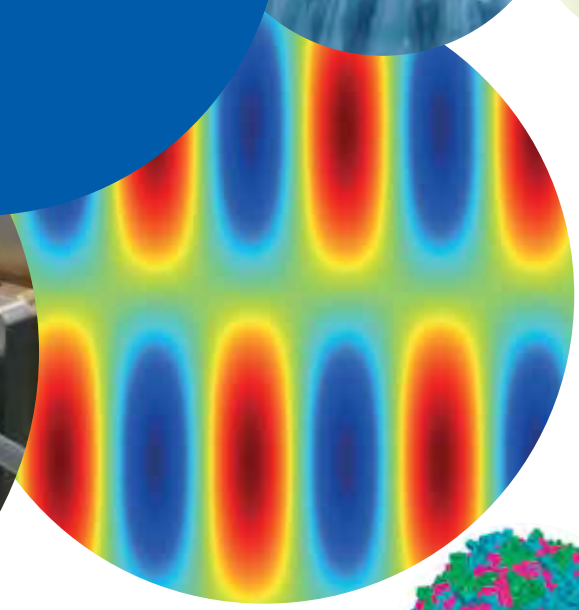
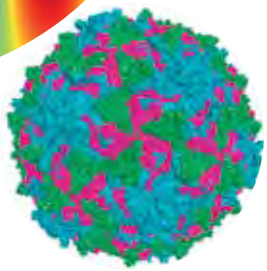
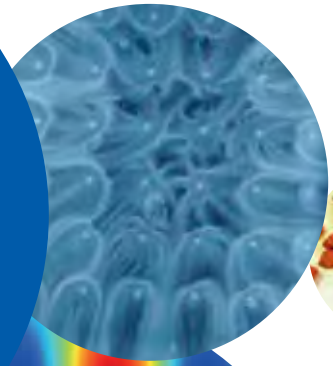
University of Stuttgart
Institute of Interfacial Process Engineering
and Plasma Technology

Annual Report 2017







Editorial notes

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Annual Report 2017

Institute of Interfacial Process Engineering and Plasma Technology
University of Stuttgart

Preface

2017 was an eventful year in which we continued our high level research and attractive teaching and started numerous sophisticated new research projects.

A joyful message first: Priv.-Doz. Dr. Susanne Bailer was appointed an extraordinary professorship from the University of Stuttgart, honoring her committed teaching and research as a Principal Investigator with us at the IGVP in a joint appointment with the Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB since 2012.

In contrast, Dr.-Ing. Walter Kasparek, another Principal Investigator, retired after more than 40 years of plasma research at the University of Stuttgart. Walter Kasparek has made a great and lasting impression on the fusion research landscape, starting with CO_2 laser scattering in fusion plasmas, then moving on to microwave and millimeter wave technology, with the development of innovative high and low power transmission line concepts, components for diagnosing and manipulating millimeter wave beams, and providing guidance to a multitude of projects in the microwave community. Dr. Carsten Lechte is his successor as head of the Microwave Technology group.

Additionally to numerous other research projects we are pleased to have been awarded e.g. the research project *Plasma-induced CO_2 conversion for the storage of renewable energies – PiCK* which is part of the *Kopernikus projects for the Energiewende*, funded by the BMBF. The subproject at IGVP *Research on CO_2 dissociation in a microwave plasma torch* is headed by Dr. Andreas Schulz, who also coordinates the entire PiCK project. He works closely with Dr. Thomas Schiestel at Fraunhofer IGB, who heads a subproject on membrane development.

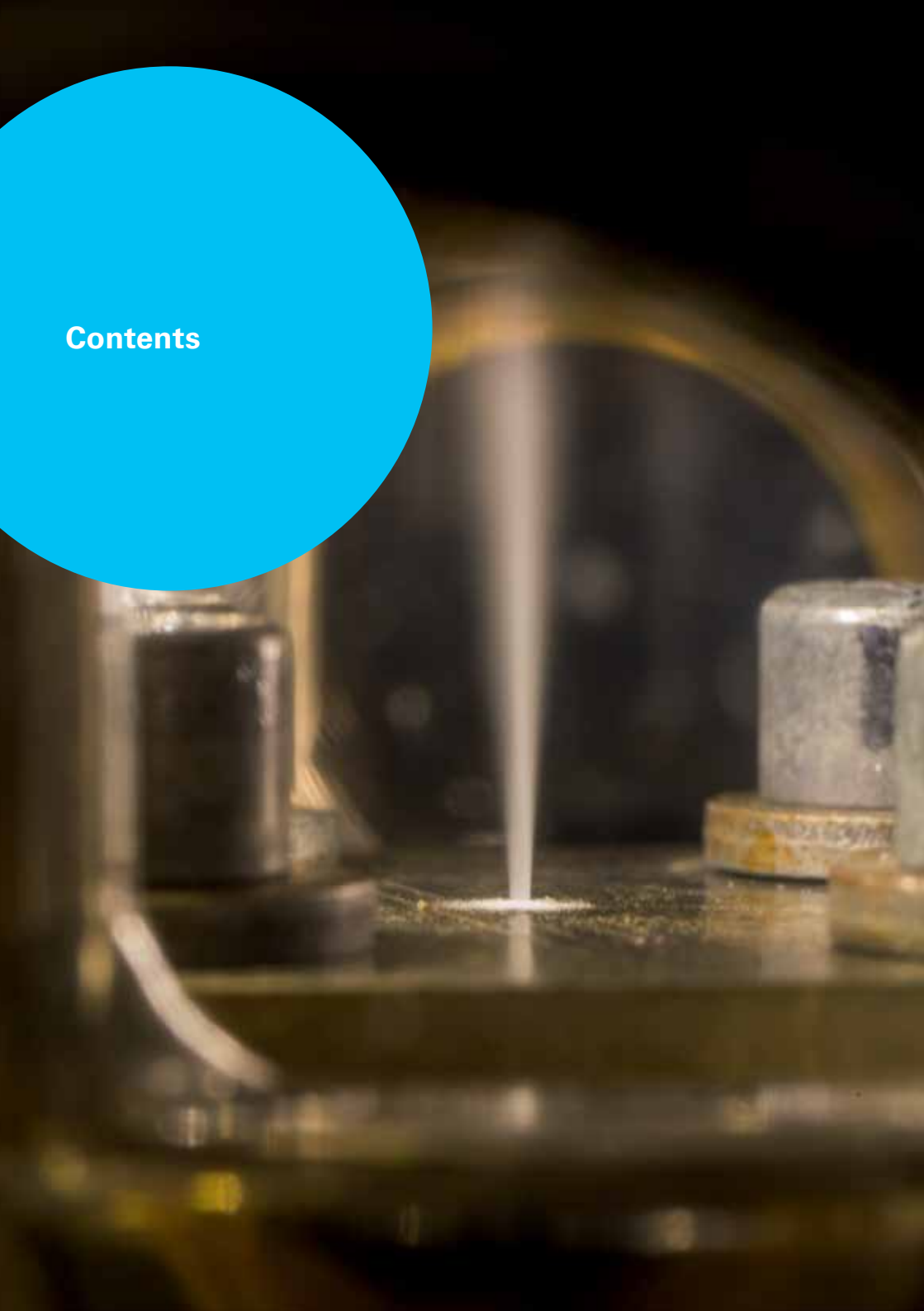
Another major success was the approval of the DFG joint project *Tribosystems for dry forming based on volatile lubricating media and laser-structured surfaces* which is funded within the DFG priority program *SPP 1676: Sustainable production through dry machining in forming technology*. Research assistant is Georg Umlauf MSc and cooperation with Dr. Jakob Barz, Fraunhofer IGB, is thankfully acknowledged.

The joint project *Highly integrated cathode subsystem – HIKS* funded by the Federal Ministry of Economics and Energy (BMWI) is another new project at the IGVP. Here, Dr. Alexander Southan heads the subproject *Development of hydrogel materials for membrane coating*, a partner project at Fraunhofer IGB on membrane development is also run by Dr. Thomas Schiestel.

An outstanding success is the award of a *High Performance Center* on mass personalization together with seven other institutes of our university and with all four Fraunhofer Institutes here in Stuttgart. Our closely joint effort dedicated to research on new enabling technologies for personalized products at an affordable price is funded by Baden-Württemberg by its Ministry of Science, Research and the Arts and the Ministry of Economic Affairs, Labour and Housing, the *Fraunhofer-Gesellschaft* and numerous industrial partners. In this center we will investigate interdisciplinary and cross-sectoral methods, procedures, processes, product systems and business models for the manufacture of personalized products. At the IGVP we focus on a modular approach on surface coatings for personalized implant materials and diagnostic systems.

We like to thank our partners for the confidence they have placed in us 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 and teaching in the fields of materials science and technology, life sciences, process engineering and plasma science.

Key Figures
In 2017, the research budget accounted for 2.64 million euros. At the end of that year, 76 scientific, technical and administrative employees, among them 27 young scientists working on a doctoral thesis, staffed the IGVP. Additionally, 44 students were researching for their master or bachelor thesis with us.

Organization and Facilities
The Institute is part of the Faculty of Energy Technology, Process Engineering and Biological 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 three IGVP facilities in Pfaffenwaldring 31, Allmandring 5b, and Nobelstrasse 12 for interdisciplinary engineering and natural scientific research.

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 physics, and the dynamic properties of plasmas and electromagnetic waves are analyzed and simulated.

Collaboration
Close cooperation of the IGVP with the Fraunhofer Institute for Interfacial Engineering and Biotechnology 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 German Federal Ministries (e.g. BMBF), the German Research Foundation (DFG), the German Federal Foundation for the Environment (DBU), the EU, the *Land* of Baden-Württemberg, various foundations and industry.
Key partners also include the Max Planck Institute for Plasma Physics (IPP) in Garching and Greifswald, the Karlsruhe Institute of Technology KIT, and the Dutch Institute for Fundamental Energy Research DIFFER in the Netherlands.

Teaching
IGVP is actively involved in the teaching of master and bachelor study programs at Stuttgart University such as Process Engineering, Medical Technology, Technical Biology, Energy Technology, Renewable Energy Engineering, Environmental Engineering, WASTE, etc.

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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Dr.-Ing. Susanne Zibek

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Konstantin Frick
Anja Grohmann
Ilka Mühlemeier
Alfonso Vidal Quintana
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Yen-Cheng Yeh (since December 2017)
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Dr. Andreas Schulz

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Bernhard Schmid
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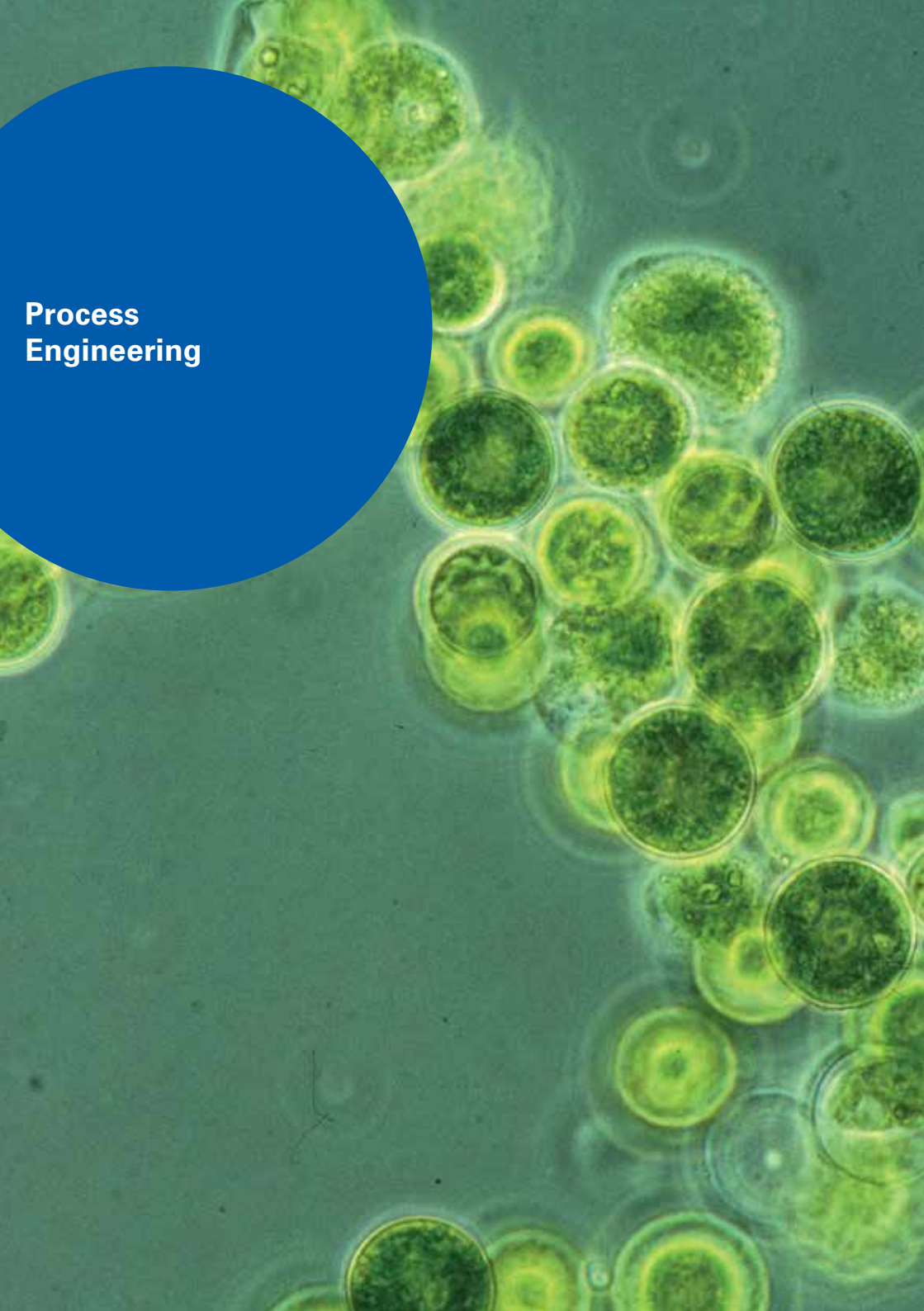
Interfacial Process Engineering


Process
Engineering

Interfaces in Bioprocess Engineering

Dr.-Ing. Matthias Stier, matthias.stier@igb.fraunhofer.de

Interfaces often play an important role in bioengineering. In processes for wastewater and exhaust air treatment microorganisms or enzymes are often immobilized on carriers in order to increase catalyst density. The microbial organisms in aerobic and anaerobic production systems are strongly affected by the ambient conditions in fermenters. For this reason there is a need for looking at the respective process in its entirety. 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 use standard fermenters but in addition also self-developed reactor systems such as the flat-panel airlift reactor (developed at Fraunhofer IGB) and 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 could potentially be used in the food and feed sector. From microalgae and other plants biosurfactants can be produced by microorganisms and be tailored in their surfactant performance. Therefore, we investigate various cascading extraction methods to get the products efficiently out of the biomass.

Industrial Biotechnology

Dr.-Ing. Susanne Zibek, susanne.zibek@igb.fraunhofer.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.

Cost-Efficient Production of Polyhydroxyalkanoates for the Manufacturing of Sustainable Packagings

Steffen Scholz, Thomas Hahn, Susanne Zibek

Despite increasing production capacities and growth rates, biobased and biodegradable polymers currently have a low market share in the overall plastics production compared to fossil-based polymers [1]. Although the biobased polymers provide comparable characteristics to their synthetic analogues [2] and greenhouse gas emissions during production have mitigated [3], access to the market is hampered since the production costs are two to three times higher than those of fossil-based polymers. Polyhydroxyalkanoates (PHA) are one of these promising biopolymers, intracellularly stored in granules by some bacteria, such as *Cupriviadus necator* or *Alcaligenes latus*, which have excellent properties but suffer from the high production costs.

Our intention is to meet these challenges, i.e. to increase marketability of the PHA and to reduce production costs. We therefore focus our efforts on raw material, process engineering as well as on downstream processing: Utilizing agro-industrial waste streams such as molasses or crude glycerol rather than purified substrates is one of the key factors to be considered within our investigations. Adapting feeding strategies or optimizing culture media is another research topic resulting in higher space-time yields and finally higher product concentration. Concerning downstream processing, pressure change technology (PCT) is applied as the method of choice substituting the commonly applied extraction with toxic and expensive solvents.

[1] H. Storz, K. D. Vorlop, "Bio-based plastics: status, challenges and trends", Landbauforschung 63, pp. 321–32, 2013.
[2] V. H. Pino-Ramos, H. I. Meléndez-Ortiz, A. Ramos-Ballesteros, E. Bucio, "Chapter 6 – Radiation Grafting of Biopolymers and Synthetic Polymers: Synthesis and Biomedical Applications A2", Thakur, Vijay Kumar, Biopolymer Grafting, Elsevier, pp. 205–50, 2018.
[3] I. D. Posen, J. Paulina, E. L. Amy, W. M. Griffin, "Greenhouse gas mitigation for U.S. plastics production: energy first, feedstocks later", Environmental Research Letters 12, p. 034024, 2017.

Collaboration: University of Stuttgart, Insitute of Microbiology, Stuttgart; LCS Life Cycle Simulation, Backnang; HPX Polymers GmbH, Tutzing; Gaplast GmbH, Peiting; WALA Heilmittel GmbH, Bad Boll; WELEDA AG, Schwäbisch Gmünd

Funding: German Federal Ministry of Education and Research (BMBF): Cost-efficient production of biopolymer polyhydroxyalkanoates (PHA) for the manufacturing of tailor-made sustainable packaging concepts for the cosmetic industry, reference no. 031B0371D

Process Development for the Production of Mannosylerythritol Lipids from Renewable Resources

Alexander Beck, Susanne Zibek

With increasing shortage of fossil resources our economy needs to be shifted towards more sustainable resource management and products. Due to their low toxicity and good biodegradability, biosurfactants have recently come into focus. Among them, mannosylerythritol lipids (MEL) are promising molecules that show superior performance regarding emulsification, foaming and even antimicrobial properties, opening up perspectives in cleaning agents and personal care.

Mannosylerythritol lipids are produced by fungi of the *Ustilaginaceae* family. They comprise a variety of molecules usually classified as MEL-A, -B, -C and -D according to their degree of acetylation on the mannosyl unit. Additionally, by modifying the length of their fatty acid side chains, MEL with desirable surfactant properties can be engineered.

The aim of this project is to develop a robust fermentation process in pilot scale in order to produce tailor-made MEL for application in the pharmaceutical and cosmetics industry. A strong focus is laid on the use of renewable resources as substrates for the bioprocess. Detailed characterization of the underlying biosynthetic pathways and structures of the biomolecules is also crucial in order to understand and enhance the MEL production in the respective microorganisms.

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

Funding: Baden-Württemberg Bioeconomy Research Program, Reference No. 7533-10-5-85B, the Baden-Württemberg Stiftung and the Ministry of Science, Research and the Arts of the State of Baden-Württemberg

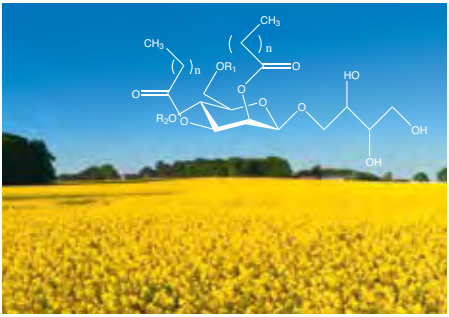


Fig. 1: Production of MEL, for example from rapeseed oil, can be performed under controlled fermentation conditions in a bioreactor.

