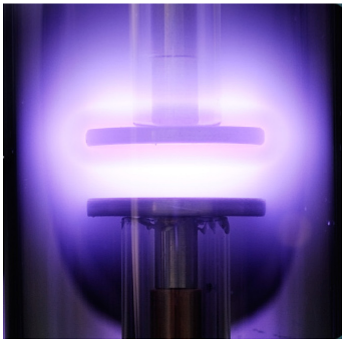
31st SYMPOSIUM

PLASMA PHYSICS & RADIATION TECHNOLOGY



Dutch Physical Society
Section Plasma and Gas Discharge Physics

Nederlandse Natuurkundige Vereniging

12 & 13 March 2019 - Congrescentrum De Werelt, Lunteren

This symposium is organized by the Section Plasma- and Gas Discharge Physics of the Dutch Physical Society.

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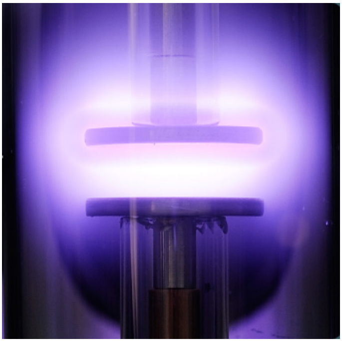

Dutch Physical Society
Section Plasma and Gas Discharge Physics

Programme & Abstracts

12 & 13 March 2019 - Congrescentrum De Werelt, Lunteren

General Information

Address

The address of Congrescentrum De Werelt is:

Westhofflaan 2
6741 KH Lunteren
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email: info@dewerelt.nl
http://www.congrescentrum.com/

Queries

If you have any questions about the conference, please contact:

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Travel to and from Lunteren

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Summaries:

The summaries of the contributions are coded as follows:

M: Keynote presentation of 40 minutes
O: Contributions selected for oral presentation of 20 minutes
A/B: Contributions selected for poster presentation

You are kindly requested to stay with your poster as long as possible

Poster Prize and Oral Prize:

Once again, there will be a prize for the best poster and the best oral contribution. The jury consists of members of the organizing committee.

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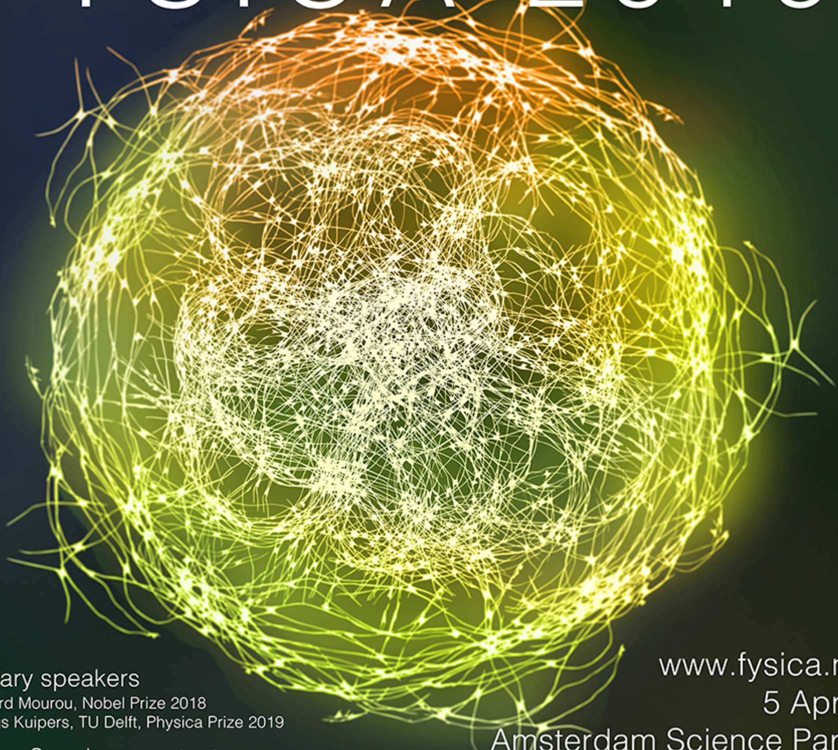

Plenary speakers
- Gérard Mourou, Nobel Prize 2018
- Kobus Kuipers, TU Delft, Physica Prize 2019

Young Speakers contest

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- Astroparticle Physics & Cosmology
- Careers session - Valorization
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Evening Program
- World in Vibration

PROGRAMME & ABSTRACTS

Programme Tuesday 12 March, 2019

09:45 - 10:20		Registration and coffee
10:20 - 10:30		Welcome (Africa room)

Fundamentals

Session leader: Jannis Teunissen (CWI)

10:30 - 10:35		Introduction
10:35 - 11:15	M1	*Force Fields for Fusion Materials and Plasma Material Interaction* by Bastiaan Braams (CWI - Amsterdam)
11:15 - 11:35	O1	*Reduction and Interpretation of the Underlying Mechanisms in H_2O-He Chemical Reaction Network in Microwave Plasma* by Samaneh Tadayon Mousavi (TU/e)
11:35 - 11:55	O2	*Monte Carlo Flux Simulations of Electrons for Plasma Modelling* by Luca Vialetto (DIFFER)
11:55 - 12:15	O3	*Efficient CO_2 Decomposition in Microwave Plasmas: Taking "Non" out of Non-Equilibrium Plasma Conversion* by Bram Wolf (DIFFER)
12:30 - 13:45		Lunch
13:45 - 14:10		Single Slide Show (Africa room)
14:10 - 15:45		Poster session 1 (Asia room): A1 t/m A Coffee and tea during session

Diagnostics

Session leader: Job Beckers (TU/e)

15:45 - 15:50		Introduction
15:50 - 16:30	M2	*Low Power, Low Pressure Plasmas for Synthesis of Advanced Nanocarbons* by Eva Kovacevic (CNRS & Université d'Orleans - France)
16:30 - 16:50	O4	*Microwave Cavity Resonance Spectroscopy applied to Pulsed Plasma Jets* by Bart Platier (TU/e)
16:50 - 17:10	O5	*Gas Heating in the Ignition Phase of Pure Molecular Plasmas assessed by Thomson Raman Scattering* by Alex van der Steeg (DIFFER)
17:10 - 17:30	O6	*Investigation Streamer Initiation from Hydrometeor* by Shahriar Mirpour (TU/e)
18:15 - 20:00		Dinner

Evening Lecture

Session leader: Gerard van Rooij (DIFFER)

20:00 - 21:00	M3	*Energy Transition: The Big Picture* by Vianney Koelman (CCER, DIFFER & TU/e - Eindhoven)

Programme Wednesday 13 March, 2019

08:00 - 09:00		Breakfast

Extreme Plasmas

Session leader: Oscar Versolato (ARCNL)

09:00 - 09:05		Introduction
09:05 - 09:45	M4	*Quantum Logic Spectroscopy of Highly Charges Ions* by Piet Schmidt (Leibniz Universität Hannover - Germany)
09:45 - 10:05	O7	*Identification of Fe-like through Ga-like Transitions in Lanthanum Ions in the 0.8-4.2nm Region from Laser-Produced Plasmas* by John Sheil (ARCNL / University College Dublin)
10:05 - 10:25	O8	*Measuring Radiative Power of Liquid Metal Vapour Shielding in Magnum-PSI* by Sven Korving (TU/e - DIFFER)
10:25 - 10:40		Coffeebreak in Asia Room
10:40 - 11:00	O9	*Magnetic Flux Pumping in Hybrid Tokamak Discharges Studied by Means of 3D Nonlinear MHD Simulations* by Isabel Krebs (DIFFER)
11:00 - 11:20	O10	*Ion Energy and Charge State Distribution in Pico- and Femtosecond Laser-produced Plasmas* by Tiago de Faria Pinot (ARCNL / VU Amsterdam)
11:25 - 11:45		Single Slide Show (Africa room)
11:45 - 12:45		Poster session 2 (Asia room): B1 t/m B Coffee and tea during session
12:45 - 13:45		Lunch

From Plasma-Wall Interaction to Plasma-Catalysis

Session leader: Gerard van Rooij (DIFFER)

13:45 - 13:50		Introduction
13:50 - 14:30	M5	*Plasma Catalysis* by Leon Lefferts (University of Twente - Enschede)
14:30 - 14:50	O11	*Surface Recombination of O Radicals Determined by its Impact on Conformal Growth of Oxides by Plasma-enhanced Atomic Layer Deposition* by Karsten Arts (TU/e)
14:50 - 15:10	O12	*Plasma Catalysis as Vibrational Activation of Surface Interactions* by Qin Ong (DIFFER)
15:10 - 15:30	O13	*Deuterium Retention in Tin Samples exposed to Fusion-relevant Flux Plasmas* by Wei Ou (DIFFER)
15:30 - 16:00		Discussion
16:00 - 16:15		Presentation NNV-prizes for "Best Poster 2019" and "Best Oral 2019"!

Summary poster session 1 - 12 March 2019

A1 Investigating hydrogen plasma-chemical processes using Optical Emission Spectroscopy in detached Magnum-PSI scenarios - Akkermans
A2 Simulation of streamer properties in CO_2 and dry air - Bagheri
A3 Energy and charge state resolving spectrometry of Sn ion emission from EUV plasma light source - Bayerle
A4 Near-wall plasma parameter measurements with the incoherent Thomson scattering diagnostic at Magnum-PSI - Van den Berg
A5 Vibrational quenching by water in a pulsed CO_2 glow discharge - Damen
A6 Let CO_2 spark! Advanced streamer imaging - Dijcks
A7 Characterization of filamentary instabilities in a magnetized RF discharge - Donders
A8 Vibrational excitement: from CO_2 to CO - Erdogan
A9 A dense plasma picture of laser created plasmas for short wavelength radiation - Schram
A10 The role of flow and quenching on efficiency of CO_2 microwave plasma - Gao
A11 Discretization scheme for systems of conservation laws of advection-diffusion-reaction type - Van Gestel
A12 Modelling vortex flow in a microwave CO_2 plasma reactor - Groen
A13 Chemical reduction: a recipe - Gulpen
A14 Investigating plasma charging of nanoparticles with microwave cavity resonance spectroscopy - Hasani
A15 Decharging of microparticle clusters in low pressure plasma afterglow - Van Huijstee
A16 Imaging of a dielectric barrier discharge used for calibrating the Stark effect in argon - Kempers
A17 Charged aerosol clouds for lightning protection - Kochkin
A18 Investigation of electrical breakdown in high pressure (0.1 to 1 MPa) CO_2 under pulsed fields - Kumar
A19 Cancelled
A20 Equipotential surfaced in the plasma sheath enlightened by a single plasma-levitated micro-particle - Lamberts

Summary poster session 2 - 13 March 2019

B1 Electric field measurements on plasma bullets in nitrogen with nanosecond electric field induced second-harmonic generation - Limburg

B2 Characterization of positive streamer discharges in pre-ionized channels - Martinez

B3 Canceled

B4 Quantum dot photoluminescence; a versatile diagnostic for plasma charging - Marvi

B5 Probing the plasma sheath with micro waves - Meijaard

B6 Investigating shock-wave-induced dynamics in tin microdroplets - Meijer

B7 Local charge measurements of microparticles in a remote plasma afterglow - Van Minderhout

B8 The development of a plasma-based lice comb - Van Mouche

B9 Activating combustion kinetics at low temperature using non-equilibrium plasma - Patel

