University of Stuttgart
Institute of Interfacial Process Engineering
and Plasma Technology

Annual Report 2016

Editorial notes

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Preface

The engineering of interfacial materials and processes as well as the mastering of plasma processes demands specific skills as well as interdisciplinary and studies. The Institute of Interfacial Process Engineering and Plasma Technology IGVP, belonging to the Faculty 4: Energy, Process and Bio-Engineeringof the University of Stuttgart offers an excellent meeting space for both experts in fundamental and application oriented research and those willing to develop such skills during their studies.

The following report highlights selected research subjects which in most cases reflect the research directed towards a dissertation. An extensive list covering peer-reviewed publications, conference contributions and a full list of master-, bachelor- and diploma theses and other student research studies is given in the annex of the report.

In the year 2016 our research was structured as before in the two sections "Interfacial Process Engineering" consisting of research on Chemical-Physical Interfaces, Biological-Medical Interfaces, Interfacial Processes and functional hydrogels within the Projekthaus NanoBioMater as well as the section "Plasma and Microwave Technology" focusing on Microwave Technology, Plasma Dynamics & Diagnostics and Plasma Technology.

Functional soft matter constituted from a wanted chemical composition and in a physical shape ready for processing by surface technology is a key challenge of the IGVP. It is addressed by designing and preparing nanostructured building blocks ready for supramolecular interactions. E.g. a variety of interfacially active low molecular weight or macromolecular precursors and their envisaged application to create new enabling technologies is presented in the section concerning the chemistry and physics of interfaces.

Natural nanostructured entities may be seen in viruses. The herpes simplex virus is a supramolecular construct with high functionality ensuring its life cycle. Surface proteins interact specifically with cellular membrane counterparts and trigger transport processes via these membranes. The release of viral capsids from the host cell's nucleus is a process called nuclear egress. A better understanding of this egress is a current focus of our interest in the section on biologically and medically relevant interfaces.

Natural processes are based on the conversion of natural substances employing natural energy sources. One approach to new technical processes with high value is to search for new ways to gain natural substances. At our institute, processes and bioreactors for production and extraction of valuable compounds are designed, analyzed, and modeled for interfacially driven processes.

The Projekthaus NanoBioMater constitutes an interdisciplinary and inter-institutional undertaking at the University of Stuttgart funded by the Carl Zeiss Foundation and the Land Baden-Württemberg. At the IGVP, we are responsible for the coordination of the Projekthaus and run a research team on functional hydrogels, which contributed a section to this report.

Our research on microwave technology is directed towards energy for tomorrow based on fusion technology. It is concerned with simulation, design and buildup of components of more effective fusion reactors and analysis, simulation and design of ameliorated processes therein. In this year's report we present originary research on e.g. antennae, mirrors, reflectors, and couplers to run fusion experiments as well as a variety of fullwave simulations of fusion plasmas.

The own stellarator experiment is the center of interest of our studies focusing on the dynamics and diagnostics of the toroidal plasma being operated in it. Here, we concentrate e.g. on the steering of microwaves considering their propagation and flow trajectories in the plasma system. Numerical investigations and simulations of the complex plasma's processes as well as design and construction of functional components for the experiment are being pursued.

The development of new microwave plasma sources from design through characterization is part of our current research in plasma technology. Plasma processes for surface activation, etching, powder treatment or deposition and encapsulation are further themes of interest to us.

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

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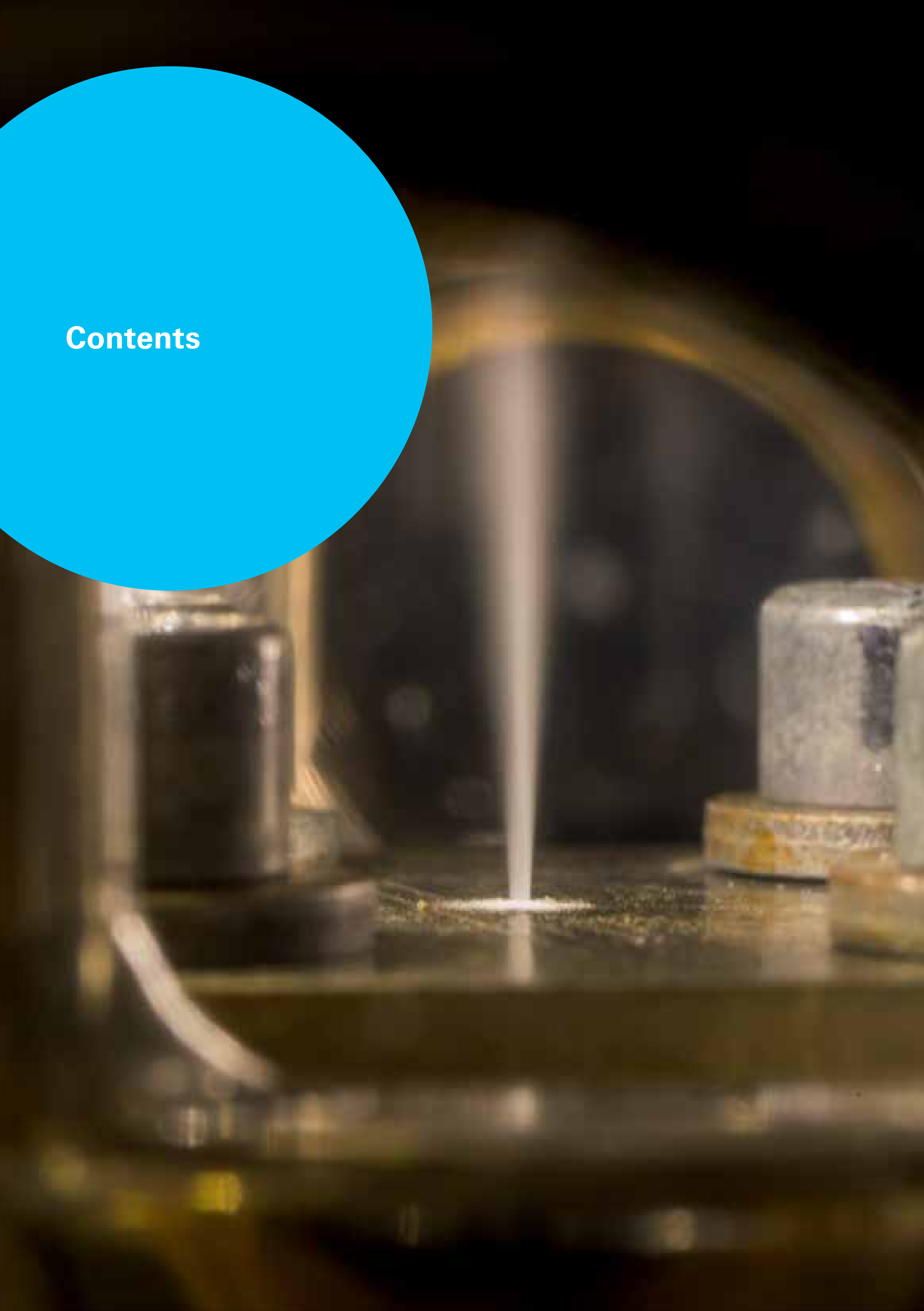

Institute of Interfacial Process Engineering and Plasma Technology IGVP

The Institute of Interfacial Process Engineering and Plasma Technology IGVP is part of the Faculty of Energy Technology, Process Engineering and Biological Engineering of the University of Stuttgart.

Key Figures
In 2016, the research budget accounted for 2.57 million euros. At the end of that year, staff of 75 scientific, technical and administrative employees, among them 41 doctoral students, worked at the three IGVP facilities – along with 55 other students researching for their master or bachelor thesis.

Facilities and Organization
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.

The institute is organized in the two departments "Interfacial Process Engineering" and "Plasma and Microwave Technology", which consist of three research groups each.

Research
The IGVP focuses on the design of functional materials and that of their interfaces and surfaces, on the biological interactions at these interfaces 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 Fraunhofer IGB makes it possible 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-Institut für Plasmaphysik in Garching and Greifswald, the Karlsruhe Institute of Technology KIT, and the Dutch Institute for Fundamental Energy Research DIFFER in the Netherlands.

Teaching

The IGVP is actively involved in the teaching of master and bachelor study programs at Stuttgart University such as Process Engineering, Medical Engineering, 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

Contact

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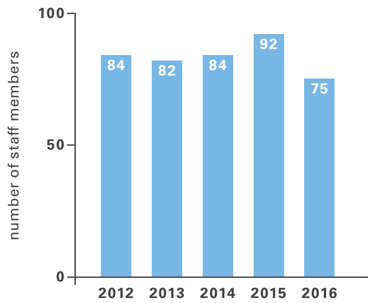
Development of staff members



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Prof. Dr. Uwe Schumacher (retired)

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Lisa Blaschke (PhD student)
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Christina Funk (PhD student)
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Manfred Krämer
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Holger Röhlinger (Head, since October 01, 2016)

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Johannes Sunke (until August 31, 2016)
David Zander (since February 03, 2016)

Chemical-Physical Interfaces

In chemical interface process engineering new functional polymeric materials, in particular polymeric nano- and micro particles, and hydrogels of biobased synthetic and bio-inspired polymers are produced in interfacial processes. Manufacturing processes, structural property relationships and downstream processing, which are constantly experimentally developed, are of particular interest. The focus of our application-oriented basic research is the formulation of biological and chemical drugs or the development of synthetic and natural biomaterials for contact with biological systems (cells). Through *in vitro* research of the fundamental mechanisms that govern cell-biomaterial and cell-cell interactions we develop functional surfaces and interfaces of biomaterials that have the ability to direct cellular responses and regulate the formation and integration of tissue.

By controlled cross-linking of synthetic or natural molecular building blocks we obtain hydrogels with adjustable mechanical and biological properties. A particular focus is the formulation of hydrogels to produce (bio)inks for additive manufacturing processes.

Main research fields of physical interface process engineering are the adaptation of the properties of material surfaces that come into contact with solid/liquid/gaseous media. At our institute we use mainly plasma technology in which surface changes can be achieved by physical and chemical interactions.

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Inkjet Printing of Novel Functional Highly Porous Polymers

Contact: Fabian Schuster

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 3D-structures. The ink droplets are placed on top of each other leading to an in situ reaction on the substrate, forming the desired structures. This technique is used to produce micro-scale polyurethane foams. Two fluids are separately stored and printed subsequently on top of each other.

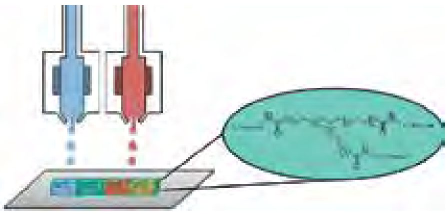


Fig. 1: Reactive inkjet printing of porous polyurethane foam structures.

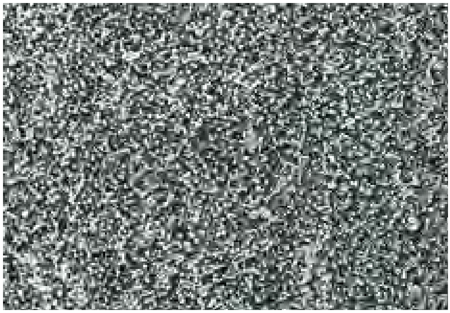


Fig. 2: Microscopic image (transmitted-light) of a printed foam structure cured at room temperature.

The first fluid contains a hydroxy-functional mixture and the second one contains a low viscous isocyante-functional compound. In this case water acts as the chemical blowing agent, as it reacts with the isocyanate to form carbon dioxide and an amine. Furthermore, investigations towards the choice and concentration of catalysts as well as the printing parameters were carried out. The obtained structures are a first step into the direction of digital fabrication of printed foams.

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

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

Functional Encapsulation of Active Ingredients by Means of Spray Drying

Contact: Michael Walz

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.

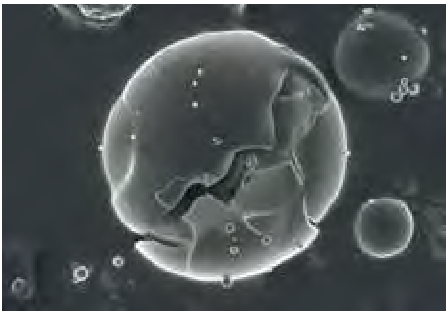


Fig. 1: Core-shell particle, produced by means of a three-fluid nozzle.

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: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart

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

Chitosan-Based Nanoparticles for Wastewater Remediation

Contact: Benjamin Riegger

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. 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 deacethylated 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.

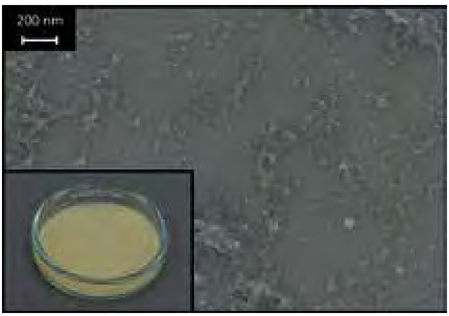


Fig. 1: SEM-picture of prepared chitosan nanoparticles. Lower left corner: raw low molecular weight chitosan powder.

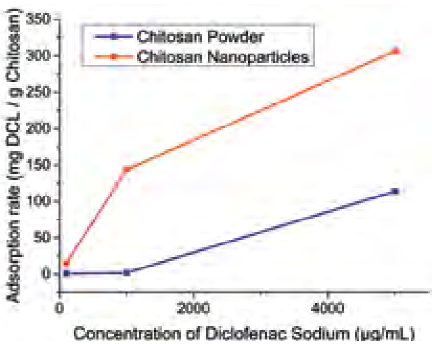


Fig. 2: Adsorption capacity of low MW-Chi-NPs for diclofenac.

Surface Active Monomers as Building Blocks for Particle Functionalization

Contact: Vanessa Albernaz

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.

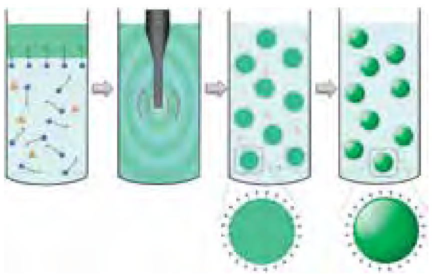


Fig. 1: Preparation of polymeric nanoparticles with functionalized surface using surfmer molecules though miniemulson polymerization.

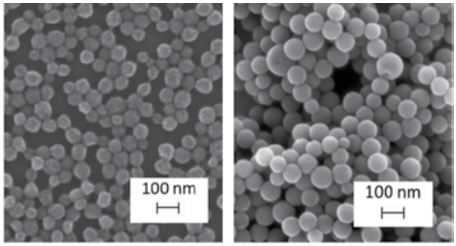


Fig. 2: Scanning electron microscopy image of PMMA-co-AUPDS and PS-co-AUPDS nanoparticles using the AUPDS surfmer molecule as the sole surfactant.

