BIENNIAL REPORT 2020/2021

LEIBNIZ INSTITUTE FOR PLASMA SCIENCE AND TECHNOLOGY

INP

FROM IDEA TO PROTOTYPE

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LEIBNIZ INSTITUTE FOR PLASMA SCIENCE AND TECHNOLOGY

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Plasma technology is a key technology that is making an important contribution to solving the overall social challenges of our time. As part of the Leibniz Association, it is important for the INP not to conduct research as an end in itself but also to keep an eye on the application and thus the usefulness for people in all projects.

In our two research divisions "Materials & Energy" and "Environment & Health", many exciting results have been achieved in 2020 and 2021. Excerpts of these are presented in this report. I would like to draw particular attention to the EU project "HiPowAR", which is exploring the use of ammonia as a synthetic fuel without CO_2 emissions. In the outlook, you will learn more about the agricultural applications of plasmas as well as their use as a possible key technology for the energy transition. You will also learn about our latest joint project "biogeniV" in which we are developing innovative technologies for the use of biogenic residues as part of the "WIR!" funding programme of the Federal Ministry of Education and Research.

The COVID-19 pandemic has also had a major impact on the work processes in our research institute. Prolonged periods of lockdown with mobile working, restricted lab operations, digital project meetings, and limited travel were both a technical and mental challenge for our scientists as well as our supporting departments such as "Administration and Infrastructure". In addition, the INP was evaluated by the Leibniz Association during this period. This evaluation procedure, which is unique in the German research landscape, regularly reviews the member institutions with regard to research quality, strategy, and working conditions.

We have managed to survive the pandemic and the evaluation quite well. I would therefore like to take this opportunity to express my sincere thanks to our employees at all locations. It is thanks to your dedicated efforts that we can present the wide range of applications for plasma technology on the following pages. I hope you enjoy reading it.

Prof. Dr. Klaus-Dieter Weltmann
Chair of the Board and Scientific Director

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Foundation stone for "FAIR" research data in application-oriented plasma research

In December 2020, Dr. Steffen Franke and Dr. Markus Becker from the Leibniz Institute for Plasma Science and Technology (INP) in Greifswald and Prof. Deborah O'Connell from the York Plasma Institute (YPI) in the UK published a unified meta-data scheme for describing research data from the field of plasma physics in the Springer Nature Journal "Scientific Data": https://rdcu.be/ccqQx .
They are thus the first to publish a scheme of this kind for research purposes in the field of plasma technology.

The authors aim to provide a means of describing extraordinarily heterogeneous research data in plasma physics. This will make it possible to filter out specific data from large amounts of data according to defined selection criteria (e.g. research data on experimentally determined plasma properties of plasma sources).

* FAIR stands for Findable, Accessible, Interoperable, Reusable.

INP Chair of the Board and Scientific Director is honoured with "Macher30 – der Ehrenpreis des Ostens"

In September 2020, the Chair of the Board and Scientific Director of INP, Prof. Klaus Dieter Weltmann, was awarded the "Macher30 – der Ehrenpreis des Ostens" in the category Science. "From idea to prototype" is the INP mission statement, which was initiated and considerably influenced by Prof. Dr. Weltmann. The strategic reorganisation of the institute that he initiated in 2003 is the main reason for the current success of the INP. Results include new scientific impulses such as plasma medicine, successful knowledge and technology transfer in the form of a spin-off concept, and a strong industrial funding rate. Macher30 is an initiative of the Verein Berliner Kaufleute und Industrieller (VBKI), the Ostdeutscher Bankenverband (OstBV), Egon Zehnder International (EZI), and the European School of Management and Technology (ESMT Berlin). Companies or projects led by the "Machern" should originate in the new federal states and have a supraregional impact. The eleven-member jury recognised Prof. Dr. Klaus-Dieter Weltmann's commitment to the East German location with its award.

EU research project "HiPowAR" launched: Ammonia as a synthetic fuel without CO_2 emissions

Together with the Hydrogen and Fuel Cell Center (ZBT) and the Fraunhofer Institute for Ceramic Technologies and Systems (IKTS), the Politecnico di Milano from Italy, PBS BRNO from the Czech Republic, and Ranotor from Sweden, the INP will develop a new membrane reactor for the direct energy conversion of renewable ammonia fuel into electricity. Compared with combustion engines and steam power plants, the membrane reactor converts energy more efficiently. This would be a breakthrough in the direct conversion of ammonia as an easily storable, carbon-free hydrogen carrier into usable energy. Although the design of the membrane reactor is quite similar to that of a fuel cell, it is simpler and less expensive than, for example, the solid oxide fuel cell (SOFC), which can also be used to directly convert ammonia into electricity. The project thus makes an important contribution to zero-emission shipping, aviation, and heavy-duty sector without CO_2 emissions. The project is funded under the Horizon 2020 research framework programme of the EU and started in 2020.

INP spin-off Nebula Biocides GmbH receives Leibniz Start-up Prize

The latest spin-off of the INP, the Nebula Biocides GmbH, was one of two winners of the Leibniz Start-up Prize in March 2021. The founders – Dr. Jörn Winter, Dr. Ansgar Schmidt-Bleker, and Prof. Dr. Klaus-Dieter Weltmann – developed a highly effective disinfectant that works against both stubborn bacterial spores and resistant viruses within 30 seconds. In particular, Clostridioides difficile spores are completely inactivated. If the new disinfection process is used on a large scale, the risk of infection (e.g. in hospitals) can be considerably reduced. The prize is endowed with € 50,000 and is awarded every year by the Leibniz Association for start-up projects that stand out through their achievements in developing innovative and viable business ideas.

Contribution of the INP to the "National Hydrogen Strategy" of the BMBF

Together with the Hydrogen and Fuel Cell Center (ZBT) in Duisburg and Inherent Solution Consult GmbH & Co KG in Rostock, the INP coordinates the research and development activities for technologies to implement the entire transport chain for green ammonia as part of the lead project TransHyDE of the "National Hydrogen Strategy" of the BMBF. At the Poppendorf location on the YARA Rostock industrial site, industry-relevant test and trial fields are being set up for the new technologies in the COIL – CAMPFIRE Open Innovation Lab. The focus is on the development of logistics structures and fuelling facilities for ammonia import and the operation of ships with green ammonia, load-flexible ammonia plants for the seasonal production of ammonia from renewable energy, and dynamic conversion technologies for stationary and mobile energy supply as well as ammonia-to-hydrogen fuelling stations.

Double award for plasma medicine researchers from Greifswald

Prof. Dr. Thomas von Woedtke, member of the Board of Directors and research programme manager at the INP, was awarded the "Plasma Medicine Award" of the "International Society for Plasma Medicine" (ISPM) at the "8th International Conference on Plasma Medicine (ICPM-8)". Every two years, selected researchers are recognised for their scientific achievements in the field of plasma medicine. After the award in 2013 to Prof. Dr. Klaus-Dieter Weltmann (INP) and in 2018 to Prof. Dr. Dr. Hans-Robert Metelmann (University Medicine Greifswald) this is the third time that the "Plasma Medicine Award" has gone to Greifswald, thereby underlining the importance of Greifswald as a science location for this medical research field.

Dr. Sander Bekeschus, head of the "Plasma Redox Effects" research group at the INP, was also recognised for his work. He received the "Early Career Award in Plasma Medicine". In this category, Dr. Bekeschus convinced the international jury with his innovative plasma-medical research work over the last 10 years and publications in top-class specialist journals.

Image of the future Centre for Life Science and Plasma Technology (Z4) in Greifswald. Completion is scheduled for 2023.

As a result of numerous projects, the Leibniz Institute for Plasma Science and Technology (INP) has proven that there is great economic potential in plasma technology applications and that innovative solutions to socially relevant problems can be found. We work closely with industry and other research institutions. The cooperation with research institutions from other fields of expertise and partners from industry form decisive key elements for future projects. The following examples should provide a small insight into our research spectrum for the coming years.

Key technology for the energy transition

Together with the Leibniz Institute for Catalysis (LIKAT, Rostock) and the Fraunhofer Institute for Large Structures in Production Engineering (IGP, Rostock), we at the INP want to play a pioneering role in the development of cost-effective and effective hydrogen technologies. With the support of the Ministry of Economic Affairs, Infrastructure, Tourism and Employment of Mecklenburg-Western Pomerania, we will establish the "Hydrogen Research Factory MV", which aims to develop new technologies for the economic production of hydrogen (H_2), ammonia (NH_3) and CO_2-neutral carbon-based fuels (e.g. synthetic methanol or green paraffin) in the Rostock region as well as the efficient practical application of these. Among other things, the INP focuses on plasmalysis processes. Because the efficiency losses are lower than for conventional electrolysis processes, these plasmalysis processes are an economically promising alternative for the production of green hydrogen. For example, plasmalysis processes require only one fifth of the necessary electrical renewable energy compared with electrolysis and thus represent an important key technology for increasing emission-free H_2 generation as well as providing urgently needed green carbon.

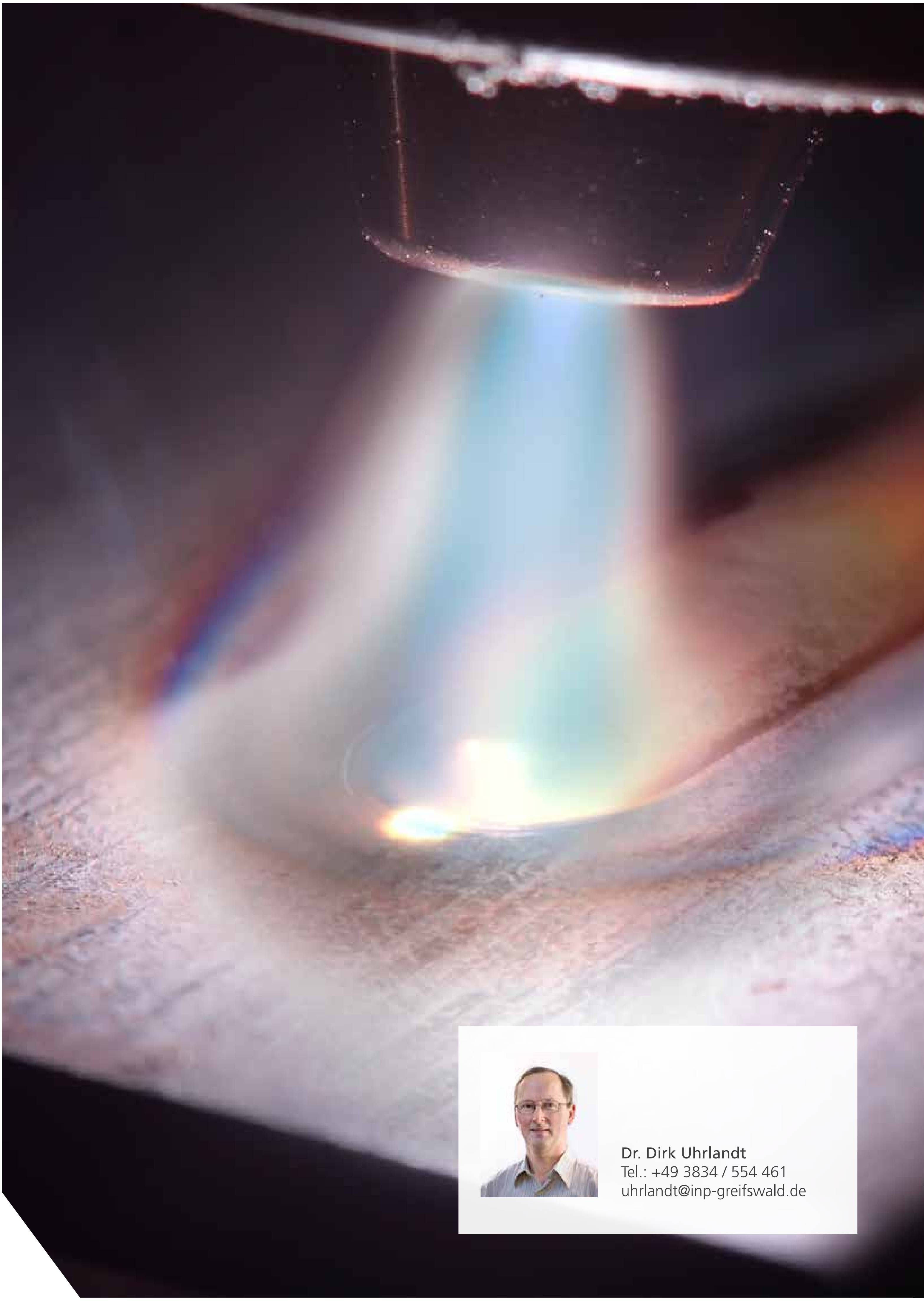
Change in the region by use of biogenic residues

Together with the Hanseatic City of Anklam and the Cosun Beet Company (sugar factory) in the "biogeniV" alliance, the INP is focusing on the latest technologies with which previously unused biogenic residues, including CO_2, can be utilised. The jury of the Federal Ministry of Education and Research (BMBF) decided to fund the Alliance in 2021. The aim is to use new business models to make the Anklam region sustainable. In the conceptual phase of the alliance, many project ideas from research and business partners have already emerged. The focus is on technologies for biomethanol production, more resource efficiency in biogas production, and the use of previously unused residues such as liquid manure and fermentation residues. All implementation concepts are tailored to regional conditions. With the approval, the INP is now in charge of a third joint project within the BMBF programme "WIR! – Wandel durch Innovation in der Region" (Innovation and structural change).

More space for innovation – Centre for Life Science and Plasma Technology (Z4)

The Hanseatic City of Greifswald is investing around €37.6 million in the construction of a Centre for Life Science and Plasma Technology. The Federal State will provide half of this amount through subsidies. Completion is scheduled for Spring 2023. In the presence of former Chancellor, Dr. Angela Merkel, former State Minister of Economics, Labour and Health, Harry Glawe, and the Lord Mayor of Greifswald, Dr. Stefan Fassbinder, the symbolic foundation stone was laid on 4 February 2020. The Centre for Life Science and Plasma Technology (Z4), a new research and start-up centre with international appeal, is being set up directly adjacent to the INP. The new building will give the staff of INP even better opportunities to cooperate with industry and develop prototypes for the market. For example, the INP will rent an eight-metre high technical centre hall, numerous offices, and specially equipped laboratories, including more laboratories with Biological Safety Level 2. The new areas will be used mainly for the research and development of climate-friendly technologies.

After a long planning and building phase, we are looking forward to finally being able to explore the new possibilities the centre has to offer. The success we have achieved in the past will continue to result in new processes and prototypes. We have set the course for this. We look forward to continued success together with you.



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RESEARCH DIVISION

MATERIALS AND ENERGY

Overview

The research division combines plasma technology topics in the fields of energy and production technology. Current areas of application are the production of functional surfaces, thin films and catalytically active materials using plasma processes as well as plasma chemical synthesis and the use of arcs in energy technology and process engineering.

The focus is particularly on the technical challenges of the energy transition. Research is being conducted into new materials for battery technology and photovoltaics as well as the synthesis and storage of hydrogen. It is also a matter of increasing the performance and reliability of the energy infrastructure with new components. Researchers are currently investigating how surfaces can be treated using non-thermal plasmas at atmospheric pressure. The interaction of thermal plasmas with electrodes and walls is also being investigated. Another focus is the development of measuring methods for various applications – from vacuum processes to arc welding. This will provide a deeper analysis of the underlying physical and chemical processes.

Research programme: Materials and Surfaces

- Functional films, additive manufacturing
- WIR! Joint project "CAMPFIRE" – Green ammonia for emission-free mobility

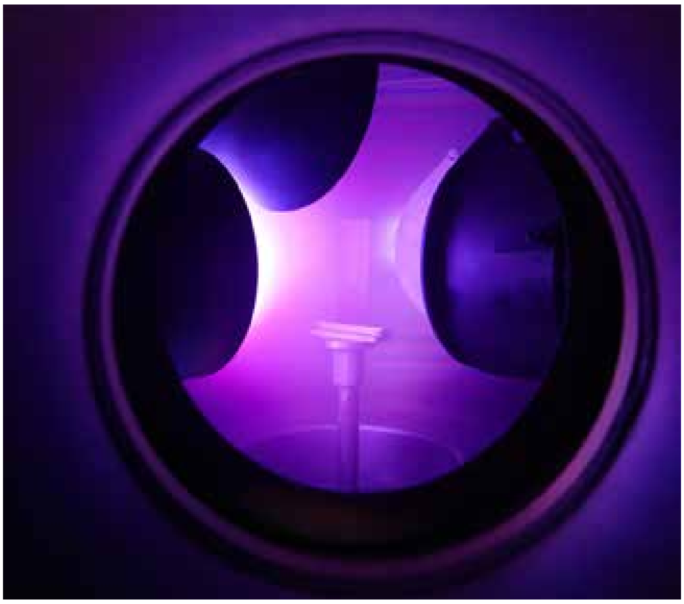
Research programme: Plasma Chemical Processes

- Plasma chemistry – fields of application
- WIR! "BiogeniV" project – use of biogenic carbon dioxide

Research programme: Welding and Switching

- Thermal plasmas for applications in process and electrical engineering
- Joint project "AutoHybridS" – autonomously controlled hybrid switch with efficient resolidification detection

Overview



Coating method: Production of ceramic coatings using the PVD process: In the reactor, three starting materials can be evaporated simultaneously by cathode sputtering (magnetron sputtering).

Plasma-assisted surface processes include structured material removal, the production of high-quality coatings, and the engineering of interface properties. They open up new perspectives for the controlled synthesis of innovative nanostructured or nanoscale materials. The research programme “Materials and Surfaces” is dedicated to research into innovative plasma processes and the application of technical plasmas for thin-film deposition and material synthesis. The fundamental plasma properties underlying these technical processes are characterised by means of experiments and numerical simulation. The aim is to correlate these quantities with the resulting microscopic chemical structure and composition of the thin-film materials synthesised as well as with the macroscopic material properties. Knowledge of these interrelationships ultimately leads to more intelligently controlled manufacturing processes and thus to better products.

FIELDS OF APPLICATION

Current fields of application for the coatings and nanostructured materials can be found in the storage and conversion of renewable energy. For example, membrane and electrode materials for electrocatalysis (battery and fuel cell technology) and hydrogen technology. One major application is the synthesis of catalytic surfaces for decentralised energy supply using hydrogen and hydrogen-containing chemical compounds or in the field of electromobility.

Further areas of application for thin coatings open up according to the special functions. For metals, protective coatings reduce the tendency to corrode and improve protection against thermal or mechanical stress. They improve the adhesion of material composites, have a decorative character, reduce gas permeation, and generate energy.

In additive manufacturing, the surface finish of metallic 3D printed components can be improved using electrolytic plasma polishing. This method also allows the consistent removal of superficial impurities.

Application-oriented outlook

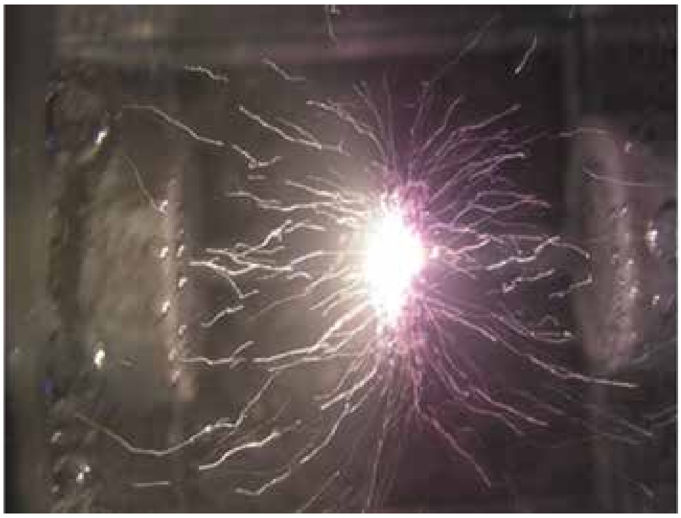
A central research topic is the synthesis of materials for renewable energy sources and catalytic processes. The major initiative "Campfire: Wind and Water to Ammonia - maritime fuels and energy storage for an emission-free future" coordinated by the INP as part of the BMBF programme 'Wandel in der Region' (WIR!) has a pioneering character for strengthening relations with industry in the field of materials for renewable energies. Innovative solutions in the field of decentralised production of ammonia from renewable energies and the use of this as an innovative energy source for emission-free maritime mobility are being developed in a consortium of research institutions and regional companies. At the INP, the production of thin-film membranes by means of a plasma-enhanced layer deposition process is being researched with the aim of making these usable for the production of ammonia from atmospheric nitrogen and water by electrolysis.

Further projects for the deposition and synthesis of nanodimensional, metallic, metal oxide, and graphitic particles and thin films are linked with applications as catalysts, membrane, and electrode materials for electrocatalysis or the hydrogen technology.

With the help of plasma-assisted coating processes, it was possible to produce support-free, highly porous platinum and iridium catalysts that act as electrode materials for PEM (Polymer Electrolyte Membrane) fuel cells and electrolysers. The layers produced in this way have eight-fold the activity of commercial catalysts when used as electrodes for H_2 electrolysis. As part of the "3DnanoMe" validation project, the manufacturing process for these metal layers is being scaled up to the dimension of fuel cell electrodes.

The EU H2020 project "HiPowAR -Highly efficient Power Production by green Ammonia total Oxidation in a Membrane Reactor" aims at direct energy conversion based on NH_3 from sustainable production. For this purpose, MIEC (mixed ionic electronic conductor) membranes are produced in a plasma process and used as O_2-permeable wall material in a pressurised membrane reactor in order to oxidise liquid NH_3 at high efficiency.

In addition to vacuum-based processes, atmospheric pressure plasma processes in liquids for the synthesis of nanoparticles are also being investigated.
Atmospheric pressure plasma spraying is being investigated for the deposition of coatings with applications in electromobility (e.g. in electric heaters of motor vehicles). In the project "Prisma" funded by the European Regional Development Fund (EFRE), the plasma properties are characterised and the layer growth is visualised. The experiments are supplemented by simulations with the aim of improving the process control. The Leibniz Competition addresses the strategic goals of the Leibniz Association. In this research programme, two projects in this competition were successfully completed in 2020/21: The results of the experimental and modelling investigations within the joint project "PLASFASER" form the basis for the synthesis of doped quartz-glass high-performance fibres. In the project "CARMON", vanadium oxide layers were succesfully investigated as a material for Li-ion batteries and supercapacitors. The crystallinity of γ-V_2O_5 and thus the electrochemical performance can be controlled as a function of the process parameters.



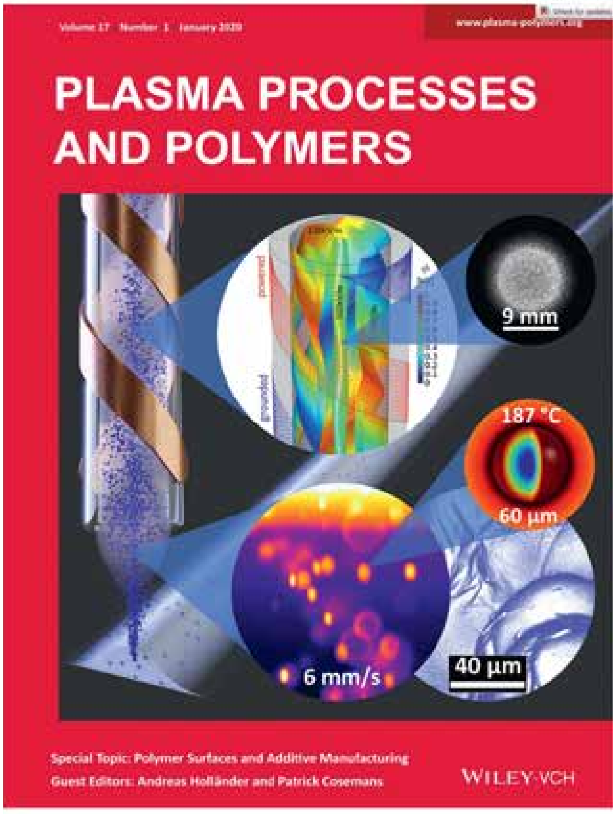
Electrical discharge in liquids: Synthesis of vanadium oxide/graphene nanohybrids as innovative battery materials

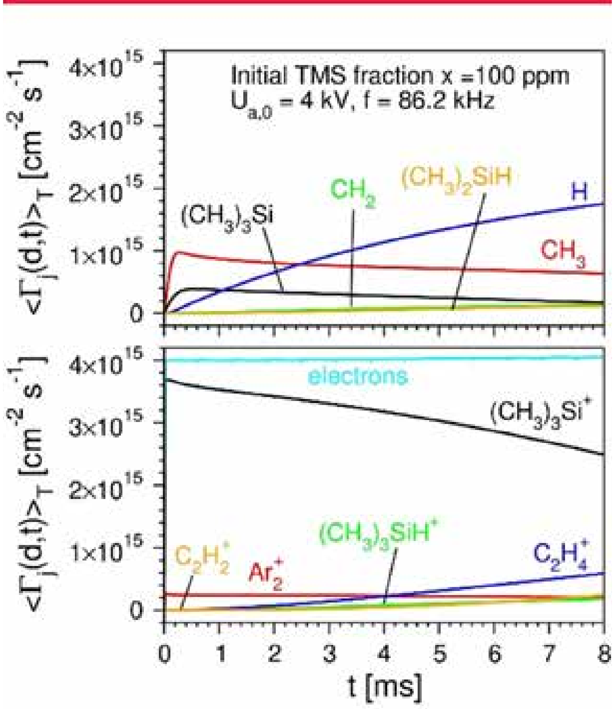
Core-funded project "Functional coatings"

The experimental and modelling investigations in the project are directed towards the study of non-thermal, reactive HF plasmas at ambient pressure conditions. These plasmas are used for the deposition of functional layers based on organosilicon substancescar by means of PECVD (plasma enhanced chemical vapour deposition). Research into the spatial and temporal behaviour of discharge filaments, in particular their self-organisation, led to the discovery of a spatially homogeneous glow discharge at atmospheric pressure as well as to the presentation of the Helixjet plasma source, a capacitively coupled HF discharge with a double-helix configuration of electrodes that can be used to generate a stable and spatially homogeneous filament-free plasma (Schäfer, J. et al., Plasma Process. Polym. 17 (2020) 1900099, DOI: 10.1002/ppap.201900099). The suitability of it was demonstrated in the coating of complex shaped components for corrosion protection coatings based on octamethyltetrasiloxane. The plasma source was also successfully used for the preparation of the material during 3D printing.

The modelling of such plasmas (Ar, 27.12 MHz) was focused on a single filament in the active zone using a phase-resolved model as well as on an overall description of the jet, including the substrate using a period-averaged model. Finally, a phase-resolved, spatially two-dimensional fluid model, which considers gas flow and heating in the active zone between the electrodes and the outflowing jet (effluent), was established. The determination of the current of the film-forming molecules directed onto the substrate allows for quantitative modelling of the film deposition (PECVD). In addition to the HF plasmas or plasma jet geometries, it was also possible to describe dielectric barrier discharges in argon for the PECVD of organosilicon films by means of time- and space-dependent fluid modelling.

Using hexamethyldisiloxane or tetramethylsilane as precursors for the thin-film formation, the modelling results provide a realistic concept for the energy absorbed per precursor molecule and the energy efficiency in such Penning mixtures. The analysis clearly shows that the influx of positive ions onto the substrate is mainly responsible for the film formation. (D. Loffhagen et al., Plasma Chem. Plasma Process. (2020); https://doi.org/10.1007/s11090-020-10121-y). This conclusion of the model calculations is supported by experimental results and thus contributes to clarifying a central question about the layer formation mechanism in these processes.





Above: Front page of the journal Plasma Processes and Polymers with graphical representation of the atmospheric pressure plasma source Helixjet (Schäfer et al., Plasma Process. Polym. 17 (2020) 1900099)
Below: Modelling of a dielectric barrier discharge (DBD) in Ar-TMS under atmospheric pressure. The wall fluxes of neutral species and of charge carriers versus time are shown (Loffhagen et al., Plasma Chem. Plasma Process. 41 (2021) 289–344).

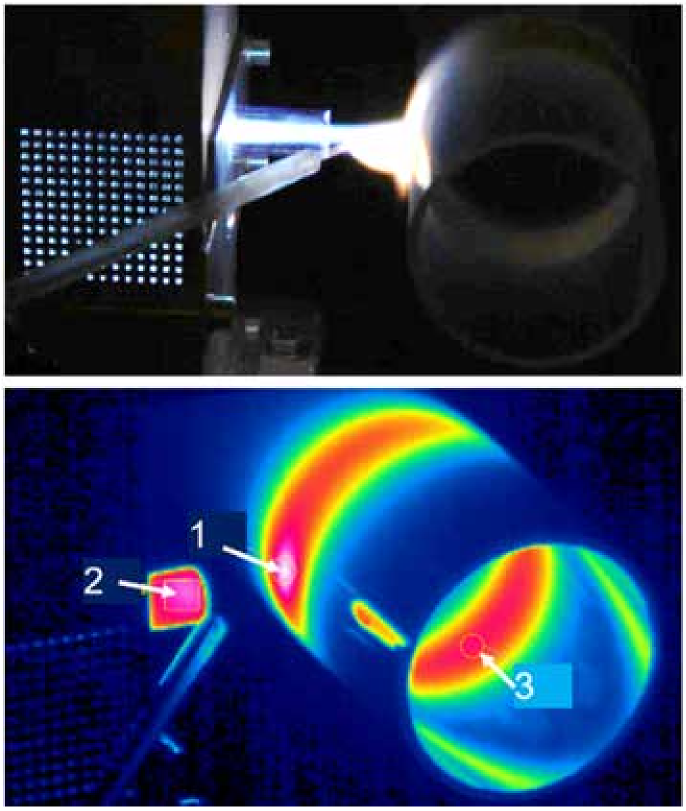
Technology-oriented outlook

The synthesis of materials for renewable energy sources remains a central research topic. In this context, the projects within the CAMPFIRE initiative have a profiling role. The establishment of the Campfire Open Innovation Lab in Rostock–Poppendorf is considered indispensable for facilitating technology transfer, industrial implementation, and commercialisation. The initiative breaks new ground in fully harnessing wind and solar energy and accelerating a new nitrogen-based hydrogen economy. The process skills of the research programme are being expanded with regard to the synthesis of new material classes and alloys with defined nanostructures (e.g. the plasma-assisted generation of MAX phases and perovskite compounds).

The transfer of plasma processes is also supported by the upscaling of processes to industrially relevant substrate sizes. Scaling up is necessary in order to make the leap from the laboratory to production. Several projects are dedicated to this topic (e.g. the implementation of roll-to-roll processes, the transition to larger plasma-in-liquid flow reactors, and the validation of plasma processes for industrially relevant substrates). Based on the BMBF-funded validation project "3DnanoMe", a roadmap for establishing a spin-off company using the EXIST funding programme of the BMWI is envisaged.

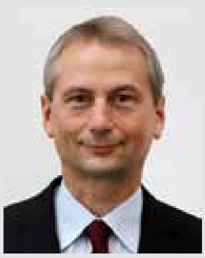
Innovative hybrid nanostructured materials are also synthesised by local atmospheric plasma processes. The capacity of plasma-induced grafting at the nanoscale to synthesise 2D graphene derivatives and progressively aggregate novel high-definition (HD) nanohybrids will be evaluated as a potential method for creating nanoarchitectures for additive manufacturing.