Development of Extraction Processes for the Cascade Utilization of Microalgae Biomass in Food, Feed and Cosmetic Applications

Felix Derwenskus, Matthias Stier

Microalgae contain a broad range of ingredients which can be used by the food, feed and cosmetic industry. Depending on the specific strain and the cultivation conditions (e.g. nutrient supply, light intensity, pH-value and temperature) microalgae are able to produce high amounts of storage lipids (which occur as triacylglycerides), proteins, polyunsaturated omega-3 fatty acids (e.g. eicosapentaenoic acid, EPA) as well as different micronutrients like carotenoids, e.g. lutein and fucoxanthin. The basic idea of this project is to fractionate different types of microalgae biomass as gentle and selective as possible by applying a combination of pressurized liquid extraction (PLE) and supercritical fluid extraction (SFE) depending on the specific product.

Fig. 1: Sample of fucoxanthin (> 90% w/w), a pigment extracted from the diatom *Phaeodactylum tricornutum*.

Thus, accessory pigments like fucoxanthin as well as fatty acids were successfully extracted from different algae, e.g. *P. tricornutum*. Subsequently, fucoxanthin was purified (Fig. 1). The extraction parameters, evaluated in the lab, can now be used to scale-up the process into technical scale. This is done in cooperation with the project partners from Fraunhofer CBP in Leuna. Currently, the microalgae extracts as well as purified fucoxanthin are investigated concerning their nutritional properties, safety and techno-functional quality, to finally make them applicable for the food and cosmetic industry.

Publication: U. Neumann, S. Louis, A. Gille, F. Derwenskus, U. Schmid-Staiger, K. Briviba, S. C. Bischoff, "Anti-inflammatory effects of Phaeodactylum tricornutum extracts on human blood mononuclear cells and murine macrophages", Journal of Applied Phycology, accepted, 2018, doi.org/10.1007/s10811-017-1352-7

Collaboration: Ulrike Schmid-Staiger, Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; Fraunhofer Center for Chemical-Biotechnological Processes CBP, Leuna; Max Rubner-Institut Federal Research Institute of Nutrition and Food, Karlsruhe; University of Hohenheim, Institute of Clinical Nutrition, Stuttgart

Funding: Baden-Württemberg Bioeconomy Research Program, reference no. 33-7533-10-5/93, funded by the Baden-Württemberg Stiftung and the Ministry of Science, Research and the Arts of the State of Baden-Württemberg

Laminarin Production with Microalgae: Process Development for the Mixotrophic Biomass Production and Extraction

Konstantin Frick, Matthias Stier

The aim of this dissertation is to establish a biotechnological process for the production and processing of laminarin derived from microalgae. The polycarbohydrate laminarin is composed of β-1,3-linked glucose molecules. It can be found in macro- and in microalgae, which use it as a storage molecule for energy and carbon.

Laminarin is similar to a compound located in the cell walls of plant pathogenic fungi. Therefore the non-specific immune system of vascular plants reacts to a contact with laminarin. This activation of the defense mechanisms of the plant can prevent infections with plant pathogenic fungi. For example, common grape wine leaves treated with laminarin are less likely to be infected with downy mildew (*Plasmopara viticola*) or *Botrytis cinerea*. The number of infections with downy mildew dropped by 75% and with *B. cinerea* by 55%. Beside its effect as an elicitor in plants, laminarin has an immunomodulating effect in animals and humans. Therefore it can be used to substitute antibiotics for example in animal breeding.

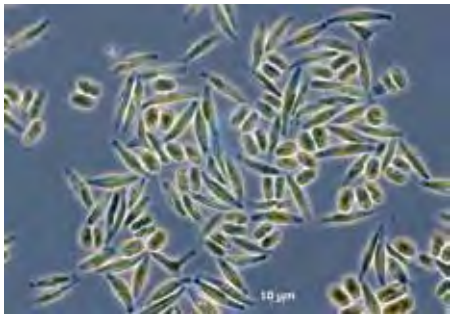


Fig. 1: The diatom *Phaeodactylum tricornutum* produces laminarin.

The project is divided into three work packages: selection of the microalgae strain and its improvement, developing a process to produce algae biomass containing a maximum amount of laminarin and extracting laminarin from the algae biomass.

Collaboration: Ulrike Schmid-Staiger, Fraunhofer Institute for Interfacial Engineering and Biotechnolog IGB, Stuttgart

Characterization of Microbial Dynamics in Anaerobic Biogas Production Systems

Anja Grohmann, Matthias Stier

The anaerobic digestion process during biogas production is very complex and therefore often a “black box” for operators. Many biogas plants do not run in an optimal way, as interferences at an early stage are currently not well defined and controllable.

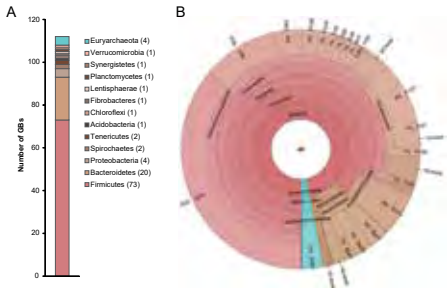


Fig. 1: (A) Phyla-based taxonomic overview. (B) Population proportions of a starting inoculum based on normalized taxonomic read counts. GB = genome bins (Grohmann et al., 2018).

There is little knowledge about the dynamics of microbial populations during the digestion at different process stages and between varying operating conditions. However, a better understanding of the role of different groups of microorganisms and their dynamics is the requirement for a complete process understanding.

As a first step, it is fundamental to improve the database for biogas microbes, because until now, half of the sequencing data cannot be assigned to known species. To generate this database, representative samples are sequenced with combined NGS technologies, to reach long reads and a high coverage, which is essential for the assembly of known genomes. The database will be the reference for further investigations on the population diversity and dynamics of sludge samples from diverse biogas plants.

A deeper understanding for the correlation between different process parameters and the microbial community and the identification of potential key players in the process dynamics represent the basis for a targeted intervention.

Collaboration: Kai Sohn, Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; Ralf Rabus, Institute for Chemistry and Biology of the Marine Environment (ICBM), Universität Oldenburg, Oldenburg; Dieter Bryniok, Hochschule Hamm-Lippstadt, Hamm

Funding: Scholarship of the Landesgraduiertenförderung Baden-Württemberg, University of Stuttgart

Development of a Bioreactor for the Conversion of Biogas

Ilka Mühlemeier, Matthias Stier

The project "Development of a bioreactor for the conversion of biogas into chemical / pharmaceutical products" is part of the biogas research area of the Bioeconomy Research Program Baden-Württemberg.

The aim of the project is to synthesize industrial and pharmaceutical products using aerobic methanotrophic organisms based on a new reactor concept.

With regard to the 2010 world market prices of carbon obtained from retail sugar (0.72 euros per kilogram) in comparison with sugar derived from natural gas (0.19 euros per kilogram), methane produced in biogas plants appears to be a location-independent and cheap alternative carbon source for a variety of industrial and pharmaceuticals products.

Fig. 1: Aerobic, methanotrophic bacteria with the first oxidation step of methane to methanol.

By using methane as a substrate for microorganisms, however, difficulties arise towards the fermentation process due to the formation of the explosive gas mixture and the substrate limitation caused by the poor water solubility of methane. This requires the development of an aerated membrane reactor, which prevents the generation of potentially explosive bubbles inside the reactor.

Funding: Baden-Württemberg Bioeconomy research program, reference no. 33-7533-10-5/103/1, of the Baden-Württemberg Stiftung and the Ministry of Science, Research and the Arts of the State of Baden-Württemberg

Use of a Comprehensive Mathematical Model for the Design of Wastewater Stabilization Ponds for Enhanced Nitrogen Removal

Alfonso Vidal Quintana, Matthias Stier

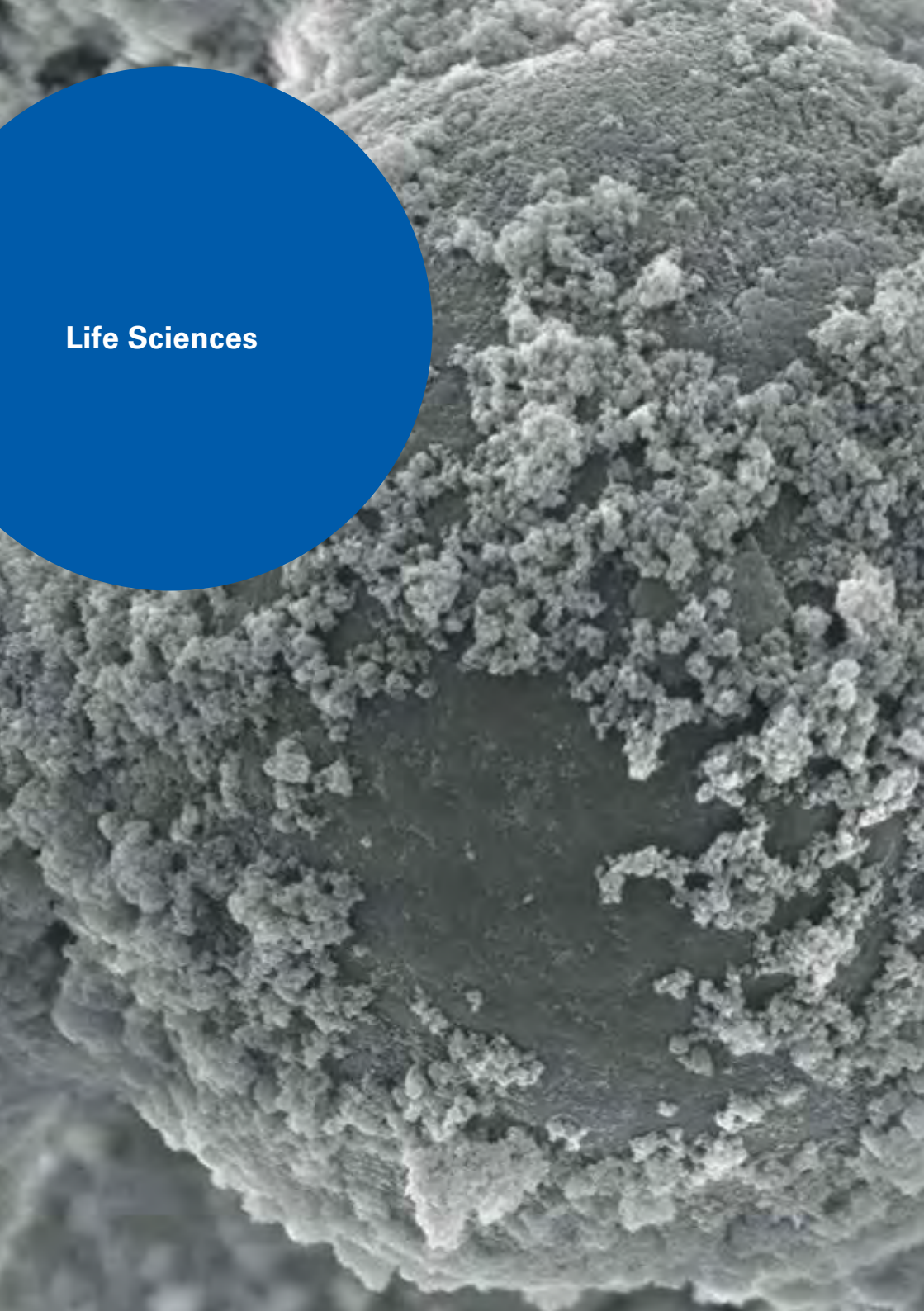
Wastewater stabilization ponds (WSP) are water treatment systems employed for over 300 years, designed and built to reduce the organic content and remove pathogens by naturally occurring processes and the influence of solar light, wind, microorganisms, and algae. The main benefit of WSP is its low cost of operation and maintenance, which makes this technology suitable for use in developing countries.

Current environmental challenges like nitrogen or phosphorus removal were never intended to be performed in WSP, and therefore little knowledge on the removal mechanisms is available to design reliable WSP for nutrient elimination. In 1982 Pano and Middlebrooks described an empirical model of nitrogen elimination with ammonia volatilization as the main mechanism, neglecting nitrification / denitrification and nitrogen uptake from algae and excluding other possible mechanisms as deposition or sorption. Currently, ponds are being designed worldwide based on this work for the United States Environmental Protection Agency and European Water Association (1982 – 2014) where the main objective is the elimination of BOD_5 (biological oxygen demand) and pathogens. Under the assumption of ammonia volatilization, WSP operating at low temperatures will not be able to succeed in eliminating nitrogen to a desirable level. Several examples around the world of ponds working under 10°C and producing effluent according to emission parameters of the most strict laws worldwide cast doubt about the real elimination mechanism of nitrogen in WSP.

Through the use of real operation data from WSP in Chile, an extensive model for the nitrogen elimination will be derived. Several elimination mechanisms (nitrification / denitrification, volatilization, algae uptake, decomposition, sedimentation, and sorption) and meteorological elements (temperature, wind velocity, sunlight intensity and photoperiod, degree of stratification of pond) will be considered using computational tools for simulation. After the validation of the model, optimization points for existing ponds can be obtained. Through an updated understandig of the nitrogen removal mechanism in WSP, recommendations for design strategies of new pond systems with enhanced nitrogen removal will be achieved as the final goal of the research.

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

Funding: Becas Chile Scholarship for Doctoral Degrees Abroad in the Advanced Human Capital Training Program – CONICYT, Ministry of Education, Government of Chile


Life Sciences

Friend or Foe – Research of Viruses

Prof. Dr. Susanne M. Bailer, susanne.bailer@igb.fraunhofer.de

Research at the department 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 and DNA microarrays 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@igb.fraunhofer.de

For more than 18 years, genetic modification and complex cultivation techniques of mammalian cells have been used in the Molecular Cell Technology group. A central aim is the development and application of cell-based screening assays and models for drug development. Various toxicity assays, antibacterial and pyrogenic/allergenic tests have been established and can be performed according to GLP (good laboratory practice). Moreover, complex epithelial 3D infection models to study host-pathogen interactions have been developed. This technological expertise is applied to identify novel immunomodulatory and antiinfective substances. A particular focus is set on reporter gene systems for the detection of immune receptor lignands (interferon- and toll-like receptors) which are also used as sensors for microbial contaminants. With our experience we are moreover developing mammalian, yeast and bacterial, as well as cell-free expression systems for the production of pharmaceutical proteins.

Nuclear Export of Herpes Simplex Virus Type 1 Tegument Proteins

Jacqueline Leimser, Christina Funk, Eileen Arnold, Susanne M. Bailer

Crucial aspects of the herpesviral life cycle occur in the host nucleus, formation of virions however takes place in the cytoplasm. Virions contain more than 25 tegument proteins many of which perform both nuclear and cytoplasmic functions suggesting their nucleo-cytoplasmic exchange is regulated. Trafficking of proteins through the nuclear pore is generally mediated by transport factors of the importin alpha- and beta-families and occurs along a gradient of the small GTPase Ran. While nuclear import of HSV1 tegument proteins has been analyzed in great detail (Fig. 1A), much less is known about their nuclear export (Fig. 1B) or the nuclear egress used for export of capsids (Fig. 1C, see also page 31). To systematically analyze nuclear export of tegument proteins present in virions of HSV1, the Nuclear EXport Trapped by RAPamycin assay (NEX-TRAP) was applied. Nine of the 22 investigated tegument proteins harbor nuclear export activity. A single leucine-rich nuclear export sequence NES recognized by the export factor CRM1/Xpo1 was identified in six of them. Together our data suggest an important role of nuclear export for the coordinated formation of progeny virions in the cytoplasm.

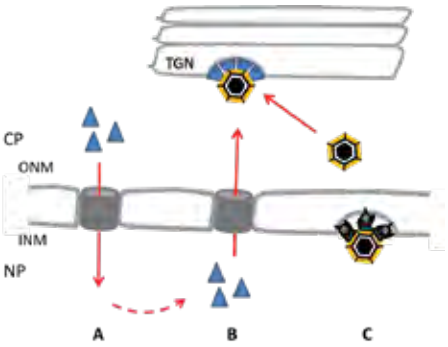


Fig. 1: Two modes of transport to the cytoplasm coexist during herpesviral infection: (A) Nuclear import and (B) nuclear export of viral proteins occurs through the central pore channel, (C) Nuclear egress, a vesicular transport involving both nuclear membranes, enables the release of viral capsids to the cytoplasm.
CP Cytoplasm; NP Nucleoplasm; ONM Outer nuclear membrane, INM Inner nuclear membrane, TGN Trans-Golgi Network

Funding: PhD scholarship of the Peter und Traudl Engelhorn Stiftung, and PhD scholarship of the Landesgraduiertenförderung Baden-Württemberg

Publication: Bailer, SM, Funk, C, Riedl A, Ruzsics Z. (2017) Herpesviral vectors and their application in oncolytic therapy, vaccination, and gene transfer. Virus Genes. doi: 10.1007/s11262-017-1482-7.

Characterization of the Herpes Simplex Virus Nuclear Egress

Débora Marques, Susanne M. Bailer

The family of herpesviruses is divided into the 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), a member of the alpha herpesvirus family, causes recurrent facial lesions or encephalitis. Morphogenesis of herpesviral virions starts in the nucleoplasm with the assembly and genome packaging of capsids but is completed in the cytoplasm. As the size of a mature nuclear capsid exceeds the nuclear pore complex diameter, the formed particle must travel to the cytoplasm by a process called nuclear egress, in which the capsid buds through the nuclear membrane. The nuclear egress complex (NEC) formed between the viral proteins pUL31 and pUL34 is conserved throughout the herpesviral family and essential for viral replication and therefore represents a potential target for panherpesviral therapy. However, due to its high complexity, several details about this mechanism remain unclear. Using a BAC mutagenesis approach, a fluorescent protein has been inserted in the HSV1 genome, allowing to follow the capsid by live imaging promoting the observation of capsids during nuclear egress and other steps of the replication cycle.

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

Collaboration: B. Sodeik, Institute of Virology, Hannover Medical School, Hannover; Z. Ruzsics, University Medical Center Freiburg, Freiburg im Breisgau

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

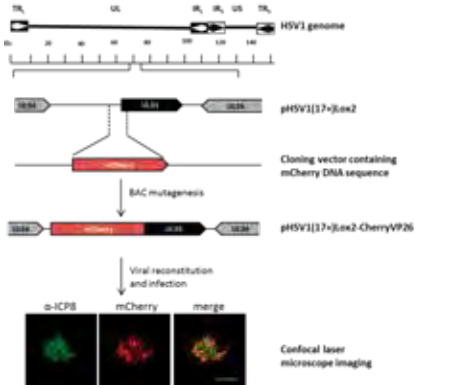


Fig. 1: Scheme showing the generation of fluorescently labeled HSV1 capsids starting with BAC mutagenesis up to the microscopic analysis. The pHSV1(17+)Lox2 and pHSV1(17+)Lox2-CherryVP26 represent the BAC containing the HSV1 genome wild type and encoding the mCherry labeled capsid, respectively. The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

The HSV-1 Tail-Anchored Protein pUL34 Contains an NLS Required for Efficient Targeting to the INM

Christina Funk, Susanne M. Bailer

Herpes simplex virus type 1 (HSV1) is one of eight human pathogenic herpesviruses that can cause life-threatening diseases besides harmless inflammations in oral regions. Nuclear egress of newly formed capsids, a crucial step of the herpesviral replication, is mediated by two essential proteins: pUL31 and pUL34 forming a complex at the inner nuclear membrane (INM).

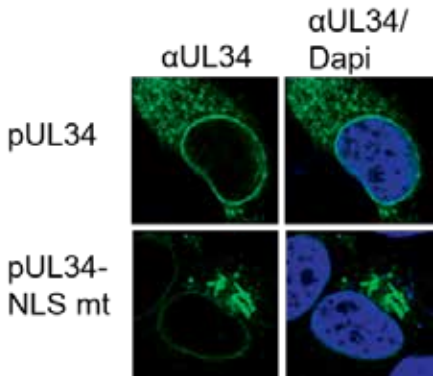


Fig. 1: INM targeting of pUL34 is facilitated by its NLS. Indirect immunofluorescence analysis of pUL34 and pUL34-NLS mt carrying mutation of its nuclear localization signal. Both proteins were expressed in HeLa cells for 20h. Nuclei were detected by Dapi.

