S19 Plasma Physics and Applications

Física de Plasmas y sus Aplicaciones (GEFP)

13/07 Wednesday afternoon, Aula 1.7

15:30-16:00 Elena de la Luna (Emilia Solano)
Resultados JET DT Campaign

16:00-16:15 K. McKay, D.J. Cruz-Zabala, E. Viezzer, R. López-Cansino, R.M. McDermott, R. Dux, and the ASDEX Upgrade Team
Investigation of the separatrix ion temperature using impurity Charge Exchange Recombination Spectroscopy

16.15-16.30 E. Sánchez, J. L. Velasco, I. Calvo, S. Mulas
A quasi-isodynamic configuration with good confinement of fast ions at low beta

16.30-16.45 Francisco Tabares, Eider Oyarzabal, Daniel Alegre, Macarena Liniers, David Tafalla, Alfonso de Castro, Kieran McCarthy and the OLMAT technical Team
OLMAT. A new Facility for testing materials under DEMO-relevant Heat Loads

16.45-17.00 E. Viezzer et al
Assessment of core-edge integrated ELM-free and small-ELM scenarios for future fusion power plants

17:00-18:00 **Coffee Break**

18:00-18:15 M. Garcia-Munoz, A. Mancini, J. Segado-Fernandez, E. Viezzer, M. Barragan-Villarejo, J. Ayllon-Guerola, D. Cruz-Zabala, M. Freire-Rosales, J. Garcia-Dominguez, J. Galdon-Quiroga, J. Garcia-Lopez, J. M. Maza, J. F. Rivero-Rodriguez, M. Toscano-Jimenez, L. Velarde-Gallardo and the PSFT team
High Confinement Regime at Positive versus Negative Triangularity in the SMall Aspect Ratio Tokamak (SMART)

18:15-18:30 A. de Castro, J. Raukema, D. Alegre, E. Oyarzábal and F. L. Tabarés
Glow Discharge studies on the direct detection of chemically eroded tin hydride

S19 Plasma Physics and Applications
Física de Plasmas y sus Aplicaciones (GEFP)

14/07 Thursday afternoon, Aula 1.7

15:30-16:00	L.J Fernandez-Menedez *Diagnóstico de plasmas inducidos por láser mediante espectroscopía de emisión con resolución especial y temporal*
16:00-16:15	V. Gonzalez-Fernandez, A. Steiger *Comparison of electric field fall strengths in a hollow cathode discharge in hydrogen and deuterium*
16.15-16.30	Paula Lozano, Antonio Tejero-del-Caz, Rut Morales, Encarnación Muñoz-Serrano *Numerical simulation of an argon atmospheric pressure plasma jet for biomedical applications*
16.30-16.45	Gonzalo Rodríguez Prieto, Luis Javier Fernández Menéndez, Luis Ernesto Bilbao Dates, Nerea Bordel García *Excitation temperatures of plasmas at times much larger than current deposition in exploding wires*
16.45-17.00	Aarón Alejo *Recent developments of high-intensity laser pulse guiding using hydrodynamic optical-field-ionised (HOFI) channels*
17:00-18:00	**Coffee Break**
18:00-18.15	Lozano P, Tejero-del-Caz A, Morales R, Muñoz-Serrano E *Validity of the Boltzmann relation in electronegative plasmas*
18:15-18:30	C. González-Gago, C. Méndez-López, L.J. Fernández-Menéndez, J. Pisonero, N. Bordel *Estudio del efecto de la nebulización sobre los parámetros de excitación en plasmas inducidos por láser*
18-30:19:30	All *General Meeting GEFP*

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Experiments with Deuterium/Tritium in JET with a Be/W wall

E. de la Luna* on behalf of JET contributors#

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In 2021, high fusion power deuterium-tritium experiments (DTE2) were performed in JET for the first time since the 1997 Deuterium-Tritium (D-T) campaigns in TFTR and JET (DTE1). This represents the culmination of a long-term plan in support of ITER that started in 2011, with the installation of plasma facing components materials similar to those that will be used in ITER (with W in the divertor and Be in the main chamber), and included several enhancements (diagnostics, heating power & new operational scenarios). ITER is a large scale international fusion project, that is currently under construction in France, aimed at demonstrating the scientific and technological feasibility of fusion energy production.

DTE2 delivered fusion energies exceeding the previous record (59 MJ compared to 22 MJ in DTE1) and demonstrated the compatibility of sustained high performance D-T plasmas (up to 5 s) with the ITER-like-wall (ILW). Experiments designed to address specific physics questions provide a unique set of data, with several notable preliminary results. In particular, isotope effects on transport and confinement and the impact of alpha particles on plasmas have been a key aspect addressed. The plasma edge (H-mode pedestal) pressure increases with the ratio of T to D and the core confinement increases in T with respect to D at high input power and high beta [1]. Reduction of turbulent transport and improvement of confinement in the presence of T was anticipated in a strong modelling effort performed before the DTE2 campaign [2,3,4]. The fusion power in the different operational scenarios performed is consistent with predictions made also before DTE2 using an integrated modelling approach [5]. Unambiguous observations of alpha particles and of alpha-driven instabilities were obtained. In particular, thermal confinement does not seem to degrade in the presence of Alfvén activity destabilized by alpha particles or ICRH, which may indicate some interplay between fast particles and main turbulence as found previously for D plasmas. Efficient core heating was demonstrated with a novel Ion Cyclotron Radio Frequency scheme considered for ITER D-T operations: a D-9Be-T three-ion scheme [6], using the Be that is naturally present in the ILW.