With regard to the development of methodological expertise, further modern techniques will become more important and technically applied in the coming years. These include:
(i) new hybrid processes (e.g. the combination of other processes (UV, laser annealing) with the plasma process)
(ii) further developments of processes such as plasma-in-liquid processes, plasma electrolytic polishing, and plasma electrolytic oxidation as well as the combination of high-impulse magnetron sputtering (HiPiMS) with plasma-based ion implantation (PBII)



Microwave plasma for the synthesis of quartz glass for high-performance glass fibres. The layer is formed on a rotating glass cylinder. Above: Plasma jet source with effluent and supply of the reactive gas, Below: Measurement of the surface temperature (1: Outer wall 3: Inner wall of the cylinder, 2: Nozzle of the plasma source) during the process by means of an IR camera. "PLASFASER" project, Leibniz competition (Baeva et al., J. Phys. D: Appl. Phys. 54 (2021) 355205).

CONTACT



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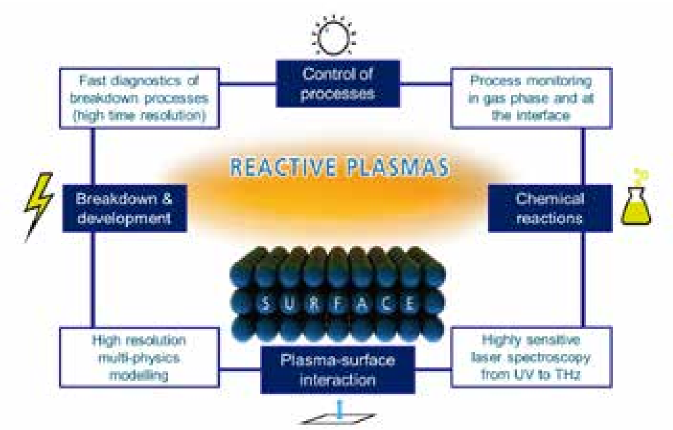
Overview



Questions and core topics of the research programme "Plasma Chemical Processes"

The research programme "Plasma chemical processes" focuses on the physics and chemistry of reactive plasmas. In addition to the chemical processes in the volume and on the adjacent surfaces, the work focuses on correlating these with discharge physics as well as with methods for controlling and monitoring.

The projects are clustered around four core topics:

- Atmospheric pressure plasma processes and reactors, especially for power-to-gas applications
- New plasma diagnostics
- Simulation of the formation of reactive plasmas, including the chemical processes,
- Development of *in situ* process control methods, including their transfer to industrial practice.

Expertise in both high-sensitivity laser absorption spectroscopy and high-time-resolution imaging and spectroscopy is used. In addition to state-of-the-art methods of IR spectroscopy, THz spectroscopy and resonator-based absorption spectroscopy, among others, were further expanded. Experimental work is closely coupled with spatially and temporally resolved numerical modelling including extensive plasma chemical kinetics.

Fields of application

Atmospheric pressure plasma reactors:
Plasmas that can be handled without complex vacuum technology are relevant for many industrial processes. A current focus is the conversion of CO_2 into other chemical compounds (e.g. CO as a feed stock for fuels and recyclables). A sound understanding of the formation of the plasmas, i.e. the processes during electrical breakdown and the interaction with the bounding surfaces, is the basis of reactor and process development. These are accessible through imaging and spectroscopy techniques and allow statements to be made about plasma parameters. Cavity-enhanced laser spectroscopy enables the spatially resolved measurement of reactive and stable species, especially in small-scale plasmas.

Process control in industrial plasma processes:
Because the empirical determination of process parameters continues to reach its limits, there is a need for sensitive methods suitable for instantaneously determining the chemical composition of the plasmas. In addition to IR absorption spectroscopy and cavity-enhanced absorption spectroscopy for molecular species, THz spectroscopy for detecting atomic species and measuring electron densities was added to the portfolio.

Plasma nitriding:
Research into the plasma nitrocarburising process to increase the surface hardness of work pieces continues in collaboration with the Freiberg University of Mining and Technology. Active screen plasma nitriding with a carbon grid, which prevents the formation of arcs and therefore enables a more uniform processing of the work pieces, can be improved with increased knowledge of the concentration of stable plasma species. For laser absorption spectroscopy, among other things, the new frequency comb system is used; this enables the simultaneous detection of several species and is now equipped with a faster detection method.

Application-oriented outlook

Among other things, the new WIR! alliance "biogeniV" is dedicated to the utilisation of biogenic carbon dioxide in the region of the eastern Mecklenburg-Western Pomerania

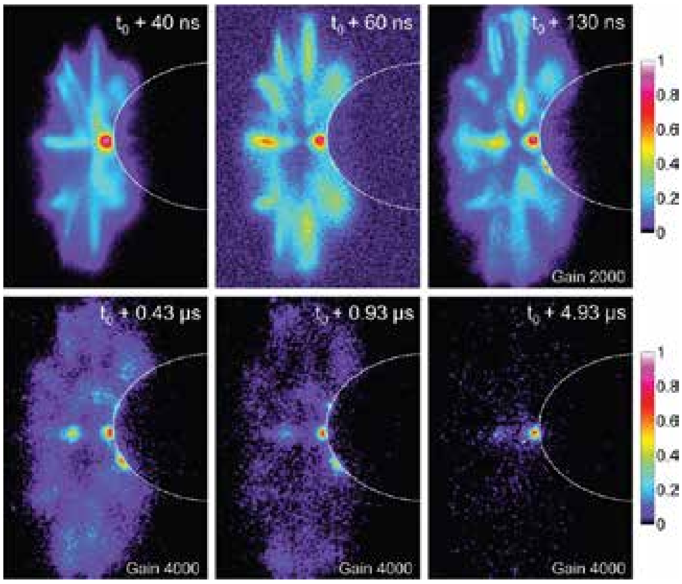
The work in the research programme aims at new processes for the direct plasma-assisted and plasma-catalytic production of basic chemical substances from simple raw materials. To produce chemical substances, carbon-containing starting materials, primarily the greenhouse gas CO_2, are to be converted into other chemical compounds under the influence of the plasmas. These serve as basic or starting materials for subsequent synthesis processes or are further converted in the plasma itself. Plasmas offer the special possibility of producing chemical substances efficiently, on site, and "on demand" using electrical energy from renewable sources in the sense of Power-to-X. In 2021, a WIR project funded by the BMBF was acquired for this purpose. Together with the Hanseatic City of Greifswald and the Cosun Beet Company in Anklam, the new "biogeniV" alliance was created with over 15 regional and supra-regional partners. This will enter its first implementation phase in 2022.

Within the framework of "biogeniV", the production of biomethanol from biogenic carbon dioxide from biogas plants is to be the main focus. To this end, catalytic processes are to be combined with plasma processes and state-of-the-art membrane technology. In addition to creating new options for the bioeconomy, the research field takes up challenges that arise during the electrification of the chemical industry as part of the energy transition. For example, other projects involve looking at the formation of carbon monoxide as a chemical feedstock, methanation, and hydroformulation.

Plasma-assisted thermochemical surface treatment to improve the surface properties of metallic components through the targeted diffusion of nitrogen and carbon into the work pieces will continue to become more important in the course of a more sustainable use of resources. The work in the research programme continues to aim at a new plasma-assisted technology, "Active Screen Plasma Nitriding", which was developed at the Freiberg University of Mining and Technology. The knowledge gained from sensitive plasma diagnostics not only leads to a better understanding of the elementary processes that make treatment results more reproducible but also to the adjustment of process conditions in order to achieve well-defined layer profiles. In addition, plasma diagnostics itself is to be further qualified as a method for process control.

In addition to the plasma nitrocarburising process, there are many industrial processes that require sensitive *in situ* process diagnostics. It will not be possible to optimise the increasingly complex manufacturing technologies by the empirical determination of process parameters and the statistical modification of these alone. Instead, this will require a sound understanding of the processes obtained through the interaction of plasma diagnostics and simulation. With classical IR absorption spectroscopy in the mid-infrared range, the relatively new cavity-enhanced absorption spectroscopy, or THz spectroscopy, sensitive methods that can overcome these challenges in perspective are being adapted or developed.

Core-funded project "Plasma chemistry"



Formation of a discharge filament on a glass surface with a grid electrode in air behind it (expansion of approx. 5 mm).
In collaboration with TU Eindhoven, Netherlands.
(Kettlitz et al., J. Appl. Phys. 128 (2020) 233302)

The research programme focuses on the investigation of the formation of plasmas at higher pressures. The aim is to understand the mechanisms of plasma generation in such a way that reactor geometries and process conditions can be targeted to certain chemical processes such as the dissociation of CO_2. The particular challenge here is that the processes are quite fast. At atmospheric pressure, these processes occur mostly at the sub-nanosecond time scale. Moreover, these plasmas are extremely small-scale objects with length scales in the micro- to millimetre range. In addition to the electrical breakdown in the volume, the formation of discharges on the adjacent surfaces is also important, especially with regard to the combination of plasmas with catalysts. This will be a future field of work in the research programme.

Imaging and spectroscopic techniques with a time resolution of up to 2 ps are therefore used to investigate the plasma generation in barrier discharges. Among other things, the influence of organic compounds or electronegative gases on plasma ignition and morphology as well as the formation of discharge channels on water or dielectrics were investigated. The figure shows how a discharge channel on the surface of a dielectric material splits into several secondary channels and spreads out along the underlying lattice structure. In addition to the dynamics of the electrical breakdown, such results can also be used to determine plasma parameters such as the reduced electric field strength. There is a long-standing cooperation with Masaryk University in Brno, Czech Republic, on this topic. In addition, an electrical characterisation of plasma reactors is carried out with the help of equivalent circuit diagrams. In addition to diagnostics, the construction of the discharge arrays is also a challenge. These are to be designed in such a way that discharge channels are generated in a localised, temporally stable, and reproducible manner.

The experimental investigations are accompanied by a model-based analysis of the processes. Hydrodynamic and kinetic approaches are used in the modelling and simulation in order to be able to describe the fast processes.

In addition, new plasma diagnostic concepts are continually being developed.

Laser absorption spectroscopy (LAS), in particular, is an important method for the detection of plasma components and the analysis of chemical processes. The frequency comb system was established as a new radiation source for the LAS. The advantage of this femtosecond laser-based system is that instead of only a single laser line, several thousand laser lines with precisely known frequency spacing are generated. It thus enables the simultaneous detection of several species in the plasma and provides insights into the different temperatures in these non-equilibrium plasmas (gas, rotational, and vibrational temperatures). Especially for applications in molecular spectroscopy, a pioneering role can be taken here in plasma research. This system is currently being used to investigate the plasma nitrocarburising process.

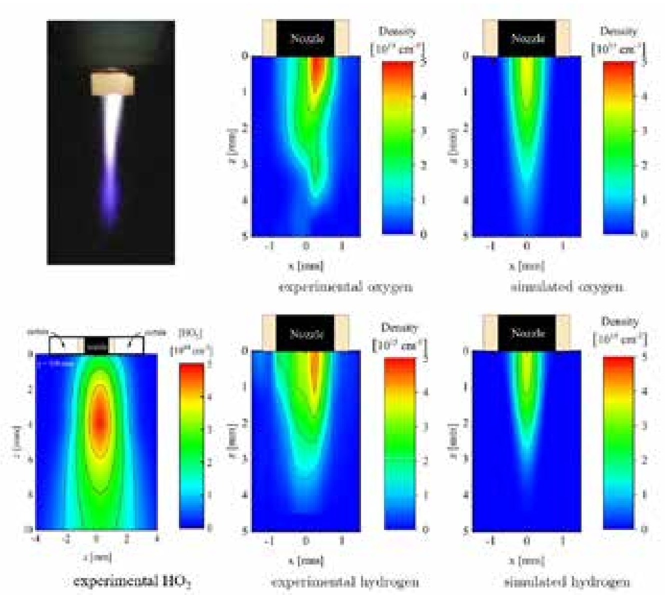
THz spectroscopy was further developed. This enables the determination of the density of atoms and ions in the ground state as well as electrons and offers a new diagnostic access for the control of coating processes.

In recent years, special attention has been paid to the investigation of the "kINPen" plasma jet. The plasma is first generated in a capillary and carried to the outside as an effluent by a stream of argon gas. This plasma source is used for the local treatment of heat-sensitive surfaces as well as wounds or skin, thus making it an important tool in the "Environment and Health" research division. The addition of moisture to the working gas leads to the production of highly reactive intermediates such as hydrogen and oxygen atoms or hydroxyl radicals. These are considered key species for biomedical application and plasma surface effects. The detection of these species and the description of plasma chemistry are a challenge to plasma diagnostics and modelling. However, it is absolutely necessary in order to be able to understand and adapt the effect of plasma treatment.

For the determination of the species concentration in the effluent of the plasma jet, the method of cavity ring-down spectroscopy was further established. The collaboration with Oxford University was further expanded, and the density distribution of hydroperoxyl radicals was determined. In cooperation with the University of York (UK) two-photon absorption laser-induced fluorescence (TALIF) was also used to determine the density of hydrogen and oxygen atoms with both axial and radial resolution at the same plasma source. The experimental results were compared with a two-dimensional reaction flow model coupled with a global 0D model for plasma chemistry. The maximum of the atomic densities is obtained at the exit of the capillary. The dissociation of water molecules and molecular oxygen in the active zone of the plasma jet (i.e. in the capillary) was determined to be the main mechanism of water and oxygen atom production. The generation and destruction of atoms, hydroxyl and hydroperoxyl radicals, and hydrogen peroxide and water are coupled with each other.

The densities of metastable argon atoms were measured by laser absorption spectroscopy at 811 nm, and the influence of humidity in the gas on the plasma was investigated.

The importance of metastable atoms is that they have sufficient energy for the dissociation of molecules. In addition, they can influence the formation of the plasma. In this species, the highest density is also obtained at the capillary exit. The addition of water to the working gas argon reduces their density because of quenching processes. The quenching cross-sections were determined from the decrease of the number density with the water content.



Morphology and spatiotemporal evolution of a single filament in a barrier discharge in a nitrogen-nitrous oxide mixture. Klose et al., Plasma Sources Sci. Technol. 29 (2020) 085011 & Plasma Sources Sci. Technol. 29 (2020) 125018).

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Overview

The investigation of thermal plasmas is the main field of activity of the research programme "Welding and Switching".

Thermal plasmas play an important role in technological applications in process engineering and for switching devices in electrical engineering. The research programme concentrates on diagnostics and the physical characterisation of the arc and develops alternatives for problem solving, monitoring and process optimisation. The areas of application range from thermal metalworking processes (arc welding, plasma cutting) to gas and vacuum switchgear and applications in chemical process engineering.

In electrical power engineering, thermal plasmas occur in the form of the so-called switching arc, which is ignited in switches when electrical devices are switched on or off. The characterisation of this predominantly transient arc discharge in interaction with the adjacent materials (electrodes, walls) in low- and high-voltage systems is the focus of interest in this research programme.

Discharge and arcing phenomena are also investigated, which occur as a result of insulation faults, impair the regular operation of electrical systems and equipment and lead to a reduction in service life and functionality.

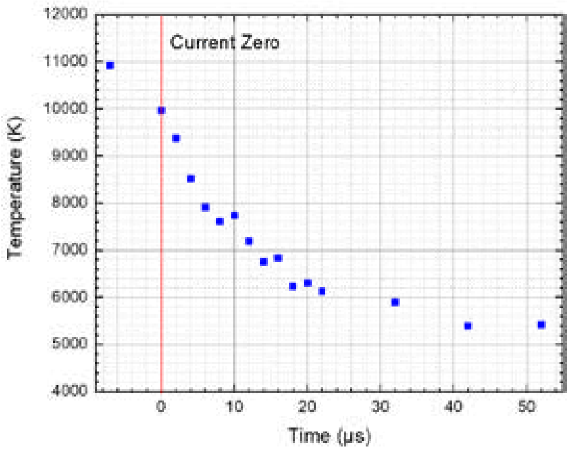
Due to the complex arc character and the dynamic interaction with its surroundings, closed model conceptions of thermal plasmas still represent a scientific challenge today. Especially for the adjacent arc regions, the involved materials and surrounding gases often determine the range and application possibilities of the model results. The constant development of novel components and electrically powered devices, changing fields of application and increasingly environmental demands require continuous research on both the arc itself and the technological adaptation to the respective boundary conditions. The scientific approach combines various diagnostic methods of an experimental as well as material-scientific nature with mathematical modelling and simulation. This enables the determination of space- and time-dependent plasma parameters, such as temperature, composition and gas dynamics.

Especially in the field of optical plasma diagnostics, the INP has a unique selling point. The research programme uses both optical emission and absorption spectroscopy as well as their combination with high-speed kinematography and high-speed two-colour pyrometry. A significant expansion of competence is taking place by the adaptation of absorption spectroscopic methods for investigating the areas adjacent to the arc.

For modelling and simulation, both the classical magneto-hydrodynamic models (Navier -Stokes and electromagnetic equations) and, increasingly, non-equilibrium models, avoiding assumptions of local thermodynamic equilibrium, are used. This results in a much higher accuracy in the description of the plasma processes in the electrode regions and the plasma-solid interaction. Furthermore, the focus is on work on radiation transport and material data for non-equilibrium plasmas.

High-current generator for simulating various current courses in the electrotechnical field: AC pulses up to 200 Hz and 15 kA amplitude, AC pulses up to 80 kA at 50 Hz, DC pulses up to 20 ms duration and 10 kA amplitude and lightning impulse currents 10/350µs up to 50 kA max.

Joint project "AutoHybridS“



Development of the plasma temperature over time during and after the current phase (post-arc) of a hybrid switched-off DC switching arc (70A, 400 V DC)

The joint project "Autonomously controlled hybrid switch with efficient resolidification detection - AutoHybridS" is funded by the BMWI and BMWK and brings together partners from industry and science.

The goal of the joint project "AutoHybridS" is the demand-oriented distribution of energy on bus systems with nominal voltages of up to 850 V DC, which are to be protected with an efficient, extremely fast-triggering switching technology.

Here, a fast DC hybrid circuit breaker is to be developed for use in industrial and on-board networks for the system integration of renewable energies and for energy recovery from electric drives.In the alliance, the solution approach is to combine the advantages of mechanical switching devices (low conduction losses, galvanic isolation) and power semiconductors (fast switching) in one device. In the envisaged new hybrid switch, switching will be achieved by the combined action of mechanical switching contacts with power electronics connected in parallel.

Here, the switching arc is extinguished by switching on a semiconductor. In order to ensure a safe current interruption, the resolidification of the switching path must be achieved before the semiconductor is blocked again. The economic design of the semiconductor requires the time of the re-solidification of the contact gap after the arc has been extinguished to be detected reliably and quickly.

The aim of the sub-project of the research programme is to develop the decisive specifications that enable the detection of resolidification. For this purpose, both spectroscopic and plasma-physical analyses on a model switching chamber and the derivation of a mathematical model are used.

A model switch was set up at INP as part of the project. Extensive high-speed camera technology and spectroscopic measurements with high temporal and spatial resolution enable the detection and characterisation of the plasma in the electrode chamber in the post-arc phase. By using suitable filters, it was possible to distinguish between the comparatively stable behaviour of the arc plasma dominated by components of the ambient gas (O, N, H) in the centre between the electrodes and the erratic behaviour of the plasma close to the electrode and dominated by electrode material (Cu), which is perceived as spots or jets. First statements on the composition and temperature of the arc plasma and the cooling residual gas after current zero crossing were determined.

In the next step, investigations using optical absorption spectroscopy are planned to determine the metal vapour density of the residual gas. For the realisation of the numerical simulation, the development of a 1D-t fluid-Poisson model was chosen as the most suitable solution from the various alternatives. With the help of the developed model, simulations were carried out for various parameter combinations. It was found that despite the high pressure and the high charge carrier densities, the plasma exhibits significant deviations from thermal equilibrium. Heating of the gas only takes place at currents above 200 A. By varying the current, a current-resistance characteristic was obtained, which is used in electrical models of the entire system by the project partner.

Core-funded project "Arcs of light"

A significant improvement in the switching capacity and reliability of arc-based switchgear requires detailed knowledge of the physical properties and dynamics of the resulting arc plasma. The areas adjacent to the plasma at the electrodes and housing walls deserve special attention. The focus of the core-funded arc project is the interaction between plasma and the surrounding medium (air, gas, vacuum), which is investigated using spatially and temporally high-resolution optical diagnostics in combination with numerical modelling.

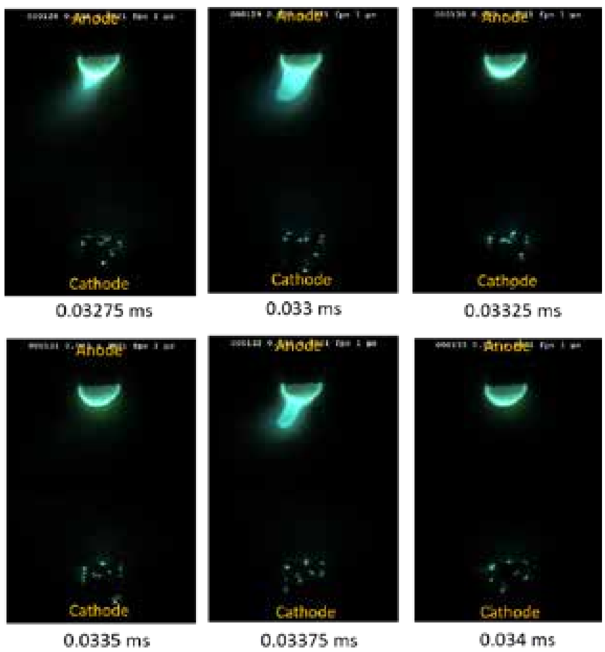
Extensive work was carried out in the core-funded project, especially on the analysis of arc foot points at the anode under vacuum. By using the experimental set-ups and high-current and high-voltage generators developed for this purpose, new insights into electrode phenomena when switching off high current amplitudes or high current densities were obtained during the reporting period.

At high current densities, a new effect was observed during the existence of the anode spot type 2, characterised by an oscillating extension of the anodic plasma cloud into the inter-electrode space.

The observed oscillating character of the anodic plasma plume was accompanied by an increase in voltage fluctuations. The observed oscillations of the plasma plume have a frequency of at least 4 kHz. A frequency analysis of the oscillations from the voltage signals indicates that the observed oscillations of the plasma plume are coupled with changes in the frequency of the voltage signal. The voltage signals show frequencies between 25 to 40 kHz. Vacuum arcs with current densities up to 100 A/mm2 were analysed.

Until now, the phenomenon of the plasma plume was considered to be an anodic plasma jet that is bounded by cathodic plasma jets. Based on the new findings on oscillations of the anodic plasma plume, the thesis of a double-layer character was put forward.

An explanation in the framework of electric double layers would be an alternative approach to explain a number of features of the plasma phenomena that occur in high-current arcs in the anode region. Further planned investigations as well as the mathematical modelling of these novel phenomena are in preparation and should provide a physical foundation for the current thesis.



High-speed images of the observed oscillations of the anode plasma cloud of a high-current arc in vacuum

Application-oriented outlook

The research programme "Welding and Switching" investigates both the behaviour and the properties of the electric arc and its interaction with the adjacent areas, such as electrodes, enclosing walls, surrounding gases or metal vapour gas in vacuum switching processes. The focus here is on gaining knowledge about the physical appearance processes and their use for adapting, optimising and developing new process variants as well as for increasing performance, improving efficiency and for plasma-based alternatives to conventional thermal processes.

The research field covers both the electrical sector and various process and production technologies in industry as well as, in the future, for the hazard-free disposal of problematic waste materials and the minimisation of the environmental impact of conventional products and production technologies.

The research programme is strongly user-oriented. In connection with industrial applications, alternative solutions for process control and for the consistent increase of process stability, cost savings and the optimal use of resources are being developed. The application and further development of optical diagnostic techniques, such as high-speed kinematography, absorption and emission spectroscopy, pyrometry and laser-induced plasma spectroscopy, make it possible not only to understand the plasma and its interaction, but also to derive easily manageable and integrable sensor concepts. Due to the urgent need to reduce the CO2 footprint of industrial processes and to store electrical energy from volatile renewable sources, alternative concepts for the targeted use of thermal plasmas in chemical process engineering and in the field of power-to-X as well as their integration into optimised energy cycles are also becoming the focus of the research programme.

Research work in the field of electrical engineering and in particular switchgear technology from the low-voltage to the high-voltage range includes the replication of the processes that occur in real life by means of experimental arrangements and model switches with optical access. This enables the application of spectroscopic diagnostics, which are essential for the experimental determination of the physical properties of the switching arc. In this area, the research programme has a unique selling point and is currently using this to investigate, among other things, the radiation properties of the arc, the erosion behaviour of the electrodes, and the effects of adjacent insulating walls. The increasing spread of industrial DC grids and the number of electric vehicles play a special role here, which require new types of technologies for current interruption, for example using hybrid switching devices. Insights into switching arcs are indispensable for the development of concepts for powerful and environmentally friendly switches.

Simulation-based design is becoming increasingly important in industrial research and the development of switching devices. This enables a significant reduction in development costs. It requires not only the development of complex magnetohydrodynamic simulation methods and suitable physical models, but also reliable transport and material data. Here, the work of the research programme, especially on arc simulation and modelling of electrode chambers, represents the current state of research and can be adapted to different conditions. In addition, the results on plasma properties obtained experimentally in the research programme provide the necessary validation tools for the simulation methods.

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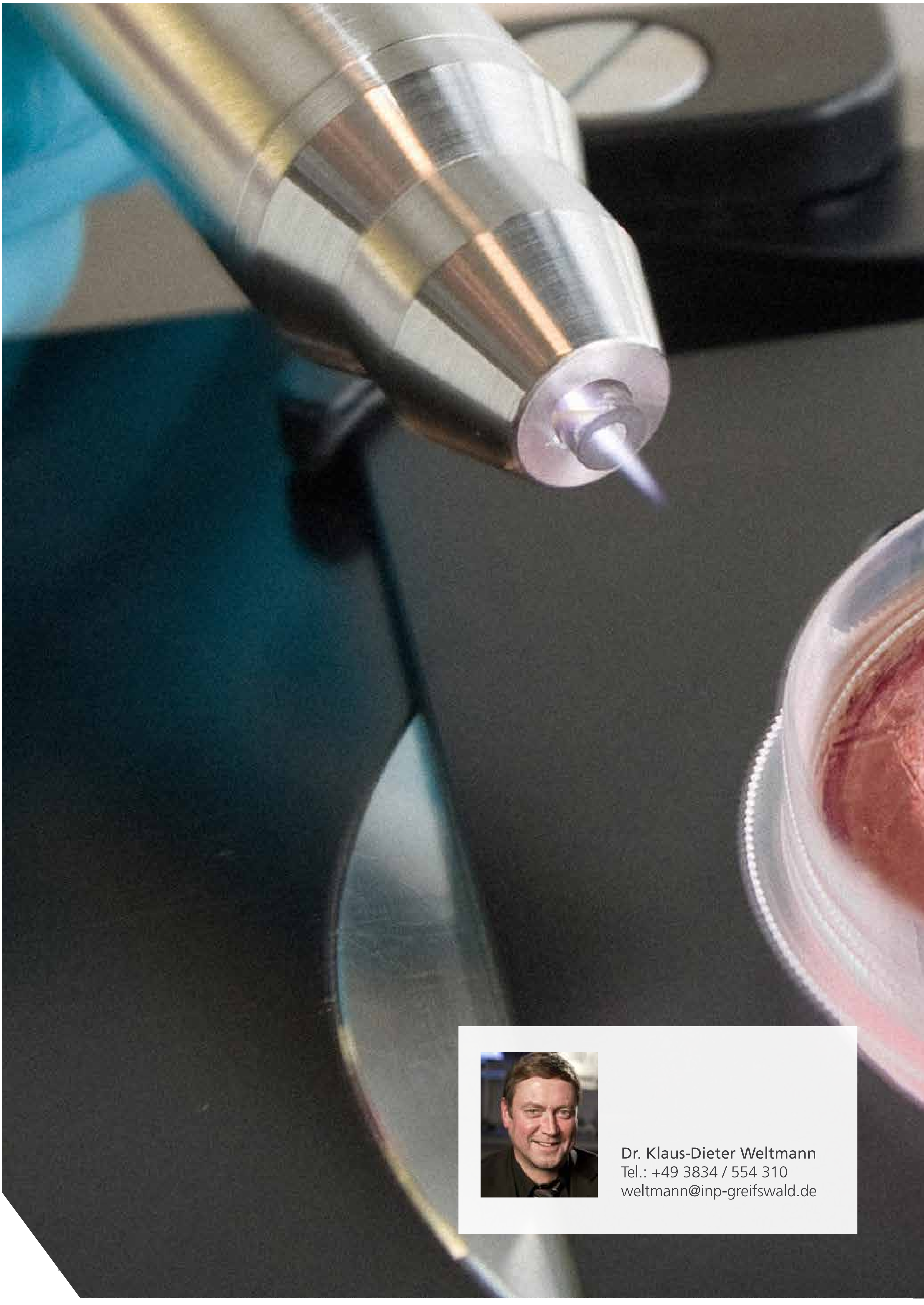

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RESEARCH DIVISION

ENVIRONMENT AND HEALTH

Overview

The research division "Plasmas for Environment and Health" uses the synergies of its three interdisciplinary research programmes: Bioactive Surfaces, Plasma Medicine, and Decontamination. The atmospheric pressure plasma sources are an essential link in this process. For example, dielectric barrier discharges as well as jet plasmas, microwave plasmas, and microplasmas are extensively investigated. The close cooperation of physicists, biologists, chemists, pharmacists, physicians, and engineers with highly specialised technicians and laboratory experts is unique worldwide.

In plasma medicine, the focus is on fundamental research into the interaction of physical plasmas with living cells and tissues. The research and introduction of new plasma-based procedures in medicine is also being promoted. In the field of bioactive surfaces, customised surfaces for life science applications are being researched. Another focus is plasma-based decontamination: Among other things, the focus here is on exhaust air purification and the disinfection of food and water as well as the treatment of agricultural goods.

Research programme: Bioactive Surfaces

- ÖkoClean – Ecological and functionally optimised pretreatment chain for the plasma coating of complex shaped cutting tools
- Process and plant development for the industrially suitable coating of surfaces with photocatalytically active titanium oxide

Research programme: Plasma Medicine

- Plasma and cell – plasma-based procedures in medicine
- Project "ONKOTHER-H: Development platform for innovative oncological therapies using the example of the most common human cancer – skin cancer"

Research programme: Decontamination

- Discharge processes in aqueous solutions
- Digestion of biomass for ingredient recovery and energy recovery

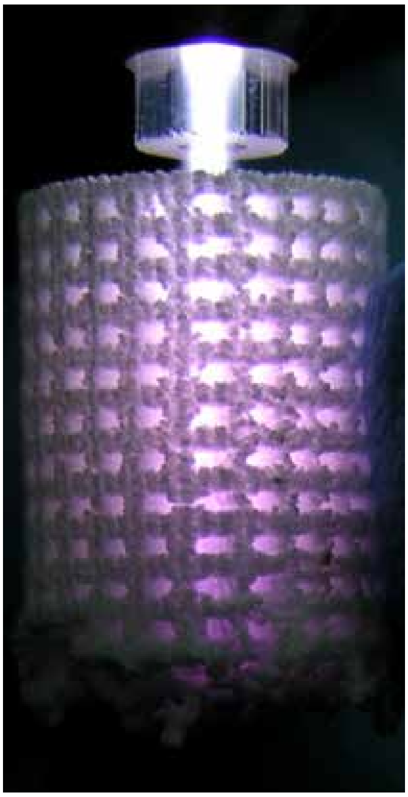
Overview

For many applications in the life sciences (e.g. hygiene, food, and medical technology), the targeted surface modification of products is necessary in order to be able to create specific properties. The plasma-based processes used in the "Bioactive surfaces" research programme are particularly well suited for this purpose thanks to their environmentally- and substrate-friendly properties. Plasma-assisted surface modifications are both versatile and user-friendly and enable the customised modification of various surface shapes and substrate materials. The polymer layers produced in this way are particularly stable, resistant, and sterilisable.

