21ST EUREGIONAL WELTPP

Workshop on the Exploration of Low Temperature Plasma Physics

November 29 and 30, 2018

"Rolduc"
Kerkrade, the Netherlands

Jointly sponsored and organized by

RUHR UNIVERSITÄT BOCHUM RUB

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

RESEARCH DEPARTMENT Plasmas with Complex Interactions

DIFFER Dutch Institute for Fundamental Energy Research

SFB-TR 87

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Ocean Optics

21ST EUREGIONAL WELTPP

Workshop on the Exploration of Low Temperature Plasma Physics

Welcome to the 21st *Workshop on the Exploration of Low Temperature Plasma Physics* (WELTPP-21). This workshop is intended for active scientists working in the field of low temperature plasma physics.

The aim of this workshop is to create a forum for young low temperature plasma scientists, that is graduate students and postdoctoral researchers, to meet, learn from each other, exchange knowledge, present results and establish new contacts. The emphasis is on the presentation of the work of the people new in this field.

The workshop is jointly sponsored and organised by Eindhoven University of Technology (TU/e) and the Research Department *Plasmas with Complex Interactions* of the Ruhr-Universität Bochum (RUB) in the framework of SFB-TR 87.

WELTPP was born in close collaboration between the research groups in Eindhoven and Bochum, that are Plasma and Materials Processing (*PMP, TU/e*), Elementary Processes in Gas Discharges (*EPG, TU/e*), The Institute of Theoretical Electrical Engineering (*TET, RUB*) and The Institute for Electrical Engineering and Plasma Technology (*AEPT, RUB*). Some years ago York Plasma Institute (*YPI*) and the Dutch Institute for Fundamental Research (*DIFFER*) joined the organisers. Since former members of the organising committee have found their own new challenges we are happy to welcome also Leuphana University of Lüneburg and Brandenburg University of Technology Cottbus-Senftenberg among the co-organisers.

Also this year **WELTPP-21** is kindly supported by Ocean Optics.

Local Organisers

Jeanne Loonen	(Eindhoven University of Technology)
Stefan Welzel	(DIFFER)

Advisory committee

Stefan Welzel	(DIFFER)
Richard Engeln	(Eindhoven University of Technology)
Jan van Dijk	(Eindhoven University of Technology)
Frederik Schmidt	(Ruhr-University Bochum)
Erik Wagenaars	(York Plasma Institute at University of York)
Jens Oberrath	(Leuphana University of Lüneburg)
Jan Trieschmann	(Brandenburg University of Technology Cottbus-Senftenberg)

Programme WELTPP at Rolduc, November 29 and 30, 2018

Thursday, November 29th

10:35 **Registration (coffee/tea in the Foyer)**
10:55 **Opening**

Session 1 **Plasmas, Charges and Surfaces** (Conference room 4)

11:05-11:25 O1 **The possible influence of charge and charged particles during ALD and plasma ALD**
D.C. Schram (Eindhoven University of Technology)

11:25-12:25 O2 **INVITED**
Surface charge in plasma catalysis: origin of observed synergies?
E. Neyts (University of Antwerp)

12:30 **Lunch in the "Grote Eetzaal"**

Session 2 **Plasma Modelling** (Conference room 4)

14:00-14:20 O3 **Synergy effects in low pressure capacitively coupled Argon-Xenon discharges**
M. Klich (Ruhr-University Bochum)

14:20-14:40 O4 **Machine learning plasma-surface interface for coupling sputtering and gas-phase transport simulations**
F. Krüger (Ruhr-University Bochum)

14:40-15:00 O5 **Analysis of the planar multipole resonance probe using a kinetic model**
M. Friedrichs (Leuphana University Lüneburg)

15:00-15:20 O6 **Laser shock peening global modeling**
V. Pozdnyakov (Leuphana University Lüneburg)

15.30 **Coffee/Tea in the Foyer**

15:30-16:30 **Rolduc historical tour**
(Registration through registration desk (max. 30 persons))

16:30-18:00 **Poster session I** (Conference room 2)
Poster numbers P1 – P15 can be posted from 12:00 hrs.

Session 3 **High Frequency Discharges** **(**Conference room 4)

18:10-18:30 O7 **Absolute atomic chlorine density measurements in the effluent of a radio-frequency atmospheric pressure plasma**
J G Boothroyd (York Plasma Institute)

18:30-18:50 O8 **Ellipsometric analysis of nanostructures in thin SiOx--films**
R. Buschhaus (Ruhr-University Bochum)

18:50-19:10 O9 **Absolute density measurements of atomic hydrogen in an ICP**
J. Ellis (University of York)

19:10-19:30 O10 **Phase-resolved monitoring and extraction of nanoparticle during particle growth cycles in an acetylene plasma**
Z. Marvi (Eindhoven University of Technology)

19:45 **Dinner in "De Verloren Zoon" & "KANA 1"**

From 21:00 the bar in "De Verloren Zoon" will be open.

Friday, November 30th

08:00 **Breakfast in the "Grote Eetzaal"**

Please return your room key to the reception before attending Session 4!

Session 4 **CO_2 Containing Plasmas** (Conference room 4)

09:00-09:20	O11	**Dissociation of CO_2 in a non-equilibrium atmospheric pressure helium plasma jet in the presence of a catalyst** T. Urbanietz (Ruhr-University Bochum)
09:20-09:40	O12	**Laser-induced fluorescence in nanosecond discharges for CO_2 conversion** L.M. Martini (Eindhoven University of Technology)
09:40-10:00	O13	**Monte Carlo flux simulation of electrons for plasma modelling** L. Vialetto (DIFFER)
10:00-10:20	O14	**On the reservoir model for CO_2-laser amplification** S.C. Selvi (Eindhoven University of Technology)
10:20-10:40	O15	**Optimizing the vibrational non-equilibrium of CO_2 microwave plasma by fast pulsing** A. van de Steeg (DIFFER)

10:45 **Coffee/Tea in the Foyer**

10:45-12:15 **Poster session II** (Conference room 2)
All poster numbers greater than P15 can be posted

12:30 **Lunch in the "Grote Eetzaal"**

Session 5 **Plasma Diagnostics** (Conference room 4)

14:00-14:20	O16	**Temporal evolution of the electron density of a nanosecond discharge in distilled water** K. Grosse (Ruhr-University Bochum)
14:20-14:40	O17	**Velocity distribution of titanium neutrals in the target region of high power impulse magnetron sputtering discharges** J. Held (Ruhr-University Bochum)
14:40-15:00	O18	**Connection between target poisoning and current waveforms in reactive high power impulse magnetron sputtering of chromium** S. Thiemann-Monje (Ruhr-University Bochum)
15:00-15:20	O19	**Measurements of the electric field, electron properties and other plasma parameters: the influence of targets** M. Hofmans (Eindhoven University of Technology)

15:20 **Closure of the workshop**

Oral presentations

O1

The possible influence of charge and charged particles during ALD and plasma ALD

D.C. Schram
Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands

There is a long existing question whether with ALD, and even more with Plasma enhanced ALD, there is an influence of charge at the surface on the deposition mechanisms. Here I will give some thoughts on the matter, not hindered by too much knowledge of ALD.

The thoughts come from a listing of possible reaction pathways, starting with charged particle interaction (Coulomb), then induced dipole interaction between a charged and neutral particle and then a chemical interaction between neutrals. At near room temperature these are ordered as > 10 nm, > 1 nm, and > 0.1 nm. This means that the interaction with charged particles have much higher rates than the chemical reactions. As an example the reaction as associative detachment in the formation of a molecule can have very high cross sections in particular at low temperature.

In pure ALD is then a next question, if deposited precursors could have a charge distribution over the surface with positive parts and negative parts. If so, then I would expect that presence of charge to be of possible influences on the process. Also the conductivity of the surface material could have influence on the process.

In plasma assisted ALD there are charged particles and there is negative surface charge because of the ambipolar diffusion restraints. It is interesting to note that this may amount to inter-particle distances which are close to the Coulomb dimensions.

So the question is, should we look into this aspect and allow other reactions than pure chemical to be of importance?

Finally, I will give a short description on what potentials can be expected. At higher electron densities the expected potentials at the surface will drop and the ion energy danger will disappear (with hydrogen this is already small). But what still remains is the negative charge at the surface, which may influence the way radicals are bonded to the surface. It could help the deposition.

