Erosion and power handling of liquid tin under high heat and particle fluxes in Pilot-PSI

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Award date:
2013
Erosion and power handling of liquid tin under high heat and particle fluxes in Pilot-PSI

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September 9, 2013

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Abstract

Liquid metals are currently under investigation for use as a plasma facing material in a tokamak divertor. Traditional wall problems like cracking, melting, and embrittlement, are mitigated by using a liquid metal. In this work, tin was exposed in the linear plasma device Pilot-PSI to a high flux, high density plasma, in order to examine the interaction of liquid tin on a CPS-target. The study of this interaction was split into two subjects:

1. Temperature dependence of erosion. The erosion of Tin was measured spectroscopically under Ar- and H-plasmas at different settings. It was found that the onset temperature of erosion was lower than would be expected by evaporation alone. In Ar-plasma this reduction was measured to be 200°C, while in the H-plasma the reduction was measured to be 505°C.

2. Quantifying power handling. Three methods were explored to quantify the heat handling capabilities of the CPS-target: Surface temperature evolution, cooling water calorimetry and spectroscopic measurement of Balmer-intensity profiles. Both temperature evolution and cooling water calorimetry show indications of reduced heat flux to the liquid-target at high power shots which could be attributed to the vapor shielding effect.
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Chapter 1

Introduction

1.1 The promise of Fusion Energy

World energy demand is rising at an ever increasing pace, as both world population and wealth keep increasing. To provide this energy, the world has always been (and still is) depending mainly on the burning of fossil fuels — gas, oil and coal. Burning fossil fuels releases carbon dioxide, which is one of the most important greenhouse gasses. Greenhouse gasses, as has become increasingly clear, have a destructive effect on the global climate and promote global warming. To meet the rising energy demand without global warming rising to unacceptable levels, the world has got to look for alternative energy sources that are both clean and sustainable.

Fusion energy is one of the few candidates that might be able to provide clean energy at a baseline level. Nuclear fusion, the process that powers the stars, is achieved by fusing two smaller nuclei together into one bigger nucleus. The resulting nucleus weighs slightly less than the two starting nuclei together, the 'lost' mass being converted to energy. Though there are thousands of conceivable nuclear fusion reactions, scientist focus on the easiest reaction of all: fusing deuterium and tritium (isotopes of hydrogen) to produce helium-4 and a neutron.

\[ ^2D + ^3T \rightarrow ^4He(3.5 \text{ MeV}) + n(14.1 \text{ MeV}) \]  \hspace{1cm} (1.1)

Getting two nuclei close enough together to make them fuse is particularly difficult as both nuclei are positively charged, thus repelling each other. To overcome the repelling force of the atoms, a gas must be heated to incredibly high temperatures in excess of 150 million °C. The resulting gas, so hot that all atoms are ionized, is called a plasma. In the sun, the massive gravitational force confines the plasma. On earth, where such a strong gravitational force is absent, the plasma is confined magnetically in a device called a tokamak. A tokamak is a donut shaped vessel encompassed with large magnetic coils.

Many tokamaks have been built already, each with progressively increased triple product — the performance parameter of a fusion reactor. Currently the largest tokamak ever built is JET, which at its peak produced a fusion power of 69% of the input power. Meanwhile engineers are building the next generation tokamak in Cadarache, France, called ITER (figure 1.1a). The main purpose of ITER is to demonstrate the viability of nuclear fusion as an energy source and is projected to have a power multiplication factor of 10, i.e. generate 10 times more power than the input power.
1.2 The Divertor: Getting the heat out

In order to remove impurities that can build up in the plasma, the magnetic field lines at the edge are 'broken up' in a special part of the tokamak called the divertor (figure 1.1b). By introducing a magnetic X-point, particles can leave the plasma tangentially to the field lines and can be removed from the confined plasma. As a result of the parallel transport of particles, an incredible heat- and particle flux will land on the divertor plates [4].

The divertor environment is incredibly harsh, featuring a steady state heat flux of 10 MW m$^{-2}$, particle fluxes up to $10^{24}$ m$^{-2}$ s$^{-1}$, and a 14 MeV neutron flux of $10^{17}$ m$^{-2}$ s$^{-1}$ [5]. After carefully testing different materials, tungsten has been selected as the most suitable for a Plasma Facing Material (PFM) in the divertor [6]. Despite being selected as the best divertor material, the tungsten divertor plates in ITER are already scheduled to be replaced after $\sim$3000 full power shots [7].

However, ITER is not the end of the line. In order to get net power out of fusion in a way that is economically feasible, reactors need to be even bigger. Construction for the prototype demonstration reactor called 'Demo' should start early in 2030 [8], while preliminary designs have already started. For Demo, the total reaction power is projected to be 3000 MW, six times higher than that of ITER [9],[10]. While Tungsten has not been tested under such extreme conditions, already under ITER conditions material degradation starts to become an important issue limiting the material lifetime.

Apart from the damage done to the PFM’s, there is a limit in the heat exhaust of the current design of the divertor. Even when considering switching to helium cooling, commercial reactors will be so power dense that removing all the heat in the divertor becomes a real challenge. Liquid metals might help in a number of ways to reduce the heat load on the divertor.

1.3 Liquid metals

Tungsten, which is the main material intended for divertor applications, will still be damaged above acceptable levels in next generation fusion reactors.
Liquid metals (LM) are superior to solids as a PFM in a lot of ways. Because they’re already molten they can’t melt or crack or anymore. The absence of a lattice structures makes the PFC resilient to neutron damage. Should macroscopic parts in the form of droplets do enter the plasma, the material can return to the wall where it is absorbed again (assuming no disruptions are triggered), or the deficit could be replenished by a supply of new LM.

On top of that, LM are expected to be especially resistant against Edge Localized Modes (ELM’s). An ELM is a plasma instability where up to 10% of the plasma’s stored energy is deposited to the edge in a matter of milliseconds, at a frequency of some tens of hertz [7]. Though immensely destructive for solid PFC’s, ELM’s can only damage a liquid surface by droplet ejection or enhanced erosion. While erosion can still lead to unacceptably large impurity concentrations in the (edge) plasma, it does not directly affect the lifetime of the PFC.

Not only material lifetime issues can be addressed with a liquid metal, but also the power handling of the divertor might be increased by using a LM as PFM. By actively pumping the LM through the divertor, heat can be removed by convection. This way the cooling capability becomes less dependent on the heat conductivity of the supporting material. However, a free flowing liquid in the divertor is prone to MHD-instabilities due to the large magnetic fields and free currents in the tokamak plasma. For this reason, the liquid needs to be constrained somehow. Different mechanism of constraining the liquid exist (see chapter 2), one of them being a Capillary Porous System (CPS), that constrains the liquid with a mesh by capillary forces [11].

Another way the liquid might help to reduce heat to the divertor is by an effect called vapor shielding [12]. When the incoming plasma particles interact with the metal vapor, the vapor particles then get ionized and radiate heat away over the entire 4\pi solid angle. Since a part of the heat is dissipated in the vapor cloud, the heat to the divertor is effectively reduced.

Given the large scala of possible advantages, LM show enough potential to be considered as an interesting divertor PFM alternative. To assess their applicability in a divertor, a good understanding of their interaction with the divertor plasma is vital. Some research has been done on enhanced erosion, metal-metal compatibility and numerical calculations of vapor shielding effects. However, only very few of these campaigns have been conducted in a high density, high flux plasma. It is essential to get a better understanding of the interaction between liquid metals and high density plasma before liquid metals can be considered as a PFM.

Since present-day tokamaks are incapable of reaching ITER-relevant plasma conditions with the flexibility that is needed for the thorough material research, the materials have to be studied in linear plasma devices. The experiments that are reported in this thesis have been carried out in Pilot-PSI, that is able to reach densities of 10^{20} m^{-3} at particle fluxes of 10^{24} m^{-2} s^{-1} [31]. Diagnostics can access the plasma via six windows in the vessel and include Thomson scattering, optical emission spectroscopy, and infrared thermography.

1.4 This work

It has become clear that liquid metals are an interesting alternative to solid walls in divertor applications. Before LMs can be used they need to be tested and characterized extensively in divertor-like plasma regimes. A fundamental understanding of the plasma-LM interaction is essential for designing liquid PFC’s. In order to start making this assessment, we have selected two questions to explore in further depth for this work:

- How does temperature dependent erosion limit the operating temperature of the liquid metal?

- Can we quantify the heat handling of a plasma-facing concept under a complex
Firstly, in Chapter 2, we elaborate on what to look at when selecting a liquid metal, and motivating the choice of working with tin. Some concepts of constraining the liquid are introduced, as well as the design and of the sample that was used in the experiments. In Chapter 3 we have a closer look at the experimental methods used; Pilot-PSI is introduced and the diagnostics that were used in the experiments are covered. In Chapter 4 we will first look in more detail to the temperature and erosion measurements before going to the results on temperature the dependence of the erosion, in an attempt to answer the first research question. Chapter 5 is dedicated to quantifying heat exhaust of liquid targets; after going through the theoretical background the experimental routine is explained and results are presented. Finally, in Chapter 6 the work is summarized and conclusions are drawn from found results. After discussing these results some recommendations are made with respect to divertor design and some suggestions are done for future research.
Chapter 2

Liquid metal

Because of the harsh conditions found in a tokamak divertor it is extremely difficult to find a suitable material for use as a Plasma Facing Component (PFC). For ITER, three suitable materials have been selected: Be for the walls, and W & C (in the form of a Carbon Fiber Composites) for the divertor [3]. Although these materials will be used in ITER The divertor is already planned to be replaced after \( \sim 3000 \) full power shots [7]. Even these materials would survive, it is unsure whether they manage to do so in a way that is economically feasible.

Apart from the erosion under steady state heat and particle loads and associated PFC lifetime issues, there is the risk of off-normal events like ELMs, VDEs and disruptions. Those events can be particularly harmful to the wall and can damage the PFC so severely that it needs to be replaced.

2.1 Current state of research

Liquid metals have been under consideration for use as an PFC for a long time, both as divertor [13] or full liquid metal wall [14]. First tokamak-size experiments with liquid PFC’s were done in the Russian tokamak T-11 [15], where the liquid metal (lithium) was contained by a mesh, the so called Capillary Porous System (CPS) [11]. Other large scale experiments involving liquid metal PFC’s were done in the TJ-II stellarator [16] and by evaporating lithium surfaces in NSTX [17]. In all cases the presence of stationary liquid Li greatly induced energy confinement times. At PPPL experiments have been done with a liquid lithium limiter in CDX-U with great success [18], and now the benefits of an entirely liquid wall are being explored in the Liquid Tokamak eXperiment [19]. At University of Illinois a system was developed to constrain and control liquid flow with a thermo-electrically driven current, dubbed Lithium/Metal Infused Trenches (LiMIT) [20]. Meanwhile, numerical simulations have been used to test the heat capacity of liquid PFC’s [21] and liquid metal experiments are starting up in linear devices at FzJ and DIFFER.

2.2 Choosing the right metal

In this section we will focus on what criteria need to be met for selecting a suitable metal. First we will give a short overview of those criteria, next we present a list with the most likely candidates and what makes them so attractive.
2.2.1 Considerations

An ideal wall material should have a combination of a lot different properties such as a high heat conductivity, low melting point, low physical/chemical erosion rates and low tritium retention. Just like selecting a solid wall material, selecting a liquid wall material implies looking at all different features of the material and comparing it against all the constraints that the divertor region will put on the material. Here some of the most important considerations for the liquid metal are listed (in no particular order):

Melting point

Though temperatures in the divertor can get high enough to melt most metals, most of the liquid metal concepts require the liquid to be conducted out of the reactor for heat exchange, tritium extraction or removing impurities from the liquid. This means that a substantial part of the liquid system will exist outside of the reactor, where it needs to be kept above melting point actively. For this reason, the melting point of the candidate material should be low to prevent clogging of the plumbing.

Atomic number

Atoms with a high atomic number will, once ionized by the plasma, acquire a high positive charge and cool down the plasma via bremsstrahlung. The higher the atomic number, the more electrons the atom will carry and the less likely the atom will ionize completely, introducing line radiation as an additional path for plasma cooling. Overall we conclude that the lower the atomic number, the more favorable the material.

Evaporation rate

Although evaporation is not a problem in terms of material lifetime anymore since the liquid can be replenished at all times, still as little impurities as possible should enter the plasma to prevent plasma degradation. A high evaporation rate will introduce impurities to the plasma faster and is therefore undesirable. The evaporation rate is related to the vapor pressure, the lower the vapor pressure the lower the evaporation of the metal.

Neutron activation

Neutron activation is an important issue for any material in a fusion reactor; it is in fact what makes the reactor nuclear in the end. Although the liquid film will not help much in terms of neutron shielding with respect to the underlying (solid) metal surface, because neutron damage is a volumetric effect, the material of choice has should not transmute into radioactive isotopes itself.

Hydrogen affinity

Apart from some special case\[1\], a high hydrogen affinity is assumed to be disadvantageous. A high hydrogen affinity means the LM can bond with hydrogen or form hydride compounds. This makes it possible for tritium to be codeposited anywhere in the reactor, possibly increasing the reactor’s tritium inventory to levels that exceed the safety limits.

---

1 In some scenarios, a liquid metal wall is suggested to absorb incoming particles to access a so called low recycling regime. These particles will not return to the plasma directly which greatly stabilizes the plasma. See also: [22]
Material compatibility

Apart from all the physics considerations, the liquid metal will have to be introduced in the reactor. It is therefore vitally important that the metal is compatible with the underlying material and does not corrode, react or mix with its containing structure.

Price/availability

Although not really an issue at this moment, we should keep in mind that in the end we want to build an economically viable reactor. Since lot of liquid metal will be required, it needs to be available and reasonably priced.

2.2.2 Candidate Metals

Lithium

Lithium is usually considered as the best candidate because of its low melting point and low atomic number. A disadvantage of Li is that it readily forms hydrides which possibly increases the tritium inventory to unacceptable levels. A lesser, but still substantial problem of lithium is that it is incredibly corrosive. It readily reacts with oxygen, water and copper, hardly ideal for a commercial reactor.

Tin

Tin is the first runner-up, melts at relatively low temperature (231 °C) but has a higher atomic number (Z = 50) and low vapor pressure. A big advantage of especially Sn is the low reactivity with hydrogen and other metals, making it compatible with most other materials in the divertor. Also, Sn has a low hydrogen affinity.

Gallium

Just like tin, gallium combines low melting point (29.8 °C), low vapor pressure, and a slightly lower atomic number (Z = 31). Gallium has the downside of being more reactive than tin, and apart from that doesn’t really have any significant advantages over it. This makes that tin a better candidate.