The targeted plasma-assisted generation of application-specific chemical functionalities makes it possible to endow many products with new properties that cannot be generated by other means. The processes for the production of antimicrobial, biocompatible, and biomimetic surfaces as well as the methods used for the plasma electrolytic fine cleaning and fine deburring of medical devices used in this research programme open up new perspectives for the application of plasma processes in the life sciences.

In order to improve the interfacial compatibility of biomaterials and to initiate specific reactions of the biosystem in contact with the surface, they are functionalised using low-temperature plasmas. On the other hand, almost independently of the substrate geometry and the material, new, specific properties for biomedical and biotechnological applications are generated on the substrates by plasma coatings. Because process costs and the simple integration of plasma processes into existing production lines are often highly important for industrial use, the research programme is investigating both processes at low pressure for the highest purity and at atmospheric pressure for short process times.

The research programme also focuses on developing processes for the production of chemically microstructured surfaces (e.g. for microfluidics and for biosensors) as well as functional layers for biosensor platforms for immobilising various biomarkers or proteins for diagnostics. In particular, the control of the wetting properties of substrates is particularly important because plasma-assisted processes can be used to adjust the wettability of surfaces or to generate certain chemical functions on the surface; these can greatly improve biological compatibility, among other things. This work is carried out in close cooperation with the junior research group "Biosensing Surfaces".



Application-oriented outlook

Fields of application

Antimicrobial surfaces

Antimicrobial surfaces mainly serve to prevent infection. In particular implants – but also tweezers, scalpels, and other medical devices that are in direct contact with the patient or medical staff – can benefit from such functionality. In order to reduce or completely prevent the colonisation of surfaces with pathogenic bacteria, various plasma-based processes are used.

These include photocatalytically active layers based on titanium dioxide (which have antibacterial and self-cleaning properties when irradiated with light) and antimicrobial layers (the effect of which is based on metallic components such as copper or silver). In order to produce the longest possible lasting antimicrobial effect, the metallic active ingredients can also be embedded in the original substrate material. This makes it possible to specifically control the release behaviour of the antimicrobial additives.

Cell-adherent surfaces

Plasma processes are also particularly suitable for equipping surfaces with reactive chemical groups such as amino and carboxyl groups. This can considerably improve the colonisation of surfaces by cells and, in particular, cell density and cell distribution as well as adhesion, proliferation, and differentiation. Furthermore, the binding of biomolecules is possible by different immobilisation strategies such as the covalent coupling of linkers and spacers.

Anti-adhesive surfaces

Anti-adhesive surface properties are of particular advantage for transient implants such as fixators or temporary screw connections. This can be achieved by means of anti-adhesive plasma coatings. Substrates coated in this way are easier to clean because dirt and oils/greases as well as organic material adhere to them with difficulty. With the plasma-supported surface modifications used in the research programme, such surfaces can be achieved quickly and in a cost-effective and environmentally-friendly manner.

Laser-plasma processes

With increasing miniaturisation and functional integration, products in the field of bioactive surfaces must also be increasingly provided with the finest structures. By means of laser-plasma hybrid processes, both coatings and high-precision ablations can be achieved. In addition to local process variants, two-dimensional process variants can also be implemented. In combination with atmospheric pressure plasmas and short laser pulses, substrates can be provided with structures down to the sub-micrometre range.

Plasma electrolytic fine smoothing and deburring

Plasma electrolytic polishing (PEP) is used in the "Bioactive Surfaces" research programme, especially for the fine smoothing and fine deburring of implants. PEP offers both economic and ecological advantages over other cleaning and polishing methods because the process is comparatively fast, simplifies the process chain and, compared with other electrochemical methods, reduces the costs for the post-treatment and disposal of hazardous chemicals.

Plasma electrolytic polishing in use as fine cleaning and deburring for medical devices

Core-funded project: Nitrogen-containing, hydrocarbon-based plasma polymer coatings (PPCHN) for use in medical technology and biotechnology

The chemical composition and topography of the material surface are crucial for cell–biomaterial interaction. In medical technology and biotechnology, most materials used are highly chemically and biologically inert and thus unsuitable for targeted interaction with biological systems. Here, plasma-based coating processes enable the customised adaptation of substrate surfaces in order to improve the interfacial compatibility of biomaterials or to achieve specific reactions from the biosystem in contact with the surface. For this purpose, thin functional layers are often deposited on the substrate. In particular, nitrogen-containing plasma polymer layers have proven suitable here.

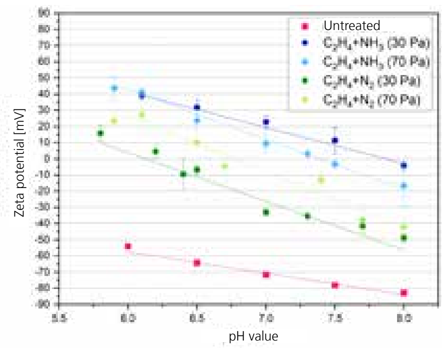
Previous studies have demonstrated the potential of nitrogen-containing plasma polymer layers for various applications (e.g. promoting selective cell adhesion and improving cell physiology) as well as in the formation of microstructured surfaces. Therefore, in the Bioactive Surfaces research programme, nitrogen-containing, hydrocarbon-based plasma polymer coatings (PPCHN) were developed through the copolymerisation of binary gas mixtures of CH_4 or C_2H_4 and NH_3 or N_2 using low-pressure microwave discharges (2.45 GHz). These do not only have a high nitrogen concentration but also ensure sufficient stability in aqueous environments with regard to the application.

In order to achieve this, the coatings must have a radical-free, defect-free, and regular structure with high resistance to ageing effects and oxidation. This can be achieved by a high degree of cross-linking within the coating. In the experimental studies, the degree of functionalisation (i.e. the proportion of functional groups) and the degree of cross-linking of the PPCHN layers were investigated as a function of the plasma polymerisation process. These layer properties were specifically adjusted by adjusting experimental parameters (e.g. process pressure, gas flow, and power) and using different process gases.

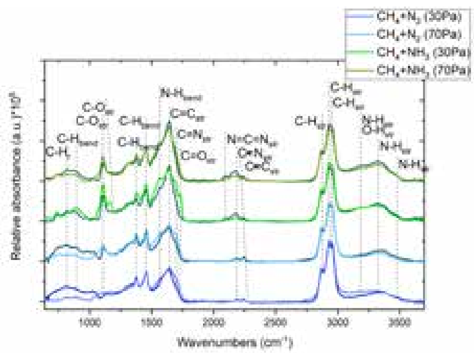
The PPCHN coatings have excellent stability in aqueous environments as well as a surface chemistry suitable for cell adhesion and proliferation. XPS analyses confirm a high N/C element ratio of ≥ 30%. By means of AFM investigations, a smooth, uniform surface morphology of the PPCHN layers was demonstrated. This is maintained even after 24 h of storage in distilled water. The measurement of the zeta potential as a function of the pH value showed a linear course. The NH_3-based PPCHN layers, in particular, exhibited zeta potentials in the positive range at a pH value of 7.4.

A comparison of FTIR measurements on freshly deposited PPCHN layers and after 24 h of storage in distilled water showed that despite low hydrolysis reactions, the chemical stability of the PPCHN layers is quite good.

It is therefore possible to use this low-pressure PECVD process to produce high-quality nitrogen-rich hydrocarbon-based polymer coatings with an adjustable degree of cross-linking. The functional groups close to the surface are particularly well-suited for the immobilisation of cells.



Comparison of the zeta potentials of different PPCHN coatings with an untreated surface



Comparison of the functional groups on different PPCHN layers before (black) and after (coloured) storage in distilled water.

Third-party funded project: Process and system development for industrially suitable coating of surfaces with photocatalytically active titanium oxide

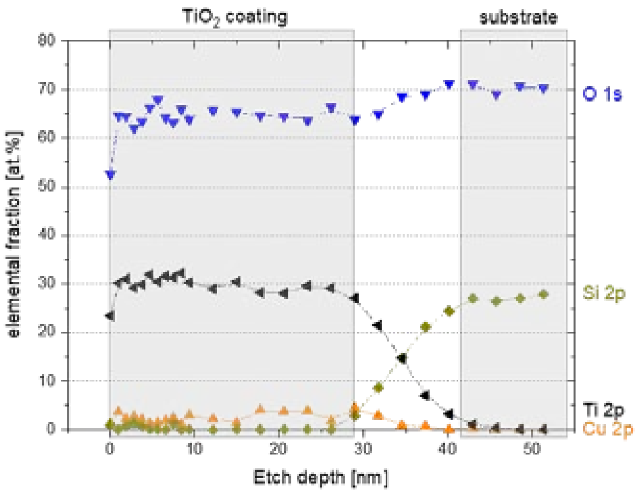
Photocatalytically active coatings based on titanium oxide are an innovative approach for the effective and commercially viable realisation of antimicrobial coatings because they are already widely used in architecture and technology. However, before the titanium oxide coatings can develop their photocatalytic and hydrophilic effectiveness, they must be activated by UV radiation. One of the main objectives of the project was therefore to generate adhesion- and scratch-resistant coatings with excellent photocatalytic activity, hydrophilicity and, in particular, activatability in the visible spectral range in order to also enable indoor applications.

A combination process of HIPIMS deposition with the simultaneous plasma-based ion implantation (PbII) of foreign atoms to adjust the photocatalytic activation threshold was used to produce adhesion- and scratch-resistant TiO_2 coatings. The combination of the HiPIMS and PbII methods had no detectable influence on the film properties. It was possible to reproducibly produce coatings as well as to extensively characterise their properties by surface analysis. The refractive indices determined by scanning ellipsometry were in the typical range of TiO_2 phase structures. The surfaces showed good photoactivity even without annealing; which was detected in various way.

Coating tests on various material demonstrators showed that an adhesive coating is possible on glass as well as on metallic surfaces (e.g. Ti, stainless steel) and plastics (PEEK). Despite long exposure of the samples to the plasma, no obvious changes in the substrate material were observed other than the colour change because of the deposited layer. The process is therefore gentle on the surface and easily transferable to different materials.

Depending on the process parameters during the production of the coating systems and the irradiation of the samples, different physicochemical states were generated by the activation. Even the initial activation of the layers and the associated photo-induced hydrophilicity considerably reduces the adhesion of micro-organisms and suppresses biofilm formation.

In addition to the INP, the Institute for Bioprocessing and Analytical Measurement Techniques e.V. (IBA) in Heilbad Heiligenstadt worked on this IGF (Collective industrial research) project of the European Research Foundation Thin Films (EFDS) (19885 BR).



Ti+C+O HiPIMS+PbII combination coatings of different thicknesses on PEEK (0/30/90/180 min treatment time)

XPS depth profile of a Ti+Cu+O HiPIMS+PbII combination coating

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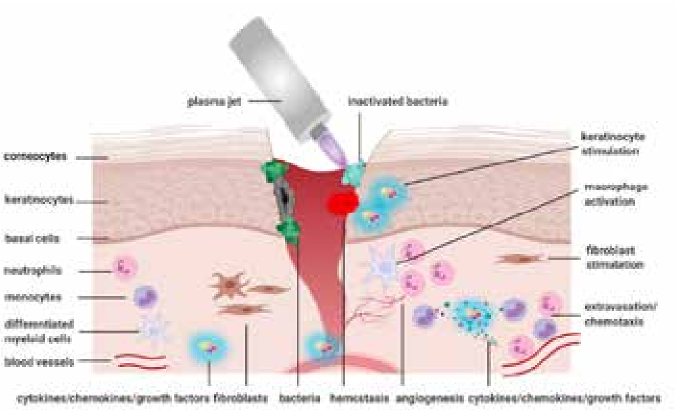
Overview

The "Plasma Medicine" research programme combines plasma physics and plasma technology and life sciences under one roof. Fundamental research on the molecular mechanisms of the interaction of cold atmospheric pressure plasma with living cells and tissues combined with application-oriented research on the possible use of plasma sources in the context of medical therapy concepts are the hallmarks of the research work of the INP in this field. The research work continues to focus on three thematic areas:

- the clarification of the biochemical and molecular mechanisms of biological plasma effects with special consideration of redox-based process
- the design, construction, and characterisation of experimental plasma sources for biomedical applications
- The support and monitoring of clinical research and therapeutic application of cold atmospheric-pressure plasma sources



Cellular target structures in the vicinity of a wound via which wound healing can be stimulated by exposure to cold atmospheric pressure plasma

For this research work, a broad spectrum of microbiological as well as cellular and molecular biology techniques is available in modern laboratories. These are combined with the plasma physics and engineering expertise established at the INP over many years in an interdisciplinary research structure. In 2020 and 2021, considerable advances in knowledge – particularly in the elucidation of the molecular mechanisms of regeneration in injured tissue through plasma application – were achieved. Valuable contributions have thus been made to put the clinical application of cold atmospheric pressure plasma sources on a solid scientific basis. On the initiative of neoplas med GmbH, a spin-off from the INP, the Federal Joint Committee (G-BA) passed a resolution in July 2021 to test the use of cold plasma in chronic wounds. Among other things, this was justified with the scientifically comprehensible concept that underlies this methodology and justifies its systematic use in the treatment of patients with chronic wounds. This is due not least to the research results achieved by the Plasma medicine research programme in cooperation with clinical partners, in particular with the University Medicine Greifswald, the University Medicine Rostock, and Klinikum Karlsburg. Together with a guideline "Rational therapeutic use of cold physical plasma", which was developed under the umbrella of the Association of the Scientific Medical Societies in Germany (AWMF) with the participation of the INP and which will be completed in 2022, important prerequisites for the further establishment of plasma medicine in clinical practice have been created.

As a branch of the INP, the Karlsburg Diabetes Centre of Excellence (KDK) at Klinikum Karlsburg has further consolidated its activities for application-oriented plasma medical research. A clinical study on plasma application in diabetic foot syndrome was conducted with the participation of the KDK. With the study results published in 2020, it was clinically proven that the wound-healing effect of cold atmospheric pressure plasma is not ostensibly based on its antimicrobial effect but rather due to a direct stimulation of tissue regeneration.

Application-oriented outlook

PLASMA SOURCES FOR MEDICAL APPLICATIONS

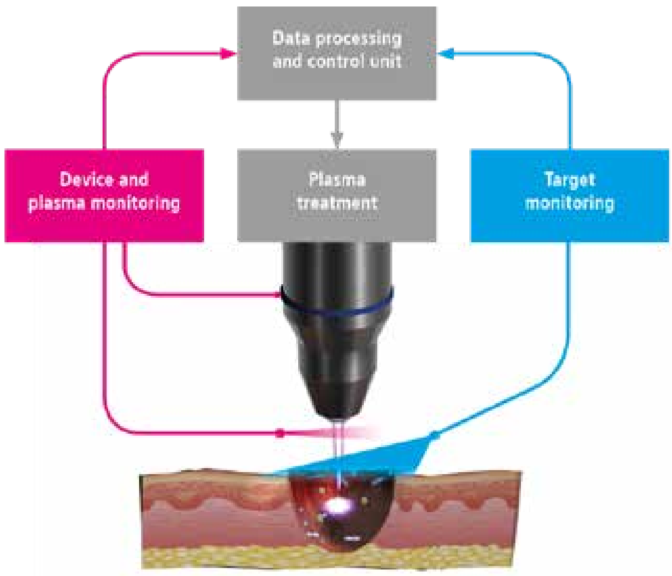
The argon-operated atmospheric pressure plasma jet kINPen, which was conceived and intensively investigated at the INP, further developed into a product by neoplas med GmbH Greifswald and CE-certified as kINPen® MED in 2013 as a Class IIa medical device, continues to form an essential basis of the application-oriented research expertise in the field of medical plasma devices. On one hand, the focus is now on the application-oriented optimisation and further development of the kINPen concept in cooperation with neoplas med GmbH. including the kINPen Dent for use in dentistry and a plasma jet array for the treatment of larger surfaces. On the other hand, research work on the use of other working gases and gas mixtures was advanced in order to open up possibilities for application-specific "plasma tuning" via specific variations in the plasma composition and the resulting variable biological effects. In all research work on plasma sources, the regulatory requirements for medical products are taken into account from the outset in order to enable the rapid transfer of research results into medical products.

The combination of medical plasma sources with imaging techniques for the real-time analysis of treated biological targets (e.g. wound surfaces) as well as with plasma diagnostics to monitor plasma parameters during treatment should lead to a new generation of feedback-controlled and automated plasma therapy systems. To this end, research work on visualising plasma effects in tissue samples and influencing plasma properties through interaction with biological structures was further advanced.

OPENING UP NEW FIELDS OF APPLICATION

After many years of application-oriented fundamental research focusing on the elucidation of molecular mechanisms of plasma-assisted wound healing, research work is now concentrating on harnessing the potential of plasma in cancer treatment. Here, too, the expertise in redox biology built up in the Plasma medicine research programme forms an essential basis for preclinical research work in cooperation with partners from medicine. Worth mentioning here are studies on plasma application for the treatment of oral precancerous lesions in cooperation with the University Medicine Greifswald and on melanoma treatment in cooperation with the University Medicine Rostock. The realisation that the plasma treatment of cancer cells also produces immunological effects opens up possibilities for the use of plasma in cancer therapy within the framework of vaccination concepts.

The possibility of using cold atmospheric pressure plasmas in dentistry, which had been discussed for some time, was further advanced within the framework of an industry-led project on the cleaning and functionalisation of implant surfaces in vivo with the participation of the INP. The result of this project will be a plasma-based medical device that will be tested for its suitability as an innovative concept for the treatment of peri-implantitis in a clinical trial planned for 2022 in combination with another mechanical treatment procedure.



Concept of a plasma medical therapy system: Combination of plasma treatment and continual plasma and target monitoring as well as the automatic adjustment of the plasma parameters to the treatment conditions

Core-funded project "Plasma and cell"

The research work in the "Plasma Medicine" research programme is mainly carried out within the framework of the BMBF-funded Centre for Innovation Competence (CIC) "plasmatis – Plasma plus Cell" as well as other third-party funded projects. This work is complemented and supported by a core-funded project entitled "Plasma & Cell". This enables preliminary research to be carried out in order to lay the foundations for later project applications and to test new medical applications for cold atmospheric pressure plasma. In addition to the CIC plasmatis, the core-funded project also offers the possibility of supervising internships and qualification work for young scientists.

PLASMA EFFECT ON PIGMENTATION OF THE SKIN

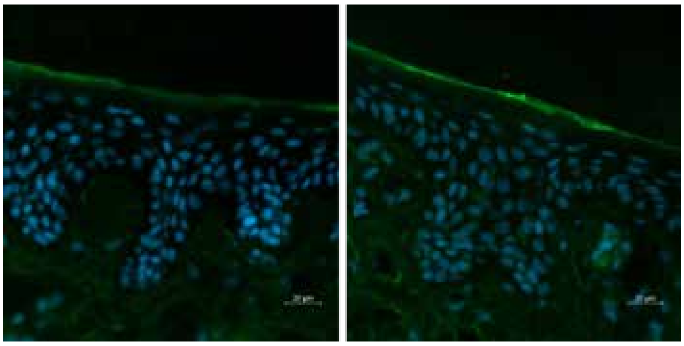
As part of a dissertation successfully completed in 2021 at the Faculty of Mathematics and Natural Sciences of the University of Greifswald, the possible use of cold atmospheric pressure plasma to influence the pigmentation of the skin was investigated. It was shown that plasma treatment with the cold atmospheric pressure plasma jet kINPen®MED exerts a rather small effect on the pigmentation of cultured melanocytes as well as human skin samples treated ex vivo. On one hand, this means that the use of cold atmospheric pressure plasma for the treatment of pigmentation disorders does not appear to be particularly effective. On the other hand, these results also prove that in the context of the therapeutic dermatological applications of the kINPen®MED, an influence on skin pigmentation as an unwanted side effect should also not be expected.

PLASMA-INDUCED OXIDATIVE CHANGES IN TISSUE BIOMOLECULES

After studies on plasma-induced changes of molecules in liquids have become an essential part of fundamental research for the elucidation of molecular mechanisms of biological plasma effects, it was possible within the framework of a medical doctoral thesis with the University Medicine Greifswald to demonstrate plasma-induced oxidative changes on biomolecules directly in tissue by means of immunohistochemical methods. The aim is to create a reference method for the direct representation of plasma effects in tissue using spectroscopic methods.

PLASMA EFFECTS IN VIVO – PRECLINICAL RESEARCH

To further elucidate the mechanisms of plasma effects on living systems, additional animal studies were conducted. Thus, the effect of a plasma treatment on the barrier function of the skin was investigated. It has been shown that as a result of plasma treatment, the uppermost skin layer (stratum corneum) is loosened. This is caused, in particular, by oxidative changes in skin lipids and modifications of cell-cell connections. Together with the intensified skin perfusion and oxygen saturation of the tissue, this led to the increased penetration of the model substance curcumin. After individual studies on patients at Klinikum Karlsburg and the KDK as well as at the University Medicine Greifswald had already shown by means of a hyperspectral camera that plasma treatment has positive effects on tissue perfusion and oxygen saturation in wounds. This was further confirmed in a systematic animal study.

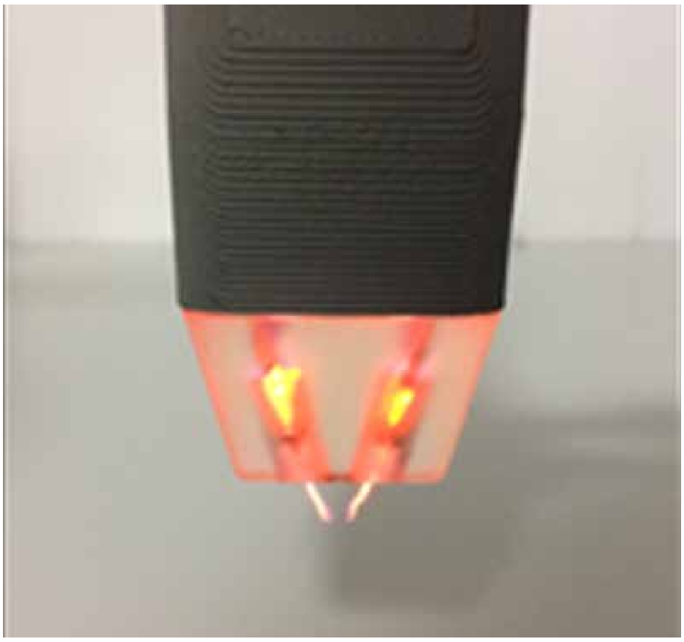


Green immunofluorescence staining of oxidatively modified thiol groups in proteins (R-SOH, R-SO_2H, R-SO_3H; Enzo: ADI-OSA-820 with anti-rabbit AF-488) on a tissue section of a pig's ear with the top layer of skin (stratum corneum) removed; left: without plasma treatment, right: after 60 s plasma treatment (kINPen)

Third-party funded projects

PROJECT CENTRE FOR INNOVATION COMPETENCE (CIC) "plasmatis – plasma plus cell"

The two junior research groups "Plasma Redox Effects" (CIC-PRE) and "Plasma Liquid Effects" (CIC-PFE), which have been funded by the BMBF since 2016 and 2017, respectively, have further expanded their expertise in the field of redox biology in particular. The focus of the junior research group CIC-PRE, which was consolidated as a research group at the INP in 2021, is on oncology and tumour immunology. The focus of the junior research group CIC-PFE is the plasma-induced modification of biological molecules in liquid phases. Here, mechanisms of redox-based biological plasma effects were further elucidated, and ways to systematically characterise the biochemical activities of plasma sources using "sensor molecules" were shown. The research groups "Plasma Wound Healing" (CIC-PWH) and "Plasma Source Concepts" (CIC-PQK), which were consolidated after the first CIC funding phase 2006–2015, form the basis for application-oriented research of the INP at the KDK.



V-Jet: Neon-powered dual plasma jet for cancer treatment

PROJECT ONKOTHER-H

The project "ONKOTHER-H: Development platform for innovative oncological therapies using the example of the most common human cancer – skin cancer" is being funded under the leadership of the University Hospital of Rostock as part of the Excellence Initiative of the state of Mecklenburg-Western Pomerania. Within the framework of this alliance, the INP is optimising cold plasma applications in cell culture models, especially in combination with novel tumour suppressive substances. Within the scope of the project, among other things, a novel, neon-operated dual plasma jet (V-jet) was technically developed for use in cancer treatment and characterised and tested in comparison with the already established argon-operated plasma jet kINPen.

PROJECT DINPLAS

In 2014, the DIN specification (DIN SPEC) 91315 "General requirements for plasma sources in medicine" was published under the leadership of the INP. The project "DINPlas – Development of a DIN standard for testing the efficacy and safety of atmospheric pressure plasma sources for medical applications", which is now funded by the BMWi, aims to adapt and optimise the methods proposed in DIN SPEC 91315 based on practical experience and to transfer them into a regular standard.

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Overview

The research programme is primarily concerned with the investigation, development, and optimisation of plasma-based methods and processes for the degradation of pollutants and micro-organisms in air, water, and on surfaces, including foodstuffs and seeds. It has been shown that plasma treatment also promotes and supports seed germination as well as the growth and stress adaptation of crops. The basics for this have been investigated in a separate research group "Plasma agriculture" and in the meantime also in various projects of the alliance "Physics for Food", which is funded by the German government within the framework of the initiative "Wandel in der Region". The research programme thus increasingly provides solutions to challenges as described in the United Nations Sustainable Development Goals, called for in the Green Deal of the European Commission, and supported by the national bioeconomy strategy of the German government. This connection and the associated demands are reflected in the development of the work areas and fields of application of the research programme.

The application of plasma-based processes in agriculture and agricultural production is thus moving increasingly more into the foreground. In various activities, the entire value chain – from pre- and post-harvest to food production and digestion processes for the recovery of biogenic residues – is covered. In addition, various methods can reduce environmental impacts (e.g. from waste water) or specifically replace chemical pesticides. Approaches for animal husbandry, with which hygienic requirements can be better met and the use of antibiotics can be reduced, are also being pursued. Plasma technologies are thus increasingly establishing themselves as an important tool in the bioeconomy.

Another important issue that has gained importance as a result of the COVID-19 pandemic is the controlling of the spread of infectious diseases (e.g. via indoor air or through contamination of protective equipment).

The mechanisms of action provided by a plasma for various applications and tasks are chemically reactive species, ultraviolet radiation, and electric fields as well as shock waves in liquids. By providing energy and operating parameters in a suitable manner, these processes can be specifically controlled. All approaches allow treatment with a relatively small increase in temperature and are therefore particularly well-suited for application on temperature-sensitive goods such as plant material. Furthermore, especially for plasmas generated in ambient air or water, no long-lasting harmful reaction products are to be expected.

As part of the "Physics for Food" project funded by the Federal Ministry of Education and Research through the "Wandel in der Region (WIR!)" programme, various plasma processes for more sustainable agriculture and agricultural production are being developed together with industrial partners.

Application-oriented outlook

Thematic area: Clean air

The research topic has been dedicated to the development of new processes for degrading pollutants and germs in gas streams and ambient air. For example, the treatment of waste gases for the machining of various materials in laser cutting processes is currently being investigated. By combining a plasma electrode with an ion wind, it was also possible to show that aerosol-borne germs in the ambient air (e.g. in hospitals) can also be efficiently broken down.

This approach is now also being investigated for air treatment in livestock stables. For use in plasma-based indoor air hygiene (plasma filters), the research programme is now also increasingly dedicated to standardisation procedures (i.e. the development of a DIN SPEC). There are currently no DIN standards that allow the different systems on the market to be compared using plasma technology.

Plasma module in a demonstrator for the treatment of process or waste water in the Anklam sugar factory. Together with other processes (e.g. ultrasound, ultrafiltration, ozonation, and activated carbon filters), the aim is to treat the water as completely as possible in order to return it to the production process.

Thematic area: Clean water

In addition to the efficient degradation of pharmaceutical residues shown in this research topic, corresponding processes are now also being investigated for the degradation of pesticides and natural toxins (e.g. cyanotoxins), which are increasingly occurring because of climate change. In addition, the reduction of antibiotic-resistant bacteria, viruses, and spores in water is increasingly coming to the fore in order to prevent the spread of zoonoses, among other things. Targeted applications focus on "hotspots" (i.e. the point of entry of contaminants).

In addition to waste water (e.g. from hospitals), this also includes the treatment of process water for comprehensive recirculation. The food industry, aquaculture plants, and laundries are of particular interest. The focus is on investigations on systems that operate under real conditions.

Thematic area: Clean food

This research topic explores plasma treatments for the food industry. Packaging as well as fruit and vegetables are to be kept microbially clean, and the shelf life of processed food is to be extended in a gentle manner. The increasing spread of "convenience food" products – also in the German market – increases the importance of hygiene and safety measures. The companies see a growing need for new processes because of the more stringent regulatory conditions. As it has been demonstrated, plasma processes can provide a much-needed alternative, for example in the implementation of a plasma process for washing ready-to-eat packaged lettuce under production conditions and on an industrial scale. There is also a need for new digestion methods to extract ingredients (e.g. food supplements from algae). Here, too, plasma processes were promising because of their more efficient release.

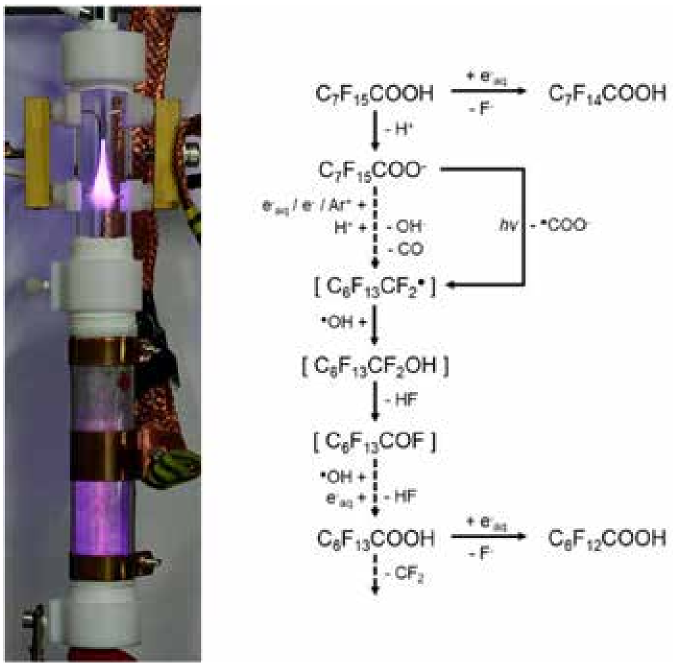
Thematic area: Clean health

The research topic has so far dealt with the possibilities of plasma-based biological decontamination in the nursing and medical sector. This includes the disinfection of surfaces, products, and systems (e.g. endoscopes) for which autoclaving is not possible. An important goal is to prevent the spread of nosocomial infections. The successful spin-off of Nebula Biocides GmbH is one result of these efforts. In the course of the COVID-19 pandemic, plasma-based processes also gained increasing importance for the reprocessing of protective equipment (e.g. FFP2 masks) and in public spaces (e.g. buses and cruise ships). In the meantime, various methods have also been developed for animal health in order to provide effective methods for soil disinfection in stables or the prevention of animal diseases.

