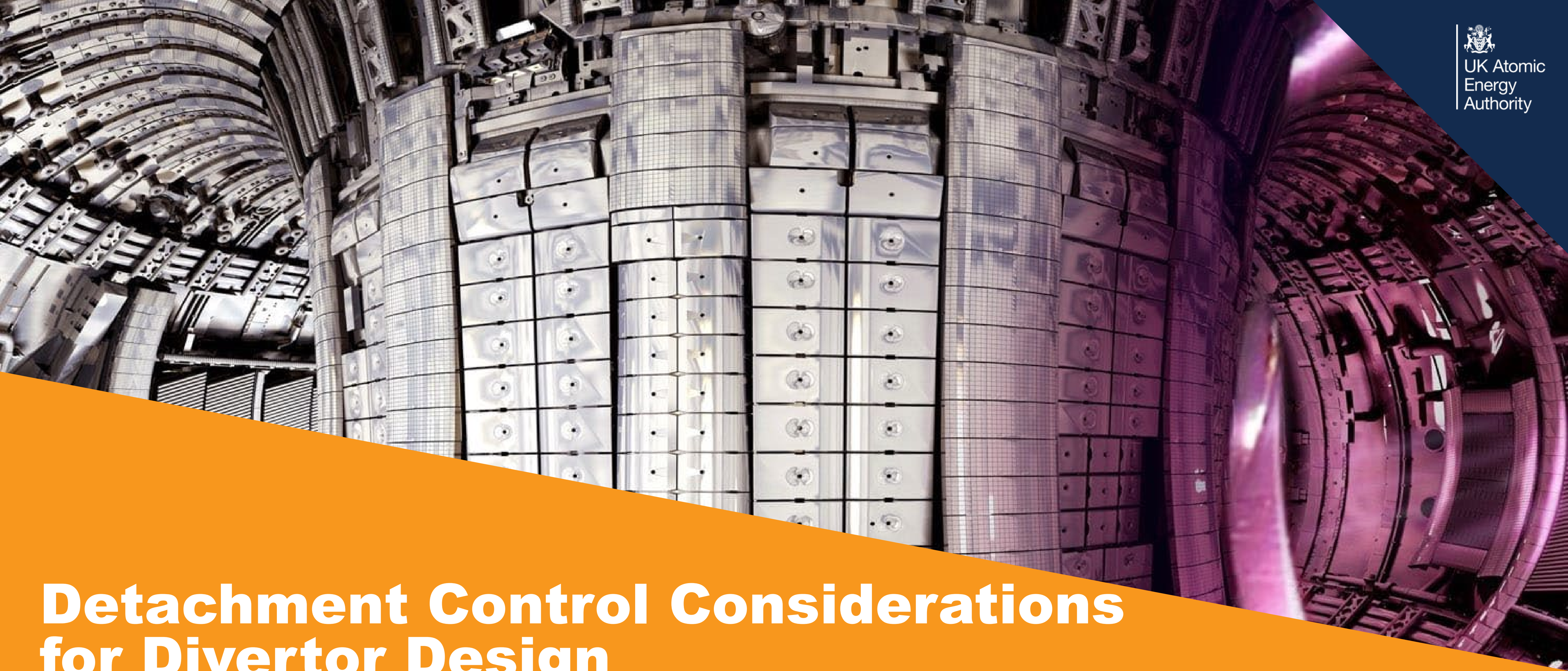

Detachment Control Considerations for Divertor Design

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IAEA 4th Technical Meeting on Divertor Concepts

This work was part funded by the RCUK Energy Programme [grant number EP/W006839/1]. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Core-Edge Compatibility for Reactors

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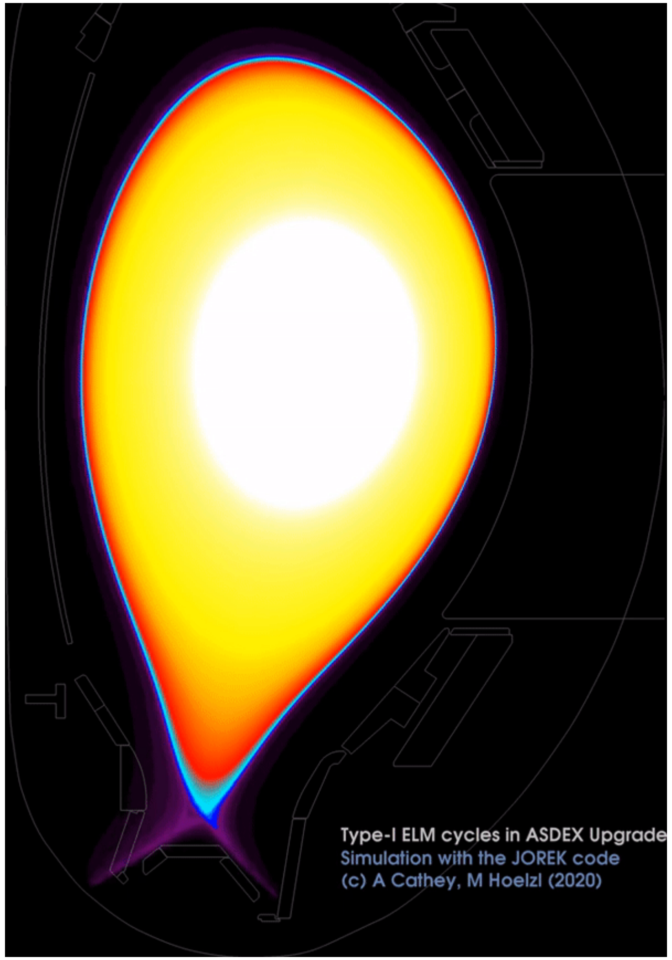

Figure 1. A JOREK simulation of type-1 ELM cycles in ASDEX-Upgrade.

For reactor tokamaks with high energy density, some **heat and particle flux mitigation strategy will be required**, unless core performance is sacrificed.

Even with acceptable steady state heat loads, we need **mitigation strategies for transient peaking in heat loads** – from **ELMs**, **Stochastic transport**, and **pellet injection**.

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Detachment

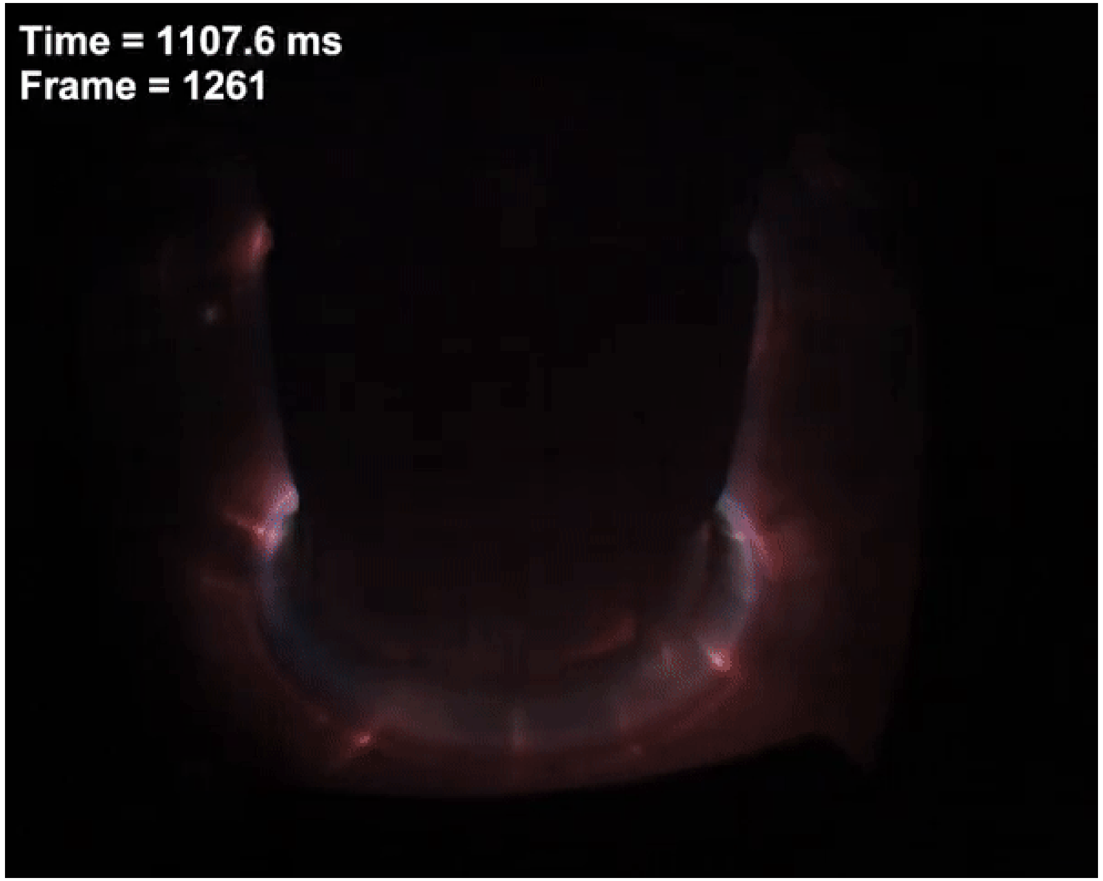

Figure 2. The effect of nitrogen impurity seeding in the COMPASS tokamak. Source: YouTube

One attractive mitigation strategy is **detachment**.

Detachment is characterized by a **significant drop in plasma power and pressure**.

This drops typically occurs **some point upstream of the target** (often referred to as the ‘**detachment front**’).

Detachment leads to more gentle, isotropic loads of power and particles. It could also act as a ‘cushion’ **against transient loads** [1].

[1] Cowley C et al. Nuclear Fusion. 2022 Jul 6;62(8):086046.

Detachment Control

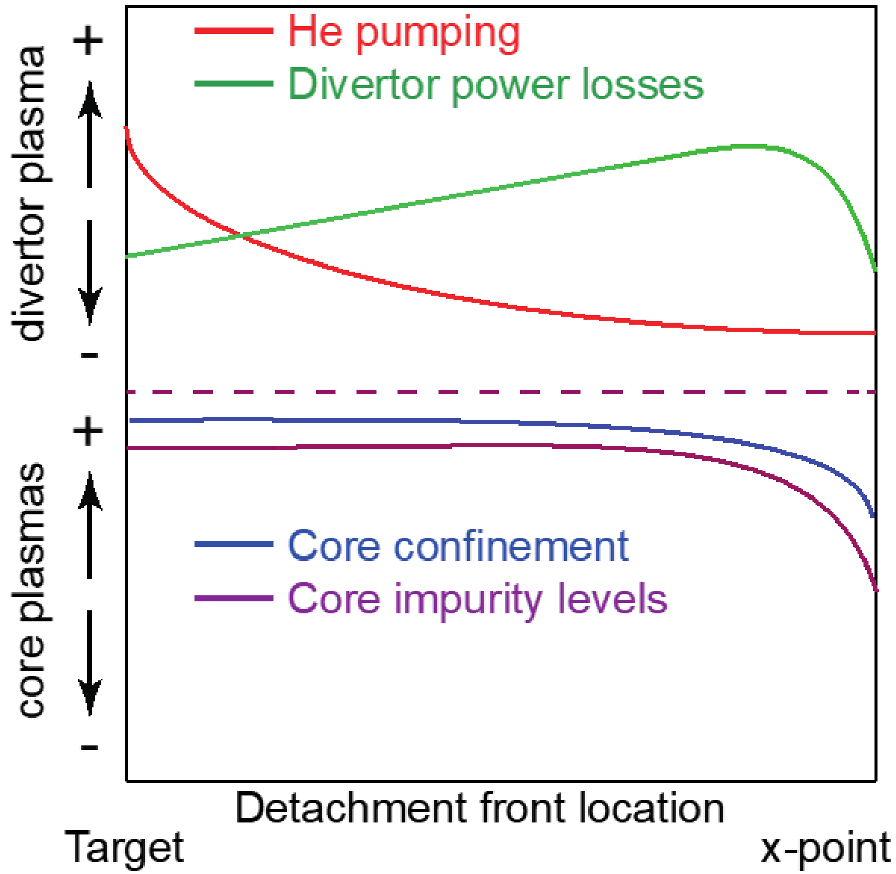

Figure 3. A diagram indicating the effects of having a detachment front in various locations. Image courtesy of B. Lipschultz.

