## Monday, June 25

10:00 Opening Ceremony

***Chairperson: Dr Evgenia Benova***

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| 10:15 | MICROWAVE DRIVEN AIR-WATER PLASMA SOURCE<br>**Dr Elena Tatarova**, *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal* | T3<br>I1 |
| 11:30 | MODELING OF NONEQUILIBRIUM RADIATION IN PLASMA SOURCES<br>**Dr Mario Lino da Silva**, *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal* | T3<br>I2 |
| 12:15 | ABSORPTION AND LIF TECHNIQUES APPLIED FOR HIGH DENSITY PLASMA DIAGNOSTIC<br>**Dr Valentin Pohoata**, *Faculty of Physics, Alexandru Ioan Cuza University of Iasi Iasi, Romania* | T3<br>I3 |

***Chairman: Dr Ilarion Mihaila***

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| 16:00 | MASS SPECTROMETRY OF ATMOSPHERIC PRESSURE SURFACE WAVE DISCHARGES<br>**Marco Antonio Ridenti**, *Laboratório Nacional de Ciência e Tecnologia do Bioetanol São Paulo, Brazil,*<br>*Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas – UNICAMP, Campinas, São Paulo, Brazil,* | T3<br>O1 |
| 16:25 | CONTINUOUSLY FILLED OPERATION MODE OF PULSED PLASMA ACCELERATOR CPU-30<br>**Prof. Anuar Zhukeshov**, *Science Research Institute of Experimental and Theoretical Physics, Kazakh National University named al-Farabi Almaty, Kazakhstan* | T3<br>O2 |
| 17:20 | A SIMPLE METHOD FOR EXPERIMENTAL DETERMINATION OF ELECTRON TEMPERATURE AND ELECTRON DENSITY IN A NANOSECOND PULSED LONGITUDINAL DISCHARGE USED FOR EXCITATION OF ATOMIC AND IONIC METAL AND METAL HALIDE VAPOUR LASERS<br>**Dr Krassimir Temelkov**, *Metal Vapour Lasers Laboratory, Institute of Solid State Physics, Bulgarian Academy of Science, Sofia, Bulgaria* | T3<br>O3 |
| 17:45 | NONEQUILIBRIUM MODELING OF PLASMA TORCHES USING A FULLY COUPLED JOULE HEATING MODEL<br>**Dr Bruno Lopez**, *Instituto de Plasmas e Fusão Nuclear, Laboratório Associado Instituto Superior Técnico, Universidade Técnica de Lisboa, Lisbon, Portugal* | T3<br>O4 |

18:10 NONEQUILIBRIUM MODELING OF PLASMA TORCHES USING A FULLY COUPLED JOULE HEATING MODEL T3

**Dr Dzmitry Tsyhanou**, *Instituto de Plasmas e Fusão Nuclear, Laboratório Associado Instituto Superior Técnico, Universidade Técnica de Lisboa, Lisbon, Portugal* O5

## Tuesday, June 26

***Chairman: Prof. Jean-Marie Noterdaeme***

9:30 THERMONUCLEAR BURN CRITERIA T1
**Dr Roger Jaspers**, *Science and Technology of Nuclear Fusion, Applied Physics, Eindhoven University of Technology Eindhoven, The Netherlands* I4

10:15 LANGMUIR PROBE MEASUREMENTS OF ELECTRON ENERGY DISTRIBUTION FUNCTION IN MAGNETIZED PLASMA T1
**Dr Tsviatko Popov**, *Faculty of Physics, St. Kl. Ohridski University of Sofia, Sofia, Bulgaria* I5

***Chairman: Dr Mario Lino da Silva***

11:30 A GENERAL ANALYSIS OF ELECTRIC PROBES T3
**Prof. Kyu-Sun Chung**, *Department of Electrical Engineering & Center for Edge Plasma Science, Hanyang University, Korea* I6

12:15 ELECTRICAL PROBES IN MAGNETIZED PLASMA T3
**Dr Ilarion Mihaila**, *Faculty of Physics, Alexandru Ioan Cuza University of Iasi, Romania* I7

## Workshop Plasmas for Environmental Issues

***Chairperson: Dr Elena Tatarova***

16:00 PLASMA-ASSISTED TREATMENT OF SUGAR CANE BAGASSE FOR ETHANOL PRODUCTION W
**Prof. Jayr Amorim**, *Laboratoire Nacional de Science et Technologie du Bioéthanol São Paulo, Brésil* I8

16:30 PRETREATMENT OF SUGARGANE BIOMASS BY ATMOSPHERIC PRESSURE MICROWAVE PLASMAS W
**Dr Francisco Dias**, Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal I9

17:30 PLASMACHEMICAL CONSERVATION OF CORRODED METALLIC OBJECTS W
**Vera Sazavska**, *Faculty of Chemistry, Brno University of Technology, Brno Czech Republic* O6

18:00 DISENTANGLING METASTABLE STATES KINETICS IN NON-THERMAL PLASMAS BY LASER DIAGNOSTICS AND MULTI-DIMENSIONAL MODELLING W
**Emile Carbone**, *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands* O7

18:30 PLASMA PARAMETERS OF A SMALL MICROWAVE DISCHARGE AT W

ATMOSPHERIC PRESSURE

**Dr Zh. Kiss'ovski**, *Faculty of Physics, Sofia University Sofia, Bulgaria* O8

## Wednesday, June 27

***Chairman: Dr Radomir Panek***

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| 9:30 | ACTIVE SPECTROSCOPY FOR FUSION REACTORS<br>**Dr Roger Jaspers**, *Science and Technology of Nuclear Fusion, Applied Physics, Eindhoven University of Technology Eindhoven, The Netherlands* | T1<br>I10 |
| 10:15 | PLASMA PERFORMANCE IN THE COMPASS TOKAMAK<br>**Dr Radomir Panek**, *Institute of Plasma Physics, Academy of Science of the CR, Prague, Czech Republic* | T1<br>I11 |

***Chairman: Dr Roger Jaspers***

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| 11:30 | OVERVIEW OF PROBE MEASUREMENTS IN COMPASS TOKAMAK<br>**Dr Renaud Dejarnac**, *Institute of Plasma Physics, AV CR v.v.i., Prague, Czech Republic* | T1<br>I12 |
| 12:15 | REMOTE GOLEM OPERATION<br>**Dr Jan Stockel** | T1<br>I13 |

***Chairman: Dr Jan Stockel***

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| 16:00 | WORKSHOP REMOTE GOLEM OPERATION<br>**Dr Jan Stockel**, *Institute of Plasma Physics Prague, Czech Republic* | |

## Thursday, June 28

***Chairman: Dr Tsviatko Popov***

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| 9:30 | PRESENT STATUS AND PROSPECTIVES OF THE FUSION RESEARCH<br>**Dr Jan Mlynář**, *Institute of Plasma Physics AS CR, v.v.i., Association EURATOM-IPP.CR, Za Slovankou 3, 182 00 Praha 8, Czech Republic* | T1<br>I14 |
| 10:15 | THE TECHNOLOGY OF HEATING AND CURRENT DRIVE IN FUSION PLASMAS (WITH SOME BACKGROUND PHYSICS)<br>**Prof. Jean-Marie Noterdaeme**, *Max Planck Institute for Plasmaphysics* | T1<br>I15 |

***Chairman: Dr Renaud Dejanrnac***

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| 11:30 | THE TECHNOLOGY OF HEATING AND CURRENT DRIVE IN FUSION PLASMAS (WITH SOME BACKGROUND PHYSICS)<br>**Prof. Jean-Marie Noterdaeme**, *Max Planck Institute for Plasmaphysics* | T1<br>I16 |
| 12:15 | SPONTANEOUSLY OCCURRING HELICAL STATES: A NEW PARADIGM FOR OHMICALLY HEATED FUSION PLASMAS<br>**Dr Emilio Martines**, *Consorzio RFX, Associazione Euratom-ENEA sulla Fusione, Padova, Italy* | T1<br>I17 |
| 14:00 | **EXCURSION** | |

## Friday, June 29

***Chairman: Dr Jan Stockel***

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| 9:30 | EQUILIBRIUM OF HIGH-TEMPERATURE PLASMA AND MAGNETIC FIELD IN THE MAGNETIC CONFINEMENT FUSION<br>**Dr Jan Mlynář**, *Institute of Plasma Physics AS CR, v.v.i., Association EURATOM-IPP.CR, Za Slovankou 3, 182 00 Praha 8, Czech Republic* | T1<br>I18 |
| 10:15 | THE TECHNOLOGY OF HEATING AND CURRENT DRIVE IN FUSION PLASMAS (WITH SOME BACKGROUND PHYSICS)<br>**Prof. Jean-Marie Noterdaeme**, *Max Planck Institute for Plasmaphysics* | T1<br>I19 |

***Chairman: Prof. Joost van der Mullen***

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| 11:30 | FIRST WALL POWER LOADING IN RAMP-UP PHASE OF ITER DISCHARGES<br>**Dr James Gunn**, *CEA, IRFM, Saint-Paul-lez-Durance, France* | T1<br>I20 |
| 12:15 | EFFECT OF GAS DISCHARGE CONDITIONS ON ATMOSPHERIC PRESSURE ARGON SURFACE-WAVE-SUSTAINED PLASMA<br>**Plamena Marinova**, *Sofia University, Sofia, Bulgaria* | T2<br>O9 |
| 12:40 | MODELLING OF MICROWAVE COAXIAL DISCHARGE AT LOW PRESSURE<br>**Todor Bogdanov**, *Sofia University, Sofia, Bulgaria* | T2<br>O10 |

16:00 **POSTER SESSION**

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| LIMITATIONS OF NORMAL MODE ANALYSIS IN A SIMPLE ANALYTIC MODEL FOR ABLATIVE STABILIZATION<br>**Prof. Ángel De Andrea González**, *Dpto. de Física. Escuela Politécnica Superior Universidad Carlos III de Madrid, Leganés, Spain* | T1<br>P1 |
| ON THE EXISTENCE OF A CONTINUOUS SPECTRUM IN SUPERNOVA REMNANTS: THE RAYLEIGH-TAYLOR INSTABILITY REVISITED<br>**Prof. Ángel De Andrea González**, *Dpto. de Física. Escuela Politécnica Superior Universidad Carlos III de Madrid, Leganés, Spain* | T1<br>P2 |
| REVISION OF THE STABILIZATION EFFECT ON THE RAYLEIGH-TAYLOR INSTABILITY BY QUANTUM EFFECTS<br>**Prof. Ángel De Andrea González**, *Dpto. de Física. Escuela Politécnica Superior Universidad Carlos III de Madrid, Leganés, Spain* | T1<br>P3 |
| 3D PARTICLE-IN-CELL SIMULATIONS OF THE TUNNEL PROBE<br>**Dr Michael Komm**, *Association EURATOM-IPP.CR, Prague, Czech Republic* | T1<br>P4 |

DETERMINATION OF THE EDGE PLASMA PARAMETERS BY DIVERTOR PROBES IN THE COMPASS TOKAMAK T1
**Dr Miglena Dimitrova** *Institute of Plasma Physics, Academy of Sciences of the Czech Republic v.v.i., Prague, Czech Republic* P5
*Emil Djakov Institute of Electronics, Bulgarian Academy of Sciences, Sofia, Bulgaria*

PLASMA POTENTIAL AND ELECTRON ENERGY DISTRIBUTION FUNCTION MEASURED BY VERTICAL RECIPROCATING LANGMUIR PROBE IN THE COMPASS TOKAMAK EDGE PLASMA T1
**Dr Miglena Dimitrova** *Institute of Plasma Physics, Academy of Sciences of the Czech Republic v.v.i., Prague, Czech Republic* P6
*Emil Djakov Institute of Electronics, Bulgarian Academy of Sciences, Sofia, Bulgaria*

PROBLEM-ORIENTED SIMULATION PACKAGES AND COMPUTATIONAL INFRASTRUCTURE FOR NUMERICAL STUDIES OF POWERFUL GYROTRONS T1
**Dr Milena Damyanova,** *Institute of Electronics of the Bulgarian Academy of Sciences, Association EURATOM-INRNE, Sofia, Bulgaria* P7

NONLINEAR EVOLUTION OF PLASMA MODES DRIVEN BY FAST IONS NEAR THE STABILITY THRESHOLD T2
**Grzegorz Galant** *Chalmers University of Technology, Gothenburg, Sweden* P8
*West Pomeranian University of Technology, Szczecin, Poland*

NEW DISCHARGE SOURCE FOR LASER SPECTROSCOPY IN METAL HYDRIDES T2
**Ivayla Bozhinova,** *Faculty of Physics, University of Sofia St. Kliment Ohridski, Sofia, Bulgaria* P9

MODELLING OF COAXIAL DISCHARGES SUSTAINED BY TRAVELLING ELECTROMAGNETIC WAVE T3
**Krasimir Ivanov**, *Sofia University, Sofia, Bulgaria* P10

EFFECT OF GAS DISCHARGE CONDITIONS ON ATMOSPHERIC PRESSURE ARGON SURFACE-WAVE-SUSTAINED PLASMA KINETICS T3
**Vladislav Marchev**, *Sofia University, Sofia, Bulgaria* P11

MODEL OF SURFACE WAVE SUSTAINED DISCHARGE AT ATMOSPHERIC PRESSURE T3
**Anton Ivanov,** *Faculty of Physics, Sofia University "St. Kl. Ohridski"5, J Bourchier Blvd., BG-1164, Sofia, Bulgaria* P12

2D MODEL OF GAS TEMPERATURE IN A NANOSECOND PULSED LONGITUDINAL He-$SrBr_2$ DISCHARGE EXCITED IN A HIGH-TEMPERATURE GAS-DISCHARGE TUBE FOR THE HIGH-POWER STROTIUM LASER T3
**Dr Krassimir Temelkov**, *Metal Vapour Lasers Laboratory, Institute of Solid State Physics, Bulgarian Academy of Science, Sofia, Bulgaria* P13

