P027(G) Parametric scaling of power exhaust in EU-DEMO alternative divertor simulations

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Link to poster: https://github.com/aejarvin/PSI_2022/

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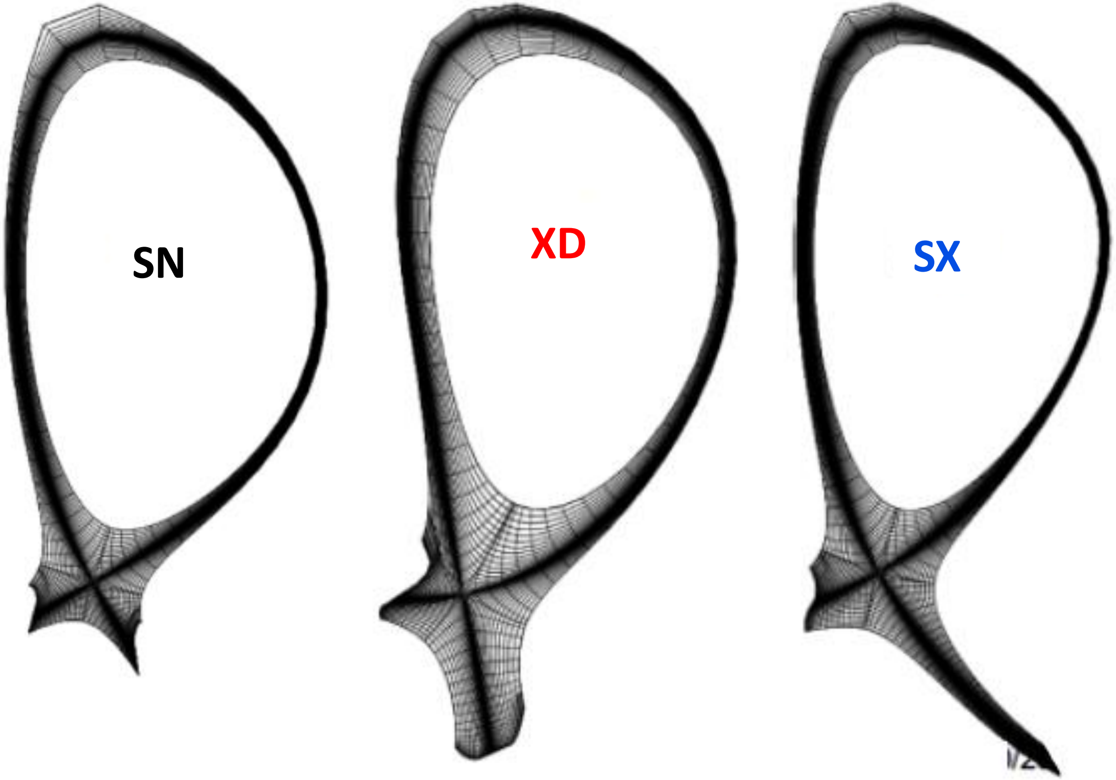
The SOLPS-ITER database of EU-DEMO alternative divertor configurations (ADC) has been investigated and compared to simple Lengyel model predictions

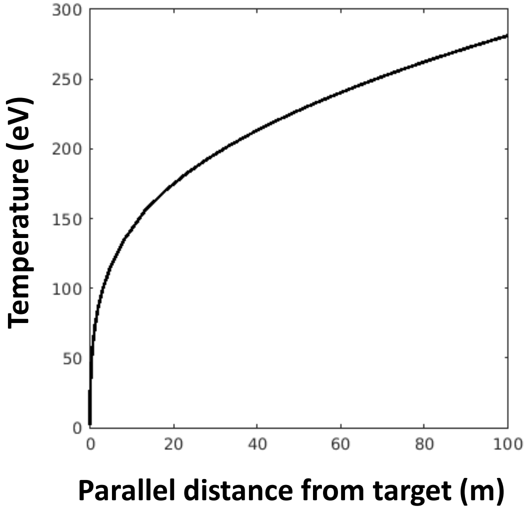
- Power exhaust is one of main challenges faced by fusion reactors