A detachment front **too near the target** and too **near the upstream** both **have their disadvantages.**

Detachment can be controlled by **fuelling, seeding radiating impurities, and varying the input power.** Sensitivity of controllers can vary from machine to machine.

Having **good control over the position of detachment** may be vital for future machines.

Aims of this Talk

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This talk aims to answer the following questions:

I) Can we develop simplified, meaningful models for detachment control?

II) What do these models tell us about how we can design divertors to optimize detachment control?

III) How well do these models agree with reality, and where are the gaps in knowledge that we need to fill over the coming years?

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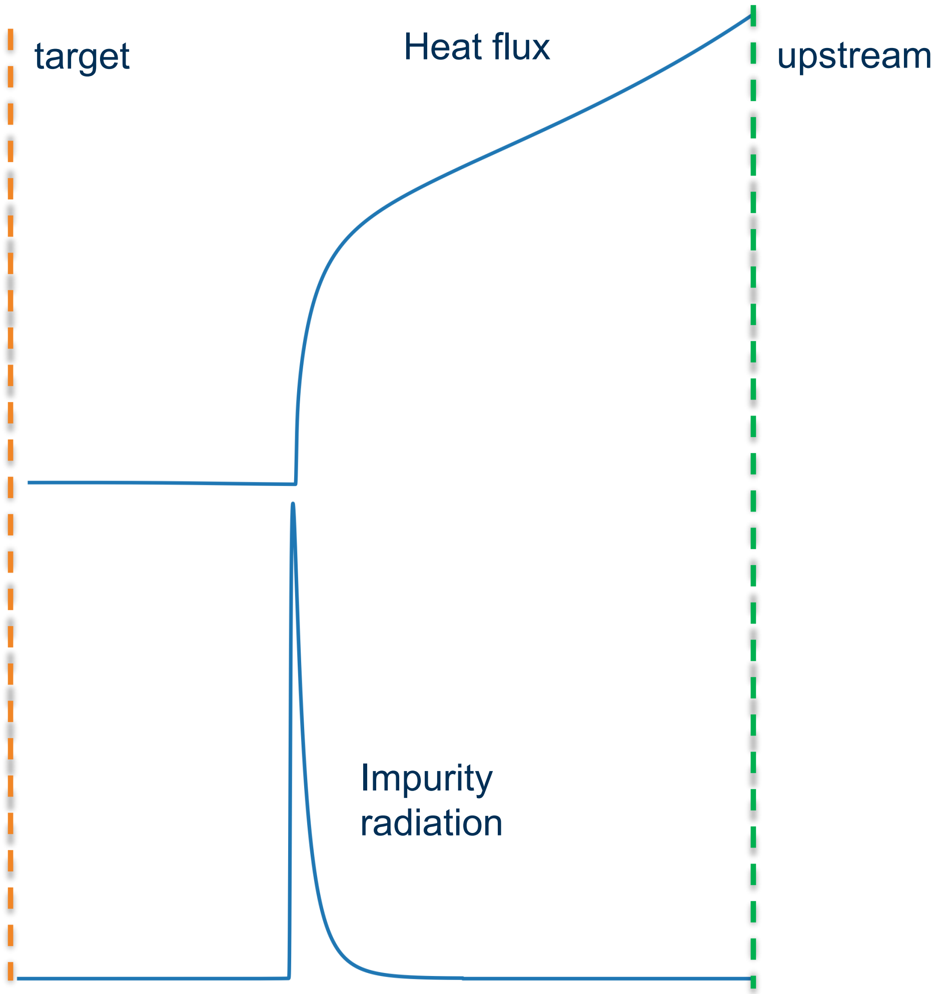
I) Can we develop simplified, meaningful models for detachment control?



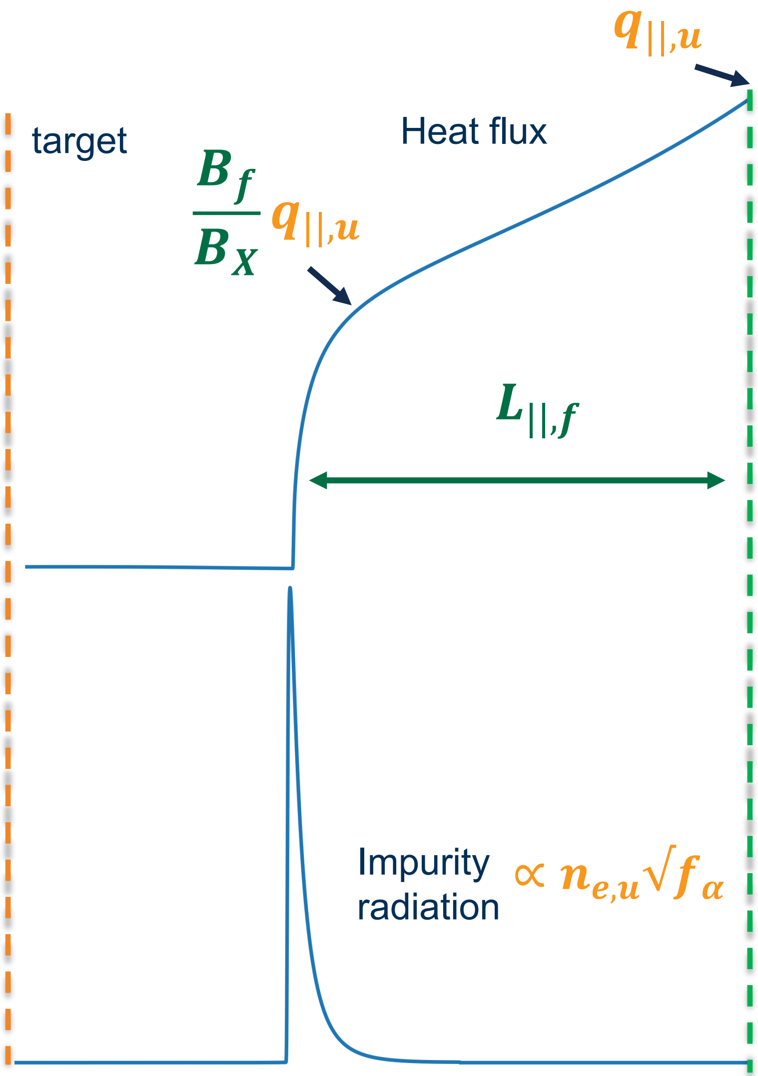
One attempt at a simplified model for detachment control is the **Detachment Location Sensitivity (DLS)** model

The DLS model [1,2] is a quasi-analytical model for **1d heat balance** in a **detached divertor plasma.**

It assumes all conducted heat flux is **dissipated by impurities at one location**, termed the **detachment front.**

[1] Cowley C et al. Nuclear Fusion. 2022 Jul 6;62(8):086046.
[2] Lipschultz B et al. Nuclear Fusion. 2016 Apr 8;56(5):056007.

DLS Model Derivation



By relating the heat dissipated at the front to conditions upstream, we can formulate an expression for the **control parameters required** for a detachment front to exist in a given location denoted by subscript f:

$$\frac{n_{e,u}\sqrt{f_\alpha}}{q_{||,u}^{5/7}} \equiv C_f = C_0 \frac{B_f}{B_X} L_{||,f}^{-2/7} \frac{B_X^{2/7}}{\langle B \rangle_{above\ f}^{2/7}}$$

Here C_f is a lumped control parameter, and depends only on **the front position and divertor configuration**.

Detachment Location Sensitivity

The DLS equation for control parameter can be differentiated to determine the **detachment location sensitivity.**

Shown below, sensitivity is the fractional **rate of change of front position with respect to control parameter**:

$$C_f \frac{ds_{pol,f}}{dC_f} = \left[\frac{1}{B_f} \frac{dB_f}{ds_f} + \frac{2}{7} \frac{1}{L_{||,f}} \frac{B_f}{B_{pol,f}} - \frac{2}{7} \frac{1}{\langle B \rangle_{||,f}} \frac{d\langle B \rangle_{||,f}}{ds_f} \right]^{-1}$$

The sensitivity tells us **how quickly a front will move given some perturbation in our controllers.** Low sensitivity means better control.

Aims of this Talk

This talk aims to answer the following questions:

I) Can we develop simplified, meaningful models for detachment control?

II) What do these models tell us about how we can design divertors to optimize detachment control?

III) How well do these models agree with reality, and where are the gaps in knowledge that we need to fill over the coming years?

Features Influencing Detachment

Detachment Sensitivity:
rate of change of front position with control parameter.
Low sensitivity = slow front movement.

2. Total magnetic field gradients slow front movement

$$C_f \frac{ds_{pol,f}}{dC_f} = \left[\frac{1}{B_f}\frac{dB_f}{ds_f} + \frac{2}{7}\frac{1}{L_{||,f}}\frac{B_f}{B_{pol,f}} - \frac{2}{7}\frac{1}{\langle B \rangle_{||,f}}\frac{d\langle B \rangle_{||,f}}{ds_f} \right]^{-1}$$

1. As control parameter increases and the front moves, we see absolute sensitivity naturally decrease.

3. Low poloidal field should slow poloidal front movement.

SOLPS-ITER Comparison

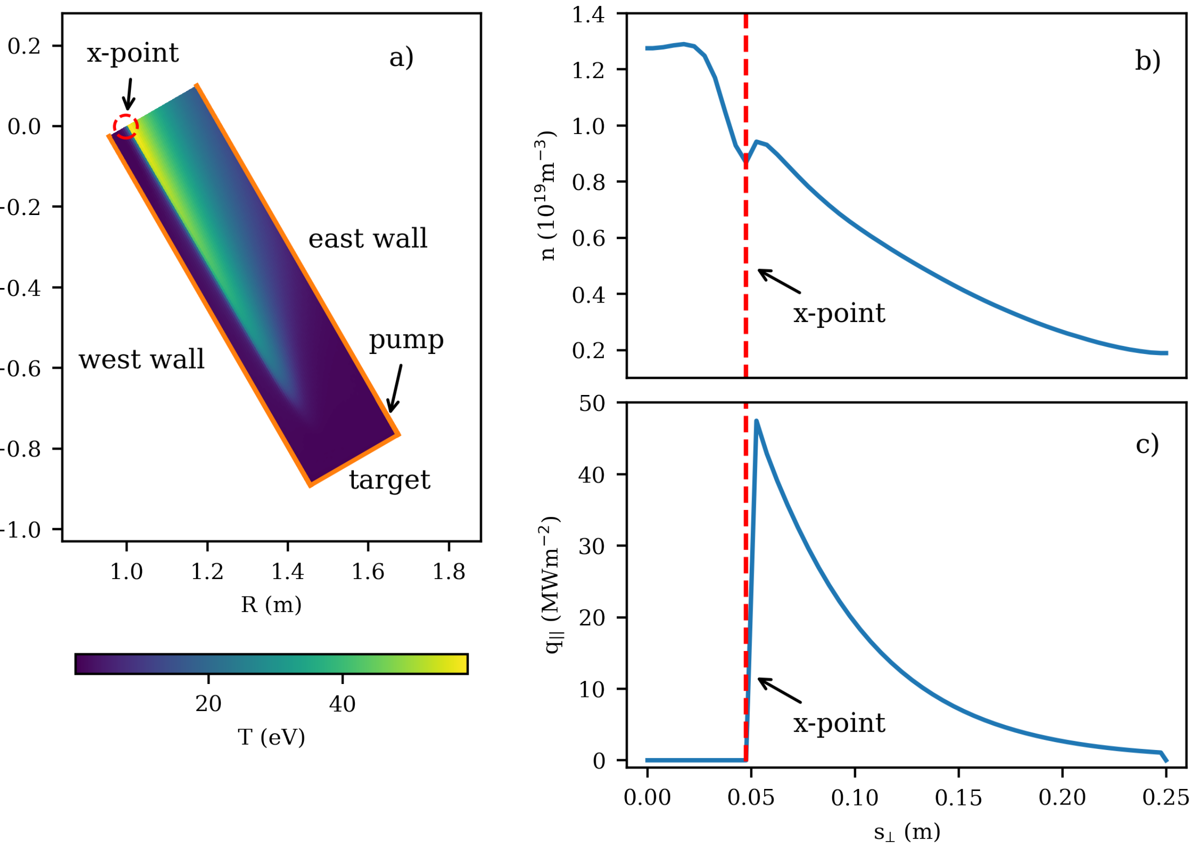


Figure 4. Left : An annotated simulation of an isolated divertor leg at 30◦ to the vertical. Right: upstream electron density and heat flux profiles for the simulation on the left.

