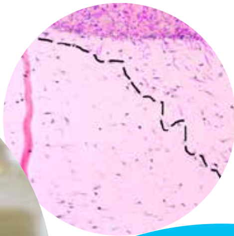
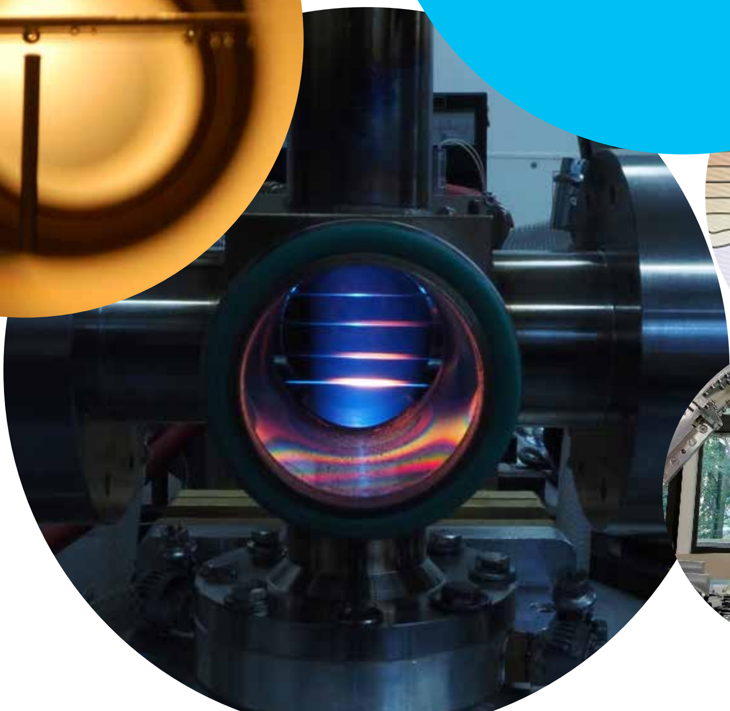
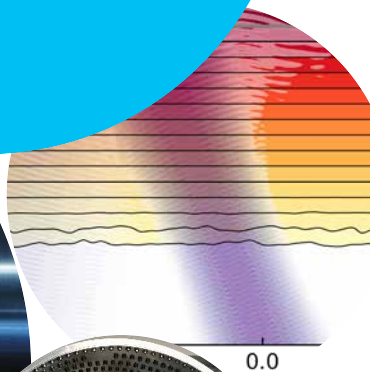
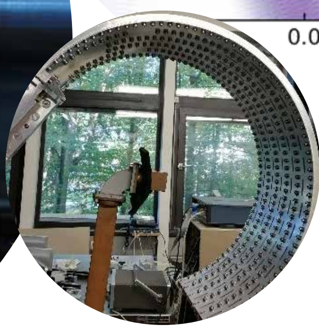
University of Stuttgart
Institute of Interfacial Process Engineering and Plasma Technology



Annual Report 2019







Editorial notes

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Annual Report 2019

Institute of Interfacial Process Engineering
and Plasma Technology
University of Stuttgart

Preface

In the current situation, the importance of efficient and modern science becomes clear to a broader public than usual. Even if some people find the statements made by scientists too ambiguous: The vast majority of people are happy to live in enlightened times in which data and facts are first collected and then evaluated in a scientific way. We consider findings obtained in this way to be the best basis for sound decisions. At the Institute for Interfacial Process Engineering and Plasma Technology IGVP of the University of Stuttgart, the approach outlined above is a matter of course and the basis for our work in research, teaching and transfer.

In our research in the field of Plasma and Microwave Technology we are targeting on new processes as well as new reactors and reactor components designed for use in various fusion experiments together with our national and international research partners. We concentrate on applying microwaves to heat the plasma, to drive plasma currents and to control and analyze magneto-hydrodynamic instabilities in present-day fusion experiments (page 60 ff). We also run our own stellarator experiment where we employ our specifically developed diagnostics based on probe arrays (p 70 ff). We aim to contribute fundamentally to master fusion plasmas that can be sustained and confined for a sufficiently long time as to achieve a positive net energy outcome from fusion reactions for utilization in future power plants. We deal with fundamentals and applications of microwave plasmas also in order to work on the development of new microwave-generated plasma sources at low and atmospheric pressure, the diagnosis and numeric simulation of these plasmas, and the development of a variety of resulting applications to alter surfaces or to drive chemical reactions such as CO_2 conversion into syngas (p 44 ff).

We also aim for new biotechnological processes to induce microorganisms to convert substances in energy-efficient ways – thus valuable substances are gained with the help of bacteria and microalgae (p 34 ff). A variety of fermenters are used including specific reactor systems such as the flat-panel airlift (FPA) reactor developed at our partner institute, the Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, or self-developed membrane reactors for the use of gaseous substrates. The spectrum of targets substances span from biobased surfactants to potential biobased fungicides in wine-making. Biological interfaces are central in our focus on infectious diseases caused by viruses, bacteria and fungi (p 28 ff). We aim to better understand the pathogenic action of viruses but also progress for virus-based technologies platforms. Genetic modification and complex cultivation techniques of mammalian cells and tissues is the fundamental base to develop new human physiologically relevant in-vitro test systems.

Functional materials are often defined by their surface and interface design. At the IGVP, we aim to understand and create complex functional materials (p 18 ff). A specific focus is on cross-linked polymers in the format of hydrogels or nanoparticles. We use synthetic or biogenic polymers to generate hybrid functional materials. Formulation flow properties are investigated to enable additive manufacturing processes like extrusion-based 3D printing or inkjet printing. Bioinspired structural materials based on functional building blocks derived from sustainable and biogenic sources such as arthropod exocuticle open a new perspective on structural materials that might prove to be useful for future building applications.

We thank all our partners, especially the Fraunhofer IGB and the Max Planck Institute for Plasma Physics IPP for the fruitful collaboration in 2019 and wish you a pleasant insight in our research activities.

Prof. Dr. habil. Günter Tovar (acting director)

Contents

Profile of the Institute

The Institute of Interfacial Process Engineering and Plasma Technology IGVP is dedicated to inter- and cross-disciplinary research, teaching and transfer in the fields of materials science and technology, life sciences, process engineering and plasma science and technology.

Key Figures
In 2019, the research budget accounted for 2.46 million euros. At the end of that year, 60 scientific, technical and administrative employees, among them 22 young scientists working on a doctoral thesis, staffed the IGVP. Additionally, 43 students were researching for their master or bachelor thesis with us.

Organization and Facilities
The IGVP is part of the Faculty 4: Energy-, Process- and Bio-Engineering of the University of Stuttgart and organized in the two departments "Interfacial Process Engineering" and "Plasma and Microwave Technology".
State-of-the-art labs, technical plants and workshops are available at the IGVP for research in natural sciences and interdisciplinary engineering. They are located at the three IGVP facilities in Pfaffenwaldring 31, Allmandring 5b at the University Campus and within the Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB in Nobelstrasse 12.

Research
The IGVP focuses on the design of functional materials and their surfaces and interfaces, on the biological interactions at these surfaces as well as on the development and engineering of interfacially driven processes.
In plasma technology, low-temperature plasmas are applied for surface activation, microwaves for stabilization of high-temperature plasmas in fusion-related plasma processes, and the dynamic properties of plasmas and electromagnetic waves are analyzed and simulated.

Collaboration
Close cooperation of the IGVP with Fraunhofer IGB enables a dynamic collaboration between researchers and lecturers of both institutions and furthermore allows to pursue projects from basic research to application. This approach is reflected in the variety of funding received by the IGVP, including funds from the *Land* of Baden-Württemberg, from Federal Ministries (e.g. BMBF), from the German Research Foundation (DFG), from the German Federal Foundation for the Environment (DBU), from the EU and from various foundations as well as from industry. Since many years, the Max Planck Institute for Plasma Physics (IPP), located in Garching and Greifswald, is another key partner of the IGVP and is enabling us to maintain a leading role in plasma technology.

Teaching
The IGVP is highly active in teaching both within master and bachelor study programs at the University of Stuttgart, especially in the programs on Process Engineering, Medical Technology, Technical Biology, Energy Technology, Renewable Energy Engineering, Environmental Engineering, WASTE and Environmental Engineering.

Thematic Focus
- Interfacial process engineering
- Nanomaterials and nanotechnology
- Biomaterials and infection biology
- Renewable raw materials, industrial biotechnology and bioenergy
- Plasma technology and plasma physics
- Microwave technology for plasmas and process engineering

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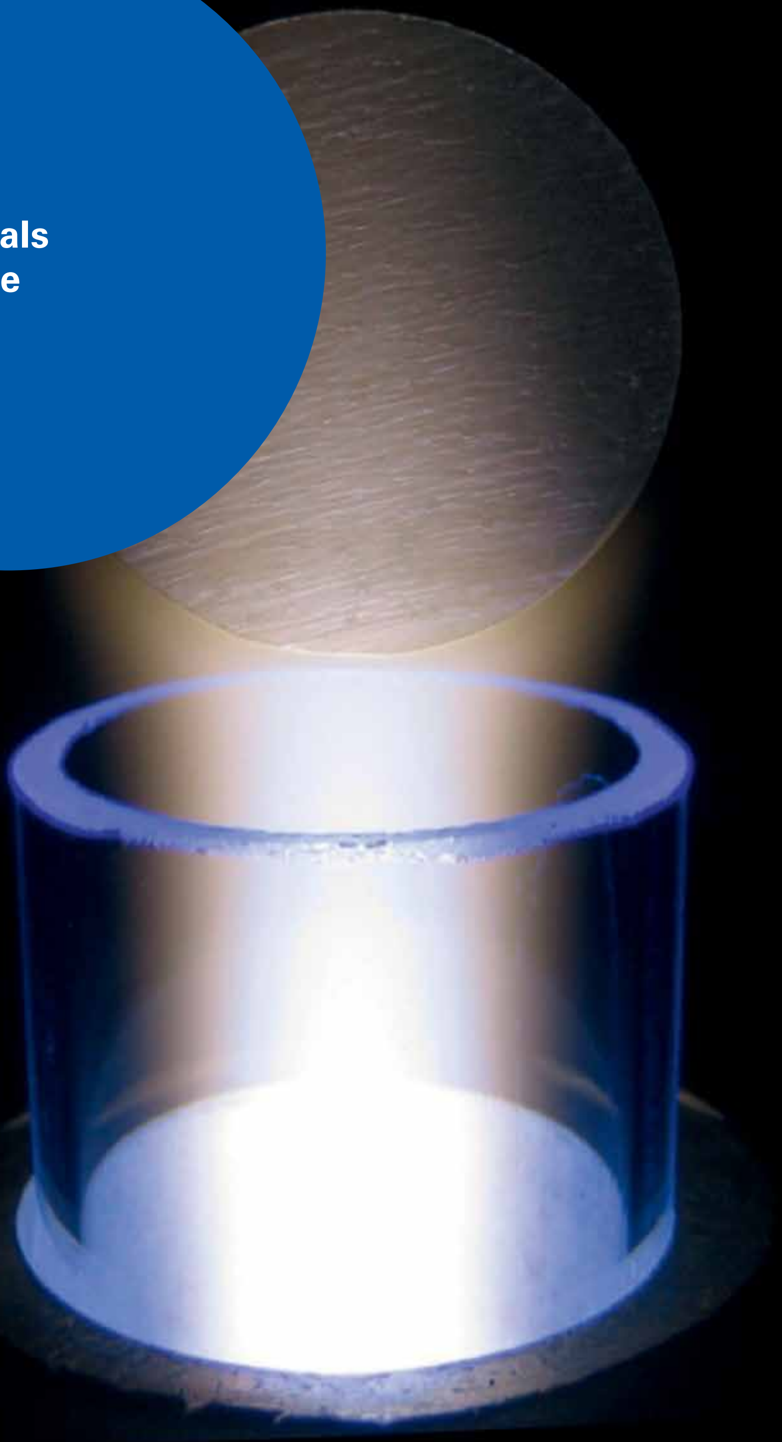
Interfacial Process Engineering

Materials Science



Functional Polymers with Defined Properties

Dr. Alexander Southan, alexander.southan@igvp.uni-stuttgart.de

Functional materials based on synthetic or biobased polymers are useful for various purposes, including separation of solutes, sensing, or tissue engineering. In these contexts, chemically, biologically, or physically functionalized groups present inside the materials or at the material surfaces drive the interaction of the materials with their environment. Therefore, our research deals with the synthesis, characterization, formulation, and processing of polymeric materials with defined functional groups or physical properties in order to tailor the response of the environment to the materials. Both the bulk and surface properties are in the focus of our research. The main research objects are cross-linked polymers such as hydrogels and nanoparticles.

The material formulations are based on the one hand on commercially available building blocks. On the other hand, custom building blocks are synthesized and characterized thoroughly if necessary. Also, formulation flow properties are investigated in detail to make them suitable for additive manufacturing processes like extrusion-based 3D printing or inkjet printing. Materials are characterized, e.g., regarding their mechanical properties, their adsorption behavior for solutes, or their interactions with human cells.

Examples are the synthesis of amphiphilic compounds for surface functionalization (p. 22), the synthesis of functional poly(ethylene glycols) for the generation of new hydrogel materials (p. 25), surface coating of polymer materials (pp. 21), or the functionalization of the extracellular matrix with azide groups (p. 27). Thus, our research covers the entire development process leading to functional polymers and spatially defined hydrogels.

Bioinspired Structural Material Chemistry

Dr. Linus Stegbauer, linus.stegbauer@igvp.uni-stuttgart.de

We focus our research around building blocks derived from sutainable and biogenic sources such as arthropod exocuticle. Through chemistry these building blocks are processed, tailored and changed in a way that we can obtain a structural material that could be potentially useful for building applications. We heavily rely on multiphase transitions such as liquid – hydrogel – solid for preparation and can modify the material chemically in each state, which optionally mechanically respond to an external stimulus such as light. Multiscalar chemical and mechanical characterization gives us powerful tools to establish the structure-property relationship. As an overall vision we aim to implement living systems in materials.

Hydrogels as Selective Functional Layers for Optical Sensors

Anastasia Tsianaka, Günter Tovar, Alexander Southan

Analytics of mixtures of different substances play a crucial role in many environmental or industrial applications. Determination of analyte concentrations, such as pharmaceutical compounds present in water bodies or reactants during industrial processes, is an important part of environmental and process monitoring. The use of methods that require a simple instrumentation and deliver prompt results is advantageous. Optical sensors are devices that fulfill these requirements.

Optical sensors based on silicon can monitor refractive index changes caused by the presence of analytes in aqueous solutions. Crucial for registering refractive index changes is the presence of a functional layer on the sensor surface that interacts with the analyte. Suitable materials for functional layers are hydrogels. Hydrogels are polymer networks which enable analyte enrichment due to their swelling properties. The introduction of functional groups in the polymer network can enable adsorption of specific analytes. This project is focused on the synthesis of functionalized hydrogels for the specific adsorption of pharmaceutical compounds such as diclofenac, metoprolol, or metal ions present in aqueous solutions, as well as on the deposition of these functional layers on the sensor surfaces. Common coating methods that lead to thin layers such as spin coating, and spatially controlled coating methods such as inkjet printing are to be employed in order to obtain fully functional optical sensors.

Collaboration: Manfred Berroth, Wolfgang Vogel and Niklas Hoppe, Institute of Electrical and Optical Communications Engineering, University of Stuttgart, Stuttgart; Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart

Funding: German Research Foundation (DFG), Project: Selective Optical Sensor-Arrays in a Silicon-Hybrid-Platform (SOSAS), Funding code TO 211/4-1

Hydrogel Coatings as Selective Membrane Layers for Moisture Recovery in Automotive Fuel Cells

Andre Michele, Günter Tovar, Alexander Southan

In view of emissions and imminent bans on cars with combustion engines, the polyelectrolyte membrane fuel cell (PEMFC) is a promising technology for automotive applications. Its performance is dependent on the state of electrolyte membrane (EM) hydration. Returning excess water generated at the fuel cell´s cathode to the EM is the most reasonable way for optimal water management. This could be carried out by using a membrane with good water vapor permeability and high selectivity. The selectivity towards reaction gases may be improved using a hydrogel coating.

For the production of hydrogels, we cross-link hydrophilic polymers with a cross-linking agent. A polymer solution is mixed with a cross-linker and coated on a porous substrate by dip-coating or spin-coating. The network formation occurs after activation with heat or UV radiation. Optimization of the hydrogel coating is carried out by varying polymers, polymer formulations and cross-linking conditions. The hydrogels are characterized by common values, e.g. the yield of the hydrogel and the equilibrium degree of swelling. In order to avoid performance loss, the stability, water vapor permeation and selectivity are tested at working conditions of the fuel cell.

Collaboration: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; Mahle Filtersysteme GmbH, Stuttgart; Fumatech BWT GmbH, Bietigheim-Bissingen; University of Regensburg, Institute of Organic Chemistry, Regensburg

Funding: Federal Ministry for Economic Affairs and Energy (BMWi), promotional reference 03ET6091D

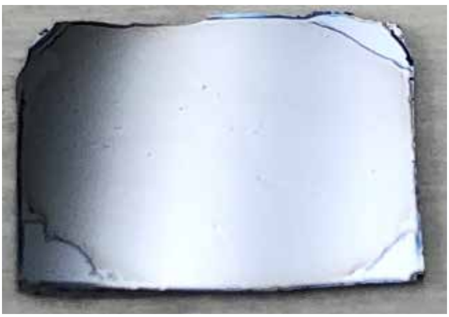


Fig. 1: Spin-coated and cross-linked hydrogel film on a silanized silicon wafer as model substrate for organic membrane carrier.

Fig. 2: Dip-coated and cross-linked hydrogel film on a membrane carrier foil.

Functionalization of Hydrogels with Polymerizable Surfactants

Jana Grübel, Günter Tovar, Alexander Southan

Poly(ethylene glycol) is a synthetic polymer which is often used in biomedical research. PEG-based hydrogels are biocompatible and are applied in tissue engineering, drug delivery and for biosensors. Due to their bioinert surface, they inhibit protein adsorption and cell adhesion. Functionalization of these hydrogels via various methods, such as binding of amino acid sequences or biopolymers, can enhance cell attachment.

We want to generate a functionalization of PEG-based hydrogels without changing their bulk properties. For this purpose, we synthesize polymerizable surfactants with a functional group. These surfactants can take part in the cross-linking process and are covalently bound into the hydrogels. With this strategy, the hydrogels are provided with a positive charge and the functionalization was confirmed by several analytical methods. The functional groups are further used to covalently bind bioactive coatings generated by inkjet printing onto the surfaces of the hydrogels. In the last step, the functionalized hydrogels will be investigated with cell culture experiments.

Collaboration: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart

Funding: PhD scholarship of the Evonik Foundation; High Performance Center for Mass Personalization

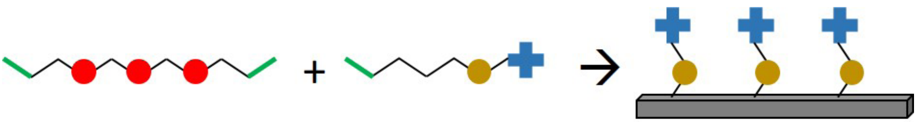


Fig. 1: Schematic visualization of functionalized PEG-based hydrogels. Polymerizable surfactants with a positive charge can copolymerize with the macromonomers to form surface-functionalized materials.

Specialized Spray Dried Drug Delivery Systems for Controlled Dosing at the Olfactory Epithelium Enabeling Nose-to-Brain Transport of Proteinaceous Active Ingredients

Lena Marie Spindler, Günter Tovar

More than one billion people suffer from diseases of the central nervous system. Besides inflammatory and neurodegenerative diseases, neuronal and psychiatric disorders come into account. A major problem in the treatment of the central nervous system disorders is the shielding blood-brain barrier (BBB). High dosing is needed to reach therapeutically effective concentrations at the target site. This implies serious side effects, which burdens patients additionally to their actual illness. A promising future approach is intranasal drug delivery, which enables direct medication of the brain and the central nervous system. The Nose-to-Brain (N2B) transport is scientifically proven, but suitable dosage forms are rare yet.

