Plasma detachment and perpendicular transport in long-leg divertor configurations

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NSTX-U / Magnetic Fusion Science Meeting
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(This talk summarizes work that was submitted to *Nuclear Fusion*, November 2022)

Outline

- Divertor physics and plasma detachment
- Our approach
  - Simulation details
  - SOLPS4.3
- Results
  - Detachment in long leg
  - Upstream perpendicular transport
  - Perpendicular transport in the leg
  - Comparison to detachment in TCV and KSTAR

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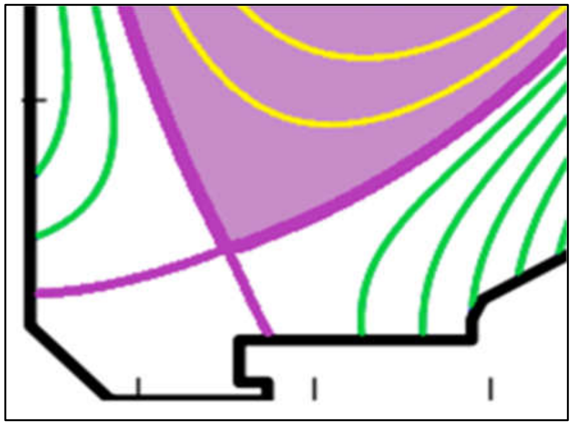
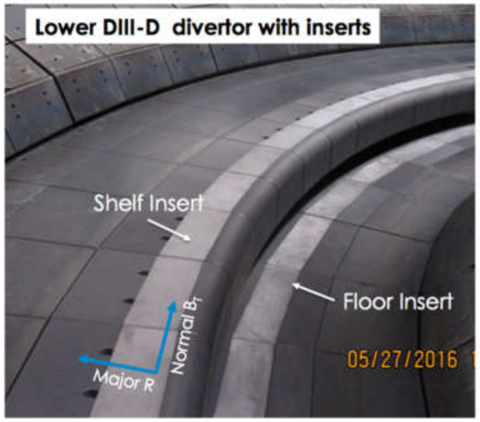
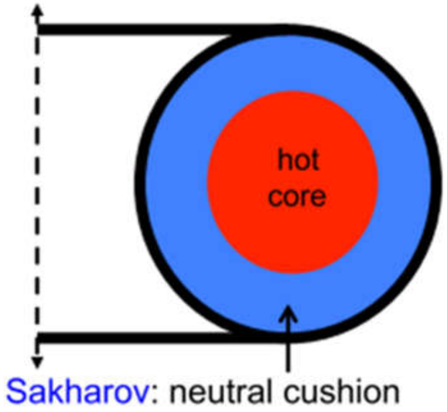
The divertor manages power and particle exhaust

- The divertor is the exhaust and fueling system for the tokamak
- Field lines **divert** the exhausted heat and particles away from fragile core plasma and into targets designed to handle extreme conditions
- Plasma hits the target plates and neutralizes back into neutral gas, forming a protective cushion of neutral gas that blocks more plasma from hitting the target that is not charged and unaffected by magnetic field lines [1]





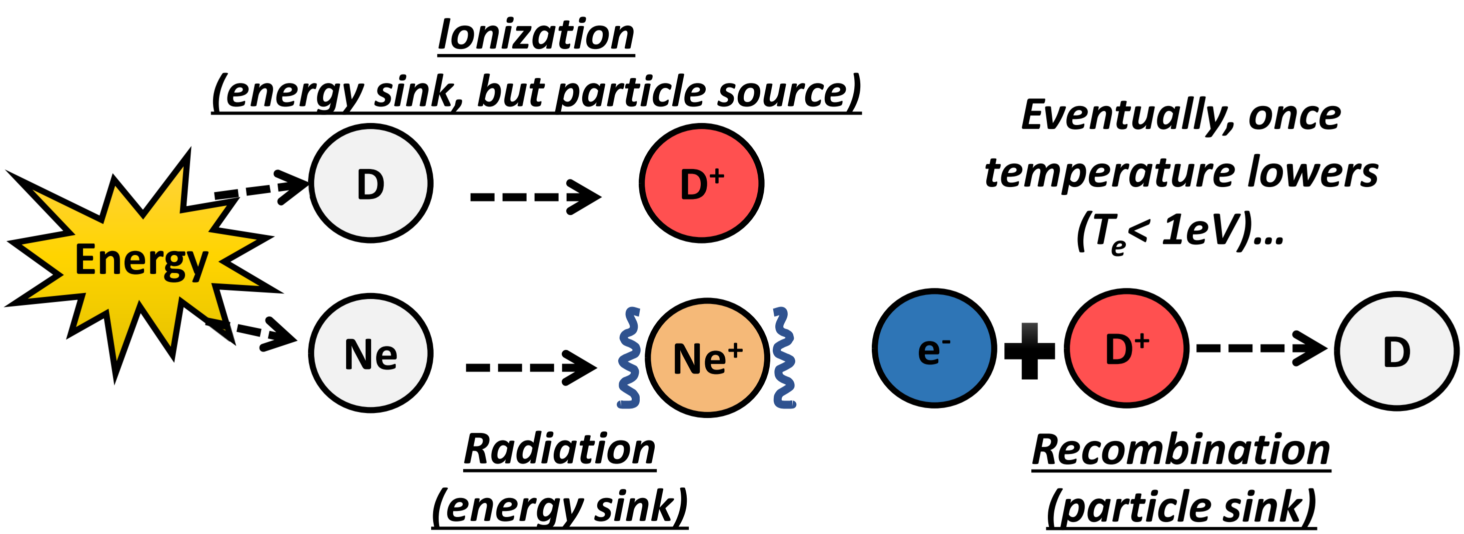


[1]

Something for everyone: divertor in a simulation, divertor in a real tokamak, divertor-ish for theorists

Divertor detachment protects material surfaces

- At present, most promising solution for dealing with heat and particle exhaust is the so-called "detached" divertor regime
- Detached regime is an extension of "high-recycling" regime, where neutral ionization in divertor volume exceeds puffing of neutrals into the volume, creating plasma-neutrals-plasma loop that sustains plasma in the divertor volume
- Three synergistic atomic processes improve the exhaust system by removing energy or plasma particle flux to the target



- These processes become more effective as a parameter related to the dissipation (e.g. density) is varied, eventually becoming so effective that they will extinguish plasma before it hits material surfaces
- *Important note: Ion-neutral friction is important for momentum balance and cooling the divertor to sub-eV temperatures, but cannot alter flux to the target*

Detachment onset

- Can be characterized by “rollover” of ion flux to the target: as a parameter related to the dissipation (e.g. density) is varied, ion flux will increase, then decrease as the plasma “detaches” from the wall

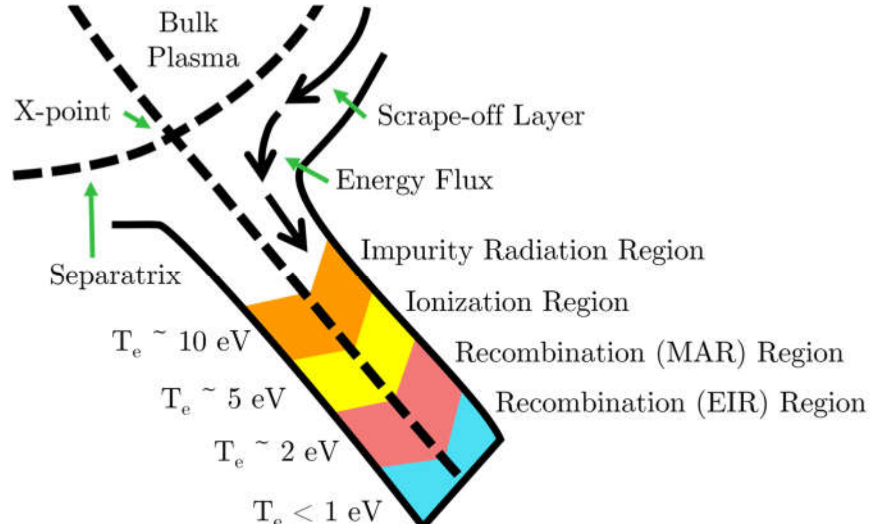
Plasma source from ionization

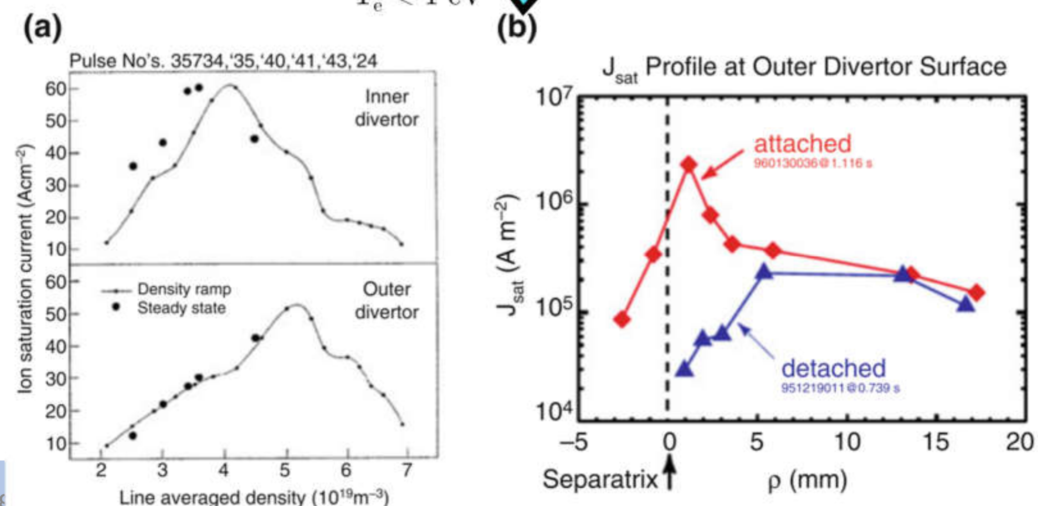
$$\Gamma_t = \boxed{\frac{Q_{SOL} - Q_{imp}}{E_{ion}}} - \Gamma_{rec}$$

