Impact of radiation distribution on detachment onset and implications for STEP divertor design

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DLS-Extended – new open-source tool

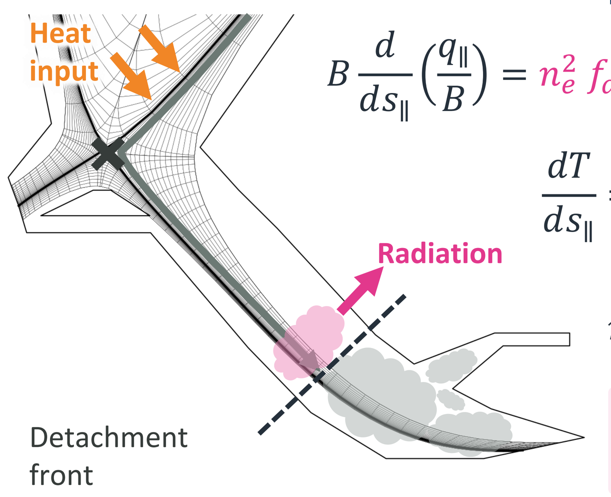
Capabilities

- Calculates detachment front movement based on changes in n_u, f_α, P_{SOL}
- Calculates conditions required for detachment access
- Considers magnetic geometry and cooling curve effects

Context

Evolution of Detachment Location Sensitivity (DLS [1,2,3]) 0.5D first-principles Lengyel-based [4] analytical model

- Now able to predict 1D profiles and include radiation width effects
- **Computational cost: 1-2s**



Equations

$$B\frac{d}{ds_\parallel}\left(\frac{q_\parallel}{B}\right) = n_e^2 f_\alpha L_\alpha(T) - Q_{in}$$

Power balance – assume impurity radiation dominates

$$\frac{dT}{ds_\parallel} = \frac{q_\parallel}{B}\frac{1}{\kappa_{e0}T^{5/2}}$$

Temperature equation – assume conduction dominates

$$n_u T_u = n_t T_t$$

Pressure equation – assume conserved

Limitations: no neutrals, pressure loss or cross-field transport!

Inputs and outputs

Inputs
Any two of n_u, f_α, P_{SOL}
Parallel B profile
X-point location
Impurity cooling curve
Detachment front location

Outputs
One of n_u, f_α, P_{SOL}
1D profiles of T_e, $q_\parallel$, Q_{rad}

Broad radiation alters benefits of Advanced Divertor Configurations (ADCs)

Two-point model scalings for detachment access [2,6,7]

Original DLS model

$$\left.\frac{n_u\sqrt{f_\alpha}}{P_{SOL}^{5/7}}\right|_{threshold} \propto [L_\parallel]^{-K_{L_\parallel}}[f_R]^{-K_{f_R}}$$