Eutectic Alloys

Apart from the pure elemental liquids, eutectic alloys are interesting to consider. A eutectic alloy is a mixture of two metals in such composition that the melting point is minimized [23]. Eutectic alloys could combine beneficial properties of different species, giving more room to tailor the liquid metal to meet all the strict criteria.

2.3 Target Design

For our target we choose to implement a CPS-design to contain the liquid metal [15]. The target will consist of a small container filled with the liquid metal, that is covered with a mesh to confine the metal after it’s molten.
2.3.1 Selected metals

We have selected Sn as the metal to work with because of its low reactivity and low melting point. The mesh and container will be made out of Mo because of its inertness, low erosion and high melting point. Before going into the target’s specifics, we will briefly overview some properties of Sn:

Table 2.1: Material properties for liquid tin at melting point [24]

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Number</td>
<td>$Z$</td>
<td>50</td>
</tr>
<tr>
<td>Atomic Weight</td>
<td>$M$</td>
<td>118.71 g mol$^{-1}$</td>
</tr>
<tr>
<td>Melting point</td>
<td>$T_m$</td>
<td>231.85 °C</td>
</tr>
<tr>
<td>Boiling point</td>
<td>$T_b$</td>
<td>2275 °C</td>
</tr>
<tr>
<td>Critical point</td>
<td>$T_c$</td>
<td>7577 °C</td>
</tr>
<tr>
<td>Enthalpy of Fusion</td>
<td>$H_m$</td>
<td>7.07 kJ mol$^{-1}$</td>
</tr>
<tr>
<td>Enthalpy of Vaporization</td>
<td>$H_{vap}$</td>
<td>296 kJ mol$^{-1}$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$\kappa$</td>
<td>32 W m$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>Electrical resistivity</td>
<td>$\rho_e$</td>
<td>$4.8 \times 10^{-7}$ Ω m</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho_m$</td>
<td>6980 kg m$^{-3}$</td>
</tr>
<tr>
<td>T-dependence of $\rho$</td>
<td>$A$</td>
<td>$-61$ kg m$^{-3}$ K$^{-1}$</td>
</tr>
<tr>
<td>Surface Tension</td>
<td>$\gamma_m$</td>
<td>0.56 N m</td>
</tr>
<tr>
<td>T-dependence of $\gamma$</td>
<td>$\partial \gamma / \partial T$</td>
<td>$-9 \times 10^{-5}$ N m K$^{-1}$</td>
</tr>
<tr>
<td>Vapor Pressure Coeff.</td>
<td>$A$</td>
<td>0.256</td>
</tr>
<tr>
<td></td>
<td>$B$</td>
<td>$-15.332$ K</td>
</tr>
<tr>
<td></td>
<td>$C$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$D$</td>
<td>0 K$^3$</td>
</tr>
</tbody>
</table>

2.3.2 Target specifics

The target will consist of a container filled with Sn, that is covered with a Mo mesh to confine the metal after it melts. First we will focus on the capillary effect and try to calculate the dimensions that are needed for the target to keep the tin in place. The capillary force is given by:

$$F_c = \frac{4 \gamma \cos \theta}{d}$$  \hspace{1cm} (2.1)

Where $F_c$ is the capillary force, $\gamma$ the surface tension of the liquid, $\theta$ the contact angle and $d$ the pore diameter. In the target, the capillary force is needed to balance the gravitational force:

$$\rho gh = \frac{4 \gamma \cos \theta}{d}$$  \hspace{1cm} (2.2)

Where $\rho$ is the density, $g$ the gravitational acceleration, and $h$ the height of the target. One important observation is that the contact angle should be at least smaller than $90^\circ$ for the capillaries to work. In other words, the surface needs to be wetted by the liquid metal (depicted in figure 2.1). The contact angle can be calculated by equating the interface energy vectors of solid, liquid and gas [26]:

$$\gamma_{SG} - \gamma_{SL} - \gamma_{LG} \cos \theta = 0$$  \hspace{1cm} (2.3)
In theory we could use this relation to find \( \theta \), but since values for \( \gamma_{SG} \) and \( \gamma_{SL} \) are hard to find experimentally or theoretically [27], it is easier to measure \( \theta \) directly for the solid-liquid combination in question. From our own experiences we know that Mo is difficult to wet with liquid Sn at room temperature, but at elevated temperatures (around 800 \( ^\circ \)C), close to perfect wetting (\( \theta = 0 \)) can be achieved. We will therefore assume \( \theta = 0 \) for calculating the design parameters.

The surface tension \( \gamma \) is known to decrease linearly with temperature until the critical temperature \( T_c \) is reached, at which the surface tension becomes identically zero. This behavior is expressed by Eötvös law [28]:

\[
\gamma(T) = \frac{k}{V^{\frac{1}{3}}} (T_c - T)
\]  

(2.4)

We note that projected temperatures in the experiment of at least some \~1000 \( ^\circ \)C are an appreciable fraction of the critical temperature \( T_c = 7577 \)\( ^\circ \)C, so the effect of reduced surface tension is definitely something we should take into account. Eqn 2.3 can be rewritten in the more practical formula:

\[
\gamma(T) = \gamma_m + \frac{d\gamma}{dT}(T - T_m)
\]  

(2.5)

Where \( \gamma_m \) is the surface tension at the melting point, \( d\gamma/dT \) the temperature slope, \( T \) the temperature and \( T_m \) the melting point. Also the density changes with temperature, given by:

\[
\rho(T) = \rho_m + \Lambda(T - T_m)
\]  

(2.6)

Which we will have to take into consideration. Here \( \rho_m \) is the density at the melting point, and \( \Lambda \) the temperature slope.

By combining above equations we can find an expression for the maximum pore size of the mesh:

\[
d < \frac{4\gamma(T)}{\rho(T)gh}
\]  

(2.7)

The target diameter (\( h \) in the equations, since the target will be standing) is dictated by the size of the plasma bundle. We want to catch the full bundle with the target, but don’t make it any bigger to ease the constraints on the CPS as much as possible. For this reason, we have selected a target diameter of 22 mm.
Table 2.2: Maximum pore diameter

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>d_{max} (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>231.9</td>
<td>1.49</td>
</tr>
<tr>
<td>1000</td>
<td>1.40</td>
</tr>
<tr>
<td>2000</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Base design

Using this value for $h$ and the material properties from Table 2.1, we can calculate the maximum pore diameter for different temperatures (Table 2.2). These values are valid under the assumption that there is complete wetting ($\cos \theta = 1$) which might not be the case, so this value should be considered as an upper bound. Since there is not a real lower bound to the pore diameter of the mesh, we include a decent safety margin and use a mesh with a pore size of 0.43 mm. With a wire diameter of 0.07 mm, this mesh has an open area of 67% and is depicted in figure 2.2.

To get the tin soaked into the mesh, the tin is molten and absorbed into the mesh before the target is exposed to plasma. This is done by putting an excess of solid tin wire on top of the mesh, and heat it with an RF-heater in vacuum up to 800°C. This high temperature is needed for the Sn to wet the Mo.

The mesh of this first design broke quickly under plasma irradiation, with Sn leaking out of the target and into the vessel. It is not clear in what order these effects appeared; the leaking of the tin would leave the mesh with no thermal contact to the cooled back of the target, resulting in rapid heating and ultimately melting/breaking of the mesh. Equally possible is that the mesh was destroyed first (by too high T-gradients for example) and as a result the Sn started leaking out.
It should be mentioned that eqn 2.5 states that the density decreases with increasing temperature, so Sn would naturally be pushed out of the mesh for a hotter target. This effect would account for a volume increase (and hence Sn-loss) of 9.9% at 1500 °C, the typical surface saturation temperature. Once the Sn is pushed out at higher temperatures, vacancies will appear when the temperature and volume decrease again.

Improved design

To improve the target, three changes were made. Instead of only one layer of mesh, the entire volume is stacked with meshes. This way there is more capillarous material, so that the Sn should stay confined even if the top layer was damaged. The top layer itself is replaced by a mesh with a larger wire diameter, 0.17 mm, so that it is more resistant to tearing or breaking due to high T-gradients. Finally, instead of using an excess of Sn and melt the surplus off afterwards, a precise amount of Sn was used so that it just fills the mesh. It is conceivable that in the previous target the surplus Sn created streamers while flowing out, providing channels for the mesh deplete itself. This mesh design is depicted in figure 2.3.

![Figure 2.3: Image of the 'improved design' target](image)

Even this new target design loses Sn during shots. As soon as the front mesh breaks, the underlying mesh will be vulnerable to the plasma beam again. In this series the target was subjected to a range of low and high power shots (shot A to F, found in table 5.1 in chapter 5). Ultimately the entire mesh stack was destroyed, with no Sn left in the sample.

For a third series of shots (6 repetitions of shot F found in table 5.1 in chapter 5), a second target was made using the improved design. The shots were performed with higher power, higher flux and without target cooling. Remarkably, this target retained most of its Sn apart from a small melt-crater in the center (figure 2.4a). This is especially remarkable since the absence of target cooling in these shots drives the target to extreme temperatures, where one would expect that evaporation would deplete the target in no-time.

Assuming the second improved target was identical to the first one, we suggest two reasons why the second target survived:
Because of the high plasma densities, the significant recycling caused the Sn to be redeposited to the target, effectively replenishing any lost Sn. Because of this, the Mo wires were always in contact with the liquid metal, and therefore can conduct their heat away.

Another reason might be that because all the shots in the third series were at high power with no intermittent low power shots, at all time the wetting of the Sn was high enough for the capillary force to retain the liquid in the mesh, causing no Sn to drip out which would leave the Mo wires unprotected. Essential in this problem is to distinguish between cause and effect, so that we can tell what is the real reason the CPS fails.

If we zoom in on the crater where the mesh did melt (figure 2.4b), we see tiny balls of metal at the ends of the mesh’s wire. Given their position on the wire, we conclude that the balls are most likely Mo-wire that was molten. Apart from the mesh and the metal balls, the crater is void of any (bulk) metal.

To understand what is exactly damaging the target, we compare the Sn-content of the mesh near the center and near the edge of the target, depicted in figure 2.5. We see that more Sn is left in the mesh near the edge (figure 2.5b) than in the mesh near the center (figure 2.5a). This is consistent with the proposition that Sn leaves the target by evaporation, which should be the highest where the temperature is highest (at the center). Another observation is that the Sn does seem to wet properly. By combining this with the fact that the mesh was molten at the center and no Sn was left there, we conclude that it is the absence of Sn that causes the mesh’s wires to heat up and melt, losing the ability to confine the bulk liquid.

We would expect the mesh to fill it’s pores with Sn before the wire could melt, so in order to understand why the pores aren’t refilled, we will look at the typical fluid velocities in the mesh. We can estimate the typical fluid velocities in the mesh with Darcy’s law [29]:

\[ q = -\frac{k}{\mu} \nabla P \]  

Here \( q \) is the specific discharge rate (i.e. typical fluid velocity), \( k \) is the intrinsic permeability, \( \mu \) the dynamic viscosity, and \( \nabla P \) the pressure gradient that drives the motion. Here we consider the pressure gradient to be due to the gravity:

\[ \nabla P = \rho g \]  

Figure 2.4: Improved target design after series of high power shots

\[ \text{(a) Target is mostly intact, except for a melt crater in the center} \]
\[ \text{(b) Microscope image of the crater at 5x magnification} \]
And we calculate $k$ with the Kozeny-Carman equation [29]:

$$k = \left[ \frac{\phi^3}{180(1 - \phi)^2} \right] d^2$$ (2.10)

Where $\phi$ is the porosity (i.e. the fractional open area) and $d$ is the wire diameter.

We take Sn parameters at 1500° ($\rho = 6.21 \times 10^3 \text{kg m}^{-3}$, $\mu = 6.9 \times 10^{-4} \text{kg m}^{-1} \text{s}^{-1}$ [30]), the mesh parameters ($\phi = 0.67$, $d = 2.7 \times 10^{-6} \text{m}$) and the gravity constant ($g = 9.81 \text{ m s}^{-2}$), and plug these in equations 2.8–2.10. The value we get for $\dot{q}$ is $2.15 \times 10^{-7} \text{ m s}^{-1}$, which means the liquid is virtually stationary during a typical shot of 10 s.

Figure 2.5: Microscope image of the mesh filled with Sn at 5x magnification
Chapter 3

Experimental

3.1 Pilot-PSI

In order to test the CPS-target with liquid Sn, it needs to be exposed by a plasma with conditions relevant to a tokamak divertor. Since no such reactors exist yet, we turn to linear plasma devices. Pilot-PSI is one of the few devices in the world that is capable of generating plasma conditions similar to those expected in the ITER divertor plasma. The plasma is characterized by high density (up to $10^{24} \text{m}^{-2} \text{s}^{-1}$) and low temperature ($\sim 1 \text{eV}$).

The device, shown in figure 3.1, consists of a cylindrical vacuum vessel 1 m long and an inner diameter of 40 cm. Vacuum pumps keep the vessel pressure during shots around $10^{-2} \text{Pa}$ to $10^{-3} \text{Pa}$. The plasma is generated by a cascaded arc source and is magnetized to confine the plasma and direct the plasma particles to the target. Five large magnetic coils generate the necessary B-field, that can be selected from 0.4 T to 1.6 T with 0.4 T intervals.

The target is positioned at the radial center of the vessel, 55 cm away from the source. It is electrically isolated from the vessel and can be operated at floating potential, positive-, or negative bias. A negative bias voltage is used to increase the ion energy, and should not exceed $-70 \text{V}$ in hydrogen or $-40 \text{V}$ in argon to prevent arcing. The target can be mounted on a copper cylinder that is water cooled, or the target can be cooled by water directly.

Pilot-PSI Acquisition system

Before or during each shot, triggers are generated to synchronize peripherals and diagnostics. A baseline of diagnostics records automatically during each shot. This includes the measured values of primary input parameters such as cathode current, bias voltage, magnetic field strength or gas flow, and a variety of pressures, temperatures and water flows.

The eight ports of the vessel provide diagnostic access for optical diagnostics. In figure 3.1 the diagnostics that were used are depicted, which we will introduce in the next section.

3.2 Diagnostics

3.2.1 Optical Emission Spectroscopy

Optical Emission Spectroscopy (OES) was used as the main diagnostic for measuring Sn-erosion in this work. The optical emission was acquired either by a spectrometer or a filtered visible
Avantes Spectrometer

The Avantes spectrometer measures time resolved optical emission spectra at a single spatial point. The spectrometer has 2-channels with a spectral range of 294.16 nm–455.40 nm and 443.58 nm–580.44 nm respectively. The CCD is 2048 pixels wide resulting in a spectral resolution of 0.079 nm/px and 0.067 nm/px respectively. The recorded spectra are time resolved and can have an integration time ranging from multiple seconds down to 1 ms. The light coming from the plasma is focussed by a lens before it’s coupled into a fiber that is connected to the spectrometer. The fiber is aligned at the center of the target where one would expect temperature and thus erosion to be highest.