In this work, spray drying is utilized as formulation method. Spray drying enables the production of microparticles and encapsulation of active pharmaceutical ingredients (API) in one step. Due to the encapsulation in functional biopolymers, such as chitosan, mucoadhesive properties are facilitated. Furthermore, a controlled release profile is adjusted, taking advantage of specific material properties in combination with an innovative hydrogel matrix as second barrier of this specialized drug delivery system. This enables continuous dosing, as well as enhanced bioavailability and protection of the encapsulated proteinaceous API against environmental conditions, such as pH, light and temperature, which might cause denaturation and loss of function.

Collaboration: Carmen Gruber-Traub, Michaela Müller and Achim Weber, Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart

Funding: This work has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement no. 721098 and is sponsored by a PhD scholarship program of the Studienstiftung des deutschen Volkes e.V.

Biomimetic Hydrogels for 3D Cartilage Equivalents

Lisa Rebers, Kirsten Borchers, Günter Tovar, Alexander Southan

Articular cartilage can be classified into three zones that differ in composition and structural organization. This superstructure is essential for mechanical properties and is maintained by the chondrocytes. Nevertheless, depth-dependent differences are considered rarely in tissue engineering (TE) approaches. Usage of biobased hydrogels as 3D-scaffolds for cartilage-TE is a promising approach. Therefore, gelatin methacryloyl (GM) is widely used. However, application of these hydrogels as cell-matrix-implants is limited by poor load-bearing capacity.

Aim of this project is the strengthening of hydrogels, based on biopolymers occurring in the natural extracellular matrix (ECM) of cartilage. As a basis, we strenghtened GM hydrogels (as collagen substitute) by a sophisticated choice of raw material (Sewald et al., 2018) and utilization of physical gelation in addition to chemical cross-linking (Rebers et al., 2019). Zonal differences in water content and strength of cartilage-ECM was emulated by varying hydrogel-composition. Robotic Dispensing will be used to manufacture hydrogels with a zonal strucutre (Stier et al., 2019). Thereby, new functional scaffolds for 3D-culture of chondrocytes are investigated and could serve as a basis for mechanically stable cartilage-equivalents.

Fig. 1: Schematic visualization of hydrogel design as functional scaffold for cartilage tissue engineering. Three biomimetic hydrogel compositions will be investigated and processed via robotic dispensing.

Publications: Sewald, L., Claaßen, C., Götz, T., Claaßen, M. H., Truffault, V., Tovar, G. E. M., Southan, A., Borchers, K. (2018) Beyond the modification degree: Impact of raw material on physicochemical properties of gelatin type A and type B methacryloyl. Macromolecular Bioscience 18, 1800168-1800178. https://doi.org/10.1002/mabi.201800168
Rebers, L., Granse, T., Tovar, G. E. M., Southan, A., Borchers, K. (2019) Physical interactions strengthen chemical gelatin methacryloyl gels. Gels 5, 4–16. http://dx.doi.org/10.3390/gels5010004
Stier, S., Rebers, L., Schönhaar, V., Hoch, E., Borchers, K. (2019) Advanced formulation of methacryl- and acetyl-modified biomolecules to achieve independent control of swelling and stiffness in printable hydrogels. Journal of Material Science: Materials in Medicine 30, 35. http://doi.org/10.1007/s10856-019-6231-0

Collaboration: Achim Weber, Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart

Funding: PhD scholarship of the Evonik Foundation

Synthesis of Furan-Functionalized Polyelectrolytes for the Production of Double Network Hydrogels via Diels-Alder Cycloaddition

Oliver Gorke, Günter Tovar, Alexander Southan

Due to their high water content, hydrogels potentially have a very broad field of application, but in most cases the mechanical strength is very low. Double network hydrogels, on the contrary, have a high mechanical stability altough containing a large amount of water (50–90%). These hydrogels, by definition, consist of a rigid, brittle, polyelectrolyte network and a soft, ductile polymer network which are interlaced.

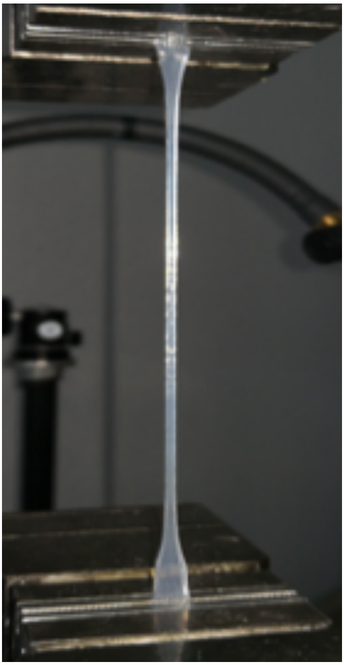


Fig. 1: Tensile test of a calcium alginate/polyacrylamide double network hydrogel.

For the investigation of the mechanical properties of double network hydrogels, it is important to produce standardized and defect-free samples for tensile and compression tests. The calcium alginate/polyacrylamide double network hydrogel system is used to establish a reproducible measurement method, which can be transferred to novel furan-functionalized polyelctrolyte/polyacrylamide hydrogel systems. For the preparation of the polyelectrolyte networks, a furan-functionalized polymer based on poly(glycidyl tosylate) or furan-modified gelatin (furfuryl gelatin) are cross-linked via a Diels-Alder cycloaddition using a bismaleimide cross-linker.

Collaboration: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB; Mikhail Itskov, Dept. of Continuum Mechanics RWTH Aachen University

Funding: German Research Foundation (DFG), Project: Mechanics of tough hydrogels, funding code SO 1387/2-1

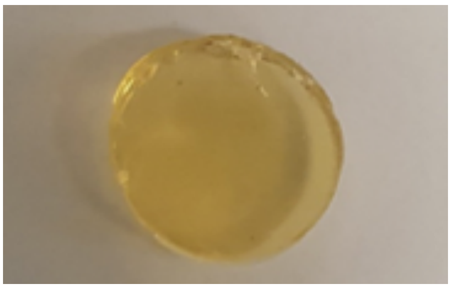


Fig. 2: Furfuryl gelatin polyelectrolyte network crosslinked via bismaleimide crosslinker.

Tribology System for Cold Sheet Metal Forming Based on Volatile Lubricants

Paul Reichle, Günter Tovar

Regarding the reduction of material loss during the production process, sheet metal forming is one of the most effective technologies in manufacturing. Usually mineral oil based lubricants are utilized to decrease friction and wear within the forming process and to facilitate removal of the part from the tool afterwards. The lubricants often contain toxic or environmentally long-time-stable additives. Typically, for lubrication the oil is spread on the sheet metal before the forming process. To ensure consistent product quality in further process steps like coating, the parts have to be cleaned cost- and time-intensively after the forming. One approach to reduce the environmental impacts and the production steps is using a volatile lubricant such as carbon dioxide (CO_2) or nitrogen for lubrication. For this, the media is injected during the process between the sheet metal and the forming tool through laser drilled micro holes with a diameter of around 350 µm (similar to a steam iron). For this application, the used CO_2 is taken out of a 60 bar gas cylinder in its liquid phase via a riser pipe. To investigate the lubrication effects in the friction zone between tool and workpiece, the wetting of different surfaces with liquid CO_2 was examined. For this, a pressure chamber was used to perform captive bubble measurements in comparable conditions to those in the forming process.

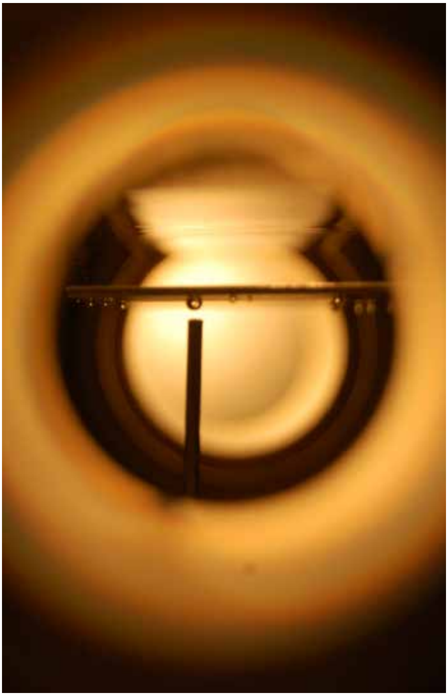


Fig. 1: Experimental setup to measure the contact angle of liquid carbon dioxide with 1.2379 tool steel via captive bubble method.

Collaboration: Georg Umlauf, Jakob Barz, Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; Manuel Henn, Thomas Graf, Institut für Strahlwerkzeuge IFSW, University of Stuttgart; Gerd Reichardt, Matthias Liewald, Institute for Metal Forming Technology IFU, University of Stuttgart

Funding: German Research Foundation (DFG), SPP 1676: Dry Metal Forming – Sustainable Production through Dry Processing in Metal Forming (TO211/3-2), for further information visit www.trockenumformen.de

Investigation and Characterization of an Azide-Modified Extracellular Matrix as Potential Biomaterial

Silke Keller, Alexander Southan, Günter Tovar

Biomaterials are materials that interact with biological systems in order to treat, augment or replace any tissue, organ, or function of the body. These materials have to meet certain mechanical requirements and have to be compatible with the body. Depending on the envisaged application, it can be desirable that they affect the biological activities and responses of cells. In a natural tissue the extracellular matrix (ECM) resembles the natural microenvironment of cells. Due to its high biological activity, the isolated ECM is a promising biomaterial for the use in tissue engineering and regenerative medicine. However, the use of ECM is limited, e.g. due to the lack of specific functional groups which are often required for their use as coatings or scaffolds. Thus, our approach is to develop an azide-functional ECM which resembles the natural ECM composition of the body and which can furthermore be addressed in a biocompatible chemical reaction (azide-alkyne cycloaddition). Therefore, we incorporate azide groups as chemical handles into the ECM by metabolic glyco engineering. This so-called clickECM can e.g. be conjugatd with alkyne-functional drugs or biomolecules or it can be immobilized on alkyne-functionalized surfaces to form stable surface coatings to enhance cell adhesion.

Publication: Ruff, S. M., Keller, S., Wieland, D. E., Wittmann, V., Tovar, G. E. M., Bach, M., Kluger, P. J. (2017) clickECM: Development of a cell-derived extracellular matrix with azide functionalities, Acta Biomaterialia 52. https://doi.org/10.1016/j.actbio.2016.12.022

Collaboration: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; Petra J. Kluger, Reutlingen University, School of Applied Chemistry, Reutlingen; University of Konstanz, Department of Chemistry and Konstanz Research School Chemical Biology, Konstanz; University of Hohenheim, Module 3: Analytical Chemistry Unit, Stuttgart

Funding: PhD scholarship of the Peter und Traudl Engelhorn Stiftung; Baden-Württemberg Bioeconomy Research Program of the Baden-Württemberg Stiftung and the Ministry of Science, Research and the Arts of the State of Baden-Württemberg (“Glykobiologie/Glykobiotechnologie”, reference no. 33-7533-7-11.9/7/2; Vector Stiftung (grant number: P2015-0052); Baden-Württemberg Stiftung (“Glycobiology/Glycomics”, grant no. P-BWS-Glyko/09); Fraunhofer Internal Program Discover (grant no. Discover 828 355)

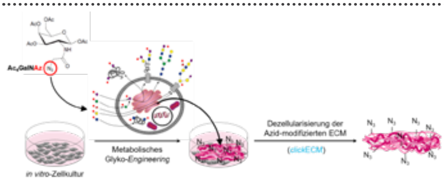


Fig. 1: Metabolic glyco-engineering to generate an azide-modified extracellular matrix (“clickECM”).

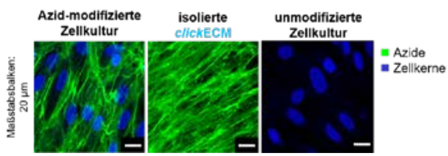
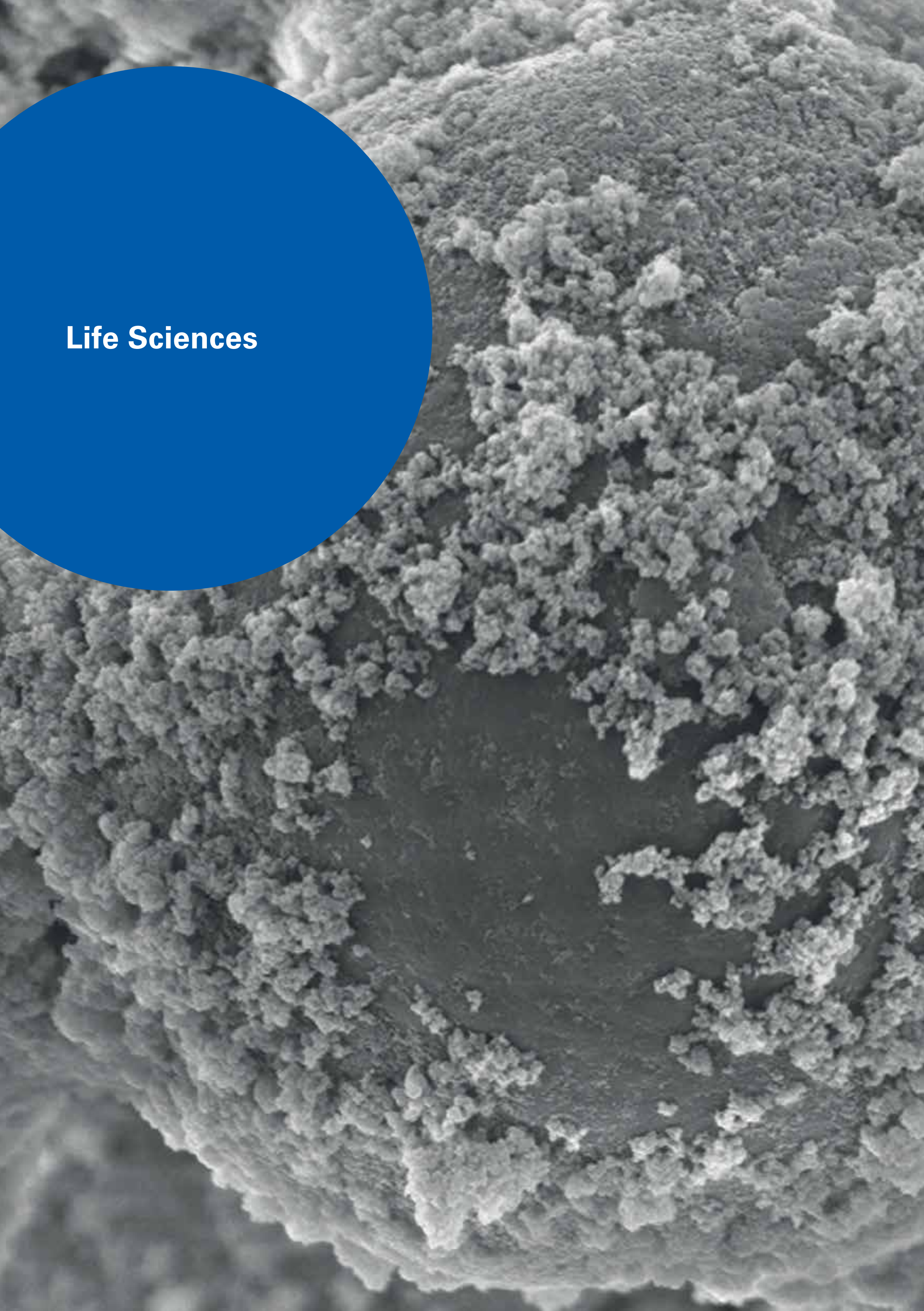


Fig. 2: Detection of the fluorophore-conjugated azides within the clickECM via laser-scanning microscopy.

Life Sciences



Friend or Foe – Research of Viruses

Prof. Dr. Susanne M. Bailer, susanne.bailer@igvp.uni-stuttgart.de

Research in the group of Biological Interfacial Process Engineering BGVT has a strong focus on infectious diseases caused by viruses, bacteria and fungi. Herpesviruses represent an important group of human pathogens including Herpes simplex virus 1 (HSV1) and Epstein-Barr virus. With the aim to identify and characterize novel panherpesviral drug targets, we follow conserved steps of virus morphogenesis, using HSV1 as prototype. These include capsid assembly in the nucleus and release to the cytoplasm using a nonconventional membrane budding process through the nuclear envelope called nuclear egress. Analysis of conventional nucleo-cytoplasmic trafficking of herpesviral proteins through the nuclear pore is complementing these approaches.

Beyond being pathogens, viruses represent attractive platforms for virus-based technologies. Virus vaccines have successfully been applied to fight infections, as exemplified by polioviruses that are close to worldwide eradication. Advanced engineering of viruses enables the development of novel vaccines that are safe, highly potent and multivalent. The same technology is used to program virus genomes for oncolytic tumor therapy. Modular functionalization of platform viruses is aimed to develop a combined tumor-immune therapy thereby translating virus-based research into medical application. Further efforts at the BGVT go into the development of diagnostic methods and devices. Multiplex PCRs, DNA microarrays and Nucleid acid-based lateral flow (NALFA) assays are developed that are ideally suited for the highly parallel detection of pathogens causing human infections and for the integration into point-of-care devices.

Diagnostic Assays, Models and Sensors

Dr. Anke Burger-Kentischer, anke.burger-kentischer@igvp.uni-stuttgart.de

For more than 18 years, genetic modification and complex cultivation techniques of mammalian cells have been used in the innovation field Cell- and Tissue Technologies. A central aim of the innovation field is the development of new human physiologically relevant in-vitro test systems. Various cell-based toxicity assays, antibacterial, antiviral and pyrogenic/allergenic tests have been established and can be performed according to GLP (good laboratory practice). Moreover, complex epithelial 3D skin and infection models with integrated immune system have been developed to test pharmaceutical substances and other active compounds as well as additives for cosmetics and food and to investigate host-pathogen interactions. A particular focus is set on reporter gene systems for the detection of immune receptor ligands (interferon- and toll-like receptors) which are also used as sensors for microbial contaminants.

Characterization of the Herpes Simplex Virus Nuclear Egress

Débora Marques, Susanne M. Bailer

The family of the Herpesviruses is divided into three subfamilies, alpha-, beta- and gamma herpesviruses, based on characteristics such as cell tropism, pathogenicity and the site of latency. Herpes simplex virus type 1 (HSV1), an alpha-herpesvirus, causes recurrent facial lesions, keratitis or encephalitis. Morphogenesis of herpesviral virions starts in the nucleoplasm and is completed in the cytoplasm requiring nuclear export of the capsid. Size limitations of the mature capsid prevent its transport through the nuclear pore complex. Instead, the particle uses an envelopment/de-envelopment process through the nuclear membranes called nuclear egress. This budding process, executed by the nuclear egress complex (NEC) composed of the viral proteins pUL31 and pUL34, is conserved throughout the herpesviral family and essential for viral replication. Therefore, the NEC represents a potential target for panherpesviral therapy. Numerous aspects of nuclear egress remain unclear. Using bacterial artificial chromosome (BAC) technology, a fluorescently tagged capsid protein VP26 is expressed [1]. This allows capsid tracking from the nuclear interior to the site of budding using live imaging to gain detailed insight into this highly complex process.