B10 Multispectral advanced narrowband Tokamak Imaging System (MANTIS) - Perek

B11 Enhanced recombination of a hydrogen plasma induced by nitrogen seeding in linear plasma device Magnum-PSI - Perillo

B12 Influence of targets on the behavior of an atmospheric He plasma jet - Van Rooij

B13 Spectroscopic studies on laser-produced tin plasma - Schupp

B14 Investigation of the effect of Argon addition CO_2 plasmas in dissociation and vibrational excitation - Silva

B15 Obtaining the electron density in a rf-driven plasma jet at atmospheric pressure using microwave cavity resonance spectroscopy - Staps

B16 Self-consistent Fokker-Planck approach to CO_2 vibrational kinetics - Viegas

B17 Dissociation of a CO_2 gas and chemical equilibrium at high temperature - Westermann

B18 What makes them pop? Nanoparticle release in EUV lithography scanners - Van de Wetering

B19 Fast spectral solution of the inelastic Boltzmann equation with applications - Wilkie

B20 Electron Kinetic Effects On Deuterium Atomic Physics in The Scape-off Layer Plasmas - Zhao

M1

Force fields for fusion materials and plasma material interaction

Bastiaan J. Braams[1]
[1] *Centrum Wiskunde & Informatica (CWI), Amsterdam, Netherlands*

I will present a perspective on the status and needs of computational tools for plasma-material interaction and primary radiation damage, using as motivation work done in a recent International Atomic Energy Agency (IAEA) Coordinated Research Project on Plasma-Wall Interaction with Irradiated Tungsten and Tungsten Alloys in Fusion Devices. In my perspective the interaction potential for molecular dynamics simulations is (almost) everything and present interaction potentials used in modelling leave much to be desired. There are very interesting ongoing developments in machine learning for interaction potentials and I will review some approaches: the Gaussian Approximation Potential (GAP) approach led by Gábor Csányi of Cambridge University, the Deep Potential Molecular Dynamics (DeepMD) approach led by Weinan E en Roberto Car of Princeton University with contributions from IAPCM (Beijing), and the Solid Harmonic Wavelet Scattering approach led by Stéphane Mallat of ENS in Paris. New approaches such as these will be important to provide computational support for studies of primary radiation damage and they will be essential in connection with experiments that rely on surrogate (charged particle) irradiation or on irradiation by neutrons from fission, spallation or a stripping reaction.

M2

Low power, low pressure plasmas for synthesis of advanced nanocarbons

Eva Kovacevic, Johannes Berndt, Cedric Pattyn, Ana Dias, Shahzad Hussain, Tyhomas Lecal and Chantal Leborgne
GREMI UMR 7344 , CNRS & Université d'Orleans, 45067 Orléans Cedex 2, France

Reactive plasmas are nowadays widely used for various applications from astrophysics to the manufacturing of new materials for technological applications. One of the great challenges of the plasma based manufacturing of new materials concerns the exact tuning of the corresponding material properties.
This contribution will focus on some aspects of low pressure, low power RF discharges sustained in the carbon containing gases used for the deposition of advanced nanomaterials used in biosensors and supercapacitors.
The authors acknowledge the support through the ANR PlasBioSens, ANR PlasmaBond, and FET OPEN project PEGASUS.

M3

Energy Transition: The Big Picture

Vianney Koelman
Center for Computational Energy Research, DIFFER and TU Eindhoven

Over the course of the twentieth century, mankind has successfully expanded fossil energy technology towards global scales. The result, affordable energy available on demand, has delivered vast economic benefits. Now mankind is facing the task of transitioning towards to a sustainable global energy system. This interactive talk by physicist and former oil and gas researcher Vianney Koelman, presents a mix of historical data and back-of-the-envelope calculations. These shed a light on the global energy transition: where are we now, where are we heading, and what is the size of the challenge ahead of us?

M4

Quantum Logic Spectroscopy of Highly Charged Ions

Tobias Leopold[1], Peter Micke[1], Steven A. King[1] J.R. Crespo Lòpez-Urrutia[3], Piet O. Schmidt[1,2]
[1] *QUEST Institut, Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*
[2] *Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany*
[3] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

Outer electrons in highly charged ions (HCI) show extreme properties in comparison to those of atoms. Their narrow optical fine-structure transitions have smaller polarizabilities and electric quadrupole moments, but much stronger relativistic, QED and nuclear size contributions to their binding energy. Consequently, they have been proposed as future clock candidates and to probe for physics beyond the Standard Model. Specifically, HCI offer the most sensitive transitions of any known atomic system to a change in the fine-structure constant [1]. HCI can readily be produced and stored in an electron beam ion trap (EBIT). There, the most accurate laser spectroscopy on any HCI was performed on the 17 Hz wide fine-structure transition in Ar13+ with 400 MHz resolution, limited by Doppler broadening in the EBIT. The lack of a suitable optical transition for laser cooling and detection can be overcome through sympathetic cooling with a co-trapped Be+ ion [2]. Techniques developed for quantum information processing with trapped ions can be used to perform quantum logic spectroscopy [3]: A series of laser pulses transfers the internal state information of the Ar^{13+} ion after spectroscopy onto the Be^{+} ion for efficient readout.

I will present how HCI can be extracted from a compact EBIT [4], charge-to-mass selected and injected into a cryogenic Paul trap containing a crystal of laser-cooled Be^{+} ions. By removing excess Be+ ions, a crystal composed of a Be^{+}/Ar^{13+} ion pair can be obtained. First results on sympathetic ground state cooling and quantum logic spectroscopy of the

Ar^{13+} P_1/2-P_3/2 fine-structure transition at 441 nm will be presented, improving the resolution by more than six orders of magnitude.

[1] M. G. Kozlov, M. S. Safronova, J. R. Crespo López-Urrutia, and P. O. Schmidt, Highly charged ions: Optical clocks and applications in fundamental physics, Rev. Mod. Phys. 90, 045005 (2018).
[2] L. Schmöger, O. O. Versolato, M. Schwarz, M. Kohnen, A. Windberger, B. Piest, S. Feuchtenbeiner, J. Pedregosa-Gutierrez, T. Leopold, P. Micke, A. K. Hansen, T. M. Baumann, M. Drewsen, J. Ullrich, P. O. Schmidt, and J. R. C. Lòpez-Urrutia, Coulomb crystallization of highly charged ions, Science 347, 1233–1236 (2015).
[3] P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, and D. J. Wineland, Spectroscopy Using Quantum Logic, Science 309, 749–752 (2005).
[4] P. Micke, S. Kühn, L. Buchauer, J. R. Harries, T. M. Bücking, K. Blaum, A. Cieluch, A. Egl, D. Hollain, S. Kraemer, T. Pfeifer, P. O. Schmidt, R. X. Schüssler, C. Schweiger, T. Stöhlker, S. Sturm, R. N. Wolf, S. Bernitt, and J. R. Crespo López-Urrutia, The Heidelberg compact electron beam ion traps, Review of Scientific Instruments 89, 063109 (2018).

M5

Plasma Catalysis

Leon Lefferts
Faculty of Science and Technology, Catalytic Processed and Materials, University of Twente, Enschede, The Netherlands

Synergy between catalysis and plasma is frequently claimed but insight in the underlying mechanisms is notably lacking. This lecture will describe how catalysis scientist have been attracted to the emerging field of plasma catalysis. Furthermore, the choice for specific catalysts that can be used in combination with specifically non-equilibrium plasmas will be rationalized based on principles and concepts in heterogeneous catalysis.

O1

Reduction and Interpretation of the Underlying Mechanisms in H_2O-He Chemical Reaction Network in Microwave Plasma

S. Tadayon Mousavi[1], J.G.M. Gulpen[1], A.J. Wolf[2], W.A.A.D. Graef[3], P.M.J. Koelman[1], and J. van Dijk[1]
[1] *Applied Physics Departement, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands*
[2] *Dutch Institute of Fundamental Energy Research (DIFFER), Eindhoven, 5600 HH, The Netherlands*
[3] *Plasma Matters B.V.*

Global warming is one of the critical contemporary problems for mankind. Transformation of CO_2 into fuels, like CH_4, that are transportable with the current gas infrastructure seems a promising idea to solve this threatening issue. The final aim of this research is to produce CH_4 by using microwave plasma in CO_2-H_2O mixture and follow-up catalytic processes. In this contribution we present a global model for H_2O-He kinetics. The results of the model are compared with measurements that have been done in DIFFER. In addition, the so-called Reaction Pathway Algorithm is used to reduce H_2O-He kinetics and to interpret the main chemical reaction network for this mixture in non-equilibrium conditions of the microwave plasma reactor.

O2

Monte Carlo Flux simulations of electrons for plasma modelling

L. Vialetto[1], S. Longo[2] and P. Diomede[1]
[1]Center for Computational Energy Research, DIFFER - Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, the Netherlands
[2]Dipartimento di Chimica, Università degli Studi di Bari, via Orabona 4, 70126 Bari, Italy

A challenging aspect in the modelling of low temperature plasmas at intermediate pressures is an accurate description of electron kinetics. In fact, several collisional processes and the non-equilibrium between electrons and heavy particles give rise to strongly structured electron energy distribution functions (EEDFs). The EEDF must be calculated from the solution of the electron Boltzmann equation. From the EEDF, it is possible to determine other important quantities, such as rate coefficients and transport parameters, essential for a complete characterization of the discharge. Fast solutions are generally obtained in stationary conditions and assuming small anisotropy of the distribution function around the direction of the electric field. However, those assumptions are not always valid for the plasma conditions of interest. As an alternative, accurate calculations can be achieved by conventional Monte Carlo techniques, at the cost of computational time. In the present work, an implementation of a method called Monte Carlo Flux is presented. This method allows calculations of the EEDF without approximations, in computational times much shorter than the ones from conventional Monte Carlo simulations. Results of the code are validated against results from other widely used Boltzmann solvers.

O3

Efficient CO_2 decomposition in microwave plasmas: taking "non" out of non-equilibrium plasma conversion

A.J. Wolf, F.J.J. Peeters, T.W.A. Righart, P.W.C. Groen, M.C.M v.d. Sanden, W.A. Bongers
PSFD, DIFFER, Eindhoven, the Netherlands

Solar fuels, CO_2-derived high density carriers, provide a means of large-scale storage and transport of renewable energy in a CO_2 neutral manner. Reduction of CO_2 to carbon monoxide is a determining step in the production cycle and requires high efficiency in view of economical viability. Microwave plasmas have shown particular promise for the efficient and scalable production of carbon monoxide, with energy efficiencies upwards of 80% reported in the literature. The consensus is that a strong vibrational non-equilibrium, and subsequent vibrational dissociation, can explain these results. Presently, at optimal plasma conditions, 50% energy efficiency under thermal conditions has been realized in attempts to reproduce this work.
In this contribution, we present our current understanding of the CO_2 microwave plasma and the role of the flow dynamics on reactor performance. Our findings are based on measurements of gas temperature, electron density, plasma shape, and conversion. The results are supported by CFD modeling of the reactor gas flow dynamics and numerical models of the EM field. It is found that thermodynamic equilibrium composition and the observed core gas temperature (3000-6000 K) are imperative in understanding the discharge contraction behavior and the resulting plasma parameters. An alternative narrative is proposed for interpretation of the non-equilibrium results from literature, and more general perspectives are given on the viability of CO_2 dissociation in microwave discharges.