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.

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

Funding: Science without Borders Program, CAPES Foundation, Brazil

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

Contact: Christiane Claaßen

Presently insufficient oxygen and nutrient supply in tissue engineering grafts due to poor vascularization is a fundamental limitation. Controlled release of pro-angiogenic growth factors is reported to be a promising approach to stimulate vascularization and thereby biointegration. Growth factor concentration and duration of delivery are critical factors.

We investigate the immobilization of growth factors in biopolymer-based hydrogels and their functional release into the surrounding tissue matrix. So far, the functionalization of gelatin and heparin with cross-linkable groups and determination of their degree of substitution were successful. 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 as well as characterization of the release kinetics were determined. Currently, their biocompatibility and bioactivity is investigated with primary human endothelial cell and chorioallantois membrane assay. Furthermore, the stable immobilization of hydrogel thin films on polyethylene terephthalate track-etched membranes is aimed.

Collaboration: K. Borchers, Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; B. Stanzel, Department of Ophthalmology, University of Bonn

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"

Fig. 1: Hydrogel preparation via thermal-redox initiated cross-linking of methacryl-modified gelatin and methacylated heparin.

Azide-Modified Extracellular Matrix as Biomaterial with Adaptable Properties

Contact: Silke Keller

Biomaterials which are commonly used in medical applications have to meet certain mechanical requirements and have to be compatible with the human body. To enhance this biocompatibility, materials are often coated with biomolecules found in the extracellular matrix (ECM). The ECM can be considered the natural environment of cells in a natural tissue. Due to its high biological activity, the isolated ECM is a promising biomaterial for the use in tissue engineering and regenerative medicine. However, the use of ECM is limited, e.g. due to the lack of specific addressable functional groups which are often required for their use as coatings or scaffolds. To overcome this limitation, Mara Ruff, a former IGVP PhD-student, developed a "clickable" ECM by performing metabolic glyco engineering on fibroblasts to introduce azide groups into the ECM. This "*click*ECM" can be covalently immobilized on complementary click-functionalized surfaces via copper-free click chemistry.

Fig. 1: Microscopic analysis of the azide-functional *click*ECM.

In my work, we further increased the denseness of the *click*ECM coatings by concentrating the coating suspension using centrifugal filters. Moreover, we cross-linked the azide-modified *click*ECM with a bi-functional alkyne crosslinking agent in order to further increase the coating thickness, denseness, and stability.

Collaboration: Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart; V. Wittmann, University of Konstanz; Aesculap AG

Funding: I kindly thank the Peter and Traudl Engelhorn Foundation for rewarding me with their PhD-Scholarship. The "*click*ECM" project is supported by contract research (Glycobiology / Glycomics, grant no. P-BWS-Glyko / 09) of the Baden-Württemberg Stiftung as well as Fraunhofer Programs (Discover, grant no. 828 355).

Biomimetic Interpenetrating Polymer Network Hydrogels for 3D-Culture of Cartilage Equivalents

Contact: Lisa Sewald

Articular cartilage is distinguished in three zones that differ in composition and structural organization. This superstructure is essential for mechanical properties and is maintained by zonal chondrocyte phenotypes. 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 preparation of interpenetrating polymer network hydrogel systems, consisting of synthetic polymers and biobased polymers 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 different compositions and biomimetic zones. In this way, new functional scaffolds for 3D-culture of chondrocytes are investigated and can serve as a basis for mechanical stable cartilage equivalents.

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

Funding: PhD scholarship of the Evonik Stiftung

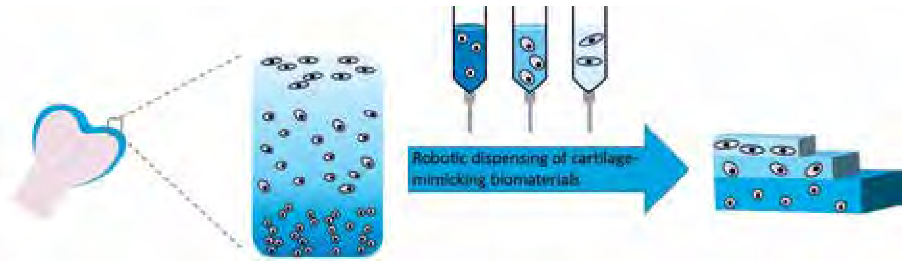


Fig. 1: Schematic representation of zonal hydrogel design as functional scaffold for cartilage tissue engineering. Three biomimetic hydrogel compositions are investigated and processed via robotic dispensing.

Hydrogels with High Biological Activity and Defined Bio-mechanical Properties

Contact: Monika Bach

Biomimetic hydrogels consist of natural or synthetic polymers. For use in tissue engineering, bioactive peptides and growth factors are integrated, which increase the bioactivity of the hydrogels. In this project synthetic hydrogels were modified with natural extracellular matrix (ECM) in order to increase their bioactivity. An azide-functionalized extracellular matrix (*click*ECM) is used as it allows to form a covalent bond between the synthetic polymer and the biopolymer using the click reaction as crosslinking reaction.

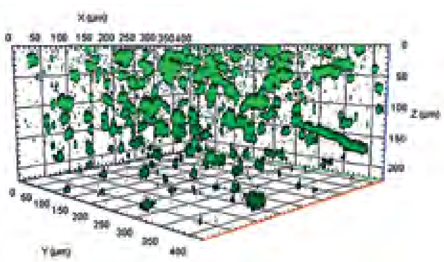


Fig. 1: *clickECM* inside hydrogel matrix; laser scanning microscopy (z-stacks).

The three-dimensional distribution of the *click*ECM within the synthetic hydrogels and the composition of the ECM were examined. It could be shown that concentrating the *click*ECM prior to integration into the synthetic hydrogel could increase the amount of proteins in the hydrogels.

The integration of the *click*ECM into the PEG-DA-hydrogels led to a significant increase in fibroblast adhesion compared to unmodified PEG-DA-hydrogels. However, a confluent cell growth was not possible. Hence, the *click*ECM has a promising potential to increase the bioactivity of synthetic polymer networks but an increase in *click*ECM protein concentration will be a key step to achieve the aim of using these hydrogels for tissue engineering applications.

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

Funding: I kindly thank the Vector Stiftung for supporting the project.

Continuous Manufacturing Process for Composite Hollow Fiber Membranes

Contact: Isabel Jesswein

Membranes with good water vapor permeability and high selectivity towards air are interesting for external humidifier 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.

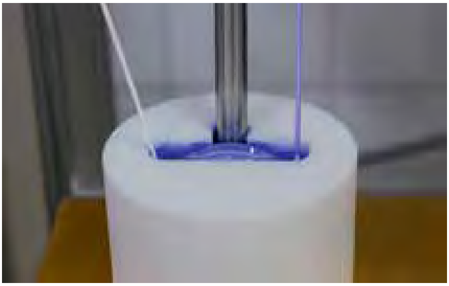


Fig. 1: Continuous dip coating of hollow fiber membrane.

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: K. Borchers, Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart

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

Bioprinting of Vascularized Bone Tissue
Contact: Annika Wenz

Bioprinting is a promising approach in bone regeneration to build up patient specific implants for treating bone defects. By extrusion-printing, suitable biomaterials and stem cells can be deposited in space-resolved 3D structures, and osteogenic differentiation of the cells then leads to the formation of bone matrix. A crucial factor in engineering bone equivalents is the implementation of a vascularization to ensure supply of the bone cells with nutrients and oxygen.

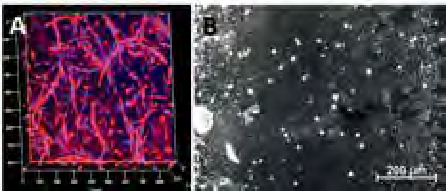


Fig. 1: (A) Formation of capillary-like structures by endothelial cells in specific hydrogel. Red: endothelial cells; blue: cell nuclei (B).

In this project, a process for building vascularized bone tissue via bioprinting is developed. Different extrudable bioinks were designed to allow either osteoblast differentiation of stem cells and bone matrix formation in the resulting hydrogels (Fig. 1A), or the development of capillary-like structures by encapsulated endothelial cells (Fig. 1B).

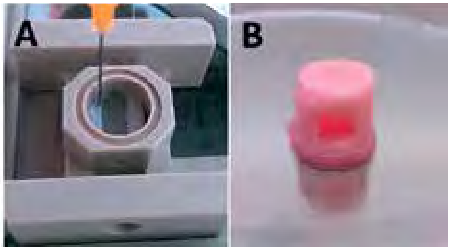


Fig. 2: (A) Extrusion-printing of bone hydrogel in perfusion bioreactor. (B) Resulting hydrogel consisting of bone (white) and vascularization hydrogel (pink).

By combining both cell types in their respective hydrogel via bioprinting, bone matrix formation and vascularization could even be reinforced. In a further step, the printing of a hydrogel construct combining osteogenic and vascular cells in a perfusion bioreactor is pursued (Fig. 2) to allow the build-up and culture of bigger constructs.

Funding: PhD scholarship of the Carl-Zeiss-Stiftung

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

Contact: Georg Umlauf

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.

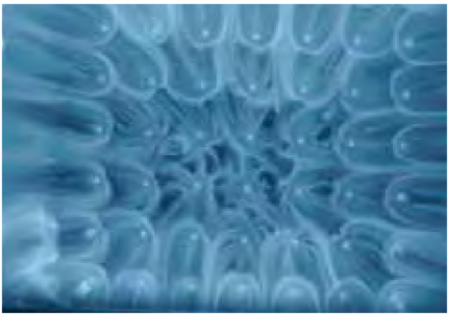


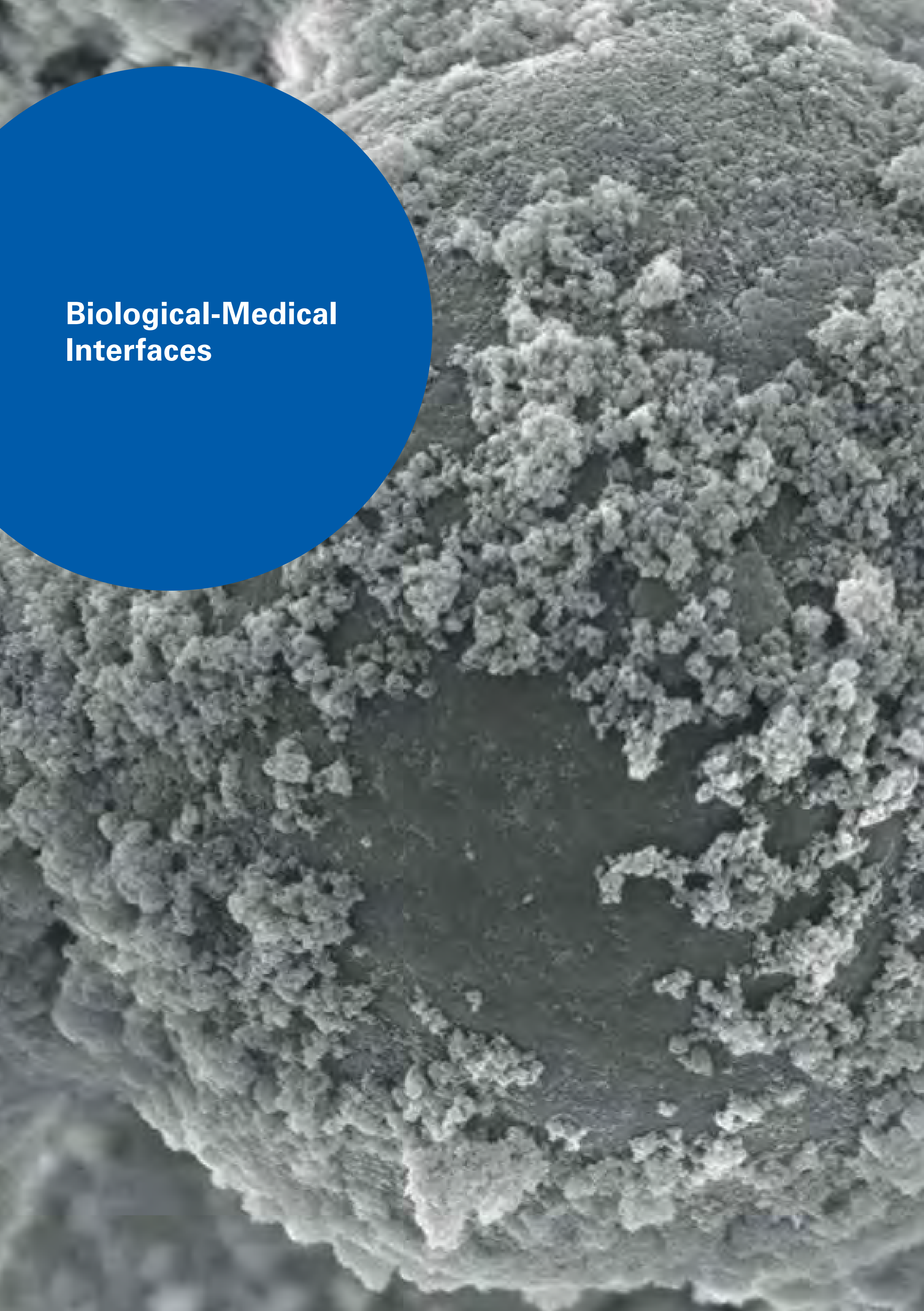
Fig. 1: Mint CO_2-outflow pattern for 7x7 microholes (diameter: 300 μm) against a borosilicate glass with 10 MPa surface pressure.

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 the 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 microhole arrangements and 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: E. Zahedi, Institut für Strahlwerkzeuge (IFSW), University of Stuttgart; C. 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”

Biological-Medical Interfaces



Research at the department of biological interfacial process engineering BGVT focuses on interactions with biological interfaces as occurring during infections of cells with viruses, bacteria and fungi. Part of the BGVT research is focused on herpesviral infections. Here, conserved and essential processes required for herpesviral propagation are analysed potentially providing novel panherpesviral drug targets. Recombinant virus engineering aims at developing innovative therapies and materials based on viruses. Finally, screening approaches facilitated by high-throughput cell-based assays and 3D tissue models are applied to identify small molecules with therapeutic potential.

Another topic of the department is the development of diagnostic methods and devices. Genome-wide methods are applied to analyze cellular and microbial systems, in particular their interaction with the environment, e.g. in infection processes. The identification of biomarkers will provide diagnostic tools to identify and follow diseases. Furthermore, DNA-microarrays are developed to diagnose diseases by a highly parallel molecular detection of various pathogens.

