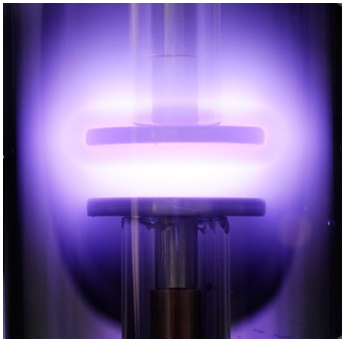
Energy resolved mass spectrometry in EUV-induced plasmas

27^{th} SYMPOSIUM

PLASMA PHYSICS & RADIATION TECHNOLOGY



Dutch Physical Society
Section Plasma and Gas Discharge Physics

Nederlandse Natuurkundige Vereniging

10 & 11 March 2015 - CongresHotel De Werelt, Lunteren

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

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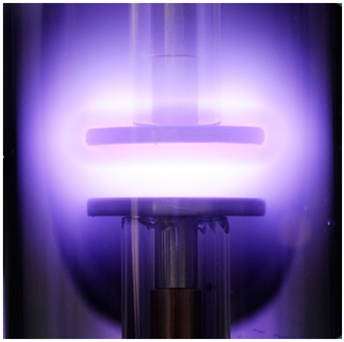

Dutch Physical Society
Section Plasma and Gas Discharge Physics

Programme & Abstracts

10 & 11 March 2015 - CongresHotel De Werelt, Lunteren

General Information

Address

The address of the CongresHotel De Werelt is:
Westhofflaan 2,
6741 KH Lunteren
tel.: 0318-484641
e-mail: info@dewerelt.nl
If you have any questions about the conference, please contact:
Anita Peeters
tel.: 040-2472550
e-mail: a.m.e.h.peeters@tue.nl

How to reach Lunteren?

The route to the conference center is signposted in Lunteren.On **http://congrescentrum.com/en/de-werelt-lunteren/route-description-de-werelt** you will find a route description to the conference center.
Lunteren has its own railway station, which can be reached from the directions Amersfoort (Utrecht) and Ede-Wageningen. You can find the train time tables on: **www.ns.nl/reisinfo**. The conference center is a 10 to 15 minute walk away from the station. Call 0318-484555 for a taxi.

Payment

The approximate cost of the attendance of the symposium amounts to €100,- (one day, NNV-member), €120,- (one day, non-NNV-member), €160,- (two days, NNV member), and €200,- (two days, non-NNV member). The fee is to be paid after the meeting on the basis of an invoice sent to you personally or to your institute/company. Payment by cash at the registration is not possible. Registration deadline is February 27, 2015. If you cancel after this date, you will still be charged the full fee. If you register after this date, accommodation cannot be guaranteed.

Summaries

The summaries of all the contributions are coded as follows:

M:	main presentations of 40 minutes by invited speakers.
O:	contributions selected for oral presentation (20 minutes).
A/B:	contributions selected for poster presentation.

Each oral presentation includes at least five minutes for discussion. There will also be an opportunity to present the orals as posters. Please bear in mind that many people in your audience will be students and colleagues from other disciplines.

Poster presentation

The size of the poster is 841 x 1189 mm (A-0). The poster session will take place on Tuesday afternoon and Wednesday morning. You are kindly requested to stay with your poster for as long as possible.

Poster prize and Oral prize

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

PROGRAMME & ABSTRACTS

Lunteren Programme Tuesday 10 March 2015

09.45 - 10.20		Registration and coffee
10.20 - 10.30		Welcome (Africa-room)
Theory and Modelling (session chair Dick Hogeweij)		
10.30 - 10.35		Introduction
10.35 - 11.15	M1	**Bernd Baumann / HAW Hamburg** Critical behaviour of the acoustic streaming field in HID lamps
11.15 - 11.35	O1	**Sjoerd Smit / Eindhoven University of Technology** Entropy generation minimization in an electron-hole plasma: a new method for optimizing solar cells
11.35 - 11.55	O2	**Anna Dubinova / CWI Amsterdam** Interaction mechanisms of streamer discharges in N_2:O_2 with dielectrics
11.55 - 12.15	O3	**Jesper Janssen / Eindhoven University of Technology** Spectral predictions in low and high pressure plasmas
12.30 - 13.45		**Lunch**
13.45 - 14.10		**Single slide show** (Africa room)
14.10 - 15.45		**Poster session 1: A1 - A22** (Asia room) Coffee and tea during session
Diagnostics (session chair Waldo Bongers)		
15.45 - 15.50		Introduction
15.50 - 16.30	M2	**Amy Shumack / FOM DIFFER** Diagnosing and understanding heavy impurity accumulation in JET
16.30 - 16.50	O4	**Marc van der Schans / Eindhoven University of Technology** Optical emission tomography: looking into plasmas with complex structures
16.50 - 17.10	O5	**Dirk van den Bekerom / FOM DIFFER** Probing vibrational ladder-excitation in CO_2 microwave plasma with a Free Electron Laser to develop a route to efficient solar fuel production
17.10 - 17.30	O6	**Ferdi van de Wetering / Eindhoven University of Technology** Fast and interrupted expansion in cyclic void growth in a dusty plasma
18.15 - 20.00		**Dinner**
Evening Lecture (session chair Job Beckers)		
20.00 - 21.00		**Jos Benschop / ASML / University of Twente** Extreme ultraviolet lithography - a case study how science supports innovation

Lunteren Programme Wednesdag 11 March 2015

08.00 - 09.00		**Breakfast**
Extreme Plasmas (session chair Edgar Vredenbregt)		
09.00 09.05		Introduction
09.05 09.45	M3	**Vadim Banine / ASML / Eindhoven University of Technology** (Plasma) physics for EUV lithography
09.45 - 10.05	O7	**Tom Huiskamp / Eindhoven University of Technology** Propagation of streamers generated with subnanosecond variable rise time, variable pulse duration, high voltage pulses
10.05 - 10.25	O8	**Oscar Versolato / ARCNL Amsterdam** Preparation of mK-temperature highly charged ions
10.25 - 10.45	O9	**Stein van Eden / FOM DIFFER** Vapor shielding of Sn in Pilot-PSI
10.45 - 11.10		**Single slide show** (Africa room)
11.10 - 12.45		**Poster session 2: B1 - B22** (Asia room) Coffee and tea during session
13.00 - 14.00		**Lunch**
Applications (session chair Richard Engeln)		
14.00 14.05		Introduction
14.05 14.45	M5	**Jeroen Koelemeij / VU Amsterdam** Probing the (un)known foundations of physics with trapped laser-cooled molecular hydrogen ions
14.45 - 15.05	O10	**Wouter Verhoeven / Eindhoven University of Technology** Ultrafast time-resolved electron microscopy
15.05 - 15.25	O11	**Floran Peeters / Eindhoven University of Technology** Dielectric barrier discharges: multi-filament dynamics and mobile charge
15.25 - 16.00		**Presentation NNV-prizes for "Best Poster 2015" and "Best Oral 2015!"**

Summary poster session 1 - 10 March 2015

A1 Coupling discharge and gas dynamics in streamer to spark transition
A2 Polarization measurement setup for polarization matching in ITER Electron Cyclotron Heating
A3 Investigation on synthesizing carbon nanostructure using extreme plasma fluxes
A4 Plasma dissociation of water for CO_2 conversion
A5 Determining the conditions of electrodeless streamer inception
A6 In-situ Fourier transform infrared spectroscopy for studying plasma-assisted atomic layer deposition of silicon nitride
A7 Probing reaction dynamics by laser scattering in CO_2 plasma
A8 A Plasimo global model for plasma assisted CO_2 conversion
A9 Modelling of the DIFFER plasma reactor for CO_2 dissociation, using Plasimo
A10 Plasma particle lofting - Experimental investigation of dust removal force
A11 Plasma-induced activation of water
A12 Rydberg Lattice Quantum Simulator
A13 Comparing He ion energy transfer to W and Fe surfaces through molecular dynamics simulations
A14 Motion and energy dissipation of secondary electrons, positrons and hadrons correlated with terrestrial gamma-ray flashes
A15 Ex-situ infrared absorption spectroscopy study of the plasma chemistry in a dielectric barrier discharge using an air-like gas mixture
A16 Determining the tokamak current density profile for real-time actuator control
A17 Modeling of fusion plasma exhaust and linear plasma jets with high flux and density
A18 Surface dynamic evolution of silica-like films grown by AP-PECVD on polymeric substrate
A19 The PLASIMO plasma modeling framework
A20 PLASIMO model of micro-plasma jet for biomedical applications
A21 Non-oxidative Coupling of Methane via Plasma Catalysis
A22 Development and understanding of plasma-assisted atomic layer deposition of silicon nitride thin films

Summary poster session 2 - 11 March 2015

B1 In-flight measurements of lightning and thunderstorm radiation
B2 Plasma-assisted catalytic CO_2 methanation
B3 Scattering ellipsometry on one single plasma levitated dust particle
B4 Application of ILDM Technique for Simplifying Complex Plasma Chemistry
B5 Lightning inception from ice particles
B6 Time-resolved rotational Raman spectroscopy in an atmospheric pressure DBD in CO_2
B7 Exploring Light Scattering on Dusty Plasmas to improve Color Management in White LEDs
B8 Measurement of charge in plasma bullets using Pockels effect
B9 Advances in discharge simulations at CWI
B10 Polarization matching in ITER electron cyclotron heating
B11 Streamer affinity for dielectric surfaces
B12 Hot H_2 in white dwarf photospheres
B13 Quantum Plasma in Rydberg Crystals
B14 Energy resolved mass spectrometry in EUV-induced plasmas
B15 Blister formation on extreme ultraviolet multilayer surfaces, induced by atomic hydrogen
B16 Expansion of the electrons in an EUV-induced plasma in argon
B17 Poster withdrawn
B18 Plasma assisted atomic layer deposition of molybdenum oxide using oxygen plasma
B19 CO_2 dissociation in microwave plasmas
B20 Nonlinear growth of tearing modes: validating the generalized Rutherford equation
B21 Application of laser-cooling and compression to create a high resolution focused ion beam
B22 Ion Velocity Distribution Measurements on the TU/e Fusor Plasma Using LIF Diagnostics

M1

Critical Behaviour of the Acoustic Streaming Field in HID Lamps

Bernd Baumann[1], Joerg Schwieger[1], Marcus Wolff[1], Freddy Manders[2], and Jos Suijker[2,3]
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[2]*Philips Lighting, Turnhout, 2300, Belgium*
[3]*Technical University Eindhoven, Eindhoven, 5612AZ, Netherlands*

For energy efficiency and particularly for cost reduction it is preferred to drive high-intensity discharge lamps at frequencies of approximately 300 kHz. However, operating lamps at these high frequencies bears the risk of stimulating acoustic resonances inside the arc tube, which can result in low frequency light flicker and even lamp destruction. The acoustic streaming effect has been identified as the link between high frequency resonances and low frequency flicker. A highly coupled 3D multiphysics model has been set up to calculate the behaviour of the thermal plasma arc and the acoustic streaming velocity field inside the arc tube of high-intensity discharge lamps. It is the fundament of an extended model that in the near future will allow the investigation of the light flicker phenomenon. In the present state it can be used to gain valuable insights into the processes affecting the flow field inside the arc tube of the lamp. Concerning computer resources the procedure is considerably less demanding than a direct approach with a transient model. Simulations of a certain lamp revealed that the velocity field suffers a phase transition to an asymmetrical state at a critical acoustic streaming force. In certain respects the system behaves similar to a ferromagnet near the Curie point.

