Experimental Sheath Heat Transmission Factors in Diverted Plasmas in JET
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ABSTRACT

The heat flux to the target plates $q_p$ is a crucial design parameter for fusion machines. It can be measured by InfraRed (IR) cameras viewing the target plates. The sheath heat transmission coefficient $\gamma$ is defined by $q_p = \gamma k T_e J_{\text{target}}$ relating $q_p$ to particle fluxes and temperature. Sheath theory predicts $\gamma$ in the range of 5…8.

We show $\gamma$ determined experimentally from a comparison of $q_p$ from IR with $T_e$ and $J_{\text{target}}$ measured by Langmuir probes for low to high recycling regimes in L-mode with carbon targets. While $\gamma$ is in the expected range at low recycling, unphysically low values are observed at high recycling.

This is compared to recent data from tungsten targets which should affect $\gamma$ via particle reflection and s.e.e. $\gamma$ shows similar trends as observed for carbon targets. However, within the experimental uncertainties no conclusion on the impact of the wall material on $\gamma$ can be drawn. We finally discuss the influence of $\gamma$ on simulation results.

1. INTRODUCTION

For fundamental understanding of the physics in the sheath building up in front of the target plates one wants to relate the conditions at the sheath edge to the energy impact onto the target plates. This leads to the definition of the sheath heat transmission factor $\gamma$ with $q_p = \gamma k T_e J_{\text{target}}$. $J_{\text{target}}$ is the particle flux entering the sheath. $T_e$ the electron temperature at the sheath edge. Analytical sheath theory leads to an expression for $\gamma$ in terms of plasma parameters [1]:

$$\gamma = \frac{q_p}{j_{\text{target}} k T_e} = \frac{2.5 T_i}{T_e} - 0.5 \ln \left( 2 \pi \frac{m_e}{m_i} \left( 1 + \frac{T_e}{T_i} \right)^2 \left( 1 - \Delta \right) \right) \left( 1 - R_{\text{eE}} \right) \left( 1 - R_{\text{iE}} \right) + \frac{\delta}{2} + \frac{\chi_i}{kT_e} \frac{1}{A}$$

$\delta$ is the secondary electron emission (s.e.e.) coefficient which is a combination of true s.e.e. and electron reflection. The terms in eq.1 shall be explained in terms of their physics:

1. The direct impact of ions entering the sheath at a temperature of $T_i$. Reflection of ions at the target is taken into account by the coefficient $R_{\text{iE}}$.
2. This term equals the sheath potential drop repelling incoming electrons. Those transfer their energy to the ions which then hit the target at a higher energy than $kT_i$.
3. The energy of the electrons which overcome the potential drop and hit the target. $R_{\text{eE}}$ is a reflection coefficient.
4. The energy gain of particles in the pre sheath. $\epsilon_{\text{pre}} \approx 0.5$
5. The electron ion recombination energy. $\chi_i = 13.6 \text{eV}$ for Deuterium.
6. The atom-atom recombination energy. $\chi_a = 2.2 \text{eV}$ for Deuterium.

