



Introduction of a new experimental device for simulating parasitic plasmas such as those expected under the divertor dome

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ABSTRACT

A low temperature plasma reactor has been developed to simulate some of the plasma/surface processes that can occur under the divertor and in the far scrape-off layer regions of tokamaks. This CASIMIR (Chemical Ablation, Sputtering, Ionization, Multi-wall Interaction and Redeposition) device is envisioned as an ITER divertor dome simulator. The goal is to address issues related to the chemistry of hydrocarbon erosion products, along with transport, transformation, and redeposition of these products in parasitic plasma environments, as already observed in different tokamaks and expected in ITER. In this paper, we will first describe the apparatus, as well as the plasma diagnostics implemented on the reactor. We will then show, by means of optical emission spectroscopy, electrical probe, and mass-spectrometry measurements that the CASIMIR device is able to generate plasma flow in accordance with the plasma characteristics simulated for parasitic discharges under the divertor roof baffle.

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1. Introduction

Parasitic plasmas may appear in unexpected locations inside tokamaks, for example under the divertor dome. This was already observed in ASDEX-Upgrade, and also predicted for ITER [1,2]. In these shadowed areas, due to lower pressure and density, parasitic discharges may indeed be ignited because of a combination of photo-ionisation of neutral gas in volume and electron-impact ionisation by photo-electrons emitted from the surface. Simulation results showed that plasma with electron density $n_e \sim 10^{10} \text{ cm}^{-3}$ and electron temperature $T_e \sim 1.7 \text{ eV}$ may be created in the system [1]. These characteristics are (at least partly) similar to low temperature plasmas encountered in plasma processing devices [3]. They nevertheless have to be investigated, since they may lead to erosion of the plasma-facing components, and to various by-products, from molecular species to co-deposited films, as well as dust or flakes [3]. In the last years, dust production studies became of importance because of the major role they may play in tritium inventory, as well as safety concerns [3].

The aim of this paper is to present the main features of a low temperature plasma reactor (CASIMIR = Chemical Ablation, Sputtering, Ionisation, Multi-wall Interaction and Redeposition) which is envisioned as an ITER divertor dome simulator. As a first step, we focused our studies on carbon targets. Our goal is to address issues related to the chemistry of hydrocarbon erosion products,

along with transport and redeposition of these products in parasitic plasma environments.

In the medium term, our objective is to answer the following questions:

- What is the chemical nature of the carbon species etched/sputtered at the graphite surface?
- What method can we use to estimate the carbon flux coming from the surface?
- What is the homogeneous chemistry that governs these species and the chemical model which can describe the plasma resulting from etching/sputtering at the carbon surface?
- What kind of model can we use to describe the nucleation phase and the whole aerosol dynamics, including the charging effects?

2. Description of the experimental set-up

2.1. The CASIMIR reactor

A schematic drawing of the device is given in Fig. 1. Basically, the CASIMIR reactor is a three-stage device.

A first chamber acts as an etching reactor. It is based on a multipolar plasma source [4], whose reactive chamber is filled with different gases: H_2 (or D_2) to favour chemical etching of a target by H (or D) atoms [5], and Ar whose ions are used to sputter more efficiently the target than hydrogen ions (H^+ , H_2^+ , H_3^+), due to higher mass [6]. A permanent magnet cage ensures plasma confinement around a substrate holder located in the centre of the vacuum

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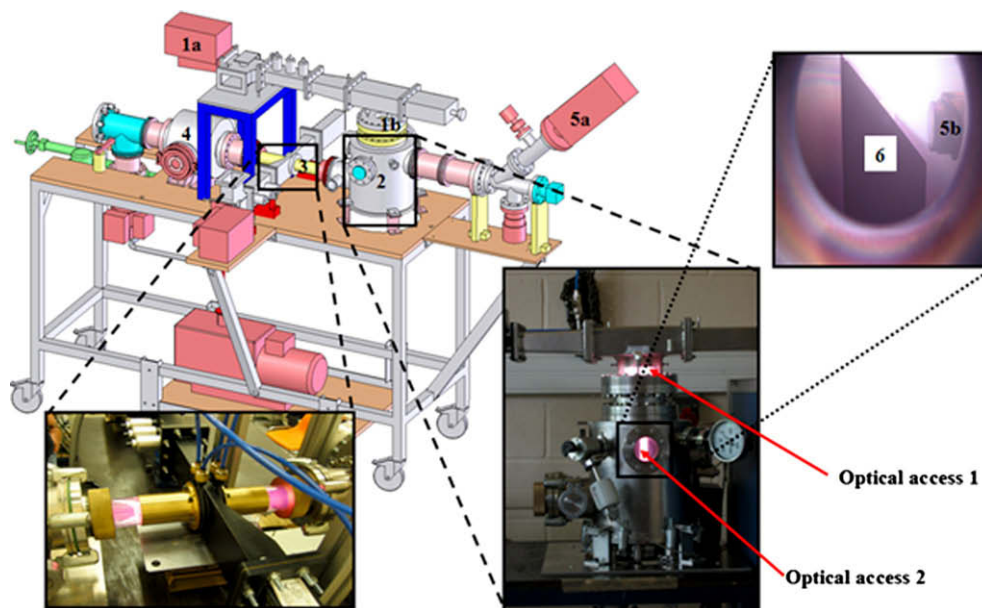


