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Synergistic effects
alteration of Tungsten's thermal properties under simultaneous laser and plasma exposure

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Synergistic effects
Alteration of Tungsten’s thermal properties under simultaneous Laser and Plasma exposure

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May 9, 2014
Preface

This project was conducted at the FOM DIFFER institute in Nieuwegein under supervision of dr. ir. G.C. De Temmerman and prof. dr. N.J. Lopes Cardozo, in the context of plasma surface interaction for fusion purposes. During the graduation project of G.G. van Eden, it occurred that the temperature peaks of tungsten exposed to a steady plasma stream and a pulsed laser would steadily increase over time. One suggested hypothesis was that the plasma exposure combined with the pulsed laser would induce a synergistic effect, altering tungsten’s thermal properties, but without an internal phase transition. This project was conducted to test this hypothesis, by exposing tungsten samples to several plasma conditions.
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Chapter 1

Introduction

1.1 Nuclear Fusion

Our society is highly dependent on a constant supply of electricity. Most contemporary supplies are based on the burning of fossil fuels, such as oil, gas and coal. Such energy sources are not infinite. To secure future supply of energy, many alternative energy sources are being investigated and improved. One such source of energy is nuclear fusion, wherein energy is extracted via the fusing of the light hydrogen isotopes deuterium and tritium, resulting in helium. Fusion, however, only occurs under extreme pressures and temperatures, and we know of no material capable of confining gas under such extreme conditions.

The current method of confining the fuel for fusion energy is a magnetic device known as a Tokamak. Rather than confining hot, neutral gas, the deuterium and tritium fuels are turned into plasma: ionized gas. As ions are electrically charged particles, it can be affected by electromagnetic fields. This allows for a way to confine the fuels via non-material means. A Tokamak is a device which uses powerful magnetic fields to confine the plasma into a toroidal shape. Eventually, the plasma particles, electrons, deuterium, tritium and helium ions, will diffuse out of the confinement area into a region known as the scrape-off layer. At the end of the scrape-off layer, these particles collide with the divertor. The divertor is a device, generally consisting of a plasma facing surface, made of strongly heat resistant material and coolant pipes embedded in the material. When the plasma strikes the divertor, it and the coolant are heated, extracting energy out of the Tokamak.

Figure 1.1: A 3D render of ITER’s divertor system
1.2 Divertor Load

As it is constantly subjected to extremely hot plasma, the divertor must be able to withstand a continuous high heat flux. The heat flux onto the divertor is estimated to be of the order of $1 \text{ GWm}^{-2}$. Few materials are able to withstand such loads. Current designs mostly incorporate carbon fibre composites in the main strike region, and tungsten on the baffles. These materials are chosen for their high thermal conductivity and in the case of tungsten, melting temperature. CFC does not melt, but it sublimes at an extremely high temperature. A lot of R&D is devoted to developing a divertor configuration that can weather these loads[3]. Even so, there are several methods planned to reduce the heat load on the divertor: injection of neutral gas or ablation pellets near the divertor region to cool the incident plasma, or modulate the magnetic field, so the plasma "scans" the surface of the divertor, rather than strike the same region continuously.

The continuous flow of plasma is not the only load on the divertor. In Tokamaks operating in high-confinement mode, a large pressure gradient develops over time across the separatrix, the edge of the confinement region. When the gradient reaches a critical value, a large amount of plasma is periodically expelled from confinement into the scrape-off layer, to relieve the pressure. As a result, the divertor is subjected to a momentary increase in the incident heat and particle fluxes. These events are called Edge Localized modes (ELMs). ELMs have been categorized into three types: type 1 ELMs are comparatively high in energy and particle content; type 3 ELMs have the least energy and particle content per event, but occur very frequently; type 2 ELMs are an intermediate between these two.

1.3 Synergistic Effects

The interplay between the steady state plasma of the scrape-off layer and the transient ELM events of materials are cause of amplified erosion effects, called synergistic effects. In the development of divertor materials, the occurrence of these synergistic erosion effects has been well documented [2] [4]. Such effect can greatly diminish the functional lifetime of a divertor. Recently, other synergistic effects were noted[5]. During combined steady state plasma and pulsed laser exposure, the temperature of the tungsten targets due to the laser pulse increased during exposure. It was postulated that the thermal properties of tungsten are somehow altered during simultaneous steady state and transient heat loads. If this is indeed the case, these effects will have great consequences for divertor lifetime. It is likely that due to these changes, the divertor will deteriorate much faster than it was designed to do. To properly incorporate these effects into future divertor design, it is imperative that the relation between these effects and the properties of the plasma are explored.

4
1.4 Problem Statement

For this internship, we inspected the properties of tungsten by exposing a selec-
tion of samples to simultaneous steady-state plasma and a pulsed laser. The pulsed laser serving as a stand-in for ELMs. The central problem statement is as follows:

Are the thermal properties of tungsten changed in any way during simultaneous steady state and transient exposure? Which properties are altered?

- Thermal conductivity
- Diffusivity

What is the relation between the changes and the properties of the plasma and laser the samples were exposed to?