Unless particle reflection is strong, as defined by $1 - R_{\text{X,Y}} \ll 1$, eq.1 yields $\gamma > 5$. Literature provides analytical expressions to estimate $\delta$ and reflection coefficients for several target-projectile combinations depending on the impact energy [2] [3]. In this paper we present a comparison of $\gamma$ in L-mode discharges with carbon and tungsten as target material. Assuming $T_i/T_e = 1$ table 1 summarizes expected values for both materials at $T_e = 10 \text{eV}$ and $40 \text{eV}$ which were derived
experimentally. It can be seen from table 1 that $\gamma$ is expected to be slightly smaller for a W divertor due to stronger particle reflections. We shall note that $\delta$ depends sensitively on target conditions. This is especially important since for the given plasma parameters term 3 in eq.1 is the leading term. Experimentally, $\gamma$ can be derived from a comparison of target heat loads, $q_p$, measured by infrared cameras to $T_e$ and particle fluxes measured by Langmuir probes embedded into the divertor. The divertor probes at JET are wedge shaped with an inclination angle of 13°. A high resolution infrared camera systems with a target resolution of 1.7mm is installed at JET to measure $q_p$ on the outer horizontal divertor target plate (tile #5) [4]. The Langmuir probe location and the strike line position derived from EFIT for the W and C divertor are shown in fig. 1. The probes were operated as single probes. $T_e$ and $j_{par}$ were derived from an asymmetric double probe characteristic fit to the probe data [5]. $j_{par}$ is the particle flux parallel B at the target which equals the ion saturation current $j_{sat}$ to the probe. The ratio of electron to ion saturation current tends to rather low values in high recycling regimes in JET [6], which is taken into account by an additional fit parameter in this model. A major uncertainty in the comparison of IR and probe data is introduced by the mapping of $j_{par}$ onto the target. This follows the relation $j_{target} = j_{par} \sin(\theta_{perp} + \alpha_{target})$, where $\theta_{perp} \approx 2-3°$ is the field line and $\alpha_{target}$ the target inclination angle with respect to the horizontal plane. With the carbon wall the horizontal target was a nearly plane surface with $\alpha_{target} = 0.9°$. However, the tungsten tile is a stack of lamellae with a geometry as shown in fig. 2. For the given task this is a rather adverse geometry because $\alpha_{target}$ varies from 0 to 15° in toroidal direction. The IR camera strictly measures $q_p$ on the target. However, due to the limited resolution of the camera the given heatflux density is an average over the lamella. For the mapping of $j_{target}$ we use an average angle of 4° for the tungsten data. Though it is clear that this averaging may introduce large errors on the derived experimental $\gamma$. A variation of $\Delta \alpha = \pm 3°$ would yield a correction factor $\Delta j_{target} = 0.5…1.5$ and thus $\Delta \gamma \approx 1/\Delta j_{target} = 0.66…2$ for $\theta_{perp} = 2°$.

2. RESULTS FROM THE CARBON DIVERTOR

We investigated data from L-mode discharges with a toroidal field on axis of $B_t = 2.5T$, a plasma current of $I_p = 2.5MA$ and a total heating power of $P_{tot} \approx 3MW$. The upstream plasma density was scanned to achieve attached regimes varying from low to high recycling conditions [7].

At low recycling the peak of the heatflux profiles matched fairly good applying $\gamma = 10$ to the probe data. This is only slightly higher than the expected value given in section 1. Figure 3 shows heatflux profiles measured at lowest and highest available densities. The Langmuir probe data were calculated using a value of $\gamma$ matching the peak of the profile. At low density profiles from probes with high spatial resolution were available from a strike point sweep of 2cm on the target. However, the IR profile was averaged over a period of 0.5s with fixed strike point. For comparison the probe data for the same period are shown as symbols. The probe data show a slightly broader profile than IR in the region $\pm 2cm$ around the peak. This suggests an overestimation of $\gamma$ with increasing distance from the peak. The wings of the IR data are not of interest here because they are prone to
reflections. This was taken into account here by subtracting a fraction of IR photons from the raw data such that the total energy on the tile matched that measured by thermocouples.

At high density a very low value of $\gamma \approx 2$ was applied to match the peak of the profile. This is in conflict with eq.1 which allows $\gamma < 5$ only for strong particle reflections. However, the latter is a weak function of temperature and should vary only slightly in the observed low temperature range. The peak $T_e$ in this high recycling regime as derived from the Langmuir probes was ~10eV.