O2 (**INVITED)**
Surface charge in plasma catalysis: origin of observed synergies?

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Plasma catalysis is often claimed to open up new routes to gas conversion for various applications, including greenhouse gas conversion into value-added chemicals, nitrogen fixation or nanomaterial fabrication [1]. One of the origins of this claim is the (sometimes) observed synergy between plasma and catalyst, resulting in a process outcome which surpasses the sum of the outcome of the plasma-only or catalysis-only process. The origin of this synergy, however, is largely unknown. While atomistic simulations are in principle ideally suited to unravel the operative mechanisms in plasma/surface interactions – and thereby the origin of synergy – there is a lack in methodologies available to account for the complexity of the problem, including the presence of radicals, surface charges, ion bombardment, vibrationally excited species, and more.

We have recently developed a computational method to account for surface charges in a plasma-catalytic-like setup [2]. In this presentation, we will show how the presence of surface charges affects the adsorption and decomposition of molecules at catalytic surfaces, and how it may contribute to the observed synergy.

[1] E. C. Neyts, K. Ostrikov, M. Sunkara, A. Bogaerts, *Chem. Rev.* 115 (2015) 13408
[2] K. M. Bal, S. Huygh, A. Bogaerts, E. C. Neyts, *Plasma Sources Sci. Technol.* 27 (2018) 024001

O3

Synergy effects in low pressure capacitively coupled Argon-Xenon discharges

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[3]Brandenburg University of Technology Cottbus-Senftenberg, 03046 Cottbus, Germany

Industrial plasma processes for etching or deposition applications require an accurate control of the ion energy at the substrate surfaces. At the same time, these plasmas contain various gas and ion species, which may imply a complex chemistry. The control of the kinetics of multiple gas and ion species is a topic of current research. We investigate a low pressure argon-xenon discharge by means of Particle-In-Cell/Monte Carlo Collision (PIC/MCC) simulations. The advantage of this noble gas mixture lies in its feasible amount of species and a corresponding simple chemistry. A symmetric capacitively coupled radio-frequency (CCRF) discharge is investigated for a variety of discharge parameters (e.g. driving voltage and gas composition). It is found that a separate control of argon and xenon ions cannot unconditionally be achieved under these conditions.

This conclusion is drawn from simulated quantities such as the plasma and ion densities, the fluxes toward the surfaces, the discharge energy balance and, in particular, the ion energy distribution functions (IEDFs) at the electrodes. Furthermore, it is shown that, besides being coupled through the gas composition, the densities of argon and xenon ions are additionally connected by a synergy effect.

O4

Machine learning plasma-surface interface for coupling sputtering and gas-phase transport simulations

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Thin film processing by means of sputter deposition inherently depends on the interaction of energetic particles with a target surface and the subsequent transport of film forming species through the plasma. The direct coupling of the two physical regimes is infeasible as the respective time and length scales differ by several orders of magnitude. However, advantage can be taken particularly from the well-separated time scales of the fundamental surface and plasma processes by evaluating both independently and coupling them through a viable plasma-surface-interface model. We proposed a variant of said interface based on artificial neural networks.

A multilayer perceptron network has been trained on data of Ar sputtering an Al-Ti composite target. The set of input data has been obtained using TRIDYN developed by Moeller and Eckstein [1]. It is demonstrated that the trained network can be successfully exploited to predict the energy distributions and angular distributions of sputtered and reflected particles

for arbitrary energy distributions of impinging particles. Computationally this method is efficient enough to allow for real time implementations in kinetic plasma simulations.

[1] W. Moeller, W. Eckstein, Nucl. Instr. and Meth. B2, 814 (1984

Contributions by Jan Trieschmann, Tobias Gergs, and Thomas Mussenbrock as well as funding by the DFG in the frame of SFB-TR 87 are kindly acknowledged.

O5
Analysis of the planar multipole resonance probe using a kinetic model

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The planar multipole resonance probe, consisting of two half-disc electrodes, can be integrated into the chamber wall of the reactor and is suited for industrial plasma diagnostic purposes, especially monitoring the process due to its minimal invasive character.
Using a fluid model, one can determine the electron density from the detected resonance frequency in the measured spectrum.
Monitoring the electron temperature requires another resonance parameter like the half-width of the resonance peak and a kinetic model is necessary to deduce a relation between the observed resonance parameter and the inner plasma parameter.
In this work such a kinetic model based on functional analytic methods is analyzed.

O6
Laser shock peening global modeling

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[2] *Helmholtz Centre Geesthacht, Institute of Materials Research, Materials Mechanics, Department of Joining and Assessment, Germany*

Nowadays in industry, new surface modification techniques to improve mechanical properties of the materials substitute the conventional methods. Laser shock peening (LSP) is one of the advanced surface processes, which looks promising for industrial application. Due to the reason that LSP deals with short timescale (ns-range) and highly intense (> 1 GW/cm^2) laser pulses, development and improvement of the computer simulation techniques are required. Simulations allow predicting the plasma and shock wave behavior, as well as residual stress (RS) distribution within the processing material. These predictions can be used to optimize the process with the minimum number of experiments.

In this work, a global model of Zhang et al. [1] is applied for macroscale LSP (mm-range). The plasma pressure temporal distributions for two cases are determined. These distributions are used as a surface loading for the residual stress prediction [2]. Predicted RS show a good agreement with the experimental results.

[1] W. Zhang, Y.L. Yao, I.C. Noyan, J. Manuf. Sci. E. - T. ASME **126**, 10 (2004)
[2] S. Keller, S. Chupakhin, P. Staron, E. Maawad, N. Kashaev, B. Klusemann, J. Mater. Process. Technol. **255**, 294-307 (2018)

O7

Absolute atomic chlorine density measurements in the effluent of a radio-frequency atmospheric pressure plasma

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[2] *Institute of Electrical Engineering and Information Technology, Ruhr University Bochum, 44801 Bochum, Germany*

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The density of atomic chlorine (Cl) in the effluent of a radio-frequency atmospheric pressure capacitively coupled argon/chlorine plasma source is investigated using a volatile organic compound marker and proton transfer reaction mass spectrometry. The plasma effluent and a nitrogen/marker compound mixture are introduced axially and radially respectively into a cylindrical flow tube. The plasma generated atomic chlorine is titrated by the marker and the remaining marker compound is measured using mass spectrometry.

Atomic chlorine can be crucial in atmospheric chemistry kinetics. Due to the highly reactive nature of atomic chlorine there is some difficulty in the direct measurement of its reactivity and concentration in the atmosphere. By changing the bath gas of the marker compound from nitrogen to an air sample, the Cl reactivity of the sampled air can be measured, a procedure similar to Sinha's comparative reactivity method [1].

The design of the plasma source investigated is similar to the 'COST reference microplasma jet' [2]. A total flow rate of 1 slm and typical mixing ratio of 1000:1 of argon to chlorine is used as the input gas flow. The bespoke flow tube reactor is assumed to be very close to atmospheric pressure and has dimensions of 20 mm diameter and 90 mm length. The plasma channel and reactor walls are constructed from borosilicate glass. The plasma channel dimensions are 5 x 50 x 0.5 mm^3, with two planar copper electrodes of width 5 mm and length 50 mm clamped to the top and bottom of the outside of the plasma channel walls. A 40.68 MHz driving voltage is supplied to the top electrode while the bottom electrode is grounded. The distance between the end of the plasma source and the flow tube is 60 mm.

[1] V Sinha, J Williams, J N Crowley, J Lelieveld, *Atmos. Chem. Phys.,* **8** (2008) 2213-2227

[2] J Golda, J Held, B Redeker, M Konkowski, P Beijer, A Sobota, G Kroesen, N St J Braithwaite, S Reuter, M M Turner, T Gans, D O'Connell, V Schulz-von der Gathen, *J. Phys. D* **49** (2016) 084003

O8

Ellipsometric Analysis of Nanostructures in Thin SiO_x-Films

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[2] *Electrical Engineering and Plasma Technology, Ruhr-University Bochum, 44801 Bochum, Germany*
[3] *Technical and Macromolecular Chemistry, Paderborn University, Germany*

In recent years, silicon oxide thin films have established themselves as barrier layers in industrial applications. Therefore, the performance of nanostructures in these layers is of scientific interest.