- Steady state particle flux
- Plasma temperature
- Target Bias
- Laser pulse length
- Laser repetition frequency
Chapter 2

Theory

2.1 Tungsten properties

Tungsten is a hard metal. Its melting temperature lies at 3695 K, or 3442 °C. The thermal conductivity at standard temperature and pressure is \( k = 173 \text{ W m}^{-1} \text{K}^{-1} \), the density is \( \rho = 19.25 \cdot 10^3 \text{ kg m}^{-3} \) and the specific heat capacity at constant pressure is \( c_p = 132 \text{ J kg}^{-1} \text{K}^{-1} \). As such, the diffusivity is \( \alpha = \frac{k}{\rho c_p} = 6.808 \cdot 10^{-5} \text{ m}^2 \text{s}^{-1} \). However, the thermal conductivity changes as a function of the bulk temperature. The density is also altered due to thermal expansion. However, since the thermal expansion coefficient of tungsten is only \( \alpha_L = 4.5 \mu \text{m m}^{-1} \text{K}^{-1} \), the changes to density are considered negligible.

2.2 Thermal Conduction

2.2.1 Macroscopic Conduction

On the macroscopic scale, all time-dependent temperature and heat distributions within a single medium can be expressed as a solution to the general heat equation:

\[
\frac{\partial u}{\partial t} - \alpha \nabla^2 u
\]  

(2.1)

Herein, \( u \) is the time-dependent temperature profile, and \( \alpha \) the diffusivity. The diffusivity is defined as follows:

\[
\alpha = \frac{k}{\rho c_p}
\]  

(2.2)

The effects of plasma which can alter the properties of exposed material are varied: impurity interstitials, vacancies and other lattice defects and outright recrystallization caused by plasma interacting with a material change the material's properties through additional points for umklapp processes, altered sound speed within the material. As a result, thermal conductivity, specific heat and diffusivity are changed during plasma exposure. These thermal properties cannot be measured directly, and must be inferred from known and measurable...
conditions, such as the temperature profile and incident heat flux. Through Function 2.1, it is possible to create a prediction on the conduction of heat, in exposed material. The heat equation can be solved via separation of variables, a technique introduced by Fourier[1]. This shows that any unsustainable distributions decay exponentially.

\[
u(\vec{r}, t) = R(\vec{r})\Gamma(t)
\]

\[
\frac{\dot{\Gamma}}{\alpha \Gamma} = \nabla^2 \frac{R}{R} = -\lambda
\]

\[
\Gamma(t) = e^{-\alpha \lambda t}
\]

Herein, \( R(\vec{r}) \) is the spacial part, \( \Gamma(t) \) is the time dependant part and \( \lambda \) is a geometrical constant of unit \( m^{-2} \). This constant relates to the spacial solution \( R \), and by extension to the problem geometry. I assumed the \( \lambda \) of each tested sample would remain constant during experimentation. Conduction is not the only cooling. Sufficiently heated targets will also radiate a significant amount heat. The total radiative power can be expressed in the form of Planck’s Law, and the Stefan-Boltzmann Law.

\[
I(\omega, T) = \frac{2\hbar\omega^3}{c^2} \frac{1}{e^{\frac{kT}{\hbar\omega}} - 1}
\]

\[
P = A\epsilon \sigma T^4
\]

In Planck’s Law, \( I \) is the radiated power per surface area, along the normal of the radiative surface, per solid angle per frequency, \( \omega \) the frequency of the emitted radiation, \( c \) is light speed, \( k \) the Boltzmann constant. In the Stefan-Boltzmann Law, \( P \) is the total radiated power, \( A \) the total radiative surface, \( \epsilon \) the emissivity and \( \sigma \) the Stefan-Boltzmann constant. Using Equation 2.5 to express temperature as a function of time, taking radiation as the only cooling method, yields the following equation:

\[
P = -\frac{\partial Q}{\partial t} = -mc_{p,v} \frac{\partial T}{\partial t}
\]

\[
T = (T_0^{-3} + \frac{3A\epsilon \sigma}{mc_{p,v}} t)^{-1/3}
\]

Steady-state heat flow and temperature profiles, such as via imposed heat fluxes, can be expressed via Fourier’s law of thermal conduction.

\[
\vec{q} = -k \nabla u
\]

\[
q = \frac{T_a - T_b}{\frac{x_a}{k_a} + \frac{x_b}{k_b}}
\]

Herein, \( T_a \) and \( T_b \) are the temperatures of medium a and b, away from the contact interface, \( x_a \) and \( x_b \) the spacial coordinates where these temperatures were taken, \( k_a \) and \( k_b \) the thermal conductivities of these media, \( h_c \) the thermal contact conductance coefficient and \( A \) is the surface area of the interface. Another important aspect to consider in the heat penetration depth of of the laser. This scales with the square root of the exposure time and the diffusivity, as follows:

\[
\delta = \sqrt{8\alpha t}
\]
2.2.2 Microscopic Conduction

Although this experiment mainly investigates macroscopic properties, it is likely that microscopic processes are in effect when the incident ions interact with the surface. On the microscopic scale, heat conduction in crystalline materials occurs through phonons: quanta of lattice vibrations. The thermal conductivity is approximated as follows:

\[ k = \frac{1}{3} C v l \]  