Fig. 1. Schematic of the CASIMIR reactor. 1a: Microwave generator for the etching chamber; 1b: Plasma coupling system of the multipolar source; 2: Etching chamber; 3: Surfaguide plasma source; 4: Redeposition chamber; 5a: Mass and energy analyser Hiden® EQP 500; 5b: Extractor of the Hiden® plasma monitoring system; 6: Carbon target (heated and biased).

chamber. The substrate is slanted, in order to optimize mass-spectrometry measurements (see Fig. 1). The reactor may be used with a gas flow (typically 100 sccm), or under static conditions, to increase the residence time of the physical/chemical erosion by-products. The working pressure ranges from 2 to 30 Pa. A 2.45 GHz microwave generator can couple up to 1200 W in the etching chamber, which the ignited plasma fills by diffusion. The substrate holder is located in this chamber and houses a microcrystalline graphite target which acts as the carbon source. It can be negatively biased (up to -1000 V) to increase the energy of the ions impacting the surface, and additionally heated up to 750 K, in order to favour chemical erosion.

The eroded (neutral) species obtained from the etching chamber are then differentially pumped and transported through a second microwave plasma reactor, made by a quartz tube going through a surfaguide [7]. In that reactor, the plasma conditions are independent of those in the etching chamber. The aim is thus to separate the heterogeneous erosion processes in the first chamber from the homogeneous plasma chemistry which may exist in the gas phase.

Finally, by-products can be collected in a redeposition chamber, especially the carbon-containing species under various forms such as films and flakes or dust.

In this paper, all preliminary measurements were performed in the etching chamber of the reactor (first-stage).

2.2. Diagnostics installed on the reactor

The excited state temperature is obtained by UV and visible Optical Emission Spectroscopy (OES) measurements: (i) by using a high resolution spectrometer (1m focal length) to estimate Doppler broadening [8] of H atom/D atom Balmer lines (H_α at 656.1 nm, H_β at 486 nm) and (ii) by recording the rotational distribution of the Fülcher- α ($d^3\Pi_u - a^3\Sigma_g^+$) molecular hydrogen/deuterium band (Q-branch, 0–0 transition from 601 to 606.5 nm, 1–1 transition from 612 to 616.5 nm) [9]. In the etching chamber, the light was collected at the positions mentioned in Fig. 1. The optical access 2 allows in particular measurements in the vicinity of the carbon target surface.

Electrical parameters (n_e , T_e , and Electron Energy Distribution Function – eedf) are monitored using an electrostatic probe. It translates in the etching chamber to perform axial (from top to bottom of the vacuum chamber) or radial (from the position of the slanted substrate to the wall) profiles of n_e and T_e .

Heavy species are analysed using a plasma monitoring system Hiden® EQP-500. This device allows mass detection up to a ratio $m/z = 500$. Neutral species, radicals, as well as negative and positive ions, can be monitored. The Ion Energy Distribution Function (IEDF) can be recorded in the range 0–1000 eV. As shown in Fig. 1, the extraction of the gas sample is performed *in situ*, just in front the slanted carbon substrate.