In this work silicon oxide layers with a thickness of 50 to 150 nm were investigated in regard to their surface properties and porosity using ellipsometry techniques. Silicon oxide layers with controlled stoichiometry were deposited on silicon wafers using an inductively coupled plasma (ICP) (O_2 and HMDSO) [1] or a microwave plasma (O_2 with HMDSO and O_2 with HMDSN) [2].

Ellipsometric porosimetry was performed on the resulting surfaces at atmospheric pressure with molecules of different sizes: water (d=0.27nm), ethanol (d=0.4nm) and toluene (d=0.6nm). This allowed for characterization of the materials porosity and surface affinity on a subnanometer scale.

Regardless of the type of discharge and stoichiometry, water and ethanol multilayer development ontop of the SiO_x material has always been observed. By comparing measured isotherms with the literature, we could conclude that samples deposited by the microwave source have smaller pores (pore size <0.4nm) than those deposited by an ICP (< 0.6nm). Independent on the partial pressure all surfaces absorb only a single toluene monolayer. Chemical characteristics of toluene aside, this is also indicative of the pore size diameter being smaller than 0.6 nm.

The type of precursor (HMDSO or HMDSN) did not visibly impact on the nanostructure contrary to previous published findings [3].

Additionally, microscopy measurements (AFM and SEM) were performed for surface analysis. The SiOx samples originating from microwave discharge possess a higher roughness value than those formed by the ICP source. An increase of layer thickness also correlates with an increased roughness, validating mathematical models.

O9

Absolute density measurements of atomic hydrogen in an ICP

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Atomic hydrogen is of great importance in understanding surface processes, particularly in technological plasmas used for material treatments[1], whether thin film deposition or the reduction of oxides. Absolute atomic densities are inherently difficult to measure, classical laser induced fluorescence is ineffective due to the requirement of VUV lasing. VUV

absorption using synchrotron radiation has been used, however, the experimental requirement is enormous. These diagnostic challenges result in two-photon absorption laser induced fluorescence being the sensible diagnostic choice for measuring absolute atomic hydrogen densities.

Absolute atomic hydrogen densities were measured in an inductively coupled plasma produced within the Gaseous Electronics Conference (GEC) reference cell by using ns-TALIF. Absolute atomic densities are measured under varying power and pressure, with a specific focus on variations across the E-H mode transition. Gas pressures between 50 and 250 Pa with powers between 200 and 1000 W have been investigated, with varying gas admixtures of He/H_2 ranging from a 6:1 ratio to a 1:6 ratio. Calibration for absolute densities have been conducted using krypton[2]. Absolute densities between $2x10^{22}$ and $6x10^{22}$ have been measured, with a large increase observed after the H-mode transition.

[1] - Katsuhiko Nomoto et al 1990 Jpn. J. Appl. Phys. 29 L1372
[2] - K Niemi *et al* 2001 *J. Phys. D: Appl. Phys.* 34 2330

O10
Phase-resolved monitoring and extraction of nanoparticle during particle growth cycles in an acetylene plasma

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[1]Elementary Processes in Gas Discharges, Department of Applied Physics, Eindhoven University of Technology, Eindhoven, Netherlands
[2]Institute of Experimental and Applied Physics, Kiel University, Germany

Controlled growth and size-selective collection of nanoparticles are desired for applications in catalysis, pharmacy and for the fabrication of nanofilms and nanodevices. Controllable particle growth in low temperature plasmas seems to be very promising for the generation of well-defined nano-sized particles.

In this work, we propose a simple scheme for the collection of nanoparticles (NPs) generated in a capacitively coupled RF plasma in Ar/C_2H_2 mixtures by the use of differently biased substrates at different positions in the particle cloud. The ever moving dust cloud, in turn, induces spatial variations of the plasma potential. By this method the nanoparticles can be guided to a certain position of the reactor where they are directionally collected. Also, the time at which the collection starts is well defined. As important parameters we monitored the self-bias voltage at the powered electrode, gas pressure and the shape of the dust cloud with by laser light scattering and a CCD camera.

Collection experiments were carried out at different distances from the RF electrode as well as different times during the growth cycles. A correlation of the collection time with the self-bias voltage and SEM results of the collected particles on Si substrates are discussed.
The SEM photographs show that different threshold potentials are needed to overcome the NPs confinement due to the spatial and temporal variation of the plasma potential inside the particle cloud. Moreover, the dispersion of the nanoparticles on the substrate is determined by the bias applied to it.

These results based on the phase resolved collection method allow to control depositions of carbon nanoparticles of a well-defined size distribution with the highest density available their growth.

O11

Dissociation of CO_2 in a non-equilibrium atmospheric pressure helium plasma jet in the presence of a catalyst

T. Urbanietz, S. Schüttler, T. Romba, C. Stewig, M. Böke, V. Schulz-von-der Gathen, A. von Keudell

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The energy efficient excitation of CO_2 in atmospheric pressure plasmas may be a method to generate solar fuels from renewable energies. This energy efficiency can be very high, if only specific states of the molecule in the plasma are populated creating a strong non-equilibrium. The non-equilibrium excitation and dissociation of CO_2 in an atmospheric helium RF plasma jet is analyzed for varying absorbed plasma powers with and without the presence of a catalyst. The concentration of CO_2 and CO as well as the vibrational and rotational temperatures of the possible degrees of freedom of the molecules are evaluated by Fourier transform infrared spectroscopy. A strong non-equilibrium excitation of CO_2 and CO has been found. Whereas the rotational temperatures are 400 K and below the vibrational temperatures for CO reaches values up to 1600 K and that of the asymmetric vibration of CO_2 of 700 K. The dependence of these excitation temperatures on plasma power is rather weak whereas a dependency on the load of the catalyst was found. A conversion efficiency up to 57 % without catalyst and 65 % with catalyst is observed in the parameter range of the experiment.

O12

Laser-induced fluorescence in nanosecond discharges for CO_2 conversion

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[2]Department of Physics - University of Trento, Italy

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The massive utilisation of solar (renewable) energy is limited by its intermittency and non-uniform spatial availability. An option to overcome these problems is energy storage that allows decoupling supply and demand. The conversion of CO_2 into C-neutral fuels by non-thermal plasmas is a promising way to convert renewable electricity into chemical energy [1]. The development of such a plasma-technology requires a deeper understanding of the chemical kinetics and the detection of transient species in the discharge. To this purpose, one needs a non-invasive, time- and space-resolved diagnostic. Laser-induced fluorescence (LIF) is the technique of choice. However, the collisional processes that modify the population of the (laser) excited state have to be taken into account. The interpretation of the LIF outcome requires, therefore, the knowledge of the proper collisional rate coefficients [2]. Recently, we have shown that it is possible to estimate the gas composition by the analysis of LIF spectra of the OH radical produced in a CO_2/H_2O discharge (Collisional Energy Transfer (CET)-LIF [3]). However, difficulties arise if the fast quenching of the OH exited-state prevents the thermalisation of its rotational population. In these cases, the knowledge of collisional rate coefficients specific to the non-thermal rotational distributions is required to exploit CET-LIF.

[1] M. Scapinello, L.M. Martini, G. Dilecce, and P. Tosi, Journal of Physics D: Applied Physics, 49, 075602 (2016).
[2] L.M. Martini, N. Gatti, G. Dilecce, M. Scotoni, and P. Tosi, Journal of Physics D: Applied Physics, 50, 114003 (2017).
[3] L.M. Martini, N. Gatti, M. Scotoni, G. Dilecce and P. Tosi, Plasma Physics and Controlled Fusion, 60, 014016 (2018).

O13
Monte Carlo flux simulation of electrons for plasma modelling

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[2]*Dipartimento di Chimica, Università degli Studi di Bari, via Orabona 4, 70126 Bari, Italy*

Modelling of non-thermal intermediate pressure plasmas for CO_2 dissociation is extremely challenging due to the complex chemical network and the non-equilibrium features of the electron energy distribution function (EEDF), that is important for the calculation of rate coefficients of any reactive process involving electrons and electron transport coefficients. The methodologies used to determine the EEDF are often based on approximations to find solutions of the Boltzmann equation. These computational methods are fast but not accurate for the plasma conditions of interest. In this work, simulations of electrons and their collisions in an atomic system are presented, based on the Monte Carlo flux method. The main advantage of the Monte Carlo flux, as opposed to other methods, is that no assumptions are made implicitly and it ensures uniform statistical accuracy in energy with a lower computational cost than conventional Monte Carlo. The methodology and results are presented, together with a comparison with analytical solutions of the Boltzmann equation and a benchmark with results from different solution methodologies.