The Institute is also involved in investigating the potential of microorganisms and enzymes for use in industrial biotechnology. Further activities include the simulation and engineering of interfacially driven processes, e.g. in membrane technology and biotechnology. Additional topics are cell-free protein synthesis as well as synthetic biology.

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Characterization of the Herpes Simplex Virus Nuclear Egress

Contact: Susanne M. Bailer, Christina Funk, Débora Marques

The family of Herpesviruses is divided into three subfamilies alpha-, beta- and gammaherpesviruses based on characteristics such as cell tropism, pathogenicity and the site of latency. Herpes simplex virus type 1 (HSV1), a member of the alphaherpesvirus 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 at cytoplasmic membranes with the secondary envelopment of the capsids. Thus, transport of the assembled capsids from the nucleus out to the cytoplasm is a critical step of the HSV1 life cycle.

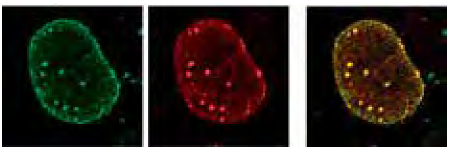

Fig. 1: Indirect immunofluorescence analysis of pUL34 (green) and pUL31 (red) expressed in HeLa cells 20 hours post transfection shows colocalization of these proteins in the nucleus.

Capsids are released from the nucleus by budding through the nuclear envelope, a process called nuclear egress. The nuclear egress complex formed between the viral proteins pUL34 and pUL31 is conserved throughout the herpesviral family and essential for viral replication and therefore represents a potential target for panherpesviral therapy. Numerous aspects of capsid nuclear egress are incompletely understood, e.g. capsid release from the site of assembly, association of viral and host proteins, and regulation of the NEC activity. State-of-the-art techniques of cell biology, biochemistry and molecular virology are performed to unravel these processes.

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

Funding: Peter und Traudl Engelhorn Stiftung; Science without Borders – CNPq

Project NanoBioMater

The Team Functional Polymers and Hydrogels, headed by Dr. Alexander Southan, links the Stuttgart University's Institute of Interfacial Process Engineering and Plasma Technology IGVP and the Institute of Organic Chemistry. In the team, the entire development process leading to synthetic functional polymers and spatially defined hydrogels is covered. The development process comprises development of functional polymers and cross-linkers, the development of new cross-linking chemistry, the formulation of hydrogels for 3D printing and the processing of spatially defined hydrogels by 3D printing (Fig. 1).

The goal of functional polymer and cross-linker development is to obtain biocompatible and biofunctional components for hydrogel formulations. Due to their excellent biocompatibility, we focus on the development of polymers which have a poly(ethylene glycol) backbone and which carry functional groups suitable for cross-linking. The polymer development deals with the synthesis and characterization of monomers as well as the resulting polymers. Additionally, we develop cross-linkers with functional groups which are complementary to the polymer-bound functional groups. The reaction of the cross-linkers and polymers results in hydrogels. Polymer and cross-linker development also is aimed at the development of systems suitable for processing of hydrogels by 3D printing.

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Surface Functionalization of Superporous Hydrogels for Additive Manufacturing

Contact: Karishma Adatia

This PhD project is focused on the development of surface functionalized, microstructured hydrogels for additive manufacturing. Therefore different narrow distributed polymers were synthesized by anionic polymerization in order to functionalize the surface of the hydrogel with defined anchor points. Afterwards the polymers were characterized by NMR, SEC, Maldi, IR, DSC, TGA and TEM, to investigate structure-property relationships and to elucidate the surface functionalization of the hydrogel.

Beyond that, a hydrogel microstructuring procedure which is compatible with additive manufacturing processes is explored, because additive manufacturing opens 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 a surface functionalized 3D microstructured hydrogel 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.

Funding: Evonik Foundation

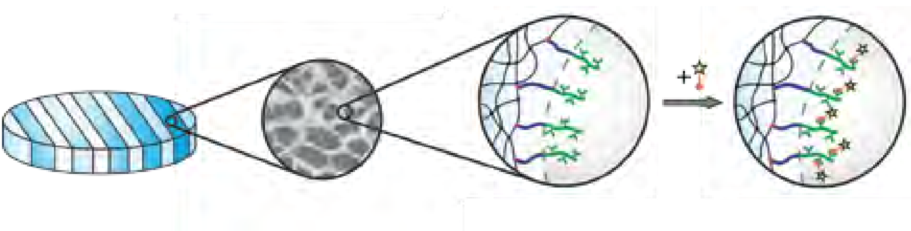

Fig. 1: Schematic depiction of the surface functionalized, microstructured, 3-dimensional hydrogel foam.

Hydrogels with Specific Charge Densities
Contact: Tobias Götz

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.

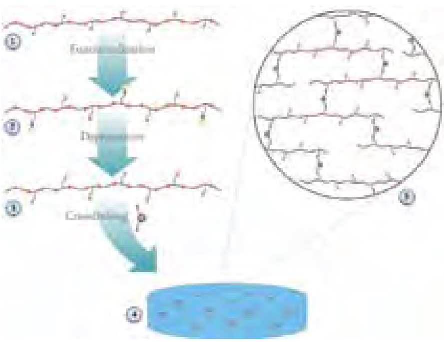

Fig. 1: (1) Allyl-functionalized polyglycerol ; (2) Side-chain functional polyglycerol with either amine or carboxy groups and photoprotected thiols; (3) Deprotection, Hydrogel formulation and cross-linking; (4) Hydrogel with specific charge densitiy; (5) Step growth network of the hydrogel.

For polycations amine groups and for polyanions carboxylic groups were chosen. Therefore the charge density in the hydrogels can be tuned by varying pH value. To prepare hydrogels one possibility for cross-linking is given by introducing thiols to prepare networks with a Michael-addition type cross-linker. These cross-linkers are able to bare a positive charge, inspired by the natural cross-linker 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; Max Planck Institute for Medical Research, Heidelberg

Funding: Baden-Württemberg Stiftung

Interfacial Processes

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 to look 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 the standard fermenter but in addition also self-developed reactor systems as flat-panel airlift reactors (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 bio-based 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.

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Process Development for the Production of Mannosylerythritol Lipids from Renewable Resources

Contact: Alexander Beck

With the increasing shortage of fossil resources our economy needs to be shifted towards sustainable resource management. Due to their low toxicity and good biodegradability, biosurfactants have recently come into focus. Here, especially mannosylerythritol lipids (MEL) are highly promising molecules that show superior performance regarding emulsification, foaming and even antimicrobial properties.

Mannosylerythritol lipids are produced by fungi of the genera *Ustilago*, *Candida* and *Pseudozyma* sp. They comprise a variety of molecules usually classified as MEL A-D due to the 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 fermentation. Characterization of the underlying biosynthetic pathways is also crucial in order to understand and enhance the MEL production in the respective microorganisms.

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

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

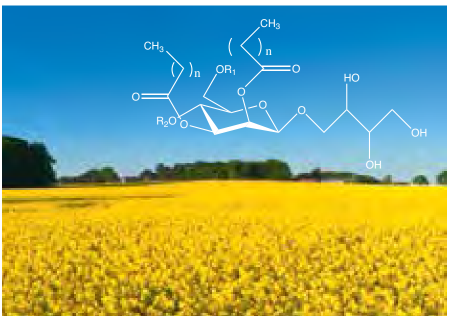


Fig. 1: Production of MEL, for example from rapeseed oil, can be performed under controlled fermentation conditions in a bioreactor.

Extraction Processes for the Cascade Utilization of Microalgae Biomass for Food and Feed Applications

Contact: Felix Derwenskus

Microalgae contain a broad range of ingredients which can be used in the food and feed sector. 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 (like 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 *P. tricornutum.*

Thus, about 90% (w/w) of accessory pigments like fucoxanthin as well as fatty acids (e.g. EPA) were successfully extracted from *P. tricornutum* by PLE. Subsequently, fucoxanthin was crystallized and purified (see figure). The extraction parameters tested in the lab can now be used to scale-up this process into technical scale. Other species like *C. vulgaris* were also extracted by supercritical fluid extraction (SFE) and thus, about 80% (w/w) of the total fatty acids could be yielded.

Collaboration: U. Schmid-Staiger, Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart

Funding: Forschungsprogramm Bioökonomie Baden-Württemberg (Az. 33-7533-10-5/93), funded by the Ministry of of Science, Research and Art Baden-Württemberg

Characterization of Microbial Dynamics in Anaerobic Biogas Production Systems

Contact: Anja Grohmann, Dieter Bryniok, Kai Sohn

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 neither well defined nor controllable.

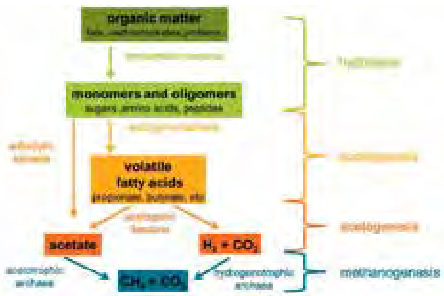


Fig. 1: Schema of the different steps in the anaerobic digestion process.

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 next-generation sequencing (NGS) technologies, to reach long reads and a high coverage, which is essential for the assembly of new 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: R. Rabus, Institute for Chemistry and Biology of the Marine Environment (ICBM), University of Oldenburg; Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB

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

Development of a Bioreactor for the Conversion of Biogas
Contact: Ilka Mühlemeier

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 project's aim is to synthesize value added products from methane using aerobic methanotrophic organisms (MOB) based on a new reactor concept. Thus, glucose can be replaced by methane as the conventional carbon source.

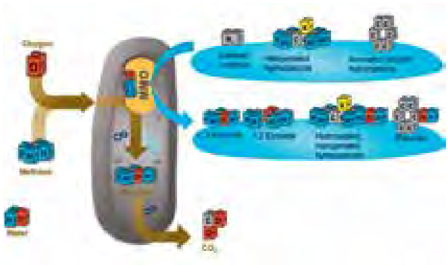


Fig. 1: Oxidation of methane to methanol as well as activation of n-alkanes by aerobic, methanotrophic bacteria.

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

Since MOB are able to activate a wide range of n-alkanes / n-alkenes, halogenated hydrocarbons and aromatic alicyclic hydrocarbons, one major goal is to investigate a sustainable way to produce precursors for the synthesis of plastics based on benzene. Therefore, several experiments concerning substrate- and product toxicity as well as the optimization of the reaction media are conducted in order to find the best conditions regarding this purpose.

Funding: Baden-Württemberg Bioeconomy Research Program (reference no. 33-7533-10-5 / 103 / 1) funded by 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

Contact: Konstantin Frick

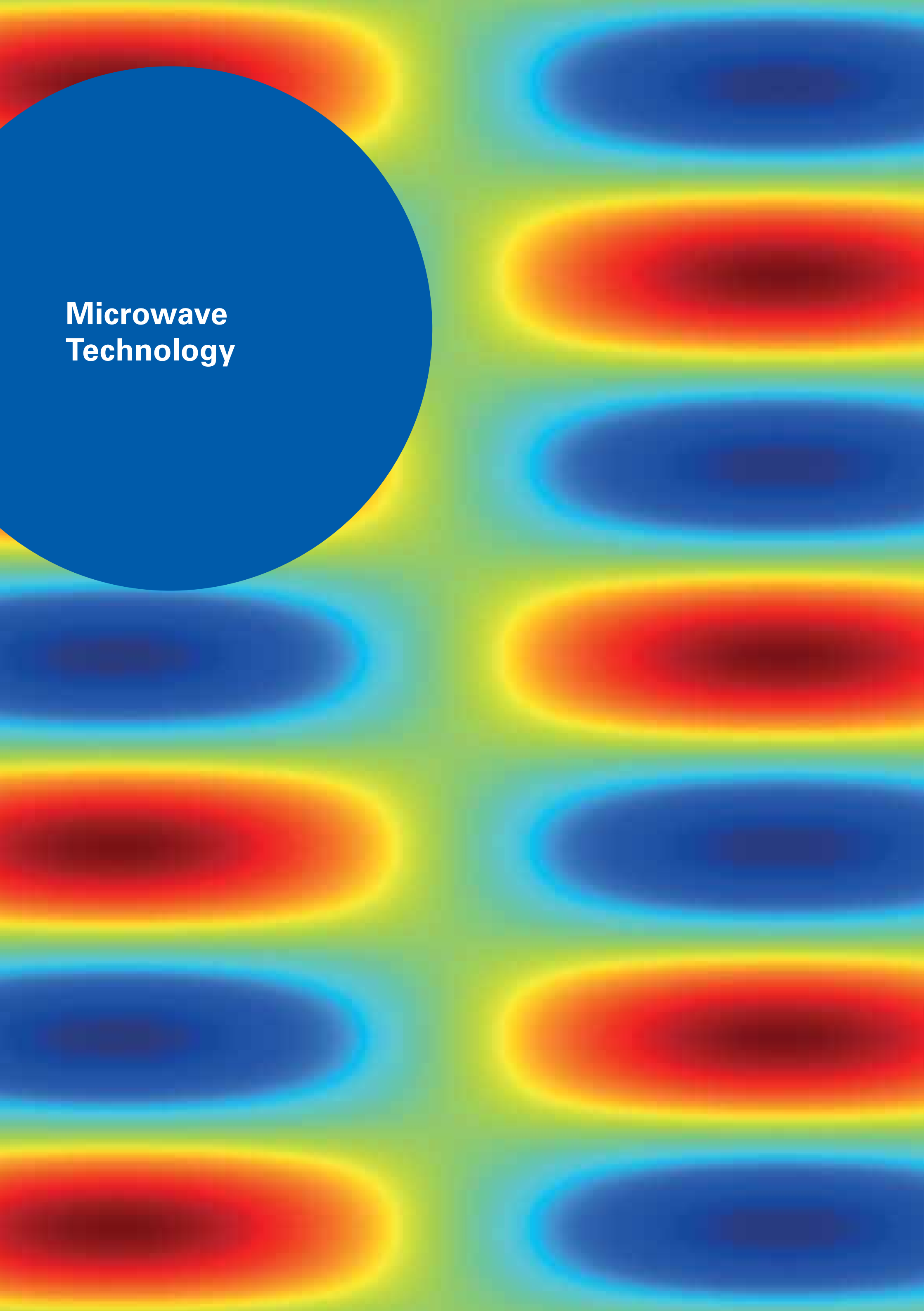
The aim of this dissertation is to establish a biotechnological process for the production and processing of laminarin derived from microalgae. The poly carbohydrate laminarin is composed of β-1,3-linked glucose molecules. It can be found in macro- and in microalgae, which use it as a storage molecule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

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: U. Schmid-Staiger, Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart

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



Microwave Technology

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.

