The plasma focus as a tool for plasma-wall-interaction studies

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Abstract. The study of the interaction of magnetized plasmas with candidate materials for fusion reactors, as for example tungsten, is a main topic in fusion research. Many studies simulate the plasma wall interaction using ion beams, while only a few use plasma simulators. Plasma foci can produce dense magnetized plasmas of deuterium and helium among other species. We used the plasma focus Fuego-Nuevo II, to expose tungsten samples to deuterium and helium plasmas. The samples were analysed by means of SEM, RBS and NRA, evidencing surface erosion, surface melting and retention of deuterium in a shallow surface layer of 250 nm amounting $6.5 \times 10^{16} \text{ D/cm}^2$. The plasma temperature has been measured at the position of the samples using a triple Langmuir probe and compared to calculations of a snowplow model. The modelling of the electrode to reach desired plasma parameters is discussed.

1. Introduction

The interaction of plasmas with wall surfaces is important for the development of magnetic confinement fusion devices such as tokamaks, as they can release impurities into the plasma, erode the surfaces or produce retention of fuel in the wall, among other effects [1]. This effects are enhanced in the event of edge localized modes (ELMs) when large loads are deposited onto the wall. In a divertor-type Tokamak the particles reaching the first wall have usually relatively low energy and low density. The ion temperature averaged over an ELM is of the order of 20-200 eV outside the separatrix [2]. The study of the interaction of plasmas (and particles) with candidate first-wall materials is carried out mainly with ion beams, while only a few use plasma devices. Plasma simulators have usually very low energies of the order of tens of eV [3], while energies up to several hundreds of eV are desired.

The plasma focus [4,5] is a simple device that can produce a hot and dense plasma. During the initial axial phase energies up to several hundreds eV can be easily obtained. This phase is characterised for producing a large plasma volume of low energy. In the radial or compression phase a short living hot dense plasma is produced (small volume, high energy). Many of the early studies

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were concentrated on the study of the production of neutrons [6], while in the last time the research is more focused on applications in many fields including materials sciences [7].

![Figure 1. Schematic diagram of the FN II electrode showing the cathode, anode and insulator together with their dimensions.](image)

2. Fuego Nuevo II results

For plasma wall interaction studies the device has to show the capability of producing surface modification (erosion, surface melting), have the flexibility of having different plasma compositions, and it is also desirable to have the capability of studying retention of plasma species and intermixing.

Fuego Nuevo II (FN II) is a Mather-type Plasma Focus device with 4.8 kJ of stored energy described in more detail elsewhere [8,9]. The coaxial electrode is formed by an inner anode made out of solid OFHC copper and an outer cathode formed by twelve brass bars. The dimensions of the electrodes are shown in figure 1. For our experiments the inner electrode had a dip in the center to minimize erosion.

Samples were prepared from a tungsten foil 0.1 mm thick, with 99.95% purity, from Goodfellow [10], handled carefully, in order to avoid contamination, cut to proper dimensions and mounted on a copper massive holder in order to provide a proper heat sink during experiments. No further treatment was performed on the samples prior to plasma exposure. They were placed at 11 cm from the end of the electrode, as illustrated in figure 2, and exposed at room temperature to 20-30 shots each using deuterium or helium as filling gas, typically around 2.5 Torr, operating the device at 4.8 kJ (38 kV 7.4 µF). Additional Ti (0.127 mm thick, 99.7% purity[11]) and Cu samples were prepared, avoiding contamination but without further treatment, and placed either at 11 cm or 30 cm from the electrode.

After exposure the samples were analysed using different techniques: electron microscopy, cross section analysis using focused ion beam milling, Rutherford backscattering and nuclear reaction analysis.
2.1 Characteristics of the FN II discharge

A typical 4.8 kJ discharge with deuterium (~ 2 Torr) has a duration of a few microseconds. During the axial phase of the discharge the current increases steadily reaching its maximum of 240 kA at approx. 1 µS, while the plasma sheet reaches the end of the electrode shortly after, the radial phase starts, and the pinch occurs at 1.2 µS. The total duration of the discharge is about 9 µS.

Due to the interaction of the deuterium plasma with the insulator and the copper / brass electrodes material is eroded and projected into the chamber, as can be observed by the deposits on a stainless steel sheet placed 11 cm from electrode end (figure 3). In the center of impact a relatively large amount of copper can be observed in distances up about 1.3 cm from the axis. For larger distances from the axis the amount of copper drops, and for distances larger than 1.8 cm copper is not visible on the sheet. In the different studies we performed looking for impurities coming from the electrode only glass and copper could be observed [12].

