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

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25th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, June 13 – 17, 2022, Korea

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

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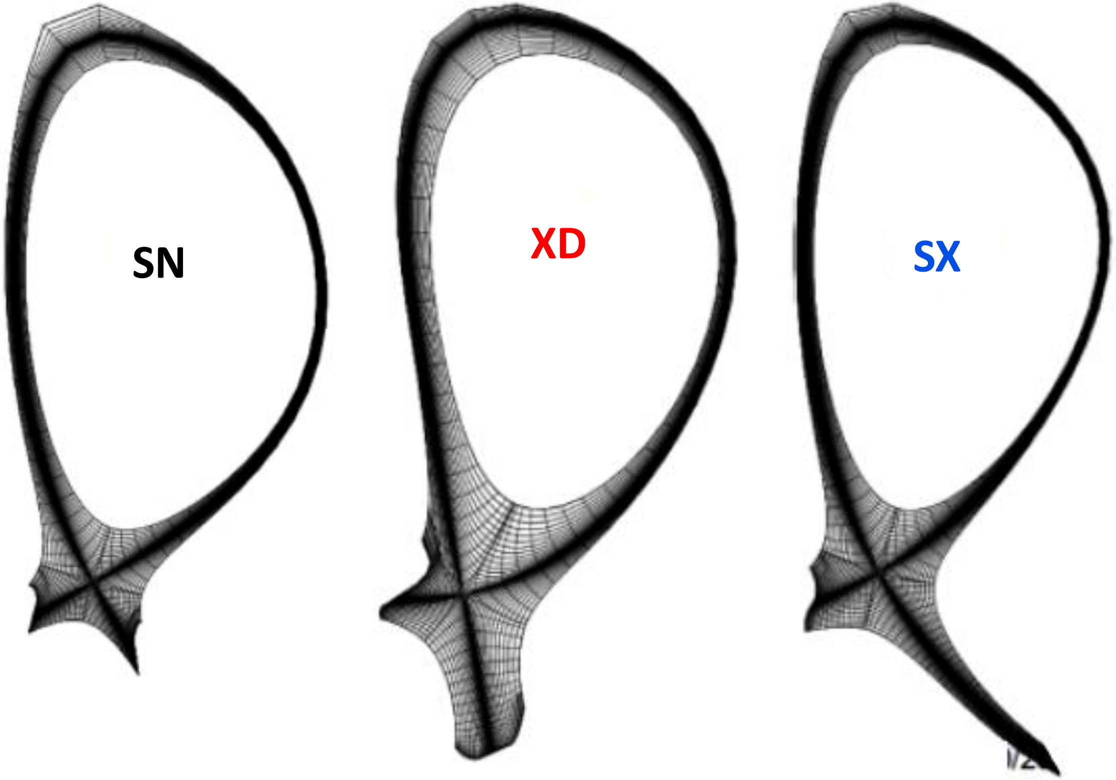
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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

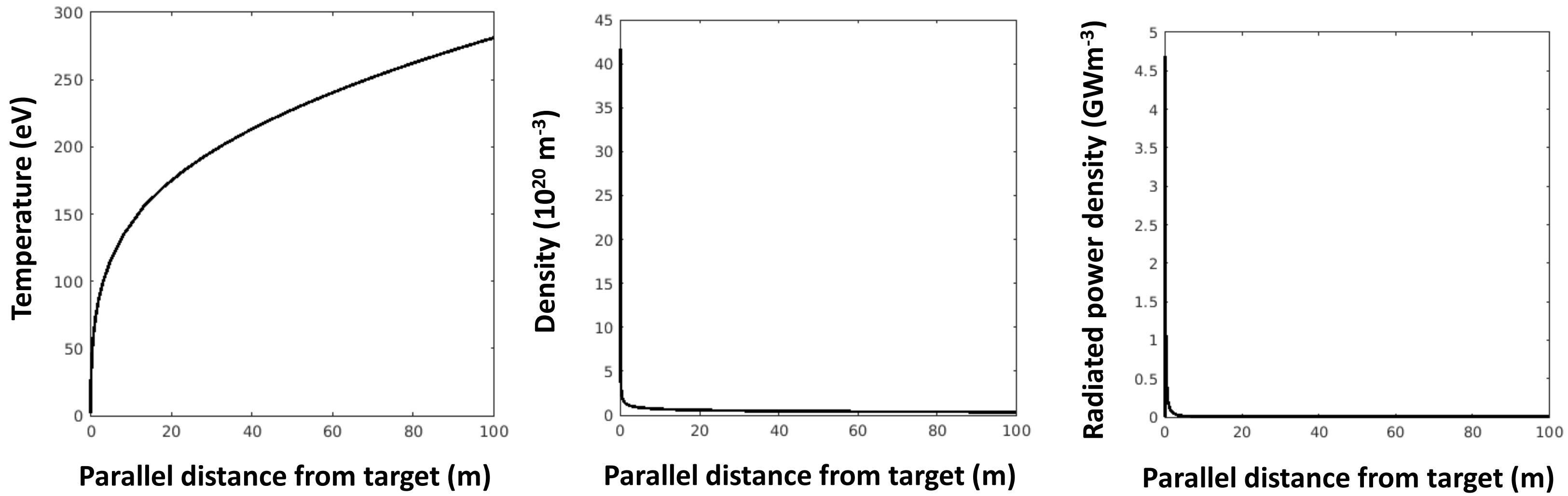
- Power exhaust is one of main challenges faced by fusion reactors