O4

Microwave cavity resonance spectroscopy applied to pulsed plasma jets

Bart Platier[1], Marc van der Schans[1], Peter Koelman[1], Ferdi van de Wetering[1], Jan van Dijk[1], Job Beckers[1], Sander Nijdam[1], and Wilbert IJzerman[2,3]

[1]*Department of Applied Physics, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands*

[2]*Department of Mathematics and Computer Science, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands*

[2]*Signify, High Tech Campus 7, 5656 AE Eindhoven, The Netherlands*

Since the development of microwave cavity resonance spectroscopy (MCRS)in the 1940s, it has been used to study various types of plasma. In this work, this diagnostic is used to investigate the decay of the electron density and collision frequency between successive discharges in an atmospheric pressure pulsed plasma jet in N_2 feed gas. A global model is used to verify the obtained experimental results.
The electron densities and effective collision frequencies are obtained from about 1 μs up to approximately 60 μs after the discharge, where the former time scale is limited by the response time of the cavity and the latter by the lower detection limit. The accuracy of the electron density is limited to one order of magnitude due to an estimation of the plasma volume. Good qualitative agreement has been found in the electron density decay rate between the numerical and experimental data. The model also reveals that the minimum seed electron density which is required for repeatable guided streamer discharges in N_2 feed gas is of the order of 10^{15} m^3.
An overview of the work will be presented.

O5

Gas heating in the ignition phase of pure molecular plasmas assessed by Thomson and Raman scattering

A. van de Steeg[1], T. Butterworth[1], and G. van Rooij[1]
[1]*DIFFER, Eindhoven, 5612AJ, The Netherlands*

The rotational and vibrational temperatures in the ignition phase of pure CO_2, N_2 and CH_4 microwave plasmas are measured by Raman scattering to study whether V-T relaxation is the main heating pathway. All three gases show a large vibrational non-equilibrium, with rotational temperatures being near ambient. Towards the end of the pulse all three gases show rapid gas heating and an equilibration of vibrational and rotational temperatures. Next to Raman scattering, Thomson scattering is applied in the N_2 and CH_4 plasmas to study the electron temperature. It is found that in this phase of the plasma there is only limited selectivity of electron energy to vibrations in N_2 and CH_4. V-T relaxation mostly explains the observed temperature evolution of CH_4, the characteristic V-T time coincides almost perfectly with our measurements, showing that the limited selectivity to vibrational excitation of the free plasma electrons has a limited effect in the heating rate of CH_4. The characteristic timescales for V-T processes in N_2 are orders of magnitude larger, which can therefore not be the prime heating mechanism. For CO_2, the timescale of V-T relaxation approaches the observed equilibration times, however it cannot fully explain the observed heating rate at these conditions. The results obtained with the combination of Thomson and Raman scattering therefore hint at the importance of electronic excitation in heat production during the ignition phase of the plasma for CO_2 and N_2, but not for CH_4.

O6

Investigation streamer initiation from hydrometeor

Shahriar Mirpour, Sander Nijdam
Department of Applied Physics, Eindhoven university of Technology, Eindhoven, The Netherlands

Despite the tremendous progress achieved in recent years in lightning research, the fundamental question of lightning physics, how lightning initiates inside thunderstorms, has remained unanswered. The measured electric field in the thunderclouds is much less than air breakdown electric field. A theory that describes this phenomenon is lightning inception from hydrometeors in which streamers initiate from the enhanced electric field region near the hydrometeors. The goal of this project is to figure out the mechanism of the inception of the lightning, the role of hydrometeors in lightning inception in a controllable environment.
All experiments in this study are performed in a plane-to-plane geometry in which a dielectric particle (TiO_2) which has similar dielectric profile like ice crystals is suspended between a high voltage and grounded electrodes. The dielectric particle is formed by polishing after annealing and pressing. A high voltage pulse is applied by a circuit which consists of a high voltage semiconductor switch (HTS 401-10-GSM, Behlke) and a 1 nF high voltage capacitor. This produces a voltage pulse with a rise time of 30 ns, a pulse width of 1 ms, with repetition rate of 5 Hz and a maximum voltage between 1 and 30 kV. The distance between suspended particle and high voltage and grounded plane is fixed to 10 mm. The experiments are operated in vacuum pressure, 300 mbar. A Photo Multiplier tube is placed in front of the vessel to capture every photon produced by the discharge around the suspended particle.
Results measured the delay between applied voltage and discharge inception (t_d). Obviously, t_d decreases with increasing voltage. Furthermore, increasing frequency decreases t_d. ICCD images demonstrate positive and negative discharges initiate from the particle, the negative discharge is more diffuse while the positive streamer is more narrow.

O7

Identification of Fe-like through Ga-like transitions in lanthanum ions in the 0.8 - 4.2 nm region from laser-produced plasmas

J. Sheil[1,2], M. Olszewski[1], K. Mongey[1], F. O'Reilly[1], P. Dunne[1], E. Sokell[1], D. Kilbane[1], C. Suzuki[3], and G. O'Sullivan[1]

[1] *School of Physics, University College Dublin, Belfield, Dublin 4, Ireland*

[2] *Advanced Research Center for Nanolithography, Science Park 106, 1098 XG Amsterdam, The Netherlands*

[3] *National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*

In this talk, I will present the results of a spectroscopic study of emission from highly-charged lanthanum ions generated in laser-produced plasmas. The spectrum, recorded in the $0.8 - 4.2$ nm region, exhibits both line and narrowband features. In terms of the former, the main contributors to the spectrum are $\Delta n > 0$ transitions in highly-charged Ni-, Cu-, Zn- and Ga-like ions. In certain cases, we predict a near-coincidence of transition energies for transitions in neighbouring isoelectronic sequences. Emission in the form of narrow, quasicontinuous bands is also a prominent feature throughout this wavelength range. Strong emission bands located below 2 nm have been attributed to $3d^n - 3d^{n-1}4f$ transitions in highly-charged Fe-like ($n = 8$) and Co-like ($n = 9$) ions. Above 2 nm, transitions of the form $3d^9 4l - 3d^9 5l'$ (where $l = 0 - 3$, $l' = 0 - 4$) between excited-state Ni-like configurations are found to make a significant contribution to the spectrum. Experimental identifications were made possible through *ab initio* flexible atomic code (FAC) computations of level structures and transition rates.

O8

Measuring Radiative Power of Liquid Metal Vapour Shielding in Magnum-PSI

S.Q. Korving [1,2], T.W. Morgan [2], S. Nijdam[1], and P. Rindt[1]
[1] *Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands*
[2] *DIFFER - Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, The Netherlands*

In nuclear fusion reactors, liquid lithium (LL) has been proposed as surface material for divertor targets; to mitigate the heat flux reaching the surface by partially evaporating and forming a vapour cloud in front of the target. The vapour cloud dissipates heat by means of radiation and particle transport of energetic neutrals [1]. However, evaporation rates should be limited to prevent contamination of the core plasma. Thus, LL divertors must endure the high heat fluxes without producing too much lithium vapour.
The goal of this project is to quantify the power radiated from vapour shielding at various fusion relevant heat fluxes and to determine its capabilities as a heat shield. We approach this by measuring the radiated power (axially resolved) in front of poorly cooled, porous tungsten, LL filled targets [2] in Magnum-PSI with a resistive metal foil bolometer [1]. We have shown that the resistive bolometer can determine the radiated energy over millisecond plasma pulses. We found at typical steady-state heatfluxes ($\approx 10\ MW/m^2$), that there was no significant radiation increase due to lithium. However, in high power ELM-like millisecond pulses (0.1-1 GW/m^2) radiation from vapour shielding significantly increased, sufficiently shielding the tungsten substrate to prevent melting. Concluding, resistive bolometry can be used to measure the energy emission of transient plasmas, and LL targets sufficiently function as a heat shield in those regimes. A next step should involve addressing the evaporation amount of lithium, and whether it would significantly contaminate the core plasma in tokamaks.

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O9

Magnetic flux pumping in hybrid tokamak discharges studied by means of 3D nonlinear MHD simulations

I. Krebs[1], S.C. Jardin[2], S. Günter[3], K. Lackner[3], M. Hoelzl[3], E. Strumberger[3], and N.M. Ferraro[2]

[1]*DIFFER — Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, The Netherlands*

[2]*Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, New Jersey 08543, USA*

[3]*Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany*

The hybrid scenario is an operational scenario for tokamaks that is characterized by a safety factor profile that is flat and close to unity in the central region of the plasma. Compared to standard scenarios, the hybrid scenario allows for extended discharge lengths through a larger non-inductive current fraction. It has good confinement and stability properties, i.a. due to the lack of sawtooth instabilities, and external current drive is facilitated by the fact that the flat central safety factor close to unity is automatically maintained. This latter property is due to a self-regulating current redistribution mechanism called magnetic flux pumping which has not been fully explained yet. As the hybrid scenario is a planned scenario for ITER operation and a candidate scenario for DEMO operation, understanding magnetic flux pumping is crucial in order to extrapolate the accessibility and properties of the scenario to these future tokamaks.

We present 3D nonlinear MHD simulations of tokamak plasmas performed with the high-order finite element code M3D-C^1. In these simulations the flat safety factor profile close to unity in the plasma core is maintained by a self-regulating magnetic flux pumping mechanism. The mechanism can be explained by a saturated $(n = 1, m = 1)$ quasi-interchange instability which generates an effective negative loop voltage in the plasma center via a dynamo effect [Jardin, Ferraro and Krebs, Phys. Rev. Lett. 115 (2015)]. It is shown under which conditions this mechanism provides a sufficiently strong loop voltage to prevent sawtoothing in the simulations and how the mechanism regulates itself to keep the central safety factor close to unity [Krebs, Jardin, Günter et al., Phys Plasmas 24 (2017)].

O10

Ion Energy and Charge State Distribution in Pico- and Femtosecond Laser-produced Plasmas

Tiago de Faria Pinto[1,2], Alex Bayerle[1], Jan Matthijssen[1,2], Randy Meijer[1,2], Dmitry Kurilovich1,2, Aneta Stodolna1,2, Oscar Versolato1,2, Kjeld Eikema1,2, Stefan Witte1,2
[1] *Advanced Research Centre for Nanolithography, Amsterdam, 1098 XG, The Netherlands*
[2] *Vrije Universiteit, Amsterdam, 1081 HV, The Netherlands*

The state of the art in extreme ultraviolet (EUV) sources for nanolithography uses high energy short pulse lasers which are focused on micro-droplets of tin, creating a plasma that emits 13.5 nm light. Undesired wavelengths and particles are also emitted, including high kinetic energy ions which may damage optical components.
At ARCNL, we have built a picosecond Nd:YAG laser system with a pulse duration tunable between 15 and 110 ps, delivering up to 175 mJ at 100 Hz repetition rate. Furthermore, we have set up an optical parametric chirped pulse amplifier (OPCPA) pumped by this ps laser, which provides 200 fs pulses at 1.5 μm wavelength and up to 12.5 mJ energy. These systems were used to produce tin plasmas from a solid flat target as well as liquid micro-droplets, with the goal of understanding ion emission from laser-produced plasmas (LPP), ablation dynamics and laser-induced droplet deformation.
We will present our latest results on ion energy and charge state distributions obtained using two independent charge state resolving measurement devices: an electrostatic analyser (ESA) as well as a Thomson parabola, as function of laser energy and polarization for durations between 200 fs and 10 ps as well as the effects of pulse parameters on droplet deformation. This study provides important insight into the initial stages of laser-produced plasma formation and plasma expansion into vacuum.

