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Predicting hydrogen isotope inventory in plasma-facing components during normal and abnormal operations in fusion devices

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ABSTRACT

Hydrogen isotope behavior and inventory in plasma-facing components (PFCs) of fusion devices are key concerns for safe, reliable, and economical operation. To accurately estimate hydrogen isotope retention and recovery in tungsten (the current leading candidate as a PFC), we have developed a model that was recently benchmarked against isotope depth profile and retention level in a tungsten target under various conditions and compared with both experimental data and simulation results. In this research, we have extended the model to include details of transient events. Therefore, one can use this model to estimate hydrogen isotope retention behavior in tungsten and potential other PFC candidates during normal operational pulse, effects of edge-localized modes (ELMs), and a possible cleaning processes scenario.

1. Introduction

In future thermonuclear fusion experiments, such as those in the International Thermonuclear Experimental Reactor (ITER), removal of hydrogen isotopes from plasma-facing components (PFCs) is a key aspect of reliable operation. Fuel loss, safety, and wall recovery issues are key engineering challenges in fusion reactor design because tritium is expensive, in short supply, radioactive, and has safety issues. Tungsten has become the leading candidate material in fusion reactor PFCs due to its low sputtering yield and high melting point. However, the quantitative prediction of tritium retention in tungsten under ITER conditions remains difficult [1].

Because hydrogen isotope retention and migration in tungsten has become a crucial problem, the transport and trapping properties of hydrogen isotopes in tungsten are critical and require further understanding. Fig. 1 in Refs. [2,3] shows a common hydrogen isotope spatial profile in metal. Spatial distribution of hydrogen isotopes in metal can be generally divided into three regions: near surface (I), subsurface (II), and bulk (III). Region I has the highest concentration because incoming hydrogen is implanted and trapped in a layer only a few nanometers thick. Region II shows the signature peak distribution of atomic diffusion in a metal lattice. In Region III, the concentration extends and diffuses gradually into the bulk and becomes less intense. In order to explain such a spatial profile and the "uphill diffusion" in Region II, the classical Gorsky effect, which in sample material contains a stress field induced by external bending, has been modified to contain a stress field induced by internal lattice distortion and was included in our previous work [3]. Worth to mention that there is no tensile strain in this deuterium irradiation on tungsten case compared to classical Gorsky effect. The bending scenario of Gorsky effect can result in one side of compressive strain and the other side of tensile strain. However in this work, we proposed that the massive amount of deuterium implantation on the surface will pressurize, distort neighbor lattices, and produce a high compressive stress area beneath the oversaturated implantation peak. The compressive stress zone will gradually decrease and relax, as extending into the bulk leaving only compressive strain area.

Such high irradiation process is extreme since normally hydrogen isotopes will diffuse into metal and will not accumulate on metal surface. The deuterium concentration in the implantation zone, under this low energy high flux/fluence irradiation condition, greatly exceeds the solubility limit and stresses the matrix lattice until plastic deformation occurs. Results from previous research [3] allow us to benchmark our model with other experimental and simulation results and establish agreement with other studies. In

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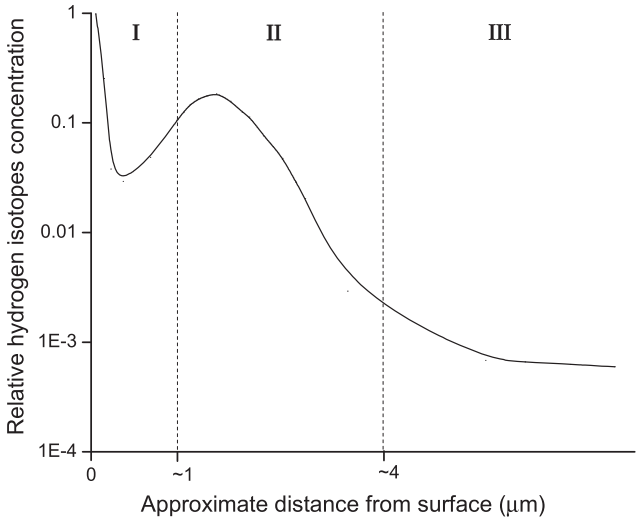

Fig. 1. Schematic diagram of hydrogen isotope depth profile in metals [2,3].

this paper, we will demonstrate possible further applications to our model. Fig. 2 schematically illustrates the accumulated hydrogen isotope wall inventory during operation, including the effect of edge-localized modes (ELMs) with certain frequencies and long ITER pulse operation.