(2.10)

Herein, \( C \) is the phonon heat capacity, \( v \) the phonon velocity, which is the sound speed of the respective medium for acoustic phonons and \( l \) is the mean free path of phonons. The mean free path is the limiting factor in the conductivity. In an ideal lattice with purely harmonic vibrations, the mean free path would be infinite, but this is not the case. Lattice vibrations are not purely harmonic and the lattice is not ideal and as such, numerous phonon interactions occur. Phonons will scatter off of lattice imperfections, such as interstitials, voids, grain boundaries and off one another, occasionally resulting in an umklapp process: a three-phonon collision, where the post-collision direction of travel is inverted along one of the lattice axes. It is possible that these synergistic effects interfere with these processes, shortening the mean free path.

2.3 Plasma Surface Interactions

The heat flux onto the targets comes from plasma particles hitting the target. The electron flux that manages to penetrate the sheath and reach the surface is as follows:

\[ \Gamma_{se} = n_{se} v_{se} = n_0 c_s \]  

(2.11)

Herein, \( n_{se} \) is the electron density at the material surface, and \( v_{se} \) the electron velocity. Next, \( n_0 \) is the electron density in the plasma bulk, and \( c_s \) is the sound speed in the plasma. Sound speed is taken to be as follows:

\[ c_s = \sqrt{\frac{k T_e + \gamma k T_i}{m_i}} \]  

(2.12)

Herein, \( k \) is the Boltzmann constant, \( \gamma \) is the adiabatic coefficient, \( T_e \) and \( T_i \) are the electron and ion temperatures, respectively, and \( m_i \) is the ion mass. The heat fluxes due to electrons and ions is as follows:

\[ q_e = 2k T_e \Gamma_{se} \]  

(2.13)

\[ q_i = (2k T_i + 3k T_e) \Gamma_{se} \]  

(2.14)
Chapter 3

Experiment

3.1 Overview

In this experiment, we exposed a collection of tungsten samples to plasma in the linear plasma device Magnum-PSI in combination with a pulsed laser. As such, the targets are exposed to divertor-like plasma. The pulsed laser serves to simulate the increased heatflux during an ELM event. Magnum-PSI can be equipped with pulsed plasma sources, which gives a more close approximation to ELM properties. However, the square time profile of the laser gives much more control over the increased heat flux. Additionally, the analysis of a square profile is much more simpler.

3.2 Equipment and materials

3.2.1 Magnum PSI

Magnum-PSI is a linear plasma device, wherein a cascaded arc source generates a plasma, which is confined in a beam via a set of magnetic coils. Originally, Magnum was designed with superconducting magnets, but at the time of the experiment, Magnum was still outfitted with non-superconductive magnets. Figure 3.1 shows a cross-section of Magnum, with the yet-to-be installed super-
Magnum consists of several chambers, which can be sealed and vented individually. Exchange and rotation of targets occurs in the Target Exchange and Analyses Chamber (TEAC). The TEAC can be sealed from the rest of the device, negating the need to aerate and pump the whole device whenever new targets are to be mounted. The samples are mounted on a rotational multi-target holder, shown in Figure 3.2. Targets are mounted via a clamping ring, which holds the targets in place. In between the copper contact surface of the target holder and the tungsten samples, one or two layers of grafoil are inserted. This ensures that the tungsten is properly secured and good thermal contact is made with the copper surface. During the experiment, there were three (3) targets mounted on the holder. Figure 3.3 shows a cross-section of the target chamber. The target holder is moved into the chamber by moving the target manipulator into the device. Likewise, the plasma source is mounted on a manipulator to allow for easy removal. The skimmers are diaphragms,
which are meant to reduce the amount of neutral particles reaching the target. As Magnum has yet to be outfitted with a superconducting magnet, it was equipped with four (4) non-superconducting, oil-cooled magnetic coils. The target chamber is outfitted with several diagnostics ports. During this experiment, the transmission of the viewports was around 71%.

3.2.2 Diagnostics

Magnum-PSI has a number of available plasma diagnostics methods. For this experiment, two diagnostics were used.

- **Incoherent Thomson Scattering**: with TS, the electron temperature and density within the plasma beam were measured near the target. The laser used emits pulses of 10 ns, with an output of at most 2 J. The wavelengths are within a range of [190, 1064] nm. Figure 3.4 shows the general set-up of the TS diagnostics system.

- **Fast Infrared camera**: A fast IR camera (FLIR SC7500MB) was set up at one of the diagnostics ports. With this, the IR emissions of the sample were recorded. By using an in-house IDL program, the temperature of the sample at its hottest point could be determined. The settings for the camera are denoted in Table 3.1.