OPTIMIZATION OF PLASMA PARAMETERS IN A LASER-ABLATION HOLLOW-CATHODE DISCHARGE FOR SPECTRAL ANALYSIS T3

**Stefan Karatodorov**, *Institute of Solid State Physics, Bulgarian Academy of Sciences, Bulgaria* P14

ELEMENTAL ANALYSIS USING SELF-REVERSED PROFILES OF RESONANCE LINES IN LASER INDUCED PLASMA EMISION SPECTRA T3
**Kiril Catsalap**, B.I. Stepanov Institute of Physics, National Academy of Sciences, Minsk, Belarus P15

EFFECT OF HYDROGEN PLASMA ON MODEL CORROSION LAYERS OF BRONZE T3
**Petra Fojtíková**, *Faculty of Chemistry, Brno University of Technology, Brno, Czech Republic* P16

DISCHARGE IGNITION IN THE DIAPHRAGM CONFIGURATION SUPPLIED BY DC NON-PULSING VOLTAGE T3
**Lenka Hlochová**, *Faculty of Chemistry, Brno University of Technology, Brno, Czech Republic* P17

TWO DIMENSIONAL LASER DIAGNOSTICS AND PLASMA MODELLING OF AN ARGON SURFACE WAVE DISCHARGE T3
**Emile Carbone**, *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands* P18

OPTICAL DIAGNOSTICS OF PLASMA PLUME PRODUCED BY HIGH-FLUENCE NANOSECOND LASER ABLATION T3
**Dr Ilarion Mihaila**, *Faculty of Physics, Alexandru Ioan Cuza University of Iasi, Romania* P19

INFLUENCE OF THE SOFT X-RAY PLASMA FOCUS RADIATION ON THE PHOTOSYNTHESIS ACTIVITY OF THE BEAN PLANT LIVES T3
**Stanislav Zapryanov**, *Faculty of Physics, Sofia University, Sofia, Bulgaria* P20

THE BRANCHING OF $He_2$ $3s\sigma^3\Sigma^+_u$ STATE FORMATION IN GLOW DISCHARGE PLASMA T3
**Kuzman Paskalev**, *Faculty of Physics, Sofia University, Sofia, Bulgaria* P21

THE DIVERSE IN EXCITATION OF v=0 AND v=1 STATES OF $He_2$ $3s\sigma^3\Sigma^+_u$ IN GLOW DISCHARGE PLASMA T3
**Kuzman Paskalev**, *Faculty of Physics, Sofia University, Sofia, Bulgaria* P22

COLLISIONAL ELECTRON SPECTROSCOPY (CES) METHOD FOR GAS-ANALYSIS T3
**Todor Patrikov**, Institute of Solid State Physics, Bulgarian Academy of Sciences, Sofia, Bulgaria P23

## Saturday, June 29

***Chairman: Dr Francisco Dias***

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| 9:30 | PLASMA ZOOLOGY IN A TEMPERATURE WILDERNESS;<br>IS THAT GONNA WORK?<br>**Prof. Joost van der Mulen**, *Faculty of Applied Physics, Eindhoven University of Technology Eindhoven, the Netherlands* | T2<br><br>I21 |
| 10:15 | TWO DIMENSIONAL PLASIMO MODEL OF A SURFATRON PLASMA AT INTERMEDIATE TO HIGH PRESSURES<br>**Dr Manuel Jimenez-Diaz**, *Department of Applied Physics, Eindhoven University of Technology Eindhoven, The Netherlands* | T2<br><br><br>I22 |

***Chairman: Prof. Kyu-Sun Chung***

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| 11:30 | 2D NUMERICAL SIMULATION OF CAPACITIVELY COUPLED RF PLASMA SHOWER DEVICE<br>**Mariana Atanasova**, *Department of Applied Sciences, Université Libre de Bruxelles, CPI 165/04, 50 av. Fr. Roosevelt, 1050 Brussels, Belgium Department for Language Teaching and International Students, SU, 27 Kosta Loulchev St., 1111 Sofia, Bulgaria* | T2<br><br>O11 |
| 11:55 | MODELING OF HIGH POWER IMPULSE MAGNETRON SPUTTERING<br>**Ekaterina Iordanova,** *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands* | T2<br>O12 |
| 12:20 | UV EMISSION FROM MICROWAVE PLASMAS<br>**Edgar.Felizardo**, *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal* | T3<br>O13 |
| 12:45 | CLOSING | |

## Monday, June 25

# MICROWAVE DRIVEN AIR-WATER PLASMA SOURCE

Elena Tatarova
*Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal*

There exists growing interest in the potential applications of microwave plasmas at atmospheric pressure since such plasmas may enable lower facility and process costs for a variety of plasma processing and manufacturing techniques currently performed under vacuum conditions. Moreover, high-density plasma sources provide suitable conditions to dissociate molecules in abatement systems, to burn out chemical and biological warfare agents, and to atomize and synthesize materials in carbon nanostructures forming systems. In this respect, waveguide-based atmospheric plasma sources driven by surface waves (SWs) are an attractive alternative to classical sources, since they are compact, electrodeless, economical, and easy to operate.

In the present work we investigate both theoretically and experimentally a microwave driven air-water plasma as a source of active species of practical interest such as $O(^3P)$ ground state atoms, UV radiation, plasma-generated NO(X), etc. A theoretical model based on a self-consistent treatment of particle kinetics, gas dynamics, gas thermal balance, and wave electrodynamics is used to analyze the performance of this plasma source. The model includes coupled equations for the plasma bulk describing the kinetics of free electrons and of excited electronic states of molecules and atoms [$N_2(A)$, $N_2(B)$, $N_2(a')$, $N_2(a)$, $N_2(C)$, $N_2(a'')$, $N(^2D)$, $N(^2P)$, $O_2(a)$, $O_2(b)$, $O(^1D)$, $O(^1S)$], the chemical kinetics involving neutral molecules and ground state atoms [$N_2$, $O_2$, N, O, $O_3$, NO, $N_2O$, $NO_2$, $NO_3$, $N_2O_5$, $H_2O$, H, $H_2$, OH, $HO_2$, $H_2O_2$, $NH_3$, $NH_2$, NH, HNO, $HNO_2$, $HNO_3$], the kinetics of positive [$N_2^+$, $N_4^+$, $O^+$, $O_2^+$, $O_4^+$, $NO^+$, $NO_2^+$, $N_2O^+$, $H_2O^+$, $H_3O^+$, $H_2^+$, $H_3^+$, $HN_2^+$, $NH_3^+$, $NH_4^+$] and negative $[O^-, O_2^-, O_3^-, H^-, OH^-, NO_2^-, NO_3^-]$ ions, the gas thermal balance and the equation of mass conservation for the fluid as a whole. The wave dispersion and power balance equations are further incorporated into the system of equations. This model describes both the SW driven discharge zone and its flowing afterglow, as integral parts of the plasma source considered. The predicted plasma-generated NO(X), $O(^3P)$ and singlet delta oxygen $O_2(a^1\Delta)$ concentrations, and the intensities of atomic oxygen lines and NO(γ) band radiation along the source are presented and discussed as a function of two external parameters, *viz*., microwave power and water vapor percentage in the gas mixture. The relative concentrations of NO(X), $HNO_2$, $NO_2$ species in the exhaust gas stream of the source have been measured by mass analysis and Fourier transform infrared spectrometry and compared with the model predictions. Emission spectroscopy has been used to detect the plasma spectra emitted in the 250 – 850 nm range. The oxygen atomic lines at 777.4 nm, 844 nm and 630 nm, corresponding to the transitions $O(3p^5P \rightarrow 3s^5S)$, $O(3p^3P \rightarrow 3s^3S)$, and $O(2p^1D \rightarrow 2p^3P)$, respectively, and the NO(γ) band radiation in the range 230-260 nm (0-1, 0-2 and 0-3 vibrational transitions), corresponding to the electronic transition $NO(A^2\Sigma^+) \rightarrow NO(X^2\Pi)$ +hν, have been detected. The rotational spectrum of the $OH\left(A^2\Sigma^+, v=0 \rightarrow X^2\Pi j, v=0\right)$ transition in the 306–315 nm range has been measured for the purpose of gas temperature determination.

The plasma source considered has been applied for the treatment of biomass and the production of hydrogen by plasma decomposition of alcohols. Results of the investigation carried out in these areas of application are presented. Potential applications of this source such as NO - therapy and plasma decontamination are also addressed.

**References:**
[1] E. Tatarova, F. M. Dias, E. Felizardo, J. Henriques, M. J. Pinheiro, C. M. Ferreira, and B. Gordiets , J. Appl. Phys. **108**, 123305 (2010).
[2] C.M. Ferreira , B. Gordiets , E. Tatarova, J. Henriques, F.M. Dias, Chemical Physics (2011) http://dx.doi.org/10.1016/j.chemphys.2011.05.024

# MODELING OF NONEQUILIBRIUM RADIATION IN PLASMA SOURCES

M. Lino da Silva

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*Instituto Superior Técnico, Universidade Técnica de Lisboa, Lisbon, Portugal*

Plasma sources, either at atmospheric pressure or low-pressure, have rich radiative features which are typically provide a priviledged source of information on the local properties of a plasma. Diagnostics, such as optical emission and absorption spectroscopy or laser spectroscopy, yield spectra with rich features that can then be replicated synthetically.

The line-by-line approach is an exact method for reproducing such experimental spectra. This method relies on a supplied spectroscopic database of level energies and transition probabilities (Einstein coeficients) for the different electronic (atoms) and rovibronic transitions (diatomic molecules).

Selection rules have then to be accounted for, as well as several other approximations which allow the problem to be tractable (separation of the electronic and nuclear motion according to the Born-Oppenheimer approximation, rotational couplings calculated according to different Hund cases, etc...). Finally, the influence of the surrounding gas/plasma has to be accounted for line broadening effects (considering a Voigt profile including Doppler and pressure (Lorentz) broadening).

The most up-to-date techniques for line-by-line modeling will be discussed in this work, firstly outlining how a precise database of line positions and intensities can be achieved, followed by a discussion on the approximations that can be applied for assuming the plasma species internal levels populations (Boltzmann or otherwise), including on the methods that can be applied for extracting information on departures from Boltzmann equilibrium distributions. Several applications of the line-by-line method to the reproduction of experimentally determined spectra obtained in several plasma sources will then be discussed.

# ABSORPTION AND LIF TECHNIQUES APPLIED FOR HIGH DENSITY PLASMA DIAGNOSTIC

Valentin Pohoata[1], Vasile Tiron[1], Laura Velicu[1], Catalin Vitelaru[1,2], Ilarion Mihaila[1], Gheorghe Popa[1]

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Laser absorption spectroscopy using diode lasers is one powerful tool that can be used to investigate a large variety of atomic species present in a plasma environment. The narrowness of the diode laser bandwidth can go as low as 10 MHz, when is placed in an external Littrow cavity system, offering the highest spectral resolution among all type of available laser sources. An important advantage in using the laser absorption technique refers to the spectral line profile which is not affected by supplementary broadening as in emission spectroscopy, giving access directly to the investigated transition profile. The diode lasers are used in different absorption spectroscopy applications [1], to measure the temperature and mean density of the investigated species, which prove the versatility and relative high spectral accuracy of such techniques.

However, the use of Tunable Diode-Laser Absorption Spectroscopy (TD-LAS) requires homogenous plasma along the laser beam radiation acting volume. Such inconvenient is eliminated by using the Tunable Diode-Laser Induced Fluorescence (TD-LIF) technique, which offers local information on the absorption profile.

Moreover, in plasma environment, various line profile broadening / splitting mechanisms may occur. Consequently, different plasma parameters may be evaluated, as gas temperature from the van der Waals (neutral collision) broadening [2, 3], electron plasma density and electric fields in plasma by Stark broadening and shifting [4], velocity distribution function of neutral gas or its temperature from Doppler shift or broadening effect [5-7]. In magnetized plasmas, when Zeeman splitting of spectral line is large enough compared to other broadening or splitting mechanisms, the magnetic field amplitude can be measured [8] or some specific particularity of hyperfine structure of atomic levels can be described [9].

**Acknowledgments**: The financial support from the Grant POSDRU/89/1.5/S/63663 is highly acknowledged.

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[2] Ionascut-Nedelcescu, A. and Carlone, C. and Kogelschatz, U. and Gravelle, DV and Boulos, MI *J. Appl. Phys.* **103**(6), 063305 (2008).
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# MASS SPECTROMETRY OF ATMOSPHERIC PRESSURE SURFACE WAVE DISCHARGES

Marco Antonio Ridenti[1,2], J. A. Souza-Corrêa[1], J. Amorim[1,2]

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[2] *Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas – UNICAMP, Campinas, São Paulo, Brazil, Zip Code: 13083-859*

By applying mass spectrometry techniques, we carried out measurements of neutral and ionic mass spectrum and their ion energy distribution in order to investigate an atmospheric argon discharge by using a surfatron surface-wave device. The motivation of this study was to obtain a better understanding of an atmospheric pressure surface wave discharge that may play a key role on new second generation biofuel technologies.

Measurements were performed by changing forward power and flow rate of the input gas. For each experimental condition, the mass spectrum and energy distributions were measured by a Hiden EQP mass/energy analyzer HPR60. The mass and energy distribution measurements of neutral and ionic species were performed with fixed flow rate (2.5 SLM) of pure argon gas (99,999%), different forward powers (50 W, 100 W and 150 W) and different flow rates (5 SLM, 7.5 SLM and 10 SLM). In the case of ions, measurements were carried out with power of 100W and fixed flow rate (2.5 SLM) of an Ar-$O_2$ gas mixture, in which we varied its relative composition. The mass spectra and energy distributions were recorded for Ar, O, $O_2$, N and $N_2$ and their ions. The axial distribution profiles of neutral and ionic mass and their energy were obtained for different experimental conditions as a function of the plasma length.