This contribution will summarize the motivation for, and the journey towards DTE2, but will focus on the execution of the DTE2 experiments and main results, describing some of the challenges encountered, and highlighting how the unprecedented observations inform the preparation for ITER and other future fusion devices D-T operations.

[1] P. Schneider AAPPS conference 2021
[2] J. García et al., Nuclear Fusion **57** 014007 (2017)
[3] F.J. Casson et al., Nuclear Fusion **60** 066029 (2020)
[4] A. Mariani et al., Nuclear Fusion **61** 066032 (2021)
[5] J. Garcia et al., Nuclear Fusion **59** 086047 (2019)
[6] Y. Kazakov et al., Physics of Plasmas **28** 020501 (2021)

Acknowledgements: This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

#See the list of authors in the paper "Overview of JET results for optimising ITER operation" by J. Mailloux et al., published in Nuclear Fusion special issue: Overview and Summary Papers from the 28th IAEA Fusion Energy Conference (virtual event, 10-15 May, 2021)

Investigation of the ion temperature in the separatrix and Scrape-Off Layer using impurity Charge Exchange Recombination Spectroscopy

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In the development of fusion technology it is critical to be able to accurately characterize the ion temperature profile of a plasma. This work determines ion temperature using Charge Exchange Recombination Spectroscopy (CXRS). CXRS consists of injecting neutral particles into the plasma to induce a charge exchange reaction with the ions of the plasma. The photons emitted in these reactions are collected by a spectrometer, producing a light spectrum that can be analyzed to give information about the emitting ions, including temperature. If the injected neutral particles are molecules, then they can potentially contaminate the ion spectral emissions with molecular line emissions, leading to inaccurate temperature measurements.

In this work, a multi-Gaussian fit is designed to identify and subtract the molecular lines from the complex spectra detected by CXRS diagnostics at the ASDEX Upgrade tokamak for discharges in different energy regimes, including H-mode, L-mode, and I-mode. Impurity temperature, rotation, and intensity profiles are determined for the three regimes using measurements at the edge of the plasma and in the Scrape-Off layer, as these regions are most likely to be affected by the injected neutral molecules [1]. The multi-Gaussian fit identified molecular contributions for all three energy confinement modes. Plasma profiles obtained using the multi-Gaussian fit to subtract the molecular contributions showed decreased temperature and intensity in the Scrape-Off layer, indicating molecular lines primarily impact this region of the plasma. The results suggest that the molecules penetrate farther in L-mode and I-mode as compared to H-mode.

1D kinetic simulations are performed to model the neutral density profile and verify where in the plasma neutral molecules are capable of impacting CXRS signals. These simulations show the molecular neutrals penetrating the farthest into the plasma in L-mode, followed by I-mode, with H-mode showing the least penetration, in agreement with the measurements described above. The findings from this work indicate molecular emissions have the potential to impact temperature measurements in the Scrape-Off layer for all three regimes, with the contributions most likely to affect the separatrix ion temperature in the L-mode regime.

[1] D.J. Cruz-Zabala et al., *Plasma Physics and Controlled Fusion*, (2022).

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A quasi-isodynamic configuration with good confinement of fast ions at low β

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The stellarator possesses some advantages with respect to the tokamak as a fusion reactor concept. Most of the current is externally generated, which reduces the hazard of disruptive current instabilities. Furthermore, the absence of inductive current allows a more straightforward steady-state operation than in tokamaks. However, the lack of axisymmetry of the stellarator implies that good confinement is not guaranteed but requires careful tailoring of the magnetic configuration. The present generation of optimized stellarators, such as HSX and W7-X, are based on magnetic configurations optimized for good neoclassical confinement of thermal species. The optimization of HSX is based on the concept of quasi-symmetry [1], whereas the optimization of W7-X relies on the notion of quasi-isodynamicity [2]. The neoclassical optimization was first demonstrated experimentally in HSX [3], and more recently, in W7-X [4]. However, HSX and W7-X do not confine fast ions (FI) sufficiently well, and further optimization is required. Recently, new vacuum quasi-symmetric configurations optimized for FI confinement have been obtained [5, 6]. In contrast, in quasi-isodynamic devices, FI confinement is known to improve with plasma pressure (β) [7] and so far has been shown to be good enough only in high-β scenarios [8].

This work presents a new four-period stellarator configuration with aspect ratio A=10 and a quasi-isodynamic magnetic field with B=5 T at the magnetic axis. Its most salient property is an excellent confinement of fast ions for moderate values of <β> (~1.5%), which improves further for reactor-scale plasmas with <β>~4%. The new configuration has been obtained using the optimization suite of codes STELLOPT [9], in which the code KNOSOS [10] has recently been included and is used to compute orbit-averaged quantities that are utilized as proxies for the confinement of energetic particles [11]. Monte Carlo full-orbit calculations with ASCOT [12] confirmed the good confinement of energetic ions predicted by the proxies computed with KNOSOS. In this configuration, the effective ripple is smaller than 0.5% in the plasma core and the Mercier MHD stability in all the plasma volume is supported by a significant magnetic well. The ballooning stability up to <β>=4% has been demonstrated using the code COBRA [13]. A preliminary evaluation allows us to foresee a small bootstrap current for <β> values up to 4%. The inclusion of turbulent transport as an additional optimization criterion will be also discussed.