The fiber is positioned at the far port with reference to the target, resulting in an viewing angle of approximately 24.5°. The spectrometer is triggered by the central triggering system so that the spectra are recorded synchronously with other measurements.

Since the erosion measurements are among the most important measurements of this work, we will discuss them separately in more detail in section 4.2 of chapter 4.

Phantom Fast Optical Camera

The Phantom camera is used to measure the spatial OES profiles discussed in section 5.3.4 of chapter 5. When used in combination with an optical bandpass filter it can record the spatial
profile of emission at a specific wavelength range. In this experiment it was used to record spatial profiles of $H\alpha$, $H\gamma$, and $H\delta$ emission. The camera has a CCD of $1280 \times 786$ pixels and was used at 60 frames per second with an integration time of between 0.9$\mu$s and 300$\mu$s.

### 3.2.2 Thermography

Surface temperatures were measured by infrared thermography. Two diagnostics were used: the infrared camera for spatial and temporal resolved IR-recordings, and a pyrometer to absolutely calibrate the IR-camera.

#### IR-camera

The FLIR A645sc infrared camera is used to measure surface temperature of the target by looking at the intensity of emitted IR radiation. Planck’s law of radiation states that a black body of a certain temperature will emit radiation via:

$$P_{bb}(T) = \frac{2\pi hc^2}{\lambda^5 \left(e^{hc/\lambda k_B T} - 1\right)}$$

(3.1)

Here $P_{bb}$ is the black body radiated power at a certain wavelength $\lambda$, $h$ is Planck’s constant, $c$ the speed of light, $k_B$ the Boltzmann constant, and $T$ the temperature. The camera is sensitive to radiation in the range of 7.5$\mu$m to 14$\mu$m, at those wavelengths $hc \ll \lambda k_B T$, so 3.1 can be approximated by:

$$P_{bb,\lambda}(T) \approx \frac{2\pi c k_B T}{\lambda^4}$$

(3.2)

This relation was factory calibrated by measuring the black body radiation all over the operational temperature range. The resulting curves relate the IR-radiation to the object temperature via the calibration function $f_{cal}$:

$$T = f_{cal}(P_{bb}) \Leftrightarrow P_{bb} = f_{cal}^{-1}(T)$$

(3.3)

In practice however, bodies are rarely perfectly black. These grey bodies, as they are called, are characterized by their emissivity, $\epsilon$. The emissivity is defined as the ratio between the radiated power $P_{rad}$ and the power a black body of the same temperature would radiate $P_{bb}$.

$$\epsilon = \frac{P_{rad}}{P_{bb}}$$

(3.4)

If we want to calculate the temperature of an object using eqn 3.3, we need to know the power it would have radiated were it a perfect black body. To get to the black body radiated power, we need to understand that the received signal consists of three main contributions: 1. The radiation emitted by the object, $P_{obj}$, 2. Any IR-radiation that is reflected by the target, $P_{refl}$, and 3. IR-radiation produced by ambient temperature (atmosphere, windows), $P_{atm}$. After taking into account the target emissivity $\epsilon$ and the transmission of the optical system $\tau$, we get an expression for the total IR-power measured by the camera $P_{meas}$ at temperature $T$ [32]:

$$P_{meas}(T) = \tau \epsilon P_{obj,bb}(T) + \tau (1-\epsilon)P_{refl} + (1-\tau)P_{atm}$$

(3.5)

\footnote{Actually $f_{cal}$ is a function of $U = cP$, the digital level recorded by the camera. This is in turn linearly proportional to the IR-power collected by the CCD. For convenience of notation, this relation is omitted in this regard.}
Since only the first term is a function of temperature\footnote{Implicitly we assume that $P_{refl}$ stays constant. This might actually not be the case if we consider e.g. the source heating up during the experiment, but as a first order approximation it is safe to assume constancy.}, it follows that we can get rid of the second and third term by subtracting the signal by a reference at a given temperature (e.g. room temperature), $T_0$:

$$P_{\text{meas}}(T) - P_{\text{meas}}(T_0) = \tau \epsilon \left( P_{\text{obj},bb}(T) - P_{\text{obj},bb}(T_0) \right)$$  \hspace{1cm} (3.6)

Because we know that the radiated power of the target $P_{\text{obj},bb}(T_0)$ can be calculated from eqn 3.3, we take $P_{\text{obj},bb}(T_0) \approx f_{\text{cal}}^{-1}(T_0)$ and divide by $\tau \epsilon$ (assuming $\epsilon$ is constant with temperature) to get:

$$P_{\text{obj},bb} = \frac{P_{\text{meas}}(T) - P_{\text{meas}}(T_0)}{\tau \epsilon} + f_{\text{cal}}^{-1}(T_0)$$  \hspace{1cm} (3.7)

Which can then be converted to a temperature using 3.3:

$$T_{\text{obj}} = f_{\text{cal}}(P_{\text{obj},bb})$$  \hspace{1cm} (3.8)

Although the background is eliminated in this way, still the transmission of the system and the emissivity of the target need to be known. Especially getting a reliable value for the emissivity can be hard, since in general it changes with temperature.

Suppose the emissivity is dependent on temperature, we’d have to make some refinements to our equations. We start from eqn 3.6, where this time:

$$P_{\text{meas}}(T) - P_{\text{meas}}(T_0) = \tau \epsilon(T) \left( P_{\text{obj},bb}(T) - \epsilon(T_0) P_{\text{obj},bb}(T_0) \right)$$  \hspace{1cm} (3.9)

$$P_{\text{obj},bb} = \frac{P_{\text{meas}}(T) - P_{\text{meas}}(T_0)}{\tau \epsilon(T)} + \epsilon(T_0) f_{\text{cal}}^{-1}(T_0)$$  \hspace{1cm} (3.10)

This time it is not possible to use eqn 3.8 since we need to know the temperature explicitly to calculate $\epsilon(T)$. We solve this problem by tabulating all values for $P_{\text{meas}}$ that correspond to different $T$, where $T$ is varied from the lowest to the highest possible temperature. To do this we combine 3.8 with 3.10 to get:

$$f_{\text{cal}}^{-1}(T) = \frac{P_{\text{meas}}(T) - P_{\text{meas}}(T_0)}{\tau \epsilon(T)} + \epsilon(T_0) f_{\text{cal}}^{-1}(T_0)$$  \hspace{1cm} (3.11)

$$g_{\text{tab}}(T) = \tau \left[ \epsilon(T) f_{\text{cal}}^{-1}(T) - \epsilon(T_0) f_{\text{cal}}^{-1}(T_0) \right] + P_{\text{meas}}(T_0) = P_{\text{meas}}(T)$$  \hspace{1cm} (3.12)

Now we can get the temperature directly from $P_{\text{meas}}$ by using

$$T_{\text{obj}} = g_{\text{tab}}^{-1}(P_{\text{meas}})$$  \hspace{1cm} (3.13)

This assumes an explicit expression or value is known for the emissivity $\epsilon(T)$.\footnote{Implicitly we assume that $P_{refl}$ stays constant. This might actually not be the case if we consider e.g. the source heating up during the experiment, but as a first order approximation it is safe to assume constancy.}
Pyrometer

The pyrometer is used to measure absolute temperatures at a single point, mainly for cross calibration with the IR-camera. The pyrometer is ‘multi-color’, meaning that it measures infrared radiation over certain spectral range. The IR-spectrum is then fitted by the Boltzmann-curve to find absolute temperatures using proprietary software. The targets used in our experiments all have a low emissivity ($\epsilon < 0.1$), which means that at a given temperature only a few percent of the radiation a black body would radiate is emitted. This translates into low IR-signals, and effectively, a high temperature at which the pyrometer starts to become sensitive. In practice this temperature lies around $\sim$700°C.

Because we need to be able to measure in a range significantly lower than that (ideally starting at room temperature), the combination of IR-cam & Pyrometer is necessary. By combining eqn 3.7 & 3.8 we can find an expression for the emissivity as a function of a known temperature $T^*$:

$$\tau \epsilon(T^*) = \frac{P_{\text{meas}}(T^*) - P_{\text{meas}}(T_0)}{f_{\text{cal}}^{-1}(T^*) - f_{\text{cal}}^{-1}(T_0)}$$

(3.14)

Here the temperature $T^*$ is provided by the pyrometer, and as long as there is pyrometer data available (i.e. upwards of $\sim$700°C) it can be used to find the variation of emissivity with temperature.

Even without finding the value for $\epsilon$ explicitly, the pyrometer serves to put a ‘higher bound’ on temperature measurements done with the IR-camera. Since most erosion is expected at high temperatures, it is important that the high temperatures are measured accurately.

3.2.3 Thomson Scattering

The electron temperature $T_e$ and electron density $n_e$ were measured with Thomson Scattering (TS). TS works by exciting electrons with a high intensity laser and measuring the photons that are emitted when the electrons relax to their original state. The electrons are not stationary, but have a velocity that is proportional to the electron temperature. The non-zero velocity of the electrons introduces a Doppler-broadening that can measured spectroscopically and is used to determine the plasma temperature via [33]:

$$w = \frac{2\lambda_0}{c} \sqrt{\frac{2 \log(2) k_B T_e}{m_e}}$$

(3.15)

Where $w$ is the FWHM of the broadened peak, $\lambda_0$ is the wavelength of the excitation laser, $c$ is the speed of light, $k_B$ is the Boltzmann constant and $m_e$ is the electron mass. The electron density $n_e$ is proportional to the total observed intensity of the scattered light.

The electrons are excited by a Nd:YAG-laser with a frequency of 532 nm. The scattered light is collected by a lens and focussed into a vertical array of fibers that looks at a distance of 17 mm from the target, by which a spatial resolution of 0.6 mm can be reached. For more information on the TS-system installed on Pilot-PSI, refer to [33].
Chapter 4

Temperature Dependence of Erosion

Erosion is an important factor that traditionally determines the lifetime of a material. For solid walls, erosion can seriously reduce the lifetime of the wall and put constraints on both the wall material and the edge plasma conditions. To be more specific, this criterion has reduced the selection of materials to Be, C, or W in ITER. For the edge plasma, the general consensus is to keep the edge plasma temperature constrained below 5 eV to prevent excessive damage by physical sputtering [34].

For a liquid wall on the other hand, erosion has virtually no implications for the wall’s lifetime; by actively replenishing the liquid wall there will always be enough LM to protect deeper lying surfaces from the plasma. This doesn’t mean we can forget about LM erosion altogether however. Still the eroded particles will end up in the plasma, potentially cooling the plasma through line radiation or bremsstrahlung, that both increase with effective ion charge (depicted in figure 4.1). Since the erosion of material into the plasma influences its parameters, a good understanding of how much material will be released into the plasma is vital.

In particular, we are interested in how the erosion is affected by the PFM’s temperature. A high temperature LM is beneficial for extracting heat, but with high temperatures the erosion might be enhanced to unacceptable levels. The aim of this chapter is therefore to find how the erosion depends on temperature, to ultimately find a temperature range within which a LM-divertor might be operated.

To address this question, first the concept of erosion is introduced in section 4.1. In section 4.2 we will elaborate on the spectroscopic measurement of the erosion, while in section 4.3 we will discuss the temperature measurements. After that we’re fully equipped to look into – and discuss the results on the temperature dependence of erosion in section 4.4.

4.1 Erosion

4.1.1 What is erosion?

Erosion is the collective term describing any particles leaving the PFC or entering the plasma, depending on your perspective. The term erosion describes a net flux of particles and doesn’t distinguish between how the particles are expelled from the surface. In general, erosion is taken

\[ \text{Erosion} = \sum_{i=1}^{n} \text{Rate}_{i} \]

Although physical sputtering is low for C, chemical erosion is a big issue because of the formation of hydrocarbons [35].
(a) Distinction between radiative cooling and dilution effects as a function of atomic number

(b) Percentage of impurity in the core plasma at which the radiated power equals half the α-heating

Figure 4.1: Effect of impurities of different species to the core plasma

to be the sum of at least two terms: evaporation $\Gamma_{\text{evap}}$, and sputtering, given by the product of the ion flux and the sputtering yield $\Gamma_{\text{ion}}Y_{\text{ps}}$, as depicted in equation 4.1. Following Doerner’s approach, Temperature Enhanced Sputtering is introduced here as a third term which is a mix of the first two, depending both on temperature and particle in-flux, $\Gamma_{\text{ion}}Y_{T}(T)$. In the following section we will explore each of these terms in greater depth.

$$R(T) = \Gamma_{\text{ion}}(Y_{\text{ps}} + Y_{T}(T)) + \Gamma_{\text{evap}}(T)$$

(4.1)

Evaporation

Evaporation is the thermal expulsion of particles from the surface. Once the material’s temperature gets high enough, the thermal energy acquired by the particles can overcome the lattice binding energy, which causes the particles to leave the surface. The evaporation rate of a material is mainly determined by the vapor pressure $p$ by

$$\Gamma_{\text{evap}} = \frac{n_{e}v}{4} = \frac{p}{4kT} \sqrt{\frac{8kT}{m\pi}} = \frac{p}{\sqrt{2\pi m kT}}$$

(4.2)

The vapor pressure is highly dependent on temperature and as a result, the evaporative flux itself is highly dependent on temperature as well. The vapor-pressure $p$ in \([\text{Pa}]\) at a temperature

\footnote{Or sublimation for solids, but since we’re dealing with liquids exclusively we will just refer to evaporation only. As a matter of fact, since evaporation and sublimation differ only by their heat of fusion which is much smaller than the heat of evaporation, the two can be regarded as the same in most practical cases.}

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$T$ in [K] is given by [25]:

$$\log p = A + \frac{B}{T} + C \log T + \frac{D}{T^3} \quad (4.3)$$

Here the values for $A$, $B$, $C$ and $D$ are material properties and can be found in literature. For tin we find $A = 0.256$, $B = -15332$ and $C = D = 0$, as tabulated in table 2.1. The empirical formula reproduces vapor pressures within 5% of the measured values, as shown in figure 4.2.

![Figure 4.2: Evaporative flux of Sn versus temperature, the dashed line gives the empirical result that agrees within 5% of measurements [39].](image)

**Physical Sputtering**

The process of knocking atoms off the surface by high energy collisions is called physical sputtering. The physical sputtering rate is given by the product of the incoming particle flux and the sputtering yield, as given by the first term in equation 4.1. The (classical) yield depends on both the incoming and target species, and varies with the incoming ion energy. In general the sputtering yield as a function of impact energy and is characterized by a steep rise at the threshold energy $E_{th}$, which is the minimal energy needed to knock the atoms out of the lattice. This is followed by a flat region and then a slow decay at high energies, as depicted in figure 4.3. The higher the particle energy, the deeper the incoming particles penetrate the material, reducing the probability that the collision cascade transfers enough energy to the surface particles for them to escape.

