Investigation of microwave sustained magnetized plasmas for wall conditioning of toroidal fusion devices

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1.Introduction

The utilization of superconducting coils in future fusion devices leads to the presence of semi-permanent magnetic fields, which impede the application of the well established DC glow discharges for wall conditioning. Using microwaves for creating process plasmas, e.g. at the Electron Cyclotron Resonance (ECR) frequency $\omega_{ce}=eB/m_e$ (1), is a promising route to develop wall conditioning methods compatible with magnetic fields. Early work on ECR-sustained process plasmas in H_2 in TEXTOR [1] has demonstrated the potential of this cleaning technique; ECR-based wall conditioning is presently used at ALCATOR C-mod [2]. Systematic studies in reactive gases are still missing, however. Important open questions are the influence of particle drifts on the homogeneity of layer deposition and removal, the fluxes and energy distribution of ions parallel and perpendicular to the magnetic field and the effect of neutrals and radicals.

2.Experimental Setup

For the investigation of these plasmas, especially for the study of deposition and erosion of films, a TOroidal MAgnetic field System (TOMAS) is operated at the Forschungszentrum Jülich in collaboration with the Ruhr-Universität-Bochum.

At this simple magnetized torus (R=0.78m, a=0.26m), ECR plasmas can be produced steady state at a fixed microwave frequency of 2.45GHz and a maximum power input of 6kW. The microwave is launched via a waveguide and a cooled quartz window located at the top of the vessel above the torus axis. Varying the coil current I_B allows to sweep the ECR-zone across the full minor diameter. The maximum B-field at the torus axis is 120mT. The base pressure of the unbaked system is below $1*10^{-5}$ Pa.

The experimental device will be described in more detail elsewhere [3].

3.Experimental Results

A.) The Plasma

Characterization of the plasma parameters is made using a moveable cylindrical Langmuir probe. The presented radial plasma profiles are measured in the equatorial plane of the vessel, 90° clockwise from the microwave launching position. For additional information a camera-video-system is used to observe the visible light emission profiles. The usage of a mass spectrometer allows measuring of the composition of the pumped out gas, especially to detect volatile reaction products.

Typical discharge condition is a gas pressure of $2.5*10^{-2}$ Pa with an input power of 1.2 kW and coil current I_B of 1700A. This corresponds to a radial position of the ECR-zone shifted outward (towards lower magnetic fields) from the launching window (r_{res}=82mm). As a typical gas we used argon, but measurements in O_2, N_2, H_2, and He have been performed too.

Change of the magnetic field

The change of the magnetic field strength by variation of the coil current allows to position the ECR-zone inward (low field) or outward directed (high field) from the launching window (r=0mm). This leads to different plasma conditions as can be seen in Fig.1 for three different ECR-positions.

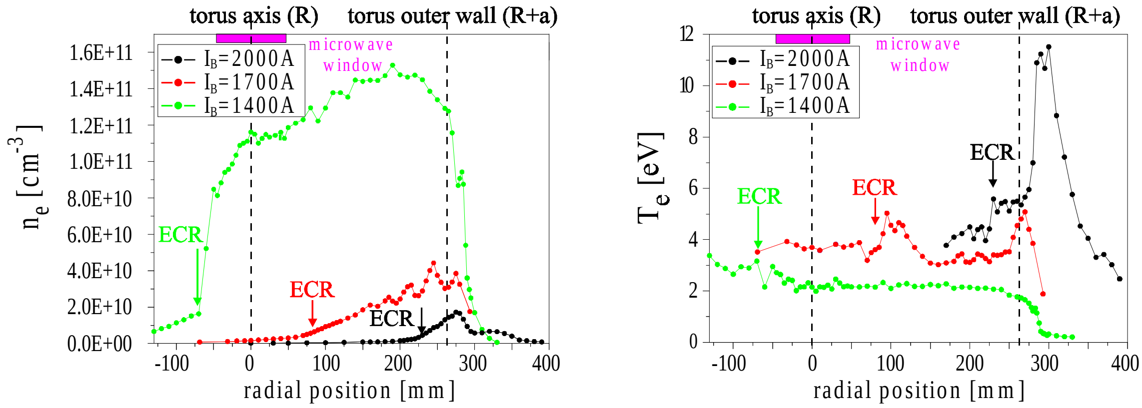

Fig. 1: Radial ne- and Te-profiles for 3 different magnetic fields respectively ECR-zone positions measured in the equatorial plane of the torus.