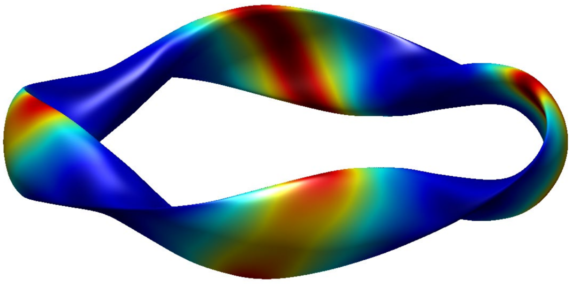

Figure 1. Magnetic field strength on the last closed flux surface of the quasi-isodynamic configuration at b=1.5%.

[1] J Nührenberg, *Phys. Lett.* A **129** (2) (1988).
[2] L. S. Hall et al., *Phys. Fluids* **18** (1995); P. Helander et al., *Plasma Phys. Control. Fusion* **51** (2009).
[3] J. M Canik, *Phys. Rev. Lett.* **98**, 085002 (2007).
[4] C. Beidler et al., *Nature* **598**, E5 (2021).
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[8] A. A. Subbotin et al., *Nucl. Fusion* **46** (2006).
[9] S. A. Lazerson et al., www.osti.gov/biblio/1617636-7pt.
[10] J. L. Velasco et al., *J. Comp. Phys.* **418** (2020).
[11] J. L. Velasco et al., *Nucl. Fusion* **61** (11) (2021).
[12] E. Hirvijoki et al., *Comput. Phys. Commun.* **185** (2014).
[13] R. Sánchez et al., *J. Comp. Physics* **161** (2) (2000).

OLMAT. A new Facility for testing materials under DEMO-relevant Heat Loads

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The OLMAT (Optimization of Liquid Metal Advanced Targets, [1]) facility has recently completed the commissioning and start-up phases. Solid and liquid tin (Sn) metallic targets were exposed to a hydrogen neutral beam injector (NBI) particle flux with power densities up to 56±15 MW/m^2, pulse duration up to 150 ms, and repetition rates up to 2 pulses/minute. These beam parameters are well above the estimates based on the typical performance of this NBI system when used for heating plasmas in the TJ-II stellarator. The parameters of the plasma generated through the interaction of the fast (32.5 keV) neutrals and ions with the target were characterized by spectroscopic methods while surface temperature and total absorbed power were followed using pyrometry and infrared (IR) thermography, and calorimetry, respectively. Targets were visually monitored using a fast-frame imaging camera and analyzed ex-situ using TEM/EDX. Electrical isolation of the target permitted recording the floating voltage during irradiation as well as for active biasing tests. In this work, a description of the facility, its operating parameters, plus first results of the exposure of solid (TZM and ITER-grade W) and Liquid Metal (LM) – Capillary porous system (CPS) targets to NBI fluxes, as well as on-going research, are provided. The intrinsic capabilities of OLMAT as a new High Heat Flux (HHF) Facility for testing solid and liquid metal divertor targets under reactor-relevant heat load conditions are assessed and compared with other existing HHF Facilities.

[1] D. Alegre et al., Design and testing of advanced liquid metal targets for DEMO divertor: The OLMAT project, *J. Fus. Energy* https://doi.org/10.1007/s10894-020-00254-5.

[#] The OLMAT Team: Ricardo Carrasco, Fernando Martin, Miguel Navarro, Andres Jimenez-Denche, Francisco Miguel Honrubia, Luis Alberto Bueno, Jose A Sebastian, Emilio Sánchez, Ana Portas, Augusto, Pereira, Angel de la Peña and Jesus Gomez.

Assessment of core-edge integrated ELM-free and small-ELM scenarios for future fusion power plants

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One of our grand challenges towards fusion energy is the achievement of a high-performance plasma core coupled to a boundary solution. The high confinement mode (H-mode) provides such a high-performance fusion core due to the build-up of an edge transport barrier leading to a pedestal. However, it also features type-I edge localized modes (ELMs) which pose a threat for steady-state operation in future fusion devices as they induce large energy fluences onto the plasma facing components, thus damaging the first wall.

For future fusion devices, we need to demonstrate the integration of an ELM-free regime at low q95, low torque with high confinement and compatible with divertor detachment. Several ELM-free and small-ELM regimes have extended their operational space in the past years, with the ultimate goal of providing an alternative core-edge solution to ITER and DEMO. Prominent ELM-free or small-ELM alternatives include the I-mode, QH-mode, EDA H-mode, quasi-continuous exhaust (QCE) and 'grassy' ELM regimes, X-point radiative scenarios and negative triangularity.

Key elements for projecting to future fusion devices include the integration of an ELM-free or small-ELM scenario with high performance, low core collisionality, high density and Greenwald fraction and a power exhaust solution. In nowadays machines, a low pedestal top collisionality and high density separatrix conditions cannot be matched simultaneously. For extrapolation to future fusion machines, compatibility with both needs to be demonstrated.

The state-of-the-art, including access conditions and main signatures, of these alternative regimes is presented. Understanding the underlying physics mechanism of the observed differences in energy and particle transport of these regimes is of paramount importance. The compatibility of these regimes with edge radiative cooling and divertor radiation to achieve detachment will be discussed. Many of these regimes partly match the operational space of ITER and DEMO, however, knowledge gaps remain. Besides compatibility with divertor detachment and a radiative mantle, these include extrapolations to high Q operations, pellet fuelling, impurity transport, energetic particle confinement, amongst others. This talk will discuss these knowledge gaps and possible strategies to close these gaps to show their applicability to ITER and DEMO.

