Parametric scaling of power exhaust in EU-DEMO SOLPS-ITER simulations

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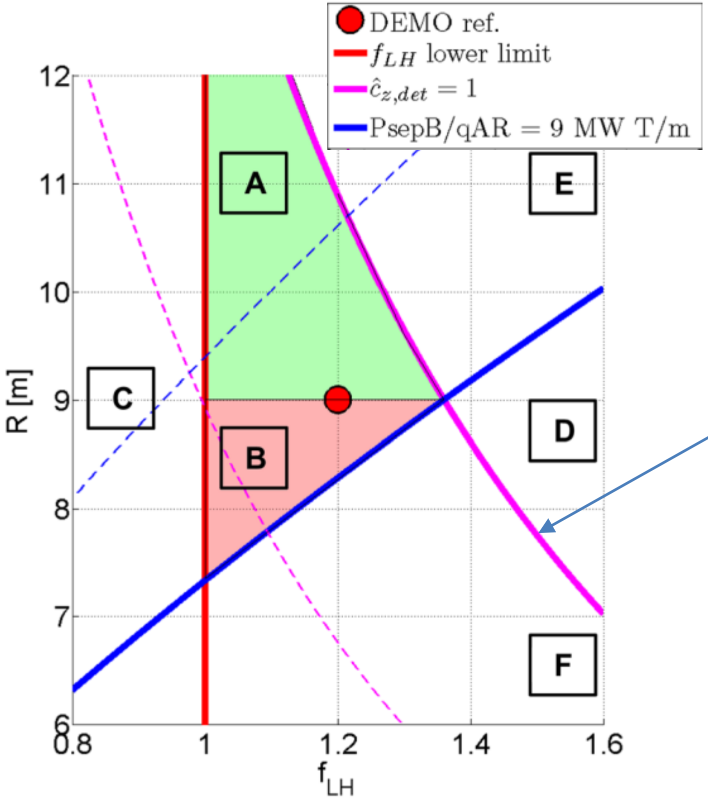
Any viable fusion power plant must integrate sustainable power exhaust with high fusion performance core



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- With a given configuration and core scenario (P_{LH}, f_{GW}), detachment is primarily controlled by the concentration of impurities in the SOL, c_z
  - ➢ Excess c_z is in conflict with core scenario needs (dilution & radiation)
- To address the need to scale c_z with other scenario and configuration parameters, several simple models have been developed. These are mostly based on Lengyel integral dissipation calculations.

➢ **How valid/reliable are the assumptions applied in these simple models?**

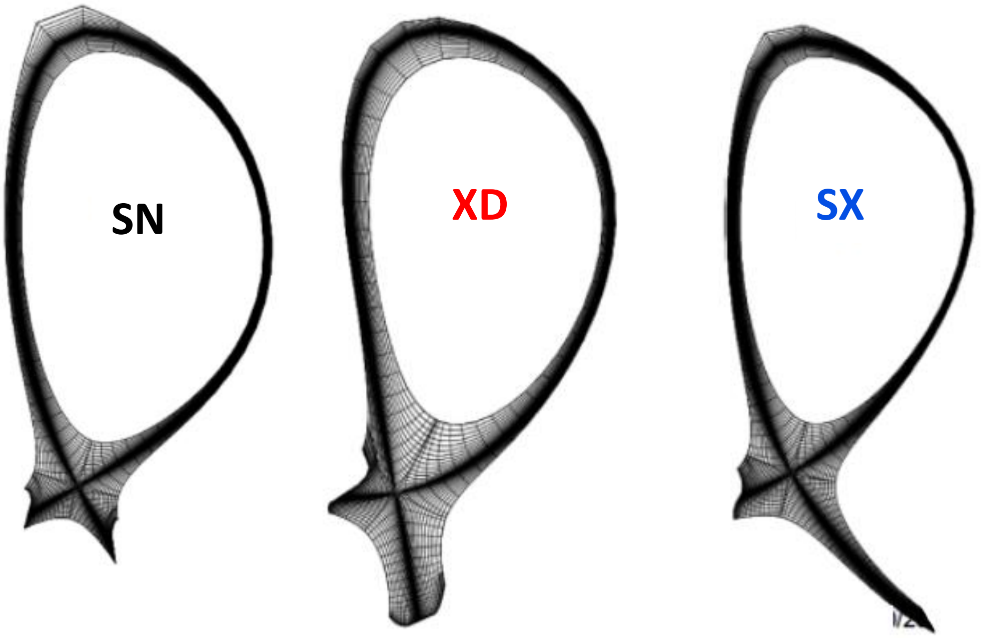
➢ **Even if not fully valid, are these simple models still useful?**