These two proteins take separate routes to the nucleus: while the soluble pUL31 travels through the central pore channel, the tail-anchored (TA) integral membrane protein pUL34 is transported along the peripheral pore membrane. The mechanism of transport of TA membrane proteins to the INM is still poorly understood. We identified a classical nuclear localization signal (NLS) within pUL34 that facilitates its targeting to the INM (Fig. 1) and viral replication. Interestingly, INM retention of pUL34 by complex formation with pUL31 is independent of the identified NLS. This suggests that targeting of pUL34 to the INM is an active process potentiated by its NLS and consequently contributing to the efficiency of capsid nuclear egress.

Funding: PhD scholarship of the Peter und Traudl Engelhorn Stiftung

Publication: Funk, C.#, Ott, M.#, Raschbichler, V.#, Nagel, C-H., Binz, A., Sodeik, B., Bauerfeind, R., Bailer, S. M. (2015) The Herpes simplex virus protein pUL31 escorts nucleocapsids to sites of nuclear egress, a process coordinated by its N-terminal domain. PloS Pathog. 11(6):e1004957.
# equally contributing first author

Human Peptides Modulate EBV Replication

Eileen Arnold, Susanne M. Bailer

With a world-wide prevalence of 95%, Epstein-Bar virus (EBV) is one of the most abundant human viruses. After primary infection, EBV establishes latency predominantly in memory B-cells and therefore poses a lifelong risk of developing EBV associated malignancies. Under certain conditions, latent EBV can undergo reactivation and switch to lytic replication. Despite extensive research efforts, our knowledge of the underlying mechanisms of EBV reactivation is still incomplete. We hypothesized that endogenous human peptides exist that have an influence on the outcome of EBV associated malignancies. Aiming to identify these modulating peptides, we screened a human peptide library with peptides < 30 kDa derived from hemofiltrate. Finally, we detected a peptide fraction with significant EBV-reactivating effects that occurred in a dose-dependent manner. Direct evidence for reactivation of latent EBV was provided by reverse transcription qPCR in different EBV-positive cell lines. Future studies aim to identify and characterize the functional peptide and to decipher the molecular mechanism of EBV reactivation induced by this molecule. New insights into the interplay between EBV and its host could advance the development of new strategies to specifically target EBV-associated diseases.

Collaboration: Pharis Biotec GmbH, Hannover

Funding: PhD scholarship of the Landesgraduiertenförderung Baden-Württemberg

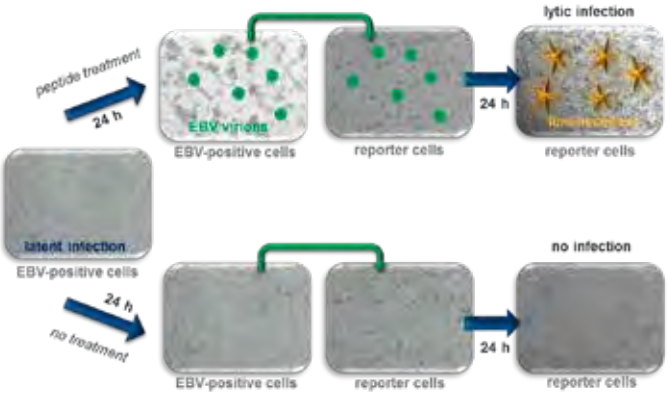


Fig. 1: Screening of a human peptide library for the identification of proviral peptides.

Development of a Poliovirus Vaccine Based on Electron Beam Irradiation

Jessica Marsal, Ines Hanelt, Susanne M. Bailer

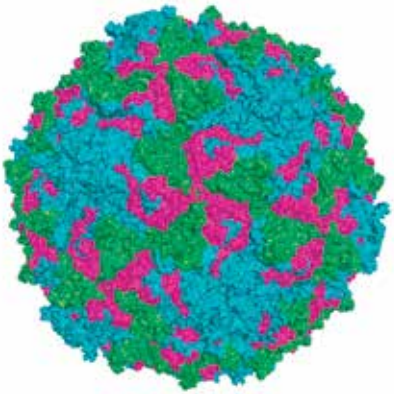


Fig. 1: Model of poliovirus type 3 (Sabin strain), with surface proteins VP1 (blue), VP2 (green) and VP3 (magenta).

Poliomyelitis is caused by the poliovirus (PV), which is a human enterovirus and occurs in three antigenically distinct serotypes: Type 1, 2 and 3. In 1% of cases the infection enters the nervous system and may damage motor neurons resulting in paralytic poliomyelitis. Although there is no cure for poliomyelitis, it can be prevented by vaccines. Two different vaccinations were developed in the past: The formaldehyde inactivated polio vaccine (IPV), which is based on three wild, virulent reference strains and the oral polio vaccine (OPV) – a live vaccine with attenuated viruses. A potential adverse effect of the OPV is its ability to revert to virulent circulating forms that may cause also poliomyelitis similar to the wildtype. Nevertheless only PV type 2 was eradicated in 1999 by means of the vaccination. With the aim of global eradication of PV we used an alternative method for vaccine development. Low-energy electron irradiation (LEEI) inactivates pathogens by damaging their nucleic acids while maintaining their surface structure and thereby antigenicity at the same time. We analyzed the genome destruction of LEEI-treated, attenuated PV strains by a gel electrophoresis system and reverse transcription qPCR and tested their antigen conservation by an indirect ELISA.

Collaboration: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; Fraunhofer Institute for Cell Therapy and Immunology IZI, Leipzig; Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart; Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology FEP, Dresden

Funding: Bill & Melinda Gates Foundation

Publication: Fertey J, Bayer L, Grunwald T, Pohl A, Beckmann J, Gotzmann G, Casado JP, Schönfelder J, Rögner FH, Wetzel C, Thoma M, Bailer, SM, Hiller E, Rupp S, Ulbert S. (2016) Pathogens Inactivated by Low-Energy-Electron Irradiation Maintain Antigenic Properties and Induce Protective Immune Responses Viruses, 8(11), pii: E319.

Immune Cell-Supplemented Epithelial 3D Models for Host-Microbe Interaction Studies

Anke Burger-Kentischer, Andreas Kühbacher

Stratified squamous epithelia such as the skin epidermis or the oral mucosa have important barrier functions and protect the body against microbial pathogens. At the same time, they are host niches for complex communities of commensal microbes. Host-microbe interactions at epithelial barriers are therefore highly regulated and depend on constant communication between the host tissue including epithelial cells and immune cells, commensal microbes and pathogens.

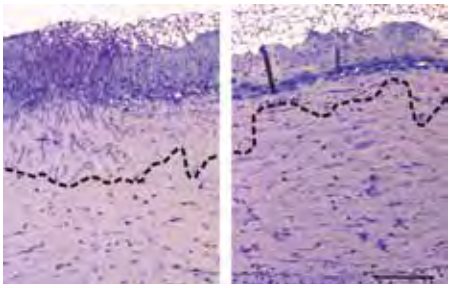


Fig. 1: Infection of skin models with *C. albicans* in the presence (right) and absence (left) of immune cells [2].

Using human 3D skin models supplemented with CD4-positive T cells and a next-generation sequencing approach we could previously identify and describe a novel antimicrobial function of dermal fibroblasts in skin defense against the pathogenic yeast *Candida albicans*. We could further show that this mechanism depends on intercellular communication between CD4-positive T cells and fibroblasts in the skin model and involved the toll-like receptor TLR2 and the cytokine IL-1β [1, 2].

Currently, this model system is not only expanded to the oral mucosa, but also to the colonization with commensal microbes in order to be able to analyze three-way communication mechanisms between individual host cell types, commensals and *C. albicans* which contribute to epithelial barrier function. This project which has started in January 2018 is supported by a postdoctoral research fellowship from the Peter und Traudl Engelhorn Stiftung.

Publications:

[1] A. Kühbacher, K. Sohn, A. Burger-Kentischer, S. Rupp "Immune cell supplemented human skin model for studying fungal infections", Methods Mol Biol, 1508: pp. 439–449, 2017, doi: 10.1007/978-1-4939-6515-1_25.

[2] A. Kühbacher, H. Henkel, P. Stevens, C. Grumaz, D. Finkelmeier, A. Burger-Kentischer, K. Sohn, S. Rupp, "Central role of dermal fibroblasts in skin model protection against *C. albicans* invasion", J Infect Dis, 215(11), pp. 1742–1752, 2017, doi: 10.1093/infdis/jix153.

Funding: Postdoctoral fellowship of the Peter und Traudl Engelhorn Stiftung

Design of Novel Synthetic Toll-like Receptor Agonist / Antagonist Compounds

Christina Kohl, Andreas Kühbacher, Anke Burger-Kentischer

As the main sensors of the innate immune system and key sensors of microbial infection in mammals, the toll-like receptor (TLR) family recognizes microbial pathogens. Given the role of innate immune machinery to provoke inflammation in host, TLRs signaling has been suggested to be involved in the development of many acute and chronic inflammatory processes. Thereby, agonists stimulate the innate immune system and are often used as adjuvants, whereas antagonists inhibit inflammation. Therefore, TLRs represent a new direction for immunotherapy.

The growing clinical needs for immuno-modulators serve as a major incentive to fully explore the TLR agonist / antagonist properties of vast sets of molecules. Traditionally this task was performed using high-throughput screening, a lengthy and costly process. The replacement of this task with computational chemistry has the potential to dramatically reduce the length and costs of these search efforts as well as provide three-dimensional binding models to the relevant receptors.

This project combines the unique molecular modeling capabilities of the Israeli company Pepticom with the candidate synthesis expertise of the German enterprise EMC microcollections GmbH and the vast TLR screening of IGVP. This project utilized these skills for the further development of agonist / antagonist molecules for a vast array of TLRs. These molecules should serve both as research tools in the complex problem of immune response modulation as well as potential drug candidates.

Publications:
M. Zatsepin, A. Mattes, S. Rupp, D. Finkelmeier, A. Basu, A. Burger-Kentischer, and A. Goldblum, "Computational discovery and experimental confirmation of TLR9 receptor antagonist leads", J Chem Inf Model 56, pp. 1835–1846, 2016
A. Burger-Kentischer, I. S. Abele, D. Finkelmeier, K. H. Wiesmuller, and S. Rupp, "A new cell-based innate immune receptor assay for the examination of receptor activity, ligand specificity, signalling pathways and the detection of pyrogens", Journal of Immunological Methods 358, pp. 93–103, 2010

Collaboration: EMC microcollections GmbH, Tübingen, Germany; Pepticom, Jerusalem, Israel

Funding: German Federal Ministry for Economic Affairs and Energy (BMWi), ZIM EUREKA, promotional reference KF260470SK3

Fig. 1: TLR4 antagonists and agonists.

Discovery of Agonists / Antagonists of Immune Receptors Involved in Serious Fungal Infections

Helena Henkel, Andreas Kühbacher, Steffen Rupp, Anke Burger-Kentischer

Fungal infections are classically treated with drugs targeting fungal structures or functions. A novel concept for the treatment of infectious diseases is based on targeting specific functions of the immune system in order to modulate antimicrobial host responses. Various immune receptors belonging to the class of pattern recognition receptors (PRRs) and cytokine receptors are involved in antifungal immunity. The aim of this project is to develop new immune-modulatory compounds (IMCs) for targeting such key molecules of antifungal defense mechanisms.

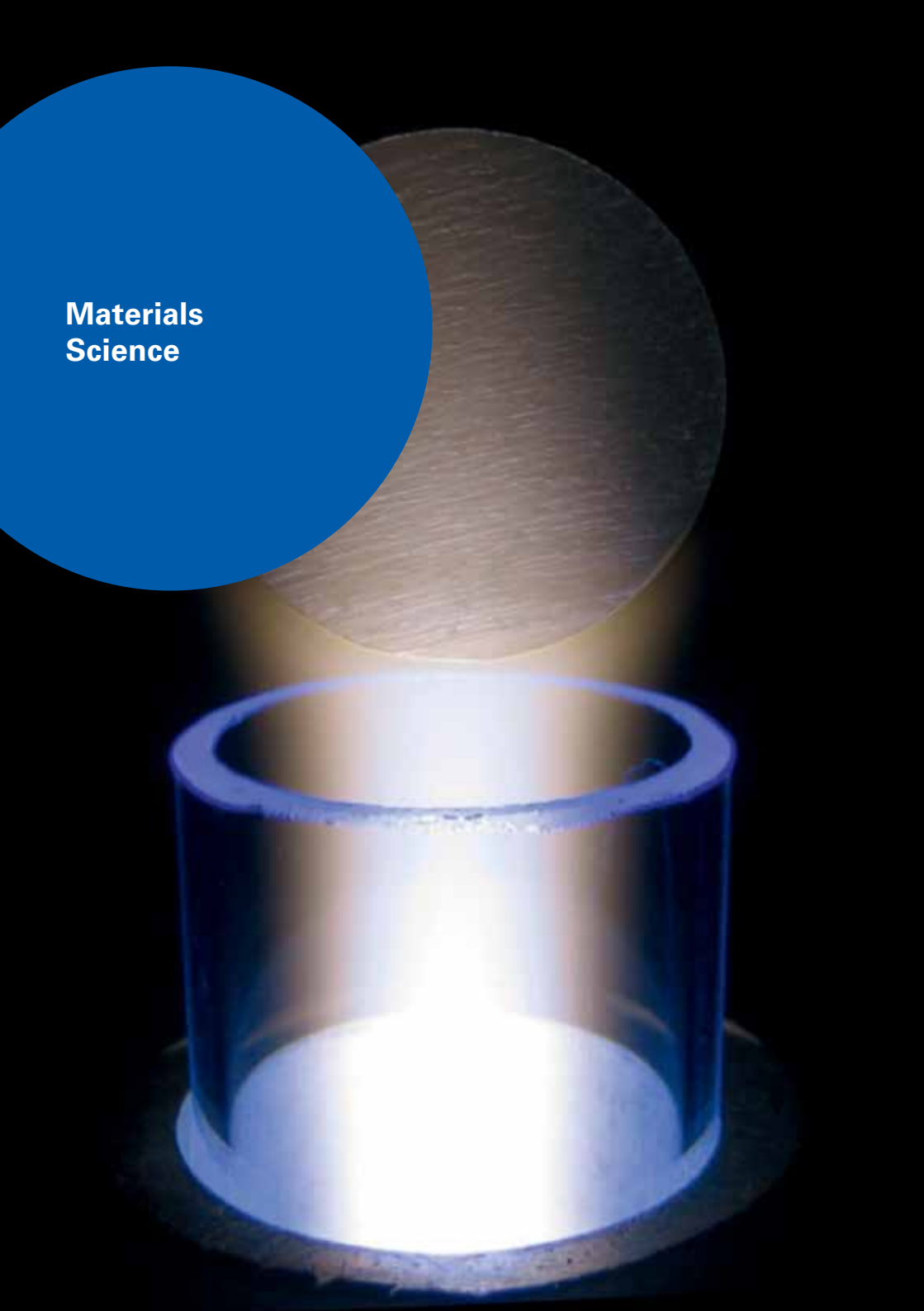
This is achieved by screening potential IMCs which have been modeled *in silico* and chemically synthesized by partners within the ERA-Net consortium "InnateFun". Agonistic or antagonistic properties of these compounds for the selected immune receptors are evaluated using cell-based reporter assays established previously.

These assays are based on the expression of a reporter gene upon ligand-receptor interaction and allowed me already to identify potential novel antagonists for the toll-like receptor TLR9. In a next step, toxicity, IC50 and EC50 values for these and other compounds will be determined. Subsequently, promising candidates will be tested for the potential to modulate an antifungal response in immune cell-supplemented 3-dimensional *Candida albicans* skin infection models. Finally, the best candidates will be tested in animal models of fungal infection by partners within the consortium.

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

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

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 functional 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 the research. The main objects of the research 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 (page 45 and 49), the synthesis of functional poly(ethylene glycols) for the generation of new hydrogel materials (page 44 and 46), surface coating of polymer materials (page 43 and 47), or the functionalization of the extracellular matrix with azide groups (page 40). Thus, our research covers the entire development process leading to functional polymers and spatially defined hydrogels.

Biomolecules from the Native Tissue Matrix

Dr. Kirsten Borchers, kirsten.borchers@igb.fraunhofer.de

Object of research are fields of application for biomolecules from the native tissue matrix i.e. collagen, gelatin, hyaluronic acid, or heparin. Due to their natural origin these polymers are largely biocompatible and can be used e.g. for drug delivery (Christiane Claaßen), biofunctional coatings or the generation of 3D cell-culture matrices (Lisa Sewald). The IGVP offers – in cooperation with Fraunhofer IGB – R&D services for application of biobased materials in (bio)medical engineering, pharmacy, tissue engineering, and cosmetics. We provide biopolymer modifications and formulation, i.e. biopolymers with reactive functions for chemical crosslinking, biopolymer solutions with tailored viscosities, hydrogels with positive or negative net charge.

*click*ECM: Development and Characterization of an Azide-Modified Extracellular Matrix as Biomaterial

Silke Keller, Günter Tovar, Alexander Southan

Biomaterials such as medical prostheses are materials that interact with biological systems in order to treat, augment or replace any tissue, organ, or function of the body. Depending on the envisaged purpose, it can be crucial that these materials build a strong compound with the surrounding tissue to fulfil their task. However, artificial or synthetic materials are often not bioactive and therefore, the attachment of cells is inhibited.

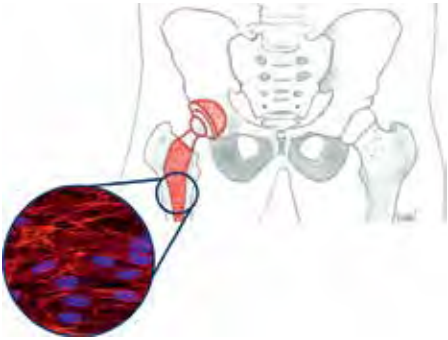


Fig. 1: Motivation of the *click*ECM project: a covalent coating of an artificial material with azide-modified *click*ECM could help to strongly incorporate a medical prosthesis into the human body by enabeling an increased cell adhesion and proliferation.

To overcome this limitation, researchers are trying to equip common materials with bioactive molecules that can be found in the natural microenvironment of the cells within a tissue. This complex 3D-assembly of biomolecules is called extracellular matrix (ECM). However, the use of ECM is limited, e.g. due to the lack of specific addressable functional groups which are often required for their use as surface coatings.

Thus, our approach was to develop a tissue-specific azide-functional ECM which can be addressed in a biocompatible chemical reaction (strain promoted azide-alkyne cycloaddition). Therefore, we incorporated azide groups as chemical handles into the ECM by Metabolic Glyco Engineering. This so called *click*ECM can e.g. be immobilized on alkyne-functionalized surfaces to form stable surface coatings to enhance cell adhesion.

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

Collaboration: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; 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; Vector Stiftung (grant number: P2015-0052); Baden-Württemberg Stiftung ("Glycobiology/Glycomics", grant number: P-BWS-Glyko/09); Fraunhofer Internal Program Discover (grant number: Discover 828 355)

Hydrogels and Hydrogel Thin-Films for Controlled Release of Growth Factors in Tissue Engineering

Christiane Claaßen, Alexander Southan, Günter Tovar, Kirsten Borchers

Presently insufficient oxygen and nutrient supply in tissue engineering grafts is a fundamental limitation due to poor vascularization. Controlled release of pro-angiogenic growth factors is reported to be a promising approach to stimulate vascularization and thereby biointegration of tissue engineered implants. We investigate the preparation of biobased hydrogels, in particular thin films of hydrogels based on methacryl-modified, cross-linked gelatin and heparin, for functional storage and release of growth factors.