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Microwave Technology for ECRH on ASDEX Upgrade

Contact: Walter Kasparek, Carsten Lechte, Burkhard Plaum

At IPP Garching, a new plasma heating system "ECRH-3" is installed, which consists of 4 gyrotrons (2 frequencies 105/140 GHz, power 1 MW, pulse length 10 s), individual matching optics, corrugated HE11 waveguide for transmission to the plasma, and steerable reflector antennas. IGVP contributes in the design and construction of components for transmission and related diagnostics (see also chapter on calorimetric loads and grating reflectors).

In 2015/16, novel two-frequency directional couplers, which are integrated in the surfaces of miter-bend mirrors where developed and specified. These couplers employ leaky wave antennas basically designed for 105 GHz; in addition, an amplitude grating overlaid on the hole coupling structure produces a receiver lobe for 140 GHz (Fig. 1). Thus the couplers provide power monitor signals at two frequencies with a relatively high suppression of interference from stray radiation. The figures show the design of the coupler with the calculated receiver pattern, and the measured patterns for both polarization planes.

Collaboration: J. Stober, D. Wagner, M. Schubert, F. Monaco, H. Schütz and B. Petzold, Max-Planck-Institut für Plasmaphysik (IPP), Garching

Funding: The work is performed within the collaboration with the Max-Planck-Institut für Plasmaphysik (IPP), Garching and Greifswald.

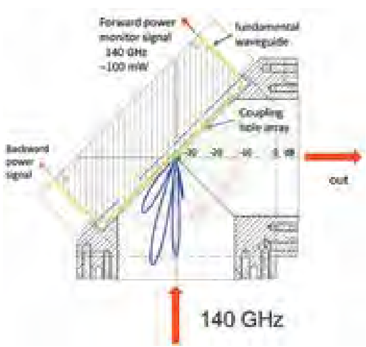

Fig. 1: Design of the power monitor integrated in a miter bend, with the 140-GHz antenna pattern of the coupling hole array. For 105 GHz, the main lobe points into the direction of the incoming HE11 mode.

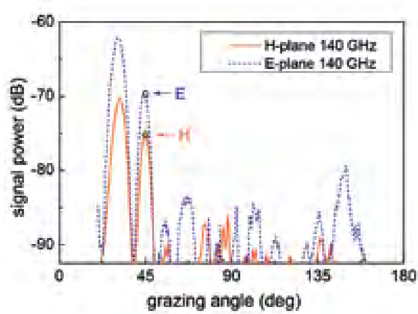

Fig. 2: Measured antenna patterns of the coupler at 140 GHz, H-plane (solid) and E-plane (dashed).

Fullwave Doppler Reflectometry Simulations for ASDEX Upgrade

Contact: Carsten Lechte

Doppler reflectometry is an important microwave diagnostic for turbulent fusion plasma. 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 fluctation 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].

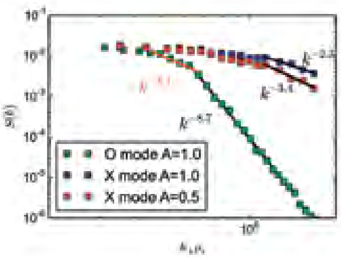

Fig. 1: Simulated wavenumber spectra from Doppler reflectometry for X and O mode, both using the same underlying density fluctuation data.

New experimental data in X and O mode polarization and accompanying plasma fluctuation data from the GENE code have been used to simulate the Doppler reflectometer response with IPF-FD3D [2]. Comparison with experimental data shows a good agreement. The data in Fig. 1 shows the big difference between O and X mode polarization. The spectrum derived from O mode scattering looks similar to the real spectrum of the density fluctatuations, albeit with power law exponent –8.7 instead of –6.7. The X mode spectrum is much more shallow. In conclusion, for X mode the density fluctuations are so large that the spectrum is non-linearly saturated, while for O mode, it is still in the linear regime.

[1] C. Lechte et al. "X mode Doppler Reflectometry k-spectral measurements in ASDEX Upgrade: Experiments and simulations" PPCF, submitted.

[2] T. Happel et al. "Comparison of detailed experimental wavenumber spectra with gyrokinetic simulation aided by two-dimensional full-wave simulations" PPCF, in review

Collaboration: G. Conway, T. Görler, T. Happel, and C. Tröster-Schmid, Max-Planck-Institut für Plasmaphysik (IPP), Garching

Funding: This work was partly performed in the framework of the Helmholtz Virtual Institute on Plasma Dynamical Processes and Turbulence Studies using Advanced Microwave Diagnostics.
The fullwave simulations were performed on Hazelhen of the High Performance Computing Centre Stuttgart (HLRS) and on bwUniCluster funded by the Ministry of Science, Research and Arts and the Universities of the State of Baden-Württemberg, Germany, within the framework programme bwHPC.

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

Contact: Walter Kasparek, Carsten Lechte, Burkhard Plaum

Collective Thomson scattering (CTS) in the millimeter wave range offers a broad range of diagnostics, e.g. for ion temperature, ion velocity distributions, magnetic field directions, and plasma waves. For the development of a CTS system at W7-X, a consortium including IPP Greifswald and Garching, DTU Risoe, and IGVP Stuttgart was established. IGVP contributes to the design of launchers and receiver antennas as well as the related transmission lines. Wherever possible, the CTS system uses components of the available electron cyclotron resonance heating (ECRH) system; especially, ECRH gyrotrons and free channels of the multi-beam waveguide (MBWG) are used. In 2016, an optical remote-steering receiver antenna for port AET10 was designed, which is matched to the waveguide remote-steering launcher on port AEN10. It is based on a double confocal imaging system, which has proven to produce minimum mode conversion loss and thus provides a large angular steering range. Investigations of a prototype are underway. The design of the transmission system and the various mirror surfaces was performed, and transferred to the engineering design. For the case that any problems with spectral purity or frequency chirp of the scattering gyrotron occur, a conceptual study on the feasibility and integration of a mode-filtering ring resonator in the generator transmission line was performed.

Collaboration: D. Moseev, H. Laqua and M. Weißgerber, Max-Planck-Institut für Plasmaphysik (IPP), Greifswald and Garching; S. K. Nielsen and F. Leipold, DTU Risoe

Funding: This work is supported by the Max-Planck-Institut für Plasmaphysik (IPP) in Garching and Greifswald.

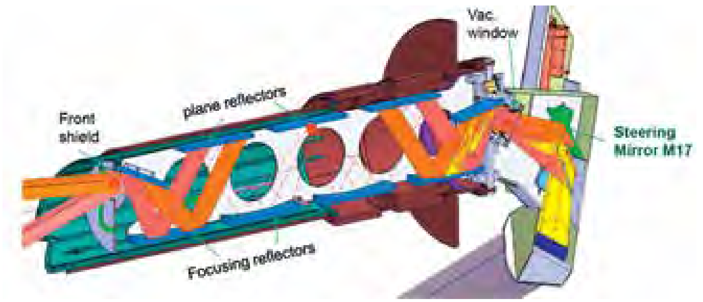

Fig. 1: Engineering design (M. Weißgerber, IPP) of the optical remote-steering receiver antenna, where steering of the scattered beam is performed by a mirror outside of the vacuum vessel.

Investigation of a Remote-Steering Antenna for ECEI and Correlation ECE

Contact: Burkhard Plaum, Daniel Iglesias

A study was performed to investigate the usability of a square corrugated waveguide as an antenna for an ECE imaging system. The idea is based on the same principles as the remote-steering antenna, which was investigated in detail for heating applications. Besides the normal operating range of the remote steering antenna, multiple additional angle-frequency combinations were found, where it can be used.

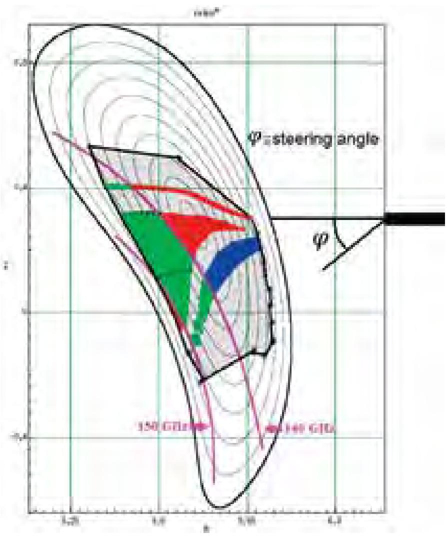

Fig. 1: Poloidal cross section at a 300° toroidal position in W7-X. 8 pairs of points (in black) are candidates for poloidal correlation ECE.

This allows the operation at different angles and frequencies simultaneously. While the view-angle of the antenna defines the direction of the radiation, the frequency of the radiation depends on the magnitude of the magnetic field. Since the profile of the magnetic field is known, the radiation received under different angles and frecuencies can be used to construct a 2D image of the electron temperature distribution.

A second application is the correlation ECE, which allows to track the movement of turbulent structures in the plasma for the investigation of the dynamic behavior. For correlation ECE, the radiation coming from two different points, which are at the same poloidal cross section and on the same flux surface, need to be detected. Additionally, if multiple such pairs exist, correlation ECE can be done for different flux surfaces simultaneously.

Collaboration: M. Hirsch and T. Windisch, Max-Planck-Institut für Plasmaphysik (IPP), Greifswald

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

Development of an Eigenmode Solver for Arbitrary Waveguide Cross Sections

Contact: Burkhard Plaum, Sander Coene

For the design and optimization of numerous microwave components, an Eigenmode solver can dramatically speed up the calculation. This is accomplished because any 2D field distribution can be expanded into a vector of amplitudes of Eigenmodes. This reduces the data size by many orders of magnitude with comparable accuracy. Especially for highly oversized waveguide components, like remote steering antennas with non-square cross sections, using Eigenmodes is the only feasible method even with todays computing capabilities. Eigenmodes are known analytically for a number of simple cross sections but in the general case they need to be calculated numerically. An Eigenmode solver was developed for the specific needs for the remote steering antenna. In particular, the accuracy of the Eigenvalues must be very high. After testing different established methods, the main challenge was to solve the problem of degenerate Eigenmodes. These Eigenmodes have identical (within the numerical accuracy) Eigenvalues and cannot easily be distinguished, but failing to do so spoils subsequent calculation because the orthogonality relation is not fulfilled. The method of fundamental solutions was implemented and extended for calculating the modal fields and separating degeneracies.

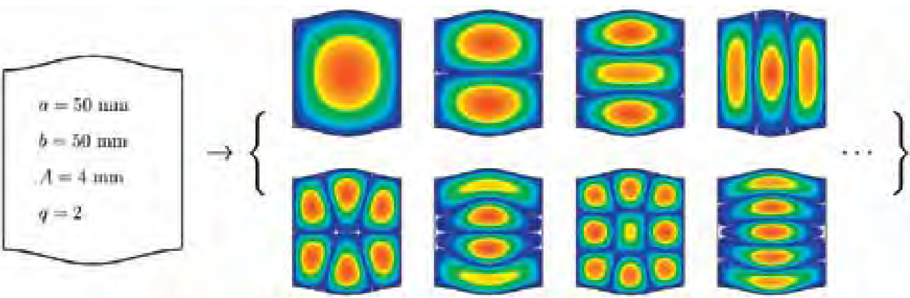

Fig. 1: Calculated Eigenmodes for a deformed waveguide cross section.

Electron Bernstein Waves Propagation in the Linear Device FLiPS

Contact: Kirill Rumintcev

Electron Bernstein Waves appear in the theoretical plasma-wave treatment when kinetic effects and background magnetic field are taken into account. For the perpendicular propagation, EBWs are not Landau damped and they do not have a high-density cutoff. These two properties make them interesting both for diagnostics and plasma heating. Electromagnetic waves can transfer their energy to the EBW through the so-called O-SX-EBW and FX-SX-EBW conversion process. The efficiency of the conversion depends on the plasma density gradient and the angle of incidence of the EM wave.

Fundamental studies of EBWs propagation are carried out in the linear magnetic field geometry of the plasma device FLiPS (Flexible Linear Plasma Stuttgart). The plasma is created by a 2.45 GHz, 4.8 kW axially propagated R-wave. The present diagnostics include an interferometer and an electrostatic probe. We also monitor the R-wave and X-wave reflection signals.

The EBWs are created through the FX-SX-B process. The X-wave is launched into the plasma with an open-ended waveguide at 2.31 GHz. The EBW wavelength and the intensity are measured by means of electrostatic probes/antennas.

A ray-tracing code which simulates EBWs propagation in the realistic FLiPS' magnetic field geometry has been developed. The simulations have shown that the EBW launched in the mid-section of the device are confined within a wave channel created by the inhomogeneous axial magnetic field. Additionally, the phase-space formalism has been successfully applied to reconstruct 2D EBW intensity distribution (Fig. 1).

Collaboration: A. Köhn, Max-Planck-Institut für Plasmaphysik (IPP), Garching

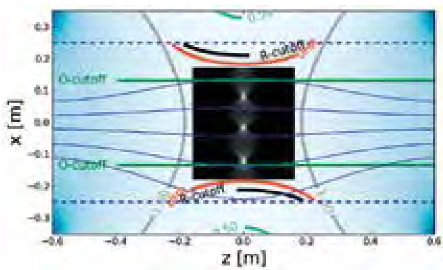

Fig. 1: Intensity of trapped EBW in the FLiPS' mid-section.

In-Vessel Reflectors for Multi-Pass ECR Heating

Contact: Burkhard Plaum

ECRH heating at higher harmonics (e.g. O2, X3) extends the operating range at the expense of a reduced absorption by the plasma. As a result, a beam with a considerable power hits the inner wall of the vacuum vessel, where it can cause a damage due to a high heat load. A solution is to place reflectors at the inner wall, which redirect the beam for a second pass through the plasma.

The design of the reflectors requires knowledge of the parameters of the incident and reflected beams, which are simulated with TRAVIS or TORBEAM. Based on the local fields on the mirror surface, an optimization code is run to obtain a grating, which maximizes the power in the wanted diffractive order. This ensures that the main power will be reflected into the right direction for the second pass. Furthermore, the phase shift between TM- and TE-polarized field needs to be minimized in order to preserve an elliptical polarization. Since the directions of the wave vectors vary across the mirror surface due to curved phase fronts, multiple grating profiles are optimized for different mirror regions and the final surface is interpolated.

Fig. 1: Inner wall of the stellarator W7-X with installed reflectors.

For W7-X, 10 reflectors were designed and manufactured from TZM. It turned out, that for 4 reflectors, a planar surface was already optimal. The others could be designed by using just 1 profile, because the phase fronts are almost planar. For ASDEX Upgrade, an interpolated mirror was designed and manufactured from graphite.

