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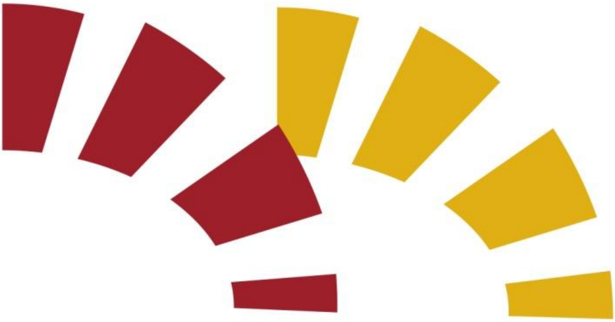
IX
INTERNATIONAL WORKSHOP
ON
MICROWAVE DISCHARGES:
Fundamentals and Applications

September 7-11, 2015
Cordoba (Spain)



BOOK OF ABSTRACTS

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IX INTERNATIONAL WORKSHOP
ON
MICROWAVE DISCHARGES:
Fundamentals and Applications

Córdoba (Spain)

September 7-11, 2015

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Preface

This book contains the abstracts of the contributions presented at the ninth International Workshop on Microwave Discharges: Fundamentals and Applications, to be held on September 7-11, 2015 in Cordoba, Spain. As for previous editions of this triennial workshop, the objectives of the meeting have been: To promote exchange of knowledge between experts in different fields both of fundamental plasma science and technological applications of plasmas, to assess the state-of-the art in this field, and to establish basic guidelines for future research.

The contributions to the workshop have been organized in four topics: 1) Plasma theory and modeling, 2) Microwave plasma generation, 3) Plasma diagnostics and 4) Microwave Plasma Applications. However, with a view to facilitate the localization in the book, the contributions are presented in the same order as they appear in the scientific program of the meeting. In this edition tribute has been made to Prof. C.M. Ferreira and Prof. Z. Zakrzewski, prominent members of the microwave discharge community and recently deceased. First, the General Lecture are presented, after that the Tributes, then the Topical Lectures and finally the Poster contributions.

Antonio Gamero
Chair of the LOC

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THE POWER ABSORBED PER ELECTRON FROM THE E-FIELD AND THE POWER LOST PER ELECTRON AS MEANINGFUL PHYSICAL PARAMETERS ALLOWING MODELING DC, RF AND MICROWAVE DISCHARGES

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The power balance in electrical discharges provides one of the basic equations in plasma modelling. As a rule, it relates the total power absorbed in the discharge from the electric field sustaining it to the total power lost in it through various processes (e.g. particle collisions, sheath and wall losses). In the case where power from the electric field is acquired essentially by electrons, this global approach to the power balance can interestingly be replaced by a power balance per electron instead. It consists in considering, on the one hand, the power absorbed from the E-field per electron, θ_A, and, on the other hand, the power lost per electron as a result of collisions with heavy particles to which smaller losses such as those in the DC ambipolar field and the plasma sheath can be added, defining θ_L. This power per electron representation brings new insight into many aspects otherwise ignored. Two different situations need to be considered from the start: i) the volume into which power is absorbed is the same as that in which losses occur. In such a case, θ_A is equal to θ_L, ii) the volume into which power is absorbed is smaller than that in which losses occur, as can be the case in a non-homogeneous plasma. These two situations are identified as Case 1 and Case 2. In Case 1, similarity (scaling) laws can be obtained such as, for example, θ/p as a function of pR where p is the discharge gas pressure and R, the radius of the plasma column. This specific similarity law is a useful generalisation of the DC discharge scaling law E/p vs. pR (E is the intensity of the discharge maintenance field) since it further applies to all types of high-frequency (HF) discharges, recalling that experimentally it is difficult, when not problematic, to determine the E-field intensity by inserting a probe into them while measuring the absorbed power is straightforward. Another feature stemming from Case 1 is that the power θ_A taken from the E field, the absorbed power, adjusts to compensate exactly for the power lost θ_L. In other words, the power lost is the dominant parameter. We use this feature to show that the E-field at electron cyclotron resonance (ECR) goes through a minimum, in contrast to what is currently believed. A further example demonstrating the utility of the parameter θ in Case 2 is examined in connexion with the excitation of periodic parametric instabilities under intense microwave electric field.

POWER MANIPULATION and LASER AGITATION

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Power Manipulation and Laser Agitation can be used for in-depth studies on the (non-)equilibrium state of plasmas. In the first case we modulate the plasma driving power and study the reaction of the plasma-as-a-whole. A special method is the power interruption (PI) technique; a sudden power switch-off followed by the subsequent re-ignition generates information on transport mechanisms like diffusion, ionization, recombination and heat transfer [1]. The second method is more refined: we agitate just one specific atomic transition, using laser induced fluorescence (LIF) and study how this disturbance propagates through the system. This provides insight in the importance and strengths of the various transition rates and probabilities [2]. To make the information obtained from these relaxation techniques (LIF and PI) more valuable it is important to know the plasma characteristics. For this we can employ Thomson scattering; the scattering of light on free electrons giving the electron density and temperature.

The first part of this contribution is devoted to time-resolved LIF. By combining high rep-rate YAG-Dye laser systems with well-known and controllable surfatron plasmas it is possible to explore the excitation kinetics in the argon atom system, ArI, and to unravel the excitation transfer between ArI and other atomic and molecular systems. Laser systems that can offer 8 ns pulses of typically 1 mJ of tunable wavelength with a rep-rate of 1 to 5 kHz are nowadays commercially available. They give at least 100 times more relevant LIF photons per unit of time than the conventional 10 Hz systems.

The second part describes the application of the power interruption method to argon surfatrons operated in the intermediate pressure regime. By analyzing the results of Thomson scattering (TS) during PI, insight was among others obtained in the importance and strength of diffusion and recombination processes. The method was applied to plasmas operated in pure argon and in argon mixtures such as Ar/H_2, Ar/O_2, Ar/N_2 and Ar/CO_2. Huge differences were found in the PI responses of different plasmas mixtures. The slow decay of the electron temperature after PI in Ar/CO_2 plasmas points towards a strong coupling between the electrons and the vibrational CO_2 system.

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2. Palomares J-M et al, Spectrochimica Acta B DOI:10.1016/j.sab2013.

RECENT PROGRESS IN BARRIER COATING DEPOSITION: MICROWAVE PLASMA CHARACTERISTICS AND CORRELATION TO THIN FILM PROPERTIES

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The barrier properties of polymers against gas permeation can be enhanced by plasma deposition of thin silicon oxide (SiO_x) films. SiO_x is of great interest, as it offers significant improvement of barrier performance and it is transparent. The deposition is performed by means of a microwave-driven low pressure plasma using gas admixtures of Hexamethyldisiloxane (HMDSO) and oxygen.

The initial stages of thin film deposition are decisive for growth and adhesion of the coating. For investigation of occurring processes, plasma diagnostics and surface analytics have to be applied. Hence, determination of absolutely quantified fluences of reactive species produced in the plasma, concentrations of HMDSO fragments and tracking of interfacial changes at the polymer surface are necessary.

As the oxygen to HMDSO ratio determines structure and barrier performance of the resulting film, investigations are performed for different oxygen to HMDSO ratios. The plasma is characterized by means of optical emission spectroscopy (OES), leading to an absolutely quantified atomic oxygen fluence towards the substrate. Additionally, electron density and temperature are evaluated and plasmas infrared absorption spectroscopy (IR-AS) based on Tunable Diode Laser(TDLs) and External Cavity Quantum Cascade Laser (EC-QCL) is used to monitor the ground state concentrations of HMDSO, and the reaction products CH_4, C_2H_2, C_2H_4, C_2H_6, CO, CO_2 and CH_3.

Crystalline aliphatic self-assembled monolayers (SAMs) of octadecanethiol (ODT) on gold surfaces are used as a sensor layer that mimics an aliphatic polymer [1]. Due to self-organization, interfacial changes can be monitored by polarization-modulation infrared reflection-absorption spectroscopy (PM-IRRAS). It is revealed, that the surface sustains a critical fluence of atomic oxygen before significant degradation occurs. Support by the German Research Foundation (DFG) within the framework of the SFB TRR 87/1 is acknowledged.

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INTERACTION OF POWERFUL MICROWAVE BEAMS WITH THE METAL-DIELECTRIC POWDER MIXTURES (PHYSICS AND APPLICATIONS)

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. Results of experimental investigation of powerful microwave beams action on the metal-dielectric compositions are presented. Dielectric surfaces with introduced metallic grains as well as dielectric powder containing small admixtures of a metallic one have been explored as an objects of irradiation. At a relatively small microwave power ($P \leq 1$ mW) all investigated targets were practically completely transparent for incident electromagnetic wave. At a relatively high power (microwave generators based on the gyratrons and powerful magnetrons, pick power $P_i \cong 50 - 100$ kW) irradiated samples effectively absorb microwave energy at the sacrifice of plasma production near the target or through the non identified processes on the contacts between metal and dielectric.

Plasma production mechanisms are discussed. Possibilities of strong nonlinear processes taking place in the course of powerful microwave beams interaction with metal-dielectric mediums for microwave air engine realization, microwave soldering, etc. are analyzed.

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ATMOSPHERIC PRESSURE MICROWAVE TORCH FOR SYNTHESIS OF NANOMATERIALS

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The research in the field of synthesis of nanoscale materials is driven by the demand for their specific properties. We have developed the synthesis of carbon nanotubes (CNTs), carbon nanowalls and iron oxide nanoparticles (NPs) using an atmospheric pressure microwave torch. Multiwalled CNTs were grown in the MPT from the $Ar/H_2/CH_4$ gas mixture [1] and their fast surface bound synthesis allowed the applications in sensor devices that require CNT growth directly on conductive silicon, without the presence of an oxide barrier layer [2]. High purity maghemite (γ-Fe_2O_3) NPs were synthesized from $Fe(CO)_5$ vapors mixed with Ar/O_2 [3]. Magnetic iron oxide NPs with the diameter below 20 nm, exhibit superparamagnetic behavior and their applications range from biomedical cancer treatment and drug delivery to sensor applications [4].

Complementary simulation and experimental study of the microwave torch operating in Ar/H_2 mixtures showed that changes in the gas temperature and hydrogen dissociation with the gas composition and input power are relatively strong and non-monotonic [5]. Therefore, understanding the phenomena taking place in microwave torch, either by means of numerical simulations or via plasma diagnostics, is a necessary step towards optimization of the nanomaterial processing.

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MD9. FUNCTIONALIZATION OF POLYMERIC MATERIALS BY SURFACE WAVE PLASMAS WITH BIOMEDICAL APPLICATIONS

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Surface properties play an important role in the functioning of a biomaterial in a physiological environment. [1] This work describes the influence of the changes that occurred on polymers and polymeric-haired surfaces by different surface wave plasmas treatments. Changes in the surface chemical composition with the generation of new functional groups, alteration of the surface roughness by etching mechanisms and modification of the wettability are the main effects affecting polymeric materials by microwave plasma activation. [2]

The influence of nitrogen plasma modification in cell proliferation, viability, and morphology of fibroblasts have been correlated with surface chemical composition, surface tension, and topography of polymeric materials employed in biomedical applications. It was found that surface roughness, amine functionalization and a hydrophilic state are beneficial factors for the cell adhesion. [3] Moreover, oxygen plasma treatments of PLGA membranes have been showed as highly beneficial for bone regeneration. [4] Therefore, the effect of the oxygen plasma functionalization on “in-vitro” degradation of biodegradable polymeric membranes has been discussed. Oxygen plasma pre-treatment has enhanced the degradation efficiency causing that carbon functional components decreased at the surface and in the interior of the membrane.