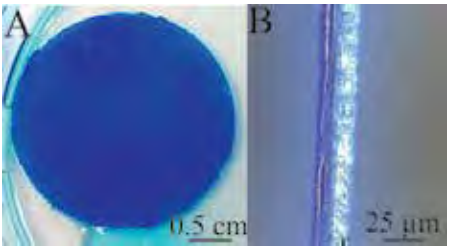


Fig. 1: A: Alcian blue staining of a hydrogel coating based on methacryl-modified gelatin and heparin on a polyethylene terephthalate membrane; B: Cross-section of the coated membrane.

We developed an analytical procedure based on NMR spectroscopy to precisely quantify the amount of cross-linkable methacryl groups tethered to the biopolymers, to achieve well controlled hydrogel preparation. Hydrogels were obtained through thermal-redox initiated cross-linking. The effect of hydrogel composition on their physico-chemical properties and the controlled release of vascular endothelial growth factor (VEGF) were determined. The release kinetics for VEGF were mainly dependent on the amounts of VEGF used for loading. The hydrogels were cytocompatible with primary human endothelial cells. A stable immobilization of hydrogel thin films on polyethylene terephthalate track-etched membranes was achieved. The coatings are now further characterized concerning their cell adhesion and pro-angiogenic response.

Publications:
C. Claaßen*, L. Sewald*, GEM Tovar, K. Borchers, "Controlled release of vascular endothelial growth factor from heparin-functionalized gelatin type A and albumin hydrogels", Gels 3(4), p. 35, 2017, DOI:10.3390/gels3040035
*contributed equally

Collaboration: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; B. V. Stanzel, Fraunhofer Institute for Biomedical Engineering IBMT, Sulzbach and Augenklinik Sulzbach, Knappschaftsklinikum Saar, Sulzbach

Funding: German Research Foundation (DFG) project BO 4252/1-1: Subretinal delivery and anchorage via angiogenesis of a polyester cell carrier for retinal pigment epithelial transplantation

Biomimetic Hydrogels for 3D Cartilage Equivalents

Lisa Sewald, Alexander Southan, Günter Tovar, Kirsten Borchers

Articular cartilage can be distinguished in 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 hydrogels as 3D scaffolds for cartilage TE is a promising approach. However, application as biomimetic cell-matrix-implants is limited by poor load-bearing capacity of common hydrogels. Utilization of two independent polymeric networks in one hydrogel enhances its mechanical load-bearing capacity and enables new possibilities to adapt physical properties.

Aim of this project is the strengthening of hydrogels, based on biopolymers occurring in the natural extracellular matrix (ECM) of cartilage. Zonal differences in water content and strength of cartilage ECM should be emulated by varying hydrogel composition. Robotic dispensing will be used to manufacture 3D scaffolds with a zonal structure. Thereby, new functional scaffolds for 3D culture of chondrocytes are investigated and could serve as a basis for mechanically stable cartilage equivalents.

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

Funding: PhD scholarship of the Evonik Foundation

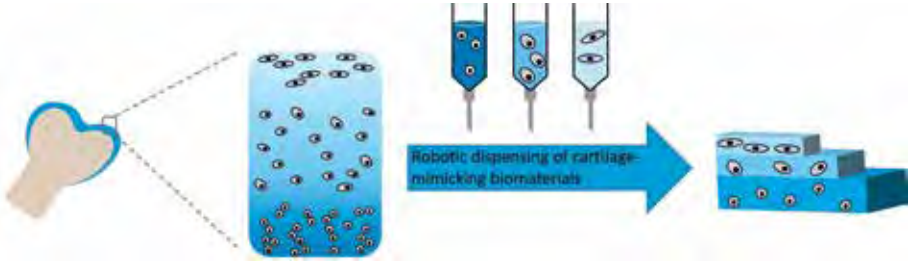


Fig. 1: Schematic visualization of hydrogel design as functional scaffold for cartilage tissue engineering. Three biomimetic hydrogel compositions will be investigated and processed via robotic dispensing.

Functionalization of Polymer Surfaces for Medical Applications

Jana Grübel, Günter Tovar, Alexander Southan

Materials like plastics and silicones are often applied in the field of medical technology, for example as implant materials. Due to their hydrophobic surface, proteins can adsorb unspecifically after implantation which can lead to an encapsulation of the implant. Surface-functionalization of potential implant materials is a strategy to increase the hydrophilic properties of their surfaces and improve their integration into the body.

We want to generate a surface-functionalization of the these materials without changing their bulk in order to maintain the mechanical properties. For this purpose we synthesize molecules which are covalently integrated into the material and present their functional groups at the material surface. These functional groups are further used to attach coatings of bioactive substances like gelatin. Dip coating as well as inkjet-printing will be tested as suitable coating mechanisms to produce stable coatings or coatings at defined positions. The functionalized implant materials will be biologically characterized with cell experiments in order to evaluate a possible application in the body. Variation in functionalization type, concentration and coating mechanism will be tested to generate individual implants.

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

Funding: High Performance Center for Mass Personalization, Stuttgart

Hydrogels with Specific Charge Densities

Tobias Götz, Günter Tovar, Alexander Southan

Hydrogels with tailor-made properties are interesting materials for different applications. Starting material for this special type of hydrogel is polyglycerol, which is modified with different moieties of functional groups like allyl ether side chains. Via thiol-ene click reactions the charge carriers are coupled to the polymer side chains. For polycations amine groups and for polyanions carboxylic groups were chosen.

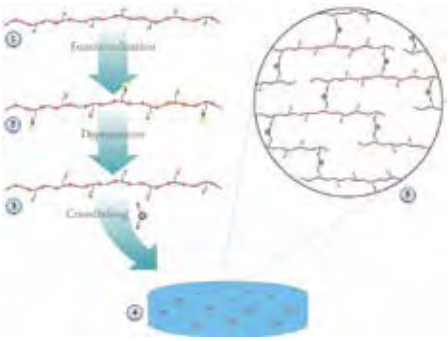


Fig. 1: (1) Allyl-functionalized polyglycerol; (2) Side-chain functional polyglycerol with either amine or carboxy groups and photoprotected thiols; (3) Deprotection, hydrogel formulation and crosslinking; (4) Hydrogel with specific charge densitiy; (5) Step growth network of the hydrogel.

Fig. 2: Step growth network hydrogels prepared with different amounts of cross-links changing their swelling behavior. From left to right: 80%, 60%, 40% and 20% cross-linking.

Therefore the charge density in the hydrogels can be tuned by varying pH value. To prepare hydrogels one possibility for crosslinking is given by introducing thiols to prepare networks with a Michael-addition type cross-linker. These crosslinkers are able to bare a positive charge, inspired by the natural crosslinker desmosin. For tailoring the mechanical properties and the biological activity of the hydrogels, the charge densities were adjusted by controlling the amount of functional side chains attached to the polymer backbone.

Collaboration: Institute of Organic Chemistry, University of Stuttgart, Stuttgart; Max Planck Institute for Medical Research, Heidelberg

Funding: BoiMatS-011 project of the Baden-Württemberg Stiftung and the Ministry of Science, Research and the Arts of the State of Baden-Württemberg

Surface Functionalization of Superporous Hydrogels for Additive Manufacturing

Karishma Adatia, Günter Tovar, Alexander Southan

This PhD project is focused on the development of surface functionalized, microstructured hydrogels for additive manufacturing. For this purpose, different polymers with narrow molecular weight distributions were synthesized by anionic polymerization in order to functionalize the hydrogel with defined anchor points. Afterwards the polymers were characterized by NMR, SEC, Maldi, FT-IR, DSC, TGA, and Langmuir isotherm experiments to investigate the structure-property relationships and to determine the capability of these polymers as hydrogel functionalization reagents.

Beyond that, a hydrogel microstructuring procedure, which is compatible with additive manufacturing processes is explored, because additive manufacturing opens up the possibility to print spatially resolved 3D materials. For this purpose, a tailor-made reagent for hydrogel microstructuring is synthesized which fulfills the requirements of the additive manufacturing process and the kinetic demands of the hydrogel curing process at the same time.

The combination of the two work packages should lead to surface functionalized 3D microstructured hydrogels for additive manufacturing. Such materials could for example be used as polymer scaffolds in tissue engineering if bioactive components are coupled to the anchor points.

Collaboration: University of Stuttgart, Stuttgart; Goethe University Frankfurt, Frankfurt am Main; Stanford University, Stanford, USA

Funding: PhD scholarship of the Evonik Foundation

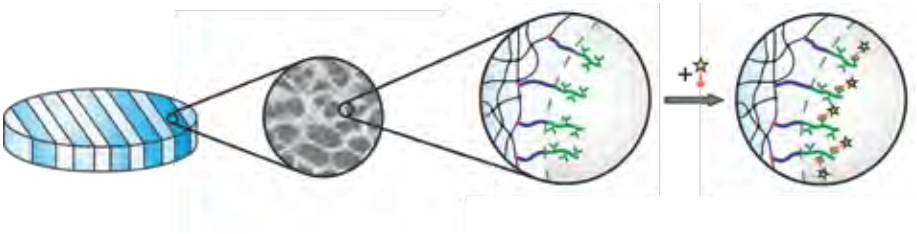


Fig. 1: Schematic depiction of the surface functionalized microstructured, 3-dimensional hydrogel foam.

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

Oliver Gorke, Günter Tovar, Alexander Southan

Due to the high water content hydrogels 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 comparable to cartilage or rubber and at the same time contain a large fraction of water (50–90%), which makes it possible to expand the field of application. These hydrogels, by definition, consist of a rigid, brittle, highly branched polyelectrolyte network and a ductile, neutral, loosely cross-linked polymer network which are interlaced.

Fig. 1: Calcium alginate/polyacrylamide double network hydrogel.

For the investigation of the mechanical properties of double network hydrogels, it is important for us to produce standardized and defect-free samples for tensile tests. In order to develop and establish suitable production processes for these samples, we use double network hydrogel systems from the literature. In addition, unknown polymer and crosslinker systems are synthesized, which can build up a polyelectrolyte network via Diels-Alder cycloaddition.

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

Funding: German Research Foundation (DFG), project number 320336785: Mechanics of tough hydrogels

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

Andre Michele, Günter Tovar, Alexander Southan

Regarding the emissions and decreasing sources of fossil fuel, the poly electrolyte membrane fuel cell (PEMFC) is a promising technology for automotive applications. The 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 crosslink hydrophilic polymers with a crosslinking agent. A polymer solution is mixed with a crosslinker and coated on a substrate by doctor-blading or spin-coating. Network formation occurs by activation with heat or UV radiation. Optimization of the hydrogel coating is carried out by varying polymers, polymer formulations and crosslinking conditions. The hydrogels are characterized by common values e.g. the yield of the hydrogel and the 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.

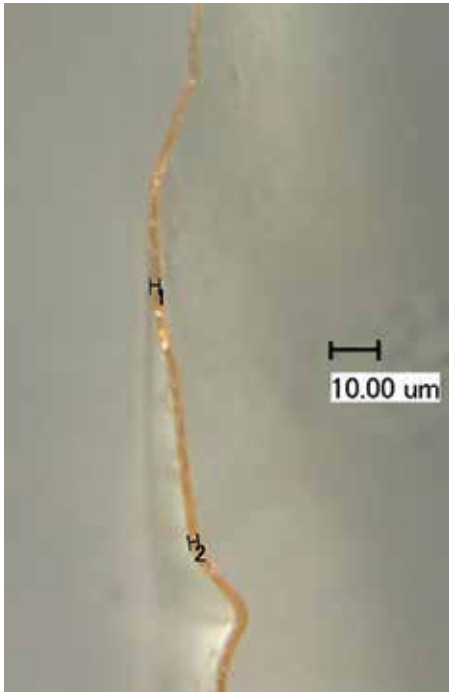


Fig. 1: Hydrogel film detached from substrate.

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

Tribology System for Cold Forming Process Based on Volatile Lubricants and Laser-Structured Surfaces

Georg Umlauf, Günter Tovar, Alexander Southan

In sheet metal forming, mineral oil-based lubricants are usually used to reduce friction and wear in the forming tools. At times toxic additives are contained in the lubricant and the deformed components have to be cleaned cost-effectively and time-intensively for further process steps. For these reasons, the absence of oil lubricants has a positive effect on the environment as well as the profitability of production processes.

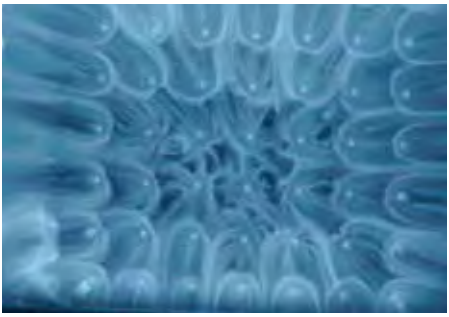


Fig. 1: Mint CO_2-outflow pattern for 7 x 7 microholes (diameter: 300 µm) against a borosilicate glass with 10 MPa surface pressure.

The ambitious approach is to integrate volatile liquid CO_2 as an interfacial medium, with a laser-structured surface. The liquid medium is injected directly into the clearance during metal forming process through laser-drilled microholes. In a new strip drawing test with optical access it was possible to make the outflow behavior visible. If the CO_2 at the nozzle outlet is freely expanded from 60 bar to atmospheric pressure, the CO_2 cools to 195 K and white dry ice is formed. Different mircohole arrangements und diameters at several surface pressures were investigated. The propagation and amount of the dry ice in the clearance is recorded and evaluated with a high-speed camera. Yet, it is still under investigation which aggregate phases are present. It is assumed that the dry ice reduces the coefficient of friction.

Collaboration: Jakob Barz, Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; Ehsan Zahedi, Institut für Strahlwerkzeuge, University of Stuttgart; Christoph Wörz, Institute for Metal Forming Technology, University of Stuttgart

Funding: German Research Foundation (DFG), SPP 1676: Dry Metal Forming – Sustainable Production through Dry Processing in Metal Forming

Surface Active Monomers as Building Blocks for Particle Functionalization

Vanessa L. Albernaz, Achim Weber, Günter Tovar, Alexander Southan

Polymerizable surfactants (also known as “surfmers”) are molecules that combine the functionalities of surface activity, polymerizability and reactive groups, so that a surfmer acts as both surfactant and monomer. Hence, during emulsion polymerization processes, surfmers are mostly on the particle’s surface and are directly incorporated into the particle's polymeric backbone, which leads to an increase in the particle's stability while allowing for the controlled display of the functional groups on the particle’s surface.

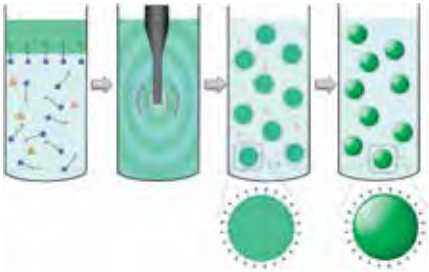


Fig. 1: Preparation of polymeric nanoparticles with functionalized surface using surfmer molecules through miniemulson polymerization.

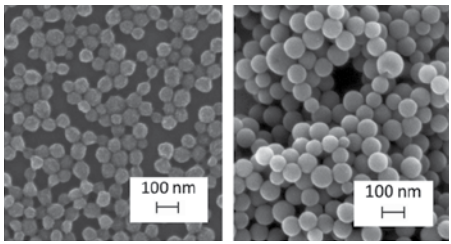


Fig. 2: Scanning electron microscopy image of PMMA-co-AUPDS and PS-co-AUPDS nanoparticles using the AUPDS surfmer molecule as the sole surfactant.

The present work presents the synthesis of two surfmer molecules and the preparation of polystyrene and poly(methyl methacrylate) nanoparticles having either active ester or thiouronium groups on the surface. With this approach, monodisperse nanoparticles with a reactive surface functionality can be obtained. The configured particles with customized functional surfaces are promising candidates for multifunctional platforms suitable for biomedical applications.

Publication: Polymers 10(4), p. 408, 2018; doi:10.3390/polym10040408

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

Funding: Science Without Borders Program, CAPES Foundation, Brazil

Reactive Inkjet Printing of Polyurethane Foam Formulation

Fabian Schuster, Alexander Southan

Inkjet printing as an additive manufacturing tool is currently a popular field in research. Especially reactive inkjet printing of two chemical reactive fluids can be used to build two- or three-dimensional structrures. Therefore, two ink droplets, each one containing one of the chemical reactive components, are placed on top of each other, leading to an *in situ* reaction on the substrate, resulting in the desired structure. The first fluid contains a low viscous (1 mPas – 30 mPas at printing temperature) hydroxy-functional formulation. The second ink is comprised of a low viscous isocyanate-functional compound. Due to chemical reaction of the two inks, polyurethane and polyurea units are formed. A multifunctional PEG is used as a crosslinking agent. Further on, water is added to the first ink formulation and acts as the chemical blowing agent, forming CO_2 gas via reaction of the isocyanate groups of the second ink. Influence of catalyst concentration as well as inkjet printing parameters were investigated. The obtained structures are a first step into the direction of digital fabrication of printed foams.

Publications:
F. Schuster, F. Ngako Ngamgoue, T. Goetz, T. Hirth, A. Weber, M. Bach, "Investigations of a catalyst system regarding the foamability of polyurethanes for reactive inkjet printing", Journal of Materials Chemistry C, 5(27), pp. 6738–6744, 2017, https://doi.org/10.1039/C7TC01784G

F. Schuster, F. Ngako Ngamgoue, T. Hirth, A. Weber "Manufacturing of micro-scale polyurethane foams by reactive inkjet printing", in NIP & Digital Fabrication Conference, pp. 32–36, 2017. Denver, Co, Retrieved from http://www.ingentaconnect.com/content/ist/nipdf/2017/00002017/00000001/art00010

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

Funding: PhD scholarship of the Friedrich-Ebert-Stiftung e.V.

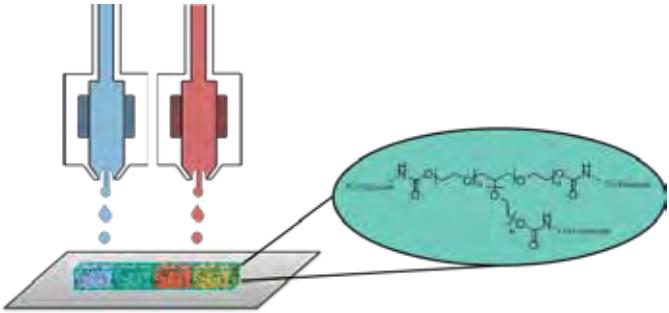


Fig. 1: Illustration of reactive inkjet printing to obtain polyurethane foam structures.

Functional Encapsulation of Active Ingredients by Means of Spray Drying

Michael Walz, Alexander Southan

The encapsulation of active ingredients is of interest to the pharmaceutical and food industry. Capsules serve to protect the active ingredients from external influences, for example, gastric juice resistance during oral administration. Using a continuous release system leads to lower drug concentrations resulting to fewer side effects. An active substance depot can release the active substance over several days to months.

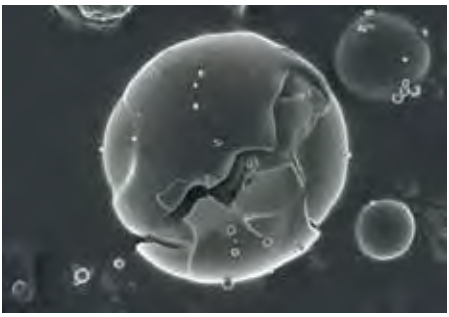


Fig. 1: Core-shell particle, produced by means of a three-fluid nozzle.

