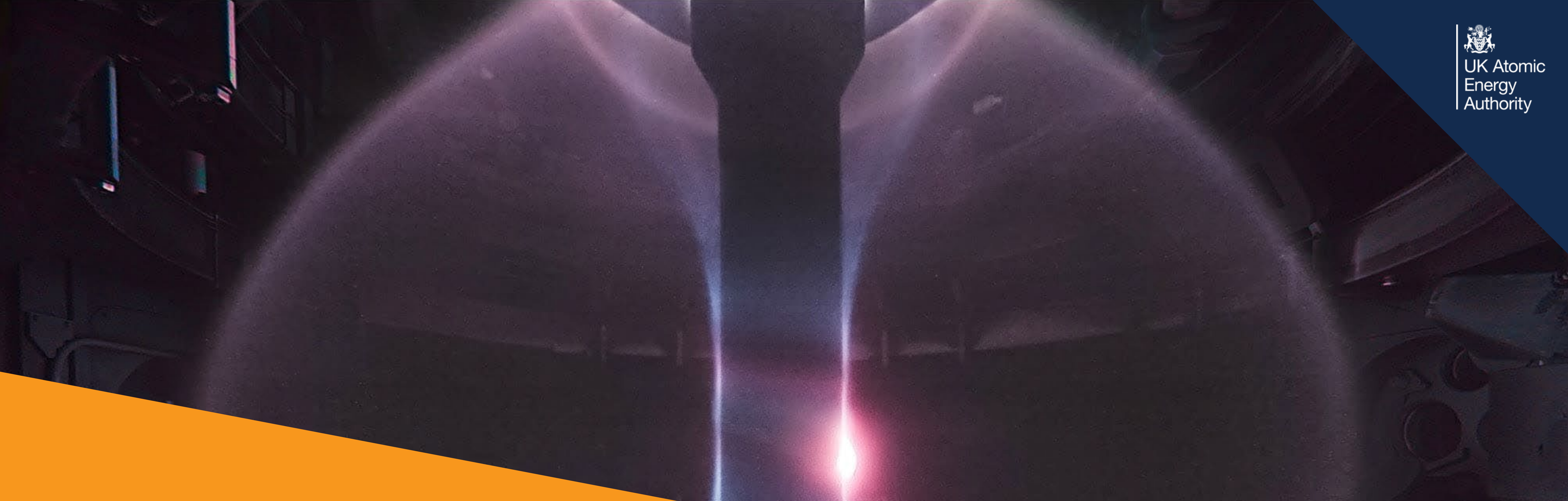

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4th Technical Meeting on Divertor Concepts, 10th November 2022

Overview of Exhaust Physics Results from MAST-U

P.J. Ryan, on behalf of the MAST-U team

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Research Councils UK Energy For a Low Carbon Future

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Overview

1. The MAST-U Super-X divertor
2. Comparison of Super-X and conventional divertor configurations
3. Detachment evolution in the Super-X configuration
4. Conclusions & Next steps

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1. The power exhaust challenge

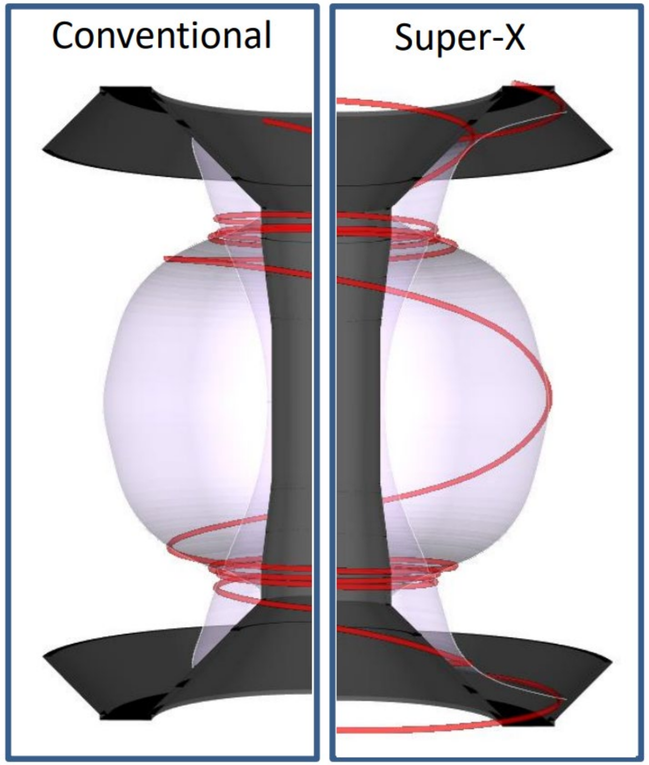
ITER solution to power exhaust might not extrapolate to future higher power devices

- Operation with a partially or fully detached divertor provides a solution to the high power loads at the target, but..
- High levels of detachment can affect the core plasma, integrated solution required

Aims of alternative divertor configurations (ADCs)

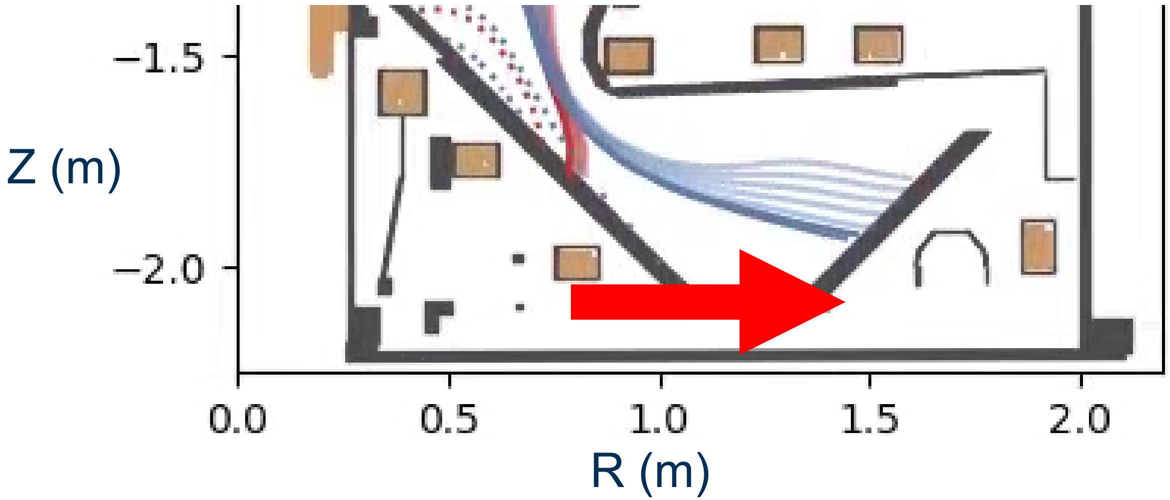
- Reduce divertor heat flux
- Promote access to detachment

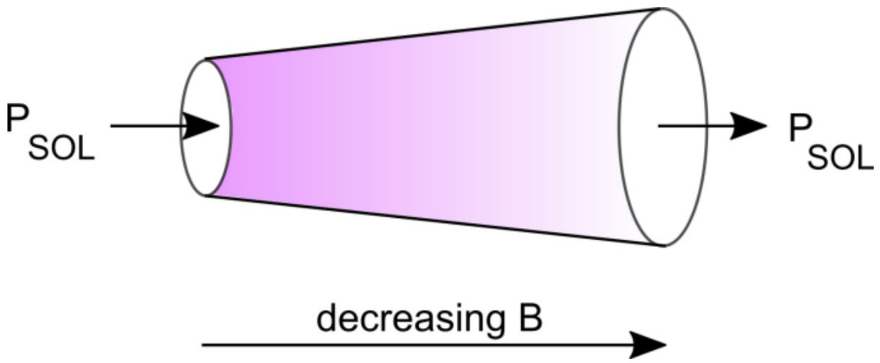
This presentation will focus on the Super-X ADC



1. General features of SXD

1. Increase outer strike point radius
2. Increased flux tube volume at large R due to reduced B-field
3. Increase connection length





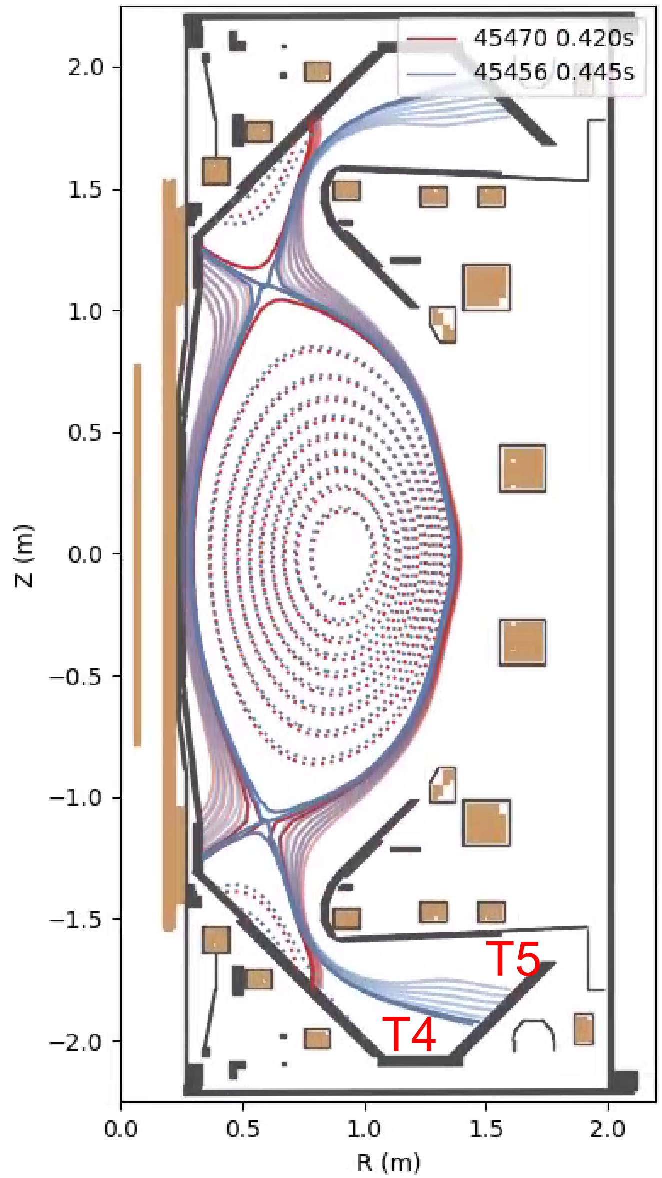
Outcome

- Increased wetted area of target
- Decrease target electron temperature and increase target plasma density
- Enhanced volumetric losses (radiative and neutrals)