[1] Nagel, C. H., Döhner, K., Fathollahy, M., Strive, T., Borst, E. M., Messerle, M., Sodeik, B. (2008) Nuclear egress and envelopment of Herpes simplex virus capsids analyzed with dual-color fluorescence HSV1(17+). Journal of Virology, 82(6), 3109–3124, doi:10.1128/JVI.02124-07

Collaboration: Beate Sodeik, Institute of Virology, Hannover Medical School, Hannover; Zsolt Ruzsics, University Medical Center Freiburg, Freiburg im Breisgau

Funding: Science without Borders – Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil

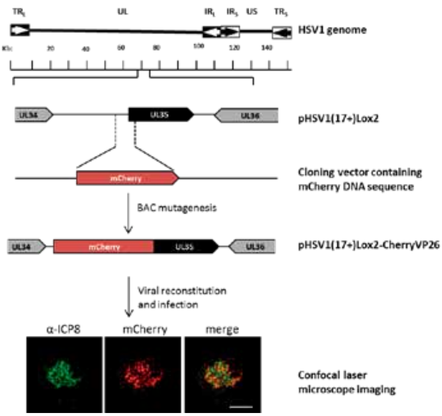


Fig. 1: Scheme showing the generation of fluorescently labeled HSV1 capsids starting with BAC mutagenesis up to the microscopic analysis. The pHSV1(17+)Lox2 and pHSV1(17+)Lox2-CherryVP26 represent the BAC containing the HSV1 genome wild type and encoding the mCherry labeled capsid, respectively. The viral protein infected cell protein 8 (ICP8) was labeled by indirect immunofluorescence to compare its distribution with the one from the mCherry.

Screening and Identification of Endogenic Proviral Substances

Eileen Arnold, Susanne M. Bailer

Epstein-Barr virus (EBV) is one of the most common human viruses worldwide. Following initial infection, EBV becomes strictly latent and contributes to cell growth and oncogenic transformation which can lead to EBV-associated cancer. Recently, a new promising therapeutic strategy for the treatment of EBV-associated tumors was reported, which is based on a targeted destruction of EBV-positive tumor cells following proviral treatment. Initial clinical studies revealed the demand of new proviral agents with higher EBV-reactivating properties and less cytotoxicity. We hypothesize that human peptides could be a promising source of new proviral agents.

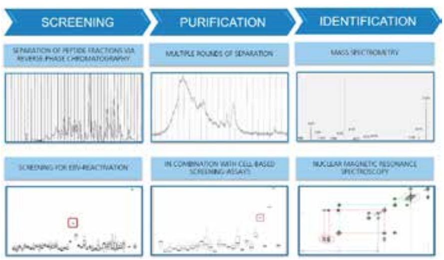


Fig. 1: Schematic outline of the strategy to identify and isolate proviral peptides from a human peptide library. A proviral peptide fraction was identified with significant EBV-reactivating effects. The proviral substance was purified in multiple rounds of separation via reverse-phase chromatography and screening for proviral activity. The purified active agent was identified by mass spectrometry analysis and nuclear magnetic resonance spectroscopy. All images are illustrated exemplarily.

To identify these proviral peptides, a cell-based reporter assay for EBV-reactivation was developed and a human peptide library was screened. Finally, a proviral fraction with significant EBV-reactivating effects was identified and isolated via reverse-phase chromatography. The purified substance was analyzed via mass spectrometry and identified as an endogenic human peptide. In further studies, the unknown molecule will be comprehensively characterized for its suitability as therapeutical drug. The identification of new proviral peptides may contribute to a promising therapy specific for EBV-associated tumors.

Collaboration: Pharis Biotec GmbH, Hannover

Funding: PhD scholarship of the Landesgraduiertenförderung Baden-Württemberg

Establishment of a 3D Human Oral Mucosa Model

Tina Rehm, Günter Tovar, Steffen Rupp,
Anke Burger-Kentischer

3D *in vitro* skin models are test systems based on *in vivo* conditions that can partially replace the use of animal models as infection models or for modelling other human skin diseases. Especially for the investigation of oral infections a human immune cell supplemented mucosa model was developed. The epidermal structure was greatly improved by optimizing the keratinocyte cultivation, their integration and cultivation inside the model. To evaluate the new models on the basis of skin- and mucosa-specific markers, the models were analyzed by immunohistochemical staining (IHC) with specific antibodies. In comparison to a normal skin model, the oral mucosa model clearly shows a different morphology and expression of specific markers and thus confirms the successful establishment of an oral mucosa model.

For integration of human immune cells in the oral model, they were isolated from Buffy Coat by density centrifugation. T cells were selected from the isolated immune cells by negative selection of CD4 or the γ/δ-T-cell receptor. Successful isolation and selection of specific T cells was analyzed by flow cytometry. The integration of T cells was successfully demonstrated.

Funding: Fraunhofer Project Center for Drug Discovery and Delivery at the Hebrew University of Jerusalem, Israel

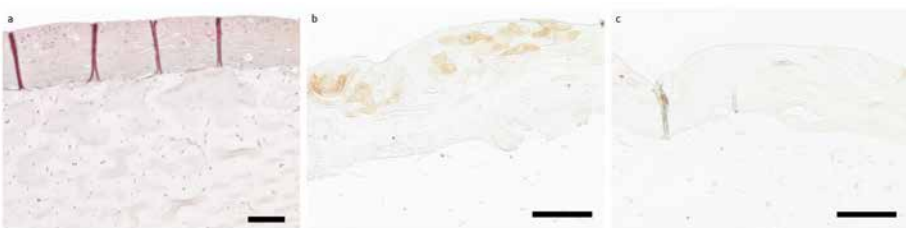


Fig. 1: Immunohistochemical staining of the new oral models. Staining for differentiation and hornification marker cytokeratin-10 (a), staining of mucosa marker cytokeratin-13 in non-basal layers (b), staining of differentation marker involucrin in suprabasal layers (c) and staining of late differentation marker filaggrin (d).

Stimulation of Innate Immune Receptors in a Human 3D Infection Skin Model with a TLR4 Antagonist against *C. albicans* Invasion

Helena Merk, Steffen Rupp, Anke Burger-Kentischer

Innate immune receptors play a key role in many acute and chronic inflammatory diseases. Therefore there is a great interest in therapeutic manipulation of innate immune receptors by antagonists and agonists. Immune receptors like the toll-like receptor (TLR), C-type lectin-like receptors (CLR) family or cytokine signaling receptors are shown to be critical for immunity of fungal infections, which remain a leading cause of morbidity.

A human immune cell-supplemented skin infection model is used to validate new TLR agonist and antagonists for the inhibition of *Candida albicans* invasion. Therefore the model is supplemented with CD4-positive T cells, which show itself a protective effect against *C. albicans* invasion (Fig. 1). By the pre-treatment of T cells with a compound active against TLR4 in an antagonistic way, we observed an increased invasion of *C. albicans* although immune cells are present (Fig. 1, right). This shows the successful validation of new immunomodulatory compounds in a human 3D skin model. Further studies aim to identify defense mechanisms by the addition of a TLR4 agonist to induce inflammatory response within the skin model.

Collaboration: EMC microcollections GmbH, Tübingen, Germany; The Hebrew University of Jerusalem, Israel

Funding: German Federal Ministry of Education and Research (BMBF), promotional reference 031L0124A

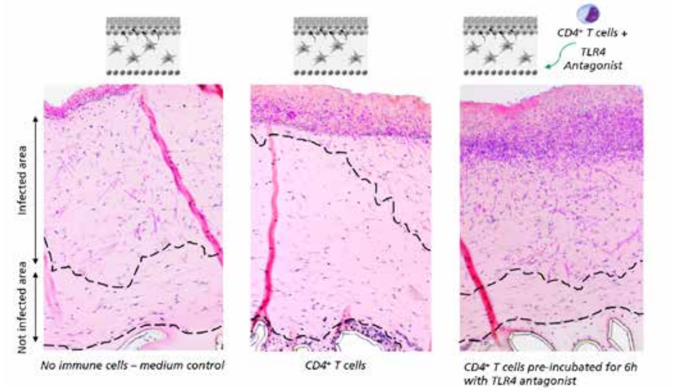
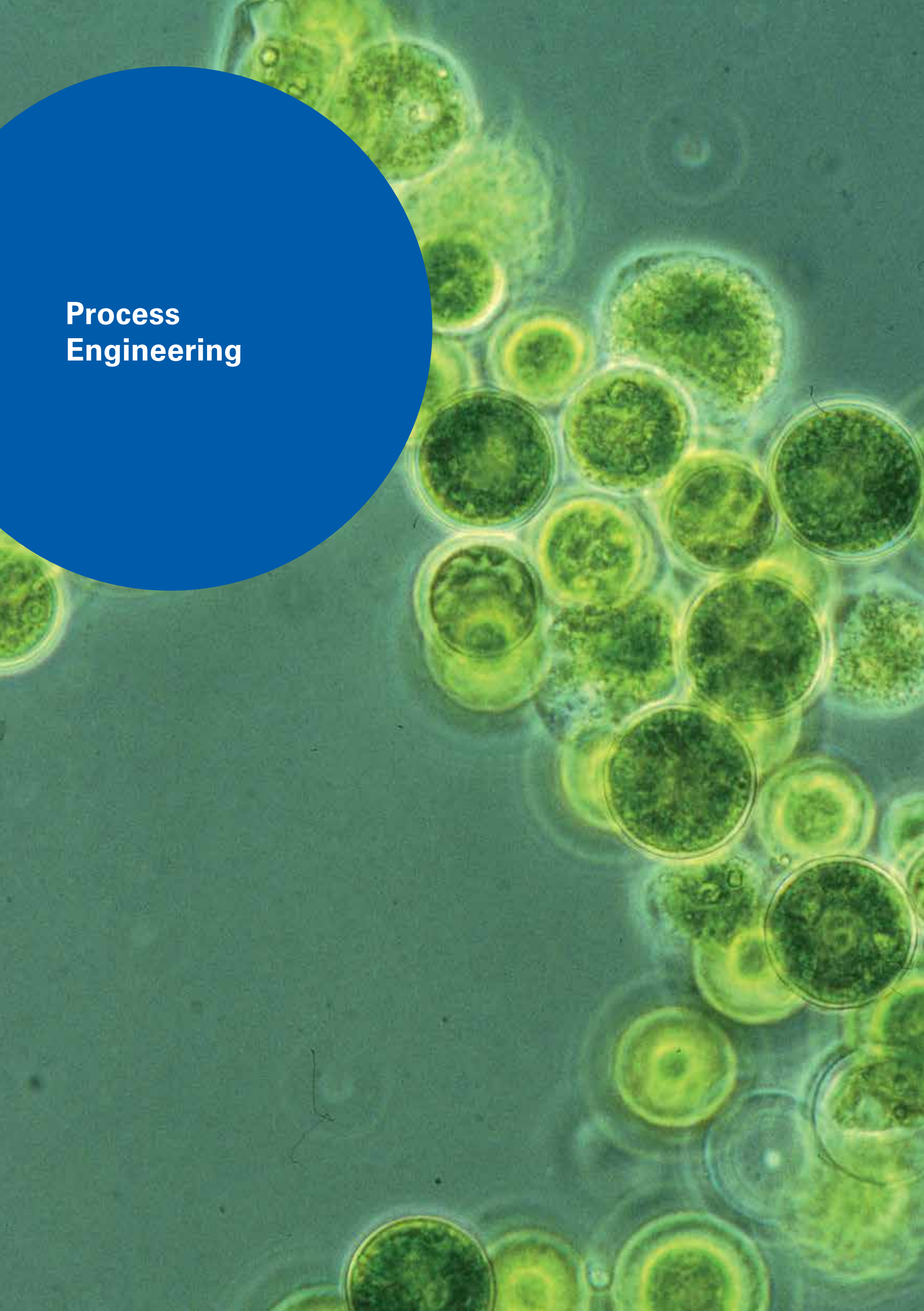


Fig. 1: Infection of skin models with *Candia albicans* in the presence of immune cells (middle picture), absence of immune cells (left) and incubation of immune cells with a TLR 4 antagonist (right).

Process Engineering



Interfaces in Bioprocess Engineering

Dr.-Ing. Matthias Stier, matthias.stier@igvp.uni-stuttgart.de

Interfaces often play a decisive role in bioengineering. In processes for the treatment of wastewater and exhaust air, microorganisms or enzymes are often immobilized on carriers in order to increase catalyst density. The microorganisms in aerobic and anaerobic production systems are strongly affected by the ambient conditions in fermenters. For this reason, there is a need for studying the respective processes in their entireties. Therefore we use on the one hand analyses in the laboratory such as next-generation sequencing and on the other hand high-tech process analysis such as mass spectrometry. We apply standard fermenters but in addition also specific reactor systems such as the flat-panel airlift (FPA) reactor (developed at Fraunhofer IGB) and self-developed membrane reactors in particular for the use of gaseous substrates such as carbon dioxide and methane instead of sugar. In this manner new products for a sustainable biobased future are developed.

For new products an effective downstream processing is also necessary. For example microalgae contain a broad range of ingredients that can potentially be used in the food and feed sector. From microalgal and plant fatty acids, biosurfactants can be produced by microorganisms and be tailored in their surfactant performance. Therefore, we investigate various cascading extraction methods in order to harvest the products efficiently from the biomass.

The transfer of innovations from research to the market is a key objective of our activities in this field. Product visions and business models are methodically developed. Since 2015, two start-up projects have been pursued.

Industrial Biotechnology

Dr.-Ing. Susanne Zibek, susanne.zibek@igvp.uni-stuttgart.de

Bioprocess engineering and industrial biotechnology are becoming increasingly important within the area of bioeconomy. The IGVP is working on topics such as the treatment of renewable resources (lignocellulose, plant oils), enzyme screening, process development and scale-up of fermentation processes. Most focus is on optimizing fermentation processes for the microbial production of biosurfactants and polyhydroxyalkanoates from 2nd generation feedstock. Another important topic is the purification of these fermentation broths. Here we work on different downstream processing techniques such as extraction, chromatography or crystallization in order to produce high-quality products being tested by industrial partners.

Recovery of Microbial Biosurfactants Mannosylerythritol Lipids (MEL) from Culture Broths

Fredy Wsbaldo Baron-Nunez, Günter Tovar, Susanne Zibek

Mannosylerithirol lipds (MEL) are microbial surfactants with promising applications in the homecare and cosmetic industry. Its production requires both vegetable oils and glucose as carbon sources. Given the amphiphilic nature of MELs, the final culture broth (CB) is an emulsion where oil and biomass are dispersed in aqueous media.

Fig. 1: Dewatering of the MEL containing culture broth by addition of chaotropic salts.

Solvent extraction is used to recover MEL from the CB, MEL and remaining oil are recovered in the organic phase while media and biomass remain in the aqueous phase. To ensure the scalability of MEL recovery, the amount of solvent used and size of equipment needs to be optimized.

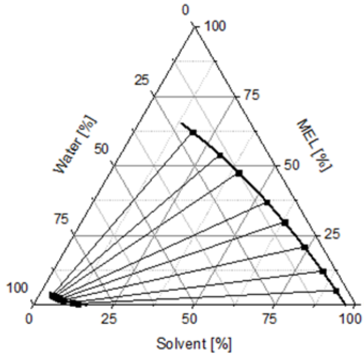


Fig. 2: Ternary diagram with the mass fractions distribution for MEL, water and solvent systems.

Dewatering of the CB by addition of chaotropic salts before the solvent extraction was achieved, around 30-60% of the CB was discarded without loss of MEL (less than 5%). In addition, characterization of the liquid liquid equilibrium of the solvent extraction system was done. Ternary diagrams were determined with the concentration distribution of all possible solvent extraction scenarios. This facilitates the understanding of the system behavior and the design equipment.

Collaboration: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart

Funding: Federal Ministry of Education and Research (BMBF), promotional reference 031B0469P

High-troughput Fermentation Screening of the PHB-producer *Cupriavidus necator* NCIMB 11599

Nicole Werner, Thomas Hahn, Susanne Zibek

In the joint project SusPackaging, we are interested in the fermentative production of polyhydroxybutyrate (PHB) as a substitute for conventional plastic in sustainable cosmetic packaging. Due to thermoplastic and elastomeric properties, we are mostly focused on the production of PHB copolymers with *Cupriavidus necator* through precursor feeding.

In our studies we are using a microfermenter system with real-time pH, DO and biomass monitoring to optimize growth and to analyze the effects of cosubstrate type, combination and concentration on PHB copolymer composition. Through screening of various growth conditions, we determined urea and a C/N ratio of 50:1 as most efficient for biomass production. Since some precursors are known to affect microbial growth, inhibition curves for five precursors were determined in this system. Levulinic acid was identified as a promising precursor for the production of PHBV, GBL, 1,3-butanediol or 1,4-butanediol for the production of P4HB. In further experiments, we are interested in the simultaneous feeding of different precursors. We could already demonstrate that the inhibitory effects by parallel feeding of two precursors are not adding up proportionally. Our effort is to develop optimal precursor feeding strategies to fine-tune polymer properties on customer demand. We already evaluated some results in a 3 L benchtop fermenter demonstrating the effectiveness of the microfermenter system for fermentation optimization.

Collaboration: University of Stuttgart, Institute of Microbiology, Stuttgart; Fraunhofer Institute for Interfacial Engineering and Biotechnology (IGB), Stuttgart; Fraunhofer Institute for Process Engineering and Packaging (IVV), Freising; LCS Life Cycle Simulation, Backnang; HPX Polymers GmbH, Tutzing; WALA Heilmittel GmbH, Bad Boll; WELEDA AG, Schwäbisch Gmünd

Funding: Federal Ministry of Education and Research (BMBF): Cost-efficient production of biopolymer polyhydroxy alkanoates (PHA) for the manufacturing of tailor-made sustainable packaging concepts for the cosmetic industry, promotional reference 031B0371D. Special thanks to Ana Lucia Vásquez (Fraunhofer IGB) for the project coordination.

Process Engineering for the Production of the Microbial Biosurfactant Mannosylerythritol Lipid (MEL)

Alexander Beck, Susanne Zibek

Mannosylerythritol lipids (MEL) produced by fungi of the *Ustilaginaceae* family are highly promising microbial glycolipid biosurfactants with possible applications in household detergents, cosmetics or personal care. The aim of this project is to establish, optimize and model a bioreactor production process of MEL that can be transferred towards industrial scale.

Fig. 1: Different structures of MEL produced from rapeseed oil depending on the employed microorganisms.

Based on an initial screening of different producing microorganisms and plant oil substrates, we selected three microorganisms showing high potential regarding titer and yield. Moreover, the MEL biosurfactants from the three organisms differ in their chemical structure. Hence, specific structures can be produced to account for diverse fields of application. The production process was then established in bench-top bioreactors (1-L to 7-L scale) to evaluate the most critical parameters: aeration, mixing and pH control. Foaming, a major challenge to address during biosurfactant production, could be reduced by mounting mechanical foam brakers onto the agitator shaft.

Based on the generated process data, a kinetic process model was established in AspenPlus modelling software during a research period in Rio de Janeiro, Brazil. With this model, different scenarios can be tested and afterwards validated in the lab. The next steps are to increase the robustness of the fermentation, to improve the space-time yield by designing a fed-batch process and then to scale-up the process into our 40-L pilot reactor. Ultimately, techno-economic and life cycle assessment can determine the economic feasibility and ecological impact of the MEL production process.

Publications: Beck, A., Werner, N., Zibek, S. (2019) Chapter 4 – Mannosylerythritol Lipids: Biosynthesis, Genetics, and Production Strategies. In D. G. Hayes, D. K. Y. Solaiman & R. D. Ashby (Eds.), Biobased Surfactants (Second Edition) (pp. 121-167), AOCS Press. https://doi.org/10.1016/B978-0-12-812705-6.00004-6
Beck, A., Haitz, F., Grunwald, S., Preuss, L., Rupp, S., Zibek, S. (2019) Influence of microorganism and plant oils on the structure of mannosylerythritol lipid (MEL) biosurfactants revealed by a novel thin layer chromatography mass spectrometry method. J Ind Microbiol Biotechnol, 46(8), 1191-1204. https://doi.org/10.1007/s10295-019-02194-2
Beck, A., Zibek, S. (2020) Mannosylerythritollipide – mikrobielle Biotenside aus dem Bioreaktor. BIOspektrum, 26(1), 100-102. https://doi.org/10.1007/s12268-020-1332-3

Collaboration: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart

Funding: Baden-Württemberg Bioeconomy Research Program (Reference no. 7533-10-5-85B), funded by the Baden-Württemberg Stiftung and the Ministry of Science, Research and the Arts

Sporisorium scitamineum – a Novel Producer of the Biosurfactants Cellobiose Lipids

Amira Oraby, Günter Tovar, Steffen Rupp, Susanne Zibek

Cellobiose lipids (CL) are biosurfactants that are produced by various microorganisms from the family *Ustilaginaceae*, the so-called smut fungi. They are associated with different antimicrobial properties and surface active behavior, which gives them potential for application in cosmetics or detergents.