For the production of encapsulated active ingredients in particles, we use the one-step process of spray drying. A polymer solution in a drying cylinder is atomized into fine droplets by means of compressed gas. The hot gas stream serves to evaporate the solvent, and the resulting particles are separated. Insoluble active ingredients must be converted into stable emulsions or suspensions prior to spray drying. In order to avoid that, the use of the three-fluid nozzle is investigated. Two mutually independent component streams can be atomized with a gas stream. In the droplets, mixing occurs due to shear forces and the active ingredient is immobilized in the particle on simultaneous drying. Using different materials, it is also possible to produce core-shell particles – the active substance is embedded in a matrix that is coated with a second material.

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

Funding: PhD scholarship of the Konrad-Adenauer-Stiftung e.V.

Continuous Manufacturing Process for Composite Hollow Fiber Membranes

Isabel Jesswein, Alexander Southan

Membranes with good water vapor permeability and high selectivity towards air are interesting for external humidifiers of polymer electrolyte membrane fuel cells, dehydration of gases or heating, ventilation and air conditioning systems. To optimize water vapor transport through membranes, composite structures with a very thin selective layer are a preferred membrane type.

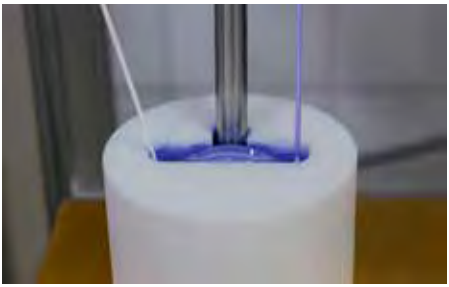


Fig. 1: Continuous dip coating of a hollow fiber membrane.

A continuous manufacturing process was designed, where hollow fibers as supporting structure are fabricated via nonsolvent-induced phase separation. Subsequently thin layers which form the selective layer of the composite membranes are made by dip coating and crosslinking.

Besides evaluating different materials as support structure and selective layer, the influencing parameters of the manufacturing process are investigated. Parameters like the surface tension and viscosity of the coating solutions or the coating velocity are correlated with the resulting coating thicknesses. Furthermore, the impact of the layer thickness on crosslinking, water vapor permeability, nitrogen permeability and thermal stability are studied.

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

Funding: Scholarship of the Landesgraduiertenförderung Baden-Württemberg, University of Stuttgart

Chitosan-Based Nanoparticles for Wastewater Remediation

Benjamin Riegger, Günter Tovar, Alexander Southan

To sustain the water quality at a high level there are different techniques available to eliminate pollutants. Next to membrane processes, sedimentation and oxidation treatment, there is waste/water treatment by adsorption techniques. Due to the easy design and the simple handling adsorption techniques especially nanoparticle-based adsorbers are eminently suitable for the removal of the stated pollutants.

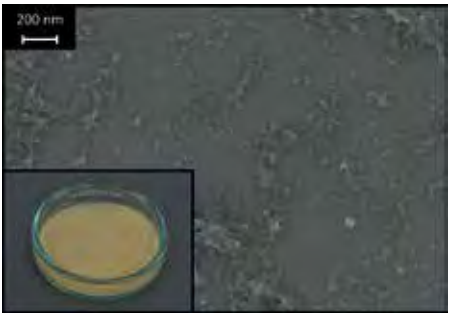


Fig. 1: SEM-picture of prepared Chitosan nanoparticles. Lower left corner: raw low molecular weight chitosan powder.

It is evident that there is a need for cheap, easy to manufacture, long-term stable and recyclable adsorbents. Hence this work shows the effort – not only to achieve the mentioned challenges – but also to prepare the desired nanoparticular adsorbent based on the renewable polysaccharide chitosan. To ensure long-term stability of the material the biopolymer is cross-linked. Chitosan nanoparticles (Chi-NPs) were synthesized via miniemulsion crosslinking technique. To achieve a stable emulsion chitosan is dissolved in aqueous media and emulsified in oil using a suitable surfactant. Highly deacetylated chitosans of different molecular weight (MW) have been used to synthesize Chi-NPs in the range of 100–250 nm (Fig. 1). Their adsorption capacity for diclofenac was evaluated via HPLC-assisted single point sorption tests at different concentrations (results shown for low MW-Chi-NPs in Fig. 2). The Chi-NPs show a superior adsorption capacity compared to untreated chitosan powder.

Publication: B. R. Riegger, B. Bäurer, A. Mirzayeva, G. E. M. Tovar, M. Bach, "A systematic approach of chitosan nanoparticle preparation via emulsion crosslinking as potential adsorbent in wastewater treatment", Carbohydrate Polymers 180, pp. 46–54, 2018, https://doi.org/10.1016/j.carbpol.2017.10.002

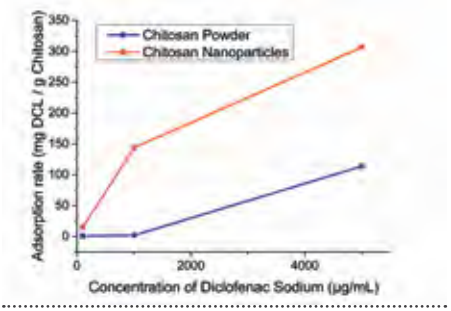
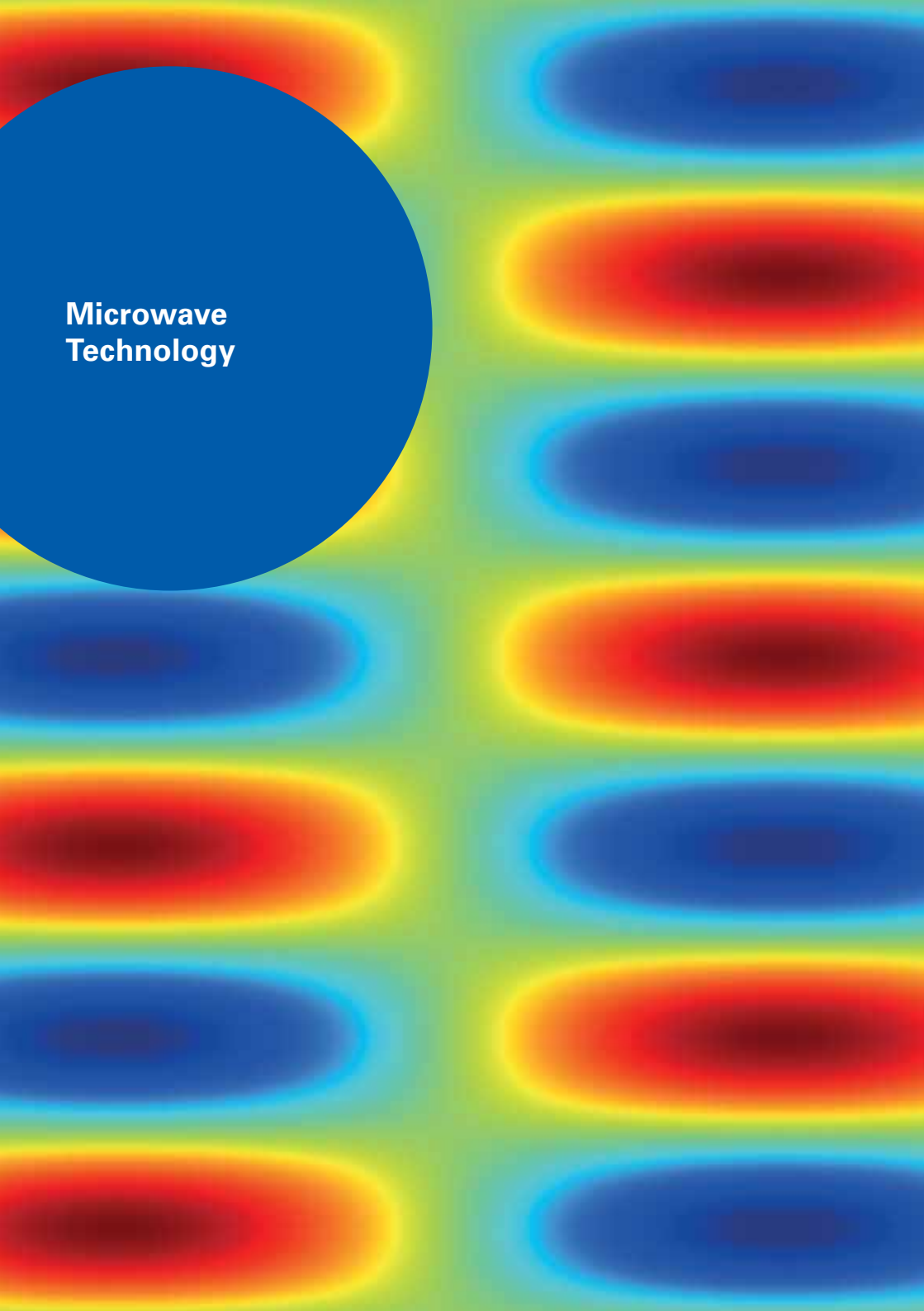


Fig. 2: Adsorption capacity of low MW-Chi-NPs for diclofenac.

Plasma and Microwave Technology

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 plasma, to drive plasma currents and to control magneto-hydrodynamic instabilities. The Microwave Technology (MT) group at 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. MT develops power combiners and switches, which could enhance the performance of the fusion test reactor ITER.

The MT group is also involved in the experiments relying on the microwave devices. The institute contributes to the stabilization of neoclassical tearing modes in ASDEX upgrade by synchronous switching of millimeter waves to follow the rotating magnetic islands, and supports technologies for steering of the launchers. In support of various fusion experiments, full-wave simulations are carried out to study wave propagation and mode conversion in plasmas. Millimeter waves are not only used for heating of high-temperature fusion plasmas, but also for diagnosis of the plasma. The MT group contributes to Doppler reflectometry for turbulence and flow investigations through simulations of experimental data and the design of components like frequency-steered array antennas. For experiments on collective Thomson scattering, dedicated transmission and antenna components are designed.

Microwave Technology for ECRH on ASDEX Upgrade

Walter Kasparek, Carsten Lechte, Burkhard Plaum

The electron cyclotron resonance heating ECRH-3 system at ASDEX Upgrade (AUG) is now operable, two gyrotrons are installed, and two others will come in 2018. In 2017, the construction of four absorber loads for gyrotron tests (cf. page 61) was finished, the loads were delivered to AUG.

The final optimization and test of the two-frequency, dual-polarization directional couplers was performed. These couplers are based on mirror-integrated array antennas with two main lobes optimized for 105 GHz and 140 GHz. By fine-tuning of the array elements, the output power of the four signals could be set to the desired level, and equalized within 3 dB. The development of mode-analyzing couplers is discussed on page 69.

Eventually, in-line ECE (electron cyclotron emission) experiments are to be performed; for this case, a resonant diplexer (MC III) is available. The polarizers behind the diplexer were equipped with motor drives to allow remote control of the polarization (Fig. 1).

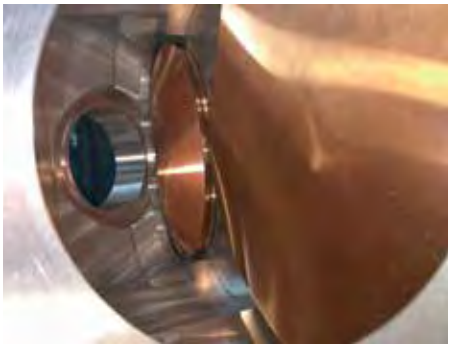


Fig. 1: Inside view of compact waveguide polarizer. A phase correcting mirror on the left wall (not visible) directs the beam from the first corrugated polarizer to the second.

To minimize the ohmic losses in polarizers, extended experiments have been performed by the AUG ECRH team. Accompanying calculations with the IPF-FD3D code agree with the measurements. Design and fabrication of holographic in-vessel reflectors to optimize ECRH scenarios with incomplete absorption are described on page 67.

Collaboration: J. Stober, D. Wagner, M. Schubert, F. Monaco, H. Schütz, and B. Petzold, Max Planck Institute for Plasma Physics (IPP), Garching

Funding: The work is performed within the collaboration with the Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald.

Receiver Antenna and Transmission Line for Collective Thomson Scattering on W7-X

Walter Kasparek, Carsten Lechte, Burkhard Plaum

The electron cyclotron resonance heating (ECRH) system on the stellarator Wendelstein 7-X (W7-X) has been upgraded by a collective Thomson scattering system. This installation uses gyrotrons and antennas (one front-steering and/or one remote-steering launcher RSL1) in common with ECRH for the probing beam, and a transmission line to the collective Thomson scattering (CTS) receiver employing a free channel of the ECRH multi-beam waveguide.

Fig. 1: Photograph of the optical remote-steering antenna (ORSA) during installation in W7-X.

For the scattering geometry with the RSL1, an optical remotely steered antenna (ORSA) has been developed and built. It is based on the multi-beam concept, where a beam pivot point located at the edge of the plasma is imaged to a point located in the vacuum window. A movable mirror outside the vacuum provides the beam steering around the point in the vacuum window and thus in the plasma. A photograph of the antenna is shown in Fig. 1.

The antenna was characterized with a 10 W test beam and thermal imaging of the radiation patterns recorded over the complete steering range of $\Delta\varphi$ = 28°. For all angles, the measurements show a high-quality beam, only at the extreme steering angles, the patterns show slight aberrations (Fig. 2). Now, the antenna is installed in W7-X, it was aligned, and is ready for CTS experiments in the next campaign.

As follow-up, work has started in the frame of a master thesis to investigate the use of multi-beam systems for imaging and remote-steering antennas.

Collaboration: D. Moseev, H. Laqua, and M. Weißgerber, Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald; S. K. Nielsen, F. Leipold, DTU Risoe

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

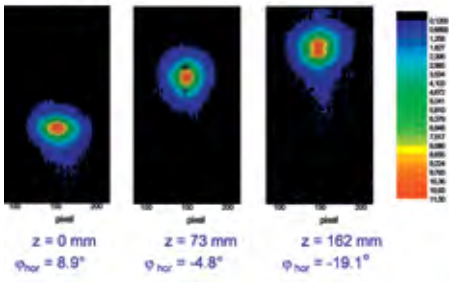


Fig. 2: Radiation patterns of the ORSA for the extreme angular positions (φ = 8.9° left, and φ = –19.1°, right), and the central position at φ = –4.8°.

Matching Optics and Diagnostics for ITER Gyrotrons

Walter Kasparek, Carsten Lechte, Burkhard Plaum

In collaboration with the European gyrotron consortium, and especially in collaboration with the Karlsruhe Institute of Technology (KIT), IGVP participates in the development of gyrotrons for ITER as well as other W7-X.

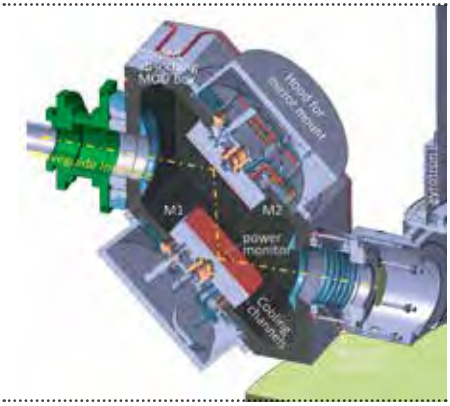


Fig. 1: Design of the evacuated matching optics box for the European ITER gyrotron, showing the main chamber with the two reflectors M1 and M2 and the two hoods housing the mirror supports with alignment and the vacuum feedthroughs for mirror cooling and positioning as well as the power monitors.

The design of the matching optics box using two phase-correcting mirrors and directional couplers for beam diagnostics for the ITER electron cyclotron resonance heating (ECRH) system was finalized; the report for grant GRT-553 was delivered. The main results – based on beam characterization of the prototype 170 GHz gyrotrons – show the possibility of a highly efficient coupling of the beam to the waveguide transmission of > 99%, and the detection of mode jumps of the gyrotron for improved reliability.

Based on these results, the design for the optics and load for the new high-power (> 2 MW) test stand "FULGOR" at KIT Karlsruhe was performed, and construction of mirrors has started. The design features confocal imaging from the gyrotron window to the absorber load via two identical mirrors and two polarizers, to allow broadband operation and thus tests of various gyrotrons without modifications.

The load is described on page 61. All components are water-cooled and designed for large beam diameters to minimize arcing problems. A twin coupler on the first mirror is designed for monitoring of the power and mode jumps, and multi-frequency operation is envisaged.

Collaboration: G. Gantenbein, T. Kobarg, and J. Jin, KIT Karlsruhe; J.P. Hogge, SPC Lausanne; F. Albajar, F4E Barcelona; C. Darbos, ITER Cadarache

Funding: This work is supported by the European Union's Fusion for Energy (F4E) Program within the Grant GRT-553.

Development of High-Power Millimeter-Wave Calorimetric Loads

Walter Kasparek, Carsten Lechte, Bernhard Roth, Achim Zeitler

For the test of gyrotrons in electron cyclotron resonance heating (ECRH) systems, high-power, long-pulse, calorimetric loads are developed. These loads consist of a cylindric box, where the inner wall of the box is covered with a meshwork formed from water-flushed Teflon pipes. The microwave beam enters the box axially through a beam concentrator, hits a conical reflector at the opposite side, and is distributed over the meshwork to be absorbed by the water.

After good experience with smaller versions, two loads with a cw capability of more than 2 MW are being built. The main design features have been further improved. Especially, the shape of the conical reflector was optimized such that a tapered profile of the power distribution along the Teflon pipes is obtained. Any convex surface areas on the cone are avoided, which reduces the sensitivity of the design with respect to misalignment.

Fig. 1 depicts the geometry of the load and approximate ray paths. The ray-tracing calculation are explained in more detail on page 59. For the case of the load developed for KIT Karlsruhe, the absorber consists of 48 parallel Teflon pipes with a total flow rate of 860 l/min which allow true cw operation.

In parallel, smaller pulse loads have been developed and built for the ECRH-3 system on ASDEX Upgrade at IPP Garching. Here, a twisted 3D meshwork of only 4 Teflon tubes provides a large thermal capacity of the water in the tubes. Thus, a pulse length of 2 s is possible at a power of 1 MW, where the flow rate is only 40 l/min.

Collaboration: J. Stober, D. Wagner, IPP Garching; H. Laqua, and T. Stange, Max Planck Institute for Plasma Physics (IPP), Greifswald; G. Gantenbein, and T. Kobarg, KIT Karlsruhe

Funding: The work is performed within the collaboration with the Max Planck Institute for Plasma Physics (IPP), , Garching and Greifswald, and the Karlsruhe Institute of Technology.

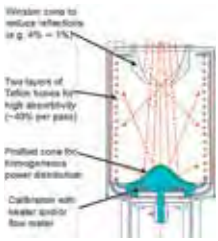


Fig. 1: Beam distribution and cooling diagram.

Fig. 2: Finished load without external shell, beam entrance at bottom.

Fullwave Doppler Reflectometry Simulations for ASDEX Upgrade

Carsten Lechte

Doppler reflectometry is an important microwave diagnostic for turbulent fusion plasmas. The incoming wave is scattered at certain density fluctuation wavenumbers, depending on frequency and angle between beam and density gradient. This way, a wavenumber resolved density fluctuation spectrum can be measured. However, the correspondence between fluctuation power and scattered microwave power is strongly non-linear and is investigated using fullwave simulations, with density fluctuations supplied by a plasma turbulence code. Earlier results for X mode polarization have shown saturation of the spectral power to occur at high fluctuation amplitudes, an enhancement at intermediate amplitudes, and linear behavior at low amplitudes. Together, these effects strongly modify the shape of the wavenumber spectrum [1].