O14
On the reservoir model for CO_2-laser amplification

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In many technological applications, such as extreme ultraviolet lithography, high-intensity CO_2-laser pulses are used, which are created in a CO_2-laser amplification system. Research concerned with CO_2-laser amplification tries to describe the dynamics of such amplification systems to be able to make predictions about its characteristics and performance. The system under consideration is a single plasma cell of the amplification system having a pre-mixture of CO_2-CO-N_2-He and infra-red radiation with a wavelength of 10.58 μm and 10.206 μm. The so-called reservoir model for CO_2-laser amplification describing the evolution the infra-red CO_2-laser radiation through the system under consideration is derived. Furthermore, a numerical implementation of the model in the PLASIMO code is used to simulate the evolution of the radiation through various cases, thereby showing its verification and the capabilities of the model.

O15

Optimizing the vibrational non-equilibrium of CO_2 microwave plasma by fast pulsing

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The energy transition faces the challenge of mitigating intermittency issues related to renewables. One solution to this problem is to synthesize hydrocarbon fuels from CO_2 with excess renewable energy. Efficient dissociation of CO_2 to CO is required in this process, which can be achieved by selective excitation of vibrational modes of CO_2. This contribution concerns how such selective excitation can be achieved by pulsing a low pressure microwave discharge.

In-situ rotational and vibrational Raman spectroscopy are applied to investigate the non-equilibrium between different degrees of freedom. It yields temperatures for rotation, for the asymmetric stretch and for the combined symmetric stretch and bending modes, the latter being assumed to be equal due to Fermi resonance.

Results show a strong non-equilibrium between the three temperatures. In the first microseconds of the pulse, the temperature of the asymmetric stretch exceeds largely the other temperatures. After several tens of microseconds the asymmetric stretch thermalizes with the other vibrational modes, irrevocably however the gas temperature starts rising, and after several tens of microseconds more the rotations and vibrations equilibrate too.

O16

Temporal evolution of the electron density of a nanosecond discharge in distilled water

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Plasmas inside liquids allow a high mass transfer of reactive species from the gas phase into the liquid. If the plasma treated liquid is interfaced with solids, very fast and efficient reaction rates for surface reactions can be realised. Such systems are relevant for the field of degradation of toxic organic compounds in liquids, plasma enhanced anodisation of metal surfaces inside an electrolyte, or as a method to recover a catalytic surface in an electrochemical cell. The physics of these plasmas and the interaction of the generated species with different surfaces need to be investigated to gain a full understanding of the chemical reactions occuring at the plasma-liquid-surface interface. The plasma propagation is monitored with Shadowgraphy imaging. The created species are investigated with optical emission spectroscopy (OES).

A 10 ns pulsed plasma with a voltage amplitude of 20 kV at a repetition frequency of 15 Hz is ignited inside destilled water. The electron density of this plasma and its temporal evolution is determined from the line broadening of the Hα-line (656 nm) and one OI-line (777 nm) measured with time-resolved OES with a temporal resolution of 15 ns. The observed electron densities rise to values in the order of 10^{25} m^{-3}.

O17

Velocity distribution of titanium neutrals in the target region of high power impulse magnetron sputtering discharges

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The velocity distribution function of titanium neutrals in the target region of a high power impulse magnetron sputtering discharge was investigated by optical emission spectroscopy. A high-resolution plane grating spectrograph combined with a fast, gated, intensified CCD camera was used to study the shape of selected optical emission lines. Doppler broadening and shift were analyzed to gain information about the velocity distribution of sputtered titanium neutrals.

The velocity distribution function was found to depend on the discharge power for target power densities up to 0.6 kW cm^{-2} . Above that value, the velocity distribution was constant. The collision processes of sputtered neutrals close to the target were found to be describable using a modified version of the Krook collisional operator. Using this interpretation, evidence for strong scattering of the titanium neutrals in the target region was found. This scattering can be explained by resonant charge exchange with previously scattered titanium ions.

O18

Connection between target poisoning and current waveforms in reactive high power impulse magnetron sputtering of chromium

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High power impulse magnetron sputtering (HiPIMS) has established itself as one of the premier methods for depositing high quality hard coatings. Reactive gases can be added to the discharge to produce hard ceramic coatings. These gases can react with the target surface which is called “target poisoning”. It has often been claimed that target poisoning is accompanied by a strong change of the current waveform but direct experimental verification is still needed.

This was addressed by connecting spatially resolved X-ray photoelectron spectroscopy (XPS) measurements with measurements of the current waveform. The XPS characterization was performed after an in-vacuum transfer of the target to avoid any oxidation or contamination.

A chromium target was used for the discharge. The Ar/O_2 mixture and the input power were varied to evaluate the racetrack oxidation state in different discharge regimes.

The transition from poisoned to metal mode by increasing the power can be achieved using a frequency of 20 Hz. This transition can as well be seen in the current shape of the discharge which converges to its non-reactive form. This is a first approach to investigate the assumed correlation.

O19

Measurements of the electric field, electron properties and other plasma parameters: the influence of targets

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Important plasma parameters are measured in a plasma jet and the influence on these parameters is studied when targets with different (dielectric) properties are placed in front of the jet. The electric field both inside and outside the capillary of the jet is measured using the Stark polarization spectroscopy technique. Plasma parameters such as electron temperature and density, gas temperature and densities of N_2 and O_2 are measured using Thomson and rotational Raman scattering. A cold atmospheric pressure helium plasma jet is used, which operates at a μs-pulsed applied voltage of 6 kV, a frequency of 5 kHz and with a helium flow of 1.5 slm. Different behaviours are observed when different targets are placed in front of the jet. Targets are found to have a profound influence on all plasma parameters studied in this work.

Poster presentations

List of Posters

Thursday, 29th November 2018

P1: **Image processing based control of global microdischarge behaviour during unipolar pulsed Plasma Electrolytic Oxidation (PEO)**
S. Böddeker, P. Hermanns, V. Bracht and P. Awakowicz

P2: **Analysis of current voltage behavior for radio frequency magnetron sputtering**
D. Engel, L. Kroll and R.P. Brinkmann

P3: **Analysis of HVDC relays in short circuit situation**
C.M. Ewuntomah and J. Oberrath

P4: **Determination of atomic Oxygen state densities in an Ar:O_2 plasma using absolute line intensities**
M. Fiebrandt, N. Bibinov and P. Awakowicz

P5: **Discretization scheme for systems of diffusion-reaction conservation laws**
R.A.M. van Gestel, J.van Dijk and J.H.M. ten Thije Boonkkamp

P6: **Chemical reduction: The Recipe**
J.G.M. Gulpen, J. van Dijk and D..B. Mihailova

P7: **Determination of electron densities by stark broadening of hydrogen lines in an electrosurgical argon plasma**
B. Hillebrand, E. Iglesias and P. Awakowicz

P8: **Calibration method for electric field values obtained using Stark spectroscopy**
S. Kempers, M. Hofmans and A. Sobota

P9: **Analytical solutions of the two-term Boltzmann equation**
P. Koelman and J. van Dijk

P10: **Using plasma-levitated micro-particles to reveal the equipotential surface in the plasma sheath**
A.J.T. Lamberts, P. Meijaard, G.M.W. Kroesen and J. Beckers

P11: **Electric field measurements on plasma bullets in nitrogen with nanosecond electric field induced second-harmonic generation**
A. Limburg, M. van der Schans and S. Nijdam

P12: **A detailed model for dielectric barrier discharge in Argon**
B. Mahdavipour, S. Dahle, J. Oberrath

P13: **Kinetic modeling and simulation of the planar multipole resonance probe**
C. Wang, M. Friedrichs, J. Oberrath and R.P. Brinkmann

P14: **Two-temperature global model for complex plasma chemistry**
S. Tadayon Mousavi, W.A.A.D. Graef, P.M.J. Koelman, J.F.J. Janssen, and J. van Dijk

