Nuclear Inst. and Methods in Physics Research B 434 (2018) 9–12

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research B

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

Proton scattering from tungsten fuzz

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ARTICLE INFO

Keywords:
Tungsten fuzz
Ion scattering
Stopping power
Surface analysis

ABSTRACT

Tungsten fuzz is a nanostructure formed on tungsten surface under helium plasma impact. In this work, we investigate this structure using the scattering of keV-energy protons. Energy spectra of scattered protons have double-peak shape that corresponds to the scattering from fuzz and underlying pure tungsten. The energy losses of protons in fuzz are estimated as the difference between primary beam energy and the energy corresponding to the local minimum between two peaks. Computer simulations with SRIM code also demonstrate double-peak shape of energy spectra of protons scattered from fuzzy target. Fuzz and pure tungsten stopping powers for protons are compared and fuzz density relative to pure tungsten is estimated and discussed. Evolution of H^+ energy spectra during fuzz irradiation by Ar^+ beam is measured and discussed.

1. Introduction

Tungsten due to its high melting temperature, high thermal conductivity and low sputtering yield is considered a well suitable plasma-facing material in divertor zone of future fusion reactors. However, tungsten surface under helium irradiation can be modified with so-called fuzz nanostructure, which is formed in linear simulators and tokamaks at ITER-relevant parameters of helium plasma [1–4] (fluence $\sim 10^{20}$–10^{21} cm^{-2}, $T \sim 1000$–2000 K and ion energy ~ 20–200 eV). The fuzz formation significantly affects an interaction of plasma components with plasma-facing surfaces [5].

The fuzz structure is very porous and consists of intertwined tungsten nanorods containing helium bubbles. In [3] tungsten fuzz density was estimated by mass loss measurements after fuzz wiping removal from a tungsten surface. It was shown that fuzz density was $\sim 6\%$ of pure tungsten density. The helium concentration was measured in [6] using thermal desorption spectroscopy, He/W ratio in fuzz was 0.13. Elastic recoil detection analysis performed in [7] showed that the helium concentration in fuzz did not exceed 7 at.%.

Ion scattering spectroscopy is a well-known instrument of surface analysis, very sensitive to surface morphology and composition. Scattering of keV-energy hydrogen ions may also provide information about surface layer thickness if atomic mass of this layer differs much from atomic mass of underlying substrate [8,9]. However, the atomic mass of the fuzz is similar to the one of tungsten itself (neglecting helium contribution to an average atomic mass of a target), but its overall density is rather very different. In this work, we investigated the features of energy spectra of protons scattered from tungsten fuzz on the tungsten substrate as a function of primary ion beam energy and spectra evolution at fuzz layer degradation under Ar^+ beam bombardment to define stopping power of protons in the tungsten fuzz.

2. Materials and methods

Tungsten fuzz samples were prepared on NAGDIS-II linear simulator (Nagoya University, Japan) [10] by irradiation of pure tungsten samples in helium plasma with the fluence $\sim 10^{21}$ cm^{-2}, sample surface temperature 1200 K and ion energy 100 eV. The thickness of grown-up fuzz layer determined from the SEM image of sample cross-section is ~ 1 µm (discussed later). Further analysis of fuzz samples was performed on the Large Mass-Monochromator (LMM) facility (NRNU MEPhI, Russia) [11]. The LMM scheme is shown in Fig. 1. Duoplasmatron ion source operating with hydrogen or noble gases is used to generate a monoenergetic ion beam with $E_0 = 1$–25 keV energies. Ion beam mass-separated with electromagnet interacts with a target, and then an energy spectrum of scattered and/or recoil ions is measured with electrostatic quarter-spherical analyzer and secondary electron multiplier. The scattering angle is 38° and incidence angle may be varied. Ion beam current density can be varied from 1 to 1000 nA/cm^2, that allows the use of hydrogen ion beam to perform nondestructive target analysis or argon beam for surface modification. The operating pressure in the interaction chamber is $\sim 10^{-7}$ mbar. Experiments were

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https://doi.org/10.1016/j.nimb.2018.07.038
Received 15 October 2017; Received in revised form 30 July 2018; Accepted 31 July 2018

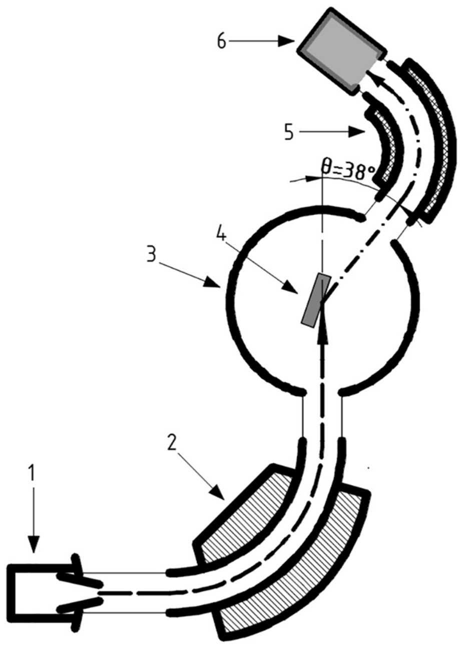

Fig. 1. LMM facility scheme: 1 – ion source, 2 – separating electromagnet, 3 – interaction chamber, 4 2013 sample, 5 – energy analyzer, 6 – secondary electron multiplier.

performed at room temperature of the target; the angle of primary beam incidence was 19° with respect to the target surface.