Plasma flux to the target

Plasma sink from recomb

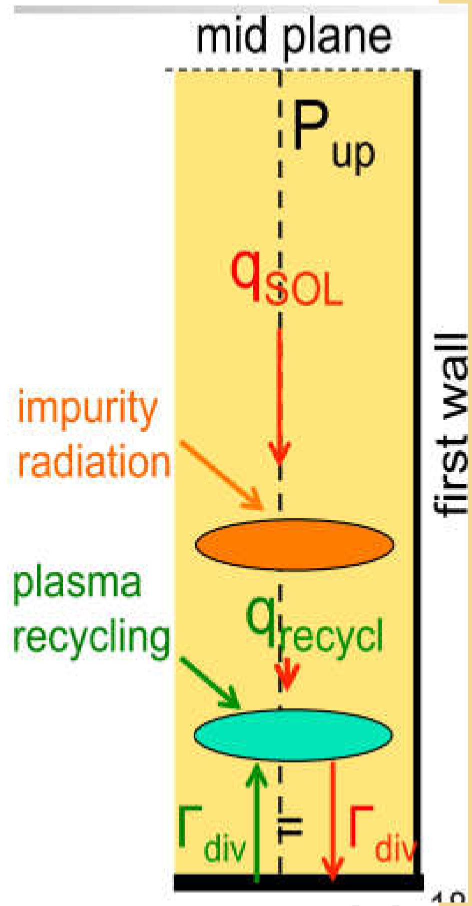
[1]





Detachment onset 2

- Rollover *can* be indicative of detachment, but does not tell the full story
- Need a physics-based model to articulate the conditions for the local onset of detachment:
  - In the high recycling regime, the upstream plasma is supported by plasma recycling in divertor, which is powered by the heat flux ($q_{recycle} < q_{SOL}$)
  - There is a critical level of $q_{recycle}$ which can support the saturated upstream pressure P_{up}
  - $(P_{up}/q_{recycle}) \sim 20$ N/MW at detachment
- Similar experimental scaling derived on AUG [2]



[1]

$$\frac{P_{up}}{q_{recycl}} \gtrsim \left(\frac{P_{up}}{q_{recycl}}\right)_{crit}$$

$$\left(\frac{P_{up}}{q_{recycl}}\right)_{crit} \sim \left(\frac{M}{I}\right)^{1/2} \sim 20\,\frac{N}{MW}$$

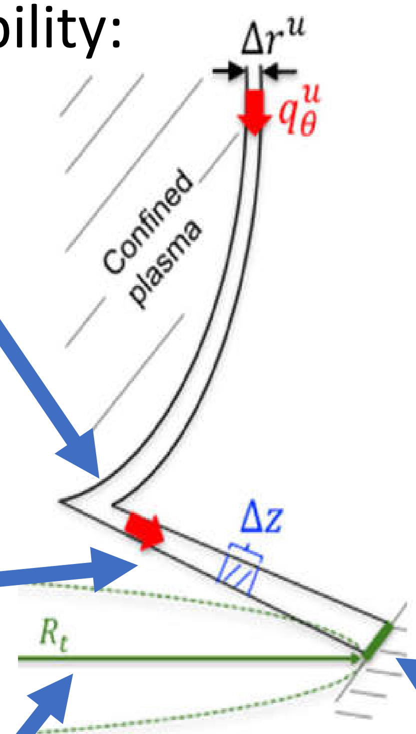
Improving detachment – long leg?

Long divertor legs are common features in many alternative divertor configurations because of several suggested benefits that could improve heat flux mitigation and stability:

Increased divertor volume = more room for impurities (increased impurity radiation Q_{rad} and decreased core contamination)

More distance from confined plasma = more room for ionization (energy sink) and recombination (particle sink) and better stability

Larger R_t can mean larger wetted area (=πr^2) to receive heat flux



Flux flaring effects

Since the divertor is a highly nonlinear, multifaceted system, it is unclear whether the existing understanding of the physics of detachment will translate to these long legs

Figure from [3]

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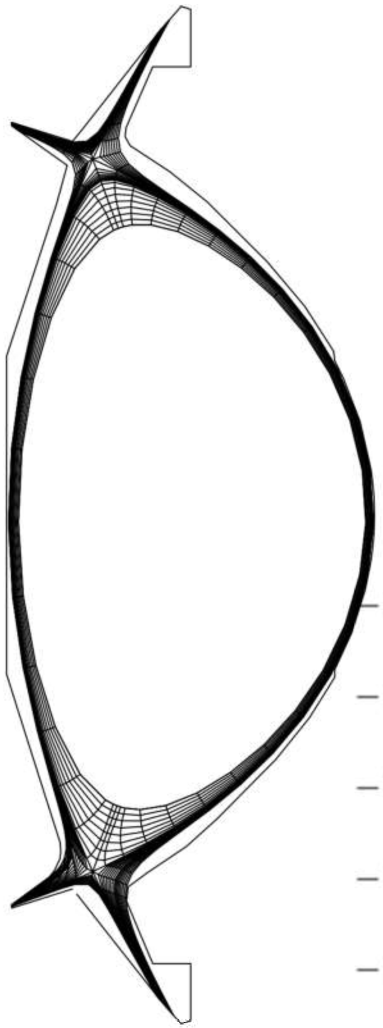
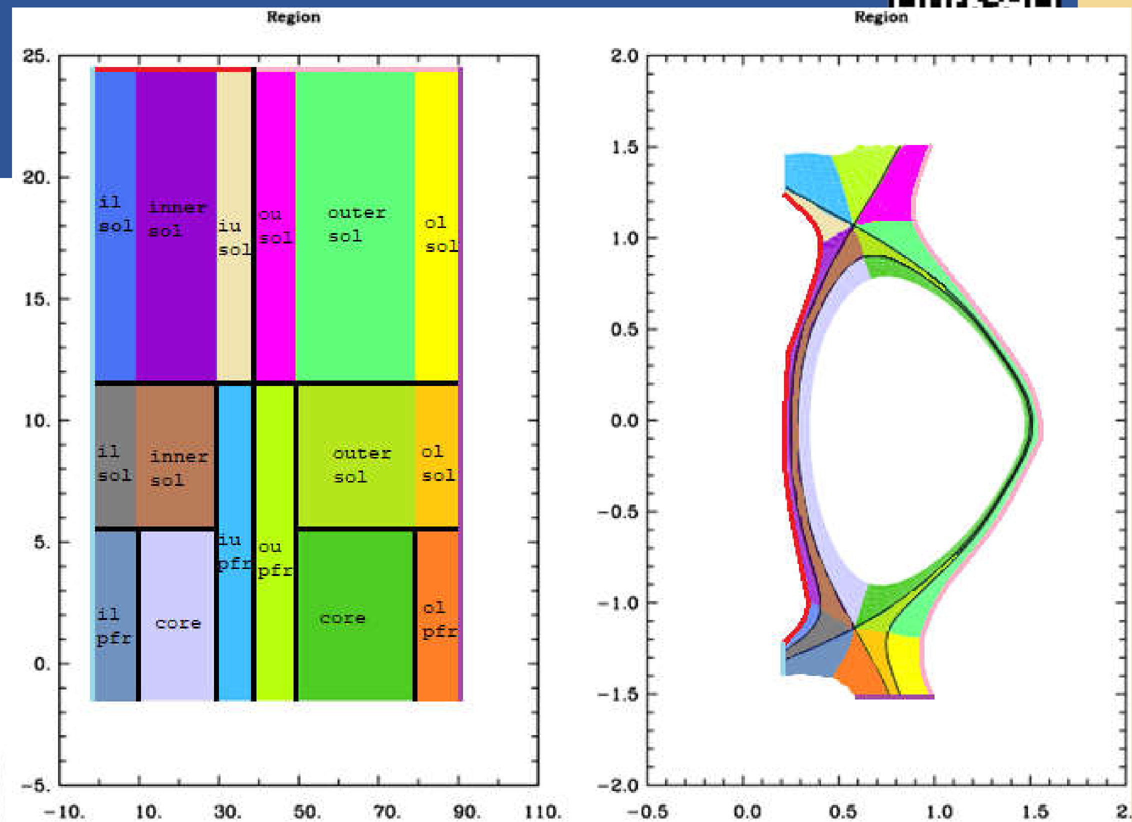
Our approach

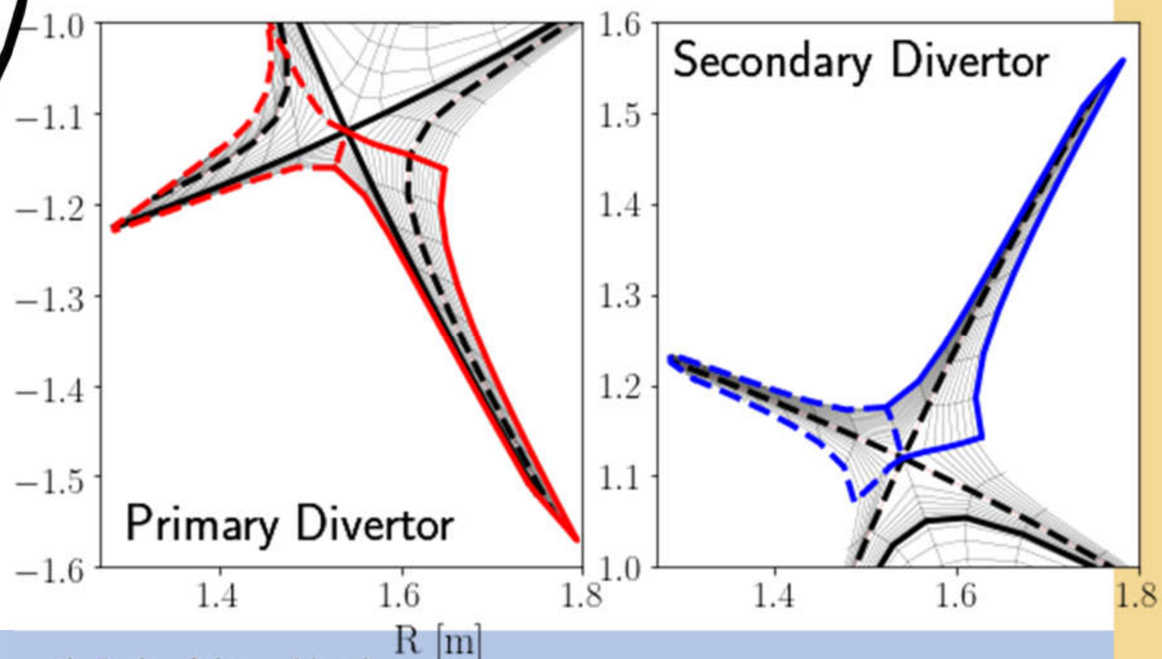
- We want to understand how our underlying understanding of detachment translates to other magnetic geometries
- Analyze detachment using SOLPS4.3 edge simulation code
- Take existing plasma equilibrium, incrementally increase one dissipation-related parameter (either density or impurity content) while holding all others constant, run to steady state
- Repeat to generate a bank of steady-state simulations that can be analyzed as individual "snapshots" that collectively emulate the transition to detachment

The grid

- Lower disconnected double null
  - Tightly baffled, long outer legs
  - Tightly baffled, short inner legs
  - Primary divertor = lower







Simulation parameters

- 30 MW input power
- Tunable parameter is total particle content (density)
- Full recycling at material surface
- D, D_2, Ne (EIRENE neutrals) and D^+, $Ne^{[1+,10+]}$ (B2 fluid)
- Trace neon impurity (kinetic neutral, full fluid equations for all charge states)
  - All simulations have ~ 1MW loss from this trace impurity radiation
- Constant transport coefficients $\chi_\perp = 1.0 m^2 s^{-1}$ and $D_\perp = 0.3 m^2 s^{-1}$ [2-4]
- Closed gas box model
  - Emulates high-recycling regime
  - No source/sink
  - Zero flux boundary condition at core
  - Feedback control to maintain particle content

Why SOLPS4.3?

