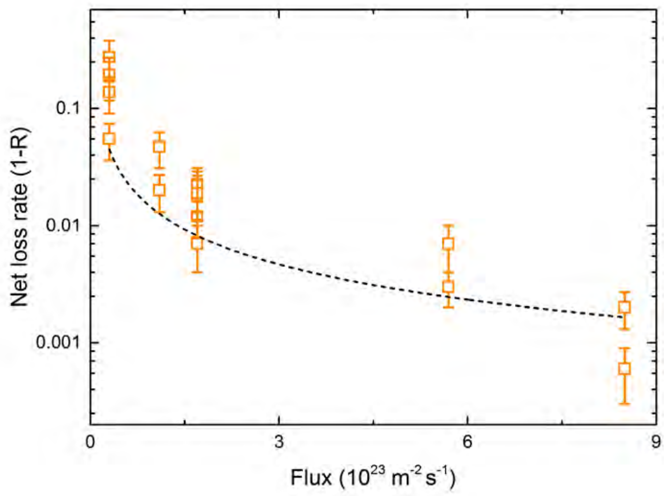
A tungsten mockup was designed, 3D-printed in collaboration with Philips Medical Systems and filled with liquid lithium. Testing on Magnum-PSI showed that the lithium effectively dissipated power by heat radiating, and that thermal gradients caused no damage to the tungsten. 3D-printing allowed a design where thermal stresses are reduced by almost 2 orders of magnitude. Thus, this revolutionary approach aims to meet the stringent demands for commercial fusion reactors.



SEM image of the 3D-printed tungsten design. Shaping on the micro-scale allows extremely effective confinement and transport of liquid metal via capillarity.

Plasma entrainment to protect from erosion

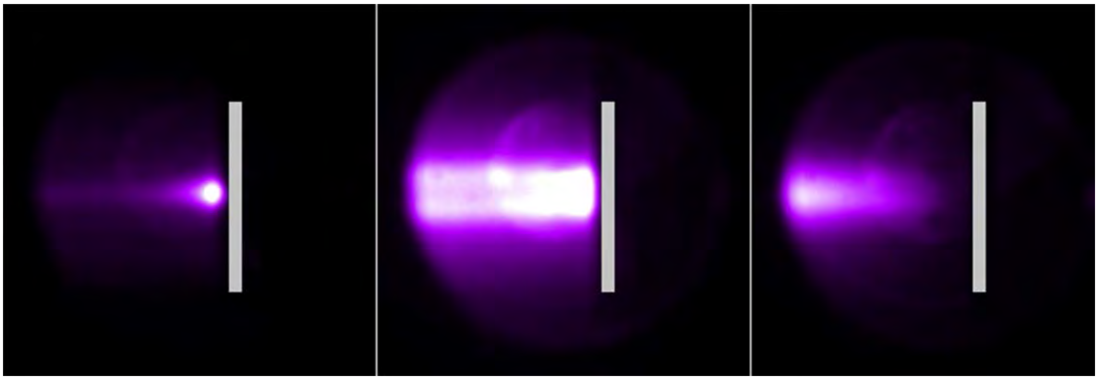
Impurities in the core of the fusion reactor are generally unwanted, leading to radiation and fuel dilution which can reduce the amount of fusion energy which is generated. However, recent experiments in Magnum-PSI have shown that release of impurities from the reactor wall might not be as bad as researchers expected. In the experiment more than 99.9% of sputtered impurities were driven back towards the surface and re-deposited locally at the highest fluxes, leading to a hugely reduced net loss rate. It was found that collisions between the sputtered neutrals and the plasma ions lead to entrainment when the plasma density gets large. The plasma flow then pulls impurities along with it towards the wall. This is a big benefit for ITER, and very helpful for liquid metals where evaporation is likely to be high, meaning their operational temperature window can be extended upwards.



The net loss of material from a surface exposed to a dense plasma drops as a function of plasma flux.

Detachment studies at Magnum-PSI

DIFFER's linear plasma generator Magnum-PSI is able to create the harsh plasma conditions which will occur in the exhaust region of the ITER fusion reactor. In ITER, the heat loads to the wall will have to be reduced to tolerable amounts by detachment, a process where radiation and other plasma-neutral processes extinguish the plasma close to the wall. However, the physics of detachment – especially in the ITER regime – are not yet fully understood. In order to study detachment, a combination of pumping and neutral gas puffing is used to control the neutral pressure around the Magnum-PSI plasma between two extremes, one corresponding to an unmitigated ITER scenario and the other to a completely detached plasma. At different stages of detachment, the plasma-neutral processes responsible for dissipating energy are studied using a wide array of diagnostics.



Stages of detachment in the Magnum-PSI plasma with the target indicated. Left: plasma 'attached' to the target at low neutral pressure. Center: radiation throughout the plasma volume causes energy losses at medium pressure. Right: plasma 'detaches' from the wall at high pressure.

RESEARCH

THEME
SOLAR FUELS

Theme leader:
Richard van de Sanden

Research groups: 10

Science staff:

permanent staff	8
post-docs	21
PhD students	18
research engineers	8

Peer reviewed publications	40
Open access	17
PhD theses	1
Invited talks	42

Personal grants:
- NWO Vici grant - Jaime Gómez Rivas
- NWO Vidi grant - Andrea Baldi
- NWO Veni grant - Koen Hendriks
- IPCS Fellowship - Richard van de Sanden
- ISPC 2017 poster pitch award - Anna Meshkova

Industrial collaborations:

NL Alliander, Ampleon, DNV.GL, Fujifilm Research, Gasunie, Lumileds, Philips, Philips Lighting, Shell, Stedin, Syngaschem

EU ENGiE (Fr), Evonik, Protemics GmbH (D)

World Atlantic Hydrogen (Ca), Facebook (US), Sasol (SA)

nationale wetenschaps agenda

The research in the Solar Fuels theme directly addresses the challenges posed in the Energy Transition route of the Dutch National Research Agenda (NWA).

The worldwide energy transition requires solutions to efficiently store and transport sustainable energy to where and when it is needed. The solar fuels research at DIFFER addresses the global challenge of efficiently converting and storing sustainable energy into fuels and chemicals, starting from water, carbon dioxide and nitrogen. These fuels offer the highest energy densities and are ideal for seasonal storage and long-distance transport of sustainable energy. Solar fuels serve as a sustainable option for heavy-duty and long-haul mobility, i.e. trucks, ships and airplanes. Moreover, the chemical products made are circular feedstock for (chemical) industries.

The Solar Fuels research and development program at DIFFER is driven by the need for cost-effective and energy-efficient production of sustainable fuels and products through the use of abundantly available materials.

In particular, DIFFER investigates using renewable energy, either directly or indirectly via electricity, for splitting of water into hydrogen and oxygen, and the reduction of carbon dioxide (CO_2) to carbon monoxide, as an important starting point for the synthesis of CO_2-neutral chemical fuels. Our research involves the synthesis and design of novel materials and processes to obtain scalable, efficient and cost-effective systems.

The concrete research areas are non-thermal chemical processes, functional materials and interfaces and light-matter interaction.