M2

Diagnosing JET heavy impurities

A.E. Shumack[1,2], J. Rzadkiewicz[3], T. Nakano[4], M. Chernyshova[5], T. Czarski[5], S. Dalley[1], N. Hawkes[1], K. Jakubowska[5], G. Kasprowicz[6], E. Kowalska-Strzeciwilk[5], K. Pozniak[6], S. Tyrrell[1], W. Zabolotny[6] and JET contributors*

EUROfusion consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

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[2] *FOM Institute DIFFER, Edisonbaan 14, NL-3439 MN, Nieuwegein, The Netherlands*

[3] *National Centre for Nuclear Research, Andrzeja Sołtana 7, 05-400 Otwock, Poland*

[4] *Japan Atomic Energy Agency, 801-1, Mukoyama, Naka, Ibaraki, 311-0193, Japan*

[5] *Association Euratom-IPPLM, Hery 23, 01-497 Warsaw, Poland*

[6] *Warsaw University of Technology, Institute of Electronic Systems, 00-665 Warsaw, Poland*

* *See the appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

The JET high resolution X-Ray crystal spectrometer has been upgraded to measure not only nickel but now also tungsten and molybdenum impurity concentrations in the plasma core. Heavy impurity accumulation measurements have high priority since the installation of the "JET ITER-like wall" (main chamber: Be, divertor: W). Tungsten and molybdenum spectral lines at around 5.2 Åhave been identified and are routinely measured, most importantly a W^{46+} M-shell transition and two Mo^{32+} L-shell transitions. Concentrations are typically 1-2.10^{-5} and 10^{-6} for W and Mo respectively, and raise the question of the source of such unexpectedly high molybdenum concentrations. Benchmarking against other diagnostics is ongoing. This contribution will introduce the subject of high impurity accumulation at JET, including an overview of other JET impurity diagnostics before outlining the upgrade of the diagnostic.

M3

Extreme ultraviolet lithography - a case study how science supports innovation

Jos Benschop[1]
[1]ASML, Eindhoven / University of Twente

Moores Law dictates that every 18 months the number of transistors on an integrated chip doubles. This is first and foremost enabled by optical lithography printing ever smaller transistor on an integrated circuit. After a short introduction into IC making and the role of lithography, Extreme UltraViolet litho will be discussed. It will be shown that a fundamental understanding of physics is essential in order to progress state-of-the art equipment. Latest results and remaining challenges will be shared. Good, bad and ugly in collaboration between academics and industry will be discussed.

M4

(Plasma)Physics for EUV lithography

V. Banine[1]
[1]*EPG, Eindhoven University of Technology, Eindhoven, The Netherlands*

Reduction of radiation wavelength and increasing numerical aperture (NA) used in Litho tools has enabled the shrink of printed features for the past three decades. The evolution of lithographic wavelengths has gone from 436 nm (aka g-line) to 365 nm(aka i-line) to 248 nm(aka KrF) to 193 nm (aka ArF) and finally to 13.5 nm (aka Extreme Ultraviolet or EUV). Starting with historical perspective long- and mid-term physical and technological challenges for high resolution imaging with EUV will be reviewed. EUV light for lithography is currently produced by Laser Produced Plasma apparatus, where EUV is emitted by high temperature plasma. EUV light propagating thorough the gas causes creation of the so-called EUV induced plasma. Conditions and specifications for an EUV emitter for lithography, the physical processes associated with it, as well as properties associated with EUV induce plasma will be discussed in the presentation.

M5

Probing the (un)known foundations of physics with trapped laser-cooled molecular hydrogen ions

J.C.J. Koelemeij[1]
[1] *LaserLaB & Department of Physics and Astronomy, VU University, Amsterdam, 1081 HV, Netherlands*

Todays most accurate clocks are based on optical transitions in atomic ions, excited by ultra-stable lasers having a linewidth below 1 Hz. Exploiting long storage times in ion traps and advanced laser cooling and manipulation methods, frequency uncertainties well below one part in 10^{-17} have been achieved. In the wake of this development, optical clocks based on vibrating molecular ions are now being set up, including simple and therefore highly calculable species such as the molecular hydrogen ion, H_2^+. While atomic and molecular optical clocks are very similar in design and operation, the underlying clockworks are fundamentally different: the frequency of atomic transitions depends primarily on the fine-structure constant, α, whereas for molecules the frequency depends on the proton-electron mass ratio, μ. In my presentation I will show recent results from an optical clock based on the molecular hydrogen ion, which is currently under construction in Amsterdam. I will furthermore show how the present and future results obtained from this clock can be used to (1) accurately determine the value of μ, (2) test fundamental physical laws such as quantum electrodynamics, the Standard Model, and general relativity, and (3) how molecular hydrogen ions can be turned into sensors of possible fifth forces ensuing from rolled-up higher dimensions or dark matter particles.

O1

Entropy generation minimization in an electron-hole plasma: a new method for optimizing solar cells

Sjoerd Smit[1], Erwin Kessels[1]
[1] *Applied Physics, Eindhoven University of Technology, Eindhoven, 5600MB, The Netherlands*

In this work the theory of nonequilibrium thermodynamics (NET) is applied to electron-hole plasmas, which is a kind of plasma that is frequently encountered in semiconductor physics. NET is used to derive the expression for the local generation of entropy in the plasma and therefore also the loss of free energy, which is a crucial parameter in the optimization of power-generating and work-performing semiconductor devices such as solar cells and LEDs. NET is therefore a powerful tool for visualizing losses in such devices; where traditionally various loss mechanisms are measured in different units, NET makes it possible to measure them all on the same scale as entropy generation.
The local information obtained by analyzing the entropy production in the electron-hole plasma makes it possible to optimize devices in a more general way compared to traditional models. With traditional models that describe semiconductor devices, the user comes up with a design and then uses transport models to predict the efficiency. These models are thus referred to as being *efficiency-predictive*. As a direct consequence, the optimization of the device design using efficiency-predictive methods is ultimately based on trial-and-error, leading to small, incremental gains in efficiency. On the other hand, the local information NET provides about entropy generation can be readily combined with variational calculus to obtain a mathematical description of the device design that minimizes the total entropy generation rate. The resulting model is therefore *design-predictive*. The variational method will be illustrated by applying it to the problem of optimizing the doping profile in a silicon homojunction solar cell.

O2

Interaction mechanisms of streamer discharges in N_2:O_2 with dielectrics

A. Dubinova[1], D. Trienekens[2], U. Ebert[1,2], and S. Nijdam[2]
[1]*Centrum Wiskunde & Informatica, Amsterdam, 1098XG, Netherlands*
[2]*Technische Universiteit Eindhoven, Eindhoven, 5612AZ, Netherlands*

Streamer discharges near insulators are notorious for being precursors to surface flashovers, which are detrimental in the high voltage technology. The ultimate goal of our research is to understand how we can avoid surface flashovers. Specifically, we study positive streamer discharge interaction with dielectric rods using a dedicated fluid streamer model in local field approximation. We designed a cylindrically symmetric setup, in which a streamer is ignited from a pin electrode and propagates towards a dielectric rod that is placed directly under the electrode. We account for the polarization effects with respect to the dielectric properties of the rods, which is possible due to the implementation of the Ghost Fluid Method in the Poisson solver. We calculate the photoelectron emission from the cylindrical surface of the rod by integrating the photon flux produced by the streamer discharge. We point out the importance of the photoelectron emission for positive streamer propagation along the rod in pure gases, like nitrogen, when the free electrons are scarce. We show that in air photoionization produces enough free electrons for positive streamers to follow the electric field lines. We perform a further parametric study to determine the mechanisms important for streamer propagation along the rod as opposed to simply following the electric field lines, and we also compare our simulation results with the dedicated experiments.

O3

Spectral predictions in low and high pressure plasmas

J.F.J. Janssen[1], J.L.G. Suijker[2], K.S.C. Peerenboom [1] and J. van Dijk [1]
[1] *Applied Physics, Eindhoven university of Technology, 5600 MB, The Netherlands*
[2] *Philips Lighting, Lightlabs, Eindhoven, 5600 JM, The Netherlands*

Emission spectroscopy remains an important tool for plasma diagnostics. However the interpretation of these spectra can be difficult. Simulations can aid in understanding these spectra. Such simulations require knowledge about the energy levels and the transition probabilities. The data required to calculate these energy levels and transition probabilities is not always available. When data is absent the possibility of generating the required properties via ab initio calculations can provide a solution. The quality of these calculated properties is evaluated and compared with measured spectra.
In mercury free HID lamp plasmas it is possible to represent the rovibrational states as a continuum. The resulting classical description is able to reproduce the observed continuum radiation as well as the absorption in the ultraviolet. In low pressure plasmas the quantummechanical description is required. The transition probabilities of the vibrational and rotational states are estimated using simple models. Comparisons between measured and simulated spectra can provide an estimate of the species densities. Due to the general structure of the model an application in the analysis of plasmas in other fields is possible as well.