It turned out that the experimentally derived $\gamma$ can be separated into two regimes. At low recycling, i.e. $j_{par} < 1.5 \times 10^24 \text{m}^{-2} \text{s}^{-1}$ the experiment yielded $5 < \gamma < 10$ with a rather clear temperature dependency. Fig. 4 shows the dependency of $\gamma$ on $j_{target}$ and $T_e$ for the entire density scan. Data were taken from two probes near the peak and the IR data viewing at the same position. The observed trend to lower $\gamma$ at lower $T_e$ could be related to s.e.e. The blue line in fig.4 shows analytical values for $\gamma$ following eq. 1. The variation in $\gamma$ in this range is due to s.e.e. which is given by

$$\delta = \delta_{\text{max}} 2.72^2 \frac{T_e}{T_{e,\text{max}}} \exp \left(-2 \left(\frac{T_e}{T_{e,\text{max}}}\right)^{0.5}\right)$$

where $\delta_{\text{max}}$ is the maximum s.e.e. occurring at $T_{e,\text{max}}$. Literature suggests $\delta_{\text{max}} = 1$ at $T_{e,\text{max}} = 300\text{eV}$ for carbon targets. In fig.4 we arbitrarily used $\delta_{\text{max}} = 1.6$ at $T_{e,\text{max}} = 250\text{eV}$ leading to $\delta (20...40\text{eV}) \approx 0.55...0.85$. Further on we used $R_Ee = 0.35$ which is higher that the value in table 1.

In the high recycling regime the probes yielded temperatures of $T_e \approx 10\text{eV}$ over a wide range of $(2 \times 10^{24} < j_{\text{target}} < 6 \times 10^{24}) \text{m}^{-2} \text{s}^{-1}$. $\gamma$ shows a clear dependency on $j_{\text{target}}$ dropping from 6 to 2 here. As mentioned before, $\gamma < 5$ could only be explained by strong particle reflections. Energy losses due to collisions are known to play only a minor role for sheath heat transmission [8]. A reasonable explanation for such low $\gamma$ would be an overestimation of $Te$ by the probes due to the occurrence of super thermal electrons. This was first suggested by Stangeby in 1995 [9] and recently confirmed for probe measurements at NSTX [10]. The existence of a super thermal electron population would actually increase $q_p$ for a given bulk $T_e$ because these can easily overcome the sheath potential drop and reach the target, whereas for the bulk electrons only the tail of the EEDF carries energy directly to the target (term 3 in eq.1). However, they affect the probe characteristics in a way that one can hardly distinguish between a plasma showing 100% fast electrons and a minority population of 2% with $T_{e,\text{fast}} / T_{e,\text{bulk}} = 10$ from standard probe analysis. The actual $\gamma$ depends sensitively on the temperature and amount of fast electrons. The latter example gives $\gamma = q_p / (T_{e,\text{bulk}} j_{\text{target}}) \approx 20$ [11].

Probe analysis would yield $T_e = T_{e,\text{fast}}$, which leads to $\gamma_{\text{exp}} = q_p / (T_{e,\text{fast}} j_{\text{target}}) = q_p / (10 T_{e,\text{bulk}} j_{\text{target}})$ = $\gamma / 10 = 2$. Assuming this to be the reason for the low $\gamma$ at high recycling, the bulk $T_e$ would in reality be significantly lower than suggested by probe analysis in the observed density range in fig. 4. In order to get an idea of what $T_{e,\text{bulk}}$ might be we plotted $j_{\text{target}}$ against $q_p j_{\text{target}}$ with a fixed $\gamma = 8$ in fig.5. This virtual $T_{e,\text{bulk}}$ goes down to 2eV. Taking into account the effect that the actual $\gamma$ would increase with $j_{\text{target}}$ due to $T_{e,\text{fast}}$ would result in even lower temperatures than those shown in fig.5.
3. RESULTS FROM THE TUNGSTEN DIVERTOR
The density scan presented in sec.2 was repeated with tungsten targets. The averaged target inclination angle of $\alpha_{av} = 4^\circ$ was used to map $j_{par}$ onto the target. The resulting dependency of $\gamma$ on $T_e$ and $j_{target}$ is shown in fig.6. The trends observed with the carbon wall could be reproduced. There was a similar strong temperature dependency at low recycling and a saturation of $T_e$ at high recycling with $\gamma$ tending to low values around 2 with increasing particle flux. A comparison of absolute values suggest $\gamma$ at low recycling to be smaller compared to carbon as predicted by theory. However, there is a large uncertainty in the given absolute values. Data from only one probe are shown in fig.6 because there is despite similar trends a significant difference of more than 50% between $\gamma$ derived from neighbouring probes as they are shown for the carbon wall. This can be partly related to the sensitivity on the angle used to map $j_{par}$. It was shown above that small variations in $\alpha$ may easily lead to $\gamma$ being off by a factor of 2. Within this uncertainty it is not possible to make a quantitative comparison between $\gamma$ for carbon and tungsten targets.