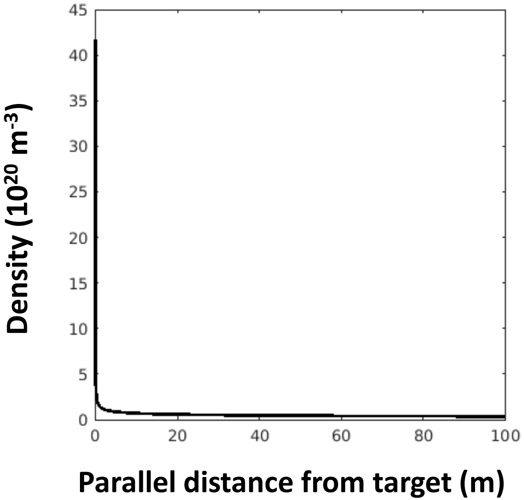
- A large database of SOLPS-ITER simulations, generated through EUROfusion ADC studies, is investigated here focusing on **single-null (SN)**, **X-divertor (XD)**, and **Super-X (SX)** [1 – 6].

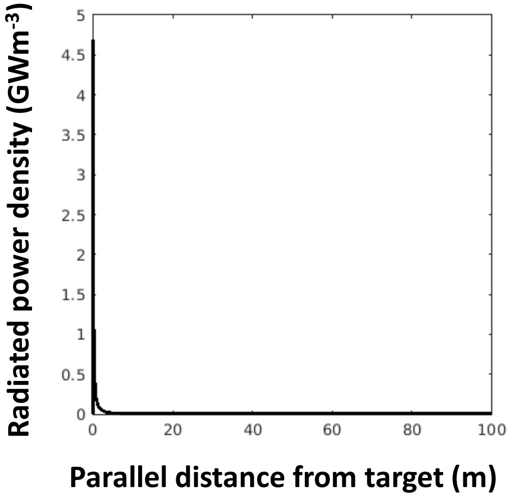


SOLPS-ITER grids of the investigated configurations [1]

The Lengyel [7] model uses simplified transport assumptions to relate SOL impurity concentration, upstream density, and heat flux to onset of detachment

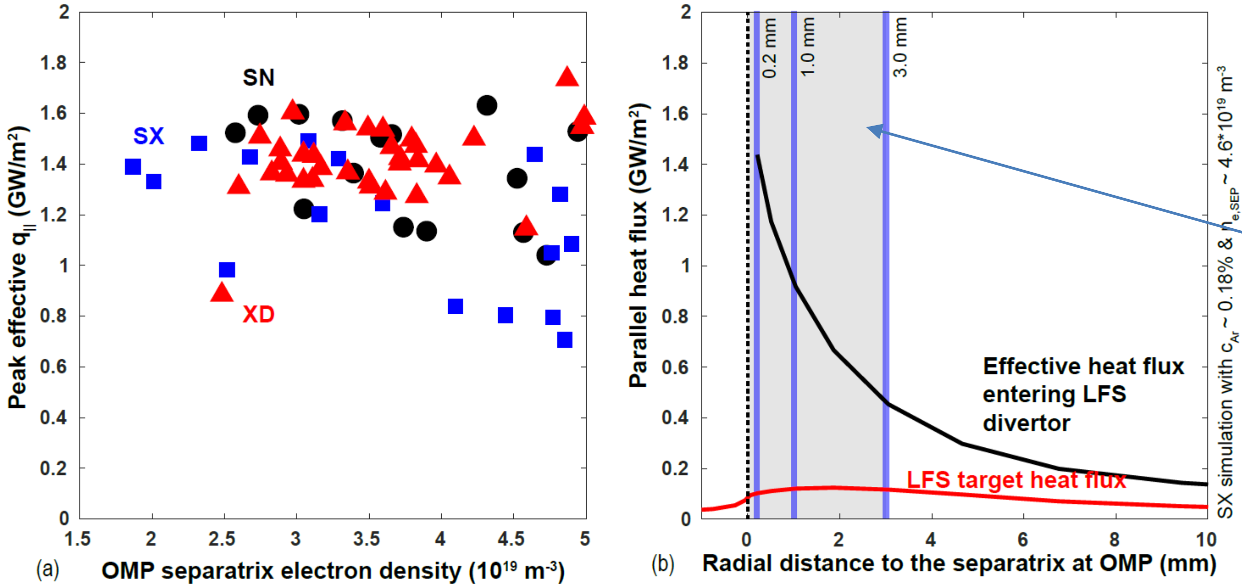






- Heat transported by electron heat conduction $q = -\kappa_0 T_e^{5/2} \nabla_{||} T_e$
- Static pressure conserved along a flux tube
- Conservation of impurity concentration along a flux tube
- **The strong temperature dependencies of heat conductivity and radiative cooling tend to generate spatially narrow radiation fronts in the Lengyel model**