O4

Optical emission tomography: looking into plasmas with complex structures

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Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600MB Eindhoven, The Netherlands

Measuring the light emitted by a plasma often offers a convenient way to obtain information on the plasma properties. To procure these plasma properties, as well as their spatial distribution in a volume discharge, the local emission coefficient is required. However, the intensity recorded by a detector is a lateral scan of the emission integrated along a line-of-sight. A commonly used technique to retrieve radial dependence in case of cylindrical symmetry is Abel inversion. When the discharge structure exhibits a more complex symmetry or no symmetry at all, a more generalised approach is required: the inverse Radon transform. Since optical access from numerous angles is now required, this technique is especially applicable to discharges in open air. A brief explanation of the Radon and inverse Radon transforms is given and the reconstructed local emission coefficient of a structured volume dielectric barrier discharge (DBD) in open air is presented. Finally, the local emission coefficient is compared to the local electric field strength obtained from simulations.

O5

Probing vibrational ladder-excitation in CO_2 microwave plasma with a Free Electron Laser to develop a route to efficient solar fuel production

D.C.M. van den Bekerom[1], G. Berden[2], A. Berthelot[3], C.A. Douat[4], R.A.H. Engeln[4], N. den Harder[1], T. Minea[1], M.C.M. van de Sanden[1,4], G.J. van Rooij[1]

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[3] *Faculty of Science, University of Antwerps, 2000, Belgium*
[4] *Faculty of Applied Physics, Eindhoven University of Technology, 5612AZ, Netherlands*

23-01-2015

Efficient energy storage is an important aspect of large scale implementation of renewable energy sources. We focus on the plasma-chemical conversion of CO_2 to CO, as a first step in fuel synthesis. This conversion is done in a 2.45 GHz, 1 kW microwave plasma at pressures between 5 and 50 mbar.

CO_2-dissociation can be very efficient in a plasma (up to 90%). The prevailing model for such efficient dissociation is that of vibrational ladder-climbing. CO_2-molecules are excited to the first few vibrational levels by collisions with plasma electrons. The molecules are excited to higher levels by intermolecular collisions, up to the point where the molecule dissociates. In contrast to e.g. dissociative excitation by electron impact, no energy is wasted in this process because at no point the molecule has a higher energy than the dissociation energy.

To gain more insight in the dynamics of vibrational ladder-climbing, a Free Electron Laser tuned to 4.35 μm (resonant with vibrational excitation of the first level) is pulsed to perturb the intrinsic vibrational distribution of the steady-state plasma. The excitation peak induced by the FEL will similarly traverse through the ladder, resulting in a small (delayed) peak of CO-production.

In this contribution, we report on measurements of the increase in CO by absorption spectroscopy using a 4.5 μm Quantum Cascade Laser. A gate-delay scan relative to the FEL pulses is performed to determine the time constant for the excitation-ladder.

O6

Fast and interrupted expansion in cyclic void growth in a dusty plasma

F.M.J.H. van de Wetering, R.J.C. Brooimans, S. Nijdam, J. Beckers and G.M.W. Kroesen

Eindhoven University of Technology, Department of Applied Physics, P.O. Box 513, 5600 MB Eindhoven, the Netherlands

Low-pressure acetylene plasmas are able to spontaneously form dust particles, resulting in a cloud of particulates up to micrometer sizes levitated in the plasma. This is called a dusty plasma. We studied a capacitively coupled RF plasma with constant flow of argon and acetylene. After the dust cloud has been formed, an ellipsoid-shaped dust-free zone (void) develops. Concurrently, the dust particles grow in size. During its expansions the void suddenly stops growing and even shrinks, to shortly thereafter resume its expansion, which we refer to as void 'hiccup'. The process is periodical and reproducible. We infer the hiccup is induced by coagulation of a new batch of dust particles inside the void. To substantiate this reasoning, the electron density is determined non-intrusively using microwave cavity resonance spectroscopy. Moreover, video imaging of laser light scattering of the dust particles provides their spatial distribution. The emission intensity of a single argon transition is measured similarly. The void dynamics preceding the hiccup are explained using a simple analytical model for the two dominant forces (ion drag and electric) working on a nanoparticle in a plasma.

O7

Propagation of Streamers Generated with Subnanosecond Variable Rise Time, Variable Pulse Duration, High-Voltage Pulses

T. Huiskamp[1], W. Sengers[1], and A. J. M. Pemen[1]
[1] *Electrical Energy Systems, Electrical Engineering, Eindhoven University of Technology, Eindhoven, 5600MB, The Netherlands*

In this contribution we show the propagation of streamers in a cylindrical plasma reactor. The streamers are generated with a subnanosecond rise time, variable pulse duration, high-voltage pulse source [1]. One side of the plasma reactor is open in such a way that we can image the entire length of the reactor. With a fully automated system we can vary the position of an ICCD camera and synchronise optical and electrical measurements. We will show time- and space resolved images and movies of the propagation of streamers generated by 1-, 5- and 9-nanosecond pulses (both negative and positive) with a 200-picosecond rise time in a 1- and 2-m plasma reactor. For the 9-ns pulses we also varied the rise-time and show the effects of this variation. For all of the results we calculate streamer velocities, streamer widths and streamer lengths.

[1] T. Huiskamp, E. J. M. van Heesch and A. J. M. Pemen, "Final Implementation of a Subnanosecond Rise Time, Variable Pulse Duration, Variable Amplitude, Repetitive, High-Voltage Pulse source," *Plasma Science, IEEE Transactions on*, vol. 43, no. 1, pp. 444–451, 2015.

O8

Preparation of mK-Temperature Highly Charged Ions

L. Schmöger[1,2], O.O. Versolato[1,2,3], M. Schwarz[1,2], M. Kohnen[2], A. Windberger[1], B. Piest[1], S. Feuchtenbeiner[1], J. Pedregosa[4], T. Leopold[2], P. Micke[1,2], A.K. Hansen[5], T.M. Baumann[6], M. Drewsen[5], J. Ullrich[2], P.O. Schmidt[2,7], and J.R. Crespo López-Urrutia[1]
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Resonance features in highly charged ions (HCIs) are of particular interest for understanding both astrophysical plasmas as well as laboratory ones. Accurate spectroscopy of HCIs has so far been limited by the high temperatures at which they are typically produced.

Here, we report on the Coulomb-crystallization of HCIs in a cryogenic Paul trap (CryPTEx) developed and built at the Max-Planck-Institut für Kernphysik in collaboration with Aarhus University, after retrapping the HCIs produced in an electron beam ion trap (EBIT). This crystallization implies a decrease in temperature over six orders of magnitude, from MK to mK regime, and provides a platform for unprecedented high-precision spectroscopy of HCIs. For cooling, the HCIs –in this case Ar^{13+} ions– are produced in and extracted from HYPER-EBIT after which they are decelerated and injected into CryPTEx, where they impinge on an ensemble of Be^{+} ions directly laser-cooled into a Coulomb crystal. After several round trips through the crystal, loosing sufficient energy, the Ar^{13+} ions end up implanted as visible defects in the Be^{+} ion crystal. We expect that they thermalize close to the mK-range Be^+ temperature, in agreement with experimentally obtained conservative upper limits to the temperature. Additionally, various configurations were studied, of large crystals and fluids over strings of several ions down to a single HCI cooled by a single Be^+ ion. This last step is a prerequisite for future spectroscopy at an ultimate 10^{-18} level accuracy using quantum logic.

O9

Vapor shielding of Sn in Pilot-PSI

G.G. van Eden[1], T.W. Morgan[1], D.U.B. Aussems[1], M.C.M. van de Sanden[1]
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One of the most important issues in realizing nuclear fusion power is the problem of heat exhaust. The requirements to withstand the extremely high particle- and heat fluxes on divertor components as expected for future fusion reactors such as DEMO are unlikely to be met by present day technology. A solution may be found in using liquid metal plasma facing components (PFCs) due to their self-healing properties, high heat removal potential and resilience to the impact of neutrons. Also by the possibility of exploiting continuous vapor shielding, where a layer of evaporated material reduces target heating and erosion, a significant reduction of the heat load arriving at the PFC can be achieved by spreading the incoming power through radiation.
This effect has been experimentally investigated by exposing liquid Sn to high-flux H/He plasmas in the linear device Pilot-PSI. The surface temperature was typically 1600-2200 °C while exposed to an ion flux of $\sim 10^{24}$ m^{-2} s^{-1} [1]. In occurrences where the Sn vapor pressure matches the plasma pressure, a decrease in absorbed power at the target, changes in the sheath potential and anomalous surface temperature effects are observed which may be explained by the vapor shielding effect. The influx of evaporated neutrals was observed to be of oscillatory nature of typically a few Hz and was found to match fluctuations of the surface temperature. The beneficial effects of vapor shielding are also demonstrated by comparing the power handling capabilities of liquid Sn to solid TZM targets by calorimetry measurements.
[1] G.J. van Rooij, J.P. Veremiyenko, W.J. Goedheer *et. al.* Appl. Phys. Lett. **90**−121501 (2007).

O10

Ultrafast Time-Resolved Electron Microscopy

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We are developing femtosecond electron beam techniques, based on 3 GHz microwave cavities accurately synchronized to a mode-locked laser, for pump-probe electron diffraction and microscopy experiments. At TU/e a femtosecond SEM setup is currently operational. Recently a new FEI Tecnai has been installed in our lab, which will be modified to allow ultrafast pulsed operation. We will use the new techniques to excite plasmons at the nanoscale with the femtosecond pulsed electron beam, and study both the emitted light, using nonlinear optical gating techniques, and the energy loss suffered by the electrons. The latter may be accomplished by a new time-resolved, TM110- cavity-based EELS technique we recently proposed. In addition we plan to study the feasibility of a femtosecond coherent electron beam splitter based on the diffraction of electrons on a standing wave of light, the so-called Kapitza-Dirac effect.

