Laser induced plasma shock wave simulation for laser shock peening

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Workshop on the Exploration of Low Temperature Plasma Physics

November 30 and December 1, 2017

"Rolduc"

Kerkrade, the Netherlands

Jointly sponsored and organized by

RUHR UNIVERSITÄT BOCHUM RUB

TU/e Technische Universiteit Eindhoven University of Technology

RESEARCH DEPARTMENT Plasmas with Complex Interactions

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20TH EUREGIONAL WELTPP

Workshop on the Exploration of Low Temperature Plasma Physics

Welcome to the 20th *Workshop on the Exploration of Low Temperature Plasma Physics* (WELTPP-20). 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 sponsored and organized by the Research Department "Plasmas with complex interactions" of the Ruhr-Universität Bochum, SFB-TR 87, and the Eindhoven University of Technology, more precisely by the groups Plasma and Materials Processing (PMP) and Elementary Processes in Gas Discharges (EPG) in close collaboration with the Dutch Institute for Fundamental Energy Research (DIFFER) and the York Plasma Institute. This year WELTPP-20 is also kindly supported by Ocean Optics B.V.

We wish you a fruitful and pleasant conference.

Organizing committee:

Jan van Dijk (Eindhoven University of Technology)
Richard Engeln (Eindhoven University of Technology)
Jeanne Loonen (Eindhoven University of Technology)
Frederik Schmidt (Ruhr-Universität Bochum)
Erik Wagenaars (York Plasma Institute)
Stefan Welzel (FOM Institute DIFFER & Eindhoven University of Technology)

Programme WELTPP at Rolduc, November 30 & December 1, 2017

Thursday, November 30th

10:30 **Registration (coffee/tea in the Foyer)**
10:50 **Opening**

Session 1 **Plasmadiagnostics** (Conference room 4)

11:00-11:20 O1 **Fast imaging of nanosecond-pulsed plasmas generated in liquids**
K. Grosse (Ruhr-University Bochum)

11:20-11:40 O2 **Measurement of Ar resonance and metastable level number densities in argon containing plasmas**
M. Fiebrandt (Ruhr-University Bochum)

11:40-12:00 O3 **Electron density at the sheath edge of a HiPIMS plasma**
J. Held (Ruhr-University Bochum)

12:00-12:20 O4 **Correlation of spatially resolved in-vacuum XPS characterization and optical diagnostics for magnetron targets in HiPIMS plasma**
S. Monjé (Ruhr-University Bochum)

12:20-12:40 O5 **Laser ablation of metal and metal-oxide targets, and applications towards plasma enhanced-pulsed laser deposition**
D. Meehan (York Plasma Institute)

12:45 **Lunch in the "Grote Eetzaal"**

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

14:00-14:20 O6 **Kinetic modelling of the planar multipole resonance probe using functional analytic methods**
M. Friedrichs (Leuphana University Lüneburg)

14:20-14:40 O7 **Power transfer and impedance matching in capacitive discharges**
F. Schmidt (Ruhr-University Bochum)

14:40-15:00 O8 **Analytic model of the plasma sheath**
L. Kroll (Ruhr-University Bochum)

15:00-15:20 O9 **Impedance modeling for DF-plasmas where one of the frequencies is well below the ion plasma frequency**
J. Kuhfeld (Ruhr-University Bochum)

15.30 **Coffee/Tea in the Foyer**

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

16:30-18:15 **Poster session** (Conference room 2)
Poster numbers P1 – P14 can be posted from 12:00 hrs.

Session 3 **CO_2 containing plasmas** (Conference room 4)

18:30-18:50 O10 **Vibrational excitation kinetics of CO_2 in a pulsed glow discharge**
B. Klarenaar (Eindhoven University of Technology)

18:50-19:10 O11 **Vibrational kinetics of non-equilibrium CO_2 plasma discharge and post-discharge: comparison with experiment**
M. Grofulović (Universidade de Lisboa)

19:10-19:30 O12 **Dimension reduction of global models using principal component analysis**
S. Bardoel (Eindhoven University of Technology

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

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

Friday, December 1st

08:00 **Breakfast in the “Grote Eetzaal”**

Please return your room key to the reception <u>before</u> attending Session 4!

Session 4	**Ions in plasmas**		(Conference room 4)
09:00-09:20	O13	**Investigation of ion dynamics in capacitively coupled Argon-Xenon discharges** M. Klich (Ruhr-University Bochum)	
09:20-09:40	O14	**Study of ion fluxes in extreme ultraviolet radiation induced hydrogen plasma** T. van de Ven (Eindhoven University of Technology)	
09:40-10:00	O15	**Surface production of negative ions on nitrogen doped diamond samples** J. Ellis (York Plasma Institute)	
10:00-10:20	O16	**IVDF and plasma parameters of CX dominated plasmas** C. Lütke Stetzkamp (Ruhr-University Bochum)	

10:30 **Coffee/Tea in the Foyer**

11:00-12:30 **Poster session** (Conference room 2)
All poster numbers greater than P14 can be posted

12:30 **Lunch in the “Grote Eetzaal”**

Session 5	**Application of high-frequency fields**		(Conference room 4)
14:00-14:20	O17	**Improving uniformity of atmospheric-pressure dielectric barrier discharges using dual frequency excitation** Y. Liu (DIFFER)	
14:20-14:40	O18	**Inactivation of *Bacillus subtilis* spores by low pressure plasma emitted UV-radiation** B. Hillebrand (Ruhr-University Bochum)	
14:40-15:00	O19	**Spatio-temporal plasma heating mechanisms in a radio-frequency electrothermal microthruster** S. Doyle (York Plasma Institute)	
15:00-15:20	O20	**Stochastic electron heating in a periodically structured electric field** P. Ahr (Ruhr-University Bochum)	

15:25 **Closure of the workshop**

Oral presentations

O1

Fast imaging of nanosecond-pulsed plasmas generated in liquids

Katharina Grosse[1], Achim von Keudell[1]
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Plasmas generated inside liquids have aroused interest over the last years particularly in the field of plasma medicine. The reactive species created in such an environment can modify surfaces which are in direct contact with the treated liquid. The physics of these plasmas and the interaction of the particles created inside the liquid with biological and metallic surfaces is not fully investigated.
The analysed plasma is generated by a high-voltage nanosecond pulser creating 10 ns pulses with varying amplitudes and pulsing frequencies. The dynamics of the discharges are monitored with Shadowgraphy imaging and the created species with optical emission spectroscopy.
Four distinct phases of the plasma development can be identified: the ignition and plasma phase (1), the generation of a shock-wave (2), the formation of a gas bubble (3) and the separating of the bubble from the high-voltage electrode (4). All phases are examined for different voltages and frequencies.

O2

Measurement of Ar resonance and metastable level number densities in argon containing plasmas

Marcel Fiebrandt[1], Bastian Hillebrand[1], Stefan Spiekermeier[2], Nikita Bibinov[1], Marc Böke[2], Peter Awakowicz[1]
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Metastable and resonant states of noble gases can have a significant impact on the plasma processes due to their large energy. Especially in low pressure plasmas, metastable and resonant state densities are often in the range of the electron density. Here, the optical branching fraction method capable of determining the resonance $1s_4$ ($^3P_1$), $1s_2$ ($^1P_1$) and metastable $1s_5$ ($^3P_2$), $1s_3$ ($^3P_0$) level number densities is compared to laser absorption spectroscopy to evaluate the reliability of the branching fraction method and its limitations. The methods are applied in argon plasmas with admixture of hydrogen, nitrogen, and oxygen at 5 Pa and 10 Pa at 500 W. The results are in good agreement and the use of a compact, low cost, low resolution spectrometer ($\Delta\lambda = 1.3$ nm) is sufficient to reliably determine the first four excited states of argon in argon-hydrogen and argon-oxygen mixtures. The addition of nitrogen results in unreliable densities, as the observed argon lines overlap with emission of the $N_2(B^3\Pi_g - A^3\Sigma_u^+)$ transition.

