SAND2020-9452C

Sandia National Laboratories

Nitrogen effects on tungsten plasma-facing surfaces

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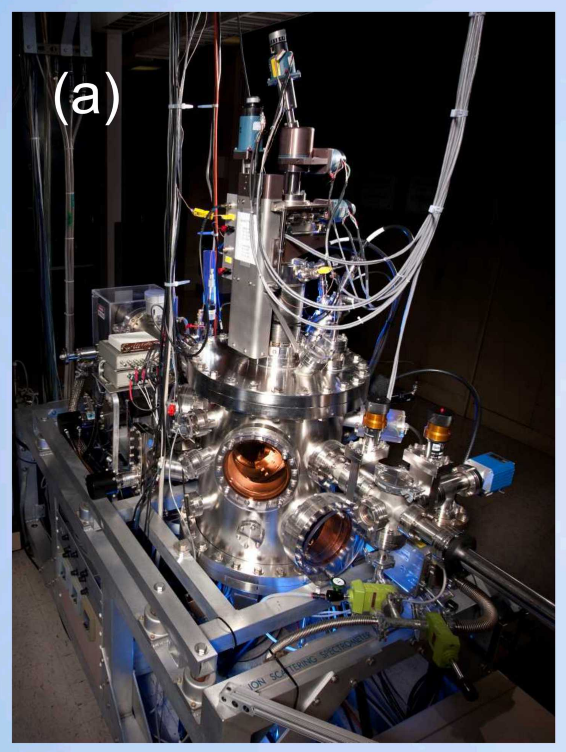
Introduction

Nitrogen seeding has been successfully used to help limit the power load at the divertor and improve energy confinement [1]. The presence of nitrogen impurities in the plasma, however, can complicate the existing plasma-material interactions, as atomic nitrogen is particularly reactive. Despite the progress made by recent works [2,3,4], a complete picture of the basic mechanisms for how nitrogen plasma can degrade plasma facing materials like tungsten is still lacking. The degradation of these materials include the generation of a dense network of defects in the first 10 nm of the surface, which could potentially have a strong effect on tritium diffusion and retention in the material, as well as promote the formation of near-surface precipitates.

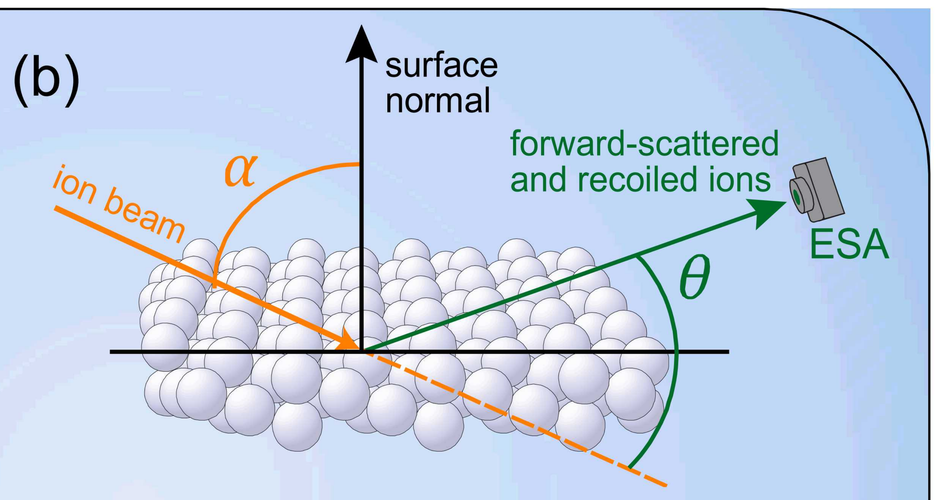
As a starting point to investigate nitrogen effects on tungsten plasma-facing surfaces, we applied low energy ion scattering to study nitrogen adsorption on tungsten surfaces, as well as developed and characterized a plasma source for generating high-flux radiofrequency nitrogen and deuterium plasmas with a Lisitano coil. This plasma source will be used in the future to perform systematic exposures of tungsten samples to sequential nitrogen and deuterium plasmas, as well as mixed deuterium-nitrogen plasma.