Within the analyzed SOLPS-ITER database, the effective parallel heat flux towards the LFS divertor ranges between 1.0 – 1.6 GW/m²

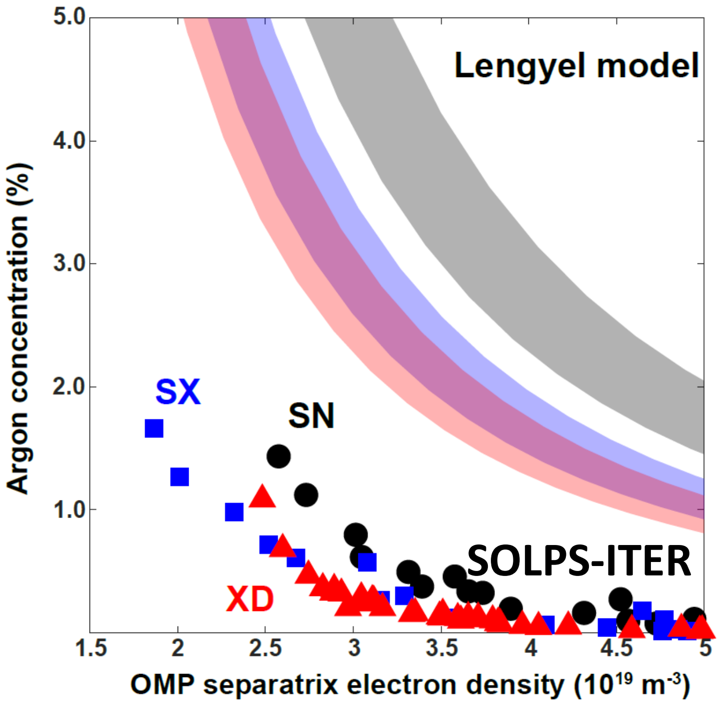


Power balance calculations (slides 6 – 7)
Focus on the LFS near-SOL: 0 – 3 mm from separatrix

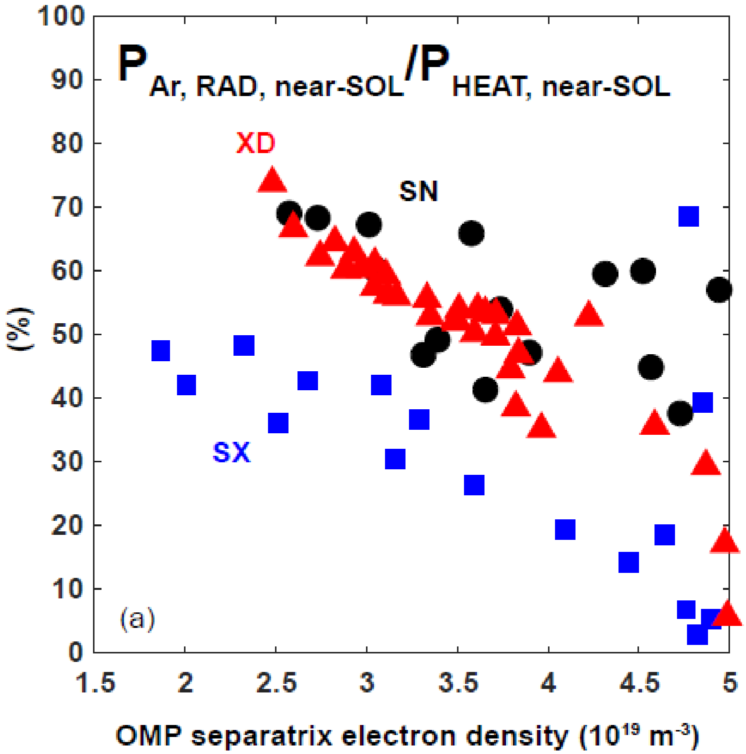
- For comparison with the Lengyel model:
- $q_{||}$: The effective heat flux entering the LFS divertor calculated by including the dissipated power between the X-point and the outer mid-plane (OMP)
- c_{Ar}: Argon concentration is taken as an average between the X-point and the outer mid-plane between 0 and 1 mm from the separatrix measured at the OMP
- $n_{e,SEP}$: Upstream separatrix electron density used