O3

Electron density at the sheath edge of a HiPIMS plasma

Ante Hecimovic, Julian Held, Volker Schulz-von der Gathen, Wolfgang Breilmann, Christian Maszl and Achim von Keudell

Department of Experimental Physics II, Ruhr-University Bochum, 44801 Bochum, Germany

In High power impulse magnetron sputtering (HiPIMS) a magnetron discharge is operated with short, high-voltage pulses with a length in the order of 100 µs at power densities of several $kWcm^{-2}$, creating a highly dense plasma. At high discharge currents, the plasma is not homogeneous but is instead organized into distinct zones of high plasma emission which rotate in ExB direction with velocities of 10 km/s. The strong emission indicates an elevated electron density inside those so called "spokes". Up to now, no measurement of the electron density inside the spokes has been performed. In this contribution, small inserts in the target surface were used to probe the local current density. Simple sheath theory was then applied to derive the electron density at the sheath edge. The electron density was found to be in the order of 10^{19} m^{-3} and to scale linearly with discharge current. The electron density inside the spokes was about 30% higher than in the plasma between the spokes.

O4

Correlation of spatially resolved in-vacuum XPS characterization and optical diagnostics for magnetron targets in HiPIMS plasma

Vincent Layes[1], Sascha Monje[1], Carles Corbella[1], Volker Schutz von der Gathen[1], Achim von Keudell, Teresa de los Arcos[2].

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In-vacuum characterisation of magnetron targets after high power pulsed magnetron sputtering (HiPIMS) has been performed using X-ray photoelectron spectroscopy (XPS). Al-Cr composite targets (circular, 50 mm diameter) in different geometries were investigated: Al targets, Cr targets, Al targets with a small cylinder of Cr inserted at the racetrack position (composite target) and Cr targets with a small disk of Al inserted at the racetrack position.

The HiPIMS discharge and the target surface composition were characterised for different power conditions. The HiPIMS plasma characterisation was done using optical emission spectroscopy (OES) and fast imaging by a CCD camera; the surface characterisation was done after in-vacuum transfer of the magnetron target to the XPS.

This parallel evaluation has provided information about: (i) lateral transport and redeposition of sputtered species on the target, (ii) oxidation state of the target surface as function original composition, position and HiPIMS plasma conditions, and (iii) correlation between local surface conditions and plasma characteristics.

O5

Laser Ablation of metal and metal-oxide targets, and applications towards Plasma Enhanced-Pulsed Laser Deposition

David Meehan, Sudha Rajendiran, Erik Wagenaars
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Metal oxide thin films, such as Zinc Oxide and Copper Oxide, find uses in many modern technologies including photovoltaics, batteries, and displays. An established method of making such films is Pulsed Laser Deposition (PLD), where a laser is used to ablate a target of the desired material, which is then deposited onto a substrate; Although PLD is easy and readily used for metal targets, oxide targets have been shown to be more challenging, being much slower and requiring carefully tuned oxygen background atmospheres to ensure the desired stoichiometry is achieved. The difference between the laser ablation of Zinc, Copper, and their corresponding oxides has been investigated computationally using the 2-dimensional hydrodynamic code POLLUX. From this we can show that metal-oxides ablate approximately 60% less mass than their metal counterparts, with comparable yet slightly cooler temperatures.

Alongside this a novel deposition technique has been developed, Plasma Enhanced-Pulsed Laser Deposition (PE-PLD), where a metal target is ablated in the presence of oxygen reactive species produced by an Inductively Coupled Plasma (ICP); Allowing for use of the easier ablated metal targets, whilst also providing additional benefits such as no need for substrate heating, and stoichiometry control of the deposited film via different operating conditions of the ICP. Initial Copper Oxide, and Zinc Oxide films have been deposited, and analysed by a variety of techniques including SEM, EDX, AFM, and others, showing film composition and growth rate over a range of PE-PLD operating conditions. PE-PLD has been shown to deposit films at a comparable rate to traditional PLD setups, with all films being uniform as a function of depth, whilst also being able to control to stoichiometry of films, with lower oxygen ICP pressures, 7.5Pa, yielding Cu_2O (211), and higher pressures, 13Pa, yielding CuO (020).

O6

Kinetic Modelling of the Planar Multipole Resonance Probe using functional analytic methods

Michael Friedrichs and Jens Oberrath
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Measuring plasma parameters, e.g. electron density and electron temperature, is an important procedure to verify the stability and behavior of a plasma process. For this purpose the multipole resonance probe (MRP) represents a satisfying solution. However, the influence of the probe on the plasma due to its physical presence makes it unattractive for processes in industrial applications. As an improvement the planar design of the MRP (pMRP) was introduced, which combines the advantages of the spherical MRP with the possibility to be integrated into the chamber wall of a plasma reactor.

Measuring the electron temperature with this probe needs a kinetic model. Such a model, based on functional analytic methods, will be presented in this work.

The authors gratefully acknowledge funding by the German Research Foundation (DFG) within the project OB 469/1-1.

O7
Power transfer and impedance matching in capacitive discharges

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[2] Electrodynamics and Physical Electronics Group,
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The power required for operating radio-frequency plasmas is usually provided by an electric generator and transferred through a matching network. The concept of impedance matching, in which the plasma is considered as a linear load, has been successfully applied in experiments and industrial applications. However, under certain conditions the plasma is known to be highly nonlinear, resulting in harmonics in the plasma discharge. Impedance matching of the fundamental frequency may not appropriately take into account the inherent higher harmonics. It is, therefore, instructive to investigate the interaction of these harmonics with the external matching network to provide a consistent picture of the matching process. In this work, a method is presented for coupling an equivalent circuit model of the plasma to an electric power supply circuit composed of linear lumped elements. In result, a comprising method to simulate the interaction between the plasma and the circuit is obtained. This is used to investigate the nonlinear interaction of the matching network and a capacitive discharge, especially the current path of the harmonics from the plasma to the external network.

O8
Analytic Model of the Plasma Sheath

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Global models are particularly suitable for incorporating the most relevant plasma characteristics. In comparison to spatially resolved simulations, e.g. PIC simulations, they are computational less demanding. They also need low computing times whereby results can be achieved faster. In this work the numerical modeling of a capacitively coupled discharge is shown. For this purpose, an existing global model [1] is extended by a sheath in front of the grounded electrode in order to be able investigate the boundary sheath behaviour in front of the driven and the grounded electrode. A first approach uses the matrix sheath model to determine the corresponding current and the voltage characteristics. Additionally an experimentally determined ion density profile is used in the model and suitable parameter variations allow a comparison of the results using the two different density profiles.
Particular emphasis is put for an variation of the area ratio of the driven to the grounded electrode. The obtained results allow conclusions about the effects of the nonlinearities as well as for the effect of the plasma series resonance.

A further improvement of the boundary sheath behavior can be achieved by incorporating thermal and dynamic effects. Moreover the ambipolar field which is particularly important for the ion dynamics is considered. This can be accomplished by using an improved sheath model.