- Implicit-explicit coupling between B2 and EIRENE results in **inherent, unavoidable particle losses**
- The ion sources due to the neutral ionization generally have both explicit and implicit components, and the plasma fluxes to the walls are implicit, leading to a violation of global particle balance during each time step for the fluid equations
- For each particle species (or "stratum"), distinguish:
  - Total ion source in B2, S* :
    - volume integral of positive plasma sources for recombination
    - volume integral of all plasma sources for other sources
  - Total neutral sources in Eirene, I* :
    - plasma fluxes onto the surfaces for recycling
    - constant influx for gas puff
    - volume integral of negative plasma sources for recombination
- They are in balance after a call to Eirene (before a B2 step), and after B2 step they evolve differently
    - Disbalance of order of several percent's of S* , I*
    - This can be an order of magnitude stronger than flux to the pump

SOLPS4.3 has particle feedback control

- This is a problem for **closed box simulations**: no influx from core or puff means perpetual particle loss as the code runs
- To avoid this, SOLPS4.3 uses a feedback control scheme to maintain particle content against inherent losses from code coupling
  - Set target waveform for particle content (N)
  - Puffing rate is adjusted based on
    - S = max(0, min(max puff rate, S+D))
    - $D = F * \left(\frac{N - <N>}{dt} + \frac{<N>_{prev} - <N>}{dt_{prev}}\right)$

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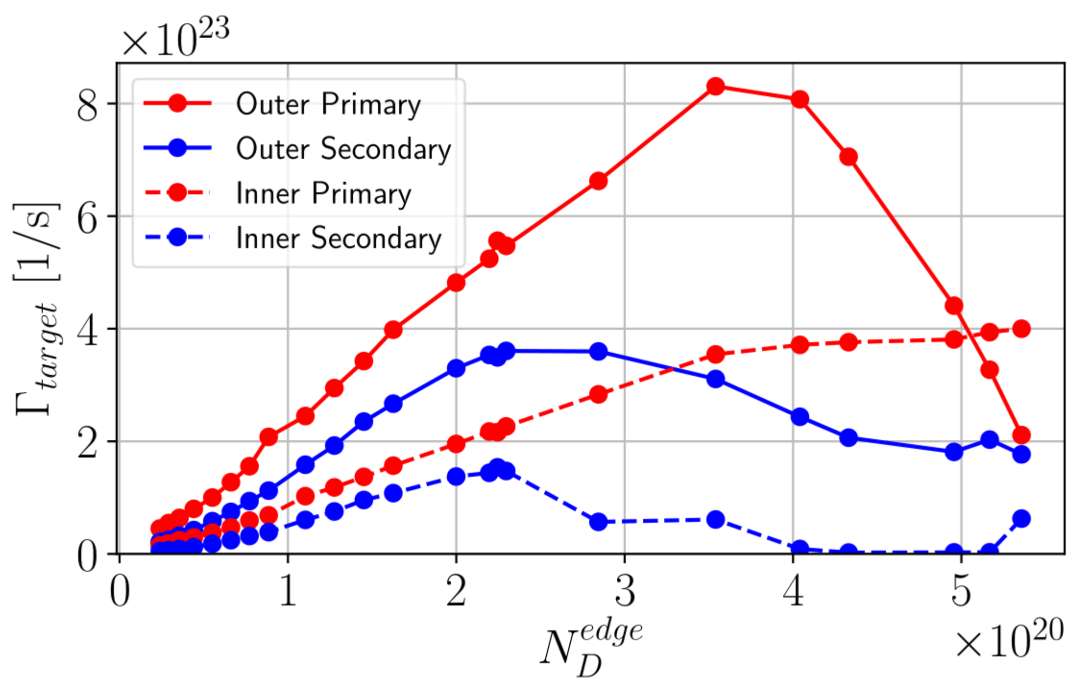
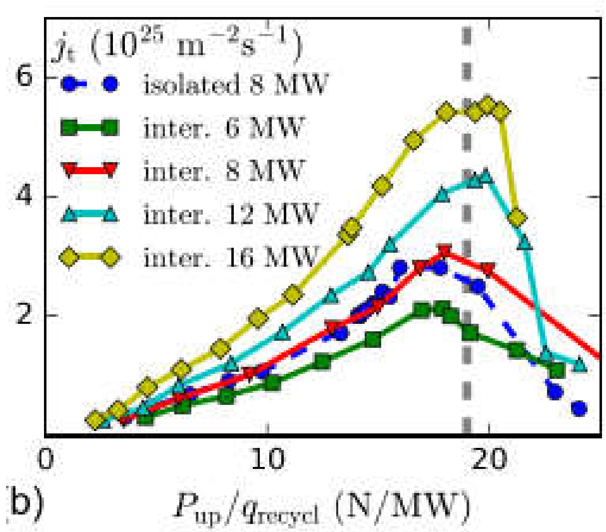
Results: Detachment criterion

- Rollover is present for all divertors except inner primary
- Very deep detachment achieved in inner secondary divertor
- Highest flux to outer primary divertor

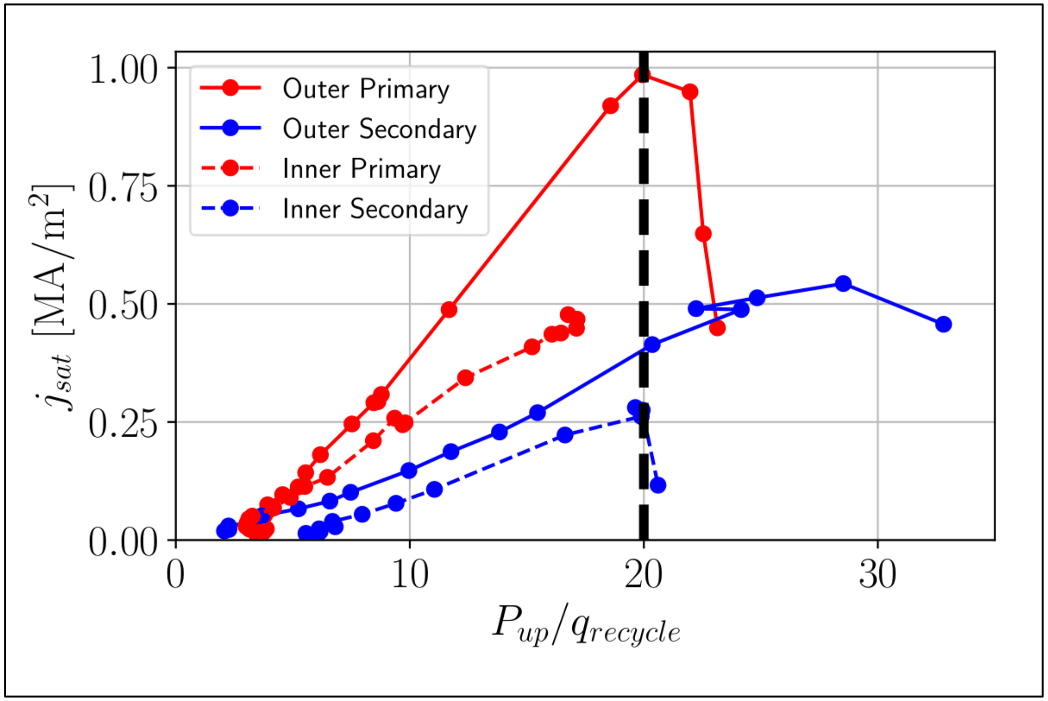


Results: Detachment criterion 2

- $(P_{up}/q_{recycle})$ ~ 20 N/MW at ion flux rollover
- Good agreement for OP and IS divertors, OK for OS, IP never detached



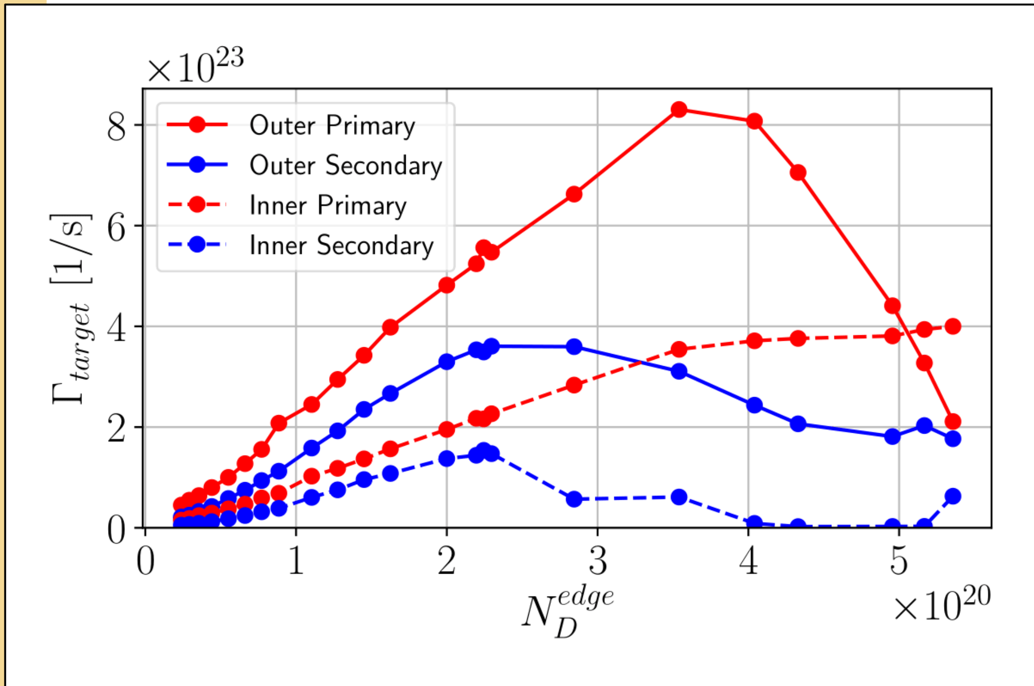
DIII-D geometries (Pshenov 2017)