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ASSEMBLING AND ENGINEERING OF 2D CARBON NANOSTUCTURES BY PLASMAS

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The ongoing focus on ecosystem sustainability puts 2D materials development in the spotlight, being now considered as one of science & technology research areas with greater strategic value [1]. Using graphene as a starting point, new isolated atomic planes can be assembled and reassembled into designed nanostructures. In the present work, free-standing graphene sheets were synthesized using microwave plasmas at atmospheric pressure conditions. The method is based on injecting hydrocarbons through a microwave plasma, where decomposition takes place, which was studied *in situ* by plasma emission spectroscopy. Free gas-phase carbon atoms and molecules created in the "hot" plasma diffuse into colder zones and aggregate into solid carbon nuclei, leading to flowing graphene sheets that gradually assemble and grow. The synthesized sheets have been analyzed by Raman spectroscopy, SEM, HRTEM, XPS and NEXAFSS. Results show that the amount of sp^3 carbon decreases as the gas temperature in the assembly zone increases, and that the synthesized graphene sheets are stable and highly ordered.

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ALTERATIONS OF STARK BROADENING SPECTRA IN MICROWAVE DISCHARGES. CORRECTIONS IN PLASMA DIAGNOSTICS SPECTROSCOPY

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The local electric field created by free electrons and free ions in a plasma alters the emission spectra giving rise to the appearance of forbidden transitions and to which is called Stark shift and Stark broadening. The analysis of these spectra is the basis of one of the most efficient diagnostics techniques to determine the electron density in a plasma [1].

In plasmas generated by microwaves, the region in which the energy of the microwaves is transferred to the plasma, the local micro-field produced by the charged particles overlaps with the microwave radiation. This alters the emission spectra, modifying its structure, and resulting in line shapes which do not correspond with which could be expected in a plasma with the electron density and temperature of the zone of interest. In other words: plasma diagnostics methods in those areas must include the effect of the plasma generator field. In general, those regions are very small, but precisely are the ones which have higher emissivity.

In this work we present a study of the Stark broadening in those conditions. Particularly, It is specially analyzed the alteration of the shape of the spectrum, which has a very different “geometry” to the one observed in the Stark profiles from the areas where the plasma is in equilibrium. The calculations has been done using techniques of molecular dynamic simulation like the used in the works [2,3]. In the examples some lines of Hydrogen and Helium have been considered [4].

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COMPUTER MODELING OF A MICROWAVE DISCHARGE USED FOR CO_2 SPLITTING

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Microwave discharges are gaining increasing interest for the conversion of CO_2into value-added chemicals, because of their high energy efficiency. Indeed, CO_2 is very efficiently excited to the vibrational levels in a microwave discharge, and these vibrational levels provide a very efficient dissociation pathway.

In this talk, I will present our modeling results for the plasma chemistry of CO_2 in a microwave discharge, including a detailed analysis of the importance of the vibrational levels, as obtained from zero-dimensional chemical kinetics modeling[1,2]. This model includes 25 vibrational levels up to the dissociation limit of the CO_2 molecule, and takes into account state-specific vibration-translation and vibration-vibration relaxation reactions, as well as the effect of vibrational excitation on other chemical reactions. I will also discuss the effects of reduced electric field, electron density and total specific energy input on the CO_2 conversion and the energy efficiency, and I will identify the limiting factors for the energy efficiency in a microwave discharge.

Furthermore, I will show the effects of N_2 on the CO_2 conversion and energy efficiency, as N_2 is an important constituent of industrial CO_2 gas flows. I will show how N_2 populates the CO_2 vibrational levels, and thus contributes to a higher CO_2 conversion. These modeling results will be compared with experiments, performed at the University of Mons.

Finally, I will present a self-consistent 2D fluid plasma model of a surfaguide discharge. This model is in first instance developed for argon, but will be extended to CO_2. Typical results of this model include the electron density and temperature profiles, the electric field distribution and the gas temperature profile. As the gas pressure is stated to play a crucial role for energy efficient CO_2 conversion [3], I will present modeling resultsin a wide range of pressure, from 10 mbar to atmospheric pressure.

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HIGH CURRENT PULSED ECR ION SOURCES

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In present time some ECR ion sources use a high frequency powerful microwave radiation of modern gyrotrons for plasma heating. Due to high radiation power such systems mainly operate in a pulsed mode. This type of ECR ion sources was developed at Institute of Applied Physics of Russian Academy of Sciences and the most part of experimental research was performed at SMIS 37 facility [1]. At SMIS 37 gyrotrons with 37,5 and 75 GHz frequencies and 100 and 200 kW maximum power respectively are used for plasma production. Such heating microwaves allow to create plasma with unique parameters: electron density > 10^{13} cm^{-3}, electron temperature 50-300 eV, ion temperature about 1 eV. The principal difference between these systems from the conventional ECR sources is the realization of a so-called quasi-gasdynamic regime of plasma confinement [2]. In accordance with the confinement regime such sources have been called "gas-dynamic ECR sources". Typically plasma lifetime in such systems is only 5-25 microseconds, which in combination with the high plasma density leads to formation of the plasma fluxes from the trap with density up to 1-10 A/cm^2. The confinement parameter (the product of plasma density and lifetime) reaches a value (> 10^8 $cm^{-3}s$) sufficient to generate multiply charged ions. In [2, 3] the possibility of multiply charged ion beams (nitrogen, argon) production with currents up to 200 mA was demonstrated. Particularly the gas-dynamic ECR ion sources are effective for generation of high current proton beams with low emittance (high brightness). In recent papers [4] the possibility of proton and deuteron beams formation with currents up to 500 mA and rms normalized emittance 0,07 pi • mm • mrad was demonstrated. These parameters are absolute record for sources of light ions of all kinds.

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N-DOPING OF GRAPHENE BY A N2-AR REMOTE PLASMA

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Plasma environments are powerful tools in materials science for allowing the creation of innovative materials and of those that would not otherwise be achievable [1]. Among different types of discharges, N_2-Ar large-scale plasma sources driven by microwaves have advantageous properties for plasma processing. In the present work a microwave plasma is used to produce pristine graphene sheets by leaking vaporized ethanol molecules through an argon plasma environment, where ethanol decomposition takes place and carbon atoms/molecules are created. The nucleation and growth processes occur in the colder regions of the plasma reactor [1-3]. Subsequently, graphene is N-doped by transferring sheets to a substrate, which is placed in the remote zone of a N_2-Ar large-scale microwave plasma. Samples were treated for different exposure times and at different relative compositions of the N_2-Ar gas mixture. A theoretical model describing the N_2-Ar large-scale plasma source has been used to calculate nitrogen fluxes towards treated nanostructures [1][4]. The N-doped graphene sheets have been analysed applying SEM and TEM, Raman and FT-IR spectroscopy techniques. The obtained results clearly demonstrate the presence of nitrogen atoms attached to the graphene scaffold. The doping level depends mainly on the nitrogen percentage in the N_2-Ar mixture.

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TRIBUTES

A TRIBUTE TO THE WORK ACHIEVED BY PROFESSOR ZENON ZAKRZEWSKI AT THE UNIVERSITÉ DE MONTRÉAL

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Zenon Zakrzewski’s stays in Montréal started in October 1968 with a 15-month post-doctoral fellowship and, following various summer stays as an invited researcher/professor, extended up to 1998, spending altogether almost 7 years in Montréal. It is on his second stay (August 1975-October 1976) that we began working together. At that time, the surfatron (a surface-wave launching device allowing sustaining long plasma column) had already been almost fully optimized. Zenon used it to characterize the properties of the electromagnetic (EM) surface wave when sustaining plasma and this was the first (of a long series) of joint publications. The various topics on which Zenon and I worked can be essentially summarized as: i) improving and/or developing various kinds of RF and microwave field-applicators allowing sustaining stable and reproducible plasma columns; ii) inventing the TIA and TIAGO microwave-plasma torches; iii) determining the properties of the corresponding (various) electromagnetic waves propagating along the plasma columns that they sustain; iv) examining the properties of the produced plasmas and their relation to the EM field sustaining them; v) proposing equivalent circuit modeling of the various RF and microwave plasma sources achieved (e.g. surfatron, surfaguide, TIA, …); v) applying (and modifying accordingly) some of these to industrial use (e.g. abatement of green-house gases used in microelectronics). As a result, Zenon and I co-authored 9 families of patents. I am extremely grateful to Zenon since without his contribution, the *scientific production* of my team would have been much less. Many of my students also benefitted from his knowledge and skill, and additionally enjoyed his humoristic comments.

Zenon’s most cited paper (325 times) :

M. Moisan and Z. Zakrzewski, Plasma sources based on the propagation of electromagnetic surface waves (a review), Phys. D: Appl. Physics, 24 (1991) 1025-1048.

MICROWAVE DISCHARGES AND PLASMA SOURCES AT THE MICROWAVE LABORATORY OF POLISH ACADEMY OF SCIENCES IN GDAŃSK, POLAND

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At the beginning, a short history of the research on microwave discharges (MDs) and microwave plasma sources (MPSs) which has been carried out at the Microwave Laboratory of Polish Academy of Sciences in Gdańsk, Poland is described. Then results of the research on MDs and MPSs and their applications, mainly for gas processing for industrial and environmental purposes are presented. In particular, the pioneered research on long MDs sustained by the electromagnetic waves is described. Some of the diagnostics methods developed in the Laboratory for studying MDs are outlined. Several types of MPSsdesigned and studied at the Laboratory, i.e. surface-wave-sustained MPSs, nozzle-type MPSs, nozzleless MPSs, plasma-sheet MPSs and microwave microplasma sources (MmPSs, antenna- and coaxial-line-based) as well as their performance are described. The experimental results on the optimization of selected MPSs are confronted with results of the modelling of the electromagnetic field distribution in them. Some examples of the applications of MPSs for the processing of gases and liquids, as well as for deactivation of microorganisms are also presented. Two types of the plasma gas processing were experimentally tested, i.e. the decomposition of volatile organic compounds (VOCs)and reforming of VOCsinto hydrogen. Results on the plasma processing of several highly-concentrated (up to 100%) VOCs, including Freon®-type refrigerants, in the waveguide-supplied MPSs showed that the microwave discharge plasma is capable of fully decomposing the VOCs at relatively low energy cost. The use of the waveguide-supplied coaxial-line-based and metal-cylinder-based nozzleless MPSs to methane reforming into hydrogen turned out to be attractive from the energy efficiency point of view. Also the microwave plasma production of hydrogen from liquids (refrigerant R-134a, ethanol and propanol) proved to be promising. The coaxial-line-based MmPSwas shown to be efficacious in the treatment and prevention of bacteria and fungus.These selected results show that the MPSsare attractive tools for the processing of gases, liquids and microorganisms.

This contribution is a tribute to Professor ZenonZakrzewski who led the Microwave Laboratory over 40 years.

TRIBUTE TO THE MEMORY OF PROF. CARLOS MATOS FERREIRA

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Prof. Carlos Matos Ferreira, Honorary Member of the International Scientific Committee and founder of the International Workshop on Microwave Discharges: Fundamentals and Applications, died unexpectedly. Due to so unhappy news the ISC wants to dedicate a tribute to his memory and his valuable commitment to our microwave discharges community.

Prof. Francisco M. Dias, coworker for many years in the Instituto Superior Técnico de Lisboa, will dedicate to Prof. Ferreira and his contribution to Microwave Discharges a Lecture during the workshop.

TOPICAL LECTURES

RESONANT ENERGY ABSORPTION AND COLLISIONLESS ELECTRON HEATING IN SURFACE WAVE DISCHARGES

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Surface waves propagate at the interface between a dielectric surface and an overdense plasma and are characterized by an electric field configuration with components both in the direction of propagation, along the interface, and in the direction perpendicular to the propagation, i.e. parallel to the density gradient from the plasma to the wall. Since the plasma is overdense the real part of the plasma permittivity goes through zero at a given location between plasma and wall. This results in the resonant excitation of plasmons, which are coherent oscillations (space charge oscillations or Langmuir waves) of the electrons. The propagation of surface waves between a plasma and a dielectric surface therefore “combines EM-wave properties and the behavior of space-charge waves in a unified way” (quoted from Aliev, Shluter and Shivarova, “Guided-wave produced plasmas”, Ed. G. Ecker, Springer Series on Atoms and Plasmas, 2000). The conversion of electromagnetic energy into electrostatic energy through this resonance phenomenon in surface wave discharges has been known for a long time and discussed in many papers. The effect of the resonance on the electron velocity distribution function has been evidenced in several experimental studies. There is however still no reliable quantitative description of this effect. Most surface wave discharge models are based on a fluid description of the charged particle kinetics and use a local description of the electron complex permittivity, which implies a purely collisional electron heating and is not valid at low pressure (an “effective” electron collision frequency is sometimes used to account for collisionless heating).

