IMPACT OF RADIATION DISTRIBUTION ON DETACHMENT ONSET AND IMPLICATIONS FOR STEP DIVERTOR DESIGN

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1. INTRODUCTION

Reactor-class devices such as STEP feature high divertor target heat fluxes which require detachment for an acceptable exhaust solution. During detachment, a protective cloud of cold, neutral gas forms at the target given sufficient energy dissipation upstream. For high-power devices, this is achieved through seeded impurity radiation which then dominates the energy losses. This fact is exploited by Lengyel based models, which can provide an analytical solution of the upstream conditions required for detachment (the detachment threshold) given inputs that include function of impurity radiation with respect to temperature (the cooling curve). The Detachment Location Sensitivity model, or DLS [1], expands this approach to predict conditions required for an arbitrary detachment front location. It considers the magnetic configuration of the divertor leg and can predict its effect on both detachment access and the sensitivity of front movement. It has previously been compared to SOLPS-ITER slab simulations, finding a good qualitative match of the magnetic configuration effects [2]. DLS makes an assumption of an infinitely thin radiation curve which we relax in DLS-Extended, a novel 1D reduced model which additionally predicts radiation distribution. The radiation region predictions are compared against SOLPS-ITER simulations of an intermediate STEP design [3] with reasonable agreement. The SOLPS simulations show broad radiation, which is predicted by DLS-Extended to reduce the detachment threshold benefit of total flux expansion (f_R) by approx. 50%, while increasing the benefit of total connection length ($L_{\parallel}$) by approx. 50% for the outer divertor. This has significant implications for our understanding of Super-X divertor detachment performance and allows a more informed optimisation of its magnetic geometry and radiation distribution to enhance detachment and minimise toroidal coil size. To the best of the authors' knowledge, this is the first detailed investigation of the interaction between impurity radiation distribution and the impact of divertor magnetic configuration design on detachment.

2. SOLPS COMPARISON

DLS-Extended is a Python reduced model solving two ODEs: a heat flux balance between the heat source and radiative losses (using fixed-fraction radiation), and the two-point model electron conduction equation. The model has no neutrals and assumes constant plasma pressure. Heat flux is assumed to be dominated by electron conduction. The detachment front position is a model input, while the required upstream conditions and profiles of electron temperature, radiation and parallel heat flux are the outputs. The model was compared against the outer divertor in a SOLPS-ITER simulation of STEP featuring a midplane D puff [3]. The STEP simulation featured full impurity transport while DLS-Extended features a fixed impurity fraction. DLS-Extended was compared against SOLPS in the 3rd SOL ring using an effective cooling curve extracted from the SOLPS simulations. The results are shown in Figure 1 and show good qualitative results, with quality of match mostly affected by particle sources originating from the PFR region. These sources are substantially stronger for rings 1 and 2, leading to a poorer match (not shown).

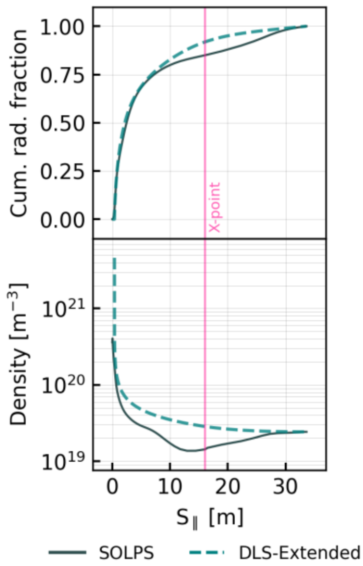

Figure 1: Comparison of DLS-Extended predictions to SOLPS showing the radiation distribution (top) and electron density (bottom).

3. IMPLICATIONS OF BROAD RADIATION

DLS-Extended was used to find the impact of broadening impurity radiation on detachment threshold., defined by a lumped control parameter of upstream conditions $C_t = n_{e,u}^2 f_{Ar}/Q_{in}^{5/7}$, linking upstream density, impurity fraction and upstream heat source [2]. A good divertor has the lowest threshold possible. We parametrise the improvement to detachment access with total flux expansion and total connection length as $C_t^{-1} \propto f_R^{K_{f_R}} L_{\parallel}^{K_{L_{\parallel}}}$. In the original DLS, two-point model considerations yield $K_{f_R} = 1$; lowering B field increases flux tube cross-sectional area, reducing the parallel heat flux proportionally. The same analysis yields $K_{L_{\parallel}} = 2/7$ due to electron conduction effects. DLS-Extended adds non-linear radiation effects causing K_{f_R} and K_{L_c} to no longer be constant. To investigate, f_R was doubled by reducing B_{target} and $L_{\parallel}$ doubled by increasing L_{div} for several cooling curves: a synthetic thin curve, three ADAS impurity curves and an effective curve extracted from SOLPS.

The resulting values of K_{f_R} and $K_{L_{\parallel}}$ are shown in Figure 2 and decomposed into four terms. The radiation distribution found in the SOLPS simulation sees an approx. 50% decrease in K_{f_R} and an approx. 50% increase in $K_{L_{\parallel}}$ compared to curve 1. The f_R impact was dominated by term α, the radiation-averaged B field B_{eff}. This is due to increased radiation upstream where there is less difference in B field strength between high and low flux expansion cases, weakening the effective total flux expansion. The $L_{\parallel}$ impact was dominated by the same term but a different effect: increased $L_{\parallel}$ reduces the average B field in the radiation region near the front, increasing the effectiveness of total flux expansion. For curves 2 and 3, term γ enhances $K_{L_{\parallel}}$ due to the presence of midplane radiation.

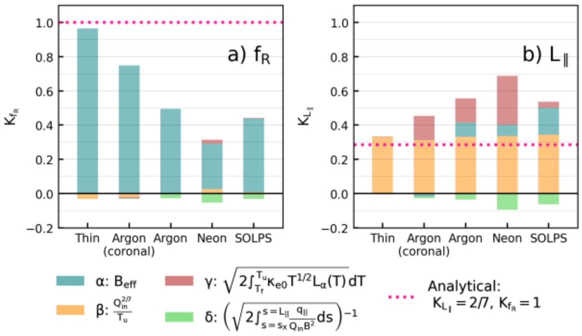

Figure 2: DLS-Extended predictions of the impact of cooling curve choice on K_{f_R}, and $K_{L_{\parallel}}$ for a number of cooling functions. The results are decomposed into four terms α, β, γ and δ.

The results show that the radiation enhancement of $L_{\parallel}$ can be significant and that this is partially due to enhancement of effective total flux expansion. At the same time, a novel radiation-driven effect can significantly reduce the benefit of f_R on detachment onset. The key effects reveal a complex interplay between f_R and $L_{\parallel}$ which could lead to detachment performance optimisation when both f_R and $L_{\parallel}$ are high, such as in the Super-X. This may result in a more optimal balance between toroidal coil size and detachment performance and allow for enhanced detachment access through radiation distribution shaping, e.g. by altering puff locations or increasing target flaring. While the present work focuses on increasing L_{pol}, $L_{\parallel}$ could also be increased by lowering the magnetic pitch, leading to a more compact divertor design. While past experiments suggested this to be ineffective [4], more studies are needed to confirm this in the presence of broad-radiating impurities and tight baffling. While higher fidelity models are required to assess neutral effects, particularly in weakly baffled scenarios, the validation of the radiation distribution prediction in this work and of the key magnetic geometry effects in [2] show DLS-Extended to be a useful tool for rapid evaluation of divertor geometries as part of a multi-fidelity detachment modelling study.

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