f_R Total flux expansion

$f_R = B_X/B_t$

$$K_{f_R}^{2PM} \approx 1$$

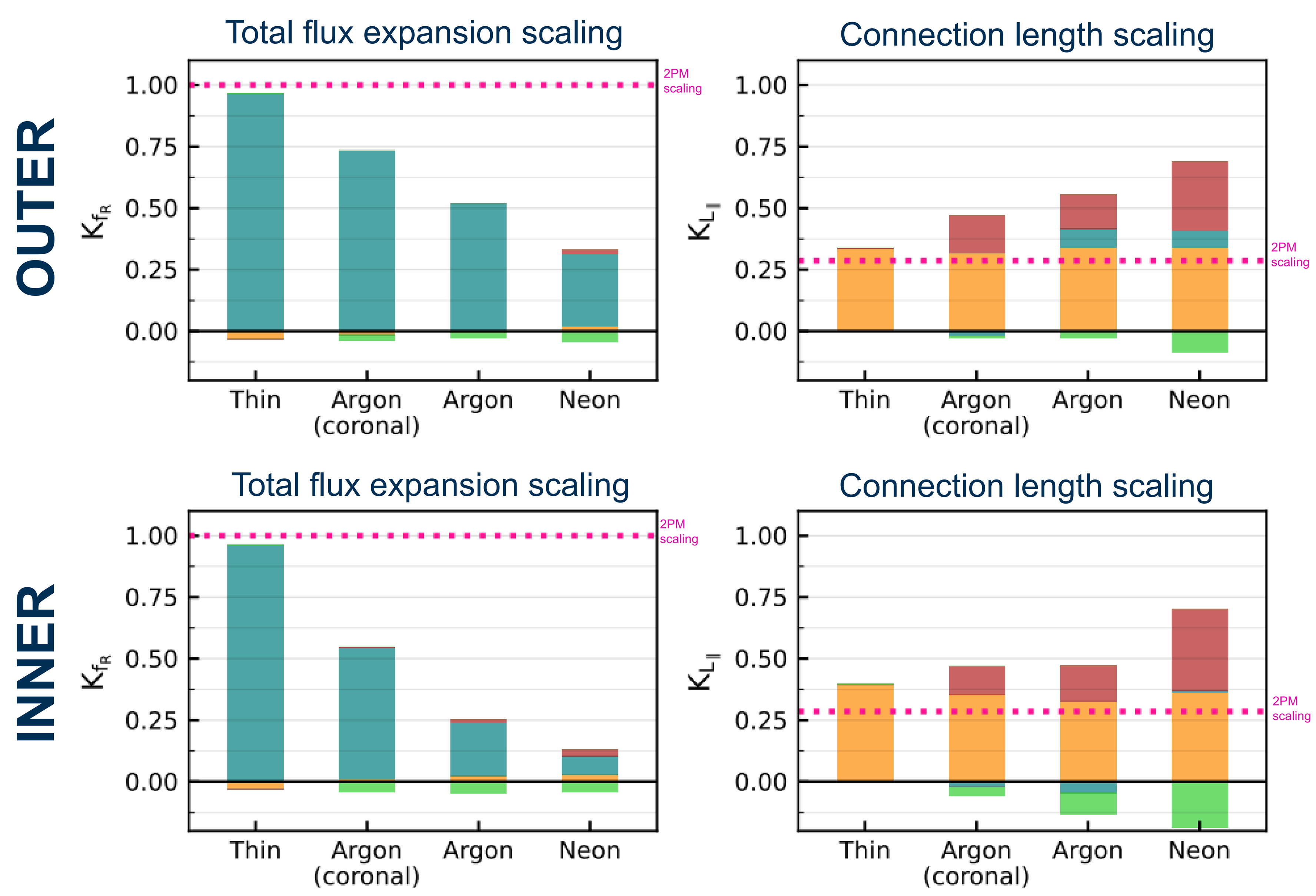
Lower B increases flux tube area, reducing $q_\parallel$, increasing radiating volume

$L_\parallel$ Parallel connection length

$$K_{L_\parallel}^{2PM} = 2/7 = 0.29$$

Greater length implies steeper ∇T for same conduction, so increases T_u and n_t

The scalings change with broadening radiation!

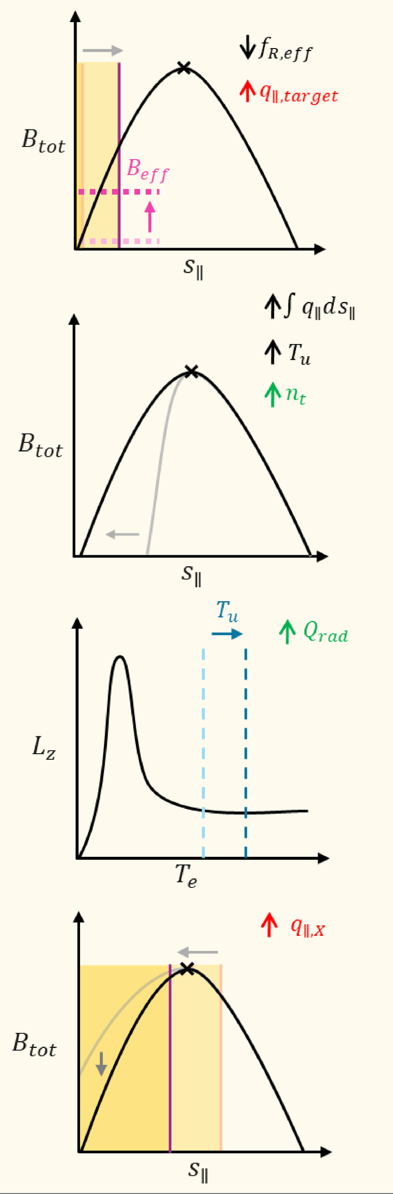


DLS-Extended was used to run the inner and outer legs of an initial STEP design [8] to test impact of doubling f_R and $L_\parallel$ for cooling curves of increasing width

Effect breakdown

Integral form of DLS-Extended

$$\frac{\sqrt{f_\alpha}n_u}{Q_{in}^{5/7}} = \frac{\sqrt{\int_{s_f}^{s_u} q_\parallel Q_{rad} ds_\parallel}}{\sqrt{\int_{s_f}^{s_u} q_\parallel Q_{rad}/B^2 ds_\parallel}} \frac{Q_{in}^{2/7}}{T_u} \frac{\sqrt{2\int_{s_x}^{s_u}\frac{q_\parallel}{Q_{in}B^2}ds_\parallel}}{\sqrt{2\int_{T_f}^{T_u}\kappa_{e0}T^{1/2}L_\alpha(T)dT}}$$