CONCLUSION
We have shown experimentally derived sheath heat transmission factors for a wide range of upstream plasma densities in L-mode. The observed $\gamma$ was in the range of 2…12 with $\gamma = 10$ matching heatflux profiles for low recycling reasonably well. This is pretty much in agreement with previous work on JET [6] and also from other machines ( [12] and references therein). There was a clear qualitative difference between low and high recycling regimes. In low recycling $\gamma$ showed a temperature dependency suggesting a significantly stronger impact of s.e.e. than suggested by widely used literature values. Assuming $\delta = 0.5…0.8$ in a temperature range of 20…40eV the observed trend could be reproduced by sheath theory. S.e.e. yields up to 0.8 are however in good agreement with experiments on the DITE tokamak [13].

A comparison of data from carbon and tungsten targets for comparable discharge conditions showed similar trends. But the complex shape of the tungsten lamellae used in the outer horizontal target of the ITER like wall in JET does not allow a quantitative comparison due to the uncertain mapping of the parallel particle flux onto the target surface. Here we used a geometrically averaged target inclination angle for the mapping. However, it is not clear how reasonable this averaging is.

A final conclusion can be drawn regarding the importance of $\gamma$ for modelling because we found its impact to be remarkably high. For the low recycling case with carbon walls we ran EDGE2D/EIRENE [14] with $\gamma = 5.5…12.5$ as boundary condition, which is the span of $\gamma$ we found experimentally for these conditions. The simulated parameters at the target plates reacted sensitively with e.g. the peak $T_e$ varying from 25…55eV compared to the experiment yielding 40eV.

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Table 1:
Figure 1: Divertor geometry together with the magnetic field configuration for both the carbon (black) and the tungsten (red) targets. The box symbols on the outer vertical target mark the position of the Langmuir probes used in this paper. The overplotted axis corresponds to the target coordinate used in subsequent plots.

Figure 2: Geometry of the lamella used in the bulk W divertor tile #5 of the ILW. $\theta_{\text{perp}}$ is the field line inclination angle. The blue line shows the maximum target inclination $\alpha$. Part of the lamella surface is flat.

Figure 3: Heatflux profiles from IR and Langmuir probes measured at low and high recycling with a carbon target. IR data and the diamond symbols are an average over 0.5s with fixed strike point.

Figure 4: Experimental $\gamma$ from a density scan with C-targets plotted against $j_t$ and $T_e$ as derived from the Langmuir probe data. Red and black symbols result from two probes at the $q_p$ profile for time periods with fixed SP. The green crosses were extracted from the SP sweep shown in fig.3. The blue line follows eq.1.
Figure 5: $T_e$ versus $j_{target}$ for the same data shown in fig. 3. The black diamonds are experimental $T_e$. The red squares show a temperature derived from $q_p j_{target} \gamma$ for a fixed $\gamma = 8$.

Figure 6: Experimental $\gamma$ from a density scan with W-targets plotted against $j_{target}$ and $T_e$. Same notation as fig. 4.