L. Lengyel, IPP Report 1/191, 1981
A. Kallenbach et al. PPCF 2016
M. Reinke NF 2017
R. Goldston et al. PPCF 2017
B. Lipschultz et al. NF2016
D.E. Post JNM 1995

The SOLPS-ITER database of EU-DEMO for single-null (SN), X-divertor (XD), and Super-X (SX) has been investigated and compared to simple model predictions

- SOLPS-ITER database, generated through EUROfusion ADC studies, is investigated here focusing on **single-null (SN)**, **X-divertor (XD)**, and **Super-X (SX)** [1 – 6].
- The investigated database:
  - No drifts
  - Fluid neutrals
  - 150 MW input power divided equally between electrons and ions
  - D_2- and Ar-injection scans (He also in the simulations)
  - Ar bundled to 3 species:
    1. Neutral argon
    2. Ar ions not fully ionized
    3. Fully ionized Ar

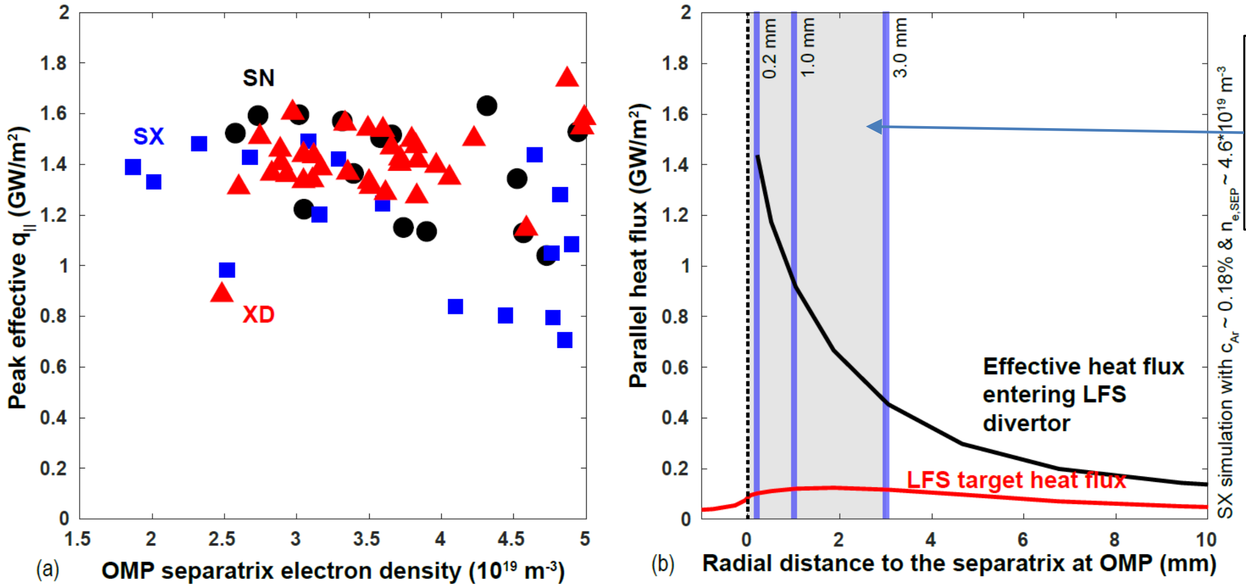
F. Subba Poster on Monday



SOLPS-ITER grids of the investigated configurations [1]