In this paper we propose for the first time a fully kinetic, self-consistent model of a surface wave discharge that includesnon-local permittivity effects and their consequence on electron energy absorption. The model is based on a 1D Particle-In-Cell Monte Carlo Collisions simulation where the electromagnetic field is represented by vector and scalar potentials. This approach is well suited to our problem since EM-wave properties and space charge wave properties can be naturally represented by vector and scalar potentials respectively.It combines harmonic (vector potential) and time dependent (scalar potential) descriptions. We show that, as expected, Langmuir waves can fully develop when the resonance location is sufficient far from the wall, and that Landau electron energy absorption plays an important role in these conditions. We also discuss the mechanisms of electron energy absorption when the resonance point is closer the wall sheath.

MULTIPACTOR RF BREAKDOWN ANALYSIS IN A PARALLEL-PLATE WAVEGUIDE PARTIALLY FILLED WITH A MAGNETIZED FERRITE SLAB

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The purpose of this work is the analysis of the multipactor effect [1] in a parallel-plate waveguide with a ferrite slab magnetized by means of a static magnetic field. To reach this aim, we developed in-house a multipactor simulation code based on the Monte-Carlo method to compute the multipactor RF voltage threshold. The software code, based on the effective electron model, allows the 3D tracking of the individual trajectories of a set of effective electrons. The current simulation model includes the space charge effect, that takes into account the coulombian interaction among electrons by means of a single electron sheet model, as well as the dielectric polarization effect of the ferrite that leads to the presence of a DC electric field. Multipactor susceptibility chart for a ferrite loaded waveguide assuming several values of the ferrite magnetization field is presented. Effective electron trajectories at some interesting points of the curves are depicted for a better understanding of the breakdown phenomenon, finding double-surface and single-surface multipactor regimes.

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OXYGEN ATOMIC DENSITY MEASUREMENT IN N_2/O_2 SURFACE-WAVE PLASMA USING VUV ABSORPTION SPECTROSCOPY WITH A COMPACT MICROWAVE PLASMA LIGHT SOURCE

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Plasma sterilization has been attracting much attention from researchers for its low temperature operation, non-toxic methods, and a short treatment time. In our previous work, an N_2/O_2 gas mixture surface-wave plasma (SWP) generated in a 30 cm diameter stainless-steel cylindrical chamber was used for low temperature plasma sterilization of *Geobacillus stearothermophilus* spores. Our results showed that UV radiation and excited oxygen atoms are the dominant lethal factors in spore inactivation in N_2/O_2 gas mixture SWP.[1-2] However, the behaviors of neutral active species in the inactivation process have not been studied enough, because only a few reliable measurement techniques for the absolute densities of radicals in reactive plasmas have been developed. Various methods, such as laser induced fluorescence spectroscopy, electron spin resonance spectroscopy, cavity enhanced absorption technique, and actinometry technique, have been developed to measure the absolute densities of oxygen or nitrogen radicals. Compared with these methods, vacuum ultraviolet absorption spectroscopy (VUVAS) technique has minimal influence on the processing plasma, and it has been widely used for the absolute radical density determination in processing plasma. In the VUVAS method, however, self-absorption of the light source should be reduced to a negligible level for reliable absorption measurement, but sometimes self-absorption can't be reduced to an allowable level for the limit of the experimental conditions.

In this work, the oxygen atomic density was measured with a proposed VUVAS method with two wavelengths at 130.22 nm and 130.49 nm, where self-absorption of the light probe at each wavelength was calibrated by taking into account the optical escape factor. The etching effect of excited oxygen atoms on spore-forming microorganisms was discussed by comparing with the measured absolute atomic densities in SWPs with different N_2/O_2 gas mixture ratios.

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OPTICAL CHARACTERIZATION OF MICROWAVE SURFAGUIDE DISCHARGE FOR CO_2 CONVERSION

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Theatmosphere pollutions nowadays are reaching the unprecedented values in history, which is related to burning the carbon-containing fuels, where the public heat production,industry, and the transport system contribute mostly [1]. Since CO_2 is one of the maingreenhouse gases, its decomposition and reformingare of great importance. The alternative energy sources such as wind and solar plants often may not represent good alternatives, due to the non-periodic energygeneration, and sometimes very distant location of the solar power plants,respectively. In this regard,namely the local greenhousegases decompositionis a challenging task. The cold plasmas in the microwave frequency range are known to be the good candidates for molecular decomposition, due to the optimum combination of their parameters [2], and in this work the conversion of CO_2 has been studied ina surfaguide-type microwave discharge.

This study covers temporal and spatial characterization of the CO_2-containing microwavedischarge region using optical emission spectroscopy (OES), including actinometry and ro-vibrational spectral analysis. The special attention is devoted to the gas temperature determination through calculation of the synthetic rotational bands of CO, as well as of the other diatomic molecules.

The obtained results clearly indicatethe spatially non-uniform CO_2 dissociation along the discharge tube. The dissociation rate of $CO_2$is found to be a function of the specific energyreaching about 80%, at 40 eV/molecule. The energetic efficiency of CO_2decompositionis found to be only$\approx$ 12%, but may reach $\approx$ 40 % at lowerspecific energy. Beside this, the distribution of the absorbed power along the discharge isanalyzed. The results confirm that the vibrational excitation plays a key role in CO_2dissociation in our case. It is also suggested that the obtained dissociation ratecan be further increased by varying the gas composition in thedischarge.

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EFFECT OF DIELECTRIC TUBE THICKNESS AND PERMITTIVITY ON MICROWAVE PLASMAS SUSTAINED BY TRAVELLING WAVE

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Microwave plasma can be sustained by electromagnetic wave traveling along the boundary between the dielectric tube and the plasma inside it. The maximum of the electromagnetic field components is just at the boundary and it decreases both in the plasma and in the dielectric, so it is classified as surface wave and the discharge is so called surface-wave-discharge (SWD). The plasma sustained in this way is axially inhomogeneous and the plasma density and wave power decrease from the wave launcher until the power becomes 0. All the wave and plasma characteristics are changing along the plasma column.

The plasma density of SWD turned out to be very sensitive to the dielectric tube thickness and permittivity due to the fact that the main part of the wave energy flux is passing through the dielectric and vacuum (air) around the tube. This strong dependence can be found in low, intermediate and high (atmospheric) pressure but it is of different types. It becomes even more important when the atmospheric plasma at open air (plasma torch) is in contact or inside water, which dielectric permittivity at microwave frequencies becomes very high.

We present theoretical investigation of the dielectric thickness and permittivity effects on the plasma and wave characteristics on the base of self-consistent model [1, 2]. The phase diagrams of the wave propagating along the plasma–dielectric boundary and sustaining the discharge, the axial profiles of the plasma density and other characteristics are presented. It is shown that the plasma density increases with the dielectric permittivity but it require more wave power to be sustained so the plasma length becomes smaller and the axial gradient increases.

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DIFFERENT PRESSURE REGIMES OF A SURFACE-WAVE DISCHARGE IN ARGON: A MODELING INVESTIGATION

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Over the last decades, many studies focused on the description of surface-wave plasmas produced by microwave discharges [1] both from a theoretical and an experimental point of view. These discharges have a wide range of applications, such as gas conversion, plasma medicine, material processing and surface treatment [2] as they offer relative simplicity and low running costs. They can be operated over a wide range of pressure (from few mtorr to several atmospheres), using different frequencies and various geometries [3]. Among these different geometries, the so-called surfaguide discharges offer the possibility to create low-temperatures plasmascoupled with a strong microwave power [3], which is of particular interest for industrial applications.

Recently, microwave discharges have been applied to CO_2 conversion and the pressure has been shown to be a key parameter to obtain better energy efficiency, which is crucial in this domain [4].

The goal of this study is to get a better understanding of the effect of the pressure on microwave discharges. The presented model is a self-consistent 2D fluid plasma model of a surfaguide discharge operated over a wide range of pressure conditions: from 10 mbar to atmospheric pressure in pure argon.A reduced set of chemistry for CO_2 plasmas is also being developed based on the set of [5]. It will be implemented in the 2D model as a next step.

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MICROWAVE DISCHARGES IN FIBERS AND CAPILLARIES

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The very confined plasmas and microplasmas have boomed in the last decade. The LPGP laboratory developed 2.45 GHz microwave excitation systems for a continuous production of plasma within dielectric tubes (hollow core fibers and capillaries) with reduced inner diameter (100 µm to 1 mm range), low power (a few Watt to a few tens of Watt), over a large pressure range (from mbar to atmospheric pressure), offering applications in several fields such as photonics or microfluidics. The present communication is dedicated to the study of two different families of microwave exciting systems, based on surfatron [1,2] and stripline [3] technologies. A double approach, coupling modeling to experiments, has been used to determine the main plasma parameters (electron density and temperature, gas temperature...), which enabled to evaluate the advantages and drawbacks of each system, depending on the aimed application, and to optimize their geometries in order to maximize the microwave power coupling to the plasma and to minimize the required power.

Concerning the modelling, the set of Maxwell equations is solved in 3D, enabling the calculation of the power coupling, and the surface wave propagation model predicts the wave propagation modes and enables the calculation of electron density profiles and coupled power, which can be experimentally validated. As far as experiment is concerned, optical emission spectroscopy is used to analyse the plasma. The gas temperature in the plasma core is determined by exploiting the N_2 and OH ro-vibration spectra and the electron density is estimated from Stark broadening. The influence of several parameters such as microwave power, gas pressure and flux, capillary/fiber inner diameter, has been studied.

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MODE OF PRODUCTION AND APPLICATION RANGE OF LENGTHY MICROWAVE TORCH EXCITED AT A CONSIDERABLY SUBTHRESHOLD FIELDS IN ATMOSPHERIC PRESSURE GASES

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Results of experimental investigation of possibility to create lengthy plasma formation in an atmospheric pressure air under the free space conditions and their applications for plasmachemical means are presented. As a source of energy Russia-produced microwave generator GIROTRON having power $P \leq 600$ kW, wavelength $\lambda \approx 0,4$ cm and pulse duration $\tau \leq 20$ ms has been applied. Microwave torch with length as high as $L \leq 50$ cm has been obtained with help of tailor made quasioptical system for microwave beam formation and underthreshold discharge initiation. Physics and parameters of such a discharge are similar to the SMS-discharge investigated in the GPI [1]

Preliminary results of plasmachemical decomposition of methane and carbon dioxide in such a gases like: $CH4$, $CH4+CO2$, $CH4+H2$, $CO2+H2$ have been obtained.

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STATE OF EQUILIBRIUM DEPARTURE OF MICROWAVE INDUCED PLASMAS FOR CO_2 DISSOCIATION

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Carbon dioxide emissions represent an environmental issue that is pushing the research on CO_2 capturing and recycling technologies. In this framework, an efficient dissociation of CO_2 is the first step in the production of neutral fuels.

Low pressure supersonic microwave induced plasmas showed energy efficiencies up to 90% [1, 2]. The non-equilibrium nature of these electrical discharges promotes the CO_2 reduction above the thermodynamic equilibrium limit (45% energy efficiency). A high vibrational excitation temperature, produced by the so-called “vibrational pumping” effect was proposed in [1, 2] as an explanation for these high energy efficiencies.