Sporisorium scitamineum is a well studied sugarcane smut fungi and producer of mannosylerythritol lipids, that was recently identified as CL producer. In order to exploit its potential for CL synthesis, the aim of this research was to examine different factors affecting its growth behavior and productivity. We were able to identify an acidic pH value of 2.5 as optimal for CL synthesis, obtaining maximum concentrations of 17.6 g·L^{-1} in 1-L bioreactors. We further screened different fermentation media compositions and carbon sources and identified sucrose as a substrate that results in high CL concentrations, while mineral salt media containing trace elements further proved to be beneficial for product accumulation.

The produced CLs were extracted from the sediment of the culture broth after several washing and separation steps, then dried and grinded to a white-yellowish powder. Structural analysis of the obtained CLs shows a high identity to known structures from literature.

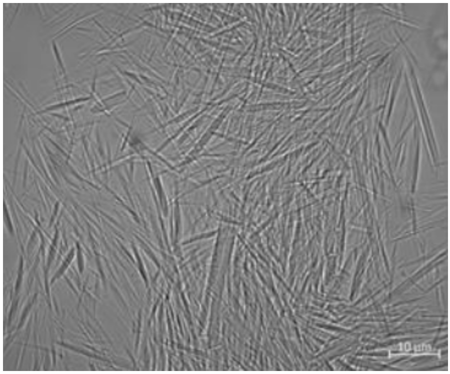


Fig. 1: Microscopic image of *Sporisorium scitamineum* culture broth containing CL crystals, which are typically precipitated as needle like crystals under acidic conditions.

Collaboration: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart

Funding: PhD scholarship of the Deutsche Bundesstiftung Umwelt DBU (German Federal Environmental Foundation), AZ: 80017/333; Federal Ministry of Education and Research (BMBF), promotional reference FKZ: 031B0469P

Selective Oxidation of Benzene and Propylene by the Aerobic Methanotrophic Bacterium *Methylosinus trichosporium* OB3b

Ilka Mühlemeier, Günter Tovar, Matthias Stier

Methylosinus trichosporium OB3b belongs to the type II aerobic methanotrophic bacteria (MOB). Due to the enzyme methane monooxygenase (MMO) these bacteria are able to use methane as their sole carbon and energy source. Furthermore, the enzyme MMO is known to oxidize other substrates like n-alkanes, n-alkenes as well as aromatic and alicyclic compounds. These features make the MOB interesting for the application in a broad variety of industrial processes.

Aiming for a continuous oxidation process with *Methylosinus trichosporium* OB3b, challenges arise due to the oxygen and the co-factor limitation over time. Thus, without optimization, the selective oxidation can only take place for about one hour. To overcome these problems a semi-continuous oxidation strategy was developed by using a novel real-time mass sprectrometer. The developed process allows the production of propylene oxide as well as phenol over several hours.

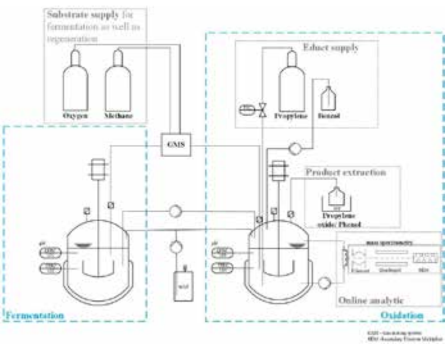


Fig. 1: P&ID flow chart of the two-stage oxidation system.

Publications: Mühlemeier, I. M., Speight, R., Strong, P. J. (2018) Biogas, Bioreactors and Bacterial Methane Oxidation. In M. G. Kalyuzhnaya & X.-H. Xing (Hrsg.), Methane Biocatalysis: Paving the Way to Sustainability (p. 213–235). https://doi.org/10.1007/978-3-319-74866-5_14

Mühlemeier, I., Stier, M., Bryniok, D., Schließmann, U., Hirth, T. (2016) Entwicklung eines Membranreaktors zur Nutzung von Methan als Kohlenstoffquelle für mikrobielles Wachstum. Chemie Ingenieur Technik, 88(9), 1384–1384. https://doi.org/10.1002/cite.201650337

Collaboration: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; Markus Pietzsch, Martin-Luther-Universität Halle-Wittenberg, Halle; Sebastian Wohlrab, Leibniz-Institut für Katalyse e.V, Rostock; James Strong, Queensland University of Technology, Brisbane

Funding: Baden-Württemberg Bioeconomy Research Program of the Baden-Württemberg Stiftung and the Ministry of Science, Research and the Arts of the State of Baden-Württemberg, reference no. 7533-10-5--/103/1

MIATEST-BW – Production of Microalgae Ingredients and Testing as a Health-Promoting Food for Humans and as an Environmentally Friendly Plant Strengthening Agent in Viticulture

Konstantin Frick, Günter Tovar, Matthias Stier

The MIATEST project deals with the production of functional ingredients from diatoms and their application in different areas. At the University of Stuttgart, the microalgae cultivation process was examined to optimize the production of the ingredients. Different cultivation conditions significantly influence the composition of the microalgae biomass. This can be used to accumulate a desired component. For example, the chrysolaminarin content can be increased from $<5\%_{w/w}$ to $>30\%_{w/w}$ by adjusting the cultivation conditions accordingly.

Fig. 1: Chrysolaminarin-rich diatom biomass, freeze-dried.

Besides the microalgae cultivation, the extraction and purification of the desired components was optimized.

The application of chrysolaminarin as a plant strengthening agent in viticulture is being tested together with the State Research Institute for Viticulture, Oenology and Fruit-growing. It is tested if chrysolaminarin can represent an alternative to existing copper based fungicides against fungal diseases. The experiments concerning the application of microalgae biomass in the field of human nutrition are carried out at the University of Hohenheim. The experiments are focused mainly on two ingredients apart from chrysolaminarin. Those are the pigment fucoxanthin and eicosapentaenoic acid, an omega-3 fatty acid. Fucoxanthin, in particular, has led to considerable interest in the industry, as it shows antioxidant, anti-inflammatory, anti-cancer and weight-reducing properties.

Collaboration: Ulrike Schmid-Staiger, Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; University of Hohenheim, Institute of Clinical Nutrition, Stuttgart; State Research Institute for Viticulture, Oenology and Fruit-growing, Weinsberg

Funding: Ministry of Science, Research and the Arts of the State of Baden-Württemberg, reference no. 7533-10-5-185A

Automation and Optimization of Microalgae Cultivation with Machine Learning Control

Yen-Cheng Yeh, Günter Tovar, Matthias Stier

Microalgae produce a variety of interesting ingredients and are therefore an ideal source for food, feed, cosmetics and fine chemicals. Although the basic mechanism of microalgae growth has been well studied, there are only a few mathematical models that can be used to model microalgae growth. Therefore, the objective is the introduction of data-based algorithms based on machine learning to develop a robust, predictive control system for large-scale cultivation of microalgae in the flat panel airlift (FPA) bioreactor.

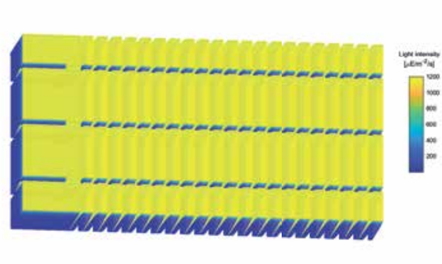


Fig. 1: Simulation of light distribution in a FPA reactor.

An essential component of this system are algorithms that enable automated optimization of microalgae growth. So-called machine learning has been widely used for prediction and optimization in different areas. To predict the growth behavior of the microalgae *Phaeodactylum tricornutum* in outdoor cultivation, so-called support vector machines (SVM) were used. The results

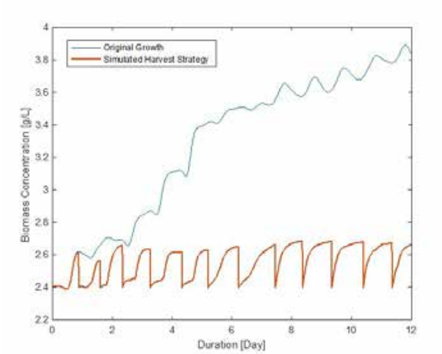


Fig. 2: Example of an optimized harvest strategy in outdoor cultivation. The blue line represents the original growth of microalgae without any harvest strategy, in which 1.2 g/L biomass is formed in 12 days. The orange line shows the amount and the timing to harvest microalgae, which produces 1.77 g/L more than the one without a harvest strategy after 12 days.

show that the SVM-based model can predict the growth rate of *Phaeodactylum tricornutum* with a correlation coefficient of 88%. At the same time, a model with Monod kinetics yields a correlation coefficient of 82%. These two models will be further validated on both laboratory and pilot scale in order to establish a model-predictive control for microalgae production.

Publications: www.igb.fraunhofer.de/en/spotlight/machine-learning-for-algae-cultivation.html

Collaboration: Bernhard Haasdok, University of Stuttgart, Institute of Applied Analysis and Numerical Simulation; Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; Fraunhofer Center for Chemical-Biotechnological Processes CBP, Leuna

Plasma and Microwave Technology

Plasma Technology

Microwave Plasmas – Fundamentals and Applications

Dr.-Ing. Matthias Walker, matthias.walker@igvp.uni-stuttgart.de

The research group on Plasma Technology (PT) works on the development of microwave-generated plasma sources at low and atmospheric pressure, the numeric simulation and diagnosis of these plasmas, and the development of a variety of resulting applications. An example of a plasma source developed at the IGVP is the so-called Duo-Plasmaline, which is operating at low pressure. The Duo-Plasmaline is a linearly extended plasma source with a length of up to several meters. It can be easily expanded to a two-dimensional plasma array by arranging several of them in parallel. Other low-pressure plasma sources utilized at the IGVP are the Planartron and an electron cyclotron resonance (ECR) heated plasma. These plasma sources are well suited for plasma-assisted surface treatment like surface activation, etching and thin film deposition. The coating and characterization of the layers, the deposition of O_2- and H_2O-permeation barriers, or scratch protection layers, and the sterilization of e.g. food packaging materials are our research topics.

In recent years the basics for large-scale and high-rate deposition of dielectric layers were investigated with the Duo-Plasmaline and demonstrated in a semi-industrial scale at the PT group. The focus of the large area plasma process was on the coating of plastic panels such as polycarbonate (PC) with substrate sizes of 6000 mm length and 3000 mm width. The basic research and layer development were performed on small substrates, typically 150×100 mm^2, and then transferred to the semi-industrial system with a length of 1000 mm and a width of 600 mm.

A current major issue is the energy storage on demand of renewable energy from wind and photovoltaic plants. The CO_2 conversion into syngas or higher hydrocarbons via a microwave plasma assisted gas conversion process at atmospheric pressure powered by renewable energy is one promising approach towards energy storage. Our plasma torch enables self-ignition and stable operation of a CO_2 plasma over a wide range of parameters as well as a flexible rearrangement of the different components to ensure the possibility to adapt to different requirements.

The PT group is also involved in experiments of a future pumping system for the planned fusion reactor DEMO. Our project partners at KIT are developing a direct internal recycling system in which hydrogen isotopes are separated from the exhaust gas via superpermeation through a metal foil pump. For this, the hydrogen molecules must be converted to atoms and ions. This is achieved with the Duo-Plasmaline.

Completion of the Project "Plasma-Assisted Ignition of Coal Powders"

Stefan Merli

In this project, the plasma-assisted ignition of coal powder was investigated for the increase of the flexibility and efficiency of coal-fired power plants. The used plasma torch, which generates a hot thermal plasma by a DC arc discharge, has a high-energy density and is therefore well suited for ignition even under difficult conditions. The plasma and the interaction with coal particles were examined using optical emission spectroscopy (OES) and a high-speed camera (HSC). The experiments were carried out in a lab-scale setup and under realistic conditions in an experimental combustion rig with up to 300 kW thermal power [1]. The ignition process was investigated for a large number of operational parameters, including different coal types. OES and HSC have given valuable information on the plasma properties and the interaction with the coal particles so that the plasma torch could be optimized and the basics for a process monitoring system could be derived.

The operation of the plasma torch with different gases (air, N_2, H_2O and CO_2) was also investigated. While air, N_2 and H_2O had a similar plasma flame, a larger and much more intense plasma could be generated with CO_2. Since CO_2 showed also an increased ignition efficiency, it is a promising alternative for air as operating gas for the plasma torch.

The project was successfully completed with the demonstration of the applicability of the plasma ignition in a large-scale combustion rig in Nagasaki, Japan, with up to 3 MW thermal power.

[1] Youssefi, R., Maier, J., Merli, S., Scheffknecht, G. (2018) Evaluation of the Ignition and Combustion Behavior of Solid Fuels with the Support of a Plasma Torch, Kraftwerkstechnik 2018 Power Plant Technology, 345–356, ISBN 978-3-934409-81-1

Collaboration: Reyhane Youssefi and Jörg Maier, Institute of Combustion and Power Plant Technology IFK, Stuttgart; Bernd Glocker, PlasmaAir AG, Weil der Stadt; Michalis Agraniotis, Mitsubishi Hitachi Power Systems Europe GmbH, Duisburg; Uwe Burchhardt, Lausitz Energie Kraftwerke AG, Cottbus

Funding: German Federal Ministry for Economic Affairs and Energy (BMWi), promotional reference 03ET7076B

Numerical Simulation of the Influence of a Magnetic Field on the Duo-Plasmaline

Stefan Merli

In future fusion power plants such as DEMO the recycling of fuel, especially tritium, is a major challenge. KIT is developing a direct internal recycling system in which hydrogen isotopes are separated from the exhaust gas via superpermeation through a metal foil pump. For this, the hydrogen molecules from the exhaust must be converted to atoms or ions. This is achieved with the Duo-Plasmaline, which generates large volume microwave plasmas. Since it is planned to install the recycling system close to the fusion reactor, the Duo-Plasmaline is exposed to high magnetic fields of up to 1 T. The influence of the magnetic field on the plasma was therefore numerically simulated in Comsol Multiphysics, where electron density and temperature, plasma reactions and microwave propagation are solved self-consistently. An argon plasma model was used for simplicity. The influence of the magnetic field was investigated over a wide parameter range and for different B-field orientations. The B-field decreases the mobility and diffusivity of the charged particles perpendicular to B which causes the electron density profile to "shrink" (Fig. 1).

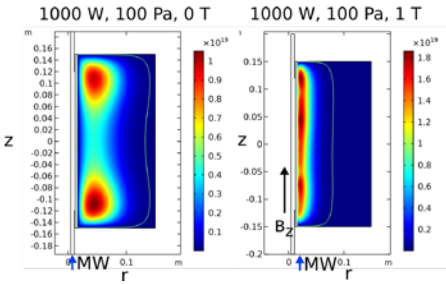


Fig. 1: Electron density distribution for 2D axisymmetric simulations without and with parallel B-field. The green contour line corresponds to the cut-off density of $7.45 \cdot 10^{16}$ m^{-3}.

The electron conductivity perpendicular to B is also reduced which decreases the microwave heating efficiency in this direction. On the other hand, additional current components can be induced due to the Lorentz force so that the plasma can be maintained. The influence of the magnetic field will be further investigated numerically for H_2 plasmas and also experimentally.

Collaboration: Yannick Kathage, Stefan Hanke and Christian Day, Karlsruhe Institute of Technology (KIT), Karlsruhe; Klaus Baumgärtner, Muegge GmbH, Reichelsheim

New Experiment for the Study of the Influence of a Magnetic Field on the Duo-Plasmaline

Stefan Merli

In addition to numerical simulations of the influence of a strong magnetic field on the plasma properties of the Duo-Plasmaline, a new setup for experimental studies was completed. For this purpose, the already existing experiment FLIPS (**F**lexible **Li**near **P**lasma experiment **S**tuttgart) was modified and adapted to the new requirements (Fig. 1). FLIPS basically consists of a large vacuum chamber (51 cm diameter, 117 cm length) with many access ports and a magnetic field coil arrangement, which can create a homogeneous axial magnetic field with up to 250 mT in the center.

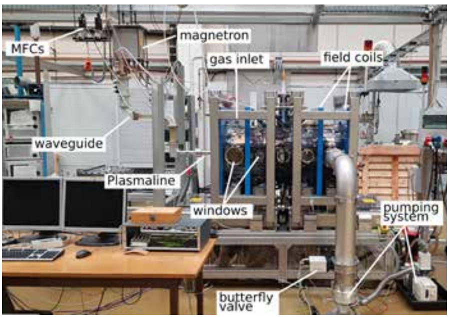


Fig. 1: Setup of the new experiment for the investigation of a strong magnetic field on the Duo-Plasmaline.

The plasma is generated by a linearly extended microwave plasma source, in this case by a one-sided Plasmaline (Gigatron). Contrary to the Duo-Plasmaline, the one-sided Plasmaline does not go through the whole vacuum chamber and is operated by microwave from one side only. The Plasmaline can be installed parallel or perpendicular to the axial magnetic field to study the influence of the B-field for different orientations. Since the Plasmaline is to be investigated for the use in an internal recycling system for hydrogen isotopes in future fusion power plants such as DEMO, H_2 and D_2 are used as plasma gases. The gas flows and the pressure can be controlled over a wide parameter range and a microwave power of up to 6 kW at 2.45 GHz is available. The magnetic flux density is precisely tunable via the coil current, so that electron cyclotron resonance effects at 87.5 mT can also be investigated.

The influence of the magnetic field on the shape, stability and ignition of the plasma is studied, among others, with optical cameras and optical emission spectroscopy and will be compared to numerical simulations.

Collaboration: Yannick Kathage, Stefan Hanke and Christian Day, Karlsruhe Institute of Technology (KIT), Karlsruhe; Klaus Baumgärtner, Muegge GmbH, Reichelsheim

Modeling of the Electron Density n_e Distribution of a Remote Plasma Source

Steffen Pauly, Andreas Schulz, Matthias Walker, Günter Tovar

In order to investigate and to optimize a microwave-powered remote plasma source (RPS) for high rate etching processes, a finite element-based model of the RPS has been developed with the aim of studying the microwave coupling into the plasma chamber and its microwave field distribution as well as the interaction of the microwave field with the plasma.

Two essential process conditions are analyzed. The first one is the ignition condition, without plasma in the RPS where the microwave propagates like in free space. If a plasma is present, which is called the operational condition, the electron density and thus the permittivity and the conductivity increase, which changes the electric field distribution in the plasma chamber.

Afterwards the result of a time-dependent and self-consistent plasma simulation is presented. An argon plasma is calculated using the fluid model. For this purpose, a selection of electron impact reactions taking place in the plasma and the associated ionization, recombination and excitation processes are considered. In addition, the equations and boundary conditions of microwave field simulations are coupled. Fig. 1 shows the electron density on a cross-section of the RPS, which occurs after one millisecond in the plasma chamber.

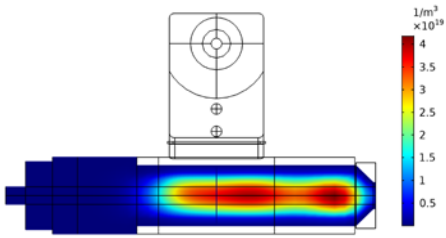


Fig. 1: Cross-section of the RPS which shows the calculated electron density distribution inside the plasma chamber at p = 160 Pa after t = 1 ms.

Collaboration: Moritz Gorath, Markus Endermann and Klaus Baumgärtner, Muegge GmbH, Reichelsheim

Study of the Electron Density n_e and Electron Temperature T_e Distribution of a Remote Plasma Source

Steffen Pauly, Bernhard Schmid, Andreas Schulz, Matthias Walker, Günter Tovar

The remote plasma source (RPS) of the Muegge company is used for example in the manufacturing process of computer chips in order to remove photoresist via plasma etching processes. In order to optimize the plasma source, a finite element-based plasma model of the RPS has been developed. To validate the simulations, additional Langmuir probe measurements are performed. The plasma parameters thus obtained are the electron density n_e and the electron temperature T_e. Fig. 1 shows a schematic view of the Langmuir probe measuring system, which is moved stepwise in the y-direction to record an electron density profile.