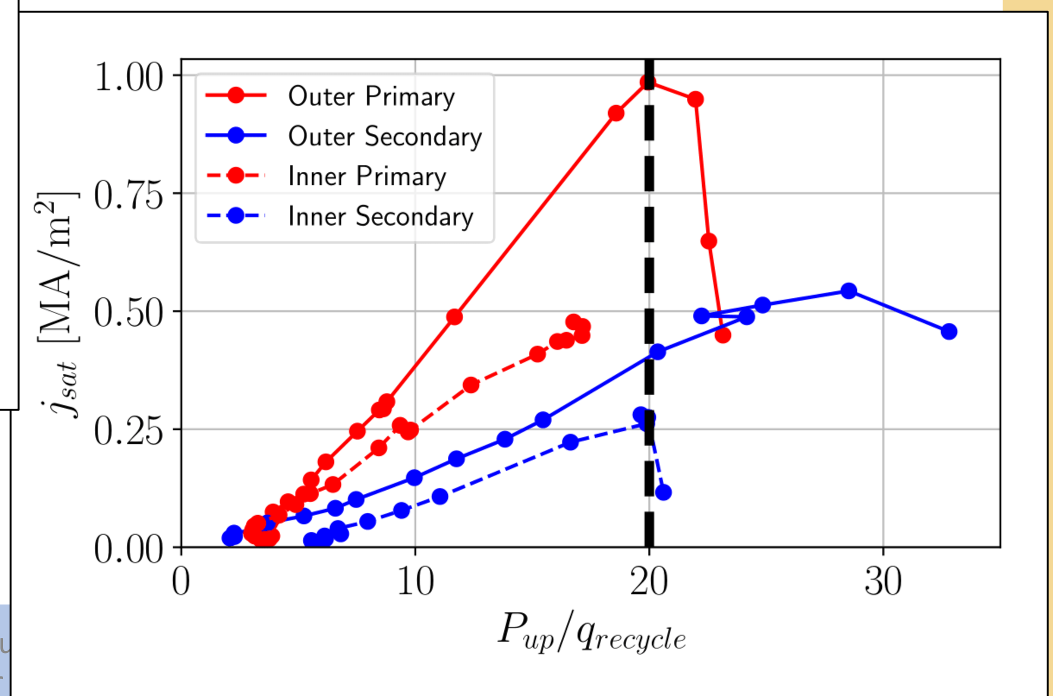


Long-leg divertor geometry

Detachment is "normal" in long leg!

- Good news for us!
- Detachment physics studies apply to new regimes!





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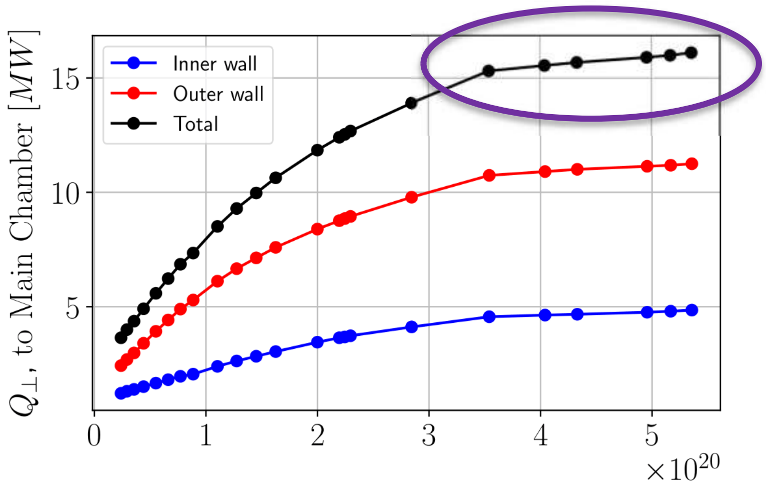
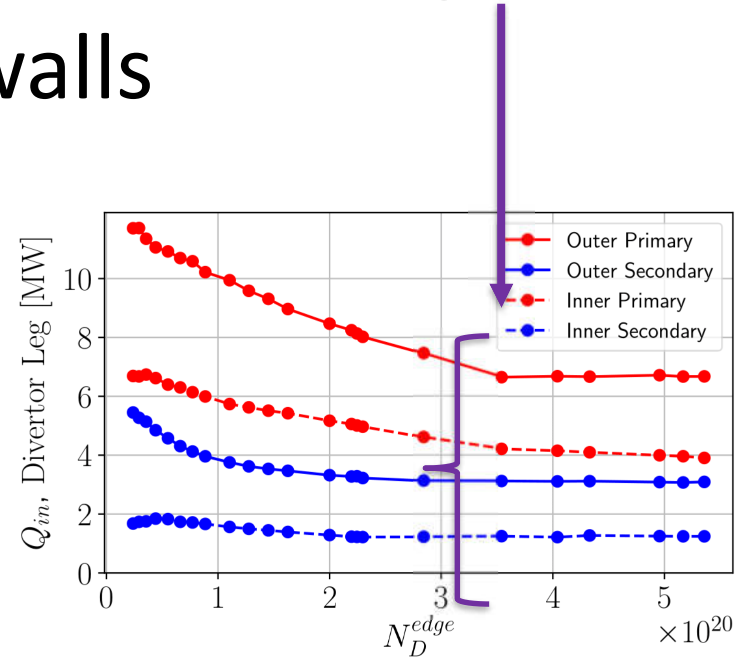
Results: Asymmetries and cross-field transport

- As density increases, heat flux becomes redirected from entering the divertor legs and towards the main chamber walls

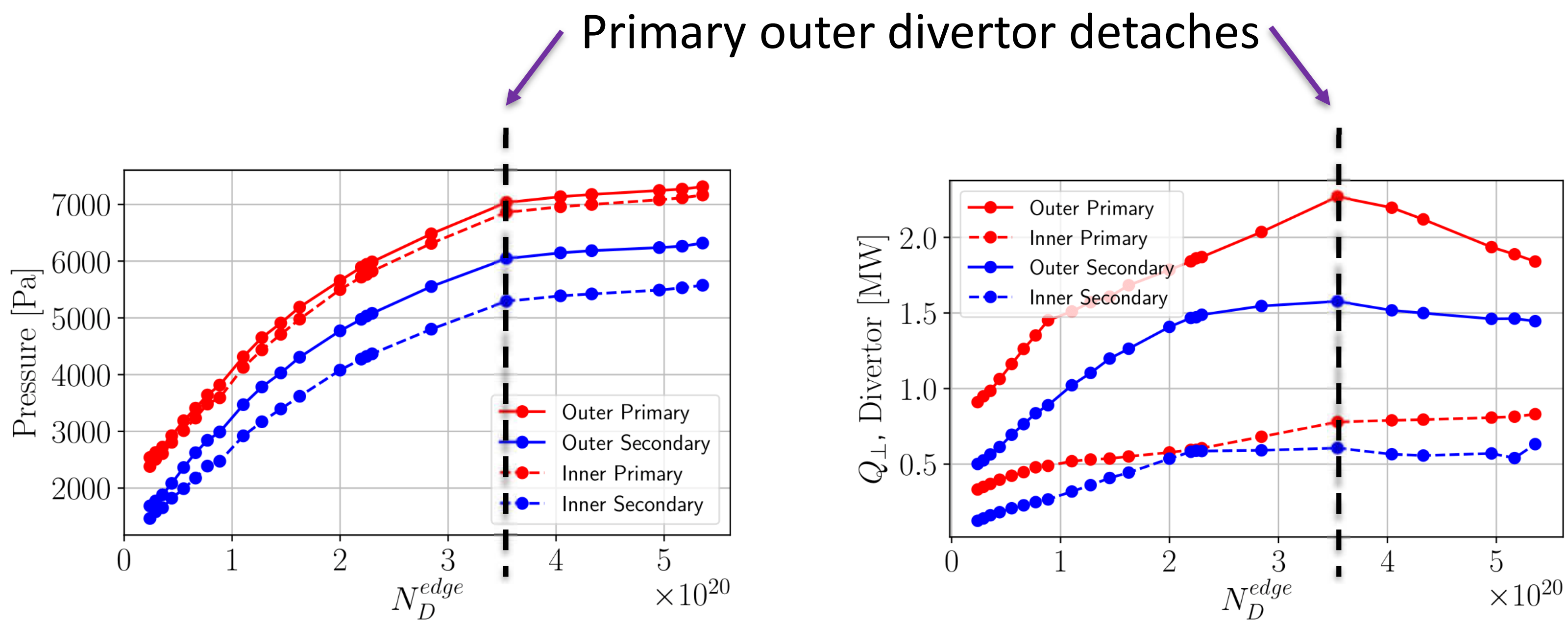


30 MW input – 16 MW to walls = "only" 14 MW to divertors (at high density)



- Remaining flux NOT interacting with main chamber walls goes into divertor legs, with prominent asymmetry in fluxes resulting from L-DDN magnetic topological configuration
  - Majority of fluxes going to primary (lower) divertor legs
  - In-out asymmetry is typical for divertor heat flux

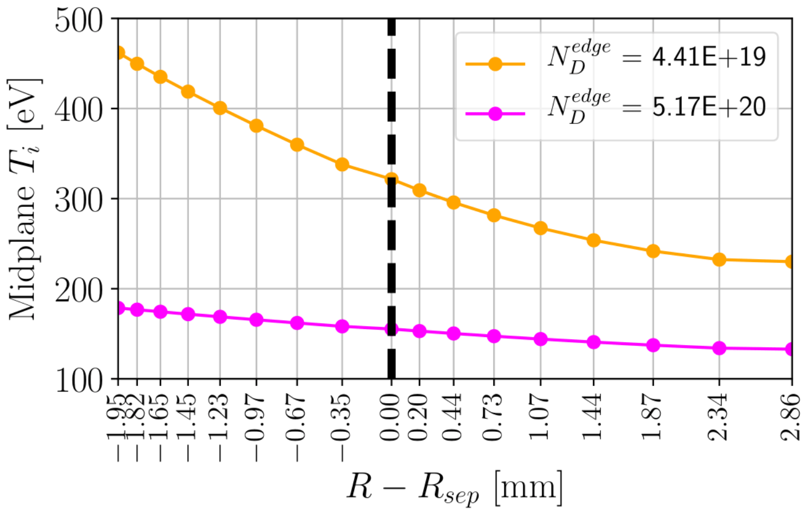
Results: Asymmetries and cross-field transport