O11

Dielectric Barrier Discharges: Multi-filament Dynamics and Mobile Charge

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Dielectric Barrier Discharges (DBDs) are used on a large industrial scale and have been studied for more than a century, with increasing interest in recent years in the areas of materials processing, plasma medicine and solar fuels. DBDs in filamentary mode consist of many small, transient microdischarges with diameters of 0.1 mm and durations on the order of several 10s of nanoseconds, distributed over the dielectric surface. We study the collective behaviour of many such filaments in air by using a fast analog circuit capable of measuring the conductively transferred charge per filament. By using miniature planar DBDs with 3.5 - 30 mm2 electrode areas, we determine charge/filament distributions without significant overlap between filaments in time, even at high filament number densities of up to 200 filaments/cm2/period. Contrary to previous work, we find that the charge/filament distributions are log-normal in nature. Furthermore, the distributions are independent of filament number density for a given DBD geometry. With conventional charge-voltage (Q-V) measurements, Lissajous figures are obtained for the miniature planar DBDs, where the slope during a discharge period has a clear staircase shape. Analysis of these Lissajous figures, for 8 different DBD geometries, reveals that filaments do not occur randomly within a discharge period, as is often assumed, but affect each others moment of ignition. Using both measurement techniques, we infer that multi-filament discharge dynamics are regulated by mobile charges deposited on the surface of the dielectric, resulting in step-wise ignition of filaments as a function of applied voltage. The mobility of deposited surface charge runs counter to the assumption commonly made in the plasma literature that

charge on a dielectric surface remains effectively stationary. The log-normal charge/filament distributions, on the other hand, do develop from locally trapped, stationary charges on the dielectric. We suggest that both mobile charges and stationary trapped charges need to be considered in models of DBDs, especially when converting data from the abundant single-filament models in DBD literature to real devices.

O12

Research at the Advanced Research Center for Nanolithography

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The Advanced Research Center of Nanolithography (ARCNL) is a new public-private partnership between the two universities in Amsterdam, UvA and VU, the foundation FOM (NWO) and the semiconductor equipment manufacturer ASML. ARCNL is focused on the fundamental physics involved in current and future nanolithography technology. Since the laboratory has become available at the Amsterdam Science Park in October 2014, the center has been rapidly building up its research facilities. The first five research teams have started already, devoted to EUV Generation and Imaging, EUV Targets, EUV Plasma Dynamics, Nanolayers, and Nanophotochemistry, and first experiments are underway. The sixth group will focus on EUV photo-electron spectroscopy, and further research groups will be established in 2015.
In this talk, the general goals of ARCNLs research will be highlighted. Special attention will be given to the studies of laser-produced plasmas from tin-droplets for the generation of powerful 13.5 nm radiation. Experiments entail the spectroscopy of a tin-droplet plasma in the EUV, deep-UV and visible wavelength ranges and on a fast time scale to follow the buildup of highly charged states that are the originators of the EUV radiation to be used for lithography. At the same time the production of energetic ions, radicals, molecular and cluster species from such a plasma will be investigated.

A1

Coupling discharge and gas dynamics in streamer to spark transition

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We study streamer to spark transition by coupling the 2D drift-diffusion model of streamers to the Euler equations for gas dynamics. The motivation behind this study stems from the need to find gases that can replace conventional gases in high-voltage circuit breaker technology. In particular, Jin Zhang and Bert van Heesch at Eindhoven University of Technology investigate now whether the conventional SF6 can be replaced by supercritical nitrogen. We focus on modelling the discharge and gas dynamics in pulsed (DC) discharges, including space charge effects, gas heating due to energy exchange between electrons/ions and the gas and secondary electron emission from the cathode. We perform simulations to capture the resulting effects, such as thermal shocks and induced pressure waves because of the coupling between the discharge and the gas.

A2

Polarization measurement setup for polarization matching in ITER Electron Cyclotron Heating

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In ITER, the world's largest nuclear fusion experimental reactor that is presently under construction, plasma can be heated by injection of high-power (20 MW) microwaves at a frequency tuned to the gyro motion of the electrons in the magnetic field. The electrons emit and absorb cyclotron waves at this frequency. For optimal absorption of the injected power one must inject the waves with a polarization such that it matches the polarization of the waves that the electrons emit in the selected heating scheme. It is estimated that a 3° mismatch in alignment of their E-vectors leads to a non-absorbed fraction of power of 1%. To optimize the alignment a scheme is investigated to measure the polarization state of the emitted electron cyclotron waves at the location of the launcher and to use this measurement to adjust the polarization of the injected waves. A polarization measurement setup at 60 GHz is currently being implemented as a proof of principle technique. The key components are an Orthomode transducer and a Vector network analyzer, allowing to measure the full polarization state of the source in the scheme. A Matlab code was written showing plots of the polarization ellipse with ideal measurement data. The technique can later be applied at higher frequencies; for this purpose, we have implemented a system (based on frequency multipliers and harmonic mixers) capable of generating and detecting frequencies in the range 90-140 GHz and 270-375 GHz. Other frequency bands can also be implemented by appropriate modification with suitable waveguide components.

A3

Investigation on synthesizing carbon nanostructure using extreme plasma fluxes

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This research explores the feasibility of using extreme conditions of heat and particle fluxes to synthesize catalytic carbon nanostructures without precursor gas injection or surface pretreatment. Previous work has shown the spontaneous synthesis of carbon microparticles using linear plasma generator PILOT-PSI with plasma fluxes up to four orders of magnitude larger than in conventional plasma-enhanced chemical vapor deposition processing [1]. To build a solid foundation for this work, experiments were performed to investigate the structural properties and their correlation with various parameters, such as ion energy, plasma flux and surface temperature. The samples are post-mortem analyzed by SEM and Raman spectroscopy. Preliminary results suggest an optimal ion energy, a lower limit for the plasma flux and a upper limit for the surface temperature. Further experiments will determine the CO_2 capture capability using thermal desorption spectroscopy (TDS).

[1] K. Bystrov, M.C.M. van de Sanden, C. Arnas, Carbon 68 (2014) p. 695

A4

Plasma dissociation of water for CO2 conversion

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Production of syngas (H2 + CO) or hydrocarbons from H2O and CO2 using thermo-chemical cycles offers an appealing path for converting renewable energy (solar; wind) into a storable form. Direct utilization of H2O and CO2 for fuel production is the most appealing from a sustainability perspective. It can be a carbon neutral process when coupled to process that capture CO2 from the air. Dissociation of H2O and CO2 by plasma-enhanced reaction can be an extremely energy efficient means as compared to thermal decomposition. It also potentially allows for in-situ production of the necessary reactive hydrogen intermediates from water as part of an integrated raction process. We present preliminary results on plasma-induced dissociation of H2O into H2 and O2 in an inductively-coupled plasma as a function of pressure and input power. Quadrupole Mass Spectrometer and Optical Emission Spectroscopy were used to monitor the performance of the plasma-conversion process.This work is part of a longer term effort to develop integrated plasma processes for CO2 conversion.

A5

Determining the conditions of electrodeless streamer inception

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Streamer discharges are widely investigated for a long time due to a large variety of implementations: air and water flow control, plasma medicine, air purification, various high voltage (HV) technologies. In HV devices surface streamers play a crucial role, since they can form a conductive channel, which (under sufficient electric field) develops into an arc, leading to short-circuiting and damage of the device. The exact conditions of the formation of these streamers are, however, poorly understood and require detailed investigations.

The goal of the present work is to provide physical understanding of the processes leading to surface streamer development. Experiments were performed in a specially designed set up with the samples of a structure most typically used in an industrial HV device. Time-resolved imaging and current shapes measurements were performed, as well as inception voltage estimation. During the experiments AC and pulsed voltage supplies were used to power the set-up.

Experimental investigations show that the presence of a dielectric surface changes the initial parameters of the environment (compared to the processes in bulk gas) making it easier for a discharge to develop. The reduced electric field is larger than that expected in bulk gas. Velocities of streamers propagating along the surface were estimated based on the time-resolved imaging of the processes and the estimated parameters were compared for discharges propagating in nitrogen and in ambient air.

A6

In-situ Fourier transform infrared spectroscopy for studying plasma-assisted atomic layer deposition of silicon nitride

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Ultrathin, conformal and highly uniform spacer materials are important for the downscaling of 3D structures in semiconductor devices. The possibilities of using plasma-assisted atomic layer deposition (ALD) to deposit such layers have been explored recently. The use of plasma species as reactants allows for more freedom in processing conditions and for a wider range of material properties compared with the conventional thermally driven ALD method.
Recently a plasma-assisted ALD process for silicion nitride (SiN_x), using BTBAS as precursor and a remote ICP N_2 plasma, has been developed and material properties of the deposited layers have been studied *ex situ*. However, the surface chemistry involved in the film growth is still unresolved. Gaining insight into the surface chemistry allows for optimization of the deposition process and exploiting the possibilities of plasma-assisted ALD even further. Therefore, the SiN_x process is studied by means of *in situ* transmission Fourier transform infrared spectroscopy (FTIR). This technique uses IR light to probe the molecular bonds present in the deposited film.
The advantage of this *in situ* setup is that the film growth can be monitored directly, showing the incorporation of carbon, oxygen and hydrogen in the film over time. Also, the cyclic nature of the ALD process enables to study interaction of precursor and plasma species with the surface separately. Initial results show a shift in nitrogen bonding on the surface after exposure to the N_2 plasma, an important step towards understanding of the role of the nitrogen plasma in this ALD process.

A7

Probing reaction dynamics by laser scattering in CO_2 plasma

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Increasing concern about climate change caused by anthropogenic CO_2 emission has resulted in rapid growth of renewable energy sources. However, a major concern is their intermittent character: temporal variations causing mismatching demand and supply. Energy storage is therefore crucial for the successful implementation of renewables.
Fuel synthesis, (storing energy in chemical bonds) is an attractive option since it offers long-term storage on a grand scale. In this contribution, a first step in the synthesis of fuels was investigated: the dissociation of CO_2 in a plasma (plasmolysis). This reaction was performed in a 1 kW 2.45 GHz microwave reactor, which is low-cost technology, switchable on a seconds timescale and doesn't use scarce materials. In addition, literature indicates that efficiencies exceeding 80 % are achievable.
Plasmolysis of CO_2 can be so efficient because of the non-equilibrium nature of the plasma. Different species in the plasma have a different temperature, i.e. an electron temperature on the order of 10000's of Kelvins while the neutral gas is close to room temperature. In a small range of plasma parameters, energy is mainly transferred into vibrational excitation of the CO_2 molecules, leading to dissociation. In this contribution, laser scattering measurements on both gas temperature and electron temperature and density will be presented. These plasma parameters will be correlated with operating parameters and CO_2 activation efficiency and will allow assessment of the main plasma chemical pathways.

