Effects of High Temperature Pulsed Helium Implantation on Tungsten Surface Morphology

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The durability and lifetime of thin tungsten or refractory metal coatings on the first walls of inertial and magnetic confinement fusion reactors is a key issue for the feasibility of such devices. Past studies at UW-Madison have indicated that tungsten, when subjected to He^+ fluences in excess of $4x10^{17}$ He^+/cm^2, shows extensive pore formation at 800 ºC.[1,2] The current study attempts to produce more realistic results by simultaneously irradiating tungsten samples with helium and hydrogen species and by investigating the effects of pulsed helium ion irradiation on tungsten.

I. MOTIVATION

Previous work by Cipiti, Kulcinski and Radel has shown extensive surface damage resulting from steady-state implantation of helium on tungsten.[1,2] However, ICF reactors will face a simultaneous bombardment of helium and hydrogen isotopes, which could affect the way helium damage occurs. These reactors will also be operating in a pulsed mode, with pulse widths of ~10 μs and frequencies of ~5 Hz.[3] This paper evaluates the effects of simultaneous helium and deuterium implantation and of performing helium implantation in a pulsed mode.

This research was performed as part of the High Average Power Laser (HAPL) program. HAPL scientists are currently focusing on tungsten as a potential material to protect the first wall from light ions, such as He, whose energy ranges from tens of keV to a few MeV. This study examines the lower portion of that spectrum.

The HAPL program also incorporates other experiments that are studying the effects of pulsed irradiation on tungsten surfaces, including the RHEPP facility at Sandia[4], the XAPPER facility at Lawrence Livermore[5], the Dragonfire facility at UCSD[6], and an infrared facility at ORNL[7]. Figure 1 shows the pulse widths and frequencies for each of these experiments relative to the reference HAPL pulse characteristics. Initial IEC experiments at Wisconsin operated at 1 ms pulse width with a 20 Hz frequency. However, subsequent experiments have indicated that operation at 200 μs pulse widths with frequencies as low as 5 Hz are possible.

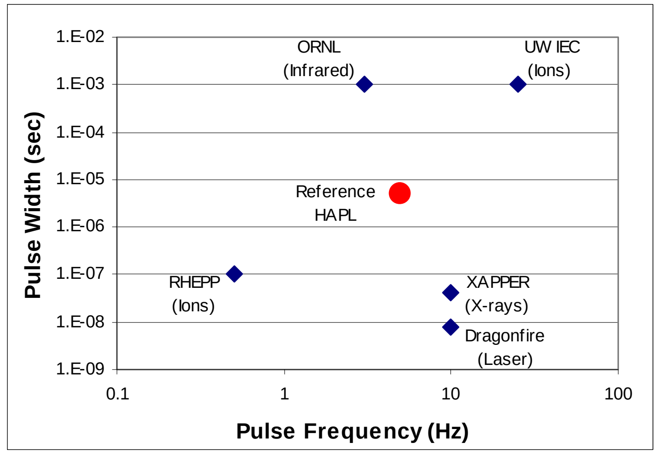


Fig. 1: Pulse capabilities of selected HAPL experimental facilities

II. EXPERIMENTAL SETUP

II.A. Inertial Electrostatic Confinement (IEC) Device

The University of Wisconsin has been studying the performance of a Inertial Electrostatic Confinement (IEC) fusion device for more than a decade.[8] It has been recently used to test the response of fusion related materials to high temperature bombardment from D and He. As seen in Figure 2, one of the UW IEC devices is an aluminum chamber 65 cm tall and 90 cm in diameter[5]. A base pressure of $\sim 10^{-7}$ torr is maintained in the device using a 1000 L/s turbo pump. Within this chamber are two conducting surfaces. The outer stainless steel anode grid is 50 cm in diameter and is kept at ground potential. The inner tungsten sample is connected to a 200 kV power supply with a high voltage feed thru.