Collaboration: H. Laqua, T. Stange and N. Marushchenko, Max-Planck-Institut für Plasmaphysik (IPP), Greifswald; M. Schubert, Max-Planck-Institut für Plasmaphysik (IPP), Garching

Synthesis of Beam Shaping Mirrors for the European ITER Gyrotron

Contact: Burkhard Plaum, Carsten Lechte

For the European ITER gyrotron, IGVP contributes to the design of the matching optics unit (MOU), which consists of two mirrors and couples the beam from the gyrotron into the HE11 waveguide. Since the parameters of gyrotron output beams vary significantly between different gyrotrons, the beams are characterized thermographically and individual beam shaping mirrors are designed. There are algorithms, which can synthesize mirrors for an almost perfect HE11 field at the waveguide entrance. However, the resulting mirror surface can contain discontinuities, which make them difficult to manufacture and unusable for high power.

There are, however, simpler methods which produce more simple mirror surfaces at the cost of slightly reduced mode purity in the waveguide. The example shows the field on the first mirror (which has an ellipsoidal shape). On the second mirror, a surface is generated from the phase difference of the actual incident beam and the wanted reflected beam. The achieved HE11 mode purity at the waveguide entrance is 99.1%.

Collaboration: G. Gantenbein, Karlsruhe Institute of Technology (KIT), Karlsruhe

Funding: This work is supported by Fusion for Energy (F4E), grant no GRT-553.

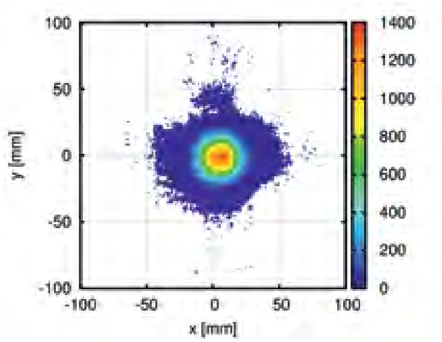

Fig. 1: Field on the first mirror based on measurements for the ITER long-pulse gyrotron.

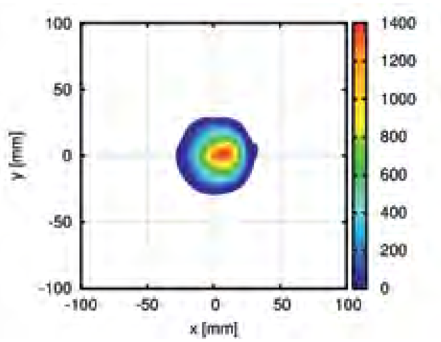

Fig. 2: Calculated field at the waveguide input after beam shaping.

Matching Optics and Diagnostics for ECRH on ITER

Contact: 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 the ITER gyrotron. The work includes the beam characterization of prototype gyrotrons at 170 GHz, the design of a matching optics unit (MOU) including power and mode monitors.

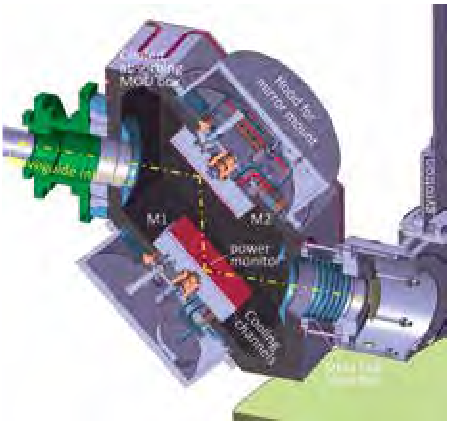

Fig. 1: Engineering design (cut through the mid-plane, T. Kobarg, KIT) of the evacuated matching optics unit for the European ITER gyrotron (at right edge of the figure).

In 2016, the work concentrated on the design of the evacuated MOU and the cooled matching mirrors. The mechanical design, which is performed at KIT, is shown in Fig. 1. The MOU includes an evacuated, cooled box made directly from a solid aluminum block, where all openings and mounts can be directly machined into the thick walls.

Absorbers on the wall and around the beam entrance reduce stray radiation in the box and the corrugated waveguide connected to the output. The two water-cooled reflectors feature 4-axes positioning, where two axes are controllable under vacuum. Various reflector surfaces were optimized and compared with respect to coupling of the gyrotron beam to the HE11 waveguide mode to be excited in the transmission line. Efficiencies of > 99% can be reached; details are given in the chapter “Synthesis of beam shaping mirrors”.

Directional couplers are integrated into the surface of the first matching reflector. A 2-channel design with sum and difference outputs allows the continuous monitoring of the power transmitted over the mirrors, and will provide an error signal in case of unwanted mode jumps of the gyrotron.

Collaboration: This work is supported by Fusion for Energy (F4E), grant no. GRT-553.

Development of High-Power Millimeter-Wave Calorimetric Loads

Contact: Walter Kasparek, Bernhard Roth, Achim Zeitler

For the test of gyrotrons in ECRH systems, high-power, long-pulse, calorimetric loads are required. Based on the successful design of a 1-MW/CW load for the ECRH-3 system at IPP Garching (test results so far: 880 kW/3 min and 1.04 MW/10 s without arcing), two new loads – a 2-MW/CW load and a compact 1-MW/1s-pulse load – have been designed and built.

The main design features have been further optimized (cf. Fig. 1). The beam concentrator at the beam input, and the conical reflector were matched to distribute the input beam power evenly on the walls of the load chamber. The structure of the absorbing meshwork from water-flushed Teflon hoses was improved to maximize the average absorption. Moreover, the structure is designed such that reflected microwaves are directed into the azimuthal direction, to avoid loss via the input aperture and thus to maximize multi-pass absorption of the residual power. Both types of loads apply highly turbulent water flows to suppress the boiling of the water in the tubes.

The 2-MW/CW load employs 36 parallel tubes with a total flow of 660 l/min, to limit the temperature rise of the water at nominal parameters to 40°C. The load was recently delivered to W7-X at IPP Greifswald and preliminarily tested with 900 kW for 100 s.

Fig. 1: 2-MW/CW load, with the outer shells removed, showing the twisted double layer of Teflon hoses with the conical reflector behind, and the water manifold on the right.

The pulsed loads are designed for minimum water flow of 40 l/min. Four Teflon hoses are twisted 3-dimensionally to maximize the water volume in the load, and thus the thermal capacity for long-pulse operation. Four of these loads are in fabrication; they will be used for commissioning and testing of the gyrotrons in the ECRH-3 system at ASDEX Upgrade.

Collaboration: J. Stober and D. Wagner, Max-Planck-Institut für Plasmaphysik (IPP), Garching; H. Laqua and T. Stange, Max-Planck-Institut für Plasmaphysik (IPP), Greifswald

Funding: The work is performed within the collaboration with the Max-Planck-Institut für Plasmaphysik (IPP), Garching and Greifswald.

Fullwave Simulations of Miter-Bend Polarizers for ASDEX Upgrade

Contact: Carsten Lechte, Walter Kasparek

High-power electron cyclotron resonance heating (ECRH) systems for fusion plasma applications are capable of transmitting multi-megawatt millimeter wave beams across some hundred meters with low losses and controlling a prescribed elliptical wave polarization. One such system at the ASDEX Upgrade tokamak uses overmoded circular corrugated waveguides for transmission of up to eight 1-MW beams at 140 GHz. Since overmoded waveguides need to be straight, any bends are formed as miter bends utilizing flat mirrors. The first two mirrors also act as polarizers. Traditionally, such two-mirror polarizers have $\lambda/4$ and $\lambda/8$ deep sinusoidal grooves to effect a phase change between the E and H polarized parts of the incoming wave.

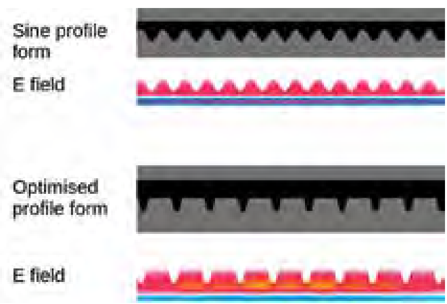

Fig. 1: Groove profiles of sine and optimized profiles, and electric field for illumination with a gaussian beam.

The smooth sinusoidal groove shape is suited to the high power densities (400 MW/m^2), but simulations show that rounded rectangular grooves with slim ridges have lower ohmic losses (Fig. 1).

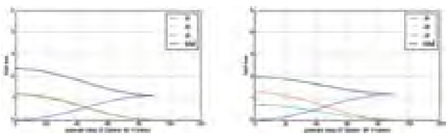

Fig. 2: Simulated losses of sine (left) and optimized (right) profiles, normalized to a flat mirror; the mirror plane is (x,y)

Fullwave 3D simulations (with IPF-FD3D) of the losses at sinusoidal an optimized groove shapes, together with measurements, have been conducted. Fig. 1 shows the losses of the two groove shapes normalized to the losses of a flat mirror. The grooves are parallel to the incident plane, and the linear polarization was varied from E to H plane. The optimized grooves for this $\lambda/8$ depth show a reduction of the losses on the order of 20%. The optimized profile will be manufactured and measured in 2017.

Collaboration: D. Wagner, Max-Planck-Institut für Plasmaphysik (IPP), Garching

Multiport Coupler

Contact: W. Alexander Zach, Walter Kasparek, Burkhard Plaum

For electron cyclotron resonance heating (ECRH) in ASDEX Upgrade, gyrotron beams with about 1 MW power at 140 GHz are guided by waveguide transmission lines into the plasma vessel to be absorbed by the plasma. Due to the high power these transmission lines need to have a diameter of multiple wavelengths ($r > 10\lambda$). This however allows for the propagation of unwanted higher order modes with comparably high losses. The preferred hybrid mode LP_{01} (or HE_{11}) should be almost solely excited. Therefore, alignment of the gyrotron beam with respect to the waveguide entrance as well as the waveguide run itself is a crucial point.

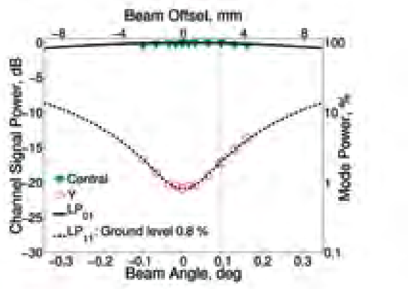

Fig. 1: Coupler output for an interferometric setup as a result of tilting the alignment mirror M3.

A set of directional couplers located in a miter bend mirror in the transmission line allows for in-situ real-time detection of the modes most likely to be excited by small misalignments ($LP_{11,even}$ and $LP_{11,odd}$), and beam mismatch (LP_{02}), as well as the main transmission mode (LP_{01}).

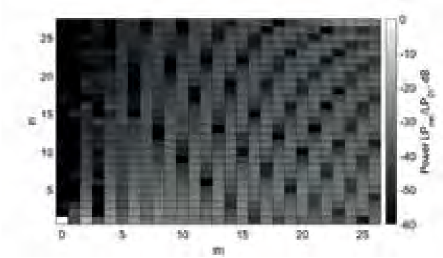

Fig. 2: Suppression of signals from high-order modes by the mode-matched coupling array with respect to the power monitor signal from LP01.

The basic working principle and high power capability could be proven in experiments at IPP Garching with a simplified interferometric setup, as seen in Fig. 1. A new prototype is being manufactured featuring two kinds of mode-matched hole-array couplers. One suppresses the coupling of LP0n and asymmetric higher-order modes (Fig. 2). The other kind isolates the LP_{02} mode by 1st order hole coupling towards a second channel.

Collaboration: J. Stober, F. Monaco and H. Schütz, Max-Planck-Institut für Plasmaphysik (IPP), Garching; H. Idei, Kyushu University

PROFUSION Code Development

Contact: Burkhard Plaum

The PROFUSION code (Programs for multimode analysis, simulation and optimization) is constantly extended and enhanced as requested by other projects. In 2016, multiple features were implemented to improve the synthesis of beam shaping mirrors for gyrotron beams and the optimization of corrugated wave bends.

A major ongoing activity is the design and optimization of specialized reflection gratings. While existing codes could verify the optimization principle, a new framework is developed, which is more flexible regarding different surface shapes and supports parallelization. For basic 3D geometry calculations, a new library was written, which simplifies operations involving vectors, lines and planes. Based on this, a number of basic routines were implemented for the calculation of local wave-vectors of microwave beams as well as fundamental parameters of diffraction gratings.

Furthermore, the fitting program for Gaussian beams was enhanced. It is used frequently to analyze measured fields or to numerically characterize the beam parameters of broadband antennas. An important parameter is the mode purity, which is percentage of power in the fundamental TEM00 mode with the fitted parameters. Also important, however, is the residual field, which is the sum of all higher order modes. This field can now be extracted and it allows the characterization of unwanted effects, like side-lobes or cross polarized components.

Collaboration: J. Stober, F. Monaco and H. Schütz, Max-Planck-Institut für Plasmaphysik (IPP), Garching; H. Idei, Kyushu University

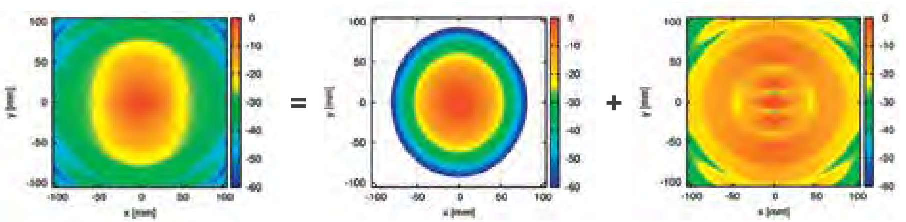

Fig. 1: Decomposition of a complex field pattern into a fundamental Gaussian beam and higher order modes.

Remote-Steering Launchers for ECRH on W7-X

Contact: Carsten Lechte, Walter Kasparek, Burkhard Plaum

The stellarator Wendelstein 7-X, recently gone into operation at IPP Greifswald, has a multi-megawatt microwave heating system at 140 GHz. In addition to the front-steering launchers, which have steerable mirrors on the front near the plasma, there are 2 remote-steering lauchers (RSL1 and RSL5) where the beam is created away from the device and transmitted to the plasma by an oversized imaging waveguide. The waveguides were designed at IGVP and manufactured by the industrial partners under the project FORMIK3.