For the case of high field coupling (I_B=1700A and 2000A) an outward directed increase of the density is observed starting near the ECR location. At I_B=1700A a ripple structure appears between r=170mm and 270mm which we tentatively explain as the manifestation of standing waves. Here the density reaches a maximum value of $n_e=4*10^{10}cm^{-3}$ near the torus outer wall. For I_B=2000A n_e is remarkable lower and an additional increase (r=300mm) in the port outside the torus geometry can be observed. This is the result of an Upper Hybrid Resonance (UHR) with $\omega_{UH}=\sqrt{c_1 \cdot n+\omega_{ce}^2}$ (2), where c_1 is a constant and n is the plasma density. The UH-resonance situation can also be found in the temperature profile where a maximum value of about T_e=11eV at the same radial position occurs. For 1700A the temperature profile shows a mean value of 4eV with local maxima up to 5eV occuring at the low field side of the ECR-zone and at the torus outer wall. The latter is the result of the UH-resonance possibly in combination with mode conversion in electron-Bernstein waves [4].

For the case of low field power coupling (I_B=1400A) the density profile shows rapid increase at the EC-resonance position (r_{res}=-70mm) and reaches a maximum value of $n_e=1.5*10^{11}cm^{-3}$ which is nearly four times higher than for I_B=1700A.The temperature profile is very flat with values around 2eV. Under these conditions we observe a well-defined, toroidal bright plasma belt just below the launching window.

Although propagation of microwave modes is strongly restricted in such overdense plasmas (e.g. O-Mode limited by cut-off density $n_{cut}=7.45*10^{10}cm^{-3}$), waves may intrude such plasmas as a consequence of their long wave length (λ_{vac}=12cm). So while the initial plasma is being produced by EC- and later UH-resonance, the density continues to increase. When it exceeds the cutoff-density below the microwave launching position, wave propagation is no longer possible. But the waves may penetrate the plasma a few centimeters deep and be reflected, which partly leads to plasma heating or mode conversion. This causes localized energy absorption at the top of the vessel below the window, while the remaining vessel is filled with plasma by particle drift.

Higher Harmonic EC-Resonances

In a combination with such an UHR dominated plasma we observed higher harmonic EC-resonances. For I_B<1050A the ECR-zone is swept out of the vacuum vessel. But the plasma keeps on burning as a result of the UHR plasma production in the upper part of the vessel. With a careful reduction of the magnetic field in combination with optimization of the microwave tuning we observe slat like bright zones on the low field side of the launching position. Comparision with the theoretical position of the Higher-Harmonic-(HH)-ECR shows very good agreement. With this method HH-ECR up to 5th order could be identified.
We were not able to start plasma at a higher harmonic resonance. A "pre"-plasma is needed to reach these discharge conditions. Another remarkable point is that it is impossible to move an HH-ECR towards the high field side of the launching window. It seems that high field side power coupling is needed to observe the Higher-Harmonic-EC-resonances [4].

B.) Filmdeposition and –erosion

The deposition experiments were performed with methane plasmas under conditions of high and low field power coupling. To measure the poloidal and toroidal film distribution full poloidal sample holders are installed at the vessel wall at 4 different toroidal positions 80°,170°, 260° and 350° clockwise from the microwave incouple position. Each of them carried 8 Si-samples at different poloidal positions. The results listed below were achieved with a gas flow of 7sccm ($p=5*10^{-2}$Pa) and a power of 1,2kW delivered to the plasma. For a better determination of the hydrogen content of the films we used deuterated methane (CD_4) for some experiments.
The layer characteristics had been measured by ellipsometry (n,k,d), the atom areal density has been measured by Electron Probe X-Ray MicroAnalysis (EPMA), and the H, respectively D-content has been determined by Thermal Desorption (TDS), Ion Beam Analysis (IBA) and Infrared Absorption Spectroscopy (FT-IRA).

n refraction index			k extinction coeff.		deposition rate [nm/min]	C concentration [10^{22} cm^{-3}]		H/C or D/C		
min	**mean**	max	**mean**	max		min	max	min	**mean**	max
1.45	**1.54**	1.68	**0.001**	0.01	up to 1	3.2	4.5	0.9	**1.3**	1.7

Table 1: Characteristics of the deposited a-C:H/D-films.