Figure 3.4: Set-up of the Thomson Scattering diagnostics
Table 3.1: Summary of relevant information of the IR-camera used

<table>
<thead>
<tr>
<th>Camera</th>
<th>Radiometric data</th>
<th>Windowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Jade</td>
<td>Calibration None</td>
</tr>
<tr>
<td>Serial number</td>
<td>202205</td>
<td>Emissivity 0.10</td>
</tr>
<tr>
<td>Frame rate</td>
<td>5599.1 Hz</td>
<td>Background temperature 20°C</td>
</tr>
<tr>
<td>Integration time</td>
<td>165 μs</td>
<td>Transmission 71%</td>
</tr>
<tr>
<td>Aperture</td>
<td>F/2.0</td>
<td>Atmosphere temperature 20°C</td>
</tr>
<tr>
<td>Filter</td>
<td>NA 3.97-4.01 060%</td>
<td>Distance 0.66 m</td>
</tr>
<tr>
<td>Orion</td>
<td>No FPA Temperature -198.6°C</td>
<td>Housing temperature 31.7°C</td>
</tr>
</tbody>
</table>

3.2.3 Tungsten Targets

For this experiment, a total of thirteen (13) tungsten discs were ground and polished to a mirror shine and subsequently degassed and annealed. The targets are thirty (30) mm in diameter. Due to problems during the grinding process, some targets had to be ground for a longer time, resulting in disparity in target thickness. The thickness of the targets by their number is as follows:

Table 3.2: Thickness of tungsten discs

<table>
<thead>
<tr>
<th>Target number</th>
<th>Thickness</th>
<th>Target number</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.85 mm</td>
<td>7</td>
<td>0.95 mm</td>
</tr>
<tr>
<td>2</td>
<td>0.90 mm</td>
<td>8</td>
<td>0.90 mm</td>
</tr>
<tr>
<td>3</td>
<td>0.85 mm</td>
<td>9</td>
<td>0.80 mm</td>
</tr>
<tr>
<td>4</td>
<td>0.80 mm</td>
<td>10</td>
<td>0.75 mm</td>
</tr>
<tr>
<td>5</td>
<td>0.80 mm</td>
<td>11</td>
<td>0.75 mm</td>
</tr>
<tr>
<td>6</td>
<td>0.90 mm</td>
<td>12</td>
<td>0.85 mm</td>
</tr>
<tr>
<td>r</td>
<td>0.70 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Of these targets, r was kept as a reserve. It was eventually called upon to replace target nr. 4, after it was deformed due to improper clamping.
3.3 Experimental Procedure

3.3.1 Measurement parameters

To investigate alterations in the targets’ thermal properties, they were exposed in Magnum to both steady-state plasma and a pulsed laser. The plasma and laser parameters were subject to a base set of values, except for the altered parameters, to improve comparability. These base settings are as follows:

Table 3.3: Base settings for the plasma source and LASAG

<table>
<thead>
<tr>
<th>Plasma</th>
<th>LASAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Flow</td>
<td>Laser energy per pulse</td>
</tr>
<tr>
<td></td>
<td>5 Pa·m³s⁻¹</td>
</tr>
<tr>
<td>Source Current</td>
<td>Laser repetition frequency</td>
</tr>
<tr>
<td>Magnum Magnet setting</td>
<td>170 A</td>
</tr>
<tr>
<td></td>
<td>10 Hz</td>
</tr>
<tr>
<td>Target bias</td>
<td>Number of pulses</td>
</tr>
<tr>
<td></td>
<td>0 V</td>
</tr>
<tr>
<td>Shot duration</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>1.1 s</td>
</tr>
</tbody>
</table>

Camera settings for this experiment were kept constant. Settings and other properties of the camera can be viewed in Appendix B. The settings that were altered are as follows:

Table 3.4: Adjusted settings

<table>
<thead>
<tr>
<th>Setting</th>
<th>range</th>
<th>Additional bias</th>
<th>Bias magnitude</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source current</td>
<td>[170:190] A</td>
<td>with and without</td>
<td>39±0.5 V</td>
<td></td>
</tr>
<tr>
<td>Bias</td>
<td>[-17:-39.7] V</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Laser Energy</td>
<td>[0:15.5] J</td>
<td>no bias</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>[10:60] Hz</td>
<td>With and without</td>
<td>39.5±0.5 V</td>
<td>Laser energy kept low at 1.01 J,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>to prevent excessive heating at higher</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>frequencies</td>
</tr>
<tr>
<td>Gas flow</td>
<td>[5:6.5] Pa</td>
<td>no bias</td>
<td>n/a</td>
<td>Earlier measurement attempted with high</td>
</tr>
<tr>
<td></td>
<td>m³·s⁻¹</td>
<td></td>
<td></td>
<td>source current and decreasing flow.</td>
</tr>
</tbody>
</table>

Source Current and Gas flow

The source current was increased with a relatively high constant flow. As such, with increasing current, the particle flux increased as the ionization in the source increases, whilst the plasma temperature remains roughly constant. By altering the source current, the effect of particle flux was investigated. By keeping the source current constant and altering the gas flow, the particle flux remains constant, but the plasma temperature is changed. By changing the gas flow, the effect of the energy of incident particles was investigated.
Bias
With increasingly negative bias, the amount of electrons incapable of passing through the plasma sheath and colliding with the surface decreases. The amount of incident ions remains unaltered, but they collide with higher energy.