A semi-empirical function was devised that gives a relation between the incoming ion energy and the sputtering yield [40]. The relation was fit for different collisions, including hydrogen
(figure 4.3a) and argon (figure 4.3b) bombardment of Sn. This relation is used later in this chapter to calibrate the measured emission data.

![Graphs showing sputtering yield of Sn sputtered by hydrogen and argon ions for different incoming ion energies.](image)

Figure 4.3: Sputtering yield of Sn sputtered by hydrogen and argon ions for different incoming ion energies.

**Temperature Enhanced Sputtering**

Sputtering as described above is assumed to be independent of the target temperature, and is only increased by increasing the impact energy of incoming ions. However, experiment has shown [38],[39], that the erosion rate can have a strong temperature dependence, even after correction for the evaporation of the metal. This motivates the introduction of a third term that accounts for Temperature Enhanced Sputtering (TES). The effect was also observed in our experiments, which is presented in section 4.4.

Just like the term 'erosion', TES is a collective term that doesn’t say how the target temperature increases the erosion of the material. It is a general term that might include any effect that results in a sputtering rate that is influenced by the target temperature. It’s good to emphasize that Temperature Enhanced Sputtering and Temperature Enhanced Erosion are not the same thing. The former, together with evaporation, contributes to the latter (as is clarified in eqn 4.1).

TES manifests itself as a decrease of the onset temperature at which erosion increases exponentially with temperature. It has been observed both in liquid (figure 4.4a) and solid (figure 4.4b) metals, but has not been investigated in high density, high flux plasma environments yet.

**Macroscopic Erosion**

Apart from the microscopic effects that were covered, liquid can be lost via macroscopic erosion in the form of droplet ejection. The droplets can potentially travel far into the plasma and could pose a serious threat by cooling down the plasma too much. Droplet ejection from a CPS-target has recently been observed in experiments with liquid Sn in TEXTOR, and was also observed during our experiments. By looking at the side view of the target, it can be seen that droplets are ejected by the target.

After the image was processed to make the droplets more visible depicted in figure 4.5, the amount of droplets was counted and found to be 160 particles per frame. With an integration
time of 30 µs, this amounts to $5.3 \times 10^6$ s$^{-1}$. Since some of the pixels in the threshold image might originate from noise rather than actual droplets, this number should be considered as a rough estimate.

At this point it is not clear what the effect of the droplets is on the plasma, so additional analysis is needed how far the droplets could travel into the plasma and how harmful they are.

Figure 4.4: Experimental observations of temperature enhanced sputtering [38]
Figure 4.5: Sequence of image processing techniques that were used to find the number of droplets ejected into the plasma.
4.1.2 Existing TES models

A number of theories have been put up to try to explain the effect of temperature enhanced sputtering. Though a lot of theories exist, there is little consensus over which theory describes the physics of enhanced erosion the best. Moreover, some may work pretty well for solids but fall apart once applied to liquids. A short review is given here:

Thermal Spike

In a thermal spike a high density of highly energetic ions are bombarded to the surface. This way an enormous amount of energy is bombarded into a small area, so that most of the target atoms will be in motion. Target particles are effectively evaporated off the surface, not sputtered. The evaporation rate is dictated by the temperature associated with the collision cascade, which can be significantly higher than the base target temperature. However, the thermal spike is only valid for keV collisions, so not applicable to the divertor regime where ion energies are in the order of eV.

Radiation Enhanced Sublimation

This theory suggest that interstitial-vacancy pairs are created by the ion bombardment of the surface. At higher temperatures, the interstitial diffuse out of the lattice and are eroded into the plasma. Since the interstitial do not need to overcome the lattice binding energy, diffusion will happen at much lower temperatures than evaporation. Arguments against the RES model include the high energies needed for the creation of a interstitial-vacancy pair (25eV for C). However, one way to create such a pair at low energy is by loop punching, where absorbed particles accumulate and push a particle out of the lattice by the high pressures rather than a high energy collision [41]. Another argument against the RES model is the fact that vacancy migration has been observed not to be dependent on incoming flux.

Radiation Activated Adatom Sublimation

Radiation Activated Adatom Sublimation is similar to RES in that the energy of incoming ions is used to lower the binding energy of the surface particle. In RAAS-theory, a surface atom is believed acquired energy from the stopping power of incoming ions. This energy is not enough to create an interstitial-vacancy pair, but enough to create an adatom. An adatom is a particle that is loosely bound to the surface, so that it takes an energy lower than the lattice binding energy to evaporate it off the surface. Though this model works for some solids and liquids, it is difficult to imagine adatoms in a liquid, where no real atomic lattices exist.

Inclusion Model

The Inclusion Model also assumes the presence of weakly bound adatoms on the surface, but proposes a different way of adatom production. The model suggests that incoming particles are implanted in the crystal lattice, reducing the binding energy through shielding and distortion of the lattice. Again, in a liquid the concept of a lattice with loosely bound atoms is difficult to imagine.

As a remark, though we call it 'Temperature Enhanced Sputtering', most models are actually some variant on 'particle enhanced evaporation'.
4.2 Measuring Erosion

To find out how much material is eroded we must find a way to measure it accurately. Weight-loss measurements are hard to conduct because of the high redeposition rates, and become impossible due to leaks in the target causing bulk liquid to drip out. The obvious alternative is Optical Emission Spectroscopy (OES). OES is a great tool for qualitative erosion analysis, as optical spectra are well documented and spectrometers can measure with a high resolution both in time and wavelength.

More challenging is to interpret the OES-spectra to get quantitative measurements. The intensity of atomic emission is proportional to the erosion rate, but this proportionality depends on plasma parameters such as temperature and density, that do not necessarily stay constant. Different lines can be excited by different atomic processes, so that the specific line one measures might not be fully proportional to the eroded flux anymore. To make things worse, OES measures almost by definition an integrated emission along the optical path, requiring the experimenter to be cautious with claims about the origin of the emission.

4.2.1 Tin spectral lines

To identify atomic line emission from tin in the spectra, OES-recordings were compared with literature values ([42], depicted in figure 4.6 and figure 4.7. In table 4.1 all Sn-lines with a relative intensity greater than 1000 are given.

Table 4.1: Sn I emission lines with a relative intensity greater than 1000 in the range of 294.15 nm to 455.40 nm

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Rel. Int.</th>
</tr>
</thead>
<tbody>
<tr>
<td>300.91333</td>
<td>12000</td>
</tr>
<tr>
<td>303.41150</td>
<td>10000</td>
</tr>
<tr>
<td>314.18232</td>
<td>2500</td>
</tr>
<tr>
<td>317.50354</td>
<td>15000</td>
</tr>
<tr>
<td>326.23310</td>
<td>15000</td>
</tr>
<tr>
<td>333.06072</td>
<td>4700</td>
</tr>
<tr>
<td>365.57764</td>
<td>1300</td>
</tr>
<tr>
<td>380.10108</td>
<td>6900</td>
</tr>
<tr>
<td>452.47344</td>
<td>2200</td>
</tr>
</tbody>
</table>

Except for the line at 314.2 nm, all lines could be identified in the measured emission spectra. The fact that there was no 314.2 nm line is most likely due to the combination of its low relative intensity and high signal attenuation by the optics in the UV-range. Lines different from those of tin were observed as well in the spectra, most notably are the plasma lines (H/Ar) and impurities like Mn and Ca. The Mn comes from the stainless steel clamping ring that contains a few percent of Mn, the Ca is present as trace elements in the source. The appearance of Ca lines in the spectra is therefore an indication of a degrading source.
Figure 4.6: Typical optical emission spectrum of Sn in an H-plasma from 294.15 nm to 455.40 nm

Figure 4.7: Typical optical emission spectrum of Sn in an Ar-plasma from 294.15 nm to 455.40 nm

4.2.2 S/XB-values

The erosion is measured by looking at line emission of neutral tin. The emission is directly proportional to the erosion \cite{18}:

\[ \Gamma = \sum_{\sigma} (S/XB)_{\sigma,j\rightarrow k} \cdot I_{\sigma,j\rightarrow k} \]  \hspace{1cm} (4.4)

Here \( \Gamma \) is the particle flux, and the sum is taken over the meta-stable states \( \sigma \) for a \( j \rightarrow k \) transition. To use this as a quantitative measurement, we need to know the S/XB-values explicitly.

The S/XB-coefficient is defined as the ratio of the effective ionization rate coefficient and the effective photon emissivity coefficient. It gives the linear relation between the measured atomic
emission rate and the particle flux of the species. S/XB-values have been calculated and/or experimentally obtained for various atoms under various conditions [43], but there is no data available for tin in plasma conditions relevant to our experiments.

In principle it is possible to measure S/XB values under relevant plasma conditions ourselves. S/XB-values could be obtained by eroding particles under plasma irradiation, measure the emitted line intensity, and weigh the mass loss of the target in order to calculate how much particles were eroded. The problem however, is that the plasma with the relevant conditions is so dense that redeposition of eroded particles becomes significant, for Li this can be up to 90%, as was recently found by in-house experiments. The high redeposition rate renders the weight loss measurement inadequate as a measure for the amount of eroded particles.

This means that either we can only do relative quantitative measurements that can be compared only within the same experiment, or we can try to find (crude) approximations for S/XB-values ourselves. We will generally stick to the former, while resorting to the latter wherever possible.

To interpret the spectroscopic measurements, the line emission of tin is divided by the plasma line emission, resulting in an estimate for the erosion yield. Note that this ratio should not be interpreted in the literal sense; a ratio of 2 does not necessarily mean that every plasma particle erodes two tin particles. Rather, if the ratio was increased by e.g. a factor 2, the erosion rate has increased with this same factor.

Finding S/XB-values

Referring to section 4.1, we recall that the (classical) erosion rate is a product of in-flux and sputtering yield. By combining this with our assumption that the ratio of an Sn line to a plasma line is proportional to the erosion we get the following relation, where we have used an argon plasma as an example:

\[ R(E) = Y_{ps}(E)\Gamma_{ion} \approx C_{\lambda} \frac{I_{Sn,\lambda}(E)}{I_{Ar}(E)} \quad (4.5) \]

Where \( R(E) \) is the erosion flux, \( Y_{ps} \) the sputtering yield, \( \Gamma_{ion} \) the measured particle in-flux, \( I_{Sn,\lambda} \) the intensity of Sn emission of wavelength \( \lambda \), and \( I_{Ar} \) the argon line intensity, all evaluated at an ion energy \( E \). Dividing eqn 4.4 by \( \Gamma_{ion} \) gives an explicit expression for the yield:

\[ Y_{ps}(E) \approx C_{\lambda} \frac{1}{\Gamma_{ion}} \frac{I_{Sn,\lambda}(E)}{I_{Ar}(E)} \quad (4.6) \]

The physical sputtering yield \( Y_{ps}(E) \) for Ar on Sn can be calculated for different incoming ion energies using the empirical fit given by [40]. Values for \( \Gamma_{ion}, I_{Sn,\lambda} \) and \( I_{Ar} \) can be obtained experimentally at different \( E \), so that an expression is obtained in the form \( y(E) = C_{\lambda} \cdot x(E) \). By analytically fitting the right hand side of eqn 4.6 to \( Y_{ps} \) with \( C_{\lambda} \) as the fitting parameter, we get the following expression for \( C_{\lambda} \):

\[ C_{\lambda} = \Gamma_{ion} \frac{\sum_{E} Y(E) \left( \frac{I_{Sn,\lambda}(E)}{I_{Ar}(E)} \right)}{\sum_{E} \left( \frac{I_{Sn,\lambda}(E)}{I_{Ar}(E)} \right)^2} \quad (4.7) \]

As can be seen from eqn 4.5, the value for \( C_{\lambda} \) can be used in much the same way as the S/XB-value, relating OES to particle erosion.

The next step is to measure the values for \( \Gamma_{ion}, I_{Sn,\lambda} \) and \( I_{Ar} \) for different incoming ion energies \( E \). The incoming ion energy is varied by applying a negative voltage to the target,
the so called bias voltage $V_{\text{bias}}$. By negatively biasing the target, the ions in the plasma are accelerated and gain energy which increases the probability to sputter a target particle. Though the ions gain energy by the acceleration of the bias voltage, their energy is not directly equal to $eV_{\text{bias}}$. The reason for this is that the plasma is not at zero potential but at its plasma potential $V_{\text{plasma}}$. Because the particles’ potentials are offset by an amount of $V_{\text{plasma}}$, only $V_{\text{bias}} - V_{\text{plasma}}$ is left for accelerating the ions to the target, giving them an energy of:

$$E_{\text{ion}} = e(V_{\text{bias}} - V_{\text{plasma}})$$

A typical plasma potential for an Ar-plasma is $-5$ V.

Since we need to be in the classical sputtering regime, the target temperature must stay as low as possible. For this reason the measurement was done using a low, steady state magnetic field of 0.2 T and an arc current of 180 A. The bias voltage was then steadily increased from 0 V to $-45$ V with steps of 2.5 V. $\Gamma_{\text{ion}}$ was measured using Thomson Scattering and found to be relatively independent on bias voltage. The average value was measured to be $1.01 \times 10^{24}$ m$^{-2}$ s$^{-1}$.

**Argon emission lines**

Because of the low plasma power used in order to keep the target temperature as low as possible, the spectrum looks a lot different from those in section 4.2.1. The spectrum at $V_{\text{bias}} = -40$ is given in figure 4.8. Still some Sn-lines can be observed, but the spectrum gets really crowded starting from $\sim 330$ nm. So crowded in fact, that it becomes difficult to decide which line belongs to which species.

![Figure 4.8: Optical emission spectrum of Sn in a low power Ar-plasma at $V_{\text{bias}} = -40$ V from 294.15 nm to 455.40 nm.](image)

To help identify the lines we look at their evolution, in this case in $V_{\text{bias}}$. First the signal was background corrected by subtracting the intensity at the left and right of the peak. Then the signal was normalized by dividing by its average intensity over the bias scan. This normalization is necessary to make it possible to directly compare the line evolutions. It can be seen from figure 4.9 that the evolution of the different lines is similar, hence we conclude they all belong to the same species, which is Ar in this case. The reference Ar-line that is selected for $I_{\text{Ar}}$ is the one at 347.59 nm (note that the non-normalized value was used here for $I_{\text{Ar}}$).

The reader may notice that only a few of the peaks in figure 4.8 were identified, which are not at all the most intense ones. This has two reasons: Firstly, the most intense peaks tend to
Figure 4.9: Intensity of Argon spectral lines at different wavelengths normalized over their average, as a function of bias voltage.

saturate at low values for $V_{\text{bias}}$, which makes it impossible to compare their evolution properly. Secondly, all the lines were compared with literature values for Ar. The lines were only identified as an Ar-line when a literature value could be found that lies within the error of the spectrometer (at most $\pm 0.5 \text{ nm}$).