O11

Surface Recombination of O Radicals Determined by its Impact on Conformal Growth of Oxides by Plasma-enhanced Atomic Layer Deposition

Karsten Arts[1], Mikko Utriainen[2], Riikka Puurunen[2,3], Erwin Kessels[1] and Harm Knoops[1,4]

[1]*Department of Applied Physics, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands*

[2]*VTT Technical Research Centre of Finland, Espoo, 02044, Finland*

[2]*Aalto University School of Chemical Engineering, Espoo, 02150, Finland*

[4]*Oxford Instruments Plasma Technology, Bristol, BS49 4AP, United Kingdom*

This work addresses the recombination of plasma radicals on different materials, which can have a strong effect on plasma-based deposition methods where the reactive radicals are needed for film growth. A key example is plasma-enhanced atomic layer deposition (plasma ALD), which uses a plasma in one of its two alternated process steps to grow a conformal film layer by layer. Due to loss of radicals through surface recombination, plasma ALD in a high aspect ratio (AR) structure such as a deep and narrow trench is typically limited up to a certain penetration depth. For the first time, we demonstrate that this penetration depth can be used to quantify the recombination probability r of plasma radicals on representative material surfaces. Such quantitative information on r is often not available in the literature and difficult to obtain by conventional methods, while it is essential for the modelling and understanding of plasma ALD in high AR structures. Plasma ALD of SiO_2, TiO_2 and Al_2O_3 using an O_2/Ar plasma are investigated as case studies, where large differences in film penetration and corresponding values of r (i.e., from 10^{-5} up to 10^{-2}) are observed. These results show that our method is a powerful and straightforward way to gain insight into surface recombination of radicals and its impact on conformal film growth.

O12

Plasma Catalysis as Vibrational Activation of Surface Interactions

Q. Ong[1], D.C.M. van den Bekerom[1], G. Berden[2], M.A.Gleeson[1], C.J. Weststrate[3], M.C.M. van de Sanden[1,4], G.J. van Rooij[1,4]
[1] *DIFFER - Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, the Netherlands*
[2] *Radboud University, Toernooiveld 7c, 6525 ED Nijmegen, the Netherlands*
[3] *Syngaschem BV, c/o DIFFER, De Zaale 20, 5612 AJ Eindhoven, The Netherlands*
[4] *Technical University of Eindhoven, Flux, De Zaale, 5612 AJ Eindhoven, the Netherlands*

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.

O13

Deuterium retention in tin samples exposed to fusion-relevant flux plasmas

W.Ou [1],T.W. Morgan[1], N.J. Lopes Cardozo[2] , J.W.M. Vernimmen[1], P. Rindt[2],R.S. Al[1], S.Brons[1]
[1]Dutch Institute for Fundamental Energy Research, Eindhoven, 5612 AJ ,The Netherlands
[2]Science and Technology of Nuclear Fusion Group, Eindhoven University of Technology, Eindhoven, 5612 AP, The Netherlands

Liquid Sn is proposed as a plasma-facing material for the divertor of fusion reactors. It is required that the H-isotope fuel arriving at the Sn surface is not strongly trapped there, but until now little to no data on H-isotope retention in Sn was known. Sn targets were exposed to D plasma in Nano-PSI and Magnum-PSI respectively, to investigate the retained deuterium inventory using Thermal Desorption Spectroscopy (TDS) and Nuclear Reaction Analysis (NRA). The D retained in both types of Sn targets was found to increase with the increasing D fluence with a retained fraction of $1\ 5 \text{ x } 10 - 5$. Typically both TDS and NRA showed a strong decrease in deuterium retention with temperature, and the total amount of D retained in the whole samples was dominated by D retained in the Sn-wall interface. When compared with tungsten, D in Sn targets is the same order of magnitude as that in W, but the retention in pure Sn is lower, indicating it is a suitable material from a fuel retention perspective.

A1

Investigating hydrogen plasma-chemical processes using Optical Emission Spectroscopy in detached Magnum-PSI scenarios

G.R.A. Akkermans*[1], R. Perillo[1], R. Chandra[1], I.G.J. Classen[1], M.R. de Baar[1]

[1]DIFFER – Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, the Netherlands

*G.R.A.Akkermans@differ.nl

In ITER and other next-generation fusion devices, divertor detachment will be critical to limit the heat and particle fluxes to plasma-facing components to tolerable levels. Detachment works through an interplay of plasma-neutral cooling mechanisms, reduction of ionization, and volume recombination.

One type of volume recombination reaction of interest in this work is Molecule-Activated Recombination (MAR). MAR is a two-step process where a molecule collides with an ion and an electron, effectively resulting in recombination of the ion-electron pair and dissociation of the molecule. MAR was theoretically predicted to provide a significant recombination sink at relatively high electron temperatures of 1-3 eV where simple electron-ion recombination (EIR) has a negligible rate, and has been experimentally investigated mainly in linear devices with electron densities typically below 10^{20} m^{-3}.

The linear device Magnum-PSI can produce plasmas in the same parameter range as the (semi-)detached ITER divertor region, with electron temperatures of $T_e \sim$ 1-5 eV and densities $n_e \sim 10^{20} - 10^{21} m^{-3}$, and is hence perfectly situated to study the effect that MAR will have on detachment in ITER.

In Magnum-PSI, conditions of detachment with a high degree of plasma-neutral interactions near the target are mimicked by seeding hydrogen gas in the last of three differentially pumped vacuum chambers, raising the neutral background pressure from 0.4 Pa to up to ∼15 Pa in the final 80 cm in front of the target. Thomson Scattering is used to measure T_e and n_e in these different conditions of varying degrees of ‘detachment’. Optical emission spectroscopy (OES) of the Balmer series

using a multi-chord Jarrell-Ash spectrometer with wide spectral range enables the determination of radial profiles of excited H^* in the plasma beam from excited state $n = 3$ up to $n \sim 10$. The observed Balmer emissions are split into their EIR and MAR contributions to determine the relative importance of these processes. OES is also used at a high spectral resolution to measure the Fulcher band. This band of molecular emissions provides information about the distribution of rotationally and vibrationally excited H_2, which can enhance the MAR rate by multiple orders of magnitude.
The experimental results are compared to numerical simulations of Magnum-PSI using the Eunomia-B2.5 code suite, a Monte Carlo neutral-fluid plasma model which contains a full set of molecular reactions and resolves the vibrationally excited states of H_2.

A2

Simulation of streamer properties in CO_2 and dry air

Behnaz Bagheri[1], Jannis Teunissen[1,2], and Ute Ebert[1,3]
[1] *Centrum Wiskunde & Informatica, Amsterdam, 1090 GB, The Netherlands*
[2] *Department of Mathematics, Centre for mathematical Plasma Astrophysics, KU Leuven, Leuven, B-3001, Belgium*
[3] *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands*

Understanding breakdown dynamics in CO_2 is of great interests for both high-voltage technology and lightning on Venus. CO_2 is a promising gas for substituting SF_6 in high-voltage switchgear due to its lower global warming potential compared to SF_6. Furthermore, around 96.5% of the planetary atmosphere of Venus consists of CO_2. Streamers are decisive for breakdown in gases and hence understanding streamer properties such as inception and propagation is essential.
In this work, we investigate streamer parameters such as velocity, radius, and stability-field in CO_2 and air for positive and negative polarities. We use an open source plasma fluid code, afivo-streamer, that allows fully three-dimensional (3D) simulations of streamer discharges. The drift-diffusion-reaction model in local field approximation is implemented. Positive streamers require a source of free electrons in front of their heads. Photoionization is one source for these electrons. In N_2-O_2 mixtures, nitrogen molecules are the source of the ionizing radiation which can be absorbed by oxygen molecules. This ionizes these oxygen molecules and generates free electrons. Even though there have been lots of studies on photoionization in N_2-O_2 mixtures, the mechanism is not clearly understood in CO_2. In the present contribution, we also discuss the corresponding mechanisms in CO_2.

A3

Energy and charge state resolving spectrometry of Sn ion emission from EUV plasma light source

A. Bayerle[1], F. Toretti[1], S. Rai[1, 2], D. Kurilovich[1], W. Ubachs[1,3], R. Hoekstra[1,2], and O. O. Versolato[1]

[1] *Advanced Research Center for Nanolithography (ARCNL), Science Park 110, 1098 XG Amsterdam, The Netherlands*

[2] *Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands*

[3] *Department of Physics and Astronomy and LaserLab, Vrije Universiteit Amsterdam, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*

Ion energy distributions from infrared-laser-produced plasmas created from both planar-solid and liquid-droplet Sn targets are measured over a wide laser parameter space. Quantitative charge-state and energy resolved spectra are obtained by a combined measurement of Faraday cup collector current and charge-separated single ion counting with a carefully calibrated electrostatic analyzer. Experimental data is compared to self-similar single-fluid solutions of plasma expansion.

A4

Near-wall plasma parameter measurements with the incoherent Thomson scattering diagnostic at Magnum-PSI

J. van den Berg, H.J. van der Meiden, J.W.M. Vernimmen, I.C.M. Classen

DIFFER - Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, the Netherlands
j.vandenberg@differ.nl

Plasma acceleration towards the wall is a key aspect of Debye sheath formation, and marks a region of interaction between plasma bulk and sheath. In the quest to long-term operation of high-power magnetically confined fusion devices, it is crucial to control the particle and heat loads on the wall. Therefore, understanding of the near-wall plasma behaviour is important.
In this research, the non-intrusive incoherent Thomson Scattering (TS) diagnostic was applied in the near-surface region of the Magnum-PSI linear plasma generator. This diagnostic provides direct, local measurements of electron density (n_e) and temperature (T_e). By incrementally moving the plasma target along the magnetic field, an axial profile of these parameters can be obtained. To enable measurements as close as $1.2\,mm$ from the target, a stray light suppression up to a factor 10^4 was achieved, while retaining high spectrometer transmission.
Within the last $10\,mm$ before the target surface, a significant drop in n_e as well as T_e was observed (up to 40 % and 30 %, respectively). Given the absence of volumetric particle sources, a density drop equates to plasma acceleration, as is expected in the plasma presheath. However, the decrease in T_e implies an energy sink for electrons near the wall. A possible reason for this is collisional interaction between the accelerating plasma and recycled neutrals. Such interaction could result in loss of plasma particles, momentum and energy within the near-wall region. In future research, deployment of the Coherent Thomson Scattering diagonstic (CTS) is foreseen, enabling direct measurements of ion temperature and velocity. Thus, the parallel conservation of particles and momentum in the near-wall plasma can be tested experimentally.

A5

Vibrational quenching by water in a pulsed CO_2 glow discharge

M.A. Damen[1], X.R.S. Cabuzel[1], B.L.M. Klarenaar[1], and R. Engeln[1]
[1] *Plasma and Materials Processing, Eindhoven University of Technology, Eindhoven, Netherlands*

Efficient conversion of CO_2 to CO for the production of hydrocarbon fuels is a key factor in high energy density storage of intermittent renewable energy sources. The efficiency of this conversion is highest when vibrationally exciting CO_2. This can be achieved using a non-thermal plasma such as a DC glow discharge. However, addition of H_2O to the discharge has been suggested to quench the vibrational levels of CO_2 efficiently, thus reducing CO_2 conversion efficiency. Addition of H_2O in a pulsed CO_2 glow discharge is studied using rotational Raman spectroscopy. This technique provides temporal information about rotational temperatures, as well as vibrational temperatures of CO_2 through the ratio of even and odd rotational peaks. Raman spectra are taken at different times during the plasma pulse to obtain temporal evolutions of the CO_2 vibrational excitation for various H_2O amounts ranging from 0% to 5%. This shows a decrease in the population of odd rotational levels, indicating efficient quenching of CO_2 vibrational populations by addition of small amounts of water.