To study the effects of geometry on detachment, we have developed **isolated-leg SOLPS-ITER simulations** in idealised geometry.

The **DLS model has been applied to these simple geometries**, and compared with SOLPS-ITER simulations.

We compare front movement with regards to a change in C_f relative to the detachment threshold, C_t.

1. Natural Decrease in Sensitivity

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Detachment Sensitivity:
rate of change of front position with control parameter.
Low sensitivity = slow front movement.

$$C_f \frac{ds_{pol,f}}{dC_f} = \left[\frac{1}{B_f} \frac{dB_f}{ds_f} + \frac{2}{7} \frac{1}{L_{||,f}} \frac{B_f}{B_{pol,f}} - \frac{2}{7} \frac{1}{\langle B \rangle_{||,f}} \frac{d\langle B \rangle_{||,f}}{ds_f} \right]^{-1}$$

1. As control parameter increases and the front moves, we see absolute sensitivity naturally decrease.

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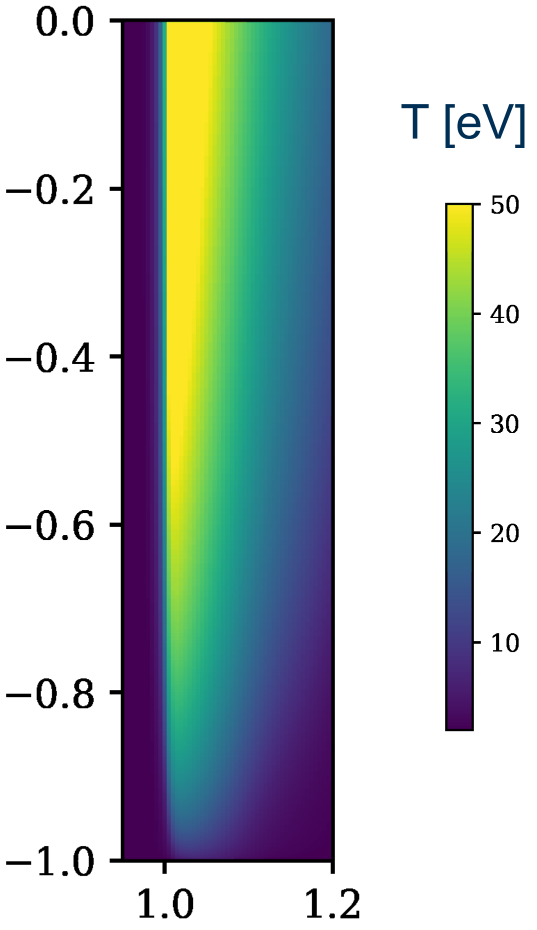
1. Natural Decrease in Sensitivity



To investigate how sensitivity varies naturally, we performed a SOLPS-ITER impurity scan on an isolated vertical leg.

1. Natural Decrease in Sensitivity

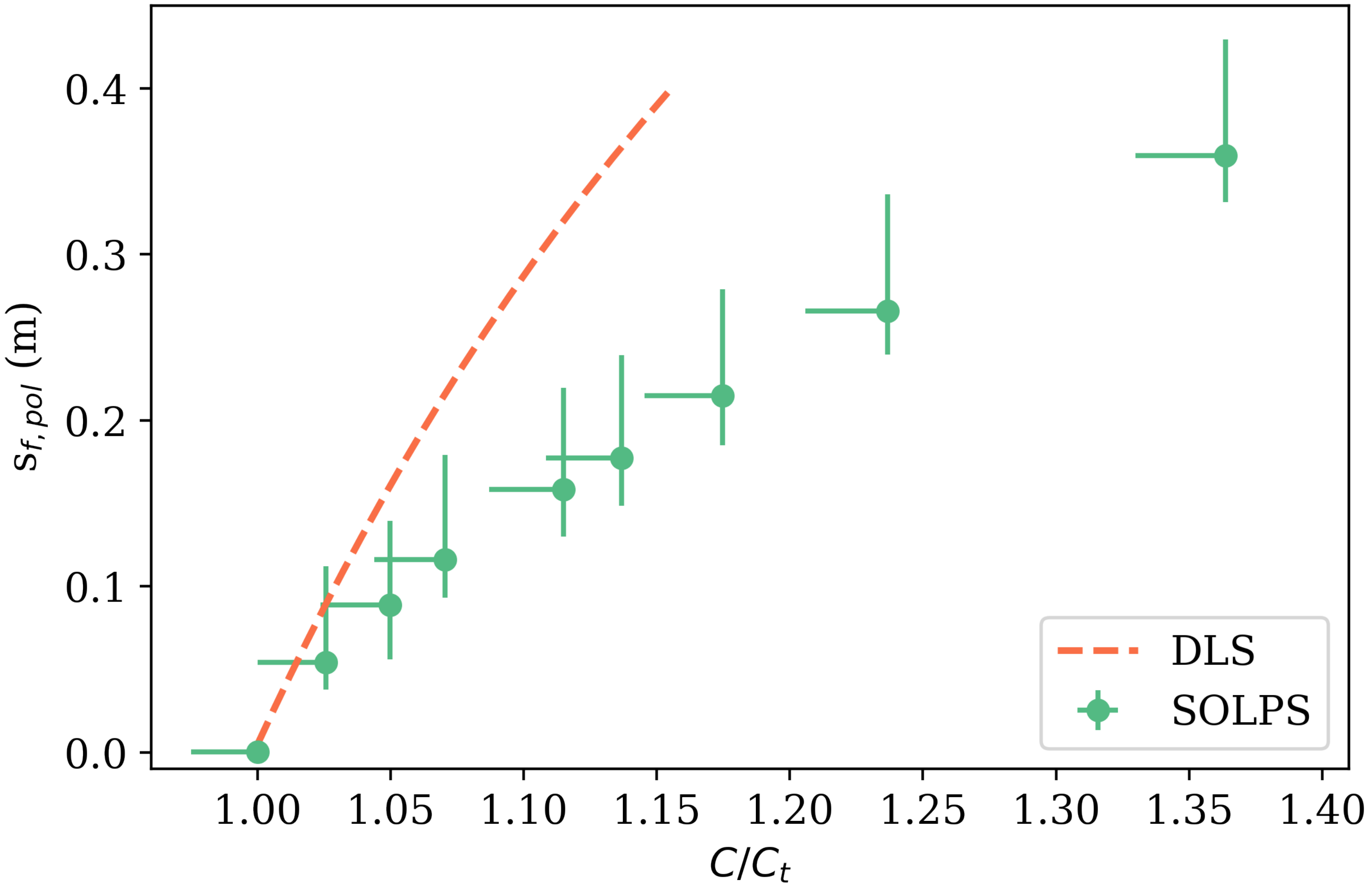


Figure 5. A plot of front position as a function of control parameter for SOLPS-ITER simulations of a vertical divertor leg.

Although the model and SOLPS do not agree perfectly, they both show a **decrease in sensitivity** as the front moves off the target.

Both SOLPS and DLS show a factor **1.5 reduction in sensitivity as the front moves closer to the x-point.**

2. Role of Magnetic Field Gradients

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Detachment Sensitivity:
rate of change of front position with control parameter.
Low sensitivity = slow front movement.

2. Total magnetic field gradients slow front movement

$$C_f \frac{ds_{pol,f}}{dC_f} = \left[\frac{1}{B_f}\frac{dB_f}{ds_f} + \frac{2}{7}\frac{1}{L_{||,f}}\frac{B_f}{B_{pol,f}} - \frac{2}{7}\frac{1}{\langle B\rangle_{||,f}}\frac{d\langle B\rangle_{||,f}}{ds_f} \right]^{-1}$$

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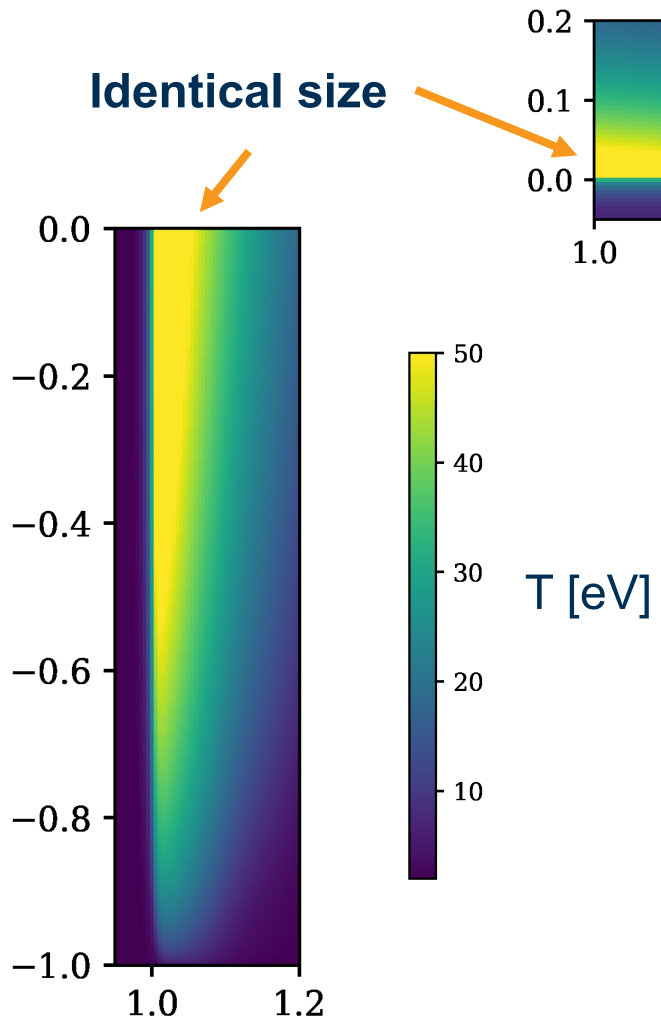
2. Role of Magnetic Field Gradients



To study the effect of magnetic field gradients, we performed impurity scans of **a vertical (left) and horizontal (above) isolated divertor leg.**

The horizontal leg, which has **strong magnetic field gradients** pointing away from the target, **should have much lower sensitivity** and better control.

