PhD Researcher Prize: Spectroscopic investigations of TCV detachment

K. Verhaegh[1,2,3], B. Lipschultz[1], B.P. Duval[2], the TCV** and EuroFusion MST1/WPTE*** teams

[1] *York Plasma Institute, University of York, United Kingdom*

[2] *Swiss Plasma Center, École Polytechnique Fédérale Lausanne, Lausanne, Switzerland*

[3] *Currently based at: CCFE, UKAEA, Abingdon, United Kingdom*

*** See author list of "S. Coda et al 2019 Nucl. Fusion 59 112023".*

**** See author list of "B. Labit et al 2019 Nucl. Fusion 59 086020".*

Abstract

Detachment is required to mitigate the power exhaust of future fusion reactors. It is induced by a complex chain of plasma-atom and molecule interactions resulting in simultaneous power, particle and momentum losses. Dissecting these processes experimentally using plasma spectroscopy and novel analysis of the Balmer line series indicated that the reduction of divertor ion sources during detachment, brought on by power limitation, reduces the ion target flux initially. As detachment evolves, lower target temperatures are obtained, which lead to volumetric momentum losses, enhanced molecular densities that lead to molecular-activated recombination; and ultimately electron-ion recombination.

Analysis methodology

The role of plasma-atom as well as plasma-molecule interactions on divertor detachment in the TCV tokamak (before installation of divertor baffles) has been analysed in detail applying a new suite of analysis techniques for the hydrogen Balmer line series [1, 2]. Initially, this analysis technique purely focussed on atomic processes (atomic ionisation and electron-ion recombination) [1, 3]. However, using only atomic processes, the measured increase of the Dα emission, during detachment induced by density ramps, could not be explained [4].

Newer analysis indicates that plasma-molecule interactions result in vibrationally excited molecules which promote the creation of molecular ions (D_2^+ and D_2^- -> D + D^-). The interaction of those species with the plasma leads Molecular Activated Recombination (MAR), leading to excited hydrogen atoms and an enhancement of Dα during detachment [2], which is indicative of significant levels of MAR [2, 5].

Experimental results

Our results indicate that during a density ramp discharge, the ion target flux reduction is induced by both a reduction of the ion source in the outer divertor leg [6] as well as ion sinks from Molecular Activated Recombination (MAR) (T_t < 4 eV) [5], whereas Electron-Ion Recombination (EIR) was shown to be small [3]. During N_2 seeding, however, MAR as well as EIR are insignificant. This can be explained by the relatively high target temperatures (T_t ~ 4-5 eV) observed during N_2 seeded detachment [5, 7]. These measurements show that 1) EIR is negligible during the early detachment phase and 2) volumetric recombination, in general, is not a requirement for detachment [3].

Measurements show that the reduction of the ion source starts as the power entering the ionisation region (P_{recl}) approaches (and limits) the power spent on ionisation (P_{ion}) [6, 7]. This 'power limitation' starts when $P_{recl} \sim 2\ P_{ion}$ and target temperatures of $T_t = E_{ion} / \gamma$ ~ 4-6 eV are reached – in quantitative agreement with new detachment threshold predictions from improvements in analytic models [6]. Reaching power limitation conditions, brings on volumetric momentum loss processes and, as the temperature decreases, plasma-molecule reactions and MAR. As T_t drops even further (when $P_{recl} \sim P_{ion}$) electron-ion recombination starts to occur but remains modest in the analysed discharges (T_t ~ 1.5 eV, $n_e \sim 10^{20}$ m^{-3}).

Comparisons against SOLPS-ITER modelling

SOLPS-ITER simulation results from [8] have been directly compared against these novel measurements. The 'atomic' aspects (e.g. electron densities, electron-ion recombination, atomic ionisation) of the SOLPS-ITER simulations are generally in quantitative agreement to the experiment [6]. However, the ion target flux does not roll-over during detachment in the SOLPS-ITER simulations. Although the portion of Dα associated with electron-impact excitation and EIR is in agreement between experiment and simulation, the simulations do not predict a strong increase of the Dα emission during detachment [7]. Likewise, molecular activated recombination is negligible in the SOLPS-ITER simulations: the impact of molecular ions is thus strongly underestimated in the simulations.

It is hypothesized [7] that this underestimation is related to the molecular charge exchange rate used for deuterium in SOLPS-ITER ($D_2 + D^+ \rightarrow D_2^+ + D$). This rate depends on the relative velocity between the reacting particles as well as the distribution of the vibrationally excited levels of the D_2 molecules (D_2 (v) - which is modelled using a simplified model). As the relative velocity is different for deuterium than hydrogen at the same ion temperature (due to the isotope mass difference), the *total effective* reaction rate for hydrogen is rescaled by the isotope mass to obtain the deuterium rate. To test whether this reaction rate rescaling is the cause of the underestimated impact of molecular ions on detachment, the converged SOLPS-ITER simulations are post-processed using a different molecular charge exchange reaction rate, where *only* the *ion-molecule interaction terms* are rescaled by the isotope mass [9]. This leads to higher D_2^+/D_2 ratios (for $T_e < 5$ eV), that lead to quantitative agreement of the total Dα and MAR ion sink between experiment and simulation [7].

