Plasma interaction with tungsten samples in the COMPASS tokamak in ohmic ELMy H-modes

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Abstract. This paper reports experimental results on plasma interaction with tungsten samples with or without pre-grown He fuzz. Under the experimental conditions, arcing was observed on the fuzzy tungsten samples, resulting in localized melting of the fuzz structure that did not extend into the bulk. The parallel power flux densities were obtained from the data measured by Langmuir probes embedded in the divertor tiles on the COMPASS tokamak. Measurements of the current-voltage probe characteristics were performed during ohmic ELMy H-modes reached in deuterium plasmas at a toroidal magnetic field \( B_T = 1.15 \) T, plasma current \( I_p = 300 \) kA and line-averaged electron density \( n_e = 5 \times 10^{19} \) m\(^{-3}\). The data obtained between the ELMs were processed by the recently published first-derivative probe technique for precise determination of the plasma potential and the electron energy distribution function (EEDF). The spatial profile of the EEDF shows that at the high-field side it is Maxwellian with a temperature of \( 5 - 10 \) eV. The electron temperatures and the ion-saturation current density obtained were used to evaluate the radial distribution of the parallel power flux density as being in the order of \( 0.05 - 7 \) MW/m\(^2\).

1. Introduction
Plasma-material interaction is an important issue for the plasma facing components in current and future fusion devices. The plasma particles incident on the material may result in a number of phenomena, such as implantation, diffusion, retention, sputtering, erosion, ionization of the eroded particles in the plasma and their re-deposition, structural modifications of the material, etc. These will affect both the plasma operation and the performance and lifetime of the plasma facing components. The nature and extent of the interaction depends both on the state of the material surface and on the local plasma parameters. For proper understanding of the interaction, these parameters need to be known.

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This paper reports experimental data obtained on the COMPASS tokamak [1] by Langmuir probes (LPs) embedded in the divertor tiles [2] during ohmic ELMy H-modes reached in deuterium plasmas. The measured current-voltage (IV) characteristics were processed by the recently published [3,4] first-derivative probe technique (FDPT) for precise determination of the plasma potential and the EEDF. The electron temperatures and densities obtained were used to evaluate the radial distribution of the parallel power flux density and the electron pressure.

Under the experimental conditions described below, we investigated the plasma interaction with tungsten samples with or without a so-called He fuzz, resulting from an exposure of tungsten to He plasma at elevated temperatures.

2. Experiment description

The samples were placed at different vertical positions $z$ (figure 1) in the scrape-off layer at the high-field side (HFS) with two different orientations of the sample set: 4 samples tangential to the separatrix surface (toroidally spaced) and 3 samples sloped toroidally by 50 degrees (radially spaced). Figure 1 is an example where the equilibrium FITing code (EFIT) reconstructions of the magnetic field surfaces are used to visualize the position of the sample. The red crosses indicate the positions of the centers of the exposed samples. The red triangles are their mappings to the divertor Langmuir probes at HFS. The orange curves show the corresponding magnetic surfaces.

The parallel power flux density at the samples position was evaluated by means of the measured data from the available divertor probes. It is assumed that the parallel power flux density remains the same at the same magnetic surface.

3. Langmuir probe measurements in the divertor region of the COMPASS tokamak

Langmuir probes (LPs) are relatively simple, inexpensive and robust diagnostic tools that are compatible with the tokamak scrape-off layer (SOL) conditions. They are readily deployable in large arrays built into the edge structures, such as limiters and divertor tiles. Because of their simplicity and the ability to perform local measurements of the electron energy distribution function (EEDF) and the plasma potential, LPs are frequently used in magnetized plasmas to characterize the edge plasma parameters [2,4,5].

The divertor probe system in the COMPASS tokamak consists of 39 single graphite Langmuir probes poloidally embedded in the divertor tiles; they are oriented parallel to the magnetic field and provide profiles with a spatial resolution in the poloidal direction down to 5 mm [2]. Each probe has an area of $S = 56 \times 10^{-6}$ m$^2$. The probes are biased with respect to the tokamak chamber wall by a triangular voltage $U_\text{p}(t)$ and swept at a frequency of 1 kHz [6].

The probe measurements were performed during ohmic ELMy H-mode shots, with toroidal magnetic field $B_T = 1.15$ T and plasma current $I_p = 300$ kA. Figure 2 is an example for shot #9348 (line-averaged electron density $n_e = 7 \times 10^{19}$ m$^{-3}$) of the plasma current, the D-alpha signal and the signal from Langmuir probe 1 (LP#1), which is at a radial position 0.396 m in the tokamak vessel.
The probe works in an ion-saturation mode (negative voltage applied of −100 V) for monitoring the H-mode. A good agreement is seen between the spectroscopy signals (the black curve) and those from the probe (the red curve); moreover, the structure of the ELMs is seen more clearly from the probe signal.

The data obtained between the ELMs were processed by the FDPT for precise determination of the plasma potential and the EEDF. The FDPT for evaluating the plasma parameters in tokamak plasma was published and discussed in detail in [3].