Low energy ion scattering

(a)



(b)



(c)

Eq. (1) $$\frac{E_S}{E_0} = \left(\frac{\cos\theta \pm \sqrt{\mu^2 - \sin^2\theta}}{1+\mu}\right)^2$$

Eq. (2) $$\frac{E_R}{E_0} = \frac{4\mu}{(1+\mu)^2}\cos^2\theta$$

Figure 1: **(a)** Photo of the angle-resolved ion energy spectrometer at Sandia/CA. **(b)** Geometry of low energy ion scattering. **(c)** Kinematic equations to describe the energy of a scattered ion (E_S) or recoiled ion (E_R) for a given scattering angle *θ*.

Low energy ion scattering (LEIS) was performed with an angle-resolved ion energy spectrometer (ARIES) in Fig. 1(a). To perform LEIS, an ion beam is directed at a glancing angle *α* onto the surface, as defined in Fig. 1(b). Forward scattered ions, as well as recoiled ions including hydrogen, are then detected by an electrostatic analyzer (ESA) positioned at a chosen scattering angle *θ*. The energy of a detected scattered ion (E_S) or recoiled ion (E_R) can be converted to the mass of a surface atom from the kinematic equations in Fig. 1(c), where E_0 is the incident ion energy and *μ* is the mass ratio of the target atom to the projectile ion. Using this analysis, peaks in ion energy spectra provide insight into the masses of surface atoms and, in turn, the surface chemical composition. In fact, this technique allows for surface hydrogen to be directly detected, which typically is not possible for most surface science techniques. The ability to detect surface hydrogen, coupled with the extreme surface sensitivity (monolayer or better), makes LEIS an attractive technique for our study.