Tin emission lines
Five lines were identified for Sn from the spectrum in figure 4.8: 300.91nm, 303.41nm, 326.23nm, 333.06nm and 425.48nm. The lines were first background corrected in the same way as the Ar-lines. Instead of normalizing the lines by their average, the Sn-lines are divided by the 347.59nm Ar-line, and this ratio was used to find a value for $C_{\lambda}$ using eqn 4.7. From figure 4.10 it can be seen that the evolution of the intensity ratio with increased bias voltage follows the theoretical curve pretty well. The fitted curves line up nicely with the theoretical yield, which gives us confidence in the method we are using. In the next section we can therefore apply the same technique to determine $C_{\lambda}$ values for the practical plasma shots.

4.2.3 What line to choose?
First we will determine the $C_{\lambda}$ values for a practical shot. The temperature increase in the target increases erosion (as we will see in section 4.4), so this complicates the calibration. To make sure we are influenced by temperature enhancements as little as possible, we look only at emission data at low temperatures. This criterium was found to be met at temperatures under 850°C.
Since we don’t have a full bias scan this time, but only scan over a temperature range we can’t fit the theoretical yield as a function of particle energy. We will therefore assume the theoretical yield to be constant and sum over the temperature:

\[
C_\lambda = \Gamma_{\text{ion}} Y_E \sum_T \left( \frac{I_{\text{Sn,}\lambda}(T)}{I_{\text{Ar}}(T)} \right) \sum_T \left( \frac{I_{\text{Ar}}(T)}{I_{\text{Ar}}(T)} \right)^2
\]  

(4.9)

The shot is an Ar-plasma with \(B = 0.4\ T\), \(I_{\text{cat}} = 110\ \text{A}\) and \(V_{\text{bias}} = -30\ \text{V}\), at which the theoretical sputtering yield for \(\text{Ar} \rightarrow \text{Sn}\) is 0.01271. The measured ion flux was \(\Gamma_{\text{ion}} = 6.18 \times 10^{23} \text{ m}^{-2} \text{s}^{-1}\), and we consider the same wavelengths as in section 4.2.2. The values for \(C_\lambda\) are given in table 4.3.

To see if the different lines increase the same way with increased target temperature, we plot a temperature scan in figure 4.11. It is apparent that even at temperatures well above 850° the erosion fluxes predicted by intensity ratios of different wavelengths is the same. This means that none of the lines is preferential according to this data.

For a line to be a good measure for the erosion flux, we consider that there are different mechanisms with which an atom can be excited. Atoms can be excited by: 1) Electronic excitation, 2) Recombination, and 3) Charge exchange. Preferably we would select a line whose excitation is dominated by electronic excitation because this is proportional to the neutral density, in contrast to recombination and charge exchange which is (also) dependent on the ion density. We assume
Table 4.2: Values of the fitting parameter $C_\lambda$

<table>
<thead>
<tr>
<th>Scaling Parameter</th>
<th>Value in $\text{m}^{-2}\text{s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{300.91}$</td>
<td>$2.1905 \times 10^{23}$</td>
</tr>
<tr>
<td>$C_{303.14}$</td>
<td>$2.4004 \times 10^{23}$</td>
</tr>
<tr>
<td>$C_{333.06}$</td>
<td>$2.8916 \times 10^{22}$</td>
</tr>
<tr>
<td>$C_{452.48}$</td>
<td>$5.1641 \times 10^{22}$</td>
</tr>
</tbody>
</table>

Table 4.3: Values of the fitting parameter $C_\lambda$ for a practical shot

<table>
<thead>
<tr>
<th>Scaling Parameter</th>
<th>Value in $\text{m}^{-2}\text{s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{300.91}$</td>
<td>$2.2351 \times 10^{22}$</td>
</tr>
<tr>
<td>$C_{303.14}$</td>
<td>$1.1904 \times 10^{22}$</td>
</tr>
<tr>
<td>$C_{333.06}$</td>
<td>$9.5165 \times 10^{21}$</td>
</tr>
<tr>
<td>$C_{452.48}$</td>
<td>$4.4116 \times 10^{21}$</td>
</tr>
</tbody>
</table>

Figure 4.11: Erosion flux estimated by OES at different wavelengths

that excitation levels with a lower energy are more likely to be excited by electronic excitation. The Grotrian plot in figure 4.12 shows the energy levels and electronic configurations of all the transitions responsible for the observed spectral lines. The lowest excited levels correspond to transitions from $5s^25p\,n_s \rightarrow 5s^25p\,n_p$. This still comprises most of the lines that are observed, so this doesn’t indicate that any line is preferential.

Having no additional selection criteria, one line was arbitrarily selected. We require the
Figure 4.12: Grotrian plot depicting the different electronic transitions in Sn and the corresponding wavelength of the emitted photons. Only transitions within the spectrometer range (294.15 nm–455.40 nm) were plotted.

line to be not too far in the UV, and not to be obfuscated by any plasma lines. The line at 333.06 nm fits this description, and hence this is the line we will use as a measure for erosion in the measurements.

4.3 Measuring Temperature

Temperature is generally measured in two ways: by direct measurement using a thermometer or thermocouple, or by looking at the emitted infrared radiation. As our experiments require surface temperature measurements in highly non-equilibrated systems, thermometers are not an option and we must resort to infrared thermography. In chapter 3 we already briefly discussed the difficulties of acquiring an absolute temperature by measuring IR-radiation. In this section we will see how these difficulties manifest themselves in practice, and what can be done to
circumvent the problems.

4.3.1 Cross Calibration

Picking up on the discussion in section 3.2.2, we conclude that to do absolute temperature measurements with the IR-camera, we need to find the emissivity of the object. To find the emissivity the IR-signal is cross calibrated with the pyrometer. To get a calibration as accurate as possible, it is of vital importance to find the position on the IR-image where the pyrometer was measuring. To this end, the pyrometer was aligned at the center of the target and the pixels that correspond to the center of the target were located in the IR-image.

![Figure 4.13: Weight of the IR-pixels used in the pyrometer cross-calibration. The shaded area depicts the position of the pyrometer view spot. This area determines the weight of each pixel in the total IR-signal.](image)

Pyrometer

The pyrometer measures at a spot with a radius of 1 mm, on the IR-image this corresponds to 1.22 pixels. To account for the size of the pyrometer spot, the IR-signal that was used for comparison is a weighted sum of the center pixel and its eight nearest neighbors. The weighting factor was determined by finding the relative area of the pixel that contributed to the pyrometer signal. Looking at figure 4.13, this means dividing the shaded area by the white area for each pixel. The weights of center, edge and corner pixels were determined to be 1.000, 0.685 and 0.234 respectively.

Since the target size on the IR-image is only 35 × 40 pixels, it is assumed that the error in determining the center can be up to 1 pixel in all directions. To estimate the error in the emissivity as a result of this uncertainty of the center pixels, the IR-signal was cross calibrated for the center pixel and its eight surrounding nearest neighbors (for each applying averaging as depicted in figure 4.13). The result is shown in figure 4.14.

Finding Emissivities

There are a few things that can be observed from this graph. We first note that the average emissivity is roughly 0.07. This value is low as expected, but higher than the literature values of 0.04–0.06. The next thing to notice is that there is a huge variation in the emissivity offset. The range of ~0.02 doesn’t seem big, but since the emissivity is so low this amounts to an appreciable relative value of 30%~50%. This means that exact location of the IR-spot is very important, and that the uncertainty in its location ultimately introduces large errors in the temperature. We see that the slope of the emissivity with temperature is significant, so we conclude that assuming a constant value for $\epsilon$ is not justified. Finally, though the offset error is quite big, the slope seems to be reasonably constant.
Because the emissivity is a material property, its value should not depend on the particular plasma it was measured in. To verify the emissivity under different settings, the measurement as described above was conducted for four shots with different bias (the details of these shots are described in section 4.4.2). The emissivity as a function of temperature was determined for the best-guess center pixel and its 8 nearest neighbors and the average is plotted against temperature in figure 4.15. The error bars depict the standard deviation of the nine traces with respect to the average value. We see that the -35V and -40V shot line up as expected, but for the -30V and -25V shot we again see offset deviations.

As a general observation, we see that the slope of the emissivity is reasonably constant and significant. This suggest that temperature dependence of the emissivity should be included in some way. Since there is little theory available on how the emissivity changes with temperature, we have to make some assumptions ourselves to incorporate the temperature effects on the emissivity. The following assumptions were thus made:

1. At room temperature we assume $\epsilon_0 = 0.05$, the average of the literature values (0.04-0.06)
2. At high temperatures $\epsilon$ is given by $\epsilon(T) = 6.86 \times 10^{-5} T + 0.004$, the linear fit
Figure 4.15: Emissivities as a function of temperature, found by correlating pyrometer with IR-camera data

3. Until it starts to increase linearly, the emissivity remains constant.

The emissivity as a function of temperature obtained this way is plotted in figure 4.16. Some comments on the assumptions made are in order here:

The first assumption seems reasonable, as there are no criteria that make any value preferential in the given range.

The second assumption is probably the hardest to defend, as it directly contradicts some of the measured data. The reasoning here is that the measured emissivities at -35V and -40V span the largest range (larger than that of -25V and -30V) and they overlap with each other. Given these datasets where some data necessarily has to be rejected, extrapolating the fit through -35V and -40V therefore doesn’t seem to be an unreasonable assumption. The series of -25V and -30V now add to the uncertainty in the emissivity, in section 4.3.2 we will see how much this influences the temperature.

The third assumption doesn’t seem so bad again. It does introduce a kink at the point where the linear dependence kicks in which is almost certainly not physical, but it’s not so bad as a first order approximation and we don’t really have anything better either. As a remark, most
erosion effects are expected to be observed at high temperatures anyway, so errors introduced by the kink are not expected to be disastrous to the results.

4.3.2 Temperature Error

Now that we have established an expression for the emissivity we should check how the uncertainties in emissivity propagate to the temperature. In other words, we’d like to find:

\[ \Delta T = \left| \frac{\partial T}{\partial \epsilon} \right| \Delta \epsilon \] (4.10)

To this end we have plotted the temperature evolution of the -40V shot for different values of \( \epsilon \) in figure 4.17a. \( T_0 \) is the time evolution of the temperature with an emissivity of \( \epsilon = 0.073 \), \( T_\pm \) are plots of the same temperature evolution but with an epsilon of \( \epsilon = 0.073 \pm 0.005 \) (one standard deviation). We find that the change in temperature due to the 1 SD change in \( \epsilon \) is equal to about 5%.

If we divide the change in temperature by the change in emissivity we get a value for \( \left| \frac{\partial T}{\partial \epsilon} \right| \), that we can plot against temperature. Plotted in figure 4.17b, this shows the propagation of an error in the emissivity at a certain temperature. We see that the propagation goes linear.
(a) The temperature evolution of a single shot, assuming either the average emissivity or one SD added/subtracted

(b) The rate-of-change in temperature with respect to emissivity, plotted against temperature. Essentially this plot should resemble a variation of the $f_{cal}$ plots.

Figure 4.17: Error propagation of emissivity

with temperature. In fact, we can arrive at this relation by recalling how the temperature is calculated:

$$P_{obj,bb} = \frac{P_{meas}(T) - P_{meas}(T_0)}{\tau \epsilon} + f_{cal}^{-1}(T_0)$$

(4.11)

$$T_{obj} = f_{cal}(P_{obj,bb})$$

(4.12)

And then differentiate relation 4.11 to $\epsilon$:

$$\frac{\partial T}{\partial \epsilon} = \frac{\partial f_{cal}}{\partial P} \frac{\partial P}{\partial \epsilon} = \frac{\partial f_{cal}}{\partial P} \cdot \frac{-\left( P_{meas}(T) - P_{meas}(T_0) \right)}{\epsilon^2}$$

(4.13)

Since $f_{cal}$ is approximately linear (especially at high temperatures where $hc \ll \lambda k_B T$ justifies this approximation), we note that:

$$\frac{\partial f_{cal}}{\partial P} \approx \text{const.}$$

(4.14)

$$f_{cal} \propto P \Rightarrow f_{cal}^{-1} \propto T$$

(4.15)

And that:

$$-\left( \frac{P_{meas}(T) - P_{meas}(T_0)}{\epsilon^2} \right) \propto \frac{f_{cal}^{-1}(T)}{\epsilon}$$

(4.16)

And finally, by combining eqns 4.14–4.16 we find that:

$$\frac{\partial T}{\partial \epsilon} \propto \frac{T}{\epsilon}$$

(4.17)

Which is what we observe in the plot. We also see from the $\frac{1}{\epsilon}$ term that the low emissivities make the propagation of an error in $\epsilon$ worse.
We note that even if the error in the IR temperature measurement would become large, when the temperature is high enough the pyrometer can still measure the surface temperature. This way, we can always tell what the upper limit of the temperature was. This is important, because we expect erosion to become significant at high temperatures.

4.3.3 Temperature Stability

![Temperature Stability Diagram](image)

Figure 4.18: The dip in temperature can be explained by a migration of bulk tin. Image A to D depict IR-recordings showing bulk tin moving over the target thus changing the temperature at the center of the target. The red line indicates the region where the intensity is half of the max value.

In quite a few cases we observe a dip in the target temperature evolution of a single point during a shot. With an exception of some of the most recent targets, the mesh that was supposed to contain the liquid tin broke for all targets at some point during the shots, as depicted in figure 4.18. Without the tin being constrained by anything, the liquid is free to move all over the target. In addition, on the pristine targets where the mesh was intact, the excess tin on top of the mesh still was able to migrate along the surface of the target. Because we’re mostly interested in surface effects, the moving liquid is a nuisance, but not insurmountable. While the moving liquid is responsible for the dips in the temperature, as long as OES and IR are aligned properly — looking at the same point of the target that is — it just provides us with an additional scan over the temperature, so to speak. This extra scan actually helps in the measurements, because it helps to distinguish between actual temperature effects and effects of starting up the plasma.

In Figure 4.18 the evolution of such a dip in temperature is followed in time. Snapshots are shown of the surface’s IR-signal during the dip. It can be seen that indeed bulk tin migrates along the surface, influencing the time-trace of the temperature.
4.4 Results

4.4.1 Experimental Procedure

Now that we know how to measure erosion and temperature, we can focus on the experiment itself. To investigate the temperature dependence of the erosion, we need to make a scan in the target temperature while maintaining a constant flux. To do this, the target described in chapter 2 was heated by the plasma for 10 s. Since the target is heated only by the plasma the target starts at room temperature, melts, and its temperature is further increased until temperature saturates at some $\sim 1200^\circ$C.

Figure 4.19: A typical shot in Pilot-PSI. The red line indicates the target temperature, the blue line the applied bias and the green line the measured intensity.