- As detachment begins, onset of recombination results in saturation of upstream pressure
- Stagnation of upstream pressure prevents further increase in heat flux to device walls: cross-field transport no longer increases
- Effect also observed in divertor legs

Upstream cross-field transport significantly altered by radial profiles

- Large gradient in T_i at lower densities contributes to significant increase in cross-field transport
- Gradient relaxes once pressure saturates; no more increase in cross-field transport



$$Q_\perp \approx -\frac{5}{2} D \frac{\partial n}{\partial r} T_i - \chi n \frac{\partial T_i}{\partial r}$$

Detachment onset, revisited

- Role of perpendicular transport is significant in the reduction of heat flux in the long leg

Energy source for plasma ionization

$$\Gamma_t = \frac{Q_{SOL} - Q_{imp}}{E_{ion}} - \Gamma_{rec}$$

Plasma flux to the target

Plasma sink from recomb

Reduction in ionization energy source due to cross-field heat flux

$$\Gamma_t = \frac{Q_{SOL} - Q_{imp} + Q_{\perp}}{E_{ion}} - \Gamma_{rec}$$

Plasma flux to the target

Plasma sink from recomb

Synergistic effect:
Recombination and cross-field transport

- Cross-field transport and flux to the walls are significant before recombination begins
- Losses to side walls (in main chamber AND divertor legs) contribute to reduction in heat flux
- Once heat flux is sufficiently reduced, recombination processes begin, and upstream pressure saturates
- Saturation of upstream pressure relaxes gradients, limiting further increases in cross-field transport

$$\Gamma_t = \frac{Q_{SOL} - Q_{imp} - Q_{\perp}}{E_{ion}} - \Gamma_{rec}$$

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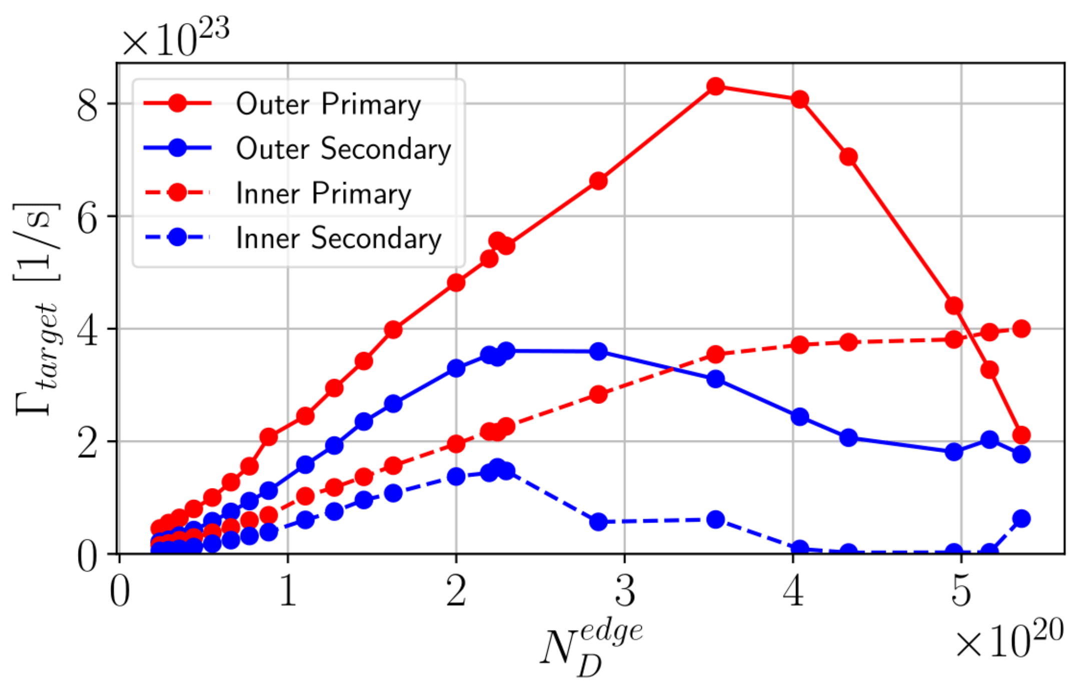
In-out detachment asymmetry

- Secondary divertor: Detachment proceeds in the inner divertor before outer (normal)
- Primary divertor: Detachment in outer divertor first, inner divertor never detaches



Seem familiar?

- Primary divertor detachment asymmetry also observed on long legs in TCV and KSTAR

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Journal of Nuclear Materials 290–293 (2001) 940–946
www.elsevier.nl/locate/jnucmat

Divertor geometry effects on detachment in TCV

R.A. Pitts [a,*], B.P. Duval [a], A. Loarte [b], J.-M. Moret [a], J.A. Boedo [c], D. Coster [d], I. Furno [a], J. Horacek [e], A.S. Kukushkin [f], D. Reiter [g], J. Rommers [a], The TCV Team [1]

Divertor closure effects on the TCV boundary plasma

O. Février [a,*], H. Reimerdes [a], C. Theiler [a], D. Brida [b], C. Colandrea [a], H. De Oliveira [a], B.P. Duval [a], D. Galassi [a], S. Gorno [a], S. Henderson [c], M. Komm [e], B. Labit [a], B. Linehan [d], L. Martinelli [a], A. Perek [f], H. Raj [a], U. Sheikh [a], C.K. Tsui [g], M. Wensing [a], the TCV Team[1], the EUROfusion MST1 Team[2]

Nuclear Materials and Energy 27 (2021) 100977

Attribute asymmetries to flux flaring effects in outer divertor

Nucl. Fusion 58 (2018) 126033 (13pp)
https://doi.org/10.1088/1741-4326/aae865

Atomic processes leading to asymmetric divertor detachment in KSTAR L-mode plasmas

Jae Sun Park[1], Mathias Groth[2], Richard Pitts[3], Jun-Gyo Bak[4], S.G. Thatipamula[4], June-Woo Juhn[4], Suk-Ho Hong[4] and Wonho Choe[1,5,a]

Attribute asymmetries to D2 accumulation and molecular effects at outer target plate due to target inclination

≈ Target effects

In-out detachment asymmetry

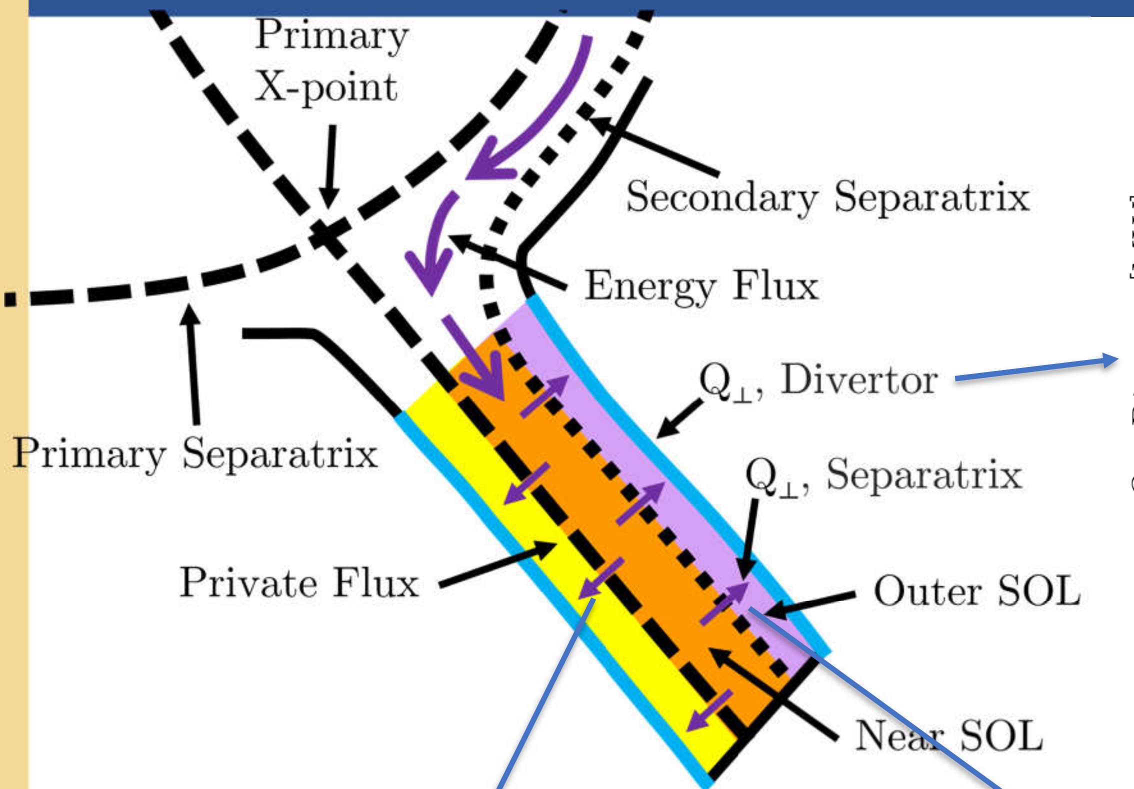
- I don't buy it
- Detachment is *enhanced* by target effects, but could not *cause* this asymmetry
- If target effects are the mechanism behind detachment in-out asymmetry, why is the effect not observed in both divertors in this work?
- Let's do an in-depth energy balance:

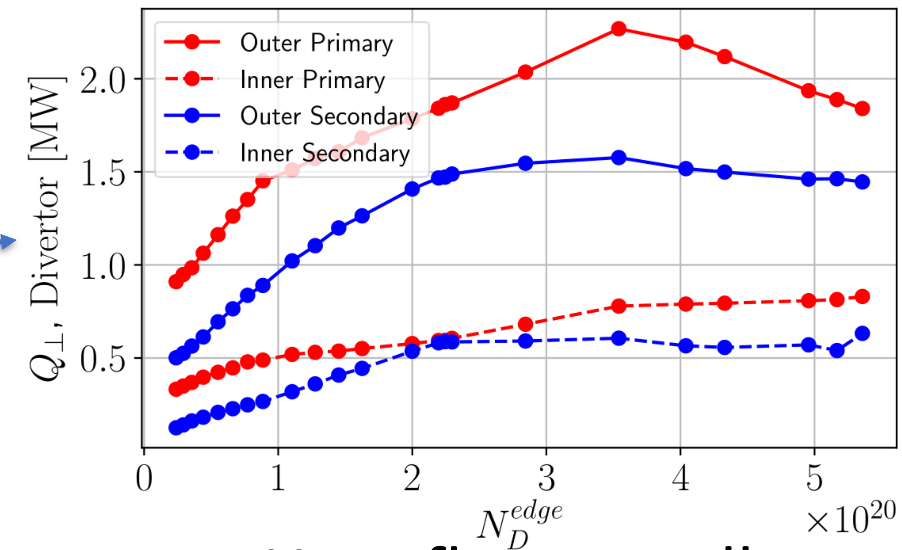
Leg	Q_{in}	$Q_{\perp}$	Q_{ion}	Q_{target}	Volume	Wall Area
Outer Primary	6.6 MW	2.3 MW	2.6 MW	1.7 MW	0.19 m^3	8.92 m^2
Inner Primary	4.2 MW	0.8 MW	1.0 MW	2.0 MW	0.13 m^3	3.81 m^2
Outer Secondary	3.1 MW	1.6 MW	1.4 MW	0.2 MW	0.16 m^3	8.88 m^2
Inner Secondary	1.2 MW	0.6 MW	0.6 MW	0.0 MW	0.09 m^3	4.25 m^2

$$\Gamma_t = \frac{Q_{SOL} - Q_{imp} - Q_{\perp}}{E_{ion}} - \Gamma_{rec}$$

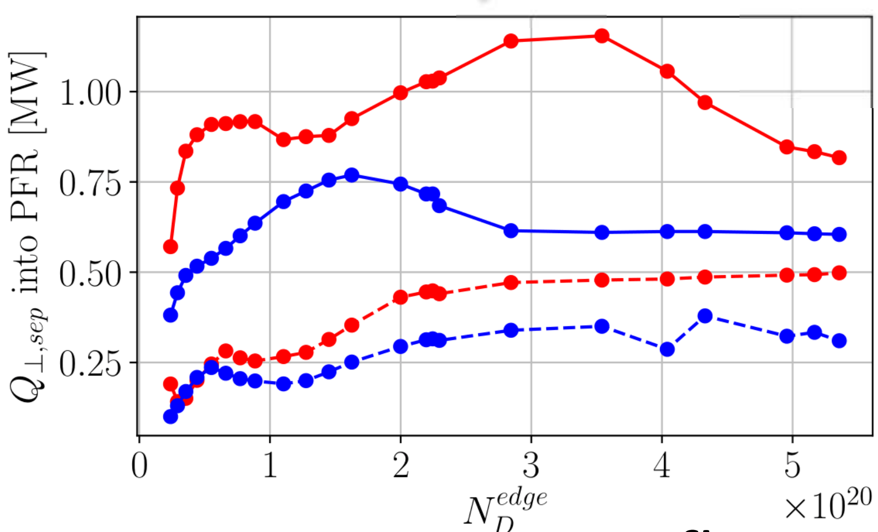
Cross-field transport to the divertor leg walls looks important! Let's look further…

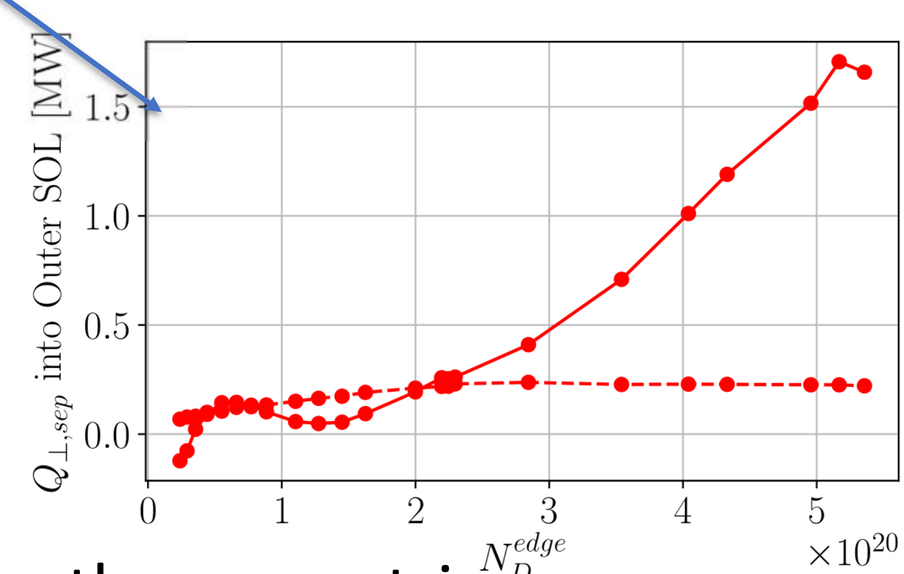
Energy balance





Heat flux to walls

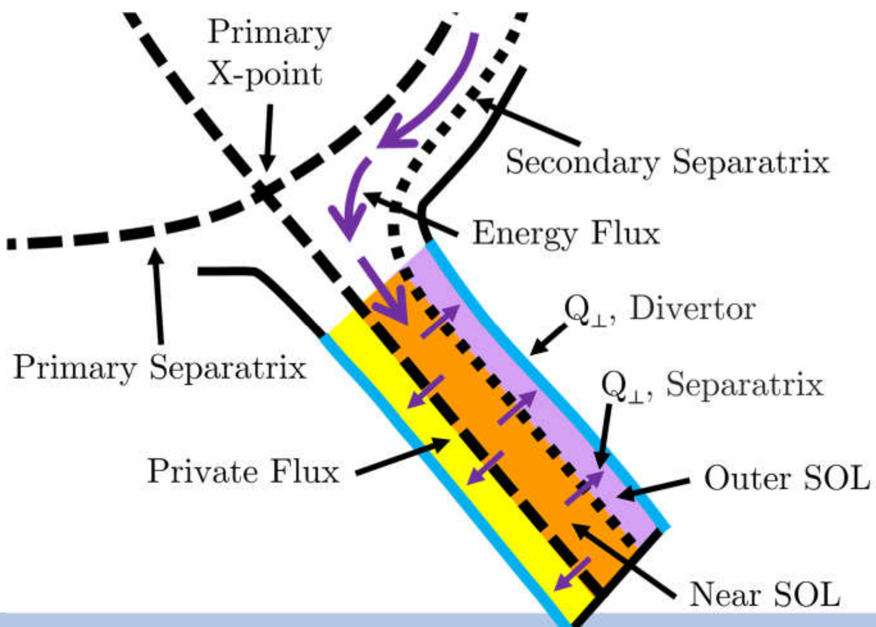




Heat flux crossing the separatrices

Energy balance

- Sorry! That was a lot of plots
- TL;DR:
  - There is significant perpendicular transport out of the main channel in the outer leg
  - Not much transport out of the main channel in the inner leg
  - Moderate transport across the separatrix in the secondary divertor



<u>The perpendicular transport acts as a mechanism to enhance heat flux spreading and delocalization in the outer divertor leg, which is not observed in any other leg!</u>

$$Q_{\perp} \approx -\frac{5}{2} D \frac{\partial n}{\partial r} T_i - \chi n \frac{\partial T_i}{\partial r}$$

Asymmetry Summary

- Secondary divertor: in before out
  - Lower power gives "normal" detachment
    - Also seen on MAST-U, but inner div data is not published
    - Inner secondary receives very low power (~1.2 MW)
  - Tightly-baffled channels with angled targets in both legs
    - Geometric effects enhance detachment in both legs
- Primary divertor: out before in
  - High power forces asymmetric, out-in detachment
  - Perpendicular transport in long leg allows for cross-field heat flux into secondary SOL and PFR, effectively increasing divertor volume for dissipation to occur
  - Significant energy losses to higher surface area side walls
  - High density and high power in inner leg prevents spreading, localizing heat flux to inner channel and preventing detachment

Overall Summary

- Personal highlights of detachment physics
- Scan of increasing particle count in a long leg divertor using the SOLPS4.3 code
- Detachment physics translate into new magnetic configuration
- Upstream cross-field transport saturates with divertor detachment
- Turbulence enhances heat flux spreading to enable detachment at high power

$$\Gamma_t = \frac{Q_{SOL} - Q_{imp} - Q_{\perp}}{E_{ion}} - \Gamma_{rec}$$

References

[1] S. I. Krasheninnikov, A. Smolyakov, A. Kukushkin. On the Edge of Magnetic Fusion Devices; Springer Nature: Switzerland, 2020.

[2] Kallenbach, A. Nucl. Fusion 2015, 55, 053026

[3] C. Theiler et al 2017 Nucl. Fusion 57 072008

[4] Lore, BP13.00004 at APS 2020

[5] A. Kuang et al 2020 Journal of Plasma Physics, 86(5), 865860505

[6] S.B. Ballinger et al 2021 Nucl. Fusion 61 086014

Initial grids and equilibria for these simulations were generated by **J. Canik** and **J. Lore** of ORNL and heavily modified for this project. See Ref. [3-5] for details on the initial design of these initial simulations.

A.S. Kukushkin provided significant technical expertise and support to this project.

***This work was submitted to *Nuclear Fusion*, November 2022

Thank you!

