Fusion Engineering and Design xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Plasma–wall interactions with nitrogen seeding in all-metal fusion devices: Formation of nitrides and ammonia

Martin Oberkofler[a,*], D. Alegre[b], F. Aumayr[c], S. Brezinsek[d], T. Dittmar[d], K. Dobes[c], D. Douai[e], A. Drenik[f], M. Köppen[d], U. Kruezi[g], Ch. Linsmeier[d], C.P. Lungu[h], G. Meisl[a], M. Mozetic[f], C. Porosnicu[h], V. Rohde[a], S.G. Romanelli[g], the ASDEX Upgrade Team and JET EFDA Contributors[1]

[a] Max-Planck-Institut für Plasmaphysik, Boltzmannstraße 2, D-85748 Garching, Germany
[b] Laboratorio Nacional de Fusion, CIEMAT, Av. Complutense 40, 28040 Madrid, Spain
[c] Institute of Applied Physics, TU Wien, Wiedner Hauptstraße 8-10, 1040 Vienna, Austria
[d] Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, 52425 Jülich, Germany
[e] CEA Centre de Cadarache, 13108 Saint Paul lez Durance Cedex, France
[f] Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia
[g] JET-EFDA, Culham Science Centre, Abingdon OX14 3DB, UK
[h] National Institute for Laser, Plasma and Radiation Physics, Bucharest, Romania

HIGHLIGHTS

- Nitrogen chemistry is a potential issue for the use of N_2 as seeding species to cool the edge of fusion plasmas.
- Surface nitride formation on Be and W in laboratory experiments.
- Reduced erosion rate of Be by injection of N in D plasma in PISCES-B.
- Ammonia formation observed in AUG and JET.

ARTICLE INFO

Article history:
Received 5 October 2014
Received in revised form 23 January 2015
Accepted 27 January 2015
Available online xxx

Keywords:
Plasma–wall interaction
Nitrogen seeding
Erosion
Nitride
Ammonia
Gas balance

ABSTRACT

Nitrogen is routinely used to control the power load to the divertor targets of tokamak fusion reactors. However, its chemical reactivity can have implications on design and operation of a fusion device. In this contribution experimental results from recent years on three topics are briefly presented. These are the formation of nitrides, the sputtering of beryllium in the presence of nitrogen and the production of ammonia. Laboratory experiments have shown that surface nitrides are formed both on beryllium and tungsten upon exposure to energetic nitrogen ions. Erosion rates of Be by energetic N ions are in good quantitative agreement with modeling. Erosion upon exposure of Be to a mixed N/D plasma is reduced with respect to a pure D plasma. Finally, the appearance of ammonia has been observed in mixed N/D plasmas as well as in the exhaust gas of AUG and JET. The production rate in AUG reached 5% of the injected N atoms in a series of three subsequent N_2-seeded discharges.

1. Introduction

Excessive local heat loads onto the divertor target plates can cause surface melting in tokamaks with metallic plasma-facing materials such as AUG and JET. In order to attenuate the local heat loads extrinsic radiating species are injected in the divertor region. Besides noble gases, nitrogen is very successfully used for this purpose because of its favorable radiative characteristics at the relevant electron temperatures around 30 eV (see e.g. [1–3]).

However, although molecular N_2 is chemically inert, its radicals and ions do react easily with many elements. As a consequence the interaction of a N containing plasma with the first wall of a fusion reactor can have various implications, ranging from the modification of material properties over increased erosion and hydrogen

* Corresponding author. Tel.: +49 8932991005.
E-mail address: martin.oberkofler@ipp.mpg.de (M. Oberkofler).
[1] See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, USA.

http://dx.doi.org/10.1016/j.fusengdes.2015.01.044
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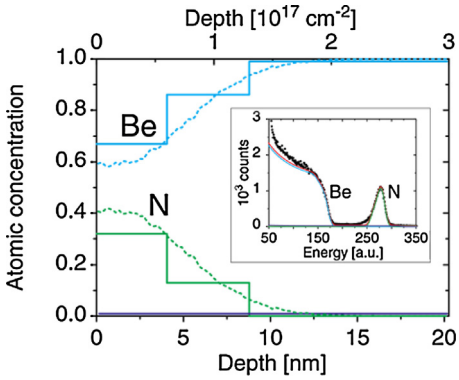

Fig. 1. Depth distribution of N and Be close to the surface of the N-implanted Be sample. The full lines are the result from adaptation of SIMNRA simulations to the RBS measurement. The dotted lines are the depth profiles resulting from a dynamic SDTrimSP calculation. The inset shows the experimental and simulated RBS spectra.

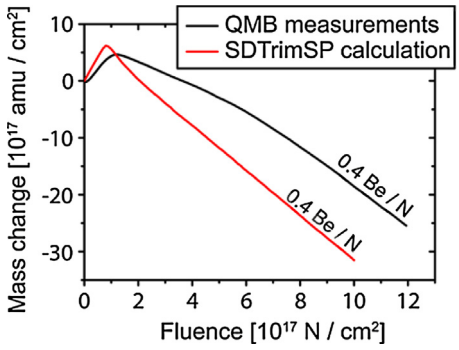

Fig. 2. Mass change of the Be-covered quartz crystal as a function of N fluence: comparison of the QMB measurements to dynamic calculations with SDTrimSP.

isotope retention to the production of ammonia. Potential safety and operational issues for ITER need to be identified and studied to evaluate the applicability of N_2 as seeding gas in future nuclear fusion devices.