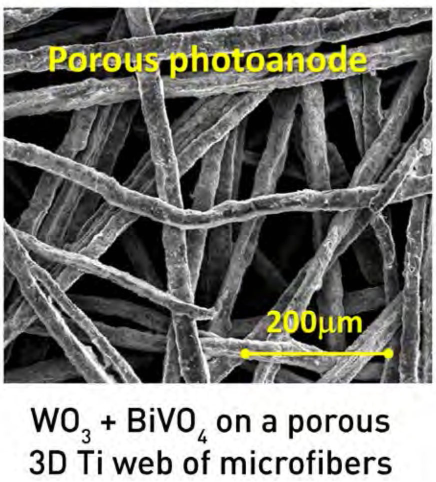
First solid-state device to create hydrogen using sunlight

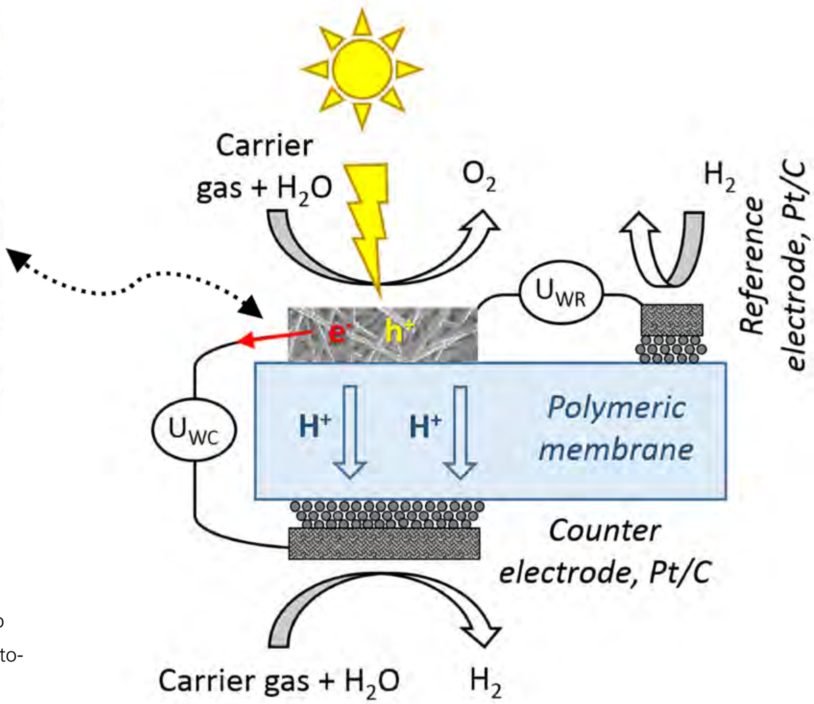
With the rise of energy and climate concerns, a large number of research teams around the world are developing devices to produce hydrogen fuel from water and solar energy. In the ideal case, these photo electrochemical (PEC) devices or cells would use the energy from incoming light irradiation to dissociate water into its fundamental components, hydrogen and oxygen. The use of semiconductor-based water-splitting systems is a promising route towards affordable production of such “solar hydrogen”.

The main challenges in the field are developing efficient photo-electrodes and a scalable reactor design. The DIFFER group Catalytic and Electrochemical Processes for Energy Applications (CEPEA) developed a design which resembles polymeric electrolytic membrane (PEM) electrolysers and is thus called PEM-PEC. This type of reactor has the advantage of being compact, robust and easily scalable. Its challenge lies in the requirement of a porous photo-electrode, rather than the planar electrode design used in conventional PEC studies.

Up to now only simple photo-anodes based on TiO_2 or WO_3 have been developed for PEM-PEC applications. These materials can absorb only a small fraction of the wavelengths in sunlight and as a result their performance is very limited. In order to adapt the PEM-PEC concept to the visible part of the solar spectrum, the CEPEA team has developed porous photo-anodes based on an interface between tungsten oxide and bismuth vanadium oxide. Exposed to sunlight and without adding any co-catalysts, this solid-state water-splitting system is the first to reach a similar performance as classical liquid-electrolyte photo-electrochemical cells.

*Visible-light-promoted gas-phase water splitting using porous WO_3 / $BiVO_4$ photo-anodes, Electrochemistry Communications, **82**, 47-51 (2017)*

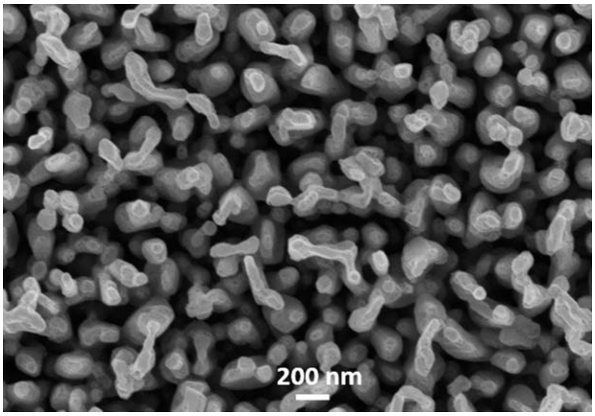




Above: synergistic WO_3 / $BiVO_4$ photo-anode for water splitting. Right: schematic of the full device. The photo-anode was built on a porous substrate to allow for implementation in the novel PEM-like photo-electrochemical cell.

Plasma structuring thin films for water splitting

Turning water splitting - the production of hydrogen fuel from water - into an application still suffers from too low efficiencies. A promising route to improvement is increasing the number of reaction sites by increasing the surface area of the electrodes to improve the conversion efficiency. The Electrochemical Materials and Interfaces group (EMI) tackled this challenge by using high ion flux, low energy plasmas known from DIFFER's fusion energy research on Magnum-PSI. They could demonstrate for the first time that thin films can be nanostructured by this method even on brittle glass substrates. Detailed electrochemical characterization showed the prospects and limitations of this new method for nanostructuring. In the next years, the team wants to optimize the technique for high-performing water-splitting electrodes and transfer it to other electrochemical applications.



- *The electrochemistry of iron oxide thin films nanostructured by high ion flux plasma exposure, Electrochimica Acta, **258**, 709 (2017)*
- *Nanostructuring of thin films by high flux low energy He plasma, Thin Solid Films, **631**, 50 (2017)*

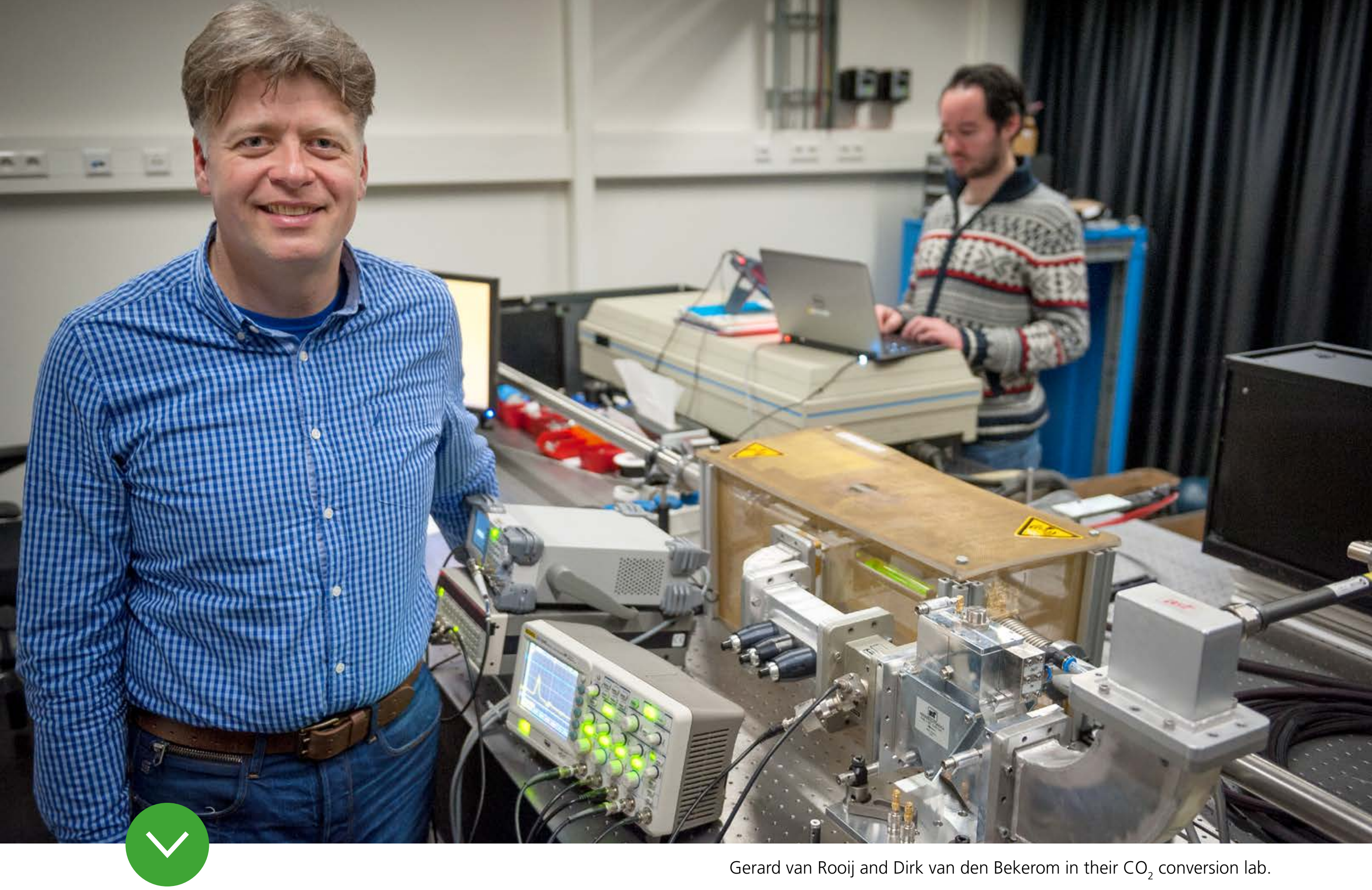
Top view scanning electron microscopy image of a plasma nanostructured thin film after annealing.