A8

A PLASIMO global model for plasma assisted CO_2 conversion

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Conversion of CO_2 is currently a hot topic in plasma physics research. Obviously, it is a way of reducing the amount of greenhouse gases in our atmosphere, but, more importantly, it is a method to store energy in chemical form, thereby relieving the discrepancy between supply and demand of many alternative forms of energy. Numerical modeling is an important aspect in the investigation of this process, but is dificult due to the complex chemistry. A global model for CO_2 is being developed using the modeling platform PLASIMO, based on a model from literature[1] that was developed in Global_kin. The model will be used to study the chemistry and identify the most important species and reactions. Additionally, the model is a candidate for advanced chemistry reduction techniques and benchmarking of global model codes.

[1]Kozák, T., Bogaerts, A. (2014). Splitting of CO_2 by vibrational excitation in non-equilibrium plasmas: a reaction kinetics model. Plasma Sources Science and Technology, 23(4), 045004.

A9

Modelling of the DIFFER plasma reactor for CO_2 dissociation, using Plasimo

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At FOM Institute DIFFER, in collaboration with the Eindhoven University of Technology, experiments are performed to investigate efficient dissociation of CO_2 in the context of storing intermittent sustainable energy in chemical form (Solar Fuels). A microwave induced, transonic plasma is used to dissociate CO_2 molecules via excitation of the proper (asymmetric) vibrational mode. One of the key parameters in the process is the reduced electric field (E/n). In order to gain insight in this reduced electric field and to provide feedback for the experiments, a model of the reactor is being set up with Plasimo. As a first step we have investigated the electric field in the reactor (in the absence of plasma)

A10

Plasma particle lofting - Experimental investigation of dust removal force

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Dust is everywhere. Sometimes it's harmless, but sometimes it needs to be removed. Especially in modern optical machinery, dust control can be of vital importance. In this research we look at dust on a surface. We focus on the behaviour under influence of a plasma.
The dust particles will stick to a surface due to the adhesive Van der Waals force. This force is hard to determine theoretically, as it highly depends on the local surface topology. Therefore, we have developed a method to experimentally measure this adhesive force. This method uses the inverse piezoelectric effect. We apply vibrations with increasing amplitude to the surface. This way we can observe which force is required for dust removal.
The required force is reduced when a plasma is applied over the surface. This may have different causes: the charging due to the plasma sheath may cause an additional force; the surface chemistry may change causing a lower adhesive force; the piezo vibrations may be influenced by the electrons. Current research is ongoing to find which of these effects causes the force reduction.

A11

Plasma-induced activation of water

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Exposure of water to airborne plasmas introduces aqueous active oxygen and active nitrogen species. Hot discharges in air produce nitrogen oxides like NO, NO_2, N_2O_3, N_2O_4 and N_2O_5, that eventually lead to the formation of e.g. nitrous acid HNO_2 and nitric acid HNO_3 in aqueous environments. Arcs and particularly non-thermal plasmas additionally produce ozone O_3 in air. Hydrogen peroxide H_2O_2 is produced either via water dissociation by streamers or from O_3 and water. Plasma-activated water PAW has a wide application range, primarily based on its antiseptic properties. Although nitrite ions and acidity play an important role, the PAW key active species is believed to be peroxynitrous acid ONOOH [2], a powerful but unstable oxidant. In cooperation with Filtex Nijmegen, experiments on skin disinfection power of PAW have been conducted at the Dermatology Department of Radboud UMC Nijmegen and also at Bactimm Nijmegen. Preliminary tests prove PAW-induced $>$ 6-log reduction of s. aureus and s. epidermidis skin bacteria. In addition, extensive tests have been performed by Flora Holland, the largest flower auction in the world, on PAW-assisted conservation of flowers. Plant life tests on roses and gerberas conclude an equal antiseptic power of PAW compared to classically applied water with dissolved "chlorine" tablets. In order to synthesize bigger (liter) quantities of PAW, a 500 W RF-based high voltage source topology has been developed, together with a continuous flow reactor design. A patent on PAW synthesis is pending.

[2]W.H Koppenol et al., Dalton Trans. 2012, **41**, pp. 13779-13787 "Peroxynitrous acid: controversy and consensus surrounding an enigmatic oxidant.

A12

Rydberg Lattice Quantum Simulator

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Storing laser-cooled Rydberg atoms in optical lattices offers the possibility to simulate quantum processes. Van der Waals forces for Rydberg atoms are many orders of magnitude greater than those of ground state atoms. Hence, a lattice of Rydberg atoms is an ideal candidate for inducing strong correlations needed for a quantum simulator. With blockade phenomena and a spatial light modulator (SLM) , a single atom in a lattice site can be manipulated.
Presently, we are working on stabilization of the excitation laser system using Electromagnetically Induced Transparency (EIT) spectroscopy and an ultra-stable reference cavity. With improvements in detection efficiency and beam shaping of excitation light, we hope to achieve better addressability of a single lattice site. This would ensure that we are not only able to create one Rydberg atom per lattice site but also block excitation in neighbouring sites. A Rydberg lattice of such form can help us to study the disorder-induced heating and access the physics in the strongly-coupled ultracold plasma regime.

[1] Van Bijnen et al, ArXiv:1407.6856 (2014)
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A13

Comparing He ion energy transfer to W and Fe surfaces through molecular dynamics simulations

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Exposing W and Fe surfaces to similar He plasma leads to different surface evolution. We investigate, through molecular dynamics simulations, if a difference in energy transferred from He to the surface contributes to this difference. W and Fe surfaces with four different orientations were bombarded with 60 eV He ions, impacting 0-10 degrees from the surface normal. There are large differences in how He ions interact with W and Fe surfaces. More than twice the number of He ions quickly escape back to the vacuum after interacting with Fe surfaces than escape back from W surfaces. However, due to the less unequal mass ratio between He-Fe than He-W, He ions transfer energy to Fe more efficiently. As a result, He atoms that reflect from Fe surfaces carry away less kinetic energy than those reflecting from W. The percentages of ions reflecting back from the surface and the average kinetic energy of the escaping He mostly cancel each other out. He ions transfer more kinetic energy to W surfaces than to Fe (0.777 vs. 0.700 averaged over the four orientations), but the difference is never more than 10 percent for any orientation. This rules out ion energy transfer as an explanation why similar plasma exposure on W leads to much thicker fuzz layers than on Fe. The result of He transferring a little more energy to W than to Fe is similar for all surface orientations, yet energy transfer to both metals is more efficient on some surface orientations than on others. This shows the limitations of binary collision approximation calculations, as these do not take the crystal lattice into account. While the difference in energy transfer between W and Fe is small, the penetration depth at which He atoms become thermalised does differ significantly. For all orientations, the penetration depth before thermalising is deeper (60.1 A vs. 25.4 A averaged over the four orientations) in W than in Fe. Ion channeling over several nm that is frequently observed in W is rarely seen in Fe.

A14

Motion and energy dissipation of secondary electrons, positrons and hadrons correlated with terrestrial gamma-ray flashes

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Thunderstorms emit terrestrial gamma-rays (TGFs) and lepton (electron and positron) beams with energies of up to at least 40 MeV. There is also strong theoretical evidence that beams of hadrons (neutrons and protons) with energies of several tens of MeV are emitted.
Some of these events have been correlated with negative lightning leaders, hot conducting plasma channels, propagating upwards in the cloud. For a particular leader geometry we present the spatial and energy distribution of photons, leptons and hadrons at ground and satellite altitude.
We initialize a photon beam with the characteristic energy distribution of a TGF at thunderstorm altitude and we use a three dimensional relativistic Monte Carlo model to trace these photons; we include the production of secondary electrons through photoionization, Compton scattering and pair production, the production of positrons through pair production as well as the production of neutrons and protons through photonuclear processes. We calculate the motion and energy dissipation of these leptons and hadrons with the feedback of electrons and positrons producing new photons through Bremsstrahlung and through positron annihilation at shell electrons.
These results give estimates of fluxes of all these species at 0 and 500 km altitude which is of particular interest for future measurement campaigns, on ground and by satellites.

A15

Ex-situ infrared absorption spectroscopy study of the plasma chemistry in a dielectric barrier discharge using an air-like gas mixture

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A high current diffuse dielectric barrier discharge was operated in a roll-to-roll reactor using an air-like gas mixture. The exhaust gas from the discharge area was studied using a Fourier transform infrared spectrometer with 7 m path length in the range from 750 to 3000 cm^{-1}. The absorption features of NO, NO_2, N_2O, HNO_2, CO, CO_2, $HCOOH$, H_2O and O_3 (only observed in high O_2 flow plasma) were identified and analysed. By fitting the molecule absorption bands by means of Q-MACSoft-HT software, the concentrations and the production rates of molecules were estimated. The gas phase reactions as well as the surface induced reactions will be discussed along with the possible reaction pathways in the dielectric barrier discharge reactor.

A16

Determining the tokamak current density profile for real-time actuator control

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The efficiency of a tokamak is highly dependent on its driven plasma current, which can be described in a current density profile. Longer pulses and better confinement, hence higher efficiencies, can be obtained by actively affecting the current density profile locally with techniques like neutral beam injection and electron cyclotron current drive.
In order to purposefully use these active techniques, clear information about the current density profile has to be obtained. Moreover, this information should be fast enough for real-time actuator control. In this contribution we will demonstrate how this can be done using an optical technique of determining the current density profile, employing the polarization angle of emitted light from the H-α transition, in combination with a predictive model of the current density profile and the measurement.