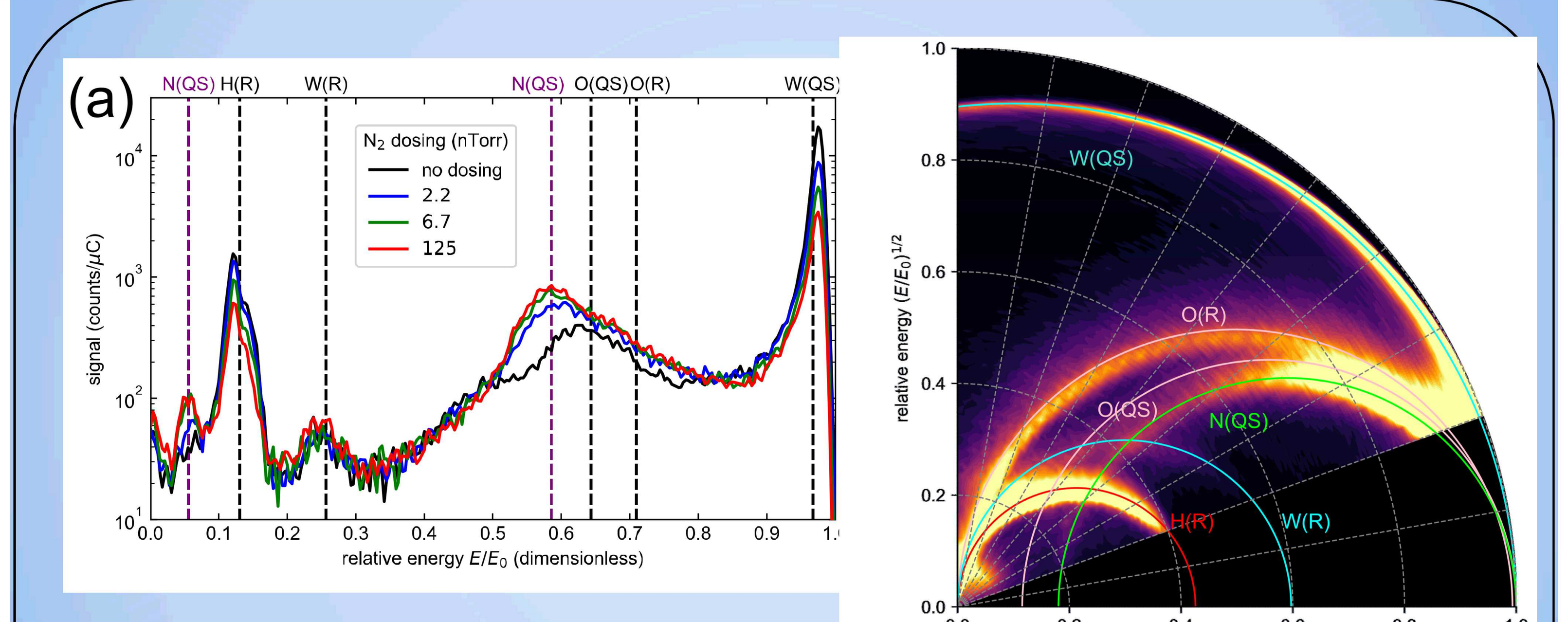


Figure 2: **(a)** Ion energy spectra for variou levels of N_2 dosing. **(b)** Collision circle plot wit N_2 dosing at a partial pressure of 50 nTorr.

Ion energy spectra were obtained with ARIES using a 3 keV Ne^+ beam incident on a polycrystalline ITER-grade W button for $\alpha = 80°$ and $\theta = 32°$. These spectra, in Fig. 2(a), were obtained for various levels of dosing with molecular nitrogen, N_2, beginning with no dosing. Peaks in the spectra were identified based on Eqs. (1) and (2), denoted X(R) for the detection a recoiled ion of species X and X(QS) for the detection of a Ne^+ that had scattered off a surface atom of species X. As N_2 was dosed onto the W surface, a peak emerged near E/E_0 = 0.58, which corresponds to N(QS). The appearance of this peak reveals that N_2 was adsorbing onto the tungsten surface and that LEIS is capable of detecting the presence of N adsorbates. Simultaneously, the H(R) peak diminished by a factor of three, an indication that adsorbed N was potentially limiting the adsorption of H_2 onto the surface.

When analyzing these spectra, there can be ambiguity in the identification of the collisions responsible for peaks at a single scattering angle θ. To overcome this ambiguity, we obtain ion energy spectra for 36 values of θ in the range $20 \le \theta \le 90$. These data are plotted in a collision circle plot [5] in Fig. 2(b), where the θ is the polar angle and $\sqrt{E/E_0}$ is the radial coordinate. When plotted in this manner, each collision type will trace out a circular arc computed from Eqs. (1) and (2). This plot validates our peak identification in Fig. 2(a).

N_2 adsorption onto the W surface did not vary with temperature as the sample was heated from 25 °C to 600 °C. As can be seen in Fig. 3(a), the N(QS) peak does not vary with temperature as the N_2 dosing was held constant. Changes in the spectra arose only from H desorption, as verified by Fig. 3(b), for which there was no N_2 dosing.