[1] Mussenbrock T, Brinkmann R P, Liebermann M A, Lichtenberg A J, and Kawamura E 2008 *Phys. Rev. Lett* 101 085004

O9

Impedance modeling for DF-plasmas where one of the frequencies is well below the ion plasma frequency

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For industrial applications, e.g. plasma enhanced chemical vapor deposition (PECVD), dual frequency (DF) plasmas are used to gain a better control over important plasma parameters. In contrast to traditional DF discharges where both frequencies are in the MHz range, here the lower frequency is 400 kHz and well below the ion plasma frequency. This means that the ion sheath dynamics play an important role and cannot be neglected. Additionally PECVD reactors are operated at pressures of a few hundred Pa, so that secondary electrons have to be considered as well.

Measurements for this case show a typical capacitively dominated impedance for the high frequency voltage (13.56 MHz) while the behavior of the low frequency current is of a resistive nature. Here, this phenomenon is investigated with a fluid simulation and a simple analytical model is developed for a better understanding of the underlying physics.

O10

Vibrational excitation kinetics of CO_2 in a pulsed glow discharge

B.L.M. Klarenaar[1], M. Grofulovic[2], A.S. Morillo-Candas[3], M.A. Damen[1], D.C.M. van den Bekerom[4], M.C.M. van de Sanden[1,4], O. Guaitella[3], R. Engeln[1]

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Efficient reduction of CO_2 to CO is a key step in the process of storing renewable energy in the form of hydrocarbon fuels. This process is believed to be most efficient when selectively exciting the asymmetric-stretch vibration of CO_2. We study the rotational and vibrational temperature dynamics of CO_2 in a pulsed glow discharge. The cylindrical plasma reactor (23 cm length, 2 cm diameter) is operated under flowing conditions in the millibar range, with a plasma current of typically 50 mA. The plasma is pulsed with a cycle of 5 ms on, 10 ms off, while the residence time of the gas is in the order of seconds.

Two diagnostics are used to study the discharge: (1) spatio-temporally resolved rotational Raman spectroscopy and (2) time-resolved infrared absorption spectroscopy. Both techniques can be used to determine rotational temperatures, and absolute densities of CO_2 and CO, while with (1) also O_2 densities can be measured. With (2), vibrational temperatures of CO_2 and CO can be measured.

Both techniques give similar temporal profiles for the gas temperature, and also molecular number densities are determined to be equal. Furthermore, from (1) the temperature and the composition of the gas are both shown to be invariant over the length of the reactor. This confirms an important assumption made for the analysis of (2): a uniform absorption medium along the line-of-sight. From (2) excitations of the asymmetric-stretch vibrational mode (1050 K) are observed, exceeding rotations and other vibrational modes (500 K) with up to 550 K. In the post-discharge, characteristic relaxation times of this vibrational mode are found to be strongly dependent on the gas temperature. This suggests that lowered gas temperatures improve selective excitation of the asymmetric mode, relevant for the efficient dissociation of CO_2.

O11

Vibrational kinetics of non-equilibrium CO_2 plasma discharge and post-discharge: comparison with experiment

Marija Grofulović[1], Tiago Silva[1], Bart L. M. Klarenaar[2], Ana Sofia Morillo-Candas[3], Olivier Guaitella[3], Richard Engeln[2], Carlos Daniel Pintassilgo[1,4] and Vasco Guerra[1]

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The main purpose of this work is to understand in detail the vibrational energy exchanges in non-equilibrium CO_2 plasmas. To that end, we develop a kinetic model that couples the electron Boltzmann equations to the rate balance equations describing the time evolution of various individual vibrational levels of $CO_2(X\ 1\Sigma+)$. We have investigated a low excitation regime, where $\nu_2^{max} = 5$, $\nu_3^{max} = 5$ and $\nu_1^{max} = 2$, resulting in 72 vibrationally excited levels. Validation of the model was done by comparing the time-dependent densities of the aforementioned states with measurements obtained by time-resolved in situ FTIR spectroscopy in a pulsed CO_2 dc discharge (at p = 5 Torr, I = 50 mA) and its afterglow. The calculated maintenance electric field during the pulse and the time-dependent populations are in excellent agreement with the measured values. Work is in progress to extend the study to the higher vibrational excitation.

O12
Dimension reduction of global models using principal component analysis

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5600 MB Eindhoven, The Netherlands

Plasma-assisted conversion of CO_2 into CO provides a promising first step of the synthesis of solar fuels. Numerical simulations of a non-equilibrium CO_2 plasma can be a useful way to study the conversion. The vibrational models of CO_2 provide an efficient path to dissociation, hence an accurate description of the transfer of vibrational energy is needed. The large number of species and reactions present in the CO_2 plasma poses a serious challenge for the simulation due to the high computational load. Chemical reduction techniques are able to reduce the amount of species for which balance equations need to be solved. As an initial reduction study we will limit ourselves to global models, for which PLASIMO is used. Principal Component Analysis (PCA) is a chemical reduction technique that transforms correlated species densities into uncorrelated variables called the Principal Components (PCs). Reduction is achieved by solving balance equations for only a few PCs instead of for all the species densities. It was shown that only two PCs need to be solved for if they uniquely describe the plasma composition. We present an extension of PCA that gives accurate results using two PCs even when uniqueness is not present.

O13
Investigation of Ion Dynamics in Capacitively Coupled Argon-Xenon Discharges

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Technological plasmas applied for etching or thin film deposition frequently consist of multiple gas and ion species. Accurate control of the ion energy is an essential requirement in these processes. The main goal of this work is to investigate the influence of the gas composition on the ion dynamics within these discharges. A low-pressure argon-xenon plasma is chosen and investigated via a Particle-In-Cell/Monte Carlo Collision (PIC/MCC) simulation. The main advantage of this noble gas mixture is its simple chemistry, which leads to a feasible number of ion species to be considered. The ion energy distribution functions (IEDFs) at the electrodes of a geometrically symmetric capacitively coupled radio-frequency (RF) discharge (Fig. 1) provide information about the ion dynamics within the discharge volume. The cross section of the interaction of argon ions with xenon neutrals is largely unknown. The same holds for the interaction of xenon ions with argon neutrals. For this reason, some model cross sections are assumed and the resulting IEDFs are determined. Additionally, a variation of the gas composition is conducted using different approaches for the Ar-Xe interaction cross sections. Furthermore, we investigate the influence of different discharge parameter (e.g., pressure and driving voltage) on the IEDF and the ion dynamics.

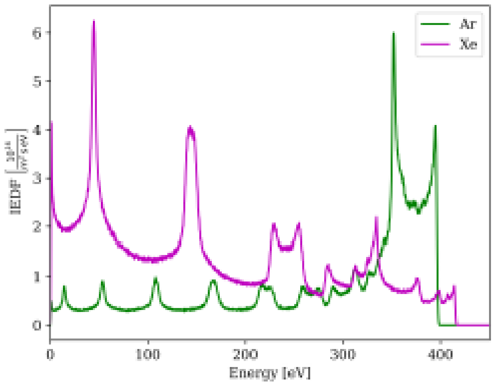

Figure 1: IEDF of argon and xenon ions obtained by PIC/MCC simulation using a 1D cartesian grid. Discharge conditions: V_{RF} = 900 V, f_{RF} =13.56 MHz, p_{gas} = 5 Pa, L_{gap} = 25 mm, 90% Ar, 10% Xe

O14

Study of ion fluxes in Extreme Ultraviolet radiation induced hydrogen plasma

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Photons induced plasmas differ from discharge plasmas in that the energy for ionization is fully supplied by photons. Plasma induced in the low density buffer gas in EUV lithography tools is thought to be the cause of the loss of reflectivity of multilayer mirrors. Ex situ tests have shown that irradiation of mirrors with energetic hydrogen ions indeed leads to mirror degradation, but the applicability to the plasma-mirror situation was not clear because the energy of ions impacting on the mirrors in EUV lithography was not known.