A17

Modeling of fusion plasma exhaust and linear plasma jets with high flux and density

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Future tokamak fusion reactors such as the ITER experiment rely on a magnetic structure called the divertor for particle exhaust at a minimum of wall erosion and plasma pollution. The Pilot-PSI and Magnum-PSI experiments at FOM-institute DIFFER are designed to study plasma-surface interactions under such conditions. For the numerical modeling of such plasma, the multi-fluid plasma code B2.5, which has been extensively used to model tokamak divertors, is coupled to the 3D kinetic Monte Carlo code Eunomia, developed at DIFFER to model the neutral particles and reactions. It is parallelized, has high flexibility to treat different geometries, and adaptive particle weights to model a narrow plasma beam in a large vacuum vessel. Eunomia solves the equilibrium density, temperature and flow velocity of neutral species under high-flux, high-density plasma conditions. The ultimate purpose is to use linear machine validation for predictive modeling of tokamak divertor plasma.

A18

Surface dynamic evolution of silica-like films grown by AP-PECVD on polymeric substrate

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The practical applications of functional films as oxygen and water permeation barriers are broad, from protecting flexible electronics like solar cells to food and medical packaging. Precise control on morphology and growth front evolution is important to produce the desired film quality for specific applications. The inorganic-like film front growth evolution produced by AP PECVD was studied on the polymeric substrate.

The set of films was grown in a roll-to-roll AP-PECVD reactor with parallel bi-axial cylindrical electrode geometry on polyethylene-2,6-naphthalate (PEN) under barrier deposition conditions. TEOS was used as a precursor for silica-like thin films and the process gasses were argon, nitrogen, and oxygen. The dynamic deposition rate was approximately 10 nm m/min and the estimated energy spent per TEOS molecule is 6.5 keV/molecule. The surface morphology was measured using AFM and analysed within the dynamic scaling theory characterized by the roughness, growth and dynamic exponents.

The evolution in morphology from a non-self-affine to rather smooth and self-affine surface was observed as the film thickness increased from 3.5 to 16.5 nm. The root mean square roughness calculated from these morphologies is shown to be insignificantly fluctuated and remains close to the original polymer substrate of 1.75 nm. Almost no change in the roughness exponent was observed for the films in the 16.5 to 212.3 nm range remaining stable at the value of 0.85.

A19

The PLASIMO plasma modeling framework

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PLASIMO is the plasma modeling framework that has been under continuous development in the EPG plasma group at the Applied Physics department of Eindhoven University of Technology since the 90s of the previous century. Since its initial form, aimed at modeling Inductively Coupled Plasmas and Cascaded Arcs, it has gained much functionality catering to a plethora of plasma applications: LTE or non-LTE, steady state or transient, flowing or non-flowing, with or without space charges, 0D to 3D. The platform, which is developed in C++, is characterized by a high degree of modularization and offers a user friendly Graphical User Interface. We present assorted applications where PLASIMO has successfully been employed.

A20

PLASIMO model of micro-plasma jet for biomedical applications

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Non-equilibrium atmospheric pressure micro-plasma jets are widely studied for use in biotechnology, including treatment of human tissue. The setup under study consists of capillary powered electrode through which helium gas flows and a grounded ring electrode placed a distance of few mm in front of the capillary. The discharge is excited by sinusoidal voltage with amplitude of 2kV and 30KHz repetition rate. The plume emanating from the jet, or the plasma bullets, propagates through a Pyrex tube and the gas phase channel of helium into the surrounding air. The aim of this work is to get insight into the plasma constituents that can affect directly or indirectly living tissue. This includes radicals, ions and electrons, UV radiation, electrical fields. The PLASIMO modeling toolkit is used to simulate the capillary plasma-jet in order to quantify the delivery of fluxes and fields to the treated tissue. The model is validated by comparison with experimental observations at various operating parameters.

A21

Non-oxidative Coupling of Methane via Plasma Catalysis

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The direct conversion of CH_4 into C_2 or higher hydrocarbons is still high on the industrial wish-list, but it remains a major scientific and technological challenge. The relevance of the problem has been very high and is even continuously increasing, given the fact that natural gas is becoming more and more important as compared to mineral oil; the recent shale-gas revolution recently strengthened this trend even further. In this project, methane activation, that is, formation of vibrationally excited molecules and free radicals, is done in a far from equilibrium microwave plasma reactor, where the resulted active species form C2 hydrocarbons or higher. The non-equilibrium condition, requires different temperatures of the plasma species $T_{gas} < T_{vib} < T_e$ that leads to a plasma catalysis effect for the dissociation mechanism.
We will report on a combined diagnostic approach of in-situ FTIR absorption spectroscopy and down stream mass spectrometry that is used to quantify the resulted species and degree of dissociation as well as establishing the rate limiting step given by the C-H bond cleavage of the methane molecule.

A22

Development and understanding of plasma-assisted atomic layer deposition of silicon nitride thin films

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Continuously increasing the transistor density on a chip is essential for the success of semiconductor industry. The inevitable size reduction of transistor components necessitates thin films of high quality, conformality and uniformity. Atomic Layer Deposition (ALD) is an excellent deposition technique to grow these layers, such as silicon nitride (SiN_x) which is considered in this work. An important application of SiN_x is as a sidewall spacer in Field Effect Transistors (FETs), where it serves as a barrier layer against water and oxygen. However, ALD of SiN_x thin films is challenging since precursor adsorption and the complex role of the plasma can be an issue.
In this work we are studying and developing plasma-assisted ALD by repeating cycles consisting of two consecutive self-limiting half-reactions. With this technique the plasma provides energetic species which are highly reactive on the surface of interest.
Therefore it is important to better understand which plasma species control important material properties. In order to do this we have conducted an experimental study in which we studied plasma and deposited material properties as a function of varying plasma and processing parameters. Via diagnostics as Optical Emission Spectroscopy (OES) and Quadrupole Mass Spectrometry (QMS) we have monitored the species present in the reactor during both half-reactions. Via diagnostics as X-ray Photoemission Spectroscopy (XPS) and Rutherford Back Scattering (RBS) we are able to study material properties by looking at composition and chemical bonds present in the film. By combining these diagnostics we have been able to gain more insight into the deposition method in this process.

B1

In-flight measurements of lightning and thunderstorm radiation

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Thunderstorms emit bursts of energetic radiation. Moreover, lightning stepped leader produces x-ray pulses. The phenomena, their interrelation and impact on terrestrial atmosphere and near space are not fully understood yet.
The In-flight Lightning Strike Damage Assessment System ILDAS was developed in an EU FP6 project (http://ildas.nlr.nl/) to provide information on threat that lightning poses to aircraft. It is intended to localize the lightning attachment points in order to reduce maintenance time and to build statistics on lightning current. The system consists of 1 E-field sensor, 8 H-field sensors and was recently advanced with 2 LaBr3 scintillation detectors to measure hard radiation inside the aircraft. One of the unique features of the system is the ability to reconstruct a lightning current direction for any instance in time. The x-rays generated by the lightning flash are measured in synchronization better than 10 ns with the lightning current information during a period of 1 second around the strike. Numerous fast x-ray bursts of 1-4 μs duration and 120 keV characteristic energy have been measured. The x-rays occur during initiation phase of a lightning leader and during attachment phases of recoil processes and return strokes. A possible indication of a long gamma-ray glow from thunderclouds has also been detected. Such glows appear as continuous background radiation enhancement for periods of several minutes.
We will present a brief ILDAS system description and a few case studies of its operation.

B2

Plasma-assisted catalytic CO_2 methanation

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Non-thermal plasma produced in (humidified) ambient conditions has not yet well been explored for CO_2 reduction to methane in the presence of a catalyst by means of a so-called Single Stage Plasma Catalysis (SPC). In these type of systems the catalyst is directly introduced in the discharge region. This technique combines the advantages derived from the highly-reactive species generated by the plasma with the high selectivity and energy efficiency gained by heterogeneous catalysis. The aim is to exploit this synergistic effect in order to enhance the CO_2 conversion to methane. This requires a fundamental understanding of the various processes taking place and especially the mutual interactions between plasma and catalyst. The dissociation of carbon monoxide on the surface of the catalyst is the rate determining step (RDS) of the CO_2 methanation reactions path (CO bond strength 11eV)[3]. It is well established that the production of excited species by means of NTP is reflected in a lower activation energy needed for the adsorption on the catalysts surface[4]. Moreover, when the antibonding orbital of the adsorbate shifts below the Fermi level of the transition d-metal, an electron fills that position causing a strenghtening of the interaction with the surface but weakening the intra-molecular bond. Considering that there are several kinds of catalysts with different features, it is of crucial importance to apply in our

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system an adequate catalyst in terms of selectivity, conversion efficiency and affinity towards CO_2, CO and H_2. Mok et al. [5] showed that the methanation of CO occurred in a $Ru/TiO_2/Al_2O_3$ packed-bed DBD reactor in a range of temperature between 240 and 300°C with a high conversion efficiency and CH_4 selectivity of 97%. Jwa et al. [6] highlighted the role of the Zeolite as catalyst support in a Nickel/Zeolite packed-bed reactor, obtaining remarkable results even if they worked at high T (200-260°C) too. Interesting results are also given by Beuls et al. [7] who described possible mechanisms of CO_2 methanation on a Rh/Al_2O_3 catalyst even if the process was not studied in the presence of NTP. It is clear that the type of catalyst may play a crucial role, together with the SPC reactor geometry and the power applied to the system. Further studies, both experimentally and theoretically, are going to be conduced.

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B3

Scattering ellipsometry on one single plasma levitated dust particle

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The formation of nano- and micrometer-sized dust particles has been investigated increasingly frequent over the last decades. In this research the etching process of a polymer particle of micrometer-size by a low pressure radio-frequency (RF) driven oxygen plasma will be investigated. Vertically, one single negatively charged microparticle is confined in the electric field in the sheath region just above the lower electrode. Horizontally, confinement is achieved in a potential well due to a specially designed electrode. A rotating compensator ellipsometer is developed and built in-house to determine in situ the radius of one single levitating dust particle with high accuracy. The results of this study help to elucidate oxygen plasma etching processes and the electric field in the sheath region at the discharge border. Preliminary results of this investigation obtained with this new setup will be presented.