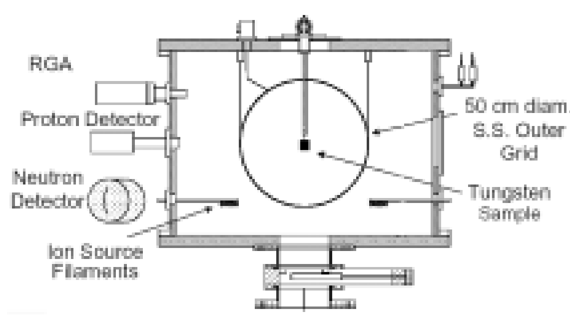


Fig. 2: IEC device with tungsten sample

During steady-state operation, helium and/or deuterium gas is fed into the chamber to produce a background pressure of 0.5 mtorr. This gas is then ionized via electron bombardment from hot tungsten filaments. A negative voltage is applied to the tungsten sample (shown in Figure 3), and the positively charged ions are attracted to it.

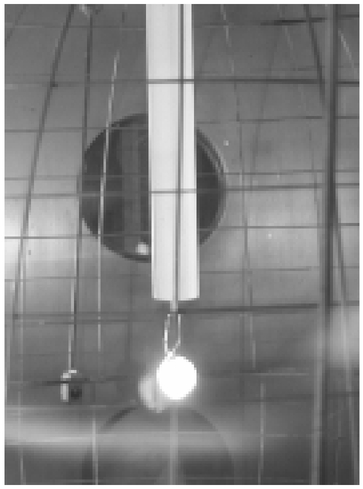


Fig.3: Tungsten sample during irradiation

II.B. Pulsed Operation

The UW-IEC steady-state device was modified to allow pulsed operation. IEC current is nominally suppressed during pulsed operation by applying a positive bias to the electron filaments. Cathode current pulses are then generated by adding a large negative bias to the filaments. The cathode voltage is maintained constant during the pulse via a 100 nF parallel capacitor.

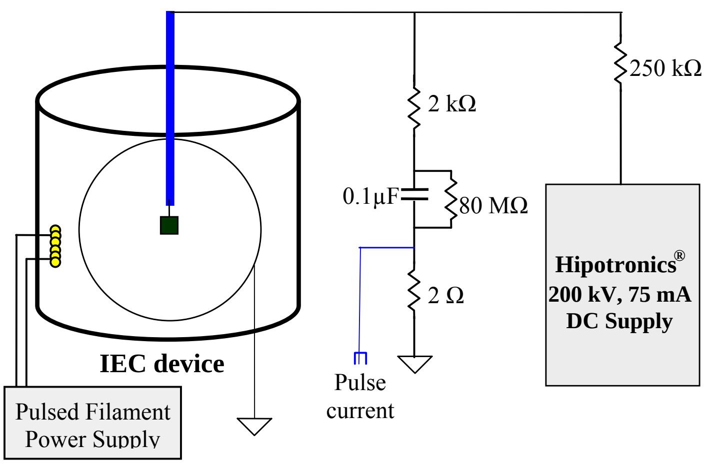


Fig. 4. High voltage circuit for pulsed IEC operation

The configuration shown in Figure 4 allows the creation of high-flux helium ion pulses at relatively constant voltages. The time-dependent current observed during the initial pulsed irradiation experiments is shown in Figure 5. Helium ion currents of 60 mA were pulsed at 25 Hz with a 1 ms pulse width. This resulted in a time-averaged current that was one-fourth of a typical steady-state irradiation, as shown in Figure 5.

Although the ion current was pulsed, the sample temperature was calculated to be nearly steady-state during irradiation. This calculation was based on the semi-infinite solid surface radiation approximation found in Carslaw and Jaegers.[9] This equation used to compute the temperature rise during a single pulse was:

$$\Delta T = \frac{2P}{Ak}\sqrt{\frac{kt}{\pi \rho c_p}} \qquad (1)$$

where P is the total power into the sample, A is the total surface area, k is thermal conductivity, ρ is density, t is the pulse width, and c_p is the specific heat. Substituting in typical values for a pulsed implantation experiment yields a temperature change of only 8 °C during a pulse.