The results showed that the peak of the positive ion energy distributions shifted to higher energies as a function of plasma length. Overall, the concentration of different neutral and ionic species were considerably dependent on plasma parameters. We also observed that under certain specific conditions the positive ion energy distribution exhibited two peaks. Another interesting result was that the axial distribution profiles of ionic mass may reach one or more maxima depending on the experimental condition. We propose some hypothesis to explain these observations based on the kinetics of reactions involving $Ar^+$ and some fundamental principles of plasma physics.

## CONTINUOUSLY FILLED OPERATION MODE OF PULSED PLASMA ACCELERATOR CPU-30

A.M. Zhukeshov, A.U.Amrenova and A.T.Gabdullina

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A pulsed plasma accelerator CPU-30 with coaxial geometry of electrodes, energy storage capacity 70 uF, up to 30 kV operating voltage was created for obtaining of powerful plasma flows. High power fluxes (up to 60 J/cm$^2$, 14 μs), generated by accelerator, can used in different applications such as surface cleaning, spraying and modification.

The performance of a PPA strongly depends on the geometry of its electrode system as well as on the mode of its operation. In this work investigate the "continuously filled" mode, then the working gas fills the space between to coaxial electrodes (diameter 9 and 3 cm, length 50 cm). That provides the ability to vary over a wide range of plasma density. This mode enables to obtain of plasma flow with a given spatial forms that look interest for different technical and technological applications of plasma accelerators. The mainly plasma parameters are: maximum flow velocity 9,6 cm/μs, electron temperature ~ 10 eV, density of plasma ~$10^{15}$ cm$^{-3}$.

The investigations are shown, that the plasma formation peculiarities and plasma parameters strongly depend on filling gas pressure before operation. So, when the pressure in the chamber below $10^{-1}$ Torr the distribution of current has diffused type and plasma has the maximum parameters specified above. At higher pressure current distributed predominantly in radial direction, but the plasma have significantly lower parameters. Studies using high voltage dividers and magnetic probes have shown that in accelerator there are HF fluctuations which have a significant influence on the process of acceleration. We investigated the role of inside electric fields on plasma formation process and it accelerating.

Numerical calculations show that the movement of particles between electrode space of plasma accelerator is depends of operating pressure or density of the plasma. At low density a condition of quasineutrality does not play a significant role, the movement of particles should be independent. Dynamics of particles in dense plasma is corresponding to the Hall's field. The concentration above which should take into account this field is $10^{15}$-$10^{16}$ cm$^{-3}$.

Researched features of plasma formation can be used to create high energy ions sources, because accelerating ions electric field far more efficiently than magnetic. By selecting the required working pressure to make such device is possible. In addition, these effects can be used for electron-ion materials production technologies in materials with given properties.

# A SIMPLE METHOD FOR EXPERIMENTAL DETERMINATION OF ELECTRON TEMPERATURE AND ELECTRON DENSITY IN A NANOSECOND PULSED LONGITUDINAL DISCHARGE USED FOR EXCITATION OF ATOMIC AND IONIC METAL AND METAL HALIDE VAPOUR LASERS

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Gas and electron temperatures together with electron density are the most fundamental plasma parameters in gas discharges and play a very important role in understanding of numerous phenomena in gaseous discharges, laser physics, plasma technologies, gas-discharge mass spectroscopy, absorption and emission spectroscopy, and plasma in general. One of the main problems in plasma physics is the determination of characteristic constants for basic processes in plasma, such as asymmetric charge transfer, Penning ionization, diffusion, heat conduction, and electron-heavy particle collisions, which are fundamentally important and widely used in the abovementioned fields.

Elastic and inelastic electron-heavy particle collisions, such as electron impact excitation, de-excitation, and ionization, as well as three-body recombination, depend on the electron temperature. Measurements of electron temperature by Langmuir probe are not suitable for pressure of helium (He) or neon (Ne) above 10 Torr, especially in high-voltage and high-current nanosecond pulsed longitudinal discharges. Laser Thomson scattering measurements of electron temperature have been proved to be effective but challenging because of the low signal and excessive stray light, as well as the complicated experimental setup. In the literature there are several models of varying degrees of complexity, which predict, among the other parameters, values of electron temperature with considerable variation, and furthermore there is no overlap.

Under conditions of Local Thermodynamic Equilibrium measurement of the relative intensities of some He and Ne spectral lines originating from different upper levels enabled us to determine the average electron temperature, as well as the time-resolved electron temperature in the discharge afterglow, in a nanosecond pulsed longitudinal discharge in He, Ne and Ne-He mixtures.

Unfortunately, spectral investigation through devices equipped with photomultiplier are prohibited for the discharge period of a nanosecond pulsed longitudinal discharge, because of the noise from high-power electrical pulses and the steep rise of voltage and current pulses of $TV.s^{-1}$ and $GA.s^{-1}$. That is why, a simple method based on the time-resolved measurement of electrical discharge parameters, such as tube voltage and discharge current, is developed and applied for determination of electron temperature and electron density in the discharge period of a nanosecond pulsed longitudinal discharge, exciting DUV $Cu^+$ Ne-CuBr, He-$Hg^+$ and He-$Sr^+$ lasers. The obtained results are in fairly good agreement with the existing self-consistent models or with the theoretical estimations.

# NONEQUILIBRIUM MODELING OF PLASMA TORCHES USING A FULLY COUPLED JOULE HEATING MODEL

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The numerical modelisation of a DC plasma source operating at low power and low mass flow rate is presented. Such plasma sources are currently used in many technological applications in both the industrial and reseach areas since they represent an efficient tool to generate non-equilibrium plasma gas flows ranging from the subsonic to the hypersonic flow regime. In arcjet facilities, the cathodic thermo-electronic emission initiated by a high-frequency high-voltage pulse gives rise to an electric arc characterized by strong electronic current densities. This results in an intensive Joule energy dissipation from the electric arc to the flowfield which causes very high electronic energies, thus leading to thermal non-equilibrium conditions between electrons and heavy particles and to a departure of electronic level populations from the equilibrium Boltzmann distribution. If molecular species are considered, the arc-heated gas is then rotationally and vibrationally excited and partially dissociated. The energy transfers from the rotational and vibrational energy modes to the translational mode need to be considered as well as ionisation processes. As a consequence, the numerical description of arcjets represents a challenging task since it requires a multi-physics approach in which hydrodynamics, thermodynamics, kinetic and the electric arc tightly coupled. The accurate modelisation of the Joule heating phenomenon is fundamental since the energy added to the flow by ohmic dissipation then enables all the other processes to occur. Joule heating being highly sensitive the thermodynamic state of the gas, a fully coupled Joule dissipation model has been developed and applied to -thermo-chemical non-equilibrium plasma for both atomic and molecular gas mixture. The present study underlines the influence of both the chemical kinetic and electric arc model on the flowfield properties.

# NONEQUILIBRIUM MODELING OF PLASMA TORCHES USING A FULLY COUPLED JOULE HEATING MODEL

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In this work, we present a multiquantum state-specific model for the simulation of High-speed Shocked Flows in Titan's atmosphere.

The atmosphere of Titan is composed from 98% $N_2$-2% $CH_4$, and therefore, chemical kinetics involving the $N_2$ molecule are predominant. Furthermore, as models of postshock relaxation processes, based on macroscopic/multitemperature models, are known to not have an accurate enough description of such physical processes, a hybrid macrsocopic/state-to-state chemical model is proposed based on a recently proposed multiquantum state-to-state rate database for $N_2$ dissociation [1], developed by our research group, using the Forced Harmonic Oscillator (FHO) Model.

The results predicted by this model are then compaired against recent shock-tube data from the University of Queensland, and the Moscow Institute for Physics and Technology (Shock-Tube VUT-1)

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## Tuesday, June 26

# THERMONUCLEAR BURN CRITERIA

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Why is it so difficult to produce net power energy for fusion reactions, when it is relatively easy to accelerate nuclei to the required energy and collide them on a solid target? In this lecture course the effect of Coulomb collisions, bremsstrahlung, helium production, energy confinement, energy efficiency etc. will be addressed to arrive at a criterion for ignition of a nuclear fusion reactor.

# LANGMUIR PROBE MEASUREMENTS OF ELECTRON ENERGY DISTRIBUTION FUNCTION IN MAGNETIZED PLASMA

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Among the contact methods of plasma diagnostics, the electric probes are the least expensive and still the fastest and most reliable diagnostic tools allowing one to obtain the values of important plasma parameters - Langmuir probes allow local measurements of the plasma potential, the charged particles density and the electron energy distribution function (EEDF). Although the electric probe method is as old as plasma physics itself, the potential of the method has not yet been fully exploited. New probe theories and designs constantly appear with the results summarized in numerous reviews and monographs. In spite of this, incorrect applications of electric probes are commonly found in the literature. The errors mainly arise from a lack of awareness about the multitude of regimes of probe operation and the limits of validity of theories.

In this work the methods for using Langmuir probes in magnetized plasmas are reviewed. The electron part of the current-voltage probe characteristic is used in order to obtain the plasma potential and EEDF (respectively electron temperature and electron density). At low values of the magnetic field up to 0.04 T the extended second derivative probe method is used, since in the range 0.04 – 0.3 T the first derivative method is applied. In high temperature turbulent tokamak edge plasma (magnetic field of 1-2 T) a modified firs derivative method is proposed and used. Comparison of the results obtained with probes perpendicular and parallel to the magnetic field results in satisfactory agreement.

The use of the Langmuir probes with perpendicular and parallel orientation to the magnetic field for negative ion density evaluation in electronegative gas discharge plasma is also discussed.

The results presented demonstrate that the procedures proposed allow one to acquire the main plasma parameters using the electron part of the current-voltage Langmuir probe characteristics in magnetized plasmas.

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**A GENERAL ANALYSIS OF ELECTRIC PROBES**

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Deduced plasma density and Mach number would be severely different from those by collisionless models if plasma were in the complex conditions with magnetic field, various atomic processes (ionization, various recombinations, and ion-neutral collision including charge-exchange), or charged states of the plasmas due to multiply-charged ions and negative ions. Hence, a general model or models would be necessary by including these parameters.

A Mach probe (MP) is an electric probe system to deduce the plasma flow velocity from the ratio of the ion saturation currents. Generally, a typical MP is composed of two directional electric probes located at opposite sides of an insulator, which is mostly used as a parallel MP, but there are other MP's such as perpendicular MP (PMP), Gundestrup probe (GP) or rotational probe (RP), and visco-MP (VMP), depending upon the shape of the probe holder, location of different probes, or the way of collecting ions. For the parallel MP (to be called an MP), the relation between the ratio of the upstream ion saturation current density ($J_{up}$) to the downstream ($J_{dn}$) and the normalized drift velocity ($M_\infty = v_d \big/ \sqrt{T_e/m_i}$) of plasma has generally been fitted into an exponential form ($R = J_{up} \big/ J_{dn} \approx \exp[KM_\infty]$). For the GP or RP, VMP and PMP, models for the deduction of Mach numbers are to be given. Normalized drift velocity of the flowing plasmas is deduced from the ratio ($R_m$) measured by an MP as $M_\infty = \ln[R_m]/K$, where $K$ is a calibration factor depending upon the magnetic flux density, collisionality of charged particles and neutrals, viscosity of plasmas, and ion temperature, etc. Existing theories of Mach probes in un-magnetized and magnetized flowing plasmas are introduced in terms of kinetic, fluid and particle-in-cell models or self- and self-similar methods along with key physics and comments.

Since the ion saturation current density is dependent upon the magnetic field, collisionality and charge states of the plasmas, the deduced density of the unperturbed plasmas should be changed accordingly, if one-directional electric probe is used. If one uses a spherical, cylindrical or planar probe exposing two sides (or all sides) of the probe to the plasma, flow effect could be canceled while other effects is still valid.

To confirm the method of deduction of Mach numbers and densities, the independent diagnostics such as laser-induced fluorescence (LIF) and laser Thomson scattering (LTS) methods will be addressed. Data of Mach probe has been compared to those by LIF and those of SP are compared to those by LTS.

# ELECTRICAL PROBES IN MAGNETIZED PLASMA

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The Langmuir probe used in magnetized plasma has clear particularities. The anisotropy induced by the magnetic field makes the current-voltage (I-V) probe characteristic dependent on the probe orientation with respect to magnetic field lines especially for both plane and cylindrical probes [1-3]. The large difference between ion and electron Larmor radius makes the probe characteristic dependent on the gas nature and pressure, probe size, magnetic field strength [4, 5].

The present work reports on the experimental results obtained with tungsten cylindrical probes in magnetized plasma having as parameters the probe length and radius, magnetic field strength, probe orientation, gas nature and pressure. Moreover, due to anisotropy produced by magnetic field it is shown that space charge around the probe and its insulated shaft related to edge effect may play an important role on kinetic of the plasma particles collected by the probe with direct consequences on real form of the probe characteristics. Also the behavior of a Langmuir probe inserted in magnetized plasma was simulated with a Monte Carlo code.

The magnetized argon or hydrogen plasma column was produced inside of a cylindrical glass tube between a multipolar plasma source placed at one end and a hollow grounded anode at the other end. The discharge current intensity in the plasma column was up to 1 A and the gas pressure ranged between $2\times10^{-4}$ and $10^{-2}$ Torr. The magnetic field strength was in the range of 0-420 mT. Cylindrical probes made of tungsten wire of 0.25, 0.5 and 1.6 mm in diameter were used with variable length from 0 to 5 mm.

The Monte Carlo code computes the trajectories of the charged particles from the magnetized plasma and calculates the particle fluxes collected by the probe. The electric field distribution around the probe was calculated by solving the Poisson equation for each value of the probe voltage.

It is shown that when increasing the probe length the so-called „classical" probe characteristic is changing and starting with a certain probe length a negative slope appears in the region above plasma potential [6].

As additional diagnosis, the global light intensity in visible range emitted by the plasma volume around the probe was recorded during the acquisition of I-V probe characteristics. The light intensity is dependent on the probe bias and exhibits a maximum which might correspond to the plasma potential. A qualitative explanation of the cylindrical probe characteristics with a negative slope is presented. The proposed model also explains the increasing of the light emission when the probe bias is close to the plasma potential.