We study a plasma induced by short (~50 ns) pulses of extreme ultraviolet radiation (EUV) in a few pascal hydrogen gas. The EUV pulse duration is much shorter than the plasma decay time, resulting in a highly transient afterglow like plasma with interesting properties.

We have measured the ion energy distribution functions using an ion spectrometer and the flux densities using a retarding field energy analyzer in an EUV induced plasma under lithography relevant conditions. The majority of ion energies have an energy below a threshold energy of 10 eV. The H^+ distribution shows a significant tail, extending almost 10 eV beyond this bulk threshold. The influence of pressure and pulse energy have been investigated. Here, the electron mean free path becomes roughly equal to the experimental geometry, resulting in interesting effects on the ion flux.

O15

Surface Production of Negative Ions on Nitrogen Doped Diamond Samples

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The generation of negatives ions play a key role in many technical applications, including but not limited to: neutral beam injection, microelectronics, and medical industries. It is well known that H^- can be produced both in the plasma volume and upon the surface of a low work function material. These processes are being utilised in the new generation of neutral beam injectors, which are used for plasma heating and current-drive in larger tokamaks. The inclusion of caesium vapour produces a higher yield of negative ions via surface interactions, however, caesium causes a plethora of problems and a replacement needs to be found.

Nitrogen doped diamond (NDD) samples of varying levels of dopant were exposed to a low pressure (2 Pa) hydrogen plasma produced by a 13.56 MHz radio-frequency generator. The levels of doping were as follows, 0 ppm, 20 ppm, 50 ppm, and 100 ppm. The 50 and 100 ppm samples contained the same crystalline face ([111]), whereas the 20 ppm contained a combination of the [111] and the [100] faces. The relative yield of H^- ions were measured by an EQP mass spectrometer. The 100 ppm NDD samples produced a higher relative yield of negative ions than the 50 ppm sample, however, the yield from the 20 ppm sample was comparable to the 100 ppm sample. The introduction of a second crystalline face appears to enhance the yield of negative ions regardless of the decrease in nitrogen doping.

O16

IVDF and plasma parameters of CX dominated plasmas

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The properties of many laboratory plasmas are determined by charge-exchange collisions. Recently Tsankov and Czarnetzki [1] developed a new diagnostic technique for this kind of plasmas. It allows a spatially resolved access to the ion velocity distribution functions (IVDF) and the plasma parameters by a single, non-invasive measurement at the wall.

Here, their work is improved and extended. The obtained results reproduce the previous measurements in a Neon plasma, however, with an increased resolution. Further, a relation between the electric field and the drift velocity is obtained and a criterion for the validity of the diagnostic is derived. Based on this criterion measurements in Argon plasma are performed under conditions where the technique is applicable. The radial variations of the plasma parameters obtained through the diagnostic are presented. The radial measurements are complemented by axial ones, which are needed for the evaluation of the radial data.

[1] Tsankov, Ts. and Czarnetzki, U. 2017 *Plasma Sources Sci. Technol.* **26** 055003

O17

Improving uniformity of atmospheric-pressure dielectric barrier discharges using dual frequency excitation

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A novel approach to improve the uniformity of atmospheric-pressure dielectric barrier discharges (DBDs) using a dual-frequency (DF) excitation consisting of a low frequency (LF) at 200 kHz and a radio frequency (RF) at 13.56 MHz is reported in this work. It is shown that due to the periodic oscillation of the RF electric field, the discharge is temporally modulated i.e. enhanced and suppressed during each RF cycle. As a result, the discharge develops more slowly with a lower current amplitude and a longer duration. Hence, the RF electric field facilitates improved stability and uniformity simultaneously allowing a higher input power.

O18

Inactivation of *Bacillus subtilis* Spores by Low Pressure Plasma emitted UV-Radiation

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Sterilization of surfaces is a crucial step in clinics or pharmaceutical industry to minimize microbial contamination and ensure the safety of patients, employees, and customers. Existing methods of decontamination based on, *e.g.*, dry or wet heat, γ- and UV-radiation, or chemicals like hydrogen peroxide and ethylene oxide are well established and efficient, nevertheless show several disadvantages. Thus, these methods might damage the material or require extensive safety measures due to radiation or carcinogenic substances.
A promising alternative is the treatment with low pressure plasmas. Due to flexible plasma conditions and different processes contributing to decontamination (*e.g.* (V)UV-radiation, radicals, heat or electric fields) they have been demonstrated to be suitable to be applied on sensitive equipment like heat-sensitive materials or electronic instruments. The inactivation of various types of microorganisms including bacterial spores and prions has been shown, but the mechanisms resulting in sterilization are still not known in detail.

To investigate the impact of plasma generated (V)UV-radiation, radicals, and metastables, a 25 liter, cylindrical stainless steel ICP reactor with a coil at the top and at the bottom is used, operated at pressures of 5 Pa at 500 W. Monolayers of *B. subtilis* spores are treated by using filters with different cut-off wavelength to shield the samples from ions, radicals and metastables. To evaluate a wavelength dependent inactivation efficiency four plasmas of different gas mixtures varying in the emitted radiation are used. The plasma emission is measured in absolute numbers from 116 to 400 nm with a monochromator equipped with a photomultiplier and a broadband echelle spectrometer.
The results are in good agreement to measurements with monochromatic light by Munakata *et al.* indicating a wavelength depending inactivation efficiency.

O19

Spatio-temporal plasma heating mechanisms in a radio-frequency electrothermal microthruster

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Charge-neutral electrothermal plasma propulsion sources are of significant interest as they potentially allow for power deposition at varying radii within the propellant gas flow. For low power, micro-propulsion sources, further understanding of the mechanisms by which electrical power is coupled into the propellant is useful for increasing thrust efficiency. Previous studies of radio-frequency (rf) plasmas have shown that the spatio-temporal heating mechanisms are coupled with the local collisionality, this is of importance to thrusters due to the large axial pressure gradient.
In this work, phase-resolved optical emission spectroscopy and numerical simulations are employed to study plasma heating in an rf (13.56 MHz) electrothermal microthruster operating in argon at 200 Pa (1.5 Torr) plenum pressure, 130 - 410 V (0.2 - 6 W). Three distinct temporal peaks in excitation are observed, corresponding to three separate electron heating mechanisms within the rf period. These findings show agreement with excitation rates obtained from 2D fluid/Monte-Carlo simulations performed using the hybrid plasma equipment model (HPEM). The electron heating dynamics are investigated with respect to the rf phase and axial distance along the thruster with reference to their distinct power deposition pathways. The relative role of each mechanism during a voltage induced alpha to gamma mode transition, where plasma heating is driven via bulk and sheath heating, respectively, is also investigated.

O20

Stochastic electron heating in a periodically structured electric field

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Recently a novel mechanism for stochastic electron heating in inductively coupled plasmas has been proposed theoretically by Czarnetzki and Tarnev [1]. It considers the movement of electrons in a plane parallel to the inductive coil, in contrast to the common case, where only the electron motion perpendicular to the planar coil is considered. It was shown that when the electrons move through a periodically structured electric field there exist the possibility for a non-local energy gain, which leads to a production of high energetic electrons.
To realize such a periodically structured electric field, a novel plasma source, the Inductive Discharge Array (IDA), has been assembled. Here, a short overview over the theory and the construction details of the source will be given. Further, recent results from optical and Langmuir probe measurements for the characterisation of the source will be presented. These show evidence for the existence of high energetic electrons at pressures below 1Pa.