High Confinement Regime at Positive versus Negative Triangularity in the SMall Aspect Ratio Tokamak (SMART)

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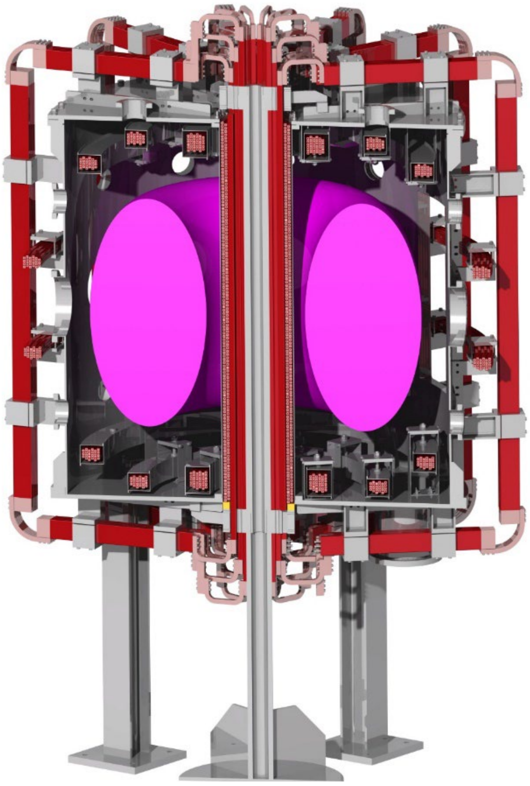
High plasma confinement mode (H-mode) is the reference regime for most future tokamak-based large fusion devices, such as ITER. H-modes are characterized by an edge transport barrier that mitigate the plasma edge turbulence and lead to large plasma pressures and, hence, fusion power throughput. H-mode plasmas presents, however, large edge pressure gradients that develop Edge Localized Modes (ELMs). ELMs are edge localized magnetohydrodynamic (MHD) perturbations that cause large intermittent power loads on the Plasma Facing Components (PFCs) and are thought to be intolerable in future burning devices. Negative Triangularity (NT) shaped plasmas emerge as an attractive baseline scenario for a future tokamak-based fusion power plant as features H-mode-like confinement parameters but without large edge pressure gradients and thus, without ELMs.



The SMall Aspect Ratio Tokamak (SMART) is a new Spherical Tokamak (ST) under construction at the University of Seville aimed at studying the prospects of Negative Triangularity (NT) shaped plasmas for high confinement plasma regimes (H-mode). SMART has been designed to operate at plasma currents I_P up to 0.5 MA, toroidal magnetic fields B_t up to 1 T and plasma pulse length up to 0.5 sec. A 1 MW Neutral Beam Injection (NBI) shall ensure H-mode access, and a flexible shaping, plasma confinement studies at Positive vs Negative Triangularities.

An overview of the SMART project together with its expected plasma performance, capabilities, and timeline will be presented.

[1] S. Doyle et al., *Fusion Engineering and Design* **171**, 112706 (2021).
[2] A. Mancini et al., Fusion Engineering and Design **171**, 112542 (2021).
[3] M. Agredano et al., Fusion Engineering and Design **168**, 112683 (2021).
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Glow Discharge studies on the direct detection of chemically eroded tin hydride

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Liquid metal divertor configurations, and in particular tin Plasma Facing Components (PFCs), are investigated to ameliorate intrinsic problems (erosion, cracking, melting, embrittlement) of traditional solid tungsten counterparts envisioned for ITER and next step magnetic fusion reactors [1]. Physical/thermal limits of tungsten determine that the handling of the extreme heat flux conditions expected in a fusion reactor divertor (~10 MW/m^2 steady state, up to GW/m^2 range during transient events-ms time scale-) will be a major challenge, especially considering that a non-sufficient lifetime will considerably undermine the technical/economic viability of the reactor. Liquid tin PFCs are aimed to handle power densities beyond the physical limits of tungsten also offering a self-healing plasma interface immune to permanent damage that may enlarge its lifetime. Supported in porous structures, tin has been exposed to different tokamak/linear and laboratory plasmas showing power exhaust capabilities that may overcome the limits of tungsten but revealing intrinsic plasma material interaction problems. In particular, droplet ejection and chemical erosion would increase the tin impurity influx to the confined plasma region (with subsequent plasma contamination and performance degradation) also originating tin re-deposition on undesired in-vessel areas. While liquid droplet ejection has been observed in plasma exposure experiments, the formation of volatile tin hydride (SnH_4) has not been directly detected yet under fusion-like plasma exposure. Volatile tin hydride tends to rapidly decompose even at room temperature conditions, thus complicating its observation and/or diagnosis. Tin hydride generation has been utilized in Extreme UltraViolet (EUV) lithography semiconductor technologies to etch mirror surfaces contaminated with tin debris, using plasmas with low energy ions and significant neutral content [2]. In these conditions, the presence of tin hydride has been indirectly inferred from associated tin deposited layers formed as a consequence of the etching process in which no physical sputtering may be claimed. In fusion related research, the formation of SnH_4 has only been vaguely postulated to explain experimental findings in which potential tin chemical erosion seems to be related to the complex chemistry between it and hydrogen isotopes [3]. In this work, direct current Glow Discharge (GD) H_2 plasma experiments (pressure between 5-35 mTorr, discharge voltage between 250-350 V, plasma current of 50-100 mA and total fluence ~10^{23} m^{-2}) have been conducted in a chamber with walls covered by a tin sheet at a temperature up to 120ºC. Liquid nitrogen cryotrap assisted mass spectrometry (CTAMS [4]) was utilized in the experiments to condense the products of the plasma-surface processes. After plasma operation, the progressive heating of the cryotrap aimed to evaporate the condensed products and a mass spectrometer (SRS 200 Residual Gas Analyzer) placed in the direct line of sight of the cold finger was employed the potential observation of tin hydride traces. During the plasma phase, optical emission spectroscopy was also utilized in an attempt to detect spectroscopic footprints of the compound in real time. Finally, post mortem surface analyses (SEM/EDS as well as profilometry) were employed in witness samples (silicon wafer substrates) and also in parts of the main tin wall exposed to plasma in order to observe and characterize potential tin depositions. The works are completed by a characterization of the neutral and ion fluxes coming from plasma and the estimations of the expected sputtered tin fluxes as well as tentative tin hydride formed ones that are compared to the limits of detection of the mass spectrometry diagnostic. The results of the experimentation are addressed focusing on their global implications and perspectives for a fusion reactor solution based on a liquid tin divertor configuration.