New Solar Fuels projects started in 2017

With a new project grant from the European M-ERA.NET, the group of Anja Bieberle will develop advanced multi-scale modelling of the processes in photo-electrochemical systems together with 3 European partners. The project will further understanding of the limiting mechanisms in the direct conversion of sunlight into fuels and will help optimize artificial leaves towards highest performance.

The research group of Mihalis Tsampas has won NWO (Shell, UTwente) and Topsector (ISPT, AkzoNobel, OCI Nitrogen, Yara) grants to create a system using a plasma environment to boost electrocatalysis and efficiently produce fuels and chemicals from sunlight and abundant resources.

In an EU consortium, the groups of Mihalis Tsampas, Waldo Bongers, Paola Diomede and Süleyman Er have won the EU project KEROGREEN with KIT, VITO, CerPoTech, HyGear and INERATEC. KEROGREEN aims at converting water and carbon dioxide to airplane fuels, following a multistep approach that involves conversion, separation and synthetic fuel production.



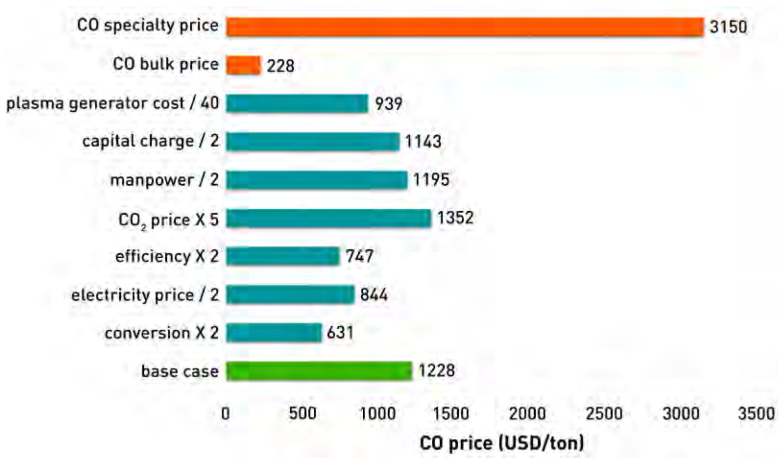
Gerard van Rooij and Dirk van den Bekerom in their CO_2 conversion lab.

Economic viability of breaking up CO_2 in a plasma

Using sustainable energy to recycle CO_2 from the atmosphere into fuels or other useful chemicals starts with breaking up this sturdy molecule. Converting CO_2 into CO by means of a plasma carries the promise of high energy efficiencies in excess of 80%. Although these ultimate energy efficiencies have not been reproduced yet, DIFFER has demonstrated efficiencies of up to 50%.

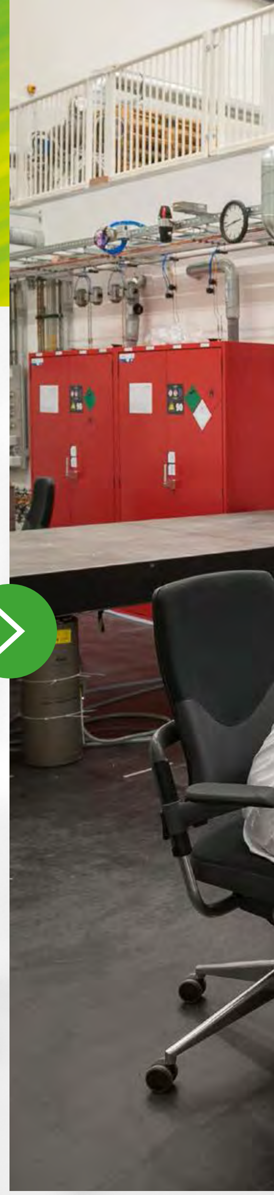
In collaboration with the company Traxxys, the Nonequilibrium Fuel Conversion group (NFC) investigated how the current efficiency of the DIFFER plasma process relates to a CO cost price on the basis of a realistic process design at industrial scale, including product separation and storage. Compared to fossil based CO production, the price estimate was in between bulk and specialty price. A sensitivity analysis indicated that via electricity price and total conversion rate the eventual price can easily be brought down to within a factor of two compared to bulk price. The results of this economics assessment were published in the context of electrification of chemical industry and validate the economic potential of the plasmolysis approach.

Plasma for electrification of chemical industry: a case study on CO_2 reduction , Plasma Physics and Controlled Fusion, ***60****, 014019 (2018)*



Sensitivity analysis for the main cost factors in the plasma CO price. Estimates of the present CO bulk and specialty prices are shown as reference.