[1] F. Militello WP-DTT1/ADC (2014-2020) report, 2021
[2] H. Reimerdes NF 2020
[3] L. Xiang NF 2021
[4] L. Aho-Mantila NME 2021
[5] F. Subba NME 2017
[6] F. Subba PPCF 2018

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



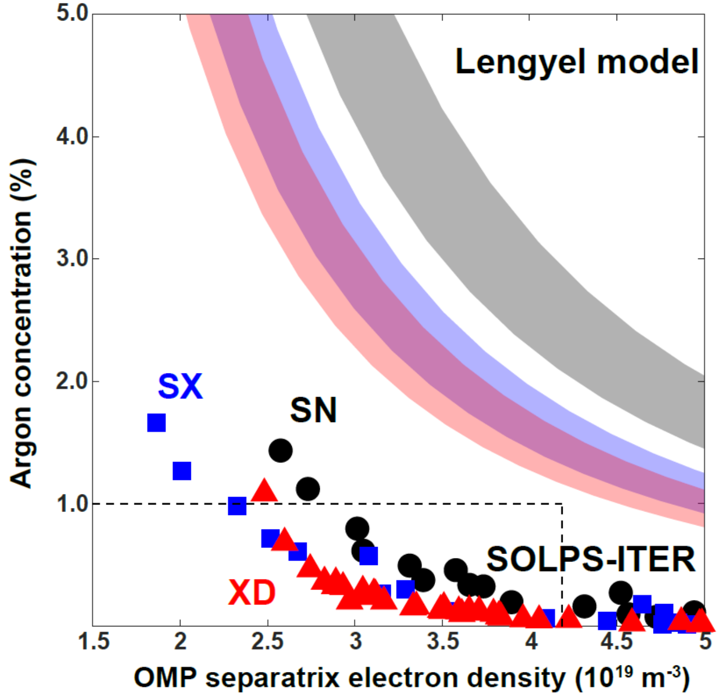
Focus on the LFS near-SOL: 0 – 3 mm from separatrix

Only including simulations with:

- $q_{targets,max}$ < 5 MW/m²
- $T_{e, targets, max}$ < 5 eV
- $n_{e, OMP, sep}$ < 5*10^{19} m^{-3}
- c_{Ar} < 2%

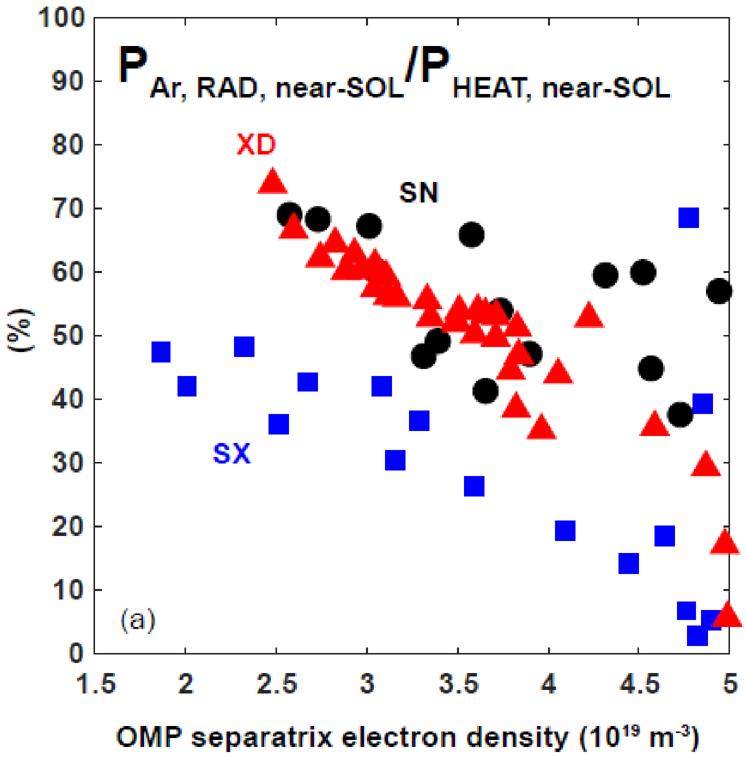
- For comparison with the Lengyel model:
  - $q_{||}$: The effective heat flux entering the LFS divertor (includes dissipated power between OMP and X-point)
  - c_{Ar}: Average between OMP and X-point within 0 - 1 mm flux tubes from the separatrix
  - $n_{e,SEP}$: OMP separatrix electron density