During measurement, the electron and ion flux to the probe tip are measured. The electron density and temperature are then calculated from the current/voltage characteristics. Fig. 2 shows the electron density n_e plotted vs. the y-position at different microwave powers. It is shown, that with increasing microwave power the electron density also increases. The obtained electron density profiles are then used to validate the simulation model.

Collaboration: Moritz Gorath, Markus Endermann and Klaus Baumgärtner, Muegge GmbH, Reichelsheim

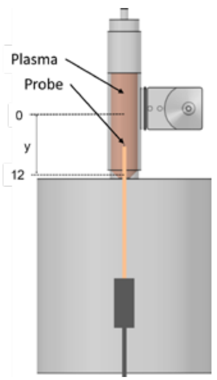


Fig. 1: Schematic view of the Langmuir probe meassurement system inside the RPS with the scan path in the y-direction.

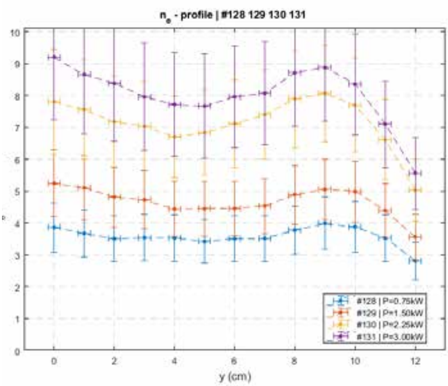


Fig. 2: The diagram shows four elctron density curves at different microwave powers plotted vs. the y-position at p = 160 Pa and an argon flow rate of f = 1 slm.

PoF IV Strategy for Synthesis of Chemical Energy Carriers Using Plasma Processes: Gas Management for Plasma Chemical Gas Activation

Andreas Schulz, Irina Kistner, Katharina Wiegers, Matthias Walker

When energy is added to a molecular gas to move it from a low chemical energy state to a higher one, this is colloquially called gas activation. Physically speaking, however, the binding enthalpy previously released during the formation of the molecules is (partially) leaded back and the binding partners of the molecules are converted into an energetically higher state. The result is an intermediate product that can easily be used for further reactions such as syntheses.

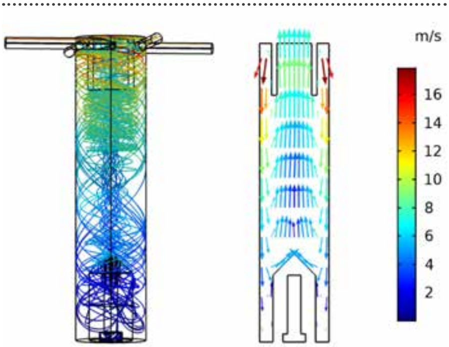


Fig. 1: Simulation of the the streamlines starting from the top at the four tangential gas feeds. The cross section view shows the exact flow direction with the help of arrows and clarifies the area of the envelope flow, the reversal point and the central forward flow.

In the case of microwave plasma based gas activation or gas conversion, a gas flow configuration is used which protects the used quartz glass tube with the aid of a rotating cold enveloping flow. The cold envelope gas flow is fed back against the process direction. At the end of the reaction zone, the gas flow reverses and forms an axial forward flow through the microwave resonance zone, where the gas is excited into the plasma state.

With this gas guide, a protective envelope flow and a hot plasma flow can be generated with the same gas. Fig. 1 shows the streamlines of the enveloping flow starting from the top at the four tangential gas feeds to the reversal point in the lower area. There the flow reverses and is led upwards along the axis. The cross section view shows the exact flow direction with the help of arrows and clarifies the area of the envelope flow, the reversal point and the central forward flow.

Collaboration: Max Planck Institute for Plasma Physics (IPP), Garching; Karlsruhe Institute of Technology (KIT), Karlsruhe; Forschungszentrum Jülich, Jülich

Generation of Nitrogen Oxide in a Microwave Plasma Torch for Nitric Acid Production

Andreas Schulz, Irina Kistner, Katharina Wiegers, Matthias Walker

Nitric acid (HNO_3) is produced industrially using the Ostwald process which is closely associated with the Haber-Bosch process, which provides ammonia (NH_3). NH_3 is oxidized with oxygen in the presence of a catalyst to form nitric oxide (NO). NO is then oxidized again to yield nitrogen dioxide (NO_2) which is then absorbed by water, yielding the desired product HNO_3. HNO_3 is the primary reagent used for the addition of nitro groups to organic molecules, for example in the production industry of pigments in inks and dyes.

Alternatively, NO can be generated directly from atmospheric nitrogen using an air plasma in a microwave plasma burner, similar to the Birkeland-Eyde process. The advantage of the microwave-based process is the free-standing plasma, which guarantees maintenance-free operation. The microwave plasma has a moderate gas temperature and an electron temperature of approximately 3600 K and 1 eV respectively. Due to the high number of collisions of the electrons with the neutral gas, it very efficiently stimulates the dissociation of nitrogen and oxygen as well.

The microwave air plasma has been investigated via optical emission spectroscopy and FT-IR absorption spectroscopy in order to determine the plasma parameters as well as the energy and conversion efficiency.

Fig. 1 shows the effluent free jet of a microwave air plasma at 1 kW microwave power and 20 slm (standard liter per minute) air flow. In the brightly glowing part of the jet, there are almost exclusively around 3% NO molecules in addition to the residual air. As the temperature decreases in the edge areas of the jet, NO reacts with the residual oxygen to form NO_2.

Collaboration: N2 Applied, Oslo, Norway

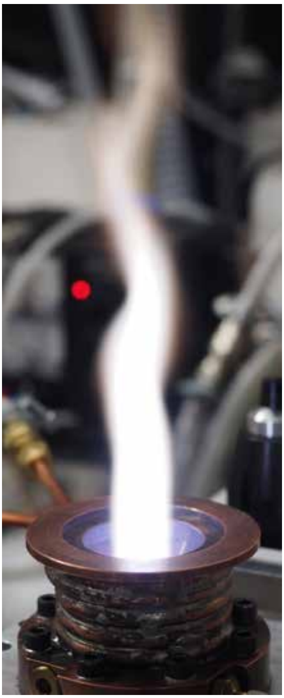


Fig. 1: Picture of the effluent free jet of a microwave air plasma at 1 kW microwave power and 20 slm air flow.

Optimization of a DBD Plasma for the Deposition of Protective Films in Heat Exchangers

Mariagrazia Troia, Andreas Schulz, Matthias Walker

Protective films in cooling systems of power plants can be beneficial in order to reduce the maintenance costs and improve the former's efficiency and lifetime. The deposition of such coatings directly inside the waterpipes can be carried out by means of an atmospheric dielectric barrier discharge (DBD) plasma fed on nitrogen and a precursor for the solid film, with the inner sides of the pipe and a moving steel head acting as electrode pairs.

In order to optimize the process, optical emission spectroscopy analyses over the UV-Vis-IR range have been carried out in order to identify and quantify the reactive species inside the plasma and the latter experimental parameters. Because of the high pressure, only emissive transitions with extremely short lifetime in the UV range could be observed.

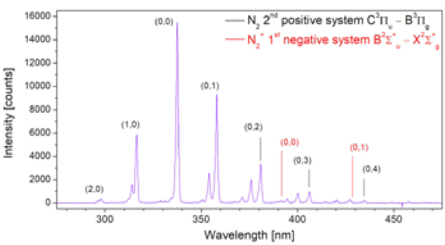


Fig. 1: Emission in the 280–470 nm range for an air plasma, with the transitions of the 2nd positive system for N_2 and the first negative one for N_2^+.

A model of such reactor has been built in order to run FEM-simulations for the cold gas flow inside the pipe. By varying the number and position of the gas inlets it is then possible to optimize the distribution of reactive species inside the plasma, resulting in reproducible, homogeneous films.

Collaboration: Sven Boehler and Florian Eder, Siemens AG Corporate Technology, Erlangen

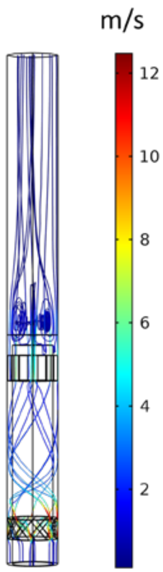


Fig. 2: Simulated streamlines of the overall velocity field for an air flow of 1 m/s.

Mineral Composites as DBD Layers in a Plasma-Adsorber-Scrubber-System for Waste Air Treatment

Mariagrazia Troia, Andreas Schulz, Matthias Walker

In order to decrease air pollution caused by bio-sources such as animal farming and both solid and liquid waste treatment, just to name a few, a low temperature microwave plasma operating in a dielectric barrier discharge (DBD) configuration can be employed in the treatment of pollutant gases such as methane. The plasma reactor consists of 16 pairs of steel electrodes interspersed with ceramic plates acting as dielectric barriers. The plasma is ignited in air by means of a high voltage applied to the electrode pairs. The ceramic barriers are embedded with TiO_2 particles, which can act as photo-catalysts in the oxidation of CH_4 to CO_2 and H_2O. Their required activation is promoted by absorption of photons in the 300–400 nm range emitted by excited N_2 species in the atmospheric air plasma, in particular the 2nd positive system $C^3\Pi_u \rightarrow B^3\Pi_g$. The degradation of CH_4 is further encouraged by the presence in the plasma phase of highly reactive species, such as atomic oxygen, and a strong emission of photons in the UV range. The reduction in CH_4 concentration can be monitored in real time by means of optical emission spectroscopy and the reduction in its rotovibrational emission bands. Process efficiency can likewise be calculated after carrying out a calibration step with reference gases.

Collaboration: Plasma Air AG, Weil der Stadt Hausen; Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA), Stuttgart; Institute of Textile Technology (ITA), Aachen; Richter Akustik & Design GmbH & Co, Melle

Funding: German Federal Ministry for Economic Affairs and Energy (BMWi)

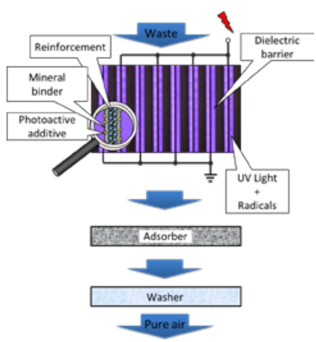


Fig. 1: Schematic representation of the reactor and the oxidation process of waste gases.

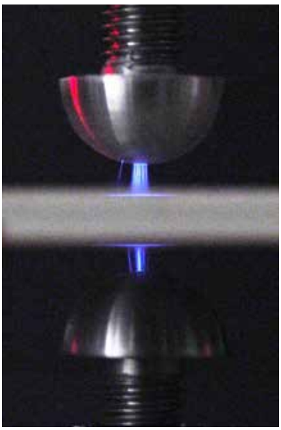


Fig. 2: Filamentary DBD discharges between a pair of electrodes and a ceramic barrier.

Ceramic Hollow Fiber Array for Oxygen Separation in a CO_2 Microwave Plasma

Katharina Wiegers, Irina Kistner, Andreas Schulz, Matthias Walker, Günter Tovar

A carbon dioxide (CO_2) plasma leads to the formation of carbon monoxide (CO) and oxygen radicals (O•), which form O_2. To produce syngas, the oxygen has to be removed from the gas mixture. For the separation of O_2, ceramic hollow fibers consisting of $La_{0.6}Ca_{0.4}Fe_{0.2}Co_{0.8}O_{3-d}$ (LCCF) are used. On the basis of preliminary tests for single hollow fibers, the working conditions for the LCCF fibers are determined. The next step is to increase the amount of oxygen which can be taken away by increasing the number of fibers. For this reason, a new fixation method has to be found. This is really challenging, because of the brittleness of the fibers and because the whole construction has to be gas tight. One construction is showed in Fig. 1. At the moment, an array consists of four fibers. In Fig. 2, the oxygen concentration through the single hollow fiber is plotted. All fibers show a different oxygen concentration. For an exact explanation further investigations of the active area of the fibers and the temperature in the plasma have to be carried out.

Collaboration: Thomas Schiestel and Frederic Buck, Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart

Funding: Federal Ministry of Education and Research (BMBF) as part of the Kopernikus Project PiCK "Plasmainduzierte CO2-Konversion"

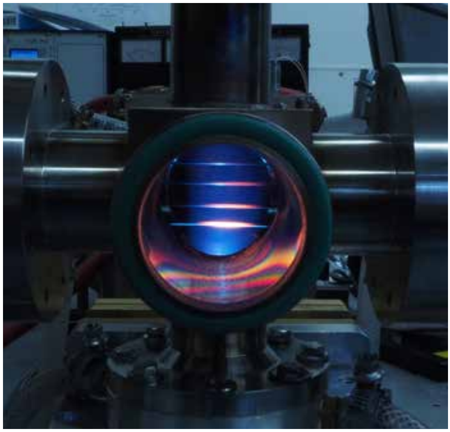


Fig. 1: A LCCF fiber array is placed vertically in the CO_2 plasma at 0.9 kW and 6 slm CO_2 flow.

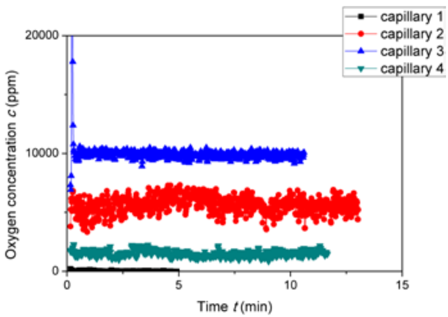


Fig. 2: Oxygen concentration of the hollow LCCF fibers. The fiber array is fixed horizontally in the plasma.

Mass Spectrometry and Fourier-Transformed Infrared Spectroscopy for Determining the CO_2 Conversion Efficiency in a Microwave Plasma Torch

Katharina Wiegers, Irina Kistner, Andreas Schulz, Matthias Walker, Günter Tovar

Mankind nowadays is strongly affected by the ongoing climate change which is caused mainly by the increasing emission of carbon dioxide (CO_2). One possibility of reducing CO_2 emissions is to ignite a plasma with the CO_2. Such atmospheric plasma is used to convert CO_2 into carbon monoxide (CO) and oxygen radicals (O•), which form O_2. One important point is the conversion and energy efficiency of this CO_2 plasma. Therefore, the volumes of CO_2, CO and O_2 have to be investigated. We were able to determine the different volume fractions via two independent analysis methods: Fourier-transformed infrared-spectroscopy (FT-IR) and mass spectrometry (MS). Process parameters like microwave power and gas flow are one major key to adjust the conversion and energy efficiency. The measurement point is 14 cm above the ignition tip, because at this position, ceramic fibers for the oxygen separation process are placed. Fig. 1 shows the good agreement between the two diagnostics methods. In Fig. 2 the conversion efficiency versus the microwave power in dependence of the used CO_2 flux is shown.

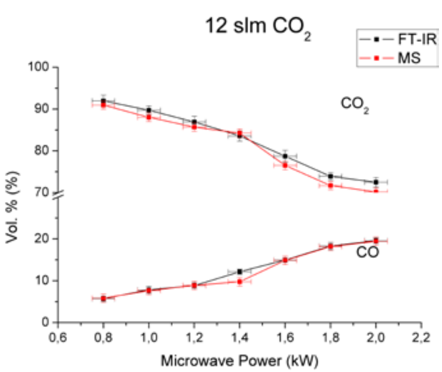


Fig. 1: The volume fractions of CO_2 and CO which are determined via FT-IR and MS with a CO_2 flow of 12 slm and 14 cm above the ignition tip.

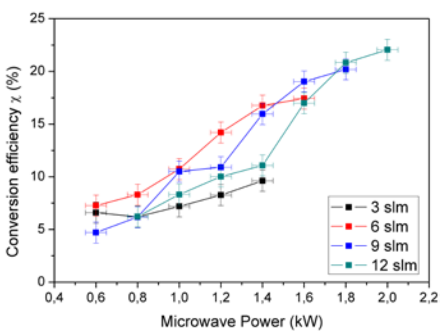


Fig. 2: CO_2 conversion efficiency for different microwave powers and CO_2 flows.

Microwave Technology

Microwaves for Plasma Heating and Diagnostics

Dr. Carsten Lechte, carsten.lechte@igvp.uni-stuttgart.de

In present-day fusion experiments, electron cyclotron resonance heating (ECRH) with microwaves in the range of 28–170 GHz at megawatt power levels are routinely used to heat the plasma, to drive plasma currents and to control magneto-hydrodynamic instabilities. The Microwave Technology (MT) group at the IGVP contributes to the development of millimeter-wave heating and diagnostic components, the experimental application of the devices and the interpretation of experimental results.

For the transmission of high-power millimeter waves, oversized (smooth and corrugated) waveguides as well as quasi-optical transmission lines are used. MT designs, simulates and tests novel microwave components as well as complete transmission systems for various fusion experiments as e.g. Wendelstein 7-X, ASDEX Upgrade, or ITER. At present, emphasis is on the development of remote-steering launchers for ECRH on W7-X, holographic reflectors at the inner wall of fusion experiments to redirect the non-absorbed fraction of an ECRH beam into the plasma in a controlled way, calorimeters for power levels in the range of 1 MW – 2 MW CW, matching optics to couple the output beams from the generators (gyrotrons) into the transmission systems, as well as in-situ power and mode monitoring devices. Many millimeter wave diagnostics rely on optimized broadband launchers and receiving antennas. MT is involved in advanced reflectometry diagnostics (antennas and backend hardware) at ASDEX Upgrade and reflectometry and electron cyclotron emission systems at Wendelstein 7-X. Our group develops power combiners and switches for megawatt beams, which could enhance the performance of the fusion test reactor ITER.

The MT group is also involved in the experiments relying on microwave devices. In support of several fusion experiments, full-wave simulations are carried out to study wave propagation in fusion plasmas. The group contributes to Doppler reflectometry for turbulence and flow investigations through simulations of experimental data and the design of optimized broadband components, including conventional antennas and frequency-steered array antennas. For experiments on collective Thomson scattering, dedicated transmission and antenna components are designed. Electron cyclotron emission (ECE) diagnostics, as installed at Wendelstein 7-X, have their own unique requirements for multi-mode transmission lines.

A Fast High-Power Microwave Diplexer Switch for ITER

Carsten Lechte

The ITER tokamak relies strongly on electron cyclotron resonance heating (ECRH) and current drive (ECCD) at 170 GHz. Control efficiency of plasma instabilities can be improved by switching between two different antennas in sync with the instability's rotation, always hitting it at the same point. The required switching frequencies are larger than 10 kHz, which rules out mechanical switches.

Our diplexer is based on a Fabry-Perot resonator that uses small changes in RF frequency (< 100 MHz) to switch the output between a resonant and a non-resonant port. The frequency change is achieved by fast anode voltage modulation of the microwave source. Fig. 1 shows the setup at the ITER gyrotron test site QST in Japan with the two outputs connected to two dummy loads.

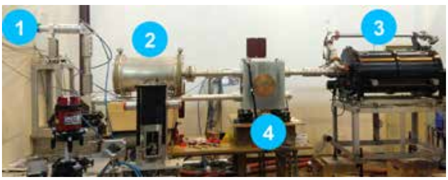


Fig. 1: Test setup at QST: 1) Incoming beam of 1 MW at 170 GHz, 2) dummy load for non-resonant output, 3) dummy load for resonant output, 4) diplexer device.

The diplexer is illustrated in Fig. 2: The actual resonator is in the horizontal plane. It consists of the two main mirrors and the two coupling mirrors. In high-power tests, switching between the two channels was demonstrated by mechanical modulation of one mirror position. Some problems were identified regarding arcing on the grating mirror and stray radiation entering the diagnostic antennas, which will be mitigated in future tests.