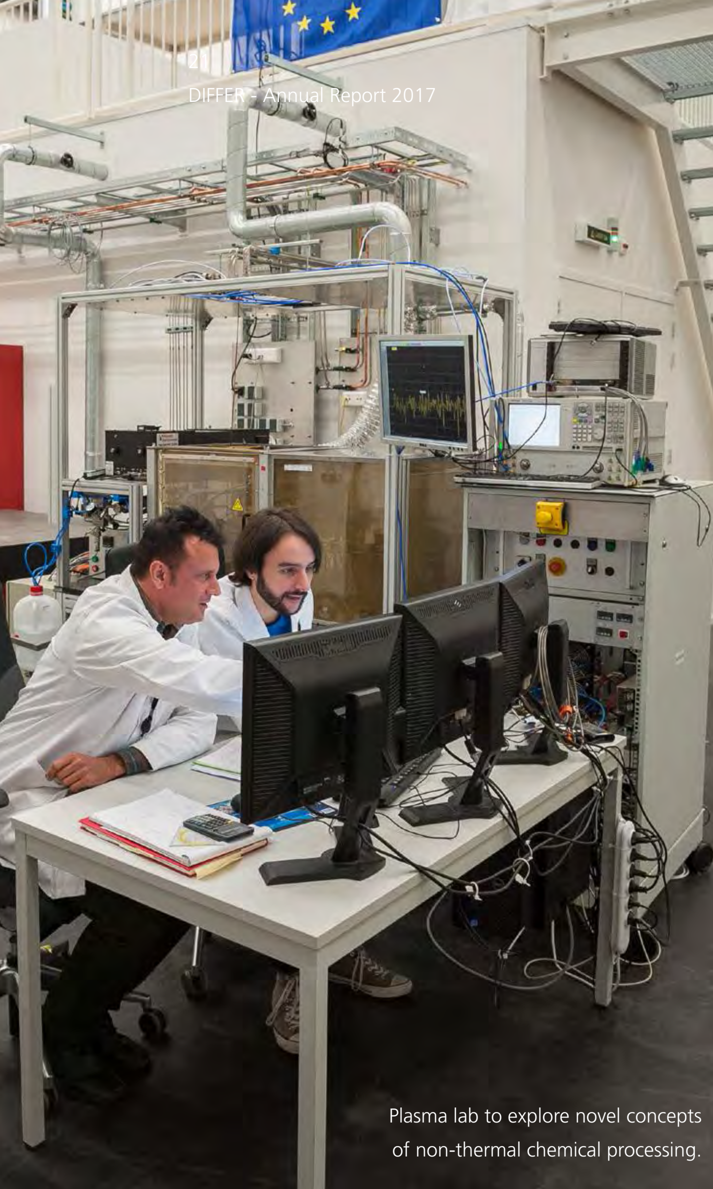
NEW SOLAR FUELS LABS OPERATIONAL



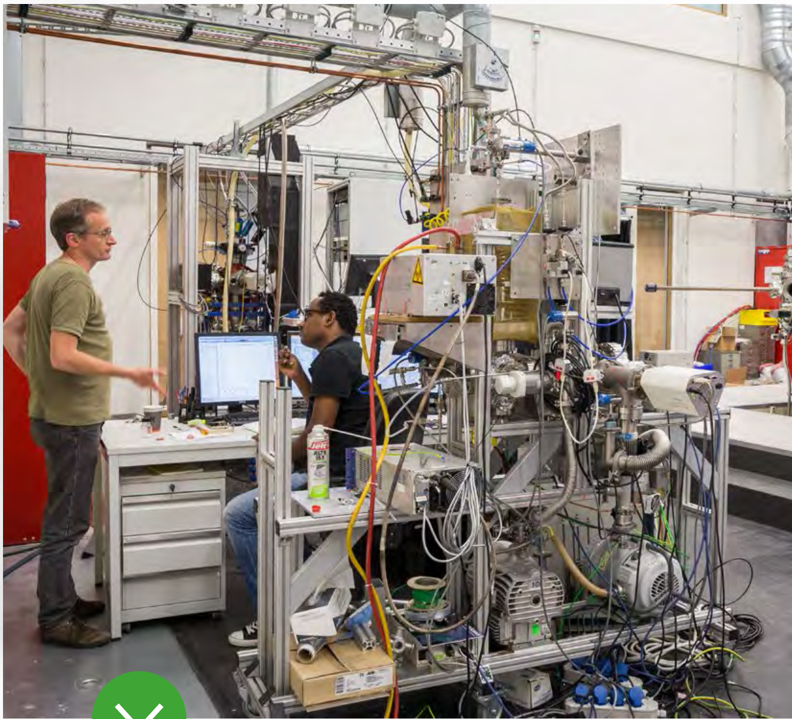
In 2017 the "heart" of the research within the Solar Fuels - the four permanent laboratories - became available in addition to the temporary lab spaces which were already furnished. Researchers will be using these labs to investigate materials, processes and systems in (in)direct conversion of sustainable energy to fuels and chemicals. These four labs are dedicated to (i) fabricate functional materials and interfaces and assess their perfomance on device level, (ii) study light-matter interaction at the nanoscale level to tailor (photo-)chemical reactions at a molecular level, and (iii) explore novel concepts of non-thermal chemical processing (e.g. in plasmas).

The Artificial Leaf lab combines a shared chemistry lab with 2 adjacent lab spaces for studies on ionic conducting membrane devices and photo-electrochemical cells.

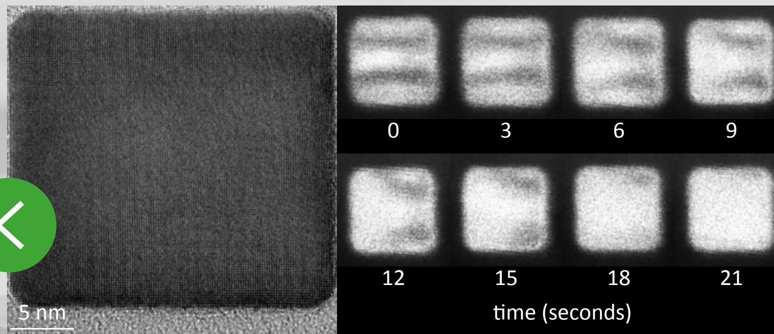
Laboratory space to study light-matter interactions at the nanoscale and tailor (photo)chemical reactions at a molecular level.



Plasma lab to explore novel concepts of non-thermal chemical processing.



Laboratory for materials and surface science studies.



(left) Electron microscope image of a palladium nanocrystal. (right) Hydrogen absorption in a single nanocrystal: the brighter regions indicate the hydrogenated areas.

Live imaging of hydrogen storage in nanomaterials

One of the major obstacles to developing a sustainable energy infrastructure is the lack of an efficient energy storage method. Nanomaterials have the potential to provide significant improvements to battery capacities and lifetimes, thanks to their size-tunable performance, fast charging and discharging characteristics, and longer lifetimes. Studying energy storage in nanomaterials is however experimentally challenging.

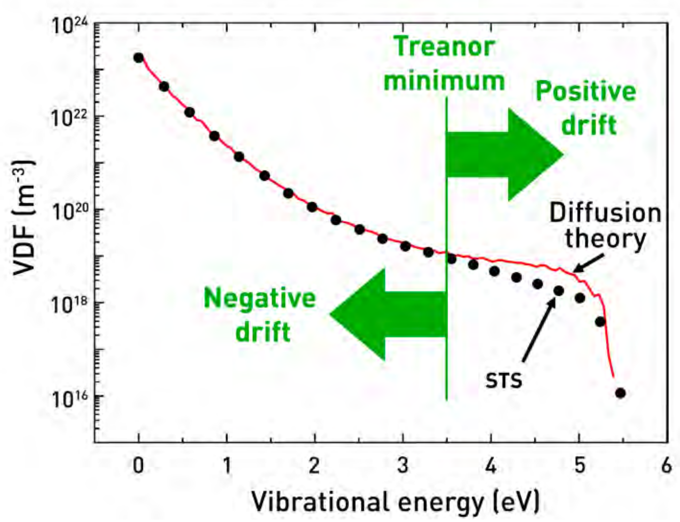
In the journal Nature Communications, the Nanomaterials for Energy Applications group (NEA) used an environmental electron microscope to visualize for the first time how hydrogen is absorbed in single metallic nanocrystals, both in real time and with nanometer resolution. They found that hydrogen atoms absorb at the corners of the particles and diffuse into their lattice in a way that minimizes deformation in the particle. The observation is important to understand the superior resistance to degradation of nanoscale battery materials during charging and discharging.