1. Features of the MAST-U SXD

- Tightly baffled divertor chambers to enhance the confinement of neutrals in the divertor
- Large volume in the divertor chambers
  - ➢ Enhance volumetric losses
  - ➢ Reduce core contamination
- 8 poloidal field coils per divertor for detailed control of magnetic geometry:
  - ➢ Vary poloidal flux expansion
  - ➢ Significant variation in strike point radius
  - ➢ Decouple magnetic geometry of core and divertor
- Super-X tile has been shaped to compensate for the TF ripple:
  - ➢ Toroidally symmetric heat flux
- Spherical tokamak geometry enhances flux tube volume expansion in the divertor

$$B_\phi \propto {}^{1}/_{R}$$



Overview

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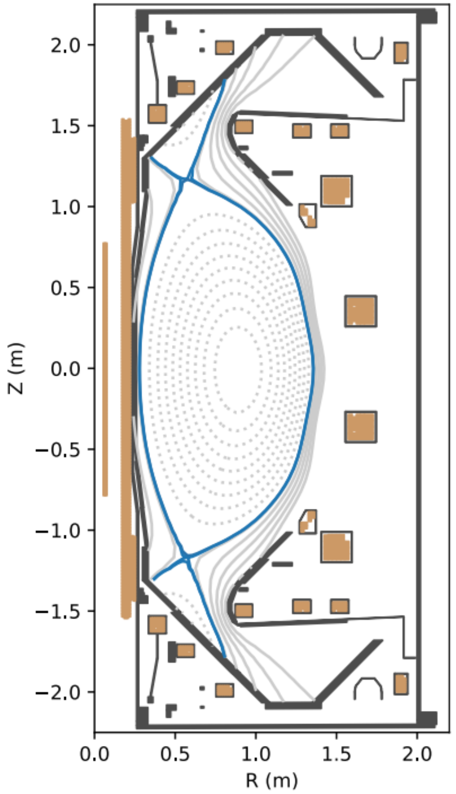
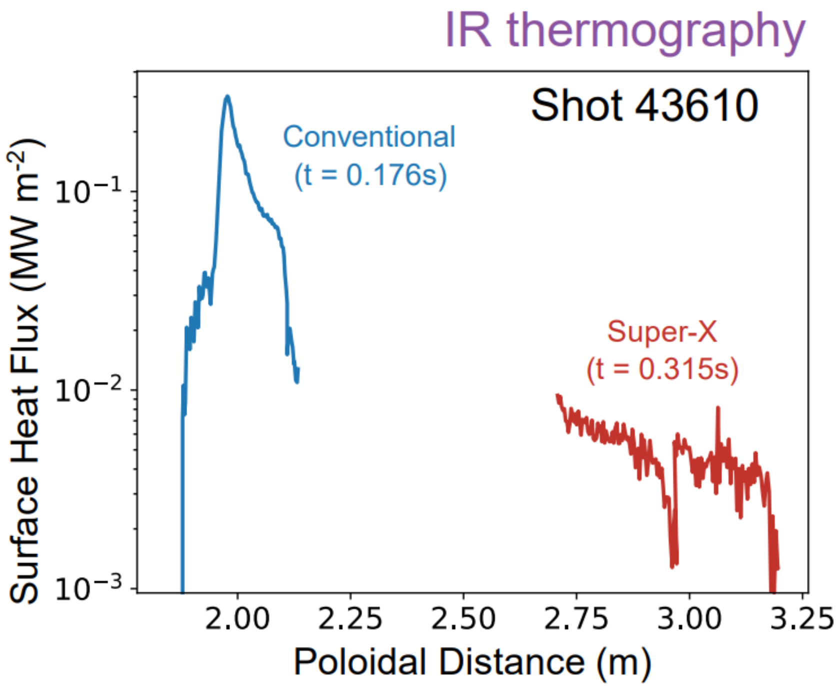
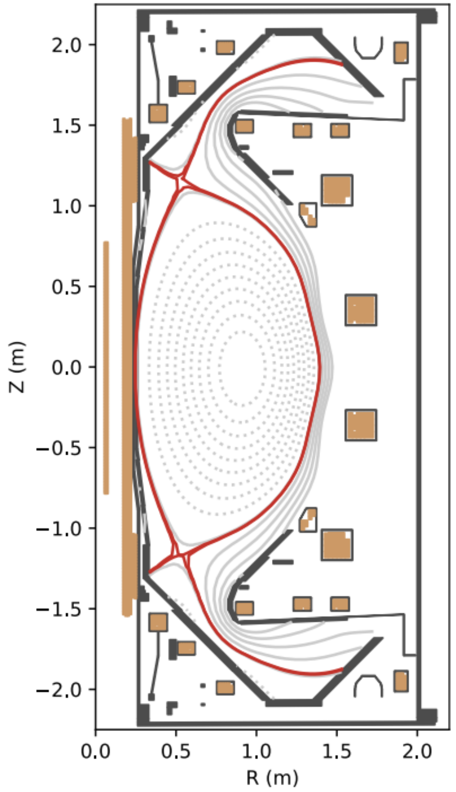
2. Significant Super-X heat flux reduction in NBI heated plasmas







- 3.2 MW NBI heated power.
- Encouraging results, but further scenario development worked required (e.g. centre column limited for SXD).

Need to demonstrate Super-X advantages in NBI heated shots

2. Conventional and Super-X Equilibria

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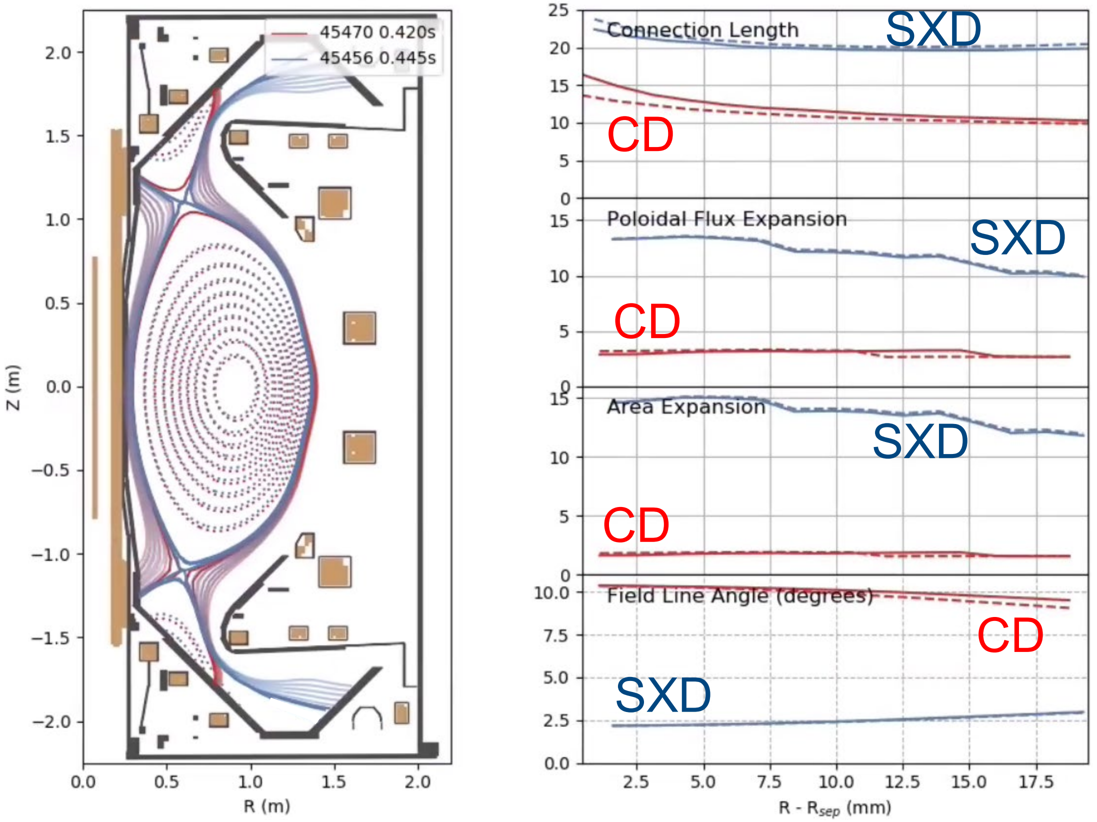
650 kA, in-board midplane fuelling (internal)