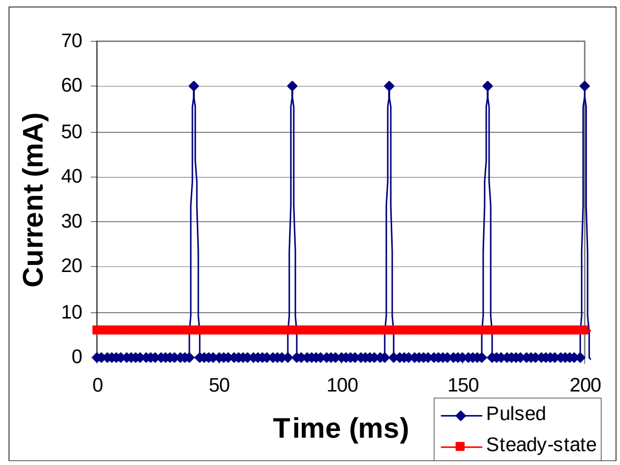


Fig. 5: Pulsed vs. steady-state irradiation current

III. RESULTS

III.A. Steady-State He^+ and D^+ Implantation

Simultaneous implantation of D^+ and He^+ was performed on tungsten samples at ~1100 °C. Previous experiments have indicated that deuterium irradiation alone does not induce pore formation.[1] Figure 6 compares polycrystalline tungsten samples irradiated with helium alone and with a helium-deuterium mixture. At $1\text{x}10^{18}$ ions/cm^2, there appears to be a slight reduction in the pore density from $1.2\text{x}10^9$ pores/cm^2 on the helium-only sample to $3.2\text{x}10^8$ pores/cm^2 on the sample run with He and D simultaneously. As the fluence is increased, however, this difference diminishes. At $1\text{x}10^{19}$ ions/cm^2 there appears to be no significant difference between the samples with and without added deuterium.

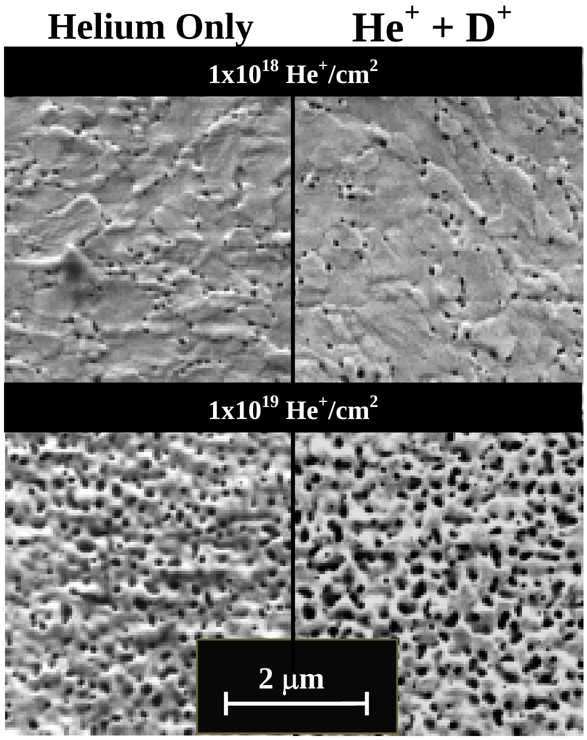


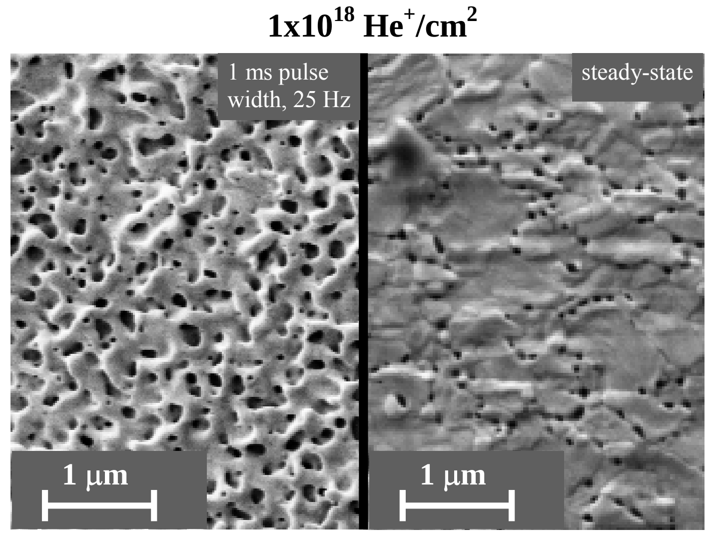
Fig. 6: Tungsten samples irradiated at 1150 °C with He and He + D at two fluences