Laser energy and repetition frequency
ELM’s cover a range of frequencies and energy content. By inspecting these two properties, the effects on thermal properties from either high-energy or high-frequency spikes were compared.

3.3.2 Measurement
During exposure, the samples were heated sufficiently to emit infrared radiation. Using the fast IR-camera, videos were made of the samples’ IR emissions during each shot. Properties and settings of the camera can be seen in Table 3.1. Plasma electron density and temperature were measured with Thomson scattering.

Figure 3.5 shows a frame during shot 58, which was part of a set of shots in preparation for the Laser repetition frequency sweep. The image is a frame at the time of a Laser pulse. The strike region is clearly visible as a bright spot. The area stuck by the core of the plasma beam is also visible, as a less bright spot. As can be seen, the Laser and plasma were not completely aligned, though they are close to each other. This alignment was kept during the entirety of the experiment, as to preserve comparability between measurements and reduce the amount of shots needed for realignment.

3.4 Analysis
The videos made by the camera are of the IR emissions of the target. Via the use of an in-house IDL program, the emission of the brightest spot on the target was used to calculate the local temperature, and plotted against time. The thermal conductivity of Tungsten during a shot was inferred using the equations for thermal conduction and plasma heatflux: Equations 2.7, 2.8, 2.13 and 2.14. By summing Equations 2.13 and 2.14, the incident heat flux density was calculated. Here, it was assumed that the ion temperature was negligible compared to that of the electrons. This heat flux density was taken
to be equal to the heat flux density inside the target, to ensure a steady state situation. Two methods were attempted to calculate the conductivity. The first was the most simple and direct one, using Fourier’s equation for heat conduction in Equation 2.7. From this the conductivity becomes:

$$k = -\frac{q}{\nabla T}$$

The temperature gradient was assumed constant along the thickness of the sample, and equal to the temperature difference between the two faces and divided by the sample’s thickness. The temperature of the exposed face was determined by forcing a horizontal fit on the pseudo-stable area of the exposure. This is illustrated in Figure 3.6, which is a time plot of shot 53. However the temperature of the substrate face of the sample could not be determined. As an alternative, the substrate face’s temperature was equaled to the coolant’s temperature, which was assumed to be 20°C. This estimate is grossly incorrect. The substrate face is not in direct contact with the coolant, and the heat is conducted across several materials. As such, the temperature of the substrate face is dependent on the thickness of the sample and the thickness and conductivity of the materials separating the sample and the coolant.

The second method was to use the coolant’s temperature, and take the different materials conducting the heat into account. Here, we use Equation 2.8, which details the effect of heat being conducted across a contact interface. However, the thermal conductivity of grafoil was not known, and neither were the thickness of the copper plate separating the coolant and the grafoil, nor the contact conductance coefficients between the tungsten and the grafoil or between the grafoil and copper. As such, no information could be gained from this approach either. As such, I used the earlier method with a fixed temperature at the substrate face, to at least have an estimate.

![Figure 3.6: The highest temperature of sample nr. 5 during exposure 53, plotted against time. A horizontal fit was forced on the plateau](image)
To inspect the time constant for the decay, one temperature peak was taken out of every shot, around four (4) to seconds (8) seconds into the shot. To get an indication of the behavior, the peaks were rescaled into a logarithmic plot, after subtracting a base temperature. From Equation 2.3, I assumed that the solution would be an infinite series of exponentials, due to the presence of a spacial constant in the exponential, related to the spacial solution. In the logarithmic scale, it is clear that there are only two significant domains: a very steep decay just after the peak laser pulse ends, and a shallow tail. The transition between the domains is very smooth, as can be seen in Figure 3.7.

![Figure 3.7: Time plot of a peak in shot 83, in logarithmic scale. The two domains and the gradual transition can be clearly seen. The graph also shows the fit used to determine the decay constant in the tail.](image)

The decay constants were determined by fitting a sum of two exponential decays over one decay period. The first point selected in this range is not highest temperature point. Because the camera is not infinitely fast, it is unlikely the end of a laser pulse is actually recorded. More than likely it falls between two frames. As such, the highest value point could be during the laser pulse, rather than after it. Therefor, the next highest point was taken as the start for the fitting domain.
4.1 Thermal Conductivity

The resulting conductivities for tungsten are noted in Table 4.1 and Figure 4.1. The "with and without laser" indicates whether the time averaged heat flux of the laser was incorporated in the total incident heat flux. As was noted before, it is unlikely anything can be gleaned from these results.