750 kA, out-board midplane fuelling

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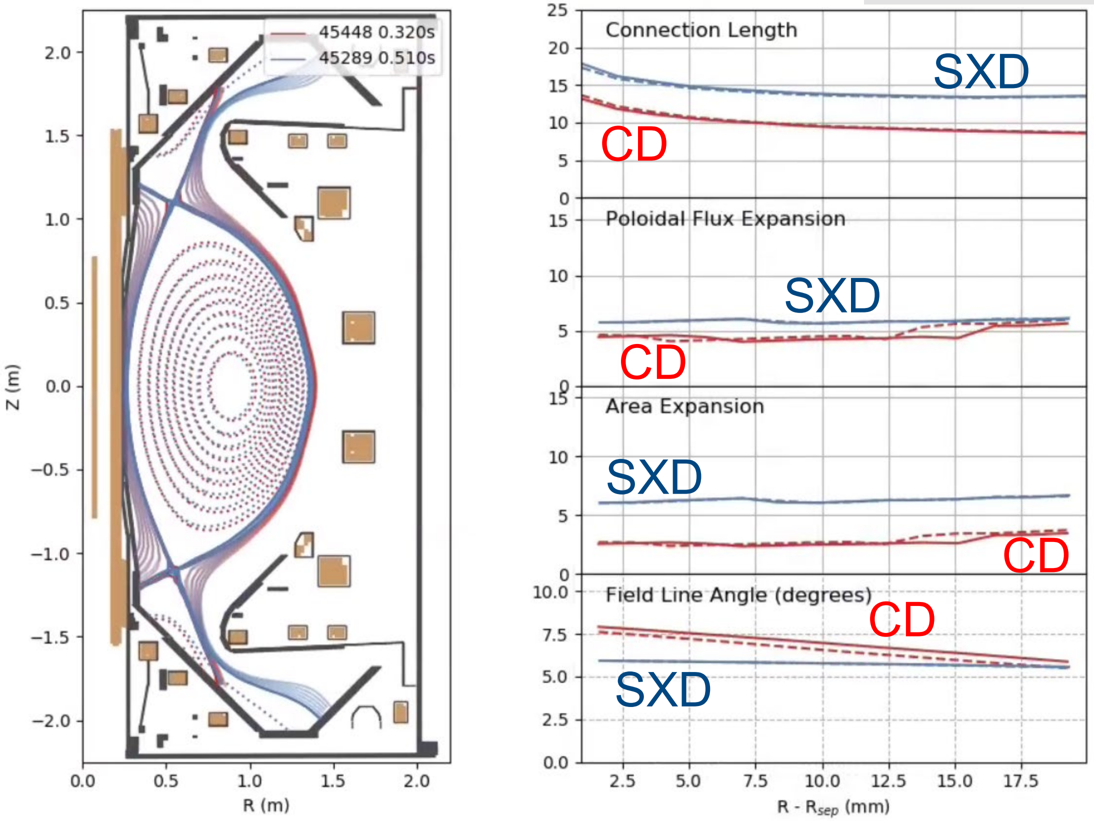

Expected heat flux reduction for Super-X configuration based on geometry:

- Reduction of ~14.5/1.8=**8.1** for the **650 kA** scenario.
- Reduction of ~6.1/2.6=**2.3** for the **750 kA** scenario.

L-mode, ohmic heated, double null

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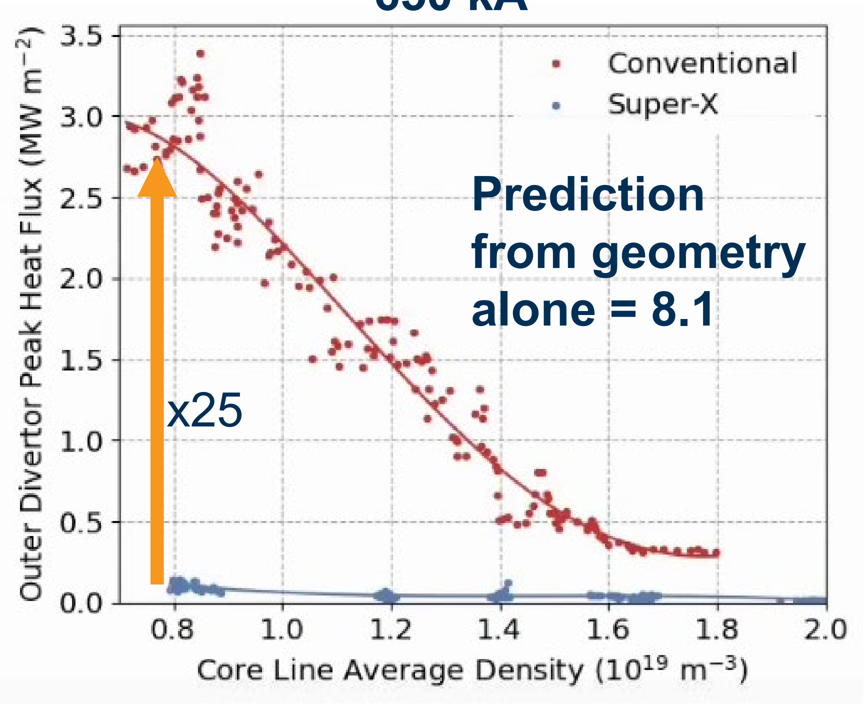
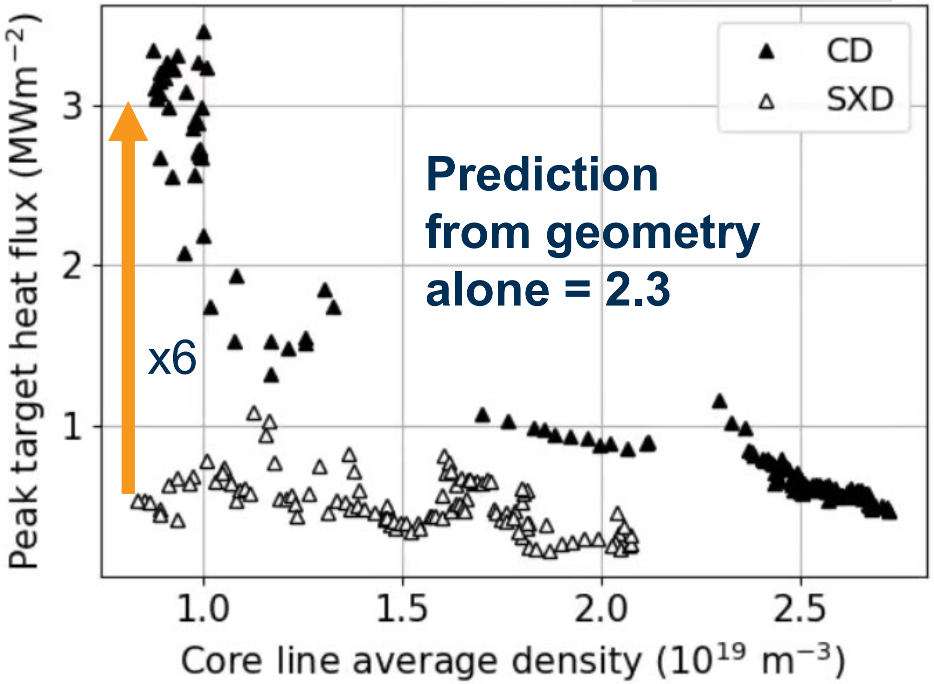
2. Super-X shows significant heat flux reduction

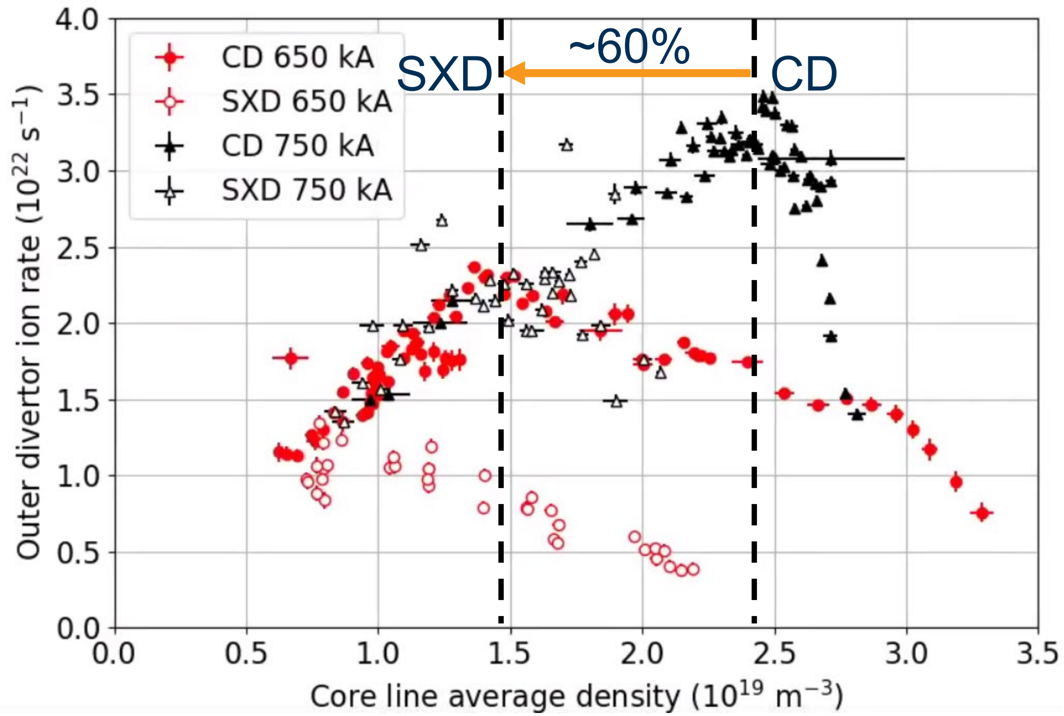




- **Preliminary IR thermography** results confirm that the peak heat flux is reduced for the Super-X configuration during attached conditions.
- Graphite tile emissivity values selected based on power balance.
- Work is on going to confirm the tile emissivity via direct measurements.

2. Improved access to detached divertor regime in Super-X configuration

Onset of detachment characterised by a "rollover" in the divertor ion flux with increasing core density.