This effect comes about because a gradient in B causes a gradient in the heat flux density that must be dissipated.

2. Role of Magnetic Field Gradients

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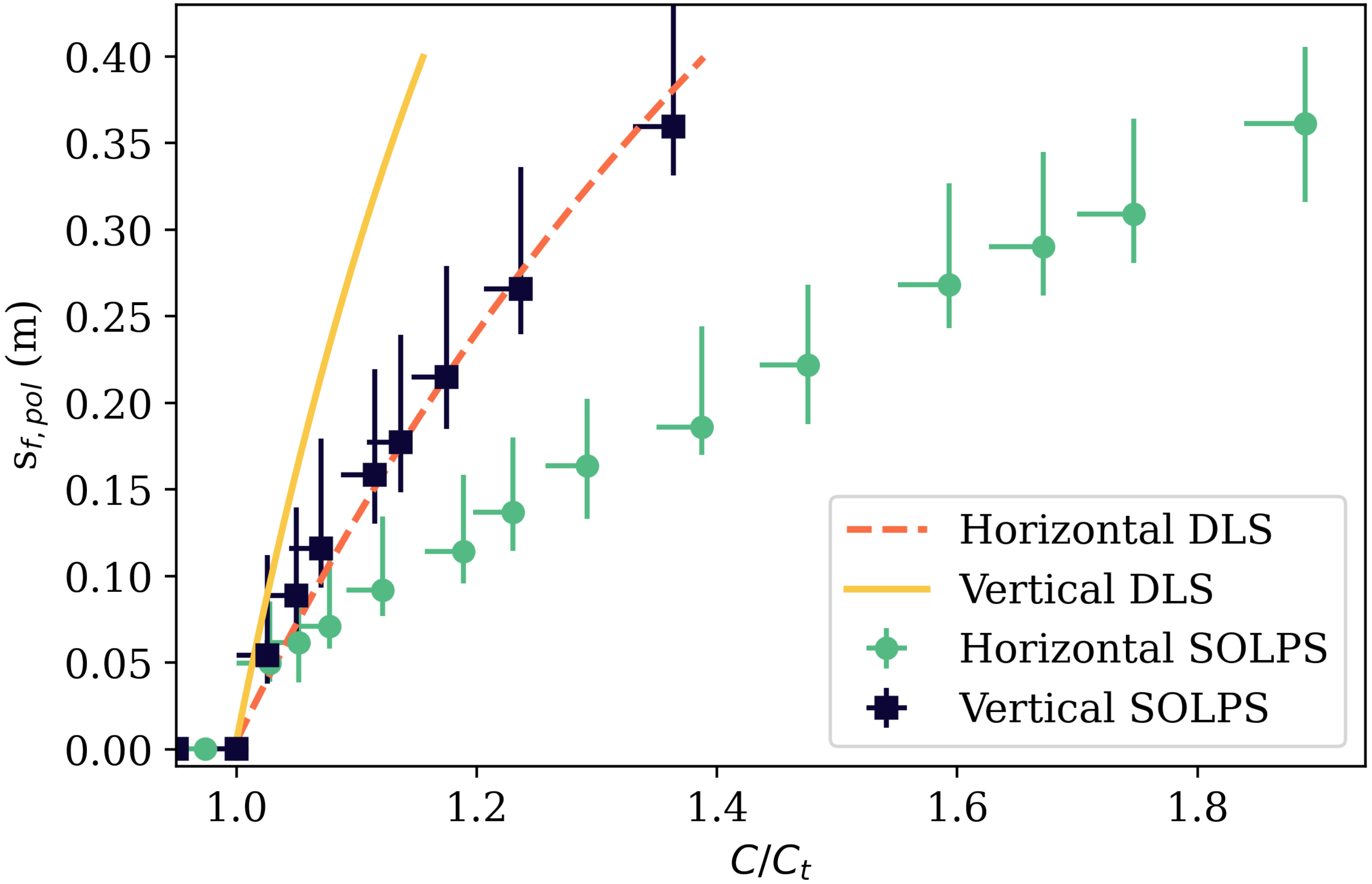

Figure 6. A plot of front position as a function of control parameter for SOLPS-ITER simulations of a vertical and horizontal divertor leg.

We indeed see that the front movement in the horizontal divertor leg is **much slower than the vertical leg.**

The sensitivity is roughly **2.5 times better** in the first 0.2m off the target in the horizontal leg.

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3. Role of Magnetic Pitch

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Detachment Sensitivity:
rate of change of front position with control parameter.
Low sensitivity = slow front movement.

$$C_f \frac{ds_{pol,f}}{dC_f} = \left[\frac{1}{B_f}\frac{dB_f}{ds_f} + \frac{2}{7}\frac{1}{L_{||,f}}\frac{B_f}{B_{pol,f}} - \frac{2}{7}\frac{1}{\langle B\rangle_{||,f}}\frac{d\langle B\rangle_{||,f}}{ds_f} \right]^{-1}$$

3. Low poloidal field should slow poloidal front movement.

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3. Role of Magnetic Pitch

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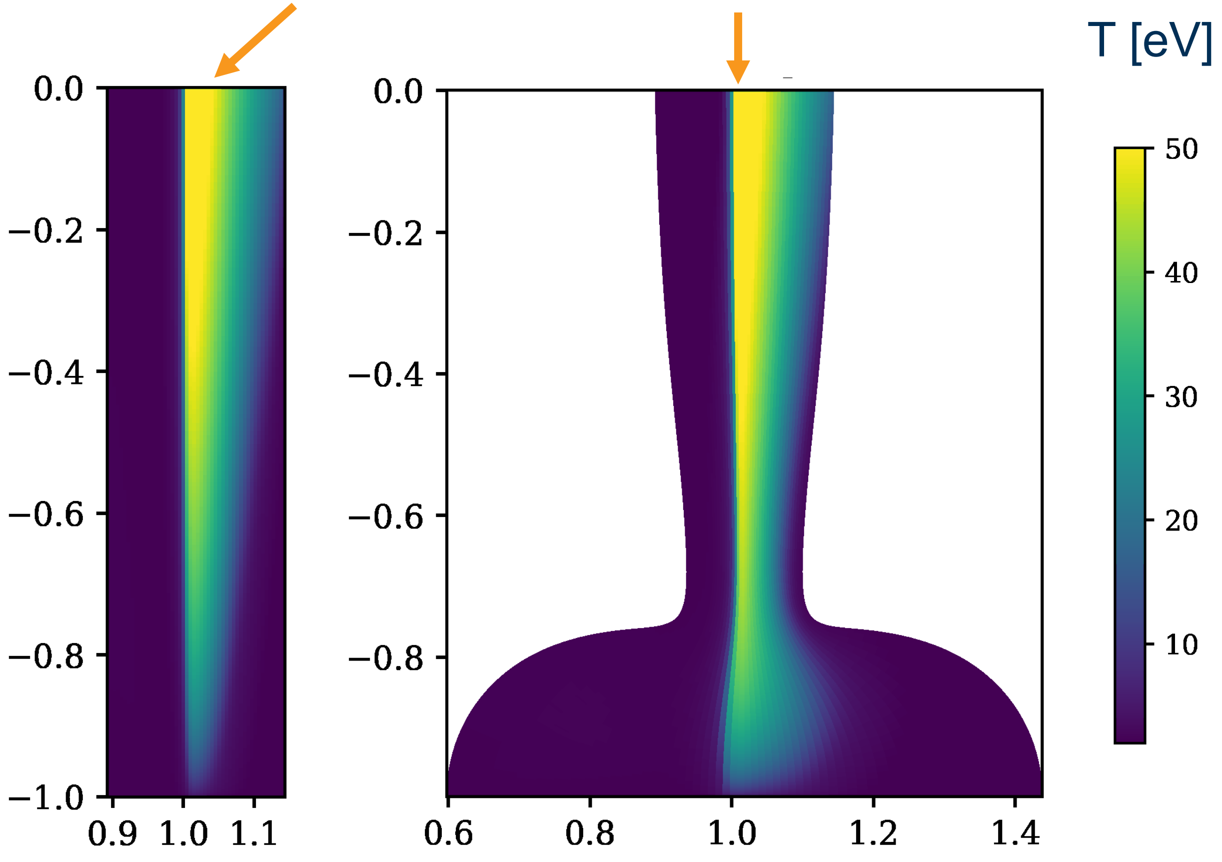
Same connection lengths and total flux expansion



To investigate the effect of magnetic pitch, we performed impurity scans in a **straight** and **poloidally flared leg**.

The two have **identical connection lengths** for the SOL ring of interest, but the flared grid has **much lower poloidal field near the target**.

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3. Role of Magnetic Pitch

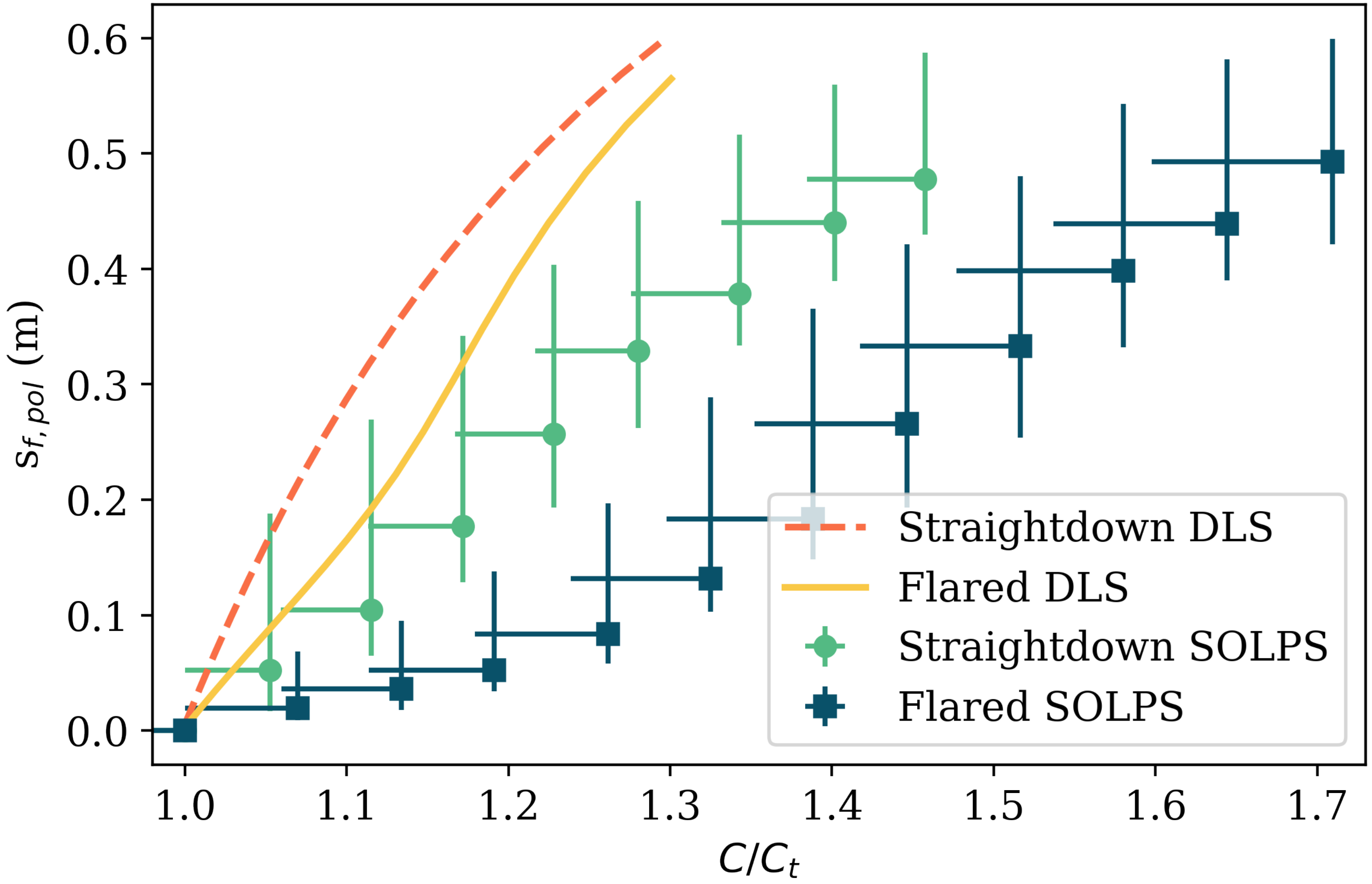

Figure 7. A plot of poloidal front position as a function of control parameter for SOLPS-ITER simulations of a straight and flared divertor leg.

