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Measurements of suprathermal hydrogen flux in CASTOR tokamak

M.E. Notkin [a,*], A.I. Livshits [a], M. Hron [b], J. Stockel [b]

[a] *Bonch Bruyevich State University, Surface Physics and Electronics Research Center, Moika 61, 191186 Saint Petersburg, Russia*
[b] *Institute of Plasma Physics, Association EURATOM-IPP.CR, Prague, Czech Republic*

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Abstract

A study of the non-equilibrium absorption of hydrogen particles by a plasma-facing absorption probe (AP) made of Group V metals in the CASTOR tokamak environment has been undertaken with the main purposes: (1) to investigate the role of nonmetallic coatings upon plasma-facing materials in D/T inventory and recycling and (2) to develop a method of the registration and diagnostic of the flux of suprathermal hydrogen. Two series of experiments were performed: with AP of Nb and of V. The absorption of suprathermal hydrogen particles coming from the tokamak plasma was investigated as a function of AP temperature, AP distance from the plasma, AP bias and of plasma pulse duration. The possibility of a reliable registration of suprathermal hydrogen was demonstrated in spite of the short plasma pulse duration and a relatively high background H_2 pressure. The composition of the hydrogen flux (molecules, atoms, ions) impinging on the tokamak walls was analyzed, including ion energy distribution.

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Keywords: Suprathermal hydrogen particles; Absorption probe; Tokamak

1. Introduction

The interactions of neutral and charged hydrogen particles with plasma-facing materials is of prime importance in the present-day fusion devices and their models, as they define D/T fuel recycling and inventory [1,2]. For that reason, measuring of the hydrogen flux from plasma, of hydrogen particle energetic distribution, and of the molecular composition and ion charge, takes on a great interest.

Hydrogen-wall interactions are governed to a great degree by the state of wall surface which conditions the processes of hydrogen absorption/desorption/accumulation. The probability, α, of the absorption of low-energy hydrogen particles ($\sim$1 to hundreds eV) in metals through a nonmetallic film typically covering the metal surface radically depends on the film thickness. In the case of a monolayer film, this probability is close to that for a clean metallic surface. However, it may decrease dramatically, if the film thickness exceeds one monolayer. In reality, the thickness of nonmetallic coating depends on temperature: at high enough temperatures, typically only one nonmetallic monolayer exists at the surface under vacuum conditions, and hence the probability of absorption of hydrogen particles whose kinetic, internal or chemical energy exceeds 1 eV (suprathermal hydrogen) is very high. At lower temperatures, both monolayer and polyatomic coatings are possible, and, correspondingly, α may vary over a wide range.

The present work was undertaken to investigate the role played by the nonmetallic coatings on plasma-facing materials in D/T inventory and in the recycling of low energy hydrogen particles in tokamak environments; another goal is developing of a method of suprathermal particle diagnostics.

A resistively heated absorption probe of Group V metals (niobium and vanadium) is used to trap the flux of hydrogen particles, the amount of which is measured dur-

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* Corresponding author. Tel.: +7 812 587 9921; fax: +7 812 587 9334.
E-mail address: notkin@qrel.sut.ru (M.E. Notkin).

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ing the post-exposure thermal desorption of the absorbed hydrogen.

The choice of the probe material is due to a very favorable combination of such parameters of hydrogen interaction with the Group V metals as a large positive heat of hydrogen solution, a high mobility of solute hydrogen depending only weakly on metal temperature, and a high chemical activity of the metal surface giving rise to stable surface films of nonmetallic elements effectively impeding the thermal desorption of solute hydrogen. Due to that, probes of these metals can operate over a wide range of tokamak operation parameters, including high particle flux densities, short pulse duration, and also in devices having a high level of the background molecular hydrogen where other known diagnostic methods may be inapplicable [2,3].

The CASTOR tokamak [4] offers a good opportunity for staging of such experiments due to a relatively high, up to 10^{20} H/(m^2 s), flux of suprathermal hydrogen particles, an easy change of probe samples, and the vacuum system free of carbon-containing impurities. On the other hand, one has to note a relatively high, up to 3×10^{-2} Pa, level of the background hydrogen, and a short, <35 ms, duration of the plasma pulse.

2. Experimental

Schematic layout of the experimental setup is presented in Fig. 1. A movable resistively heated absorption probe (AP) of the investigated material (0.02 mm niobium foil, or 0.025 vanadium foil) with plasma facing surface area, S_{probe}, ~50 cm^2 is placed in a bakeable vacuum chamber connected to a CASTOR tokamak port through a gate valve. The AP is fixed at movable rod of magnetic drive, and it can be transported along the system axis over a ~100 cm distance. AP can be located at different distances from the tokamak plasma during the absorption experiments, and it can be moved into the experimental chamber which can be separated from the torus during the Castor bake-up, as well as for AP conditioning, for the analytical degassing experiments, experiments on AP surface modification, etc.