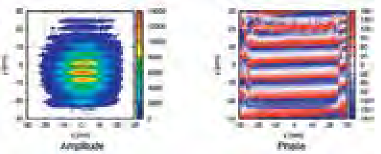

Fig. 1: Near field measurement of the output beam at steering angle 12.7°

The low-power characterization of the imaging qualities via high-resolution scanning of the near field of the RSL output is shown in Fig. 1 for a steering angle of 12.7°. The phase front on the right has a tilt of 12.6°, in excellent agreement with the desired angle. The amplitude plot of the beam shows an interference pattern with an overlayed beam that is tilted to other way. This is caused by stray radiation which amounts to only a few percent of the full power. The beam is also shifted downwards by 5 mm. Extensive analysis has shown that, due to the internal corrugation, the effective electric length of the waveguide is slightly too short. This effect was compensated by a modification of the beam steering mechanism, and thus does not diminish the usable steering range. The internal corrugation also causes a rotation of the polarization. Fig. 2 shows the expected and the measured cross polarization. In the relevant steering angle range from 0 to 17°, the effect is easily compensated by leading the input polarization.

High-power tests and first application in Wendelstein 7-X are planned for 2017.

Collaboration: V. Erckmann und H. Laqua, Max-Planck-Institut für Plasmaphysik (IPP), Greifswald; M. Weißgerber, Max-Planck-Institut für Plasmaphysik (IPP), Garching; 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.

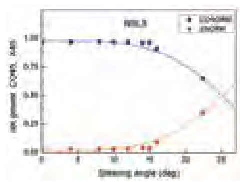

Fig. 2: Co- (CO) and cross- (X) polarization measurement for RSL5 with empirical overlay.

Plasma Dynamics and Diagnostics

Fundamental studies of waves in and confinement of magnetized plasmas are carried out at the torsatron TJ-K and the tokamak ASDEX Upgrade at the Max-Planck-Institut für Plasmaphysik (IPP) in Garching. Furthermore, plasma diagnostics such as laser-induced fluorescence and probes are developed for the application in fusion and low-temperature plasmas.

The torsatron TJ-K at IGVP is a small fusion experiment operated with a low-temperature plasma. The reduced temperature enables probe measurements inside the core of a toroidally confined plasma with high temporal and spatial resolution. At the same time, the dimensionless parameters, which govern plasma turbulence, are similar to those in the edge region of fusion plasmas. Therefore, the experiments conducted at IGVP are relevant for fusion plasmas, too.

Turbulent transport and confinement are key issues in fusion research. Confinement studies at IGVP concentrate on understanding the microscopic properties of turbulent transport. Multi-probe arrays have been developed to measure the fluctuations of the plasma parameter in two-dimensional planes with high temporal resolution. The experimental results are compared with high-level turbulence codes, where the probe arrays are realistically simulated.

The investigation of plasma waves is focused on the propagation and the absorption of the electron-cyclotron wave as well as on Alfvén waves, which are either externally excited or detected as an element of the parallel dynamics of drift-wave turbulence. Electron-cyclotron-resonance heating is one of the major heating schemes for fusion plasmas (see Microwave Technology).

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Numerical Investigation of Microwave Propagation in TJ-K

Contact: Lennart Bock, Gabriel Sichardt, Eberhard Holzhauer

The plasma of the stellarator TJ-K allows electron cyclotron radiation to propagate through the whole torus via multiple reflections and to be detected with a dedicated diagnostics. In a first step, a 2D full wave simulation was used to analyze microwave propagation in both, toroidal and poloidal cross section. Plasma density profiles and magnetic background fields were chosen to correspond to the experimental parameters. The simulation incorporates the geometry of the receiver system including an antenna at the outer port and a reflecting mirror on the inside wall of the torus. Different geometrical configurations were simulated to optimize the weighting function of the receiving system. Furthermore, the importance of the resonator geometry of TJ-K with its highly reflective walls was investigated.

In a next step, the simulation geometry was extended to 3D and implemented in the IPF-FD3D code in order to cover the full toroidal geometry of the stellarator for analyzing the weighting function to its full extent. It is planned to examine the resonator properties of the system with respect to its Q factor and to consider density fluctuations.

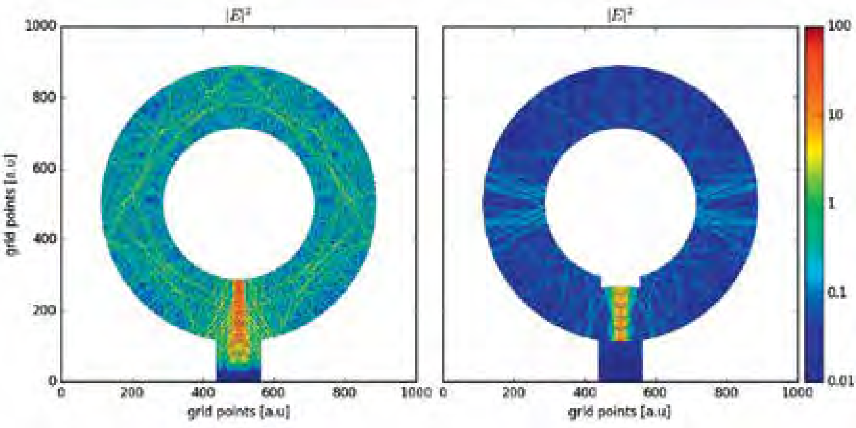

Fig. 1: Weighting function from a 2D run in the toroidal cross section including the antenna at an outer port without a mirror (left) and with a mirror (right). For a Gaussian beam with a frequency of 16 GHz the weighting function with the mirror is mostly pronounced between antenna and mirror, in contrast to the configuration without a mirror.

Scaling of Zonal Flow Power with Shearing Rate

Contact: Rafael Carmona, Til Ullmann, Mirko Ramisch

The study of zonal flows (ZF) has a great interest within the field of nuclear fusion, since these low frequency shear flows play a very important role in improved magnetic plasma confinement.

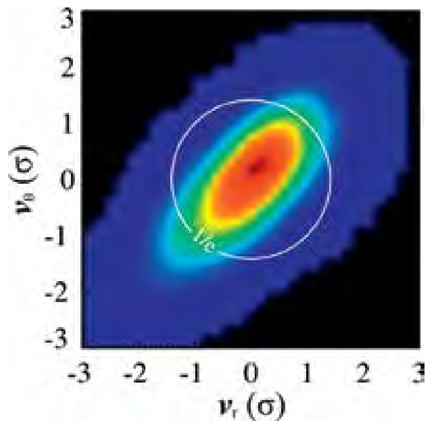

Fig. 1: 2D probability density function (PDF) of perpendicular velocities where the mentioned asymmetry is strongly present. The 1/e level corresponds to the one of a normal Gaussian distribution (by courtesy of B. Schmid).

These flows are driven by gradients in turbulent Reynolds stress $R = \langle \tilde{v}_r \tilde{v}_\theta \rangle$, which measures the asymmetry in the distribution of perpendicular velocity components. Correspondingly, a non-vanishing R, as demonstrated in Fig. 1, reflects an average vortex tilt in the turbulent fluctuations. Thus, an already present background shear flow is expected to favour the zonal flow drive by tilting eddies.

In this work, the dependence of ZF amplitude on background ExB flow shear is investigated. To this end, the shearing rate of radially localized, stationary poloidal ExB flows is controlled via external plasma biasing. Different types of biasing electrodes are employed. Radial profiles of the ExB flow are measured by means of a movable emissive probe. At the same time, fluctuations in plasma density and potential are acquired using a poloidal Langmuir probe array, whose 64 pins are situated on one magnetic flux surface in the shear region. 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 detected, experimentally, and correlated with background flow shear.

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

The Influence of Magnetic Field Curvature on n_e Intermittency

Contact: Stephen Garland, Mirko Ramisch

The influence of magnetic field curvature on the level of intermittency of density fluctuations has been investigated using a poloidal array of 64 equally spaced, flux surface aligned, probes, located just inside the separatrix. One way of determining the degree of intermittency of a time series $f(t)$ is by evaluating high order structure functions, $S_q(\tau) = \langle (f(t+\tau)-f(t))^q \rangle$, with $q \in \mathbb{R}$, and looking for power law scaling with the time delay between points, $S_q(\tau) \sim \tau^{\zeta_q}$. In practice, such a power-law scaling can be obscured by undulations in the structure functions. This problem can be overcome by using the method of extended self-similarity (ESS), which proposes that these undulations are equivalent in all structure functions and therefore can be eliminated by plotting all structure functions against S_3. 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.

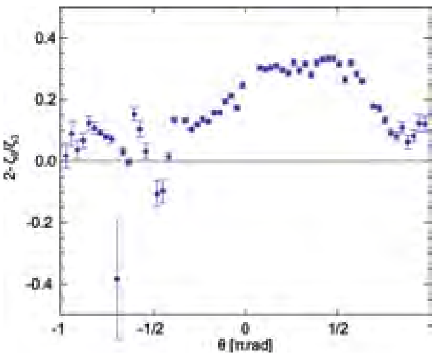

Fig. 1: The deviation of the exponents of the sixth order normaliszed structure function, ζ_q/ζ_3, from the non-intermittent reference value of 2, as a function of the poloidal angle θ for a hydrogen plasma.

This quantity as a function of the poloidal angle θ is shown in Fig. 1. The poloidal variation of the degree of intermittency of density fluctuations exhibits a maximum above the mid-plane, between $\theta = 0$ and $+\pi$. This coincides with the region where the normal curvature is negative, and the geodesic curvature is positive. Simulations including a geodesic curvature component will be carried out to determine if this is the expected trend.

Collaboration: P. Manz, Technical University of Munich

Funding: Max-Planck-Institut für Plasmaphysik (IPP), Garching; Max-Planck-Institut für Plasmaphysik (IPP), Greifswald

Drift Wave Turbulence in Regions of High Local Magnetic Shear

Contact: Stephen Garland, Mirko Ramisch

The influence of local magnetic shear on drift wave turbulence has been investigated using a 2D scanning probe and the conditional averaging technique. Previous measurements using a poloidal array of equidistant Langmuir probes measuring the ion saturation current, $I_{\mathrm{i,sat}}$, showed decreases in the poloidal correlation length, l_θ, in regions characterized by high local magnetic shear, as can be seen from the upper plot in Fig. 1. The poloidal probe array measures in one dimension, and therefore, it isn't possible from this analysis to determine what exactly happens to the drift waves in these regions; are they tilted, do they become elongated, or do they reduce in size overall?

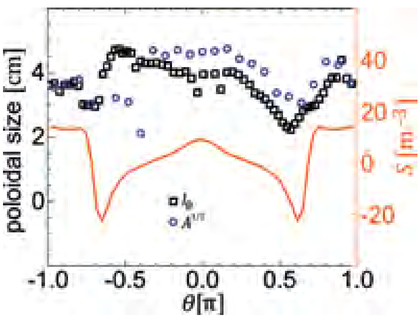

Fig. 1: The poloidal drift wave size as a function of poloidal angle θ. Size is measured using two different methods, resulting in a poloidal correlation length, l_θ, and the typical drift wave length scale determined from the conditionally averaged drift wave area, A. The local magnetic shear, S, is plotted in red.

To answer this question, 2D Langmuir probe measurements were made in a poloidal cross section and the conditional averaging technique was employed to obtain the average 2D fluctuations corresponding to high amplitude drift waves. The drift wave bounding contour was taken to be at $max\,(I_{\mathrm{i,sat}})/e$, where $max\,(I_{\mathrm{i,sat}})$ is the local maximum in the drift wave structure. A strong resemblance is seen between $A^{1/2}$ and l_θ, indicating that the reduction in correlation length in the high shear regions is due to a reduction in drift wave cross sectional area. This result agrees with expected damping of drift waves in regions of high local magnetic shear. In addition, investigations suggest that there is little influence of the local magnetic shear on the ellipticity and tilt of drift wave structures in the poloidal cross- section.

Collaboration: G. Fuchert, Max-Planck-Institut für Plasmaphysik (IPP), Greifswald

Funding: Max-Planck-Institut für Plasmaphysik (IPP), Garching; Max-Planck-Institut für Plasmaphysik (IPP), Greifswald

Determination of Magnetic Field Direction using O-Mode Interaction with the RH-Cutoff

Contact: Eberhard Holzhauer

A plasma slab with a radial density gradient and a horizontal magnetic field represents a simple geometry well suited to benchmarking the full-wave code. An electromagnetic wave with O-mode polarization will pass through the right-hand (RH) cutoff without reflection, preserving its polarization. Angular misalignment of the emitter antenna with respect to the value predicted from theory results in the partial reflection of the X-mode component. Thus, an angular sweep of the antenna identifies the angle of minimum reflection from the RH-cut-off. In an experiment this method can serve to diagnose the orientation of the confining magnetic field with respect to the antenna aperture.

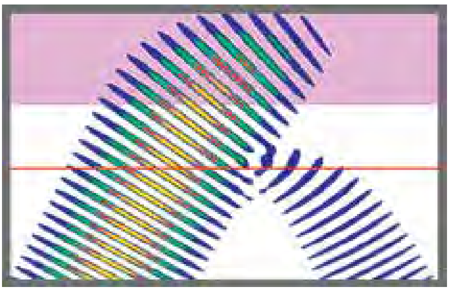

Fig. 1: Transmitter beam pattern and reflected power in the antenna plane: Only positive values of the electric field pattern are shown. The dotted regime shows the absorber region. The emitter antenna is misaligned by 5 deg. The X-mode component of the antenna beam is reflected from the RH-cutoff (horizontal red line). The amount of reflected power is 0.45%. For perfect alignment the reflected power drops by almost 2 orders of magnitude indicating the sensitivity of the method.

The IPF-FDMC-Code is used to explore the applicability of this method. The calculations confirm that the amount of reflected power is a sensitive measure of the angular misalignment. Finite beam size of the emitter antenna results in a diverging beam with X-mode components. These are also reflected from the RH-cutoff and thus can partially mask the position of the minimal reflected power needed for optimum alignment. These calculations are performed for the simple slab geometry so they may serve to benchmark similar calculations performed with the WKBeam code at IPP Garching.

Collaboration: A. Köhn, Max-Planck-Institut für Plasmaphysik (IPP), Garching

Collisionality Dependence of Intermittency in Plasma Fluctuations

Contact: Kyle Reuther, Stephen Garland, Mirko Ramisch

In the hydrodynamic limit the collisionality c is infinitely high, $c \rightarrow \infty$. In this limit, the density is passively advected in the turbulent flow field and simulations have shown that it behaves intermittently. In the adiabatic limit, $c \rightarrow 0$, on the other hand, the density couples to the plasma potential and is not expected to behave intermittently.

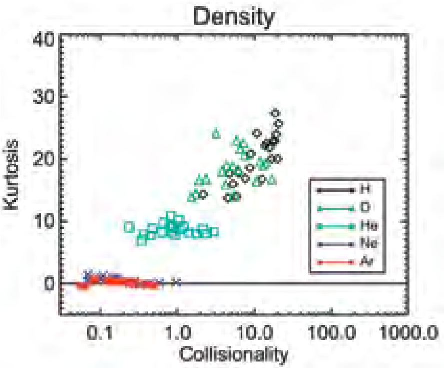

Fig. 1: The kurtosis of $I_{\mathrm{i,sat}}$ signals, filtered at a characteristic frequency using a wavelet transform, as a function of plasma collisionality.