We see that the front movement in the flared divertor leg is **much slower in the flared region than the straight leg.**

The sensitivity is roughly **2 times better** in the first 0.2m off the target in the flared leg.

3. Role of Magnetic Pitch

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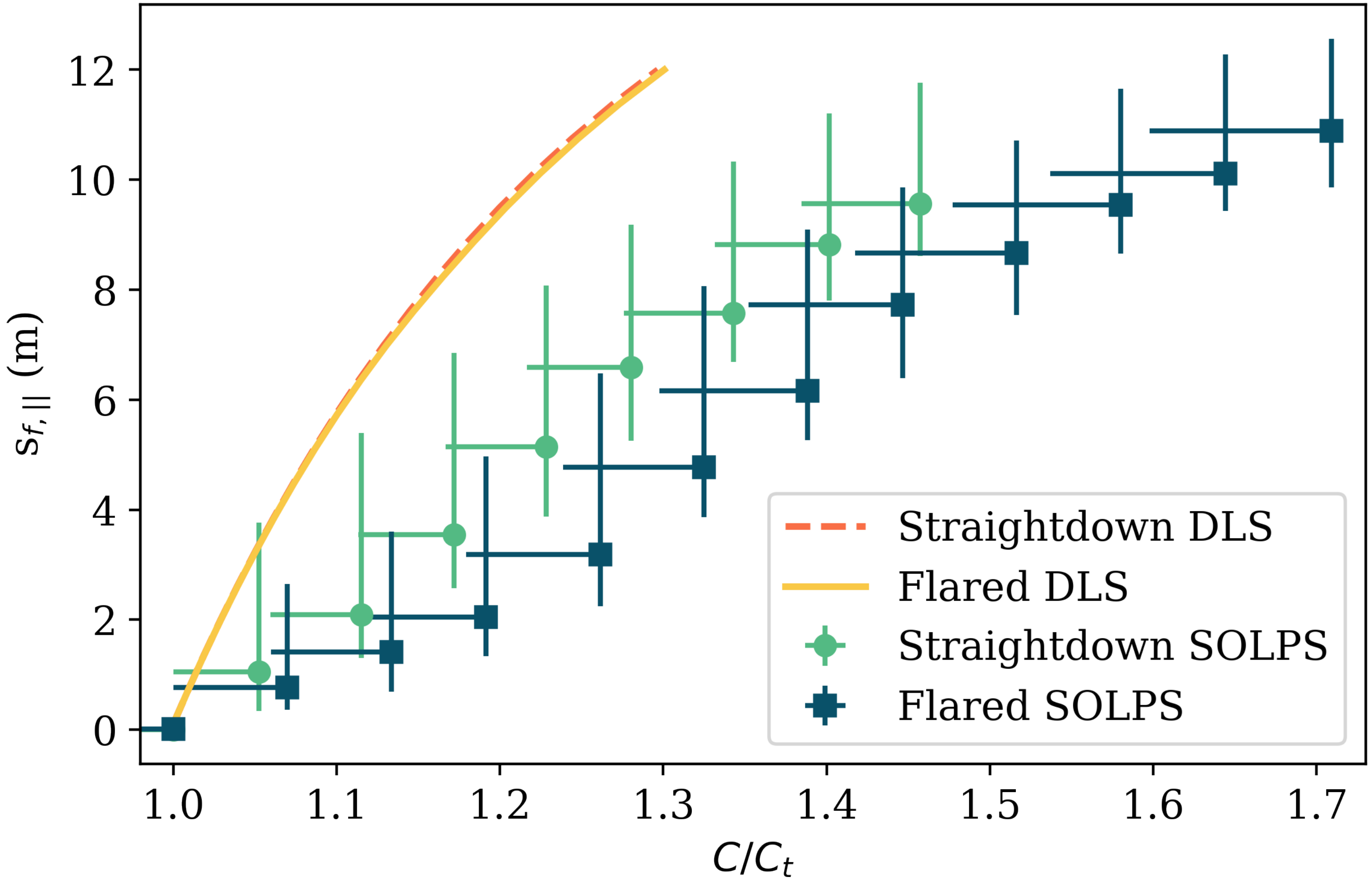

Figure 8. A plot of parallel front position as a function of control parameter for SOLPS-ITER simulations of a straight and flared divertor leg.

It is important to note that the sensitivity **does not change significantly in the parallel direction,** $s_{f,||}$.

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Aims of this Talk

UK Atomic Energy Authority

This talk aims to answer the following questions:

I) Can we develop simplified, meaningful models for detachment control?

II) What do these models tell us about how we can design divertors to optimize detachment control?

III) How well do these models agree with reality, and where are the gaps in knowledge that we need to fill over the coming years?

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Accuracy of Model Predictions

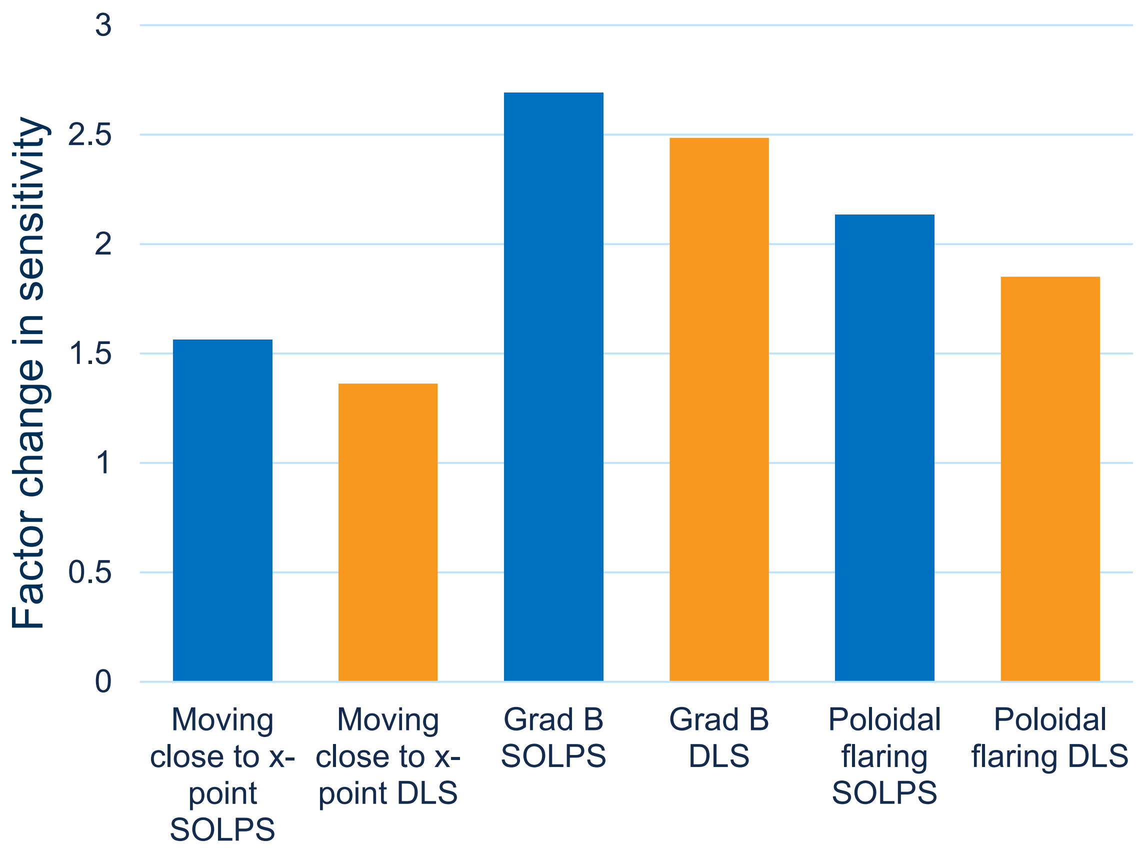

Figure 9. The factor difference in sensitivity in a region of interest when a given divertor geometric feature is varied.

Overall the **effects of certain geometric features on detachment** location sensitivity are **well-predicted by the DLS model.**

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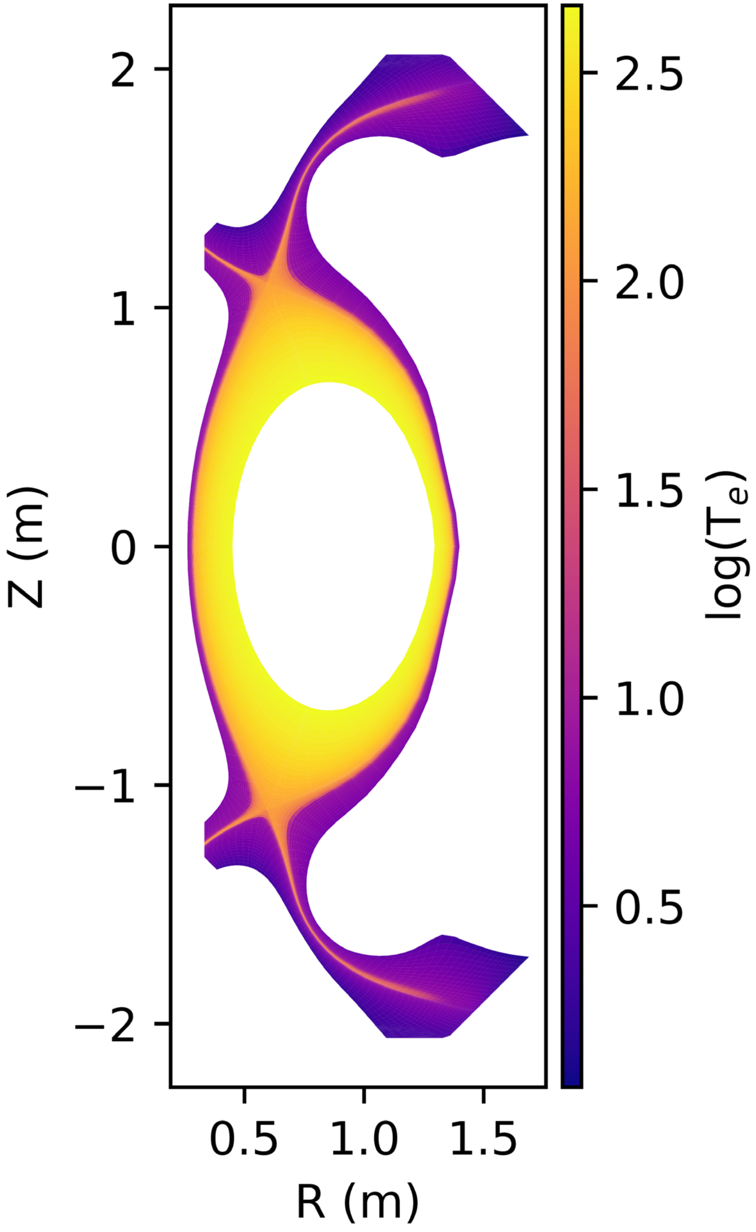
Model Agreement at High Power

Figure 10. The electron temperature profile for a full-geometry MAST-U argon-seeded simulation.