4. Results and discussion
Results of the evaluation of the poloidal distribution of the ion-saturation current density, \( J_{\text{sat}} \), and the plasma potential, \( U_{\text{pl}} \), during two ohmic ELMy H-mode deuterium discharges are presented in figure 3 a and 3 b. The discharges differ slightly in the line-averaged electron density \( n_e = 7 \times 10^{19} \text{ m}^{-3} \) (#9348 – black symbols) and \( n_e = 5 \times 10^{19} \text{ m}^{-3} \) (#9593 – red symbols). An important fact is that discharge #9348 is without a sample inside the chamber. During shot #9593, the tungsten samples were inserted at a position \( R = 0.39 – 0.41 \text{ m}, z = -333 \text{ mm} \). In figure 2 a one can see the positions of the strike points indicated by dashed lines as provided by EFIT during the steady-state phase of the discharges, at 140 ms (see figure 2). The positions for shot #9348 are for inner strike point \( R = 0.45 \text{ m} \) and for outer, \( R = 0.485 \text{ m} \). For shot # 9593, these are respectively \( R = 0.453 \text{ m} \) and \( R = 0.486 \text{ m} \). The \( J_{\text{sat}} \) profiles agree with the results from the EFIT reconstruction within 5 – 7 mm.

In the divertor region during the shots in question, it was found that the EEDF at the HFS is Maxwellian with a temperature of 4 – 10 eV (figure 4 a)). In the private flux region (PFR), it differs from the Maxwellian, but can be approximated by a bi-Maxwellian distribution. In figure 4 a, the triangles represent the temperature of the low-energy electron fraction, while the squares, the temperature of the high-energy electrons in the bi-Maxwellian EEDF. The dots indicate the temperature of the Maxwellian EEDF. It is seen that the bi-Maxwellian distribution appears around the inner strike point, a position evaluated from the probes, namely, a maximum signal on \( J_{\text{sat}} \). Figure 4 b) presents the corresponding electron densities (represented by the same symbols as used in figure 4 a).
Using the results for the electron temperatures and densities obtained by probe measurements, one can calculate the parallel power flux density by using the following equation [7]:

\[ Q_e = 7.5T_e \Gamma_{se} \]  

(1)

Here we assumed that \( T_i = T_e \) and the particle flux density \( \Gamma_{se} = J_{sat}/e \), where \( J_{sat} \) is the ion-saturation current density.

Figure 5 shows the calculations of the parallel power flux density for different shots when the tungsten sample is at different \( z \) positions in the plasma. It is seen that the position of the sample does not affect the plasma parameters in the divertor. The heat flux on the samples corresponds to the open magnetic surface which crosses the divertor at the radial position 0.385 – 0.415 m. Then, the parallel power flux density on the sample surfaces is about 0.02 – 0.5 MW/m². On HFS during H-mode, the power flux density profile increases exponentially as \( Q_e = Q_0 \exp(-R_{sep}/\lambda_{q}) \), where the decay length in the inner divertor is \( \lambda_{q} = 0.012 \) m and \( Q_0 = 2 \) MW/m² (the dashed black line in figure 5) for the discharges when the sample interacts with the plasma. The higher values in the spatial profiles for shot #9348 of the electron densities and of the power flux density are due to the higher line-averaged density.

5. Results of the plasma interaction with tungsten samples

Under the experimental conditions described, we studied the plasma interaction with tungsten samples, with or without a pre-grown He fuzz. He fuzz is a nano-scale fibrous structure that forms on a tungsten surface exposed to helium plasma. Its low density, together with the tendency to increase the occurrence of unipolar arcing, may make it susceptible to (locally) enhanced erosion in tokamak conditions, especially during transient events such as ELMs [8]. Four tungsten samples after an exposure in COMPASS (in an orientation roughly parallel with the tokamak wall) are shown in figure 6. Arc traces on the fuzzed samples are clearly visible. These consisted of localized melting of
the fuzz structure and a reduction of its thickness in the affected areas. However, the melting did not penetrate through the fuzz thickness into the bulk. A significantly higher number of arc traces was observed after an exposure with sample surfaces roughly perpendicular to the tokamak wall. Due to the frequent occurrence of hot dust particles originating from the holder, it was not possible to isolate individual arcing events and correlate them with particular ELMs. This is a subject of an ongoing investigation.

Figure 6. Exposed tungsten samples in a graphite holder. Sample 3 was only ground tungsten, samples 1, 2 and 4 had He fuzz grown under different conditions. Arc traces on the fuzzy samples are seen, mainly in the vertical direction.

6. Conclusions
This paper reports experimental results of plasma interaction with tungsten samples with or without pre-grown He fuzz. Under the conditions investigated, arcing was observed on the fuzzy tungsten samples, resulting in localized melting of the fuzz structure that did not extend into the bulk.

The parallel power flux densities were obtained from data measured by Langmuir probes embedded in the divertor tiles on the COMPASS tokamak. Measurements of the current-voltage (IV) probe characteristics were performed during ohmic ELMy H-modes reached in deuterium plasmas. The data obtained between the ELMs were processed by the first-derivative probe technique to evaluate the electron temperatures and densities.

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