The temperature- and erosion measurements are triggered synchronously by the triggering system and recorded with respect to time. An example of a typical shot is shown in figure 4.19. Here we see that when the B-field and bias are turned on, the target temperature is steadily increasing. We make sure that the analyzed data is taken within our so called ‘measurement window’, the times at which both magnetic field and bias are on. This ensures that any observed effects are measured under stationary plasma conditions.
4.4.2 Ar-plasma

We want to measure how erosion of liquid tin depends on the temperature of the surface. We know that erosion is a combination of evaporation and sputtering, which might include a temperature dependent term. For this reason our first experiment will be in an Ar plasma, which is known to sputter Sn particles already at moderate bias voltages ($E_{th} = 11.9822$ eV). Although a fusion plasma consists of mainly D and T, not Ar, measurements in Ar are still relevant for fusion plasma’s. In a tokamak, so called ‘seeding impurities’ (N$_2$, Ne, Ar) are introduced in the edge plasma to help cool the plasma by radiating the power away. It is in fact these seeding impurities, not the hydrogen plasma, that do the worst damage to the wall in terms of sputtering.

We know that classical sputtering is increased with increased (negative) biasing, and we want to see if the same is true for the temperature dependent part. This suggests to do temperature-evolution shots (as described in 4.4.1) for different bias voltages and compare the results, to see what effect the bias-voltage has on the erosion. Four shots were compared with a bias voltage of $-25$ V, $-30$ V, $-35$ V and $-40$ V respectively.

![Figure 4.20: Erosion of tin under Ar-plasma at different bias voltages. The temperature dependency increases significantly with increased bias voltage.](image)

In figure 4.20 the Sn-erosion measured by the 333.06 nm line is plotted against the temperature. First of all, we see that at low temperatures ($T < 800$ $^\circ$C) erosion is increased with increased negative bias, which is expected for classical sputtering. The sputtering rate at $-25$ V
is really small, but by comparing this with the plot in figure 4.10 (Note: $V_{\text{bias}} = -25\,\text{V} \Rightarrow E_{\text{ion}} = 20\,\text{eV}$, see eqn 4.8) we see that the yield should be really small at this bias voltage.

The next thing we observe is that the erosion starts to increase exponentially at around $\sim 1000\,^\circ\text{C}$. An exponential increase at such a low temperature is something that can not be explained by classical theory (evaporation), so this does indicate that there is indeed a TES term involved here. By plotting the erosion on a logarithmic axis we get a better view on what exactly is going on, this can be seen in figure 4.21.

From the log-plot it becomes apparent that the exponential increase in erosion for bias voltages from $-30\,\text{V}$ to $-40\,\text{V}$ all seem to follow the same curve. Hence we conclude the effect doesn’t depend on applied bias voltage (or ion energy). Even the erosion at $-25\,\text{V}$ takes the same slope as the others once the exponential increase becomes significant. Because little sputtering is expected at this bias voltage (see the plot in figure 4.10), this implies that the erosion is due to an thermal effect rather than a sputtering effect.

![Figure 4.21: Logarithmic plot of erosion of tin under Ar-plasma at different bias voltages.](image)

4.4.3 H-plasma

In the second experiment a H-plasma was used, as this is the more common plasma species in a typical divertor region. For the H-plasma, similar results have been observed as for the experi-
In figure 4.22 the erosion flux is plotted against surface temperature, for bias voltages from $-45\,\text{V}$ to $-70\,\text{V}$ (at bias voltages lower than $-45\,\text{V}$, no erosion was observed).

The $400\,\text{°C}$ at which the erosion starts to become appreciable is way lower than the temperature of $1400\,\text{°C}$ at which classical evaporation becomes significant. Even if we’re not confident about the emissivity of Sn in this case, the fact that the pyrometer didn’t record any values means the temperature was indeed not exceeding $\sim 1000\,\text{°C}$.

In order to make quantitative observations, we have determined $C_{\lambda}$-values in a different way. Since the sputtering threshold of $\text{H} \rightarrow \text{Sn}$ is so high, the incoming ion energy is not high enough to sputter Sn-particles ($V_{\text{bias}}$ higher than $\sim 70\,\text{V}$ causes arcing). What we therefore did, is relate the absolute line intensities of Sn in Ar-plasma and Sn in H-plasma with each other. Recall that we got (equation 4.5):

$$R \approx C_{\lambda,\text{Ar}} \frac{I_{\text{Sn},\lambda,\text{Ar}}}{I_{\text{Ar}}} \quad (4.18)$$

Here we have added the label $\text{Ar}$ to keep track of which plasma the Sn-line is coming from. In other words, $I_{\text{Sn},\lambda,\text{Ar}}$ means: 'The intensity of an Sn-line at wavelength $\lambda$ in an Ar-plasma'.
The same is obviously true for an H-plasma:

\[ R \approx C_{\lambda,Ar} \frac{I_{Sn,\lambda,Ar}}{I_{Ar}} \approx C_{\lambda,H} \frac{I_{Sn,\lambda,H}}{I_{H}} \]  \hspace{1cm} (4.19)

Now we will make one challenging assumption: we assume that at an equal erosion rate, the absolute intensities \( I_{Sn,\lambda,Ar} \) and \( I_{Sn,\lambda,H} \) are the same regardless of the plasma species they’re in. This allows us to drop the plasma species label and get back our original term \( I_{Sn,\lambda} \). This assumption is true as long as the plasma temperatures are comparable, and the charge exchange rates are equal.

Having made this assumption it’s straightforward to arrive at the following equation:

\[ R \approx C_{\lambda,Ar} \frac{I_{Sn,\lambda}}{I_{Ar}} \approx C_{\lambda,H} \frac{I_{Sn,\lambda}}{I_{H}} \Rightarrow C_{\lambda,H} \approx C_{\lambda,Ar} \frac{I_{H}}{I_{Ar}} \]  \hspace{1cm} (4.20)

Because the intensities of the plasma lines are reasonably constant over time and temperature, this results in one constant value for \( C_{\lambda,H} \) that was determined to be \( 3.1536 \times 10^{21} \text{ m}^{-2} \text{ s}^{-1} \) for \( \lambda = 333.06 \text{ nm} \). We remark that the approximation \( I_{Sn,\lambda,Ar} = I_{Sn,\lambda,H} \) seems rough, but even if the error is large it is still useful to at least compare the data with the empirical evaporation curve of Sn.
One could argue that the increase in OES-signal is due to evaporation of Sn at a position other than the point where the temperature and OES is measured. If the temperature profile is highly non-uniform for example, Sn might evaporate from hot spots and subsequently cross the optical path of the OES, which in turn is observed as an increase of erosion at a moderate temperature. To see if this is the case, a new time-trace of the temperature was made, but this time at every frame the maximum temperature is plotted rather than the temperature at the same specific spot. The results can be found in figure 4.24a. The position on the target where the maximum temperature was found is given in figure 4.24b, where the area of the red dots is equal to the frequency of that pixel being the hottest.

We see that indeed the maximum temperature can be quite a bit higher than the temperature of the center at some frames, and the maximum temperature of $\sim 1100^\circ$C would result roughly in the evaporation we're measuring. However, we note that the maximum temperature goes down with time, while the erosion goes up with time. This indicates that we are indeed looking at erosion from the center and that the erosion onset temperature is indeed much lower than would classically be expected.

We conclude this chapter by looking into the errors in the erosion values. The error in the erosion would be mainly due to the uncertainty in the determination of the $C_\lambda$ values. One thing that we have not touched in this matter is the ion energy, given by equation 4.8. The ion energy was determined from the bias voltage and the plasma potential, assumed to be $-5$ V. For the Ar-plasma, this value was assumed to be such that it produced curves that fitted the theoretical yield in figure 4.10. In a way, this means the value was verified for the Ar-plasma shots. For the H-plasma, this value might actually differ a lot, making the $-5$ V a lower estimate (in magnitude). This means that the magnitude of the plasma potential could be higher than we have assumed for the H-plasma, which would effectively mean that the ion energy is lower than assumed, making the case of TES even stronger.

As a final remark, we note that even if the error in the erosion would be significant, the classical evaporation curve still does not agree with measurements if the error is taken into account.
(a) Temperature in the center compared to the maximum temperature at any given time-frame

(b) Location of the maximum temperature. All maximum temperatures were found on the target itself. The area of the spot is a measure for the frequency a maximum was found there.

Figure 4.24: Location and value of the maximum target temperature
Chapter 5

Heat Exhaust

The heat flux to the divertor plates is massive, and exhausting all that heat is a difficult challenge in a tokamak. In a divertor, the thermal conductivity and thickness of the wall material puts a limit to the steady state heat flux. For ITER, this upper bound is 10 MW m$^{-2}$ [6]. To prevent component damage, the materials used in the divertor should transfer this heat to the cooling water as quickly as possible, this holds for liquids just as well as for solids.

While the ITER divertor is water-cooled, DEMO’s divertor is might be cooled by superfluid He [48] which has inferior cooling capabilities compared to water, but this is still under discussion. In any case, DEMO’s thermal power output will be much larger than ITER’s [9]. Since the heat flux is already at the materials’s limit in ITER, the consequence is that the heat to the divertor must be reduced one way or another. Liquid metals might help to reduce the heat to the target through an effect called Vapor Shielding. The effect suggests that the plasma interacts with the vapor cloud and provides a volumetric dissipation of the power before it reaches the target plate.

But before we can find what the influence of the liquid metal is on the exhausted power, we need a way to measure by how much the target power is reduced. A metric needs to be devised that measures how well a material transfers incoming heat to the coolant, such metric should help to characterize Sn and other liquid metals in the future, enabling us to compare their performance to that of solid metal walls and assess their viability in a divertor.

To summarize, in this chapter we want to measure the heat exhaust capabilities of the liquid target. In order to do that, we need to develop a way to quantify the heat exhaust capability and find out how the target behaves under divertor conditions.

To this end, we will first look into methods for studying the thermal response in section 5.1, resorting to thermography (section 5.1.1) and cooling water calorimetry (section 5.1.2). After that we will focus on vapor shielding in section 5.2. In section 5.2.1 the effect will be explained in more detail, while in section 5.2.2 we will focus on how to measure the effects to the plasma. Finally in section 5.3 we will present the results of these measurements.

5.1 Quantifying Heat Exhaust

From the introduction it has become clear that it is important to be able to quantify the heat exhaust capabilities of a (liquid) wall material. In the end, experiments in linear devices such as Pilot-PSI should assess how viable a specific material is in a divertor environment where plasma and heat are strongly coupled. The need for a good benchmark is therefore twofold: it’s necessary to quantify the effect of vapor shielding in our experiments, but more importantly it is needed to
be able to test and compare different liquid metals over time and to find out which is the most suitable in the end.

In this work we have chosen to pursue two methods: Thermographic measurements, explained in section 5.1.1, and calorimetric measurements, explained in section 5.1.2.

5.1.1 Thermographic Measurements

Under similar cooling conditions, increased heat directed to a target will result in a rise of the surface temperature. The surface temperature can therefore be used as a measure for the heat to the target. As is discussed in section 4.3, measuring surface temperatures with the IR-cam can be difficult. The moving liquid distributes the heat in uncontrollable ways, and drips of hot metal provide a way to remove heat that is not accounted for. Moreover, for a fair comparison, the same meticulous calibration of the emissivity should be conducted for the reference material (Mo in this case).

However, thermography can be used without finding exact values for the emissivity. By looking at the temperature evolution, one can still get an idea of how heat is directed to a target. To illustrate this, consider e.g. the temperature of one target steadily rising, and the temperature of another target starting with the same rise, but then suddenly saturating. This would be an indication of an additional heat loss channel for the second target. Though absolute emissivities are not necessary, the temperature dependence would be necessary to accurately interpret the temperature evolutions.

5.1.2 Calorimetric Measurements

For calorimetric measurements, the difference in temperature of the incoming and outgoing cooling water is measured as a function of time. By integrating the temperature difference over time, an expression for the removed heat can be found:

$$Q_{out} = c \rho \phi \int_{t_0}^{t_1} \Delta T(t) \, dt$$  \hspace{1cm} (5.1)

Where $c$ is the specific heat of water, $\rho$ the density of water, $\phi$ flow rate of the cooling water, and $\Delta T(t)$ is the measured temperature difference at time $t$. The heat removed by the cooling water $Q_{out}$ is then a measure for the total heat to the target. The advantage of a calorimetric approach is that details are evened out and it is possible to compare integral values. However, the rise in temperature of the cooling water is rather slow compared to the shot duration because of the relatively large heat capacity of the target. It is therefore only possible to look at total exhausted heat (i.e. integrated over time) and not the instantaneous power exhaust.

Since calorimetry takes into account all heat that is directed to the target, it would be difficult to observe the rather subtle effect of vapor shielding. The effect is expected to be significant only in the center of the target where erosion is substantial, which is only a small fraction of the total plasma wetted area.

5.2 Vapor Shielding

Now that we know how we can quantify the heat to the target, we will first review the vapor shielding effect. After elaborating on the vapor shielding effect itself in section 5.2.1, we will present some techniques how the effect might be observed experimentally in section 5.2.2.
5.2.1 What is Vapor Shielding?

When atoms are ejected from the surface, either by sputtering or evaporation, they interact with the plasma particles. If the mean free path of neutral Sn is not too long, the atoms will be ionized by the plasma and return to the target. During the plasma-vapor interaction, energy is transferred to the impurity (Sn) ions that can radiate the power away. Effectively, energy is dissipated in the vapor this way, reducing the net power to the target.

This effect is called Vapor Shielding and has been documented in literature [50], [45]. A regime where vapor can be confined near the surface and provide efficient vapor shielding is of high interest for power exhaust in future reactors [12].