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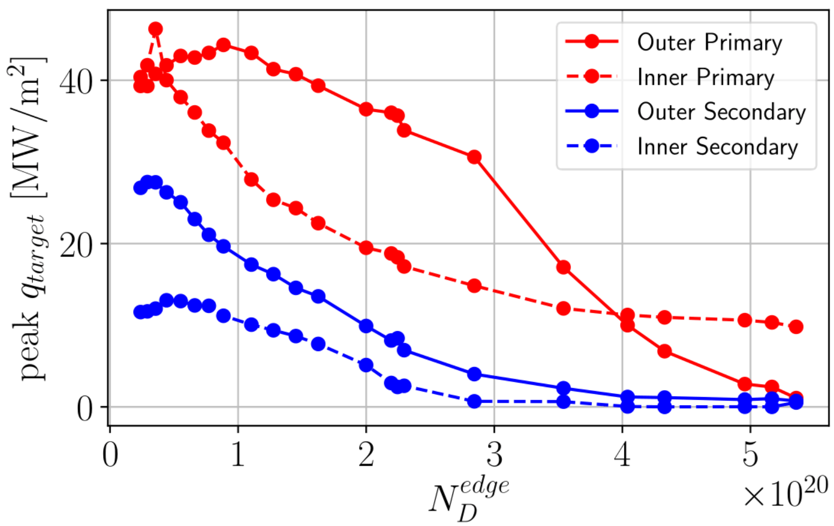
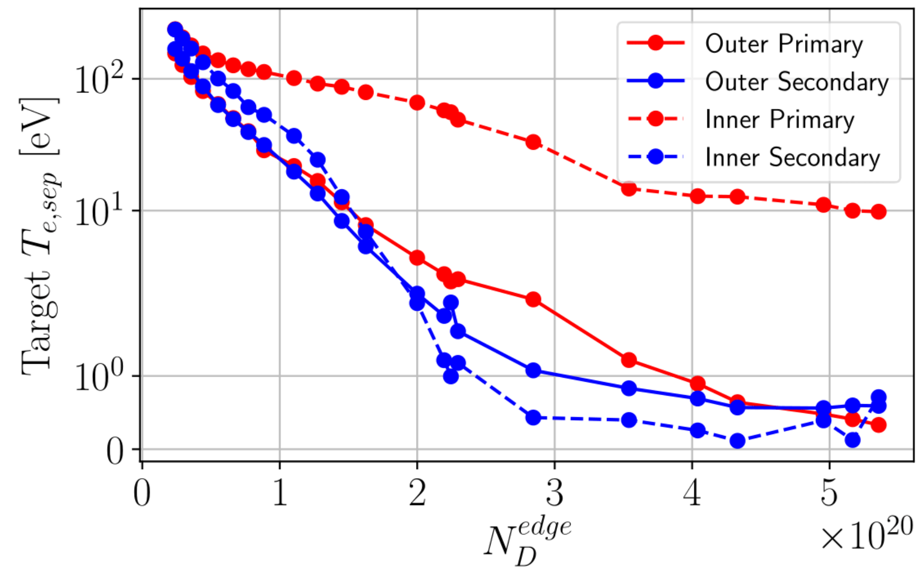
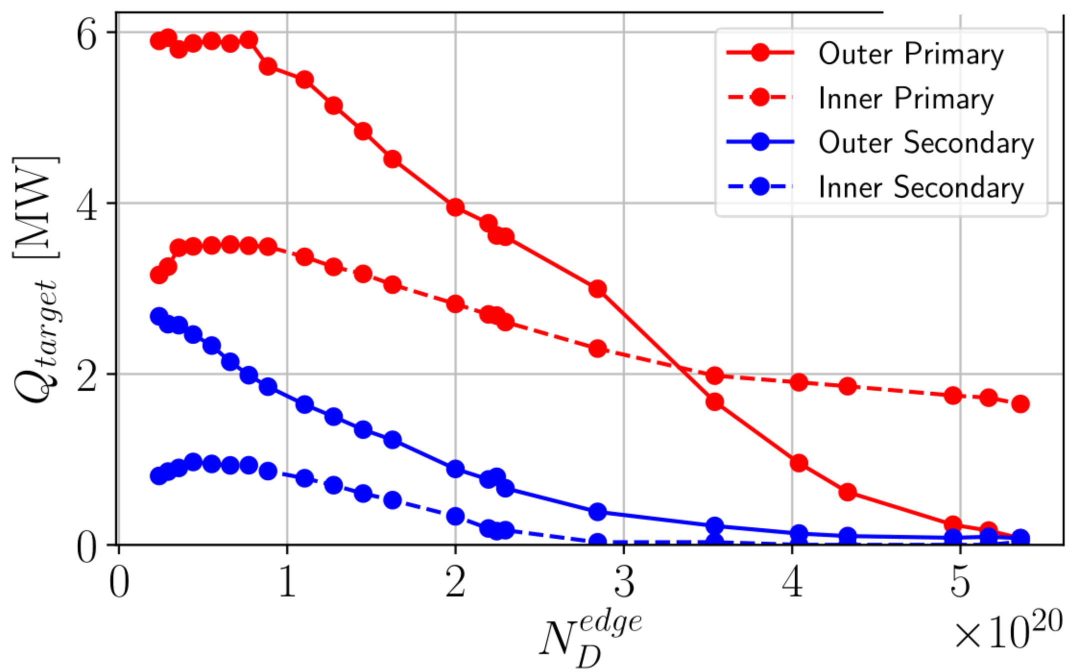
Backup slides