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# PLASMA-ASSISTED TREATMENT OF SUGAR CANE BAGASSE FOR ETHANOL PRODUCTION

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Nowadays, the cellulosic ethanol is an important alternative way to many liquid biofuels using renewable biomass rich in polysaccharides. To be used as feedstock for ethanol production, the bagasse from sugarcane mills needs to be pretreated in order to expose its main constitutive. These activities are being developed at the Brazilian Bioethanol Science and Technology Laboratory (CTBE) which is a national laboratory that aims at contributing for the maintenance of Brazilian leadership in the sustainable production of ethanol from sugarcane. To accomplish this goal, the Center invests internally and through strategic partnerships in basic research and technological innovation. The present work proposes the use of different pretreatment processes to better expose the cellulose for hydrolysis and fermentation. An ozonizer based on atmospheric pressure DBD device was employed to treat wet sugarcane bagasse. The power supply (10.0 kHz and 13.0 kV) was connected to the DBD set-up composed of two coaxial electrodes separated by a ceramic tube. The system was fed by 0.9 slm of oxygen, purity of 99.999%. An optical fiber was connected to the entrance slit of a monochromator (0.55 m focal length and 1800 lines/mm grating) and placed perpendicular to a quartz absorption cell (i.d. 0.8 cm). Ozone concentrations were determined before and during the bagasse treatment. The experiments, lasting 6h, were carried out by monitoring the absorption of ozone molecules on Hg emission line at 253.65nm. The detector used to record the spectra was a CCD 1024x256 pixels. Mass spectrometry is used to monitor the volatile species during the treatment. Removal of lignin was achieved and the results will be shown during the presentation.

# PRETREATMENT OF SUGARGANE BIOMASS BY ATMOSPHERIC PRESSURE MICROWAVE PLASMAS

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Nowadays, increasing attention and effort are focused on the production of renewable fuels, especially bio-ethanol from lignocellulosic biomass. This process generally involves hydrolysis of the cellulose to produce simple sugars. Sugarcane biomass consists of cellulose, hemicelluloses and lignin, which are packed together in the cell wall. To reach a fermentable condition, the biomass requires relatively harsh pretreatment processes. Some of the important objectives of pretreatment of biomass are to break the lignin-hemicellulose complex, increase the porosity of the biomass and disrupt or loosen-up the crystalline structure of cellulose. A number of chemical, physical and biological pretreatment techniques are used with different success and cost-effectiveness, depending on the type and size of biomass [1, 2]. In this work, a microwave plasma torch is applied as a pretreatment technique for sugarcane bagasse.

A 2.45 GHz microwave plasma torch operating at atmospheric pressure in Ar-steam-air mixtures and in pure air plasmas has been applied for sugarcane bagasse pretreatment. Sugarcane baggase, crushed to a 0.5 mm size, is supplied by *Usina da pedra*, *Brazil*. Using pure air plasma is particularly interesting from the economical point of view. The samples of dry biomass (~2 g) have been exposed to the afterglow plasma jet. The highly reactive plasma environment provides suitable conditions to destroy the lignin and hemicellulosic wrapping. The samples have been placed in the afterglow at different distances from the discharge end (d = 2 - 10 cm) and were treated for different exposure times (t = 2 - 20 min). Pretreatment conditions were optimized with respect to microwave power and gas flux and composition. Scanning Electron Microscopy (SEM) has been applied to analyze the morphological changes of the treated samples.

While the sugarcane fibers of untreated samples have a smooth surface, treated fibers have exfoliated surface with numerous defects such as deep cracks, pits and corrugations. The steam has been introduced by bubbling Ar gas through water heated up to 70°C. The surface is significantly damaged as compared to the untreated sample as seen from the figures. The deterioration of the surface morphology is much more pronounced when air plasma is used for the treatment. As a rule, prolonging the exposure time increases the morphological changes of the surface. The porosity of the sample tends to increase with the delivered microwave power and the total gas flow.

The results obtained demonstrate significant surface modification due to the plasma etching effect resulting in destruction of the lignin layer. The exhaust gas streams have been analyzed by mass spectrometry and Fourier-Transform Infrared Spectroscopy (FT-IR). Optical spectroscopy has been applied to identify the main active species.

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# PLASMACHEMICAL CONSERVATION OF CORRODED METALLIC OBJECTS

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Plasmachemical process for conservation of metallic objects is a new way of effective and fast treatment of corroded objects. This process consists of two main steps: corrosion removal and deposition of a protecting film.

Removal of corrosion products is based on plasmachemical reduction of corrosion layers by radio-frequency (RF) low pressure hydrogen plasma. This careful method is intended for the treatment of metallic archaeological objects. This technology is usually used for iron artifacts, but we remove corrosion products also from copper, bronze and brass samples. Plasmachemical treatment of corroded metallic objects provides several significant advantages compared with conventional restoration techniques, such as preservation of tiny details and the quality of the object surface. Moreover, the traditional process of artefacts preservation is a significantly longer term procedure.

The optical emission spectroscopy of created OH radicals was used for the process monitoring. Integral intensity of OH radicals was used for the quantitative analysis of oxygen removal from the corrosion layers. Corroded and treated objects were analyzed by a SEM-EDX method in order to determine changes of their surface elemental composition caused by hydrogen plasma.

Surface of treated object is highly reactive and inclines to rapid oxidation by air oxygen. To prevent this process, it is necessary to protect the surface by a barrier thin film preventing the penetration of oxygen (as well as the other corrosion agents) to the surface. The barrier film must not change optical properties and have to be removable without damage of object. Suitable barrier films are parylene (poly-para-xylylene) coatings and $SiO_2$-like high density films.

Parylene coatings are chemically inert, conformal and transparent with excellent barrier properties but relatively small adhesion. Parylene coatings are prepared by a standard chemical vapor deposition (CVD) method. $SiO_2$-like high density films have very good barrier properties and excellent adhesion. Plasma enhanced chemical vapor deposition (PECVD) enables preparation of $SiO_x$ based thin films with higher flexibility due to variable incorporated organics groups.

The coatings were characterized by various methods in order to obtain information about their thickness (ellipsometry), chemical structure (FTIR), surface morphology (LCSM, SEM) and barrier properties (OTR). Standard corrosion tests were performed to determine the effectiveness of corrosion protection.

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# DISENTANGLING METASTABLE STATES KINETICS IN NON-THERMAL PLASMAS BY LASER DIAGNOSTICS AND MULTI-DIMENSIONAL MODELLING

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Due to their high reactivity and usually long life time, metastable states can play an important role in plasma kinetics. In non-equilibrium, high pressure plasmas they can even overcome the densities of the ion species and become, *de facto,* the most important species, both for the plasma kinetics and for the applications[1]. However, as they do not emit any radiations, their direct experimental detection can be very complex.

The combination of laser diagnostics, namely Thomson scattering and Laser Collisional Induced Fluorescence (LCIF)[2], and zero dimensional (up to 2D) modelling of plasmas sources allows to unravel both experimentally and theoretically the pathways of creation of metastables.

In this contribution, we will present the 2D modelling of an Argon atmospheric RF plasma shower[1] which is widely used for environmental-friendly applications, e.g. surface cleaning. Due to its small size and embedded structure, it is however highly complicated to apply any direct diagnostic techniques. We will show that it is nevertheless possible to study and validate *plasma chemistries* while investigating rather similar plasma sources and translating them into a general kinetics frame via global models. A surface wave discharge (SWD) was investigated by LCIF and Argon metastable kinetics could be monitored directly via the nanosecond time resolved response of the 811 nm Argon line. A path for the validation of plasma models for which experimental data is hardly attainable is proposed.

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# PLASMA PARAMETERS OF A SMALL MICROWAVE DISCHARGE AT ATMOSPHERIC PRESSURE

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Environmental and industrial applications of microwave discharges at atmospheric pressure require the development of reliable diagnostic methods for monitoring of the plasma parameters. This study presents a double probe diagnostics system for determination of the plasma parameters of a small microwave plasma source. Plasma source is based on a surface wave sustained discharge at 2.45 GHz. It works with argon gas at atmospheric pressure both in continuous and pulse regimes.

In the theory for calculation of plasma parameters from double probe characteristics usually is assumed that the electron energy distribution function is close to Maxwellian. In atmospheric pressure plasmas the tail of EEDF is close to Maxwellian if the plasma density is higher than the specific value. The EEDF shape at different values of electron concentration can be obtained by solving the Boltzmann equation. Self-consistent model of the small microwave discharge is developed and it includes surface wave dispersion relation, Boltzmann equation under the local approximation and heavy particles balance equations. The effect of the EEDF tail of the atmospheric pressure plasma on the double probe characteristics is investigated. Electron temperature and plasma density are calculated from the current-voltage double probe characteristic with an appropriate theory for ion saturation current. Initial information for gas-discharge parameters such as gas temperature, gas flow velocity are taken into account.

# ACTIVE SPECTROSCOPY FOR FUSION REACTORS

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A brief introduction into the spectroscopy of fusion plasmas is presented. Basic principles of the emission of ionic, atomic and molecular radiation are explained and a survey of the effects, which lead to the population of the respective excited levels, is given. Line radiation, continuum radiation, opacity and line broadening mechanisms are addressed.

To access the hot plasma core however a fundamental hurdle should be taken, since the fully ionized particles do not emit line radiation. Active spectroscopic techniques have been develop of which charge exchange recombination spectroscopy and Thomson scattering are treated in some detail.

# PLASMA PERFORMANCE IN THE COMPASS TOKAMAK

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The COMPASS tokamak, which has recently started operation in Institute of Plasma Physics in Prague, represents a smaller device for study of fusion plasma. Despite of its size, it has a large potential to contribute to solution of several principal problems of the ITER tokamak operation as well as to address some of basic physics phenomena. The COMPASS tokamak is equipped by a comprehensive set of plasma diagnostics with a high spatial and temporal resolution with a focus on edge plasma, which is essential for full understanding of underlying physics in this region.

In this contribution, basic features of the COMPASS tokamak will be described. Results on plasma performance in the ohmic regime will be shown for circular cross section of the plasma column as well as for D-shape plasmas with the X point configuration. The problems connected to the stabilization of plasma position will be also discussed. Afterwards, the system for the additional plasma heating by means of the injection of the beam of energetic hydrogen atoms will be introduced. Finally, some of key problems of present tokamak research like pedestal physics, Edge Localized Modes mitigation using resonant magnetic perturbations, will be addressed including plans for research on the COMPASS tokamak in these fields.

# OVERVIEW OF PROBE MEASUREMENTS IN COMPASS TOKAMAK

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Measurements in the edge plasma of tokamaks are needed in order to evaluate particle and energy fluxes reaching the wall. The plasma on the open magnetic flux surfaces that intersect solid objects, the scrape-off layer (SOL), plays an important role in the global behavior of the plasma. Fueling and impurity transport are both governed by the electron density and temperature as well as by the plasma flows inside the SOL. In tokamaks Langmuir probes (LPs) are frequently used to characterize the edge plasma. The perturbation generated by a probe in the SOL can be described by plasma models that relate the measurements to the unperturbed quantities that would exist if the probe were absent. Generally, the models, which contain the same equations that are used to model the SOL itself, assume that the velocity distributions of charged particles are Maxwellian. This might not be true if collisionality is low enough, in which case probe measurements are strongly influenced by kinetic effects.

In this paper, we will briefly review the theory of Langmuir probes in strongly magnetized plasmas. We will see that even if LPs are simple diagnostics, the interpretation is not straightforward. Then we will present the different kind of electrostatic probes installed in the COMPASS tokamak, as well as the probes that are in development and which will be added to our diagnostic range in a near future. LPs remains valuable diagnostics to estimate local plasma parameters and IPP Prague has a 30 year long experience with electrostatic probes in tokamaks. This know-how still benefits COMPASS to characterizing the edge plasma and LPs are precious, robust diagnostic for tokamaks. Finally, experimental results from available probes, in the COMPASS divertor and on the 2 reciprocating manipulators, will be presented and discussed.

# BASICS OF REMOTE OPERATION OF A TOKAMAK

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This tutorial lecture is devoted to introducing the tokamak principle on a very basic level with the aim to prepare participants for remote operation of the GOLEM tokamak from Kiten during the satellite workshop, which is held on June 27, 2012 afternoon. Attention will be paid to the formation of toroidal magnetic and electric fields in the tokamak vessel, breakdown of the working gas and ohmic heating.

Next, the GOLEM tokamak, operational at the Faculty of Nuclear Physics and Physical Engineering, will be described with sufficient details. In particular, we will focus on the description of:

- Power supplies
- Vacuum and gas handling systems
- Necessary steps for conditioning of the tokamak vessel (baking and glow discharge cleaning)
- Available diagnostic tools (magnetic and optical diagnostics, probes, HXR spectrometer and fast camera)
- Structure of the GOLEM database.

Participants will be informed how to read experimental data, Simple examples of data processing will be presented (e.g. how to calculate the edge safety factor and to estimate the electron temperature, ...).

## PRESENT STATUS AND PROSPECTIVES OF THE FUSION RESEARCH

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This talk will provide, on a rather popular level, an up-to-date overview of the present status in the fusion research. It will be focused on the current challenges, the new major projects and future research concepts, with an ample use of illustrations throughout the presentation. Recommendations for further reading shall be included.

To start with, the present major research centres in both the Inertial Confinement Fusion (ICF) and Magnetic Confinement Fusion (MCF) will be overviewed. This will cover in particular the National Ignition Facility NIF, the Joint European Torus JET, as well as EAST, K-STAR and some other examples. Next, the ITER mission will be detailed. The ITER construction status will be presented, and the role of the Domestic Agencies explained, with a special mention of F4E. Broader Approach agreement shall be presented, including the JT-60SA satellite tokamak and the IFMIF EVEDA programme and prospective, in relation to major existing challenges in the fusion research. Some other proposed concepts will be mentioned, e.g. Fusion for Neutrons, the Ignitor project and the hybrid reactors. Last but not least, status of the conceptual project for the first MCF power plant DEMO will be discussed, in comparison to the ICF power plant design.