L-mode, ohmic heated, double null

- Each data set was produced by combining data from several shots that had different core densities.
- **Detachment threshold is 60% lower in the Super-X configuration**, in good agreement with analytic models [1] and simulations [2]. $n_{e,thres} \propto 1/R_{target}$
- **750 kA scenarios rollover at higher core densities.**

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[1] B. Lipschultz, F. I. Parra, I. H. Hutchinson Nucl. Fusion 56 056007 (2016)
[2] D. Moulton et al., Proc 44th EPS Conf. 2017

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2. SOLPS 650 kA results: good agreement for SXD only

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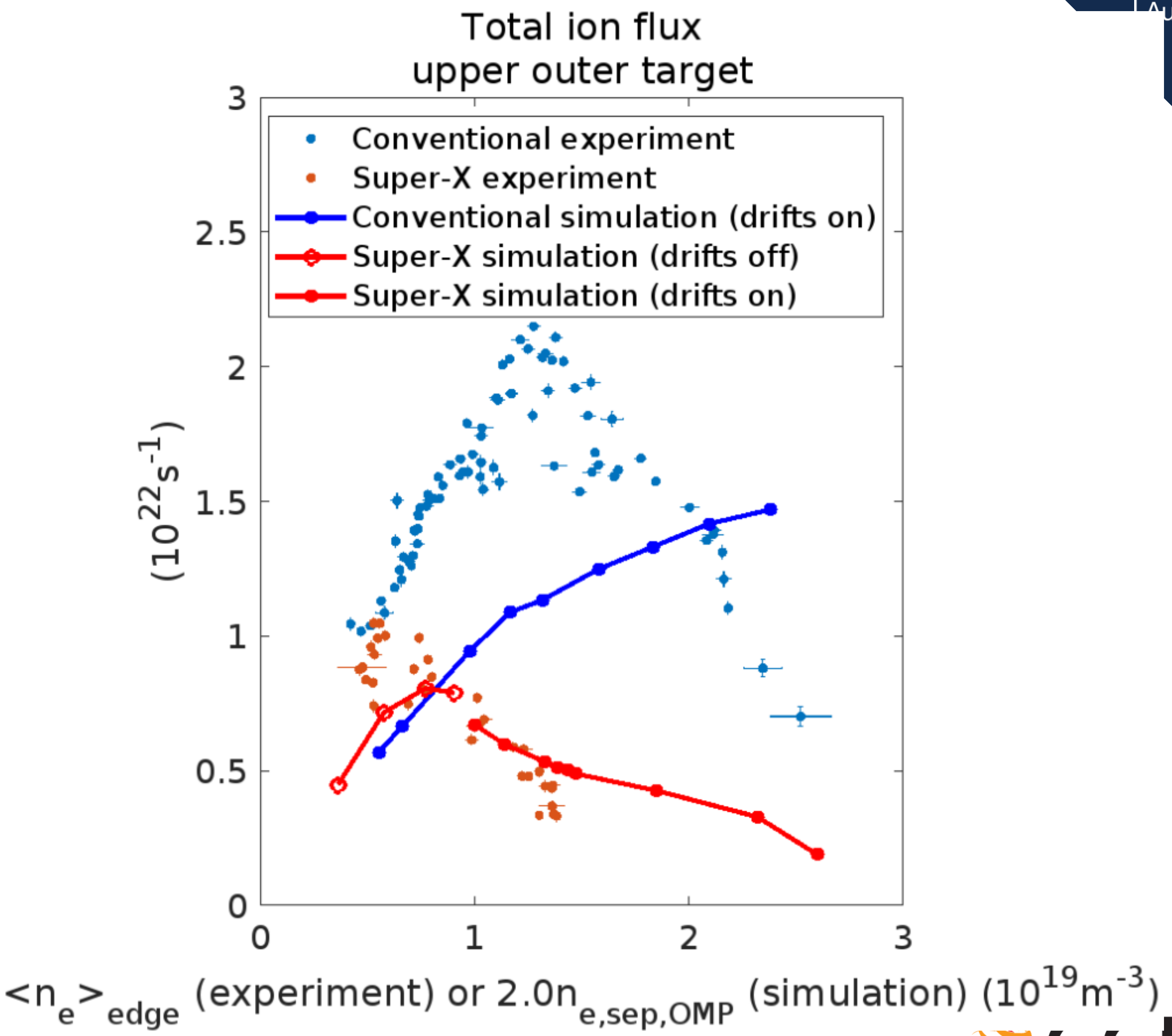
Super-X configuration

- Simulations have good agreement with experimental rollover.

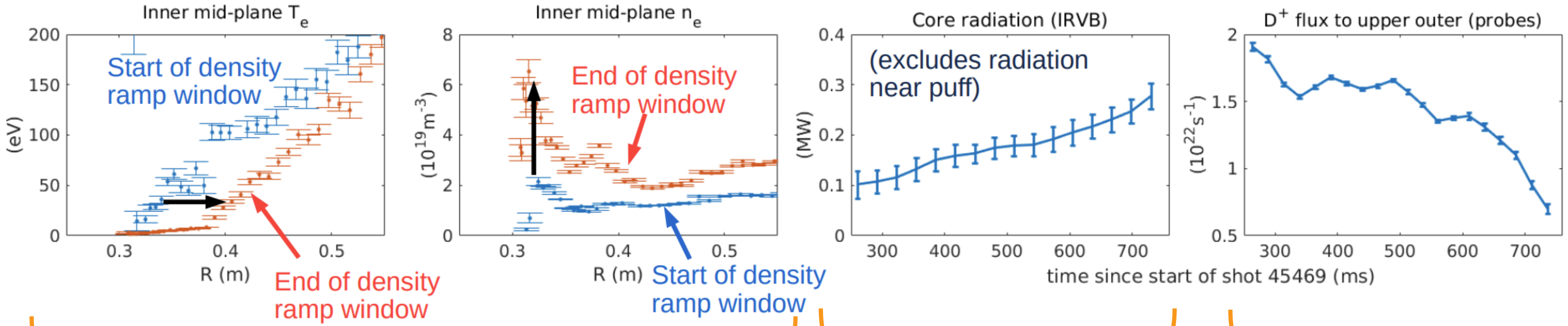
Conventional configuration

- The simulations do exhibit a rollover, but solutions beyond rollover are not stable.
- Simulations overestimate the rollover density compared to experiment.
- **Inboard midplane puff strongly cools plasma on closed field lines.**
- The power crossing the separatrix decreases, which reduces the power available for ionisation and outer target flux.



2. Higher input powers required in future experiments

Conventional 650 kA experimental data



In-board midplane plasma cooling

Increasing core radiation

Decreasing target ion flux

True rollover for the conventional divertor would be at higher core density, thereby improving the comparative performance of the Super-X divertor

2. No loss of confinement with detached Super-X configuration

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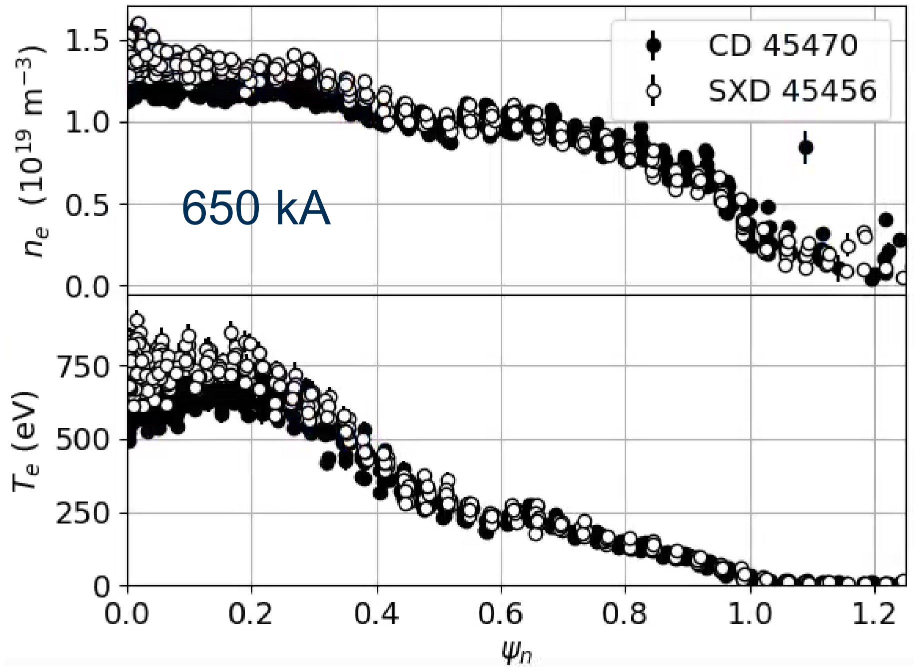

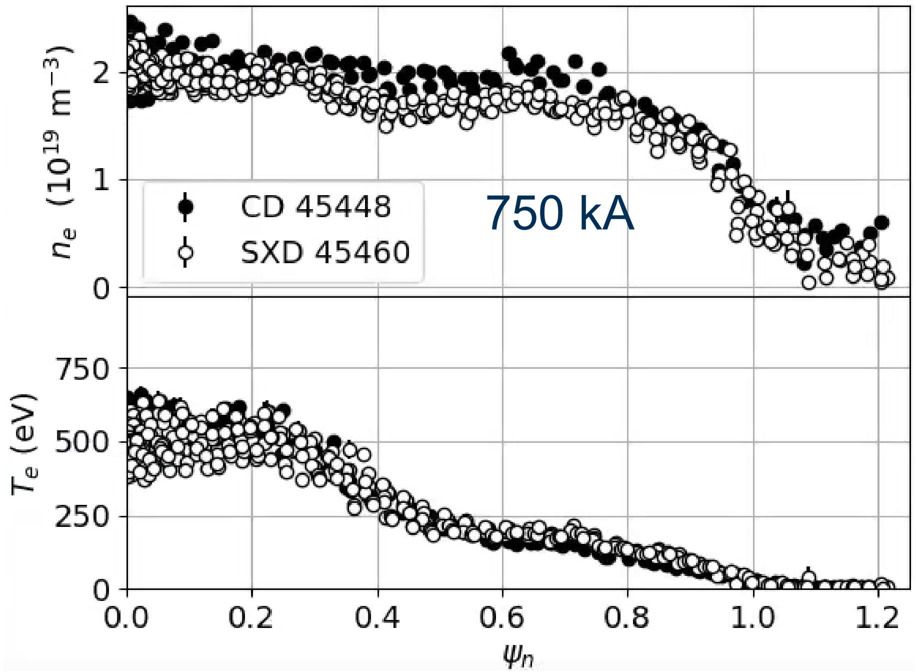

- Comparison of midplane Thomson scattering profiles.
- Attached conventional divertor and detached Super-X divertor.