To test the performance of the model in reactor-relevant conditions, we have performed **high power (200-500MWm^{-2} upstream) fixed fraction argon simulations** of the real MAST-U Super-X geometry.

Model Agreement at High Power

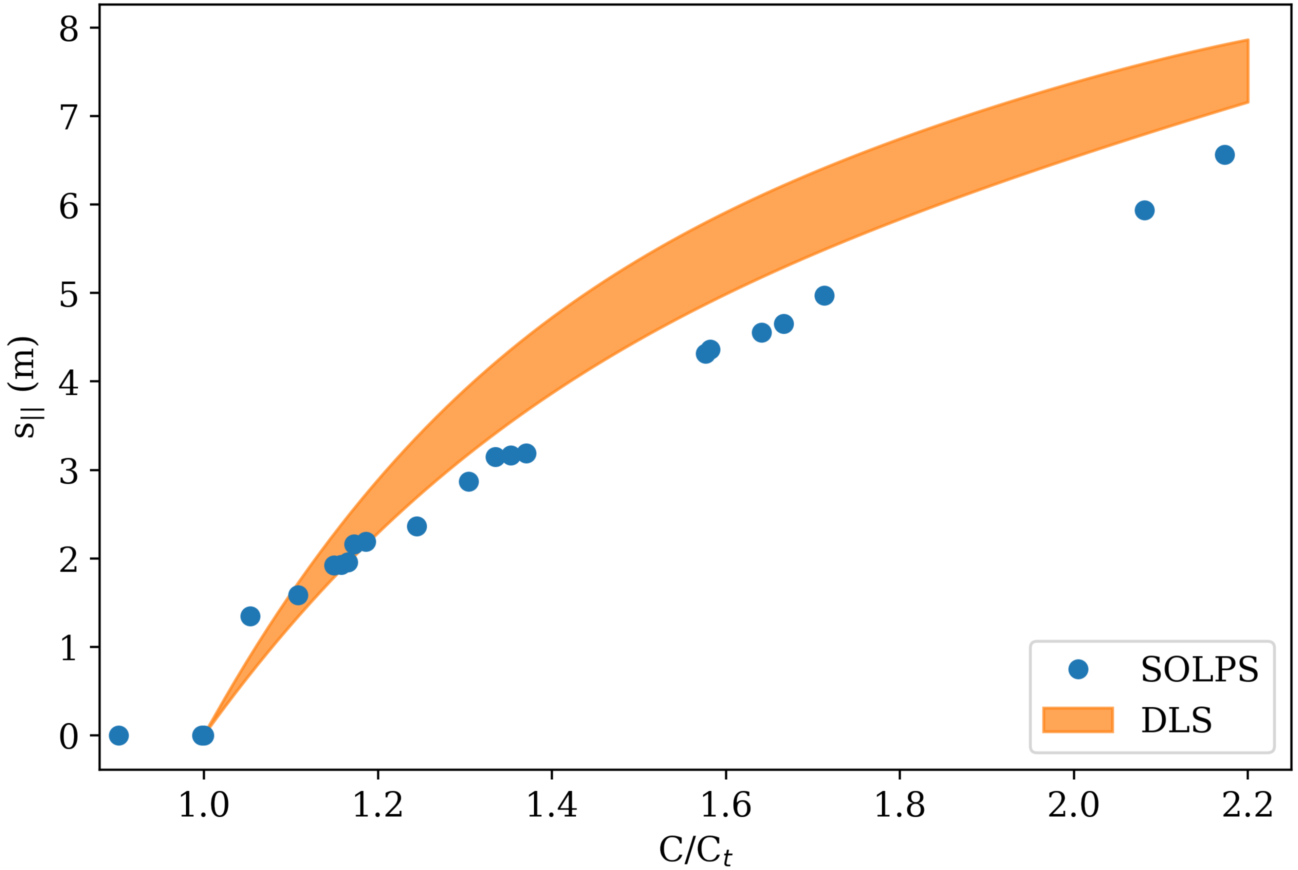


Figure 11. A plot of parallel front position as a function of control parameter for SOLPS-ITER simulations of a MAST-U double null Super-X divertor.

Overall we see **better agreement** between an extended DLS model and SOLPS-ITER in this reactor-relevant regime.

This is still a relatively simple fixed fraction SOLPS-ITER case with **no drifts, currents, puffing or impurity transport.**

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Open Questions

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- Is there any simple way **to include surfaces and neutrals** in simple models for detachment control?

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What the Model Doesn't Tell us: Baffling

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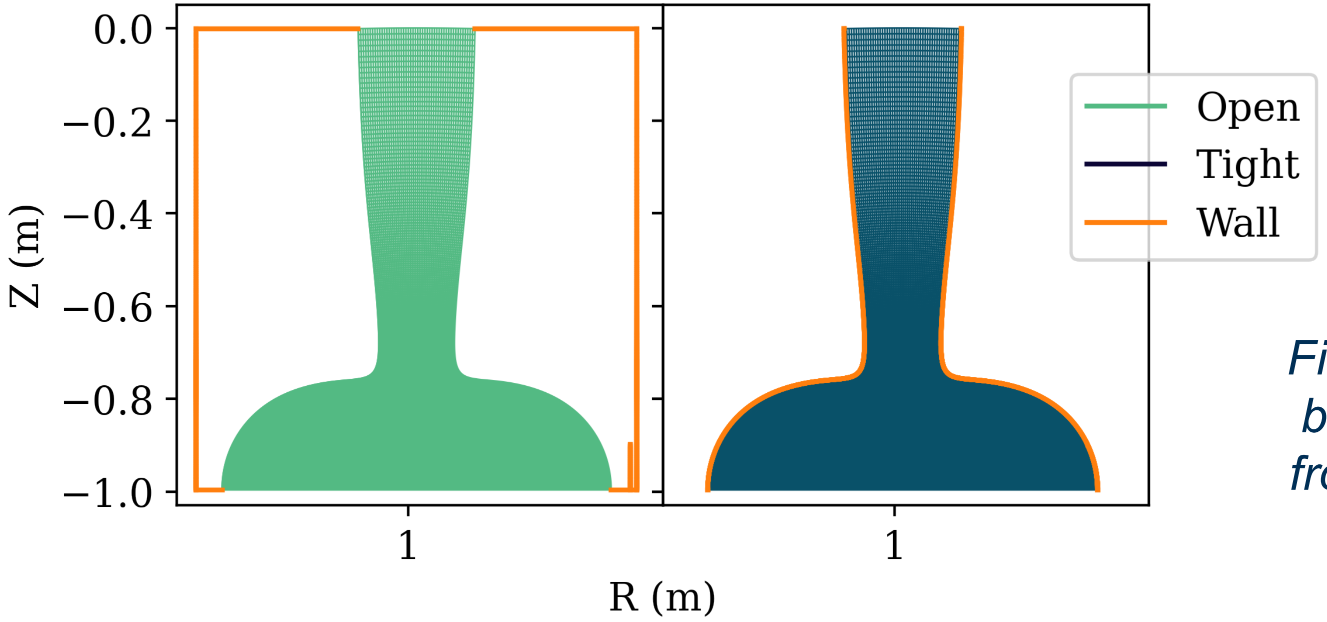
Going from **an open to a tightly baffled region** seems to **decrease the sensitivity of a detachment front** in the region of closure variation.



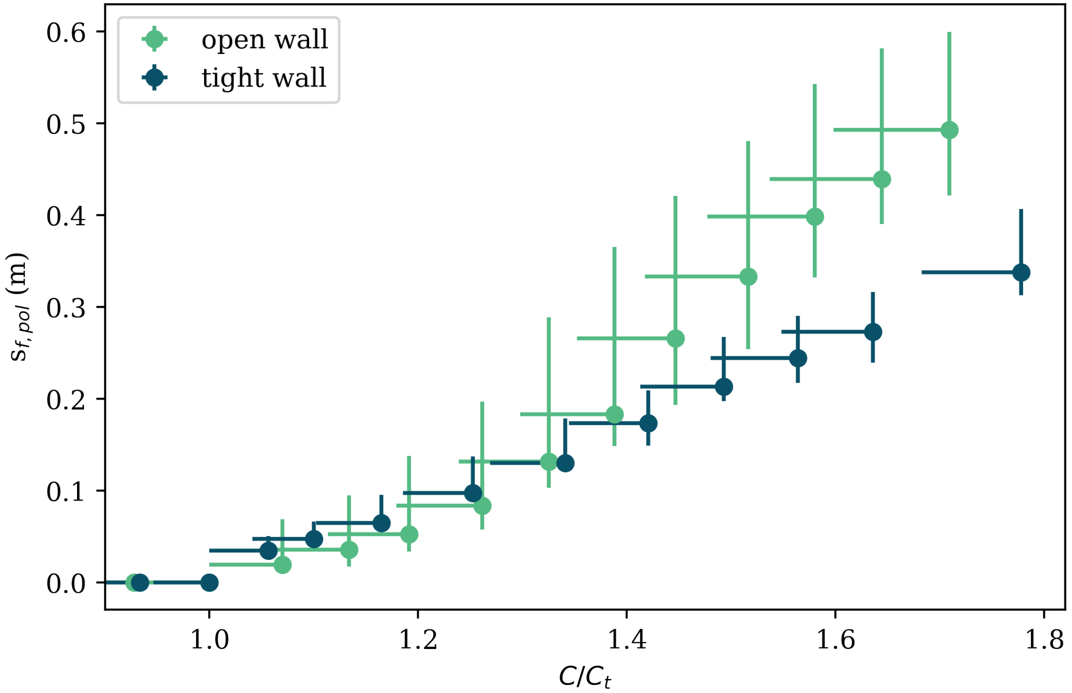


Figure 12. Left: poloidal diagrams of a open and tightly baffled flared divertor leg. Right: A plot of detachment front position as a function of control parameter for the open and tightly baffled legs.

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Open Questions

- Is there any simple way **to include surfaces and neutrals** in simple models for detachment control?

- Do **more complex simulations and experiment agree** with the conclusions predicted here? (ongoing work on experimental comparison in MAST-U)

- How do we **relate front position with target conditions?** (This involves study into complex atomic and molecular physics)

- How do we relate the **control parameters** in these simple models with **real controls** (ie, how does impurity fraction vary with impurity injection rate)?

Other Considerations

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Of course, **a detached divertor is not the only valid solution** to core-edge performance. Alternative solutions could include:

- Liquid lithium divertor with vapor shielding.
- X-point radiator.

However, **good control of these plasma states** would also be required.