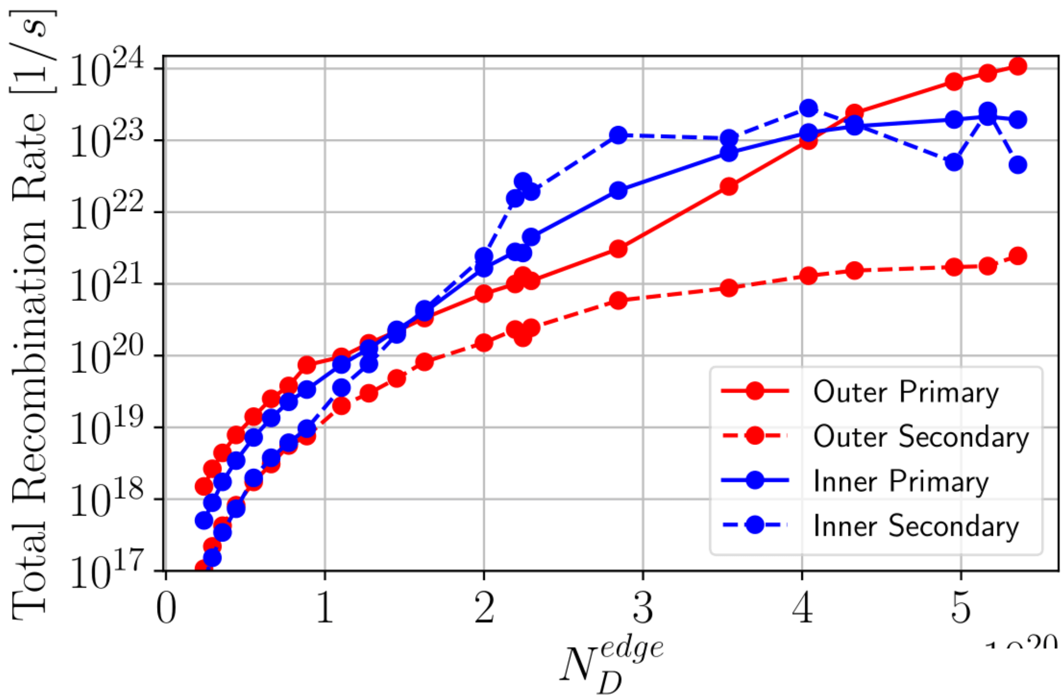
Target profiles

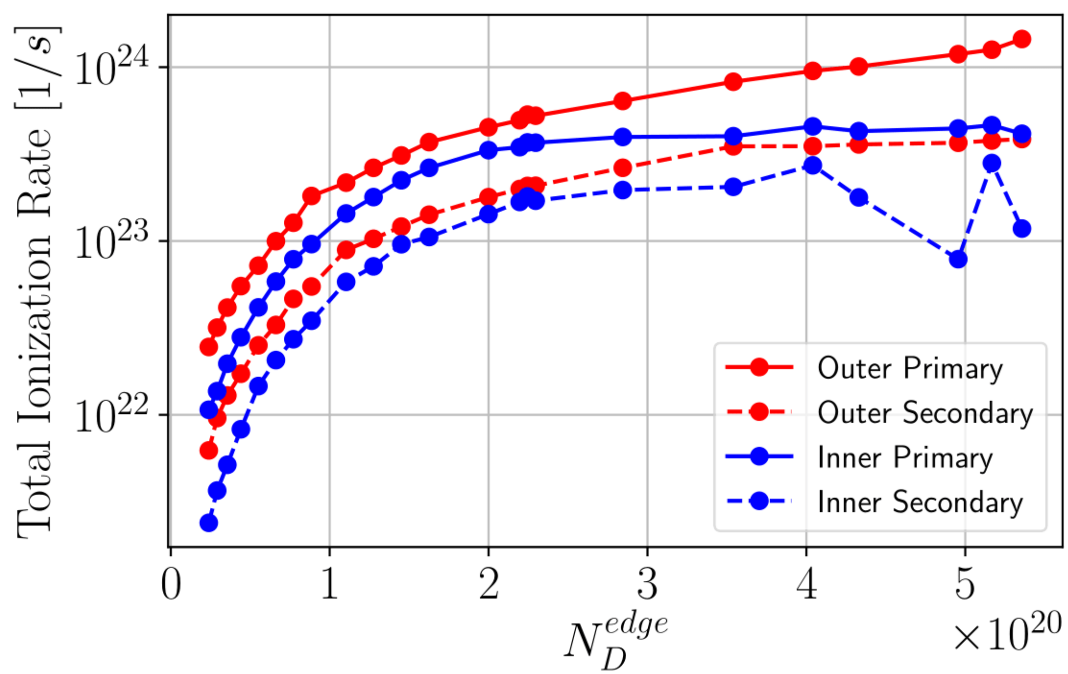




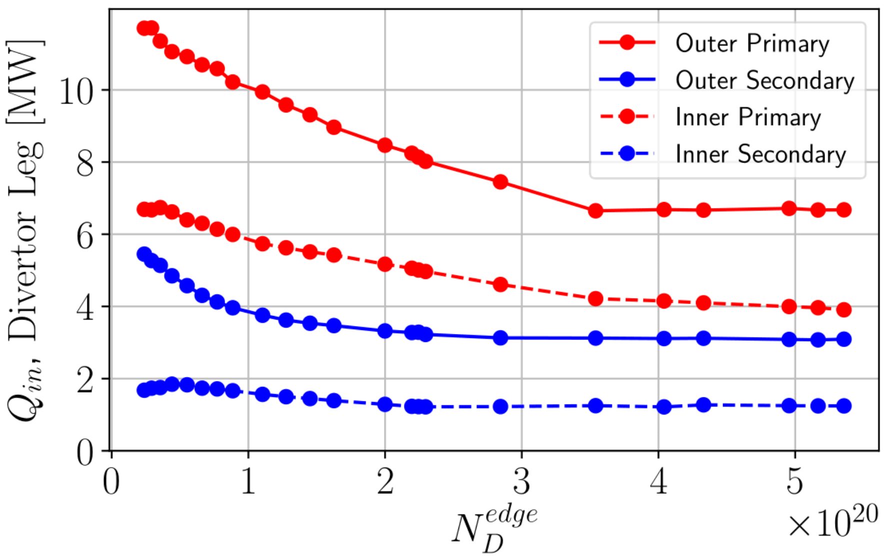


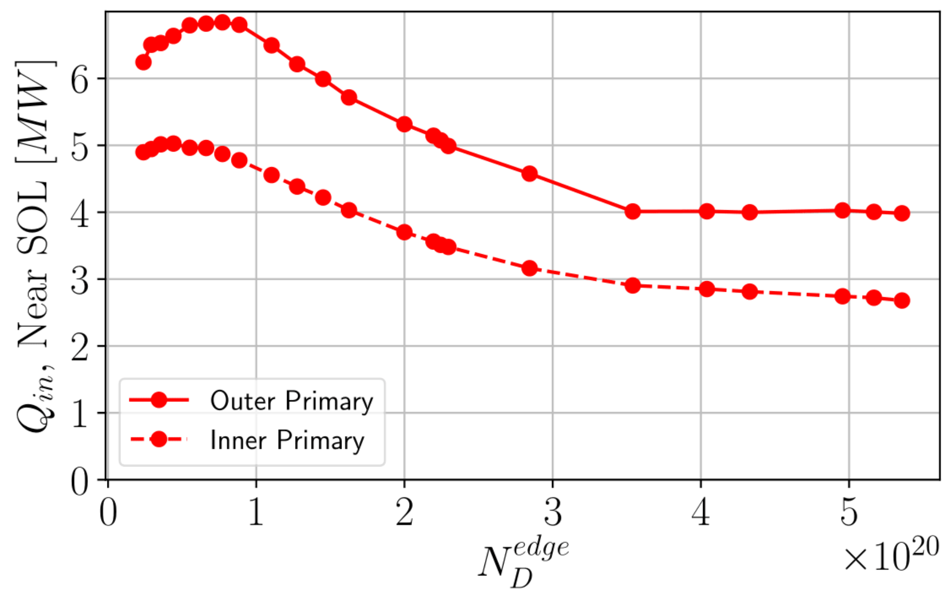
Atomic processes

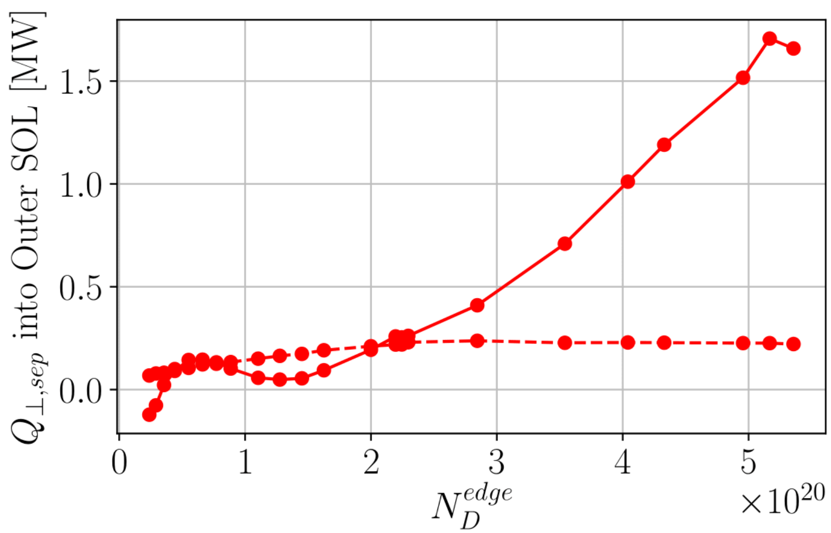


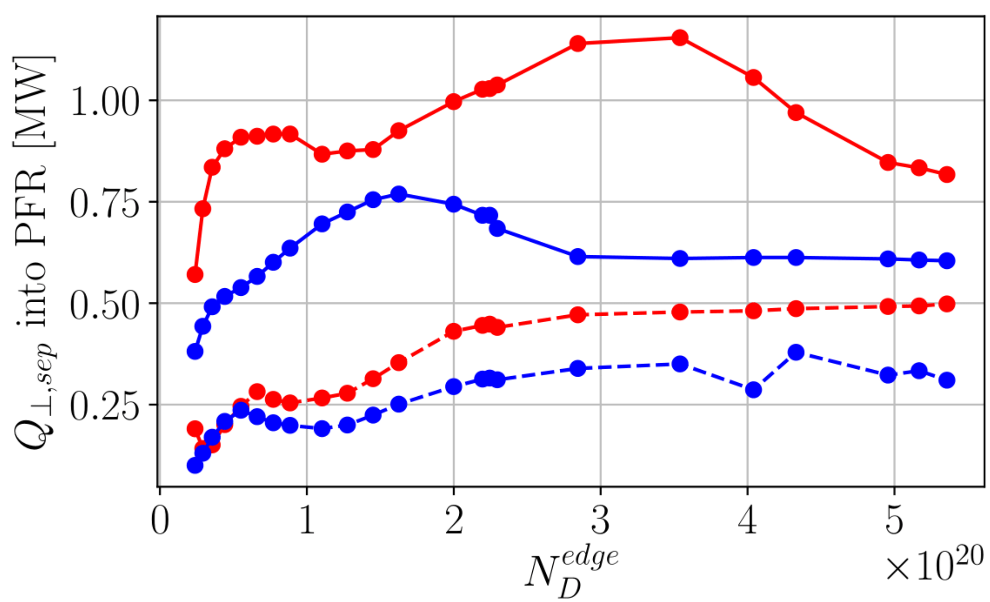


Heat flux distribution



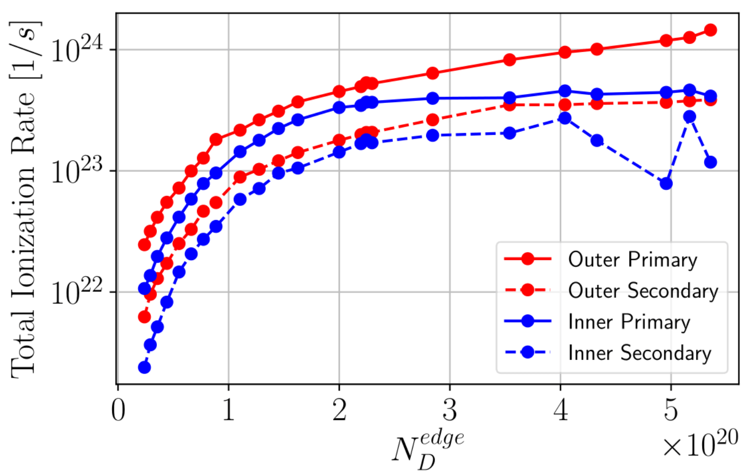


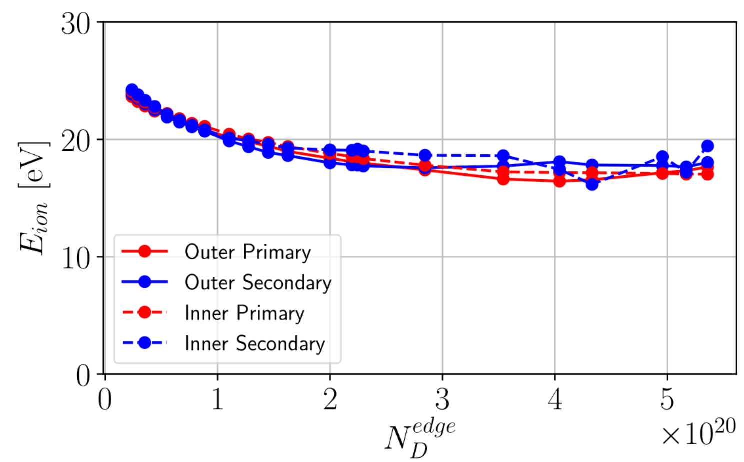




Ionization Energy

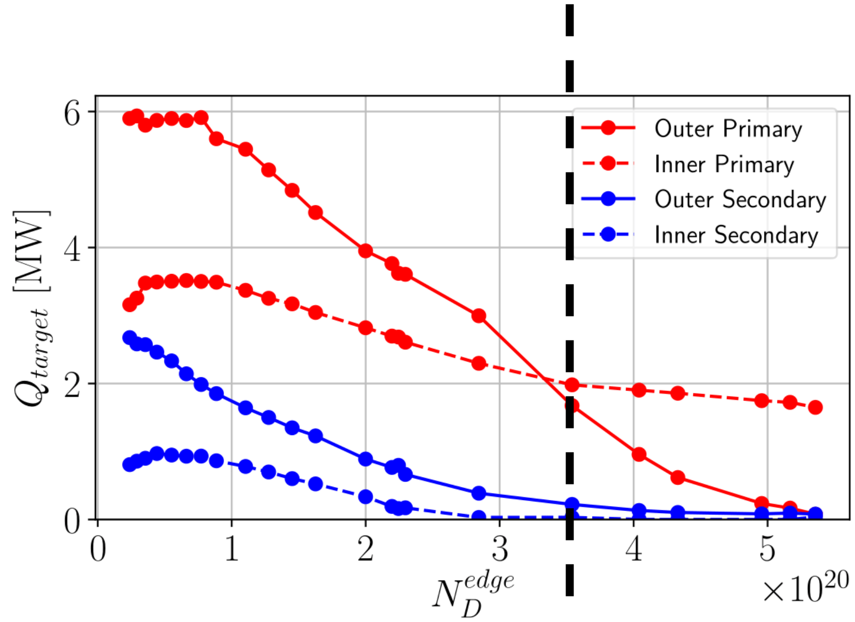
- Reduction in heat flux to divertor legs due to cross-field losses allows "typical" detachment to proceed: dissipative processes are effective enough to mitigate incoming heat flux
- Average ionization cost goes down as density is increased





Results: Asymmetries and cross-field transport

- Plasma in standard divertors usually detaches at the inner target before the outer target
  - This is the case for the secondary divertor, which carries significantly less heat flux
- Here, the plasma in the primary divertor detaches at the outer target before the inner target
- Perpendicular transport and influence of target geometry drive in-out asymmetry



Leg	Q-in	Q-wall	Q-ion	Q-target
Outer Primary	6.6 MW	2.3 MW	2.6 MW	1.7 MW
Inner Primary	4.2 MW	0.8 MW	1.0 MW	2.0 MW
Outer Secondary	3.1 MW	1.6 MW	1.4 MW	0.2 MW
Inner Secondary	1.2 MW	0.6 MW	0.6 MW	0.03 MW

Future work

- How does impurity radiation spread along the divertor leg?
  - Mechanisms of impurity spreading in long legs is still unclear
  - UEDGE modeling with low-fidelity fixed-fraction impurity radiation calculations show desirable radiation spreading, but is this realistic?