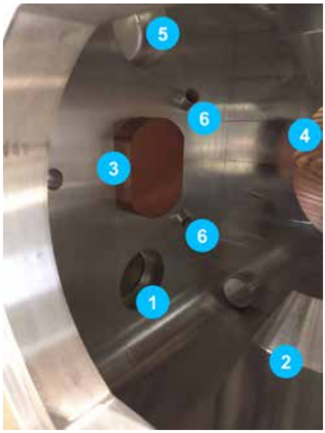


Fig. 2: Half of diplexer interior, looking through the hole for the other main resonator mirror: 1) input port, 2) matching mirror, 3) grating mirror for coupling into the resonator, 4) resonator main mirror, 5) non-resonant output port, 6) diagnostic horns for power measurements; the resonant output (not visible) is opposite the non-resonant port.

Collaboration: Kristiaan Broekens, Wimar Klop, TNO, Netherlands Organisation for applied scientific research, Amsterdam, Netherlands; Hiroshi Idei, Research Institute for Applied Mechanics, Kyushu University, Fukuoka, Japan; Ken Kajiwara, QST, Naka Fusion Institute, National Institutes for Quantum and Radiological Science and Technology, Naka, Japan

Design of Array Antennas for the Stellarator TJ-K

Burkhard Plaum, Liu Qiao

For ECRH-heating of the stellarator TJ-K, several frequency steerable array antennas for a frequency range of 7.9 to 8.4 GHz have been developed. They consist of waveguides with slots in an equidistant arrangement. The location and orientation of the slots determine the amplitude and polarization (X- or O-Mode) of the radiated fields. The longitudinal distances between the slots cause a frequency dependent phase shift $\Delta\varphi$ of the radiated fields, which, in turn, results in an angle, under which the total beam is radiated. To reduce the beam divergence perpendicular to the steering plane, five waveguides, which are connected via a power splitter, are operated in parallel.

Numerous simulations of antennas and the power splitter were done in a straight configuration (Fig. 1) for a single waveguide and the complete array. The parameters were optimized in order to get the best field pattern and minimal reflections in the waveguide feed. In the final setup the waveguide is bent to fit into the vacuum vessel of TJ-K and characterized experimentally (Fig. 2).

Fig. 2: Field measurement of the bent antenna.

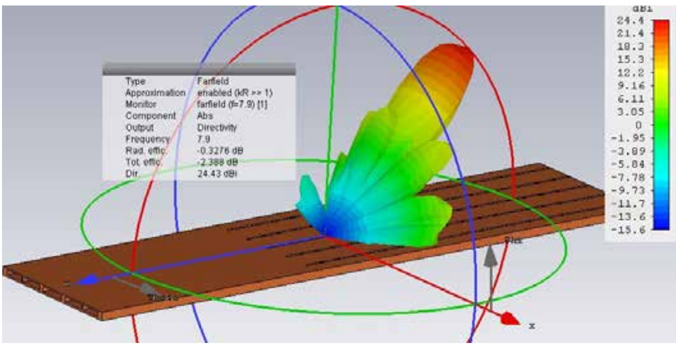


Fig. 1: Simulated radiation pattern of the O-Mode antenna with longitudinal slots.

Development of Diffraction Gratings for Advanced ECRH Scenarios

Burkhard Plaum

The development of specialized diffraction gratings continued in 2019. They are used to redirect the remaining power of an ECRH beam back into the plasma for a second heating pass in the case of an imperfect absorption, e.g. when heating at higher harmonics. The main focus was on the development of a grating for the first plasma in ITER. The design is challenging because of the extreme angles, where the incident beam has an angle of incidence of around 60° while the diffracted beam is almost perpendicular on the mirror.

An extensive parameter study was performed to obtain the possible efficiencies of optimized gratings as a function of the angles of the incident and diffracted waves. The results can be seen in Figs 1 and 2 for the –2nd and –3rd orders respectively. In general the efficiency is higher, if the difference between the angles is small. For larger differences these plots can be used to quickly identify the best diffraction order.

Another improvement was the optimization for a linear polarization as required for the ITER first plasma. It allows choosing a polarization angle such, that the combined losses at the grating and in the EC resonance become minimal.

Funding: ITER Organization

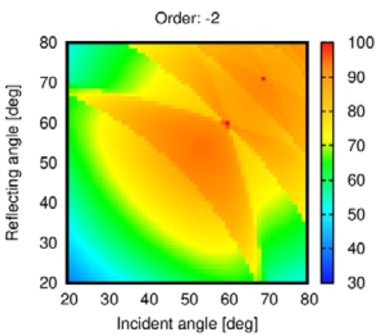


Fig. 1: Efficiencies of optimized gratings as a function of the angles for the –2nd order.

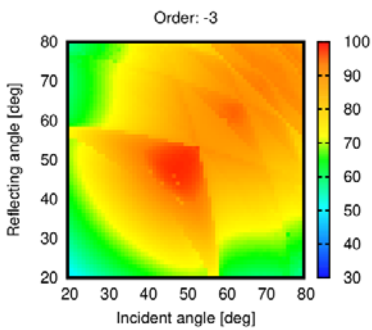


Fig. 2: Efficiencies of optimized gratings as a function of the angles for the –3rd order.

Fullwave 3D Simulations of High-Power Reflecting Gratings for ITER and ASDEX Upgrade

Carsten Lechte

The reflecting grating tiles discussed on page 64 are designed in an extensive optimization process that only considers local properties. While it is possible to characterize the overall performance of the grating tile by low-power laboratory measurements, this rarely is comprehensive and can only be performed after fabrication. Using the 3D version of the IPF-FD3D code, the grating is illuminated by the nominal input beam, and the outgoing wave is decomposed by FFT into plane waves for analysis of all scattering orders.

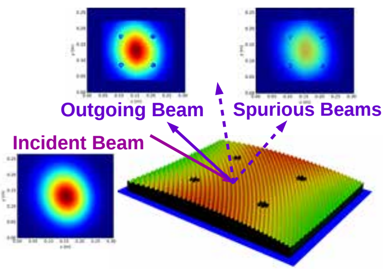


Fig. 1: Generic reflecting grating simulation setup in 3D.

Fig. 2 shows the spectral analysis for one of the optimized ITER gratings. The ITER gratings have to deal with some degree of overlap between neighboring beams. This shows up in Fig. 1, which shows the spectral decomposition of the scattered beams. The main output order –1 has a strongly localized spectrum, but also a long tail to the left. This is caused by the truncation of the grating, where the beam overlaps with the neighboring grating. Furthermore, a significant portion of the power (21.8%) is reflected directly (order 0). Given the geometrical and polarization constraints, it is not possible to achieve better efficiency.

Publication: A. Moro et al. (2020) Fusion Engineering and Design 154, 111547. DOI:10.1016/j.fusengdes.2020.111547

Collaboration: Martin Schubert, Jörg Stober, Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald; Alex Bruschi, Francesco Fanale and Alessandro Moro, Institute for Plasma Science and Technology (ISTP-CNR), Milan, Italy

Funding: This work is supported by the Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald

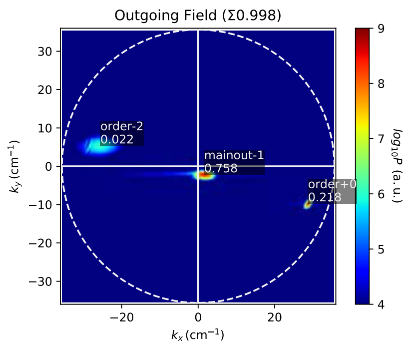


Fig. 2: Plane wave decomposition of the outgoing beams. The various grating orders are displaced by a constant vector. The main output order (+1) contains 75.8% of the incident power. Order 0 is the straight reflection.

Hardware Plasma Diagnostics for ASDEX Upgrade and Wendelstein 7-X

Burkhard Plaum

The development of hardware components for plasma diagnostic systems at ASDEX Upgrade and Wendelstein 7-X was continued. For the top-launch reflectometer in ASDEX Upgrade, the setup consisting of a horn antenna and three mirrors (one movable) was given. As for most diagnostic systems built into existing machines, space was extremely limited. In particular, the dimensions of the mirrors were very small making losses due to the beam truncation the major issue. The system was simulated with the PROFUSION-tools under consideration of the realistic field of the horn antenna (including higher order modes) as well as the beam truncation by the rectangular mirrors.

By doing a large number of parameter scans (see e.g. Fig. 1), a suitable horn antenna and focal lengths for the mirrors could be found: Fig. 2 shows the calculated horizontal and vertical profiles of the beams for 50 GHz and 104 GHz respectively. The maximum truncation losses are about 37% for 50 GHz.

Further developments include an optical frontend for a Michelson interferometer for W7-X as well as several other horn antennas.

Collaboration: Garrard Conway, Max Planck Institute for Plasma Physics (IPP), Garching; Matthias Hirsch, Hans Oosterbeek, Max Planck Institute for Plasma Physics (IPP), Greifswald

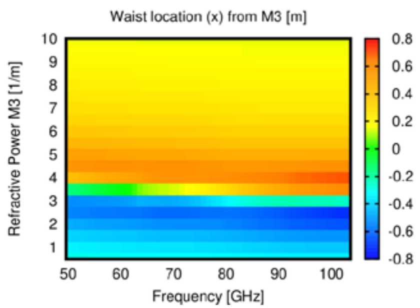


Fig. 1: Distance of the horizontal beam waist from the last mirror M3 as a function of the refractive power of M3 and the frequency. The design goal is 500 mm.

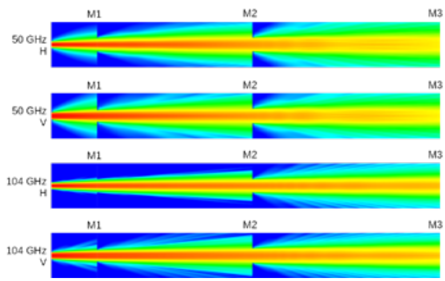


Fig. 2: Horizontal and vertical beam profiles in the top-launch reflectometer for 50 GHz and 104 GHz.

Fullwave Doppler Reflectometry Simulations for ASDEX Upgrade

Carsten Lechte

Doppler reflectometry is a microwave scattering diagnostic. It can measure the density fluctuation wavenumber spectrum in fusion plasmas. This is important for characterizing the plasma turbulence, which is an unwanted phenomenon in all plasmas. Like RADAR, probing beams are emitted, but the interpretation of the scattered signal is not straightforward. Fig. 1 shows the problem: Experimental measurements of the same turbulent spectrum at different polarizations (O-, X-mode) disagree with each other, as well as with simulations of plasma turbulence (GENE). These simulations were tailored to the experimental scenario.

The fullwave simulations constitute a synthetic diagnostic, which take the simulated plasma turbulence and calculate the scattering and receiving process of the Doppler reflectometer. Fig. 2 shows that the fullwave simulation spectrum based on the turbulence simulations now agrees with the experimental X-mode simulations. Doppler reflectometry in fusion plasmas has a non-linear power response at small wavenumbers, which explains the different shapes of the spectra in Fig. 1. This effect is stronger in X-mode, which accounts for the differences between spectra measured in X- and O-mode.

[1] Lechte, C., Conway, G., Görler, T., Happel, T. and the ASDEX Upgrade Team (2020) Plasma Sci. Technol. 22, 064006. https://doi.org/10.1088/2058-6272/ab7ce8

Collaboration: Garrard Conway, Tobias Görler and Tim Happel, Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald

Funding: This work is supported by the Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald

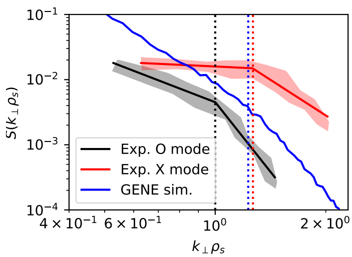


Fig. 1: Spectral power of fluctuations at the normalized wavenumber $k_\perp \rho_s$. In experiment, the measured quantity is the received scattered power, whereas in the GENE simulation, the density fluctuations were used directly.

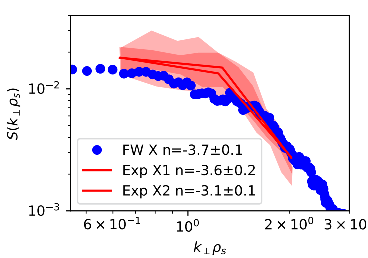


Fig. 2: Spectra of experimental X mode (red lines) and fullwave (blue circles) Doppler reflectometry.

Comb Reflectometer Backend for Fusion Plasmas

Walter Kasparek

Conventional reflectometers only send and receive a single frequency at the time. Several simultaneously launched frequencies of a Doppler reflectometer could obtain, in a single measurement, the radial distribution of the fluctuation spectrum or, with a frequency-scanned antenna, the wavenumber spectrum of the fluctuations at a fixed radius. For applications at ASDEX Upgrade, the transmitter-receiver electronics of such a comb-reflectometer for millimeter waves in the W-band (75–110 GHz) is in development.

For the generation of the frequency comb with difference frequency f_C, a mixture of three frequencies is generated via double-side-band mixing of fC with the main generator frequency. After multiplication by 6 in a VDI-hextupler and subsequent amplification, comb spectra of typically seven lines with $0.1 \leq f_C \leq 6$ GHz and a power range of < 10 dB are obtained, which can be shifted over the whole W-band. The total output power is typ. 100 mW.

In the heterodyne receiver, a fundamental mixer is used for down-conversion of the fluctuation signals to frequencies below 18 GHz. In three parallel mixing stages, signals are separated and down-converted to three intermediate frequencies around 900 MHz.

The final detection system applies I-Q-mixers to convert the seven signals into 14 fluctuation signals in the frequency range 0–10 MHz, which allows the detection of both amplitude and phase, and consequently the propagation direction of the plasma fluctuations. At present, a major part of the components has been delivered and the hardware is under construction.

Publication: Happel, T., Kasparek, W., Hennequin, P., Höfler, K., Honoré, C. and the ASDEX Upgrade Team (2020) Design of a variable frequency comb reflectometer system for the ASDEX Upgrade tokamak. Plasma Sci. Technol. 22, 064002. https://doi.org/10.1088/2058-6272/ab618c

Collaboration: Tim Happel and Klara Höfler, Max Planck Institute for Plasma Physics (IPP), Garching; Pascale Hennequin and Cyrille Honoré, Laboratoire de Physique des Plasmas (LPP), Palaiseau, France

Funding: Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald

PROFUSION Code Development

Burkhard Plaum

The PROFUSION code (Programs for multimode analysis, simulation and optimization) is constantly extended and enhanced as requested by other projects. In 2019 the focus was on the development of diffraction gratings as well as some tools, which work with analytical Gaussian beams.

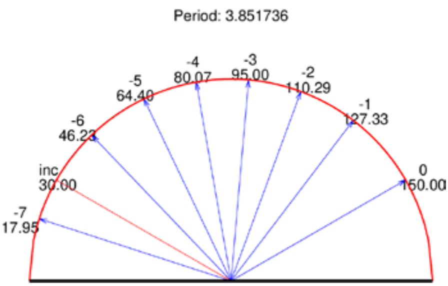


Fig. 1: Normalized period and existing diffraction orders for a grating with -3rd order, Θ_{in} = 30° and Θ_{out} = 95°.

Notable additions were:

- Optimization of diffraction gratings for linear polarization with a given angle between the E-field and the grooves.
- A generic binary file format for reflector surfaces and routines for ASCII export, which became neccessary for the ITER grating.
- A tool to visualize the existent grating orders for a given order and angles (see Fig. 1).
- Parallelized synthesis of the 3D grating from optimized 2D gratings.
- Transformation of the polarization vector from the beam coordinates to the mirror surface and back. This is important in order to obtain the necessary polarizer settings for complicated beam setups.
- Generation of mirror surfaces and milling data for focusing mirrors from the focal lengths, the parameters of the input beam and the angle of incidence.
- A set of tools (generation, propagation, lens) to perform simple Gaussian beam calculations on the command line or in skripts.
- A frontend for the calculation of the mode conversion in waveguide tapers with rectangular cross section.

Plasma Dynamics and Diagnostics

Plasma Dynamical Processes in Generation and Confinement

Dr. Mirko Ramisch, mirko.ramisch@igvp.uni-stuttgart.de

Key issues of fusion research are to find conditions under which hot (beyond 10 million Kelvin) and dense fusion plasmas can be sustained and confined for a sufficiently long time as to achieve a positive net energy outcome from fusion reactions for utilization in future power plants. Conceptually, these plasmas are confined in toroidal magnetic field configurations allowing for central peak energy densities. Steep density gradients in the plasma edge region, however, can prevent electromagnetic waves from reaching absorption layers for efficient heating. Moreover, plasma fluctuations arising from these gradients can cause turbulent cross-field transport of particles and heat out of the confinement region and, thus, affect thermal isolation of the plasma.

At the IGVP, the stellarator experiment TJ-K is operated with low-temperature plasmas for the purpose of conducting fundamental research in the fields of plasma/microwave interactions and plasma turbulence. To capture the non-linear spatio-temporal plasma dynamics, specifically developed diagnostics, e.g. probe arrays, are employed. Studies on wave-conversion processes aim at a detailed understanding of efficient heating scenarios incorporating wave scattering processes at turbulence-distorted boundary layers. The microscopic turbulent dynamics across the interface between confined plasma and scrape-off layer determines the global confinement. The mechanisms of self-generated flows and flow/turbulence interactions are studied in dependence on the magnetic field geometry in view of possible transport control or optimization options.

Experimental investigations are supported by complementary simulations using high-level codes developed on-site or at the Max Planck Institute for Plasma Physics (IPP).

The Depolarizing Effects of Plasma Density Fluctuations on Microwave Beams

Alf Köhn, Eberhard Holzhauer

Microwaves are an indispensable tool for heating and diagnostics purposes in fusion plasmas. On their propagation path entering the plasma or leaving it, the microwaves have to traverse the plasma boundary, a region where significant plasma density fluctuations are known to occur. These perturbations can spoil heating efficiencies or result in ambiguous diagnostics results.

At the plasma boundary, where the background electron density is low, the dispersion relations for X-mode and O-mode propagating in the plasma are not well separated and perturbations in the plasma density can in principle lead to unwanted coupling between them. In this project, we analyze quantitatively the spurious coupling by means of full-wave simulations. We have set up a geometry where only an O-mode is excited in the plasma. The cut-off of the X-mode is included in the computational domain to act as a mode-filter. This allows for easy detection of the coupling via measuring the reflected X-mode component. A normalized fluctuation level of 100% was found to result in an unwanted coupling on the order of 1%.

Publication: Köhn, A. et al., 46th EPS Conference on Plasma Physics (Milan, 2019), http://ocs.ciemat.es/EPS2019PAP/pdf/P4.1078.pdf

Collaboration: Pavel Aleynikov, Max Planck Institute for Plasma Physics (IPP), Greifswald

Funding: Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald

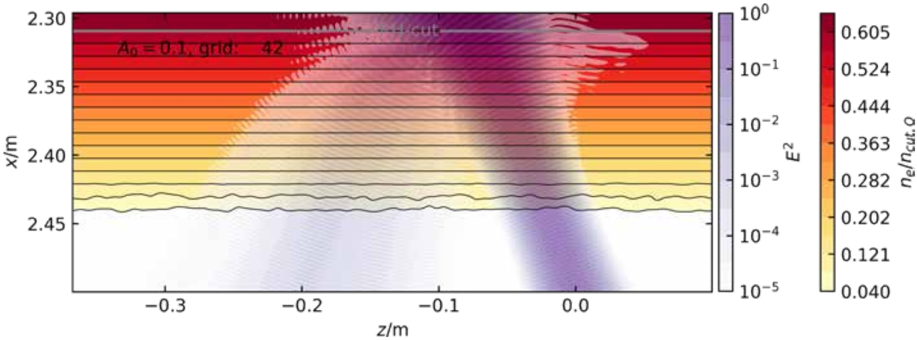


Fig. 1: Full-wave simulations illustrating the unwanted coupling of an injected O-mode to an X-mode which is reflected at the corresponding cut-off at the top of the computational domain.