This study indicates the addition of a simultaneous deuterium ion current has a minimal effect on the damage caused by helium irradiation in tungsten at fusion first wall-relevant temperatures. Therefore future experiments, including the pulsed implantation study discussed in this paper, can confidently be performed with helium ions alone. This simplification allows for more accurate measurement of helium fluence while still providing realistic results.

III.B. Pulsed Helium Implantation

Pulsed helium implantation of polycrystalline tungsten was performed at 1150 °C using the Wisconsin IEC device. Fluences of $1x10^{18}$, $6x10^{18}$, and $1x10^{19}$ He^+/cm^2 were delivered to the samples in 1 ms pulses at 25 Hz. Micrographs of these samples were then compared to previous steady-state results at the same fluences and temperatures.

Figure 7 shows results for both pulsed and steady-state irradiation to $1x10^{18}$ He^+/cm^2. It is clear from this comparison that more damage has resulted from the pulsed irradiation. While the steady-state sample only has pores collecting at grain boundaries with a pore density of $1.2x10^9$ pores/cm^2, the pulsed sample appears close to a saturation density with larger pore size.

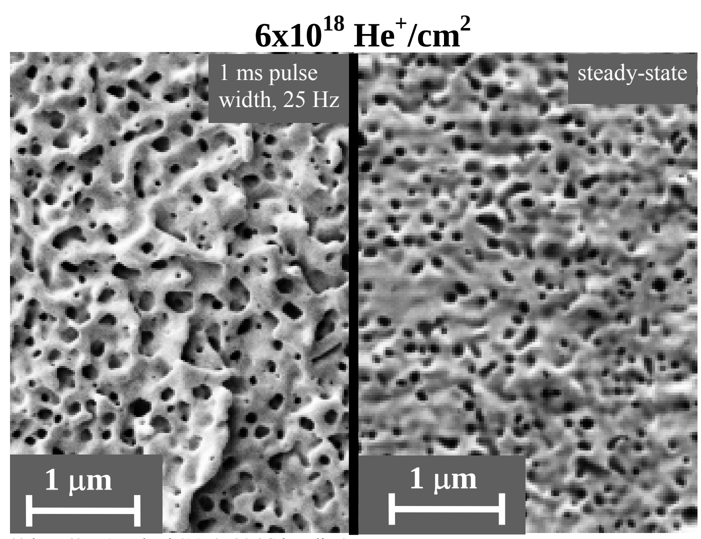


40 kV, 60 mA Pulsed (1170±20 °C baseline) 12 minute runtime

30 kV, 6 mA Steady-State (1150±20 °C) 3 minute runtime

Fig. 7: Pulsed and steady-state tungsten samples irradiated at ~1150 °C to $1x10^{18}$ He^+/cm^2

When the implanted helium fluence was increased to $6x10^{18}$ He^+/cm^2 at 1150 °C, the pore density of the steady-state sample increased dramatically, reaching $3.7x10^9$ pores/cm^2. In contrast, the pore density on the $6x10^{18}$ pulsed He^+/cm^2 sample did not significantly increase from the lower fluence, as shown in Figure 8. However, there does appear to be a change in the surface morphology at the grain boundaries. This change may indicate a shift towards more macroscopic damage mechanism as the pulsed helium fluence is increased.