3. Results

3.1. OES characterisation

Below the divertor of ASDEX-Upgrade, the neutral temperature in the high-recycling regime was estimated around 0.1 eV (~ 1160 K) [1]. In order to check if the gas temperature in the CASIMIR reactor matches this requirement, OES measurements were performed in pure H_2 or D_2 discharges to estimate temperature of the excited hydrogen species. Doppler broadening measurements on H atom/D atom Balmer- α lines yield temperatures in the 800–1600 K range inside the microwave coupling system (optical access 1) and around 400 K lower in the diffusion chamber (optical access 2), when (i) varying the pressure from 2 to 30 Pa for a constant microwave power fixed at 800 W, or (ii) varying the microwave power from 500 to 1200 W for a constant pressure fixed at 3 Pa. The rotational distribution of the Fülcher- α molecular hydrogen/deuterium band and the corresponding Boltzmann plot gives temperatures in the 500–900 K range inside the microwave coupling system (around 150 K lower in the diffusion chamber), for the same conditions as above. The temperature is similar for H_2 and D_2 discharges, but 100–300 K higher in Ar/ H_2 (or D_2) mixture (50:50) at equivalent power, due to the lower thermal conductivity of argon.

The values measured at different location in the CASIMIR reactor are of the correct order of magnitude with respect to what can be expected from a parasitic plasma simulator.

One can remark that the excited state temperatures are found (slightly) out-of-equilibrium between atomic and molecular species, as expected in such a low temperature discharge. Hotter H-atoms may be produced depending on the different kinetic paths possible [10] (H_2 dissociative excitation, H_2 dissociative ionisation, or direct electronic impact excitation of H atoms). The dominant path is strongly dependent on the shape of the eedf, which we measure by electrostatic probe characterisation.

3.2. Electrostatic probe characterisation

We measure the electronic temperature T_e and density n_e , by means of a Langmuir probe. Fig. 2 shows the radial eedf profile obtained in the etching chamber, from the substrate location to the reactor wall. A non-Maxwellian behaviour can be observed, with two well-distinguished populations of electrons (typical energies around 2.7 and 6.3 eV). Noticeable changes of the relative populations of low-energy and high-energy distributions along the reactor radius can be seen (the same behaviour is observed along the reactor vertical axis). These two electronic populations may play an important role in the H-atom formation kinetics (which is the main chemical etching agent), as mentioned in the previous paragraph. At the substrate location, the electron density is measured around $1.3 \times 10^{10} \text{ cm}^{-3}$. The n_e and T_e measured values are reasonable when compared to those obtained by modelling of parasitic plasma under the divertor roof baffle of ASDEX-Upgraded, i.e. $n_e \sim 10^{10} \text{ cm}^{-3}$ and $T_e \sim 1.7 \text{ eV}$ [1].

3.3. Mass-spectrometry characterisation

Since neutral gas temperature and n_e and T_e parameters measured in the CASIMIR reactor are in good agreement with simulated parasitic plasma parameters, we started preliminary mass-spectrometry measurements to check the possibility of etching a carbon target with such low-temperature low density plasmas, without any carbon precursor in the gas phase.

Typical mass spectra obtained with the Hiden® EQP-500 plasma monitor are given in Fig. 3, for three different gas mixtures (H_2 , Ar, and Ar/ H_2), in the range 0–50 atomic mass units (a.m.u.). D_2 may be

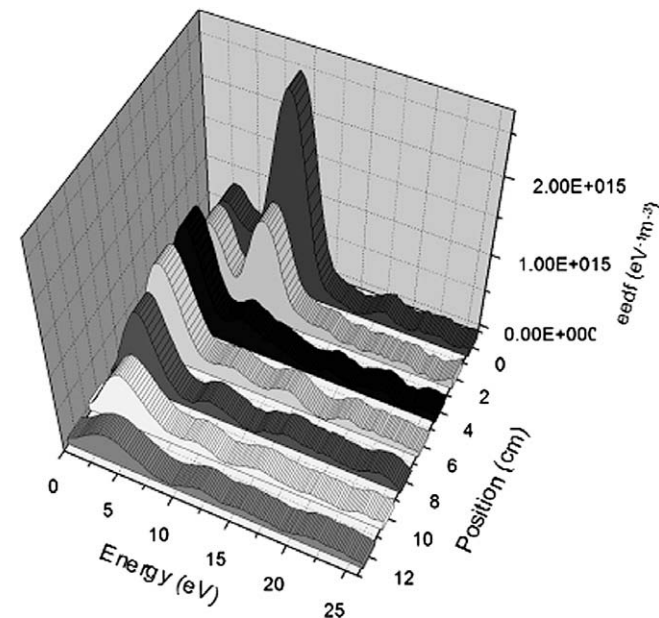


Fig. 2. Radial profile of the electron energy distribution function measured by electrostatic probe measurements.