Core-funded project: Plasma processes as tools for the bioeconomy

The efforts of the research programme are now strongly characterised by the development of various plasma processes and technologies in various fields of application of the bioeconomy. Whilst the application-oriented third-party-funded projects aim to develop the economic advantages of plasma processes, the accompanying core-funded project strives to increase the understanding of the connections between how plasma is used and the processes that are fundamentally possible with it. The main focus is on mechanisms and reactions of active components provided by the plasma with organic material (i.e. plant cells, algae, and micro-organisms) and corresponding molecular processes in aqueous solutions. For many applications the chemically reactive species formed are decisive. Accordingly, it is determined for various methods how operating parameters, especially the way in which electrical energy is supplied, affect the formation of reactive species such as hydroxyl radicals or hydrogen peroxide.

For example, the breakdown of pulsed discharges was characterised as a function of pulse duration and pulse voltage as well as the conductance of the water with a time resolution of only a few nanoseconds and related to the respective formation rates. As a result, shorter pulse durations have been shown to be associated with higher efficiency because it becomes increasingly difficult (i.e. more lossy) to increase the discharge volume for longer propagation times.



Experimental plasma system for the detailed investigation of oxidation and reduction processes and how they contribute to the degradation of perfluorooctanoic acid, among other things. Operating parameters and plasma chemical processes can be specifically related to each other.

The results can thus directly explain the decreasing efficiency for the degradation of pharmaceutical residues. Similar relationships were found for the degradation of cross-links of polymer structures in a biomass model substrate by a plasma generated with microwave excitation. For the inactivation of micro-organisms, the indirect reaction chemistry resulting from the plasma being introduced into the liquid has proven to be decisive. In particular, the peroxynitrite formed from hydrogen peroxide and nitrogen oxides is more effective than the starting components. However, under certain circumstances, this substance can decompose again quite rapidly without becoming effective. The formation and degradation were therefore determined by time-resolved *in situ* spectroscopy. Formation rates and retention times of peroxinitrite depend strongly on the buffer capacity of the aqueous solution and ultimately determine the antimicrobial effectiveness. Conversely, the understanding of these processes offers the possibility of adjusting the generation processes (i.e. the operating parameters for the plasma) in such a way that optimal results can be achieved. In addition to oxidation and reduction this also includes mechanisms of action such as pulsed electric fields and shock waves. These can be specifically amplified in spark discharges (e.g. by means of electrical control). This method – with pressures well above the stress limit of the cell wall – has proven itself especially for the extraction of temperature-sensitive ingredients from robust microalgae. Conversely, the reaction chemistry and temperatures play only a subordinate role without any harmful influence on the extracted substances. In addition to these direct processes, indirect effects (e.g. the influence on biological processes) will also play a greater role in future.

Third-party funded projects on the digestion of biomass for ingredient extraction and energy recovery

A rapidly and successfully developing topic directly related to the bioeconomy is the digestion and upgrading of biomass through the support of plasma-based processes. The treatment of fermentation residues, in particular liquid manure, was an obvious choice in order to improve their digestion and make them available for further energetic utilisation in biogas plants. For this purpose, relatively stable polymer structures have to be broken up as much as possible. Together with Power Recycling Energyservice (PRE) GmbH, a process that combines an ultrasound process already in use with plasma treatment was developed. For this purpose, the plasma is ignited and maintained by microwave radiation directly in the biomass substrate in the ultrasonic field. Whilst ultrasound acts mainly mechanically on cell walls, plasma provides another efficient mechanism for disruption through the various radicals formed. This is done at normal pressure, ambient temperature, and without the addition of chemicals. The effectiveness is immediately evident in a drop in viscosity and suggests synergies that could lead to substantial energy savings. As a result, the micro-organisms can better utilise the fermentation residue treated in this way after it is returned to the biogas plant, and the overall energy yield is increased. Apart from this, the method also offers several other advantages and possibilities. In addition to energy recovery, substrate residues can also be used as a nitrogen-rich biofertiliser.

Digests have to be much more subtle if valuable. In many cases, sensitive ingredients are to be extracted from biological material. The cell structures have to be broken down to such an extent that the target substance can be extracted as completely, purely and with as little effort as possible whist retaining its structure. A special potential for highly effective ingredients lies dormant in various species of microalgae. Many of these have a particularly strong cell wall, and processes need to be developed to break this down efficiently and gently. A new approach developed at the INP uses spark discharges for this purpose. These are triggered by high-voltage pulses. The sparks are ignited directly in the algae suspension and generate shock waves with a pressure of about 500 MPa in the immediate vicinity of the discharge. These shock wave mechanically break open the cell wall. This process is particularly suitable for the extraction of heat-sensitive compounds and was investigated for this purpose together with the Institut für Getreideverarbeitung (IGV) GmbH for the more efficient extraction of basic substances for food supplements. Other possibilities are the extraction of carotenoids or natural dyes such as phycocyanin.

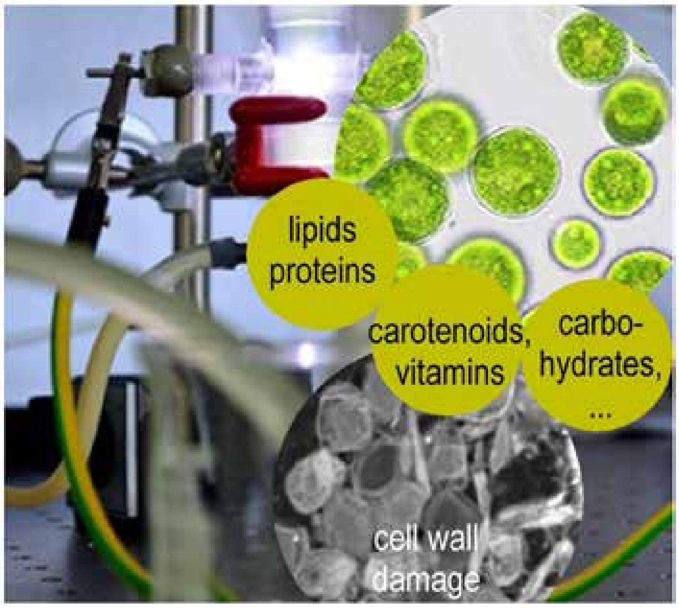


Illustration of the gentle disruption of microalgae by spark discharges generated in suspension with 100 ns high-voltage pulses. The shock waves can release various temperature-sensitive ingredients.

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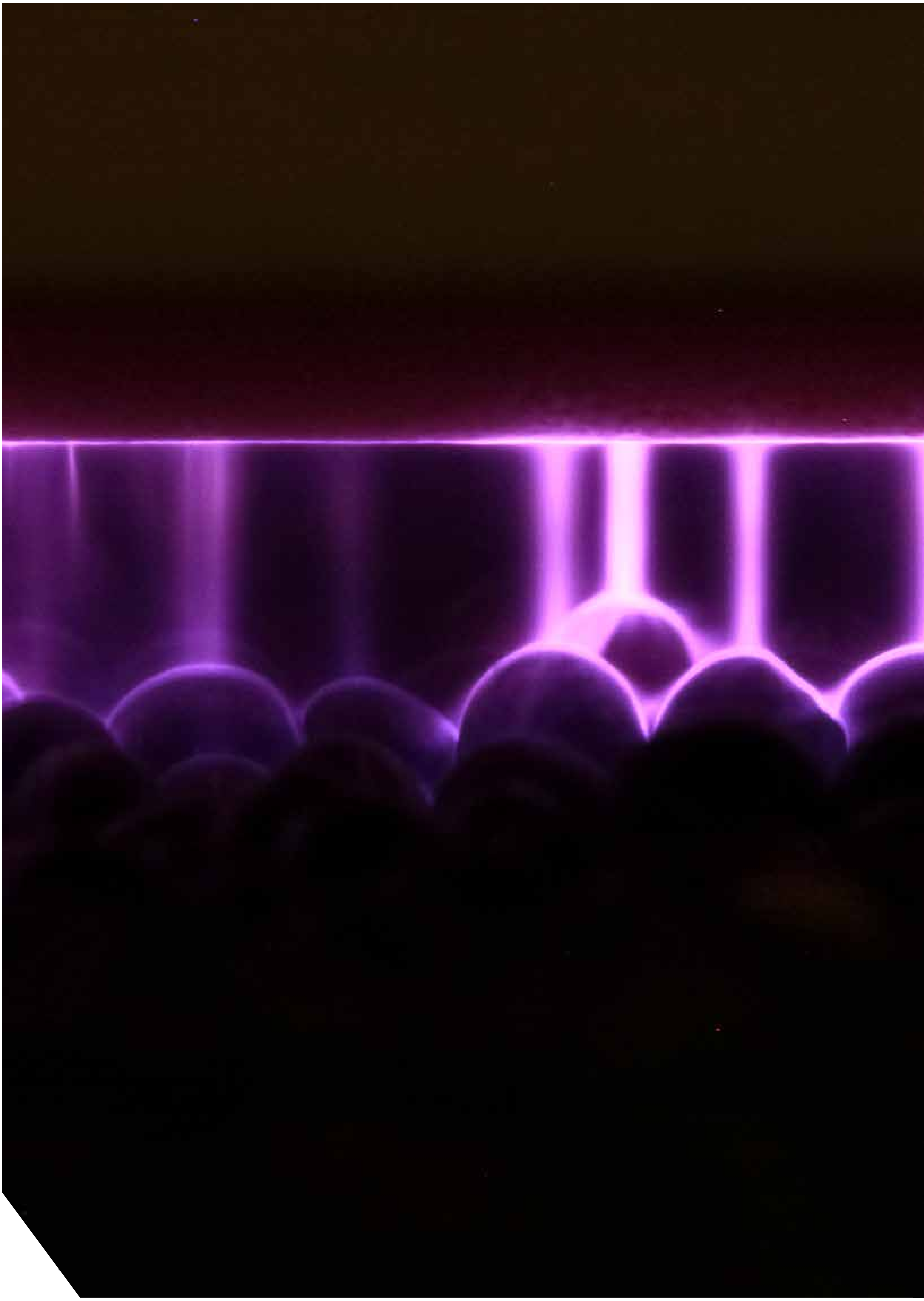


RESEARCH GROUPS

Overview

The successful research work of the Centre for Innovation Competence "plasmatis" is continued in a second funding phase with two new junior research groups: "Plasma Liquid Effects" and "Plasma Redox Effects". The research groups of the first funding phase were consolidated and a self-financed junior research group in the field of biosensing surfaces was estalished. In addition, for research groups are established at the INP.

The (junior) research groups independently pursue interdisciplinary research topics outside of operational activities or research assignments – an opportunity for junior researchers to gain initial management experience and build their own profiles.

CIC plasmatis – Plasma Redox Effects

CIC plasmatis – Plasma Liquid Effects

Biosensing Surfaces

Plasma Source Concepts

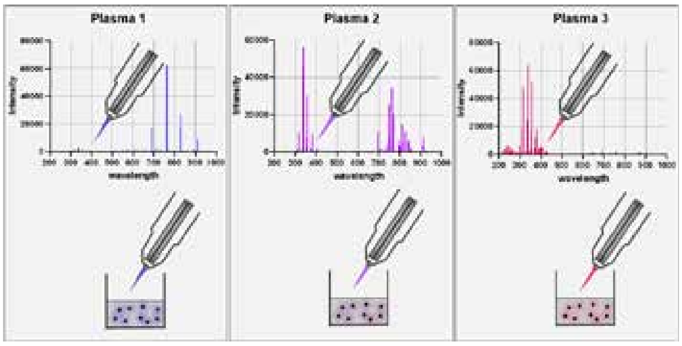
Plasma Wound Healing

Plasma Agriculture

Materials for Energy Technology

CIC plasmatis
Plasma Redox Effects

Gas plasma treatment is now an established procedure for treating chronic and infected wounds and ulcers. During treatment, the technology generates a mixture of different components; of these, reactive oxygen species (ROS) and reactive nitrogen species (RNS) play a central role in mediating efficacy. These ROS/RNS are not only evolutionarily conserved antimicrobial agents known from many fields but also play a crucial role in cell signalling and wound healing mechanisms. Preclinical studies in animal models as well as recent clinical findings also suggest that the wound healing properties of gas plasma treatment also take place in isolation from antimicrobial effects. This indicates that direct cell changes by the gas plasma-generated ROS/RNS are possible, thereby opening up a number of new fields of application for medical plasma technology.

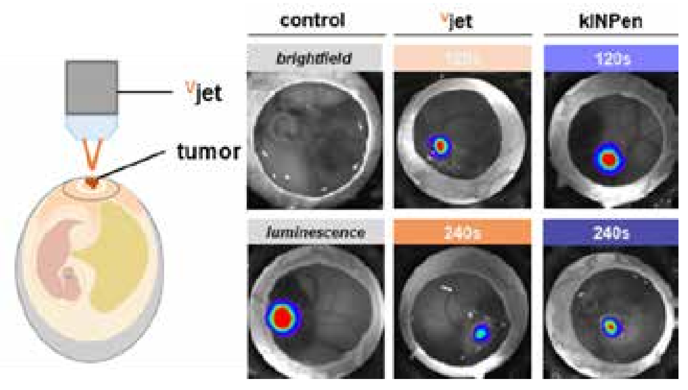


Principle of adjusting the gas plasma generated ROS/RNS by changing the working gas feed into the one plasma jet, which leads to different ROS/RNS input into treated samples. Schematic illustration, not to scale. DOI: 10.3390/vaccines9050527

The identification and investigation of such new fields of application beyond descriptive wound healing to the mechanisms and concepts of therapeutic radicals of gas plasma technology as well as redox effects in cells is the main task of the research group "Plasma Redox Effects" of the INP. It emerged in 2021 from the junior research group "Plasma Redox Effects", which had existed for more than five years. The research group has explored different topics within the framework of projects funded by various founders (e.g. BMBF, EU, DFG, Mecklenburg-Western Pomerania state funds, the Head and neck tumour research foundation (Stiftung Tumorforschung Kopf-Hals), the Ferdinand-Eisenberger foundation, and the Gerhard-Domagk foundation). The main focus of the work is in oncology and tumour immunology, which is the focus of this report. Further research is being conducted on toxicity-associated redox effects after polymer exposure as well as on the antiviral effects of gas plasma technology and its optimisation in the context of redox chemistry-adapted inactivation for combating antibiotic-resistant germs in wounds.

A central result of the "Plasma Redox Effects" research group was the establishment of a new dogma as an explanatory basis for the sensitivity or resistance of different tumour cell types to gas plasma-induced cell death. For example, a broad screening of over 35 cell lines showed that basal metabolic activity was most predictive of resistance to gas plasma-mediated tumour cell inactivation (Free Radical Biology and Medicine, DOI: 10.1016/j.freeradbiomed.2021.02.035). This study also failed to confirm two previous dogmas proposing the cell membrane-based expression of aquaporins as well as ROS/RNS-producing and redox-regulating proteins and enzymes as predictive factors. In addition, the study puts into perspective the often assumed but rarely investigated selectivity of gas plasma treatment towards tumour cells compared with non-tumour cells. In the screening, there were both more sensitive and more resistant tumour cell types compared with healthy cells.

Furthermore, a better understanding of the redox regulation of gas plasma-treated tumour cells was gained. The overexpression of antiporter xCT thus confers better protection against gas plasma-induced inactivation because increased antioxidant-acting glutathione can be produced (Redox Biology, DOI: 10.1016/j.redox.2019.101423).



New v-Jet plasma source and anti-tumour effect in benchmark comparison against the kINPen in vascularised 3D tumour organoids in the TUM-CAM model. Both sources showed tumour-toxic activity. DOI: 10.1038/s41598-020-80512-w

Decisive progress has been made in the field of tumour immunology. On one hand, it was shown that the composition of the working gas of the kINPen plasma jet does not only have a decisive influence on the anti-tumour effect in a syngeneic melanoma model of the mouse but also that the infiltration of immune cells into the tumour tissue is considerably changed as a result. Even additive-stimulating effects of immune cell infiltration were achieved by combination treatment with gas plasma and a clinically relevant anti-tumour procedure. Furthermore, vaccination of healthy mice with melanoma cells inactivated by gas plasma resulted in considerable protection against the growth of live tumour cells that were later injected. Gas plasma therapy of melanoma can thus induce immunogenic cell death (ICD) (Advanced Science, DOI: 10.1002/advs.201903438).

In order to obtain a fundamental understanding of the immunologically relevant effect of gas plasma treatment in biological systems for the first time, the immunogenicity of gas plasma-generated ROS/RNS on a model protein was investigated in a further study. Once again, we were able for the first time to provide conceptual proof that this effect is controllable by varying the admixing gases in the plasma jet and thus changing the profile of the ROS/RNS produced. Protein modification of ROS/RNS led to increased T cell activation in mouse T cells specifically reactive to the model protein. When mice were inoculated with gas plasma-treated protein in order to establish immune protection against the model protein, these mice were significantly better protected against the growth of melanoma cells genetically engineered to artificially express this model protein (Advanced Science: 10.1002/advs.202003395).

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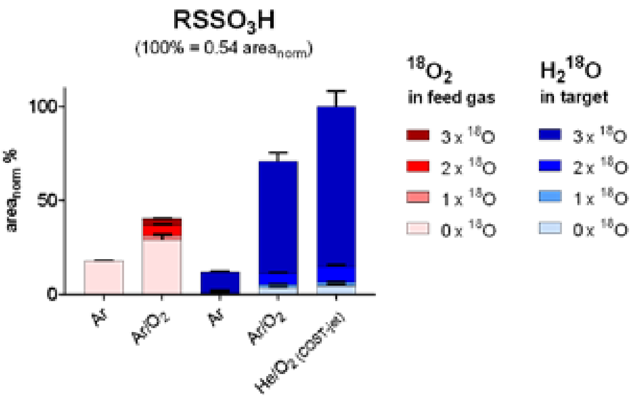
CIC plasmatis
Plasma Liquid Effects

The junior research group "Plasma Liquid Effects" investigates the interaction between cold plasmas and the species or photons they emit on biomolecules, especially proteins and lipids. The idea behind this is to be able to draw conclusions about the chemically active reactive species based on the detectable modification of the molecules. The hypothesis is tested with respect to the extent to which modifications in the biomedical-clinical context contribute to the effectiveness of cold plasmas.

Cold plasmas show good efficacy in stimulating wound healing and combating malignant diseases. They also have a pronounced antimicrobial property; however, this seems to be of secondary clinical importance. As recent research results have shown, these characteristics only seem to contradict each other. Rather, they are an expression of the interaction of plasma-generated reactive oxygen and nitrogen species (ROS/RNS) with cellular redox signalling processes that act as modulators and amplifiers of plasma-generated ROS/RNS (see also report of the "Plasma Redox Effects" research group). The composition of the effluent of the argon plasma jet kINPen varies depending on the distance to the active zone. Of particular relevance for the chemical processes at the treated target are singlet oxygen, the complex of atomic oxygen and hydroxyl radicals, and nitric oxide.

In order to better understand the chemistry of the short-lived species, the chemical reactions at the gas-liquid interface were studied. It was shown that at the interphase there is an intensive exchange between the molecules/ions of the liquid phase and those from the gas phase. By means of electron spin resonance spectroscopy and dye experiments, it was possible to demonstrate that many reactions for the formation and degradation of nitrogen monoxide, nitrogen dioxide, and peroxynitrite take place here (Jablonowski 2018, Lackmann 2019, Breen 2020). Nitric oxide forms a central point around which the chemically more active RNAs are formed through the interaction of atomic oxygen and hydroxyl radicals, among others. Using cysteine and tyrosine (Lackmann 2019, Bruno 2020) or peptides (Wenske 2020, 2021), it was shown that nitration and nitrosylation take place especially at the phenolic ring of tyrosine or the electron-rich heterocycles of tryptophan. However, the extent of occurrence of such modifications is small (≤ 5%) compared with the chemical groups caused by ROS – probably because of degradation processes caused by ROS.

Atomic oxygen is one ROS that is particularly active at the interphase. It reacts with all molecules present in the boundary layer (including water, nitric oxide (see above), amino acids, peptides, and proteins) forming either products (Sgonina 2021) or secondary reactive species (Wende 2015, Wende 2020). These include hydroxyl radicals and hypochlorite ions (in the presence of chloride ions). Because the latter are relatively long-lived, they lead to oxidation and chlorination processes on free amino groups, alkyl residues, and aromatic rings in both peptides and proteins – even after the plasma treatment has ended (Wenske 2021, among others). The range is from 1 to 10% and is strongly modulated by the supply of chloride ions. In turn, the secondary hydroxyl radicals react with existing molecules and lead to comparable modifications. Using heavy oxygen isotopes, it was shown

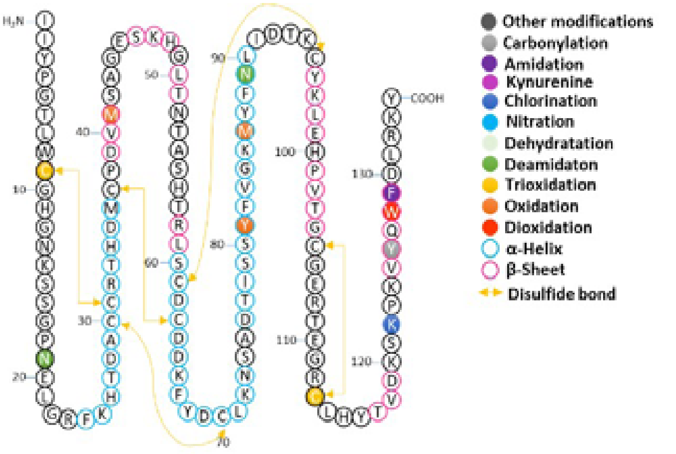


Direct treatment of cysteine (Wende 2020). The molecular composition of the compound cysteine S-sulfonate ($RSSO_3H$) after labelling the gas phase with $^{18}O_2$ (red) and the liquid phase with $H_2{}^{18}O$ (blue). It is clear that the proportion of oxygen atoms from the target outweighs that from the gas phase.

that primary and secondary species are incorporated into product molecules. However, the ratio between the two differs, thereby indicating different reaction pathways both at the interphase and in the fluid body (Wende 2020). Amino acids were used for these studies, and experiments with proteins and lipids are currently under way. Initial results are promising and suggest differences.

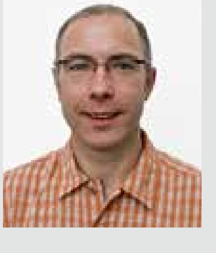
Because of its special electronic structure, singlet oxygen is another important reaction partner with a relatively high selectivity. It probably does not lead to the formation of secondary species from the molecules at the interface but rather mostly to 4+2 cycloaddition reactions with suitable structures. These include mainly the heterocyclic rings of tryptophan and histidine and the formation of ring-open oxidation products (including kynurenine derivatives) (Wenske 2021, Nasrin 2021). Mostly amino acids found on the surface of the protein are affected by such changes because the short lifetime (a few µs) of singlet oxygen does not allow further penetration into the protein. This was shown with the enzyme phospholipase A_2 (PLA_2), the activity of which is reduced by the plasma treatment. This is caused by the singlet oxygen-induced ring opening at tryptophan 128 and the accompanying change in secondary structure with loss of binding ability to the lipid membrane. This inactivation can be of interest in the fight against cancer because the active PLA_2 causes pro-inflammatory and pro-carcinogenic effects. A clear influence of plasma treatment on the physiological value of other proteins is also emerging (Clemen 2021, Krüger in prep., Yu in prep).

Also lipids are oxidised by plasma-generated species. Using supported lipid bilayers (SLB) of different compositions, it was shown that indirect plasma treatment has a much lower chemical potential than direct treatment. Nevertheless, loss of membrane properties occurs because of the formation of pores and changes in molecular orientation (Ravandeh 2020, 2021, Nasri 2022). It can be assumed that the cell membrane of eukaryotic cells also shows such behaviour.



Non-enzymatic post-translational modifications in the protein PLA_2 after direct treatment with the kINPen. By changing the secondary structure, the protein loses its activity (Nasri 2021).

CONTACT



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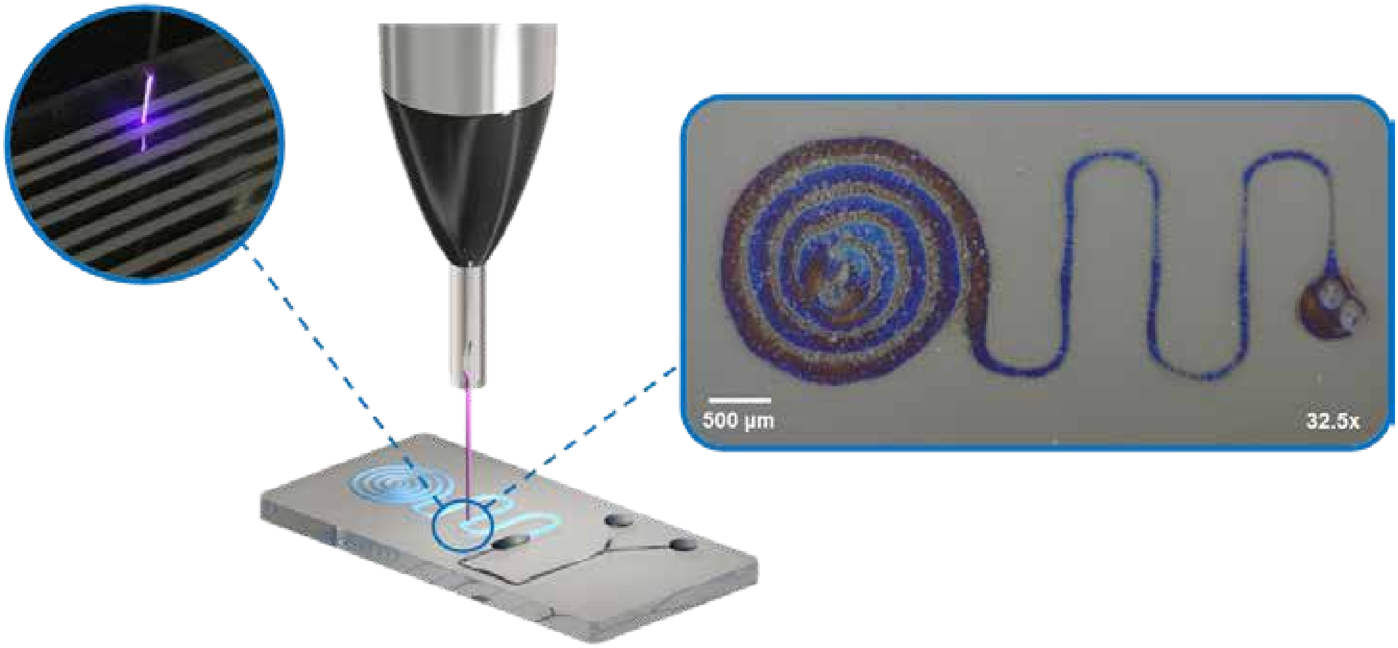
Biosensing Surfaces



Schematic representation of the SurfAP3® plasma printer for the structured generation of functional layers and hydrogels with photographic images of the plasma discharge on an open microfluidic channel and a chemical structure generated with SurfAP3® on a silicon wafer.

In an interdisciplinary research environment at the interface of polymer chemistry, material sciences, and plasma technology, the junior research group "Biosensing Surfaces" (BSO) works on the development and characterisation of novel functional layers for applications in medicine, biotechnology, environmental analysis, and food technology.

For biosensory and microfluidic applications, the control of physical, chemical, and biological interface properties is essential to ensure the best possible performance in interaction with the biological environment. Plasma-assisted surface modification processes are an innovative approach for the targeted generation of desired surface functionalities or for the realisation of completely new surface characteristics through the deposition of thin layers.

Plasma printing

Chemically structured surfaces in the sub-millimetre to micrometre range are a particularly valuable platform in microfluidics.

Typical liquid volumes in chip labs (lab-on-a-chip) are in the microlitre – even nanolitre – range. Using microfluidic technologies, this can drastically reduce sample and reagent quantities, speed up reactions, increase throughput, and enable resource-conserving measurements. Particular interest is therefore being shown in the use of multiplex arrays for the simultaneous use of many analytes on a single micro-lab chip. This requires areas of defined chemical and physical properties on the surface that can be produced on any substrate – for example, by means of a plasma printing process developed in the junior research group "Biosensing Surfaces".

This innovative process enables the site-selective deposition of plasma polymer coatings with structure sizes of 50 to 250 µm and layer thicknesses in the range from 20 to 150 nm. A special atmospheric pressure plasma jet developed at the INP is used for this purpose. The proprietary plasma printing technology and the SurfAP3® process have been filed for a European patent. In addition, the technical advancement of plasma printing technology has enabled better reproducibility, faster processing, and deposition on various substrate materials commonly used in the microfluidic and biosensor industries.

Functional films

The core of every biosensor is the biological recognition structure, which can consist of an enzyme, an antibody, DNA, or entire cells.

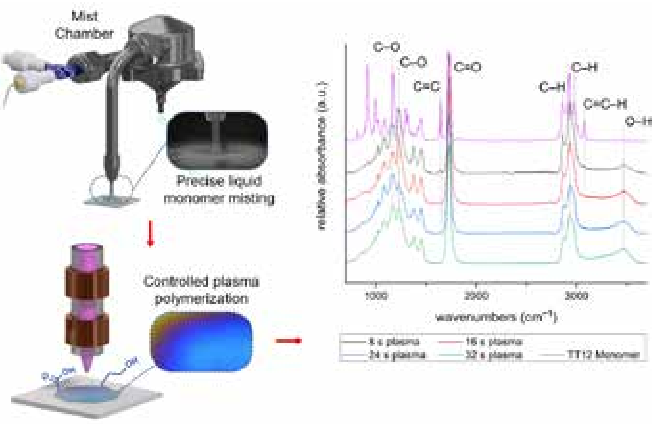
In order to selectively detect the analyte in the sample, a surface modification of the biological recognition film is necessary. The surface chemistry of the recognition structure must be such that no unspecific interactions occur and that there is targeted coupling of the analyte binding partner on the sensor surface. Especially for measurements in real samples it is crucial that the functionalised surface has a sufficient immobilisation density and a sufficiently high binding activity so that even low concentrations can be detected. One focus of the work of the "Biosensory surfaces" junior research group is therefore the generation of thin plasma-polymerised layers that are enriched with oxygen-containing functional groups and with which the efficient coupling of the analyte can be reliably achieved. Investigations into the chemical composition, morphology, and stability of the plasma-polymerised layers in the aqueous milieu showed unique functionality and excellent adhesion to the substrates and emphasised the particular suitability of the chosen approach.