P15: **Clustered micro-particles in remote plasma afterglow**
B. van Minderhout, A. Post, T. Peijnenburg, P. Blom, J.M. Vogels, G.M.W. Kroesen and J. Beckers

Friday, 30th November 2018

P16: **Emergence of multiple streamers during short and long pulsed discharges**
S. Mirpour and S. Nijdam

P17: **The development of a plasma-based lice comb**
L.C. van Mouche and A. Sobota

P18: **Experimental proof of the magnetic ssymmetry effect in a capacitively coupled rf plasma**
M. Oberberg, P. Awakowicz and J. Schulze

P19: **Application of a twin-surface dielectric barrier discharge for the plasma-assisted removal of oxygen traces from hydrogen-containing gases**
K. Ollegott, P. Wirth , N. Peters, P. Awakowicz, M. Muhler

P20: **Characterization of a twin-surface dielectric barrier discharge for the plasma-assisted removal of oxygen traces from hydrogen-containing gases**
P. Wirth, K. Ollegott, M. Fiebrandt, M. Muhler and P. Awakowicz

P21: **Plasma catalysis as vibrational activation of surface interactions**
Q. Ong, D.C.M van den Bekerom, M.A. Gleeson, C.J. Weststrate, G.J. van Rooij

P22: **Spatial and temporal behavior of an atmospheric He plasma jet**
O.J.A.P. van Rooij, M. Hofmans and A. Sobota

P23: **CO_2 decomposition in microwave plasmas; a computational investigation**
C.E.M. Schoutrop, J. van Dijk, W.A.A.D. Graef

P24: **Measuring surface charge on nanoparticle using FT-IR spectroscopy**
T.J.A. Staps, R. Brookhuis, G.W.M. Kroesen and J. Beckers

P25: **Investigating the argon RF-plasma sheath using multi-mode microwave cavity resonance spectroscopy**
P. Meijaard, B. Platier and J. Beckers

P26: **The injection of nanoparticles into a low pressure microwave plasma**
S.F.W. Telkamp, T.J.A. Staps and J. Beckers

P27: **Self-consistent diffusion approach to CO_2 vibrational kinetics**
P. Viegas, M. C. M. van de Sanden, S. Longo and P. Diomede

P28: **Characterizing the temperature profile of a sub-atmospheric CO_2 microwave plasma by Thomson Scattering**
T. van Vught, S. Dijcks and S. Nijdam

P29: **Conversion of CO_2 into CO in CO_2/Ar glow discharges**
A.Silva, A.S. Morillo-Candas, A. Tejero-del-Caz, V. Guerra, O. Guaitella

P1

Image processing based control of global microdischarge behaviour during unipolar pulsed Plasma Electrolytic Oxidation (PEO)

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Producing ceramic layers on lightweight metals (Al, Mg, Ti) by Plasma Electrolytic Oxidation is a promising method for industrial application. In comparison to classical anodization the resulting properties like substrate hardness, wear and corrosion resistance are improved. Layer growth and surface imperfections of the ceramic layer are affected by microdischarges, which are generated stochastically on the surface of the substrate. The average size of microdischarges rises with the oxide layer thickness. Too much energy per discharge can lead to detrimental effects regarding surface quality. By changing the duty cycle of the applied pulsed voltage, it is possible to change the size and amount of discharges during a single pulse. Therefor it is possible to limit the maximum size of discharges to certain values.

The Authors present an experimental setup to regulate the size of the microdischarges by changing the duty cycle of the applied unipolar pulsed voltage from 0.5 to 0.024 and thereby changing the frequency from 2.5 kHz to 4.9 kHz. A CCD-Camera records microdischarges with an exposure time of 20 milliseconds and a repetition rate of 1 Hz. A MATLAB code labels individual discharges by means of size and intensity using adaptive thresholding. This information is fed back to a PI-controller regulating the duty cycle of the next pulse. Optical Emission Spectroscopy is used to compare the behaviour of relative spectral line intensities in the controlled and uncontrolled case. A scanning-electron-microscope (SEM) is used to observe and analyze imperfections, like cracks and open pores in coated samples.

P2

Analysis of current voltage behavior for radio frequency magnetron sputtering

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Magnetron sputtering is an established technology to deposit thin films on large substrates. Employing RF power (instead of the conventional DC power) allows to sputter not only electrically conductive materials but also dielectrics like optical coatings. This contribution presents a global model for such an RF driven magnetron which is an extension of a previously published lumped circuit description of unmagnetized RF discharges [1]. As its predecessor, the model represents the discharge by separate bulk and sheath zones which communicate via Kirchhoff relations. The extension accounts for the presence of a magnetized region with reduced electric conductivity [2,3]. The model evaluates quickly and may be used for the purpose of model based control. By applying several parameters like electron

density, electron temperature or pressure, the current voltage behavior of the discharge can be analyzed.

[1] T. Mussenbrock et al., PSST 16, 377385 (2007)
[2] D. Bohm, The characteristics of Electrical Discharges in magnetic fields (1949)
[3] S.M. Rossnagel, H.R. Kaufman, J. of Vacuum Science and Technology A 5, 88 (1987)

P3
Analysis of HVDC relays in short circuit situation

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Plasma arcing during switching in high voltage direct current relays has been a major problem for relay manufacturers over the years. In short circuit situations, there is a rapid increase of the direct current with respect to time, which initiates opening of relay contacts. Subsequently, the contacts levitate. The opening and levitation produce high temperature plasma arcs between the contacts. The relays mostly do not survive these arcs because, they excessively heat, melt, boil, and vaporize the contact spots. To prevent permanent damage of the relays, a detailed understanding of the exact processes within the relays under such high currents, in both the closed state and levitation state must be attained. In this work, a Panasonic AEV14012 relay is being analyzed. Initial static simulations of the closed relay under input currents ranging from 0.1 kA to 2.5 kA have been carried out to validate the relay model, and quantify its heating, as well as the cooling effects of the hydrogen gas in the ceramic chamber of the relay. The cooling effects of external busbars connected to the relay during its normal operation, are also captured by these initial simulations. The electromagnetic repulsion force resulting from the flow of these currents in opposite directions at the contact spots is also calculated. It is observed from the initial results that, the relay alone heats up significantly under the applied currents, with temperatures at the contact spots going beyond the melting temperature of the contact materials. After incorporating the external busbars and the hydrogen gas into the simulations, temperatures went down significantly. It is established from the results that, although both the hydrogen and the busbars cool the relay, the cooling from busbars is predominant. The generated electromagnetic repulsion force is negligible compared to the amount of force required to open the relay contacts. It is therefore expected that, the vaporization of the contact spots will initiate the contact opening process, and hence the arc formation.

P4

Determination of atomic Oxygen state densities in an Ar:O_2 Plasma using absolute line intensities

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To determine the atomic oxygen flux on biological samples in a double inductively coupled plasma system in Ar:O_2 atmosphere at 5 Pa, a collisional radiative model was established. The model takes into account self-absorption and cascading effects and yields the densities of the ground state and first six excited states of atomic oxygen. As input parameters, the electron density, EEDF, gas temperature, as well as argon metastable and resonant state densities are needed. Furthermore, the intensities of four emission lines of atomic oxygen are considered (130.4 nm, 135.6 nm, 557.7 nm, 777.5 nm) measured with two calibrated spectrometers ranging from 116 nm to 800 nm. By varying the oxygen concentration, the results were analysed and compared for plausibility and possible missing processes or false rate coefficients.

P5

Discretization scheme for systems of diffusion-reaction conservation laws

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In continuum physics conservation laws play a key role, for example when simulating reacting species in a plasma. The continuity equations are coupled through multi-species diffusion and a complex reaction set. In particular we consider a general system of conservation laws of diffusion-reaction type with a non-linear source. In order to solve the conservation laws numerically an appropriate discretization technique needs to be used. For space discretization we employ the finite-volume method.

The numerical flux vector is determined from a local inhomogeneous ODE-system. The numerical flux vector consists of a homogeneous flux, corresponding to the homogeneous ODE-system, and an inhomogeneous flux, representing the effect of the non-linear source.

The numerical results are presently limited to only the homogeneous ODE-system, where the new numerical scheme shows second order convergence for various Damköhler numbers. Moreover the scheme shows improved accuracy over the standard central difference scheme.