5.2.2 Spectroscopic analysis

The vapor shielding effect manifests itself by strong interactions with the plasma. Ideally we would look at the spatial distribution of atomic Sn to analyze the plasma-vapor interactions. However, since optical band pass filters for Sn emission lines were not available at the time of measurement, we resort to the measurement of hydrogen Balmer emission profiles. The strong plasma-vapor interactions we expect in the vapor shielded regime, result in an increase of electron density. An approximation for the neutral density can be given by the intensity of hydrogen emission lines [51]:

\[ I_{H_\lambda} = C_{H_\lambda} k_{H_\lambda} n_e \]  

(5.2)

Here \( I_{H_\lambda} \) is the measured intensity at a specific wavelength \( \lambda \), \( C_{H_\lambda} \) a constant dependent on \( \lambda \) and \( n_e \) the electron density. \( k_{H_\lambda} \) is the rate constant for excitation of hydrogen, and is given by

\[ k_H = \frac{1}{\sqrt{2m_e}} \int \sqrt{E} \sigma_H(E) f(E) dE \]  

(5.3)

Where \( m_e \) is the electron mass, \( E \) the energy, \( \sigma_H(E) \) the excitation cross-section and \( f(E) \) the energy distribution function. By dividing two intensities of line-emission at a different wavelength, this ratio reduces to the Boltzmann-factor:

\[ \frac{I_{H_b}}{I_{H_a}} = \frac{C_{H_b}}{C_{H_a}} \exp \left( -\frac{\Delta E_{ab}}{k_B T_e} \right) \]  

(5.4)

Here \( I_{H_{a,b}} \) is the measured intensity of a line at \( a \) or \( b \), \( \Delta E_{ab} \) is the energy difference between the levels \( a \) and \( b \), \( k_B \) is the Boltzmann constant and \( T_e \) is the electron temperature. \( H_a \) and \( H_b \) can be any emission line of hydrogen, as long as \( \lambda_{H_a} > \lambda_{H_b} \). We will focus only on optical emission, i.e. the Balmer series for hydrogen. Equation 5.4 can be rewritten to get an explicit expression for \( T_e \):

\[ T_e \sim \frac{1}{\log \frac{I_{H_a}}{I_{H_b}}} \]  

(5.5)

To measure the intensity profiles of the different Balmer-lines, the same shot was repeated multiple times while each time the profile of a different Balmer line was measured. The profiles were measured by an optical camera that was equipped with a narrow band pass filter to select a specific emission line. The lines that were measured are \( H_\alpha, H_\beta \) and \( H_\gamma \). \( H_\beta \) was not measured because the pass band of the corresponding filter includes the SnI line at 498.0 nm.
Abel Inversion

Measuring the profiles in this way will result in line integrated values of the local emission. What we really want is to find local values, that are a direct measure for the density. For a cylindrically symmetrical system, the line integrated values can be considered as an Abel-transformation of the emission data:

\[
I(y, z) = \int_{r}^{R} \frac{e(r, z)r}{\sqrt{y^2 - r^2}} dy = A[e(r, z)]
\]  

(5.6)

Where \(I(y, z)\) is the line integrated value that is measured at vertical position \(y\) and axial position \(z\), and \(e(r, z)\) is the local emission at radial coordinate \(r\). The radial values can then be calculated by taking the inverse transform:

\[
e(r, z) = A^{-1}[I(y, z)]
\]

(5.7)

The two most common techniques to calculate the inverse transform is by either: 1) Fitting a simple function and calculate the inverse analytically, or 2) Calculate the inverse numerically with matrix multiplication. Since the profiles that were recorded can be quite complex, fitting them with a simple function results in much loss of detail. For this reason a numerical transformation was chosen.

It can be shown [52] that for discrete data, the Abel transform reduces to a matrix multiplication:

\[
y = Ax \iff x = A^{-1}y
\]

(5.8)

where \(y\) is the line integrated measurement and \(x\) the local emission. Note that a \(y\)-vector is measured for every axial coordinate \(z\) (comprising the 2D-recording). The matrix \(A\) and its inverse \(A^{-1}\) depend only on the geometry of the measured system, this means that it has to be calculated only once and can then be applied to every vector \(y\) of line integrated data. For details on calculating the inverse matrix \(A^{-1}\) refer to [52].

The definition of the transform requires the intensity vector \(y\) to start at the center of symmetry (in this case the center of the plasma beam). One implication is that since the camera measures the entire 2D-profile, the transform can be applied to either the upper or lower half of the recorded image. In this work both halves were transformed and compared to each other as a consistency check. Another implication is that finding the center becomes extremely important. In this work the center was found by fitting a Gaussian function to \(y\) for each axial coordinate \((z)\).

After transformation the center of the profile (near \(r = 0\)) is particularly noisy. The noise was removed by removing the 6 pixels in the center and replacing them by interpolations of the remaining data with a Gaussian fit.

5.3 Results

5.3.1 Experimental Procedure

To examine what the influence of the liquid is on the heat exhaust, 6 shots with increasing power were performed for both a liquid Sn target and a Mo reference target under H-irradiation. Table

\footnote{i.e. a function for which an inverse exists}
Table 5.1: Details of the compared shots

<table>
<thead>
<tr>
<th>Shot</th>
<th>$I_{cat}$ (A)</th>
<th>$B$ (T)</th>
<th>$V_{bias}$ (V)</th>
<th>$Q$ (slm)</th>
<th>$n_e$ ($10^{20}$ m$^{-2}$s$^{-1}$)</th>
<th>$T_e$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>170</td>
<td>0.4</td>
<td>0</td>
<td>2.5</td>
<td>1.44</td>
<td>0.75</td>
</tr>
<tr>
<td>B</td>
<td>170</td>
<td>0.4</td>
<td>-30</td>
<td>2.5</td>
<td>0.96</td>
<td>0.50</td>
</tr>
<tr>
<td>C</td>
<td>190</td>
<td>0.8</td>
<td>0</td>
<td>2.5</td>
<td>6.46</td>
<td>1.28</td>
</tr>
<tr>
<td>D</td>
<td>190</td>
<td>0.8</td>
<td>-30</td>
<td>2.5</td>
<td>5.33</td>
<td>0.89</td>
</tr>
<tr>
<td>E</td>
<td>190</td>
<td>1.2</td>
<td>0</td>
<td>2.5</td>
<td>15.4</td>
<td>1.85</td>
</tr>
<tr>
<td>F</td>
<td>190</td>
<td>1.2</td>
<td>-30</td>
<td>2.5</td>
<td>12.5</td>
<td>1.64</td>
</tr>
</tbody>
</table>

*Shot F was repeated multiple times as needed for the spectral measurements. The discussion in section 5.4.3 and section 5.4.4 is based on these repetitions.

5.1 summarizes the specifics of each shot, divided into three sections: shot label, input–, and output parameters. The input parameters listed are cathode current $I_{cat}$, magnetic field $B$, bias voltage $V_{bias}$, and gas flow rate $Q$. An increased $I_{cat}$ increases ionization in the source, resulting in more ions and a consequent higher electron density. Increasing the magnetic field greatly increases both electron density and temperature. Though an increasing $V_{bias}$ results in a slight decrease of temperature and density, it affects the source voltage that also increases, causing the total input power to rise. The output parameters include electron density $n_e$ and electron temperature $T_e$. The comparison of these 6 shots for the two targets is the basis of the results in section 5.3.2 (*Solid & Liquid target comparison*) and 5.3.3.

Since shot F showed the most evidence of reduced heat to the target (as will be revealed in section 5.3.3), multiple shots with were performed these same parameters in order to record the different profiles discussed in section 5.2.2. In total, 5 shots were done for the Mo-target and 6 shots for the Sn-target, with conditions of shot F. These shots are the basis of the results presented in 5.3.2 (*Long Term Temperature Increase*) and 5.3.4. To emphasize, shot A–F are not the same as shot F1–F6; shot A–F are all different shots, while shot 1–6 are identical shots, performed with the conditions of shot F (table 5.1).

5.3.2 Target Temperature Evolution

Solid & Liquid target comparison

Firstly the surface temperature evolution of the Mo and Sn targets was compared. The temperature was measured with the IR-cam, so the emissivity of the targets has to be known. The emissivity for Sn is known (see previous chapter), but for Mo there is no temperature dependent data available. We will therefore assume that the emissivity is similar to that of W, for which T-dependent data is available. Even if the absolute emissivity value is incorrect, it does account for an temperature increased emissivity which makes it possible to compare the evolutions of Mo and Sn. The temperature evolutions can be seen in figure 5.1a and 5.1b for Mo and Sn respectively. For the low power shots (A&B) the temperature evolves similarly. In shots C, D, and E, the target temperature of the Mo-target saturates to the same value of $\sim$475°C, while the temperature of the Sn target keeps increasing. For shot F it is observed that while the temperature of the Mo-targets increases further, the temperature of the Sn-target decreases by 30%.
Long Term Temperature Increase

To record the profiles for different Balmer-lines as described in section 5.3.3, multiple shots were performed with the same input parameters. It is assumed that for each shot all plasma– and
target conditions are identical. Since plasma conditions are the same, the target temperature should be the same as well under the same target conditions. By looking at how the target temperature evolves over multiple shots, we can therefore get a hint of how the target is damaged over time. A total of six shots were performed with the liquid target in place.

(a) Time evolution of the temperature at the center of the target, measured for the consecutive shots with identical input parameters. The magnetic field is plotted as a reference to see at what time the temperature is expected to stabilize.

(b) Infrared image of the target at the beginning of each shot. In the center progressive damage can be observed for increased shot numbers.

Figure 5.2: Damaging of the target over multiple shots

By looking at the first shot in figure 5.2a, it can be seen that the temperature saturates
within a second of the B-field reaching its peak and then slowly decreases as the magnetic field decreases. The temperature evolution of the shot F2 is similar to that of shot F1. For shot F3, a rise in temperature during the shot is observed. In fact, this rise in temperature continues in shot F4 until a maximum temperature is reached in shots F5 and F6. Since the machine parameters (cathode current, magnetic field, bias, etc.) were identical for these shots, we conclude that this must be the result of changes in the target.

This conclusion is further supported by looking at the condition of the target before each shot. From figure 5.2b we see that up to shot F3, no visible damage was done to the target. At the start of shot F4 a small damaged area in the center becomes visible, which is consistent with the onset of rising temperature in shot F3, and the damaged area increases for shot F5 and F6. The final cumulative damage can be seen in picture 2.4a (chapter 2).

To get an idea of how reproducible the temperature measurements are, we could look into the Mo-target temperature during the identical shots. Following the same reasoning, the Mo-target should not change during shots and hence should show the same target temperature evolution for every shot.

In figure 5.3 we see that although the evolution seems to be consistent for shot F2–F5, there is a large variation in the absolute measured temperature of roughly $\sim 12\%$. This emphasizes the fact that only the evolution of the target temperature is a valid measure to use for target comparison.

![Figure 5.3](image-url)  
*Figure 5.3: Five shots with identical input parameters (shot F) on a Mo-target*
5.3.3 Calorimetry

(a) At low power (shot C), the heat directed to the target is similar for liquid and solid targets.  
(b) At high power (shot F), the liquid target receives less heat than a solid target.  

Figure 5.4: Comparison of increase in cooling water temperature for Mo and Sn target, under different plasma conditions.

For the 6 shots (for Mo and Sn) that were presented in table 5.1, the source input power was plotted vs. the total heat absorbed by the cooling water (figure 5.5). The source input power was calculated by:

\[ P_{in} = UI \]  

Where \( P_{in} \) is the input power, \( U \) the source voltage and \( I_{cat} \) the cathode current (i.e. source current). For the low power shots, the exhausted heat was comparable (figure 5.4a). Intuitively this is what one would expect, since erosion of Sn will not be significant at the low temperatures reached in the low power shots. Effectively, this means there is not be much difference in the cooling mechanisms of the liquid and solid target.

Only for highest power shots in the series, a decrease of absorbed power in the liquid target was observed (figure 5.4b), which we conclude is an indication of vapor shielding. We note that the typical systematic error in the cooling water curves is 1%, so indeed we can attribute the observed difference to real effects rather than a variance in the shot parameters.

The decreased heat loading at high power is not proportional to the source power, so other parameters are playing a role here. We see for example for shot E and F, that both have similar source power, the reduction in heat load is much higher for shot F (\( V_{bias} = -30 \) V) than for shot E (\( V_{bias} = 0 \) V)

5.3.4 Profiles

After having done ‘macroscopic’ measurements, that quantify global effects of the target, we will now turn the direct measurement of plasma vapor interaction.

Axial Electron Density Profile

In section 5.2.2 we have motivated why looking at the electron density can say something about the plasma-vapor interactions: we assume that a strong interaction will be characterized by a high electron density.
The Balmer-lines that were measured are $H_{\alpha}$, $H_{\gamma}$ and $H_{\delta}$, recorded from shot F4, shot F2 and shot F6 (figure 5.2a) respectively. To compare how the temperature and associated erosion influences the density profiles, the shot (and corresponding Balmer line) with the most significant temperature variation was selected, i.e. shot F2 ($H_{\gamma}$).

In figure 5.6 the temperature evolution and the corresponding OES-signal of shot F2 is plotted. A strong rise in temperature is observed around 2.0 s, while after 3.0 s the temperature steadily declines due to the declining B-field. An important observation is that the OES doesn’t follow the sudden rise at 2.0 s.

The axial profile of $H_{\gamma}$ was plotted at different time slices as depicted by the colored dashed lines in figure 5.6. The profiles were measured at 2.06 s, 4.0 s, 6.0 s, 8.0 s and 10.0 s. The value of 2.06 s was chosen such that it is in the center of the temperature peak and that the frames over which is averaged all have the same temperature.

The plots of these profiles are depicted in figure 5.7. The first thing to remark is that the intensity is significantly higher for the shot with an Sn-target. One would expect that densities are indeed higher for a shot with the liquid target, but one should keep in mind that the target temperature for the shots with Sn-targets were significantly higher than for shots with Mo-targets. It is therefore more rigorous to look at the relative changes in emission. It can be observed that the $H_{\gamma}$ intensity for shots with the Sn-target at 2.06 s is significantly lower than at later time frames. Judging by the erosion at that time-frame (see figure 5.6) indeed less Sn erosion is observed, which would account for a decrease in vapor-liquid interactions.

Some of the curves for Mo-target shots gently decline at $r = 0$, this is an error in the Abel-transform rather than a physical effect. At this point the target holder came slightly into view, which breaks symmetry of the profile making the Abel-transform unreliable.
Figure 5.6: Temperature evolution and OES-signal of the $H_\gamma$-shot (shot F2), the dashed lines indicate at which time-frame the axial profile is evaluated (see image 5.7)

Before moving to the next section, we comment on the validity of the electron density estimates. We have assumed the $H_\gamma$ intensity to be proportional to the electron density. However, in reality the source of emission is a bit more complicated. Balmer emission is emitted by neutral hydrogen, since only hydrogen neutrals have electrons that can be excited. The electrons are assumed to be excited by electronic excitation, which is proportional to the electron density. This means that the intensity is proportional to the product of $n_{H^0}n_e$, rather than only the electron density. Since the emission is also proportional to the neutral density, it is not an ideal estimate for the electron density.

Axial Electron Temperature Profile

The interaction of plasma with Sn-vapor is assumed to cause the plasma to lose additional heat. The effect would be that less heat is directed to the target, which would be caused by a reduction in electron temperature near the target. Hence, a decreased electron temperature near the target would be an additional indication for the vapor shielding effect.

In order to measure the electron temperature the ratio of two different hydrogen lines must be taken. This makes selecting the frames of interest more difficult, since care must be taken that the plasma conditions for the two different shots are as similar as possible. The lines that are considered are $H_\alpha$ and $H_\delta$, since their respective shots (shot F4 and shot F6) have a similar temperature range (figure 5.8), and also the erosion is comparable. Since the temperatures of the two shots overlap only twice, we are restricted to the time-frames at 1.9 s and 9.8 s.