B4

Application of ILDM Technique for Simplifying Complex Plasma Chemistry

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Complete numerical description of plasma involves solving complex set of space and time dependent conservation and rate equations. Due to the large number of species and reactions the numerical simulation of such plasma models becomes computationally very expensive. In addition to high computational load and time the amount of data generated is massive, and the interpretation becomes very difficult. One of the solutions to overcome these problems is to employ Chemical Reduction Techniques(CRT) used in combustion research. The CRT we apply here is ILDM (Intrinsic Low Dimensional Manifold).
ILDM simply uses the fact that, due to wildly varying time scales, the reaction system is not evenly sensitive to all the reactions but some reactions are very fast and attain steady state in short interval of time. Hence, fast time scale variation becomes less important and the full description of the system can be given by the slow time scales without any significant loss in chemical kinetics. The ILDM technique finds the lower dimensional space (manifold) inside a complete state-space such that after a short interval of time the fast time scales of the system will quickly move onto this low dimensional manifold and the full system description can be given by this lower dimensional manifold. By constructing the low dimensional manifold the reaction space is described in terms of only a few parameters and it becomes possible to tabulate the results in terms of those few parameters. By generating the look-up table, for given values of controlling parameters the remaining parameters are given explicitly.

B5

Lightning inception from ice particles

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The electric fields in thunderclouds can exceed the breakdown value only locally near hydrometeors. But are the electric fields high enough and the regions large enough to initiate a streamer discharge? And where would a sufficient density of free electrons come from to start the discharge in the humid air that rapidly binds electrons in water-clusters?
For the first time it is demonstrated quantitatively that a positive streamer discharge can develop from an ice particle under thundercloud conditions. We propose the first quantitative model (based on cylindrical fluid description of positive streamers) in which the thundercloud electric field is locally enhanced due to the dielectric properties of ice and free electrons are produced by an extensive air shower. The extensive air showers are modeled in detail by CORSIKA and the electromagnetic part is extended to thermal energies.

B6

Time-resolved rotational Raman spectroscopy in an atmospheric pressure DBD in CO_2

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The production of renewable energy is increasing worldwide, hence the mismatch between the energy demand and availability of renewable energy forms a challenge. A promising method for storing energy is a CO_2-neutral fuel cycle, where CO_2 is dissociated to CO before transforming it into value-added hydrocarbons. The dissociation process is studied in a dielectric-barrier discharge (DBD) using *in situ* rotational Raman spectroscopy.

The DBD used is designed as a quartz tube in parallel plate configuration, with a discharge gap of 3 mm. The flow of CO_2 is set around 1 slm, the plasma power input is set in the order of 10 W.

Rotational Raman spectroscopy is performed using a Nd:YAG laser operated at 10 Hz with a pulse energy of 45 mJ and frequency doubled wavelength of 532 nm. The obtained scattering signal, collected at an angle of 90° with respect to the incident laser, consists of Raman and Rayleigh scattered light and stray light. The unwanted stray and Rayleigh scattered light is successfully filtered out by a volume Bragg grating (VBG) acting as an ultra-narrow-band notch filter.

Fast and selective triggering of the laser, accurately synced to the rising and falling edge of the pulsed wave power source, will pose a challenge in scheduled experiments. Time-resolved measurements give the possibility to gain insight into the heating mechanisms of the plasma, relevant for understanding the chemistry involved with the dissociation process in a DBD.

B7

Exploring Light Scattering on Dusty Plasmas to improve Color Management in White LEDs

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The market share of Light Emitting Diodes (LEDs) in the lighting world is growing quickly (4% in 2013 to an expected 74% in 2030), mainly due to the high energy efficiency compared with traditional lamps. However, the white light which is produced by LEDs does not have the same color temperature as is produced by (for example) incandescent lamps which are perfect black body radiators. Blue light from the LED propagates through a slab of scattering material, where phosphor particles convert the light to different wavelengths, composing white light. To study the extremely complex scatter process inside this phosphor layer, a cloud of negatively charged dust particles being confined inside a plasma is used as a dynamic scatter sample. Due to this negative charge, dust particles are being confined by the electrostatic field in the plasma sheath at the border of the discharge. By changing the plasma parameters, particle cloud properties like density and configuration can be controlled carefully. Hence, utilization of a dusty plasma to study scattering of light has the advantage that properties of the sample can be changed I) in-situ and II) by just turning a knob. A sophisticated setup is designed and developed, allowing spectroscopic measurements at 360° around the dust cloud. The functionalities of this setup will be presented, along with preliminary measurements and upcoming research plans.

B8

Measurement of charge in plasma bullets using Pockels effect

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This work presents the measurements of the electric field and charge in plasma bullets produced in a non-thermal helium atmospheric pressure plasma kHz-powered jet at 30 kHz, using the Pockels effect in the Sénarmont setup. By varying the distance between the electrodes, size of the ground, flow rate and other discharge parameters the goal is to obtain a better understanding of the bullet generation and propagation mechanism. Time resolved electric field measurements at the crystal should give further insight at the surface interactions between the jet and a dielectric substrate.

B9

Advances in discharge simulations at CWI

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Our group has performed time-dependent discharge simulations for more than a decade, with a focus on streamers. Over the course of several years, it became clear that we needed a 'better' Poisson solver to improve our simulation models. This Poisson solver had to be efficient and compatible with adaptive grid refinement, and ideally, also allow the inclusion electrodes and dielectrics.
We have now gotten closer to this goal. In my talk, I will first introduce AFiVO, a framework I have developed for finite-volume simulations on adaptive quadtrees (2D) and octrees (3D), optimized for multi-core machines. Then I will discuss the implementation of a multigrid solver in this framework, and show how electrodes can be included. After that, I will do my best to impress you with a couple of simulation examples, which will include streamer simulations.
All the code discussed in my talk (AFiVO, the multigrid solver and the examples) is open source and available online.

B10

Polarization matching in ITER electron cyclotron heating

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Electrons in magnetized fusion plasmas both emit and absorb electromagnetic radiation. This phenomenon is commonly exploited for diagnostic or heating purposes in fusion experiments: ITER, the world's largest tokamak currently under construction, will be equipped with 20 MW of microwave sources for plasma heating. These microwaves are injected at fixed frequency so that absorption can only occur at a specific resonant area, which allows for a fairly accurate and localized power deposition. However, the wave absorption and propagation properties are dependent on, amongst other factors, the injected wave polarization. In the specific ITER heating scheme (O1), the microwave polarization has to be parallel to the magnetic field to maximise absorption. For any other polarization angle, part of the injected power will be reflected before reaching the desired target and can become a thermal load for the vessel and its components.

We investigated the possibility of measuring the polarization of the electron cyclotron emission coming from the plasma at the same frequency and along the same line of sight of ITER electron cyclotron heating, in order to develop a control system to adjust the injected wave polarization. Using a ray tracing code, we showed that polarization scrambling at the vessel walls pollutes the signal at the antenna, making the measured polarization differ from the actual polarization state. Wall reflections need to be modelled accurately to determine the magnitude of this effect, which must be taken into account to determine the desired polarization from the measurements.

B11

Streamer affinity for dielectric surfaces

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Solid insulation materials in gas insulated high voltage (HV) devices are often weak points in terms of preventing electric breakdown, for instance because the insulator surface facilitates propagation of discharges. The understanding of the underlying fundamental physics of these discharges is poor and has to be improved to enable knowledge-based design rules for HV devices. In this research work, the streamer-like initial phase of electric breakdown is investigated.
We designed and built a setup to study discharges along the surface of dielectric samples. A tunable positive high voltage pulse is applied to a needle placed 16 cm above a grounded cathode plane, causing streamer inception. The needle-plane geometry is situated inside a gas filled vessel, allowing us to control pressure and gas composition inside the vessel. We then place a dielectric sample (30 x 2 x 150 mm) in the discharge gap at various positions. We use epoxy resin samples with different fillers to vary dielectric permittivity. Streamers are studied using an ICCD camera. An extensive parameter study was performed to obtain a parameter regime where streamers propagate along dielectric surfaces (creeping). We found that a streamers affinity for a dielectric surface depends on gas composition, pressure, voltage, pulse repetition frequency, sample position and sample material. We also investigated correlation between subsequent surface streamers using stereo-photography. Preliminary results seem to indicate that subsequent surface streamers in air often follow the same path in the initial stage of the discharge.

B12

Hot H_2 in white dwarf photospheres

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In the spectrum of two white dwarf stars (GD 133 and G29-38), recorded with the Cosmic Origins Spectrograph aboard the Hubble Space Telescope, Lyman band transitions were observed in absorption against the background light from the star. The observations cover the range 114-144 nm in the vacuum ultraviolet. Analysis of these spectra show that the spectral features can be assigned to H_2 molecules in layers of the photosphere at a temperature of 11700 and 14500 K. At these temperatures the partition function peaks at rotational states $J = 9 - 11$, while transitions from $J = 23$ were observed. The strongest transitions are in the $B - X$ (0,3), (0,4) and (1,3) bands. The spectra were modeled based on renewed calculations of the $B - X$ Lyman system, yielding very good agreement by taking into account the intensity contribution of some 1500 lines. The gravitational field in the photospheres of these white dwarfs is determined to be 10^4 times that on the Earth's surface. Based on a statistical analysis of the H_2 spectra, and a calculation of sensitivity coefficients $K_i = d \ln \lambda_i / d \ln \mu$, we deduce an important result: the fundamental dimensionless proton-electron mass ratio $\mu = m_p/m_e$ does not depend on the gravitational potential (quantitatively $\Delta\mu/\mu < 10^{-5}$ at $\phi = 10^4 \phi_{Earth}$). This can be considered as a sensitive test of Einstein's equivalence principle.