P6
Chemical reduction: The Recipe

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Numerical simulations are a great tool to study plasma physics. However, the nature of a plasma leads to the significant presence of a particle's or a molecule's (ro-vibrational) excited and/or ionized states. For a single element, this might still be computable, but when a molecule or multiple different elements are present the computation time quickly skyrockets.

The sheer amount of particles and reactions makes full-fledged plasma simulations infeasible. To still be able to model complex plasmas, often, chemical reduction is applied. Chemical reduction allows for the decrease of computation time by reducing the amount of species and/or reactions taken into account. This is done in a way such that the simulated physics is still correct and relevant for the application.

Multiple chemical reduction methods have been suggested and tried before. The usage of an Intrinsic Low-Dimensional Manifold and Principal Component Analysis [1] decrease the dimension of the solution space. A third tool, Pathway Analysis [2], links chemical reactions in 'Pathways' and can be used to reduce the computation time by deleting the insignificant ones.

These are, however, methods that are not universally applicable and bounded by limitations. In this work a recipe is developed which attempts to combine the known tools in a novel way to reduce certain complex chemistries based on known input parameters.

[1] Tafizur Rehman. *Studies on Plasma-Chemical Reduction*. PhD thesis, Eindhoven University of Technology, August 2018.
[2] Ralph Lehmann. An algorithm for the determination of all significant pathways in chemical reaction systems. *J. of Atmospheric Chemistry*, 47(1):45–78, Jan 2004.

P7
Determination of electron densities by stark broadening of hydrogen lines in an electrosurgical argon plasma

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Argon plasma coagulation (APC) is a contactless electrosurgical procedure for superficial hemostasis, devitalization and ablation of biological tissue. Argon gas is lead through the APC instrument to the surface of the patient and due to an applied high frequency voltage a plasma is ignited. The frequency of the alternating current

that is flowing through the patient needs to be over 100 kHz due to undesired muscle and neural stimulations of lower frequencies.

As electrosurgery is frequently used since the mid of the 19th century, there are many different types of electrodes (including e.g. electrosurgical scalpels) and current waveforms for various clinical issues. The main advantage of the APC is the possibility to treat a great area within short time period by moving the device across the tissue. Because this treatment technique is contactless tissue sticking to the electrode is prevented, which plays a major role by hemostasis of bleeding wounds.

Although this technique is well established, physical parameters of the plasma during Argon plasma coagulation are rarely scientifically investigated. For plasma characterization, optical emission spectroscopy (OES) with a high resolution relatively calibrated Echelle spectrometer was used. The electron densities were obtained by stark broadening of hydrogen lines in terms of using Voigt profiles for fitting data points. In contrast to commercial applications an admixture of 5 % H_2 was added to the process gas to increase the hydrogen emission.

P8
Calibration method for electric field values obtained using Stark spectroscopy

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The investigation of Stark shifts in the emission spectra of atoms can be used to measure electric fields inside plasmas. For hydrogen and helium there exist strong quantum-mechanical theories which link the shifts to the electric field. Such a theoretical foundation does not exist for argon. This problem can be avoided by making a calibration of the Stark effect in argon. By measuring the current and voltage values of a homogeneous He/Ar dielectric barrier discharge, the electric field can be determined. The obtained field values can be linked to shifts in the spectra of the plasma, thus creating a calibration for the electric field as a function of argon Stark shifts. This calibration method can be verified by applying Stark spectroscopy on the helium in the plasma.

P9
Analytical solutions of the two-term Boltzmann equation

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Models of low temperature plasmas often contain a description of the chemistry. In many cases these chemistries are highly non-linear, with a major contribution of the electrons. Electrons are energetically not in equilibrium with the rest of the species in many such cases. Therefore the energetic electrons can be used to enhance certain

chemical processes. To correctly capture these process in a model one needs to determine the transport coefficients and rate coefficients, for which Boltzmann solvers can be used. These Boltzmann solvers do have a finite number of test cases for validation purposes. The Maxwell-Boltzmann solution, Druyvesteyn solution or derivatives from them are such solutions. Test cases that contain the influence of inelastic processes are, however, not available to the best of our knowledge. In this work an analytical solution for the two-term approximation of the Boltzmann equation will be presented for the case that inelastic processes are present. We will show an excellent agreement in results between the widely used Boltzmann solver BOLSIG+ with the analytical result.

P10
Using plasma-levitated micro-particles to reveal the equipotential surface in the plasma sheath

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The structure of the plasma sheath surrounding complex geometries in contact with a low pressure radiofrequency plasma is revealed, using plasma-levitated micro-particles under hyper gravity conditions. Currently, the exact shape of the equipotential surface above geometries other than a flat surface is far from understood.

To reveal elementary processes on a fundamental level, charged plasma-levitated micro-particles are used as probes in the plasma sheath. The levitation of the micro-particle is driven by a force balance between several (plasma-induced) forces on the particle and the gravitational force. The latter is utilized to achieve probing with one and the same micro-particle at different locations throughout the plasma sheath without affecting the surrounding plasma.

In the current experiments, a single micro-particle is confined by a sharply edged indent in the bottom electrode surface. By changing the angle and magnitude of the gravitational vector, the levitated particle will scan the plasma sheath to provide insight in the shape of the equipotential surface at different heights above the bottom electrode. In this contribution we present preliminary results of experiments which were recently conducted.

P11

Electric field measurements on plasma bullets in nitrogen with nanosecond electric field induced second-harmonic generation

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Plasma bullets are guided ionization wave discharges generated by non-thermal pulsed plasma jets and injected into atmospheric pressure air. They propagate along the axis of the jet and are highly reproducible and periodic, which makes it possible to perform time resolved measurements. Information on the electric field of these bullets is essential in order to develop applications and extend the theory on streamers. However, direct electric field measurements on these transient discharges are often invasive or do not contain the electric field outside of the discharge.

In this work, a possible non-invasive method for measuring electric fields at atmospheric pressure with electric field induced second-harmonic generation (EFISHG) is proposed. A nanosecond pulsed Nd:YAG laser emitting at 1064 nm will be used as a source. Its light will non-linearly interact with the electric field of the discharge, thereby producing frequency doubled light. Therefore, this method is not bound to the dimensions of the discharge. Future measurements will be performed on a discharge generated between two parallel plate electrodes to test the method and calibrate the set-up. Thereafter, the same method will be applied on plasma bullets in nitrogen, propagating approximately 140 ns over a distance of several millimeters, to obtain information on the distribution of the axial and radial components of the electric field and on the temporal development of this field. The resolution of this measurements will be determined, and the results will be compared to results obtained in earlier used methods.

P12

A detailed model for dielectric barrier discharge in Argon

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Dielectric-barrier discharges (DBD) are devices which have a lot of applications such as surface modification, plasma chemical vapor deposition, plasma medicine, pollution control, gas and air cleaning.

Filamentary DBDs are created as a number of short time duration individual breakdown channels known as microdischarges. Most of the chemical reactions of DBDs take place in their microdischarges. The aim of this work is to study the

microdischarges at low temperature and atmospheric pressure condition in an argon DBD to analyze the microdischarge creation, the chemical reactions, and physical mechanisms that occur. The microdischarge is simulated by a 2D fluid model with argon in a planar geometry. One of the electrodes which is connected to the power supply is covered with dielectric. Through the simulation, parameters like electron density and electron average charge are investigated. To validate the simulation results, OES and electrical measurements were performed in a planar DBD with the same configuration. Finally, the experimental and simulated results will be compared.

P13
Kinetic modeling and simulation of the planar multipole resonance probe

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Active Plasma Resonance Spectroscopy (APRS) is a well-established plasma diagnostic method: A radio frequency signal is coupled into the plasma via a probe, excites it to oscillations, and the response is evaluated via a mathematical model. Many APRS probes are invasive and perturb the plasma by their physical presence. Therefore, the planar Multipole Resonance Probe (pMRP) was designed which can be integrated into the chamber wall and minimizes the perturbations.

In this work, a kinetic model is developed to investigate the behavior of the pMRP in the low pressure regime. The model consists of the collision-less Vlasov equation, which is coupled to the Poisson equation under the electrostatic approximation. The equations are linearized around the equilibrium and solved by integrating along the unperturbed trajectories. This model overcomes the limitation of the cold plasma model and covers the kinetic effects.