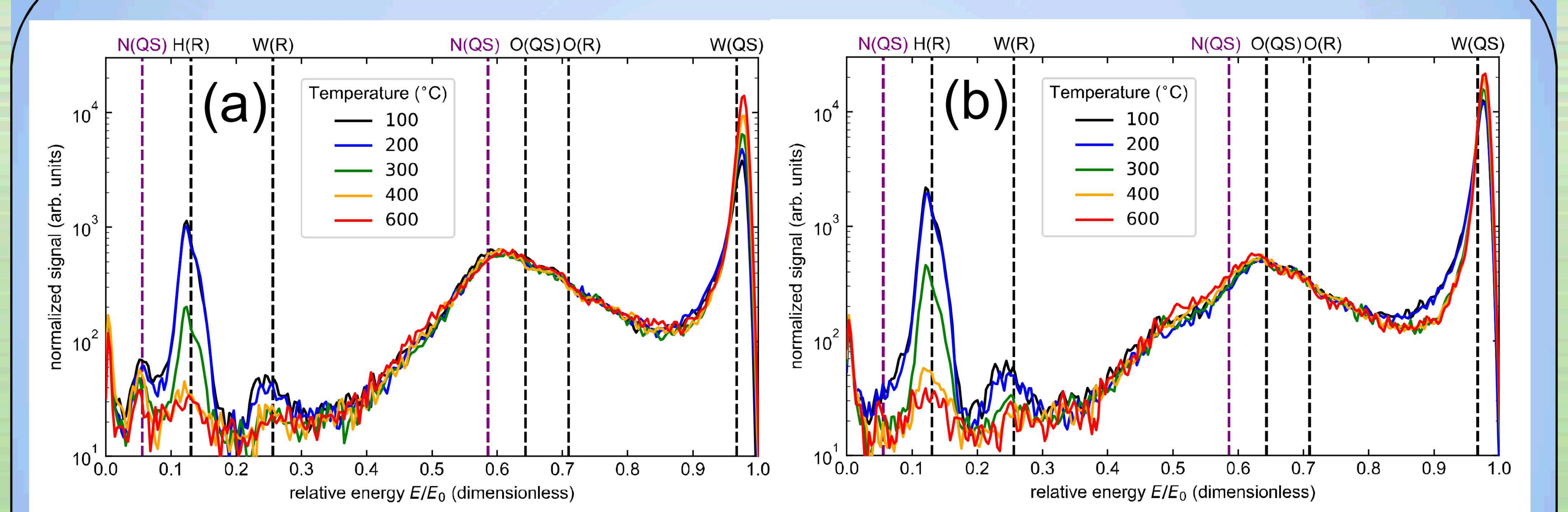


Figure 3: Ion energy spectra with the sample heated to various temperatures **(a)** with N_2 dosing at 50 nTorr partial pressure and **(b)** without N_2 dosing.