40 kV, 60 mA Pulsed (1170±20 °C baseline) 72 minute runtime

30 kV, 6 mA Steady-State (1130±20 °C) 18 minute runtime

Fig. 8: Pulsed and steady-state tungsten samples irradiated at ~1150 °C to $6x10^{18}$ He^+/cm^2

When the steady-state implanted helium fluence was increased to $1x10^{19}$ He^{+}/cm^{2} at 1150 °C, the pore density decreased slightly to $1.9x10^{9}$ pores/cm^{2}, as shown in Figure 9. However, the surface appears to have roughened in a similar fashion to the pulsed sample at $6x10^{18}$ He^{+}/cm^{2}. The pulsed sample, however, has been damaged to the point of having a coral-like structure form in addition to the uniform pore density covering the surface.

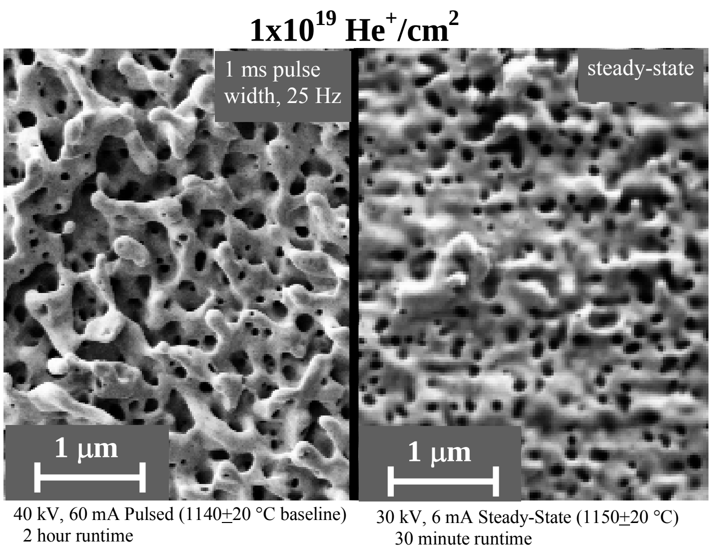


Fig. 9: Pulsed and steady-state tungsten samples irradiated at ~1150 °C to $6x10^{18}$ He^{+}/cm^{2}

Pulsed irradiation resulted not only in increased pore density on the surface, but also in an increased semi-porous layer beneath the surface. Figure 10 shows Focused Ion Beam (FIB) images of these surface layers at two fluences for both pulsed and steady state implantation. As either steady-state or pulsed fluence is increased, the additional helium bubbles create and extend a semi-porous surface layer.

In addition to the morphological changes, the samples pulsed at 1150 °C also experienced a measurable change in mass. Theoretical calculations based on physical sputtering rates predict that the sample would loose ~0.2 mg after 10^{19} He^{+}/cm^{2}. However, the sample actually lost 4.2 mg, or roughly 1.1 μm uniformly from the surface, suggesting that other mechanisms of mass loss must be taking place. The mass loss for three samples subjected to pulsed helium implantation is summarized in Table 1 below.

	$1x10^{19}$ He^{+}/cm^{2}	$6x10^{18}$ He^{+}/cm^{2}	$1x10^{18}$ He^{+}/cm^{2}
Mass Loss (2 g sample)	4.2±0.1 mg	3.6±0.1 mg	0.5±0.1 mg
Thickness Loss (Uniform)	1.1±0.03 μm	0.93±0.03 μm	0.13±0.03 μm

Table 1: Mass loss for pulsed samples (1 ms pulse width, 25 Hz, 1150 °C)

One possible explanation for the higher-than-expected could be increased sputtering coefficients for non-perpendicular ion incidences. However, this would not increase the physical sputtering loss enough to account for the observed mass loss, even assuming the forward-sputtered material is not re-deposited on the sample.[10] Another possible explanation is the loss of the small protrusions during the irradiation process.