As can be seen, no data regarding the supposed conductivity is plotted for measurements involving bias. During measurement, rather than settle at a steady state surface temperature, targets with a sufficiently large bias imposed had a steadily increasing surface temperature. Since no steady state is reached, this would imply that either the incident heat flux is so high, it takes significant more time to establish a steady state, or the heat flux increases over time. The first option is very unlikely, as the broadening of the beam lowers the heat flux, thus decreasing the heat flux density. Regarding the second option, while ions would collide with the surface with more energy, due to the bias, the number of electrons reaching the surface will diminish as lower energetic electrons cannot surmount the additional bias. Moreover, the increase in energy of the ions is entirely dependent on the bias, not on time. Even so, with a constantly increasing surface temperature, it is not possible to determine the conductivity.
Table 4.1: Conductivities of tungsten, under different plasma exposures, rounded to 3 significant numbers.

<table>
<thead>
<tr>
<th>Varied quantity</th>
<th>Value</th>
<th>Conductivity</th>
<th>Error</th>
<th>Conductivity with laser subtracted</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas flow (P_a \cdot m^4 s^{-1})</td>
<td>5</td>
<td>0.753</td>
<td>2.540 \times 10^{-2}</td>
<td>0.753</td>
<td>2.54 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.738</td>
<td>2.43 \times 10^{-2}</td>
<td>0.738</td>
<td>2.43 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>0.564</td>
<td>2.00 \times 10^{-2}</td>
<td>0.564</td>
<td>2.00 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>5.6</td>
<td>0.573</td>
<td>2.25 \times 10^{-2}</td>
<td>0.573</td>
<td>2.25 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>5.9</td>
<td>0.538</td>
<td>2.31 \times 10^{-2}</td>
<td>0.538</td>
<td>2.31 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>6.2</td>
<td>0.675</td>
<td>3.14 \times 10^{-2}</td>
<td>0.675</td>
<td>3.14 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>0.266</td>
<td>1.34 \times 10^{-2}</td>
<td>0.266</td>
<td>1.34 \times 10^{-2}</td>
</tr>
<tr>
<td>Source Current A</td>
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<td>0.296</td>
<td>1.04 \times 10^{-2}</td>
<td>0.296</td>
<td>1.04 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>0.295</td>
<td>9.29 \times 10^{-3}</td>
<td>0.295</td>
<td>9.29 \times 10^{-3}</td>
</tr>
<tr>
<td></td>
<td>190</td>
<td>0.382</td>
<td>1.08 \times 10^{-2}</td>
<td>0.382</td>
<td>1.08 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>0.338</td>
<td>1.04 \times 10^{-2}</td>
<td>0.338</td>
<td>1.04 \times 10^{-2}</td>
</tr>
<tr>
<td>Pulse frequency, without bias (H_z)</td>
<td>10</td>
<td>0.748</td>
<td>2.78 \times 10^{-2}</td>
<td>0.748</td>
<td>2.78 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.690</td>
<td>2.54 \times 10^{-2}</td>
<td>0.690</td>
<td>2.54 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0.695</td>
<td>2.59 \times 10^{-2}</td>
<td>0.695</td>
<td>2.59 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>0.526</td>
<td>1.94 \times 10^{-2}</td>
<td>0.526</td>
<td>1.94 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.625</td>
<td>2.25 \times 10^{-2}</td>
<td>0.624</td>
<td>2.25 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.570</td>
<td>2.05 \times 10^{-2}</td>
<td>0.570</td>
<td>2.05 \times 10^{-2}</td>
</tr>
<tr>
<td>Pulse energy (J)</td>
<td>3.03</td>
<td>0.535</td>
<td>1.94 \times 10^{-2}</td>
<td>0.535</td>
<td>1.94 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>6.06</td>
<td>0.476</td>
<td>1.69 \times 10^{-2}</td>
<td>0.476</td>
<td>1.69 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>9.1</td>
<td>0.504</td>
<td>1.78 \times 10^{-2}</td>
<td>0.504</td>
<td>1.78 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>12.1</td>
<td>0.510</td>
<td>1.79 \times 10^{-2}</td>
<td>0.510</td>
<td>1.79 \times 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>15.2</td>
<td>0.385</td>
<td>1.32 \times 10^{-2}</td>
<td>0.385</td>
<td>1.32 \times 10^{-2}</td>
</tr>
</tbody>
</table>

4.2 Diffusivity

The resulting decay constants are noted in Table 4.2 and Figures 4.2 and 4.3. In Figures 4.2c, 4.2d, 4.2e, 4.2f, 4.3a and 4.3b, there is a clear dependence of the decay constant on the varied input parameter. This goes for both the decay immediately after the peak, and in the tail of the decay. In 4.2f and 4.3b, both decay constants look to be directly proportional to their respective input parameter. In both Figures 4.2e and 4.3a, the time constant increases for increasing values of pulse energy and bias, followed by a sharp decrease. It is likely this decrease comes from a recrystallization. Regarding the bias, as was noted in Section 4.1, the base temperature of the sample slowly increases the base temperature during the exposure. The increase in base temperature is very small however on the timescale of a single peak. While there seems to be a clear relation between the source current and decay times in Figures 4.2c and 4.2d, there are not enough data points to make any reasonable inference.