The Lengyel model overpredicts the argon concentration for LFS divertor detachment in EU-DEMO by a factor of 5 – 10 relative to SOLPS-ITER

- The standard Lengyel model would predict no solution within acceptable range of upstream argon concentration
- Fortunately, SOLPS-ITER indicates that an operational space does exist in the range of $n_{e,SEP}$ lower than 60% of n_{GW} and c_{Ar} < 1%.
- Due to the variation of connection length between the configurations, the Lengyel model predicts lower c_{Ar} for SX and XD than for SN, which looks qualitatively consistent with SOLPS-ITER.
  - However, the Lengyel model might not predict this result based on right reasons!

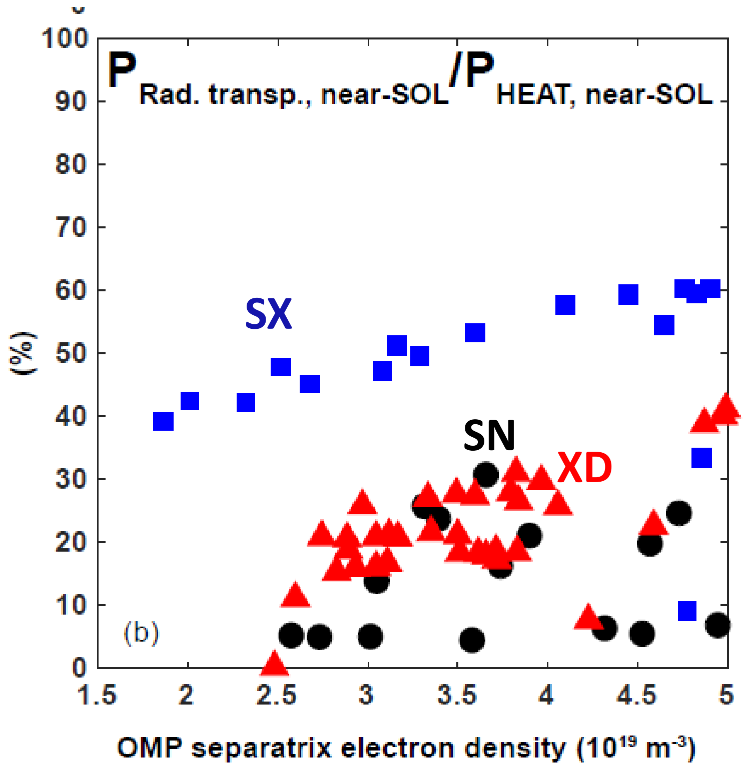


In the SN and XD configurations, argon radiation provides only 40 – 60% of the total radiation in the LFS near-SOL and in the SX as little as 20 – 40%



- While the standard assumption in applying the Lengyel model is that most of the dissipation is due to the primary radiating impurity, the SOLPS-ITER simulations indicate that only 40 – 60% of dissipation in the SN and XD configurations and 20 – 40% in the SX configuration is due to argon radiation.
- This would already reduce the c_{Ar} prediction by the Lengyel model by a factor of 2 – 4.
- For the LFS near-SOL, cross-field transport is the dominant competing process (next slide)

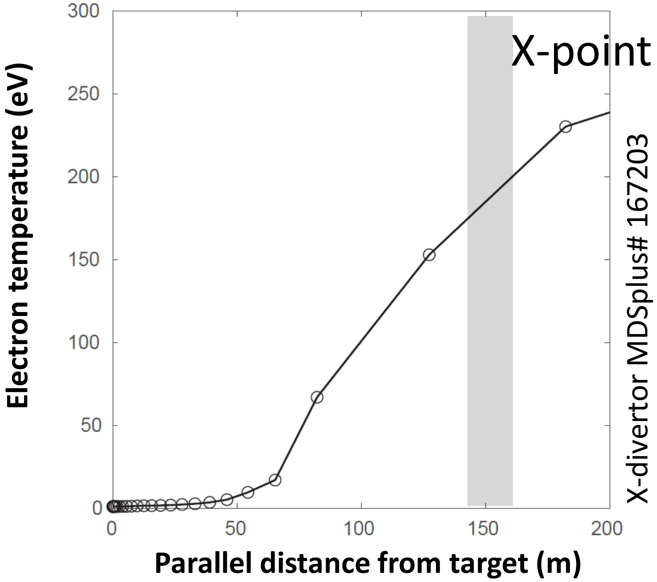
The primary dissipation mechanism competing with argon radiation in the LFS near-SOL is cross-field transport