In the final part, the present status of the fusion research will be put into context with the situation in the energy supply, and some more audacious, long term thinking on the possible future of fusion research will be outlined.

# THE TECHNOLOGY OF HEATING AND CURRENT DRIVE IN FUSION PLASMAS (WITH SOME BACKGROUND PHYSICS)

Jean-Marie Noterdaeme

*Max Planck Institute for Plasmaphysics*

Plasmas need to be heated to high temperature for fusion to occur.

Over the years, a number of heating methods have been successfully developed.

In order for a heating method to be successful, it must be able to achieve four steps:

1. transform electrical energy into some other form of energy (such as particle energy or electromagnetic energy)
2. transport this outside of the plasma from the location of generation to the plasma (using e.g. waveguides)
3. transport this inside the plasma (e.g. with waves)
4. absorption inside the plasma of this energy and thermalisation.

The lecture shows the technological aspects and physics background of those 4 steps in the case of 4 heating methods (NBI, ECRH, LH, ICRF), providing a sound basis for engineers and scientists working or planning to work in this area.

# SPONTANEOUSLY OCCURRING HELICAL STATES: A NEW PARADIGM FOR OHMICALLY HEATED FUSION PLASMAS

Emilio Martines and the RFX-mod team

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The Reversed Field Pinch (RFP) is a toroidal configuration for magnetic confinement of plasma, which constitutes a possible alternative to the tokamak in the quest for a fusion reactor. In the past, the RFP was considered unable to achieve good confinement properties, due to the intrinsic presence of MHD modes in the nonlinear saturated stage. These modes are responsible for the configuration sustainment, through the so-called dynamo process, but also cause magnetic chaos.

This picture is now changed, thanks to the realization that a single mode is sufficient to sustain the configuration. This chaos-free condition, labeled Single Helicity (SH) state, has been observed to actually occur in numerical simulations. In RFX-mod, the largest RFP device in the world, operating in Padova (Italy), a condition labeled Quasi Single Helicity (QSH) has been observed to occur spontaneously. The QSH state exhibits the dominance of a single MHD mode, with the others (secondary modes) having a reduced amplitude.

The QSH state is found to occur more frequently as the plasma current is increased. More specifically, the persistence, that is the fraction of the flat-top phase in which the plasma stays in QSH state, is found to increase with plasma current, while the normalized amplitude of the secondary modes decreases with current, giving rise to purer and purer QSH states.

At high plasma current levels a transition in the magnetic topology of the QSH state is observed. The X-point of the magnetic island formed by the dominant mode annihilates with the O-point corresponding to the main magnetic axis of the discharge, and the island O-point survives as the new magnetic axis. This new magnetic axis is helically shaped, and the ensuing state has been therefore labeled Single Helical Axis (SHAx) state. The resulting plasma is reminiscent of those formed in helical devices, but its occurrence is spontaneous. The transition to the SHAx state is also observed on thermal measurements, through the formation of a hot helical core surrounded by an internal transport barrier.

A reconstruction of the equilibrium configuration has been implemented in a code named SHEq, where SHAx states are modeled as pure Single Helicity (SH) states, composed of the superposition of an axisymmetric toroidal and of the dominant mode eigenfunction m/n=1/7 neglecting the effect of the residual secondary modes. This eigenfunction is obtained solving the force-free Newcomb equation, which provides the perturbation to the poloidal and toroidal flux functions, $\psi P$ and $\psi T$, over the whole plasma volume.

Through the definition of a new poloidal angle, defined with respect to the helical axis, flux surface averages of any quantity can be computed. In particular, the surface-averaged ohmic input power has been calculated and plugged into the averaged power balance equation, yielding an evaluation of the thermal conductivity, which turns out to be around 10 m2/s in the region of the internal transport barrier.

The problem of determining the safety factor, q, was solved by using a transformation to action-angle coordinates, which naturally descends from the Hamiltonian description of the magnetic field lines. The resulting q profile is almost flat in the inner bean-shaped region.

## EQUILIBRIUM OF HIGH-TEMPERATURE PLASMA AND MAGNETIC FIELD IN THE MAGNETIC CONFINEMENT FUSION

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In this contribution, basics of the force equilibrium between high temperature plasma and magnetic field shall be explained using both the fluid description in the ideal magneto-hydrodynamic (MHD) and the description of trajectories of charged plasma particles.

Fundamental facts shall be reviewed first, including the difference between equilibrium and stability and basics of plasma behaviour in an external magnetic field. Next, the simpler case of plasma equilibrium in a cylindrical field will be studied, in particular with respect to the basic MHD relation among the plasma pressure gradient, the electric current density and the external magnetic field. The major part of the talk shall be then focused on the most widespread magnetic field configuration in the magnetic confinement fusion experiments, the tokamak (notice that the international project ITER is a tokamak). The conditions for equilibrium in tokamaks will be detailed, with a special attention given to the shape of the magnetic field lines. The requirement for a vertical magnetic field will be explained as well as the resulting additional electric current in the plasma known as the Pfirsch-Schlüter current.

Towards the end of the talk, the general MHD equilibrium formula for the tokamaks, i.e. the Grad-Shafranov equation will be mentioned, and its applications to the real tokamak operations discussed. In the concluding remarks, the practical connection between plasma equilibrium and plasma stability will be clarified and the significant role of a real-time control of plasma position underlined.

# FIRST WALL POWER LOADING IN RAMP-UP PHASE OF ITER DISCHARGES

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During the ramp-up and ramp-down phases of discharges in the ITER tokamak, the plasma will be limited on the berylium tiles of the first wall. Scaling laws for the value of parallel power flux q// at the last closed flux surface (LCFS), and its e-folding length λq in the scrape-off layer (SOL) are needed in order to optimize tile shaping. Present design work refers to the ITER physics basis [Nucl. Fusion 39, 2391(1999)] which proposes a scaling law that is derived from L-mode plasmas in X-point divertor tokamaks: $\lambda_q = (1 \pm 1/3) 3.6 \times 10^{-4} R^2 P_{SOL}^{-0.8} q_a^{0.5} n_e^{0.9} Z_{eff}^{0.6}$

Data from relevant-sized limiter plasmas are scarce. Therefore, a series of ohmically heated, circular plasmas was made in Tore Supra to verify the scaling law. The parameter ranges obtained were 0.2<PΩ<1.4 MW, 3.4<qa<11.5, and 0.3<ne<4.9×1019 m-3 ; they were decoupled from one another by doing a series of plasma current ramps for different fluxes of injected gas, and for several values of magnetic field 2.4<B<3.8 T. Mach probes and a retarding field analyzer (RFA) were employed to measure electron and ion components of the power flux.

As a criterion for acceptance of a set of SOL profiles, we impose that the radially integrated power flux measured by the probes has to equal the convected SOL power, PSOL= PΩ-Prad. Standard Langmuir probe techniques suffer from a number of flaws that make this criterion impossible to respect in most cases. Several parameters needed to calculate the heat flux through the sheath are subject to large errors or not measured at all. The effective collecting area of small convex probes is hugely underestimated. Therefore, significant effort was invested to improve the accuracy and reliability of probe measurements. With the help of 1D and 2D kinetic simulations, we have developed new kinds of probes and new ways to interpret probe data. For example, the tunnel probe, a new type of concave Langmuir probe, eliminates uncertainties in effective collecting area and thus provides absolutely calibrated measurements of ion current density, which give nearly perfect agreement with density measurements by a nearby interferometer chord. Simple integration of the RFA ion current characteristic provides a direct measurement of the parallel ion power, with no knowledge required about ion temperature, collisionality, sheath potential, or surface properties.

The measured λq in Tore Supra does not fit the scaling law prediction. More than half of the measurements lie outside the allowed uncertainty of ±33%. The scatter is not due to random experimental errors, but instead to different trends than those predicted by the scaling law. For example, at constant PSOL the measured λq decreases with density, whereas the ITER scaling law predicts the opposite behaviour. A simple, robust empirical scaling law for inboard-leaning plasmas has been found : $\lambda_q \propto P_\Omega^{-0.5}$ .

# EFFECT OF GAS DISCHARGE CONDITIONS ON ATMOSPHERIC PRESSURE ARGON SURFACE-WAVE-SUSTAINED PLASMA

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Surface wave sustained discharges have many applications such as light sources, surface treatment, chemical analysis, bio and medical applications because this discharges are easy to operate, stable and sustain plasma in wide range of discharge conditions: gas pressure from a few mTorr to several atmospheres; wave frequency from 10 MHz to above 10 GHz; plasma radius from 0.5 mm up to 12.4 cm; plasma length from a few millimetres up to several meters.

In this work a theoretical investigation of the effect of gas discharge conditions on atmospheric pressure argon surface-wave-sustained plasma is presented. Argon plasma column sustained by travelling electromagnetic surface wave is studied by means of a self-consistent model. This model consists of both electrodynamics of wave propagation and kinetics of the electrons and the heavy particles. Basic relations in the model are ***Boltzmann***'s equation, particles balance equations and Maxwell's equations. The model is applied to plasma column in a dielectric tube at atmospheric pressure. Because of the high pressure it is necessary to account for the effect of electron and heavy particles interactions on the wave propagation. Therefore the electron–neutral collision frequency in the expression for the plasma permittivity is considered. Using the full expression for the plasma permittivity a complex dispersion equation is obtained. Its solution gives dependences between the plasma density and the propagation and attenuation coefficients, usually presented through phase and attenuation diagrams.

The kinetic part of the model gives the electron energy distribution function (EEDF) and all rate coefficients for the elementary processes which allow to obtain the number densities of ions and excited atoms, electron mean energy, electron–neutral collusion frequency, the mean power for sustaining an electron-ion pair and other plasma characteristics.

The wave energy balance equation solved together with the electron energy balance equation provides a link between electrodynamics and kinetics. As a result the axial distributions of all above mentioned wave and plasma characteristics are obtained.

The self-consistent model built up in this way allows us to study the influence of the discharge conditions (plasma radius, dielectric tube thickness, dielectric permittivity) and some key plasma parameters (electron–neutral collusion frequency and the mean power for sustaining an electron-ion pair) on the phase and attenuation diagrams, plasma density and temperature, and the length of the plasma column in a dielectric tube.

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# MODELLING OF MICROWAVE COAXIAL DISCHARGE AT LOW PRESSURE

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Microwave discharges sustained by travelling electromagnetic waves are intensively investigated in the past decades both theoretically and experimentally. The cylindrical surface-wave sustained plasma column is studied in detail. The coaxial structure is relatively new type of plasma source, which was proposed recently [1,2]. In the coaxial structure the plasma is produced outside the dielectric tube in a low-pressure chamber and a metal rod is arranged at the dielectric tube axis. The plasma is both radially and axially inhomogeneous.

The purpose of this work is modelling of axially inhomogeneous plasma sustained in coaxial structure at low pressure. We suppose that the electron number density, the wave number $k$ and the wave amplitude are slowly varying functions of the axial coordinate $z$. The plasma is considered as a weakly dissipative medium, i.e. $\nu < \omega$, where $\nu$ is the electron-neutral collision frequency for momentum transfer and $\omega = 2\pi f$ is the wave angular frequency. We assume that the plasma density is radially constant and the electron temperature is constant in both the radial and axial direction. We present an axial collisionless cold electron plasma model (fluid model) based on Maxwell's equations for propagation of azimuthally symmetric, dipolar and quadrupolar surface wave. The high-frequency surface-wave energy balance equation is derived from Poynting's theorem. Loses of wave power ($S$) is equal to the absorbed power ($Q$) per unit column length. The wave power absorbed by the electrons is expended in ionization, excitation, heating of the neutral gas, etc. At low pressures the main process for plasma production is the direct ionization from the ground state and the loss of charged particles is due to the diffusion to the wall. In this case the absorbed power $Q$ is proportional to the electron number density $n$.

Results for metal–vacuum–dielectric–plasma coaxial configuration and possibility of discharge creation from azimuthally symmetric, dipolar and quadrupolar wave modes are obtained. 3D plots for electric and magnetic field components are presented, too.

**Acknowledgments:** This work was supported by the Fund for Scientific Research of the University of Sofia under Grant 84/2012.

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## POSTER SESSION

# LIMITATIONS OF NORMAL MODE ANALYSIS IN A SIMPLE ANALYTIC MODEL FOR ABLATIVE STABILIZATION

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The Rayleigh-Taylor instability may arise in Inertial Confinement Fusion (ICF) experiments. Moreover, this instability can inhibit the fusion process. Simple analytic models for ablative stabilization have been treated in the literature[1-2]. We consider the following density profile: infinite exponential blow-off plasma with a constant density gradient, followed by a finite shell of constant density. In order to show how the modes appear in the response of a surface discontinuity to an initial perturbation, we consider the initial value problem (IPV). The main difference from the standard analysis is that solutions to the linearized equations of motion, which satisfy general conditions, are obtained in terms of Fourier-Laplace transforms of the hydrodynamics variables. These transforms can be inverted explicitly to express the fluid variables as integrals of Green´s functions multiplied by initial data**.** In addition to discrete mode (surface mode), a set of continuum modes appear, due to branch cut in the complex plane, not treated explicitly using normal mode analysis [3-5]. Thus it seems that at least in certain cases, such as infinite exponential density, the normal-mode analysis cannot replace the Laplace transform technique completely.