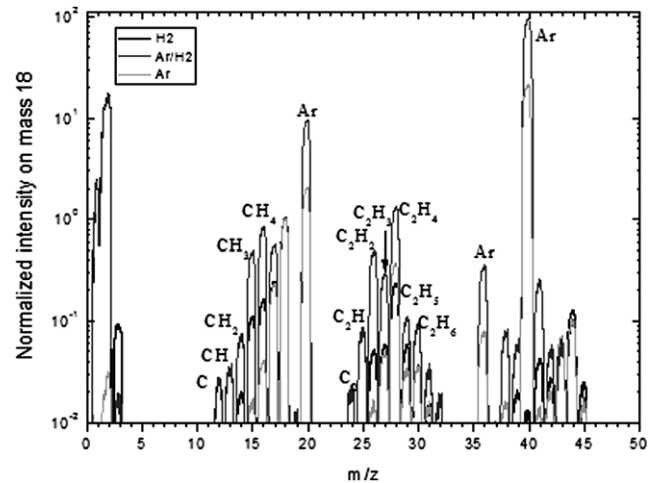


Fig. 3. Mass spectra obtained in etching chamber of the CASIMIR reactor for different gas mixtures.

used instead of H_2 to eliminate mass assignment degeneracies. We first focused our studies on detection of light neutrals (<50 a.m.u.). In order to certify that a given species is really present in the plasma and not coming from electronic dissociation of bigger molecules within the ionisation chamber of the mass spectrometer, we performed threshold mass ionisation measurements, by varying the energy of the electrons emitted from the mass spectrometer filament. Fig. 4 gives the example of the CH_3 radical: the electron energy threshold for ionisation of the radical via the reaction $CH_3 + e^- \Rightarrow CH_3^+ + 2e^-$ is equal to 9.8 eV, whereas the decomposition of the CH_4 molecule in the ionisation chamber of the mass spectrometer following the reaction $CH_4 + e^- \Rightarrow CH_3 + H + 2e^-$ requires 14.25 eV. By testing each peak obtained in Fig. 3, it is possible to determine where the detected species is created (in the plasma or in the mass spectrometer). As already observed in other low temperature plasmas [3], the first measurements show a synergistic effect between the physical sputtering due to Ar ions, and chemical etching due to H or D atoms. Indeed, almost no carbon (C, C_2 , or C_3) was detected in pure Ar discharges. Only a few light hydrocarbons can be detected in pure H_2 (or D_2) discharges. The mixture Ar/ H_2 (or D_2) is on the contrary the most efficient in terms of etching (see Fig. 3).

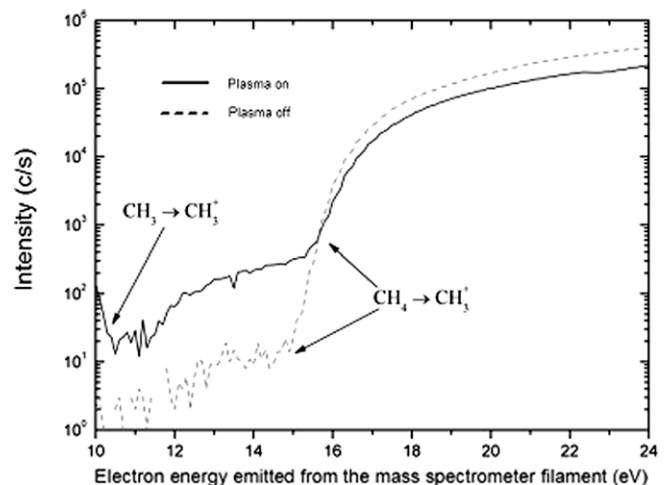


Fig. 4. Threshold detection of the CH_3^+ ion in the mass spectrometer coming from CH_4 dissociation or CH_3 radical ionisation.

4. Conclusion

We have presented in this paper the main features of a low-temperature plasma reactor whose ambition is to simulate some of the plasma-surface interactions expected in the divertor and far scrape-off layer regions of tokamaks (parasitic plasmas). Plasma characteristics were measured in good agreement with simulated tokamak parasitic plasmas. With the help of the presented plasma diagnostics (OES, Langmuir probe, mass spectrometry), this reactor may be used (i) to study the first steps of the chemical and physical etching processes of a carbon target, (ii) to follow the different stages of nucleation and growth of carbon dust without carbon precursors in the gas phase, and (iii) to provide basic kinetics data that may be used in modelling of dust growth.

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