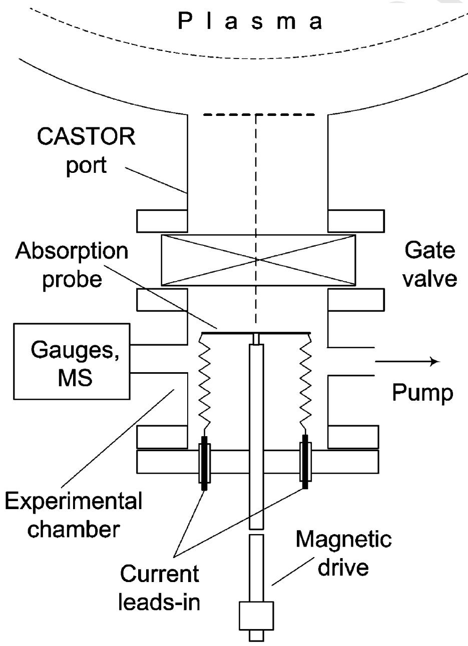

Fig. 1. Experimental layout.

The AP chamber is pumped by a 200 l/s TMP (40 l/s for hydrogen). The pressure is measured by a mass-spectrometer and a set of vacuum gauges. The state of AP surface (coating type and thickness) can be varied *in situ* by controlled reactions with specially introduced chemically active gases. One can obtain clean Nb(V) surface by heating the probe to a high temperature. At the first step of this study, the probes were only heated to moderate temperatures (1900 K for Nb, and 1600 K for V) in vacuum, which leads to the dissolution of polyatomic oxide films, with only O monolayer remaining on the surface [5].

Measurements of the absorption of hydrogen from plasma were performed in two steps. First, the probe was moved into the CASTOR torus and put at a desirable distance from the plasma. Then, an operational hydrogen pressure was established, and a plasma shot was executed. After the exposure to plasma, AP was moved back into the separate chamber. The amount of the absorbed hydrogen was measured at H_2 thermal desorption from the probe by its heating to 1300 K with the gate valve closed. A typical example of thermodesorption curve is presented in Fig. 2, curve 1. The area under this curve is proportional to the number of hydrogen particles absorbed both from the plasma and from the background molecular hydrogen.

Second, the above procedure was fully repeated, but without plasma shot. A corresponding thermodesorption curve is presented in Fig. 2, curve 2; it refers to the desorption of hydrogen absorbed only from the background hydrogen. The number of suprathermal hydrogen particles absorbed from the plasma is proportional to the difference of the areas under the curves 1 and 2 (the hatched area in Fig. 2).

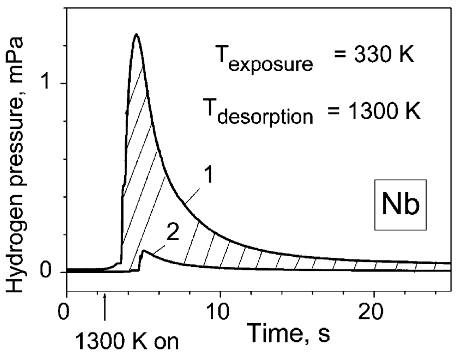

Fig. 2. Hydrogen thermodesorption from the probe at the permanent pumping with a speed 40 l/s for hydrogen: (1) suprathermal particles and (2) molecular hydrogen.

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3. Experimental results and discussion

3.1. Dependence of the absorption of hydrogen from plasma on probe location

The dependence of the amount of hydrogen accumulated from the suprathermal hydrogen flux on probe location is presented in Fig. 3; it demonstrates a strong dependence of hydrogen accumulation on the distance between AP and plasma. AP position just in line with the tokamak wall is indicated in Fig. 3 as "0" position, which corresponds to a 94 mm distance from the tokamak vessel centre. The "minus" sign refers to an AP shift toward the plasma.

The flux of suprathermal particles consists of both neutral atoms and ions. As the concentration of neutral hydrogen atoms is presumably equidistributed over the whole range of possible AP location, the observed dependence is most probably due to the ions whose flux is different at different distances from plasma because of shielding by the CASTOR limiter, walls, etc., and due to the presence of magnetic field. One can assume that the independence of hydrogen accumulation on probe location (the right branch of the curve in Fig. 3) indicates at the absence of an input from ions. Based on this result, the experiments with neutral particles were performed over this range of probe location.