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Diagnóstico de plasmas inducidos por láser mediante espectroscopía de emisión con resolución especial y temporal

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La espectroscopía de plasmas inducidos por láser, o *Laser-Induced Breakdown Spectroscopy* (LIBS) en inglés, es una técnica basada en el análisis espectral de la emisión de un plasma generado mediante pulsos de radiación láser de alta intensidad y corta duración (ns), que son enfocados sobre la superficie de un determinado material alcanzando altos valores de irradiancia (10^{12} W/cm^2). De esta forma es posible vaporizar y excitar el material, creando un plasma de unos pocos milímetros de tamaño cuya vida media es del orden de cientos de microsegundos [1]. LIBS se emplea habitualmente con fines analíticos ya que proporciona de manera directa y simultánea información de la composición elemental del material irradiado a partir del análisis espectroscópico de la luz emitida por el plasma, permitiendo la determinación de todos los elementos de la tabla periódica, en cualquier tipo de muestra y ambiente. Sin embargo, la determinación de elementos halógenos en LIBS está limitada, ya que presentan señales atómicas de baja intensidad [2]debido fundamentalmente a que tienen energías de excitación e ionización elevadas (>10 eV). La espectroscopía de emisión molecular se ha mostrado como una buena alternativa para la detección indirecta de estos elementos analizando la emisión de moléculas diatómicas formadas por un halógeno y un elemento alcalinotérreo presente en el plasma.

En un estudio previo, nuestro grupo investigó la formación de la molécula de CaF en los plasmas inducidos por láser (LIP), encontrando que su emisión no es homogénea sino que predomina en las regiones más bajas del plasma [3]. Con el objetivo de conocer con mayor detalle las causas de este comportamiento, en este trabajo se presenta un diagnóstico del LIP donde se determinan parámetros fundamentales del mismo como su temperatura de excitación (T_{exc}) y su densidad electrónica (n_e) cuando se utilizan muestras de CaF_2. El cálculo de T_{exc} se realiza mediante diagramas de Boltzmann empleando la radiación atómica del Ca, mientras que el cálculo de n_e se lleva a cabo mediante la determinación del ensanchamiento Stark que sufre la línea H-alpha. Como novedad, se emplea un equipo experimental que permite conocer la distribución espacial y temporal de estos parámetros a medida que el plasma evoluciona. En líneas generales, se ha encontrado que el predominio de la radiación molecular de CaF está ligado a las zonas del plasma en la que se tiene una menor excitación, es decir, donde se registran unos valores más bajos de T_{exc} y n_e.

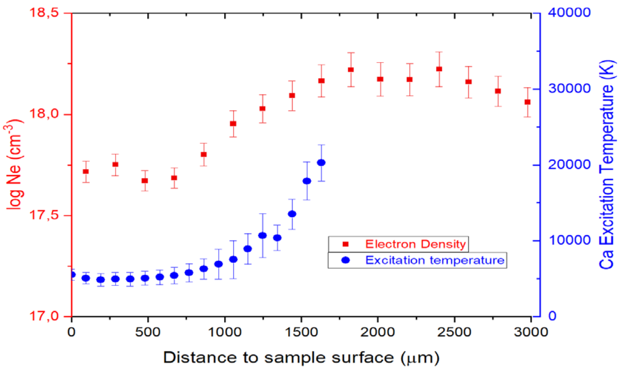

Figura 1. Densidad electrónica (rojo) y temperaturas de excitación (azul) en función de la altura medida sobre el eje vertical de simetría del plasma.

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Comparison of electric field fall strengths in a hollow cathode discharge in hydrogen and deuterium

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The relevance of the electric field strength (E-field) present in plasmas has involved many efforts to designing innovative strategies to bring reliable measures to the plasma physics community. Namely, atomic hydrogen (H) isotopes are excellent candidates for E-field measurements and the Stark splitting caused by an external E-field is very well known. Nevertheless, studies concerning deuterium (D) are not so common. Undoubtedly, there is an undeniable interest in the comparison between the two isotopes because D atoms are twice as heavy than H atoms.

In this work, we present a detailed comparison of high-resolution E-field strengths falls measurements performed in a hollow-cathode glow discharge operated in 600 Pa pressure. The cathode employed is made of tungsten to guarantee a pure plasma, avoid as maximum the generation of sputtering. The comparison between the D and H measurement are shown in Fig.1. The error bars represent the uncertainties of the determination of the E-field [1].

The E-field measurements are analysed in the frame of two classical discharge models: Rickards [2] and Wronski [3]. Rickards model calculates the energy distribution of ions and neutrals at the cathode of a glow discharge and uses Monte-Carlo simulation to calculate charge exchange collisions. On the other hand, Wronski considers the motion of ions by solving the Boltzmann equation for the ions which are generated in the cathode fall of an abnormal glow discharge. These two models allow to determine important discharge parameters such us the ions energy and their mean free path.