A6

Let CO_2 Spark!

Advanced streamer imaging

S. Dijcks[1], S. Nijdam[1]
[1] *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands*

Streamers are the precursors to sparks, which have unwanted effects in high voltage equipment. An example of this is a circuit breaker. Here high voltages are switched by physically opening the electrical circuit. The arc which short circuits the separated electrodes is extinguished by an electronegative gas. After extinguishing, the circuit needs to remain broken for a successful switching operation. Therefore, new streamers which can create new conducting paths between the electrodes, need to be prevented.
The electronegative gas of choice for the best performance in circuit breakers is SF_6. However, due to its extreme potency as a greenhouse gas alternative gasses are under investigation. This project focuses on CO_2 and its discharge properties.
Due to the complex nature of streamers, and the simplified conditions used in numerical modeling of streamers, we attempt to simplify the streamer morphology in our experiments. These simplified streamers can then be fully diagnosed using stroboscopic and stereoscopic imaging techniques for optimal comparability of these experiments to their simulations.

A7

Characterization of filamentary instabilities in a magnetized RF discharge

Tim Donders[1], Hendrik Jung[2], and Franko Greiner[2]
[1] *Applied Physics, Eindhoven University of Technology, The Netherlands*
[2] *Institut für Experimentelle und Angewandte Physik, Kiel University, Germany*

Magnetized plasmas in a planar radio frequency capacitively coupled discharge system show filaments, tube-like regions of hotter and/or denser plasma along the magnetic field lines. The diameter of the filaments depends strongly on the absolute value of the magnetic induction. We investigate the interplay between filaments and a nanodust cloud for different magnetic inductions. This provides information on the dust confinement in a magnetized plasma and the nanoparticles can be used as tracers for the visualization and analysis of the filamentary instabilities. Given that the filaments preferably occur at facing electrode surface, switching towards a hollow electrode design helps to prevent the formation of filaments. In this configuration, stable nanodusty clouds can be grown in a magnetic field with a strength of up to 4 T.

A8

Vibrational excitement: from CO_2 to CO

A. Erdogan[1], Q. Ong[1], D.C.M. van den Bekerom[1], G. Berden[2], M.C.M. van de Sanden[1,3], G.J. van Rooij[1,3]
[1] *DIFFER - Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, the Netherlands*
[2] *Radboud University, Toernooiveld 7c, 6525 ED Nijmegen, the Netherlands*
[3] *Technical University of Eindhoven, Flux, De Zaale, 5612 AJ Eindhoven, the Netherlands*

CO_2 plasmas are a promising approach towards mitigating intermittency issues of sustainable energy sources by efficient conversion and storage of electrical energy into chemicals. In this approach, CO_2 is decomposed to CO, which can be used to produce hydrocarbons. In the former USSR, over 90% energy efficiency was achieved in the net reaction $CO_2 \rightarrow CO + O_2$. The prevailing but yet unverified model explaining the high energy efficiency is based on vibrational ladder climbing: vibrational energy is transferred via collisions until the dissociation potential is reached.
Here, we report on a reference experiment to study this mechanism. The rationale is that plasmas are complex due to various species such as radicals, ions, electrons, etc. To reduce complexity, a MIR laser is used to vibrationally excite CO_2. This approach allows us to focus on vibrationally excited species as no other species are present in the reactor. The first experimental signatures of the vibrational ladder climbing mechanism has been found. Experimental conditions are varied in order to have a better understanding of the vibrational ladder climbing mechanism.

A9

A dense plasma picture of laser created plasmas for short wavelength radiation.

D.C. Schram[1],
[1]*Department of Applied Physics, Eindhoven University of Technology, Eindhoven, 5600MB, The Netherlands*

If a solid (or fuel) is exposed to a high energy, then several processes occur together and in sequence. At the start the energy density adsorbed is very high, the dimensions limited and the initial temperature is high, as long as electron neutral collisions dominates. There is fast ionization in very short time and a plasma is created with rising electron density, The resistivity is high and depending on the available power the plasma is higher and higher ionized. The coupling between electrons and ions causes the ion temperature to rise, leading to higher pressure and the plasma starts to expand. The expansion velocity is sonic and higher than the drift velocity of the plasma away from the laser. The result is a dense plasma, with a decreasing density but higher temperature. Still at the expected densities the importance of free bound radiation grows, whereas line radiation decreases because of growing importance of loss of excitation by ionization.
The present experiments have a procedure to have two pulses, the initial and one delayed. This procedure leads to a decreasing electron density, which is a loss, as all radiation depends on the product of electron and ion densities. But there may be a reason for this: at high electron density the line form of recombination radiation becomes too wide to be acceptable. This is caused by non-Debye character effects at high electron densities. Then a smaller electron density is needed and thus a second pulse approach; there is still enough density to give sufficient radiation. Here helps the way the plasma expands and the lower electron temperature after the expansion. It is another explanation of the processes, but if true, it can help to improve the radiation.

A10

The role of flow and quenching on efficiency of CO_2 microwave plasma

Juehan Gao[1], F.J.J. Peeters[1], T.W.H. Righart[1], A. J. Wolf[1], H.J.M. Bouwmeester[2],
M.C.M. van de Sanden[1] and W.A. Bongers[1]

In our sustainable society a storage technology is needed aiming to convert surplus electricity from renewable energy sources like wind and solar power into fuels compatible with the current energy infrastructure. Electrically driven high-temperature electrolysis, using solid oxide cells, and plasmolysis are considered as most promising. In the project, a hybrid technology is investigated by integrating plasmolysis, electrolysis and membrane separation. The targeted hybrid approach for dissociation of CO_2 combines the strengths of plasmolysis and electrolysis, and relieves main disadvantages of both methods. Their integration serves to selectively pump away oxygen from the plasma gas mixture, preventing in this way backward reactions of CO and O_2 towards CO_2, while shifting the equilibrium towards CO, and/or to enhance CO_2 dissociation by additional electrolysis. At the plasma dissociation of CO_2 itself, the gas temperature is very important parameter for gaining an optimal energy efficiency. In the present work, a novel technology is explored by combining an axial injection into forward vortex plasma. The effect of the axial flow coupled together with tangential flow to the energy efficiency of plasma is not well known until now. The result reveals the plasma gas temperature remains mostly unaffected by the axial injection coupled to forward vortex plasma, but the energy efficiency of CO_2 dissociation was significantly enhanced using the hybrid flow approach. Therefore, it is concluded that the axial injection increase the quenching to reduce unwanted back-reactions of CO and O_2 towards CO_2.

A11

Discretization scheme for systems of conservation laws of advection-diffusion-reaction type

R.A.M. van Gestel[1], J.van Dijk[1], and J.H.M. ten Thije Boonkkamp[2]
[1] *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, 5612AZ, The Netherlands*
[2] *Department of Mathematics and Computer Science, Eindhoven University of Technology, Eindhoven, 5612AZ, The Netherlands*

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 advection-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 [1]. The numerical flux vector is a superposition of a homogeneous flux, corresponding to the homogeneous ODE-system, and an inhomogeneous flux, taking into account the effect of the non-linear source.
The novel scheme is applied to a multicomponent system. The numerical results show that the scheme exhibits uniform second order convergence in all Peclet and Damköhler matrices, while maintaining mass conservation without discretization error.
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A12

Modelling vortex flow in a microwave CO_2 plasma reactor

P.W.C. Groen, F.J.J. Peeters , M.C.M. van de Sanden,
and W.A. Bongers
DIFFER, Eindhoven, 5612 AJ, The Netherlands

Microwave plasmas are expected to be beneficial in energy efficiency over other types of plasma, when regarding CO_2 molecule dissociation. At DIFFER a microwave plasma reactor setup, called InitSF, is used to investigate CO_2 dissociation. An important element is the stabilisation of the plasma flow through a quartz tube, and the cooling of the tube walls. Both are realised by using a vortex gas flow through the tube. It is thought that the downside to this technique is a resulting increased residence time of the molecules, which causes an increased probability of unwanted back reactions. By modelling the flow, using the CFD software ANSYS FLUENT, it is hoped to gain insight in the flow characteristics, and possibly come up with a means to mitigate the residence times. This is also of importance to a new to be built reactor, upscaling InitSF for higher powers and flow rates. Results of the modelling so far are presented.

A13

Chemical Reduction: A Recipe

J.G.M. Gulpen[1], S. Tadayon Mousavi[1], J. van Dijk[1], and D.B. Mihailova[2]
[1]*Applied Physics (Group EPG), Eindhoven University of Technology, Eindhoven, 5612AZ, The Netherlands*
[2]*Plasma Matters B.V., Eindhoven, 5612AJ, The Netherlands*

Numerical simulations are a great tool to study plasma physics. However, the nature of a plasma leads to the presence of large numbers particles or molecules in different states. For a single element, this might still be computable, but when a molecular gas or mixture of elements is present the computation time 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 reactions considered. This is done in a way such that the simulated physics is still correct and relevant for the application.

PLASIMO's[1] implementation of a Pathway Analysis algorithm[2] is used to analyze reaction chains and their combined rates. By doing so, the most important pathways for chemical conversion in chemically complex models can be identified. Based on this analysis a chemical reduction of said model can be performed, strongly reducing the complexity of the model whilst maintaining accuracy.

Other chemical reduction methods have been suggested and implemented before. The usage of an Intrinsic Low-Dimensional Manifold (ILDM) and Principal Component Analysis (PCA)[3] decrease the dimension of the solution space. However, like the Pathway Analysis reduction, these methods are not universally applicable and bounded by limitations. The outlook of this work is to develop a recipe which attempts to combine the known tools in a novel way to reduce certain complex chemistries based on known input parameters.

Results will be shown for chemical reduction based on the Pathway Analysis algorithm. This method has been applied to helium-water and molecular hydrogen chemistries. The reduced chemistries are compared to the full complex models and are also compared to a more 'naive' reduction method.

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A14

Investigating plasma charging of nanoparticles with Microwave Cavity Resonance Spectroscopy

Mohammad Hasani, Zahra Marvi, Job Beckers

Applied Physics, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands

Heretofore, microparticles have been employed as *in situ* diagnostic tools to acquire data from plasma with various techniques e.g. Microwave Cavity Resonance Spectroscopy (MCRS). Utilizing various properties of dust microparticles, plasma diagnosis has been carried out. Ushering in the uncharted territories, it has been proposed that by injecting nanoparticles, we will be able to investigate charging processes hitherto unknown. Due to stochastic nature of plasma charging of nanoparticles, there are scarce analytical and numerical literature elaborating on parameters involved in these processes. Employed in multimode, MCRS is capable of delivering spatially and temporally resolved information about electrons detached from nanoparticles. Therefore, one way to investigate plasma charging of nanoparticles is that by introducing nanoparticles and applying laser-induced photodetachmen to detect released electrons using MCRS technique.

This contribution discusses plans for investigating plasma charging processes and fluctuation dynamics of nanoparticles being hitherto unknown in minimized scales of a few nanometers by utilizing MCRS and laser-induced photodetachment of dust nanoparticles.