No significant impact of the divertor configuration on the upstream profiles, despite different divertor conditions

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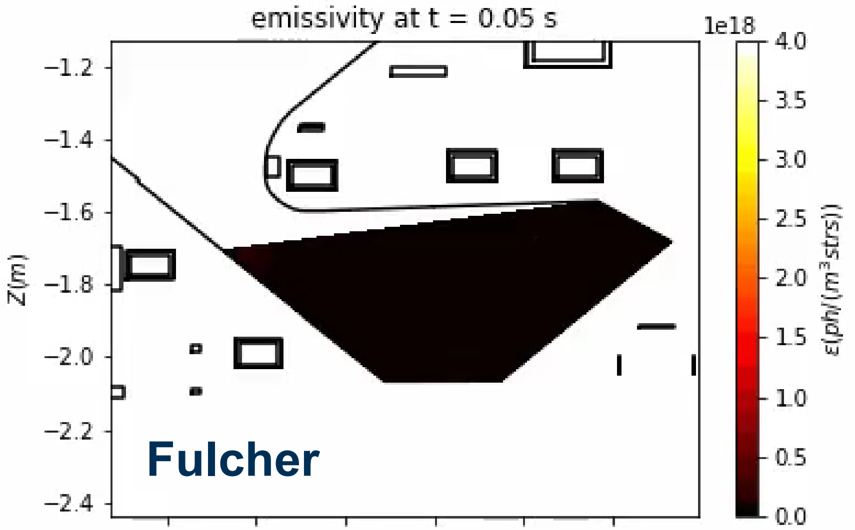
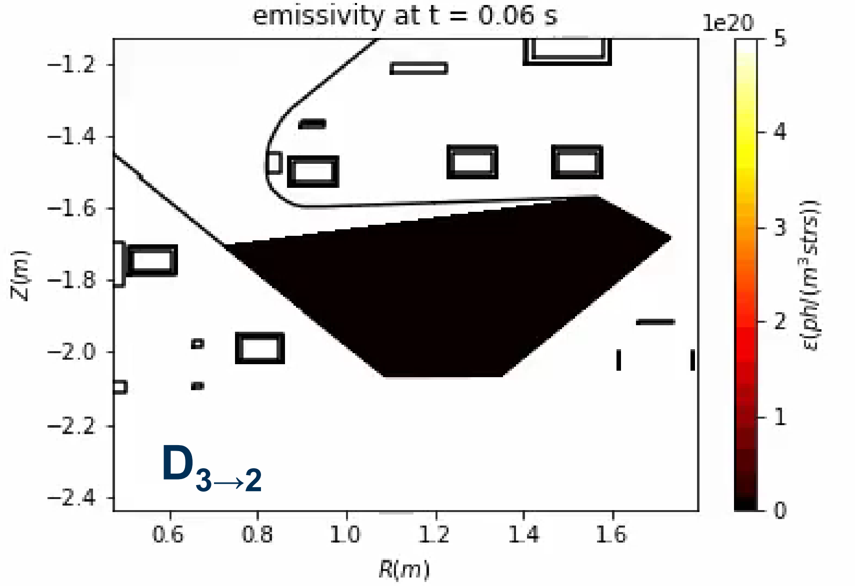
3. SXD detachment evolution (ohmic)

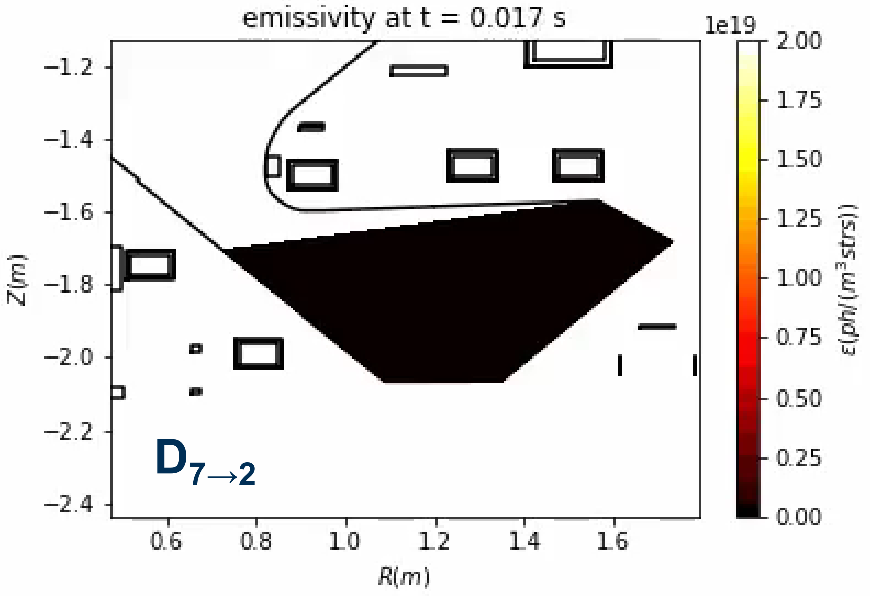
- **Fulcher** emission: proxy for the ionisation front and electron impact excitation.
- $D_{3\rightarrow 2}$ emission: plasma-molecular interactions, electron impact excitation, and electron-ion recombination.
- $D_{7\rightarrow 2}$ emission: dominated by electron-ion recombination.

L-mode, ohmic heated, double null





Shot 45371



3. Plasma-molecular interactions important for MAST-U

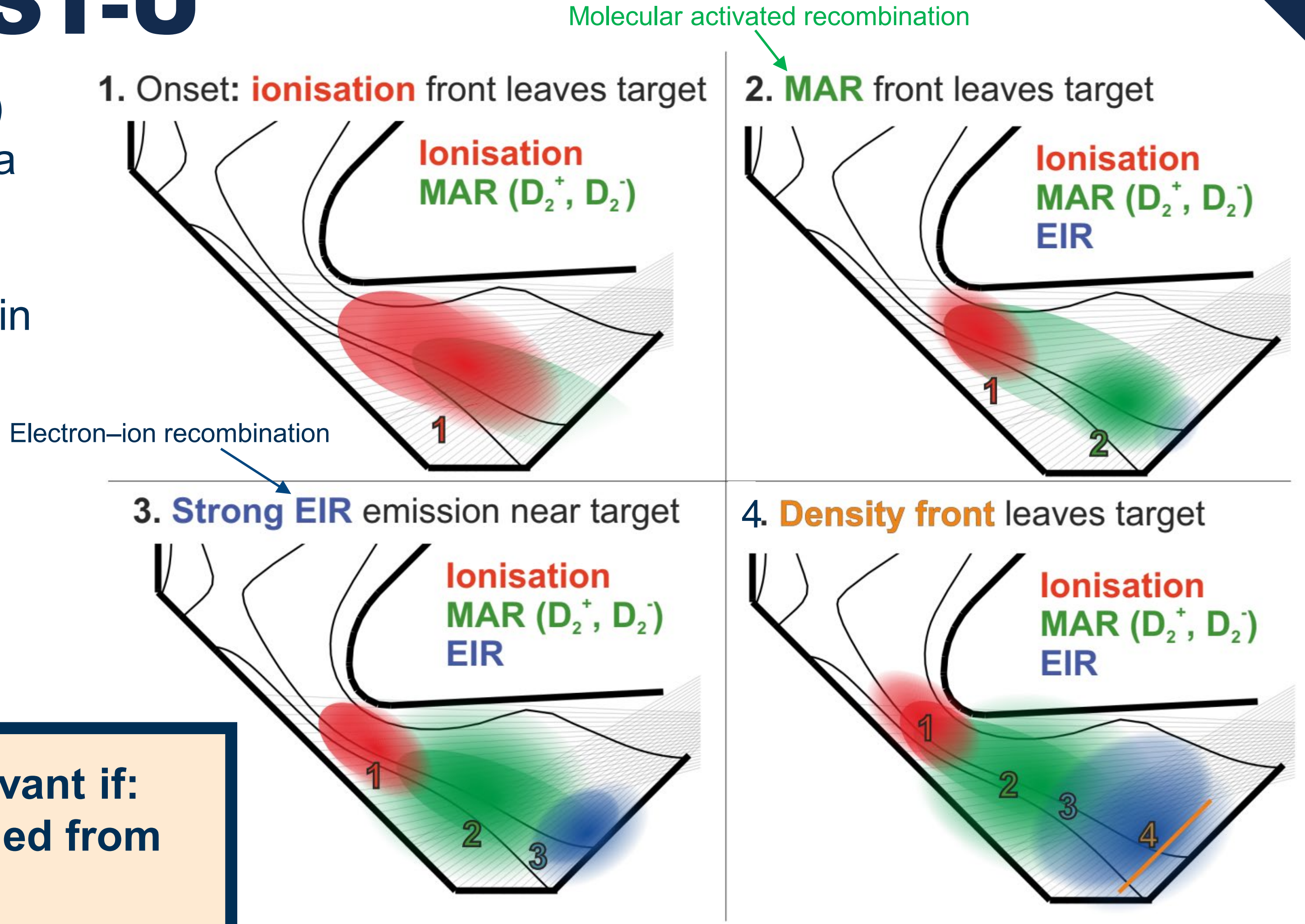
- **Plasma-molecular chemistry (D_2^+ , …) starts at detachment onset** and plays a critical role in the MAST-U Super-X divertor.
- Molecular CX for D & T underestimated in plasma edge modelling. -> **D_2^+ grossly underestimated (for T_e << 5 eV).**

These interactions impact:

1. Neutral atom source (MAD)
2. Hydrogen emission
3. Ion sinks (MAR)

These interactions may be reactor relevant if:

1. **Ionisation front significantly detached from target**
2. **Molecular density enhanced in divertor**



K Verhaegh et al 2021 Plasma Phys. Control. Fusion 63 035018

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4. Conclusions

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- Significant outer target heat flux reduction for the Super-X configuration compared to the conventional configuration.
- For the Super-X configuration, the ion flux to the outer divertor rolls over at ~60% lower core density compared to the conventional configuration in ohmic plasmas.
- Similar electron temperature and density profiles in core during detached Super-X and attached conventional configurations.
  - ➢ An increase of the detachment window and/or larger power dissipation in the divertor would allow the operation of future tokamak reactors with lower core impurity fractions and core radiation, which would benefit core performance.
- Plasma-molecular interactions play a strong role in the detached MAST-U Super-X divertor.
  - ➢ Plasma-molecular interactions could be important in tightly baffled ADCs: greater molecular density and deeper detachment with the ionisation region significantly lifted off the target.
  - ➢ Plasma molecular interactions are not properly included in SOLPS-ITER simulations.

