Design and qualification of a low pressure / high density ECR dipolar plasma reactor used for synthesis of mixed material dust

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In this paper we present an experimental and theoretical qualification of a low pressure / high density ECR plasma reactor. The main application is the synthesis mixed material dust (C / W / Be-*like*), in order to simulate plasma-wall interaction in the divertor regions of controlled fusion devices. Plasma experimental characterization by means of Optical Emission Spectroscopy, Langmuir Probe and Mass Spectrometry is completed with electromagnetic simulations. Examples of composites dusts generated in the device are also presented.

Electron Cyclotron Resonance (ECR) sources are well-known to be able to produce low pressure / high density plasma. An innovative dipolar plasma source has been developed and first characterised by the group of J. Pelletier [1-3]. This technology has been chosen to develop our process system: CASIMIR II, which is a low temperature high density plasma reactor envisioned to simulate some plasma/surface processes occurring under the divertor dome and in the far Scrape-off Layer (SOL) regions of tokamaks. The CASIMIR II (Chemical Ablation, Sputtering, Ionization, Multiwall Interaction and Redeposition) device is composed of 16 dipolar plasma sources close enough together to ensure large enough homogenous plasma density (from 10^{10} cm^{-3} to 10^{12} cm^{-3} depending on the nature of the gas and pressure). See Fig. 1-a a picture of the reactor working with H_2 plasma. The idea is to study the formation under plasma exposure of mixed materials with compositions similar to those foreseen in fusion devices (C/W/Mg, stand-in for Be).

A comprehensive study of the magnetic field strength within the CASIMIR vessel was performed, using the electromagnetic toolbox of the Multiphysics software Comsol©, compared with set of measurements obtained thanks to a gaussmeter. The CASIMIR ECR sources indeed include a permanent magnet for electron confinement and a microwave supply which heats the electrons. The plasma is thus generated at the electron cyclotron resonance location, here 875 G for a 2.45 GHz excitation frequency. We first did a magnetostatic study, mapping the magnetic field lines and determining the magnetic flux densities around the magnet. Second, we did an electrostatic study, mapping the electric field at the entrance of the microwave supply port. This was done for a single source, then a pair of sources, and finally for the full 16 sources in the exact CASIMIR II configuration. Experimental results obtained in CASIMIR II in pure hydrogen are presented with its corresponding magnetic configuration.

See Fig. 1-b a Comsol© simulation of the 16 MW (MicroWave) sources configuration, with alterning polarities in order to ensure a maximum usable plasma volume. Fig 1-c represents a comparison of the calculated and measured magnetic field density along the radius of the reactor. A good agreement is obtained.

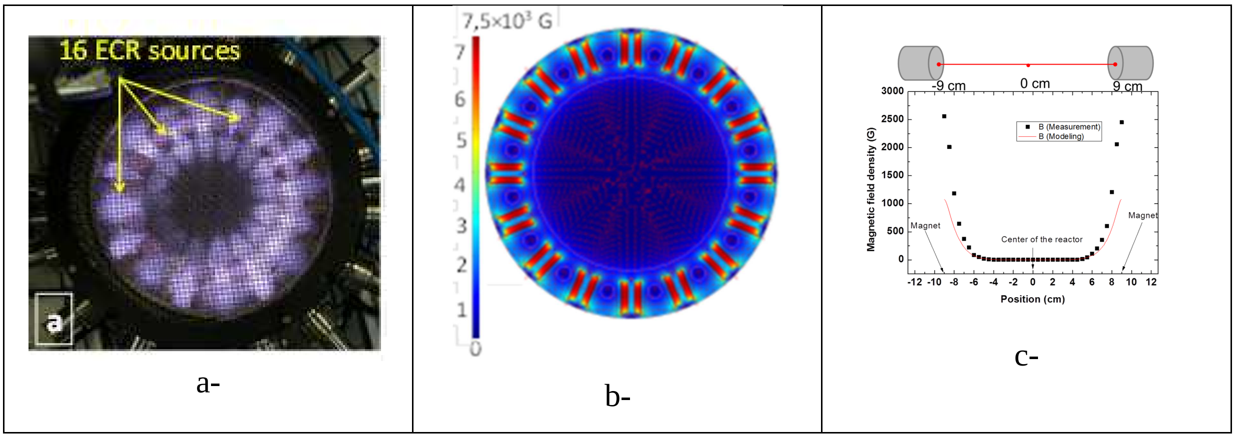

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Fig. 1: a) Picture of CASIMIR II in pure hydrogen plasma, b) Magnetic configuration of CASIMIR II, c) Comparison modelling/measurement of the magnetic field density in the reactor