The realistic fluctuation levels coming from the plasma turbulence code have driven both O and X into a saturated state. When the fluctuation level is artificially scaled down by several orders of magnitude, a strong dip appears in the spectrum (Fig. 1, dashed lines). This was inconsistent with the input turbulence spectrum and did not conform to the saturation-enhancement model. It was now found that the hole is an artifact of the the data export from the turbulence code, which can be fixed by going to a higher resolution (the "hi" variant in Fig. 1). The hole then completely disappears from the spectrum.

With this explanation, the confidence in the code has been further increased and previous results are validated.

Publication:
[1] C. Lechte et al., "X mode Doppler Reflectometry k-spectral measurements in ASDEX Upgrade: Experiments and simulations" Plasma Phys. Contr. Fus. 59 (7), 2017, doi:10.1088/1361-6587/aa6fe7

Collaboration: G. Conway, T. Görler, T. Happel, Max Planck Institute for Plasma Physics (IPP), Garching

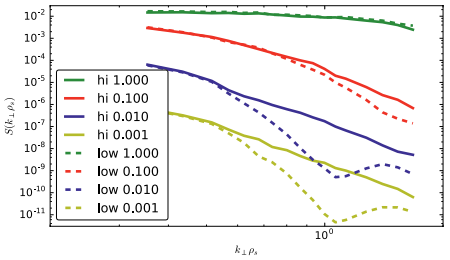


Fig. 1: Doppler wavenumber spectrum comparison between low (dashed) and high (solid) interpolated turbulence data for four different global scalings of turbulence strength.

Optimization of High-Power Calorimetric Load Geometry

Carsten Lechte

The high-power load type introduced on page 61 was originally designed "by hand". Because of the strong single-pass absorption, it is important to spread the incoming beam homogeneously onto a designated part of the lateral cylinder surface. For the shape of the reflecting cone, only a few rays were followed, and at the edge, an analytical continuation was used. The new loads built in 2017 were designed with a simple raytracing code that automatically calculates the optimal cone shape that effects a given axial power distribution using thousands of rays. As additional constraint, no convex (focussing) shape is allowed.

The optimized cone is then illuminated by misaligned input beams and beams at other frequencies if multi-frequency operation is desired. A heat map of power density enhancement factors directly shows the consequences of misalignments and mismatches. A more detailed analysis shows the axial power distribution. The final cone shape is given as a fitted polynomial.

A misalignment usually results in strongly increased power density at the edges of the designated absorption region but due to the geometry, very little power is directed outside this region (Fig. 1). It is expected that the new loads are more resilient against misalignment and capable of multi-frequency operation.

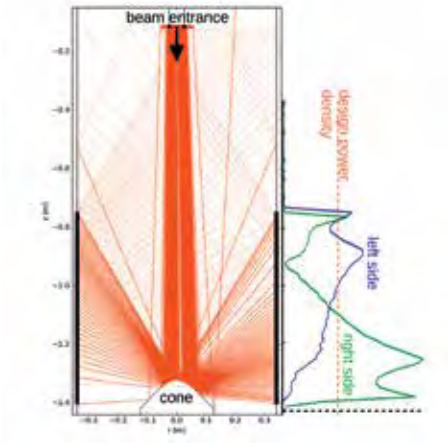


Fig. 1: Raytracing result with tilted input beam and consequent inhomogenous axial power deposition.

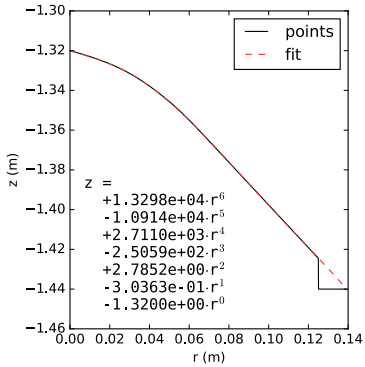


Fig. 2: Specification of finished reflector cone.

Remote-Steering Launchers for ECRH on W7-X

Carsten Lechte, Walter Kasparek, Burkhard Plaum

The stellarator Wendelstein 7-X (W7-X) at IPP Greifswald has a multi-megawatt microwave heating system at 140 GHz. The microwave beams have a diameter of about 10 cm and are transmitted and launched using a system of mirrors. In addition to the front-steering launchers, which have steerable mirrors on the front near the plasma, there are two remote-steering launchers (RSL1 and RSL5) where the beam is created away from the device and transmitted to the plasma by an oversized imaging waveguide, which is basically a pipe that ends flush with the vacuum vessel wall. The waveguides were designed at IGVP and manufactured by the industrial partners under the project FORMIK[3].

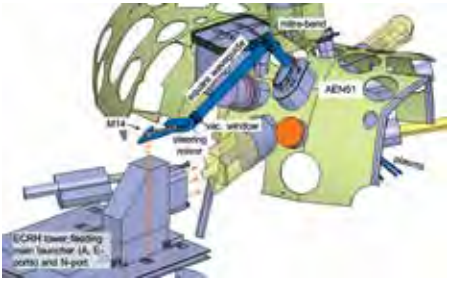


Fig. 1: Geometry of the remote steering launcher for microwave heating (blue elements).

The absence of any mirrors and mechanics at the waveguide exit gives great flexibility in the placement of the launcher. While the front steering launchers use large ports on the outboard equatorial plane, the RSL offers access through small ports near the top or bottom, where the magnetic field that confines the plasma has different properties. Furthermore, this beam is used in collective Thomson scattering as the probing beam, because the geometry demands for the receiving antennas cannot be met otherwise (see page 59 for CTS).

High power tests at W7-X have confirmed the steering capabilities, however some unexpectedly high losses at large steering angles have been observed.

Collaboration: V. Erckmann, H. Laqua, and M. Weißgerber, Max Planck Institute for Plasma Physics (IPP), Garching and Greifswald; A. Bechtold, NTG Neue Technologien GmbH, Gelnhausen; B. Szepaniak, Galvano-T GmbH, Windeck/Rosbach

Funding: German Federal Ministry of Education and Research (BMBF), promotional reference 03FUS0017B

A Series-Fed Frequency-Steered Phased Array Antenna for Doppler Reflectometry

Stefan Wolf, Walter Kasparek, Carsten Lechte

In a toroidal plasma, Doppler reflectometry (DR) allows investigating electron density fluctuations with finite wavenumber $k_\perp$. The injected microwave beam's frequency determines the cut-off density (i.e. the radial position) of the probed region. The beam's tilt angle selects the wavenumber satisfying the Bragg condition for backscattering. The plasma's rotation velocity can be calculated from the Doppler shift of the backscattered signal's frequency. By varying the injected frequency, radial profiles can be reconstructed. By varying the tilt angle, $k_\perp$-spectra of the fluctuations are resolved.

A second pair of phased array antennas (PAA) for use in the stellarator Wendelstein 7-X (W7-X) was completed in 2017. In adherence to W7-X regulations, the feed networks had to be further reduced in size. They feature a slightly focussing beam to reduce the spot size and improved waveguide connectors to facilitate installation and maintenance. They were used in the Op 1.2a campaign showing that, given enough plasma density with corresponding signal levels, the PAAs work.

Fig. 1: Three 5th generation feed networks. The two in front where installed in W7-X and used during Op 1.2a.

During bake-out for vacuum cleaning, dirt of unclear origin was found in and removed from the feed networks. It is currently investigated whether more rigorous cleaning after manufacturing can improve the PAAs' performance.

Collaboration: G. Conway, Max Planck Institute for Plasma Physics (IPP), Garching; T. Windisch, Max Planck Institute for Plasma Physics (IPP), Greifswald

Funding: This work was performed in the framework of the Helmholtz Virtual Institute on Plasma Dynamical Processes and Turbulence Studies using Advanced Microwave Diagnostics.

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 2017, the focus was on the optimization of reflecting gratings. Based on exiting codes, a new parallelized optimization framework was written. Furthermore, the collection of 2D and 3D geometry routines was completed. Currently these are used mainly for the synthesis of gratings but they are implemented as universal functions, which can be used by other code modules as well.

Another development was a generator for astigmatic Gauss-Hermite modes. In addition, the tool for fitting a Gaussian beam to a given field distribution was extended to determine the residual fields in terms of Gauss-Hermite modes. These modes can be used to study mode conversion phenomena in quasi-optical transmission lines and remote-steering antennas, where a beam is transmitted via a sequence of planar and focusing mirrors. The figures show the amplitude (power density) and phase of an astigmatic TEM_{22} field.

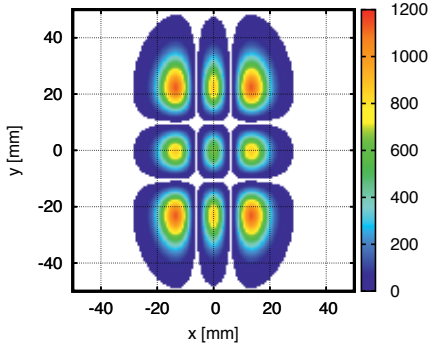


Fig. 1: Power density of an astigmatic TEM_{22} mode.

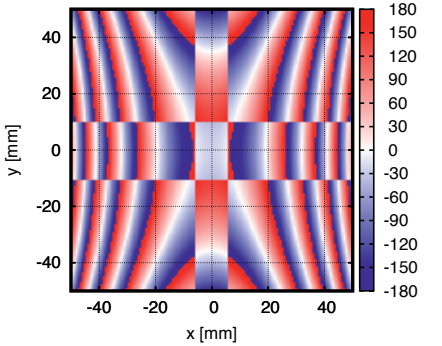


Fig. 2: Phase of an astigmatic TEM_{22} mode.

Development of Reflection Gratings for Advanced Electron Cyclotron Resonance Heating (ECRH) Scenarios

Burkhard Plaum, Walter Kasparek, Achim Zeitler

When heating fusion plasmas at higher harmonics of the electron cyclotron frequency, the absorption efficiency can be reduced. This leads to a significant transmitted beam power hitting the wall at the high field side (HFS). To protect the wall and to use the remaining power, one method is to place a specialized reflector at the HFS, which directs the beam back into the plasma for a second heating pass. The reflector needs to conform to the tiles at the HFS, which are often non-planar.

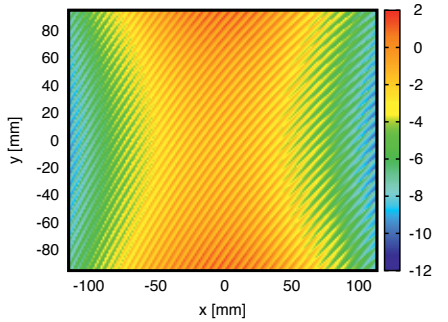


Fig. 1: Synthesized profile of a reflecting grating for ASDEX-Upgrade. Visible are the grooves, which are milled into the saddle-type surface of the tile.

The direction of the reflected beam is chosen such that the absorption of the second heating pass is maximized and the wall area at the low field side (LFS), which is hit after the second pass, contains no sensitive components. Additional requirements are a refocusing of the beam and polarization independence of the reflection characteristics. All these conditions can only be fulfilled with a grating. The design process involves the decomposition of the 3D field problem into a series of 2D reflections of plane waves. After the single 2D gratings are optimized, the final 3D grating can be synthesized. After reworking existing codes and parallelizing the 2D optimizations, a reflector tile for ASDEX-Upgrade was designed (Fig. 1).

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

A Simple Versatile Parallelization Framework for Distributed Optimization Tasks

Burkhard Plaum

Many frameworks exist for parallelizing computer codes across multiple CPUs and machines. The most important task is the synchronization of the processes for exchanging intermediate results.

In some cases, however, computational problems can be split into jobs, which can be executed independently. One example is the optimization of reflecting gratings where the 3D problem is split into a number (≈ 100) of 2D problems. For each of these, 10 optimizations are run with different random numbers. This results in about 1000 independent jobs.

A job queue was developed as part of the PROFUSION package to distribute the jobs across an arbitrary number of computers and CPU cores. The only requirement is, that the computers run on a recent linux system and have access to a common network (NFS) directory. The commands for the jobs are stored in a text file. A shared directory contains stamp files corresponding to the jobs. When a job is started, the stamp file is created with zero length. After the job is finished, one byte is written into the file.

To determine if a job is already running on another node, we try to create the stamp file. The creation fails if the file already exists. Since this operation is atomic on recent linux NFS implementations, no other locking mechanisms are necessary.

Other features include detection of available cores, the estimation of the remaining time and the stopping and restarting of the jobs on single computing nodes.

Multiport Coupler

W. Alexander Zach, Walter Kasparek, Carsten Lechte, Burkhard Plaum

For electron cyclotron resonance heating (ECRH), gyrotron beams with about 1 MW power at 140 GHz are guided by oversized waveguide transmission lines into the plasma vessel to be absorbed by the plasma. Coupling from the gyrotron source to the waveguide is done via matching mirrors in free space. Small alignment errors of the system lead to excitation of higher order modes inside the waveguide beside the main transmission mode (HE_{11}). Those modes have comparably higher losses and can in the worst case result in local fields exceeding the breakdown limit of the medium inside the waveguide.

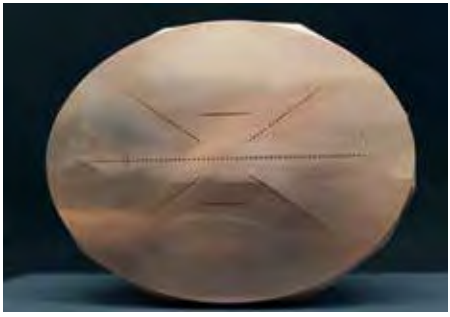


Fig. 1: Multiport coupler for detection of beam misalignment.

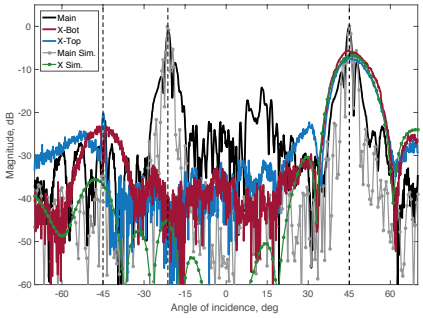


Fig. 2: Radiation pattern of main mode power monitor and X-polarization couplers.

For alignment control, a set of hole-array couplers located in a miter bend mirror probes the field inside the waveguide. A prototype (Fig. 1), specialized for detection of the tracer modes for beam offset and tilt ($LP_{11,even}$ and $LP_{11,odd}$) as well as for beam waist mismatch (LP_{02}) in combination with a main mode power monitor has been manufactured and tested at low power. A good agreement of the hole-array properties with simulation results was found (Fig. 2). Signal processing of the 140 GHz information is done at the kHz range after down-mixing, using a frequency-shifted part of the power monitor signal.

Collaboration: J. Stober, F. Monaco, and H. Schütz, Max Planck Institute for Plasma Physics (IPP), Garching; H. Idei, Kyushu University

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 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 Max Planck Institute for Plasma Physics (IPP).

Microwave Beam Broadening due to Turbulent Plasma Density Fluctuations

Alf Köhn, Eberhard Holzhauer

Microwaves play an indispensable role in plasma experiments for heating and diagnostic purposes. In fusion experiments, for example, microwaves in the electron cyclotron frequency range are commonly used to diagnose the electron temperature or to drive localized currents. The latter case can be employed to stabilize the so-called neoclassical tearing mode (NTM), an MHD instability, which can lead to a complete loss of the plasma confinement. The injected microwave beam has to pass, however, the plasma boundary where substantial plasma density fluctuations with fluctuation levels up to 100% are known to occur. This can lead to a broadening of the beam and thus spoil the required good localization for the NTM stabilization. We have numerically investigated the beam broadening as a function of the fluctuation parameters. Two different codes were used: the full-wave code IPF-FDMC, developed at IGVP, and the wave-kinetic equation solver WK-Beam, developed at IPP, which treats the effects of fluctuations in the limit of the Born approximation. The full-wave results were used to benchmark the WKBeam code.

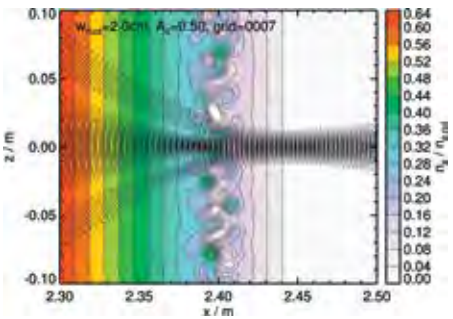


Fig. 1: Electron plasma density together with a snapshot of the absolute value of the wave electric field as obtained from full-wave simulations. The deteriorating effect of the fluctuation layer on the beam quality can clearly be seen.

Substantial broadening by a factor of up to two was found for scenarios predicted for the ITER tokamak. It was also found that such scenarios can be well described with the WKBeam code.

Publication: A. Köhn et al., Plasma Phys. Control. Fusion, submitted (2017); https://arxiv.org/abs/1712.03751

Collaboration: Omar Maj, Emanuele Poli, Max Planck Institute for Plasma Physics (IPP), Garching; Antti Snicker, Aalto University

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

Progress of the Electron Cyclotron Emission Receiving System for TJ-K

Gabriel Sichardt, Eberhard Holzhauer, Mirko Ramisch

The setup of the diagnostic system analyzing electromagnetic radiation generated by the gyration of electrons (electron cyclotron emission, ECE) at the stellarator TJ-K has been continued. The numerically optimized mirror has been installed in the vessel and first measurements were conducted. Experiments show only a low degree of polarization which supports the prediction from full-wave simulations that multiply reflected ECE dominates the receiver signals.

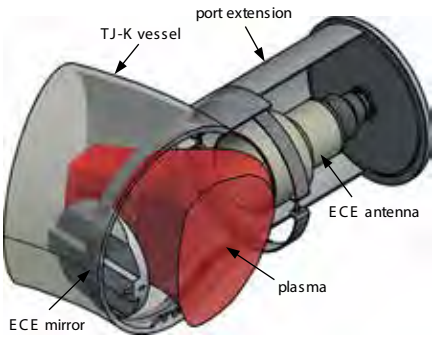


Fig. 1: Schematic view of the toroidal section of TJ-K containing the ECE diagnostic setup. By means of a phase shifter and a movable short, the length of the resonator between mirror and waveguide-to-coaxial coupler and the coupling factor to the detector can be tuned.

A hot-cold calibration was used to obtain the radiation temperature. The effective optical depth was deduced from comparison to expected temperatures. It is however three orders of magnitude larger than calculated for a single-pass emission. This larger effective optical depth is a consequence of multiple reflections in the vessel.

Current investigations are dedicated to a receiver signal dominated by radiation from the well-defined volume between antenna and mirror using an optimized resonator setup.

Electron trajectories were simulated to calculate toroidal net currents. To this end measured 1D density profiles were mapped to the entire confinement region and are extended to the scrape-off layer. The 3D density distribution will be used as a weighting function for the calculation of toroidal net currents as well as more realistic full-wave simulations. Trapped particles were shown to contribute only insignificantly to toroidal net currents.

As a next step, the influence of plasma turbulence on ECE propagation and resonator properties will be investigated.

Collaboration: Alf Köhn, Max Planck Institute for Plasma Physics (IPP), Garching

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

Numerical Investigation of Microwave Propagation in TJ-K

Lennart Bock, Gabriel Sichardt, Eberhard Holzhauer

The optically thin plasma of the stellarator TJ-K allows electron cyclotron radiation to propagate through the whole torus via multiple reflections until it is detected with a dedicated diagnostic system. The previous 2D simulation geometry for microwave propagation investigations was extended to 3D and implemented in the IPF-FD3D code in order to cover the full toroidal geometry of the stellarator.

Density profiles for the confinement region were measured using Langmuir probes and then mapped to the entire confinement region. This density distribution and the full 3D magnetic field geometry were taken into account in the simulations. The results confirm the improvement of the focusing of the electron cyclotron emission (ECE) diagnostic system by a mirror opposite the antenna by more than a factor of two. These simulations showed however that ECE being reflected around the torus and passing the plasma multiple times still contributes around 87% to the received power.