A15

Decharging of microparticle clusters in low pressure plasma afterglow

J.C.A. van Huijstee[1], B. van Minderhout[1], T. Peijnenburg[2], P. Blom[2] and J. Beckers[1]

[1] *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands*

[2] *VDL Enabling Technologies Group, Eindhoven, 5600 JW, The Netherlands*

Contamination by nano- and microparticles forms a serious issue in vacuum applications. When these particles interact with a plasma, they will attain a negative charge. This property allows us to prevent particles from reaching sensitive surfaces by applying an external electric field, thus creating a plasma seal. Previously most research has focused on charging processes concerning spherical particles.
In this work we investigate the charging of both single spherical microparticles and clusters of these particles, in a low pressure ICP (Inductively Coupled Plasma). Our setup consists of a vertical glass tube, where particles fall through an ICP and decharge in the afterglow before their charge is measured. A grounded grid is implemented to ensure that there is no significant electron density at the place of measurement for any realizable combination of pressure and plasma power. Using a high speed camera, the trajectories of particles between two parallel electrodes are recorded, from which their charge can be inferred. It is possible to distinguish clusters from singlets by their vertical settling velocity. Combining both, we aim to explore the charging of clusters to provide a better understanding of charging processes involving nonspherical microparticles. First results are presented.
[1]

[1] The poster "Local charge measurements of microparticles in a remote plasma afterglow" is associated to this work

A16

Imaging of a dielectric barrier discharge used for calibrating the Stark effect in argon

S. Kempers[1], M. Hofmans[1], and A. Sobota[1]
[1] *Department of Physics, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands*

The Stark shifts of the spectral lines of a plasma can be used to determine the local electric field. This can be done for helium, but is difficult for argon, as a complete quantum mechanical description of the effect has not been developed yet. Other methods for determining the electric field will be used to calibrate the Stark method, namely deducing the electric field from the voltage characteristics, as well as applying the line ratio method on the emission spectrum of the argon plasma. These methods will be applied on a parallel plate dielectric barrier discharge. Imaging of the plasma is done via an ICCD camera with nanosecond integration time and is used to determine the mode of operation, either diffuse or filamentary. Because the calibration methods rely on a diffuse plasma, only this mode can be used for electrical and spectroscopic measurements.

A17

Charged aerosol clouds for lightning protection.

Pavlo Kochkin[1]
[1] *Birkeland Centre for Space Science, University of Bergen, Bergen, 5007, Norway*

Cold plasma has now been increasingly used for many theoretical and practical applications. Its ability to trigger complex chemical reactions is investigated in rapidly emerging fields of plasma medicine, plasma agriculture, energy storage and CO2 splitting. In this work we want to demonstrate yet another way of using cold plasma for generating charged water aerosols.
The charged aerosol clouds are in particularly interesting for simulating real-life scenario in lightning protection. Lightning imposes significant threat to aircraft and wind turbines. Electrical stress to both of them are always unwanted and can lead to significant economical and physical damage. Due to increased air transportation and wind energy generation studying how lighting interacts with floating and grounded objects can allow for better protection/mitigation strategies.
We developed an experimental setup that is able to generate charged water clouds of several cubic meters. The core element of the setup is a plasma-nozzle where glowing discharge is mixed with high-pressure steam. The electric field in the vicinity of the cloud can reach air-breakdown values and trigger spark discharges to/from the cloud. The setup will be used for detailed study of how lighting interacts with aircraft and wind turbines.

A18

Investigation of electrical breakdown in high pressure (0.1 to 1 MPa) CO_2 under pulsed fields

Siddharth Kumar[1], Tom Huiskamp[1], A.J.M. Pemen[1]
[1] *Electrical Energy Systems, TU Eindhoven, Eindhoven, 5612 AJ, Netherlands*

Sulphur hexafluoride (SF_6) is an insulating gas which is used in high-voltage circuit breakers due to its unique insulating properties. However, it is an extremely potent greenhouse gas with a global warming potential (GWP) of 23900! Also, it produces toxic by-products during electrical arcing. Hence, environment friendly and easier to handle alternative insulating gases are being investigated.

Carbon dioxide (CO_2) is a promising alternative insulating gas and is the focus of this research. The electrical breakdown strength of CO_2 under pulsed electric field is investigated. The voltage pulses are generated using a 500 kV Marx generator and have a rise time of 700 ns. A rod-plane electrode geometry is used for the experiments to study the electrical breakdown phenomena under non-homogeneous electric fields. The rod has a hemispherical tip with a diameter of 20 mm and the gap distance between the electrodes is 30 mm.

The electrical breakdown strength of CO_2 is measured experimentally from 0.1 to 1 MPa under both positive and negative polarities. The results show that breakdown strength of CO_2 is greater under positive polarity and shows higher scatter in the breakdown voltage when compared to negative polarity. The polarity effect is inverse to that of air and currently, experiments are under way to understand this phenomena by using additional diagnostics such as high-speed imaging and measurement of the pre-discharge currents.

A19

Plasma impact on discharges

Vladimir Kvon[1], Andrei M. Yakunin[1], Ferdi van de Wetering[1], Selwyn Cats[1],Andrey Nikipelov[1],Dmitry Astakhov[2,3], Slava Medvedev[2,3], Vladimir Ivanov[2], Pavel Krainov[2], and Mark van de Kerkhof[1]
[1]*ASML B.V., De Run 6501, 5504 DR Veldhoven, the Netherlands*
[2]*Institute for Spectroscopy RAS, Fizicheskaya street 5, 108840 Troitsk, Moscow, Russia*
[3]*ISTEQ B.V., High Tech Campus 9, 5656 AE Eindhoven, the Netherlands*

Particle release and material damage are critical issues for the extreme-ultra-violet (EUV) lithography machines. Some parts of an EUV scanner are exposed to high voltages in the presence of low pressure hydrogen. The present design of the scanner is safe to avoid Paschen breakdown. However, EUV creates a hydrogen plasma near surfaces close to critical elements of the scanner. Presence of the plasma can substantially modify conditions of the breakdown. Conditions of a plasma stimulated breakdown may have significant deviations from the classical Paschen. Therefore, new guidelines are required for future designs of the scanner. In this work, we investigate a plasma stimulated breakdown by performing off-line experiments and modelling of the hydrogen plasma-triggered discharge.

A20

Equipotential surfaces in the plasma sheath enlightened by a single plasma-levitated micro-particle

A.J.T. Lamberts [1], P. Meijaard[1], G.M.W. Kroesen[1], and J. Beckers[1]
[1] *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, 5600 MB, the Netherlands*

In a low pressure radiofrequency plasma the equipotential surface in the plasma sheath surrounding complex geometries is determined using negatively charged plasma-levitated micro-particles under hyper gravity conditions.
Micro-particles are used as probes in the plasma sheath to reveal elementary processes on a fundamental level. These particles levitate due to a force balance between several (plasma-induced) forces on the particle and the gravitational force. The latter is enlarged with a centrifuge to achieve probing with the same micro-particle at different locations throughout the plasma sheath without disturbing the surrounding plasma. In the current experiments, a single micro-particle is confined by a sharply edged indent in the bottom electrode surface. By actively changing the angle and magnitude of the gravitational vector, the positions of the particle will provide insight in the shape of the equipotential surface at different heights above the bottom electrode. In this contribution we present preliminary results of the equipotential surface at different heights in the plasma sheath.

B1

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

Anne Limburg [1], Marc van der Schans[1], and Sander Nijdam[1]
[1] *Applied Physics, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands*

Plasma bullets are guided ionization wave discharges generated by non-thermal pulsed plasma jets flowing into atmospheric pressure air. They propagate along the axis of the jet and are highly reproducible and periodic, which makes it possible to perform phase resolved measurements. Information on the electric field of these bullets is essential extend the theory on streamers and in order to develop applications and. However, direct electric field measurements on these transient discharges are often invasive or limited by the photon emission and assumptions.
In this work, a non-invasive method for measuring electric field distributions at atmospheric pressure with electric field induced second-harmonic generation (EFISHG) is presented. A nanosecond pulsed Nd:YAG laser emitting at 1064 nm is used as a source. The laser beam non-linearly interacts with the background gas and the electric field, which results in frequency doubled light of which the intensity scales quadratically with the electric-field. Electric field measurements on a two parallel plate electrode configuration, used to test the method and calibrate the set-up, are presented. Furthermore, the results of the same method applied on plasma bullets in nitrogen, propagating approximately 140 ns over a distance of several millimeters, are shown. In this way, information about the spatial and the temporal development of the electric field strength and polarization is obtained. This method is not bound to the dimensions of the discharge.
In ongoing research, the resolution of these measurements, the influence of the laser on the plasma bullet and the quality of the calibration will be determined. Furthermore, a pico- and femtosecond laser will be used to perform the similar measurements and obtain a higher temporal resolution.

B2

Characterization of positive streamer discharges in pre-ionized channels

A. Martinez[1], J. Teunissen[1,2], and Ute Ebert[1,3]
[1] Centrum Wiskunde & Informatica, Amsterdam, 1090 GB, The Netherlands, [2] Department of Mathematics, Centre for mathematical Plasma Astrophysics, KU Leuven, Leuven, B-3001, Belgium, [3] Department of Applied Physics, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands

The goal of this study is to explore a big parameter space for streamer discharges which can be used by experimentalists to validate the simulation models and make predictions about their own discharge experiments.
Due to advancements in streamer simulation codes which produce results in considerably less time than before (minutes instead of hours/days) using the afivo framework, we are now in a position to explore a vast parameter space to try and characterize how the streamer properties are dependent on variables like background electric field, background ionization, length of the streamer, etc.
In general streamer simulations include a homogeneous background ionization but in this study we are interested in the influence of a pre-ionized channel on the streamer properties. By changing the width of this pre-ionized channel we add an extra variable to the big parameter space which we are exploring.

B3

Laser induced fluorescence in a nanosecond pulsed discharge for CO_2 dissociation

L.M. Martini[1,2], M. Ceppelli[2], M. Scotoni[2], G. Dilecce[3,2] and P. Tosi[2]
[1]*Departement of Applied Physics, Eindhoven University of Technology, Eindhoven, 5612 AP, The Netherlands*
[2]*Departement of Physics, University of Trento, Trento, I-38123, Italy*
[3]*P.Las.Mi Lab NANOTEC, CNR, Bari, I-70126, Italy*

Laser Induced Fluorescence (LIF), intended as a way to measure the concentration of transient species, involves, as the observable, the fluorescence from an electronically excited state M^* prepared by absorption of resonant laser light. Collision energy transfers (CET) processes involving M^* and the background molecules have a heavy influence on the fluorescence outcome. This is generally considered as a shortcoming since quantitative use of LIF for the characterization of the transient species M requires a detailed knowledge of the collision frequencies. Reversing the point of view, this knowledge allows to use the laser prepared electronic state M^* as a transient quantum sensor for the medium composition, that can be used in hostile environments characterized by rapid changes (sub-μs scale) of temperature, pressure and gas composition. In this contribution we present the general aspects of LIF in a collisional environment, introduce the concept of CET-LIF, and describe its application to the measurement of the CO_2 dissociation in a nanosecond repetitively pulsed (NRP) spark discharge, using OH(A) as a molecular sensor.