In Figure 4.3d, there is a data point missing, compared to Figure 4.3e. the decay constant resulting from the fit was several degrees of magnitude higher than the others, and similar high uncertainty. Similar results can be seen in Figures 4.3c.
Figure 4.1: Plots of calculated values of tungsten’s thermal conductivity for the alteration of several plasma and laser properties and 4.3f. Likely, this stems from the low pulse energy during these exposures. Due to the low raise in temperature, the pseudo-steady-state is reached more quickly. On this scale, the time resolution is likely insufficient for accurate measurements. With the lower peak temperature, the noise in the measurement becomes much more prevalent. It is likely that the large spread in data points and large errors comes from the noise and the low time resolution.
Table 4.2: Resulting decay constants, rounded to three significant numbers

<table>
<thead>
<tr>
<th>Varied quantity</th>
<th>Value</th>
<th>Decay constant in the tail</th>
<th>Error</th>
<th>Decay constant near the peak</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas flow $Pa\cdot m^4s^{-1}$</td>
<td>5.0</td>
<td>2.41⋅10^{-2}</td>
<td>7.43⋅10^{-4}</td>
<td>8.81⋅10^{-4}</td>
<td>1.56⋅10^{-5}</td>
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<td>5.3</td>
<td>2.63⋅10^{-2}</td>
<td>7.09⋅10^{-4}</td>
<td>1.16⋅10^{-3}</td>
<td>1.68⋅10^{-5}</td>
</tr>
<tr>
<td></td>
<td>5.6</td>
<td>2.30⋅10^{-2}</td>
<td>8.75⋅10^{-4}</td>
<td>8.75⋅10^{-4}</td>
<td>1.70⋅10^{-5}</td>
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<tr>
<td></td>
<td>5.9</td>
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<td>7.18⋅10^{-4}</td>
<td>9.33⋅10^{-4}</td>
<td>1.92⋅10^{-5}</td>
</tr>
<tr>
<td></td>
<td>6.2</td>
<td>2.33⋅10^{-2}</td>
<td>6.63⋅10^{-4}</td>
<td>1.287⋅10^{-3}</td>
<td>2.036⋅10^{-5}</td>
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<td>5.59⋅10^{-4}</td>
<td>1.31⋅10^{-3}</td>
<td>2.04⋅10^{-5}</td>
</tr>
<tr>
<td>Source Current $A$</td>
<td>170</td>
<td>2.16⋅10^{-2}</td>
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<td>8.89⋅10^{-4}</td>
<td>1.67⋅10^{-5}</td>
</tr>
<tr>
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<td>1.29⋅10^{-3}</td>
<td>1.94⋅10^{-5}</td>
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<tr>
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<td>5.12⋅10^{-4}</td>
<td>1.04⋅10^{-4}</td>
<td>1.78⋅10^{-5}</td>
</tr>
<tr>
<td>Pulse frequency, without bias $H_z$</td>
<td>20</td>
<td>4.35⋅10^{-3}</td>
<td>8.94⋅10^{-4}</td>
<td>2.99⋅10^{-4}</td>
<td>3.87⋅10^{-5}</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>5.64⋅10^{-3}</td>
<td>1.04⋅10^{-3}</td>
<td>2.65⋅10^{-4}</td>
<td>2.77⋅10^{-5}</td>
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<tr>
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<td>3.42⋅10^{-3}</td>
<td>4.14⋅10^{-4}</td>
<td>1.97⋅10^{-4}</td>
<td>2.85⋅10^{-5}</td>
</tr>
<tr>
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<td>2.01⋅10^{-3}</td>
<td>4.36⋅10^{-4}</td>
<td>4.00⋅10^{-5}</td>
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<tr>
<td></td>
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<td>1.12⋅10^{-2}</td>
<td>2.43⋅10^{-3}</td>
<td>3.55⋅10^{-4}</td>
<td>2.25⋅10^{-5}</td>
</tr>
<tr>
<td>Pulse frequency, with bias $H_z$</td>
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<td>9.58⋅10^{-4}</td>
<td>2.11⋅10^{-4}</td>
<td>4.69⋅10^{-5}</td>
</tr>
<tr>
<td></td>
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<td>5.46⋅10^{-4}</td>
<td>2.76⋅10^{-5}</td>
</tr>
<tr>
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<td>5.85⋅10^{-4}</td>
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<td>2.19⋅10^{-5}</td>
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<tr>
<td></td>
<td>40</td>
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<td>7.80⋅10^{-5}</td>
<td>3.51⋅10^{-4}</td>
<td>7.80⋅10^{-5}</td>
</tr>
<tr>
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<td>9.03⋅10^{-3}</td>
<td>7.02⋅10^{-5}</td>
<td>4.73⋅10^{-4}</td>
<td>5.14⋅10^{-5}</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>2.16⋅10^{-3}</td>
<td>5.09⋅10^{-4}</td>
<td>2.64⋅10^{-4}</td>
<td>2.97⋅10^{-5}</td>
</tr>
<tr>
<td>Target Bias $V$</td>
<td>-17</td>
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<td>6.35⋅10^{-4}</td>
<td>9.65⋅10^{-4}</td>
<td>1.52⋅10^{-5}</td>
</tr>
<tr>
<td></td>
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<td>2.81⋅10^{-2}</td>
<td>8.48⋅10^{-4}</td>
<td>1.10⋅10^{-3}</td>
<td>1.61⋅10^{-5}</td>
</tr>
<tr>
<td></td>
<td>-26</td>
<td>2.01⋅10^{-2}</td>
<td>5.81⋅10^{-4}</td>
<td>1.15⋅10^{-3}</td>
<td>1.85⋅10^{-5}</td>
</tr>
<tr>
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<td>-32</td>
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<td>9.96⋅10^{-4}</td>
<td>1.85⋅10^{-5}</td>
</tr>
<tr>
<td></td>
<td>-39.7</td>
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<td>3.68⋅10^{-4}</td>
<td>7.37⋅10^{-4}</td>
<td>1.51⋅10^{-5}</td>
</tr>
<tr>
<td>Pulse energy $J$</td>
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<td>3.47⋅10^{-2}</td>
<td>2.47⋅10^{-3}</td>
<td>5.86⋅10^{-4}</td>
<td>1.08⋅10^{-5}</td>
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<tr>
<td></td>
<td>6.06</td>
<td>2.98⋅10^{-2}</td>
<td>1.57⋅10^{-3}</td>
<td>8.01⋅10^{-4}</td>
<td>1.40⋅10^{-4}</td>
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<tr>
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<td>9.1</td>
<td>2.34⋅10^{-2}</td>
<td>6.87⋅10^{-4}</td>
<td>1.08⋅10^{-3}</td>
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<td>7.07⋅10^{-4}</td>
<td>1.19⋅10^{-3}</td>
<td>1.68⋅10^{-5}</td>
</tr>
<tr>
<td></td>
<td>15.2</td>
<td>2.40⋅10^{-2}</td>
<td>4.57⋅10^{-4}</td>
<td>8.08⋅10^{-4}</td>
<td>1.50⋅10^{-5}</td>
</tr>
</tbody>
</table>
(a) The decay constant plotted against the gas flow to the plasma source, after the laser pulse.