As part of the work of the junior research group, equipment and methods for the plasma-based synthesis of functional thin films from liquid starting materials were designed, developed, and evaluated. In particular, the development of a customised cloud chamber enabled the reproducible production of homogeneous thin plasma polymer coatings. For the first time, a controllable process was successfully demonstrated. With this process, the degree of cross-linking of the polymer chains of plasma polymers can be selectively adjusted in atmospheric pressure plasma processes.

Synthesis of thin hydrogel films

Because of their stimulus-responsive properties, hydrogels are ideal for applications in microfluidics and medical technology. Because of their high water content and tissue-like mechanical properties and the resulting biocompatibility, hydrogel films are also suitable for the development of biomedical sensors.

In particular, the "Biosensory Surfaces" junior research group investigated the synthesis of hydrogel layers by means of plasma polymerisation at atmospheric pressure. It was possible to generate acrylate-based hydrogel layers with thicknesses of up to 10 µm. These show controlled and reversible swelling behaviour depending on the pH value of the buffer solution used. Further investigations have shown that the targeted adjustment of the film thickness and the associated characteristic creasing favours the immobilisation of biomolecules. These layers were produced with high reproducibility and long-term stability. The characterisation of the layers and their deposition on screen-printed electrodes showed their practical applicability in electrochemical biosensing. For example, for the detection of glucose and the parasympathomimetic alkaloid esterin.



Schematic representation of part of the automated process for producing plasma-polymerised thin films at atmospheric pressure. The FTIR spectra of an acrylate-based monomer used and the corresponding plasma-polymerised films obtained at different polymerisation times show that the process allows the adjustment of the cross-linked polymer chains.

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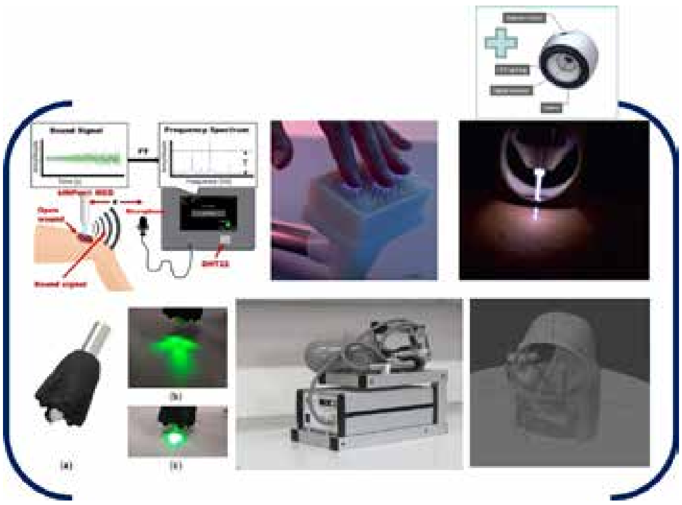
Plasma Source Concepts

The "Plasma Source Concepts" research Group is part of the CIC plasmatis and emerges from the "Extracellular effects" junior research group. The objective of the research group is to address issues relating to cold plasma sources at atmospheric pressure (CAPs) – from the fundamentals and characterisation to the development and production of wire frames, functional models, and prototypes. With the fundamental research findings, there is a sound scientific approach to designing new plasma sources that are tailored to clinical needs.

The work in the research groups focuses on plasma medicine with device development and further development for plasma medical applications and fundamentals. In addition, in close cooperation with the "Plasma Sources" department of the INP, the expertise of the source concepts has also been transferred to almost all research programmes at the INP. Either employees or plasma sources developed by them are found in the research programmes "Plasma Chemical Processes","Bioactive Surfaces", and "Decontamination". The source development or optimisation is applied synergistically with the expertise generated in the CIC plasmatis to the fields of pollutant removal and surface functionalisation.

While the transfer of expertise to other research programmes can further stimulate impulses there, the medical-technical skills are being expanded across the board, especially in the field of medicine at the Karlsburg Centre of Excellence. Thus, sensor and robotics impetuses for the improvement of application acceptance are provided, and new trends such as the application of neuronal networks for wound area determination are tested as part of student qualification work. The use of artificial intelligence as part of a cooperation with the dermatology department in Rostock under Prof. Steffen Emmert came third in the inspired ideas competition in Mecklenburg-Western Pomerania.

In addition to our own direct range of topics, we cooperate intensively with the three other CIC plasmatis groups – both in projects and in the area of basic research in particular. Together with the "Plasma Redox Effects" junior research group, various projects were applied for. The project "Plasma Plus Corona" ultimately received a positive decision from the BMBF. Investigations with different plasma sources and their optimisation for antiviral efficacy are thus carried out jointly. Furthermore, research is conducted in collaboration with the junior research group "Plasma Redox Effects" and "Plasma Liquid Effects" with regard to fundamental phenomena of the plasma sources used in the experimental routines and published jointly. Finally, two joint bilateral funding projects are under way with the "Plasma Wound Healing" research group. These involve developing a scaled-up plasma jet array "Multijet" in collaboration with the neoplas med GmbH as well as developing an accompanying outpatient sensor unit for mobile treatment documentation with the Orthopädie-Technik-Service aktiv GmbH in Greifswald.



Device concept in the Ambuplas project – combination of acoustic operating time detection, visualisation of the effective area, and compatibility with different plasma sources

Furthermore, in the field of plasma sources, various work has been carried out in the context of projects and student theses. In the process, concepts of dielectric barrier discharges (DBDs) as well as plasma jets have been further investigated and partly newly developed and patented. In the field of DBDs, the focus is on the application for the degradation of natural gas odours (PlasmODOR) as well as for exhaust air treatment in laser cutters (SafeCutter). Both of the latter projects as well as the extensive work in the group have provided motivation for a more intensive examination of the plasma-gas flow interaction. A particle image velocimetry (PIV) system was commissioned as a bridge from the fundamental research on plasma-gas flow interaction as well as for application optimisation. A Bachelor's thesis on the investigation of vortex formation by plasma ignition in a DBD exhaust air treatment arrangement was also successfully completed.

In addition to the DBD-based project variety, a project to develop a dental plasma source in combination with a water jet device (PeriPLas) has been running since 2017. This project started in November 2021 with a multi centre study, including a plasma source "periINPlas" developed by the "Plasma Source Concept" research group. This plasma source has passed a preliminary CE test. The study is expected to last at least one year.

For the further conceptual development of plasma jets and DBDs, the application of 3D ceramic printing was explored in greater depth. New concepts have been developed; however, these still need to be tested and verified experimentally. In addition to the 3D ceramic printing of various materials, a system for detailed 3D scanning was acquired. Among other things, this can scan wound areas of patients and make them available in a reproducible way by means of 3D printing.

Finally, a publication and a positive funding decision on the characterisation of CAPs with regard to ion densities were successfully obtained from the German Research Foundation (DFG). The DFG is funding work on ion density measurement using high-frequency signals from the plasma; this includes funding for a doctoral candidate and a scientific employee in the field of plasma modelling of the INP.

Plasma source periINPlas in Revision level 2.1 in the preliminary investigations for the multi-centre clinical trial that started in November 2021.

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Plasma Wound Healing

The "Plasma Wound Healing" research group deals with the question: Does the wound healing effect of cold plasmas depend on the aetiology of the wounds or also on the spectrum of microbiological colonisation? Furthermore, the individually optimised plasma treatment of different patients and their specific wounds plays a central role in its applied clinical research.

Cold plasmas are complex mixtures of free electrons and ions, UV radiation, visible light, heat, and numerous excited species. Especially the excited oxygen and nitrogen species together with UV radiation and electric fields are responsible for the biological effectiveness of the plasmas. These cold plasmas influence the cellular redox balance and can be adjusted to either stimulate or kill cells depending on their composition and the duration of treatment. Here, the sensitivities of the treated cells differ greatly. This is due to different antioxidative potentials of the different cell types and their ability to regenerate. Cold plasmas are therefore suitable for killing bacteria. Here, multi-resistant germs show the same reduction rates as non-resistant strains. It has been shown that a balanced plasma treatment of human cells can also lead to their stimulation.

Plasma treatment of a diabetic foot with chronically infected wound

The aim of the "Plasma Wound Healing" research group is to transfer the fundamental results into the clinical practice of wound treatment. Special attention is given to deepening and adapting the research results of the CIC plasmatis on wound healing by finding differences between human cells and the micro-organisms found in chronic wounds. The aim is to identify molecular differences in radical defence, metabolism, and cell repair between human skin cells as well as the immune system and the micro-organisms in the wound. For this purpose, wound swabs – also known as exudates – are taken and examined for their cellular and soluble components.

For these investigations, the Karlsburg Diabetes Centre of Excellence (KDK) works in close cooperation with the Klinikum Karlsburg. The aim is to develop a plasma treatment tailored to the patient or wound in order to further optimise wound healing with the aid of cold plasmas.

The clinical examinations include detailed analyses of wound exudates. These are supplemented by imaging, microbiological smears, and the analysis of messenger substances (growth hormones, cytokines). This should help to optimise the camera system (BacteriaCam) as well as to provide information whether plasma treatment leads to growth stimulation.

The latest research activities of the research group focus on the influence of cold atmospheric pressure plasma on stem cells. In a project funded by tBi, progenitor cells are isolated and processed from the abdominal fat of patients with chronic wounds. Together with the company HumanMed, the ActiHeal project aims to test whether the use of cold atmospheric pressure plasma can promote the isolation and cultivation of stem cells from human abdominal fat tissue.

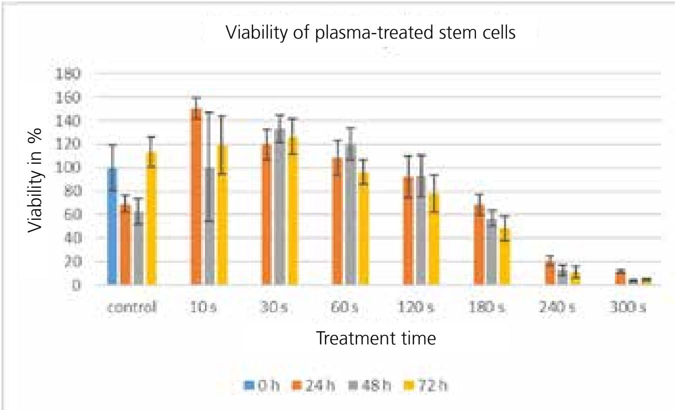
On one hand, plasma shall lead to improved isolation by positively influencing the separation of the cells from the aspirated cell clusters. This is based on the findings from cell culture that the adherence of cells can be influenced by plasma treatment. This could reduce – or even replace – the current use of enzymes.

Another important aspect is the examination of the plasma-treated progenitor cells after they have been cultured. Here, the focus is on questions about the tolerability of the plasma treatment. Furthermore, it will be investigated whether the proliferation of the isolated progenitor cells can be positively modulated by treatment with cold plasma. Initial trials show promising results (Fig. 2). Samples from different donors. In future, it will be analysed which signals are triggered in the stem cells by the plasma treatment. For this purpose, the growth factors and cytokines secreted by the cells are to be analysed. With this data, we hope to gain an insight into how these cells react to plasma treatment so it can then be optimally adapted to the stem cells.

It will then be examined whether cold plasma possibly also influences the differentiation of stem cells. For this purpose, flow cytometry and histology as well as the use of specific markers will be used to analyse whether the plasma-treated progenitor cells can differentiate into cells of the connective tissue or skin.

It was shown that cold plasma has a positive influence on the growth of stem cells isolated from human adipose tissue.

Based on these data, it will be tested whether the plasma-treated cells can positively influence wound healing by first isolating and purifying the stem cells taken from the patient and then applying them in concentrated form to the wound. By using exogenous cells, it should thus lead to accelerated wound healing.



Short treatment times with cold plasma lead to the increased cell proliferation of stem cells.

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Plasma Agriculture

Small-scale seed treatment using corona discharge (funnel plasma source)

The "Plasma Agriculture" (PAK) research group develops innovative plasma processes with the aim of increasing the resistance of plants to abiotic and biotic stress factors before harvesting accompanied and assuring growth and yield. This includes plasma-based seed decontamination processes that can improve seed health, storage, and transport. Plasma treatment can also have a stimulating effect on plant germination. The underlying processes of stimulated seed germination and improved resistance of plants are investigated both in fundamental and application-oriented research. The research refers to the knowledge gained in plasma medicine on the stimulating effects of cold plasma on RONS-based physiological processes such as wound healing.

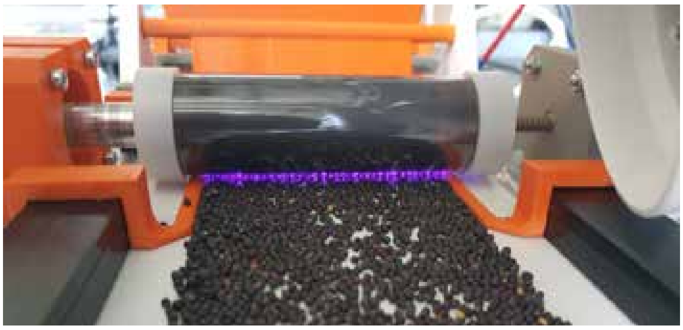
The research group first plans to investigate the effects of direct and indirect cold plasma processes on plants and then develop suitable plasma sources on a laboratory scale. The results of these experiments then form the basis for potential applications in agricultural plant production. Against the background of the planned stricter EU regulations on plant protection products and climate change, alternatives that will make it possible to reduce the use of chemicals in the fields or, where bans already exist, to offer an alternative are to be provided.

The simultaneous preservation of seed germination capacity is important in cold plasma processes, which aim at the microbial decontamination of the seed surface. The laboratory analyses of the PAK research group therefore include microbiological work to test decontamination by cold plasma on the seed surface. Bacterial spores are first used as model organisms for phytopathogenic fungal and mould spores. On the other hand, standardised seed germination tests are carried out. There are also analyses of the seed surface such as hydrophilic tests, element analyses, and water absorption during germination.

In order to investigate the effects of plasma-treated water (PTW) on plant growth and stress adaptation, it was first necessary to establish suitable cultivation conditions as well as the PTW application for lupin and barley. For this purpose, two CLF air-conditioning cabinets were purchased. In these cabinets, the temperature, humidity, and LED lighting can be precisely controlled on a diurnal basis. Furthermore, analyses to record biomass parameters and biochemical parameters were started. In December 2021, the PAK research group was also able to move into a new laboratory in which the phytobiological and biochemical work on the cellular effects of plasma treatment on plants can be intensified. The extraction of various cell contents and their qualitative and quantitative analysis at the nucleic acid, protein, and metabolite level will now take place here. One focus is to investigate changes in the enzyme activity of the plant antioxidant system.

In 2020, the implementation projects of the joint project "Physics for Food – Eine Region denkt um!", an initiative of the BMBF programme "WIR! – Wandel durch Innovation in der Region", started. The PAK research group at the INP is involved with projects on seed treatment ("Physics for Seeds") and the treatment of growing plants ("Physics for Crops"). In the course of seed and plant treatment, plot trials were carried out under real conditions with industrial partners at 10 different locations, where winter cereals, rapeseed, and lupin were sown. Approximately 225 kg of cereals, 2 kg of oilseed rape, and 18 kg of lupin were treated and delivered to partners for sowing in 2020 and 2021, and more than 600 litres of plasma-treated water (PTW) were produced for spray application per field trial year. In addition, important phytopathological work was initiated by an external company on a laboratory scale to inactivate yield-reducing micro-organisms such as the pathogens causing leaf drought in wheat or root neck and stem rot in lupin. The results show a successful reduction of the pathogens up to complete inactivation on the seed.

The design, construction, and application of plasma sources with different electrical parameters as well as the characterisation of the plasma sources with regard to temperature, reactive species, pH value, and other physical quantities are another important part of the work of the research group. In addition, usable concepts for upscaling and integration into common process technologies of cold plasma processes are being created with the aim of application in agriculture and industry. The work is also embedded in the ongoing project "Physics for Food" and is made possible by the good cooperation with the "Plasma Biotechnology" and "Plasma Sources" department of the INP within the "Decontamination" research programme.



Continuous treatment of rapeseed by means of dielectric barrier discharge (conveyor belt plasma source)

In 2021, a special budget was also approved for the "Physics for Food" project. Several large pieces of equipment were purchased here for the INP. These include incubators for determining plant germination under controlled and standardised conditions and an ultra-low temperature freezer for storing plant sample material.

The COVID-19 pandemic that broke out at the end of 2019 also posed challenges for the work of the PAK research group. As in many places, this led to restrictions in the number of people per laboratory and office space and thus required scheduled work. In addition, scientific exchange shifted primarily to the digital realm. During this time, three publications on the main work of the research group were published in application-oriented journals (Nishime et al., 2020; Brust et al., 2021; Wannicke et al., 2021). In addition, two Master's theses on the influence of plasma-treated water on growing plants and the influence of cold plasma on seed hygiene and seed vitality were successfully carried out and completed in 2021. A one-year guest visit by a Chinese student planned for 2020 started in February 2021 and supported the research group in its microbiological work. Because of the contact restrictions during the pandemic, the 3rd International Workshop on Plasma Agriculture (IWOPA), which was originally planned as a live event at the INP for 2020, had to be postponed. In 2021, this took place as an online event with 67 participants from 19 different countries and 56 contributions with lectures, recorded presentations, and posters. The PAK research group was present as co-organiser of the conference as well as with posters and a talk on the topic "Plasma-derived nitrogen-species: Fertilisers or signalling factors in plant growth and development?".

2021 also saw the start of the third-party funded "LuzNutz" project funded by the Federal Office for Agriculture and Food (BLE). Until 2024, investigations into the suitability of plasma technology for alfalfa will be carried out in cooperation with the Julius Kühn Institute – Federal Research Centre for Cultivated Plants (JKI), the Leibniz Institute of Plant Genetics and Crop Plant Research (IPK), and Saatzucht Steinach GmbH & Co KG. The EU COST network PlAgri is also running until 2024. It was launched in October 2020 and offers excellent opportunities to make the ongoing topics on pre-harvesting at the INP visible and to network internationally (even if this was achieved only digitally in 2020 and 2021).

As part of "Physics for Food", a large-scale trial on the germination behaviour of plasma-treated red clover seeds in the IPK greenhouses in Malchow on the island of Poel as well as young lupin and barley plants for PTW application in the CLF climate chamber.

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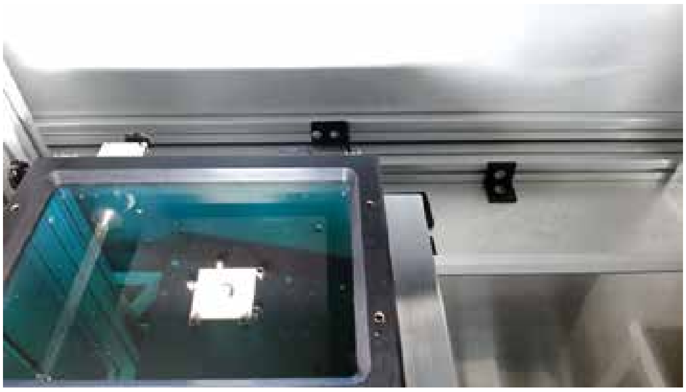
Materials for Energy Technology

In the area of materials for energy technology (MET), research and development work on novel processes for the production of nanomaterials for energy technology was further expanded. Within the framework of collaborative projects of the BMBF WIR! Alliance "CAMPFIRE", the research group is developing a number of the core innovations of the alliance: ceramic thin films, catalysts, membranes, and redox-active materials for the future hydrogen economy based on ammonia. Applications include electrolysers, fuel cells, and batteries as well as catalysts for chemical mass conversions such as ammonia crackers and micro-Haber-Bosch processes. The partner network of company and institute partners was further expanded in close networking with the CAMPFIRE partners, and a stronger application focus was set for materials and process development. The collaborative projects are primarily funded by the BMBF WIR programme and BMBF TransHyDE lead project as well as within the framework of BMWK AiF IGF. In Horizon 2020 FETProActiv, an EU project with five other European partners was acquired and successfully launched. Funded by a BMBF WIR! CAMPFIRE, the working group for the CAMPFIRE Open Innovation Lab (COIL) considerably expanded the reaction technology and analytical infrastructure. Examples of new processes are selective laser annealing in combination with co-sputter processes as well as modular flow reactors for the generation of nanoparticle suspensions by means of plasma-in-liquid (PiL) processes. Another important area of expertise was developed for the production of ammonia- and hydrogen-resistant coatings based on plasma electrolytic deposition processes.



Selective laser annealing to produce perovskite membranes as electrolyte materials for high-temperature electrolysers and fuel cells

Co-sputtering processes

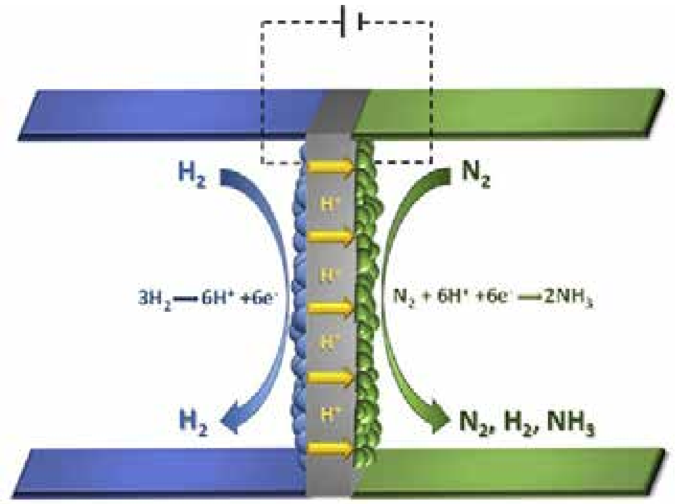
Ceramic thin films, catalysts, and redox active materials

Complex oxides and carbides (e.g. perovskites and MAX phases) are produced by means of co-sputtering and plasma-in-liquid processes. The development work focuses on the homogeneity of the complex materials, which consist of ordered crystal structures based on several cations. Perovskites (ABO3) pose the particular challenge that, depending on the stoichiometry and doping, the defect structure of the anion lattice must also be optimised for the desired properties (proton conduction, oxygen ion conduction, electronic conduction, or catalytic activity). The production of ceramic thin films on high-temperature sensitive substrates is another new research approach in the research group. In this context, the ceramic thin film must have high crystallinity and phase purity even without traditional sintering processes. For example, novel selective laser annealing processes were developed to optimise perovskite membranes for the membrane-electrode units of metal-supported high-temperature fuel cells and electrolysers as well as corrosion protection coatings on metallic bipolar plates. Further progress was made in the generation of graphene-based membrane and electrode materials and synthesising catalysts using combined PVD/CVD and PiL processes. For example, the PiL batch reactor was converted into a modular flow reactor, thereby considerably improving yield and process reliability for the production of nanohybrids. Using the PiL suspensions, screen printing and dip coating processes have been developed for the production of membrane electrode units or reactor components, and new approaches for suspension stabilisation are being developed in close cooperation with partners. Applications for these nanomaterials include polymer membrane fuel cells, batteries, and catalysts for Kellogg advanced ammonia processes for decentralised ammonia synthesis.

Structure and properties

In order to characterise the properties of the nanomaterials produced by plasma processes, the research group has further expanded the analytical portfolio available at the institute. New characterisation methods to be highlighted include physical and chemical gas adsorption, permeation, thermal gravimetry, dilatometry, electron microscopy with *in situ* Focused Ion Beam (FIB) for the preparation and investigation of cross-sections, and profilometry as well as measurement jigs and gas analytics for the investigation of conductivity, impedance, catalytic activity, and redox activity.

Proton conducting electroceramic thin-film membrane



Schematic of a membrane electrode unit for the solid-state synthesis of ammonia.

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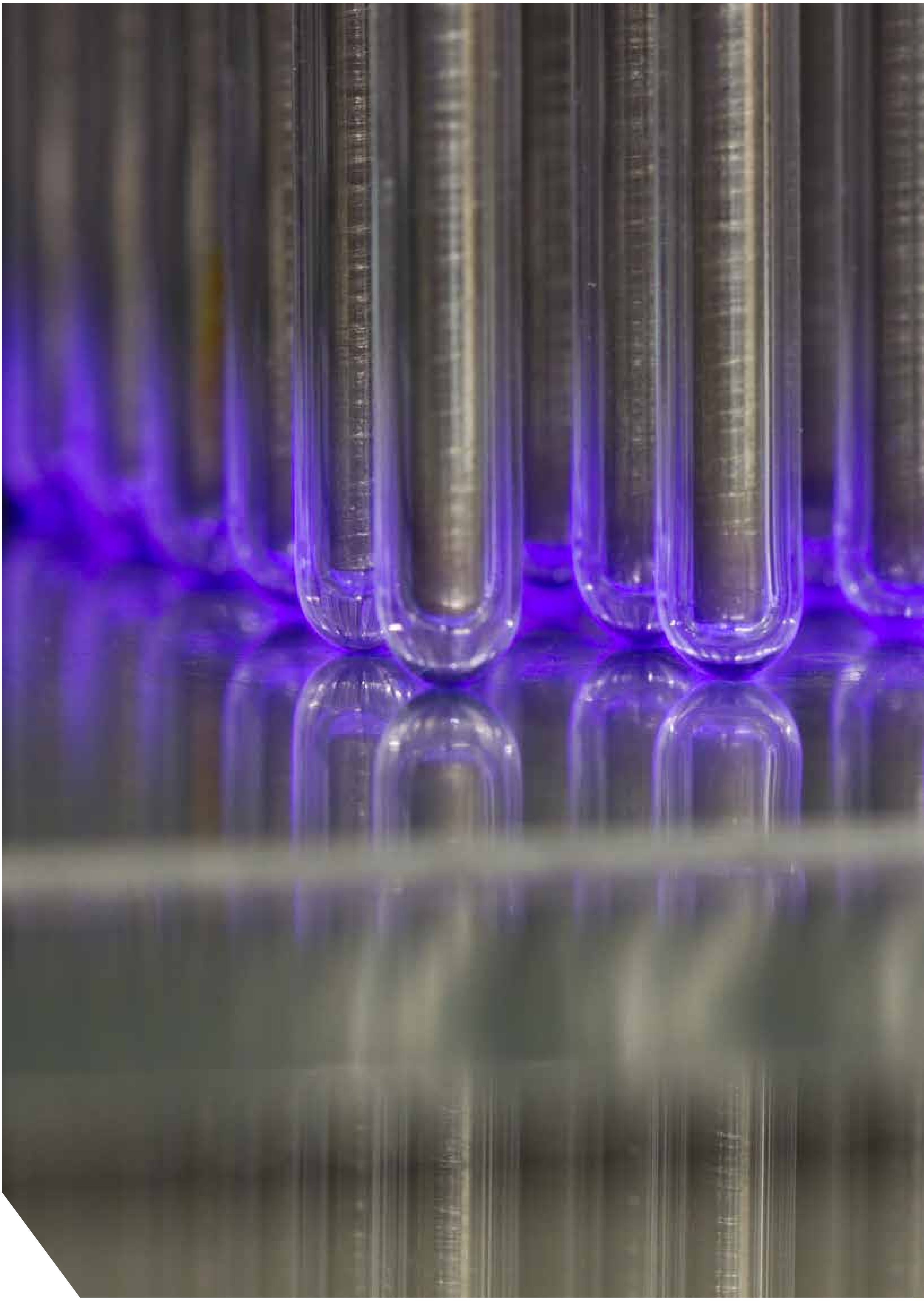

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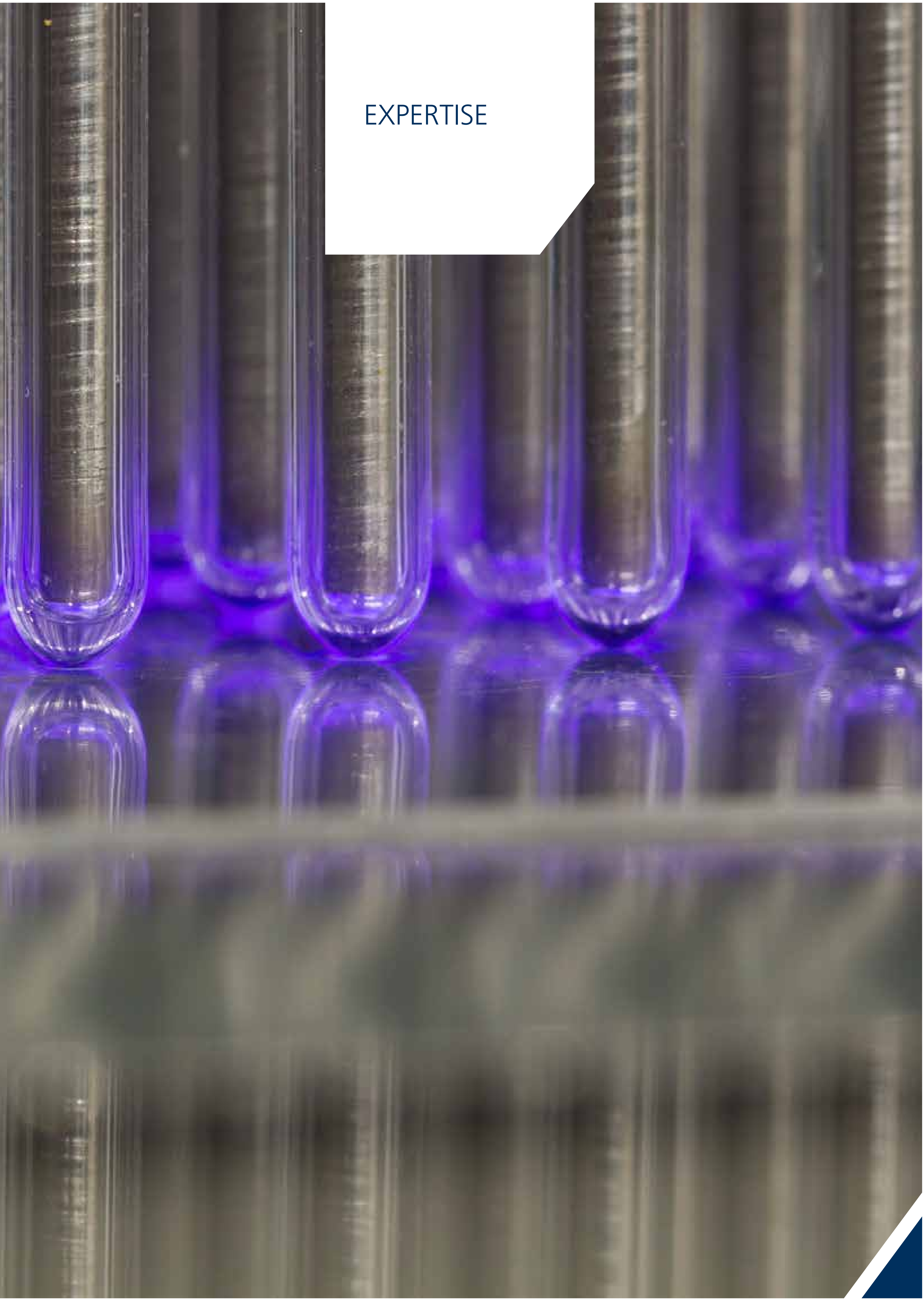

Plasma biotechnology

The department "Plasma Biotechnology" bundles the expertise in the process development of processes based on the interaction of plasma with biological material.