We present some results of an extensive measurement campaign realized to fully characterize the plasma inside the CASIMIR reactor, both when excited by a single ECR source and in the complete reactor. Electronic parameters (electron density and temperature, and more accurately the energy distribution function), gas temperature, neutrals and ions relative densities, and ion energy distribution functions, were collected in various reactor operating conditions. The parameters varied were the gas pressure (10^{-3} to 10^{-2} mbar), the injected microwave power (1 to 3 kW), and gas mixtures (H_2, D_2, Ar). Examples of results are given on Figure 2.

Fig. 2-a represents radial profile of the electron density obtained in H_2-plasma thanks to a Langmuir probe (Scientific Systems©), at P = 10^{-2} mbar for power ranging from 0.5 to 3 kW. It shows a relatively homogeneous distribution which is an important feature for the application of the reactor. Fig. 2-b shows the Ion Energy Distribution Function of H_3^+, still at 10^{-2} mbar, for

1, 2 and 3 kW of MW Power, obtained using a plasma monitor Hiden EQP 500. Ion energy increases linearly with the injected power. Nevertheless, in order to ensure an efficient etching of the targets, an additional negative bias is required. Fig. 2-c represents gas temperature measurements made on H-atom (translational temperature from Doppler broadening on H_α line at 656 nm, showing two populations of atoms) and on H_2-molecule (rotational temperature from Boltzmann plot of the Fülcher band at 600 nm).

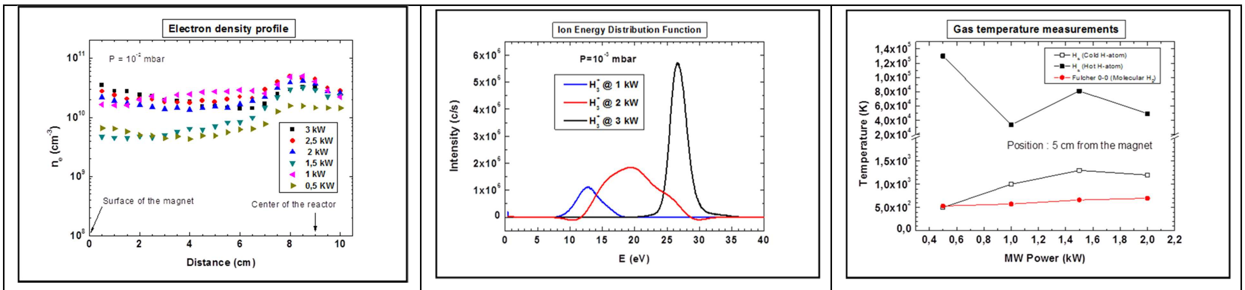

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Fig. 2: a) Radial profile of the electron density, b) Ion Energy Distribution Function of H_3^+ in the centre of the reactor, c) H-atom and H_2-molecule temperature measurements

An energy balance of a reactor with a single ECR source was also performed in order to estimate the *power absorbed by the plasma* to the *power supplied to the system* ratio P_{abs}/P_{sup}, as explained on Fig. 3-a. Power lost by microwave heating is measured through temperature elevation of water from the cooling system. Thermal imaging was also performed using a calibrated IR source located at the normal position of the plasma (see Fig. 3-b). Approximately 25 % of the injected power is absorbed by the plasma.