This result has been tested experimentally in TJ-K. Collisionality was varied over 3 orders of magnitude by varying the gas type, neutral gas pressure, and heating power. Langmuir probe ion saturation current measurements at the plasma edge were taken and a scale separation in frequency space was performed using a wavelet decomposition. In order to compare data with different experimental parameters, frequencies were normalizsed to c_s/L_n, where c_s is the sound speed and L_n the density gradient length scale, resulting in a characteristic frequency f_c. A time series was taken to be intermittent if its kurtosis increased with f_c. The kurtosis at a given f_c was then selected as an indicator of the degree of intermittency (the higher the kurtosis, the higher the level of intermittency). The result of this analysis is shown in Fig. 1. A general trend of increasing intermittency with collisionality can be seen, in line with expectations from simulations, although it should be noted that in the case of Ar and Ne, no intermittency seems to be present.

Collaboration: P. Manz, Technical University of Munich

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

Poloidal Reynolds Stress Asymmetry

Contact: Bernhard Schmid, Mirko Ramisch, Ulrich Stroth

The poloidal dependence of the Reynolds stress and the connected zonal flow drive have been studied at the stellarator experiment TJ-K. Measurements with a poloidal probe array, which consists of 128 Langmuir probes with 32 probes on each of four neighbouring flux surfaces, were carried out in the triangular cross section of the plasma.

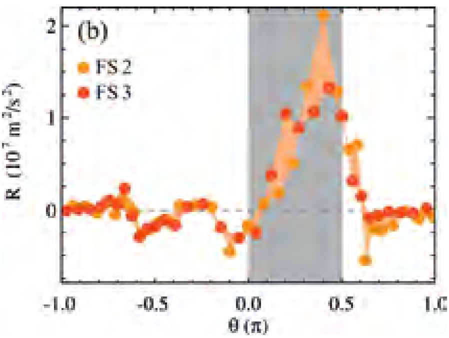

Fig. 1: The poloidal profile of the Reynolds stress $R(\theta)$ on the two neighbouring flux surfaces (FS2 and FS3) is presented. The Reynolds stress is non-zero on the outboard side and is strongly asymmetric.

The probe configuration allows to measure the Reynolds stress and its radial gradient over the whole poloidal circumference. This gives the unique possibility to study the locality of the Reynolds stress in a complex toroidal magnetic geometry. It is found that the Reynolds stress is not homogeneously distributed along the flux surface but has a strong poloidal asymmetry where it is concentrated on the outboard side with a maximum above the midplane. The average tilt of the turbulent structures is thereby reflected in the asymmetry of the probability distribution function of the perpendicular velocity components. Using a conditional averaging technique the temporal dynamics reveal that the zonal flow drive, which is the radial Reynolds stress gradient, is also maximal in this particular region.

The results suggest an influence of the magnetic field line curvature, which controls the underlying plasma turbulence. The findings are a basis for further comparison with turbulence simulations in 3D geometry where a direct magnetic field dependence could be studied.

Collaboration: P. Manz, Technical University of Munich

Funding: Max-Planck-Institut für Plasmaphysik (IPP), Garching; Max-Planck-Institut für Plasmaphysik (IPP), Greifswald

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

Contact: Gabriel Sichardt, Eberhard Holzhauer, Burkhard Plaum, Mirko Ramisch

A diagnostic system analyzing electromagnetic radiation generated by the gyration of electrons (electron cyclotron emission, ECE) is being set up at the stellarator TJ-K. This non-invasive diagnostics promises to deliver electron temperature profiles along the line of sight, time-resolved electron temperatures and detection of non-thermal electrons.

A new in-vessel antenna has been designed and optimized numerically for the relevant frequency range using the PROFUSION simulation package. Due to this optimization an enhancement of the signal strength is expected and the optimization data was used for full wave simulations. The new antenna is now mounted directly on the vacuum vessel which improves the reproducibility of measurements.

The vessel geometry of TJ-K favors multiple reflections of microwave radiation inside the torus. Full wave simulations show that a mirror opposite the antenna concentrates the sensitivity region of the receiving system well, i.e. between antenna and mirror. Further simulations have been conducted using the optimized parameters of the antenna and a representative TJ-K plasma density profile resulting in the optimal mirror curvature in horizontal and vertical direction.

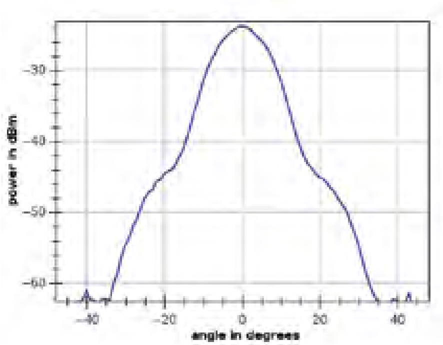

Fig. 1: Measured antenna pattern of the new in-vessel antenna for 14 GHz. The pattern shows good symmetry and about 20 dB between the main lobe and the not very pronounced side lobes.

The new receiving system is expected to open the way for localized measurements of the microwave radiation emitted by the electrons, to reduce previous uncertainties from antenna adjustment and to provide information about the system's response with respect to emission in the ECE frequency range of TJ-K.

Collaboration: A. Köhn, Max-Planck-Institut für Plasmaphysik (IPP), Garching

Funding: Max-Planck-Institut für Plasmaphysik (IPP), Garching; Max-Planck-Institut für Plasmaphysik (IPP), Greifswald

Simulation of Electron Trajectories in TJ-K for Toroidal Net Current Investigations

Contact: Gabriel Sichardt, Mirko Ramisch

Along with temperature measurements, the electron cyclotron emission measurement system for the stellarator TJ-K is designed for the detection of non-thermal electrons. Previous measurements have revealed the existence of toroidal net currents in TJ-K while their generation mechanism has not yet been fully explained. A possible source of a toroidal net current in a stellarator relies on the dependence of electron drift orbits on the velocity orientation within the magnetic field geometry. Therefore, drift orbits of non-thermal electrons are investigated numerically.

Simulations using the guiding center approximation have been shown to match full trajectory simulations within the expected range of a Larmor-radius even for velocities up to 0.83 c in TJ-K's geometry. As a result of this agreement, the guiding center approximation is employed for the drift orbit investigations providing the possibility to simulate electron trajectories in reasonable computational time. The simulation program has been extended to run in parallel in order to cope with large numbers of electrons.

Currently, first simulations with a Maxwellian velocity distribution are conducted. As a next step, a perturbed Maxwellian velocity distribution with an additional small population at high energy representing non-thermal electrons will be used. These simulations are meant to show whether the dependence on direction of electron drift orbits can explain the observed toroidal net currents.

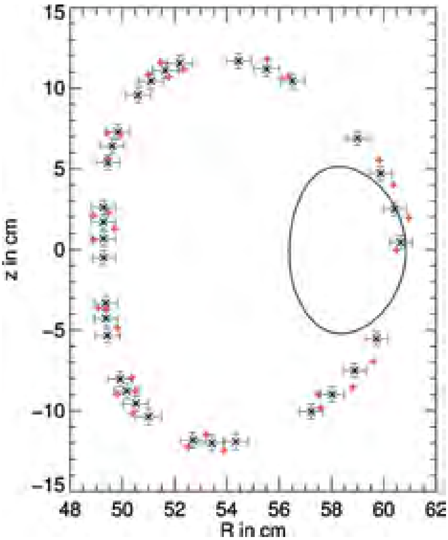

Fig. 1: Electron drift orbit in the guiding center approximation (black ×) with Larmor radius as error bars, drift orbit from full trajectory simulation (red +) and flux surface (black solid line) in the extreme case of 415 keV ($2.5 \cdot 10^8$ ms^{-1}).

Funding: Max-Planck-Institut für Plasmaphysik (IPP), Garching; Max-Planck-Institut für Plasmaphysik (IPP), Greifswald

Identification of the Generating Mechanism for Microwave Radiation at TJ-K

Contact: Gabriel Sichardt, Eberhard Holzhauer

Plasmas generally emit microwave radiation, which can serve as a non-invasive diagnostic. In the stellarator TJ-K, microwave radiation in the frequency range relevant for the electron cyclotron emission (ECE) diagnostic was investigated with respect to its generating mechanism. As possible candidates, Coulomb bremsstrahlung and ECE were examined. In case of ECE the emitted power density per frequency interval and solid angle is proportional to electron density n_e and the square of the electron temperature T_e. Coulomb bremsstrahlung shows a proportionality to n_e^2 and is inversely proportional to $T_e^{1/2}$.

A measurement campaign covering more than 80 different plasma configurations differing in neutral gas pressure, gas type and heating power was conducted to examine the dependence of the emitted power. The emission at the fixed frequency of 16.1 GHz was compared to density and temperature values obtained from Langmuir probe measurements. In conclusion, the results agree well with the model for electron cyclotron emission.

Collaboration: A. Köhn, Max-Planck-Institut für Plasmaphysik (IPP), Garching

Funding: Max-Planck-Institut für Plasmaphysik (IPP), Garching; Max-Planck-Institut für Plasmaphysik (IPP), Greifswald

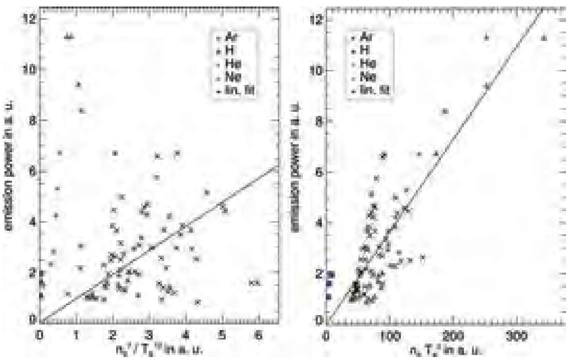

Fig. 1: Emitted power at 16.1 GHz for different gases, neutral gas pressures and heating powers against the expected proportionality for bremsstrahlung (left) and ECE (right). In case of accordance with theory, a linear curve is expected. For ECE a quasi-linear behavior with a variance of 1.55 is seen. In case of bremsstrahlung with a variance of 7.2 no linear trend is seen.

The Dependency of Turbulent Transport on Shear Flows

Contact: Til Ullmann, Mirko Ramisch

Poloidal E×B shear flows play a crucial role in the reduction of radial turbulent transport $\Gamma = \langle \tilde{v}_r \, \tilde{n} \rangle$. Theory predicts a reduction of Γ with the shearing rate Ω according to $\Gamma \propto \Omega^{-4}$ on a rational surface, where a magnetic field line is closed after m toroidal and n poloidal turns. In detail, the transport can be described by the real part of the cross-power spectrum of radial potential and density fluctuations, and factorized into cross-amplitude $h_{\phi n} \propto \Omega^{-3}$ and cross-phase $\sin \delta_{\phi n} \propto \Omega^{-1}$ contributions. At a location close to the rational surface, the predicted Ω-dependence of Γ drops to $\Gamma \propto \Omega^{-1}$.

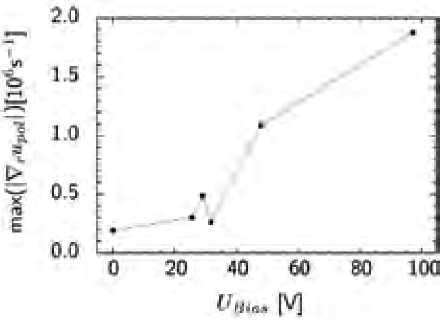

Fig. 1: Behavior of the flow shear in dependency of the bias voltage. In general, the shearing rate increases with the bias voltage. Discontinuities may result from transitions in the equilibrium.

In order to test the transport's shearing rate scaling, plasma biasing via a ring electrode, biased positively with respect to ground, is used at TJ-K for controlling the shearing rate of imposed stationary flows. The applicability of this method could already be demonstrated (see Fig. 1): Ω generally increases with the bias voltage. Possible transitions in the equilibrium need to be identified for detailed scaling studies in a next step. Then, the cross-field transport will be measured with a poloidal 64-pin probe array. Stationary poloidal shear flows are determined from measurements of radial potential profiles, for which movable, swept and emissive electrostatic probes are used. Spectral contributions to turbulent transport will be correlated with the deduced shearing rate and compared to theoretical predictions.

Collaboration: A. Köhn, Max-Planck-Institut für Plasmaphysik (IPP), Garching

Funding: Max-Planck-Institut für Plasmaphysik (IPP), Garching; Max-Planck-Institut für Plasmaphysik (IPP), Greifswald

Plasma Technology

The division plasma technology works on the development of new micro-wave-generated plasma sources at low pressure and atmospheric pressure, the characterisation 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 utilised 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 characterisations of insulating layers, O_2- and H_2O-permeation barriers, or scratch protection layers, and the sterilisation 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. It 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.

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Diagnostic and Modelling of a Microwave Plasma Torch at Atmospheric Pressure

Contact: 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 plasma model was set up which contains balance equations to describe the electron and particle densities as well as the electron energy. In addition, a set of reaction mechanisms was chosen to represent an argon plasma. The effect of a changing electron density distribution on the electric field was calculated by means of the Drude theory.

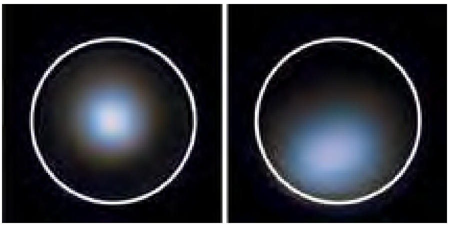

Fig. 1: Left: Plasma with tangential gas supply in the center of the tube. Right: Plasma without tangential gas

The simulations resulted in a maximum electron density in the range of 1020 m^{-3}, which is in good accordance to experimental values. Furthermore the results show the plasma sticking to the wall of the confining quartz tube, which faces the incoming microwave.

In contrast, the plasma in the experiment is usually found in the center of the tube. This is supposed to be an effect of a rotational gas flow enveloping the plasma which has not yet been considered in the simulation. To verify the direct correlation between the tangential flow and the position of the plasma, qualitative experimental investigations were carried out. These confirm that the rotational gas flow prevents the hot plasma from touching and damaging the wall of the quartz tube (see Fig. 1, left). But as soon as the gas supply is switched off, the plasma shifts towards the wall (see Fig. 1, right). This behavior corresponds very well to the simulation results.