It is planned to model the density in the scrape-off layer more realistically and to include density fluctuations. Furthermore, the effect of the distribution of absorbent and emitting regions for ECE will be investigated and the polarization selectivity of the antenna will be considered.

In supplemental simulations, 2D geometries are used to demonstrate multimode resonator properties of TJ-K in considerably less computational time than in 3D.

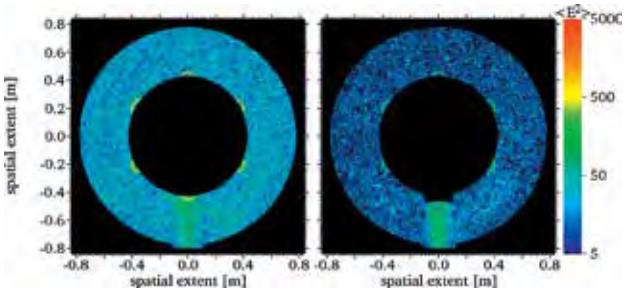


Fig. 1: Antenna weighting function from a 3D simulation without a mirror (left) and with a mirror (right). For a Gaussian beam with a frequency of 16 GHz the weighting function with the mirror is more pronounced between antenna and mirror, in contrast to the configuration without a mirror.

Hasegawa-Wakatani Plasma Turbulence Simulations

Stephen Garland, Mirko Ramisch

Drift-wave turbulence is common at the edge region of magnetically confined fusion plasmas, and contributes to the outward radial transport of particles and heat, degrading the confinement time and resulting in high heat loads on the reactor walls. The basic characteristics of drift-wave turbulence are captured by the 2D Hasegawa-Wakatani model, which consists of two coupled equations, for the plasma density, n, and the vorticity, Ω:

$$\partial_t n + \{\phi,n\} + L_n^{-1}\partial_y \phi = C^{-1}(\phi - n)$$
$$\partial_t \Omega + \{\phi,\Omega\} = C^{-1}(\phi - n),$$

where ϕ is the plasma potential, related to the vorticity by $\Omega = \nabla^2\phi$, $\{a,b\} = \partial_x a \partial_y b - \partial_x b \partial_y a$ is the Poisson bracket, L_n is the gradient length scale, and C is the collisionality. The collisionality parameter changes the coupling strength between the density and potential, which in turn alters the statistical properties of the density field. Fig. 1 shows the n, ϕ, and Ω fields for two simulations, one at low collisionality (C = 0.67) and one at high collisionality (C = 5). By comparing the plots in the figure it can be seen that the density field closely resembles the potential for C = 0.67, which is to be expected due to the strong coupling with the potential. However at higher collisionality the density and potential become decoupled resulting in the density more closely resembling the vorticity. This has implications for the intermittent properties of the density, since the potential is known to be self-similar, whereas the vorticity is suspected to have an intermittent character.

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

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

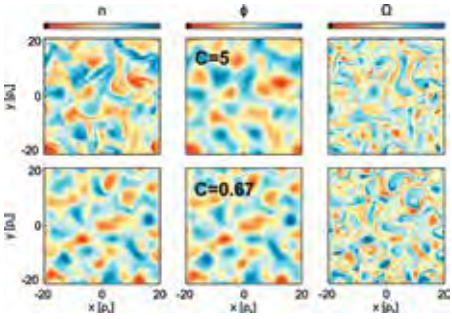


Fig. 1: The density, potential, and vorticity fields from Hasegawa-Wakatani simulations for two different collisionalities, C=5 (top row), and C=0.67 (bottom row). Distances are measured in units of the drift scale, ρ_s.

Intermittency in Drift-Wave Turbulence

Stephen Garland, Mirko Ramisch

The intermittent properties of plasma drift-wave turbulence were investigated by means of Hasegawa-Wakatani simulations, and the results compared to experiments at the stellarator TJ-K. Intermittent signals are said to be "bursty" in nature. One method used to quantify the degree of intermittency of a time series $f(t)$ is evaluation of high-order structure functions, $S_q(\tau) = \langle (f(t+\tau) - f(t))^q \rangle$, with $q \in \mathbb{R}$. The structure functions are inspected for a region of power law scaling with the time delay between points, $S_q(\tau) \sim \tau^{\zeta_q}$, where the parameter ζ^q contains information on the intermittent properties of $f(t)$. Using the extended self-similarity (ESS) method, if the resulting ratio ζ_q/ζ_3 scales as $q/3$ then no intermittency is present. A measure of the degree of intermittency can therefore be found in the deviation of ζ_6/ζ_3 from its non-intermittent prediction of 2, which is equal to the so-called intermittency exponent μ. Part a) of Fig. 1 shows μ as a function of collisionality for the three variables simulated in Hasegawa-Wakatani simulations. The changing density-potential coupling leads to an increase in the intermittency level as collisionality is increased, from the non-intermittent potential to the intermittent vorticity field. This increase in intermittency level is also observed in the experimental Langmuir probe data obtained in the edge region of TJ-K, shown in comparison to the simulation results in part b) of the figure.

Publication: S. Garland et al., Phys. Plasmas 24 (11), p. 112307, 2017

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

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

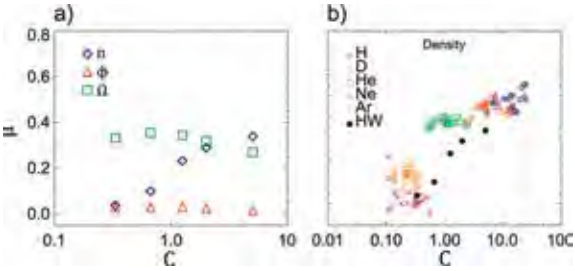


Fig. 1: a) The intermittency level, μ, of the three simulated quantities, n,ϕ and Ω as a function of the collisionality, C. b) The intermittency level in the density fluctuations as a function of collisionality for the simulated data (solid circles) and the experimental data for all available working gases.

Energy Transfer during Zonal Flow Occurrence

Bernhard Schmid, Mirko Ramisch

The driving mechanism of zonal flows is governed by the nonlinear energy transfer between small scale turbulent modes and the zero mode in the potential. Using the modified Ritz method, developed by Kim et al. [1], to solve the wave coupling equation, it is possible to study the different energy transfer channels connected with the zonal flow development. Data measured with a poloidal probe array, which consists of 128 Langmuir probes with 32 probes on each of four neighbouring flux surfaces, is used to estimate the energy transfer function from density and potential fluctuations. Applying a conditional averaging technique, results in the time resolved transfer function shown in Fig. 1, where positive values indicate energy gain of the zonal flow and negative energy loss.

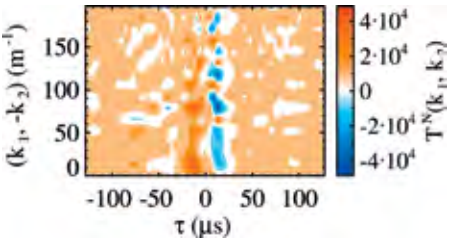


Fig. 1: Temporal evolution of the nonlinear energy transfer function around the zonal flow occurrence. Nonlinear energy transfer is important for the zonal flow growth ($\tau \leq 0$) and its damping ($\tau > 0$).

Prior to the zonal flow maximum ($\tau = 0$ μs) the overall energy transfer is positive and gets negative as the zonal flow decays. The mode resolved energy transfer reveals a complex transfer pattern along the zonal flow evolution. While the energy input from large scale structures quickly ceases away, becoming a sink for the zonal flow energy, selected small scale structures ($k_1 = -k_2 > 66$ m^{-1}) keep on pumping energy to the zonal flow. This shows the non-local character of the drift wave-zonal flow interaction and further points towards an energy transfer between the zonal flow and the geodesic acoustic mode (GAM), whose major component is at $k_1 = -k_2 = 12$ m^{-1}, i.e. m = 1 in the experiment.

[1] J. S. Kim, R. D. Durst, R. J. Fonck, E. Fernandez, A. Ware, and P. W. Terry, Phys. Plasmas 3, p. 3998 (1996)

Publications:

B. Schmid et al., Phys. Rev. Lett 118 (5), p. 055001, 2017

B. Schmid et al., New J. Physics 19, p. 055003, 2017

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

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

Shearing Rate Dependence of Reynolds Stress

Til Ullmann, Bernhard Schmid, Mirko Ramisch

Turbulence generated zonal flows (ZFs) are known to contribute to the regulation of turbulent transport and, therefore, are suspected to be involved in spontaneous transitions from low to high confinement regimes in toroidal fusion plasmas. ZFs are driven by radial gradients of the turbulent Reynolds stress which de facto measures the tilt of vortices.

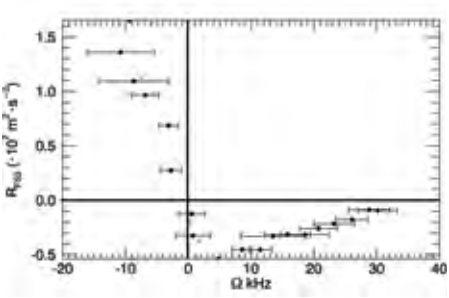


Fig. 1: The behavior of the Reynolds stress in dependence of the shearing rate. For a shearing rate of zero, the Reynolds stress value approaches zero, too.

Hence, equilibrium shear flows constitute a seed flow for initially tilting vortices, initiating the ZF drive and stimulating its self amplification. In this contribution the dependence of Reynolds stress on background flow shearing rates is investigated experimentally. To this end, the poloidal ExB background flow in the stellarator TJ-K is controlled via plasma biasing.

A ring shaped electrode is positioned in the plasma and set on a positive potential with respect to the vacuum vessel. This application even allows to equalize the pressure driven ExB background flow and thus annihilate the flow shear. The trend of the Reynolds stress with the shearing rate is analyzed. The background shearing rate is calculated from the plasma potential measured with a movable emissive probe. The Reynolds stress is computed from the potential fluctuations measured by an array of 128 Langmuir probes. In Fig. 1, the Reynolds stress is plotted over the shearing rate. The Reynolds stress is initially decreasing and is approaching zero where the shearing rate is zero. This is consistent with circular vortices in absence of vortex tilt through flow shear.

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

Zonal Flow Enhancement through Equilibrium Shear Flows

Rafael Carmona, Til Ullmann, Mirko Ramisch

In toroidal magnetic plasma confinement, zonal flows (ZF) play an important role in regulating drift-wave turbulence and, thus, edge cross-field transport. These flows are driven by gradients in turbulent Reynolds stress, which is related to an average vortex tilt in the turbulent fluctuations. Thus, an already present background shear flow is expected to favor the ZF drive by tilting eddies.

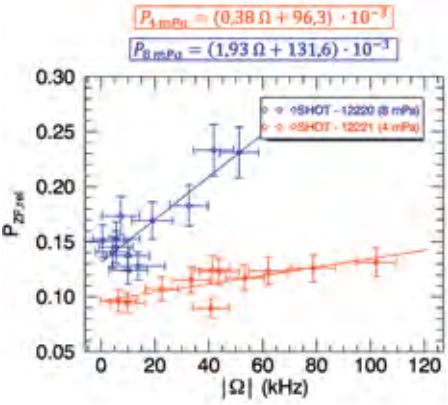


Fig. 1: Dependence of the relative zonal flow power on the absolute shearing rate. With an increase of the shearing rate an increase of the relative zonal flow power is found.

In this work, the dependence of ZF amplitude on background ExB flow shear is investigated in helium and hydrogen plasmas as an indication of the ZF self-amplification effect. To this end, the shearing rate of radially localized and stationary poloidal ExB flows is controlled via external plasma biasing, and deduced from radial plasma potential profiles measured with a movable emissive probe. At the same time, fluctuations in plasma density and potential are acquired using a poloidal 64-Langmuir probe array situated on one magnetic flux surface. The amplitude of the poloidally averaged potential fluctuations has proven useful as a good approximation for the time-varying ZF. This way, ZF power is determined, experimentally, and correlated with background flow shear. Power-law fits show that the shearing rate scaling of ZF power is, with an uncertainty of 20%, nearly linear for low shear. This result substantiates the assumption of ZF enhancement via an initial tilt of vortices through background ExB shear flows.

Funding: Erasmus Mundus Master program "European Master of Science in Nuclear Fusion and Engineering Physics"

Plasma Technology

Microwave Plasmas – Fundamentals and Applications

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

The division plasma technology works on the development of new microwave-generated plasma sources at low pressure and atmospheric pressure, the characterization of these plasmas, and the development of a variety of resulting applications. An example of a plasma source developed at IGVP is the so called Duo-Plasmaline which is operating at low pressure. The Duo-Plasmaline is a linearly extended plasma source and can be expanded by combining several of them to a homogeneous two dimensional plasma array. Other at the IGVP utilized low pressure plasma sources are the Planartron and an ECR-plasma. These plasma sources are well suited for plasma assisted surface treatment like surface activation, etching, and thin film deposition. The coating and various characterizations of insulating layers, O_2- and H_2O-permeation barriers, or scratch protection layers, and the sterilization of food packaging materials and herbs are our main research topics.

A current major issue is the development of plasma sources for the coating of large areas. This is desired equally from the ecological and economical view. The energy-efficient and resource-friendly material consumption of the plasma process reduces costs, but it also must keep pace with the cycle times of modern production technology.

In recent years the basis for large-scale and high-rate deposition of dielectric layers were investigated with a microwave plasma process and demonstrated in a semi-industrial scale at the plasma technology division of the Institute. 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 x 100 mm^2, and then transferred to the semi-industrial system with a length of 1000 mm and a width of 600 mm.

Vibrational Excitation Strategy for CO_2 Decomposition

Irina Kistner, Andreas Schulz, Matthias Walker

Currently there is a paradigm shift that completely redefines the value of energy forms where electrical energy from renewable sources is suddenly becoming a cheap alternative. However, the use of renewable energy sources is affected by their intermittency and a significant geographical mismatch between availability and demand. Consequently, energy storage and transport are necessary in order to tackle the problem of demand and supply. This can be achieved via the synthesis of liquid fuels from raw materials such as CO_2.

At IGVP CO_2 is converted by a microwave plasma into CO and O·. CO is then available as syngas.

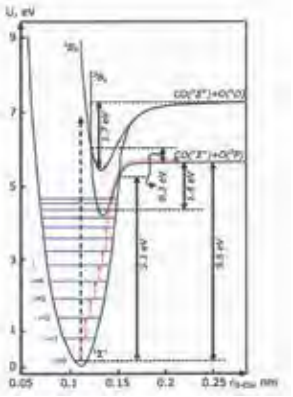


Fig. 1: Potential energy curves of CO_2 with additional indicated vibrational levels[1].

The strategy of the energy efficient dissociation mechanism is the tentative vibration excitation of the CO_2 molecule. In Fig. 1 the potential energy curves are shown with the indicated vibration energy levels in the electronically ground state $^1\Sigma^+$ [1]. The energy difference $\Delta E_{(\nu;\nu+1)}$ between two vibration levels ν decreases with higher vibration quantum number $\nu'>\nu$. The excitation works then like an energy level ladder where CO_2 molecules at lower vibration levels ν can transfer sufficient energy by collisions to molecules in higher levels ν' to climb up one step further to $\nu'+1$. For example, this would mean for a collision of two molecules in the same vibration level $\nu=n$:

$$CO_2(^1\Sigma^+_{(\nu=n)}) + CO_2(^1\Sigma^+_{(\nu=n)}) \rightarrow CO_2(^1\Sigma^+_{(\nu=n-1)}) + CO_2(^1\Sigma^+_{(\nu=n+1)}) + \Delta E,\ n>0$$

The aim is to decrease the energy per molecule value, so that only the lower vibration levels of the CO_2 ground state get populated without energy transfer into kinetic energy. Then the gas temperature can be kept low accompanied with an efficient CO_2 dissociation process.

[1] A. Fridman, Plasma Cemistry, Cambridge University Press, New York, 2008

Collaboration: Emile Carbone, Ursel Fantz, Max Planck Institute for Plasma Physics (IPP), Garching

Investigation of a Microwave Plasma Torch for CO_2 Gas Conversion

Irina Kistner, Andreas Schulz, Günter Tovar, Matthias Walker

Since electricity from renewable sources of energy is subject to fluctuations, energy storage on demand plays a crucial role to create a reliable grid system. The CO_2 conversion into syngas or higher hydrocarbons via a plasma assisted gas conversion powered by renewable energy is one promising approach towards energy storage. To make this power-to-gas concept beneficial over other technologies it is of particular importance to improve the energy and conversion efficiency of this process.

On the basis of preliminary tests and technological requirements for a microwave plasma unit for CO_2 conversion a modular plasma torch consisting of a cylindrical and a coaxial resonator has been constructed and put into operation. This plasma torch enables a self-ignition and stable operation of an air 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. Via the FEM simulation program COMSOL Multiphysics® a model of this plasma torch has been developed and the electric field distribution inside the plasma torch has been investigated to optimize the configuration and to determine the most suitable operation conditions.

Collaboration: Mario Dünnbier, Muegge GmbH, Reichelsheim

Funding: German Federal Ministry of Education and Research (BMBF), Kopernikus projects for the Energiewende

Fig. 1: Modular microwave plasma torch in operational mode.

Fig. 2: Simulation of the electric field distribution inside the resonator. The electric field reaches up to $1.26*10^6$ V/m at the nozzle tip, if the tip is located 8 mm below the resonator base.

Oxygen Removal from an Air Plasma via a Ceramic Capillary

Irina Kistner, Andreas Schulz, Günter Tovar, Matthias Walker

In order to produce syngas, which is a mixture of carbon monoxide and hydrogen, the oxygen contained in a CO_2 plasma has to be removed. For this purpose a tubular reactor (Fig. 1), which can be connected to the microwave plasma torch, has been constructed, such that a ceramic capillary can be placed in a gland sealing inside the reactor and has been tested preliminary with an air plasma. Argon is used as the carrier gas and the oxygen concentration is measured as a function of time for volume flow rates of the carrier gas between 20 and 70 ml/min and for microwave powers between 0.4 and 1 kW.

Fig. 1: Tubular reactor with a ceramic capillary inside. Argon flows from the left side through the capillary and the oxygen was measured with a ZrO_2 detector.

Since the temperature of the capillary rises with higher microwave power and hence the activation energy for diffusion is decreasing, the oxygen permeation and concentration is increasing with increasing microwave power. On the basis of the stationary

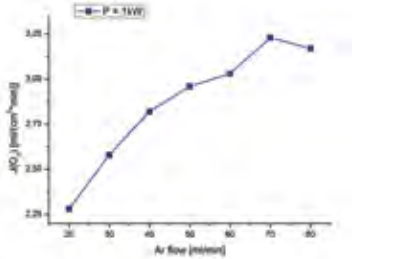


Fig. 2: Oxygen current density for different Argon flow rates and a microwave power of 1 kW.

concentration of the oxygen and the capillary area accountable for the permeation, the current density of the oxygen molecules $J_s(O_2)$ was calculated for different argon flow rates and 1 kW of microwave power (Fig. 2). As shown in the figure the current density increases with increasing argon flow until about 50 ml/min, where it starts to turn into saturation. Hence, for low argon flow rates the oxygen isn't removed completely and leads to a lower partial pressure gradient and thus to a reduced oxygen permeation. Once the argon flow, where no change in the oxygen current density is observed, is determined, the diffusion coefficient of the oxygen molecules through the ceramic membrane can be calculated.