For this purpose, expertise is available both in the development, tuning, and diagnostics of special plasma sources optimised for the task at hand as well as in the diagnostics of the biological system treated.

In addition, the optimisation of the necessary procedures is another focal point.

Current thematic priorities are the development of plasma processes for hygienisation in the post-harvest sector with a focus on the food sector as well as innovative methods for process analysis and monitoring.

Examples of the current activities of the "Plasma Biotechnology" department are:

- the development of a hygienisation process based on Reactive Nitrogen Species (RNS), which allows both dry and wet treatment with a basic device;
- the development of optical sensors for process monitoring based on special diode laser systems.

The application-oriented research work is carried out mainly on the basis of joint projects with considerable industrial participation.

Technological equipment

Auxiliary Decontamination Unit (ADU):
Two-stage self-igniting atmospheric microwave excited plasma torch for RNS process gas generation (plasma processed air – PPA) with process control for operation of peripheral devices, capacity: 100 slm. Units for the production of plasma processed Water (PPW)
Total capacity: 2,000 l

Various peripheral devices for dry and wet treatment of e.g. bulk goods, fruit and vegetables, and meat products in batches of up to 200 kg

MinMIP

Fluid bed dryer with plasma gas generators (ADU)

Small microwave excited plasma torch for chemical diagnostics and biological applications

Standard microbiological methods
- Proliferation assays
- Live-dead determination
- Biofilms
- Micro-organisms of risk groups 1 and 2

Standard methods of quality monitoring
- Water content
- Sugar content
- Colour changes (lab system)
- Texture measurement

Treatment device for products in RPC (reusable plastic container) with plasma gas generator (ADU)

Optical diagnostics
- Optical emission spectroscopy (OES)
- Fourier transform infra-red spectroscopy (FTIR)
- Thermometry
- Laser diode absorption spectroscopy
- Fluorescence microscopy

High-frequency measurement technology
- Various spectrum and network analysers from 10 Hz to 50 GHz
- Microwave interferometer

Flow simulation
- Numerical flow simulation based on StarCCM+

CAD construction

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Plasma Diagnostics

The scientists and researchers of the department "Plasma Diagnostics" focus their application-oriented research activities on process monitoring and process control, especially in molecular plasma processes. Here, both fundamental and application-relevant questions in the field of materials and energy are addressed. The focus is on the time- and space-resolved, qualitative and quantitative chemical analysis of molecular plasmas, both in the gas phase and on surfaces.

The department "Plasma Diagnostics" works with the most modern methods and is continually expanding the existing expertise as well as the spectrum of measuring devices and methods, in particular laser-based plasma diagnostics. Spectroscopic problems are investigated in the spectral range from ultraviolet to terahertz.

The application of modern methods of plasma diagnostics is the key to understanding complex plasmas. Molecular plasmas, which contain many different species, are characterised by numerous interesting and useful properties. Its wide-ranging technological applications range from resource-saving surface treatments (e.g. in the semiconductor industry) to disinfection and sterilisation processes, exhaust gas cleaning and gas scrubbing, particle decomposition, and the treatment of water, air, and hazardous waste.

Plasma diagnostics allows the absolute measurement of energy and temperature distributions as well as the densities of stable and transient species in plasma by means of probe diagnostics, absorption spectroscopy, and optical emission spectroscopy, thus enabling the determination and elucidation of all relevant chemical processes.

In addition to the characteristion of plasma processes to answer fundamental and application-relevant questions, diagnostic methods are also used and further developed in the department in order to monitor and control technological plasma processes. By the first-time use of state-of-the-art frequency comb systems (FCs) in the mid-infrared spectral range, a completely new approach to the elucidation of plasma-surface interactions shall be opened up. FCs are to be used as radiation sources in broadband, resonator-based direct frequency comb spectroscopy (CEDFCS). This method will allow the simultaneous detection of a large number of transient reactants in the immediate vicinity of the surface. For this purpose, novel detection methods using FCs as light sources have recently been developed. This concerns both frequency comb-based Fourier transform spectroscopy and a Virtually Imaged Phased Array (VIPA) spectrometer.

A compact THz spectrometer based on THz quantum cascade laser technology was developed in a Senate Competition Committee (SAW) project Leibniz Cooperative Excellence funded by the Leibniz Association. The system can be used in a wide range of application scenarios for the highly sensitive detection of atoms and molecules in plasmas.

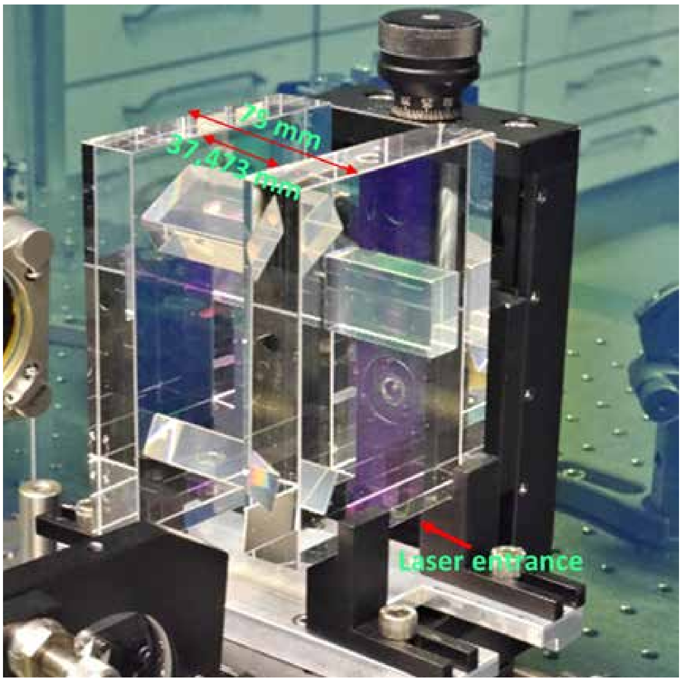


Photo of an air-spaced VIPA with laser coupling in the lower part of the coupling window

APPLICATION LABORATORY PLASMA DIAGNOSTICS

Specially equipped laboratories for diagnostics on chemical plasma processes simulated in practice with the latest measuring equipment are available for the investigations. The following methods are used to quantitatively determine important parameters (e.g. species densities and their temperatures and the energy distribution of charged particles) and to characterise all relevant chemical reaction paths:

- Laser-induced fluorescence and absorption spectroscopy with coherent light sources in the spectral ranges:
  - UV-VIS: pulsed dye laser
  - Mid-IR: diode laser, quantum cascade laser, interband cascade laser, lead salt laser, frequency comb laser system
  - THz: Quantum cascade laser, terahertz time-domain spectroscopy

- Resonator-based laser spectroscopy:
  - CRDS – cavity ring-down spectroscopy
  - CEAS – cavity-enhanced absorption spectroscopy
  - OF-CEAS – optical feedback cavity-enhanced absorption spectroscopy
  - CEATRS – cavity-enhanced attenuated total reflectance spectroscopy)

- Absorption spectroscopy with non-coherent light sources (FTIR spectroscopy from VIS to mid-IR)

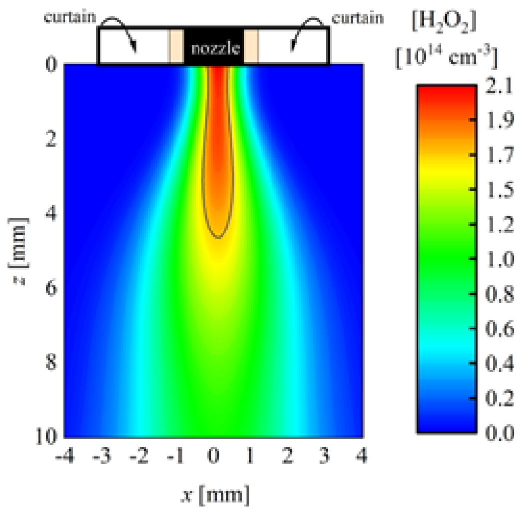
- Optical emission spectroscopy (UV-VIS: Grating spectrographs with CCD and iCCD cameras)

- Probe diagnostics (Langmuir probe also suitable for time-resolved measurements)

- Mass spectrometry (quadrupole to 200 amu)

The diagnostic methods are also suitable for mobile use and can therefore be used for external measurements directly on site.

In 2019, the first application laboratory for plasma diagnostics with a focus on atmospheric pressure sources was established. In this laboratory, various diagnostics of the institute are bundled in one place in order to provide a single point of contact for the characterisation of atmospheric pressure plasmas. Here, important parameters such as electron density or atomic and molecular particle densities will be quantified in different sources.



A contour plot of the H_2O_2 particle densities in the effluent of the kINPen-sci

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Plasma Life Science

In the department "Plasma Life Science", the effects and potential uses of cold atmospheric pressure plasma on biological systems are investigated with a focus on the biological effects. The media studied in this context are diverse and range from bacteria to microalgae and cells to tissues. Application-oriented fundamental research is of particular interest here. The basic principles of the use of plasma for various purposes are being investigated. The antibacterial effect of plasma is the focus for the decontamination and inactivation of bacteria and fungi in various environments (e.g. liquids, air) or on surfaces. More recent approaches combine plasma and biotechnology in the field of biopharmacy and environmental chemistry. Possibilities for digesting microalgae are being investigated in order to obtain their bioactive components. Furthermore, plasma-assisted processes are being researched with the aim of degrading environmental chemicals. In cell biology, the main focus is on investigations that support clinical applications in order to better understand their fundamentals or to be able to develop new applications. New plasma sources are also tested for their biological effectiveness or antimicrobial effectiveness. In parallel, the department "Plasma Life Science" performs model calculations of plasma interactions for life science issues.

Technological equipment

Microbiology

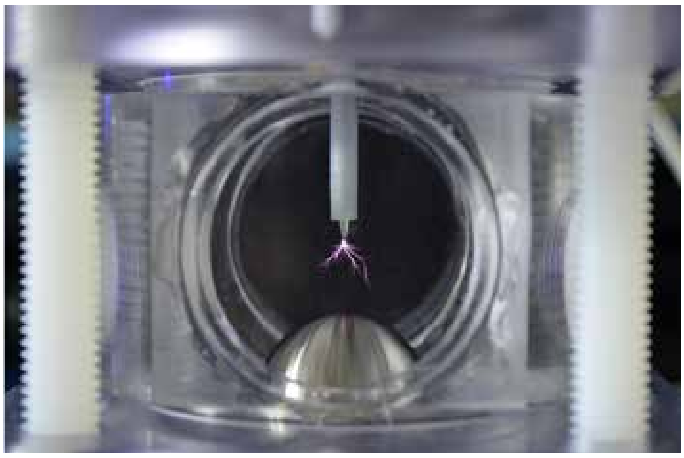
Performance of all common microbiological tests (e.g. quantitative determination of the number of living cells using a spiral plate system), safety cabinets for sterile work, spectrophotometer for determining the optical density. An existing strain collection includes various bacteria (also risk group L2), yeasts, and fungi. Plasma sources to be tested can be set up in the laboratories and connected to the in-house gas supply. Liquids, food, and surfaces serve as examination media.

Fluid analysis

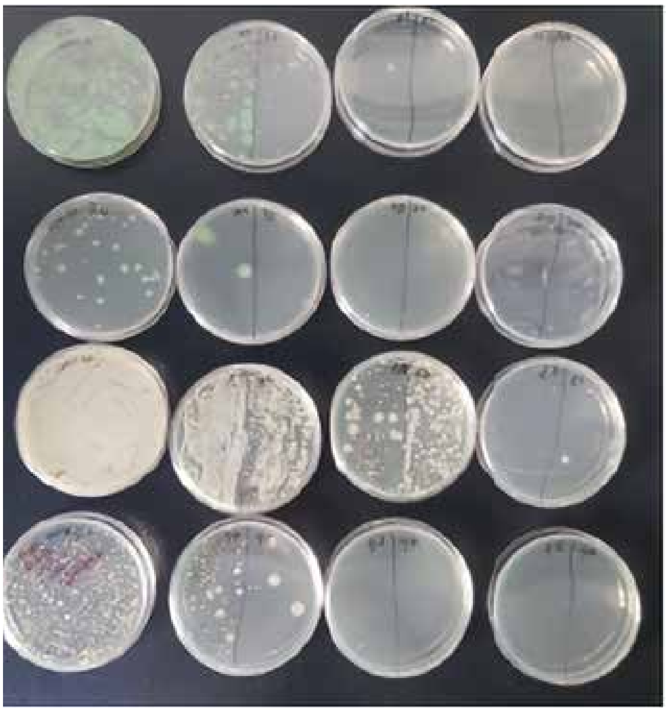
Various chromatography systems such as IC (ion chromatography) and HPLC (high performance liquid chromatography) are available. Changes in ion composition (e.g. nitrate, nitrite) or special substances such as amino acids in plasma-treated liquids can be investigated. The application-oriented analysis also includes chemical analyses from industrial waste water, among other things.

Protein analysis

Various techniques for the quantitative and qualitative analysis of proteins. In addition to standard methods of protein detection in multi-plate format (ELISA, photometric assays), Western blots using membrane transfer and high-throughput capillary systems are available. Well-established protocols can be used to generate samples for mass spectrometric analyses in the CIC.



Representation of a discharge in water between a needle and a hemispherical electrode. It was generated with a 100 ns voltage pulse with an amplitude of approx. 60 kV.



Detection of bacteria in swabs from chronic diabetic wounds before (Series 1 and 3) and after (Series 2 and 4) treatment with cold physical plasma.

Genetic engineering:
There is expertise and equipment for carrying out genetic engineering work at security levels S1 and S2. Thus, non-viral and adenoviral gene transfer systems can be produced. A therapeutic effect is achieved by transferring genes with the help of overexpression vectors or gene inhibitors (siRNA). These therapeutic genes can be used in the treatment of acute and chronic wounds as well as various tumours (e.g. skin tumours). Non-viral gene transfer systems have a transient (time-limited) effect in cell culture systems. In contrast, adenoviral vectors are currently the most efficient gene transfer system because they have the highest in vivo transduction rates and express the gene product to be transferred for up to three months. In addition to extensive expertise in gene expression, methods such as quantitative real-time PCR and global microarray analysis are applied.

Cell culture and histology
Expertise and equipment for performing histological analyses. Through close cooperation with clinical partners, we are also able to conduct and support patient-oriented research. Thin sections are prepared from excised tissue samples using a freezing microtome or microtome. This is followed by immunohistochemical staining or immunofluorescence staining. These histological techniques are also used for animal experiments that are carried out through collaborations.

Microscopy
Fluorescence microscopy is used especially for the analysis of fluorescence-labelled tissue sections. A confocal laser scanning microscope is also available.
Atomic force microscopy (AFM) is used to image surfaces in a non-destructive manner and with high resolution – even on living cells – and to determine the mechanical properties of a sample. With this technique, elastic moduli can be determined.

Outlook
The broad spectrum of methods opens up a wide range of topics from clinical to industrial research. Most of the existing methods and expertise can be excellently combined and can complement one another. This results in a multitude of further investigation possibilities for research in the field of Plasma Life Science.

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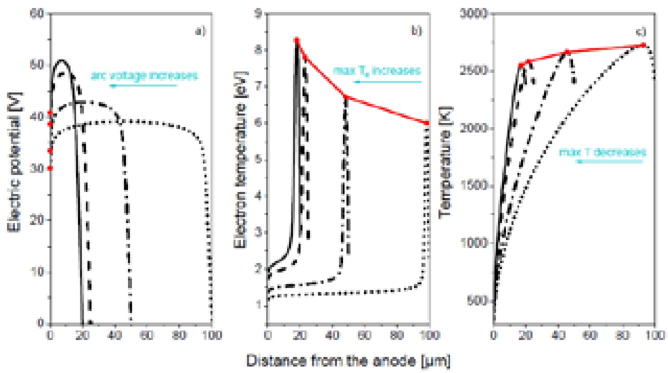
Plasma Modelling

The modelling and simulation of plasma sources and plasma processes is an essential complement to laboratory experiments in plasma research. Model-based parameter studies make it possible to optimise technological plasmas in a targeted manner and to open up new areas of application. This can reduce the practical implementation of costly and time-consuming experiments. The model calculations also make it possible to determine physical quantities that are experimentally inaccessible or difficult to access. In this way, fundamental phenomena can be investigated, and the understanding of measurement data can be supported.

At the INP, models of low-temperature plasmas at atmospheric and low pressure with scientific and technological potential for use are developed and applied. The spectrum of models ranges from the description of individual plasma effects to the complete modelling of plasma sources and processes. The current focus is on plasma surface technology and projects to support the energy transition, environmental protection, and health. Examples of applications are plasma processes for film deposition, for the degradation or conversion of pollutants and for the controlled generation of reactive species for plasma medical applications as well as welding, cutting, and switching processes. In the sense of the sustainable and FAIR (Findable, Accessible, Interoperable, and Reusable) handling of data, the storage, networking, and subsequent use of research data is supported through the research and development of solutions for data management.

The modelling of the plasmas requires different sub-steps. This includes the development of an adequate model, the formulation of hydrodynamic or kinetic equations for the plasma species, the use of corresponding equations for the electric and magnetic field, and the development of suitable conditions at the edges of the solution area. Furthermore, the problem-specific input data has to be researched, evaluated, and prepared. The complexity of the overall description of plasma processes means that sub-problems (e.g. the plasma-chemical modelling of reactive plasmas, the determination of the electric field configuration, the kinetic description of the electrons and ions, and the treatment of radiation transport) are sometimes treated separately. However, the primary aim is a ‘self-consistent modelling’. Here, all relevant phenomena are resolved in a coupled manner. In this way, the interactions of the sub-problems can be adequately captured, and predictive results can be achieved.

For solving the resulting system of ordinary and partial differential equations, which models the different physical phenomena and couples them with each other, suitable numerical methods are to be developed or adapted and applied. Depending on the problem, commercial software packages, open source programmes, and self-developed in-house codes are used for this purpose. The results of the model calculations are then to be interpreted in terms of content, adequately visualised, and published in peer-reviewed journals.



Results of the modelling of a thermal micro-arc within the DFG project "Theoretical description and modelling of arcs at small currents and small electrode distances" (Project number 390828847). The spatial variation of the electric potential (left), the electron temperature (centre), and the gas temperature (right) with variation of the electrode distance and a current density of 10^6 A/m^2 is shown.

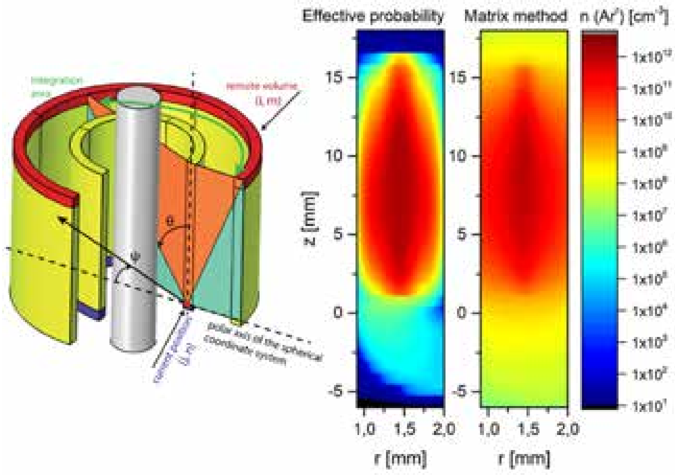
The problem-specific models and numerical methods of the INP are characterised by high efficiency, stability, and accuracy. The verification, validation, and benchmarking of models and programs are used on an ongoing basis in order to check and maintain the quality of the models and programs developed. The model calculations and plasma simulations are carried out on our own high-performance computing clusters. The availability of these enables us to deal with complex, multi-dimensional problems.

Both thermal and non-thermal plasmas are modelled. The investigations are geared to the current topics of the research programmes at the INP and often take place in close coupling with experimental work as well as in cooperation with national and international partners from research institutions and industry.

Among other things, investigations serve to provide a better physical understanding of the temporal and spatial change of individual plasma components, the fields that occur in the plasma, and the impact and radiation processes as well as the interaction of plasma species with walls, electrodes, and organic components.

In the field of thermal plasmas, the focus is currently on plasma spray processes and investigations into small-scale arc plasmas. Whilst the former focus on optimising applications, the latter also involve fundamental investigations such as the interaction of the plasma with the electrodes. For this purpose, new models that allow a consistent non-equilibrium description of plasma and boundary layer were developed.

Investigations on non-thermal plasmas cover primarily barrier discharges, plasma ion sources, and plasma jets. The focus is on studies on the optimisation of plasma-chemical processes, on plasma-surface interactions, and on the stability of filament-generated discharges. Here, too, fundamental model developments took place. Among other things, these enable a more precise and spatially multidimensional description of plasma-physical effects such as the radiation transport.



Results of modelling a non-thermal plasma jet in argon at atmospheric pressure from S. Valin et al., Plasma Sources Sci. Technol. 30 (2021) 115001. The geometric dependence of the volume element and non-local radiation contributions in the plasma jet (left) as well as a comparison of the density of the resonance atoms with approximation of the radiation transport by effective lifetime (middle) and with calculation by matrix method (right) are shown.

Furthermore, the area of research data management has become further established in the department. In close cooperation with all research programmes, standards for the storage and documentation of research data from the diverse research methods at the INP are gradually being developed. This does not only fulfil the new requirements for sustainable data management in the sense of the FAIR principles but also enables the broader use of modern data science methods.

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Plasma Surface Technology

In the department "Plasma Surface Technology", plasma-assisted processes for the modification of surfaces are investigated. These are used in various industries. Plasma processes play a central role in the targeted adjustment of surface properties both in the high-tech sector (e.g. in automotive engineering, aerospace industry, the energy conversion photonics, microelectronics, tool coating, textile industry, and plastics processing) and in the life science sector (e.g. in biomedical engineering for implants, medical instruments, biosensors, and the food industry).

Plasma processes in surface technology range from structured material removal (e.g. etching or fine cleaning) to the adjustment of interface properties (e.g. to control bondability or printability) to the production of thin functional layers with applications for protection against corrosion, heat, or mechanical abrasion, electrochemical applications (e.g. electrodes and membrane materials as well as layers for optical systems). The process-related advantages of plasma processes include a low thermal load on the components, comparatively improved environmental friendliness, and precise controllability as well as an extremely low influence on the basic material properties.

The expertise includes:

Interface engineering
- Modification of metal, ceramic, glass, and plastic surfaces
- Antimicrobial surfaces
- Adjustment of the adhesion for material composites
- Hydrophilic/hydrophobic surfaces
- Biocompatible surfaces
- Cell-adhesive/anti-adhesive surfaces
- Textile treatment

Process development for the deposition of thin films:
- Hard materials
- Wear protection
- Corrosion and oxidation protection
- Optical films
- Scratch-resistant surfaces
- Photocatalytically active surfaces
- Decorative layers, surface finish
- Fine plasma cleaning
- Plasma-based polishing, deburring, and cleaning of metals
- Polishing of 3D-printed metal components

Technological equipment

Various plasma processes are used under low and normal pressure conditions; these are continually being further developed. Both laboratory and industrial scale systems are available for this purpose – in some cases, multi-chamber systems coupled to double-door systems and quasi *in situ* surface analysis (XPS):

- Processes in DC, DC-pulsed, high-frequency, and microwave plasmas
- Ion implantation (PIII and PIII&D)
- Magnetron sputtering
- High power impulse magnetron sputtering (HiPIMS)
- Plasma spraying
- Plasma electrolytic oxidation and polishing processes
- Plasma ion assisted deposition (PIAD)
- Plasma enhanced chemical vapour deposition (PECVD)
- Surface modification by means of atmospheric pressure discharges (DBD, Plasmajet)

Thermal atmospheric pressure plasma spray process for the production of functional coatings. Shown here: Oxide layer on metallic implant

Surface analysis is one of the specialities of the INP. The existing spectrum of diagnostic procedures, the expertise in operation, and the methodology for evaluating the measurement data are continually being expanded and improved.

Analysis of topography and morphology

High resolution scanning electron microscopy (HR SEM)
- Scanning transmission electron microscopy (STEM)
- Atomic force microscopy (AFM)
- Profilometry
- White-light interferometry
- Light microscopy with 3D function

Determination of chemical composition, bond, and structure
- High-resolution X-ray photoelectron spectroscopy (XPS)
- Energy dispersive X-ray spectroscopy (EDX)
- X-ray diffractometry (XRD)
- FTIR spectroscopy

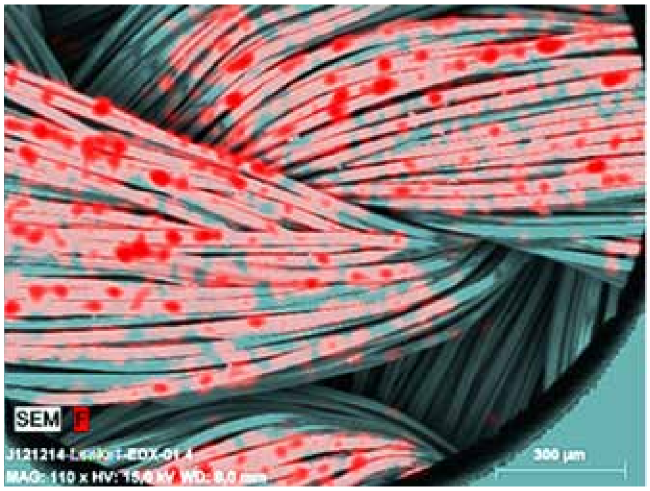
Determination of wear resistance
- Abrasion test
- Dome grinding process

Investigation of mechanical properties
- Microindenter
- Nanoindenter
- Measurement of the adhesive strength of bondings

Determination of contact angle and surface energy
- Contact angle measuring instruments

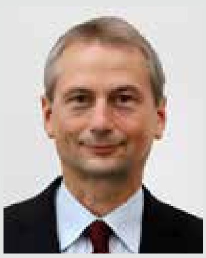
Determination of the optical properties
- UV–VIS spectrophotometry
- Optical ellipsometry

The following thematic areas are the subject of current developments in the application of plasma surface technology processes at the INP:
- Surface finish of 3D-printed work pieces
- Plasma smoothing of conductive surfaces
- Development of modern plasma processes for film deposition under normal pressure
- High-rate separation process under normal pressure (plasma spraying)
- Use of plasma-based methods for process control and regulation
- Use of *in situ* surface analysis



Electron microscope image of a textile fabric. Superimposed is the signal from the chemical analysis using energy dispersive X-ray analysis (EDX). Shown in red pseudocolour are traces of silicon-containing aggregates that were deposited in the textile during plasma treatment.

CONTACT



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Plasma Process Technology

In the past reporting period, expertise on plasma-chemical CO_2 reduction, biomass treatment, and plasma-assisted vacuum processes for the production of highly porous layers for electrocatalysis was expanded and/or deepened.

For the splitting and reduction of CO_2, non-thermal plasmas are basically suitable to overcome the high activation energies of the reactions. Dielectric barrier discharges (DBD) play a special role here because they allow the simple use of catalysts. For this purpose, various arrangements such as single-stack, multi-stack, and coaxial designs have been manufactured; these can be used in both the atmospheric and high-pressure ranges. The high-pressure range is particularly interesting for the chemical industry because many syntheses are carried out under these conditions.
For the construction of these plasma sources or individual components, 3D printing processes based on synthetic resins were tested. According to current knowledge, the synthetic resins prove to be sufficiently stable for present use.

For the treatment of biomass, a process that ensures a combination of a microwave discharge and an ultrasonic source with a common field of action was developed. Both sources together generate synergy effects; these come into play especially for the reuse of fermentation residues from biogas plants for repeated fermentation and thus additional methane production. This process is available in the form of a 40-litre demonstrator that is suitable for both batch and continuous operation.

For electrochemical applications in electrolysis or fuel cells, catalytic layers are synthesised using vacuum-based methods. In particular, patented processes such as PVD (physical vapour deposition), magnetron sputtering, and plasma ion assisted deposition are used. Only by combining these coatings with chemical or electrochemical leaching processes is it possible to produce highly porous metal films that have high electrocatalytic activities in relation to their mass per unit area. Complementary electrochemical and surface analytical characterisation methods are available. In particular, a method for the investigation of gas diffusion electrodes in a half-cell arrangement was introduced.

Plasma sources for chemical synthesis
- Dielectric barrier discharges
  - Single-stack reactor
  - Multi-stack reactor
  - Coaxial arrangements for high pressure syntheses

Biomass treatment
- KombiMax demonstrator; includes two 1 kW ultrasonic sources, one 500 W microwave source, and one 40 l receiver

MEA manufacturing
- ND-SP Ultrasonic Spray Coater® 11/3 fully integrated, X-Y working range of 300 × 300 mm
- LaboPress P150H, 150 mm × 150 mm

Experimental equipment: Plasma technology PVD, PECVD
- PIAD vacuum coating system, M 900
- UNIVEX 400 with Loadlock

Plasma technology, powder modification
- Rotary drum reactor, HF or microwave excitation, vacuum process: Activation or coating (PECVD) of bulk materials
  Pyrolysis of bulk materials

Porous platinum film on a gas diffusion layer

Characterisation of nanostructure, morphology, crystal structure, molecular structure, and porosity

- Keyence digital microscope: 2D and 3D images with up to 1000x magnification
- BET sorption measurement, Quantachrome NOVA2000: Determination of the specific surface of solids by nitrogen adsorption.
- FTIR spectrometer: Bruker VERTEX 70v: digital FTIR vacuum spectrometer for measurements in the MIR (8000 to 350 cm^{-1}) and FIR (600 to 50 cm^{-1}) range
- MasterSizer 2000 from Malvern Instruments: Measurement of the particle size distribution of powders in the range from 20 nm to 2 mm
- Bruker D8 Advance X-ray diffractometer with high resolution LYNXEYE detector:
- X-ray diffraction (XRD) on polycrystalline films and powders to identify crystal phases and crystallite sizing. X-ray reflectometry (XRR) to determine film thickness and roughness. Rietveld analysis
- Scanning electron microscopy/EDX, Joel (Germany) GmbH, plus cross section polisher, IB-09010CP, Joel (Germany) GmbH: Cross-section polishing unit for producing mirror-smooth surfaces, which cannot be polished mechanically

Characterisation of optical, electrochemical, and photochemical properties

- PerkinElmer Lambda 850 UV/Vis spectrophotometer with L6020322 150 mm integrating sphere: Measurement of transmission, scattering, and reflection
- µ-Autolab 2 potentiostat, electrochemical measurements
- Autolab Bipotentiostat 302N, Electrochemical activity measurements
- ATV in-line 4-point probe with Keithley 2400 Sourcemeter, measurement of the specific electrical resistance of surfaces and thin films
- Im6e Potentiostat, Zahner GmbH, Electrochemical characterisation
- PCS Photoelectrochemical Photo Current Spectra System, Zahner GmbH
- CIMPS Fast Light Intensity Transient System, Zahner GmbH, photoelectrochemical measurement
- COLT Coating and Laminate Tester, Zahner GmbH, AC-DC-AC tests on coatings and laminates
- Nordic Electrochemistry potentiostat with positive feedback for iR compensation at high currents for GDE measurements

Outlook on future priorities

- Development and stabilisation of methods for the production of highly porous catalyst films for electrocatalysis
- plasma chemical conversion of substances in gases and liquids for the use of CO_2
- Combination of plasma and electrocatalysis for the synthesis of chemical storage of electrical energy
- Combination of plasma and ultrasound for the disintegration of biological substrates

KombiMax demonstrator during field test at a biogas plant

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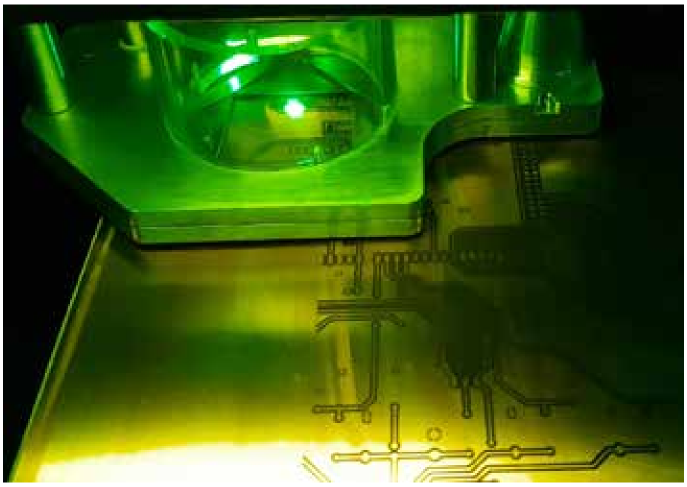
Plasma Sources

The development and characterisation of plasma sources and systems represents a core strength of the INP. For these tasks, the “Plasma Sources” department provides a broad spectrum of methodological expertise in the technical, engineering, and physical fields. In close coordination with the research programmes, devices and systems are developed in a targeted manner according to the requirements of the respective applications. In addition to plasma source development, basic characterisation of plasma sources is also carried out – as is integration into complete systems and the development of peripheral assemblies such as high-voltage generators.