The layers are soft amorphous hydrogen-carbon (a-C:H/D) films with characteristics shown in Table 1. It is obvious that these layers have a very high H/C or D/C values (≈1.3) compared to hard films. The measured values are in good agreement with published data [6]. Although the thickness distribution [7] of the deposited films shows a inhomogeneity in poloidal and toroidal position (fig.2), we found no systematic variation in the layer characteristics (n,k,H/C,D/C).
Fig. 2 show regions where no layers are deposited (white). These areas are limited poloidally by the intersection of the ECR-zone with the vacuum vessel and can be found on the low field side of the resonance zone. The wall is completely covered towards the inside from the ECR.

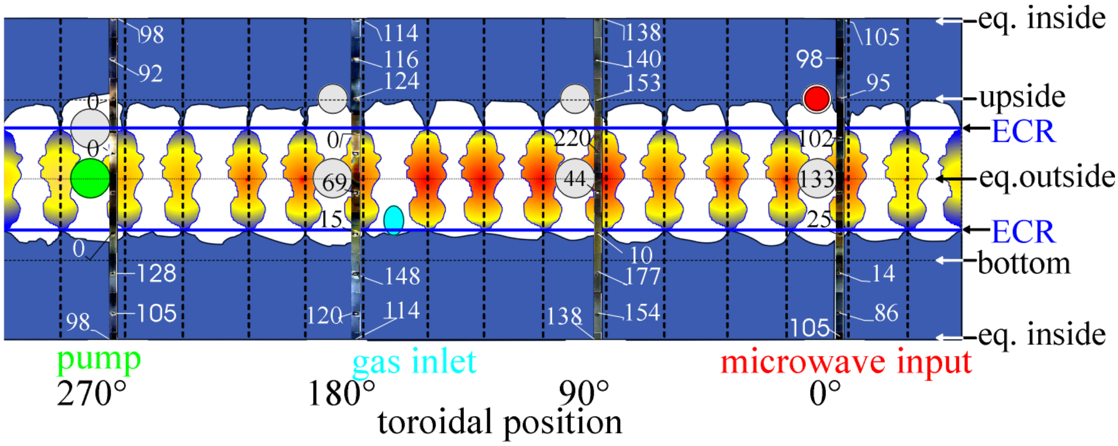

Fig. 2: Toroidal and poloidal film thickness distribution after a CD_4-plasma (5h) with high field incoupling (I_B=1700A, P=1.2kW). Thickness given in nm, measured by ellipsometry. The white regions are areas without deposition as a result of wall parts acting like "limiters".

To explain the toroidal thickness distribution on the low field side of the vessel wall one has to take into account, that the vessel is not a perfect torus but a 16-fold polygon indicated by the dashed vertical lines (corners) in fig.2. The radial difference between the tangency point and the corner of the polygon is 10mm relative to an ideal torus. Hence the other areas are "shadowed". The model we propose to explain the distribution is the following: The protruding vessel wall works like a "limiter" with a higher plasma wall contact and as a result with a higher power load. The films are build up partly by neutral hydrocarbons and can be eroded by hydrogen ions. The radial transport of hydrogen ions is limited by the magnetic field and we find net deposition in the shadowed areas (corners). At the parts of the wall working like a "limiter" we have a high flux of hydrogen ions to the wall. As a result we have net erosion. This crude model can also explain the deposition inward directed from the ECR-zone, because in that region the plasma density is nearly zero but the deposition can be achieved by neutral hydrocarbons, which motion is not limited by the magnetic field.

Erosion

To remove the deposited layers and to have a well-defined machine status before every deposition campaign we used oxygen-ECR-plasmas and sometimes also discharges with hydrogen. The progress of the film erosion was monitored by the composition of the exhausted gas by a mass spectrometer. The end of the cleaning procedure was indicated by constant signals of O, CO_2, H_2O and other gases. During the discharge the position of the ECR has been changed to hit all parts of the vessel wall. Under nearly same discharge conditions as for the deposition the erosion time is comparable to the time of deposition.

After the opening of the machine thin residual layers could be found in the edges of the vessel.

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