The aim of this ongoing research is to elucidate the role of vibrational excitation in the CO_2 dissociation by non-equilibrium plasmas. The study is made on pure CO_2 microwave discharges, under conditions of intermediate to high pressure (0.1 – 1 atm) needed to achieve the high production demanded in industry. A set of advance diagnostic techniques are used to characterize the plasma excitation and the CO_2 dissociation processes.

FTIR spectrometry and quantum cascade lasers are used to measure the conversion degree and energy efficiency. Laser scattering techniques are used to measured electron and gas temperatures. Finally, the resonant infrared radiation produced by a free electron laser is used to probe the vibrational excitation. At intermediate pressures in the order of 100 mbar we obtain conversion degrees and energy efficiencies of 30% and 40% respectively, with a high gas temperature in the order of 1 eV. These results indicate the plasma is close to thermal conditions and consequently a minor role of the vibrational excitation is expected in the CO_2 dissociation process.

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EMISSION SPECTROSCOPY OF DIPOLAR PLASMA SOURCE IN LOW PRESSURE HYDROGEN

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Method of emission spectroscopy was used to study the plasma characteristics of the dipolar plasma source [1] in hydrogen at pressures 0.001 – 0.01 Torr, microwave power 200-1200 W, microwave frequency 2.45 GHz. Spectral composition of plasma emission was investigated in the range of wave length 601–627 nm. Functions of distributions over rotational (J=1–5) and vibrational (v=0–2) levels were determined for excited state $d^3\Pi^-_u$ of hydrogen molecules. Gas temperature T_g, rotational $T_{rot}(d^3\Pi^-_u)$ and vibrational $T_v(X^1\Sigma^+_g)$ temperatures were determined on the basis of collisional-radiative models [2-4].

It was found that the distribution function for the lower rotational levels of $H_2(d^3\Pi^-_u)$ is Boltzmann distribution. Temperature $T_{rot}(d^3\Pi^-_u)$ changes in the range 205–325 K. The distribution function for the lower vibrational levels of H_2 in the excited state $d^3\Pi^-_u$ differs from the Boltzmann distribution. The magnitude of the vibrational temperature is 3100±400 K, translational temperature is in the range 420-650 K. The obtained values of Tg and $T_v(X^1\Sigma^+_g)$ suggests that the discharge at low pressures in hydrogen is an effective source of vibrationally excited hydrogen molecules.

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ARGON MICROWAVE PLASMAS AS SOURCES OF VACUUM ULTRAVIOLET RADIATION

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Plasmas operating at microwave frequencies have the potential to become alternative sources of vacuum ultraviolet (VUV) radiation, with application in several domains of science and engineering [1]. In this work, microwave driven discharges in argon are investigated as sources of VUV radiation, at low-pressure conditions (0.1 – 1 mbar). A classical surface-wave sustained discharge at 2.45 GHz, with a waveguide-surfatron based setup as the field applicator, has been used as plasma source [2]. VUV radiation has been detected by emission spectroscopy in the 30 – 125 nm spectral range and the experimental spectra show the presence of emissions from excited argon atoms and ions. The most intense spectral lines correspond to the atomic resonance lines, at 104.8 nm and 106.7 nm, and to the ionic lines, at 92.0 nm and 93.2 nm. Emissions at lower wavelengths are also detected, including lines with no information concerning level transitions in the well-known NIST database (such as the atomic line at 89.4 nm). The relative intensity of all the measured spectral emissions with variations of the discharge pressure and microwave power delivered to the launcher has been investigated. The plasma electron density has been determined using optical emission spectroscopy in the visible. The experimental results were analysed using a 2D self-consistent theoretical model based on a set of coupled equations including the electron Boltzmann equation, the rate balance equations for the most important electronic excited species and for charged particles, the gas thermal balance equation, and the wave electrodynamics.

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NON-THERMAL MICROWAVE PLASMA DISSOCIATION OF CO_2 WITH HIGH ENERGY AND CONVERSION EFFICIENCIES BY CHEMICAL EQUILIBIUM SHIFT

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CO_2has attracted much attention as the primary greenhouse gas. Its conversion to renewable fuels represents part of the solution for reducing emissions and addressing energy storage. Plasma-assisted CO_2 conversion is regarded as a promising route for the production of CO_2 neutral fuels. Relatively high energy efficienciesover 50 % havebeen verified using microwave plasmas in the collaboration of DIFFER and IPF Stuttgart [1,2]. However, in non-thermalplasma, the achievement of both high energy and conversion efficiencies is still a great challenge [3]. Apart from the high electron temperature and low gas temperature (non-equilibrium), the plasma-assisted CO_2 dissociation process involves also the chemical equilibrium process, i.e. $CO_2 \leftrightarrow CO + 1/2O_2$, in which the recombination of CO and O_2 could result in a low conversion efficiency. One possible route is to remove the generated O_2, promoting a shift in the chemical equilibrium towards CO. Such an enhanced CO formation would lead to an increase in conversion efficiency while keepingthe energy efficiencies at the usual high levels. Therefore, the combination of plasma dissociation and oxygen separation techniquecould boost a breakthrough in the production of CO_2-neutral fuels with both high energy and conversion efficiencies at the same time.

In this study, a 2.45 GHz 1kW microwave plasma source is used to assess the efficiencies of the process. The CO_2 depletion and products formation aremeasured downstream by mass spectrometer. Preliminary results of experiments will be shown, where the oxygen was reduced just after the plasma.

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INVESTIGATION OF MICROWAVE DISCHARGE IN CAVITY REACTOR EXCITED IN THE TM$_{013}$ MODE

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Results of the study of continuous microwave discharge in hydrogen and hydrogen-methane mixture are presented. Microwave discharge is ignited in a cylindrical resonator excited in the TM$_{013}$ mode at a frequency of 2.45 GHz. Such kind of discharge is used for chemical vapor deposition of diamond films [1]. Growth rate of diamond films in CVD reactors depends on the concentration of atomic hydrogen, which is determined by the value of microwave power density (MWPD) in the plasma [2]. The MWPD is defined as the ratio of the absorbed microwave power to the plasma volume. In our experiments the discharge was investigated by method of optical emission spectroscopy over a wide pressure range of 80 - 350 Torr and at MWPD varying from 50 to 550 W/cm^3. Spatial distribution both of integrated luminosity of plasma and of atomic hydrogen Hα line emission intensity when varying the gas pressure and microwave power were measured. The dependence of the dissociation degree of atomic hydrogen was investigated by means of actinometry. To measure the gas temperature the emission of Swan band of C$_2$ radical was used[3].

To calculate the dimensions and parameters of the microwave discharge plasma the self-consistent two-dimensional model was used, described in detail in [4]. The spatial distributions of Hα intensity and microwave power density were obtained by numerical modeling and the connection between these distributions was established. The boundary of plasma volume on these spatial distributions with accuracy of 10% was defined. Finally the plasma volume was defined on the basis of experimental spatial distributions of intensity and the MWPD was calculated. Based on these results we propose a method of experimental determination of MWPD, allowing unify the calculations of MWPD in various types of microwave plasma chemicalreactors.

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PROBLEM OF MICROWAVE BREAKDOWN IN THE VEHICLE-BORNE COMPONENTS AND WAY OF ITS PREVENTION

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This work is devoted to the radical methods finding for microwave secondary electron emission discharge ("multipactor") prevention. Discharge which limits microwave power received or transmitted by satellite-borne equipment [1].

The main result of research is elaboration of an original technology of nano-structural carbon films deposition on a metallic samples. It was demonstrated in a preliminary experiments that these films are manifesting almost all properties providing possibilities of their application in the interest of a multipactor hindering. As a substrate Cu and Al samples have been studied. By way of example maximal secondary electron emission yield for Cu sample coated by nano-structural carbon was as small as σ_{max} <1,5, first cross-over value was as high as $\varepsilon_1 > 100$ eV and time stability in air was as long as $\tau >$ 12months. Thus elaborated in GPI technology presents a fundamental mean for preclusion of a board multipactor excitation limiting microwave power receiving and transmitting on the board/ Physical reasons of such a properties exhibiting by treated samples are discussed.

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MICROWAVE-EXCITED ATMOSPHERIC PRESSURE PLASMA JET USING MICROSTRIP LINE FOR THE SYNTHERSIS OF CARBON NANOMATERIALS

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Atmospheric pressure plasma jet (APPJ) has preferable properties to chemical vapor deposition (CVD), which can provide high-speed depositions and also eliminate expensive and complicated vacuum systems. To date, many APPJ devices have been developed using various kinds of electrical power sources with wide frequency ranges from direct current to microwave. Their properties and structural configurations strongly depend on their electrical power sources. Among those APPJ devices, a microwave-excited plasma allows relatively high-density radicals and high nonequilibrium level because electrons in plasmas are oscillated in response to the applied electromagnetic field, while ions are relatively stationary.

In this work, we have developed an atmospheric pressure CVD technology for the synthesis of carbon nanomaterials using a specially-designed microwave-excited APPJ which is based on microstrip line instead of conventional lumped-waveguide [1-4]. Nanocrystalline diamond films were successfully deposited on silicon substrate using the microwave-excited APPJ with a mixture gas of $Ar/CH_4/H_2$ even in ambient air [4].Our APPJ technology using microstrip line allows a low-cost fabrication, a low-power operation, simple circuit elements, and a compact system. Furthermore, the APPJ technology can produce a large-area plasma using the configuration of the nozzle array and microstrip lines. In the presentation, we will introduce our APPJ technology with recent experimental results.

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SURFACE TREATMENTS FOR CONTROLLING THE MULTIPACTOR DISCHARGE OF MICROWAVE COMPONENTS

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The control of secondary electron emission (SEE) for improving the power limit of vacuum microwave equipments prone to multipactordischarge was studied. Among other parameters, the multiplication of electrons of the multipactor discharge depends on the secondary electron yield of the electron bombarded surface. The main objective is the decrease of the secondary electron emission yield (SEY) under electron impact on the surfacesof the microwave devices. SEY data of dielectric materials are crucial for determining multipactor parameters in many devices. The principle of SEY tests in dielectric materials consists in bombarding the sample with low-electron dose. Thus, single current pulses of 200 ns of low intensity, 6nA, were used to reduce the electron dose received by the sample ($< 10^6$ electrons/pulse) in order to avoid charging of the tested surface. In this work the variation of the SEY with the primary electron energy will be discussed for various types of technical surfaces. Alumina ceramics and aluminium, usual material in wave guide manufacture, exhibit unacceptably high SEY values for multipactor prone devices. In this work, surfaces covered with aluminium and microstructuredaluminaare used as templates to obtain low-SEY surfaces. The lowest and stable SEY was achieved for microstructured alumina covered by conductive layers, SEY<1 for all incident or primary electron energy range (0-5000eV). Gold or carbon deposition on microestructured alumina is found to be a very efficient technique for reducing SEY.

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PLASMA-ASSISTED CATALYSIS FOR CONVERSION OF CO_2 AND H_2O OVER SUPPORTED NICKEL CATALYSTS

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In this work weinvestigatethe plasma-assisted dissociation of CO_2 and H_2O mixture,for production of syngas and related chemical building blocks such as methanol and formic acid.In addition to plasma treatment which supplies energy for dissociation of the molecules, a catalyst is assisting the reactions.

The surface wave sustained discharge used in this work was generated at 915 MHz using a pulsed microwave generator. Titanium oxide (different polymorphs) supported NiOcatalyst was placed in the post discharge. The NiO supported on TiO_2 catalysts were prepared byimpregnation of titanium oxides powder followedbyplasma activation.The composition of the post-discharge gas is analyzed by gas chromatography which allows following the concentration of H_2, O_2, CO and CO_2.