Direct visualization of hydrogen absorption dynamics in individual palladium nanoparticles, Nature Communications ***8****, 14020 (2017)*

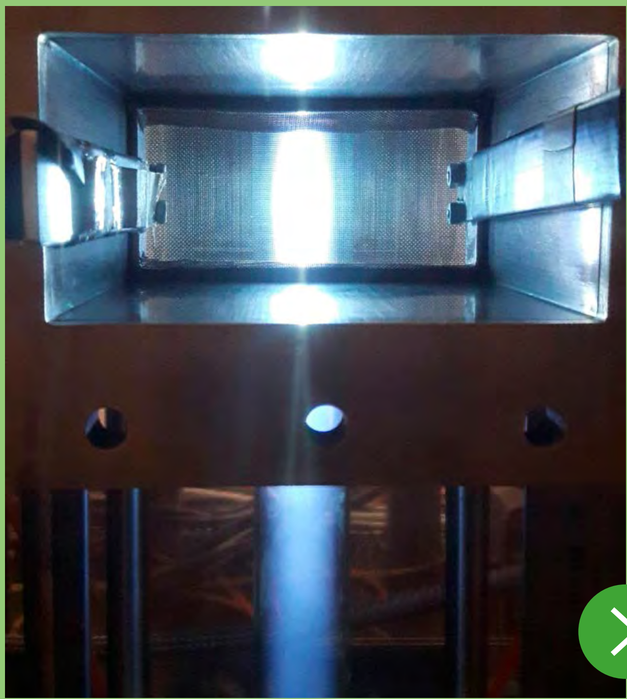
Vibrational energy drift-diffusion: key to CO_2 dissociation

Dissociation of CO_2 molecules in plasma is a subject of enormous importance for carbon capture and for developing carbon-neutral fuels. Vibrational excitation of molecules plays an important role in the process, where the vibrational temperature is a measure of energy stored in the molecules. The complexity of the present state-to-state (STS) models, that allow accurate descriptions of molecular processes by considering the vibrational levels as individual species, makes it difficult to find key parameters. As an alternative, the Computational Plasma Physics and Chemistry group (CPPC) developed a numerical method based on the drift-diffusion equation for vibrational energy. Results agree with STS, but also reveal the presence of a positive drift, a "flow" which begins at a well-defined energy and pushes molecules to dissociation. In perspective, this flow could be controlled by the reactor settings, through adjusting the vibrational and gas temperature. The possibility of describing dissociation kinetics as a transport process therefore provides insight toward the goal of achieving efficient CO_2 conversion.

Insight into CO_2 dissociation in plasmas from numerical solution of a vibrational diffusion equation, Journal of Physical Chemistry C, ***121****, 19568 (2017)*



The improved diffusion approach reproduces results from the state-to-state approach and describes molecular processes in terms of drift-diffusion in vibrational energy.



'Reverse vortex' plasma reactor to efficiently use microwaves to break up CO_2 into the base molecules for clean fuel production.

TRACING THE STEPS OF WATER SPLITTING

INTERVIEW - Aafke Bronneberg

Working in DIFFER's Electrochemical Materials and Interfaces group on a Marie Curie Fellowship, postdoc Aafke Bronneberg is investigating exactly which steps are involved in splitting water into hydrogen and oxygen on a metal oxide surface. The end goal: more efficient production of CO_2-neutral hydrogen fuel from water and sunlight.

"It all hinges on which intermediate steps happen when H_2O splits at the catalytic surface", she explains, "and a surface sensitive technique is essential to visualize the exact intermediate steps to form O_2 and H_2." Bronneberg designed an infrared spectroscopy experiment that should be sensitive and fast enough to spot the different reaction steps as they happen.

"From there, we can compare to models and find out how to tune our catalytic materials to optimize the reaction. I'm one of just a few people in the world trying these operando measurements. When the setup starts delivering results, we'll see just what the bottleneck steps in water splitting are!"

Control of flowing CO_2 plasmas

In the Solar Fuels research line of using sustainable electricity to turn CO_2 into fuels, the Plasma Solar Fuels Devices group (PSFD) is designing an optimized plasma reactor to break up CO_2 into feedstock molecules for fuels or other chemicals. Microwaves transfer electrical energy to CO_2 molecules by ionizing a small amount of CO_2. Ionization produces electrons which can move freely with the microwave field and transfer its energy to the slow-moving CO_2 molecules.

For optimal gas densities, temperatures and microwave field strength, CO_2 can be dissociated into CO and O_2 with a very high theoretical efficiency (≤ 90%). In practice, it is very challenging to maintain optimal conditions in high power, industrially relevant systems. For instance, equilibrium gas temperatures in microwave plasmas in excess of 3000 K are no exception.

Controlling the CO_2 gas flow pattern in the reactors is essential in order to maintain a colder plasma. To this end, the group studies a variety of reactor flow configurations, with the aim of minimizing unwanted heating and maximizing energy efficiency. In 2017, the group achieved energy efficiencies greater than 50% under industrially relevant conditions using a reverse vortex configuration.

*Plasma-driven dissociation of CO_2 for fuel synthesis, Plasma Processes and Polymers, **14**, e1600126 (2017)*

NETWORK BUILDING

WORKING TOGETHER ON ENERGY RESEARCH

Collaboration is key to accelerate the energy transition and reach the world's climate target of limiting global warming to 2 °C at most, and preferably 1.5 °C.

At DIFFER, we invest in an energy research community in the Netherlands and beyond. We focus on connecting the relevant disciplines and actors, from fundamental and applied research, development and prototyping, to enterprises and industry. We strive to foster cross-disciplinary collaborations that will lead to necessary breakthroughs for mid- and long-term sustainable technologies.

An active Dutch research community on Solar Fuels

The research on Solar Fuels within the Netherlands has received considerable impulse from the NWO programs Towards biosolar cells (2010), CO_2-neutral fuels (2012), Plasma conversion of CO_2 (2014) and Solar-to-Products (2016). DIFFER brings these researchers and companies together to form an active solar fuels community.

The community came together at the workshop Renewable Energy Driven Chemistry organized by DIFFER group leaders in April 2017. Almost 130 participants had an inspiring day at DIFFER with a compact program of contributions from the associated programs.

As with the other programs relevant for energy research, DIFFER was involved in the preparations of the NWO program Materials for Sustainability and hosted a match-making event for researchers and companies. In the beginning of 2018, 15 research projects were granted by NWO, among which a project lead by DIFFER researcher Süleyman Er.

The Dutch solar fuels research community together at DIFFER for an inspiring, in-depth workshop.

NERA representing national energy research

Within the Netherlands Energy Research Alliance (NERA), a scientific board was appointed to advise the NERA Board and profile itself as a sparring partner to NERA's stakeholders. This board consists of renowned Dutch scientists and is chaired by DIFFER director Richard van de Sanden. Representing the broad Dutch energy research, the scientific board will give its input on (strategic) choices and criteria for mission driven innovation programs aligned to the Top sectors and the Dutch Climate and Energy policy.

The routes developed for the Dutch National Research Agenda (NWA) have positively influenced the Dutch government in their decision for a structural impulse to applied and fundamental research. Meanwhile the NERA made an inventory of the publicly funded research projects over the last few years. Linking these projects to the challenges of the NWA route Energy Transition sketched the direction of the energy transition in the Netherlands. This inventory was presented during the 2017 work conference of the Top Sector Energy.

Important step national program on ECCM

The topic of electrochemical conversion and materials (ECCM) is a connecting technology addressing innovation priorities of the Top Sectors Energy, Chemistry, and High Tech Systems and Materials (HTSM). This technology will lay the foundation for future clean and synthetic energy carriers and materials for applications such as seasonal storage, transport and mobility fuels, and (chemical) feedstock.