P14
Two-temperature global model for complex plasma chemistry

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Low temperature plasmas are promising in solving contemporary problems for mankind like global warming. For example, plasma assisted CO_2 conversion is a useful method to obtain carbohydrate fuels. One of the main challenges of this field is the analysis of the reaction kinetics in complex chemistries. In order to analyze the underlying mechanisms for physical behaviors of non-equilibrium plasmas, finding

insights about chemical processes is inevitable. Global models or zero-dimensional models are well-known to give basic insights about the plasma chemistry. Having the gas temperature calculation next to electron temperature is essential in many cases. The gas temperature calculation has been added to the Global Model module of PLASIMO in this work.

Validation test cases and results for complex chemistry will be presented to show the performance of the new feature.

P15
Clustered micro-particles in remote plasma afterglow

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Low pressure plasmas are known to charge particles negatively when these particles are larger than about 10 nm. From an application point of view, this charging allows particles to be filtered out of a gas flow using electric fields. Consequently, plasmas can be used as particle seals to protect delicate elements in vacuum systems from particle contamination. Up to now research has focused on the plasma charging of spherical particles. However, in almost all applications, particles consist of clusters or agglomerations. Therefore, it is of utmost importance to understand the plasma-charging of clusters which can significantly differ from the charging of spherical particles.

To study the charge of clusters, we have developed an *in situ* cluster size detection technique based on the settling velocity of these clusters. Using this method, first cluster charge measurements are presented. We study the charge of clustered micro-particles in the Plasma Particle Charging Investigation (PPCI) setup. In this setup, micro-particles fall through a spatially limited region of plasma where through interaction with the plasma they are charged. The particle charge is measured by accelerating the particles in an externally applied electric field.

P16
Emergence of multiple streamers during short and long pulsed discharges

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Despite many studies on lightning inception, the question how lightning initiates inside thunderstorms is still unanswered. It is commonly believed that lightning breakdown is preceded by so-called streamer discharges. Two of the most important steps in streamer formation are the formation of an initial avalanche and the

successful avalanche-to-streamer transition. Both cause a delay between the initiation of an applied electrical field around a conductor or dielectric particle (e.g. a hydrometeor) and streamer inception. This study aims to investigate the physical processes involved in streamer inception by means of controlled laboratory experiments. For this purpose we investigate the formation of the streamers during a train of pulses. The experimental setup consists of a point-to-plane configuration connected to a high-voltage pulse generator. The pulses were applied with a pulse width of 100 ms (long) and 1 ms (short). The initial light emitted from the streamer is collected by a photo-multiplier tube. Preliminary results show that for initiating the second and later discharges, a minimum delay from the first discharge is required. The outcome of this study will improve the knowledge about initiation of streamer discharges.

P17
The development of a plasma-based lice comb

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In the field of plasma medicine, cold atmospheric pressure plasmas are used for their anti-bacterial properties. Their macroscopically cold temperature and ability to operate in atmospheric pressure air enable these plasma sources to treat heat sensitive surfaces, including human skin. The aim of this project is to use a radiofrequency CAP to kill lice and their nits. The plasma lice comb should offer a side-effect free alternative to the presently used (often ineffective) chemicals and combs. The end product should be safe, reliable and easy-to-use lice comb that terminates all lice and nits without harming the host.

P18
Experimental proof of the magnetic asymmetry effect in a capacitively coupled rf plasma

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In recent publications, the Electrical Asymmetry Effect was used to control discharge parameters like symmetry, DC self-bias, and energy distribution functions in capacitively coupled radio frequency discharges. For that, excitation voltages with consecutive harmonics were used with locked variable phases to adjust the voltage waveform. In several theoretical publications it was predictet, that also a magnetic field with a decreasing strength between the electrodes influences the discharge symmetry. This was introduced as the Magnetic Asymmetry Effect (MAE). So far, only simulation results exist about the MAE. In this work, we present first experimental investigations of the MAE in a low pressure single frequency

(13.56 MHz) rf capacitively coupled discharge with a magnetron-like magnetic field configuration and a geometrical asymmetry. By increasing the radial magnetic flux density applied at the powered electrode the inhomogeneous profile perpendicular to the electrodes changes. The magnetic field allows to control DC self-bias, mean ion energy at the electrodes and the symmetry parameter. Measuring DC self-bias voltage and ion energy distribution function as well as the rf current at the grounded electrode, driving voltage and neutral gas pressure verifies the MAE experimentally and allows a control of process relevant values.

P19
Application of a twin-surface dielectric barrier discharge for the plasma-assisted removal of oxygen traces from hydrogen-containing gases

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Steel mill gases (H_2, CO, CO_2) are a promising future feedstock for the synthesis of chemical products, as their utilization would significantly lower the CO_2 emission of steelmaking. However, oxygen has to be removed from these gases, to not exceed safety-relevant concentrations. Traditional purification methods reach their limits due to the complex gas mixtures and the variety of impurities.

A twin surface dielectric barrier discharge is tested in the plasma-assisted removal of oxygen traces from hydrogen-containing feed gases. The used electrode configuration is composed of grid-like metal traces on both sides of an alumina plate.

The current-voltage characteristics of the discharge are monitored and used to determine the power dissipated into the plasma. The input power ranges from 2 W to 38 W depending on the applied voltage and the gas composition. With increasing hydrogen concentration, the conversion of oxygen increases as well, whereas an increased oxygen concentration leads to a lower degree of conversion. It was possible to reach a maximum conversion of 90 %.

P20

Characterization of a twin-surface dielectric barrier discharge for the plasma-assisted removal of oxygen traces from hydrogen-containing gases

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Recycling management is important for the steel industry to reduce the carbon footprint and remain profitable. The energy-efficient purification of waste gas is a key challenge to obtain syngas. Syngas is a gas mixture containing hydrogen that can be used as a feedstock for the production of chemicals.

We operate a twin surface dieletric barrier discharge to remove oxygen traces in a hydrogen-nitrogen gas mixture. The electrode consists of an aluminium oxide plate with a grid-like metalization on both sides. The low temperature atmospheric pressure is characterized electrically to calculate the dissipated power in the discharge. Absolutely calibrated optical emission spectroscopy is used in combination with simulation to solve the Boltzmann equation in local approximation. This allows the determination of gas temperature, the reduced electric field and electron density. Preliminary results show a homogeneous discharge along the electrode.

To measure reactive species generated in the plasma the design of a molecular beam mass spectrometer is discussed. The three stage differentially pumped setup allows collisionless transport of particles from atmospheric pressure to high vacuum that is required inside the mass spectrometer.

P21

Plasma catalysis as vibrational activation of surface interactions

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Plasma-catalytic reactor configurations, combining plasma and catalysis in close proximity, have demonstrated synergistic effects and allow for increased selectivity and conversion, reduced operating temperature, and reduced catalyst loadings. Nevertheless, the fundamental understanding of the interaction of plasma-activated species with surfaces, and in particular direct experimental insight, is virtually absent.

The reverse Water Gas Shift Reaction (rWGS) is used as a model reaction to elucidate the efficacy of vibrational excitation in activating the reaction on a catalytic surface. It is an equilibrium-limited endothermic reaction for producing synthesis gas ($CO + H_2$) from CO_2 and excess H_2. Reported will be on vibrational excitation of CO_2 in plasma as well as on benchmarking experiments with a mid-IR laser to selectively excite the CO_2 molecules into a higher vibrational state allowing the resulting excited species interact with a hydrogen loaded palladium surface.

P22

Spatial and temporal behavior of an atmospheric He plasma jet

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The behavior of the plasma jet is of importance to perform the spectroscopic measurements. The non-thermal atmospheric He plasma jet consists of plasma bullets (guided ionization waves) and operates by applying high voltage pulses of 4 - 6 kV with a frequency of 0.3 - 5 kHz and a pulse length of 0.16 - 5 μs. In order to determine the position of the plasma bullets as a function of time, imaging of the jet is performed using an ICCD camera. Apart from the positions, velocities of the bullets are determined from the imaging results for different voltages, frequencies and pulse lengths.