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



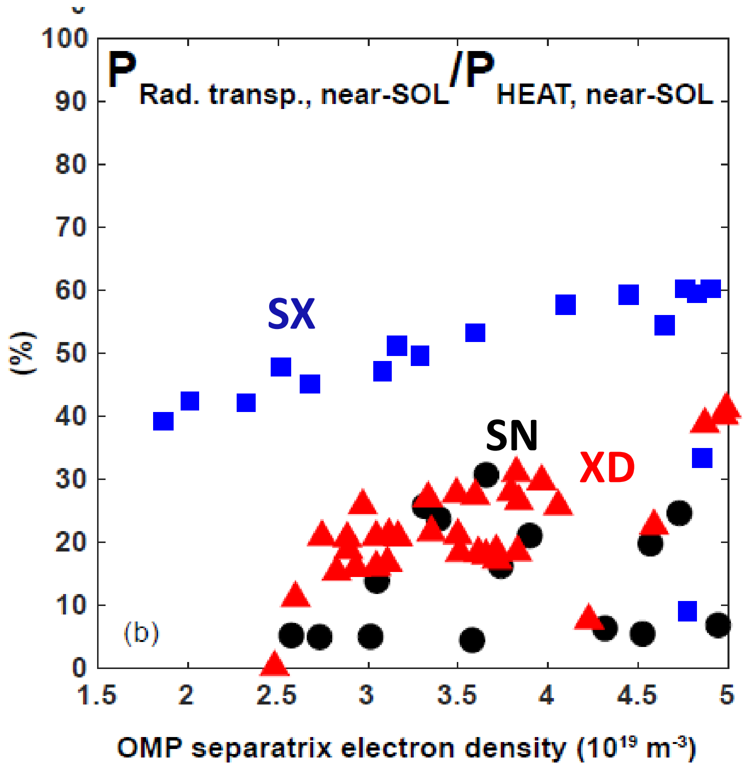
- Lengyel model would predict no solution within acceptable range of c_{Ar} (< 1%)
  - ➢ Consistent with R. Goldston et al. PPCF 2017 projecting very high impurity concentration for EU-DEMO
- However, SOLPS-ITER predicts detached solutions in the range of $n_{e,SEP} < 0.6 {*} n_{GW}$ and $c_{Ar} < 1\%$
- Due to increase of L_{CONN} from SN to SX and XD, Lengyel model predicts lower c_{Ar} for these ADCs, which is qualitatively consistent with SOLPS-ITER
  - ➢ **However, the Lengyel model is likely to predict this result based on different reasons than SOLPS-ITER!**

A factor of 2 – 4 lower c_{Ar} relative to Lengyel model is explainable by dissipation through other processes than Ar radiation in SOLPS-ITER