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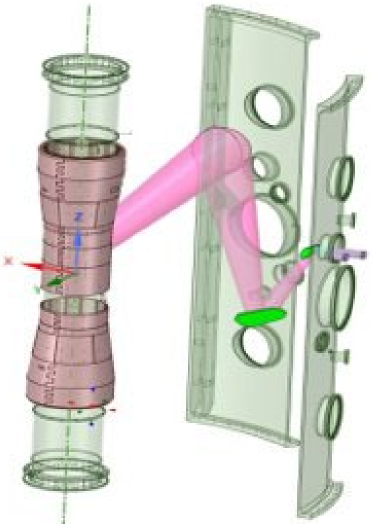
4. Next steps

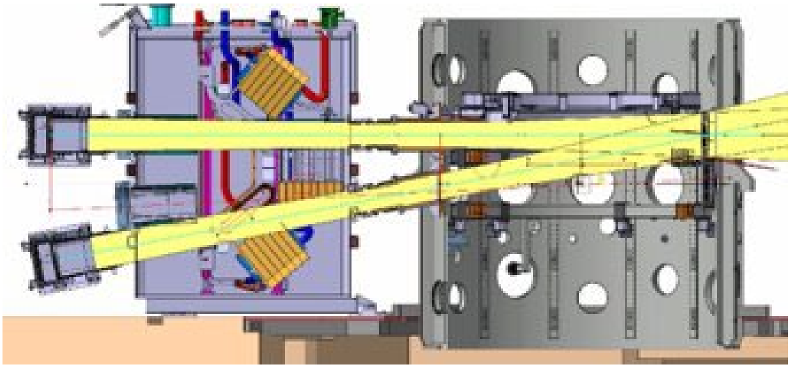
1. High-performance ELMy H-mode with a Super-X divertor:
   a) Impact on pedestal.
   b) Expand to include other configurations such as snowflake, X-divertor and X-point target.
2. Detachment front sensitivity and active feedback control.
3. Impurity transport in the divertor.
4. Impact of divertor configuration on cross-field transport.

Higher plasma current and auxiliary heating to maximise the heat flux entering the divertors.