Special emphasis is placed on activities for the development of atmospheric pressure plasma systems. Diagnostic, control, and regulation systems can be an integral part of the units. For the development of the devices, the INP has special laboratories in which the plasma sources are designed, manufactured, and characterised. Components and assemblies can be manufactured directly on site using rapid prototyping technologies such as 3D printing and laser cutting. This enables the direct implementation of novel plasma source concepts in various devices.



The solder side of a PCB is precisely structured in a laser process.

The “Plasma Sources” department is often responsible for up to medium technological readiness level (TRL), i.e., prototype stage. Development work is also carried out with partners from industry, and technology transfer is achieved. All devices and systems are consistently developed according to the requirements of the respective application right from the concept stage.

The range of tasks of the “Plasma Sources” department includes the conception and design of electrical and mechanical assemblies. Electrical and electronic circuits are designed and functionally simulated, and circuits are implemented in circuit boards that are manufactured on site by the students themselves. Since 2021, a state-of-the-art laser system has been available for this purpose (see figure on the right). Mechanical assemblies are developed in CAD work flows and manufactured using the optimum technology and depending on the requirements for materials and design features.

State-of-the-art 3D printing and laser cutting processes complement classic procedures. The "Plasma Sources" department also closely cooperates with the mechanical workshop at the INP to carry them out.

The plasma systems are characterised through electrical, optical, and spectroscopic investigations. This area includes FTIR spectroscopy for gas phase analysis with which plasma-generated reactive species (e.g. H_2O_2, NO_X, and O_3) can be detected down to the ppb range.

In addition to the development and production of devices and systems, the “Plasma Sources” department also carries out tests for the entire INP as well as maintenance and repair of devices and technical support for our various partners. The applications of these devices are quite broad. Important examples of this are:

Medical plasma sources

Like all products used in medicine, the development of medical plasma sources is subject to increased requirements.

This demand is met by taking legal requirements (e.g. standards for electrical safety) into account right from the development stage. In addition, analyses of parameters relevant for approval such as irradiance and leakage currents are carried out.

Agricultural culture

For research purposes in agricultural culture, plasma sources are used to treat seeds, for example, in order to improve germination. Furthermore, plasma systems are used for the treatment of liquids. The scaling of the systems is one of the central engineering challenges of system development in this area. Small functional demonstrators are optimal for preliminary tests on a laboratory scale. For applications beyond this, including in the research environment, considerable upscaling is required whilst maintaining many critical operating parameters.

Decontamination

Plasma sources for the treatment of chemical or microbiological contaminations are designed as assemblies for integration into application-specific devices and systems. This allows the implementation of applications in indoor air hygiene, exhaust gas treatment, and surface decontamination. For example, a plasma applicator for decontaminating grab rails and handrails was recently developed jointly with partners from industry as part of a Central Innovation Programme (ZIM) project. Furthermore, plasma arrays for degrading contaminants in water (e.g. pharmaceutical residues) as well as systems for extracting thermosensitive substances from microalgae using spark discharges are being developed.

Peripheral devices and systems

In larger systems, the interaction of the plasma sources with other modules may be necessary for diagnostic, control, and regulation purposes. In order to ensure optimal compatibility between different components, close coordination with project and research partners always takes place during development. Furthermore, in addition to the plasma sources, peripheral devices and systems are also developed in-house if required. The figure shows a material recognition system that uses a camera and a trained artificial neural network to determine the material of work pieces for a desktop laser cutter. A plasma process is being developed in parallel to clean the exhaust gases from the laser cutter; this can be adapted by communicating with the peripheral material recognition system.

Because of the large number and variety of systems developed and supported, systems for internal departmental data management were expanded, especially in 2020 and 2021. In addition to a comprehensive plasma source catalogue, parts of which are also accessible externally, patents are also given special consideration here.

Camera-based material recognition system. The top cover has been removed in order to reveal the camera.

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Plasma Radiation Technology

The department is dedicated to the experimental analysis of technological plasmas in various applications of electrical power engineering (high current, high voltage, and switchgear engineering) and process engineering (welding technology, thermal conditioning of metallic surfaces). Electrical and optical diagnostic methods are used for quantitative analysis. One focus is on emission spectroscopy. Research is currently focussing on the investigation of switching arcs in arresters and contactors, vacuum arcs in circuit breakers, and arcs in welding technology as well as micro arcs and spark discharges. The further development of methods of high-speed kinematography coupled with optical emission and absorption spectroscopy serves to optimise the physical properties of the plasmas under investigation in practical model arrangements and laboratory experiments. The focus is on increasing the sensitivity and spatial resolution of optical methods, extending their applicability to cold boundary layers and surfaces, and detecting and characterising spatially asymmetric plasmas with high dynamics, robustness to interference in real applications as well as flexible and mobile use. In addition to the quantification of local properties in the arc, the determination of surface temperatures and other properties (e.g. electrodes in various arc applications) is also of interest.

Based on the expertise in diagnostics, application-specific non-invasive sensor and control systems are developed. In addition to state-of-the-art diagnostic systems, the department has access to the latest equipment in welding, high-current, and high-voltage technology as well as vacuum technology.

A view into the arc laboratory: Synthetic test circuit (right in picture, the in-house development of the INP), vacuum chamber with pump system and drive (left in picture).

Technological equipment

Arc laboratory

- Synthetic test circuit for switchgear with maximum current up to 80 kA and return voltage up to 42 kV
- Impulse current generator with variable current form (AC variable frequency 16–1000 Hz, pulsed DC, lightning current pulse)
- Vacuum chamber for investigations on high current vacuum arcs
- Electrical and optical metrology

Arc welding laboratory

- Test stands with fixed torch holder and flexible movement of test work pieces under the torch, including gas supply, extraction, and radiation protection
- Power sources from various manufacturers as well as a freely programmable source
- A 5 kW steam burner
- Electrical and optical metrology

High voltage laboratory

- HV generator for AC voltages up to 100 kV, DC voltage up to 130 kV, pulse voltage up to 135 kV
- Partial discharge diagnostics (conventional according to IEC 60270, frequency response analysis, acoustic sensors, UHF sensors, measurements of the dielectric response, resistance meters

Continuous current laboratory (University of Rostock site)

- Continuous current test rigs (max. 3000 A)
- Climate laboratory with climate chamber for cooling and heating cycles (–70 to 180°C) and heating cabinets (250°C)
- Thermographic camera
- Thermal probes
- Resistance measuring devices (nΩ to µΩ)

Low voltage switch and spark diagnostic laboratories

- Test stands with suitable power generators to simulate realistic operation
- Measuring stations for optical examinations of small-scale and low-light objects (micro arcs, partial discharges, lightning current discharges)
- Optical calibration sources

Equipment for optical measurements

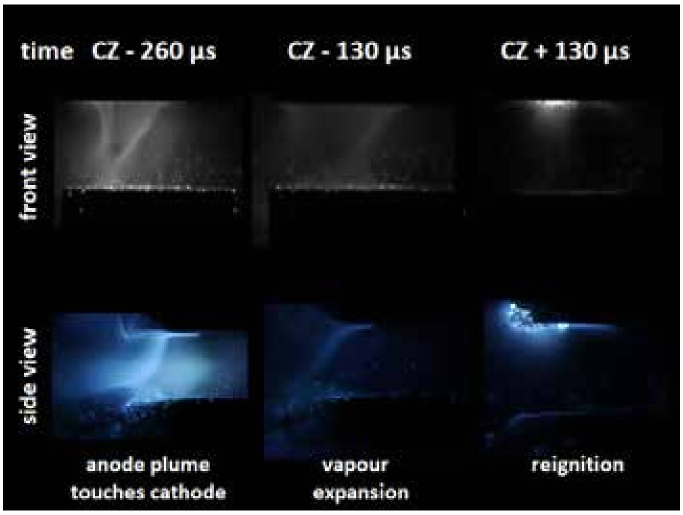
The following equipment for optical measurements is available to all laboratories:

- Mobile and stationary measuring stations for imaging optical emission spectroscopy and optical absorption spectroscopy
- High and very high speed camera technology
- Technology for thermography/pyrometry

The department has an X-ray facility for computed tomography for non-destructive diagnostics of electrodes or material samples.

Future priorities

- Extension of existing expertise in the field of thermal plasmas to the topic of plasma pyrolysis and thermal gas reforming
- Expansion of expertise in the areas of green switching technology, autonomous power grids, and electromobility
- Further development of quantitative diagnostics in the field of high-pressure and ultra-high-pressure electric arcs
- Adaptation of existing optical measurement methods for temperatures below the melting point for studies of the cooling dynamics of metallic surfaces and the analysis of their energy balance
- Construction and commissioning of an energy laboratory in the Center for Life Science, including various high-current generators, a 5 kV/1000 A high-power battery, and suitable measurement technology
- Construction of a measuring station with plasma torch for studies on plasma separation processes for waste disposal and material conversion
- Direct measurements of particle densities using spectroscopic methods and determination of the gas temperature for quantitative investigations to characterise thermal non-equilibrium plasmas



Snapshots of a vacuum arc around the current zero crossing (CZ) during thermal re-ignition as a result of strong electrode material evaporation. Current 10 kA.

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Karlsburg Diabetes Centre of Excellence

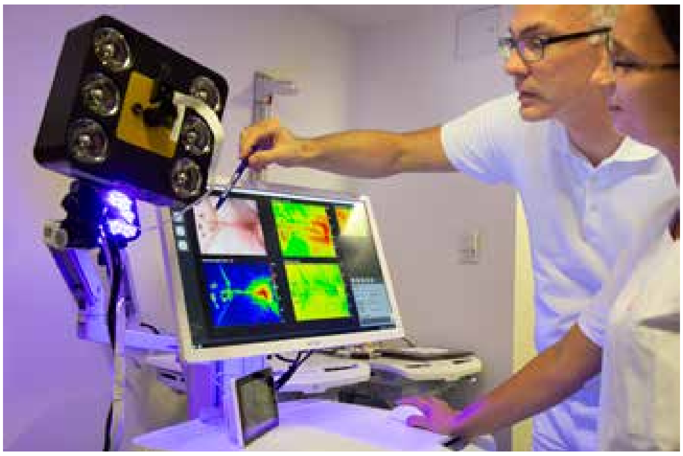
The Karlsburg Diabetes Centre of Excellence (KDK) is a cooperation initiative of Klinikum Karlsburg and the INP. It stands for clinic-oriented collaborative research and supports the development of innovative medical products, procedures, technologies, and diagnostics in the field of wound healing and plasma medicine. For this purpose, new laboratories were created at Klinikum Karlsburg. The short paths between clinic and research ensure direct exchange between clinic staff and patients as well as researchers and industrial clients. This enables rapid product development with short iteration steps from idea to market approval and direct feedback loops. Research results can thus be transferred much more quickly into clinical application in cooperation with companies from the medical sector. This will greatly benefit patients.

The structural equipment of the Karlsburg Diabetes Centre of Excellence was supported by the Ministry of Economy, Labour and Health of Mecklenburg-Western Pomerania and the EU with about €2.5 million from the European Regional Development Fund of the EU.

The KDK will strategically focus on "research and development" with the transfer into industrial and medical practice as well as "market-oriented services". The basis for this is the existing practical experience and professional expertise as well as the establishment of a quality management system. In the last two years, the focus was on the further expansion of expertise for clinic-related application-oriented research as a supporting pillar in diabetology and wound healing, primarily through collaborative projects (e.g. in the areas of plasma medicine, wound therapy, diagnostics, and prevention).
In a clinical bicentre study led by the Heart and Diabetes Centre NRW, cold plasma therapy at the KDK was examined in more detail on diabetes patients with superficial, infected, chronic wounds. The statistically significant positive influence of cold plasma on wound healing was published in 2020.

In the joint project "Sensor Sole" funded by the "TBI", a sensor-based shoe insole capable of high-resolution monitoring of the foot sole temperature was developed and researched together with the Orthopädie-Technik-Service aktiv GmbH in Greifswald and the Institute of Diabetes "Gerhardt Katsch" Karlsburg (IDK). Temperature monitoring of the sole of the foot is intended to detect impending inflammation at an early stage. In a pilot study, the prototype was tested on neuropathic patients with diabetic foot syndrome for its functionality and handling. Using the temperature measurement data obtained from a wide range of comparison groups, it was possible to develop an algorithm that can detect real temperature hotspots as an indication of existing inflammation. Within the framework of a clinical study, this new temperature measurement method is to be established by producing the first small series of insoles of different sizes with temperature sensors and testing their everyday use in diabetes patients.

In cooperation with Diaspective Vision GmbH, University Medicine Greifswald and the Wismar University of Applied Sciences, a spectrometer-based system for assessing and documenting the microbial load of wounds during the healing process was developed and clinically tested in the joint project "BacCAM" funded by the TBI. In a bicentric study of the KDK and the Clinic and Polyclinic for Skin Diseases of the University Medicine Greifswald on patients with infected diabetic ulcer or ulcus cruris, the new method based on hyperspectral imaging in fluorescence mode with an excitation wavelength of 405 nm was successfully used for the direct detection of bacteria in wounds.



Further collaborative projects were launched in 2020 and 2021. These include the collaborative project "ActiHeal" together with Human Med AG, University Medicine of Rostock, and the University of Rostock, the collaborative project "New diagnostic options for type 1 diabetes mellitus" together with Euroimmun AG and University Medicine Greifswald, and "AmbuPlas" in cooperation with the Orthopädie-Technik-Service aktiv GmbH in Greifswald and the University of Rostock.

Based on these topics and projects, the needs of industry in the development of innovative medical devices and diagnostics are identified. At the same time, the strengths of the KDK are further developed. In parallel, new areas of application are also being developed based on the specialist spectrum of Klinikum Karlsburg. For example, initial contacts have already been established in cardiac surgery; these will flow into possible project applications.

In the long term, services in demand and preclinical testing will be certified according to corresponding DIN/ISO standards, and a preclinical test centre for medical devices will be set up within the KDK in cooperation with other local partners over the next few years. This is primarily geared to the needs of customers in the context of medical device approval and offers a service for the rapid implementation of approval-relevant issues and the fulfilment of normative and legal product requirements. Especially in joint projects, products and diagnostics can be developed and tested in accordance with the applicable regulations, taking into account the relevant DIN/ISO standards. Especially the inclusion of ISO standard 13485 for quality management with a focus on medical device development emphasises the special characteristics of the KDK for projects with SMEs and spin-offs as well as larger companies.

To make the strengths visible to the outside world, a separate homepage was set up; this has been online since January 2022.
Under the link https://kompetenzzentrum-karlsburg.de you will find further information on the KDK.

CONTACT

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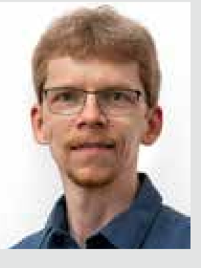

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Organisation, infrastructure, management, and support for science

Modern research institutions require professional science management, a lean and efficient administration, and a modern infrastructure tailored to the needs of a research institution. At the INP, this is professionally ensured in the organisational departments “Administration & Infrastructure”, "Management Support" and, since 2020, also in the "Board Department" units that report directly to the Board of Directors.

These organisational units are service units for the researchers and thus make a major contribution to the success of the institute.

Administration and infrastructure

The “Administration & Infrastructure” department at the INP provides organisational support for the scientific departments and research groups. It organises the smooth running of operations and comprises the “Human Resources” (including travel expense management), “Finances” (with procurement, accounting, and asset and third-party funds management), “Infrastructure” (with facility management and mechanical workshop), and “IT” subject areas.

For data processing, the INP maintains a data network, continually, expands it, and maintains the connection of the INP network to external networks. The provision of a modern, powerful and, above all, secure IT infrastructure is essential for a research institute such as the INP. The further digitalisation of administrative processes will become even more important.

The complexity of the applicable legal provisions in the areas of public procurement law, procurement, financial accounting, taxes, financial statement of the business years, and third-party funding management, which a modern research institute must implement, have steadily increased in recent years. It is therefore is an important task of the administration, especially of the “Finances” subject area, to adequately support the scientists in implementing the administrative tasks and provide assistance so that they can focus on their research tasks.

	2020	2021
Number of ongoing projects	115	137
Third-party funding volume	€10.2 million	€10.1 million
Number of award procedures	80	85
Number of orders	2500	2900
Number of transactions by financial accounting	4495	4517
Number of bookings by financial accounting	26000	28000

The "Infrastructure" subject area looks after the building services, the facilities, and the building as well as all construction measures for the technical equipment and the smooth integration of the new workspaces in the Centre for Life Science and Plasma Technology, which is scheduled to go into operation in 2023. The "Infrastructure" subject area also includes the mechanical workshop, where work pieces for the scientific experiments are manufactured.

The team of the "Human Resources" subject area is responsible for all administrative tasks concerning our employees. In addition to coordinating job advertisements, employment contracts, and payroll accounting and supporting the onboarding of new colleagues, the colleagues also keep an eye on the health of the workforce and organise preventive medical check-ups and other additional health offers.

Science management: Management Support and Board Departments

About half of the total budget of the INP is made up of competitive third-party funding from federal and state ministries, the German Research Foundation, the European Union, and industry. The department "Management Support" advises the Board of Directors, the research division managers, and the research programme managers in matters of research strategy and patent law. Its task is to advise and support INP scientists in the acquisition of third-party funds. It provides information on new funding guidelines and is jointly responsible for the preparation of proposals. It acts from the point of view of the funding authorities and thus contributes to increasing the quality of the INP project applications. The department "Management Support" also supports the transfer of technology and knowledge as well as process management and is responsible for its own projects. It also supports the institute in the implementation of large-scale projects by providing project coordinators.

Since 2020, various overarching special tasks have been located in central, supporting management units: "Board Departments". In detail, these are the “Communication” unit with the tasks of public relations, internal communication and event management, the “Legal and Patents” unit responsible for legal issues and patent matters, the “Research Coordination” unit, which is active across research divisions in the areas of acquisition, networking, research, and contacting potential project partners and funding bodies as well as for the coordination of processes within the research divisions, and the “Special Tasks” unit in which major projects are managed.

Knowledge and technology transfer

The institute motto – FROM IDEA TO PROTOTYPE – outlines not only outline the statutory mission to conduct application-oriented fundamental research but also the use of the research results. The INP conducts public research funding projects in order to increase knowledge for socially relevant topics. The Institute continually publishes the results of these projects in peer-reviewed journals, at national and international conferences, and at events for the general public.

For application-relevant topics of economic interest, the INP makes its knowledge available as a customer solution. These mostly bilateral industrial projects help our economic partners to benefit directly from the latest findings of research work at the INP.

For its own technology transfer, INP was the first Leibniz institute ever to spin off its own company, neoplas GmbH (www.neoplas.eu). According to the motto “From prototype to product”, later pilot customers, for example, are included in the development work during the start-up phase. If certain recycling activities have proven to be economically viable, these may result in further spin-offs. Knowledge that is economically exploitable and is not initially to be offered as a customer solution can thus be developed to market maturity in a new spin-off: “From prototype to market”. In recent years, four more spin-offs have followed this principle. The most recent spin-off was Nebula Biocides GmbH in 2019.

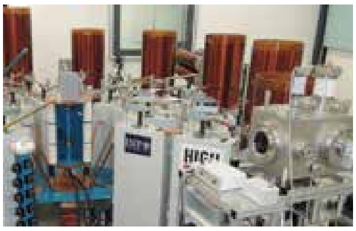
APPLICATION LABORATORIES

Application laboratories at the INP

The INP has a wide range of diagnostic methods for the analysis of plasma processes and plasma sources with a special focus for applications and for users. Here you can get an overview of our application laboratories:

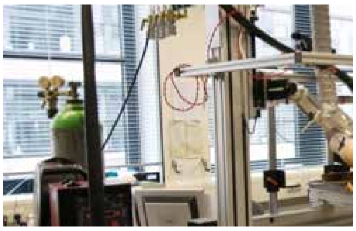
Laboratory for surface diagnostics

The laboratory has state-of-the-art technical equipment for analysing the properties of materials as well as the interaction of these materials with their environment. In addition, new types of material surfaces, which have special functions, are produced here using plasma technology.



Arc laboratory

With specific test arrangements and the unique coupling of specific diagnostics, statements can be made about the reliability and service life of switchgear in low, medium, or high voltage technology.

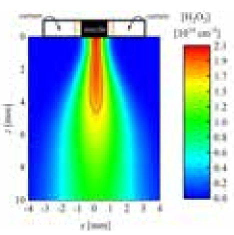


Arc welding laboratory

In the laboratory, welding processes are simulated under practical conditions in order to carry out investigations into process reliability, stability, and efficiency in arc welding using the latest measuring equipment.

High current/high voltage laboratory

The focus is on the development of methods and processes that increase the service life and reliability of electrotechnical equipment with special consideration of the environmental
compatibility and energy efficiency.



Plasma diagnostics laboratory

The focus of this laboratory is on different diagnostics, especially for the characterisation of atmospheric pressure plasmas. For example, important parameters such as electron density or atomic and molecular particle densities are quantified here in different sources.

Microbiological laboratory

The microbiology laboratory is a Safety Level 2 laboratory in accordance with Section 44 of the Infection Protection Act (IfSG), which permits activities with pathogens in accordance with Section 49 IfSG and Section 13 of the Ordinance on Biological Agents. In addition, the laboratory is well networked through cooperations with accredited and certified testing laboratories in the field of hygiene and can thus draw on a wide range of expertise

Laboratory for plasma decontamination

In this laboratory, plasma sources and plasma processes for the disinfection and sterilisation of bio-relevant materials and medical products – especially for the hygienisation of food products – are developed. In addition to various plasma diagnostic methods (e.g. OES, LIF, and MW interferometry), in-house microbiological laboratories are available for the examination and optimisation of the plants.

Laboratory for high frequency technology

The laboratory focuses on the provision, optimisation, and development of methods and systems in high-frequency technology. Their use ranges from the small signal range for diagnostic applications to the large signal range for driving microwave plasma sources.

New application laboratories at the INP

Laboratory for materials characterisation

The Laboratory for materials characterisation offers a comprehensive range of analytical techniques for the preparation and examination of materials. Among other things, the crystallographic properties such as phase composition, crystallite size, cell geometry, and occupation of lattice sites can be studied. Furthermore, electrochemical methods can be used to resolve the conductivity of the materials in terms of their grains and grain boundaries as well as the underlying transport processes. A new addition to the portfolio are set-ups for determining gas permeation (hydrogen, oxygen) in materials.

PiL Materials Lab

The "PiL Materials Lab" is a new application laboratory with a range of batch and flow reactors as well as a portfolio of pulsed high-voltage generators for the rapid synthesis of nanoparticle suspensions from liquid or solid precursors at atmospheric pressure. A unique combination of expertise in chemistry, physics, and engineering enables the precise tailoring of modular synthesis routes for hybrids and complex nanomaterials such as electrode and membrane materials and catalysts.

Laboratory for PVD processing and coatings

The Institute has concentrated its long-standing expertise in thin-film and nanomaterial synthesis using vacuum- and plasma-based methods in this new application laboratory. Reactors for simultaneous multi-target sputtering and high-performance pulse magnetron sputtering as well as plasma-ion assisted deposition are used. In combination with in-house engineering expertise, this paves the way for novel material and coating designs for energy applications, corrosion protection, and barrier coatings.

Application laboratory for life science

The laboratory provides an extensive array of equipment for modern analytical and molecular technologies. The extensive instrumental equipment enables a thorough and multi-layered treatment of current research questions in the life sciences.
The influence of plasma on biological systems can be studied at all levels – from organisms to tissues (organs) to cells to sub-cellular molecules.

Synthesis laboratory for green ammonia materials

The Institute has concentrated its long-standing expertise in thin-film and nanomaterial synthesis using plasma-based vacuum processes for material synthesis in this new application laboratory. Reactors for simultaneous multi-target sputtering in unbalanced closed-field configurations or material treatment by selective laser annealing are used. In combination with in-house engineering expertise, this paves the way for novel material and coating designs for sustainable ammonia technologies and energy applications, corrosion protection, and barrier coatings.

Link: https://www.inp-greifswald.de/de/kompetenzen/applikationslabore/

MISSION STATEMENT

We see ourselves as the leading institution in Germany in the field of plasma research and technology in the comprehensive combination of basic research and applications.

As part of the Leibniz Association, the INP is a non-university research institution engaged in application-oriented fundamental research on low-temperature plasma physics.

GOOD SCIENTIFIC PRACTICE

We deliver excellence in science and technology through good scientific practice.

Our research work is conducted in accordance with the guidelines for ensuring good scientific practice of the Leibniz Association and the DFG. This includes a consistent orientation towards the international state of the art in research and technology, the continuous development of scientific methods, a thorough working method including critical thinking, a deep respect for the scientific work of the individual, and the promotion of broad cooperation.

STRATEGY

The realisation of long-term goals and sustainable results is the strategy of the Institute.

The institute ensures a creative environment with the aim of offering its employees the best possible working conditions and opening up new perspectives. Future-oriented topics of overall social and international relevance and with high scientific standards are the focus of our work. On the basis of a sound overall strategy, it is thus possible to help shape trends in politics, business, and research.

EQUAL OPPORTUNITY

We offer fair and balanced living and access opportunities for all.

The INP is actively committed to gender equality. It also provides opportunities for persons with disabilities and creates family-friendly working conditions. The topics of equal opportunities, freedom from discrimination, family friendliness and compatibility of family and career are an integral part of the institute culture at all organisational levels. We see it as the responsibility of all of us to live and ensure this.

COMMUNICATION AND SPIRIT

We are open, fair, and respectful with each other.

We respect cultural diversity. Interdisciplinarity and cooperation within the institute are the basis of our success. We encourage independent action and codecision by all employees in the areas of responsibility based on the matrix structure.

PROMOTION OF YOUNG TALENT

We promote young talent at all levels of the institute – and beyond.

In the competition for the “best minds”, the promotion of young talent in all fields of activity is of particular concern to us. With our application-oriented fundamental research, we inspire the next generation for topics relevant to society as a whole. We enable specific experiences in research and in cooperation with industrial partners. For us, the promotion of young talent includes all phases of qualification – from school, studies, and apprenticeships to career.

INTERNATIONALISATION

We operate both nationally and internationally.

From Greifswald, we cooperate with internationally recognised research institutes. We help our scientists take advantage of international exchange opportunities and promote the research fellowships of international colleagues at our institute. The active participation in shaping the European Research Area is one of our priorities.

TRANSFER OF RESEARCH SERVICES

The results of our research have both social and economic benefits.

Our research is realised in specific applications. This includes the publication of scientific results and their transformation into both products and services.

Gender equality and reconciliation of work and family life

High-quality results can be achieved only at a research institute with highly motivated employees. They must be given the best possible encouragement in their professional and personal development by their managers as well as support when it comes to balancing a career and family. The Leibniz Institute for Plasma Science and Technology (INP) is therefore actively committed to gender equality. This is an integral part of the philosophy of the INP and is anchored in the statutes and guidelines of the institute. This issue receives considerable attention from the Institute management in terms of strategic planning for gender equality and the implementation of individual activities. In the past two years, the proportion of women has been maintained at around 40%.

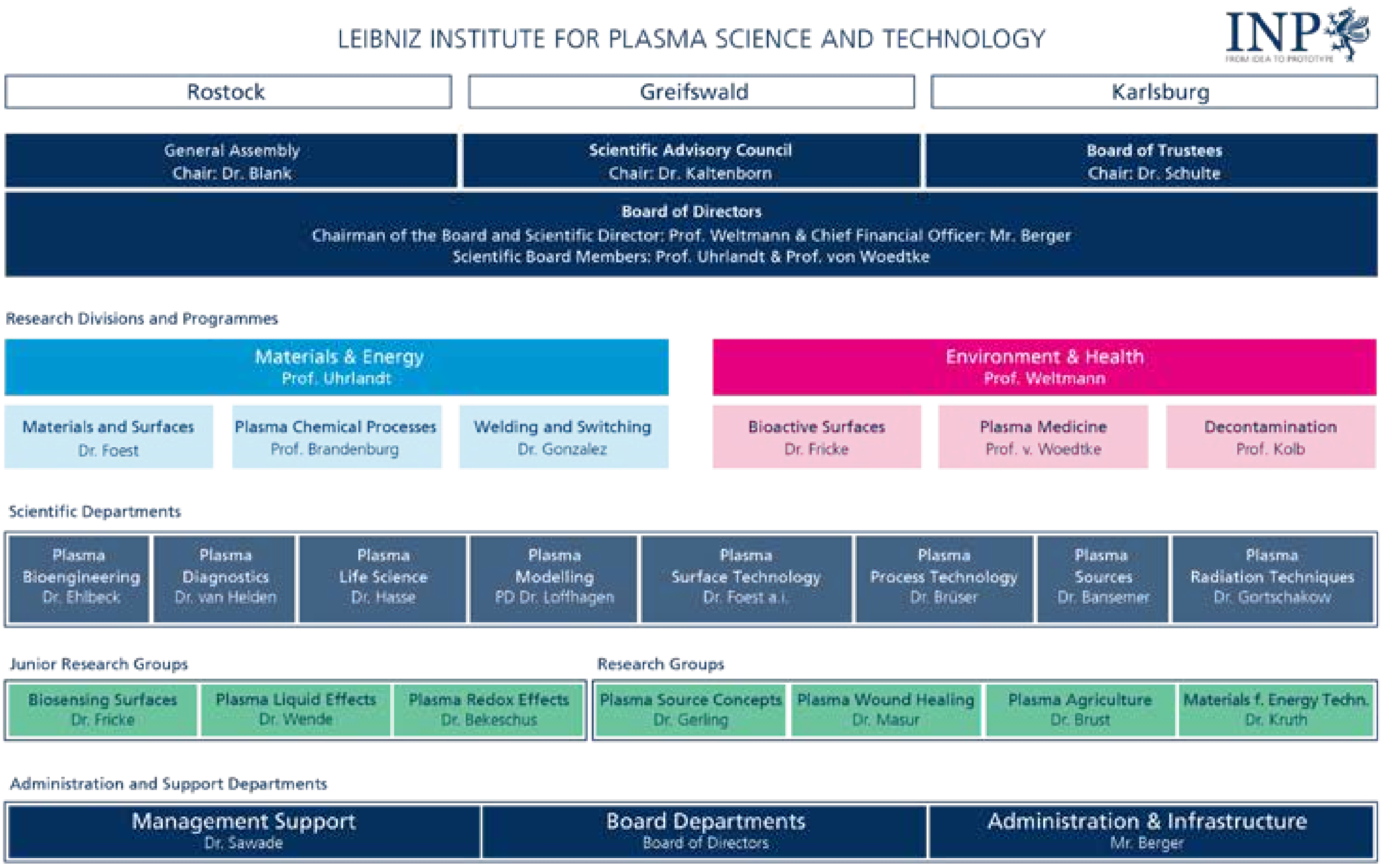
Because good commitment to gender equality is more than quotas and laws, we create specific family-friendly working conditions: The services offered to our employees range from individual working time and work location agreements, including an agreement on "mobile working" that is currently in force, to a parent-child room that can be used in the event of childcare shortages.