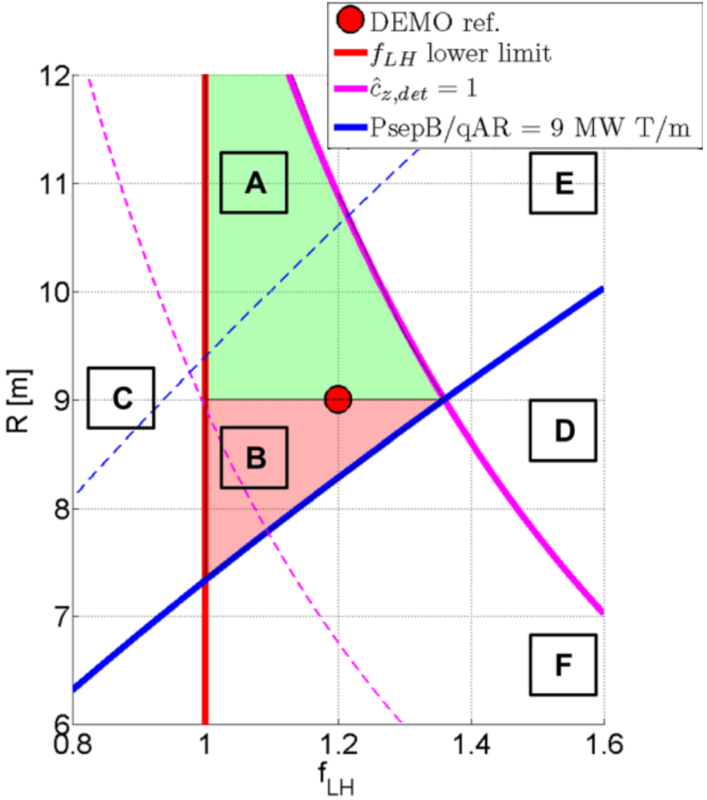
- The standard Lengyel model assumes that the dissipation is strongly dominated by the primary radiating impurity
- SOLPS-ITER simulations show Ar radiation contributing only 40 – 60% of dissipation in the SN and XD configurations and 20 – 40% in the SX configuration in the LFS near SOL

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



- SX is predicted to have x2 larger cross-field transport heat loss than the XD and SN
  - ➢ Proportional to the total surface area of SOL - PFR boundary in LFS: SN ~ 80 m^2, XD ~ 130 m^2, and SX ~ 280 m^2.
- SX maintains most of the near-SOL divertor leg plasma T_e > 20 eV (long leg with gradient in total field)
  - ➢ Large surface area and temperature gradient lead to heat significant heat transport to PFR in SX
- Obviously, this conclusion is subject to the uncertainty of the cross-field transport coefficients that user must specify in SOLPS-ITER
- Recycling processes provide the remaining heat loss of about 20%

What if we simply calibrate the Lengyel model with SOLPS-ITER to acknowledge the fact that some dissipation mechanisms are missing in the simple model?



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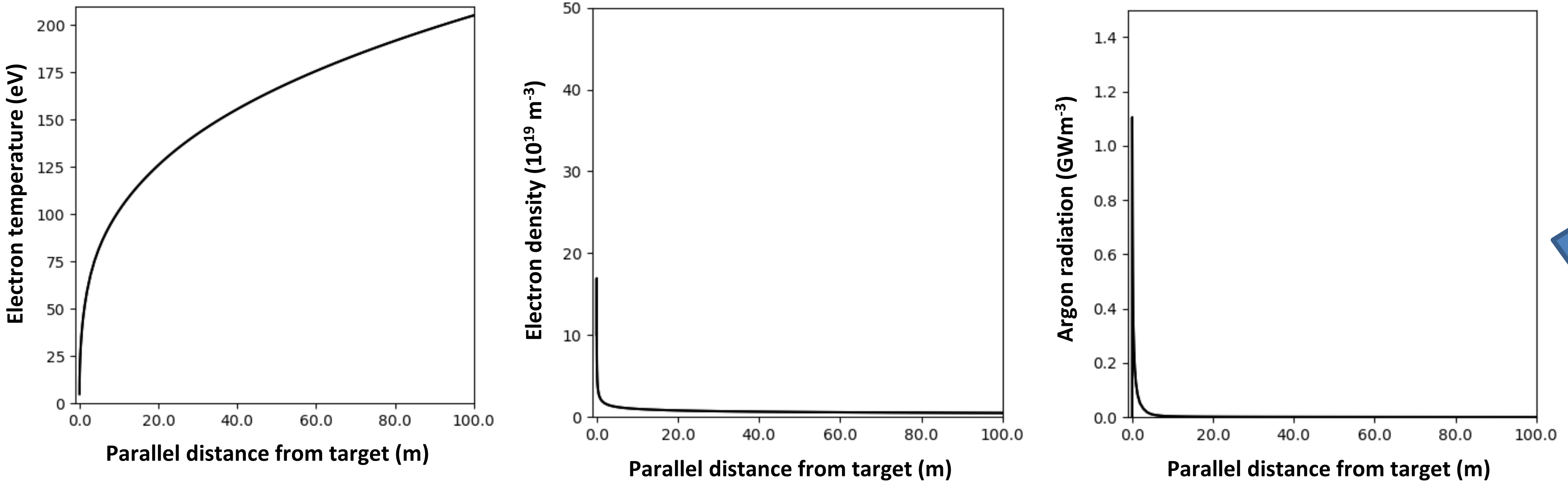
- This type of approach has been used for scaling of c_z for configuration and scenario parameters in EU-DEMO
- This is an OK approach, **if** Lengyel integral does give a reasonable approximation for scaling of Ar radiation with c_z
- The next few slides aim to convince you that Lengyel model **does not really approximate Ar radiation that well**