The obtained results show that pure CO_2 conversion efficiencyis remarkably enhanced on plasma treated NiO/TiO_2 (Rutile), while NiO/TiO_2 (Anatase) did not affect CO_2 conversion. Conversely, for CO_2/H_2O mixtures NiO/TiO_2 (Rutile) showsless activity for the conversion CO_2 than the others TiO_2 crystalline phases.Theplasma activation processaffects also the activity of the different catalysts. The catalytic activities of these catalystswere compared toget a better understanding of the relationship between the plasma-catalyst interactions and the synergistic effect. The different catalysts were characterized by XRD, Raman spectroscopy and BET, before and after utilization in order to characterize the evolution of their chemistry, specific surface and size.

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THE KEY-ROLE OF THOMSON SCATTERING IN THE CHARACTERIZATION OF MICROWAVE PLASMAS

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The wide variety of microwave plasmas (MW) and corresponding applications forms an obstruction in the classification and characterization of MW plasma sources. To tackle this problem, we need a solid basis for the validation of models and the cross-validation of experimental methods. This can be offered by laser Thomson scattering (TS). As TS is the scattering of (laser) light on free electrons we get direct information of the electron density and temperature. So, in contrast with the often used method of Optical Emission Spectroscopy we do not need much modelling for the deduction of the main plasma properties out of the signal. On the other hand TS is costly and experimental demanding.

In this contribution we will address the benefits of TS but also the complications that can come into play. A classical problem for TS experiments is the false stray-light that might deteriorate the detection limit. This originates form the fact that TS is not very efficient. Typically only one out of 10^{15} photons directed to the plasma will be scattered and detected. When TS is applied to atmospheric MW plasmas we get extra problems due the presence of molecules. This implies that the Thomson and Raman spectra will overlap, so that disentangling methods are needed to get the pure TS signal. Another characteristic, often found in MW plasmas is the low ionization degree which can induce deviations in the electron energy distribution function (EEDF). These deviations mainly affect the tail of the EEDF; an energy region that is not easy to measure with TS. Finally, the laser heating of the electron gas is another issue that has to be considered.

Various case-studies will be presented for MW plasmas of atmospheric and low pressures. Comparison with other types of plasmas will be presented as well.

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STUDY OF STRONGLY NON-UNIFORM NON-EQUILIBRIUM MICROWAVE PLASMA IN NITROGEN BY MEANS OF PROBE AND OPTICAL METHODS

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One of the important problems in the physics and applications of non-equilibrium gas discharge low temperature plasma is the study of the structure of discharges. This is especially important in the study of strongly inhomogeneous discharges in which the plasma composition and physico-chemical processes depend on the spatial coordinates. Non-equilibrium electrode microwave discharge (EMD) at pressures of 0.5-20 Torr can be attributed to this type of discharges [1, 2].

In this paper we describe the first results of a study of the axial and radial distributions of plasma parameters of the EMD in nitrogen at a pressures of 1- 5 Torr and incident power of 60-100 W (frequency 2.45 GHz). Double electric tungsten probes (probe diameter is 100 mm, length of the bare part is 2.1 mm, the distance between the probes is 2.8. mm), spectrograph AvaSpec 2048 and high speed video camera K-008 were used. Probe voltage- current characteristics were measured with isolated from the ground oscilloscope Tektronix TPS2024. Special system provides the move probes in longitudinal and radial directions. Single probe was used in some experiments. The results obtained using the single-probe and double-probe techniques are in satisfactory agreement.

Some results were presented in [3, 4]. Spatial distributions of electron temperature, plasma density, emission spectra in the range of wave length 300-700nm, total plasma emission were determined. Emission spectra were used for calculation of the microwave field strength in plasma.

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WAVE AND PLASMA CHARACTERISTICS OF SURFACE-WAVE-SUSTAINED DISCHARGES AT VARIOUS GEOMETRICAL CONFIGURATIONS AND AZIMUTHAL WAVE MODES

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Electromagnetic wave travelling along a dielectric tube can produce plasma inside the tube (cylindrical plasma column) or outside it [1]. When at the tube axis is arranged a metal rod and plasma is sustained outside the tube this configuration is called coaxial structure. If the dielectric is a thick cylinder without metal inside the plasma also can be sustained around it in some conditions and we call it plasma around dielectric cylinder. Depending on the radial configuration of the different media (metal (m), vacuum (v), dielectric (d), plasma (p)) in the waveguide structure the electromagnetic wave traveling along it can produce plasma with different characteristics.

The cylindrical plasma column is usually produced by azimuthally symmetric wave (azimuthal wave number $m = 0$). In some special conditions it can be produced by dipolar wave ($m = 1$) but again only one azimuthal wave mode propagates and sustain the plasma, i.e. the single-mode regime of operation is typical for the cylindrical plasma column configuration. When the plasma is produced outside the dielectric tube or thick dielectric cylinder various wave modes can propagate and produce plasma, i.e. a multy-mode regime of operation occurs.

A theoretical investigation of the wave and plasma characteristics is presented for the following geometrical configurations: p-v, p-d, p-d-v, p-d-v-m, v-p, d-p, m-v-p, m-d-p, m-v-d-p. The ability of the electromagnetic wave at various azimuthal wave modes to sustain plasma is investigated. It is found out that this ability strongly depend on the geometry parameters like the radial size of the different media and the dielectric permittivity (discharge conditions).

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MINIMALISTIC SELF-CONSISTENT MODELING OF PLANAR MICROWAVE SURFACE WAVE DISCHARGES

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Surface-wave (SW) plasmas travelling along a plasma-dielectric interface have been used for years to sustain plasma columns, planar plasmas in processing chambers [1], as well as for plasma diagnostics [2]. In the present contribution we demonstrate that the essential behaviors can be reproduced in a simple self-consistent model taking into account (a) microwave intensity profile determined by launcher details and electron density profile, (b) electron heating and cooling by the microwave and elastic/inelastic collisions, respectively, (c) diffusion of hot electrons out of regions of strong electron heating, (d) gas ionization by the hot electrons, (e) ambipolar diffusion of ions and electrons towards the walls, and (f) Bohm-velocity loss of charged particles escaping into the plasma sheath at the walls. The simplest possible geometries are an infinite plasma slab irradiated by an oblique planar microwave and a cylindrical surface-wave plasma chamber with a ring slot antenna at the top [1].

Modeling at higher pressures is facilitated by the short mean electron mean free-path. Microwave power is absorbed locally, leading to one-to-one relation of microwave intensity and electron temperature. At very low pressure the opposite holds: electron diffusion is so fast that electron temperature and ionization frequency are almost uniform along the entire discharge.

In the present contribution we focus on the more realistic intermediate case where the electron’s path from the place it is heated to the place it expands its energy for ionization and other inelastic collisions is not long enough to ensure uniform electron temperature along the entire discharge, but still long enough to destroy the local balance of electron heating and collisional power losses. At such conditions there is no one-to-one relation between microwave intensity and electron temperature and qualitatively correct modeling must take into account heating of the electron plasma component via diffusion of hot electrons out of regions of strong microwave field and strong electron heating.

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INFLUENCE OF THE OPERATING CONDITIONS ON AR MICROWAVE PLASMA CHARACTERISTICS: MODELLING AND EXPERIMENT

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Surface-wave sustained discharges have been extensively studied in the past 20 years [1]. The application of the intermediate pressure microwave discharges for greenhouse gas conversion to valuable chemicals [2] requires a careful investigation of their characteristics. In the present work, we study, both by modelling and experimentally, the Ar plasma sustained by a surfaguide wave source operating at 2.45 GHz, and at a gas pressure in the range of 250-5300 Pa (2-40 Torr). The applied power varies from 50 to 500W in the experiments. A 2D fluid plasma model is coupled with a self-consistent model of electromagnetic field using the software Plasimo [3]. The gas flow is taken into account by solving the mass, momentum and energy balance equations for the plasma bulk. The electron temperature is experimentally estimated by using an extended corona model associated to different emission line ratios [4], while the electron density is estimated from the balance of creation and loss mechanims for Ar metastable states. The influence of the applied power and gas flow rate on plasma characteristics is under investigation.

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LOCALIZED MICROWAVE INTERACTIONS WITH METALLIC DUSTY-PLASMA COLUMNS

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The paper reviews in a unified approach various experiments in which dusty-plasma columns were excited in air atmosphere from hotspots induced by localized microwaves in solid metals [1]. Similar effectshave been observed in experiments conducted with various metals, such as copper, aluminum, iron, and titanium [2]. These dusty-plasmacolumns contained nanoparticles and larger agglomeratesof up to sub-micron sizes.Experiments conducted with mixtures of thermite powders also generated exothermic energy [3]. The various experimental setups and results are presented, including scattering and calorimetric measurements, as well as ex-situ observations of the interaction products. The plasma columns are experimentally and theoreticallycharacterized, and some of their main parameters are estimated [4].Various models of dustyplasma-columns excitedfrom solid metals by localized microwaves are discussed, and their potential applications are considered.

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ACHIEVING INTENSE MAINTENANCE ELECTRIC FIELD IN A DISCHARGE SUCH THAT PERIODIC PARAMETRIC INSTABILITIES ARE GENERATED

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The intensity of the maintenance electric field of a given discharge is one of its internal parameters. Under ambipolar diffusion conditions, it is almost exclusively set by particle losses, which are related to the dimensions of the discharge vessel and to the gas pressure, and ultimately are determined by the electron energy distribution function. To raise the intensity of this E-field in such a case, one needs to reduce the volume into which the electromagnetic power is absorbed relative to the diffusion volume, i.e. the volume within which electrons transfer their power through collisions to heavy particles.

To show this, we consider the power balance relating the power lost per electron through collisions with heavy particles, θ_L, to the power absorbed (over a period of the microwave field) per electron in the discharge, θ_A. The power θ_A, which depends on E_0^2, the square of the amplitude (intensity) of the maintenance electric field, adjusts to compensate for the power lost θ_L. The analysis presented is achieved for a particular microwave discharge configuration that is known to provide an intense E_0-field, which means $x \geq \lambda_{De}$, where x is the oscillation amplitude of electrons in the E_0-field and λ_{De} the electron Debye length [1]. Such a condition allows one to observe periodic parametric instabilities at or close to the electron-plasma frequency f_{pe} and at their corresponding ion-plasma frequency f_{pi}, [2]..

A 2-D hydrodynamic calculation is performed, which yields the value of the x/λ_{De}ratio through a global energy balance equation: (volume over which power is absorbed in the discharge) times θ_A = (discharge diffusion volume) times θ_L, to which must be added the power lost in the ambipolar field E_a and in the plasma sheath. The present considerations could possibly be extended to obtain a better insight into DC, RF and microwave micro-discharges, characterized by an unusually high level of absorbed power density.

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MICROWAVE SUSTAINED PLASMA MICRODISCHARGE AS POWER-INDUCED LIMITER ELEMENT IN MICROSTRIP DEVICES

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Plasma has been a known technology as power-induced limiter in microwave circuits for decades: Transmit/Receive tubes are used in Megawatts Radar systems with rectangular waveguide [1]. Nowadays, most applications containing microwave systems are achieved as microstrip devices. We present here a new power-induced limiter which presents specifications adapted to this technology.

The operating principle aims at generating a plasma MHCD [2] inside a millimetric hole between a cathode and the microstrip ground plane used as a DC anode. Note that this discharge is located under the microstrip ground plane so that it does not modify the microwave circuit properties at relatively low DC current. Then, the microwave power transferred by the microstrip device can ignit a plasma that fills the upper part of the hole, and finally changes the behavior of the microwave device.

We present here the limiter's characteristics as well as their dependence to hole dimensions, to the pressure, to the MHCD current. We finally discuss the influence of adding microwave power to a DC ignited plasma.

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POSTERS

DIFFERENT PRESSURE REGIMES OF A SURFACE-WAVE DISCHARGE IN ARGON: A MODELING INVESTIGATION

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Over the last decades, many studies focused on the description of surface-wave plasmas produced by microwave discharges [1] both from a theoretical and an experimental point of view. These discharges have a wide range of applications, such as gas conversion, plasma medicine, material processing and surface treatment [2] as they offer relative simplicity and low running costs. They can be operated over a wide range of pressure (from few mtorr to several atmospheres), using different frequencies and various geometries [3]. Among these different geometries, the so-called surfaguide discharges offer the possibility to create low-temperatures plasmascoupled with a strong microwave power [3], which is of particular interest for industrial applications.