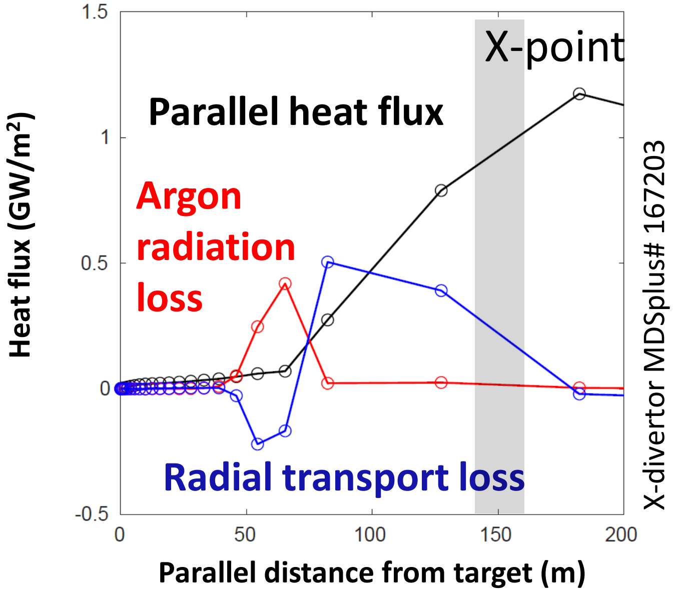


- The SX configuration is predicted to have a factor of 2 larger cross-field transport loss than the XD and SN configurations
- The total surface area of common SOL - PFR boundary in LFS is about 80 m^2 in SN, 130 m^2 in XD, and 280 m^2 SX.
- Coupled with a plasma solution in SX that maintains most of the near-SOL divertor leg plasma above 20 eV, leads to large radial transport losses of heat
- Electron cooling due to recycling processes is around 10 – 20% and the remaining heat loss is due to other processes, such as CX

The SOLPS-ITER simulations indicate that a significant fraction of the heat arriving to the argon radiation zone is transported by convection or cross-field

- The basic assumption of the Lengyel model that the radiation front is powered by heat conduction only is in conflict with the SOLPS-ITER predictions
- Example for a flux tube near the separatrix in LFS for an X-divertor case in Figures below. **Radial transport source** from nearby flux surfaces is powering the **argon radiation zone**.





The SOLPS-ITER simulations indicate that a significant fraction of the heat arriving to the argon radiation zone is transported by convection or cross-field

- For the entire database investigated here:
  - Most of the argon radiation in near-SOL LFS occurs at plasmas at T_e < 20 eV. (SN / XD about 80%, SX about 60%)
  - In these temperatures, only about 50% of the radiated power is powered by parallel electron heat conduction.
  - The end result is expansion of the radiative volume and enhanced total radiation for a given impurity concentration relative to models assuming electron heat conduction only
  - Including the cross-field and convective effects systematically would be needed for the simple models to actually capture the radiative dissipation appropriately.
  - It remains to be seen in future studies how much the model can be reduced from the full complexity of SOLPS-ITER, while still capturing these effects.
    - Convective processes for example have been included in Kallenbach PPCF 2016 [8].
    - Also surrogate modelling and reduced model development through ML/AI methods may prove to offer a promising way forward [Wiesen FO35(J) & Dasbach P038(G) this conference]

The Lengyel model lacks fundamental physics mechanisms relevant for the LFS divertor dissipation and its scaling between conditions and configurations

- The Lengyel model overpredicts the argon concentration for LFS divertor detachment in EU-DEMO by a factor of 5 – 10 relative to SOLPS-ITER simulations
- The simulations indicate that in the LFS near-SOL other dissipative mechanisms, such as cross-field heat transport, can reduce the argon radiation contribution by a factor of 2 – 4.
    - Obviously, the impact of the cross-field heat transport depends on the assumptions made with the user-specified transport coefficients
- The simulations indicate that the Lengyel model type assumption of the radiative front powered only through parallel heat conduction can be highly inaccurate and lead to a significant underprediction of the radiative volume and total radiation for a given impurity concentration

References

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