Our employees come from a wide range of nations and have varied career paths. We are committed to equal opportunities and non-discrimination at all levels of the institute. We support our employees with customised personell development opportunities, which are discussed in regular meetings. In 2021, the Gender Equality Officer and her deputy have supported the successful application for the "HR Excellence in Research Award" of the European Commission. The award is a sign that the INP cares about creating an ideal working environment for excellent research.

We have already received three TOTAL E-QUALITY awards for our gender equality work. In 2020, we applied for a further extension and were once again able to convince the jury with our gender equality work. TOTAL E-QUALITY Deutschland e.V. recognises the successful and sustainable commitment of organisations and companies to equal opportunities in the workplace. The award was developed with the help of the Federal Ministry of Education and Research (BMBF) and the European Union and is given for exemplary action in the sense of personnel management oriented towards equal opportunities.

The work of the Gender Equality Officer is an important driver for further strengthening equality at the INP. New elections for the position of Gender Equality Officer and Deputy Gender Equality Officer are scheduled for spring 2022. The Gender Equality Officer has their own budget with which their can set priorities in their work. In close cooperation with the Board of Directors and the works council, the Gender Equality Officer organises workshops and advises employees on issues such as reconciling family and work.

Recognition for successfully implemented equal opportunities awarded by TOTAL E-QUALITY Deutschland e.V.



Board of Trustees

The Board of Trustees is the supervisory body of the INP to which the members of the state and federal government also send their representatives.

It decides on all essential scientific, economic, and organisational issues of the INP.

Members (2021)

Dr. Björn Schulte
Federal Ministry of Education and Research

Woldemar Venohr
Federal Ministry of Education, Science and Culture Mecklenburg-Western Pomerania

Dr. Wolfgang Schareck
University of Rostock

Dr. Wolfgang Motz MD
Klinikum Karlsburg

Dr. Christiane Gebhardt
BLUE CITY Development
Drees & Sommer

Prof. Dr. Albert Sickmann
Leibniz-Institut für Analytische Wissenschaften – ISAS – e.V.

Scientific Advisory Council

The Scientific Advisory Council is the advisory body of the INP. The members active in the research field of the institute include internationally renowned scientists from university and non-university research as well as industry. The Scientific Advisory Council advises the Board of Trustees and the Board of Directors on all important scientific and organisational issues, in particular on long-term research planning.

Members (as of 2021)

Dr. Uwe Kaltenborn (Chair of the Board)
HIGHVOLT Prüftechnik Dresden GmbH
Dresden

Ernst Miklos
The Linde Group, Unterschleißheim

Dr. Jürgen Lademann
Charité University Medicine Berlin

Dr. Jean-Michele Pouvesle
GREMI – Université d'Orleans, France

Dr. Wolfgang Motz MD
Klinikum Karlsburg

Dr. Manfred Thumm
Karlsruhe Institute of Technology (KIT)

Dr. Satoshi Hamaguchi
Osaka University - Center for Atomic
and Molecular Technologies (CAMT)

Dr. Annemie Bogaerts
University of Antwerp

Dr. Ursula van Rienen
Faculty of Computer Science and Electrical Engineering
University of Rostock

Dr. Alexander Fridman
Drexel University

Dr. Anne Bourdon
Ecole Polytechnique – Laboratoire de Physique des Plasmas
(LPP) Palaiseau

General Assembly

The general Assembly is the highest decision-making body of the INP. It elects the Board of Trustees, decides on amendments to the statutes, receives the report of the Board of Directors on the general situation of the INP, and approaches the activities of the Board of Directors.

Members (as of 2021)

Dr. Wolfgang Blank (Chair)
WITENO GmbH

Dr. Björn Schulte
Federal Ministry of Education and Research

Woldemar Venohr
Federal Ministry of Education, Science and Culture
Mecklenburg-Western Pomerania

Dr. Dagmar Braun
Braun Beteiligungs GmbH, Greifswald

Prof. Dr. André Melzer
University of Greifswald

Dr. Stefan Fassbinder
Mayor of the University and Hanseatic City of Greifswald

Mario Kokowsky
DEN GmbH

Dr. Jürgen Meichsner
University of Greifswald

Dr. Arthur König
Former Mayor of the University and Hanseatic City of Greifswald

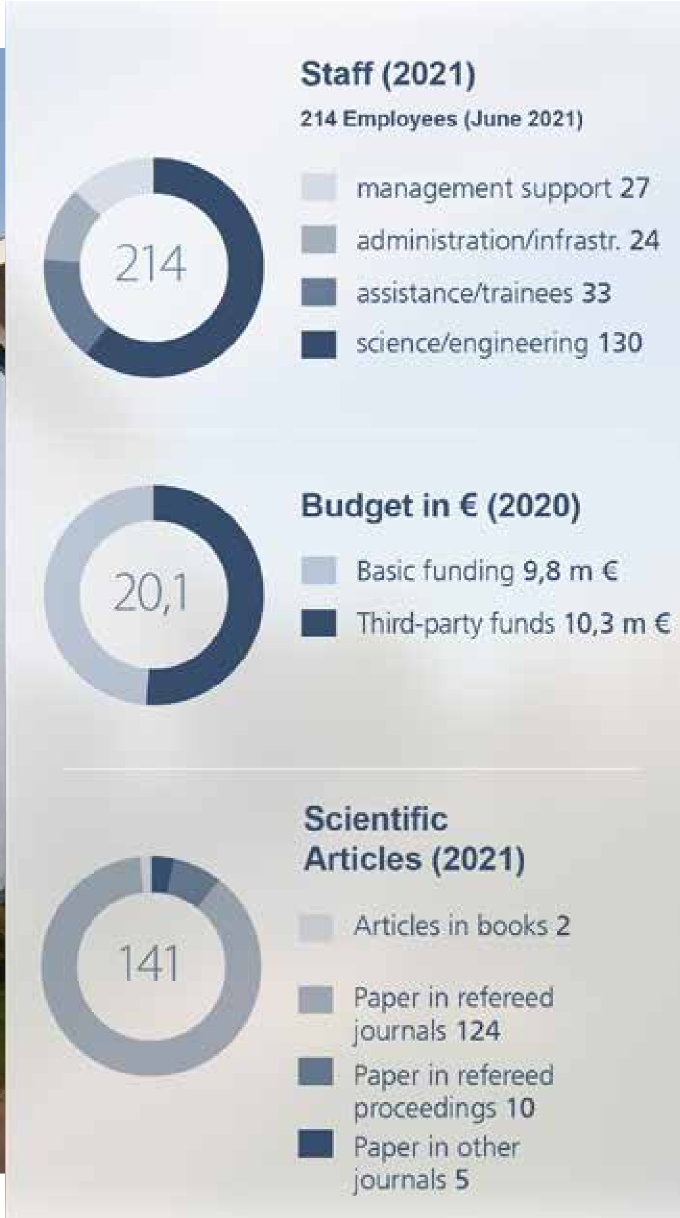
Facts and figures

Budget

The total budget amounted to €20.1 million in reporting year 2020 and €20.3 million in reporting year 2021. Personnel expenses were €11.4 million (2020) and €12.4 million (2021), and operating expenses were €5.5 million (2020) and €4.4 million (2021). €2.8 million was invested in INP equipment in 2020 and €3.6 million in 2021.

Personnel

As of June 2021, the INP has 214 employees, 137 of whom work in scientific and technical areas and 77 in scientific support. Just over 39.6% of employees are women.



Memberships of the INP

- RWI - Regionale Wirtschaftsinitiative Ost Mecklenburg-Vorpommern e.V.
- Deutscher Bibliotheksverband e.V.
- idw - Informationsdienst Wissenschaft
- German Water Partnership e. V.
- HYPOS Hydrogen Power Storage & Solutions East Germany e.V.
- Nationales Zentrum für Plasmamedizin e.V.
- Europäische Forschungsgesellschaft Dünne Schichten e.V.
- enviMV e.V. - Umwelttechnologiennetzwerk aus Mecklenburg-Vorpommern
- Deutsche Lichttechnische Gesellschaft e.V.
- Deutsche Physikalische Gesellschaft e.V.
- Forschungsvereinigung Schweißen und verwandte Verfahren e. V. des DVS
- DECHEMA - Gesellschaft für Chemische Technik und Biotechnologie e.V.
- IUTA - Institut für Energie- und Umwelttechnik e. V.
- Carbon Concrete Composite e.V.
- BdP - Bundesverband deutscher Pressesprecher e.V.
- INPLAS - Kompetenznetz Industrielle Plasma-Oberflächentechnik e.V.
- BVMW - Bundesverband mittelständische Wirtschaft, Unternehmerverband Deutschlands e.V.
- WTI - Wasserstofftechnologie-Initiative e.V.
- Hydrogen Europe Research association (former N.ERGHY)
- Greifswald University Club e.V.
- GFaI - Gesellschaft zur Förderung angewandter Informatik e.V.
- Initiative Chronische Wunden e.V.
- Forum MedTech Pharma e.V.
- Deutsche Gesellschaft für Plasmatechnologie e.V.

COOPERATIONS

- AJ Drexel Plasma Institute
- Albutec GmbH, Rostock
- Alpes Lasers SA
- Brno University of Technology, Czech Republic
- C3 e.V.
- CentraleSupélec, University Paris-Saclay
- Centre for Mathematical Plasma-Astrophysics
- Centre Suisse d'Electronique et de Microtechnique
- Centrum Wiskunde & Informatica
- Charité Berlin
- Chongqing University, China
- Christian-Albrechts-Universität zu Kiel
- CINOGY GmbH, Duderstedt
- College of Electrical and Information Engineering, Hunan University
- Comenius University in Bratislava, Slovakia
- Costa Rica institute of Technology
- Cosun Beet Company
- CSIRO Manufacturing
- Cytocentrics Bioscience GmbH
- Deutsche Zentralbibliothek für Wirtschaftswissenschaften (ZBW)
- DLR - German Aerospace Center
- DLR-Institute of Networked Energy Systems
- Dockweiler AG
- DST Diagnostische Systeme & Technologien GmbH
- Dutch Institute for Fundamental Energy Research (DIFFER)
- EFDS - European Society of Thin Films
- Eindhoven University of Technology TU/e
- Empa, Swiss Federal Laboratories for Materials Science and Technology, Plasma & Coating Group
- Hochschule Stralsund
- Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH), Berlin
- Forschungsverbund Mecklenburg-Vorpommern e.V.
- Fraunhofer Institute for Applied Optics and Precision Engineering IOF
- Fraunhofer Institute for Electronic Nano Systems
- Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM
- Fraunhofer Institute for Material and Beam Technology IWS
- Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology FEP
- Fraunhofer Institute for Surface Engineering and Thin Films IST, Braunschweig
- Fraunhofer Institute for Surface Engineering and Thin Films IST, DOC Dortmunder OberflächenCentrum GmbH
- Fraunhofer Institute for Technology and Advanced Materials IFAM
- Fraunhofer-Research Institution for Large Structures in Production Engineering IGP
- Fraunhofer-Institut für Keramische Technologien und Systeme IKTS
- Fudan University, China
- Greifswald
- Groupe des Couches Minces (GCM) and Department of Engineering Physics, Polytechnique Montreal
- Helmholtz-Zentrum Rossendorf, Dresden
- Hochschule Neubrandenburg
- Holon Institute of Technology, Israel
- IHK Neubrandenburg

- INM – Leibniz Institute for New Materials
- Innovent e.V.
- INPLAS - Network of Competence Industrial Plasma Surface Technology
- Institut für Energietechnik, Energieverfahrenstechnik und Umwandlungstechniken regenerativer Energien (EVUR)
- Institut für Werkzeugmaschinen und Fabrikbetrieb, TU Berlin
- Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, Budapest, Hungary
- Institute of High Current Electronics
- Institute of Plasma Physics of the Czech Academy of Science, Czech Republic
- Instituto de Astrofisica de Andalucia (IAA-CSIC)
- Instituto de Plasmas e Fusão Nuclear
- Instituto Superior Técnico
- International Sakharov Environmental University, Belarus, Russia
- Justus-Liebig Universität
- Karlsruhe Institute of Technology, Karlsruhe
- Kaunas University of Technology, Lithuania
- Klinikum Karlsburg
- KTH Royal Institute of Technology Stockholm
- Kwangwoon University; Seoul, South-Korea
- Laboratory on plasma and conversion of energy, Toulouse, France
- Leibniz Institute for Baltic Sea Research (IOW)
- Leibniz Institute for Catalysis (LIKAT)
- Leibniz Institute for Crystal Growth
- Leibniz Institute for Farm Animal Biology (FBN), Dummerstorf
- Leibniz Institute of Photonic Technology (IPHT), Jena
- Maritime University of Szczecin, Poland
- Masaryk University, Brno, Czech Republic
- Max-Planck-Institut für Eisenforschung GmbH
- Menlo Systems GmbH
- Ministerium für Wirtschaft, Bau und Tourismus MV
- Nagoya University, Japan
- National Institute for Laser, Plasma and Radiation Physics, Bucharest, Romania
- neoplas GmbH
- Nicolaus Copernicus University, Torun, Poland
- North Carolina State University
- Old Dominion University Norfolk, Virginia
- Paul-Drude-Institut für Festkörperelektronik (PDI)
- PBRC, Kwangwoon University, Seoul, Korea
- Peking University, China
- Plasma Advanced Research Center, University Iasi, Romania
- PlasmaMedic LTD, Israel
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- Technische Universität Berlin
- Technische Universität Braunschweig
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1. Baeva, M.: **Arcs of short length between copper electrodes - challenges in their modelling and diagnostics.** 7th Plasma Science Entrepreneurship Workshop, Virtual Event/Internet 2020

2. van Helden, J.H.: **Comprehensive quantitative plasma diagnostic using a mid-infrared frequency comb to analyse industrial plasma processes.** 47th Intern. Conf. on Plasma Science (ICOPS), Virtual Event/Internet 2020

3. Wende, K.: **Data reprocessing in omics-driven approaches in plasma medicine.** 73rd GEC, Virtual Event/Internet 2020

4. Makhneva, E.; Barillas, L.; Farka, Z.; Pastucha, M.; Skldal, P.; Weltmann, K.-D.; Fricke, K.: **Fabrication of biosensing coatings with tailored functionality by using atmospheric-pressure plasma polymerization.** 7th Intern. Congr. on Energy Fluxes and Radiation Effects, Virtual Event/Internet 2020

5. Baeva, M.: **Modelling of atmospheric-pressure direct-current arcs.** Int. Conf. Phys. Low Temp. Plasma (PLTP), Virtual Event/Internet 2020

6. Gortschakow, S.; Franke, St.; Gonzalez, D.; Methling, R.; Uhrlandt, D.; Batrakov, A.; Popov, S.: **Optical diagnostics of vacuum arc discharges for switching applications.** 7th Intern. Congr. on Energy Fluxes and Radiation Effects, Virtual Event/Internet 2020

7. Weltmann, K.-D.: **Physical Applications in Life Science.** Int. Symp. Phys. Ion. Gases (SPIG2020), Virtual Event/Internet 2020

8. Gortschakow, S.: **Properties of Vacuum Arcs Generated by Switching RMF Contacts at Different Ignition Positions.** 7th ITG Intern. Vacuum Electronics Workshop (IVEW) Virtual Meeting/Internet 2020

TALKS 2021

1. Baeva, M.: **An overview of the theoretical description and modelling of low-current arcs at small gap distances.** DPG-Tagung Sektion SMuk, Virtual Event/Internet 2021

2. Höft, H.; Becker, M.; Kolb, J.; Huiskamp, T.: **Breakdown and development of sub-ns pulsed sparks in short gaps.** IEEE Pulsed Power and Plasma Science Conference, Virtual Event/Internet 2021

3. Bekeschus, S.: **Challenges and opportunities of gas plasma technology in oncology and immunology.** Therapeutic ROS and Immunity in Cancer (TRIC), Virtual Event/ Internet 2021

4. von Woedtke, T.: **Cold atmospheric pressure plasma for wound healing: state-of-the-art and perspectives (keynote lecture).** Plasma Processing and Technology Int. Conf., Virtual Event/Internet 2021

5. Bekeschus, S.: **Cold plasma technology for targeting cancer - role of redox and immunity.** 4th Int. Symp. of Experimental Pathology, Virtual Event/Internet 2021

6. Kolb, J. F.; Zocher, K.; Schneider, M.; Gros, P.; Rataj, R.; Hahn, V.; Schulz, T.; Schmidt, M.; Honnorat, B.; Brüser, V.; Leinweber, P.; Weltmann, K.-D.: **Degradation of Residual Agrochemicals by Non-thermal Plasma.** 3rd Intern. Workshop on Plasma Agriculture (IWOPA), Virtual Event/ Internet 2021

7. Brandenburg, R.; Kolb, J.; Weltmann, K.-D.: **Future in Plasma Science: Environment and Gas Conversion.** 38. ak-adp Workshop, Virtual Event/Internet 2021

8. Masur, K.: **Influence of Cold Atmospheric Pressure Plasma on Wound Healing.** 9th Intern. Symp. on Functional Materials, Virtual Event/Internet 2021

9. van Helden, J.H.: **Infrared laser spectroscopy to characterize low and atmospheric pressure plasmas.** 48th Intern. Conf. on Plasma Science (ICOPS), Virtual Event/Internet 2021

10. Miebach, L.; Sliker, B.H.; Mohamed, H.; Nießner, F.; Snook, A.E.; Bowne, W.B.; Miller, V.; Bekeschus S.; Campbell, P.M.: **Non-thermal plasma initiates immune cell activation and response in models of pancreatic adenocarcinoma.** 7th Intern. Workshop on Plasma for Cancer Treatment (IWPCT), Virtual Event/Internet 2021

11. von Woedtke, T., Kolb, J.: **Physical Plasma: Innovative Concepts for Hygiene.** 3rd InnoPIP Network Meeting, Virtual Event/Internet 2021

12. Brust, H.; Wannicke, N.; Nishime, T.; Wagner, R.; Bousselmi, S.; Bretschneider, E. S.; Werner, J.; Horn, S.; Ehlbeck, J.; Timm, M.; Bendt, H.; Kolb, J. F.; von Woedtke, T.; Weltmann, K.-D.: **Plasma derived nitrogen species: Fertilizers or signaling factors in plant growth and development?.** 3rd Intern. Workshop on Plasma Agriculture (IWOPA), Virtual Event/Internet 2021

13. van Helden, J.H.: **Recent progress in infrared laser spectroscopy to characterize low and atmospheric pressure plasmas.** 74th GEC, Virtual Event/Internet 2021

14. Bekeschus, S.; Menz, J.; Freund, E.; Wende, K.; von Woedtke, T.; Schmidt, A.: **The surface marker and gene expression signature linked to plasma-induced toxicity in cancer cells - a comprehensive screening.** 8th Int. Conf. on Plasma Medicine, Virtual Event/Internet 2021

15. von Woedtke, T.; Metelmann, H.-R.; Emmert, S.; Weltmann, K.-D.: **Wound treatment by cold atmospheric plasma: state of evidence.** 13th Int. Symp. on Advanced Plasma Science and its Applications for Nitrides and Nanomaterials, Virtual Event/Internet 2021

16. Wende, K.; Nasri, Z.; Clemen, R.; Weltmann, K.D.; von Woedtke, T.; Bekeschus, S.: **Zur Rolle der Plasmachemie in der medizinischen Anwendung.** 7. Workshop Plasmamedizin des AK-ADP, Magdeburg/Deutschland 2021

INVITED TALKS 2020

1. Masur, K.: **Cold Atmospheric Plasma (CAP) for biological and medical applications.** 30th European Wound Management Association Conf., Virtual Event/Internet 2020

2. von Woedtke, T.; Weltmann, K.D.: **Cold plasma for medical application.** Special PSE Conference, Erfurt/Germany 2020

3. Zhang, G.; Uhrlandt, D.; Gött, G.: **Comparison of fall voltages in GMAW with different shielding gases.** 73th IIW Annual Assembly and International Conference, Virtual Event/Internet 2020

4. Kolb, J.: **Degradation of a cyanobacterial toxin by non-thermal plasmas.** Natural Toxins: **Environmental Fate and Safe Water Supply, Virtual Event/Internet 2020 .**

5. Ravandeh, M.: **Effect of reactive species generated by cold physical plasma on biomimetic membranes.** Baltic Redox Workshop, Virtual Event/Internet 2020

6. Gortschakow, S.; Kozakov, R.; Pieterse, P.; Uhrlandt, D.; Hilbert, M. ; Kurrat, M. : **Electro-Optical Diagnostics of Single Partial Discharges.** Intern. Conf. on Dielectrics (ICD), Virtual Event/Internet 2020

7. Kolb, J.: **Functionalization of 3D printed, piezoelectric barium titanate-hydroxyapatite composite scaffolds with bioactive glass.** ELAINE 2020, Virtual Event/ Internet 2020

8. Bruno, G.: **Gas plasmas as source of reactive species: cysteine as molecular beacon.** 22nd Paris Redox Conference, Virtual Event/Internet 2020

9. Bekeschus, S; Menz, J; Freund, E; Wende, K; Schmidt, A.: **Gene expression signatures associated with the sensitivity to oxidant-induced cell death in 30 cancer cell lines.** Baltic Redox Workshop, Virtual Event/Internet 2020

10. Gonzalez, D.; Franke, St.; Khakpour, A.; Methling, R.; Gortschakow, S.; Uhrlandt, D.: **High-Speed Video Spectroscopy in a Vacuum Arc during High-Current Anode Modes.** 6th ITG Int. Vacuum Electronics Workshop, Bad Honnef/Germany 2018

11. Masur, K.: **Kaltplasma (CAP) für biomedizinische Anwendungen.** 3. Nürnberger Wundkongress, Virtual Event/Internet 2020

12. Wenske, S.: **Oxidative PTMs in peptides and proteins Identification strategies and physiological implications.** Baltic Redox Workshop, Virtual Event/Internet 2020

13. Wenske, S.: **Oxidative PTMs in peptides Understanding the physiological consequences of physical plasma.** 19th Human Proteome Organization World Congress, Virtual Event/Internet 2020

14. Bruno, G.: **Physical plasmas as source of reactive species: cysteine as molecular beacon.** Baltic Redox Workshop, Virtual Event/Internet 2020

15. Schnabel, U.; Stachowiak, J.; Bourke, P.; Ehlbeck, J.: **Plasma treated water: From bench to prototype for fresh food safety.** 34th EFFoST Int. Conf., Virtual Event/Internet 2020

16. Schnabel, U.; Stachowiak, J.; Bourke, P.; Ehlbeck, J.: **Plasma treated water: From bench to prototype for fresh food safety.** 6th Joint Conference of the DGHM VAAM, Leipzig/Germany 2020

17. Schmidt-Bleker, A.: **Sporizides in situ Desinfektionsverfahren auf Basis kurzlebiger Wirkstoffe.** Aseptikon, Virtual Event/Internet 2020

18. Kewitz, T.: **Study of the local segregation of multi-component powders during a plasma spray process..** 47th Intern. Conf. on Plasma Science (ICOPS), Virtual Event/Internet 2020

19. Kewitz, T.; Testrich, H.; Quade, A.; Fricke, K.; Fröhlich, M.; Foest, R.; Weltmann, K.-D.: **Study of the local segregation of multi-component powders during a plasma spray process for biological applications.** Special PSE Conference, Erfurt/Germany 2020

20. Nasri, Z.: **The impact of reactive species on the barrier properties of asymmetric lipid bilayer models.** Baltic Redox Workshop, Virtual Event/Internet 2020

21. Sadiek, I.; Hjälten, A.; Foltynowicz, A.: **Towards a Transferable Standard for Nitrous Oxide Isotopomer Ratio.** Conference on Lasers and Electro-Optics, Virtual Event/Internet 2020

22. Striesow, J.: **Tracing lipid oxidation by exogenous small reactive species.** 8th European Lipidomics Meeting, Virtual Event/Internet 2020

23. Striesow, J.: **Tracing lipid oxidation by exogenous small reactive species.** Baltic Redox Workshop, Virtual Event/Internet 2020

TALKS 2021

1. Berner, J.; Seebauer C.; Metelmann, H.-R.; Bekeschus, S.: **Adaptive Responses of Head and Neck Cancer Cells upon Repeated Exposure to Gas Plasma over Ten Weeks In Vitro.** Therapeutic ROS and Immunity in Cancer (TRIC), Virtual Event/Internet 2021

2. Gelbrich, N.; Burchardt, M.; Zimmermann, U.; Stope, M.; Bekeschus, S.: **Antineoplastische Effekte von kaltem atmosphärischen Plasma in der Uroonkologie: Neue Behandlungsmöglichkeiten für Harnblasenkrebs.** 15. Nordkongress Urologie, Oldenburg/Deutschland, 2021

3. Weihe, T.; Schnepel, K.; Gründlich, B.; Schnabel, U.; Stachowiak, J.; Ehlbeck, J.: **A plasma-based process for the decontamination of cold-smoked salmon.** Alternative Food Processing Technologies - Science meets Industry (EFCE event), Virtual Event/Internet 2021

4. Wei, W.; Kolb, J. F.: **Application of Deep Learning (DL) in EIS-based Analysis for Microstructural Information of Osseous Tissue.** 5th Intern. Conf. on Biomedical Engineering and Applications, Virtual Event/Internet 2021

5. Bernhardt, T.; Manda, K.; Hildebrandt, G.; Stachs, O.; Bekeschus, S.; Vollmar, B.; Emmert, S.; Böckmann, L.: **Assessment of cold atmospheric pressure plasma as innovative therapy for treatment of radiation dermatitis using a mous emodel.** Therapeutic ROS and Immunity in Cancer (TRIC), Virtual Event/Internet 2021

6. Kruth, A.: **CAMPFIRE-Wind and Water to Ammonia Maritime Fuel and Energy Storage for a Zero Carbon Future, World Energy Storage Day Global Conference, online, 2021.** World Energy Storage Day Global Conference, Virtual Event/Internet 2021

7. Bekeschus, S.: **Cancer Redox Biology.** 7th Intern. Workshop on Plasma for Cancer Treatment (IWPCT), Virtual Event/Internet 2021

8. Barrilas, L.: **Chemical surface patterning by maskless Atmospheric-Pressure Plasma Printing for biosensing applications.** 31st Anniversary World Congress on Biosensors, Virtual Event/Internet 2021

9. Wende, K.: **Cold plasma-driven biomolecule modifications - key or lock to effectiveness?.** 74th GEC, Virtual Event/Internet 2021

10. Wende, K.: **Cold plasma-driven biomolecule modifications - key or lock to effectiveness?.** 7. Workshop Plasmamedizin des AK-ADP, Magdeburg/Deutschland 2021

11. Sagwal, S.K.; Bekeschus, S.: **Combination therapy with cold physical plasma and novel molecules using the cutaneous and squamous melanoma in vitro.** Therapeutic ROS and Immunity in Cancer (TRIC), Virtual Event/Internet 2021

12. Nasri, Z.; Memari, S.; Bekeschus, S.; Weltmann, K.-D.; von Woedtke, T.; Wende, K.: **Development of an Electrochemical Sensor for In-Situ Monitoring of Reactive Species Produced by Cold Physical Plasma.** 8th Int. Conf. on Plasma Medicine, Virtual Event/Internet 2021

13. Schäfer, M.; Semmler, M.L.; Bernhardt, T.; Glatzel, A.; Frey, A.; Sagwal, S.K.; Hein, M.; Langer, P.; Kaufmann, D.; von Woedtke, T.; Bekeschus, S.; Fischer, T.; Emmert, S.; Böckmann, L.: **DNA toxicity and mutagenicity of cold atmospheric pressure plasma and small molecules in skin cancer treatment.** Therapeutic ROS and Immunity in Cancer (TRIC), Virtual Event/Internet 2021

14. Gerling, T.; Grollmisch, D.; Hahn, V.; von Woedtke, T.; Weltmann, K.-D.: **Effect of Treatment Angle on the Distribution of Plasma Cocktail Components.** 8th Int. Conf. on Plasma Medicine, Virtual Event/Internet 2021

15. Brust, H.; Wannicke, N.; Werner, J.; Bousselmi, S.; Pan, Y.; Wagner, R.; Stachowiak, J.; Ehlbeck, J.; Weltmann, K.-D.: **Effects of Plasma Treated Air and Plasma Treated Water on Plant Seed Germination and Inactivation Potential of Bacterial Cells and Spores.** 8th Int. Conf. on Plasma Medicine, Virtual Event/Internet 2021

16. Miebach, L.; Freund, E.; Liedtke, K.; Partecke, L.; Bekeschus, S.: **Efficiacy and immunogenicity of plasma-oxidized saline in the treatment of peritoneal carcinomatois.** Therapeutic ROS and Immunity in Cancer (TRIC), Virtual Event/Internet 2021

17. Vilardell Scholten, L.; Hahn, V.; Weltmann, K.-D.; Gerling, T.: **Electric Field in Plasma Medicine: an Approach to Measurement and Effects in Wound Treatment.** 8th Int. Conf. on Plasma Medicine, Virtual Event/Internet 2021

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2. Jonathan Zücker/PQK: **Visualization of ion wind impact on air flow** (TU Berlin, 01.01.-31.03.2021)

3. Kleiser, Felix: **In-/ Ex-Situ Messungen der Laserabsorptionsspektroskopie am Prozess der Biopyrolyse** (Uni Greifswald, 15.07.2021)

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5. Sturm, Tristan: **Untersuchung des Einflusses von nichtthermischen Plasmaquellen auf die elektrischen Parameter einer PEM-Zelle** (Universität Greifswald, 01.08.2020-31.01.2021)

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3. Doi, Ujmir: **Evaluation of Corona Discharge for Various Conductor Materials** (Uni HRO, Elektrische Energietechnik, 16.07.2020)

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