The comparison between deuterium and hydrogen shows very clear trends. In first place, from the Rickards models the conclusion is that the maximum E-field in deuterium is higher than in hydrogen, due to the higher isotope mass. To the contrary, the length of the cathode region is shorter in deuterium than in hydrogen. As a result of this the ion mobility is more restricted in deuterium than in the lighter hydrogen.

From Wronski model, it is possible to determine the ions energy, leading in higher maximum values for deuterium near the cathode surface, but decreasing faster than hydrogen ones through the cathode region. Nearly identical mean free path is obtained for both isotopes despite their mass difference.

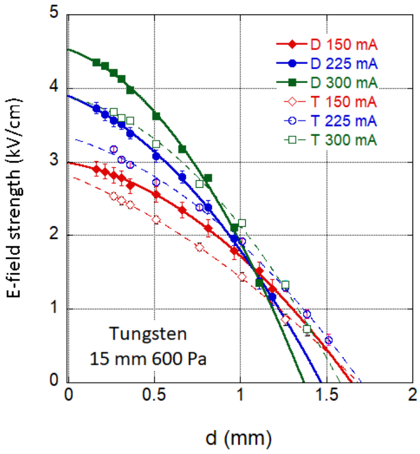

Figure 1. E-field strengths for deuterium (solid lines) and hydrogen (dashed lines); measured in a tungsten cathode of 15 mm of diameter and a pressure of 600 Pa. Figure extracted from [1].

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Numerical simulation of an argon atmospheric pressure plasma jet for biomedical applications

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A new research line for the modelling of Cold Atmospheric Plasma (CAP) for biomedical applications is currently being developed in our group. Several studies have shown that CAP-based treatments produce higher degrees of apoptosis when applied to cancer cells, restoring its chemical-resistant sensitivity to specific drugs, and improving its ability to absorb different molecules. All of these suggests that this technology can be used as support in combination with conventional chemotherapy and radiotherapy treatments [1].

We have studied one of the most used plasma devices in practice for biomedical applications called atmospheric pressure plasma jet, APPJ. This technology presents several advantages such as the possibility of controlling the energy distribution of the charged particles and the wide variety of chemical species that can be created in the plasma [2].

We have simulated an APPJ using a multifluid model comprising continuity equations for the species considered in the kinetic model and the electron energy, Poisson´s equation for the electric field and the gas thermal balance equation. After discretizing the equations by considering a control volume formulation combined with an exponential scheme [3], we have developed a Fortran90 code to solve the resulting algebraic system by using a modified implicit procedure for a 5-point formulation based on the Lower-Upper (LU) factorization of the system matrix [4]. Finally, the temporal evolution was implemented using the Gauss-Seidel scheme.

In this communication we present results obtained for an Argon plasma jet with a geometry similar to that used by Greifswald kINPen [5]. A central cathode with 2 mm diameter is surrounded by a quartz tube of 3 mm radius, in contact to a ring anode with a 1mm thickness (see Figure 1). The cathode was grounded, and the anode was polarized to 2 kV pulsed voltage with 1000 ns on-time and 100 ns rise and fall-times.

Figure 2 shows the potential distribution at 200 ns with de plasma successfully created along the tube. We are currently working to include the advection of the Ar flux in the model to describe the plasma jet outside the tube.

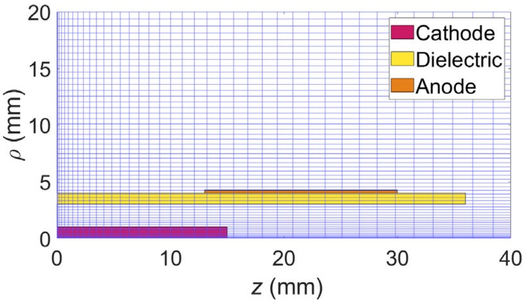

Figure 1. Computational domain (zoom).

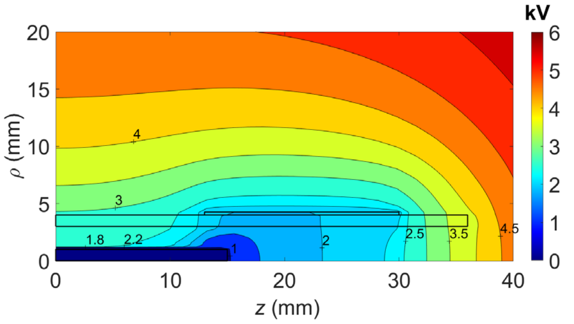

Figure 2. Voltage distribution at 200 ns.

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Excitation temperatures of plasmas at times much larger than current deposition in exploding wires

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Exploding wire systems consist on pulsed electrical power devices that force the pass of a large, on the order of kilo-amperes, current through a thin, short metal wire. These exploding wires generate transient plasmas which can be mantained several hundreds of microseconds after the electrical discharge. Using the *AL*ambre *EX*plosivo (ALEX) system located at the INEI research center of C. Real, dependent on the Engineering School of Ciudad Real, University of Castilla-la Mancha, plasmas at times much longer than total electrical energy delivery time had been explored. Exploration was made analyzing the plasma emission spectra at different times after the electrical delivery at wavelengths from 450 to 650 nm, that allow for the calculation of the excitation temperatures of copper atoms from the wire. Together with photos from an image converter and another streak camera, they show that the measured excitation temperature, see fig. 1, are associated with stable plasma structures.