Recently, microwave discharges have been applied to CO_2 conversion and the pressure has been shown to be a key parameter to obtain better energy efficiency, which is crucial in this domain [4].

The goal of this study is to get a better understanding of the effect of the pressure on microwave discharges. The presented model is a self-consistent 2D fluid plasma model of a surfaguide discharge operated over a wide range of pressure conditions: from 10 mbar to atmospheric pressure in pure argon.A reduced set of chemistry for CO_2 plasmas is also being developed based on the set of [5]. It will be implemented in the 2D model as a next step.

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NUMERICAL SIMULATION OF FORMATION OF VAPOR BUBBLES IN LIQUID *N*-HEPTANE INITIATED BY A MICROWAVE DISCHARGE INSIDE LIQUID

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For the last decade non-equilibrium plasma located inside gas bubbles in liquids has been a subject of intense research as it can be effectively used to realize plasma chemical reactions. This work continues the studies carried out in TIPS RAS [1, 2]. The model we consider can be presented as follows: microwave energy is introduced by means of a coaxial line into a glass filled with *n*-heptane. Plasma appears at the tip of the coaxial line, and a vapor region is generated.

We use a two-dimensional axisymmetric model, which includes a system of Navier-Stokes equations for two-phase subsonic flow of incompressible liquid and compressible gas, heat conduction equation, Maxwell's equation for the microwave field, Boltzmann equation for electrons, and the balance equation for an electron density and concentration of *n*-heptane in a gas phase. Preliminary calculations of kinetics of thermal decomposition *n*-heptane were performed using scheme developed in [2] to obtain the rate of gross-reaction of n-heptane decomposition.

It was shown that dynamics of bubble evolution significantly depends on the incident microwave power. It can happen that the bubble disappears, or puffs up and stays in place, or becomes a pillar of superheated steam. The plasma is formed only in the vicinity of the central electrode. The plasma is absent inside the bubble when it floats to the liquid surface. The gas temperature in the vicinity of the central electrode, formed due to microwave energy input in plasma and endothermic reaction of the decomposition of *n*-heptane, is about 1300 K. This value agrees with the experimental data [2].

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AGEING OF METAL SURFACES TREATMENT WITH AN ARGON-NITROGEN MICROWAVE AFTERGLOW

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The afterglow [1] of an atmospheric-pressure argon-nitrogen (96%:4%) microwave (2.45 GHz) plasma sustained with 125 W using a surfatron [2], was used for treating the surface of two different metallic samples (aluminum and steel). Samples were exposed at a distance of 3 cm measured from the end of the discharge. In order to rule out the possible effects of temperature on the surface wettability, a comparison with samples heated (>150 ºC) using a conventional hot plate.

Wettability of the samples was measured using the sessile drop technique during the 48 hours following the treatment. Small deionized water drops (<10 μl) were deposited on the surface of treated and control samples and photographs were taken using a digital camera. The images were analyzed using a spherical drop model [3] in order to determine the contact angle of the drop with the surface.

The contact angle significantly decreased after the treatment, reducing from 84º to 20º in the case of the steel samples and from 71º to 18º in the case of the aluminum samples. No significant modification in the contact angle was detected in the case of the samples heated with the hot plate. The original properties of the plasma-treated samples partly recovered after the first 10 hours of treatment, with the contact angles increasing to 60º (aluminum) and 66º (steel) after this first period. After that, the contact angle slowly increased until its value and recovered its original value after 48 hours.

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SYNTHESIS OF MULTI-WALLED CARBON NANOTUBES BY MICROWAVE PLASMA AT ATMOSPHERIC PRESSURE

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Chemical Vapor Deposition (CVD) has been the most used technique for the synthesis of both carbon nanotubes (CNTs) and graphene. However, this technique requires the use of harsh conditions and metal catalysts that increase enormously the production costs. For this reason, during the last years the scientific community has focused their attention on the development of new techniques.

In this communication, we present the synthesis of Multi-Walled Carbon Nanotubes using atmospheric-pressure microwave sustained plasmas. Aliphatic alcohols such as ethanol and isopropanol were used as carbon source. In addition to nanostructured carbon materials formed on the plasma exit, molecular hydrogen was also generated during the alcohol decomposition.[1]The experimental setup used has been designed and patented by our group (Figure 1).[2]

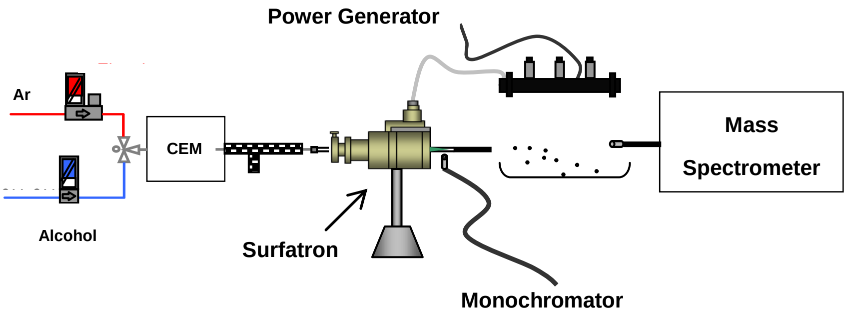

Figure 1. Experimental Setup

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ACTIVE CONTROL OF NEARWALL FLOW IN SUBSONIC DIFFUSER UNDER THE INFLUENCE OF PLASMA

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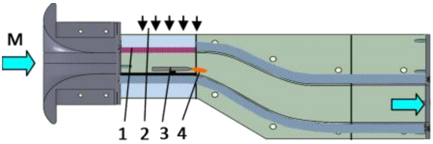
The results of experimental investigation and numerical modeling of plasma formations effects by microwave (MW) radiation of 12.4 cmwavelengthinitiated under Mach number M_{in} = 0.1-0.8 and total airflow parameters $P_t = 10^5$Paand T_t = (280-290)K in the diffuser channel with a lemniskate input and an expansion ratio of 1.8 are presented. Tests were conducted with various types of electrodes and options for their location in the diffusing two dimensional S-duct to ensure initiation of plasma formations under continuous and pulsed-continuous supply of MW energy with a change of the frequency f = (100-200) Hz and the discharge duration τ= (100-300) ms and a maximum pulse power equal to N = 6 kW. Different placing and angle position of electrodes affected on nearwall flow and initiation of plasma discharges.



Scheme of test duct

1 – MW transparence wall, 2 – MW flow, 3 – electrode unit, 4 – MW discharges

Numerical study was conducted with the use program code “ESI-CFD”, intended for calculation of 3D viscous turbulent gas flows under the process of solution of Navier-Stocks equations averaged by Reynolds procedure with MW energy deposition and without it.Energy deposition was simulated by volume energy source in the area of MW discharges.

As a result of preliminary tests the equipment for the generation of MW radiation and data acquisition system operation were calibrated and last one was adjusted to MW radiation influence. At low speeds M_{in} = 0.1-0.45 total pressure lossesdefined as exit area averaged in considered S-duct without energy supply for various electrode assemblies, do not differ from the corresponding values for the smooth channel. With increase of incoming flow velocity to M_{in} = 0.5-0.8 total pressure losses are increased by 0.5-1%. Under the MW energy deposition level of 0.5% to 1.5% of the incoming air flow energy the total pressure losses in the duct growsby (0.5-1)% at speeds corresponding M_{in} = 0.5-0.8 in comparison with flow without MW discharges. At lower M_{in} = 0.1- 0.4 there is anincrease oftotal pressure by 0.2-0.5%. The comparison of experimental and numerical data allows to note the qualitative agreement between them.

ARGON MICROWAVE PLASMAS AS SOURCES OF VACUUM ULTRAVIOLET RADIATION

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Plasmas operating at microwave frequencies have the potential to become alternative sources of vacuum ultraviolet (VUV) radiation, with application in several domains of science and engineering [1]. In this work, microwave driven discharges in argon are investigated as sources of VUV radiation, at low-pressure conditions (0.1 – 1 mbar). A classical surface-wave sustained discharge at 2.45 GHz, with a waveguide-surfatron based setup as the field applicator, has been used as plasma source [2]. VUV radiation has been detected by emission spectroscopy in the 30 – 125 nm spectral range and the experimental spectra show the presence of emissions from excited argon atoms and ions. The most intense spectral lines correspond to the atomic resonance lines, at 104.8 nm and 106.7 nm, and to the ionic lines, at 92.0 nm and 93.2 nm. Emissions at lower wavelengths are also detected, including lines with no information concerning level transitions in the well-known NIST database (such as the atomic line at 89.4 nm). The relative intensity of all the measured spectral emissions with variations of the discharge pressure and microwave power delivered to the launcher has been investigated. The plasma electron density has been determined using optical emission spectroscopy in the visible. The experimental results were analysed using a 2D self-consistent theoretical model based on a set of coupled equations including the electron Boltzmann equation, the rate balance equations for the most important electronic excited species and for charged particles, the gas thermal balance equation, and the wave electrodynamics.

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MICROWAVE PLASMA BASED METHOD APPLIED TO CARBON NANOSTRUCTURES PRODUCTION

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During the few past decades, unique plasma environments have been used to generate various novel materials and allowed the development of long existing ones [1]. Graphene, a one atom thick layer of sp^2 hybridized carbon atoms, attracts strong interest from academia and industry due to its unique properties and great potential for applications. Furthermore, clusters of nanodiamonds reveal unique optical, mechanical and biological properties that have attracted a great interest for an extensive range of applications [2].

The purpose of the present work is to develop microwave plasma-based methods to synthesize different carbon nanostructures, such as free-standing graphene sheets and amorphized nanodiamonds. To this end, methane was injected into a surface wave sustained argon plasma where the decomposition of CH_4 takes place and atomic and molecular carbon are created [3][4]. Microwave powers in the 1 kW range was applied and samples were produced at different compositions of Ar-CH_4 gas mixtures, while maintaining atmospheric pressure in the chamber. The carbon nanostructures were analysed applying scanning electron microscopy (SEM) and Raman spectroscopy. Optical emission spectroscopy was also performed to identify the carbon species involved in the nucleation processes.

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RESONANT ENERGY ABSORPTION AND COLLISIONLESS ELECTRON HEATINGIN SURFACE WAVE DISCHARGES

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Surface waves propagate at the interface between a dielectric surface and an overdense plasma and are characterized by an electric field configuration with components both in the direction of propagation, along the interface, and in the direction perpendicular to the propagation, i.e. parallel to the density gradient from the plasma to the wall. Since the plasma is overdense the real part of the plasma permittivity goes through zero at a given location between plasma and wall. This results in the resonant excitation of plasmons, which are coherent oscillations (space charge oscillations or Langmuir waves) of the electrons. The propagation of surface waves between a plasma and a dielectric surface therefore "combines EM-wave properties and the behavior of space-charge waves in a unified way" (quoted from Aliev, Shluter and Shivarova, "Guided-wave produced plasmas", Ed. G. Ecker, Springer Series on Atoms and Plasmas, 2000). The conversion of electromagnetic energy into electrostatic energy through this resonance phenomenon in surface wave discharges has been known for a long time and discussed in many papers. The effect of the resonance on the electron velocity distribution function has been evidenced in several experimental studies. There is however still no reliable quantitative description of this effect. Most surface wave discharge models are based on a fluid description of the charged particle kinetics and use a local description of the electron complex permittivity, which implies a purely collisional electron heating and is not valid at low pressure (an "effective" electron collision frequency is sometimes used to account for collisionless heating).