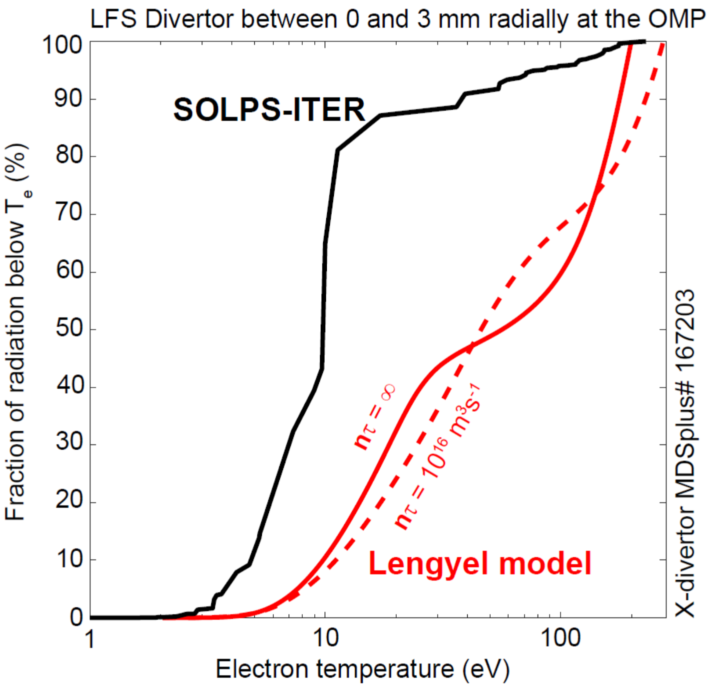
The Lengyel model uses simplified transport assumptions to relate SOL impurity concentration, upstream density, and heat flux to onset of detachment