MU04 (2024)
1.6 MW EBW Heating & Current Drive

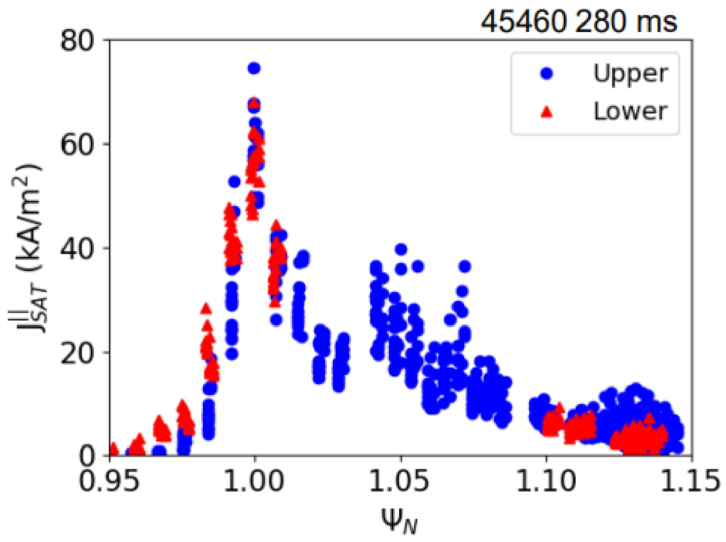


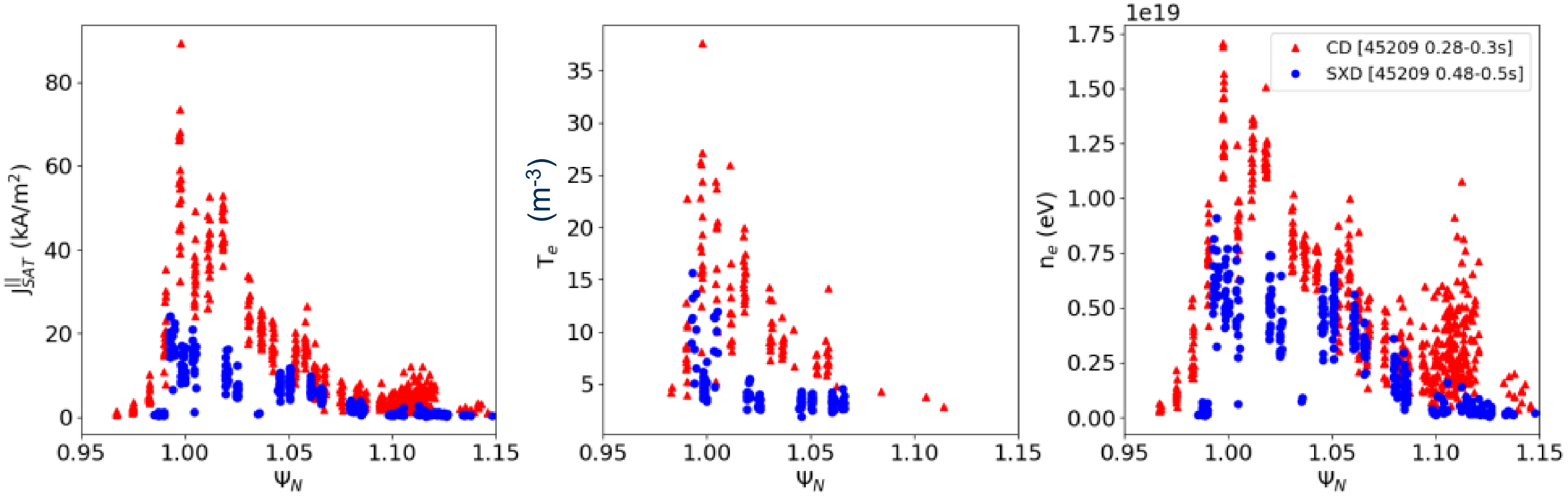
MU05 (2025)
Additional 5 MW NBI heating



Extra slides

Balanced up/down 750 kA





2 point model predictions

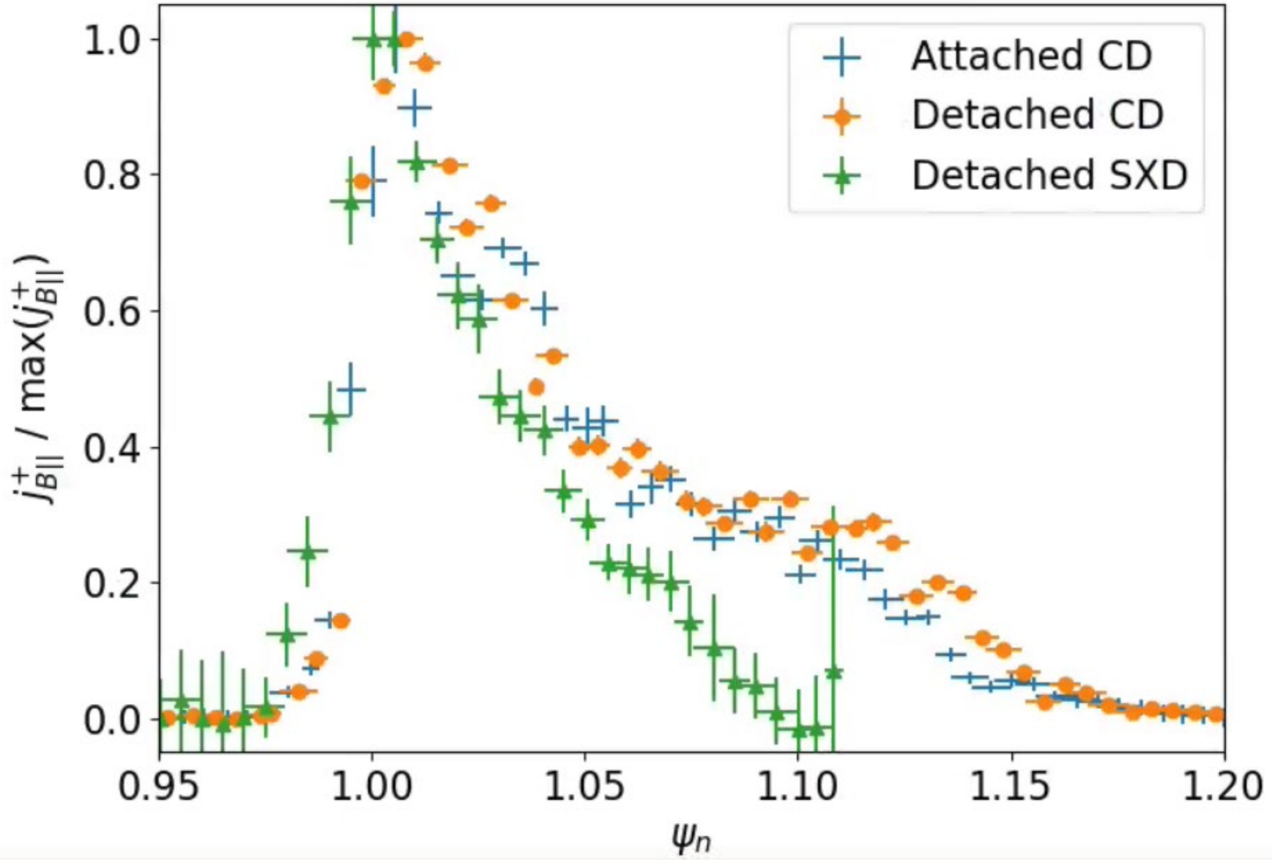
$j_{sat}^{tgt} \propto R_t$

$T_e^{tgt} \propto R_t^{-2}$

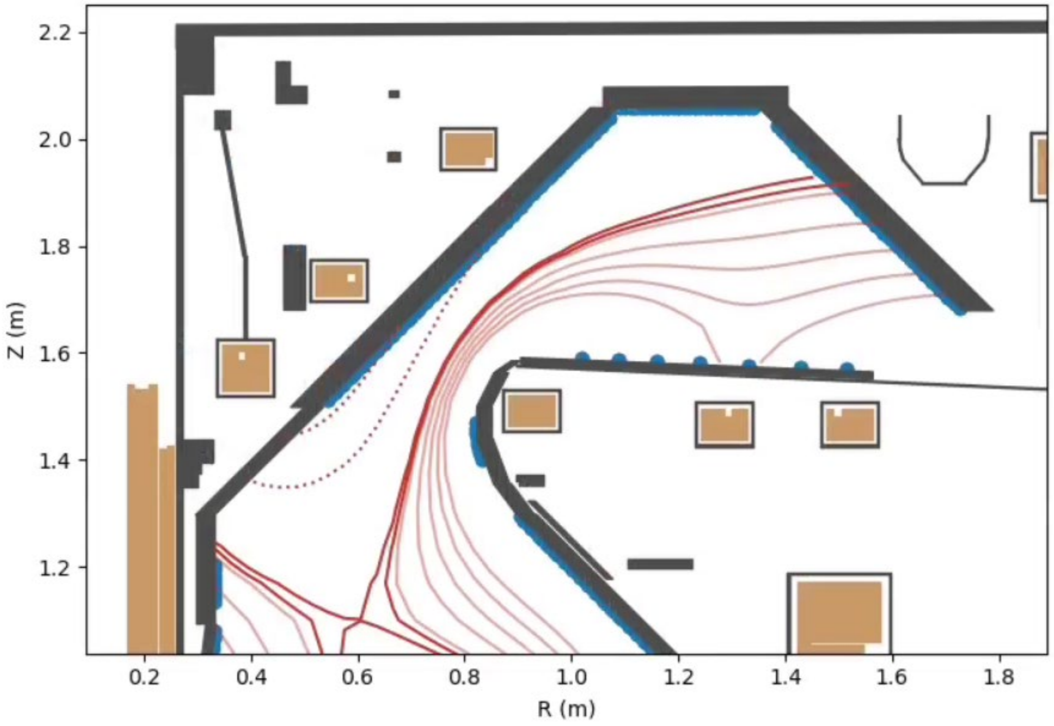
$n_e^{tgt} \propto R_t^2$

2PM: $T_e^{SXD} = 0.3\ T_e^{CD}$

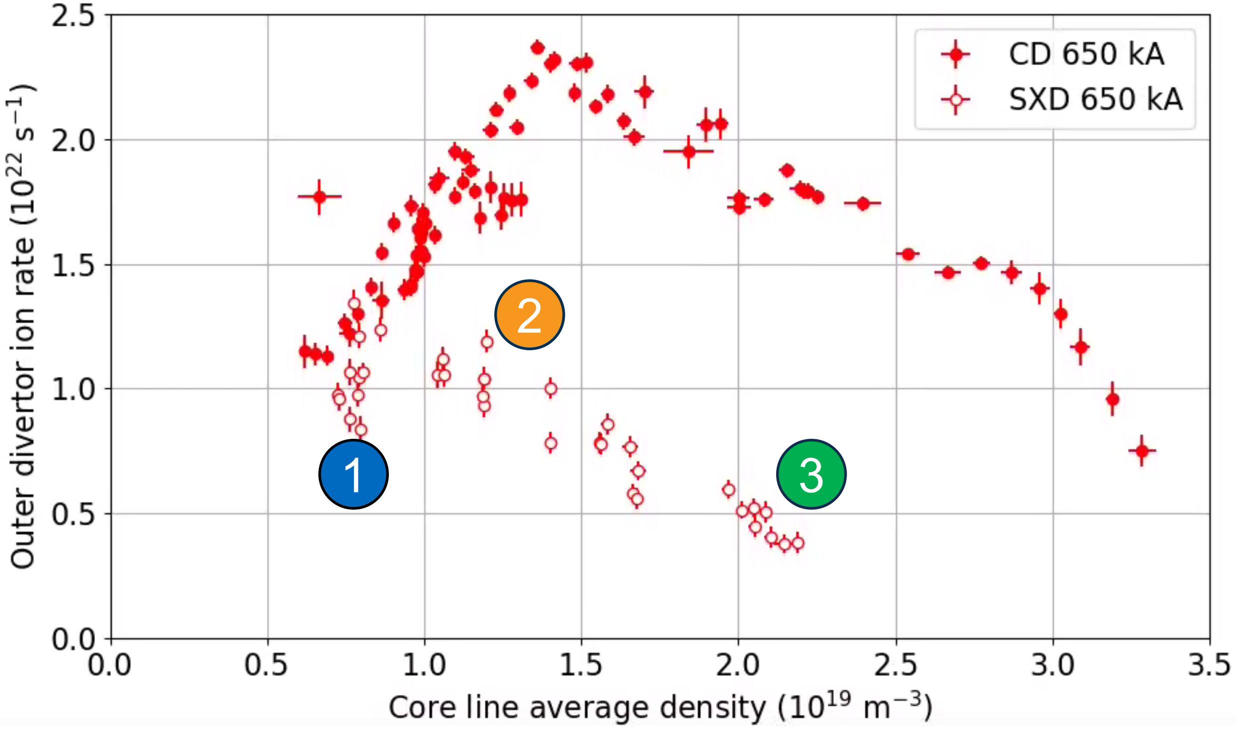
Expt.: $T_e^{SXD} = 0.5\ T_e^{CD}$



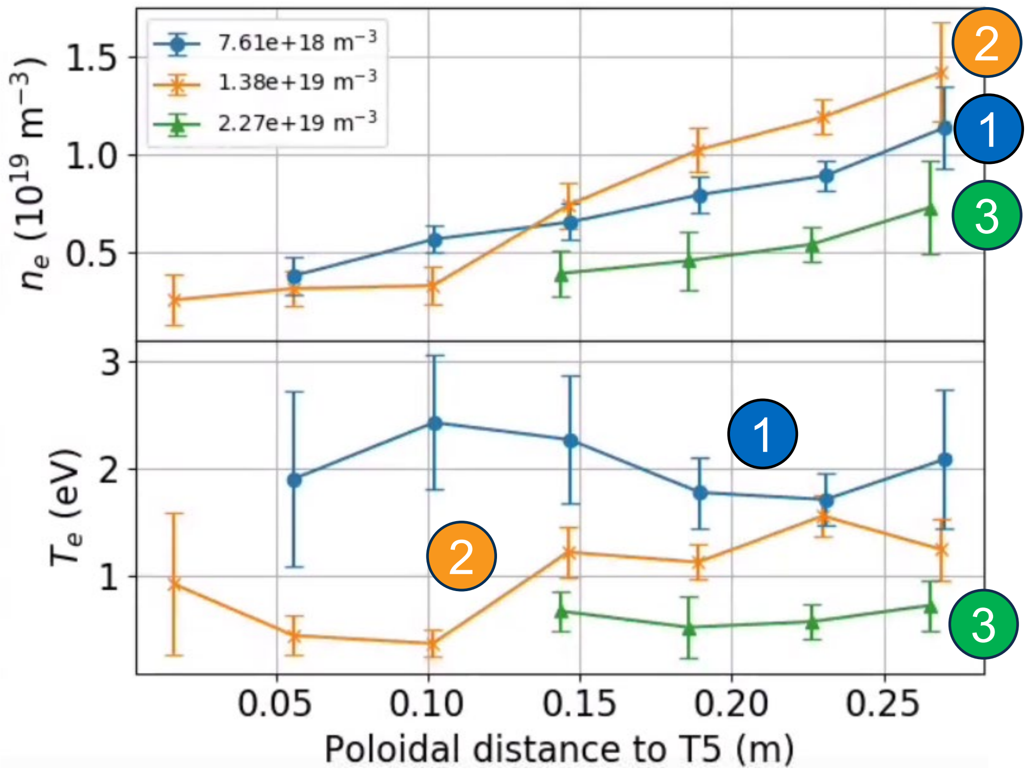
Max psin
=1.085



2. Divertor Thomson scattering measurements consistent with detachment onset



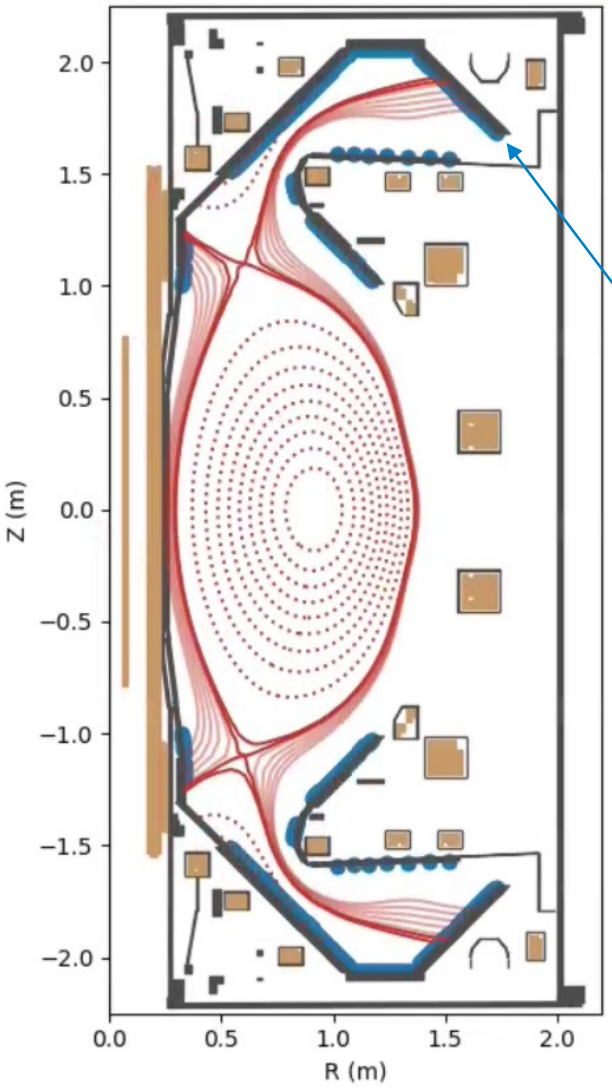
Super-X

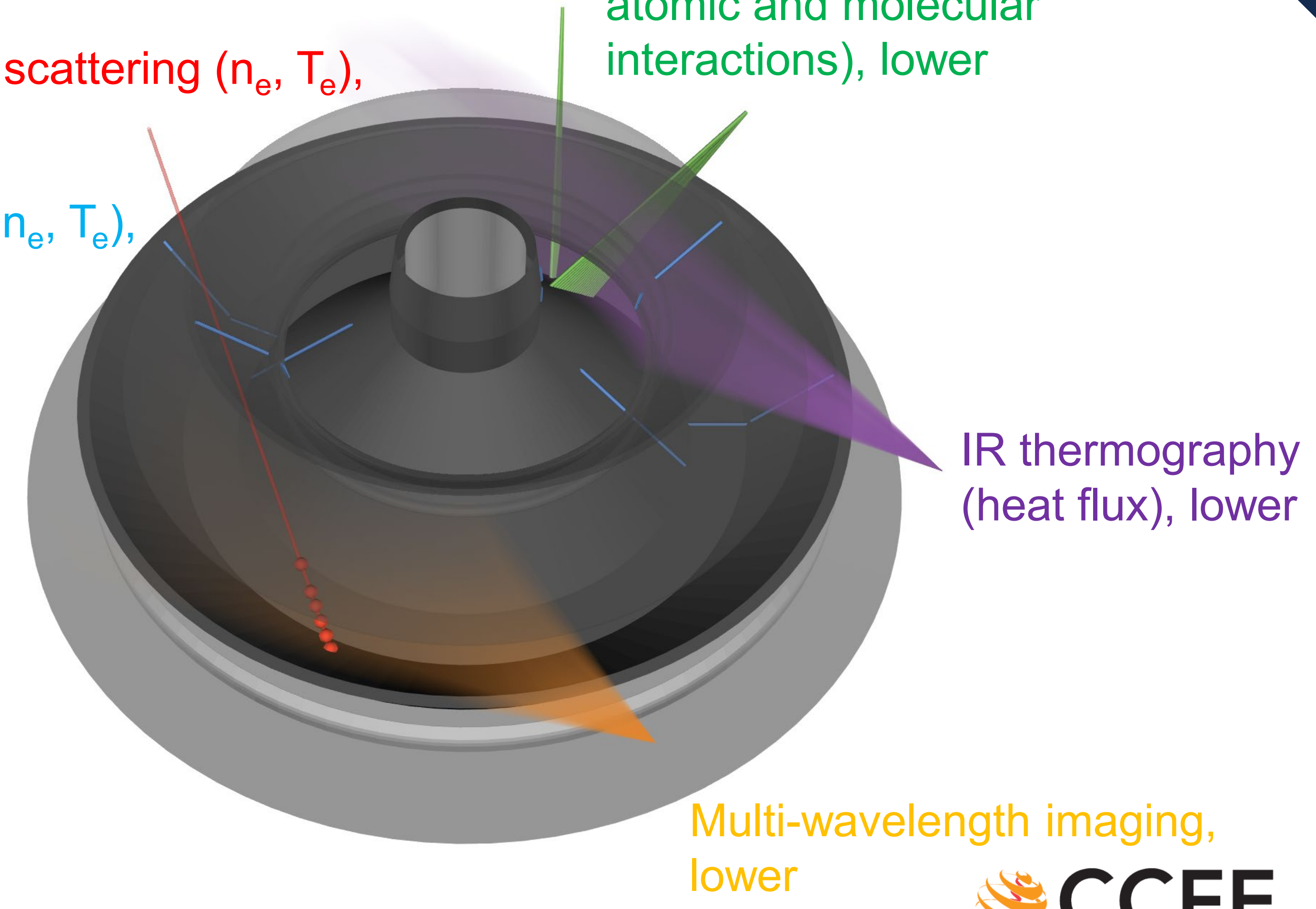


- Scattering volumes were located in the private flux region ($0.98<\Psi_n<1$).
- Thomson scattering measurements of electron density are consistent with a "rollover".