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# ON THE EXISTENCE OF A CONTINUOUS SPECTRUM IN SUPERNOVA REMNANTS: THE RAYLEIGH-TAYLOR INSTABILITY REVISITED

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The Rayleigh-Taylor instability (RTI) can be helpful in analyzing astrophysical flows, as in the case of supernova remnants interacting with the circumstellar medium. In the present work we investigate the linear Rayleigh-Taylor instability of an interface of two superposed fluids with exponential density in plane geometry. This approximation is appropriate for supernova remnants, because the temperature is a slowly varying function of both coordinate and time near the contact discontinuity[1] . The fluids are considered to be infinite, compressible and isothermal. The lower fluid is of decreasing exponential density, while the upper fluid is of increasing exponential density. In order to show how the modes appear in the response of a surface discontinuity to an initial perturbation, we consider the initial value problem (IPV). It was found useful to phrase of stability as initial value problem (IPV) in order to ensure the inclusion of certain continuum modes otherwise neglected**.** In addition to discrete mode (surface mode), a set of continuum modes due to a branch cut in the complex plane, not treated explicitly in the literature, appears. It will be seen that an ambiguity of the usual normal mode method is avoided. [2-4]

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# REVISION OF THE STABILIZATION EFFECT ON THE RAYLEIGH-TAYLOR INSTABILITY BY QUANTUM EFFECTS

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The effect of quantum dispersion on the Rayleigh-Taylor (RT) instability in inhomogeneous system can be of relevance in astrophysical environments, ultracold plasmas and inertial fusion plasmas. Therefore, in the present work we investigate the influence of quantum pressure on the Rayleigh-Taylor instability. Previous authors concluded that the quantum pressure always stabilizes RT instability. On the other hand, here we show that, in some density profiles, this stabilization cannot occur completely[1]. We consider the following density profile in plane geometry: infinite exponential with a constant density gradient, followed by an infinite shell of constant density.

In order to show how the modes appear in the response of a surface discontinuity to an initial perturbation, we consider the initial value problem (IPV). It was found useful to phrase of stability as initial value problem (IPV) in order to ensure the inclusion of certain continuum modes otherwise neglected**.** In addition to RT mode, a set of continuum modes due to a branch cut in the complex plane, not treated explicitly in the literature, appears. Thus it seems that at least in certain cases, such as an infinite exponential density, the normal-mode analysis cannot replace the Laplace transform technique completely [2-4] .

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# 3D PARTICLE-IN-CELL SIMULATIONS OF THE TUNNEL PROBE

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Tunnel probe is a new type of a Langmuir probe designed for measurements of density and electron temperature and their fluctuations in the scrape-off layer of tokamaks. Unlike conventional Langmuir probes, the tunnel probe has its collector retracted into a cylindrical tunnel, which contains the sheath expansion, and therefore has precisely defined collecting area. The tunnel probe has been successfully tested in CASTOR tokamak and is now being routinely operated at TORE SUPRA.

The theory of the tunnel probe assumes that the probe axis is perfectly aligned with the magnetic field. This can be hardly achieved in experimental conditions and so the question of probe sensitivity to the misalignment has been present from the beginning of the probe development. Experimental studies at CASTOR showed little sensitivity for misalignments up to 5º, however more theoretical insight into the behavior of a misaligned probe was sought for, especially with the emerging possibility of using a segmented tunnel probe for ion temperature measurements.

Tunnel probe behavior can be studied numerically by using particle-in-cell simulations. The probe calibration was made using a 2D cylindrical code. For studies of misaligned however, a full 3D code is required. Such code named SPICE3 has been developed in collaboration between IPP in Prague and CEA Cadarache in France. A series of simulations has been performed for plasma conditions relevant to experiments in CASTOR and TORE SUPRA for varying misalignments between 0º and 20º. The results show agreement with the CASTOR experiment and confirm low sensitivity to misalignments.

# DETERMINATION OF THE EDGE PLASMA PARAMETERS BY DIVERTOR PROBES IN THE COMPASS TOKAMAK

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In magnetized plasma, the interpretation of the electron part of the current-voltage (*IV*) characteristics above the floating potential still remains difficult because the electron part of the *IV* characteristics is significantly distorted due to the influence of the magnetic field. This is why, in strongly magnetized tokamak plasmas, the ion saturation branch of the *IV* and the part around the floating potential are usually used when retrieving the plasma parameters. We recently published results of applying the first-derivative method to process the electron branch of the *IV* characteristics measured in tokamak edge plasma by Langmuir probes (LPs) to evaluate precisely the plasma potential and the electron energy distribution function (EEDF).

In this paper we report experimental data obtained on the COMPASS tokamak by LPs embedded in the divertor tiles and processed using the first-derivative probe method. The resulting values of the electron temperature and density are used for model calculations to restore the *IV* characteristic based on an extended formula for the electron probe current. Comparison of the modelled *IV* characteristics with the experimental ones shows a satisfactory agreement.

The measurements of the current-voltage (*IV*) characteristics in the tokamak divertor area were performed by a newly developed Langmuir probe system. The system is partially controlled by a computer allowing simultaneous and independent feeding and registration of signals. The new boards include active low pass filters which smooth the signal before it is recorded by the DAS. Thus, the signal is less noisy and the data processing is much easier.

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# PLASMA POTENTIAL AND ELECTRON ENERGY DISTRIBUTION FUNCTION MEASURED BY VERTICAL RECIPROCATING LANGMUIR PROBE IN THE COMPASS TOKAMAK EDGE PLASMA

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Langmuir probes (LP) allow local measurements of the plasma potential, the charged particles density and the electron energy distribution function (EEDF).

The knowledge of the real EEDF is of great importance in understanding the underlying physics of processes occurring at the plasma edge in tokamaks, such as the formation of transport barriers, plasma–wall interactions, and edge plasma turbulence.

In magnetized plasma, the electron part of the *IV* characteristics is distorted due to the influence of the magnetic field. This is why the kinetic theory developed in the non-local approach may be used for the evaluation of the EEDF from the first-derivative of the electron current of the *IV* characteristics.

In this work we present the first results for the evaluation of the EEDFs by using data obtained by a vertical reciprocating probe at the edge plasma area of the COMPASS tokamak using the first-derivative probe method. It is shown that the EEDFs in some cases are not Maxwellian but can be approximated as bi-Maxwellians with one predominant low-temperature electron population and one minority component of hotter electrons. The comparison of the results obtained using the first-derivative probe method with the results provided by the traditional method shows a satisfactory agreement.

The results presented demonstrate that the first-derivative method allows one to acquire additional plasma parameters using the electron part of the current–voltage characteristics in strongly magnetized tokamak edge plasmas.

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# PROBLEM-ORIENTED SIMULATION PACKAGES AND COMPUTATIONAL INFRASTRUCTURE FOR NUMERICAL STUDIES OF POWERFUL GYROTRONS

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Powerful gyrotrons are necessary as sources of strong microwaves for electron cyclotron resonance heating (ECRH) and electron cyclotron current drive (ECCD) of magnetically confined plasmas in various reactors (most notably ITER) for controlled thermonuclear fusion. Adequate physical models and efficient problem-oriented software packages are essential tools for numerical studies, analysis, optimization and computer-aided design (CAD) of such high-performance gyrotrons operating in a CW mode and delivering output power of the order of 1–2 MW. In this report we present the current status of our simulation tools (physical models, numerical codes, pre- and post-processing programs etc.) as well as the computational infrastructure (see Fig. 1) on which they are being developed, maintained and executed. In more details we review the latest extensions and improvements in the problem-oriented software packages GYREOSS and GYROSIM and illustrate their capabilities with recent results of numerical experiments. Finally, we present an outlook and formulate some tasks for further development of the used physical models and codes in the framework of an ongoing collaboration between IHM-KIT (Germany), CRPP-EPFL (Switzerland), IE-BAS and FP-SU (Bulgaria).

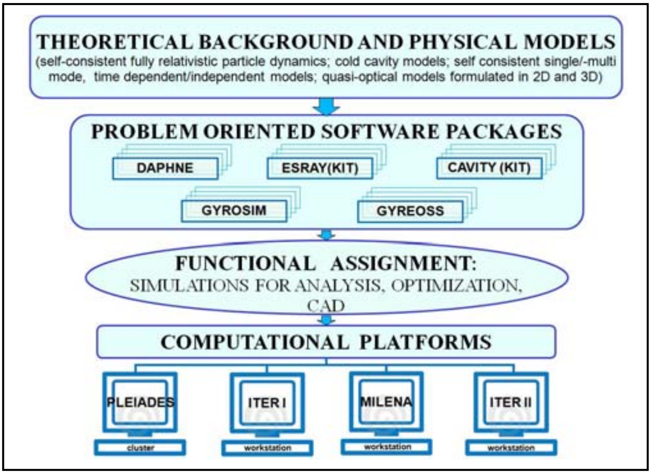


Fig. 1 *Simulation tools and computational infrastructure*

# NONLINEAR EVOLUTION OF PLASMA MODES DRIVEN BY FAST IONS NEAR THE STABILITY THRESHOLD

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In fusion plasmas, high-energy ions arising from plasma heating as well as being generated in fusion reactions may lead to the occurrence of wave micro-instabilities. The presence of thermonuclear instabilities may in turn cause anomalous losses of plasma energy and high-energy particles and consequently may have direct impact on the operation scenarios and ignition conditions. The investigation of the initial phase of these instabilities is connected with the identification of the stability thresholds with respect to wave excitations by fast ions as well as with the study of the nonlinear dynamics of the wave – fast ion system above the stability threshold. The theory describing the nonlinear dynamics of a driven mode near a marginal stability has been developed by H. Berk and B. Breizman et al. and was applied to study the dynamical properties of both the Toroidal Alfven Eigenmodes and the fishbone instability excited by high – energy ions in tokamak plasmas. However, this theory is limited to the case of a single plasma mode and in practice many modes with different wave numbers will be excited in the system. Therefore, the BB theory has been extended to the case of two different plasma modes, as a first step towards a multimode theory. Numerical analysis of the two-mode model revealed interesting features of the behavior of amplitudes, depending on types of collision operators.

# NEW DISCHARGE SOURCE FOR LASER SPECTROSCOPY IN METAL HYDRIDES

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Investigation of the electronic structure of metal hydrides (MH, for example NiH and FeH ) is of interest in the area of astrophysics[1], catalysis and often served as tests of ab initio[2] and semiempirical electronic structures[2]. In this contribution we present a discharge tube, designed for production of MH. Its special feature is a dark region (free from discharge emission) with a relatively high concentration of hydride molecules. The first results from laser absorption measurements in NiH are presented and discussed. It was found that in Ar atmosphere (or in Ar-$H_2$ mixture) there is a large dark region, but NiH concentration is low. In the tube volume there is a significant concentration of molecules only in pure $H_2$ atmosphere, but the discharge covered the whole tube volume.

For better understanding of the elementary processes in the gas discharge and how the metal hydrides are formed in our case, we have started computer simulations and we will present the recent results.

**Acknowledgements:**
Partial support from the National Science Fond of Bulgaria within the Rila 5 project kindly acknowledged.

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# MODELLING OF COAXIAL DISCHARGES SUSTAINED BY TRAVELLING ELECTROMAGNETIC WAVE

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Gas discharge can be produced and sustained by travelling electromagnetic waves in various geometries: planar, spherical, cylindrical and coaxial. Electromagnetic wave travelling along a dielectric tube can produce plasma outside the dielectric tube when there is a metal cylinder at the tube axis. Since the plasma is acting as outer conductor, this configuration is named coaxial discharge. A coaxial discharge is a new type of surface-wave-sustained discharges (SWD). It is studied very intensively since 1998 for the purpose of various possible applications. Complemented with a series of experiments, the modelling research provides valuable physical insight into the basic phenomena taking place and helps the design and optimization of the different reactors.

It is well known that in case of SWD at cylindrical geometry mainly the azimuthally symmetric waves produce and sustain plasma. As opposite to this case in coaxial geometry there are both experimental [1] and theoretical [2] indications, that higher wave modes may also produce and sustain plasma in some conditions. In order to find out these conditions theoretically we have built one-dimensional fluid model. The basic relations in our model for describing wave propagation and plasma characteristic are the local dispersion relation and wave energy balance equation obtained from Maxwell's equations. The CSWD (coaxial SWD) is axially and radially inhomogeneous, so the local dispersion relation gives the so called phase diagrams (the dependence of plasma density via the plasma frequency on the wave number). Solving the local dispersion equation together with the wave energy balance equation we obtain the axial profiles of the plasma density, the wave number, the electric field components, and the wave power.

The purpose of this work is to investigate theoretically the behaviour of wave phase diagrams and axial profiles at various discharge conditions and to find appropriate conditions for creating plasma at different wave modes. The possibility of multimode regime of operation is examined. Results for metal–vacuum–plasma and metal–dielectric–plasma configurations will be presented.

**Acknowledgments:** This work was supported by the Fund for Scientific Research of the University of Sofia under Grant 84/2012.

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# EFFECT OF GAS DISCHARGE CONDITIONS ON ATMOSPHERIC PRESSURE ARGON SURFACE-WAVE-SUSTAINED PLASMA KINETICS

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Surface-wave-sustained discharges are studied by the means of self-consistent model in two different configurations: plasma-vacuum, plasma-dielectric-vacuum. The model is based on self-consistently linked kinetic and electrodynamic sets of equations describing both the gas discharge properties and the wave propagation characteristics along the axially inhomogeneous Argon plasma column. A steady-state Boltzmann equation in an effective field approximation coupled with a collisional–radiative model for Argon discharge is numerically solved together with Maxwell's equations for an azimuthally symmetric TM surface wave. The Argon ground state and seven excited states (4s, 4p, 3d, 5s, 5p, 4d, 6s) considered as blocks of levels are taken into account. Such model gives the opportunity to present 3D plot of the electron energy distribution function (EEDF) and axial profiles of the mean electron energy, mean power per electron and effective electron–neutral collision frequency.

Using the results achieved by this model we can compare the plasma parameters for the two configurations. Varying the gas-discharge conditions we can obtain dependence between plasma density and number densities of ions, excited atoms, electron mean energy, electron–neutral collusion frequency, the mean power for sustaining an electron-ion pair and other plasma characteristics along the plasma column and the electron energy distribution function (EEDF). Using the results achieved by this model we can compare the plasma parameters for the two configurations. Such discharges sustained in atmospheric pressure have applications in the fields of medicine and biology so it is important to understand how to achieve a discharge with the necessary plasma properties required for the applications.