B4

Quantum dot photoluminescence; a versatile diagnostic for plasma charging

Zahra Marvi , Tim Donders , Job Beckers
Applied Physics, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands

Nanoparticle charging in a plasma is an important, yet largely unexplored territory. This is about to be changed due to quantum dots (QDs). These tiny particles have great potential for the use as fluorescent probes due to their charge-dependent photoluminescence (PL). The goal of this research to take advantage of the charge-induced spectral shift of the emitted PL spectrum to improve knowledge about the plasma charging process. The proposed experiments combine three fascinating processes: The fully controlled injection and evaporation of water-dissolved QDs inside a low pressure RF plasma, the ability of a plasma discharge to charge and confine nanoparticles, and the monitoring the surface charge-induced shift in the PL spectrum of the confined QDs in the plasma. To this aim, an stabilized 405 nm CW diode laser is used to excite the confined QD's. Their photoluminescence emission spectrum is dispersed by a monochromator, and recorded by using an ICCD camera. With our first results we have shown that each of these individual steps is possible. In the future, we will combine them for in-situ spatiotemporally resolved monitoring of the nanoparticle charge distribution during plasma charging.

B5

Probing the plasma sheath with micro waves

Meijaard P., Platier B. and Beckers J.
Department of Applied Physics, Eindhoven University of Technology, 5600 MB, The Netherlands

13th February 2019

The plasma sheath of radio frequency discharges is far from understood. Even today, the exact spatial space charge distribution and - connected to that - fundamental processes such as Debye shielding and solid particle charging within the plasma sheath of radiofrequency discharges lack understanding. Nonetheless these plasmas are applied abundantly in industry because the plasma-induced electric fields enable crucial plasma material processing mechanisms. The reason for the lack of understanding regarding fundamental processes in the plasma sheath is the fact that local values of the electron density in this region are extremely difficult to measure. Multi mode Microwave Cavity Resonance Spectroscopy (mm-MCRS) is a non-invasive technique that has recently been applied to spatially resolve the electron density in expanding EUV photon-induced plasma. In this contribution we apply mm-MCRS to resolve the electron density distribution throughout the RF plasma sheath. Preliminary results are presented.

B6

Investigating shock-wave-induced dynamics in Tin microdroplets

Randy Meijer[1], Tiago de Faria Pinto[1], Dmitry Kurilovich[1], Ruben Schupp[1], Hao Zhang[1], Oscar Versolato[1], Kjeld Eikema[12], Stefan Witte[12]
[1]*ARCNL, Amsterdam, 1098XA, The Netherlands*
[2]*LaserLaB, Faculty of Sciences, Vrije universiteit, Amsterdam, 1081 HV, The Netherlands*

The interaction of intense laser pulses with micron-sized metallic droplets is a subject of specific importance for the development of laser-based extreme ultraviolet light sources. When a sufficiently intense laser pulse is incident on such a metallic micro-droplet, rapid absorption of the laser pulse energy can produce a high-frequency shock wave at the surface of the droplet. This shock wave propagates through the droplet, and may be sufficiently intense to induce cavitation near the center, as well as spallation of a thin layer upon reflection from the opposing surface. Together these effects lead to a spectacular deformation of the droplet. Plasma generated by laser impact can play a role in this deformation as well; affecting the deformation initiated by the shockwave. We investigate this deformation over a large range of laser intensities, pulse durations, and droplet sizes.

B7

Local charge measurements of microparticles in a remote plasma afterglow

B. van Minderhout[1], T. Peijnenburg[2], P. Blom[2], G.M.W. Kroesen[1] and J. Beckers[1]
[1] *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands*
[2] *VDL Enabling Technologies Group, Eindhoven, 5651 GG, The Netherlands*

Nano- to micrometer sized particle contamination becomes an increasingly significant problem for many industries (high precision production, lithography, electron microscopy, etc.). An effective solution for this problem are low pressure plasmas, because they are known to give particles a uniform negative charge if they are larger than about 10 nm. With this charge, the particles' path can be controlled by electric fields. For this reason we study the charging of micro-particles in spatial plasma afterglow.
In the previous edition of this conference, we reported charge measurement together with a novel model describing the particle charge. We discussed that the difference between measured and modeled particle charge could be due to collisional effects and plasma shielding. In addition to this discussion, we can now conclude that the remote plasma afterglow does not shield the particles' charge. We have strong indications that the transition from ambipolar to free diffusion of ions and electrons determines the final particles' charge.
[2]

[2] The poster "Decharging of microparticle clusters in low pressure plasma afterglow" presents first clusters charge measurements

B8

The development of a plasma-based lice comb

L.C. van Mouche[1], A. Sobota[1]
[1]*Applied Physics, University of Technology, Eindhoven, 5600MB, The Netherlands*

Over the last decade, in the field of plasma medicine cold atmospheric pressure plasmas (CAP) have been tested for their anti-bacterial properties. Their ability to operate in the atmosphere without the use of a vacuum pump, combined with their macroscopically cold temperature makes these plasmas suitable to treat vulnerable and heat sensitive surface, like human skin.

In this project, CAP are investigated for their ability to kill lice and their nits. In an iterative process parameters such as the temperature, amount of reactive species and UV emission are optimised to increase the mortality rate of the lice, while remaining well within safety regulations. The plasma lice comb should offer an effective and side-effect free alternative of killing lice, properties that are lacking in current methods. The final product needs to be an convenient, reliable and inherently safe product for the host that terminates all lice and nits.

B9

Activating Combustion Kinetics at Low Temperature Using Non-Equilibrium Plasma

Ravi B. Patel[1], Charlie Oommen[2] and M. Joy Thomas[3]

[1]*Dept. of Applied Physics, Eindhoven University of Technology, Netherlands,* [2]*Dept. of Aerospace Engg., Indian Institute of Science, Bangalore, India,* [3]*Dept. of Electrical Engg., Indian Institute of Science, Bangalore, India*

Plasma-assisted combustion (PAC) is emerging as a promising field as it can improve combustion properties such as ignition, lean combustion, flame stabilization and emission control in regimes where it is normally difficult to achieve the desired level of performance. Plasma can enhance the combustion main through two pathways: Thermal pathway and Non-thermal (kinetics) pathway. Thermal pathway is governed by overall gas temperature which is due to the plasma heating effects whereas kinetic pathway depends on electron temperature. In the kinetic pathway, plasma produces active species and radicals (O, O(1D), O(1S), O_3, H etc.) which have a huge role in activating and accelerating combustion kinetics. These active species and radicals are produced via electron impact excitation, vibrational, dissociation and ionization reactions, the rate of which depends on the reduced electric field (E/N) or electron temperature (T_e). Recently, non-equilibrium plasmas specially nanosecond pulse discharge plasmas have been demonstrated to maximize kinetic combustion enhancement due to its effective energy loading into dissociative and ionization reactions. Radicals can be produced at such rates that large volume ignition can be achieved in hydrocarbon-air flows at low plasma temperatures (< 500 K). This poster presents a study on the effect of reduced electric field (E/N) on premixed methane-air mixture combustion at low temperature (< 500 K). A coaxial reactor designed and built for the experiments has the flexibility to be configured for various discharge gaps (D.G.) and pressure conditions such that the discharge can be operated at various E/N. Volumetric DBD plasma was established using 30 kV nanosecond pulses with repetition rate up to 3.5

kHz. A gas chromatographic technique was employed for product species characterization and methane conversion due to low temperature oxidation relation with various discharge gap and pressure conditions were obtained. Optical emission spectroscopy was used to estimate reduced electric field (E/N) for various discharge gap operating conditions. Results from gas chromatography and emission spectroscopy were combined to establish relation between low temperature oxidation and reduced electric field.

B10

Multispectral Advanced Narrowband Tokamak Imaging System (MANTIS)

A. Perek,[a] W.A.J Vijvers,[a] Y. Andrebe,[b] M. de Baar,[a] I.G.J. Classen,[a] B.P Duval,[b] C. Galperti,[b] B. L. Linehan,[c] T. Ravensbergen,[a] and K. Verhaegh[d]

[a]DIFFER – Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, the Netherlands, [b]Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland, [c]Plasma Science and Fusion Center, Massachusetts Institute ofTechnology, 77 Massachusetts Avenue, NW17 Cambridge, MA 02139, U.S.A, [d]York Plasma Institute, University ofYork, Heslington, York YO10 5DQ, U.K

This work presents a novel, real-time capable, 10-channel Multispectral Advanced Narrowband Tokamak Imaging System (MANTIS). The system was build on a proven optical design [1] with real-time capabilities [2]. The hardware and software requirements are presented together with the complete system architecture. Tailored real-time algorithms exploiting the system capabilities are presented together with benchmarks comparing polling and event based synchronisation. The real-time performance is demonstrated with a density ramp discharge performed on TCV and differences between different plasma species behaviours are qualitatively described. The image quality of the system is assessed with emphasis on effects resulting from the narrowband interference filters. Some filters are found to create an internal reflection images that are correlated with the filters' reflection coefficient. This was measured for selected filters where significant absorption (up to 65% within $\sim 70\,\mathrm{nm}$ of the filter center) was measured. The majority of this was attributed to the filter's design and several filters' performance is compared.

[1] B.L. Linehan et al. Rev Sci Instrum 89, 103503, 2018
[2]W.A.J. Vijvers et al. JINST 12, C12058, 2017

B11

Enhanced recombination of a hydrogen plasma induced by nitrogen seeding in linear plasma device Magnum-PSI.

R. Perillo*[1], G.R.A. Akkermans[1], I.G.J. Classen[1], W. A. J. Vijvers[1], R. Chandra[1], K. Jesko[1,2] J.W.M. Vernimmen[1], M.R. de Baar[1] and the MAGNUM-PSI team[1]

[1] *DIFFER – Dutch Institute for Fundamental Energy Research, Eindhoven, the Netherlands*, [2] *CEA, IRFM, France*

In this work we investigate the effects induced by the presence of nitrogen in a detached-like hydrogen plasmas in linear plasma machine Magnum-PSI. Detachment has been achieved by increasing the background neutral pressure in the target chamber by means of H_2/N_2 puffing and two cases of study have been set up, i.e. at 2 and 4 Pa. A scan among five different N_2/H_2+N_2 flux ratios seeded have been carried out, at values of 0, 5, 10, 15 and 20 %. A n_e decrease while increasing the fraction of N2 has been observed for both background pressures, resulting in a plasma pressure drop of $\sim 30\,\%$. Te remains constant among all scans. The peak intensity of $NH^*(A^3\Pi -> X^3\Sigma^-, \Delta v = 0)$ at 336 nm measured with optical emission spectroscopy increases linearly with the N_2 content, together with the NH_3 signal in the RGA. A further dedicated experiment has been carried out by puffing separately H_2/N_2 and H_2/He mixtures, being helium a poorly-reactive atomic species, hence excluding a priori any nitrogen-induced molecular assisted recombination. Interestingly, plasma pressure and heat loads to the surface are enhanced when increasing the content of He in the injected gas mixture. In the case of N_2, we observe an opposite behaviour, indicating that N-H species actively contribute to convert ions to neutrals. Recombination is enhanced by the presence of nitrogen. Numerical simulations with two different codes address the role of NH_x species behaving as electron donor in the ion conversion with H^+ by means of N-MAR i.e. $NH + H^+ \rightarrow NH^+ + H$, followed by $NH^+ + e^- \rightarrow N + H$. Considering the experimental findings and the qualitative results obtained by modelling, N-MAR process is considered to be a possible plasma-chemical mechanism responsible for the observed plasma pressure drop and heat flux reduction.