2. Implantation of nitrogen into plasma-facing materials and retention in nitrides

Upon injection of N_2 into the 'scrape-off layer' of fusion plasmas the molecules are dissociated and/or ionized. Energetic N ions are implanted into the plasma-facing surfaces. As a consequence chemical compounds can form. In fact both plasma-facing materials foreseen in ITER, beryllium and tungsten, are known to form stable nitrides [4,5]. It is important to clarify whether the formation of nitrides appreciably affects material properties of the first wall and to what extent they constitute a sink and subsequently also a possible source for N.

To study the interaction of energetic N ions with Be surfaces laboratory experiments have been performed in an ultra-high vacuum apparatus [6]. In a fusion reactor like ITER the Be surfaces in the main chamber are exposed to a continuous flux of D ions on the order of 10^{17} atoms/cm^2/s [7]. The induced sputtering keeps the surfaces free of impurities, in particular of oxygen. In a controlled laboratory experiment a base pressure of 1×10^{-10} mbar is necessary to sufficiently suppress oxidation (after cleaning by argon sputtering and annealing) for the duration of an experiment and allow investigations on a clean metallic Be surface. Such a surface has been exposed at room temperature to a mono-energetic beam of N_2^+ ions at various energies and fluences. Fig. 1 shows results from Rutherford backscattering analysis (RBS) performed after implantation of N at 2.5 keV/atom under an incidence angle of 45° to a fluence of roughly 1×10^{18} N/cm^2 [6]. RBS analysis was performed with ^{4}He at 800 keV under a scattering angle of 105° and a surface-detector angle of 7.5° to increase the depth resolution. The nonetheless strongly peaked N signal (see raw data in the inset of Fig. 1) indicates a very shallow layer with considerable N content. The N and Be depth profiles in the sample have been reconstructed from the RBS spectrum using the SIMNRA code [8]. They are in good agreement with a dynamic simulation of the N implantation with SDTrimSP [9,10]. In this simulation the maximum N concentration was limited to 40%, which corresponds to the N atomic fraction in the stoichiometric nitride Be_3N_2. This approach relies on the assumption that any N in excess of the thermodynamically stable stoichiometry would not remain bound inside the material but instead diffuses to the surface and desorbs in the form of N_2.

The measured depth profiles remain unchanged upon annealing to 1000 K. The nitride formation is therefore a strong sink for N impinging on metallic Be surfaces in a fusion experiment. Thermal release or diffusion of N into greater depths does not occur. The surface nitride can however be removed by erosion caused by other impinging species (see Section 3).

Also on W the implantation of energetic N leads to the formation of surface nitrides [5,11]. Laboratory experiments have shown that the implantation of N into W at ambient temperature is well described by SDTrimSP. In agreement with the known phase of WN, the N concentration for these simulations was limited to 50%. A diffusive loss of N from W only sets in at about 850 K. However, the N saturation areal density under ion bombardment already decreases above 500 K. In a reactor this could lead to an increased loss of N from W plasma facing components with increasing surface temperatures in long plasma discharges or under thermal excursions.

The results for both Be and W alleviate concerns about modified material properties such as a reduction in conductivity or melting point, since the thickness of the N-enriched surface layer is limited to the ion implantation depth which is on the order of some nm.

However, recent experiments on W raise the concern that the presence of a surface nitride layer might increase hydrogen retention by acting as a diffusion barrier for implanted hydrogen isotopes [12,13].

3. Erosion of beryllium by energetic nitrogen ions and mixed deuterium-nitrogen plasmas

The ultimate aim of injecting a seed impurity into the fusion plasma is to reduce the heat load and the sputtering rate at the divertor targets. This is achieved above a certain level of locally radiating impurities [14]. However, energetic impurity atoms originating from charge exchange reactions could cause excessive erosion at the main chamber walls: the sputtering threshold for impurities is generally lower than that for hydrogen isotopes due to their higher mass and nuclear charge and the corresponding collision kinematics.

To quantify the sputtering of main chamber Be plasma-facing surfaces by energetic N ions a series of in-situ laboratory experiments has been performed. The sputtering yield was measured by the quartz microbalance (QMB) technique [15]. Quartz crystals were coated with Be layers of 500 nm thickness by means of thermionic vacuum arc deposition [16] and mounted on a QMB setup (see Fig. 2). These surfaces were bombarded with mono-energetic N ions under perpendicular incidence at a flux of about 2×10^{13} N/cm^2/s and at a base pressure $<10^{-10}$ mbar. The sample temperature upon exposure to the ion beam was 465 K. At this temperature the resonance frequency of the crystal is to first order independent of temperature changes thus providing

Please cite this article in press as: M. Oberkofler, et al., Plasma–wall interactions with nitrogen seeding in all-metal fusion devices: Formation of nitrides and ammonia, Fusion Eng. Des. (2015), http://dx.doi.org/10.1016/j.fusengdes.2015.01.044