On behalf of these Top Sectors, Richard van de Sanden chaired a national advisory committee for the Ministry of Economic Affairs and Climate. The ECCM report advised on the governance, regulations, education, research and development, and recommended setting up a national multi-year public-private program to accelerate the transition to a sustainable energy and feedstock system.

As follow-up to the ECCM report, DIFFER together with TNO and Delft University of Technology are asked to develop a research roadmap identifying the technology and regulation efforts to be made towards 2050.

On behalf of the Top Sectors Energy, Chemistry and HTSM, Richard van de Sanden offers the ECCM advisory report to the DG's Sandor Gaastra and Bertholt Leeftink of the Ministry of Economic Affairs and Climate.
Report available at www.co2neutraalin2050.nl

COORDINATING THE DUTCH CONTRIBUTION TO EUROFUSION

René Schoonen (head of finance), Ed van Wijk (project office manager), Dam Nguyen (financial administrator)

INTERVIEW - René Schoonen en Ed van Wijk

As the national consortium member of EUROfusion, DIFFER is the gateway for Dutch knowledge institutes to participate in this European fusion research programme. Head of financial affairs René Schoonen and Project Office Manager Ed van Wijk work behind the scenes to coordinate the Dutch contribution to this Horizon2020 programme.

René Schoonen: "At the start of the year, we had four Dutch Linked Third Parties; recently, the Fusenet Fusion Education Network joined as a fifth." Linked Third Parties can participate in EUROfusion activities under the responsibility of DIFFER. Ed van Wijk: "After the Consortium Agreement and the Grant Agreement, this means ongoing work in project management, time registration and cost declarations - all to be checked by our own accountant and by a visiting accountant from the European Committee."

Although cost declarations were already on the duo's desk under EUROfusion's predecessor EFDA, Van Wijk stresses that Horizon2020 involves new procedures. Both Schoonen and Van Wijk were involved in the select working group that set up the EUROfusion Consortium Agreement - "A very worthwhile opportunity", thinks Schoonen, "because we got to learn the consortium's inner workings."

The knowledge translates well: "In 2017, DIFFER's Solar Fuels department became Coordinator for the new M€ 4.8 KEROGREEN project", says Van Wijk. There were only a few weeks' time to prepare the Consortium Agreement between KEROGREEN's six European partners. "Our experience with EUROfusion gave us the know-how and confidence that we could set up the required framework in time."

EUROfusion
Linked Third Parties in the Netherlands

Map base by http://www.freepik.com

30	Consortium members
150+	Linked Third Parties via Consortium members
26	EU member states plus Switzerland and Ukraine

TU/e Technische Universiteit Eindhoven University of Technology

FuseNet The European Fusion Education Network

NRG

UNIVERSITEIT TWENTE.

CWI Centrum Wiskunde & Informatica

OUTREACH

KNOWLEDGE TRANSFER TO SOCIETY

One of DIFFER's goals is transferring knowledge to society at large. The institute welcomes young talent for research projects in the upper levels of high school, in the bachelor and master phase, and as technical apprentices. DIFFER also runs a strong outreach program to the general public, either via the media or directly in the form of open days.

Reach of activities for target groups

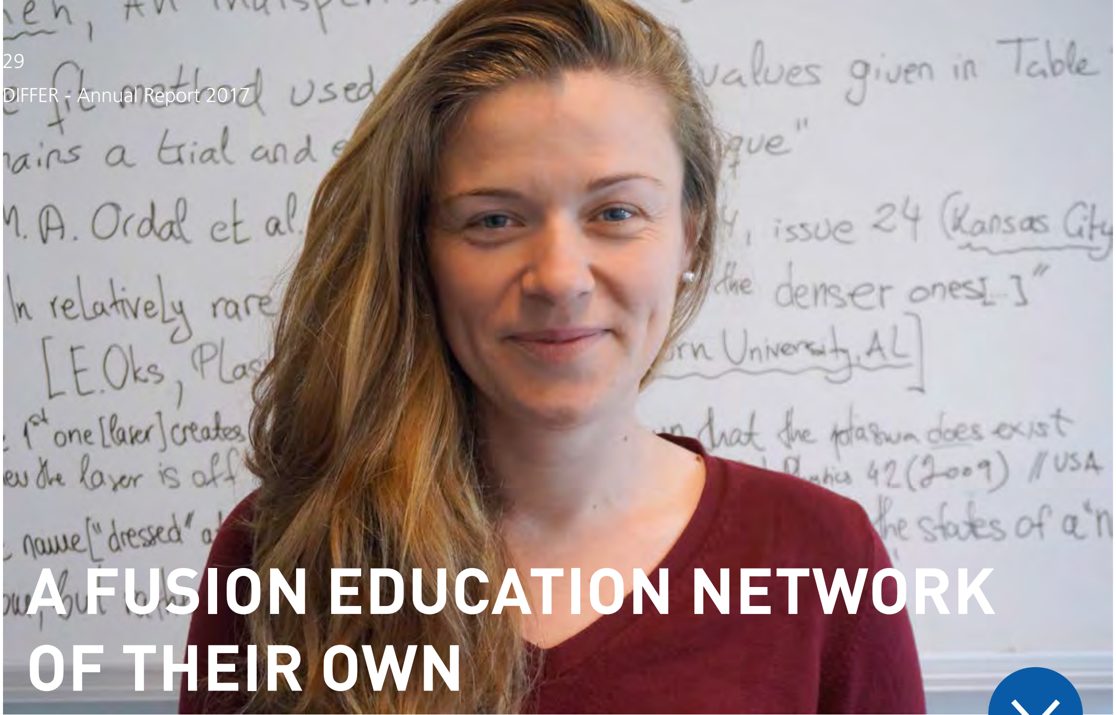
Education (high school and up)	4032
Lab tours	151
Presentations	63
Plasma Lab experiments	10
Fusion Road Show	3764
TU/e teachers days	44
General public	880
Open House Day	800
Public talks	80

Young Brainport Summer School

Forty international high school students visited DIFFER on August 21st 2017 as part of the second annual edition of the Young Brainport Summer School (YBSS). The students got an inspiring introduction to nuclear fusion and toured laboratories for fusion and solar fuels research. YBSS was inspired by the successful Perimeter Institute summer school and welcomes top physics students from around the world to the Eindhoven area. Participants visit local research institutes, Eindhoven University of Technology and high-tech companies.

Record number of visitors during Fusion Days 2017

How much CO_2 does New York City produce in a day? How long on an excercise bike to compensate a barrel of oil? DIFFER's Erik Langereis, Arian Visser and Gieljan de Vries challenged some 3750 upper level high school students and their teachers with these questions during the sixth edition of Antwerp University's Fusion Days. In addition to the main event - DIFFER's Fusion Road Show - visitors were treated to live experiments, expert lectures, and Q&A sessions about nuclear fusion and the energy transition.



A FUSION EDUCATION NETWORK OF THEIR OWN

INTERVIEW - Branka Vanovac

Fusion research is a truly international undertaking. As a case in point, take Branka Vanovac from Bosnia-Herzegovina, employed as a PhD researcher at the Dutch institute DIFFER and seconded to the ASDEX-Upgrade facility in Munich. Not everyone has the same level of access to studying and working abroad, explains Branka when we meet during a discussion at the Dutch Physics@Veldhoven conference.

"Montenegro, Serbia and Bosnia-Herzegovina are not part of the EU and don't have a dedicated research group in fusion anymore. This makes it hard for even talented students to get into the fusion community." With four fellow PhD students from the region who work at European fusion institutes, Branka set up the Fusion Education Network (FOM, in Serbian) to improve matters.