In order to minimize the influence of the impurities coming from the electrode all our samples were placed off-axis and at distances larger than about 1.8 cm from the center of impact. This also possible reduces the influence of the ion beam on the samples.

The evolution of the plasma after the collapse of the plasma column at the pinch has not been extensively studied, since the attention in this device was focused on the neutron production. An intense ion beam together with the formation of a plasma dome and an additional “bubble” structure above the dome are observed [13]. The ion beam can reach energies in excess of 1 MeV according to different measurements under different filling gases and pressures [14,15], having a broad energy distribution. The angular distribution is also broad reaching angles of 80 degree [15]. There is apparently no information of the ions produced compared to the number of particles in the plasma or a model that could help us estimate the ion flux expected a target position. Specific measurements of the ion distribution or energy have not been performed in the FN II.

Besides the ion energy and flux it is also important to characterize the plasma that arrives at target position. To evaluate this a series of measurements using a triple Langmuir probe (TLP) were performed [13] giving plasma electron temperatures of the order of 65 eV.
2.2 Erosion and melting of tungsten samples
After exposure to 25 shots with 4.8 kJ each with deuterium the surface shows regions with partial melting together with region with erosion. Figure 4 shows SEM micrographs of tungsten samples before and after exposure. The images have both a magnification of 4000X. The image before exposure shows a clear structure of laminated crystallites on the left and a rough surface structure on the right. The image on the right (b) shows a very smooth surface, evidencing erosion. Some of these areas show a black deposit, whose composition according to Energy Dispersive X-ray-Spectroscopy (EDS) is essentially iron and chromium, which may come from the clamps used to fix the sample. Higher magnifications of the eroded areas show a smooth surface without voids or cracks even for the highest magnification used: 60000X (not shown here). The exposure to helium plasmas shows a similar picture.

Figure 5. SEM micrographs of tungsten unexposed (a) and exposed (b) to 25 shots deuterium. Magnification 4000X.
Figure 6 shows a SEM micrograph of a region with the formation of small tungsten droplets. This micrograph has a higher magnification than the previous images. An EDS study (not shown here) demonstrates that the composition of the droplets is essentially tungsten. The droplets have sizes of the order of 1 μm with a broad distribution. Formation of droplets is observed also in the case of helium plasmas.

2.3 Deuterium retention in tungsten

In order to study the retention of deuterium in the tungsten samples, some of them were analysed by means of nuclear reaction analysis (NRA) in an ion beam facility. In this technique $^3$He ions with energies above 690 keV produce protons and helium ions by means of the nuclear reaction $D(^3$He,$^4$He)p. As well as $^4$He ions and protons are detected in a certain solid angle and account for the amount of deuterium in the sample. The nuclear reaction has a narrow energy window allowing the measurement of a very shallow surface layer of about 250 nm. Increasing the ion energy the penetration is larger and the maximum of the reaction is shifted towards larger depths allowing probing at higher depths, the scale conversion, however, is non trivial [16].

Figure 7 shows the result of the NRA analysis of a tungsten and a titanium sample exposed at the same time to 25 shots of deuterium with 4.8 kJ each. The energy of the probing ions was varied from 690 keV to 2400 keV, to probe into the depth. In tungsten a high amount of deuterium is observed in the near surface region ($6.5 \times 10^{16} \text{ D/cm}^2$), falling rapidly into the depth. With a probing energy of 1200 keV the deuterium signal 1/7 of that in the surface. This indicates, that deuterium is retained in a near-surface layer of about 250 nm. Extensive EDS studies have been performed to look for co-deposited species that could be responsible for the deuterium retention. The impurities found [12] mainly iron cannot explain the large amount of retained deuterium. 250 nm agree well with the range of 20 keV deuterium ions in tungsten [12].

In titanium we observe, that a significant amount of deuterium is detected in the near surface region, increasing for probing energies around 1800 keV and falling for higher probing energies. Titanium is a material that forms hydride with deuterium, thus retains well deuterium. The reduced amount in the near surface region evidences that the sample was heated during exposure, thus allowing some of the retained deuterium to de-trap.
Figure 7. Deuterium content in tungsten (solid squares) and in titanium (open circles) exposed to 25 D shots in FN II according to NRA. The energy of the probing 3He ions was varied from 690 keV to 2400 keV.