3. Results and discussion

Fig. 2 shows the energy spectra of protons scattered from the analyzed tungsten fuzz sample for several primary beam energies. The spectra have double peak shape that is not typical for one-component targets. However, the analyzed sample can be considered to consist of two components: the fuzz layer and the bulk tungsten that only differ in density. Therefore, we assume that two peaks on the spectra correspond to reflection from the fuzz (higher energy peak 2) and the underlying bulk tungsten (lower energy peak 1). With increasing of primary beam energy, more particles transmit through the fuzz layer and reflect from bulk tungsten, that results in increasing of lower energy peak amplitude. At primary beam energies less than $E_0 = 13\,\text{keV}$ most of the

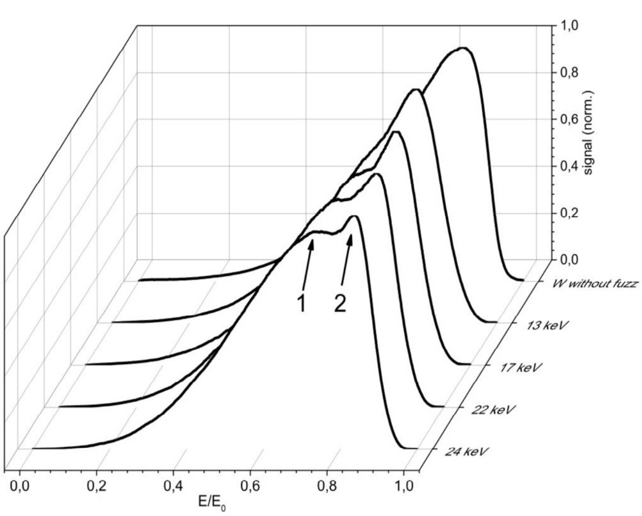

Fig. 2. Energy spectra of protons scattered from the analyzed tungsten fuzz sample for several primary beam energies and the spectrum of tungsten without fuzz. Peak 1 – reflection from bulk tungsten, peak 2 – reflection from fuzz.

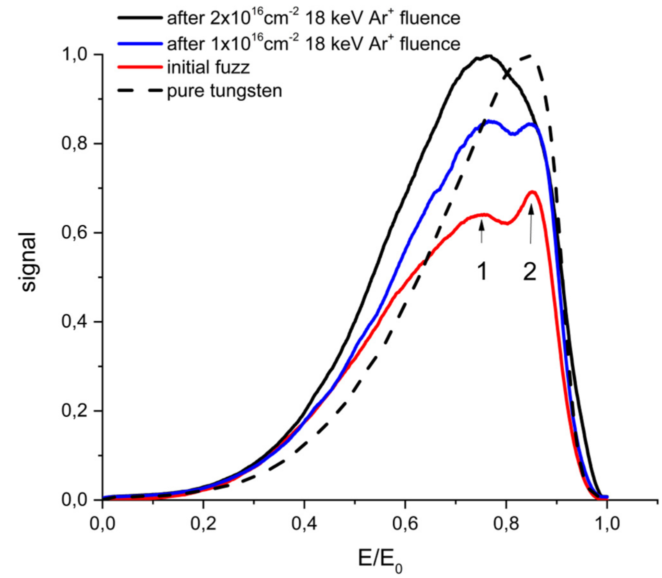

Fig. 3. Evolution of H^+ with $E_0 = 25\,\text{keV}$ spectra during the fuzz sample irradiation by Ar^+ 18 keV beam. Peak 1 – reflection from the bulk tungsten, peak 2 – reflection from the fuzz. The reference spectrum from a pure tungsten is represented by dash line.

detected protons are scattered from the fuzz layer, and the contribution of pure tungsten to the spectra becomes negligible.

Fig. 3 shows the evolution of energy spectra of scattered protons with $E_0 = 25\,\text{keV}$ during the sample irradiation by Ar^+ 18 keV ion beam that was performed in two steps. After the first irradiation step, the amplitude of the peak 1 relative to the peak 2 has increased, without the noticeable change of peak 1 position, while the thickness of fuzz layer has reduced approximately 1.6 times, as one can see comparing Fig. 4a and b. The possible reason could be argon ion-induced helium release [12] and fuzz condensation, that leads to the increase of fuzz mass density. The energy losses in modified fuzz layer remain roughly the same despite of less ion range in the fuzz. Small shift of peak 1 to higher energies and its growth after the irradiation corresponds to less energy losses of protons in the fuzz layer and the increase of their penetration through this layer. After the second irradiation with Ar ions the high energy peak in spectrum of scattered protons practically disappears, even though the SEM image (Fig. 4c) demonstrates that some nanostructures (~0.5 μm in thickness) remain on the tungsten surface. This could mean that the higher energy peak on the initial double-peak spectra corresponds to the scattering from the fuzz layer that was removed after two steps of Ar^+ irradiation. Knowing the thickness of removed fuzz layer (0.5 μm according to Fig. 4a and c) and assuming straight line projectile trajectories, one can calculate the total path of 25 keV protons in the removed part of the fuzz layer to be ~3.1 μm for the geometry of experiment, while the maximum range of protons in pure tungsten under our experimental conditions is ~30 nm. Energy losses of protons in the removed part of the fuzz layer were roughly estimated as the difference between primary beam energy and the energy corresponding to the local minimum between two peaks. For protons with $E_0 = 25\,\text{keV}$ the stopping power of removed part of the fuzz is found to be about 1.6 eV/nm (the total energy losses divided by the total path), while for pure tungsten it is ~150 eV/nm (SRIM [13] data).

Assuming that energy losses are proportional to a material density, one can evaluate the average density of the removed part of the fuzz layer as compared with a pure tungsten as ~1/94, that is more than five times less than in [3], where the fuzz density compared to pure tungsten was estimated as ~1/17. The reason of this difference may be due to the fact that the fuzz density is non-homogeneous and is increasing with the depth, that is consistent with [14], where the