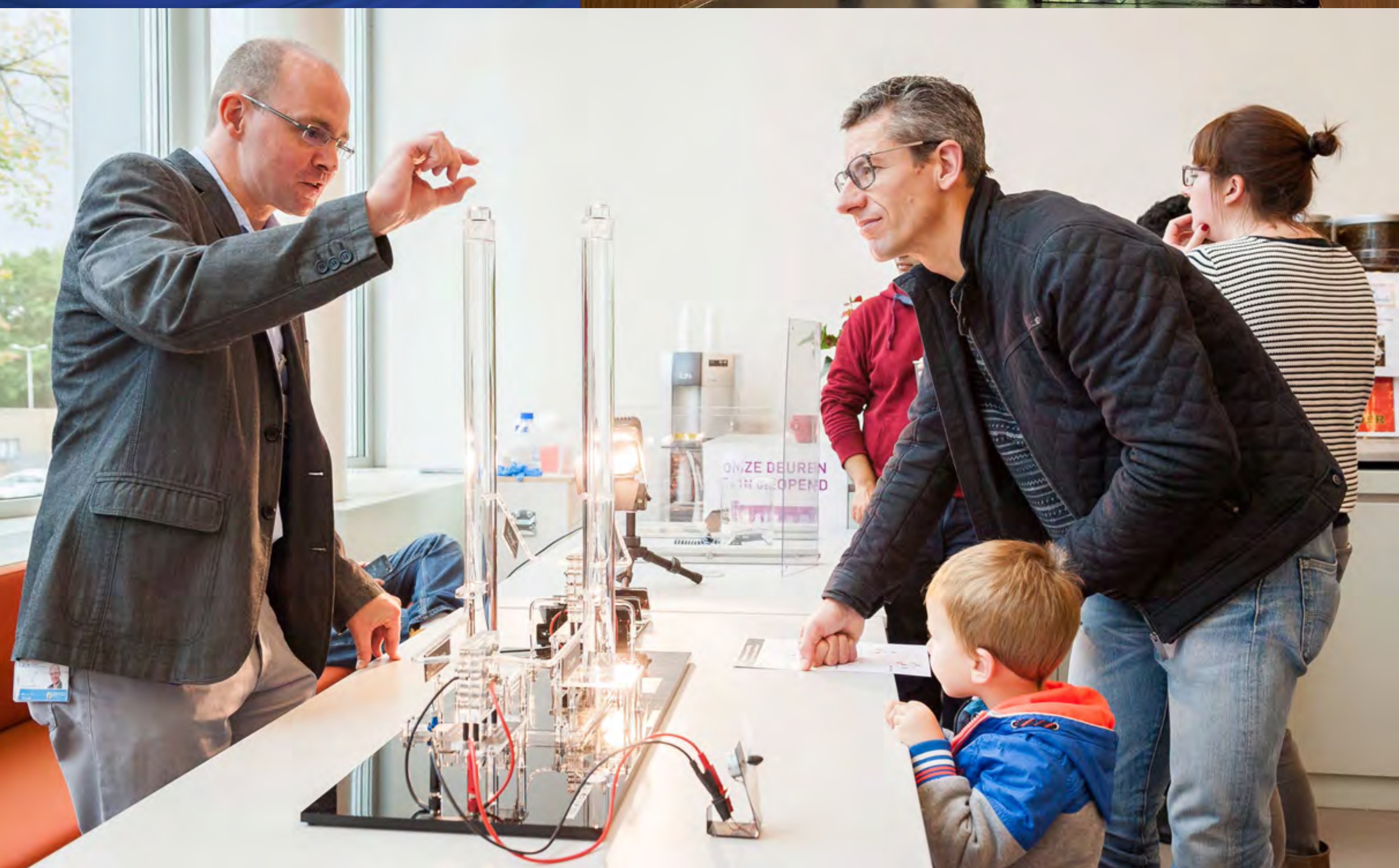
"We organized workshops at the University of Novi Sad and Belgrade to get undergraduate students interested in fusion research", says Vanovac, who then arranged experimental access for 'her' students at the Czech fusion experiments GOLEM and COMPASS. A dedicated website and blog (in Serbian) allows the team to keep in touch with their over 50 students so far. "This project sure takes a lot of our time", the student-turned-teacher admits, "But it's well worth it to get students from our countries more involved in fusion research."

Local energy cooperative discusses Solar Fuels

A big theme in the energy transition is how to change the large scale energy infrastructure to match new, fluctuating sources such as solar PV and wind power. But what about the individual energy producer? On 25 October 2017, DIFFER's Erik Langereis joined local energy cooperative Waalre Energy Lokaal for a discussion on the future of Solar Fuels and their role and impact in a sustainable energy infrastructure.

OPEN HOUSE DAY 2017

DIFFER's annual open day is the institute's main event to talk with the general public about how our research can help create a sustainable future. The 2018 Dutch Science Weekend saw 800 visitors come to DIFFER to discuss future energy solutions with the experts, participate in workshops, get hands-on experience with splitting water into hydrogen fuel, or visit the many labs and outreach talks. With visitors giving an average appreciation score of 8.3 out of 10, the open day clearly was a great success.

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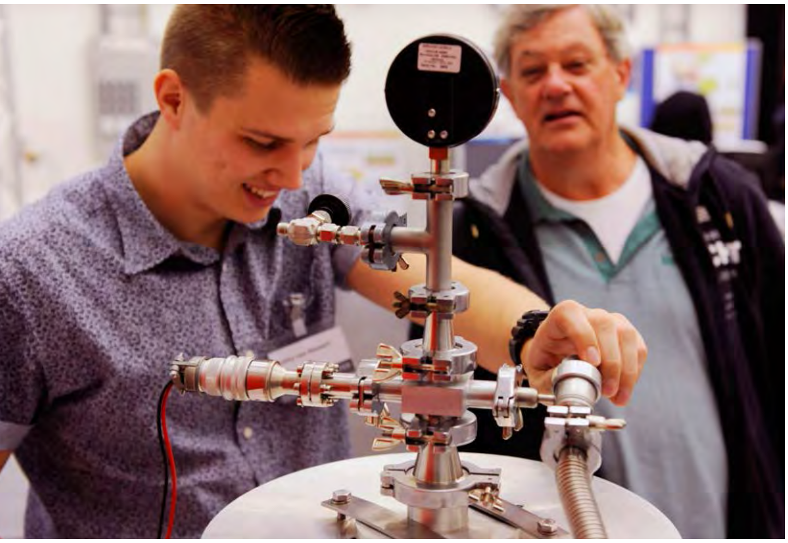


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FACTS & FIGURES

Output

- **3** PhD theses
- **100** Publications
- **40** Open access
- **70** Invited talks
- **76** Other talks
- **119** Posters
- **6** Editorships

Organizational chart

Director
Theme leader
M.C.M. van de Sanden

Theme leader
M.R. de Baar

Institute manager
Wim Koppers

THEME FUSION ENERGY

- Computational Plasma Physics and Chemistry – P. Diomede
- Fusion Facilities and Instrumentation – H. van Eck
- Integrated Modelling and MHD – E. Westerhof
- Integrated Modelling and transport – J. Citrin
- Plasma Edge Physics and Diagnostics – I.G.J. Classen
- Plasma Material Interactions – T. W. Morgan