- 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].



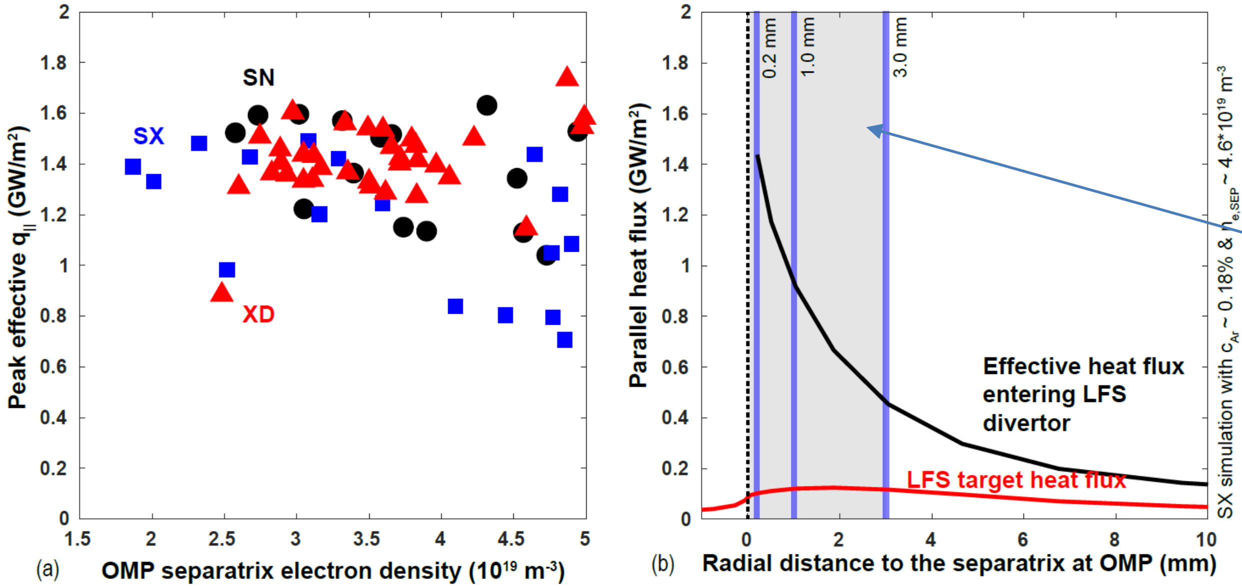
SOLPS-ITER grids of the investigated configurations [1]