In this paper we propose for the first time a fully kinetic, self-consistent model of a surface wave discharge that includesnon-local permittivity effects and their consequence on electron energy absorption. The model is based on a 1D Particle-In-Cell Monte Carlo Collisions simulation where the electromagnetic field is represented by vector and scalar potentials. This approach is well suited to our problem since EM-wave properties and space charge wave properties can be naturally represented by vector and scalar potentials respectively.It combines harmonic (vector potential) and time dependent (scalar potential) descriptions. We show that, as expected, Langmuir waves can fully develop when the resonance location is sufficient far from the wall, and that Landau electron energy absorption plays an important role in these conditions. We also discuss the mechanisms of electron energy absorption when the resonance point is closer the wall sheath.

INVESTIGATION OF MICROWAVE DISCHARGE IN CAVITY REACTOR EXCITED IN THE TM$_{013}$ MODE

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Results of the study of continuous microwave discharge in hydrogen and hydrogen-methane mixture are presented. Microwave discharge is ignited in a cylindrical resonator excited in the TM$_{013}$ mode at a frequency of 2.45 GHz. Such kind of discharge is used for chemical vapor deposition of diamond films [1]. Growth rate of diamond films in CVD reactors depends on the concentration of atomic hydrogen, which is determined by the value of microwave power density (MWPD) in the plasma [2]. The MWPD is defined as the ratio of the absorbed microwave power to the plasma volume. In our experiments the discharge was investigated by method of optical emission spectroscopy over a wide pressure range of 80 - 350 Torr and at MWPD varying from 50 to 550 W/cm^3. Spatial distribution both of integrated luminosity of plasma and of atomic hydrogen Hα line emission intensity when varying the gas pressure and microwave power were measured. The dependence of the dissociation degree of atomic hydrogen was investigated by means of actinometry. To measure the gas temperature the emission of Swan band of C_2 radical was used[3].

To calculate the dimensions and parameters of the microwave discharge plasma the self-consistent two-dimensional model was used, described in detail in [4]. The spatial distributions of Hα intensity and microwave power density were obtained by numerical modeling and the connection between these distributions was established. The boundary of plasma volume on these spatial distributions with accuracy of 10% was defined. Finally the plasma volume was defined on the basis of experimental spatial distributions of intensity and the MWPD was calculated. Based on these results we propose a method of experimental determination of MWPD, allowing unify the calculations of MWPD in various types of microwave plasma chemical reactors.

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OXYGEN ATOMIC DENSITY MEASUREMENT IN N_2/O_2 SURFACE-WAVE PLASMA USING VUV ABSORPTION SPECTROSCOPY WITH A COMPACT MICROWAVE PLASMA LIGHT SOURCE

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Plasma sterilization has been attracting much attention from researchers for its low temperature operation, non-toxic methods, and a short treatment time. In our previous work, an N_2/O_2 gas mixture surface-wave plasma (SWP) generated in a 30 cm diameter stainless-steel cylindrical chamber was used for low temperature plasma sterilization of *Geobacillus stearothermophilus* spores. Our results showed that UV radiation and excited oxygen atoms are the dominant lethal factors in spore inactivation in N_2/O_2 gas mixture SWP.[1-2] However, the behaviors of neutral active species in the inactivation process have not been studied enough, because only a few reliable measurement techniques for the absolute densities of radicals in reactive plasmas have been developed. Various methods, such as laser induced fluorescence spectroscopy, electron spin resonance spectroscopy, cavity enhanced absorption technique, and actinometry technique, have been developed to measure the absolute densities of oxygen or nitrogen radicals. Compared with these methods, vacuum ultraviolet absorption spectroscopy (VUVAS) technique has minimal influence on the processing plasma, and it has been widely used for the absolute radical density determination in processing plasma. In the VUVAS method, however, self-absorption of the light source should be reduced to a negligible level for reliable absorption measurement, but sometimes self-absorption can’t be reduced to an allowable level for the limit of the experimental conditions.

In this work, the oxygen atomic density was measured with a proposed VUVAS method with two wavelengths at 130.22 nm and 130.49 nm, where self-absorption of the light probe at each wavelength was calibrated by taking into account the optical escape factor. The etching effect of excited oxygen atoms on spore-forming microorganisms was discussed by comparing with the measured absolute atomic densities in SWPs with different N_2/O_2 gas mixture ratios.

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MULTIPACTOR RF BREAKDOWN ANALYSIS IN A PARALLEL-PLATE WAVEGUIDE PARTIALLY FILLED WITH A MAGNETIZED FERRITE SLAB

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The purpose of this work is the analysis of the multipactor effect [1] in a parallel-plate waveguide with a ferrite slab magnetized by means of a static magnetic field. To reach this aim, we developed in-house a multipactor simulation code based on the Monte-Carlo method to compute the multipactor RF voltage threshold. The software code, based on the effective electron model, allows the 3D tracking of the individual trajectories of a set of effective electrons. The current simulation model includes the space charge effect, that takes into account the coulombian interaction among electrons by means of a single electron sheet model, as well as the dielectric polarization effect of the ferrite that leads to the presence of a DC electric field. Multipactor susceptibility chart for a ferrite loaded waveguide assuming several values of the ferrite magnetization field is presented. Effective electron trajectories at some interesting points of the curves are depicted for a better understanding of the breakdown phenomenon, finding double-surface and single-surface multipactor regimes.

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USE OF STATIC MAGNETIC FIELDS FOR MULTIPACTOR MITIGATION IN COAXIAL TRANSMISSION LINES

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The main aim of this work is the analysis of the mitigation of a multipactor discharge [1] existing within a coaxial waveguide structure by means of the use of a DC magnetic field. In a first step, multipactor numerical simulations were performed assuming that the coaxial waveguide was immersed in an axial DC homogenous magnetic field. To reach this goal, we developed in-house a multipactor simulation code based on the effective electron model. Numerical simulations show the capability of an axial DC homogeneous magnetic field to prevent the discharge, whenever the strength of the applied magnetic field is over an onset that depends on the specific RF frequency. Then, a long solenoid was designed and manufactured to implement a DC homogeneous magnetic field over a coaxial sample, which was inserted within. An experimental test campaign was carried out to confirm the theoretical predictions, finding good agreement between both of them. In a second stage, we explored the feasibility of using permanent magnets to achieve the multipactor mitigation. First, the magnetic field of a permanent magnet was numerically computed in order to perform multipactor simulations. Preliminary theoretical results support the feasibility of multipactor mitigation for a certain frequency range of the RF signal. Due to that, a neodymium permanent was designed and manufactured in order to carry out a second test campaign. Experimental results are in agreement with theory and multipactor mitigation was found when using permanent magnets.

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MICROWAVE DISCHARGE AS AN IGNITOR AND ACTUATOR OF METHANE-OXYGEN MIXTURE COMBUSTION

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Results are presented from experiments on the ignition of methane-oxygen mixtures in a closed cylindrical chamber with the use of SSD (sliding surface discharge) localized in a small volume. A distinctive feature of this type of discharges is the existence of an 'incomplete combustion wave', which plays an important role in preparing the gaseous medium to the volume combustion based on branching chain reactions. It has been found that the ignition of methane-oxygen mixtures is characterized by the presence of chemical ionization processes which are responsible for the formation of a nonequilibrium plasma with electron density as high as ne ≈ 10^{12} cm^{-3}, observed not only at the stage of developed flame, but also at the stage of incomplete combustion wave [1]. It offers an opportunity to control the ignition process by introducing auxiliary microwave radiation into the incomplete combustion wave. In this case the microwave energy absorption behind the front of the predecessor wave will cause the latter to accelerate. The report presents the results of preliminary experiments for studying 'microwave acceleration'.

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MICROWAVE-EXCITED ATMOSPHERIC PRESSURE PLASMA JET USING MICROSTRIP LINE FOR THE SYNTHESIS OF CARBON NANOMATERIALS

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Atmospheric pressure plasma jet (APPJ) has preferable properties to chemical vapor deposition (CVD), which can provide high-speed depositions and also eliminate expensive and complicated vacuum systems. To date, many APPJ devices have been developed using various kinds of electrical power sources with wide frequency ranges from direct current to microwave. Their properties and structural configurations strongly depend on their electrical power sources. Among those APPJ devices, a microwave-excited plasma allows relatively high-density radicals and high non equilibrium level because electrons in plasmas are oscillated in response to the applied electromagnetic field, while ions are relatively stationary.

In this work, we have developed an atmospheric pressure CVD technology for the synthesis of carbon nanomaterials using a specially-designed microwave-excited APPJ which is based on microstrip line instead of conventional lumped-waveguide [1-4]. Nanocrystalline diamond films were successfully deposited on silicon substrate using the microwave-excited APPJ with a mixture gas of $Ar/CH_4/H_2$ even in ambient air [4].Our APPJ technology using microstrip line allows a low-cost fabrication, a low-power operation, simple circuit elements, and a compact system. Furthermore, the APPJ technology can produce a large-area plasma using the configuration of the nozzle array and microstrip lines. In the presentation, we will introduce our APPJ technology with recent experimental results.

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SURFACE WAVE PLASMA CVD TECHNOLOGIES FOR THE SYNTHESIS OF NANOCRSYTALLINE DIAMOND AND GRAPHENE FILMS

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Surface wave plasma (SWP) is sustained by electromagnetic surface wave (SW) propagating along the plasma-dielectric interface. SWP can provide uniform large-area plasmas and, furthermore, produce overdense plasmas without the application of an external magnetic field. The spatial property in a SWP is described by two regions in a chamber: the SW-excited plasma region with high electron temperature (~10 eV) and the bulk plasma region with low electron temperature (1-3 eV). The property is preferable from the viewpoint of the synthesis of carbon nanomaterials because they allow high-density radicals and low-energy ion bombardment of substrates.

In this work, advanced SWP-CVD technologies have been developed for the synthesis of carbon nanomaterials including nanocrystalline diamond and graphene films [1-5]. Three-dimension simulation code, based on the finite difference time domain (FDTD) method, was developed [1]. The simulation code reproduces the patterns of SW modes in the SW-excited plasma region. The simulation code has been used to design a microwave multi-slot antenna for the production of a large-area SWP. Uniform plasmas with an area of 600×400 mm^2were produced using the multi-slot antenna. Large-area nanocrystalline diamond and graphene films were successfully deposited with low temperature [3,4]. In addition, the useful control method of the plasma-dielectric boundary sheath potential in the SW-excited plasma region was developed, which enhances the performance of SWP in CVD applications [2,5].

Acknowledgements

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NON-THERMAL MICROWAVE PLASMA DISSOCIATION OF CO_2 WITH HIGH ENERGY AND CONVERSION EFFICIENCIES BY CHEMICAL EQUILIBIUM SHIFT

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CO_2 has attracted much attention as the primary greenhouse gas. Its conversion to renewable fuels represents part of the solution for reducing emissions and addressing energy storage. Plasma-assisted CO_2 conversion is regarded as a promising route for the production of CO_2 neutral fuels. Relatively high energy efficiencies over 50 % have been verified using microwave plasmas in the collaboration of DIFFER and IPF Stuttgart [1,2]. However, in non-thermal plasma, the achievement of both high energy and conversion efficiencies is still a great challenge [3]. Apart from the high electron temperature and low gas temperature (non-equilibrium), the plasma-assisted CO_2 dissociation process involves also the chemical equilibrium process, i.e. $CO_2 \leftrightarrow CO + 1/2O_2$, in which the recombination of CO and O_2 could result in a low conversion efficiency. One possible route is to remove the generated O_2, promoting a shift in the chemical equilibrium towards CO. Such an enhanced CO formation would lead to an increase in conversion efficiency while keeping the energy efficiencies at the usual high levels. Therefore, the combination of plasma dissociation and oxygen separation technique could boost a breakthrough in the production of CO_2-neutral fuels with both high energy and conversion efficiencies at the same time.

In this study, a 2.45 GHz 1kW microwave plasma source is used to assess the efficiencies of the process. The CO_2 depletion and products formation are measured downstream by mass spectrometer. Preliminary results of experiments will be shown, where the oxygen was reduced just after the plasma.