(b) The decay constant plotted against the gas flow to the plasma source, at the end of the decay.

(c) The decay constant plotted against the current over the plasma source, after the laser pulse.

(d) The decay constant plotted against the current over the plasma source, at the end of the decay.

(e) The decay constant plotted against the laser pulse energy, after the laser pulse.

(f) The decay constant plotted against the laser pulse energy, at the end of the decay.

Figure 4.2: The exponential decays near the peak and in the tail of the decay.
(a) The decay constant plotted against the bias over the source, after the laser pulse.

(b) The decay constant plotted against the bias over the source, in the tail of the decay.

(c) The decay constant plotted against the laser pulse frequency, without an imposed bias, after the laser pulse.

(d) The decay constant plotted against the laser pulse frequency, without an imposed bias, in the tail of the decay.

(e) The decay constant plotted against the laser pulse frequency, with an imposed bias, after the laser pulse.

(f) The decay constant plotted against the laser pulse frequency, with an imposed bias, in the tail of the decay.

Figure 4.3: The exponential decays near the peak and in the tail of the decay.
Chapter 5

Discussion

5.1 Thermal Conductivity

It was not possible to reliably determine the exact quality of the connection of the samples to the heat sink: the thermal contact coefficients between tungsten and grafoil, between grafoil and copper and the thermal conductivity of grafoil. Ideally, the connection to the heat sink would be negligible. As it was not possible to reliably determine the quality of this connection, I chose to resort to a more crude approximation of the thermal conductivity. Looking at Table 4.1, it shows that the resulting thermal conductivities are several degrees of magnitude below the actual value, which shows that the interposing layers between the tungsten and heatsink cannot be neglected.

5.2 Diffusivity

While the resulting time constants are not the diffusivity itself, they do scale with the diffusivity. The diffusivity looks to be unaffected by the gasflow. Near the peak, the decay constant, and by extension the diffusivity, looks to be dependent on the target bias, pulse energy and source current. In the tail similar, dependencies can be seen. It could be that these are the results of synergistic effects, or simply caused by the temperature dependence of the diffusivity. To relieve doubt on this issue, it would serve to compare the calculated decay constants to the theoretical values of tungsten’s diffusivity at the corresponding temperature. To make a good comparison however, the geometric constant $\lambda$ in Equation 2.3 must be known.
Chapter 6

Summary and Conclusion

In summary, we conducted an experiment to test if the thermal properties of Tungsten are altered under synergistic effects. To test this, we exposed several samples to a steady-state hydrogen plasma flow with a pulsed laser superimposed. The surface temperature on the laser strike point of the samples were measured via an infrared camera. By analyzing the time profile of the temperature, I tried to determine the thermal conductivity and the diffusivity. I did not succeed at calculating the conductivity, as I did not know the relevant properties of grafoil. Rather than determine the actual diffusivity, I calculated the exponential decay constant. There seems to be a clear correlation between the decay constant and varied input parameters: source current, pulse energy and target bias. However, as of yet there’s no clear indication that this is caused by synergistic effects, rather than the temperature dependence of the thermal conductivity of tungsten.
Bibliography