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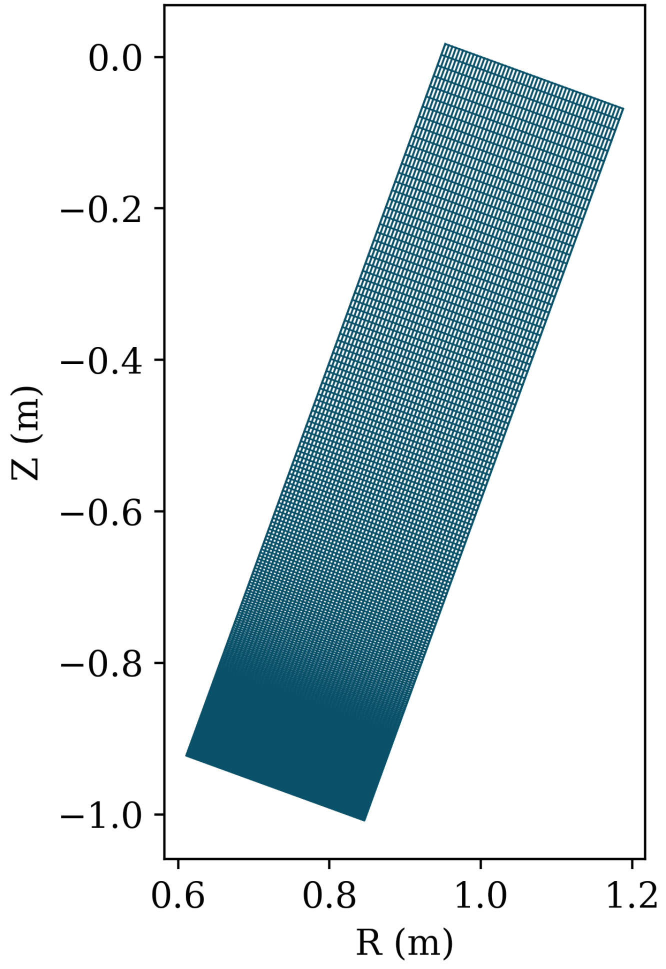
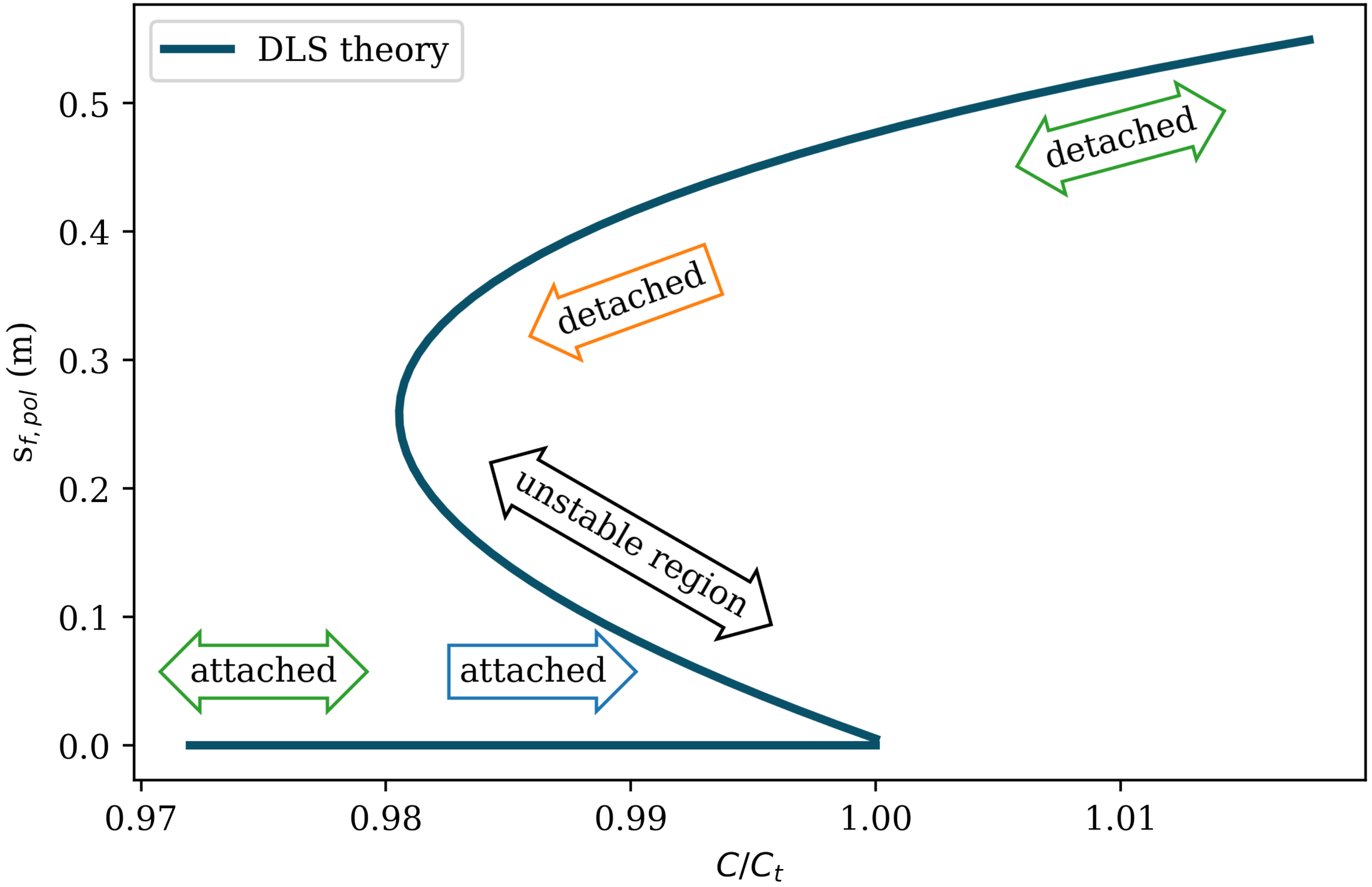
Summary

- The DLS model is a useful tool to predict the **relative effects of divertor characteristic on the controllability of detachment fronts**.
- The DLS model correctly predicts the affect of **magnetic field gradients**, **poloidal field variation**, and **nearness of a front to the x-point** on detachment control.
- Agreement between the DLS model and full-geometry SOLPS simulations **appears better in reactor-relevant conditions.**
- Divertor **features such as closure do affect detachment control**, but are not yet implemented in simple models, and should be further studied over coming years.
- The DLS model also does not model physics such as **impurity transport, and the relationship between front position and target conditions**. This should also be studied further

Negative Sensitivity

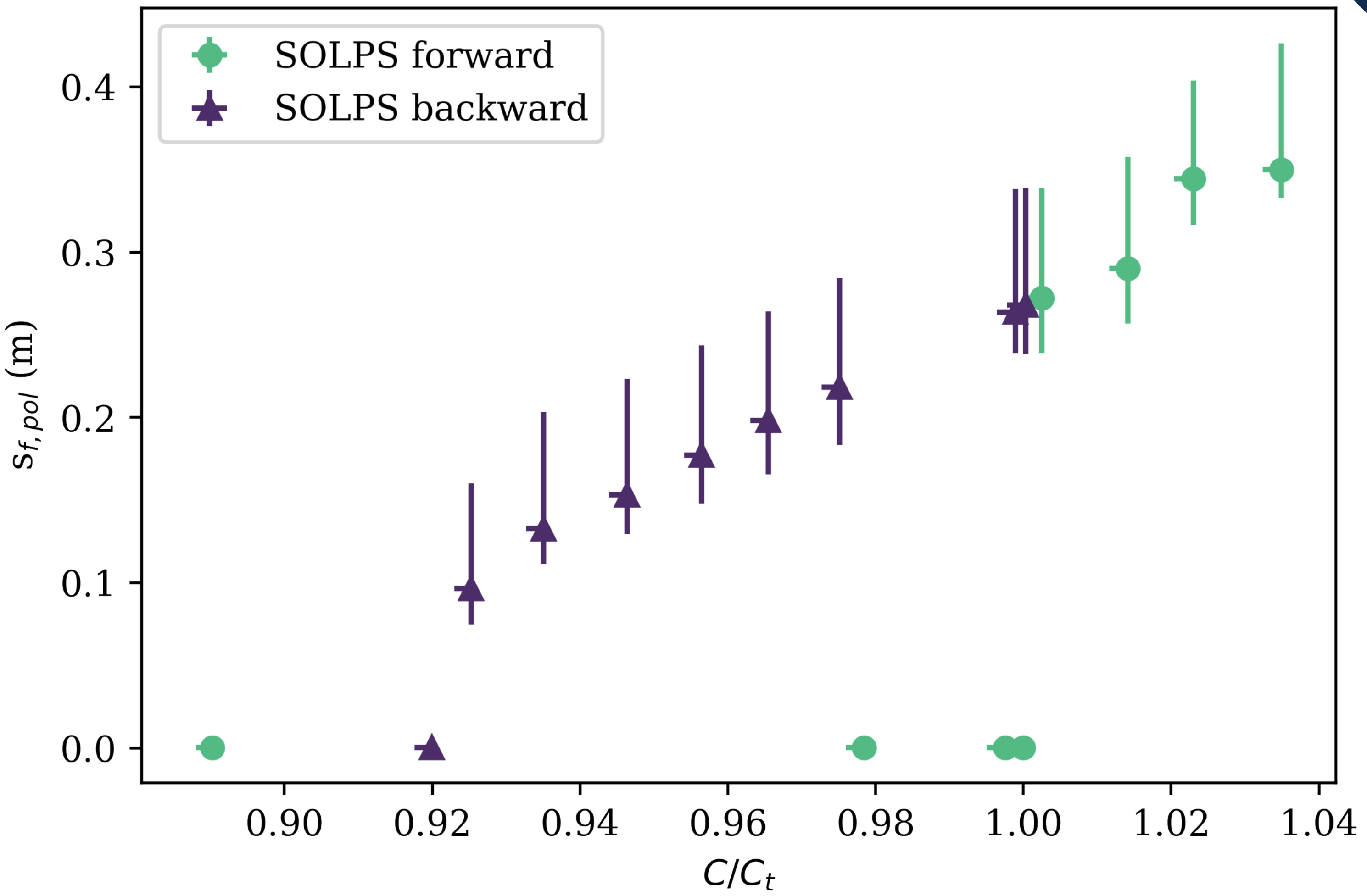




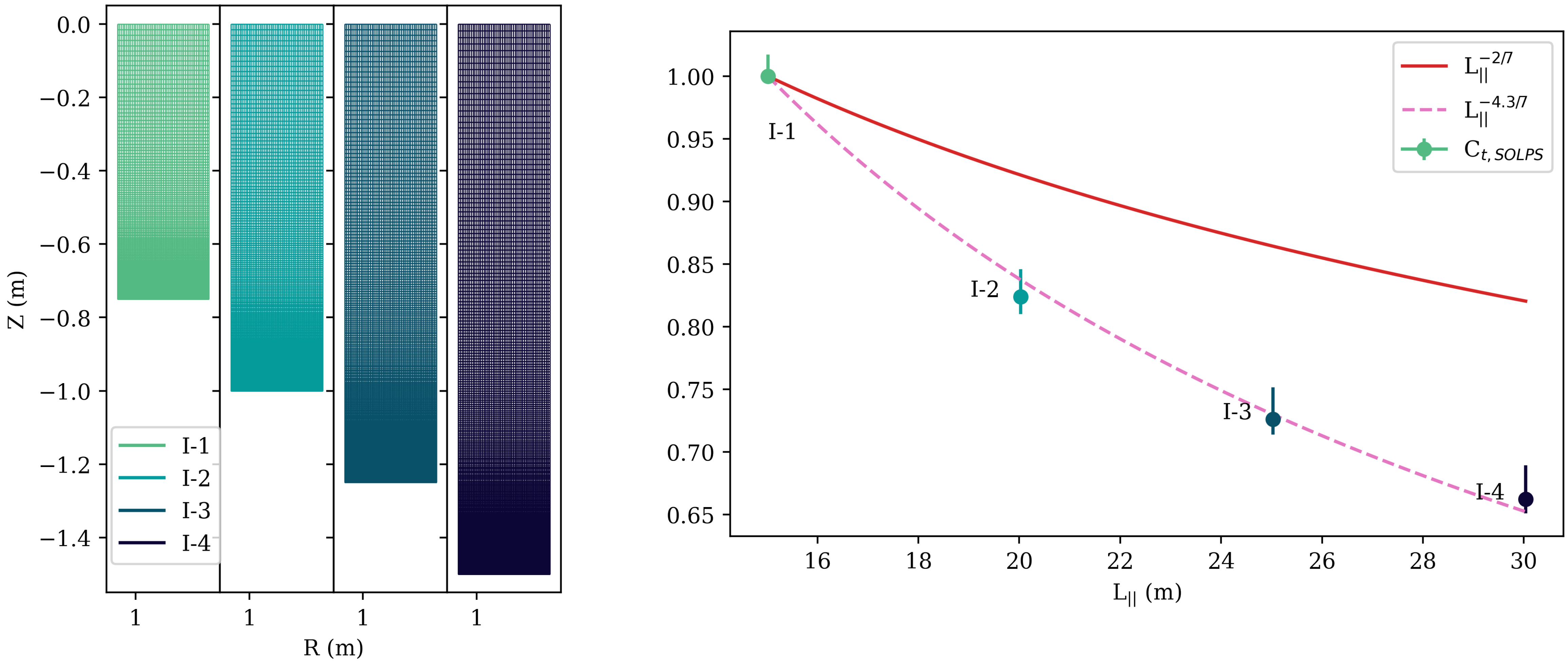
Negative Sensitivity

Negative sensitivity corresponds to regions where no stable detachment front exists.