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EEPF MEASUREMENTS IN A SURFACE WAVE DISCHARGE IN ARGON AT LOW PRESSURE – EVIDENCE OF RESONANT ENERGY ABSORPTION?

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The propagation of surface waves between a plasma and a dielectric surface has been a subject of study for a long time [1]. More specifically, the conversion of electromagnetic energy into electrostatic energy through the resonance phenomenon where the real part of the plasma complex permittivity goes to zero has been investigated experimentally in several papers (see, eg Refs. [2-3]). For example, Nagatsu *et al.* [3] presented very unusual electron energy probability functions (EEPF) measured in a surface wave plasma at 915 MHz and showing the presence of a rather large population of high-energy electrons near the dielectric-plasma boundary.

In this paper, we propose an experimental characterization of a surface wave discharge excited at 2.45 GHz. Langmuir probes measurements in Argon at 10 mtorr show important changes in the shape of the EEPF with input power. When the power decreases, the EEPF evolves from a Maxwellian distribution to a distribution with a much hotter tail. Measurements with respect to pressure and spatial position along the dielectric surface will be discussed. The experimental results will be put in perspective with results from a self-consistent kinetic model (1D Particle-In-Cell Monte Carlo Collisions simulation) also presented at this conference.

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MICROWAVE SUSTAINED PLASMA MICRODISCHARGE AS POWER-INDUCED LIMITER ELEMENT IN MICROSTRIP DEVICES

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Plasma has been a known technology as power-induced limiter in microwave circuits for decades: Transmit/Receive tubes are used in Megawatts Radar systems with rectangular waveguide [1]. Nowadays, most applications containing microwave systems are achieved as microstrip devices. We present here a new power-induced limiter which presents specifications adapted to this technology.

The operating principle aims at generating a plasma MHCD [2] inside a millimetric hole between a cathode and the microstrip ground plane used as a DC anode. Note that this discharge is located under the microstrip ground plane so that it does not modify the microwave circuit properties at relatively low DC current. Then, the microwave power transferred by the microstrip device can ignit a plasma that fills the upper part of the hole, and finally changes the behavior of the microwave device.

We present here the limiter's characteristics as well as their dependence to hole dimensions, to the pressure, to the MHCD current. We finally discuss the influence of adding microwave power to a DC ignited plasma.

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LOCALIZED MICROWAVE INTERACTIONS WITH METALLIC DUSTY-PLASMA COLUMNS

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The paper reviews in a unified approach various experiments in which dusty-plasma columns were excited in air atmosphere from hotspots induced by localized microwaves in solid metals [1]. Similar effects have been observed in experiments conducted with various metals, such as copper, aluminum, iron, and titanium [2]. These dusty-plasma columns contained nanoparticles and larger agglomerates of up to sub-micron sizes. Experiments conducted with mixtures of thermite powders also generated exothermic energy [3]. The various experimental setups and results are presented, including scattering and calorimetric measurements, as well as ex-situ observations of the interaction products. The plasma columns are experimentally and theoretically characterized, and some of their main parameters are estimated [4]. Various models of dusty plasma-columns excited from solid metals by localized microwaves are discussed, and their potential applications are considered.

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MODE OF PRODUCTION AND APPLICATION RANGE OF LENGTHY MICROWAVE TORCH EXCITED AT A CONSIDERABLY SUBTHRESHOLD FIELDS IN ATMOSPHERIC PRESSURE GASES

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Results of experimental investigation of possibility to create lengthy plasma formation in an atmospheric pressure air under the free space conditions and their applications for plasmachemical means are presented. As a source of energy Russia-produced microwave generator GIROTRON having power $P \leq 600$ kW, wavelength $\lambda \approx 0{,}4$ cm and pulse duration $\tau \leq 20$ ms has been applied. Microwave torch with length as high as $L \leq 50$ cm has been obtained with help of tailor made quasioptical system for microwave beam formation and under threshold discharge initiation. Physics and parameters of such a discharge are similar to the SMS-discharge investigated in the GPI [1].

Preliminary results of plasmachemical decomposition of methane and carbon dioxide in such a gases like: CH4, CH4+CO2, CH4+H2, CO2+H2 have been obtained.

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USING A MICROWAVE PLASMA JET FOR WATER TREATMENT

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The use of a microwave (2.45 GHz) surface wave sustained discharge to induce changes in water properties has been investigated. The reactor consisted of a plasma-jet over liquid configuration, in such a way that the spatial afterglow of the microwave plasma column was directed to water. A *surfatron* device was used to couple the energy coming from a microwave power supply to the support gas (argon) within a quartz reactor tube opened to the air. Microwave power was set at 150 W and argon flow rate ranged between 350 and 1400 sccm. The plasma treatment generated H_2O_2 species in water in all the cases studied.This plasma reactor was able to generate up to 10 mg/L of H_2O_2 after 30 min treatment on a 8 mL water sample. The energy yield for hydrogen peroxide formation, for the most favorable case studied (F_{Ar} = 1400 sccm), was 1.1 g/(kW·h), falling high range of the values reported by Locke et al. [1] for different electric discharges above liquids. Conductivity and pH of the water also underwent changes upon its exposure to this plasma jet effluent. All these changes in water properties helped to understand the ability of jet to induce methylene blue degradation in aqueous solutions.

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MEASURING THE ELECTRON DENSITY OF A NON-THERMAL MICROWAVE (2.45 GHZ) PLASMA AT ATMOSPHERIC PRESSURE

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In this work, we present an alternative method to measure the electron density from the difference of Lorentzian widths of two Balmer series hydrogen lines (H_β and H_α), especially convenient for non-thermal plasmas. When using this method, previous measurement of the gas temperature (so van der Waals contribution to the Lorentzian part of the line profile) is not required. The method applies to plasmas in which the Stark profile of H_β and H_α lines profiles can be approximated to a Lorentz function and, as a consequence, the experimental shapes of these lines can be assumed as a Voigt function. We have applied this method to the determination of the electron density of a non-thermal microwave-induced plasma at atmospheric pressure. The results obtained have been compared to those obtained using both H_β and H_α Stark broadenings and CS Model, and peak-separation method [1], and a good agreement has been found. Also, comparison between the values of the Stark broadening of the Ar I 603.2 nm line experimentally obtained using the electron density estimated from the new method, and the theoretical value of this broadening calculated by Christova *et al*. in Ref. [2] and Dimitrijevic *et al*. in Ref.[3], was done.

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DETECTION AND IDENTIFICATION OF SPECIES IN THE TRANSFORMATION OF HYDROCARBONS IN A MICROWAVE PLASMA REACTOR

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Different hydrocarbons have been transformed in an argon microwave surface-wave plasma reactor at reduced pressure. Optical emission spectroscopy has been used for identifying the species generated in the plasma whereas gas chromatography, mass spectrometry, X-ray diffraction and FTIR spectroscopy have been employed for analyzing and quantifying all compounds present in the reaction products.

The main species detected in the plasma were Ar, H, NH, CN, OH, N_2, CH, and C_2 (Swan system), thus suggesting that in the plasma region a complete dissociation of the hydrocarbon molecules took place initially through the cleavage of C-C and C-H bonds.

Regardless of the reacting paraffin, the main products were methane, acetylene and C3 and C4 hydrocarbons but particularly hydrogen and ethylene, both of a great interest for the petrochemical industry. In most cases, a carbon film deposits on the reactor tube. It consisted of an amorphous hydrogenated carbon film with a high sp^3 coordinated carbon proportion.

Conversion and selectivity were dependent on the applied power and the hydrocarbon flow rate as well as on the feed position. Thus, at low powers (100–150 W) the conversion to hydrogen was quite selective whereas at high powers (>300 W) or slow hydrocarbon flow rate ethylene resulted to be the major product. Furthermore, the reaction could be preferentially conducted toward ethylene or hydrogen depending on whether the light paraffin was fed into the plasma column or the afterglow region, respectively.

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TOLUENE DESTRUCTION USING A MICROWAVE ARGON PLASMA TORCH

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The plasma produced by Axial Injection Torch (T.I.A.) has been proved by our group to be a useful device to the destruction of halogenated VOCs (chlorinated compounds) [1,2]. This work tries to study its applicability to other type of VOCs, the BETXs compounds. These products are found in petroleum derivatives and cause contamination of soils and water, with notorious harmful effect in the human health.

In this study, a argon plasma in atmospheric pressure is used for toluene elimination in different conditions of microwave power, gas flow and contaminant concentration. The DRE (Destruction or Removal Efficiency) of this plasma has been determined. Efficiency values up to 90% have been obtained for all conditions.

Similar DRE dependences on microwave power and gas flow than the previous obtained with chlorinated VOCs are found. Although a different behavior with contaminant concentration was obtained. In previous papers [1,2], it showed that the chlorinated contaminants favored destruction efficiency due to the added chlorine plays a rule in this destruction. Contrary, DRE decreases with toluene concentration by absence of this kind of halogen.

Byproducts of this destruction procedure have been also determined using a combined analysis by Gas Chromatography (FIT detector) and Mass-Chromatography. CO and CO_2 gases have been found together hydrocarbon compounds: residuary toluene, benzene, etc.

Finally, spectroscopic studies of the plasma have been conducted in order to determine the elements and radicals present in the plasmas during the destruction.

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MD-9. Scientific Program and Timetable

Sunday 6		Monday 7		Tuesday 8		Wednesday 9		Thursday 10		Friday 11
		Breakfast		Breakfast		Breakfast		Breakfast		Breakfast
	9:00	Registration	9:00	GL-4 I.A.Kossyi	9:00	Excursion	9:00	GL-7 E. Tatarova	9:00	GL-10 V. Skalyga
			9:40	TL-7 K. Gadonna			9:40	TL-16 I. Montero	9:40	TL-23 E. Jerby
			10:05	TL-8 A.M.Davydov			10:05	TL-17 G. Chen	10:05	TL-24 M. Moisan
	10:40	**Opening Ceremony**	10:30	coffee break			10:30	coffee break	10:30	coffee break
	10:55	GL-1 M. Moisan	10:55	GL-5 L. Zajíčková			10:55	GL-8 M.A. Gigosos	10:55	GL-11 F. M. Dias
	11:35	TL-1 J.P. Boeuf	11:35	TL-9 J. Palomares			11:35	TL-18 J. van der Mullen	11:35	TL-25 L. Liard
	12:00	TL-2 B. Gimeno	12:00	TL-10 Yu. A. Lebedev			12:00	TL-19 M.A. Gogoleva	12:00	**Closing Ceremony**
	12:25		12:25				12:25			
	13:00	Lunch	13:00	Lunch	13:00	Lunch	13:00	Lunch	13:00	Lunch
	14:30	GL-2 J. van der Mullen	14:30	Tribute to Prof. Zenon Zakrzewski (M. Moisan)	14:30	GL-6 M.C. López-Santos	14:30	GL-9 A. Bogaerts		
	15:10	TL-3 M. Nagatsu	15:10	Tribute to Prof. Carlos M. Ferreira (F. M. Dias)	15:10	TL-11 S. Espinho	15:10	TL-20 E. Benova		
	15:35	TL-4 N. Britun	15:35	coffee break	15:35	TL-12 S. Wang	15:35	TL-21 I. Ganachev		
Registration	16:00	coffee break	16:00	Poster Session	16:00	coffee break	16:00	TL-22 V. Georgieva		
	16:25	GL-3 P. Awakowicz			16:25	TL-13 M.A. Lobaev	16:25	coffee break		
					16:50	TL-14 I.A.Kossyi	16:50	ISC meeting		
	17:05	TL-5 E. Benova								
					17:15	TL-15 J Kim	17:15			
	17:30	TL-6 A.Berthelot								
					17:40		17:40			
	17:55		17:55							
Welcome Party	19:00	Dinner	19:00	Dinner	19:00	Dinner	19:00	Conference Banquet		