[1] U. Czarnetzki and Kh. Tarnev, Phys. Plasmas 21, 123508 (2014)

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[1] Institute of Theoretical Electrical Engineering, Ruhr-University Bochum, Germany
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S. Mirpour, S. Nijdam
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F. Kogelheide[2], B. Offerhaus[2], N. Bibinov[2], J.-W. Lackmann[3], P. Awakowicz[2], K. Stapelmann[1]
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Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands

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[1] Electrical Engineering and Plasma Technology, Ruhr-University Bochum, Germany
[2] Chemical Engineering and Macromolecular Chemistry, University of Paderborn, Germany

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[3]Plasma Matters B.V., Den Dolech 2, 5612 AZ Eindhoven, The Netherlands

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M.C. de Peuter[1], A. Sobota[1] and W.F.L.M Hoeben[2]
Eindhoven University of Technology, Eindhoven, The Netherlands.
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Insitute of Product and Process Innovation, Leuphana University Lüneburg, Germany

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L. Schücke[1], F. Mitschker[1], Ch. Hoppe[2], T. de los Arcos[2], G. Grundmeier[2] and P. Awakowicz[1]
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J.P.W.F. van Dongen, B. Platier, F.M.J.H. van de Wetering, J. Beckers
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P27: **(De)charging of particles advancing through spatial plasma**

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P1

Applying tailored voltage waveforms for control of the electron dynamics in atmospheric pressure plasmas

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Atmospheric pressure plasmas have recently been investigated due to their potential for technological and biomedical applications. They are very efficient sources for chemically reactive species, for example reactive oxygen and nitrogen species. Precise control of these reactive species is important for control of the application. The chemical kinetics is initiated by the electrons, energised through the external electrical power input. Therefore, precise control of the power input and electron dynamics should provide control of the radicals and other reactive species in the plasma. We investigate using non-sinusoidal waveforms to control the plasma electron dynamics on nano-second timescales. Similar strategies have been applied to low pressure plasmas for ion energy control [1-3]. Due to the strongly collisional environment and associated short electron energy relaxation times in atmospheric pressure plasmas, close coupling of the electrons and chemical species, allows control of the chemical pathways.

In this work a fundamental frequency of 13.56 MHz, and adding up to 5 harmonics drives a capacitively coupled atmospheric pressure plasma. The source geometry is the same as that of the *COST Reference Microplasma Jet* [4]. Different waveform shapes including pulse- and sawtooth-type are applied. Helium is used as a carrier gas with small mixtures nitrogen and argon (0.05% each). The temporally asymmetric waveforms applied to a geometrically symmetric plasma induces an asymmetric plasma, accompanied by the formation of a dc self bias. Phase resolved optical emission spectroscopy (PROES) is employed to study the excitation dynamics in spatio-temporal with high resolution [5]. There is also a significant change in the electron excitation mechanisms depending on the waveform and number of harmonics. Control of excitation in both space and time can be achieved, strongly suggesting potential for control of the chemical pathways.

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P2

Ion energy distributions in plasma-assisted atomic layer deposition

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Atomic layer deposition (ALD) is a method used in semiconductor industry to deposit conformal and uniform thin films with accurate thickness control. This method is becoming increasingly important with the miniaturization of device components. Instead of using a gas or a vapor (e.g., H_2O), plasma-assisted ALD employs a plasma in the second half-cycle of the growth process (e.g., an O_2 plasma to grow an oxide). Aside from the radicals generated in the plasma, the ions can assist in surface reactions as well. However, the exact role of ions in plasma-assisted ALD is unclear. Moreover, the effect of the plasma conditions on the ion energy distribution is generally unknown.
This work explores these open questions by measuring the ion energy distributions of several plasmas (grounded and substrate-biased) employed in plasma-assisted ALD. The diagnostic tool used for these measurements, namely a Retarding Field Energy Analyzer (RFEA) probe, is the main focus of this contribution. Furthermore, possible effects of the found distributions on the ALD process will be discussed.

*Both authors contributed equally to this poster presentation.

P3

Theoretical and experimental analysis of microplasma created by a microstrip split-ring resonator

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Microplasma sources are desirable for small scale applications with low power consumption, such as miniature mass spectrometers. For this purpose it is necessary to create a discharge with a long lifetime and a wide range of operating pressures. One possibility to create such a plasma is the microstrip split-ring resonator (MSRR), powered by a microwave source. To create a plasma inside the gap of the MSRR, it is important to properly design the geometry of the resonator, such as the length of the resonator and the angle of the gap-position, to match the impedance of the resonator to the power supply.
The authors present a microstrip split-ring resonator driven at a frequency of 2.45 GHz. The resonator creates a low pressure plasma which is ignited by two molybdenum electrodes inside the plasma chamber. Characteristic wave parameters are simulated by 3D-FEM simulation to optimize the input reflection factor for the given frequency and materials. For the estimation of plasma parameters spectral lines of nitrogen gas admixtures are recorded with an absolutely calibrated, high resolution spectrometer.

P4

Spatially resolved temperature measurements using Two-photon Absorption Laser-Induced Fluorescence

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Efficient conversion of CO_2 to CO for the production of hydrocarbon fuels is a key factor in overcoming the intermittent nature of renewable sources. The efficiency of this conversion is highest when selectively exciting CO_2 in the asymmetric stretch vibrational mode. This can be achieved using a non-thermal plasma such as a microwave discharge.
Local CO_2 conversion dynamics in a microwave discharge are studied using in-situ Two-photon Absorption Laser Induced Fluorescence (TALIF) near 230 nm to resonantly excite CO from the $X^1\Sigma^+$ to the $B^1\Sigma^+$ state. This technique can yield both spatially- and temporally resolved rotational temperatures and (relative) CO densities from the subsequent fluorescence.
Rotational temperatures can be obtained by fitting the CO absorption spectrum. Calibration measurements on room temperature CO were performed to verify the fitting accuracy. Additionally, (relative) number densities can be obtained from the absolute TALIF signal intensity, although quenching and absorption by CO before the detection volume significantly affect the detected signal, thus making the measurement and subsequent analysis challenging.

P5

Planeterrella

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The Northern Lights are created by charged particles from the Sun travelling to the Earth. Those particles excite our atmosphere creating the aurorae we see. The Planeterrella is built on this concept and simulates this aspect by using two aluminum spheres, representing the sun and the earth. Inside those spheres are magnets placed reconstructing the earth’s magnetic field lines. This device is able to simulate different aspects of astrophysical phenomena.
An interesting phenomena that we observe in our Planeterrella are sparks visible on the surface of the sphere with a negative potential. A previous experiment showed that those sparks are the result of electric discharges and that they create erosion spots on the spheres. The reason for this investigation is to further understand the cause of those sparks and how to manipulate them.
Connecting the negatively charged sphere to an oscilloscope and measuring the current of it shows many peaks per second. We now perform experiments to try to link those current peaks to the number of sparks. A possible conclusion could be that a local discharge on the aluminum spheres creates those sparks and temporally raise the current.

P6

Analysis of a lumped circuit model for radio frequency magnetron sputtering

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Today´s industry would not be conceivable without plasma technology. During the last decades magnetron sputtering gained a high technological significance for deposition of high quality thin films. However, the process may be prone to a drift of plasma parameters, due to for instance changes of the surfaces during the deposition or heating of the background gas. For a better control of the process a model based control is needed which inhibits the drift of important parameters. Due to the lack of appropriate models this work aims to develop one. A lumped element model with its corresponding system of differential equations, which was proposed a few years ago, is used [1]. Since this model is especially suitable for capacitively coupled radio frequency discharges without a magnetic confinement, it has to be adapted for magnetron discharges. One possible method how to expand this model is shown in this work. The magnetized region is represented by a magnetic resistance, taking Bohm-diffusion into account [2,3]. The sheath region is modeled with an improved ion density profile.