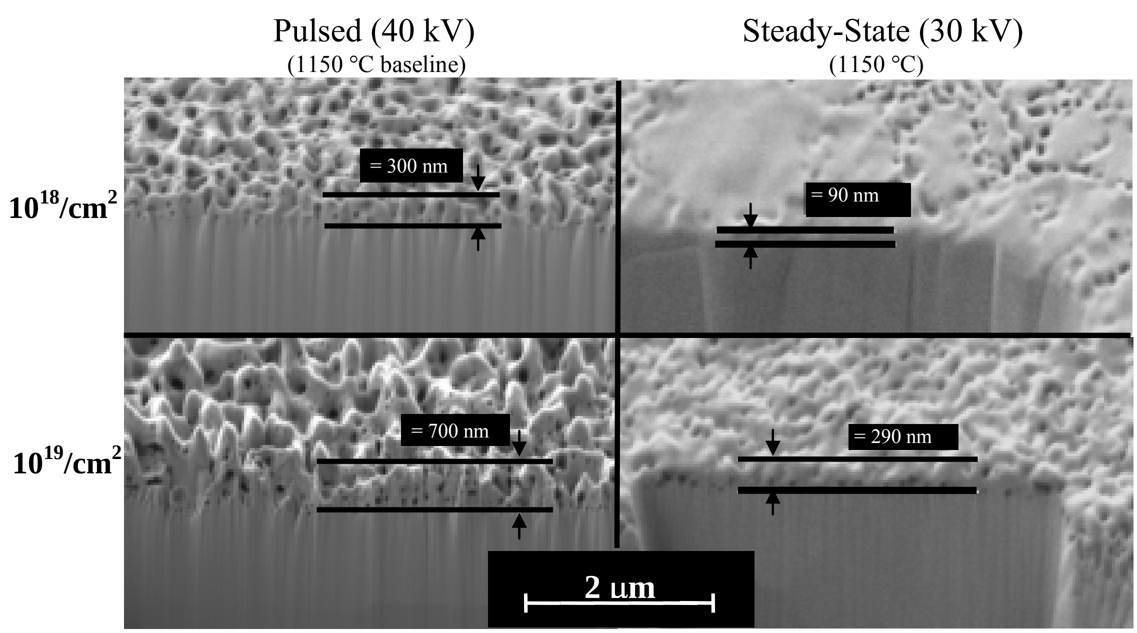


Fig. 10: Focused Ion Beam (FIB) Images of Tungsten Irradiated with Pulsed and Steady-State Helium Currents

IV. CONCLUSIONS

The Inertial Electrostatic Confinement (IEC) fusion device at the University of Wisconsin is now able to perform both steady-state and pulsed irradiation experiments. This device is capable of generating 0.2-2 ms D^+ or He^+ pulses of up to 1 ampere at 10 Hz.

Pulsed helium implantation of polycrystalline tungsten was performed at 1150 °C using the Wisconsin IEC device. Fluences of $1x10^{18}$, $6x10^{18}$, and $1x10^{19}$ He^+/cm^2 were delivered to the samples in 1 ms pulses at 25 Hz. Micrographs of these samples revealed increased surface damage at all fluences compared to steady-state irradiation. At $1x10^{18}$ $He+/cm^2$, the steady-state sample only exhibits pores collecting at grain boundaries with a pore density of $1.2x10^9$ pores/cm^2, while the pulsed sample appears close to a saturation density with larger pore size.

When the steady-state implanted helium fluence was increased to $1x10^{19}$ He^+/cm^2 at 1150 °C, the pore density decreased slightly to $1.9x10^9$ pores/cm^2. The pulsed sample, however, has been damaged to the point of having a coral-like structure form in addition to the uniform pore density covering the surface.

Tungsten samples pulsed at 1150 °C at fluences ranging from 10^{18}-10^{19} He^+/cm^2 experienced a measurable change in mass. Theoretical calculations based on physical sputtering rates predict that a tungsten sample would loose ~0.2 mg after 10^{19} He^+/cm^2. However, the sample actually lost 4.2 mg, or roughly 1.1 μm uniformly from the surface, suggesting that other mechanisms of mass loss must be taking place.

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