B13

Quantum Plasma in Rydberg Crystals

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We explore the dynamics of ultra cold Rydberg gases. We use the stochastic variational method on a basis of correlated Gaussians to simulate the Rydberg gas in a frozen gas approximation.
In such a gas, the excited atoms show large Van der Waals interactions, leading to a blockade radius R_b, within which the energy levels of nearby unexcited atoms in the gas shift. The remaining atoms are therefore effectively blocked from entering the Rydberg regime, within the blockade radius R_b, as they are no longer resonant with the excitation laser. As a result, the gas will fill with Rydberg atoms that can not be arbitrarily close together. As the gas saturates, the Rydberg atoms will form crystals due to their mutually exclusive nature.
From first principles, we seek to describe the transition to strongly coupled plasmas, where the interaction energy dominates the kinetic energy. This regime is difficult to reach from ultracold plasmas, which heat up, or from ground state gases, due to lack of interaction strength. Rydberg crystals, within the frozen gas approximation, are ideal for studying these transitions because of the strong interactions and ordered crystal structure.
The system exhibits very rich behaviour, due to the blockade effect, which we try to model using tools from few-body physics.

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B14

Energy resolved mass spectrometry in EUV-induced plasmas

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The development of the next generation lithography tools, utilizing light with a wavelength of 13.5 nm, brings along new plasma physics. EUV photons induce a plasma in the low pressure background gas. While the electron densities have been measured recently, there has been very little experimental research conducted on ion densities and energy distributions. Simulations have been carried out to predict ion densities and energy distributions. These predictions however, still have to be verified experimentally.
We present the first results of measurements of ion densities and ion energy distributions in EUV induced plasmas. The plasma is created using an EUV beam produced by a pulsed xenon pinch discharge. Ion densities and their energy distributions are measured using an electrostatic quadrupole probe (EQP). This high transmission probe combines a mass spectrometer and a sector-field energy analyser, enabling it to measure ion mass and energy simultaneously.

B15

Blister formation on extreme ultraviolet multilayer surfaces, induced by atomic hydrogen

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In applications like extreme ultraviolet (EUV) lithography, highly EUV reflecting Mo/Si multilayer mirrors are used in place of lenses for imaging. A typical multilayer consists of a periodic layered structure, with each layer ∼3–4 nm thick. To maintain the reflectivity of the multilayer mirror throughout its lifetime, contaminants, such as carbon, need to be removed from the mirror surface. An appropriate way to achieve this is to expose the mirror's surface to hydrogen ions and radicals. Unfortunately, hydrogen not only cleans, it also gets incorporated in the multilayer structure itself. In some cases, excessive hydrogen exposure can eventually lead to the irreversible process of blister formation on the mirror surface. To prevent multilayers from hydrogen induced blister formation, we are investigating the formation process in more detail. Although it is known that amorphous silicon readily absorbs hydrogen, the absorption of hydrogen, followed by the formation of blisters is not yet well understood for multilayer systems. We are currently investigating the hypothesis that the formation of blisters is accelerated by the inherent stress formed at the Mo/Si interface. Therefore, an experimental setup, in which samples can be exposed to controlled fluences of low energy hydrogen ions (50-200 eV range) has been constructed. We show that the inherent stress of the multilayer changes with hydrogen exposure. Furthermore, by analyzing the morphology of the blisters, we show that the blisters are highly strained. We also observe that blister growth is limited and that new blisters are formed rather pre-existing blisters continue to grow.

B16

Expansion of the electrons in an EUV-induced plasma in argon

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There is an increasing global demand for more computational power and memory capacity. To achieve further miniaturization of semiconductors, the next logical step is to use lithography machines based on Extreme Ultra- Violet (EUV) radiation at 13.5 nm (92 eV). The topic of this contribution is the physical processes, which occur in a low pressure gas such as Ar and H_2 (0.1–10 Pa) due to absorption of EUV photons and the creation of EUV induced plasma. The long term impact of such a plasma on the lithography machine is of main interest for the industry.
The electron density is measured with microwave cavity resonance spectroscopy (MCRS). In MCRS measurements the resonant frequency of a specific mode in a cavity is determined, this frequency depends on the electron density in the cavity. In principle, this is an averaged density of the entire cavity. However, by combining several resonant modes, we can obtain information on the spatial distribution of the electron density.
In this contribution we show that we can obtain information about the expansion of an EUV-induced plasma in argon by combining the TM_{010} and TM_{110} mode.

B18

Plasma assisted atomic layer deposition of molybdenum oxide using oxygen plasma

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Recently films of molybdenum oxide (MoO_x) have attracted interest due to their optical, electrical and catalytic properties. Films of MoO_x have been used for a variety of applications, for instance as hole extraction layers in solar cells [1] and as starting material for atomically thin layers of molybdenum disulfide, which are showing great potential for application in nanoelectronics [2].
This work presents a plasma assisted atomic layer deposition process to deposit films of MoO_x using bis(tert-butylimido)bis(dimethylamido) molybdenum, $(NtBu)_2(NMe_2)_2Mo$, as metalorganic precursor and oxygen plasma as oxidant. Although this precursor has been used with ozone [3], an O_2 plasma process has not been reported in literature. O_2 plasma as oxidant can offer benefits, such as increased growth rate, absence of ozone and low temperature compatibility.
The growth rate was determined to vary between 0.78 and 1.44 Å/cycle, depending on the deposition temperature. The optical and electric properties of the deposited films were investigated for varying plasma exposure time and deposition temperature. Using *in-situ* Spectroscopic Ellipsometry the film growth was monitored, while the stucture was studied by Atomic Force Microscopy and Raman Spectroscopy. Moreover, X-ray Photoelectron Spectroscopy and Rutherford Backscattering Spectroscopy were used to determine the chemical composition of the layers. Current work focuses on O_2-H_2 plasmas to enhance H-incorporation in the film, thereby possibly enabling effective surface passivation of c-Si.

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[2] Y.-C. Lin, *et al.*, Nanoscale, 2012, **4**, 6637
[3] A. Bertuch *et al.*, J. Vac. Sci. Technol. A, 2014, **32**, 1

B19

CO_2 dissociation in microwave plasmas

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Plasma-assisted gas conversion is considered as a building block within the concept of CO_2-neutral fuels, that is the production of synthetic fuels from intermittent, renewable electricity sources and (re-)cycling of CO_2 in a closed loop. Earlier studies have shown that the energy efficiency of CO_2 dissociation into CO may clearly exceed 50 % in high-frequency plasmas. CO_2 conversion in such plasmas is therefore a promising initial step in the full process chain from CO_2 towards fuels.
The aim of this study was two-fold: (i) to establish reactor design criteria to be able to achieve these efficiencies, and (ii) to (globally) characterise the discharge. A vortex-stabilised microwave plasma operated in undiluted CO_2 was studied throughout a wide range of gas flow rates and pressures (50–1000 mbar). Gas flow rates were varied to adjust the specific injected energy between 0.4 and 4 eV/molecule. Stable reaction products (CO_2, CO, O_2) were measured downstream by means of mass spectrometry and complementary tunable laser absorption spectroscopy. The emission from the plasma (200–2500 nm) was recorded spatially-resolved to map the distribution of excited atoms (C, O) as well as electronically (CO, C_2) and vibrationally (CO_2) excited molecular species. Depending on the (external) plasma parameters conversion efficiencies between a few and 25 % were achieved. Typically, low CO_2 conversion degrees are linked to energy efficiencies as high as 40 %, i.e. close to the desired range.

B20

Nonlinear growth of tearing modes: validating the generalized Rutherford equation

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The nonlinear growth of neoclassical tearing modes (NTMs) in tokamaks is commonly discussed in the framework of the generalized Rutherford equation (GRE). The GRE is an ordinary differential equation for the temporal evolution of the width, w, of the magnetic island associated with the NTM. It is obtained through averaging of the governing equations over the entire plasma domain covering the magnetic island, and thereby neglects many possible details of the island properties.
We present results from a 2D reduced MHD code that is developed specifically to validate the generalized Rutherford equation. The region encompassing a magnetic island is modelled as a planar slab with periodic boundary conditions in the direction of the helical angle. Radial boundary conditions are provided by the linear, ideal MHD equations in the exterior region. The code uses finite differences in the radial direction and a Fourier expansion in the helical angle. In the early linear phase of the mode, the exponential growth matches the predicted growth rate. When the island width exceeds the resistive layer width, the mode enters into the nonlinear regime and the island width grows proportional to time in quantitative agreement with the Rutherford equation. Only the fundamental Fourier harmonic is found to play a significant role, with higher harmonics remaining very small.

B21

Application of laser-cooling and compression to create a high resolution focused ion beam

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Ultra-low temperature (1 mK) ion beams can be created by photo-ionization of a laser cooled and compressed thermal atomic beam. When such an ion beam is introduced to a lens system, a focused ion beam (FIB) is formed which can be used to image, etch and deposit structures on the nanometer scale. Calculations and simulations have shown that an atomic beam brightness of $10^7\ \mathrm{A\,/\,m^2\,sr\,eV}$ can be achieved within a compact 7 cm long magneto-optical compressor (MOC). Particle tracer simulations taking all lens aberrations into account indicate that such an atomic beam, once fully photo-ionized, can be focused to a spot of 1 nm at a current of 1 pA, surpassing the industry standard for milling and deposition: the liquid metal ion source.

This contribution will report on the experimental realisation and the first laser cooling and compression experiments.

B22

Ion Velocity Distribution Measurements on the TU/e Fusor Plasma Using LIF Diagnostics

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We present an experimental study of the ion velocity distribution function (IVDF) of micro-channel structures a Farnsworth-Hirsh type spherical Inertial Electrostatic Confinement (IEC) discharge (Fusor). The structures are formed by converging ions, attracted towards the negatively biased semi-transparent cathode grid which is centrally positioned within a spherical grounded vacuum vessel, creates a highly non-thermal keV plasma core with enhanced fusion rates in the central region of the reactor. The work is conducted on the Fusor reactor developed at Eindhoven University of Technology, which supports a maximal DC acceleration voltage of 120kV at 100mA. Prior work on similar devices shows a link between the formation of virtual cathodes and the fusion rate performance of the discharge[1]. The goal of this project is to experimentally investigate the occurrence of such virtual cathodes as function of the key operational parameters by considering the IVDF of the accelerated ions. The low-lying $3d^4F_{7/2}$ metastable Ar-II ionic state velocity profile is studied by space-resolved Doppler-shifted laser-induced fluorescence spectroscopy. Preliminary results show only a thermal distribution of the probed species indicating that initial ionization and acceleration takes place mainly via other ionic states.
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