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# MODEL OF SURFACE WAVE SUSTAINED DISCHARGE AT ATMOSPHERIC PRESSURE

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Self-consistent model of a small microwave plasma source based on a surface wave sustained discharge at 2.45 GHz is presented in this study. Plasma source creates dense plasma with stable parameters at atmospheric pressure both in continuous and pulsed regimes [1]. The model includes dispersion relation of azimuthally symmetric surface waves sustaining the discharge in a high permittivity ceramic tube ($\varepsilon_d$ = 9.3) and the radial distribution of the field components at curtain values of the electron density are obtained. The electron Boltzmann equation under the local approximation is solved together with the heavy particle balance equations. A collisional-radiative model for argon discharge at atmospheric pressure is implemented in the model. The changes in the EEDF shape with the value of the electron density are investigated.

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# 2D MODEL OF GAS TEMPERATURE IN A NANOSECOND PULSED LONGITUDINAL He-$SrBr_2$ DISCHARGE EXCITED IN A HIGH-TEMPERATURE GAS-DISCHARGE TUBE FOR THE HIGH-POWER STROTIUM LASER

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One of the main problems in plasma physics is the determination of characteristic constants for heavy particle collisions in plasma, such as asymmetric charge transfer, Penning ionization, diffusion, and heat conduction, which are fundamentally important and widely used in gaseous discharges, laser physics, plasma technologies, gas-discharge mass spectroscopy, absorption and emission spectroscopy, and plasma in general.

Characteristic constants, such as cross sections and rate constants for heavy particle collisions (asymmetric charge transfer, Penning ionization, and etc.), diffusion and heat conduction coefficients, depend on the gas discharge temperature. Moreover, in metal or metal halide vapour lasers the gas temperature distribution is of great importance for the achievement of high output characteristics and for the stability of the laser operation as well, because it controls not only laser level kinetics, i.e. the creation of inverse population, but also determines the concentration of the active particles, i.e. particles, on whose transition laser oscillation is obtained. Experimental techniques for gas temperature determination, using measurements of Doppler broadening of spectral lines and focal distance of thermal lens, are definitely imprecise.

Assuming that the gas temperature varies only in the radial direction and using the calculated thermal conductivities through experimental data fit, rigid sphere and 12-6 Lennard-Jones inter-atomic interaction approximations, analytical solution of the steady-state heat conduction equation was found in our previous works for various discharge tube constructions for uniform and non-uniform power input, respectively. The average gas temperature was also found by averaging the radial gas temperature distribution over the radius. Unfortunately, despite the tremendous efforts, analytical solution of the abovementioned steady-state heat conduction equation for 2D (r, z) and 3D (r, φ, z) cases encountered some insuperable obstacles.

An active volume scaling in bore and length of a Sr atom laser excited in a nanosecond pulse longitudinal He-$SrBr_2$ discharge is carried out. Considering axial symmetry and uniform power input, 2D model (r, z) is developed by numerical methods for determination of gas temperature in a new high-temperature discharge tube with additional incompact $ZrO_2$ insulation in the discharge free zone, in order to find out the optimal temperature regime for achieving of a maximal multiline average output power.

# OPTIMIZATION OF PLASMA PARAMETERS IN A LASER-ABLATION HOLLOW-CATHODE DISCHARGE FOR SPECTRAL ANALYSIS

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We report a novel analytical scheme of a modified laser ablation-hollow cathode discharge (LA-HCD) for elemental analysis. The aim of this research is to gain knowledge of the process of plasma plume formation, its transient characteristics and temporal evolution, after the ablation pulse. This information is essential for defining the optimal conditions for high resolution and sensitivity of elemental analysis of multi-component materials by laser induced breakdown spectroscopy at minimal destruction of the sample.

The discharge tube is similar to a conventional hollow cathode glow discharge lamp. The cathode is a hollow cylinder in which the discharge is confined. The laser beam enters the hollow cathode (HC) through one of the open ends and is focused at the opposite end where the sample is placed. The sample is ablated by the laser beam and the ablated material is excited in the discharge zone. In our experiments the sample is a copper disc which acts also as an anode. The novelty of the registration scheme - detection of the axial side-emission from the discharge, is due to the on-axis slit cut along the hollow cathode cylinder. Such registration scheme allows axial resolution of different ablated species, as well as investigation of their temporal evolution. This is very important when multi-component samples are analyzed. Moreover, this registration scheme enables decoupling of the laser and the analytical signals. In this report we present initial studies of the novel LA-HCD set-up with a modified HC.

The performance of the hollow cathode discharge (HCD) as an excitation medium is optimized by varying the input parameters: gas pressure and input voltage. Under the optimal input parameters, measurements of the electric field distribution in the cathode fall are performed, using Stark spectroscopy. The results for the electric field distribution are compared to results from existing HCD models.

The efficiency of the LA-HCD as a tool for elemental analysis is tested at various conditions: type and pressure of the ambient gas, discharge voltage, current and laser pulse parameters.

# ELEMENTAL ANALYSIS USING SELF-REVERSED PROFILES OF RESONANCE LINES IN LASER INDUCED PLASMA EMISION SPECTRA

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Monitoring and controlling techniques of laser induced plasma (LIP) become considerably important due to broadening of LIP application field. One of the problems which complicate a spectral analysis is a self-reversion of profiles of emission lines. The profile self-reversion is a consequence of an absorption of plasma own radiation within the LIP. Conventionally, the cases when absorption is significant are avoided to simplify the spectra analysis. However, the absorption could not be neglected for the lines of a base element (an element having a maximal concentration) or resonance lines. Existing analytical models gives the expressions which include both parameters of self-reversal profile and plasma ones. Regrettably, the theoretical models do not consider such effects as a Stark shift and a dependence of a line broadening on plasma inhomogeneity. Also the models have no solutions for the resonance lines. In practice, the lines could have a self-reversed profile even for concentrations lesser than 10% for the typical parameters of a LIP excitation.

In this paper, the application of resonance self-reversed line profiles to the elemental analysis by laser-induced plasma spectroscopy has been investigated by numerical simulation. The numerical modeling has been applied to study a dependence of the line profiles in emission spectra of inhomogeneous absorbing plasmas on the plasma inhomogeneity and self-absorption degree. Atomic lines broadened mainly by quadratic Stark effect have been considered. The relations are found between the self-absorption degree, inhomogeneity rate and the line profile features. The self-absorption degree of laser-induced plasma is evaluated by the measurement of parameters of self-reversed profiles. The evaluated self-absorption degree allows restoring the true intensity of base element lines and to use it as an internal intensity standard. The relations are tested by experimental measurements of emission spectra of LIP of the metal targets of known composition (standards). The targets were excited by pulses of Nd-YAG laser. The energy and duration of the pulses are 50 mJ and 12 ns, correspondingly. The excitation parameters are typical for an elemental analysis by LIBS methods. The self-reversed spectra of aluminium and copper resonance lines were measured and calculated. The measured concentration ratio of an impurity to a base element is compared with a standard one. The tests show an accuracy improvement achieved by the founded relations.

# EFFECT OF HYDROGEN PLASMA ON MODEL CORROSION LAYERS OF BRONZE

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Together with mechanical cleaning, desalination and surface treatment, hydrogen plasma treatment is a part of conservation process leading to protection of archeological artifacts. Advantages of the method are non-destructivity and no contact with aggressive chemicals. The conservation process has to be performed very specifically, because of uniqueness of every archeological artifact. It is not possible to perform research on real artifacts, therefore using of model samples is necessary. Nowadays, hydrogen plasma treatment is commonly used for iron artifacts. For copper alloys, especially bronze, the optimized conditions during the treatment have not been determined yet. The aim of this study is to determine save conditions of plasma treatment on bronze model samples. Bronze samples (containing Cu, Sn and traces of Pb) with size of 10 x 10 x 5 $mm^3$ were used.

The first step was the preparation of model corrosion layers. In order of the defined roughness, the surface of each sample was grinded on an electric grinder with a sandpaper P600. The bronze samples were placed into the dessicator, where they were exposed to hydrochloric acid vapor as a model corrosive environment because chlorine compounds play a typical role as bronze corrosion accelerators. After 14 days, the corrosion process was stopped. The samples were treated in hydrogen plasma and one sample stayed non-treated as a reference for analysis.

The application of reduction process in low-pressure low-temperature hydrogen plasma followed. Our experimental equipment was constructed according to the design of professor Vepřek, and was further improved. A quartz cylindrical reactor with two outer copper electrodes was used. Plasma discharge was generated in pure hydrogen by a RF generator. Each corroded sample was treated at different conditions (dissipated power and continual or pulsed with variable duty cycle mode). When atomic hydrogen reacts with oxygen from the corrosion layer, OH radicals are produced. Therefore, the relative intensity of OH radicals was monitored by optical emission spectroscopy during the experiment in order to monitor the running process.

The plasma treated samples were analyzed by a scanning electron microscope in order to obtain chemical composition by energy dispersive x-ray analysis as well as surface morphology.

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# DISCHARGE IGNITION IN THE DIAPHRAGM CONFIGURATION SUPPLIED BY DC NON-PULSING VOLTAGE

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Electrical discharges generated in water solutions have been intensively studied for utilize them in numerous applications such as water treatment, plasma sterilization, surface treatment, lithotripsy, nanotube synthesis, etc. Various electrode configurations, voltage regimes as well as reactor constructions have been investigated by different researchers. A common feature of the discharge ignition in water is the initiation of physical and chemical processes, e.g. UV irradiation, shockwave formation, and production of reactive species (radicals, ions, and molecules with high oxidation potential). They can be subsequently utilized in the previously mentioned applications. However, detailed diagnostics of the formed plasma is necessary for a proper control of the required process [1].

This work deals with the ignition of the discharge in the diaphragm configuration generated in water solutions containing supporting NaCl electrolyte. The reactor has volume of 110 ml and it is made of polycarbonate. HV electrodes made of stainless steel are placed in this reactor. Ceramic (Shapal-M$^{TM}$) diaphragm is placed in the barrier separating the cathode and the anode space. An electric power source supplies the reactor by constant DC voltage up to 4 kV and electric current up to 300 mA. The discharge ignition is compared in the reactor with different sizes of diaphragms. Measurements are carried out with the same conductivity. Images of plasma streamers and bubble formation are taken by an ICCD camera iStar 734. Electrical characteristics are measured by an oscilloscope LeCroy LT 374 L in order to determine breakdown moments at different experimental conditions.

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# TWO DIMENSIONAL LASER DIAGNOSTICS AND PLASMA MODELLING OF AN ARGON SURFACE WAVE DISCHARGE


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In this contribution we present the spatial characterization of a surface wave discharge (SWD) plasmas at intermediate pressures (5 mbar – 80 mbar) by laser scattering techniques. These techniques, namely Thomson and Rayleigh scattering (TS and RyS), provide precise and direct measurements of important plasma parameters like electron density and temperature and gas temperature ($n_e$, $T_e$ and $T_g$). With these advanced methods the well known surface wave discharge can be studied in a different and theory-independent way, validating results from previously established characterizations and with higher accuracy.

The first step was the determination with TS measurements of the axial dependence over the plasma columns of $n_e$ and $T_e$ [1]. This axial profile "picture" has been completed now with the $T_g$ measurements along the columns with RyS [2] and with the characterization of the very end of the of the discharge with TS [4]. Simultaneously, the radial profile of $n_e$ and $T_e$ has been measured with TS showing its dependence and contraction with pressure [3].

A two dimensional model for the investigation of SWDs was developed using the Plasimo platform [5]. The model permits the study of the differences between the plasma surrounded by the surfatron cavity, *i.e.* the "inside" plasma, and the plasma in front of it, *i.e.* the "outside" plasma. The results are compared with the experiments and a good agreement is found.

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# OPTICAL DIAGNOSTICS OF PLASMA PLUME PRODUCED BY HIGH-FLUENCE NANOSECOND LASER ABLATION

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Laser ablation by nanosecond pulsed laser implies interactions between laser radiation and target material [1], between laser radiation and ablation plasma plume [2, 3] and, finally, between ablated particles within plasma plume [4]. Experimental methods (optical and electrical), theoretical models and numerical simulations were used to describe laser radiation-target interaction, as well as the dynamics of the ejected particles and the plasma plume [5-7].

In this paper two optical methods of plasma diagnostics are presented, which are used for investigation of the plasma plume produced by laser ablation on manganese (Mn) and nickel (Ni) solid target.

The diagnostic techniques used were fast ICCD imaging and optical emission spectroscopy. The ICCD images allows us to find the spatial distribution of total light emission produced by plasma plume at different instant time of the plasma plume time evolution. Time samples of 5 ns were taken using a Princeton digital camera (model PI MAX). These pictures are used for finding the spreading velocity of the plasma plume. The emission spectrum of the plasma plume allows us to find the spatio-temporal distributions of plasma plume components (as atoms and ions of the target material). From these distributions the expansion velocity of atoms and ions were estimated.

The experiments were carried out on a plasma produced into a vacuum chamber (p = 7 x $10^{-6}$ Torr, residual pressure) by irradiation of Mn and Ni targets with a Nd:YAG laser (10 ns, 10Hz, 532 nm). The radiation emitted by the ablated particles (atoms and ions) was analyzed with a monocromator and the dispersed light has been recorded by a fast response photomultiplier (Hmamamatsu). Plasma parameters evolutions, like Mn and Ni atoms and ions expansions velocity or spectral line intensity, with the change of laser beam intensity (5mJ-45mJ) are presented. The ICCD recording of the total optical emission of the plume evidenced the presence of two different structures in the plasma plume for both target materials.

**Acknowledgments**: The financial support from the Grant POSDRU/89/1.5/S/63663 is highly acknowledged.

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# INFLUENCE OF THE SOFT X-RAY PLASMA FOCUS RADIATION ON THE PHOTOSYNTHESIS ACTIVITY OF THE BEAN PLANT LIVES

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A 3 kJ plasma focus device was used to study the influence of the soft X-ray on specimens of leaves of green bean. The irradiation of the various groups of samples sorted in a special sandwich-like structure by the PF X-ray emission  was provided through 10 μm Al foil at each stage (of the sandwich) with different doses in the range of 10 ÷10000 mSv.