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P7

Spectral kinetic simulation of ideal multipole resonance probe

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Active Plasma Resonance Spectroscopy (APRS) denotes a class of industry-compatible plasma diagnostic methods which utilize the natural ability of plasmas to resonate on or near the electron plasma frequency. One particular realization of APRS with a high degree of geometric and electric symmetry is Multipole Resonance Probe (MRP). The Ideal MRP (IMRP) is an even more symmetric idealization which is suited for theoretical investigations. In this work, a spectral kinetic scheme is presented to investigate the behavior of the IMRP in the low pressure regime. The scheme consists of two modules, the particles pusher and the field solver. The particle pusher integrates the equations of motion for the studied particles. The Poisson solver determines the electric field at each particle position. The fluid model is studied to provide the initial conditions of simulation for optimization reason. The proposed method overcomes the limitation of the cold plasma model and covers kinetic effects like collisionless damping.

P8

Characterization of a spark discharge of spark plugs for modern combustion engines using optical methodes

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In principle, the ignition technology of modern combustion engines has not changed since the last 100 years. A very high voltage pulse is generated by an ignition coil. Between the electrodes of a spark plug the HV pulse causes a spark discharge which is used to ignite the petrol-air mixture. The duration of the high-energy phase of the spark discharge amounts only a few 100 ns. In this phase, an ignitable petrol-air mixture must be near the electrodes of the spark plug to push the flame front.
Usually spark plugs work in a pressure range of up to 40 bars close to the ignition point. For the characterization of a spark discharge, a high pressure experimental setup is used to avoid measurements inside a cylinder of an Otto engine. A discharge vessel with quartz windows allows spectroscopic investigations. The plasma parameters of the ignition spark, namely gas temperature, electron density are determined in pure nitrogen for different pressures. The transient behavior of the spark is investigated with a short time ICCD camera. The used camera can capture four consecutive pictures with a minimum exposure time of 3ns. The results of the characterization of the standard spark discharge is the base to invent alternative ignition systems. These are believed to reduce petrol consumption at the same engine power compared to a conventional ignition system, there are many approaches to optimize the ignition technology.

P9

Determination of plasma parameters in a low pressure, microwave driven microplasma by means of optical emission spectroscopy

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Micro-electromechanical systems (*MEMS*) have a broad area of application in modern technology. *Lab-on-a-chip devices* are enabled by the shrinkage of sensors to micrometer scale. The authors present a micro-fabricated mass spectrometer equipped with a low pressure plasma source driven at a frequency of 2.45 GHz. An antenna creates a cylindrical shaped plasma volume of 250 µm in radius and 300 µm in height surrounded by borosilicate glass and electrically conducting silicon. The low pressure microplasma is used as an electron source and therefore electron density, power efficiency and gas consumption are key parameters for optimization.
Absolutely calibrated, space- and time-averaged optical emission spectroscopy (OES) is used to measure gas temperature and electron density in noble gas atmosphere with small additions of nitrogen. Space-resolved spectral line analysis is performed by means of a CCD-Camera with bandpass interference filters. The pressure inside the discharge chamber is estimated by the pressure drop induced by micro capillaries.

P10
Calculating vibrational-vibrational rates of CO_2

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The increasing concentration of CO_2 in the air and the accompanying climate change is a motivation for alternative sources of energy. One of the possible sources is the conversion of CO_2 back into fossil fuels using plasmas. The dissociation of CO_2 to CO is a crucial step. The most energy efficient path uses vibrational pumping. The vibrational-vibrational kinetics are poorly understood. Numerical models use empirical scaling relations to describe these kinetics. The accuracy of these modeling results is unknown.
The aim of this project is to calculate the vibrational-vibrational transfer rates. One method of obtaining these rates is to calculate the potential energy surface (PES) in advance and subsequently using a statistical analysis of various CO_2-CO_2 collisions on this PES. The number of dimensions of the system is too large to calculate the potential energy surface using ab initio methods. Therefore an analytical PES is constructed based on Zuniga et al and Bartolomei et al. The analytical potential is used for the trajectory calculations. By varying the initial conditions and by sampling several trajectories, the reaction rates can be deduced.
In a later stage of the project the improved reaction rates will be used to simulate the microwave reactor using PLASIMO. At first the improved rates will be used in a global model. After that a 2D model will be considered as well. This model will couple equations for momentum, continuity, Te, Th and electromagnetics self-consistently. The model will be used to optimize the reactor.

P11
“Bystander effect” Or how the plasma induce the cancer cells to diffuse the death cell signals

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Due to the low penetration depth of the reactive species in the tissue, one of the most important question in the cancer treatment by non-thermal plasma is the mechanism of the tumor ablation in in-vivo studies. The aim of this study is to investigate the effect of non-thermal atmospheric pressure on cancerous tumor and the possible interaction. In this line a 10 kV – 8 KHz power supply employed in order to expose to solid tumor (In-vivo assay) and the cells (in-vitro assay). In in-vivo assay the 4T1 breast cancer cell line were injected to the 5 female Balb/C mice ($1*10^5$ cell/ml). After 10 days of the injection, the tumor was growth about 4*4*2 (mm^3). After that the mice were treated by atmospheric plasma jet for 3 minutes and followed up for measurement by 21 days after the plasma exposure. Moreover, the computer simulation (COMSOL Multiphysics) were performed in order to find the depth penetration of ROS which generated by plasma in tumor tissue. In in-vitro assay the MDA-MB-231 Breast cancer line were exposed by plasma for 90, 270, 470, 920 seconds. After 24 hour incubation the treated and no-treated samples were counted by MTT assay and the inflammation genes (TNF-α, NF-κb, COX-2) expression was measured the order to find the interaction mechanism. The results showed that the plasma stopped the tumor growth rate in comparison of the non-treated samples after 21 days of the plasma treatment but the computer simulation showed that the ROS reactive agents penetrate only about 150±20 µm in the tissue (0.075 of the whole tissue in Z direction). The in-vitro assay proof that the plasma active the inflammation response of the cancer cells which belongs to the cancer cell signaling. In conclusion this is the first study that demonstrates the mechanism of the plasma – cancer tumor interaction which showed the “Bystander effect” or “Death cell signaling” occurs in the inhibition of the tumor growth by non-thermal atmospheric pressure plasma.

P12

SAINT: Science and Innovation with Thunderstorm

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Despite the tremendous progress achieved in recent years in lightning research that has led to understanding of many physical process in lightning discharges, the fundamental question of lightning physics, how lightning initiates inside thunderstorms, has remained unanswered. This project focuses on the inception of lightning to figure out the physical interpretation of the phenomenon that occurs at the initiation of the lightning. Due to the atmospheric observations, it was obtained the required electric field for breakdown in lightning inception is significantly lower than electric breakdown in air. There are two major hypotheses which may describe this phenomenon: a) Relativistic Runaway Electrons Avalanche, b) Initiation assisted by hydrometeors. Because of some major problems the first theory is less common, thus the second hypothesis seem to be more dominant. However, the exact mechanisms and roles of these theories are still obscure. The goal of this project is to figure out the mechanism of the inception of the lightning, the role of hydrometeor and also energetic electrons in a controllable medium. In this regard, by using artificial particles to mimic ice particles in a controllable vessel in different physical conditions, such as pressure, working gas type, and free electron sources, we are going to evaluate the role of the different mechanisms in the inception of the lightning. Thus, results of this project may reveal some of the mysteries of lighting inception. The main goal of this project is to find out the possible mechanisms of the inception of lightning in a simulated atmosphere. For further exploration, effect of different environmental properties such as pressure and working gas type on the inception of lightning will be evaluated.