P23

CO_2 decomposition in microwave plasmas; a computational investigation

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Renewable forms of electricity generation have the property that they are intermittent; the sources are not always available when they need to be. Furthermore not all energy consumption is in the form of electricity. Sources like fossil fuels can be used to bridge the gap between supply and demand, however they are harmful to the environment when used to produce energy.

An alternative is to store excess electricity produced from renewable sources in a carbon-neutral manner. One method is to decompose CO_2 into CO. In turn the produced CO can be used as a base ingredient for the production of carbon-based fuels via the Fischer-Tropsch process. These fuels present a fully carbon-neutral storage medium for energy, compatible with existing infrastructure.

A promising method for the decomposition of CO_2 is a microwave plasma reactor. In such a reactor the specific geometry used favors a process known as vibrational laddering, enhancing the CO_2 dissociation. Numerical simulation is a valuable tool for unraveling the physics of such a process and allow for further optimization.

However at the time of writing a full 2D/3D numerical simulation of such a system is currently out of reach. The complex reaction mechanisms present a strong computational challenge even on modern high-end hardware, as each of the hundreds of reactions and intermediate reaction products have to be taken into account at each gridpoint.

The current project entails reducing the complex CO_2 chemistry to a more computationally efficient form. Then introduce a set of discretization algorithms that respect the coupling between chemical species present in the plasma. Finally present a standardized method for the exchange of simulation data via an extension of the LxCat webportal.

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P24
Measuring surface charge on nanoparticle using FT-IR spectroscopy

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Ultrafine or nanoparticles are known to induce adverse effects on human health and the environment. This motivates the development of low-cost particle sensors operating in ambient air, which often comprise an atmospheric plasma that charges the particles for subsequent electronic measurements. However, it is non-trivial to predict the surface charge on nanoparticles, since the particle charging dynamics is a complex process. Therefore, a dusty or complex plasma is envisaged as a model system to study the particle charging dynamics under conditions with reduced complexity.

Injection of nanoparticles (20 – 300 nm) into a low-pressure radio-frequency plasma is a relatively novel method to produce a dusty plasma with well-defined dust properties, e.g., refractive index. For example, a characterization of nanoparticles injected into such a plasma can be found in [1], where Mie scattering has been used to obtain nanoparticle size and density distribution. This opens up the possibility to use infrared spectroscopy for measuring the surface charge non-invasively, endeavors of which can be found also in [1].

Nanoparticles immersed in plasma are charged to a surface potential that relates strongly to the electron temperature. Surplus electrons on the nanoparticles' surface influence the surface or bulk conductivity, which alters the scattering and absorption behavior of said particles through the refractive index. The interaction of electromagnetic waves in the infrared spectral range with charged particles has been studied theoretically in [2], which provides an analytical basis for the experiment. The goal is to measure and compare infrared transmission spectra obtained from a cloud of nanoparticles that are charged under various conditions such as varying electron temperature.

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P25

Investigating the argon RF-plasma sheath using multi-mode microwave cavity resonance spectroscopy

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Knowledge of electron densities in the argon RF-plasma sheath is paramount when it comes to researching this region. Being highly interesting from fundamental perspective, plasma sheath dynamics dominates many industrial applications. For instance, ions accelerated in the plasma sheath can be used for many types of surface modification and ion bombardment processes. To allow further understanding of this peculiar region and improvement of the applications involved, we propose to study the plasma sheath by means of multi-mode microwave cavity resonance spectroscopy (MCRS).

Recently, it was shown that the MCRS technique is capable of spatially resolving the electron density by combining multiple resonant microwave modes. These measurements will now be applied to the spatial region of the RF plasma sheath and are complementary to a micro-particle probe levitating in the same region under hyper-gravity conditions. In this contribution, design and implementation of this novel diagnostics are discussed.

P26

The injection of nanoparticles into a low pressure microwave plasma

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The presence of nanoparticles in low pressure industrial plasmas often causes unwanted contamination, but it can also lead to performance improvement in, for example, solar cell technology. Therefore, understanding the behavior of nanoparticles in a plasma is of key interest for various industries. In this study, two different techniques to insert and disperse Al_2O_3 nanoparticles in a low pressure microwave plasma have been developed and tested, consequently creating a dusty plasma. The intensity of laser light scattered by the injected particles is measured using a CCD camera. Using post-processing software, an average background image is subtracted from the acquired images after particle injection. This provides insight into the development and efflux of dust clouds over time as well as their spatial distribution. Distinct repetitive patterns in the measured intensity over time are observed, which are caused by various effects due to plasma-particle interactions.

P27
Self-consistent diffusion approach to CO_2 vibrational kinetics

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In recent years, much attention has been dedicated to low-temperature plasmas to convert greenhouse CO_2 into new carbon-neutral fuels or useful chemicals. Microwave (MW) discharges are considered one of the most promising plasma systems for CO_2 conversion due to their ability to use vibrational excitation to decompose CO_2 with high energy efficiency. At DIFFER, to optimize energy and conversion efficiencies, CO_2 MW plasma reactors are studied experimentally. To further understand the underlying mechanisms of CO_2 dissociation in MW plasmas, including the role of vibrational kinetics, numerical modelling is essential. Recently, some of the authors have presented a new approach to calculate the vibrational distribution function of the asymmetric stretching mode of CO_2, based on the drift-diffusion Fokker-Planck (FP) equation. This has been demonstrated to be an alternative, potentially more computationally efficient, to the state-to-state (STS) approach for the kinetics of individual vibrational levels. Moreover, the description of vibrational kinetics as a transport process allows to have a new insight into processes leading to CO_2 dissociation. In this work, the FP approach is self-consistently coupled to a global model describing a CO_2 plasma in the conditions of a MW plasmolysis reactor. First results for species number densities and temperatures of the different degrees of freedom, obtained with both the STS and the FP approaches, will be compared and discussed.

P28
Characterizing the temperature profile of a sub-atmospheric CO_2 microwave plasma by Thomson Scattering

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Understanding streamer behavior is important in many electric applications like circuit breakers.In a circuit breaker, after breaking a circuit an arc is formed, heating the gas around it and pressures are generally above atmospheric pressure. An electronegative gas is then used to extinguish the arc and to prevent secondary discharges. Currently, mostly SF_6, a strong greenhouse gas, is used for this, but companies are investigating whether this can be replaced by CO_2.

To fully understand the streamer behavior and chances of additional discharges, parameters of the hot CO_2 gas should be known at temperatures up to a few thousand Kelvin. Therefore, a method for creating a controllable plasma torch with a well-

defined temperature distribution is required. In this project, a microwave CO_2 plasma source at medium pressure (around 100 mbar) was constructed. Its characteristics are analyzed with optical analysis by Thomson and Raman scattering.

The obtained spectra of a 62 and 94 mbar CO_2 plasma were used to determine the spatial electron temperature and electron densities. These lie in the expected regime of 0.8-1.4 ±1.5 eV and of 2.2-3.5 ±3.0 10^{19} m^{-3} respectively. However, the estimated errors of these values are of the same order of magnitude as the results themselves and thus too large to draw meaningful conclusions from. Furthermore, the fitted number densities of the particles present do not add up to the experimentally measured pressure values. This could point to an error in the fitting procedure. Multiple possible causes were explored and none of them could explain the mismatching results.

P29
Conversion of CO_2 into CO in CO_2/Ar glow discharges

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The first step towards the creation of solar fuels from CO_2 is the conversion of this molecule into CO. In this work the effects of Argon addition on CO_2 dissociation are studied in low-pressure glow discharges.

Vibrational temperatures of CO_2, gas temperature and conversion factor are measured with Fourier Transform Infrared Spectroscopy. For all the working conditions studied, the addition of Argon improves conversion but at the cost of a slight hampering of energy efficiency. Furthermore, the vibrational temperatures measured do not suffer significant variations with Argon content. The kinetic processes leading to these results are studied with the implementation of a kinetic scheme for the Ar/CO_2 mixture in a simulation tool that couples the solution of the Boltzmann equation for electrons with a system of rate balance equation for the heavy species: LoKI. The simulations are able to reproduce the measured variations of conversion and reduced electric field with varying Argon content. The simulation results show that the addition of Argon improves conversion mostly via modification of the electron distribution function and, consequently, enhancement of dissociation via electron impact, with simulated electron temperatures increasing significantly with Argon addition.