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

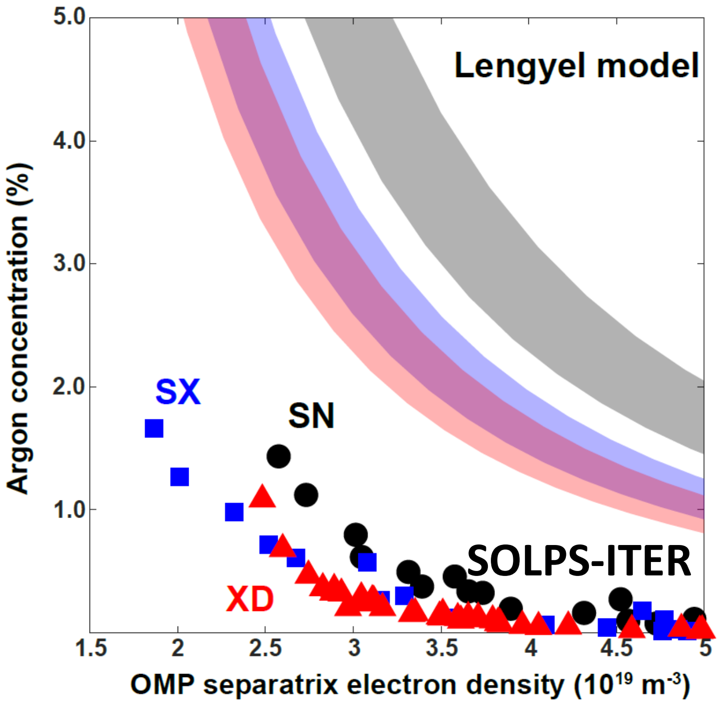


Power balance calculations (slides 6 – 7)
Focus on the LFS near-SOL: 0 – 3 mm from separatrix

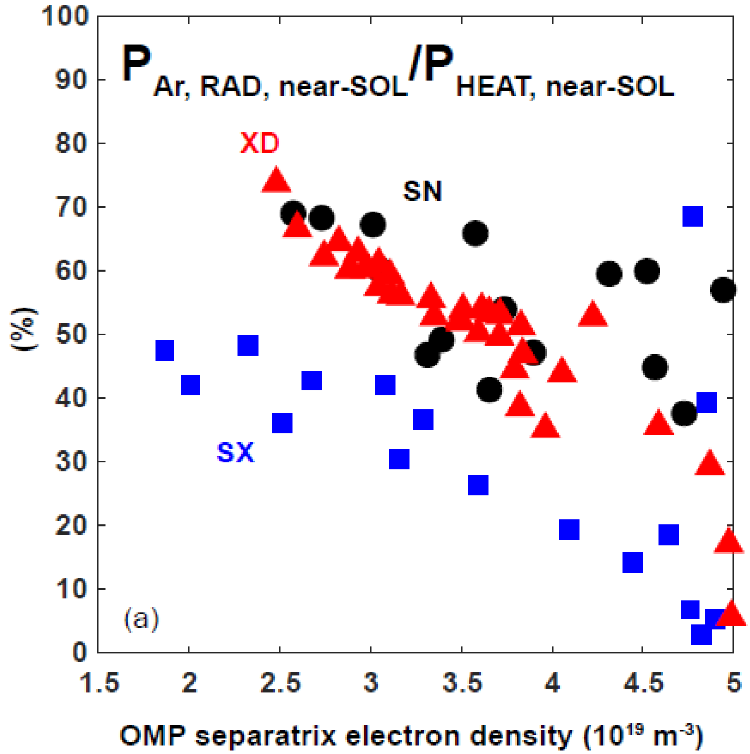
- For comparison with the Lengyel model:
- $q_{||}$: The effective heat flux entering the LFS divertor calculated by including the dissipated power between the X-point and the outer mid-plane (OMP)
- c_{Ar}: Argon concentration is taken as an average between the X-point and the outer mid-plane between 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!