3. Modelling of the electrode

Many models have been developed to simulate Plasma Focus discharges [15]. So called “snowplow” models have shown to predict reasonable well current-sheet velocities, however, these models require of a “sweeping” efficiency to fit experimental data. These models as well as other MHD models, coupled with an external circuit equation, can describe the plasma parameter of the run-down phase [15]. We use the “snowplow” model with external circuit equation presented by Lee and Saw [17] since it was applied in the past to the FN II finding good agreement with experiments. This model describes the evolution of the plasma during the run-down phase and the compression phase, but does not consider any dome or bubble structures formed after collapse of the pinch.

Table 1 shows the results of the calculations for selected electrode and pressure parameters. T axial is the plasma temperature in eV reached at the end of the electrode, T pinch the temperature reached in the pinch, C the capacity of the capacitor bank, V its charging voltage, and P the deuterium pressure in Torr. The electrodes dimensions of the first 3 row correspond to the FN II electrode. The details of the calculations are presented elsewhere [18].

In the first row, which reproduces the parameters of our experiments, the axial temperature reaches 126 eV. Assuming, that only this plasma component reaches the target, this is the highest expected temperature at target position. The TLP measurement gave 65 eV (section 2.1). Since the plasma has to travel form the end of the electrode to the target position a distance two times larger than the length of the electrode, it is expected that it gives up some energy to the neutral gas, thus the measured value seems in reasonable agreement with the model calculations. The TLP measurement can have contributions of the plasma of the run-down phase as well as contributions from the dome and bubble structures, that we cannot separate in this moment; we have to assume, that the experimental results are a combination of the three contributions. To confirm the accuracy of the model calculations, accurate measurements of the plasma temperatures in both positions are required, specifically the study of the dome and bubble structures would be needed.
Table 1. Plasma temperatures of the axial ($T_{\text{axial}}$) and radial ($T_{\text{radial}}$) phases according to the snowplow model for discharges using an electrode the dimension given by Inner Radius, Outer Radius and Length, and operated with a capacitor of capacitance C at voltage with a deuterium pressure P in the chamber.

| $T_{\text{axial}}$ (eV) | $T_{\text{pinch}}$ (eV) | Inner Radius (cm) | Outer Radius (cm) | Length (cm) | C (uF) | V (kV) | P (Torr) |
|-------------------------|------------------------|-------------------|-------------------|-------------|-------|-------|--------|
| 126                     | 1300                   | 2.02              | 5.5               | 4.8         | 7.4   | 38    | 2      |
| 200                     | 2100                   | 2.02              | 5.5               | 4.8         | 7.4   | 38    | 1      |
| 29                      | 259                    | 2.02              | 5.5               | 4.8         | 7.4   | 38    | 10     |
| 11                      | 97                     | 3                 | 5                 | 2.5         | 7.4   | 10    | 2      |

Nevertheless, the measured plasma temperatures at target position is in the desired range of temperatures for PWI studies. The penetration depth of these energies is far less than the penetration depth of deuterium as observed by NRA. This plasma component cannot explained the observed deuterium retention. The temperatures expected at pinch are of the order of 1.3 keV, much higher than the temperatures of the axial phase, but still to low to explain the penetration depths of D in W. The energy of this plasma component is to high to be observed with a TLP, and did not appear in or measurement. A penetration depth of 250 nm can only be caused by deuterium ions in the range of 20 keV. We have to assume that these ions are part of the ion beam produced after the collapse of the pinch. Thus, the main component of the retained deuterium has to come from the ion beam, rather than the plasma projected into the chamber. To take advantage of the axial plasma component, either the pinch has to be inhibited, or the ion beam has to be blocked.

The second row shows the expected plasma temperatures for the same experimental parameters, but with a lower pressure (1 Torr). In his case the axial final temperature is significantly higher than for 1 Torr, the same happens with the pinch temperature. Increasing significantly the pressure (third row) would produce lower plasma temperatures. Another way to obtain lower temperatures would be selecting shorter electrodes with a narrower gap and operating them at lower voltages (fourth row). This parametric study shows, that there is room to select energies suitable for plasma wall interaction varying the operation parameter of the plasma focus or selecting a more suitable geometry. For a fixed geometry, tailoring the operation parameters, a wide range of plasma temperatures, suitable for PWI studies can be produced.

4. Conclusions

The plasma focus has been evaluated as a device for the study of plasma wall interactions. The plasmas of this device, operated with deuterium, produce erosion and retention in fusion relevant materials like tungsten. The plasma at target position has been measured with a triple Langmuir probe and found to be in the range suitable for plasma wall interaction studies. The retention of deuterium is attributed mainly to the ion beam produced after the pinch. For a fixed electrode geometry the temperature of the plasma of the axial phase can be adjusted changing the operation parameters like capacitance and voltage of the voltage source and the pressure in the chamber.
Acknowledgments
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