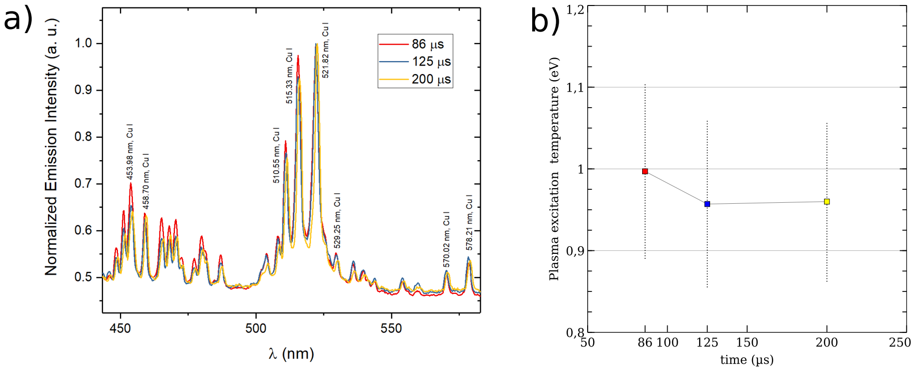

Figure 1. **a)** Spectra taken at times much larger than energy deposition time, 25 μs, at fixed voltage of 25 kV in the capacitors bank. **b)** Electrons excitation temperature after the beginning of the electrical discharge at zero μs.

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Recent developments of high-intensity laser pulse guiding using hydrodynamic optical-field-ionised (HOFI) channels

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Laser wakefield electron acceleration has attracted significant attention over the last decades, due to its ability to generate acceleration gradients three orders of magnitude greater than those achieved in conventional accelerators. However, in order to realise a multi-GeV laser-driven plasma accelerator stage, the laser pulse must remain focussed as it propagates through tens of centimetres of low-density ($1 \times 10^{17}\,\mathrm{cm}^{-3}$) plasma. Such propagation lengths are orders of magnitude greater than the Rayleigh range, and hence some form of wave-guiding is required. We recently introduced hydrodynamic optical-field-ionized (HOFI) plasma channels [1], where a plasma channel is formed by the hydrodynamic expansion of a plasma column formed by OFI with elliptically-polarised laser pulses. Since the electron energies generated with OFI are independent of the gas density, channels can be formed with much lower axial densities than is possible with collisional heating, a crucial requirement to build an electron acceleration stage [2].

Here we present several recent experimental developments on HOFI channels. Firstly, we report on the generation of the longest, free-standing waveguide to date, as HOFI plasma channels with lengths of up to 100 mm and on-axis densities as low as $7 \times 10^{16}\,\mathrm{cm}^{-3}$ have been generated and employed to guide laser pulses with intensities greater than $1 \times 10^{17}\,\mathrm{W\,cm}^{-2}$ [3]. These channels were found to exhibit a power attenuation length of 102 mm, in good agreement with numerical calculations considering the measured transverse electron density profiles.

In order to increase the attenuation length, we have also introduced a variant of the HOFI scheme, the conditioned HOFI (CHOFI) channels [4]. In CHOFI, the transverse wings of an intense laser pulse guided by the HOFI channel ionise the collar of neutral gas surrounding the shock front, to form a deep, low-loss plasma channel. We demonstrate through experiments and numerical simulations that the CHOFI channels exhibit power attenuation lengths of $L_{att} = (21 \pm 3)\,\mathrm{m}$, more than two orders of magnitude longer than achieved by regular HOFI channels. We present hydrodynamic and particle-in-cell simulations which demonstrate that meter-scale, low-loss CHOFI waveguides could be generated with a total laser pulse energy of about 1 J per meter of channel.

Finally, future high-repetition rate, multi-GeV plasma accelerator stages will also require waveguides capable of operating at such rates. We present experimental results demonstrating that HOFI channels can be stably generated at kHz-scale pulse repetition rates [5]. Further, we experimentally demonstrate the stable generation of HOFI channels at a mean pulse repetition rate of 0.4 kHz for a period of 6.5 h without degradation of the channel properties due to the effects of heating or damage to the laser optics, and we determine the fluctuations in the key optical parameters of the channels in this period.

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Validity of the Boltzmann relation in electronegative plasmas

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Electronegative plasmas are widely used in industry and medicine processes such as purifying, etching, microelectronic industrial applications, or synthesis of biomaterials. [1] In this context, many authors have developed different models to describe oxygen discharges. In all these models, the plasma-sheath transition plays a key role to understand most of these plasma applications. In order to model this transition, negative ions are normally supposed to follow the Boltzmann relationship with their own temperature. [2]

As pointed out by several authors [3], we show this relationship is inappropriate when different generation-loss processes are considered in the sheath by describing the plasma-sheath transition near a polarized wall using a multifluid model. To this aim, charged particles are described by the continuity equations including the generation-loss processes, the momentum transfer equations keeping the corresponding inertia terms and finally, the Poisson's equation. The electric potential and particle density profiles for an oxygen discharge are obtained. As a result, although electrons always are well described by the Boltzmann relationship due to their negligible mass, negative ions do not fit this relationship when they are generated into the sheath due to the source terms appearing in the continuity equations.

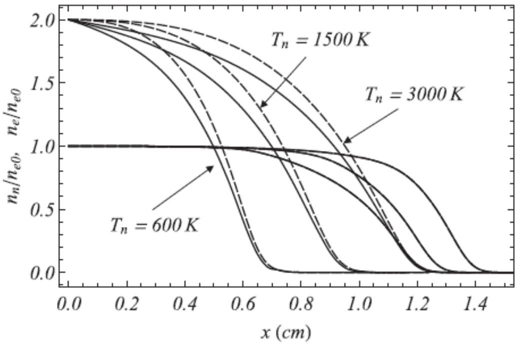

Figure 1. Negative particle density profiles (O^- and e) for different values of T_e obtained from the model (solid lines) and their corresponding Boltzmann relationship (dashed lines) for a negative ion O^- density at the plasma $n_{n0} = 2n_{e0}$.