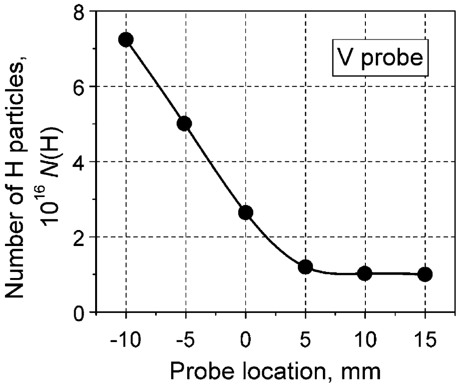

Fig. 3. Dependence of hydrogen accumulation on probe location. T(exposure) = 373 K, T(desorption) = 1123 K, floating potential.

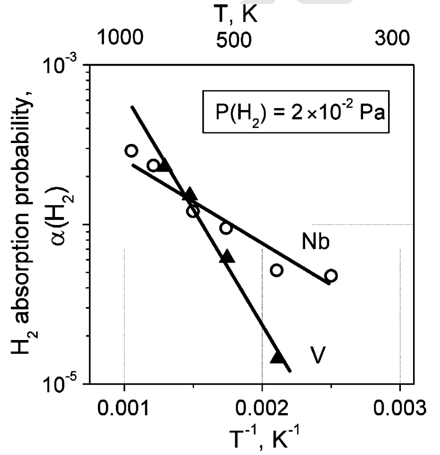

Fig. 4. Temperature dependence of hydrogen molecule absorption probability.

3.2. Absorption of hydrogen molecules

One can characterize the state of AP surface with regard to hydrogen absorption by the dependence of the kinetics of molecular hydrogen absorption on probe temperature (Fig. 4). We defined the sticking coefficient of hydrogen molecules, α_{H_2}, from our experimental data as follows $\alpha_{H_2} = N(\text{abs})/N(\text{inc})$. Here N(inc), the amount of hydrogen molecules falling onto the probe surface, equals $K_1 \times P_1(H_2) \times t$ where $P_1(H_2)$ is hydrogen pressure measured during AP exposure, t is exposure time and K_1 is a proportionality coefficient. The amount of hydrogen molecules absorbed by the probe, N(abs), equals to the amount of hydrogen desorbed from AP at thermodesorption, and it can be experimentally measured as described in Section 2.

As it follows from the data presented in Fig. 4, $\alpha_{H_2} = 2.1 \times 10^{-2} \exp -(28.2\ \text{kJ/kT})$ for the vanadium probe, and $\alpha_{H_2} = 1.5 \times 10^{-3} \exp -(13.6\ \text{kJ/kT})$ for the niobium probe. These values are typical of an H_2 molecule absorption by Nb and by V through a surface covered by nonmetallic (e.g. O) impurity monolayer resulting from the specimen annealing under vacuum conditions [5] (note that $\alpha_{H_2} = 0.1$–0.3 for a clean Nb surface [6]). According to our experience, that means that the probe surfaces are in a state giving rise to superpermeation, at least over the investigated temperature range, and hence one can reckon on an effective absorption of suprathermal particles.

3.3. Absorption of hydrogen atoms

The number of suprathermal particles absorbed during the tokamak discharge, N_H, was measured as function of AP temperature (Fig. 5, curve 3) and of plasma pulse length (Fig. 6). One can see that the amount of absorbed

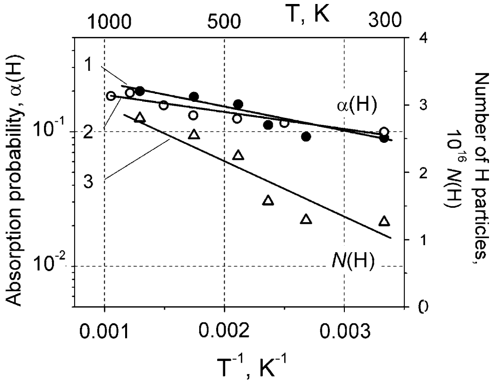

Fig. 5. Temperature dependencies of hydrogen atom absorption probability, (1) vanadium, (2) niobium and of hydrogen accumulation during plasma discharge (3).

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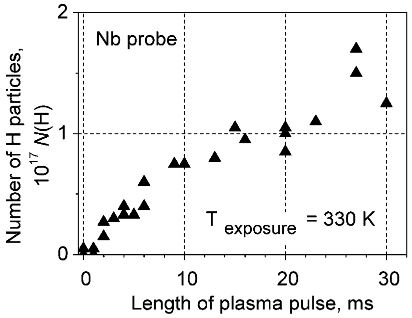

Fig. 6. Dependence of hydrogen absorption on pulse length.

suprathermal particles depends weakly on probe temperature and is approximately proportional to pulse length. The number of hydrogen atoms absorbed during plasma discharge amounts up to $\sim 10^{17}$ atom H, depending on probe temperature and on plasma pulse length (Figs. 5 and 6).