The retained fraction during the pulsed operation can be given by

$$R_{pulse} = \frac{N_{wall}}{N_{inj}} \tag{1}$$

where N_{wall} is the wall inventory accumulated during the pulse and N_{inj} is the integrated particle injected in the wall. The retained fraction after the ELMs can be represented by

$$R_{ELMs} = \frac{N_{wall} - N_{ELMs}}{N_{inj}} \tag{2}$$

where N_{ELMs} is the hydrogen-isotope particle released after ELMs. The retained fraction can then be given by

$$R_{short} = \frac{N_{wall} - N_{ELMs} - N_{rec}}{N_{inj}} \tag{3}$$

where N_{rec} is particle recovery/release after the end of the shot. Finally, the long-term retention, including wall inventory accumulated during the pulse N_{wall}, integrated particle injected in wall N_{inj}, hydrogen-isotope particle released after ELMs N_{ELMs}, particle recovery/release after the end of the shot N_{rec}, recovery overnight N_{night}, recovery during cleaning (isotope removal) procedures N_{clean} … etc., can be expressed as

$$R_{long} = \frac{\sum\left(N_{wall} - N_{ELMs} - N_{rec} - N_{night} - N_{clean}\cdots\right)}{N_{inj}} \tag{4}$$

The goal of this work is quantitative determination of the retained amount from a regular pulse during operation, as well as how the ELM and cleaning (removal) process will affect the hydrogen isotope retention level.

A critical issue for ITER is minimizing fuel inventory and safely removing hydrogen isotopes from PFCs without shutting down the reactor, venting the vacuum vessel, deconditioning the plasma-facing surfaces, and causing excessive exposure to radioactive materials. Two main methods are now available for overnight cleaning and removal of hydrogen isotope from PFCs. The first is in-situ detritiation by oxygen treatment to produce T_2O/DTO [4]. The second method uses continuous-wave Nd laser beam scanning at high speed to heat the walls to higher temperatures (e.g., 2300 K) for short durations (e.g., 10 ms). Skinner et al. [5] reported that the laser cleaning method can remove up to 87% of the tritium from JET (Joint European Torus) PFCs, which are composed of carbon and beryllium. Although the laser detritiation method is not part of the current ITER plan and we consider tungsten instead of carbon and beryllium in our research, we will use intense laser heating, i.e., the 2300 K cleaning for 10 ms, in our simulations to evaluate the effectiveness of the method in hydrogen isotope removal.

2. Model and methods

2.1. Governing equations

We have developed an integrated model to describe hydrogen isotope behavior in tungsten based on the Gorsky effect and a general chemical potential as described in Ref. [3]. The conditions

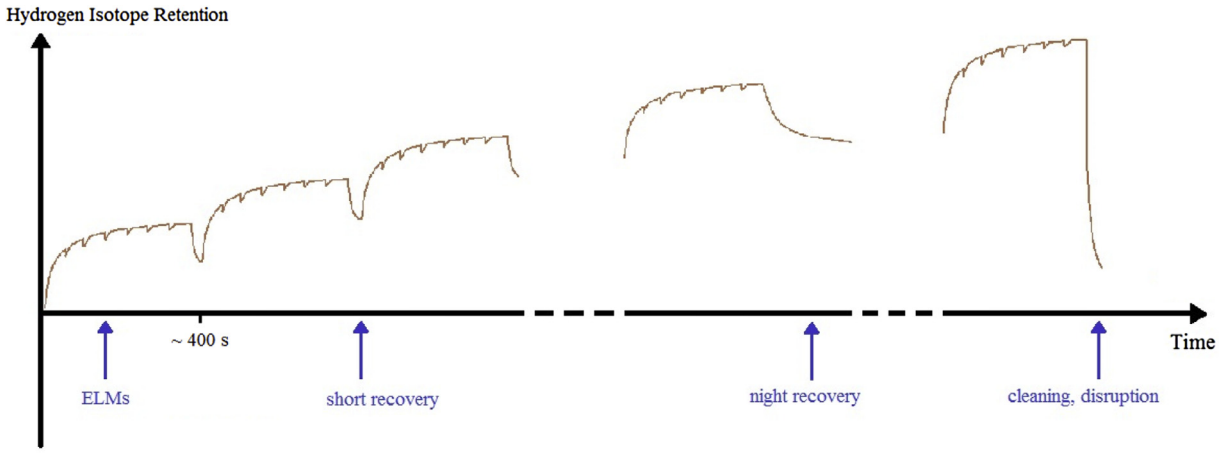

Fig. 2. Schematic view of particle balance, showing wall inventory buildup during a shot and recovery after the shot. Recovery after cleaning procedures and/or a disruption is also illustrated.