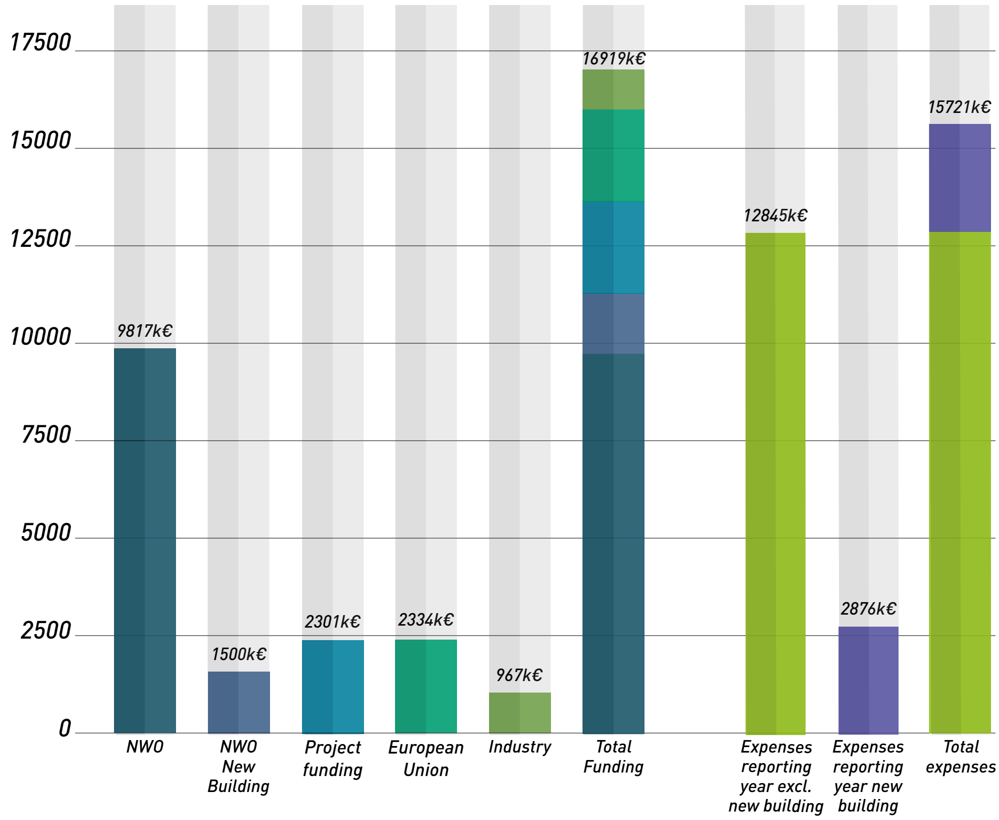
THEME SOLAR FUELS

- Atmospheric Plasma Processing of Functional Films - H.W. de Vries
- Catalytic and Electrochemical Processes for Energy Applications – M. Tsampas
- Electrochemical Materials and Interfaces – A. Bieberle
- Materials and Surface Science – M.A. Gleeson
- Molecular Solar Energy (TU/e) – R. Janssen
- Nanomaterials for energy applications – A. Baldi
- Nonequilibrium Fuel Conversion – G.J. van Rooij
- Photonics for Energy – J. Gómez Rivas
- Plasma Solar Fuels Devices – W.A. Bongers
- Solar Fuels Facilities & Instrumentation – S. Welzel

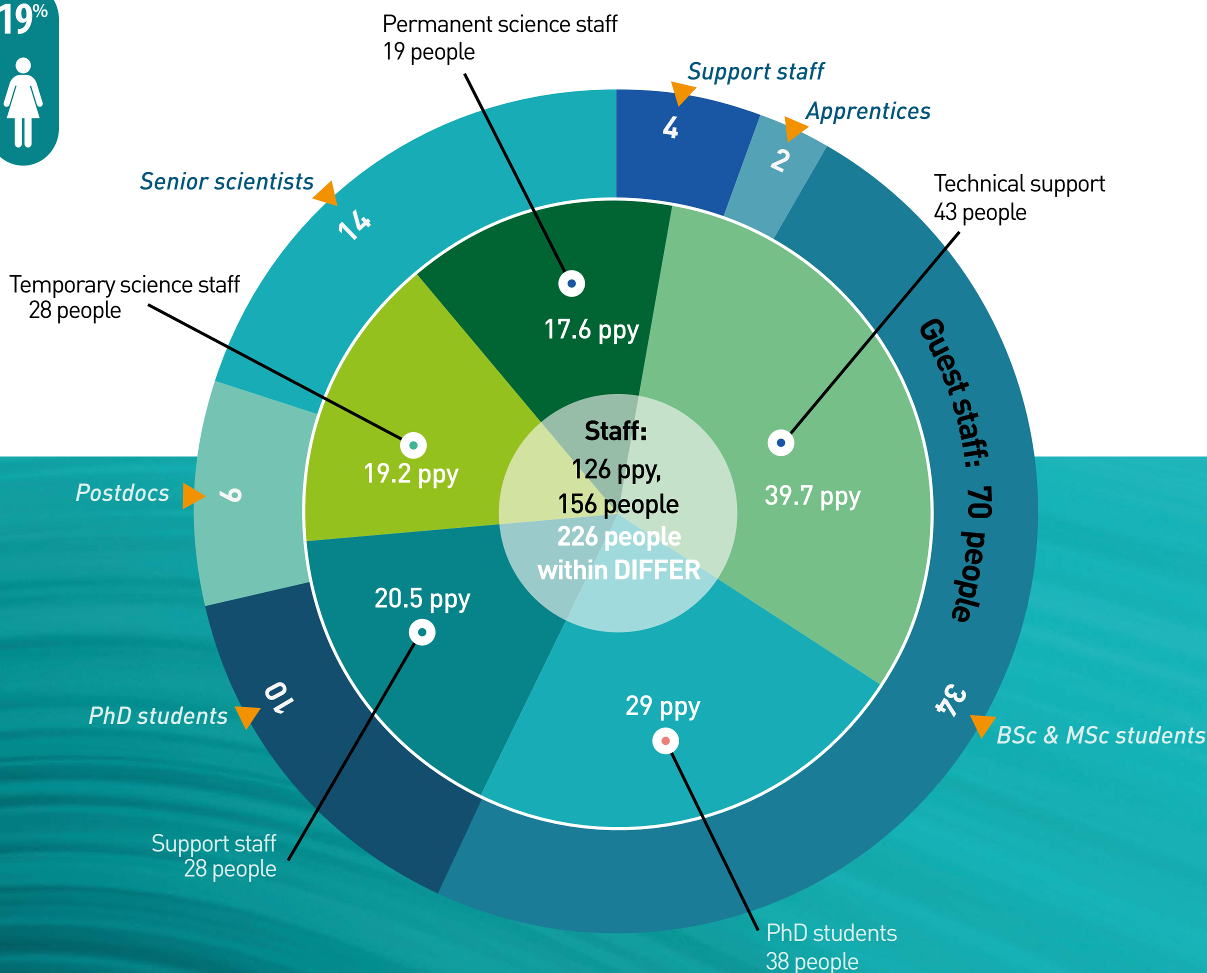
SUPPORT FACILITIES

- Communication – F.T.M.E. de Vries
- Electronics & ICT – A. Broekema
- Facility Management – J.E. Kragten
- Financial Administration – M.P.M. Schoonen
- Management Support – W.R. Koppers
- Mechanical Techniques – F.J. van Amerongen
- Occupational Health & Safety – A.M.M. Arends
- Personnel & Organization – H. Tamsma
- Technical Service – K. Grootkarzijn

Funding and expenses 2017



Staff



Committees

Management Team
M.C.M. van de Sanden (institute director; theme leader Solar Fuels)
W.R. Koppers (institute manager)
M.R. de Baar (theme leader Fusion Energy)

Scientific Advisory Committee
G. van der Steenhoven (KNAW)
C. Bourdelle (CEA)
R. van de Krol (Helmholtz - Zentrum Berlin)
D. Lincot (Institut de Recherche et Développement sur l'Energie)
E.B. Stechel (Arizona State University)
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Works Council
B.S.Q. Elzendoorn
A. Ho
G. Kaas
D.M.S. Ronden
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