- Electron temperature decreases in the divertor as core density increases.

1. Extensive Suite of Divertor Diagnostics

MAST-U has a range of divertor diagnostics for exhaust studies





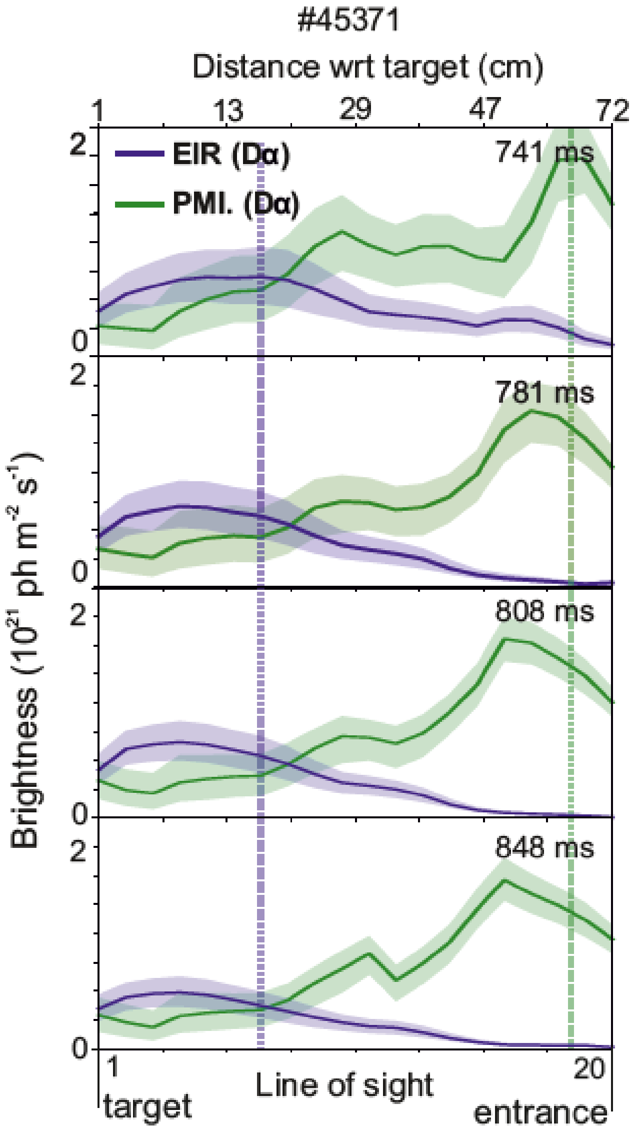
3. Reversible detachment processes

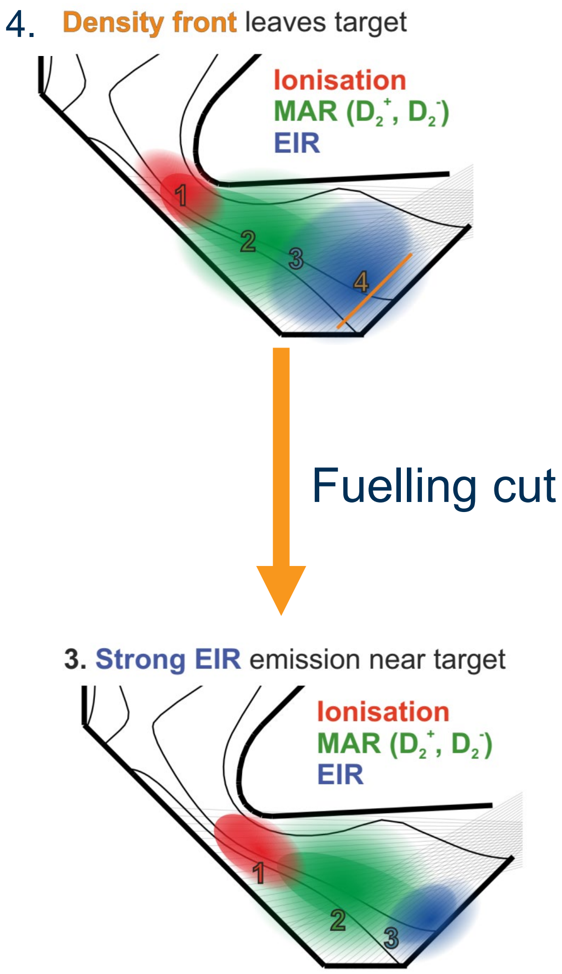
- Balmer Spectroscopy technique for Plasma-Molecular Interaction (BaSPMI) [3] implemented.
- Disentangles the Balmer line emission from the various plasma-atom and plasma-molecular interactions.

Stage 4 detachment reverses to stage 3 in 50 ms after **lower divertor fuelling cut at 750 ms**:

- Molecular activated recombination and electron-ion recombination fronts move back towards the target.

A promising result for detachment control





[3] K Verhaegh et al 2021 Plasma Phys. Control. Fusion 63 035018

1. Toroidally symmetric heat flux on ripple compensated Super-X tile

IR camera temperature data