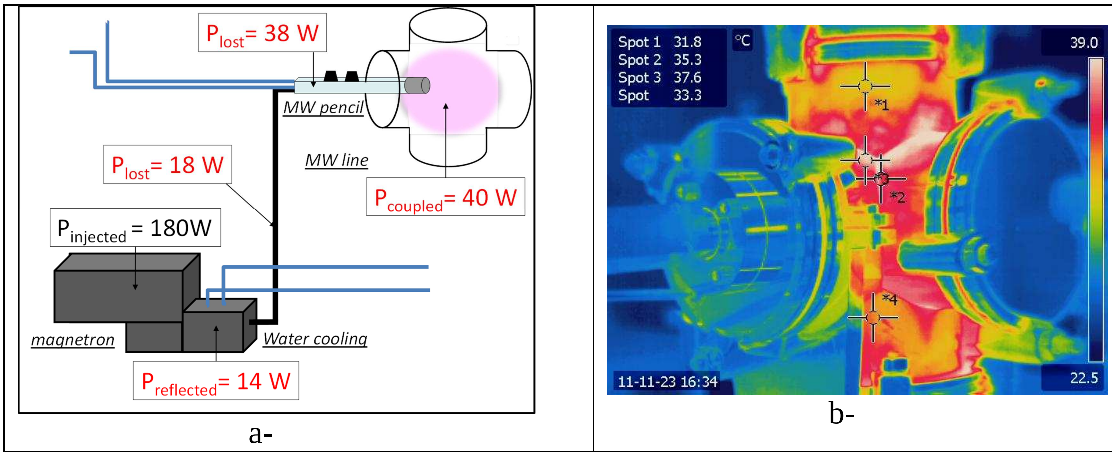

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Fig. 3: a) Estimation of power losses in a single source reactor, b) Thermal imaging of the reactor, in order to estimate the power coupled to the plasma

First results of target exposure to the plasma are presented. Fig. 4-a shows different a set targets used in the CASIMIR II reactor, made of Carbon, Tungsten, and Tungsten Carbide. Fig. 4-b represents a SEM picture of carbon dust obtained in the reactor after Hydrogen ion bombardment. TEM imaging exhibits nanoparticles aggregate, with concentric graphitic domains around amorphous nuclei. Fig. 4-c shows tungsten nanoparticles incorporated in a tungsten film obtained after argon sputtering of a solid W-target.

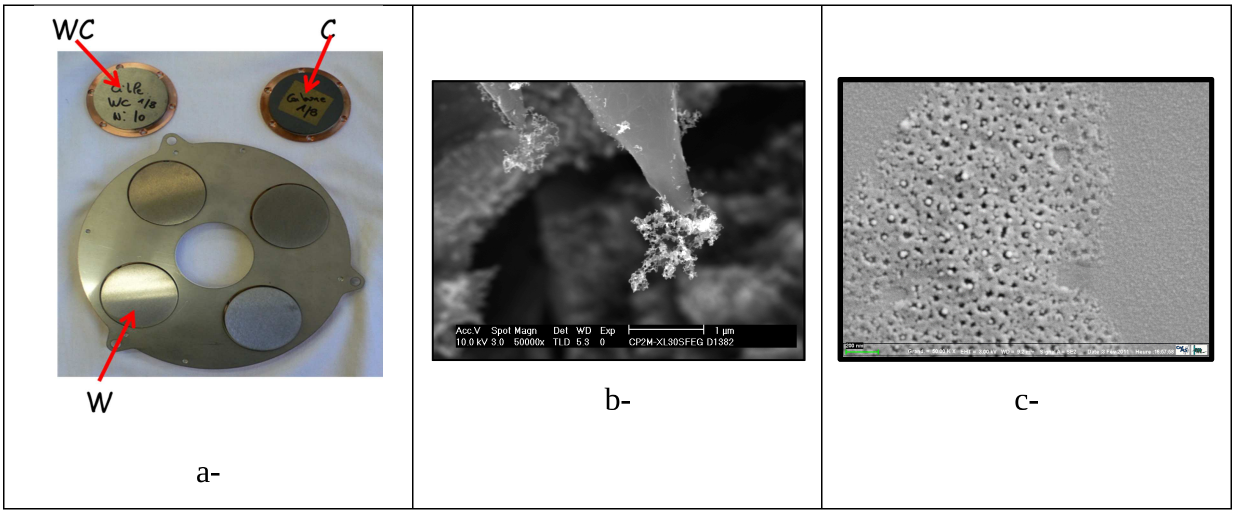

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Fig. 4: a) example of targets used in the CASIMIR I reactor (C; W ; and WC), b) carbon dust synthetized from etching of pure C-target, c) Tungsten nanoparticles incorporated in a film after sputtering of a W-target

References

[1] A. Lacoste, T. Lagarde, S. Béchu, Y. Arnal and J. Pelletier *Plasma Sources Sci. Technol.* **11,** 407 (2002)
[2] T. Tran *PhD Thesis* Université Joseph Fourier Grenoble, France (2006)
[3] A. Lacoste, T. Lagarde, S. Béchu, Y. Arnal and J. Pelletier *Plasma Sources Sci. Technol.* **18**, 015017 (2009)

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