Plasma Electron Acceleration Below the Electron Cyclotron Frequency

Alf Köhn, Mirko Ramisch

Overdense plasmas, where the plasma density exceeds the cut-off density of the injected microwave, are routinely achieved in the TJ-K stellarator. In such heating scenarios, the power absorption usually occurs at the electron cyclotron frequency or at its harmonics. Within this project an operational regime at TJ-K is described, where the absorption takes place well below the electron cyclotron frequency: microwave energy is deposited at the so-called O-resonance after coupling to Whistler waves at the plasma boundary. High-energy electrons have been detected in this heating regime, with energies up to the MeV regime. We have described this novel scheme for plasma-electron acceleration from simple physics considerations taking into account the 3D structure of the confining magnetic field, yielding values for the electrons' energies which are in agreement with experimentally found values. The acceleration was identified to take place in the vicinity of the O-resonance where large wave electric fields can occur. Toroidal net currents, larger by an order of magnitude than those currents usually driven by microwaves in TJ-K, were also detected and could be successfully included in the physics model for the electron acceleration and be ascribed to the high-energy electrons. The experimentally observed decrease of the toroidal net current with increasing collision frequency between electrons and neutrals is in agreement with the model.

Publication: Köhn, A. et al., submitted to New J. Phys.

Collaboration: Ulrich Stroth, Max Planck Institute for Plasma Physics (IPP), Garching

Funding: Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald

Calculation of Decorrelation Times with the Elliptical Model Method

Til Ullmann, Bernhard Schmid, Günter Tovar, Mirko Ramisch

In magnetized fusion plasmas a critical ratio of the shearing rate to the decorrelation rate of turbulent eddies is linked to a reduction in the amplitude of turbulent fluctuation. If the ratio exceeds one, then the rotational shear has a quenching influence on the turbulence. In preparation for future analysis at the stellarator TJ-K, the decorrelation time is first estimated to allow the classification of different shear regimes and to test the quenching theorem later.

In the stellarator TJ-K, the turbulence can be analyzed in time and space by arrays of Langmuir probes inside the confinement region of the low-temperature plasma. This allows calculating cross-correlation functions (CCF) in time, poloidal space and, to some extent, in radial space. The decorrelation time can be calculated from the elliptical model which, in contrast to the auto-correlation, includes the distortion of turbulent structures. This method is named after the elliptic shape of the contour lines of the two-dimensional, spatio-temporal CCF.

In Fig. 1, the 2D-CCF is shown in poloidal space and time for a specific reference probe pin on the high-field side. The correlation length can be read out from the y-intercept of the 1/e contour line ($l_d \approx 1.4$ cm). The decorrelation time is the maximum delay time of the 1/e contour ($\tau_d \approx 20$ μs). Finally, the decorrelation rate is calculated from the inverse decorrelation time ($\gamma_d \approx 50$ kHz).

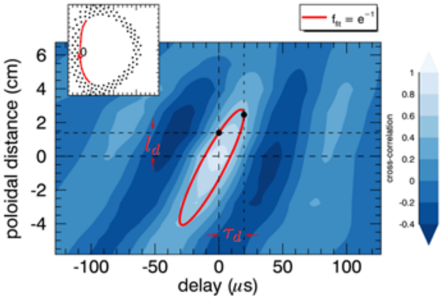


Fig. 1: The cross-correlation function in polodial space and time for a reference Langmuir probe on the high-field side as indicated by the inlay. The y-intercept refers to the decorrelation length (l_d = 1.4 cm) and the decorrelation time (τ_d = 20 μs) is the maximum delay time of the 1/e elliptical contour ellipse.

The data analysis with the elliptical model has been successfully implemented. In future studies the decorrelation rate will be compared with the shearing rate in order to systematically classify different shear regimes.

Collaboration: Peter Manz, Max Planck Institute for Plasma Physics (IPP), Garching

Funding: Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald

The Impact of Shear Flows on Non-linear Three-Wave Interaction in Drift-Wave Turbulence

Til Ullmann, Bernhard Schmid, Günter Tovar, Mirko Ramisch

Shear flows in the edge of magnetized fusion plasmas have attracted much interest because of their effect on turbulence, in particular their capability of regulating turbulent transport. Drift-wave (DW) turbulence is governed by non-linear three-wave interactions under resonance conditions in wave-number and frequency space: $k_1 + k_2 = k_3$ and $f_1 + f_2 = f_3$. Moreover, the set of possible couplings is restricted by the DW-dispersion relation. In this regard, shear flows change the set of coupling drift waves in favor of small wavenumbers, i.e. large structures such as zonal flows (ZF). This kind of flows taps energy from the turbulence and reduces it.

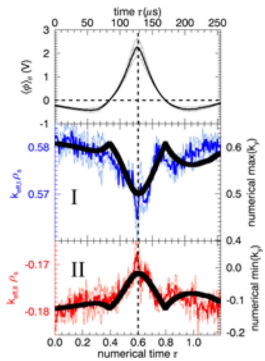


Fig. 1: Top: Temporal evolution of the conditionally averaged zonal flow. Middle, bottom: Effective wavenumber for positive (I) and negative (II) sector. Thick lines indicate numerical results. With increasing shear the set of possible couplings in the DW turbulence decreases in favor of large-scale structures.

At the stellarator TJ-K, ZFs can be detected by an array of 128 Langmuir probes distributed on four different flux surfaces. Potential fluctuations measured with the array can be resolved in wavenumber space. A time resolved bicoherence-spectrum evaluates how strong the single three-wave interactions are. With wavenumbers weighted by the bicoherence an effective wavenumber can be calculated for positive and negative wavenumbers. High and low absolute values indicate a broad and narrow coupling space, respectively. As shown in Fig. 1 the effective wavenumber for positive and negative sectors (bottom and middle figure) decreases to lower absolute values with the upcoming ZF (figure top) and again increases with vanishing ZF. The thick line in the lower figure show the theoretically expected behavior, which agrees well with the experimental result. This can be seen as the first experimental evidence that the coupling space decreases in the presence of a shear flow in favor of large scale structures.

Publication: Ullmann, T. et al., 46th EPS Conference on Plasma Physics (Milan, 2019) http://ocs.ciemat.es/EPS2019PAP/pdf/P5.1064.pdf

Collaboration: Peter Manz, Max Planck Institute for Plasma Physics (IPP), Garching

Funding: Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald

Temperature and Density Measurement in Technological Plasmas

Bernhard Schmid, Steffen Pauly, Stefan Merli, Alf Köhn, Mirko Ramisch

Plasma simulations, incorporating main molecular reactions, are used for a detailed understanding of technological plasma sources. In order to validate these simulations, quantitative measurements of electron temperature and density are needed. Small geometries with high energy densities and plasma etching and deposition form a rather harsh and inaccessible environment. Nevertheless, probe diagnostics are a comfortable way to gain information on these plasma parameters. Specifically, Langmuir probes, double probes and emissive probes are deployed in the Duo-Plasmaline, built at the IGVP, and the Remote Plasma Source (RPS) from Muegge GmbH.

With a fit to the U-I-characteristics of single swept Langmuir probes, as well as double probes, the electron temperature can be calculated from the electron current. Furthermore, the ion-saturation current is proportional to the electron density. The measurements of the electron temperature are in very good agreement among each other and with simulations. On the other hand, density values show a broader range of uncertainty as the absolute density value also depends on the effective probe surface (Fig. 1).

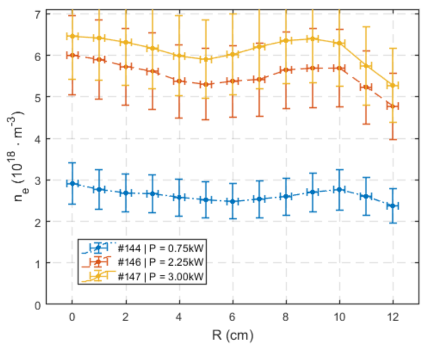


Fig. 1: Axial density profiles in the RPS (center at R = 0 cm). The overall density increases with increasing heating power P.

To validate the different approaches emissive probes are used to calculate the electron density from the plasma frequency [1]. The plasma oscillation is excited by a two stream instability induced by the electron emission current. With these possibilities at hand, a higher accuracy of the deduced plasma parameters in the 3D plasma volume will be achieved.

[1] Shirakawa, T., Sugai, H. (1993) Japan. J. Appl. Phys. 32: 5129

Collaboration: Muegge GmbH, Reichelsheim, Germany

Funding: Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald

Diagnostics for Direct Temperature Fluctuation Measurements

Mirko Ramisch, Bernhard Schmid, Til Ullmann

Simultaneous time resolved measurements of plasma characteristics like temperature T, density n and plasma potential ϕ are required to capture the non-linear dynamics of turbulent particle and heat transport in magnetically confined plasmas. At TJ-K, a classical triple probe, consisting of a double probe and a floating probe of equal tip size, is newly employed to measure electron temperature fluctuations $\tilde{T}_e$. When the current to each of the double probes saturates at values of the ion-saturation current for sufficiently large probe bias ($U_{bias} = U_+ - U_-$), the difference of potentials between positively biased and floating probe is approximately proportional to the electron temperature $U_+ - U_{fl} = (k_B T_e/e) \ln 2$.

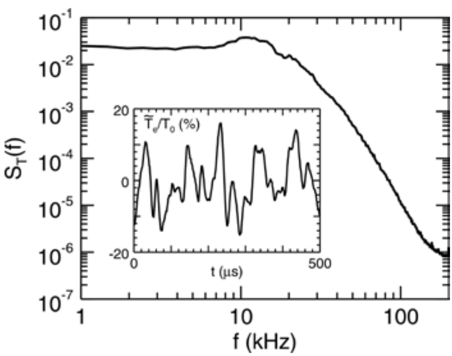


Fig. 1: Spectral power distribution in measured electron temperature fluctuations, a section of which shown in the inlay as level relative to the mean value.

First test measurements were carried out in a helium discharge. Fig. 1 shows the turbulent character in the power spectrum of temperature fluctuations with a power-law decay over a broad dynamical range. A section of the corresponding time trace close to the separatrix is shown in the inlay. Relative fluctuation levels around 15% were found with a trend towards increasing values beyond the separatrix, both as typical for density and plasma potential fluctuations in TJ-K standard discharges. As the evaluated temperature is methodically coupled to the floating potential U_{fl}, it needs to be carefully tested how useful the $\tilde{T}_e$ signal is for correlation analyses with interpretations of U_{fl} and ion-saturation current as plasma potential and density, respectively.

Funding: Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald

Artificial Neural Network-Based Analysis of Langmuir Probe Characteristics

Mirko Ramisch, Alf Köhn, Bernhard Schmid

Low-temperature plasmas allow for the use of Langmuir probes to obtain information on, e.g., the electron temperature (T_e) by fitting a theoretical curve to experimentally measured current-voltage characteristics of the probe. T_e determines the strength of exponential increase in electron collection with increasing probe bias in a limited range around the floating potential. Hence, the reliability of the fit with parameter T_e depends on the choice of the fit interval, which complicates an automated treatment of dozens of characteristics. While an algorithm can find a reasonable local optimum in fit-parameter space, a human evaluator may have an eye for the global optimum.

One way to incorporate this kind of intuition in automated data analyses is to employ artificial neural networks (ANNs). First tests for the applicability of ANNs in analyzing probe characteristics were carried out with a basic feedforward network including one hidden layer. The probe response current – ordered according to increasing bias voltage – is fed in, whereas the output consists of the characteristics' fit parameters. The network is trained on sets of a randomly shuffled selection of evaluated fit parameters via backpropagation of error. Fig. 1 demonstrates, taking radial T_e profiles in a typical neon discharge at the TJ-K stellarator as an example, that the tested simple ANN architecture is capable of linking probe characteristics with fit parameters within the experimental uncertainties.

Funding: Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald

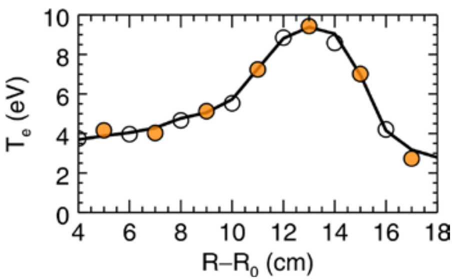


Fig. 1: Electron temperature profile (solid line) as evaluated from probe characteristics in comparison with "fitting" results of a neural network (circles) trained on selected data (open circ.) and generalized to intermediate positions (filled circ.).

Publications

Publications

Peer-reviewed publications

1. Adatia, K., Keller, S., Götz, T., Tovar, G. E. M., Southan, A. (2019) Hydrogels with multiple clickable anchor points: synthesis and characterization of poly(furfuryl glycidyl ether)-block-poly(ethylene glycol) macromonomers. Polymer Chemistry 10, 4485–4494. DOI: 10.1039/c9py00755e

2. Atanasova, P., Atanasov, V., Wittum, L., Southan, A., Choi, E., Wege, C., Kerres, J., Eiben, S., Bill, J. (2019) Hydrophobization of tobacco mosaic virus to control the mineralization of organic templates. Nanomaterials 9(5), 800. https://doi.org/10.3390/nano9050800

3. Barz, J., Haupt, M., Oehr, C., Hirth, T., Grimmer, P. (2019) Stability and water wetting behavior of superhydrophobic polyurethane films created by hot embossing and plasma etching and coating. Plasma Processes and Polymers 16(6), 1800214. http://dx.doi.org/10.1002/ppap.201800214

4. Beck, A., Haitz, F., Grunwald, S., Preuss, L., Rupp, S., Zibek, S. (2019) Influence of microorganism and plant oils on the structure of mannosylerythritol lipid (MEL) biosurfactants revealed by a novel thin layer chromatography mass spectrometry method. Journal of Industrial Microbiology and Biotechnology 46, 1191–1204. http://dx.doi.org/10.1007/s10295-019-02194-2

5. Brand, H. v. d., Bongers, W. A., Stober, J. K., Kasparek, W., Wagner, D., Doelman, N., Klop, W., Giannone, L., Reich, M., Westerhof, E., de Baar, M. R., the ASDEX Upgrade team and the EUROfusion MST1 team. (2019) Inline ECE measurements for NTM control on ASDEX Upgrade. Nuclear Fusion 59(1). https://doi.org/10.1088/1741-4326/aaeea9

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7. Claaßen, C., Rebers, L., Claaßen, M. H., Borchers, K., Tovar, G. E. M., Southan, A. (2019) Expanding the range of available isoelectric points of highly methacryloylated gelatin. Macromolecular Chemistry and Physics 220(14), Art. 1900097. http://dx.doi.org/10.1002/macp.201900097

8. Dehli, F., Rebers, L., Stubenrauch, C., Southan, A. (2019) Highly ordered gelatin methacryloyl hydrogel foams with tunable pore size. Biomacromolecules 20(7), 2666–2674. https://doi.org/10.1021/acs.biomac.9b00433

9. Derwenskus, F., Metz, F., Gille, A., Schmid-Staiger, U., Briviba, K., Schließmann, U., Hirth, T. (2019) Pressurized extraction of unsaturated fatty acids and carotenoids from wet *Chlorella vulgaris* and *Phaeodactylum tricornutum* biomass using subcritical liquids. GCB Bioenergy 11(1), 335–344. https://doi.org/10.1111/gcbb.12563

10. Eiben, S., Koch, C., Altintoprak, K., Southan, A., Tovar, G. E. M., Laschat, S., Weiss, I. M., Wege, C. (2019) Plant virus-based materials for biomedical applications: Trends and prospects. Advanced Drug Delivery Reviews 145, 96–118. https://doi.org/10.1016/j.addr.2018.08.011

11. Funk, C., Raschbichler, V., Lieber, D., Wetschky, J., Arnold, E., Leimser, J., Biggel, M., Friedel, C. C., Ruzsics, Z., Bailer, S. (2019) Comprehensive analysis of nuclear export of herpes simplex virus type 1 tegument proteins and their Epstein-Barr virus orthologs. Traffic 20(7), 152–167. https://doi.org/10.1111/tra.12627

12. Gille, A., Stojnic, B., Derwenskus, F., Trautmann, A., Schmid-Staiger, U., Posten, C., Briviba, K., Palou, A., Bonet, M. L., Ribot, J. (2019) A lipophilic fucoxanthin-rich *Phaeodactylum tricornutum* extract ameliorates effects of diet-induced obesity in C57BL/6J mice. Nutrients 11(4), Art. 796. https://doi.org/10.3390/nu11040796

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14. Holdmann, C., Schmid-Staiger, U., Hirth, T. (2019) Outdoor microalgae cultivation at different biomass concentrations – Assessment of different daily and seasonal light scenarios by modeling. Algal Research 38, Art. 101405. https://doi.org/10.1016/j.algal.2018.101405

15. Huber, B., Hoch, E., Calderon, I., Borchers, K., Kluger, P. (2019) A versatile perfusion bioreactor and endothelializable photo cross-linked tubes of gelatin methacryloyl as promising tools in tissue engineering. Biomedizinische Technik 64(4), 397–406. DOI: 10.1515/bmt-2018-0015

16. Köhn, A., Austin, M. E., Brookman, M. W., Gentle, K. W., Guidi, L., Holzhauer, E., La Haye, R. J., Leddy, J. B., Maj, O., Petty, C. C., Poli, E., Snicker, A., Thomas, M. B., Vann, R. G. L., Weber, H. (2019) The deteriorating effect of plasma density fluctuations on microwave beam quality. EPJ Web of Conferences 203. https://doi.org/10.1051/epjconf/201920301005

17. Krutkin, O. L., Altukhov, A. B., Gurchenko, A. D., Gusakov, E. Z., Irzak, M. A., Esipov, L. A., Sidorov, A.V., Chôné, L., Kiviniemi, T. P., Leerink, S. Niskala, P. Lechte, C., Heuraux, S., Zadvitskiy, G. (2019) Validation of full-f global gyrokinetic modeling results against the FT-2 tokamak Doppler reflectometry data using synthetic diagnostics. Nuclear Fusion 59(9). https://doi.org/10.1088/1741-4326/ab1cfb

18. Krutkin, O. L., Gusakov, E. Z., Heuraux, S., Lechte, C. (2019) Nonlinear Doppler reflectometry power response. Analytical predictions and full-wave modelling. Plasma Physics and Controlled Fusion 61(4), Art. 045010. https://doi.org/10.1088/1361-6587/ab0236

19. Liewald, M., Tovar, G. E. M., Wörz, C., Umlauf, G. (2019) Tribological conditions using CO_2 as volatile lubricant in dry metal forming. International Journal of Precision Engineering and Manufacturing-Green Technology. https://doi.org/10.1007/s40684-019-00069-6

20. Moseev, D., Stejner, M., Stange, T., Abramovic, I., Laqua, H. P., Marsen, S., Schneider, N., Braune, H., Hoefel U., Kasparek W., Korsholm S. B., Lechte C., Leipold F., Nielsen S. K., Salewski M., Rasmussen, J., Weißgerber M., Wolf, R. C. (2019) Collective Thomson scattering diagnostic at Wendelstein 7-X. Review of Scientific Instruments 90, Art. 013503. https://doi.org/10.1063/1.5050193

21. Nellinger, S., Keller, S., Southan, A., Wittmann, V., Volz, A.-C., Kluger, P. J. (2019) Generation of an azide-modified extracellular matrix by adipose-derived stem cells using metabolic glycoengineering. Current Directions in Biomedical Engineering 5(1), 393–396. https://doi.org/10.1515/cdbme-2019-0099

22. Neumann, U., Derwenskus, F., Flister, V. F., Schmid-Staiger, U., Hirth, T., Bischoff, S. C. (2019) Fucoxanthin, a carotenoid derived from *Phaeodactylum tricornutum* exerts antiproliferative and antioxidant activities in vitro. Antioxidants 8(6), Art. 183. https://doi.org/10.3390/antiox8060183

23. Novosel, E., Borchers, K., Kluger, P., Mantalaris, A., Matheis, G., Pistolesi, M., Schneider, J., Wenz, A., Lelkes, P. (2019) New approaches to respiratory assist: Bioengineering an ambulatory, miniaturized bioartificial lung. ASAIO journal (American Society for Artificial Internal Organs) 65(5), 422–429. ISSN: 1538-943X