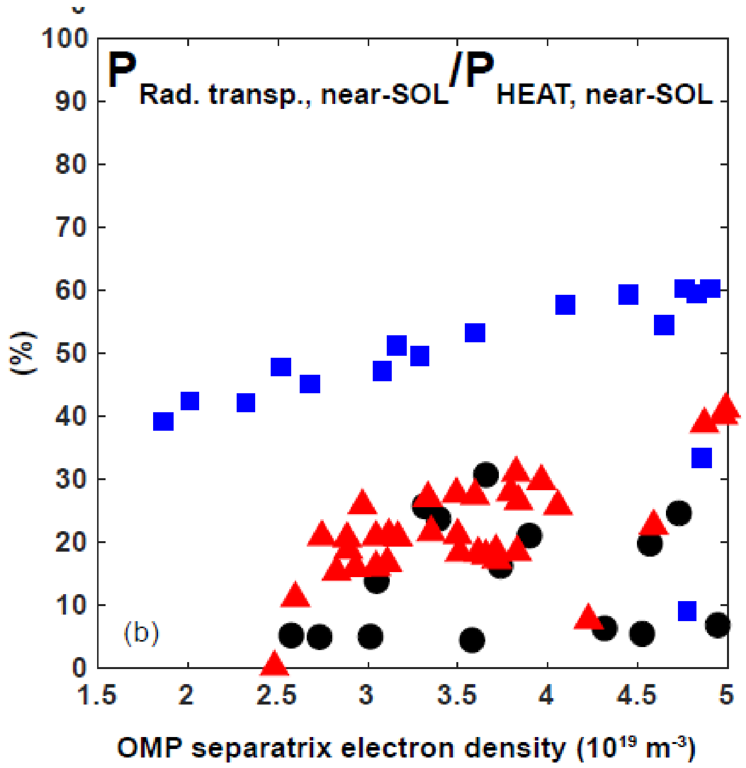


In the SN and XD configurations, argon radiation provides only 40 – 60% of the total radiation in the LFS near-SOL and in the SX as little as 20 – 40%



- 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)

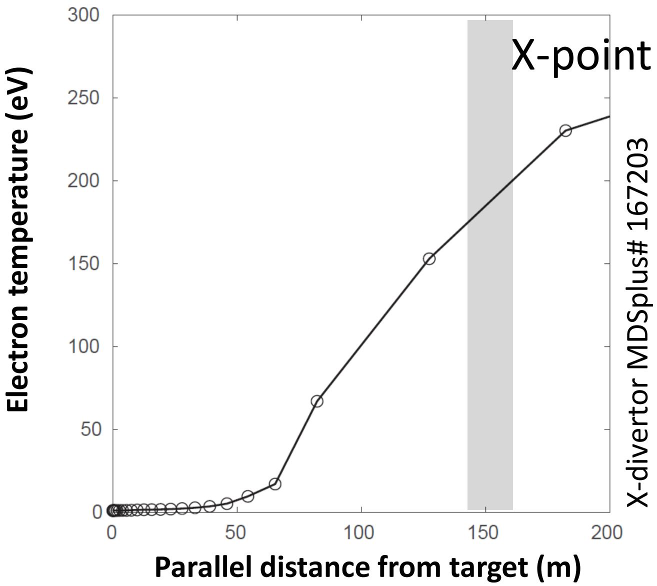
The primary dissipation mechanism competing with argon radiation in the LFS near-SOL is cross-field transport

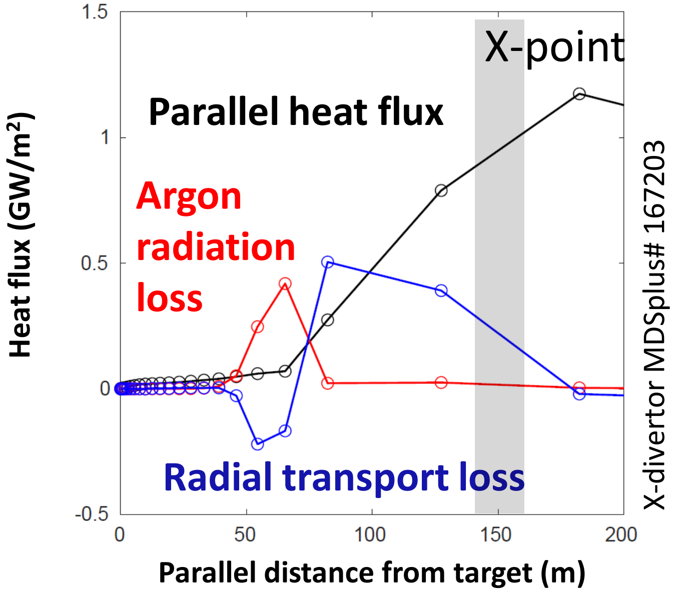


- The SX configuration is predicted to have a factor of 2 larger cross-field transport loss than the XD and SN configurations
- The total surface area of common SOL - PFR boundary in LFS is about 80 m^2 in SN, 130 m^2 in XD, and 280 m^2 SX.
- Coupled with a plasma solution in SX that maintains most of 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

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- **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].**

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.
- 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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