Concerning the probability of hydrogen atom absorption, we take its magnitude from the known data on the implantation coefficient, α_H, at sufficiently high temperatures: when it is guaranteed that the oxygen coating does not exceed one monolayer. For instance, one can take $\alpha_H \approx 0.2$ as a typical value for the energy range around 10 eV ($\alpha_H \approx 0.2$ is ascribed to our experimental data for suprathermal hydrogen: Fig. 5 curves 1, 2, left axis). As one could have expected it, the probabilities of hydrogen atom absorption for niobium (curve 2) and vanadium (curve 1) probes are very close to one the other.

3.4. Bias experiment

The study of the absorption of hydrogen ions was carried out with the same procedure as above (Section 2), but vanadium probe was electrically biased with respect to the CASTOR walls and was placed at a position where there is a measurable ion flux (see above). A typical dependence of the ion current on probe bias voltage is presented in Fig. 7 for two AP positions (see also Fig. 3).

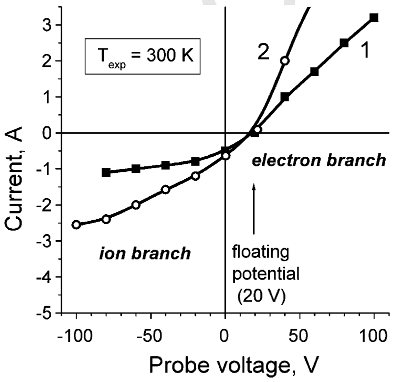

Fig. 7. Dependence of ion current onto the probe on probe bias voltage for two radial positions of the probe: (1) $r_p = 94$ mm (“0” position), (2) $r_p = 84$ mm.

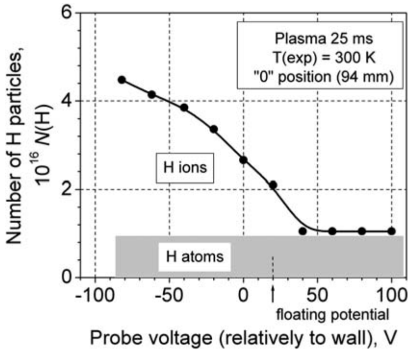

Fig. 8. Dependence of hydrogen accumulation on ion energy.

The results of the corresponding thermodesorption experiments (Fig. 8) demonstrate that hydrogen absorption does not depend on probe bias over the range +(40–100) V. One can suggest that such an independence means that the input of ions into hydrogen absorption is negligible over this energy range, hydrogen accumulation in the probe being due only to the input of neutrals.

The absorption of neutral hydrogen atoms does not depend on probe bias and thus it was possible to measure it separately. The results of these measurements are presented in Fig. 8 as a gray bar. The difference between the total desorption from the probe and the desorption indicating the input of neutral atoms yields the input of hydrogen ions. It follows from these data that the probability of hydrogen ion absorption weakly depends on ion energy over the whole investigated energy range and equals $\alpha_H = 0.75 \pm 0.05$. These numeric estimates are made on the presumption that the ion flux consists of H^+ ions [4].

Besides, AP being actually a Langmuir probe, its biasing permits to measure energy distribution of ions in the vicinity of CASTOR wall.

4. Conclusion

From a practical point of view, the possibility of a reliable registration of suprathermal hydrogen particles (atoms and ions) from tokamak plasma with the absorption probes made of superpermeable niobium and vanadium was demonstrated in the CASTOR tokamak conditions with its short plasma pulse and a relatively high background H_2 pressure. The absorption of suprathermal hydrogen particles from plasma was investigated as function of probe distance from the plasma, probe bias, and plasma discharge duration. These results provide the opportunity to study composition of the hydrogen flux (molecules, atoms, ions) impinging upon the CASTOR liner and to evaluate the fluxes of each component, as well as the energy distribution of hydrogen ions.

Absorption of 7 eV Franck–Condon atoms [4] and of low energy (up to hundreds of eV) ions by the Group V metals, niobium and vanadium, with the surface covered with oxygen monolayer film (Section 2) was studied from the viewpoint of physics. It was demonstrated that such a film

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does not impede the absorption of suprathermal hydrogen particles, but it suppresses their recycling, which results in an inventory of up to $\sim 10^{17}$ atom H from the plasma, substantially exceeding that from hydrogen molecules.

The absorption of suprathermal hydrogen particles by niobium and vanadium probes was found to be very close to each other. The absorption probability of hydrogen atoms was found to weakly depend on metal temperature over temperature range 300–1000 K. The absorption probability of hydrogen ions does not depend on ion energy over the range 20–100 eV.

The measured number of H atoms absorbed during a standard 25 ms discharge is in a reasonable agreement with that estimated from the plasma parameters.

The continuation of the present work will be aimed at modifications of the probe surface with the purpose to strongly suppress the absorption of hydrogen molecules and to increase in this way the sensitivity of suprathermal particle registration. Another promising idea is developing of a method to measure the amount of absorbed hydrogen based on the dependence of probe material resistivity on the concentration of solute hydrogen.

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