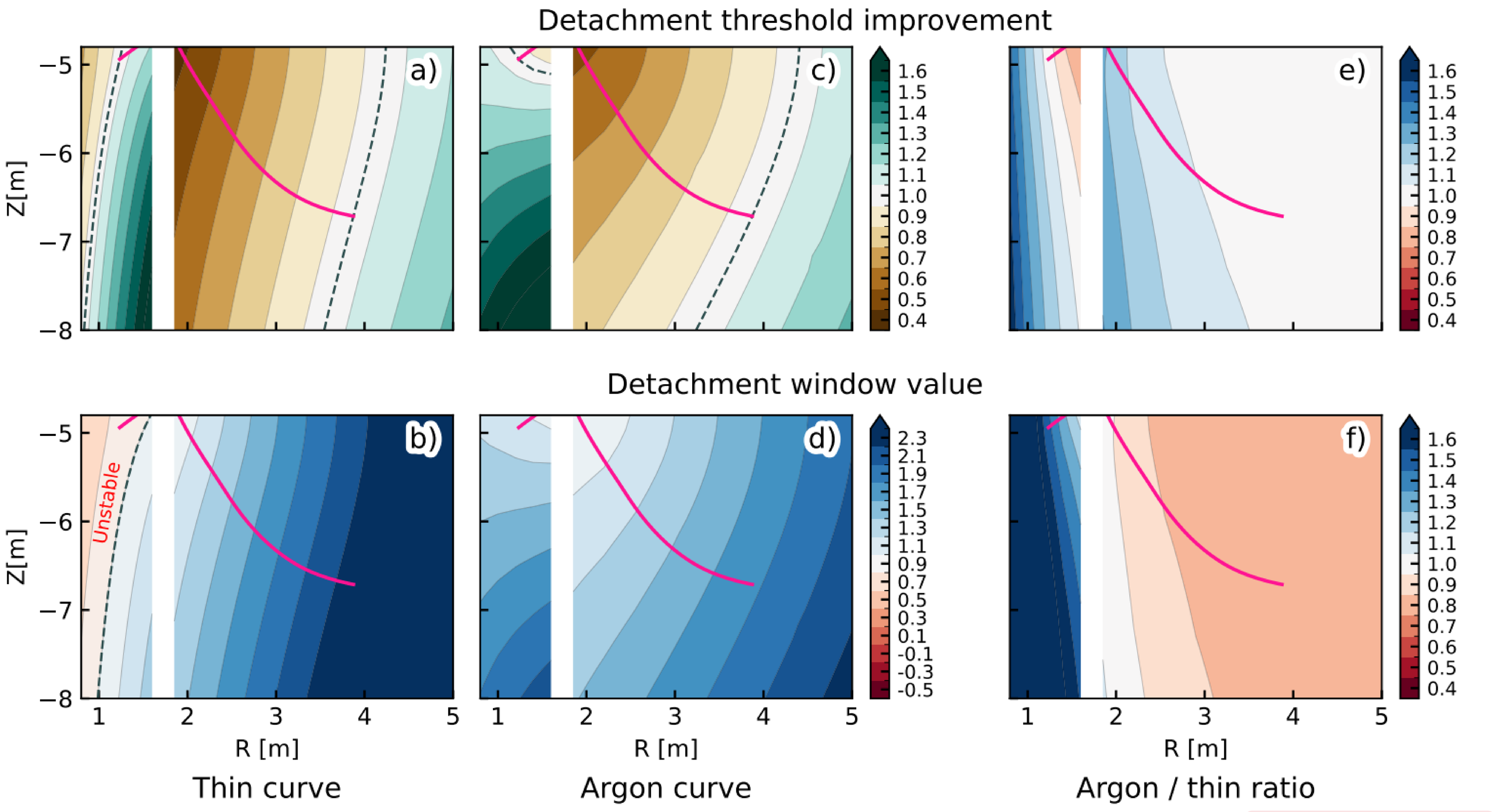
2PM total flux expansion effect + novel effect: radiation "averages out" variations in B field

2PM connection length effect: More length -> Increased $q_\parallel$ integral increases T_u, n_t

Lengyel integral: If radiation can extend past T_u, lengthening $L_\parallel$ increases cooling curve integral (more radiation)

If upstream radiation has reduced, this increases heat flux entering the divertor