P13

Spatially-resolved characterisation of a dielectric barrier discharge in controlled atmosphere

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Non-thermal atmospheric-pressure plasmas, such as the employed dielectric barrier discharge (DBD) are regarded as advantageous for various biomedical applications since they make a contact- and painless therapy possible [1]. Understanding the physical and chemical impact of such plasma sources on biological tissue is mandatory in order to prevent adverse health for the patient. In order to tailor the chemistry regarding its biomedical impact on biological samples and to ensure stable conditions for the characterisation of the discharge, the DBD was mounted in a vessel. Optical emission spectroscopy was carried out to determine the plasma parameters, i.e. electron velocity distribution function, electron density n_e and reduced electric field E/N [2,3]. Since interactions between plasma and biological samples often occur in liquid environments, such as wounds, long-living chemically-active species in plasma-exposed liquid were detected using colorimetric assays as well as terephthalate dosimetry.

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P14

Streamer Discharge Splitting Characteristics in Liquid Dielectric under Impulse Voltage and AC Voltage

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The electrical behavior of transformer oil subjected to high electric-field and the possible breakdown phenomena is of great practical interest, since this dielectric liquid has been widely used in high-voltage power apparatus and pulse power systems. Compared with the discharge mechanisms and behaviors derived from various gas atmosphere, the initiation and evolution are more complicated, and the ionization mechanism behind are not well-known yet. This paper presents experimental investigation of streamer discharge process in transformer oil under sub-microsecond pulse excitation and alternating current voltage (AC). The diverse breakdown events are observed through intensified charge-coupled device (ICCD). The experiment results reveal that the streamer is of a stochastic nature that elongates the discharge channel with great uncertainty. Three typical kinds of streamer profiles are obtained from dozens of snapshots: a single filamentary shape, tree-like with symmetric branches and more than one main channel. It is interesting to notice that our experimental results on streamer shapes are in good agreement with the modes depicted by [1]; that positive streamers usually have a filamentary shape with small branches in the center, while streamers from a negative electrode are bushier than that from a positive electrode, and are often with charged particle cloud in the middle, which possibly imply that physical mechanisms behind both polarity streamers are different. From the viewpoints of classical electric theory, the discharge is more likely to grow at the points where the electric field is highest. These points are the tips of the branches. If this effect would be dominating, the breakdown would just propagate along a straight line toward the ground. However, from our experimental observation, a strong tendency of ramifying and slanting is usually found in most pictures obtained, which may indicate that the complicated process has a stochastic nature instead of a deterministic rule [2]. It is therefore believed that the combination of electric and stochastic effect that rule the channel formation.

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P15

Uncertainty analysis for Global Models with a large chemistry

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Global Models are spatially averaged models that are powerful for studying plasma chemical processes. Uncertainty in the results from a global model needs to be determined numerically due to the typical non-linearity in the plasma chemical reactions. This is done by running the model various times, with the input of the model varied each simulation stochastically. For Global Models with a large set of reactions this method becomes infeasible due to the large number of required simulations. In that case the input data for the uncertainty analysis needs to be reduced. In this poster we will present an efficient method to do so.

P16
PLASIMO modelling of hollow cathode discharges

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Hollow cathode discharges are widely used in the field of atomic spectrometry, ion sources, plasma processing and surface treatments. The main challenge in modelling of hollow cathode discharge is to describe the combination of both fluid and non-local phenomena. Such non-local phenomena are for instance pendulum electrons and the dynamics in the cathode fall region. These cannot be described with pure fluid models. A kinetic description is needed, for example based on a Monte Carlo model.
Monte Carlo methods are widely used to describe the kinetics of the electrons and other species and to derive transport coefficients of charged species. The result of such calculations can be combined with “fluid-based methods” to provide the electric field distribution and to evaluate the densities and transport rates of charged species. The result is a so-called "*hybrid model*", that allows describing discharges that are composed of different regions where different processes play role.
PLASIMO’s Drift-Diffusion and Monte-Carlo modules are used to simulate the hollow cathode discharge and to describe numerically the various processes in the plasma. Preliminary results will be presented.

P17
Dust particles suspended in an argon Rf-discharge sheath, while using gravity as a variable

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Everywhere a low pressure plasma is in contact with solid surroundings, an anisotropic plasma sheath region is induced. This plasma sheath is regulated by charge separation, which is induced by local depletion of free electrons, inducing high electric fields. From fundamental perspective and in many applications involving low pressure plasmas (sputtering, etching, particle synthesis and mitigation), the plasma sheath plays a crucial role.
Experimentally obtaining information about the physical structure and dynamics of the plasma sheath without disturbing the corresponding local plasma parameters has appeared extremely challenging. Hence, these data are rarely available in literature. Therefore, a theoretical framework for this region is far from complete and fully descriptive.
We present an experimental campaign, using a single negatively charged microparticle suspended in the plasma sheath as a local diagnostic microtool to probe its surroundings. To have perfect control over the position of the particle in the plasma sheath, varying apparent gravitational levels induced by our in-house 1-10g centrifuge facilities are used. Adding apparent gravity (being a non-intrusive force seen from the

plasma perspective) is currently the only possible way to achieve spatially resolved "probing" of the plasma without disturbing the plasma itself.
First measurements obtaining the charge of the particle, its floating potential and the momentum transfer from streaming ions to the plasma-confined microparticle are presented. These parameters have been obtained spatially resolved within the anisotropic boundary of the plasma.

P18

Influence of ion energy and atomic oxygen flux on the deposition of silicon oxide barrier films

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Polymers, like polyethylene terephthalate (PET), are widely used e.g. for packaging, but offer limited barrier properties against gas permeation. The barrier properties of these polymers can be enhanced by plasma deposition of thin silicon oxide (SiO_x) films. SiO_x is of great interest, as it is transparent and offers significant improvement of barrier performance. The deposition is performed by means of a microwave-driven low pressure plasma using gas mixtures of Hexamethyldisiloxane (HMDSO) and oxygen. A pulsed substrate bias controls the energy of ions and the atomic oxygen flux impinging on the substrate.
Detailed analysis of the plasma is performed to quantify ion energy and atomic oxygen flux. Deposited films are investigated applying oxygen permeation measurements, x-ray photoelectron spectroscopy and ellipsometry. The influence of a change in process parameters such as substrate bias pulse duration and temporal pulse position on ion energy and atomic oxygen flux is studied. This is correlated to the change in film properties. It is shown that an increase of ion energy as well as an increase of atomic oxygen flux independently yield in barrier films with excellent barrier properties for food packaging. Good barrier films are highly cross-linked with a smooth morphology.

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P19
Validation of He-H_2O Global Model with experiment

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Global warming is one of the critical contemporary problems for mankind. Transformation of CO_2 into fuels that are transportable with the current infrastructure seems a promising idea to solve one part of this threatening issue. The final aim of this research is to produce CH_4 by using a microwave plasma in CO_2-H_2O mixture and subsequent catalytic processes. In this contribution we present a global model for He-H_2O chemistry. We compare the results of modeled electron density with measured one at DIFFER microwave reactor for different concentrations of H_2O in He and pressures.