For this study, we consider a 100 mTorr discharge mainly composed of oxygen molecules O_2, oxygen atoms O, positive ions O_2^+, negative ions O^-, metastables $O_2\left(a^1\Delta_g\right)$, and electrons e. The values of the parameters on which the model depends are: the neutral particle density $n_g = 1.61 \times 10^{21}\ m^{-3}$, the neutral temperature $T_g \sim 600 - 3000\ K$, the metastable density $n_* = 0.1n_g$, the oxygen density $n_O = 0.2n_*$, the electron density $n_{e0} = 2.4 \times 10^{15}\ m^{-3}$, the electronegativity $n_{n0}/n_{e0} \sim 0.5 - 4$, and the neutral-ion collision cross section $\sigma_c \sim 0 - 10^{-18} m^2$. The main generation-loss processes present in the discharge are ionization $(O_2 + e \to O_2^+ + 2e)$, dissociative attachment $(O_2 + e \to O^- + O)$, detachment by metastable $\left(O^- + O_2(a^1\Delta_g) \to products\right)$, detachment by atomic oxygen $(O^- + O \to e + O_2)$ and recombination $(O^- + O_2^+ \to O + O_2)$.

Figure 1 illustrates the effect of negative ion temperature on the negative ion density and electron density profiles. Solid lines represent these profiles obtained from the model while dashed lines correspond to the expression of the Boltzmann relationship obtained from the electric potential profile. Electrons always follow the Boltzmann relationship (dashed lines and solid lines overlap) but negative ions differ from this relation. Similar results are obtained for different values of the electron temperature, the mean free path for neutral-ion collisions and electronegativities.

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Estudio de la distribución espacio-temporal de los parámetros de excitación en plasmas inducidos por láser en atmósferas enriquecidas en gases nobles

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La determinación de halógenos mediante Espectroscopía de Ruptura Inducida por Láser (*Laser Induced Breakdown Spectroscopy*, LIBS) supone un desafío debido a la baja eficiencia de emisión atómica de estos elementos en el rango espectral propio de los sistemas de detección típicamente empleados en LIBS (200-1000 nm). Esto ha motivado la necesidad de llevar a cabo nuevas investigaciones dirigidas a mejorar la sensibilidad de la técnica para estos elementos. En este sentido, la detección de halógenos a partir de la emisión molecular se ha mostrado como una buena alternativa. En el caso particular del F, la recombinación de este elemento con un alcalinotérreo (Ca) se ve favorecida en el plasma inducido por láser (LIP), de modo que la emisión de la molécula de CaF es eficazmente detectada en los sistemas LIBS convencionales. Por otro lado, se ha observado que la generación del LIP en atmósferas constituidas por gases nobles da lugar a un incremento de las señales atómicas [1,2]; sin embargo, los posibles beneficios sobre las señales moleculares todavía no han sido explorados.

En nuestro grupo de investigación se llevó a cabo recientemente un estudio de la dinámica de las emisiones atómica y molecular, mediante medidas con resolución espacial y temporal en distintas atmósferas soplando un flujo continuo de diferentes gases (aire, He o Ar) sobre una muestra de CaF_2 puro. En dicho estudio se observaron diferencias significativas de distribución y evolución temporal entre la emisión atómica (Ca) y la molecular (CaF) (ver Fig. 1), que podrían estar ligadas a las variaciones de temperaturas y densidades electrónicas a lo largo de la pluma del plasma. Es por esto que, en el presente trabajo, se han obtenido las densidades electrónicas (N_e) y las temperaturas de excitación (T_e) analizando sus variaciones espacio-temporales a lo largo de la pluma del plasma para las distintas atmósferas y se ha evaluado su relación con la distribución de la emisión de especies atómicas y moleculares. Las N_e se obtuvieron a partir del ensanchamiento Stark de la línea H-alfa mientras que T_e se calculó a partir de la emisión de Ca I mediante diagramas de Boltzmann. Se ha observado que los parámetros observados muestran una distribución inhomogénea a lo largo de la pluma del plasma y que su distribución varía además en función del gas soplado sobre la muestra.

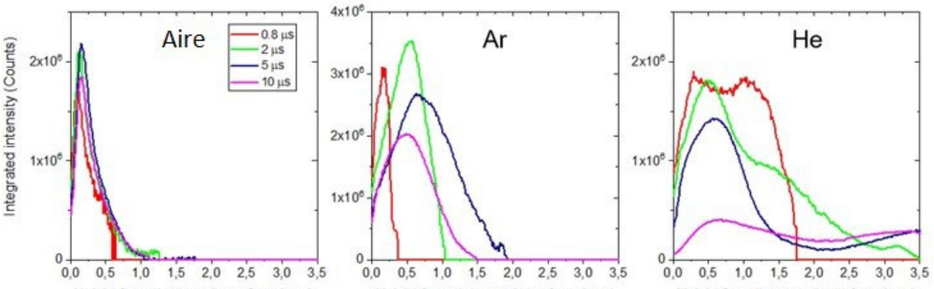

Figura 1. Distribución espacio-temporal de la señal integrada de CaF en diferentes atmósferas (aire, He y Ar).

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