Discussion

The generality of these results on the TCV tokamak to other devices and reactors need further investigation. TCV operates with a carbon wall at relatively low electron densities and power levels, which likely increases the ratio between MAR and EIR. The TCV conditions result in large mean-free-paths which impacts the behaviour of neutral atoms and molecules. Molecules are more likely to reflect of a metal wall than of a carbon wall. All of this could change the molecular density as well as the vibrational distribution of the molecules.

However, ionisation estimates from JET also indicate the importance of the reduction of the ion source in the roll-over of the ion target flux [10, 11]. Comparing Dα measurements from JET to atomic expected behaviours is qualitatively suggestive of the presence of MAR [11].

The validity of different molecular rates, as well as the model assumptions made for modelling the distribution of D_2 (v) (which has a strong impact on the effective reaction rates), requires further experimental and modelling investigations.

Conclusion

Detachment is induced by a complex chain of plasma-atom and molecule interactions resulting in simultaneous power, particle and momentum losses. Dissecting these processes experimentally using novel analysis of the Balmer line series indicated that the reduction of the divertor ion source during detachment, brought on by power limitation, is an important element of detachment. As detachment evolves, lower target temperatures are obtained which lead to volumetric momentum losses, enhanced molecular densities resulting in molecular-activated recombination; and ultimately electron-ion recombination.

More experimental as well as modelling investigations are required to monitor the evolution of these processes on other devices and to make sure that they are sufficiently accurately captured by plasma-edge modelling. That would increase confidence in plasma-edge simulations and increase their predictive capabilities for extrapolation to fusion reactors.

References:

1. Verhaegh, K., et al., *Novel inferences of ionisation & recombination for particle/power balance during detached discharges using deuterium Balmer line spectroscopy.* Plasma Phys. Control. Fusion, 2019. **61**(125018) DOI: https://doi.org/10.1088/1361-6587/ab4f1e.
2. Verhaegh, K., et al., *A novel hydrogenic spectroscopic technique for inferring the role of plasma–molecule interaction on power and particle balance during detached conditions.* Plasma Physics and Controlled Fusion, 2021. **63**(3): p. 035018 DOI: https://doi.org/10.1088/1361-6587/abd4c0.
3. Verhaegh, K., et al., *Spectroscopic investigations of divertor detachment in TCV.* Nuclear Materials and Energy, 2017. **12**: p. 1112-1117 DOI: https://doi.org/10.1016/j.nme.2017.01.004.
4. Verhaegh, K., *Spectroscopic Investigations of detachment on TCV*, in *Physics*. 2018, University of York: York, http://etheses.whiterose.ac.uk/22523/.
5. Verhaegh, K., et al., *A study of the influence of plasma–molecule interactions on particle balance during detachment.* Nuclear Materials and Energy, 2021. **26** DOI: https://doi.org/10.1016/j.nme.2021.100922.
6. Verhaegh, K., et al., *An improved understanding of the roles of atomic processes and power balance in divertor target ion current loss during detachment.* Nuclear Fusion, 2019. **59**(126038) DOI: https://doi.org/10.1088/1741-4326/ab4251.
7. Verhaegh, K., et al., *The role of plasma-molecule interactions on power and particle balance during detachment on the TCV tokamak.* arXiv preprint arXiv:2106.03430; submitted to Nucl. Fusion, 2021 DOI: https://doi.org/10.13140/RG.2.2.28008.19206.
8. Fil, A., et al., *Identification of the primary processes that lead to the drop in divertor target ion current at detachment in TCV.* Contributions to plasma physics, 2017. **58**(6-8) DOI: https://doi.org/10.1002/ctpp.201700171.
9. Kukushkin, A.S., et al., *Role of molecular effects in divertor plasma recombination.* Nuclear Materials and Energy, 2017. **12**: p. 984-988 DOI: https://doi.org/10.1016/j.nme.2016.12.030.
10. Lomanowski, B., et al., *Spectroscopic investigation of N2 and Ne seeded induced detachment in JET ITER-like wall.* Nuclear Materials and Energy, 2019,. **20**(100676) DOI: https://doi.org/10.1016/j.nme.2019.100676.
11. Lomanowski, B., et al., *Interpretation of Lyman opacity measurements in JET with the ITER-like wall using a particle balance approach.* Plasma Phys. Control. Fusion, 2020. **62**(6): p. 065006 DOI: https://doi.org/10.1088/1361-6587/ab7432.