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

Funding: German Federal Ministry of Education and Research (BMBF), Kopernikus projects for the Energiewende

Flexibility of SiO_x-Based Oxygen Barrier Layers Deposited in an Electron Cyclotron Resonance Plasma

Mariagrazia Troia, Andreas Schulz, Matthias Walker

In order to be employed as barriers in encapsulations of flexible devices such as OLEDs, SiO_x polymer-like thin films obtained through Plasma Enhanced Chemical Vapor Deposition (PECVD) in an electron cyclotron resonance (ECR) reactor, with HMDSN and O_2 as feed gases, need to be flexible and able to sustain several bending cycles without compromising their barrier properties. The best barrier layer, obtained by means of an O_2/HMDSN feed ratio of 40:1 and 100 nm thick, has thus been subjected to up to 50 cycles of compressive and tensile stress, for two curvature radii of 1.8 and 0.75 cm, respectively.

Results in Fig. 1 of its normalized oxygen transmission rate, measured after each cycle, show no worsening for the bigger curvature radius and a small increase, followed soon by a stable phase, for the smaller one. Such increase lies still in the acceptable dispersion range for the performances of such barriers. A similar study for different thicknesses shows how even after 50 cycles the barrier performances of these layers are still comparable to those of the unbent references, over almost two orders of magnitude (Fig. 2).

Funding: This project is partly funded by the German Federation of Industrial Research Associations (AiF e.V.) as a transnational project within the Collective Research NETworking (CORNET) program.

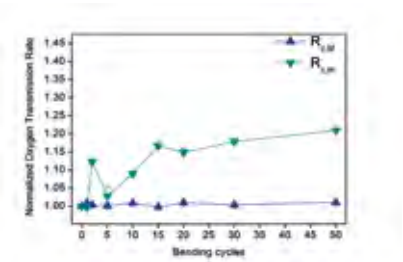


Fig. 1: Normalized oxygen transmission rates for a 40:1 barrier film for a curvature radius of 1.8 cm ($R_{c,M}$) and 0.75 cm ($R_{c,m}$).

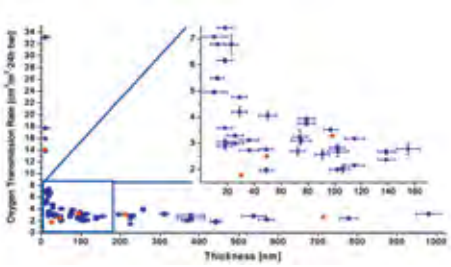


Fig. 2: In red, normalized oxygen transmission for different thickness after 50 bending cycles (red dots) compared to the unbent reference barriers (blue dots).

Effect of Power and Plasma Feed Composition on the Barrier Properties of PEVCD SiO_x Thin Films

Mariagrazia Troia, Andreas Schulz, Matthias Walker

Physical properties of Plasma Enhanced Chemical Vapor Deposited films depend greatly on the operating parameters of the plasma, mainly the gas feed composition that affects in turn the chemical composition of the products, but also the operating power, as it influences the internal energies of the particles in plasma, therefore their reactivity, degree of dissociation and so on. A preliminary investigation has been carried out for the optimization of such parameters in a PECVD process in order to obtain the best SiO_x barrier layers in an electron cyclotron resonance (ECR) cold plasma.

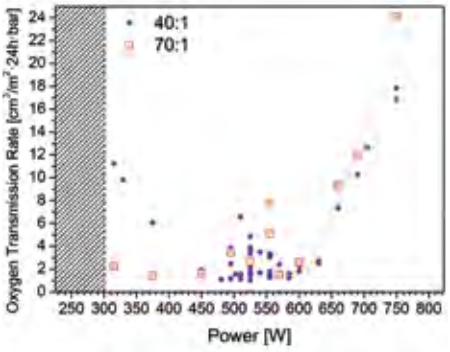


Fig. 1: Oxygen transmission rates as a function of the operating power for two different O_2/HMDSN mixtures: in grey the range in which the power is too low to ignite a stable plasma.

As shown in Fig. 1, an insufficient operating power can be counterbalanced by an excess of reagent (in this case oxygen), just as a limited fraction of O_2 in the feed can be made more efficient with an increase in power, leading to the same chemical and morphological composition that ensures good barrier properties.

It is thus possible, by varying two parameters at the same time, to extend the range of operability while at the same time keeping constant the properties of the final films. The limiting factor in this case is the power, that can prevent a stable plasma to be ignited, when too low, or cause thermal damages to the substrate that compromise the barrier integrity (dashed line in the graph).

Comparison of HMDSN- and HMDSO-Based Barrier Deposited via an Electron Cyclotron Resonance Plasma

Mariagrazia Troia, Sandra Gaiser, Andreas Schulz, Matthias Walker

While hexamethyldisilazane (HMDSN) and hexamethyldisiloxane (HMDSO) are conventionally considered as interchangeable precursors for the deposition of silica-like layers in plasmas, extensive comparisons between samples obtained at the same operating parameters show how the range in which such films can be employed as oxygen barrier layers is significantly wider for HMDSN: the reduction in oxygen transmission rate takes place for much smaller plasma feed ratios and remains excellent even for very high values of the latter: In comparison, HMDSO-based films possess only a relatively narrow minimum, with both high and low ratios being of no practical use (Fig. 1).

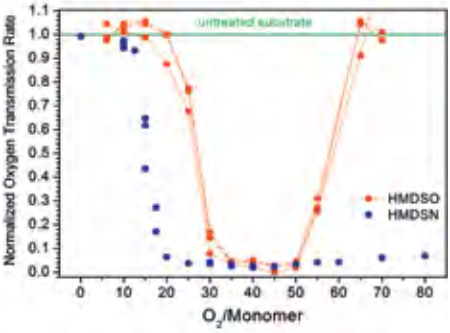


Fig. 1: Oxygen transmission rates for HMDSN- (blue) and HMDSO-based (red) inorganic layers deposited and tested in the same operating conditions.

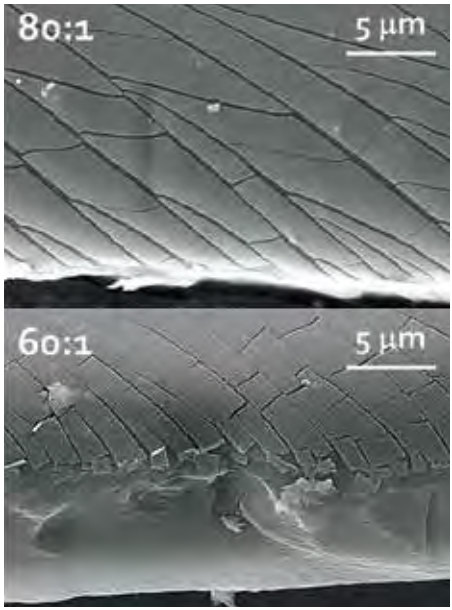


Fig. 2: Scanning electron microscope pictures of artificial cracks for high O_2/monomer ratios samples (top picture with HMDSN, bottom picture with HMDSO as monomer).

HMDSN-based films of various thicknesses possess moreover very good stability over two orders of magnitude and retain their barrier properties even after being subjected to strong bending, suggesting a much more resilient structure and a wider range of applications. Analysis at the scanning electron optical microscope confirms how HMDSO-films are in fact more brittle, as can be observed by their jagged, angular cracks.

$-(CH_x)_x$ as Sacrificial Groups for Protection of OLEDs in Plasma Deposition Processes

Mariagrazia Troia, Andreas Schulz, Matthias Walker

Because of the extreme sensitivity of their active layers against O_2, OLEDs require a protective layer before their proper encapsulation process with non-equilibrium microwave-powered plasmas. Such a layer, requiring a completely O_2-free process (hence HMDSN and H_2 being employed as precursors the plasma feed), possesses little to none barrier properties against O_2 permeation; on the other hand, the relatively abundant $-(CH_x)_x$ in its bulk can act as sacrificial groups, intercepting oxygen radicals before the latter reach the OLED surface and being etched and/or oxidized in return. Through *ex-situ* IR analysis of various layers after being exposed to a subsequent barrier deposition step, and layers exposed to a pure oxygen plasma acting as a reference, and fitting of their methyl peaks, it has been possible to evaluate the abundance of such sacrificial groups before/after, and monitor their oxidization as a function of exposure time, in order to find the better chemical composition that can ensure an adequate protection degree of the OLEDs in the first encapsulation step. A 40:1 H_2/HMDSN ratio in the plasma feed provides enough methyl groups and enough resistance against etching to be successfully employed as protective, and then intermediate film, in a multilayer encapsulation.

Collaboration: Wim Deferme, Inge Verboven, IMO-IMOMEC, UHasselt, Diepenbeek, Belgium

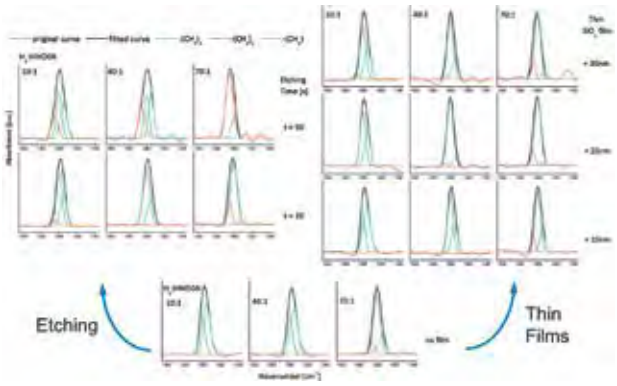


Fig. 1: Fitting of the single components of the methyl band for etched organic films, as reference (left) and films exposed to a subsequent barrier deposition (right).

Modelling of a Microwave Plasma Torch at Atmospheric Pressure

Sandra Gaiser, Andreas Schulz, Matthias Walker

To study a microwave plasma torch at atmospheric pressure numerical simulations were carried out using the software COMSOL Multiphysics®.

A two-dimensional numerical model of an argon plasma in a microwave plasma torch was set up. Low and atmospheric pressure regimes were described by appropriate sets of reaction mechanisms. The electron and heavy particle transport was taken into account by using fluid equations. The Drude theory describes the frequency dependent permittivity and conductivity of the plasma and is used to calculate the deposited power of the microwave which was coupled in to heat the plasma.

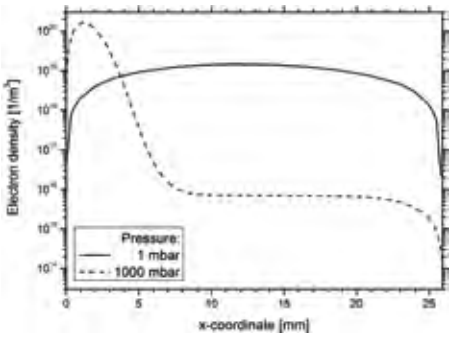


Fig. 1: Electron density profiles for an argon plasma at 1 mbar and 1000 mbar.

The simulation results show one-dimensional electron density profiles along the x-axis of the plasma area (Fig. 1). At atmospheric pressure the maximum density is one order of magnitude higher than for the low pressure case. This leads to a displacement of the microwave field and a plasma heating restricted to the left hand side from where the microwave is coupled in. As a result the electron density gets higher in this area. Recombination processes in the plasma volume prevent electrons from diffusing to the center of the plasma which is why the density is decreasing here. For the case of 1 mbar recombination takes place only at the walls since the collision frequency is low. Therefore electrons can diffuse through the whole plasma area and the electron density increases towards its center.

Collaboration: Eight project partners from Germany in the AiF/DFG cluster project OGAPLAS

Funding: This work was funded by the German Research Foundation (DFG).

Scale-up of a Spice Powder Sterilization Process with a Dielectric Barrier Discharge

Stefan Merli, Andreas Schulz, Matthias Walker

Spice powders often exhibit contamination with germs, which can lead to a faster spoilage or to serious health issues after consumption. Common methods for sterilization, such as hot steam sterilization, are technically complex and lead to a loss of flavorings.

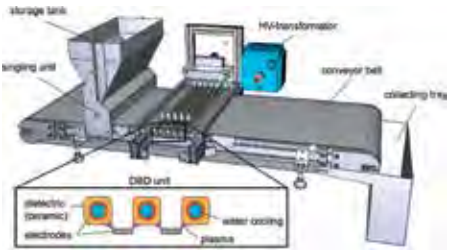


Fig. 1: Scheme of the upscaled pilot plant for the sterilization of spice powders with a DBD.

Therefore, a mild sterilization process of pepper powder using a non-thermal atmospheric plasma was investigated. In previous works, different configurations of dielectric barrier discharges (DBD) were tested for their applicability to treat the sensitive powder. Hence, a remote treatment with an array of eight parallel DBD electrode pairs was realized on a small lab-scale experiment, which showed a germ reduction of 5 orders of magnitude on bacterial spore test stripes (*Bacillus atrophaeus* and *Geobacillus stearothermophilus*) and 3 orders of magnitude on artificially contaminated pepper powder (*Bacillus subtilis*).

The DBD configuration was then upscaled to a semi-industrial pilot plant with a treatment width of 50 cm for the sterilization of larger amounts of pepper powder (Fig. 1). The plant included a conveyor belt, storage and collection containers, a singling unit for the powder and water-cooled DBD electrodes to reduce the thermal load during the treatment. All in all, a germ reduction of up to 5 orders of magnitude was achieved on bacterial spore test stripes and 1.5 orders of magnitude on pepper powder. Despite the high sterilization efficiency on the spore stripes, the setup has to be further optimized regarding the electrode geometries and the powder singling in order to improve the results on the pepper powder.

Collaboration: B&F Elektro GmbH, AFS Entwicklungs- und Vertriebs GmbH, Arotop food & environment GmbH

Funding: German Federal Ministry for Economic Affairs and Energy (BMWi) – ZIM cooperation project

Investigation of DC Arcjets for the Ignition of Coal Powders

Stefan Merli, Andreas Schulz, Matthias Walker

The growing trend of renewable sources of energy forces coal-fired power plants to increase their flexibility. The utilization of oil or gas as the conventional method for start up faces several issues with more frequent shut downs and start ups. The application of arcjets is therefore an interesting alternative for direct start up with coal. In this project, dc arcjets were investigated for their ability to ignite different types of coal under cold start-up conditions. The plasma of the arcjets was first characterized by optical emission spectroscopy (OES) to determine the composition and gas temperature of the plasma jet. A gas temperature of around 9000 K was determined via the Boltzmann-plot method at the exit of the plasma burner.

Subsequently, a small lab-scale experiment with a corresponding burner geometry and a special coal particle injection was set up to study the basic interactions of the plasma with small amounts of coal particles of different types via OES and high speed camera measurements.

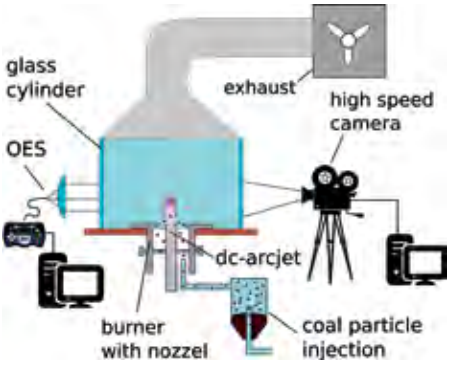


Fig. 1: Scheme of the setup for the investigation of the interaction of coal particles with an arcjet plasma.

Additionally, the arcjets were tested in a technical scale pulverized fuel combustion rig with a thermal power of up to 300 kW. The experiments were carried out for different fuel types (hard coal, lignite, biomass) at varying operating parameters such as air to fuel ratio, thermal load and arcjet lance position in order to determine the optimal conditions for ignition and maintenance of a stable coal flame.

Collaboration: Institute of Combustion and Power Plant Technology (IFK), University of Stuttgart; Mitsubishi Hitachi Power Systems Europe GmbH; Lausitz Energie Kraftwerke AG

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

Modeling and Study of a Microwave Plasma Source for High-Rate Etching

Steffen Riegger, Andreas Schulz, Günter Tovar, Matthias Walker

Photoresists are used in the industry for lithographic processes to produce surface structures in the sub-micrometer range. After the manufacturing processes the cured photoresist must be removed. For this purpose we investigate a remote plasma source (RPS) with pure oxygen as etching gas. The generated oxygen radicals react with the substrate surface atoms forming gaseous molecules.

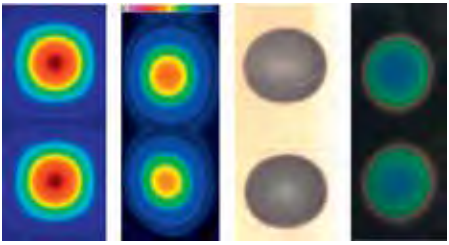


Fig. 1: Different methods showing the electric field distribution in a rectangular waveguide. From left to right: FEM simulation, heated up substrate photgraphed with a thermo camera, heated up thermo paper, heated up substrate with a liquid crystal sheet on it.

Using a FEM-based simulation software a model of the RPS has been developed in order to investigate the microwave distribution and the microwave coupling in the plasma source.

To validate the simulations, the simulated electric field configuration in a rectangular waveguide is compared with experiments. Therefore different substrates (e.g. PMMA, PVC, PET) are heated up with microwaves in a closed rectangular waveguide and afterwards evaluated with different methods. Fig. 1 shows from left to the right the calculated electrical field distribution, the heated up substrate photograhed with a thermo camera, a thermo paper which was heated up between two substrates and the heated up substrate with a sheet of liquid crystals on it. Depending on the heat flux, the liquid crystals change their polarization and therefore their color. In a next step, the electric field distribution inside of the RPS will be measured and compared with the FEM simulations.

Collaboration: Mario Dünnbier, Klaus Baumgärtner, Muegge GmbH, Reichelsheim

Study of a Microwave Plasma Source for High-Rate Etching with a High-Speed Camera System

Steffen Riegger, Andreas Schulz, Günter Tovar, Matthias Walker

Remote plasma sources (RPS) are used in the industry to produce surface structures in the sub-micrometer range. One important field of application is the microsystem technology, which deals mainly with the development and production of semiconductor devices or micromechanical components such as micro gear-wheels. To study the ignition processes in a RPS, the plasma is investigated with a high speed camera system. With a frame rate of 420,000 frames per second, 350,000 images in 0.83 seconds are taken, of which 266,000 images are used for the evaluation. Using an IGVP written program code, the average light intensity of the images is saved in dependance on time and afterwards evaluated with Origin.

The images show that the plasma is ignited at the top of the chamber, where the microwaves are coupled into the RPS (Fig. 1). For the evaluation with Origin, the average light intensity of the images is plotted vs. time. This uncovers, that at the beginning of the ignition process the plasma goes out and ignites again. It also shows, that the plasma flickers on different frequencies, which is clearly recognizable when considering the Fourier transformation (Fig. 2). The reason for the flickering is the power supply technology used for the RPS system.

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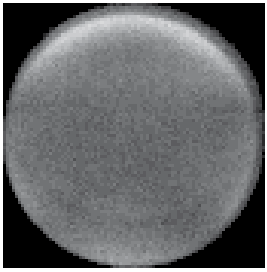

Fig. 1: High-speed image of the plasma ignition, where the plasma ignites on the top of the plasma chamber, where the microwaves are coupled in.

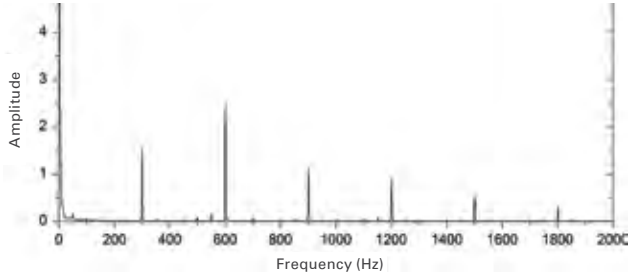

Fig. 2: Fourier transformation of the plotted average light intensity of 266,000 high speed images, during the plasma ignition process.

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Publications

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87. S. Bruttel, "Konstruktive Optimierung einer elektrochemischen Zelle zur Phosphorrückgewinnung", University of Stuttgart, seminar paper, 2017.

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