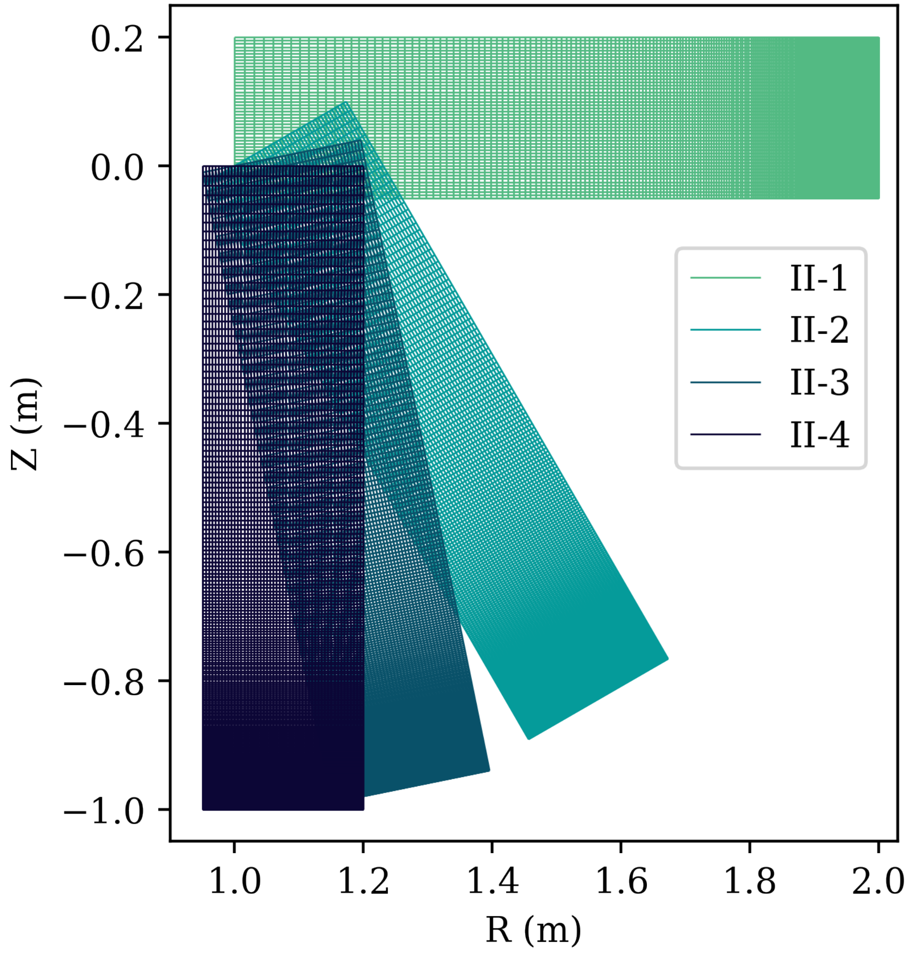
It creates bifurcated detached and attached solutions.

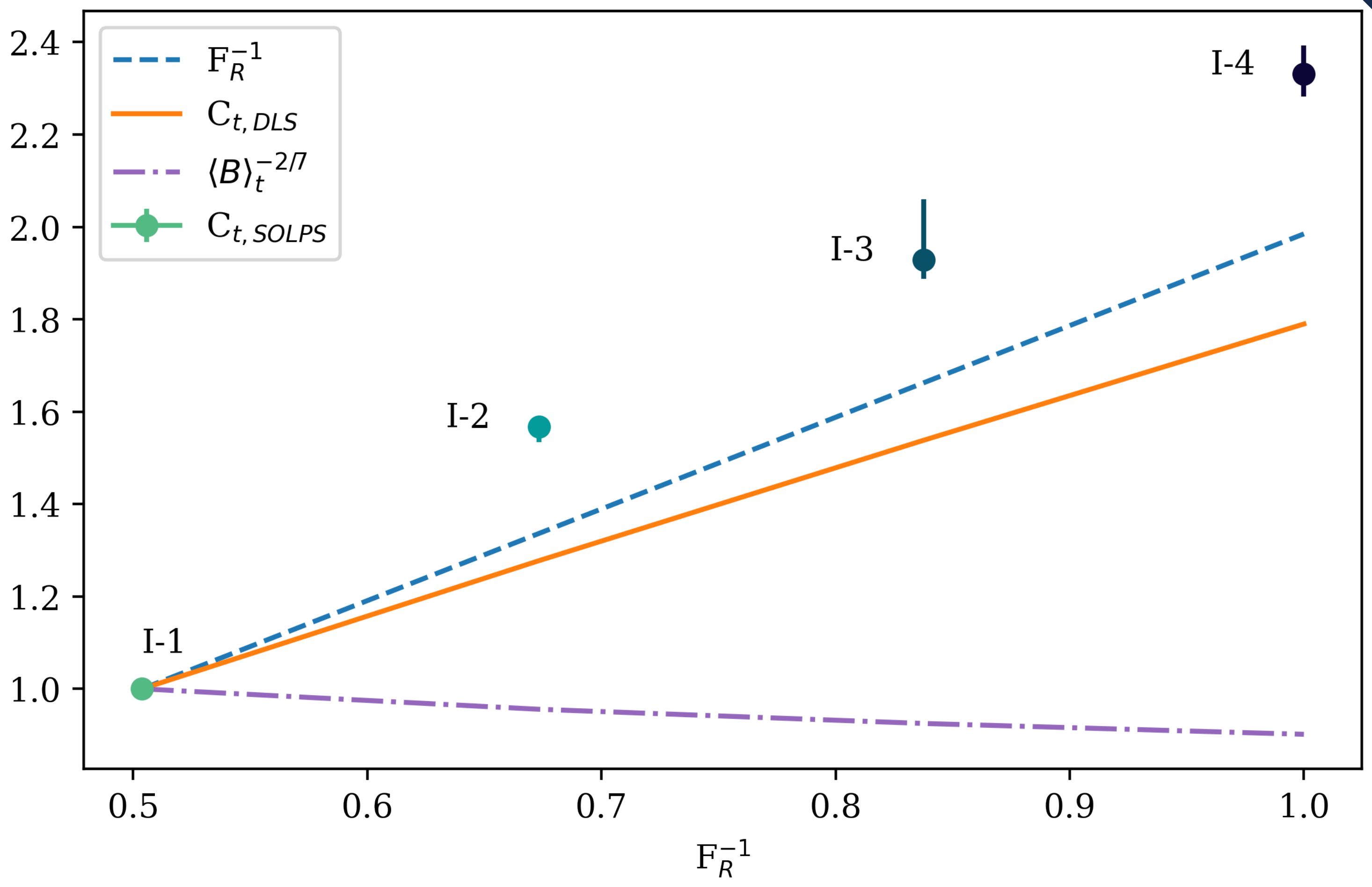


Detachment Onset - 1

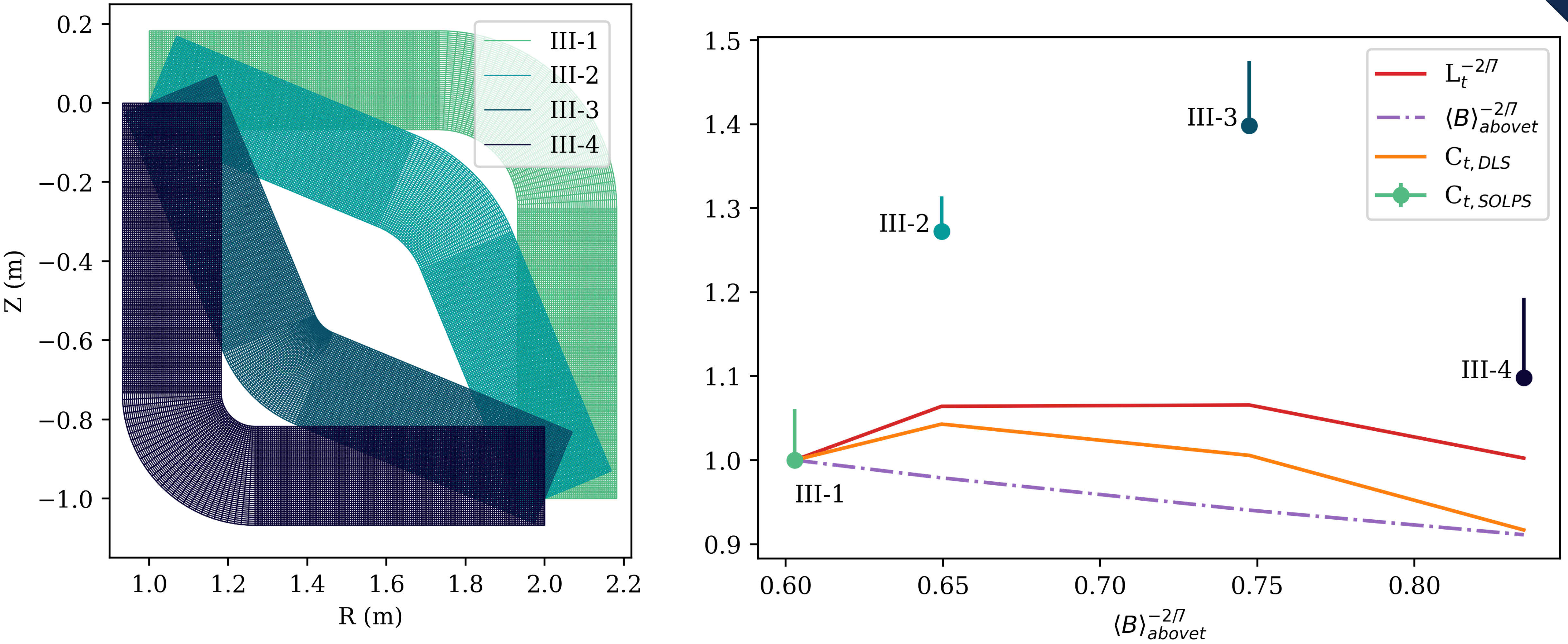


Detachment Onset - 2





Detachment Onset - 3



Tracking Front Movement

In simulations we preform control parameter scans (impurities), and track detachment front movement.

The location of detachment is determined by taking the smallest physical region containing at least 50% of heat loss.