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

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

Studies on the Gap Penetration for the Surface Activiation of Polystyrol in Medical Engineering

Contact: Miriam Kahlert, Andreas Schulz, Matthias Walker

In medical engineering there is often the need to improve the cell adhesion on polymer surfaces for example in tissue engineering. Therefore the surface can be activated with plasma processes increasing the surface energy. The activation improves the wettability to fluids like nutrient solutions for biological cultures. On plain objects there is an equal distribution of the activation, whereas on objects with a wall or with small diameters it dependents on the gap penetration of the plasma.

Medical petri dishes are often used for cell cultures. Although they have a small wall of about 14 mm the experience shows that the influence on the surface conditions is huge. To investigate in which way the height of the wall had an influence on the gap penetration of the plasma, the geometry of the petri dishes were transformed into a model, where the heights of the wall can be varied. The petri dishes consisting of polystyrol were activated in the Duo-Plasmaline with an argon plasma for 1 second. Directly afterwards the contact angles on different positions of the sample were measured with different measuring fluids. Fig. 1 shows the trend of the contact angle of glycerin on the side wall of the petri dish.

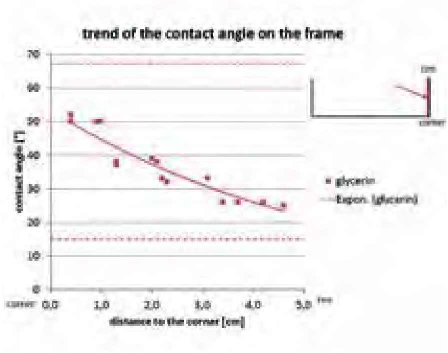

Fig. 1: Trend of the contact angle of glycerin on the side wall of a petri dish. The measuring points are fitted with a compensation curve. The dashed lines show the minimal and maximal values for the contact angle of glycerin on an untreated and a 1 second treated flat substrate.

The contact angles in the corner are higher than on the rim, due to the decreasing gap penetration of the plasma.

Sterilization of Spice Powders with a Dielectric Barrier Discharge

Contact: Stefan Merli, Andreas Schulz,
Matthias Walker

Spice powders often exhibit contamination with germs during manufacturing, storage and processing or due to the natural contamination of the raw material. In the dried state, these pathogens can survive for a long time and can have serious health consequences during the preparation of food. Common methods for sterilization, such as hot steam sterilization, are technically complex and lead to a loss of flavorings.

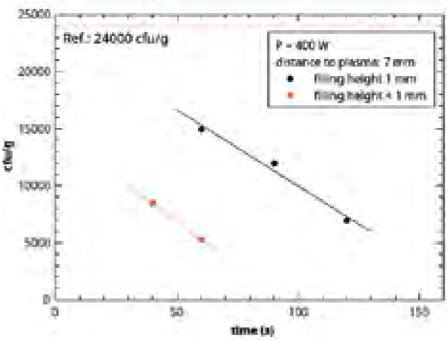

Fig. 1: Sterilization kinetics over the treatment time at two filling heights of the powder.

In this project, a mild decontamination method using a dielectric barrier discharge (DBD) is investigated. The DBD is a non-thermal plasma whose gas temperature is close to room temperature, which allows a mild treatment of the spice powders. The sterilizing effect is based on the reactive species generated in the plasma, such as oxygen radicals, ozone, nitric oxides as well as UV radiation, which damage the cell walls or the DNA of the germs and thus kill the pathogens.

Different DBD configurations were developed and their sterilization effectivity was investigated. With this, a reduction of the germ load from 10^6 cfu/g to < 10 cfu/g could be achieved in 120 s on contaminated cellulose test stripes. When treating the spice powders, the power of the plasma, the treatment time, the distance to the plasma and also the singling of the powder were identified as important parameters for the effectivity. Fig. 1 shows the sterilization kinetic over the treatment time and at different filling heights. All in all, a reduction of 3 orders of magnitude of the colony forming units could be achieved so far.

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

Funding: German Federal Ministry of Education and Research (BMBF)

Setup and First Investigations of a Low Pressure Microwave Plasma Source for High Rate Etching

Contact: Steffen Riegger, Andreas Schulz, Matthias Walker

In the "Semiconductor Frontend" a low pressure microwave plasma source is used for chamber cleaning. The plasma source is a Remote Plasma Source (RPS) where the plasma is generated and exists only in the chamber of the RPS. Only radicals escape out of the RPS. Thats why the RPS is used for etching processes where ion bombardement and high thermal strain is unwanted. The etching process is a chemical process, where the radicals react with the substrate surface atoms forming gaseous molecules. The benefit is a damage-free substrate surface.

For the investigation the RPS is connected to the top plate of our Plasmodul. In addition to the top plate, the Plasmodul consists of further modular components. The bottom plate includes a quartz glass window for spectroscopic investigations. Between is a modular part with windows to observe the etching processes and a module which contains the substrate holder. The whole plant contains several flanges to connect messuring units to research the etching process.

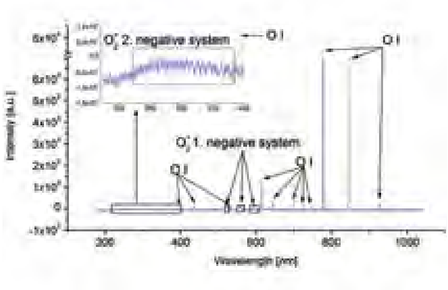

Fig. 1: Spectrum of the oxygen plasma used in this work.

The spectrum of the oxygen plasma (Fig. 1), which is used here, shows the typical 777 nm and 844 nm atomic oxygen lines. In the UV-area are several molecule bands which belong to the O_2^+-2nd negative system $A^2\Pi_u$–$X^2\Pi_g$. In addition, between 500 nm and 600 nm molecule bands which belong to the O_2^+-1nd negative system $b^4\Sigma_g^-$–$a^4\Pi_u$ can be observed.

Spectroscopic Study of a DBD-Discharge for Waste Gas Treatment

Contact: Andreas Schulz, Stefan Merli, Matthias Walker

Biological sources of air pollution like animal farms, food processing, sewage and waste handling industries are of increasing concern as the risks posed by the pollutants from these sources are understood more profoundly. The current method investigates the possibility of using a low temperature plasma to treat pollutant gases. Multiple parallel powered steel electrodes separated by ceramic plates to create a dielectric barrier discharge was set up at IGVP.

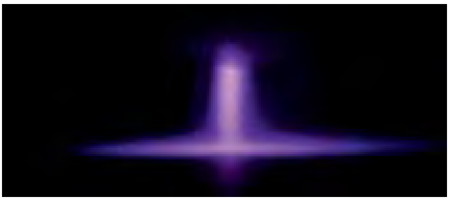

Fig. 1: Single discharge filament of a DBD.

A dielectric barrier discharge (DBD) in air is typically formed by an ensemble of micro-discharges. To study the formation, shape and spectral composition of the micro-discharges, a single discharge filament was split off in small bypass electrodes. Fig. 1 shows a discharge filament burning between a spherically formed metal electrode (top) and a flat ceramic barrier (below). Spectroscopic investigations show that the blue-violet light emission origins from the 2nd. positive system of the N_2 molecule $C^3\Pi_u$ to $B^3\Pi_g$ [1]. The 2nd positive system can be observed radiantly due to the very short lifetime of $3.8 \cdot 10^{-8}$ s of the $C^3\Pi_u$ state [2]. All other excited states relax by collisions with other molecules, for example to generate oxygen radicals by the reaction:

$N_2(B^3\Pi_g) + O_2 \rightarrow N_2(X^1\Sigma_g^+) + 2\,O\cdot$

The ion component of the plasma can be observed by only one transition of the 1st negative system of the N_2^+ molecule ion:

$B^2\Sigma_u^+ - X^2\Sigma_g^+$

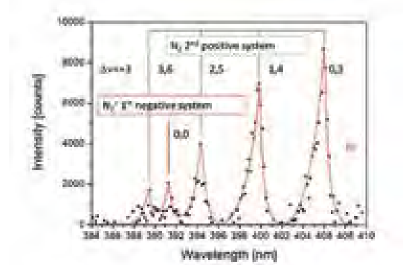

Fig. 2: Spectrum of a DBD air discharge.

In Fig. 2 the spectral region from 384 nm to 410 nm shows between the N_2-bands the very weak $\Delta n = 0$ vibrational transition of the N_2^+-band at 391.44 nm.

[1] R.W.B. Pearse and A.G. Gaydon, London, New York, 1976.

[2] Alf Lofthus and Paul H. Krupenie, J. Phys. Chern. Ref. Dato, Vol. 6, No. 1, 1977

Funding: German Federal Ministry of Education and Research (BMBF)

CO_2-Based Test for the Detection of Defects in Oxygen Barrier Layers

Contact: Mariagrazia Troia, Andreas Schulz, Matthias Walker

The barrier performances of plasma-deposited thin films are severely limited by the presence of punctual micro- and submicro-metrical defects. In order to determine their density in silica-like barrier layers, their origin and contribution to the overall oxygen transmission rate, a new test for their detection has been developed and optimized: a polyethylene terephthalate foil, coated with the barrier to be tested, is interposed between a pure CO_2 atmosphere and a limewater solution: the CO_2 permeates first through the defects in the barrier layer, causing the in loco formation of calcium carbonate crystals:

$$Ca(OH)_2 + CO_2\,(\uparrow) \xrightarrow{H_2O} CaCO_3\,(\downarrow) + H_2O\ ;$$

Subsequent investigations by means of optical and scanning electron microscope allow their surface density to be calculated. The latter's trend shows a very good accord with the one for oxygen transmission rates for all the investigated oxygen-to-precursor ratios. Best barrier layers show a reduction in defects density of around 40 and a barrier improvement factor of 50. Similarly, bad barrier layers show crystal densities close to those of uncoated PET foils, with a barrier improvement factor of only 1.1.

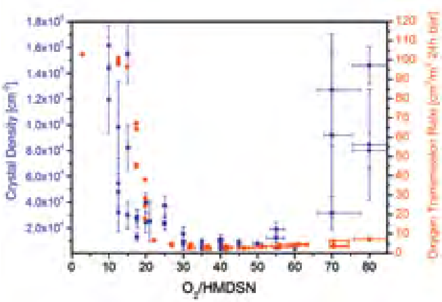

Fig. 1: Numerical crystal densities (blue) and normalized oxygen transmission rates (red) for different oxygen-to-monomer ratios in plasma feed for the deposition of silica-like barrier films.

Shape and size of $CaCO_3$ crystals also show a tight correlation with the barrier properties of the investigated samples.

Polymeric Films as Organic Buffers in a Multi-layered Plasma-Deposited Encapsulation of OLEDs

Contact: Mariagrazia Troia, Andreas Schulz, Matthias Walker

In order to improve the performances of barrier films for organic devices, polymeric layers are often interposed between the proper barrier ones (see Fig. 1), in order to decouple the punctual defects that limit the latter's performances and increase the diffusion length for the permeand gas (Vitex® technology). The first organic layer also shields the sensitive device from harmful atomic oxygen in the plasma during the barrier deposition step.

Organic layers of different compositions have been deposited from different hexamethyldisilazane (HMDSN) and H_2 feeds by means of an Electron Cyclotron Resonance low-pressure plasma. The films have been subsequently etched in a pure oxygen plasma for different times, and their residual thicknesses and chemical composition (IR absorbance analysis) have been evaluated. The same procedure has been then repeated for the same organic films, this time coated by very thin barrier layers. Further comparison of the two sets of IR analysis allowed to quantify the damage sustained by organic layers during the barrier deposition step.

The results allowed to find the optimal HMDSN / H_2 feed to produce an organic layer that can resist to the oxygen etching effect and provide at the same time the required minimum shielding of the underlying organic device.

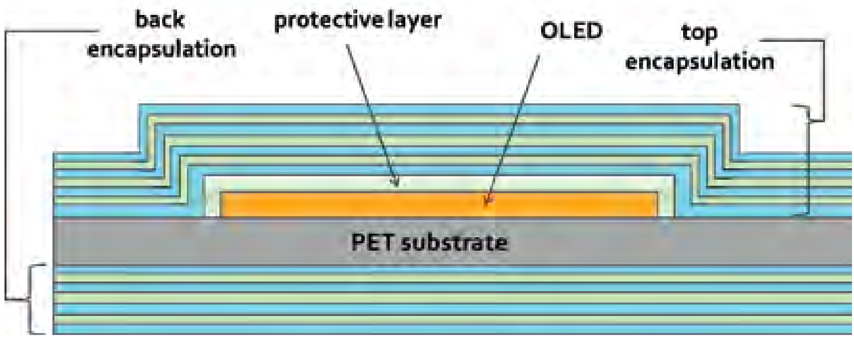

Fig. 1: Schematic of a multilayer encapsulation (top and back) of an organic light-emitting device and its substrate.

Thickness Optimization of Plasma-Deposited Oxygen Barrier Layers for Bendable OLEDs Encapsulation

Contact: Mariagrazia Troia, Andreas Schulz, Matthias Walker

Active layers and electrodes in OLEDs are quickly degraded by oxygen and water vapor, thus requiring the highest degree of protection amongst electronic devices. Silica-like layers with a barrier improvement factor of more than 50 have been deposited by means of an Electron Cyclotron Resonance low-pressure plasma. Hexamethyldisilazane (HMDSN) was employed as precursor and mixed with O_2. Gas feed have been studied and optimized, with the optimal oxygen / monomer ratio found to be equal to 40:1. A study of the barrier performances of such thin films vs. their thickness has thus been performed.

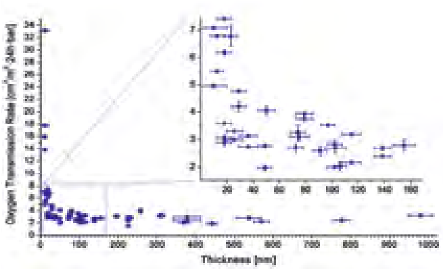

Fig. 1: Normalized oxygen transmission rate as a function of film thickness for silica-like, plasma-deposited barrier coatings with an oxygen / monomer ratio of 40.

As shown in Fig. 1, the resulting oxygen transmission rates show a sharp decrease after only 40 nm (corresponding to a stable film), reaching a steady value that remains practically constant – albeit limited by the presence of punctual defects in the film – for almost two orders of magnitude, up to 1 micron. Films also showed a very good adhesion to the polymeric substrate and a high tolerance to several cycles of compressive / tensile stresses. By comparison, most of the plasma-deposited barrier layers present an upper limit around a few hundred nanometers after which the internal stress in their volume becomes too much, causing the film to crack and to lose all its barrier properties.

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Bachelor-, Master-, Diploma Theses, and Student research studies

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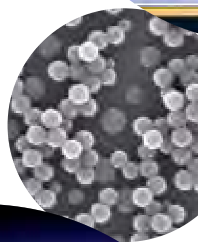

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