Nitrogen & hydrogen plasma source

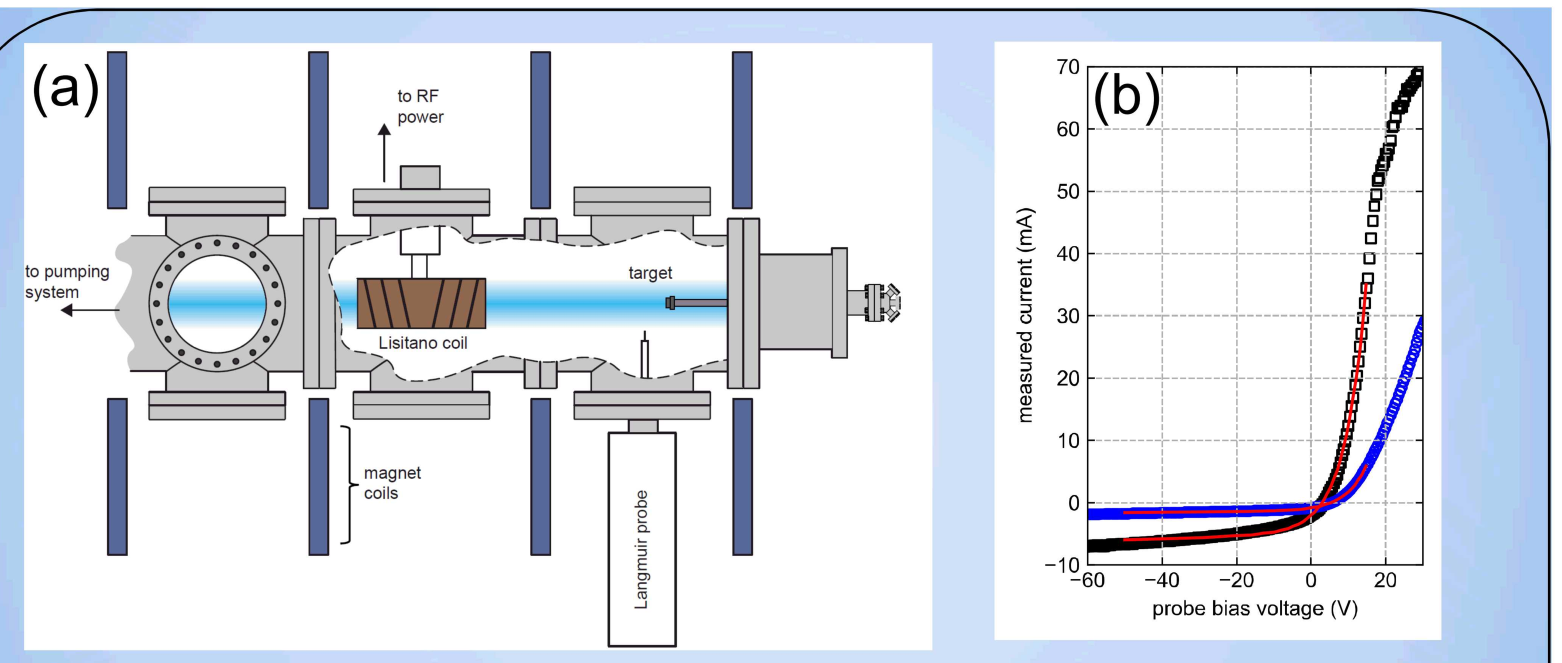


Figure 4: **(a)** Schematic of RF-powered linear plasma source. **(b)** IV traces obtained with a Langmuir probe for the N_2 (blue circles) and D_2 (black squares) plasmas. Plasma conditions were obtained by fitting each set of data to the red curves.

Nitrogen and deuterium plasma were generated by partially ionizing 5 mTorr of N_2 or D_2 gas, respectively, within the cylindrical chamber of Fig. 4(a). The plasmas were sustained by a Lisitano coil [6] driven at 400 MHz with 240 W of power, and magnetic coils that provided 185 G through the central column of the chamber. Plasma conditions, provided below, were obtained with a Langmuir probe that was inserted into the plasma column. IV traces, like those shown in Fig. 4(b), were fit to $I = a n_p \sqrt{T_e}\left(1 + \frac{x_s}{a_p}\right) + b n_p \sqrt{T_e} \exp\left(\frac{U - V_p}{T_e}\right)$, where a and b are constants related to the probe geometry and $\frac{x_s}{a_p}$ is a correction for sheath expansion. The obtained plasma conditions, in particular the ion flux, are within the appropriate range for investigating the early stages of nitrogen and hydrogen effects on tungsten surfaces.

	N_2 plasma	D_2 plasma
Electron temperature T_e (eV)	5.56	5.64
Plasma density n_p (10^{10} cm^{-3})	5.57	8.52
Plasma potential V_p (V)	31.6	23.7
Ion flux Γ_i (10^{16} cm^{-2} s^{-1})	8.55	2.10

Future work

With the now-characterized plasma source, we intend to expose ITER-grade W samples to sequential and mixed N_2 and D_2 plasmas. Deuterium retention will be determined with thermal desorption spectroscopy, while changes to the morphology of the surface will be characterized with helium ion microscopy and spectroscopic ellipsometry. Low energy ion scattering will be performed to aid in the interpretation of the effects of N_2 and D_2 plasma exposure. With a combination of these techniques, we hope to shed some light on the effects of nitrogen plasma on tungsten surfaces.

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C.-S.W., J.A.W., and R.D.K. acknowledge support from the U.S. Department of Energy Office of Fusion Energy Sciences, through the Materials and Fusion Nuclear Science program.

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