24. Rebers, L., Granse, T., Tovar, G. E. M., Southan, A., Borchers, K. (2019) Physical interactions strengthen chemical gelatin methacryloyl gels. Gels 5(1), Art. 4. https://doi.org/10.3390/gels5010004

25. Riehle, N., Thude, S., Kandelbauer, A., Tovar, G. E. M., Lorenz, G. (2019) Synthesis of soft polysiloxane-urea elastomers for intraocular lens application. Journal of visualized experiments (JoVE) 145. DOI: 10.3791/58590

26. Schuster, F., Hirth, T., Weber, A. (2019) Reactive inkjet printing of polyethylene glycol and isocyanate based inks to create porous polyurethane structures. Journal of Applied Polymer Science 136(3), Art. 46977. https://doi.org/10.1002/app.46977

27. Seibert-Ludwig, D., Hahn, T., Hirth, T., Zibek, S. (2019) Selection and optimization of a suitable pretreatment method for miscanthus and poplar raw material. GCB Bioenergy 11(1), 171–180. https://doi.org/10.1111/gcbb.12575

28. Shendi, D., Marzi, J., Linthicum, W., Rickards, A. J., Dolivo, D. M., Keller, S., Kauss, M. A., Wen, Q., McDevitt, T. C., Dominko, T., Schenke-Layland, K., Rolle, M. W. (2019) Hyaluronic acid as a macromolecular crowding agent for production of cell-derived matrices. Acta Biomaterialia 100, 292–305. https://doi.org/10.1016/j.actbio.2019.09.042

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30. Stier, S., Rebers, L., Schönhaar, V., Hoch, E., Borchers, K. (2019) Advanced formulation of methacryl- and acetyl-modified biomolecules to achieve independent control of swelling and stiffness in printable hydrogels. Journal of Materials Science: Materials in Medicine 30(3), Art. 35). https://doi.org/10.1007/s10856-019-6231-0

31. Volz, A.-C., Omengo, B., Gehrke, S. A., Kluger, P. (2019) Comparing the use of differentiated adipose-derived stem cells and mature adipocytes to model adipose tissue in vitro. Differentiation 110, 19–28. https://doi.org/10.1016/j.diff.2019.09.002

32. Zahedi, E., Woerz, C., Reichardt, G., Umlauf, G., Liewald, M., Barz, J., Weber, R., Foerster, D. J., Graf, T. (2019) Lubricant-free deep drawing using CO_2 and N_2 as volatile media injected through laser-drilled microholes. Manufacturing Review 6, Art. 11. https://doi.org/10.1051/mfreview/2019011

Books

33. Beck, A., Werner, N., Zibek, S. (2019) Chapter 4 – Mannosylerythritol Lipids: Biosynthesis, Genetics, and Production Strategies. In Douglas G. Hayes; Daniel K. Y. Solaiman; Richard D. Ashby (Ed.), Biobased Surfactants: Synthesis, Properties, and Applications (121–167). London: Academic Press and AOCS Press. https://doi.org/10.1016/B978-0-12-812705-6.00004-6

34. Rais, D., Zibek, S. (2019) Biotechnological and biochemical utilization of lignin. In Kurt Wagemann; Nils Tippkötter (Ed.), Biorefineries (Vol 166, Advances in Biochemical Engineering/Biotechnology, 469–518). Cham: Springer International Publishing. https://doi.org/10.1007/10_2017_6

Other publications (extended abstracts, unrefereed publications)

35. Balk, M., Jin, J., Endermann, M., Schneider, J., Baumgärtner, K.-M., Pauly, S., Merli, S., Schulz, A., Walker, M. Tovar, G. E. M. (2019) Microwave Plasma Sources for High-rate Applications. IMPI's 53rd Annual Microwave Power Symposium, June 2019, Las Vegas, Nevada, USA.

36. Conway, G. D., Lechte, C., Poli, E., Maj, O. and the ASDEX Upgrade Team (2019) Recent progress in modelling the resolution and localization of Doppler reflectometry measurements. In Proceeding of the 14th International Reflectometry Workshop (IRW14), May 2019.

37. Fanale, F., Bruschi, A., Darcourt, O., Farina, D., Figini, L., Gandini, F., Hernderson, M., Hunt, R., Moro, A., Platania, P., Plaum, B. (2019) Quasi-Optical design of ECRH mirrors for ITER first plasma operations. In Proceeding of the 44th International Conference on Infrared, Millimeter, and Terahertz Waves, September 2019, Paris, France.

38. Köhn, A., Holzhauer, E. (2019) The depolarizing effect of plasma density fluctuations on microwave beams. Proceeding of the 46th EPS Conference on Plasma Physics, Milan, Italy, 2019 (Vol. 43C, P4.1078).

39. Lechte, C., Conway G. D., Görler, T., Happel, T. and the ASDEX Upgrade Team (2019) Fullwave Doppler reflectometry simulations for turbulence spectra using GENE and IPF-FD3D. In Proceeding of the 14th International Reflectometry Workshop (IRW14), May 2019.

40. Merli, S., Schulz, A., Walker, M. (2019) Hochrateabscheidung von Schutzbeschichtungen mit einem Mikrowellenplasma. 14. ThGOT Thementage Grenz- und Oberflächentechnik und 6. Kolloquium Dünne Schichten in der Optik, March 2019, Zeulenroda-Triebes, Germany, ISBN 978-3-00-058187-8.

41. Müller, R., Baumgärtner, K.-M., Balk, M., Schneider, J., Merli, S., Schulz, A., Walker, M., Tovar G. (2019) Functional coatings deposited from low-pressure microwave plasmas. IMPI's 53rd Annual Microwave Power Symposium, June 2019, Las Vegas, Nevada.

42. Pauly, S., Schulz, A., Walker, M., Gorath, M., Baumgärtner, K.-M., Tovar, G. E. M. (2019) Modelling and study of a microwave plasma source for high-rate etching. AMPERE 2019 (17th International Conference on Microwave and High Frequency Heating. Editorial Universitat Politècnica de València). http://dx.doi.org/10.4995/Ampere2019.2019.9757

43. Plaum, B. (2019) Simulation of microwave beams with PROFUSION. Technical report, IGVP, University of Stuttgart, February 2019.

44. Rebers, L., Borchers, K., Hoch, E., Stier, S., Schönhaar, V., Weber, Achim (2019) Printable glycosaminoglycan graded gelatin methacryloyl acetyl hydrogel, NIP & Digital Fabrication Conference, Printing for Fabrication 2019, 48–51. https://doi.org/10.2352/ISSN.2169-4451.2019.35.48

45. Ullmann, T., Schmid, B., Manz, P., Ramisch, M. (2019) Shrinking of resonant manifold under flow shear at the stellarator TJ-K. Proceeding of the 46th EPS Conference on Plasma Physics, Milan, Italy, 2019 (Vol. 43C, P5.1064).

46. Troia, M., Schulz, A., Walker, M. (2019) Non-destructive test for the analysis of defects in thin barrier films. 14. Thementage Grenz- und Oberflächentechnik und 6. Optik-Kolloquium, March 2019, Zeulenroda-Triebes, Germany.

47. Wagner, D., Stober, J., Kircher, M., Leuterer, F., Monaco, F., Münich, M., Schubert, M., Zohm, H., Gantenbein, G., Jelonnek, J., Thumm, M., Meier, A., Scherer, T., Strauss, D., Kasparek, W., Lechte, C., Plaum, B., Zach, A., Litvak, A. G., Denisov, G. G., Chirkov, A., Malygin, V., Popov, L. G., Nichiporenko, V. O., Myasnikov, V. E., Tai, E. M., Solyanova, E. A. and the ASDEX Upgrade team (2019) Completion of the 8 MW multi-frequency ECRH system at ASDEX upgrade. In Proceeding of the 44th International Conference on Infrared, Millimeter, and Terahertz Waves, September 2019, Paris, France.

Conference contributions – Posters

48. Baron Nunez, F.-W., Zibek, S. (2019) Intensification of the of downstream processing of Mannosylerythritol lipids. Himmelfahrtstagung 2019, Intensification and digitalisation for integral bioprocessing, May 27–29, 2019, Hamburg, Germany.

49. Baron-Nunez, F. W., Zibek, S. (2019) Prospective strategies for downstream process of mannosylerythritol lipids. Biosurfactants Conference, September 25–27, 2019, Stuttgart-Hohenheim, Germany.

50. Beck, A., Grunwald, S., Preuss, L., Radermacher, S., Kövilein, A., Rupp, S., Zibek, S. (2019) Microbial production of mannosylerythritol lipids (MEL) from lignocellulosic feedstock. 4. Statusseminar: Forschungsprogramm Bioökonomie Baden-Württemberg, January 8, 2019, Stuttgart-Hohenheim, Germany.

51. Beck, A., Zibek, S. (2019) Bioreactor production of the microbial glycolipid mannosylerythritol lipid (MEL) from renewable resources. 15th International Conference on Renewable Resources & Biorefineries (RRB-15), June 3–5, 2019, Toulouse, France.

52. Brebeck, G., Mühlemeier, I., Stier, M., Schließmann, U., Hirth, T. (2019) Development of a bioreactor for the utilization of biogas as a feedstock. 4. Statusseminar: Forschungsprogramm Bioökonomie Baden-Württemberg, January 8, 2019, Stuttgart-Hohenheim, Germany.

53. Brookman, M. W., Köhn, A., Martin, E. H., Thomas, M. B., La Haye, R. J., Woodward, D. J. L., Leddy, J. B., Peysson, Y., Yan, Z., Barada, K., Rhodes, T., Lau, C. H., Vann, R. G. L., Austin, M. E. (2019) Transport fitting of modulated power measurements resolves RF beam scattering. 24th Joint US-EU Transport Task Force Meeting, March 18–21, 2019, Austin, Texas, USA.

54. Brookman, M. W., Köhn, A., Thomas, M. B., Holland, L., La Haye, R. J., Leddy, J. B., Peysson, Y., Yan, Z., Barada, K., Rhodes, T., Vann, R. G. L., Austin, M. E. (2019) Microwave scattering due to density fluctuations in the DIII-D Tokamak. 61st Annual Meeting of the APS Division of Plasma Physics, October 21–25, 2019, Fort Lauderdale, Florida, USA.

55. Dehli, F., Rebers, L., Stubenrauch, C., Southan, A. (2019) Highly ordered gelatin methacryloyl hydrogel foams with tunable pore sizes. 33rd Conference of the European Colloid and Interface Society, September 8–13, 2019, Leuven, Belgium.

56. Derwenskus, F., Schmid-Staiger, U., Schließmann, U., Hirth, T. (2019) Microalgae biorefinery – cascaded fractionation of microalgae ingredients for food and feed applications. 4. Statusseminar: Forschungsprogramm Bioökonomie Baden-Württemberg, January 8, 2019, Stuttgart-Hohenheim, Germany.

57. D'Isa, F., Hecimovic, A., Carbone, E., Fantz, U., Kistner, I., Schulz, A., Walker, M., Tovar, G. E. M. (2019) Characterisation of a 2.45 GHz microwave atmospheric pressure plasma torch in N_2 and CO_2. DPG-Frühjahrstagung, March 17–22, 2019, Munich, Germany.

58. Gorke, O., Tovar, G. E. M., Southan, A. (2019) Synthesis of water-soluble furan-functionalized polyelectrolytes and polyelectrolyte networks. Frontiers in Polymer Science, May 5–8, 2019, Budapest, Hungary.

59. Grübel, J. (2019) Functionalisation of polymers with isothiouronium groups for improved biointegration of implant materials. ProMatLeben – Polymere. September 3–4, 2019, Berlin, Germany.

60. Kistner, I., Schulz, A., Walker, M., Tovar, G. E. M., Buck, F., Schiestel, T., Widenmeyer, M., Chen, G., Weidenkaff, A. (2019) Untersuchung einer Mikrowellenplasmaquelle für die CO_2 Konversion. 19th Symposium on Plasma Technology (PT19), June 17–19, 2019, Cottbus, Germany.

61. Kistner, I., Wiegers, K., Schulz, A., Walker, M., Tovar, G. E. M. (2019) Investigation of a microwave plasma torch for CO_2 gas conversion. DPG-Frühjahrstagung, March 17–22, 2019, Munich, Germany.

62. Kriem, L., Rupp, S., Schließmann, U. (2019) The use of confocal raman microscopy for oral bacteria differentiation. 6th European Congress on Biofilms (EUROBIOFILMS 2019), September 3–6, 2019. Glasgow, UK.

63. Merli, S., Kistner, I., Schulz, A., Walker, M., Tovar, G. E. M., Buck, F., Schiestel, T., Widenmeyer, M., Chen, G., Weidenkaff, A. (2019) Microwave plasma reactor for CO_2 decomposition. The 72nd Gaseous Electronics Conference (GEC), October 28 – November 1, 2019, College Station, Texas, USA.

64. Michele, A., Tovar, G. E. M., Southan, A. (2019) Thermally induced cross-linking and decomposition of poly(vinyl alcohol) under influence of p-toluenesulfonic acid. Frontiers in Polymer Science, May 5–8, 2019, Budapest, Hungary.

65. Nellinger, S., Keller, S., Southan, A., Wittmann, V., Kluger, P. J. (2019) Generation of an azide-modified extracellular matrix by adipose-derived stem cells using metabolic glycoengineering. BMT 2019 – the Biomedical Engineering Congress – the 53rd Annual Conference of the German Society for Biomedical Engineering, September 25–26, 2019, Frankfurt am Main, Germany.

66. Neumann, U., Becker, M., Frick, K., Derwenskus, F., Bischoff, S. C., Schmid-Staiger, U., Stier, M., Tovar, G. E. M. (2019) MIATEST – Herstellung von Mikroalgenpräparationen und Testung als gesundheitsfördernden Nahrungsstoff für den Menschen sowie als umweltschonendes Pflanzenstärkungsmittel im Weinbau. 4. Statusseminar: Forschungsprogramm Bioökonomie Baden-Württemberg, January 8, 2019, Stuttgart-Hohenheim, Germany.

67. Pauly, S., Schmid, B., Schulz, A., Walker, M., Tovar, G. E. M., Baumgärtner, K. (2019) Modeling and study of a remote plasma source for high-rate etching, DPG-Frühjahrstagung, March 17–22, 2019, Munich, Germany.

68. Ramisch, M., Garland, S., Schmid, B., Ullmann, T. (2019) Formation of turbulent transport in 3D stellarator geometry. DPG-Frühjahrstagung, March 17–22, 2019, Munich, Germany, P18.65.

69. Schulz, A. (2019) Microwave plasma reactor for CO_2 decomposition. KEROGREEN Workshop on plasma catalysis for renewable fuels and chemicals, November 15, 2019, Eindhoven, The Netherlands.

70. Spindler, L., Rebers, L., Hoch, E., Braun, J., Granse, T., Southan, A., Borchers, K., Weber, A. (2019) Crosslinkable gelatin derivates with high degree of modification and low solution viscosities for simplified processing by spray drying and inkjet-printing. Controlled Release Society Annual Meeting & Exposition. July 21–24, 2019, Valencia, Spain.

71. Spindler, L. M., Gruber-Traub, C., Tovar, G. E. M., Weber, A. (2019) Controllable release of biotin through in situ ionic crosslinking and encapsulation in sodium alginate by means of spray drying. Controlled Release Society Annual Meeting & Exposition. July 21–24, 2019, Valencia, Spain.

72. Spindler, L. M., Gruber-Traub, C., Tovar, G. E. M., Weber, A. (2019) Encapsulation of active ingredients and in situ ionic crosslinking of alginate by means of spray drying. ProMatLeben – Polymere, Doktoranden- und PostDoc-Konferenz, September 3–4, 2019, Berlin, Germany.

73. Troia, M., Schulz, A., Walker, M., Hirth T. (2019) Vergleich der Barriereeigenschaften von Plasmapolymerisierten HMDSN- und HMDSO-basierten Schichten. 19th Symposium on Plasma Technology (PT19), June 17–19, 2019, Cottbus, Germany.

74. Ullmann, T., Schmid, B., Manz, P., Ramisch, M. (2019) Three-mode coupling under imposed E × B shear. DPG-Frühjahrstagung, March 17–22, 2019, Munich, Germany, P18.66.

75. Vidal Quintana, A. A., Waelkens, B., Schließmann, U. (2019) Biogas potential analysis on WWTPs in Baden-Württemberg. 4. Statusseminar: Forschungsprogramm Bioökonomie Baden-Württemberg, January 8, 2019, Stuttgart-Hohenheim, Germany.

Conference contributions – Oral presentations

76. Beck, A. (2019) Bioreactor production of the microbial glycolipid mannosylerythritol lipid (MEL) from renewable resources. Biosurfactants Conference, September 25–27, 2019, Stuttgart-Hohenheim, Germany.

77. Fantz, U., Jelonnek, J., Link, G., Soldatov, S., Walker, M., Schulz, A., Kistner, I., Carbone, E., Hecimovic, A., D'Isa, F. (2019) Conversion of CO_2 into added-value chemicals like CO using MW plasmas – A collaborative project of KIT/IGVP/IPP. KEROGREEN Workshop on plasma catalysis for renewable fuels and chemicals, November 15, 2019, Eindhoven, The Netherlands.

78. Frick, K. (2019) Best practice lab reactors: cultivation conditions, important parameters, sterilisation and inoculation, control and feeding system, sampling and OD/DW determination. Workshop Algal Biotechnology Techniques and Opportunities for the Sustainable Bioeconomy, November 12–13, 2019, Stuttgart, Germany.

79. Hanke, S., Day, C., Giegerich, T., Igitkhanov, J., Kathage, Y., Luo, X., Varoutis, S., Vazquez Cortes, A., Härtl, T., Busniuk, A., Livshits, A., Merli, S., Schulz, A., Walker, M., Baumgärtner, K., Hofmann, J. (2019) Progress of the R&D programme to develop a metal foil pump for DEMO. 14th International Symposium on Fusion Nuclear Technology, Septermber 22–27, 2019, Budapest, Hungary.

80. Kasparek, W., Happel, T., Hennequin, P., Höfler, K. (2019) Development of a frequency-comb reflectometer. 31st Joint Russian-German Workshop on ECRH and Gyrotrons, June 3–8, 2019, Lenggries, Germany.

81. Keller, S., Wittmann, V., Tovar, G. E. M., Southan, A., Bach, M., Kluger, P. J. (2019) Development and characterization of an azide-functional cell-derived extracellular matrix as biomaterial. 30th Annual Conference of the European Society for Biomaterials (ESB) in tandem with the 26th Annual Conference of the German Society for Biomaterials (DGBM), September 9–13, 2019, Dresden, Germany.

82. Kistner, I., Schulz, A., Walker, M., Tovar, G. E. M. (2019) Perovskite hollow fibers for oxygen separation in a CO_2 plasma. IPP ITED Ringberg Seminar 2019, April 1–5, 2019, Kreuth, Germany.

83. Köhn, A., Holzhauer, E., Thomas, M. B., Vann, R. G. L., Leddy, J. B., Holland, L., Maj, O., Guidi, L., Poli, E., Snicker, A., Weber, H., Brookman M. W. (2019) Reduction of microwave beam quality due to plasma density fluctuations (invited). DPG-Frühjahrstagung, March 17–22, 2019, Munich, Germany, P15.2.

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113. Rais, D. P. (2019) Identifizierung und Charakterisierung bakterieller Lignin-modifizierender Enzyme, University of Stuttgart.

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119. Dikmen, B. (2019) *Title protected*, University of Stuttgart, Seminar paper.

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121. Jansen, F. (2019) Development of a 3D-printed low-cart video laryngascope for low and middle income countries, University of Stuttgart, master thesis.

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132. Rauleder, R. (2019) Oberflächencharakterisierung von Polymethylacrylar-basierten Folien mit gezielter Oberflächenfunktionalisierung, Reutlingen University, bachelor thesis.

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