The method, used for analysis of photosynthetic activity in living system was proposed by Strasser et al [1]. According to the procedure given by these authors, the probe treated by ionising radiation (soft X-rays in this case) is illuminated afterwards with certain visible light pulses (627 ± 10nm) and then the prompt and the delayed fluorescence emission (735 ± 15 nm) of the sample is recorded *in vivo*. The changes of fluorescence intensity during dark to light transition, so called “induction curves” are derived and analysed by the JIP-test [1].

The first results of similar treatment of the leave samples are derived in the present study.

It seams that we observe the same tendency as the one obtained by the same team in our previous work with X-ray irradiation of the *Chlamydomonas reinhardtii* [2].

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# THE BRANCHING OF $He_2$ $3s\sigma^3\Sigma^+_u$ STATE FORMATION IN GLOW DISCHARGE PLASMA

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The influence of two processes - (i) - metastable atom $2^3S_1$ to metastable molecule $2s\sigma^3\Sigma^+_u$ conversion and - (ii) - the vibrational relaxation of recombined molecular ion $He_2^+$ upon the intensities of $He_2$ $d3s\sigma^3\Sigma^+_u \rightarrow b2p\pi^3\Pi_g$ (0-0) band has been investigated.

The plasma source used was a positive column of helium glow discharge (R=0.9 cm), operating at gas pressure of 2.6÷70 Torr and discharge current of 10÷100 mA. The discharge is viewed on-axis and spectra obtained by 0.4 m МДР-2 monochromator.

Assuming that the thermalised “low N” (N≤9) rotational levels origin is the conversion of a metastable while the excesses in the “high N” levels (N≥13), neighboring $3s\sigma^3\Sigma^+_u$ (v=1) state are due to the recombination of molecular ion; the two processes was possible to be distinguished through their different influence on the spectra upon the gas pressure and discharge current variations. The concentration of no-thermalized molecules bears relatively small dependence of the discharge current, but posses a sensitive decrease with the pressure growth. The rate coefficient $K_{22}$ and its dependence upon the pressure have been evaluated from the experimental data. The results are in agreement with the values, measured by Pitchford [1] and Deloche [2].

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# THE DIVERSE IN EXCITATION OF v=0 AND v=1 STATES OF $He_2$ $3s\sigma^3\Sigma^+_u$ IN GLOW DISCHARGE PLASMA


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Contrasting differences in the behavior of the population between v=0 and v=1 states in the emission spectra of He2 3sσ3Σ+u are found to exist in the glow discharge plasma. The plasma source of the spectra was a positive column of helium glow discharge (R=0.9cm), operating at gas pressure of 2.6÷70 Torr and discharge current of 10÷100 mA. The discharge was viewed on-axis and spectra obtained by 0.4 m МДР-2 monochromator, coupled with PM in analog mode.

The experimental data have shown that:

1. While the low rotation levels of v=0 state are thermalized, such a thermalization thus is not existing for v=1 state.
2. The relative rate of population of v=1 versus v=0 states largely exceeds the state of equilibrium; it is increasing with the current growth and decreasing for larger pressures.
3. The v=0 concentration is going toward saturation with the current growth (i.e. $n_e$) for pressures above 10 Torr, in contrast with the steady increase of the v=1 concentration, an increase bearing dependence of the pressure values.

The analysis of the experimental results, based on the existing data for rate coefficients is pointing toward different sources of excitation of v=0 and v=1 levels, the latest being formed mainly via vibrational relaxation of recombined molecular ion $He_2^+$.

# COLLISIONAL ELECTRON SPECTROSCOPY (CES) METHOD FOR GAS-ANALYSIS

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The available methods for detection of chemical compositions in gas phase – gas chromatography, mass spectrometry, traditional electron spectroscopy, photoelectron and Auger spectroscopy are characterized by complexity of the apparatus, namely - large dimensions, the ionization and detection chamber are separated, transportation of the charged particles in electric or magnetic field to the detector, high vacuum requirements to prevent scattering of the detected particles at their trajectory. These devices are expensive for common practical use. A large number of industrial, medical and scientific applications require small and simple in technical performance gas analyzers that do not require gas pumping and vacuum for their operation. Therefore, the development of new and innovative methods for analysis that could be widely used for control of the gaseous medium in various industrial processes, gas chromatography and power plants is of great interest for the practice.

In this study, the CES method, whose basic principles are patented [1, 2], is practically implemented and further developed. In contrast to the classical electron spectroscopy, which requires high vacuum for its use, the method of CES enables identification of gas impurities in a main gas in collisional regime of movement of the particles at high pressures. There, the different groups of electrons do not have time to relax in energy by collisions in the volume and behave independently of each other. Such behavior of the electrons occurs when the requirements for nonlocal formation of the EEDF are fulfilled. Condition for nonlocality exists over some characteristic length that is less than the energy relaxation length for electrons, where the electrons lose predetermined negligible portion of their energy due to elastic electron - atom collisions. The nonlocal plasma of a short steady-state microdischarge is a suitable medium for creation of compact gas analyzer, whose dimensions can be dramatically reduced compared to the exciting devices.

An original design of microplasma gas analyzer is proposed and experiments are carried out to determine gas admixtures by the CES method. The nature of the CES method gives the opportunity to develop a gas analyser simple in technical performance and having small size. Selective registration of groups of fast electrons created in Penning ionization of the impurities by metastable helium atoms is made. Records of the energy spectra of penning electrons are carried out by means of an additional electrode - sensor, located at the boundary of the discharge volume. The sensor has a large collecting area to enhance significantly the sensitivity of the measurements. Maxima in the electron energy spectra are recorded in helium with small admixtures of noble and molecular gases at pressures of 7 – 90 Torr by measuring the sensor current and its derivatives with respect to the applied voltage. It is demonstrated that the obtained maxima appear at the characteristic energies corresponding exactly to the expected maxima for penning electrons of the known gas impurities used. The measured energy of penning electrons and their number density could be utilized in principle for detection of gas impurities like poison gases, gas pollutions in the atmosphere or in the industry etc.

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# PLASMA ZOOLOGY IN A TEMPERATURE WILDERNESS; IS THAT GONNA WORK?

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The increasing success of high-tech plasma applications is based on the fact that plasmas produce large effluxes of photons and radicals. These drive plasmas to non-equilibrium conditions. The higher the effluxes are, the larger the equilibrium-departure will be and the more the laws of classical statistical mechanics, ruled by the famous Boltzmann exponent $\exp(-E/k_B T)$, will lose validity.

A method often found to characterize non-equilibrium plasma conditions is to employ several temperature-types. So, one can find expressions like $T_e > T_{ion} > T_{ex} > T_{vib} > T_{rot}$ showing that the electron temperature is larger than the "temperature" associated to ionization, excitation, vibration and rotation.

One might wonder what the use of such a chain of inequalities is. Even if the temperature-values are given we remain with the question of the factual meaning of entities like $T_{ex}$ or $T_{ion}$. A thermodynamic meaning in the sense of representing the mean energy of a certain particle-type is, and can, seldom be given.

A more precise characterization of high-tech plasmas demands apart from temperatures inequalities also for the determination of the fluxes and number densities of active species.

In this contribution several temperature-manifolds will be addressed and discussed.

# TWO DIMENSIONAL PLASIMO MODEL OF A SURFATRON PLASMA AT INTERMEDIATE TO HIGH PRESSURES

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We present a two-dimensional model for the interaction between the plasma and the microwave field in a surface wave discharge [1], based on a non-LTE fluid description - solving equations for species densities, field flow velocity, gas and (effective) electron temperature – and a harmonic form of the Maxwell equations for the electromagnetic model - solving equations for the Ez, Er and Hφ EM field components and the absorbed power density.

The model delivers, among others, the properties of a surfatron plasma source in two dimensions.

We show:

1) that the metal structure surrounding the column inside the launcher affects the surface wave and thus the plasma substantially,

2) how the pressure changes the axial dependency of the electron density from a linear to a non-linear decay regime, and

3) a comparison of the 2D model results with experimental measurements [2-5] of the electron density and temperature in the axial direction along the plasma column.

The plasma conditions are: argon gas, pressure range of 660 to 8800 Pa, an inner tube radius of 3.1 mm and a microwave frequency of 2.45 GHz (vacuum wavelength of 12 cm). Note that we use the qualification "intermediate to high pressure" to refer to the pressure range for which "ambipolar diffusion" loses dominance due to the increasing effect of volume recombination.

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# 2D NUMERICAL SIMULATION OF CAPACITIVELY COUPLED RF PLASMA SHOWER DEVICE

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A capacitively coupled RF discharge at atmospheric pressure is studied by means of a time-dependent, two-dimensional fluid model. The plasma is created in a stationary argon gas flow between two multi-holes perforated electrodes, forming a shower [1]. The inner electrode is powered with a frequency of 13.56 MHz, the outer electrode is grounded. The model solves the mass balance equations for the relevant active species and the electron energy balance equation in conjunction with the Poisson equation for the field sustaining the plasma. The mass balance equations of the active species are calculated using the drift-diffusion-convection approach, thus taking the bulk velocity into account. The velocity field is calculated with the Navier–Stokes module of the Plasimo toolkit. Three different sub-studies were carried out in order to explore step-by-step the complex interplay between the geometry and the gas flow: a) a flowless classical parallel plates' geometry, b) a flowless perforated parallel plates' configuration and c) the plasma shower. Strongly non-Maxwellian kinetics is found. As a consequence the excited species are much more abundant than the charged particles. Molecular ions are the dominant ion species and they unbalance even more the ion/metastable ratio via dissociative recombination to the metastables making them the main active species in the plasma. The effect of the shower holes and the recirculation gas flow within the electrodes on the plasma is examined. The perforation of the electrode's plates modifies the spatial distributions of the E-field, leading to an intra-hole field augmentation and therefore to activation of these regions of the plasma. As the most effective outward transport mechanism, the gas flow is the basis of the formation of the post-discharge region. In addition to modifying the distribution of the plasma particles in the spatial afterglow, the flow recirculation reduces the wall losses and facilitates the ionization and excitation processes in between the plates. Thus it plays a key-role in the stabilization of the discharge.

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# MODELING OF HIGH POWER IMPULSE MAGNETRON SPUTTERING

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The basic idea of high power impulse magnetron sputtering (HiPIMS), is that by applying high power to a magnetron supplied in short and very intense pulses one can increase the plasma density from $10^{15}$ $m^{-3}$ for conventional dc magnetron sputtering (CdcMS) to above $10^{19} m^{-3}$ for HiPIMS. Advantages of HiPIMS are the uniform deposition of structures with high aspect ratios, interface modification through ion irradiation and increased film density. It is thought that these advantages are generally associated with the large degree of ionization of the sputtering flux; although there is still dispute on the fractional ionization of the metal atoms.

We model the plasma column in front of the racetrack using a fluid approach. This implies that the deposition mechanism is not addressed. In addition to the main gas particles (argon atoms and ions) we also describe the behavior of the sputtering and thus the density of metal (ions). We describe only the active part of the cycle; thus not the recombination phase.

Before presenting model results we have done some sanity checks in order to find out whether the model outcome depends on the model-features. So, for instance we investigated whether the choice of the grid refinement, the size of the time-step and the initial conditions have influence on the model results. The outcomes from the sanity checks are that 1) the output parameters do not depend on variation of the width of the electrodes 2) the change of the initial density values do not influence the output results; 3) by changing the time-step can be seen that the resulting densities are the same.

Results were obtained at different pressure, voltage and gas temperature. The work will continue with replacing the constant B-Field with a B-field profile; the investigation of the influence of the input conditions on the EEDF, and consequently on the electron related transport and reaction rate coefficients.

# UV EMISSION FROM MICROWAVE PLASMAS

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Ultraviolet (UV) and Extreme ultraviolet (EUV) light sources are of great importance in applications ranging from photochemistry to astrophysics. In this work, UV emissions from He, Ar, $H_2$ and Ar-$H_2$ surface wave microwave plasmas operating at low-pressures (0.1 – 2 mbar) are investigated.

The surface wave induced plasma source is created using a waveguide surfatron-based setup. The power is provided by a 2.45 GHz generator, coupled to a waveguide (WR-340) system, which includes an isolator, directional couplers, a 3-stub tuner, and a waveguide surfatron as the field applicator. The discharge takes place inside a quartz tube with internal/external radii of 3/5mm inserted perpendicularly to the waveguide wider side. The background gas is injected into the discharge tube at flow rates from 20 to 100 sccm under laminar flow conditions. The EUV end-on emission is detected by a Horiba Jobin-Yvon Plane Grating Monochromator (PGM) operating in the 8 -125 nm (155 - 9.9 eV) spectral range. The VUV PGM is connected to one of the tube ends.

Ultraviolet spectra in the range 10 – 120 nm, particularly the atomic emissions of the well-known 30.4 nm line of He II [transition $H^{2+}$ ($^2S$ - $^2P^0$)] and the Lyman $\alpha$ and $\beta$ lines of atomic hydrogen at 121.6 nm and 102.6 nm ($L_\alpha$ and $L_\beta$) were detected for different settings of pressure and microwave power delivered to the launcher. Molecular emissions of the $H_2$ ($C^1\Pi_u \rightarrow X^1\Sigma_g^+$) Werner and $H_2$ ($B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$) Lyman bands in the range 100 – 120 nm were also detected. The dependence of the integral intensity on the power was determined for both the molecular and atomic emissions. The experimental results are compared with theoretical results of a self-consistent theoretical model which was developed. This model is based on a set of equations including the electron Boltzmann equation, the thermal balance equation, the local surface wave dispersion as derived from Maxwell's equations and the rate balance equations for vibrationally excited molecules, $H_2$ ($X^1\Sigma g^+$, $v$), electronic excited states of $H_2$ and H ($n$ = 2–8), ground-state neutrals ($H_2$, H) and ions ($H^+$, $H_2^+$, $H_3^+$, $H^-$).