Divertor design implications



DLS-Extended was used to evaluate 150 alternative STEP inner and outer strike point locations for thin and realistic radiation curves, capturing impact on detachment access (threshold) and detachment stability (density window)

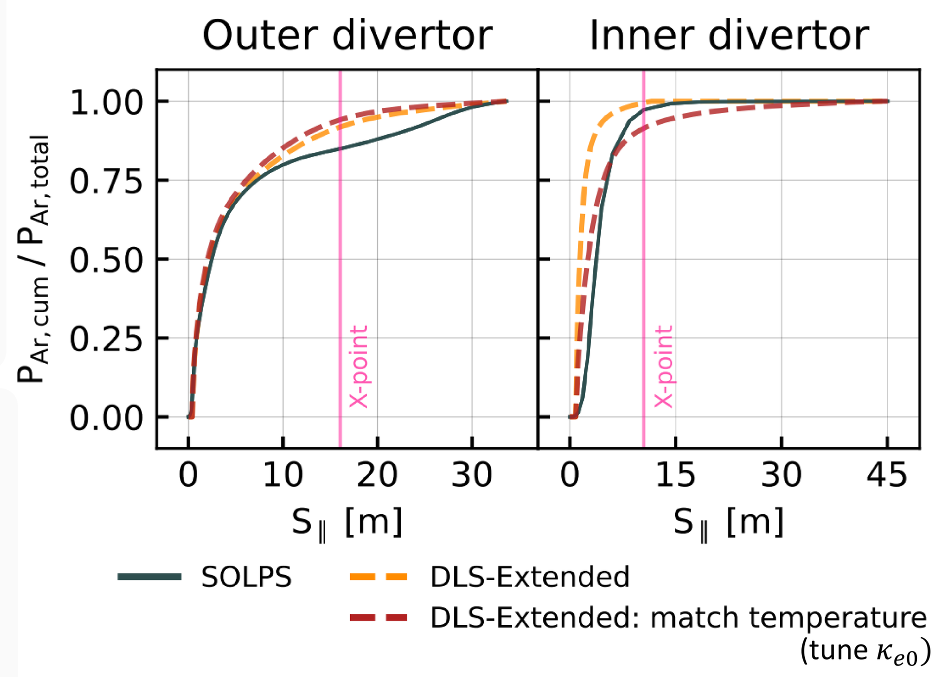
Detachment window: size of parameter space in chosen actuator between reattachment and XPR e.g. $n_u^{XPR}/n_u^{threshold}$

	Implications
1	Potential to reduce machine height without impacting detachment
2	Potential to reposition outer leg to better meet engineering constraints
3	Potential to substantially improve inner divertor detachment performance with longer leg

Comparing DLS-Extended to SOLPS-ITER

Radiation distribution predictions compared to existing STEP SOLPS-ITER simulations [8] on single SOL ring

SOLPS shows broad radiation, DLS-Extended matches well (if no sources/sinks nearby)



Conclusions

DLS-Extended is a powerful, first-principles tool for:

- Guiding equilibrium design or high-fidelity simulations
- Highly interpretable, first-principles physics studies

It was used to find:

- Novel radiation effects impacting magnetic geometry benefits
- Routes to optimising the STEP divertor design

Need experiments and high-fidelity simulations to confirm!

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[1] Lipschultz, B., et al. (2016). Sensitivity of detachment extent to magnetic configuration and external parameters. *Nuclear Fusion, 56*(5), 056007.
[2] Cowley, C., et al. (2022). Optimizing detachment control using the magnetic configuration of divertors. *Nuclear Fusion, 62*(8),
[3] Myatra, O., et al. (2023). Predictive SOLPS-ITER simulations to study the role of divertor magnetic geometry in detachment control in the MAST-U Super-X configuration.
[4] Lengyel, L. L. (1981). *Analysis of radiating plasma boundary layers.*
[5] Rognlien, T. D., et al. (1992). A fully implicit, time dependent 2-D fluid code for modeling tokamak edge plasmas. *Journal of Nuclear Materials, 196–198*, 347–351.
[6] Stangeby, P. C. (2000). The Plasma Boundary of Magnetic Fusion Devices. *The Plasma Boundary of Magnetic Fusion Devices.*
[7] Petrie, T. W., et al. (2013). Effect of changes in separatrix magnetic geometry on divertor behaviour in DIII-D. *Nuclear Fusion, 53*(11).
[8] Osawa, R. T., et al. (2024). Assessment of the impact of fuelling puff location on divertor impurity compression and enrichment in STEP. *Nuclear Fusion, 64*(10).

GitHub

Docs