P20
Spatially resolved emission and absorption measurements in a twin surface dielectric barrier discharge ignited in defined gas mixtures

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In the last decades extensive studies have been performed on dielectric barrier discharges (DBDs) in several fields of applications of non-thermal atmospheric pressure plasmas. Their applicability ranges from health-promoting effects on the human skin to air decontamination combined with a rather good scalability [1,2]. Further insight into their physical and chemical properties is mandatory for a proper configuration of plasma sources for a given application. In our case a twin dielectric barrier surface discharge is ignited in defined gas mixtures (variation of the fractions of N_2 and O_2). The surface discharge electrode is made of an aluminium oxide plate working as a dielectric barrier and grid-structured copper traces on each side of the plate. The electrode is connected to a high voltage plasma generator with external transformer. The reduced electric field and electron density are determined in synthetic air and in nitrogen with spatial resolution using an absolutely calibrated ICCD camera with optical bandpass filters in conjunction with a collisional radiative model for nitrogen and numerical simulation [3]. They are in good agreement with OES data obtained with an absolutely calibrated echelle spectrometer for different nitrogen/oxygen fractions. Furthermore, spatially resolved ozone densities along the electrode obtained using an ICCD camera with optical filters are presented.

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P21

Optical spectroscopic investigations of a He plasma jet in a controlled atmosphere

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The performance of a plasma reactor is highly influenced by the flow behaviour of the species in the reactor. In chemical reactors residence time distribution measurements are carried out to obtain insight into the reactor characteristics e.g. death spaces, the tracer method is used for this purpose. In plasma reactors helium can be used as a tracer material to determine the actual flow through a vessel, due to its inert properties and by the ability to accurately be detected with spectroscopy. To obtain knowledge on spectral characteristics a plasma jet can serve as an excellent source. In the framework of this project, a non-thermal atmospheric fast pulse helium plasma jet in a controlled atmosphere is investigated by optical emission spectroscopy measurements to explore the effect of the surrounding gas on the spectral properties of the jet.

P22

Laser induced plasma shock wave simulation for laser shock peening

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Improvement of material surfaces has become an integral part of industrial operations. This is to improve the mechanical and metallurgical properties such as fatigue life, corrosion, wear and erosion resistance. However, among the recently advanced surface modification techniques is laser shock peening (LSP). When focusing a short (3-30 ns range) and intense (>10^{13} W/m^2) laser pulse onto a metallic target, surface layers instantaneously vaporize (ablation phenomenon) into a high temperature (about 10 000 K) and high pressure (> 1 GPa) surface plasma. This plasma induces shock waves during expansion from the irradiated surface and a mechanical impulse transfers to the target.
In this work a 1D pressure distribution is determined for different laser parameters as a result of LSP simulation, based on a global model of Zhang et al. [1,2]. The influence of laser parameters on the results of processing is investigated. It is shown numerically that decreasing laser wavelength, increasing pulse energy and using confining medium result in increasing of plasma pressure which results in higher and deeper residual stresses.

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P23

Comparative investigation of plasma deposited gas barrier coatings for polymers using hexamethyldisiloxane and hexamethyldisilazane

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Polymers such as polyethylene terephthalate (PET) or polypropylene (PP) are widely used for packaging of food and beverages. A limiting factor for the shelf life of such products are the gas permeation properties of the polymer packaging. The plasma deposition of thin silicon oxide (SiO_x) films on these polymers can greatly enhance gas barrier performance, while maintaining transparency and being chemically inert. The coatings are deposited using a gas mixture of oxygen and a silicon containing monomer, within a microwave-driven low pressure plasma reactor. Previous research on the topic has been successfully conducted using the monomer hexamethyldisiloxane (HMDSO), which is now extended to the use of hexamethyl-disilazane (HMDSN) to gain further insight into plasma chemistry and film deposition.
Deposition processes are analyzed by means of mass spectrometry, to quantify monomer densities and monomer depletion within the plasma, which are subsequently correlated with film properties. Deposited films are characterized by means of stylus profilometry, oxygen permeation measurements, fourier transform infrared spectroscopy (FTIR), and x-ray photoelectron spectroscopy (XPS). Deposition rates are directly linked to monomer densities and depletion, while oxygen transmission rates are correlated to the chemical structure of the deposited films.

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P24

PLASIMO's 5T-amplifier model for CO_2-laser amplification

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In many technological applications, such as the process of extreme ultraviolet lithography, high-intensity CO_2 laser pulses are used. The PLASIMO 5-temperature amplifier model is an implemtation of the so-called 5T-model [1] coupled with an equation that describes the evolution of the photon density [2]. The model describes the evolution of the photon density with a wave-length of 10.58 µm through a CO_2-N_2-He gas mixture. However, the system under consideration has a pre-mixture of

CO_2-CO-N_2-He and in addition radiation with a wavelength of 10.206 µm. To accurately simulate the CO_2 laser pulses, the PLASIMO 5T-amplifier model has to be extended to account for the admixture of CO, the second wavelength radiation, rotational relaxation [3], and spontaneous emission. The extended PLASIMO 5T-amplifier model is presented together with preliminary results.

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P25

Electric field four-wave mixing with focused laser beams: validity of the plane-wave approximation

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Electric field four-wave mixing is a plasma diagnostic that can be used for polarization resolved measurements of the electric field in atmospheric pressure discharges containing H_2 or N_2. Two incident laser beams are used to simultaneously induce two four-wave mixing processes: coherent anti-Stokes Raman scattering and coherent IR generation. The ratio between the two is directly related to the electric field. To attain the required laser intensities and spatial resolution, the incident laser beams are focused. However, in the analysis the plane-wave approximation is always used for the incident laser beams and phase matching is usually neglected. When the electric field to be measured is non-uniform, as is almost always the case, these assumptions limit the maximum spatial extent of electric field distribution. In the plane-wave approximation, the condition for the spatial extent of the field follows solely from where phase matching can be neglected. However, when the spatially varying characteristics of the focused beams are considered, the situation becomes more complex. In this work, we explore the validity of the plane-wave approximation in the electric field four-wave mixing diagnostic by a mathematical description of the four-wave mixing processes with Gaussian beams and comparing the results with experiments.

P26

Measuring electric field inside microwave cavities for plasma diagnostics

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Microwave Cavity Resonance Spectroscopy (MCRS) has been used to acquire the electron density of different types of plasmas. The electron density determined by MCRS is weighted by the squared electric field profile of the specific resonant mode. To acquire spatial information of the electron density, one needs to identify the modes after which they can be combined in the analyses of the data. In this work, the characterization is done by moving a barium titanate bead through the entire cavity by an XYZ stage. The local electric field is determined by measuring the frequency shift of each resonant mode using a network analyser. Measured and calculated electric field profiles of multiple cavities will be presented.

P27

(De)charging of particles advancing through spatial plasma

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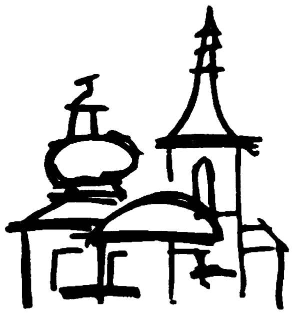
For many industries (high precision production, lithography, electron microscopy, nuclear fusion, etc.) nano- to micrometer sized particle contamination becomes an increasingly significant problem. One direction these industries explore, is to use plasma as particle mitigation tool. Plasmas are able to charge particles after which their path can be controlled using electric and magnetic fields. For this reason, there is a need for knowledge about the charging dynamics of particles when these particles enter and leave the discharge at predefined velocities.
The charge of micrometer sized particles in a spatial plasma afterglow is measured using particle trajectory analysis. Furthermore, a novel model is established that describes particle decharging in a spatial plasma afterglow. This combination allows one to determine the real particle charge and the plasma shielding simultaneously.



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