The axial profiles at the two time-frames are plotted in figure 5.9. The first thing to observe is that the electron temperature in a shot with an Sn-target is higher than in a shot with a Mo-
target. This is not what one would expect, since the Sn-particles were assumed to cool down the plasma. However, if we take the same approach as before and look only at the relative change, we see that the temperature for a shot with Sn-target reduces over time, whereas in a shot with a Mo-target the temperature stays reasonably constant.

Figure 5.7: Comparison of axial $H_\gamma$-plots for Mo and Sn targets at different time frames
Figure 5.8: Temperature evolution and OES-signal of the $H_\alpha$ and $H_\delta$

Figure 5.9: Comparison of axial $T_e$-plots for Mo and Sn targets at different time frames
Chapter 6

Discussion & Conclusions

The main purpose of this work was to assess how viable a liquid metal is as a PFM in a divertor environment. In order to address this problem we have formulated two questions on which we have focussed our experimental work:

- *How does temperature dependent erosion limit the operating temperature of the liquid metal?*

- *Can we quantify the heat handling of a plasma-facing concept under a complex plasma environment?*

Having performed the experiments and presented the results, we will now try to interpret our findings in order to answer these research questions in the following section.

6.1 Conclusions

We will start with addressing the first research question. We have motivated that the erosion is an important factor in assessing liquid metals, since particles that penetrate far into the plasma can potentially cool down the plasma too much. In order to prevent excessive erosion, there is an upper limit to the operating temperature of a liquid metal. In particular, we were interested in how TES might reduce this maximal temperature, which is currently driven by the evaporative flux. By examining the erosion observed for the liquid Sn in *chapter 4*, we will now try to answer what is exactly this limit and how much it is influenced by TES.

6.1.1 Tin Erosion

To examine the temperature dependence of tin erosion, liquid tin was first subjected to an Ar-plasma, because physical sputtering was expected because of the low sputtering energy threshold. After that we’ve examined the erosion in H-plasma shots, because they are more similar to the conditions found in a divertor.

Ar-plasma

For the argon plasma, S/XB values were obtained by fitting line intensity ratios with the theoretical sputtering yield. These S/XB values were used to spectroscopically determine the eroded
flux of Sn under plasma irradiation.

It was found that the erosion as a function of temperature consists of a reasonably flat region that is consistent with classical sputtering, and a sudden increase of erosion comparable to that expected for evaporation. However, the temperature at which this increase starts was observed to be significantly lower than the temperature expected by taking only classical evaporation into account, this is in accordance with TES observed and described by [38]. Comparing the observed erosion with the theoretical prediction for sputtering + evaporation (figure 6.1), we find an onset of exponential erosion at a temperature of 985 °C, compared to a theoretically expected value of 1185 °C, a reduction of 200 °C.

![Figure 6.1: Plot of measured Sn-erosion versus target temperature in an Ar-plasma, compared to the theoretically expected erosion (sputtering + evaporation). The sputtering yield was taken at -30 V.](image)

H-plasma

For the hydrogen plasma, determining S/XB values directly was not possible because of the high sputtering threshold energy for H → Sn. After assuming the absolute Sn emission intensity is equal in H and Ar plasma’s, the S/XB values for Ar could be used so that it was still possible to make absolute quantitative observations. At low temperatures, no erosion of Sn was found. This is consistent with the high threshold energy, which predicts no sputtering should occur at ion energies of 70 eV. In the hydrogen plasma, large increase in erosion was also observed, again at much lower temperatures than would be theoretically expected. The peak erosion of $3.4 \times 10^{21} \text{ m}^{-2} \text{s}^{-1}$ was measured at 675 °C, while the evaporation curve predicts this erosion value at 1180 °C, a reduction of 505 °C.

The second research question was motivated by the fact that the target plate material dictates

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the maximum allowable heat flux in the divertor. For this reason, we want to be able to assess the heat handling capabilities of a liquid target in a consistent way, so that the performance of different liquid metals might be compared in the future. In this case study the heat handling capabilities of Sn were measured, with a focus on the influence of the vapor shielding effect.

6.1.2 Heat Exhaust

First we will discuss the different techniques that were explored to quantify the heat exhaust capability, after that we will focus on the conclusions about liquid Sn as a case study.

Quantifying Heat Exhaust

Three techniques were used to assess the heat handling of Sn: Temperature evolutions, cooling water calorimetry and spectroscopy.

The target temperature evolution of a liquid target was compared to a solid reference target. An accurate determination of the emissivity is required to make an absolute comparison between two targets. Still, the absolute temperature measurement varies from shot to shot and a potentially changing emissivity makes the reproducibility questionable.

Cooling water calorimetry is a reliable measurement with a good reproducibility. It is a direct measure of heat incoming to the target, but is not very sensitive to the relative subtle effects of different targets.

The spectroscopic profiles were used as a direct measure of plasma-vapor interaction by measuring $H_{\alpha}$, $H_\gamma$ and $H_\delta$, profiles. These intensities were used to calculate approximations for electron temperature and –density. The electron temperature measured in this way are difficult to interpret.

Heat Handling of Tin

The liquid Sn target was characterized by the three techniques mentioned above to characterize the heat handling and find evidence of vapor shielding. To this end, the liquid Sn target was compared to a (solid) Mo reference target for shots with different input powers. At low power shots, no evidence of a reduced heat was found either by temperature evolution or cooling water calorimetry. Only at high power shots, a reduced heat towards the target was observed for the liquid target by calorimetry, which one could interpret as an indication of vapor shielding. This reduction is supported by temperature evolutions; at high power the surface temperature of the liquid target decreases while the surface temperature of the solid target increases. By comparing the details of different shots, it appears that the bias voltage plays an important role in reducing the heat to the target.

Profiles of Balmer emission lines were recorded and used as a measure for electron density and –temperature. The intensity of $H_\gamma$ was used as a measure for the electron density. It was observed to be higher for shots with a liquid target, which one would expect because of the plasma-vapor interaction. The $H_\gamma$-intensity was observed to increase with time and consequently with measured erosion, as is expected. The electron temperature was measured by measuring the ratio of $H_\alpha$ and $H_\delta$ emission. The electron temperature was found to be higher for the shot with the liquid target. This in contrast to the expectation of a decreased temperature due to additional dissipation paths (i.e. radiation). The electron temperature does decrease with increased erosion, as would be expected when plasma-vapor interactions become significant.
6.1.3 CPS-target

During the erosion and heat handling experiments, we have adopted a CPS-design for use in Pilot-PSI. Apart from the physics of the liquid metal that we have tried to characterize, we have gained experience in the design and use of the CPS-target, which we will illustrate here.

The CPS-like mesh was tested in a realistic fusion-like divertor plasma environment. A single mesh with a small wire diameter is effectively unable to retain liquid metal, after which the mesh is completely destroyed. Stacking meshes helps to retain the bulk liquid metal, but still vacancies appear in the mesh. The vacancies might be created by Sn leaving as a vapor rather than a liquid, because the vapor is not constrained by the mesh.

It has been observed that the mesh melts at places where large amounts of Sn left the mesh, implying that the mesh overheats in the absence of Sn and is ultimately destroyed, not the other way around (a destroyed mesh not being able to retain Sn). The 'improved'-design target was observed to break after a variety of low, medium and high power shots, but to stay reasonably intact after multiple high power shots. This suggests that Sn is better retained in high power shots, but since the targets are not machined very precise and the target history can play a large role, it is hard to make solid conclusions.

6.2 Discussion

In this work we have explored some of the basic concepts of a liquid metal in a divertor plasma environment. Characterizing the LM is one thing, but in the end the real question is how this affects the design of a future LM divertor. In this section we will therefore try to illustrate what implications this work has on the design of such divertor, and what open questions still remain.

6.2.1 Implications for Divertor Design

Since we have only looked at a small selection of problems out of the broad spectrum of issues associated with liquid metals as PFM, we will not be able to comment yet on how feasible a LM in a divertor is. This work should rather be considered as one of the many experiments that are needed for a full LM divertor design. However, our measurements do allow us to comment on some of the concepts needed in a LM divertor.

Maximum Operating Temperature

We have already presented at what temperatures there is an onset of erosion, but this is not the same as a maximum LM temperature. To find a maximum temperature, we follow the typical approach of allowing the erosion to be maximally 10% of the incoming particle flux. In the Ar-plasma measurements, the ion flux was $6.18 \times 10^{23} \text{m}^{-2} \text{s}^{-1}$, we find that a 10% erosion flux is achieved at 1180°C. Taking only sputtering and evaporation into account, this temperature would be 1380°C for the particle flux that was considered.

However, one should keep in mind that the impurities that threaten to cool down the plasma are only a problem if indeed they get to the hot core plasma. Sufficient particle recycling would reduce the effective erosion into the plasma. In other words: the penetration depth, i.e. how far the wall particles penetrate the plasma, should be small enough. Numerical simulations suggest that the mean-free-path of Sn particles could be as low as 1.5 mm for the ARIES-AT conceptual tokamak divertor [10].
Vapor Shielding

Although indications of the vapor shielding effect have been observed, based on the small amount of data we will not speculate on how much the heat flux might be reduced in a LM divertor.

CPS in a tokamak

We have observed that a mesh without Sn will be destroyed by the plasma. This means that in a real reactor care should be taken that the mesh is always filled with liquid metal to prevent the CPS from breaking. Under steady state this might be trivial, but ELMs could erode much Sn in a small time-frame, possible depleting the mesh before it can be refilled. As we have seen at the end of chapter 3, the motion of the liquid is greatly impeded by the mesh which could cause problems with transients.

6.2.2 Future Research

As stated, this work is far from a complete assessment of the viability of LM divertors. Since this experiment was the first of its kind in the high flux plasma of Pilot-PSI, naturally there are a lot of open ends. In this section we will try to suggest follow-up strategy as best as possible, based on what we have found in our experiments.

Mesh Damage

The target that was used still leaks tin during shots. Apart from getting tin all over the machine, this means that parameters change from shot to shot. To investigate exactly what causes the mesh to break, one should make an optical recording of the target during a shot, equipped with a filter to block the hydrogen emission. By simultaneously measuring the target temperature profile and particle flux, it might be possible to find a parameter window at which the mesh is not damaged and is able to confine the liquid metal to the target.

Apart from the short term damage to the mesh that complicates the experiments, the viability of the mesh itself as a PFC needs to be assessed. In the short term, Sn and Mo do not react, but in the long term Sn might form alloys with Mo, potentially compromising the structural integrity. First compatibility measurements from FzJ show that Sn indeed attacks the Mo, but does not react with W. A CPS is only viable in a reactor if the mesh retains it’s structural properties, so it is important to predict long term damage of the mesh’s wires.

Sn-Profile Measurement

Looking at the target to see when it breaks is one way to qualify the target damage, another is to look in more depth to the release of Sn atoms. Not only will this help to assess target damage, but it would give a great insight in the erosion of Sn itself.

By using a selective bandpass filter suited for Sn-emission lines, the emission plume of Sn could be monitored and compared against other parameters such as target temperature or plasma conditions.

As motivated in the discussion section, knowing the Sn penetration depth is an important measure in assessing the applicability of liquid metals in a divertor. The filtered optical profiles could be used to estimate this penetration depth, and help to find conditions to reduce this depth and confine the eroded particles to the edge.

Having found local emission values, one is in the position to relate the photon flux to the ion flux via true S/XB-values. To measure these, one would need to measure the exact amount of Sn that corresponds to the light being emitted. Direct measurement of mass loss is difficult...
because of the high redeposition rates, so different techniques would have to be developed. One possibility is to use a laser pulse to induce erosion of the target. This laser-induced ablation could be calibrated with mass loss in a plasma-less environment, such that it is known how much particles are ejected with one laser pulse. Now that we know this amount, we could relate the observed emission to the number of laser shots, which was related to a specific number of particles, to close the circle.

Physics of TES

TES is an effect that is proportional to both temperature and particle in-flux. It is therefore important to distinguish what effect is the driving force behind TES, both from a fundamental point of view and as a way to predict effective penetration lengths. Thermal effects produce low energetic particles that will not move very far into the plasma until they are re-ionized and sent back to the wall, while sputtered particles on the other hand are high energetic particles that might penetrate deep into the plasma before they get ionized, reaching the core plasma and cooling it down. Also, with high enough recycling self-sputtering can become significant. The nature of the TES, be it thermal or sputtering, might thus change the penetration depth of the neutral tin.

The different ejection velocities corresponding to the two effects might be measured as a doppler shift using a high resolution spectrometer. The resolution of the spectrometer is dictated by the expected energy of the particles, which is in the order of the plasma temperature for thermal (∼1 eV), and the lattice energy for sputtered particles (3.07 eV). Assuming a resolution of 0.5 eV would be enough to pick up this difference, the resolution should be at least 1.4 × 10^−3 nm/px.

Finding the nature of the erosion helps to sort out what physics is behind the temperature enhancements. Another way is to test the observed effect quantitatively against the existing models. Both the RAAS-model and Inclusion Model expect a linear relation with particle in-flux, so in order to validate the models the flux dependence needs to be examined in a systematical approach. The difficulty here is that there is always a coupling between temperature and particle flux in a linear device. Increased/decreased target cooling could help here to get in the same temperature range at different fluxes.

Physics of Vapor Shielding

Just like finding out why TES is happening, it is important to look in more detail to the physics of the vapor shielding phenomenon. The physics of the vapor shielding need to be examined and quantitatively compared with results. This enables one to optimize the plasma and target parameters where the heat reduction is most significant. Only if we really understand what is happening when the plasma and vapor interact, it will be possible to implement LMs in a divertor.

6.3 Final Words

With the characterization of Sn-erosion in Pilot-PSI we have made a first step in assessing the viability of liquid metals in the divertor of a future reactor. As can be deduced from the large list of future research suggestions, we have a long way to go before we can give a definite answer to whether liquid metal PFM in a divertor is viable. However, the potential benefits of liquid metals appear to be attractive enough to continue investigating the possibilities of a liquid metal divertor.
Bibliography


[16] J. Sanchez, M. Acedo, A. Alonso et al., Confinement transitions in TJ-II under Li-coated wall conditions, 2009 Nucl. Fusion 49 104018


[22] Leonid E. Zakharov, The basics of the LiWall Fusion (LiWF) concept, KSTAR Seminar, April 24, 2009, National Fusion Research Institute, Daejeon, Korea


[34] M. de Baar, M. Groth, A. Loarte, et al., Report of the STAC Ad Hoc Group on ’A strategy to address exhaust issues in the EU Fusion programme’, STAC 44/4.1 17-06-2013


[46] D. Majeski, Liquid metal walls, lithium, and low recycling boundary conditions in tokamaks, ITER School 2009