B12

Influence of targets on the behavior of an atmospheric He plasma jet

O. van Rooij[1], M. Hofmans[1], and A. Sobota[1]
[1] *Departement of Applied Physics, Eindhoven University of Technology, Eindhoven, 5600MB, The Netherlands*

The helium plasma jet generates a non-thermal plasma at atmospheric pressure and consists of guided ionization waves (plasma bullets) that are generated by applying short high voltage pulses of 4-6kV with a frequency of 5kHz and a pulse length of 1μs to the high voltage electrode of the jet. The behavior of the plasma bullets is observed by imaging the position as function of time by using an ICCD camera. From the obtained spatial information, velocities of the plasma bullets are determined. The behavior of the plasma bullets is influenced by the target on which the jet operates and whether the target is grounded or not. Conducting targets show a return stroke on impact of the plasma bullet. Measuring the bias on non-grounded conducting targets demonstrate charging of the materials.

B13

Spectroscopic studies on laser-produced tin plasma

R. Schupp[1], F. Toretti[1], J. Scheers[1], Z. Bouza[1], D. Kurilovich[1], W. Ubachs[1,2], R. Hoekstra[1,3], and O. O. Versolato[1]
[1] *Advanced Research Center for Nanolithography (ARCNL), Science Park 110, 1098 XG Amsterdam, The Netherlands*
[2] *Department of Physics and Astronomy and LaserLab, Vrije Universiteit Amsterdam, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*
[3] *Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands*

Laser-produced plasmas (LPP) from liquid tin micro-droplets are employed as sources of extreme ultraviolet (EUV) light in nanolithography. Serendipitous alignment of electronic transitions in multiply charged tin ions enables the efficient conversion of drive laser energy into radiation within the technologically relevant 2% bandwidth around 13.5 nm wavelength. To predictively model the EUV emission a detailed understanding of the atomic structure of tin ions is required. We will present recent calculation results from the Los Alamos suite of atomic codes and compare them to experiment. To benchmark specific atomic transitions Electron-beam-ion-trap measurements are used which enable charge-state-resolved spectroscopy of highly charged ions. Further, we experimentally explore how to maximize the potential of Nd:YAG laser driven LPP systems and how to mitigate possible detrimental effects of opacity.

B14

Investigation of the effect of Argon addition to CO_2 plasmas in dissociation and vibrational excitation

A. Silva[1,2,3], A. S. Morillo-Candas[2], A. van de Steeg[1], O. Guaitella[2], V. Guerra[3], G. van Rooij[1]

[1]*DIFFER - Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, the Netherlands*

[2]*LPP - Laboratory of Plasma Physics, École Polytechnique, Sorbonne Université, CNRS, Palaiseau, France*

[3]*IPFN - Institute for Plasmas and Nuclear Fusion, Instituto Superior Técnico, Universidade de Lisboa, Portugal*

The use of non-thermal plasma to efficiently activate CO_2 splitting has been recently under investigation. The most energetically efficient way to split CO_2 is to vibrationally excite the molecule until its dissociation point. In this work both diagnostics and modelling tools are used to understand how Argon addition affects conversion and vibrational excitation of CO_2 in continuous glow and pulsed microwave discharges. It is found that, in the glow discharge, adding Argon increases dissociation and does not modify significantly the vibrational populations of CO_2. However, in the MW discharge case, higher vibrational temperatures are measured for increasing Argon fractions. The modelling results, validated with the experimental data, point to the conclusion that Argon significantly affects the electron kinetics, increasing electron temperature and decreasing the reduced electric field needed to sustain the discharge.

B15

Obtaining the electron density in a rf-driven plasma jet at atmospheric pressure using microwave cavity resonance spectroscopy

T.J.A. Staps[1], B. Platier[1], and J. Beckers[1]
[1]*Department of Applied Physics, University of Technology Eindhoven, Eindhoven, 5612 AZ, The Netherlands*

Atmospheric pressure plasma jets are used for many applications such as surface treatment, deposition of coatings and biomedical applications. Since the plasma temperature remains close to the ambient, the treatment of delicate surfaces with thermal limits becomes possible at atmospheric pressure. Since the electron density plays a key role in the physics and chemistry of the discharge, there have been several endeavors to measure the electron density using diagnostic techniques such as Stark broadening and Thomson scattering.
In this contribution, we use microwave cavity resonance spectroscopy (MCRS) as a relatively simple, low-cost and non-invasive diagnostic method for measuring the electron density at atmospheric pressure. Microwave cavity resonance spectroscopy has been used for low pressure plasmas, but the extension of the technique towards atmospheric pressure discharges requires a more intricate analysis due to electron-neutral collisions. We reveal first measurements of the shift in resonance frequency due to the presence of a radio-frequency plasma jet in a resonance cavity. Moreover, the results are accompanied by an analysis with respect to electron density and effective collision frequency.

B16

Self-consistent Fokker-Planck approach to CO_2 vibrational kinetics

P. Viegas[1], M. C. M. van de Sanden[1], S. Longo[2], and P. Diomede[1]
[1] *Center for Computational Energy Research, DIFFER - Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, the Netherlands*
[2] *Dipartimento di Chimica, Università degli Studi di Bari, via Orabona 4, 70126 Bari, Italy*

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. To further understand the underlying mechanisms of CO_2 dissociation in low-temperature plasmas, including the role of vibrational kinetics, numerical modelling is essential. Most of the present literature on the subject is based on the State-to-State approach (STS) which is convenient but time consuming and jeopardizes the computational efficiency of multidimensional models. The authors have developed a new approach which is based on reconsidering the powerful and mathematically appealing drift-diffusion approach to vibrational kinetics developed mostly in the 70s. In this approach, the vibrational distribution function of the asymmetric stretching mode of CO_2 is assumed to be the solution of a Fokker-Planck (FP) equation. The new method developed by the authors is based on numerical and semi-analytical solutions and allows us to remove some approximations limiting the original approach. In this work, the FP approach is self-consistently coupled to a global model describing a CO_2 plasma. Results obtained with the FP model are validated through comparison with STS results and the FP approach is shown to be much more computationally efficient.

B17

Dissociation of a CO2 gas and chemical equilibrium at high temperature.[0.4cm]

R.H.J. Westermann [1], B. Wolf[1], E. Westerhof[1], M.C.M. v.d. Sanden[1]
[2]*Fusion physics, Dutch Institute For Fundamental Energy Research ,Eindhoven, PO Box 6336 5600 HH, The Netherlands*

Recently CO2 dissociation is the topic of many studies, as a first step in the recycling of CO2 for a sustainable energy supply. In this investigation, we study the behavior of a pure CO2 gas at increasing temperature, and the chemical reactions coming up therein by a numerical simulation. We use the cantera open source software toolkit [reference 1] to study the chemical equilibrium composition of a CO2 gas at high temperature as a first step to a time dependent modelling of a plasma reactor for CO2 dissociation. Using cantera the chemical equilibrium composition is calculated on the basis of the minimization of the Gibbs free energy. The obtained equilibrium concentrations are compared to the equilibrium concentrations obtained by time integration at constant pressure and temperature to steady state of the set of reaction rates given by Butylkin et al. [reference 2]. The results of the latter method appear to be shifted with respect to the results from the Gibbs free energy minimization by approximately +100 K. We discuss the possible origin of this discrepancy and the consequences of these differences for the apparent energy efficiency of CO2 dissociation and the expected accuracy in further time dependent calculations using the Butylkin reaction set.
[reference 1] https://cantera.org/ [reference 2] PhD thesis Niek den Harder and references therein.

B18

What makes them pop? Nanoparticle release in EUV lithography scanners

Ferdi van de Wetering[1], Andrei Yakunin[1], Andrey Nikipelov[1], Christian Cloin[1], Vladimir Kvon[1], Dmitry Astakhov[2,3], Fabio Sbrizzai[1], and Mark van de Kerkhof[1]

[1]ASML Netherlands B.V., De Run 6501, 5504 DR Veldhoven, The Netherlands [2]Institute for Spectroscopy RAS, Fizicheskaya street 5, 108840 Troitsk, Moscow, Russia [3]ISTEQ B.V., High Tech Campus 9, 5656 AE Eindhoven, the Netherlands

With the introduction of the NXE:3400B scanner, ASML has brought EUV to High-Volume Manufacturing (HVM) for sub-10nm node lithography. The stringent yield requirements of HVM brings particle defectivity to the forefront as a key business driver, besides excellent imaging and pattern placement.

Particle defectivity is shorthand for any particles on wafer or reticle which can drive the Critical Dimension of the structures imaged in resist to deviate significantly from their nominal value. The maximum allowed particle size on reticle is about 50 nm, but will shrink to roughly 30 nm in the coming years, which presents a new regime for the different forces acting on these particles in a plasma environment.

These nanoparticles are affected in several ways by the EUV-induced low-pressure H_2 plasma environment in our scanners: particles will be charged and are also acted upon by several forces. The plasma and stray electric fields result in the electrostatic force, whereas streaming plasma ions result in the so-called ion drag force. The flow of hydrogen results in neutral gas drag. Release of these particles is affected in several ways, such as absorption of fast (>76 eV) electrons and development of (sheath) electric fields, plasma etching and surface changes due to hydrogen radicals (of the particle and/or substrate).

In this presentation, we will discuss the specifics of our EUV-induced H_2 plasma in more detail, how this couples to the transport of particles and their release from critical surfaces, and how we get a handle on these mechanisms through modeling and experiments.

B19

Fast spectral solution of the inelastic Boltzmann equation with applications

George J. Wilkie
Multiscale Dynamics Group, Centrum Wiskunde & Informatica, Amsterdam, 1098XG, The Netherlands

Recent advances in applied mathematics (Gamba and Rjasanow, Journal of Computational Physics 2018) make direct solution of the Boltzmann equation particularly accessible to routine simulations on local workstations. No approximations apart from numerical discretization are used in solving the full nonlinear Boltzmann collision operator. A recently-developed implementation of this algorithm, LightningBoltz, has been optimized, parallelized, and rigorously benchmarked. Features include general large-angle, inelastic, and/or self-collisions. Collision matrices are pre-computed and stored on an online database, making time advancement remarkably efficient. Also discussed are possible future applications for this tool including discharges, reentry blackout, tokamak divertors, runaway electrons, carbon sequestration, and more.

B20

Electron Kinetic Effects On Deuterium Atomic Physics in The Scape-off Layer Plasmas

Menglong Zhao[1], Alex Chankin[2], and David Coster[2]
[1]*Dutch Institute For Fundamental Energy Research, Eindhoven, 5612AJ, The Netherlands*
[2]*Max-Planck-Institute für Plasmaphysik, Garching, 85748, Germany*

Power exhaust is one of the critical issues for future tokamak designs. Kinetic effects of electron parallel transport may play an important role in the research of power exhaust. The Kinetic Code for Plasma Periphery (KIPP), which solves the Vlasov-Fokker equation for electron parallel transport, was coupled to a 1D version of SOLPS with an iterative algorithm to study the kinetic effects in a systematic way. The KIPP-SOLPS coupling algorithm allows us to incorporate kinetic electrons into the already sophisticated fluid model (B2) self-consistently. This work studies electron kinetic effects on deuterium atomic physics in the scrape-off layer plasmas. It shows that, for typical SOL plasma profiles of a medium size tokamak, non-local electron parallel transport contributes to the non-Maxwellian tails of electrons near the target which reduces the electron target temperature. However, the non-Maxwellian tail has negligible impact on the atomic physics processes of deuterium. Across a wide range of plasma conditions in the scrape-off layer, KIPP-SOLPS coupling simulation results with an inelastic collision operator implemented are not significantly different from results that use a simpler uniform cooling scheme. The uniform scheme is thus recommended rather than including computationally intensive inelastic collision physics.