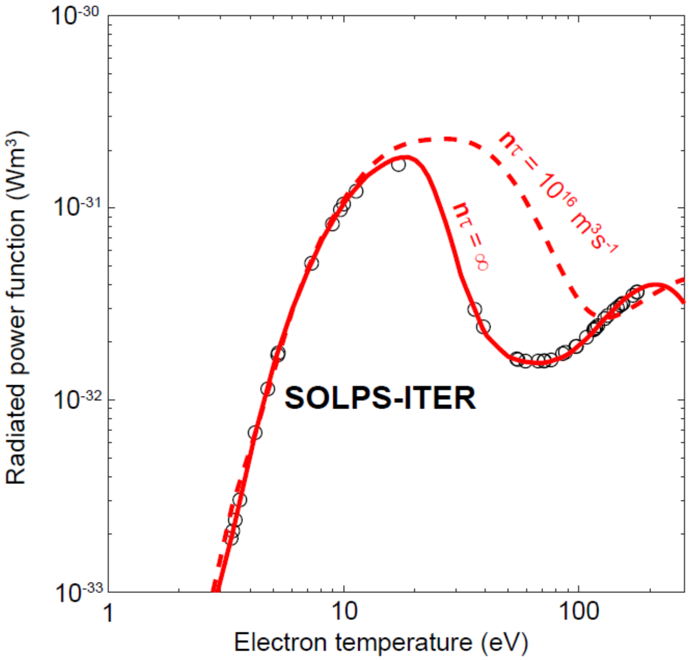


- Heat transported by electron heat conduction $q = -\kappa_0 T_e^{5/2} \nabla_{||} T_e$, Static pressure conserved along a flux tube, Conservation of c_Z along a flux tube
- **The strong T_e dependencies of heat conductivity and radiative cooling tend to generate spatially narrow radiation fronts in the Lengyel model → Spatial extent of radiating region in T_e < 15 eV is very low**

L. Lengyel, IPP Report 1/191, 1981

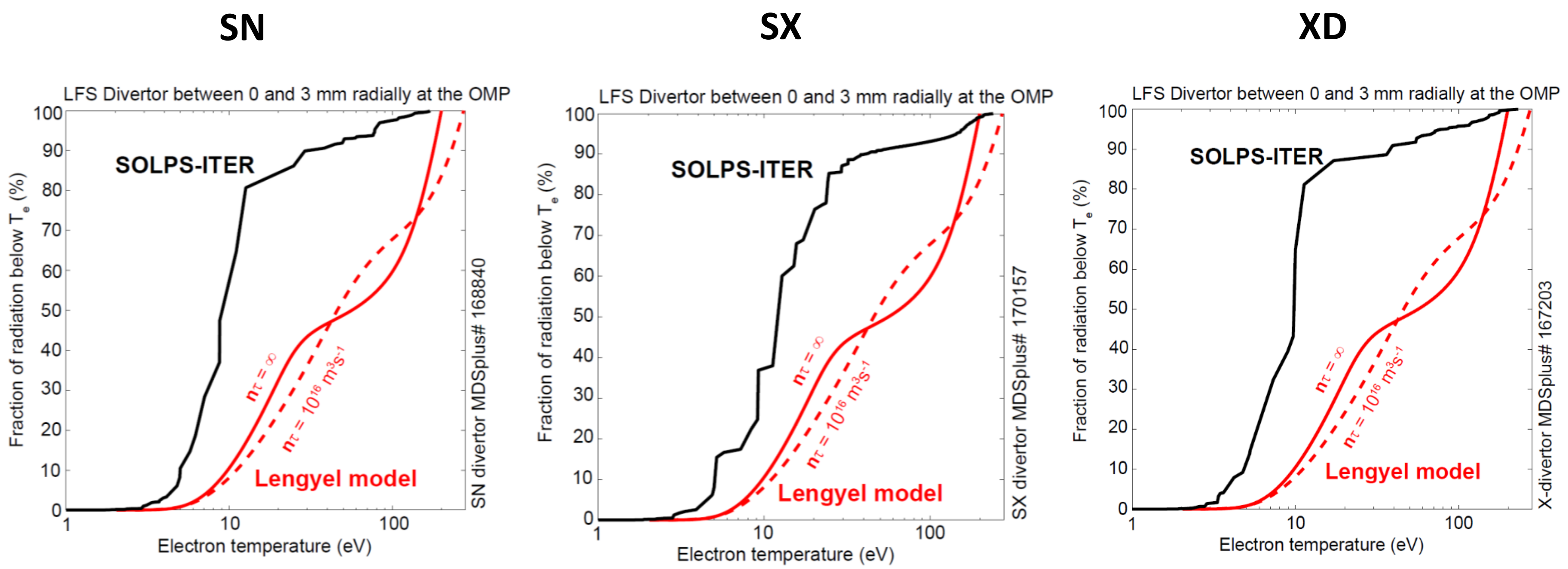
SOLPS-ITER predicts nearly 85% of LFS divertor near SOL Ar radiation to occur in T_e < 11 eV, c.f. Lengyel model less than 30%





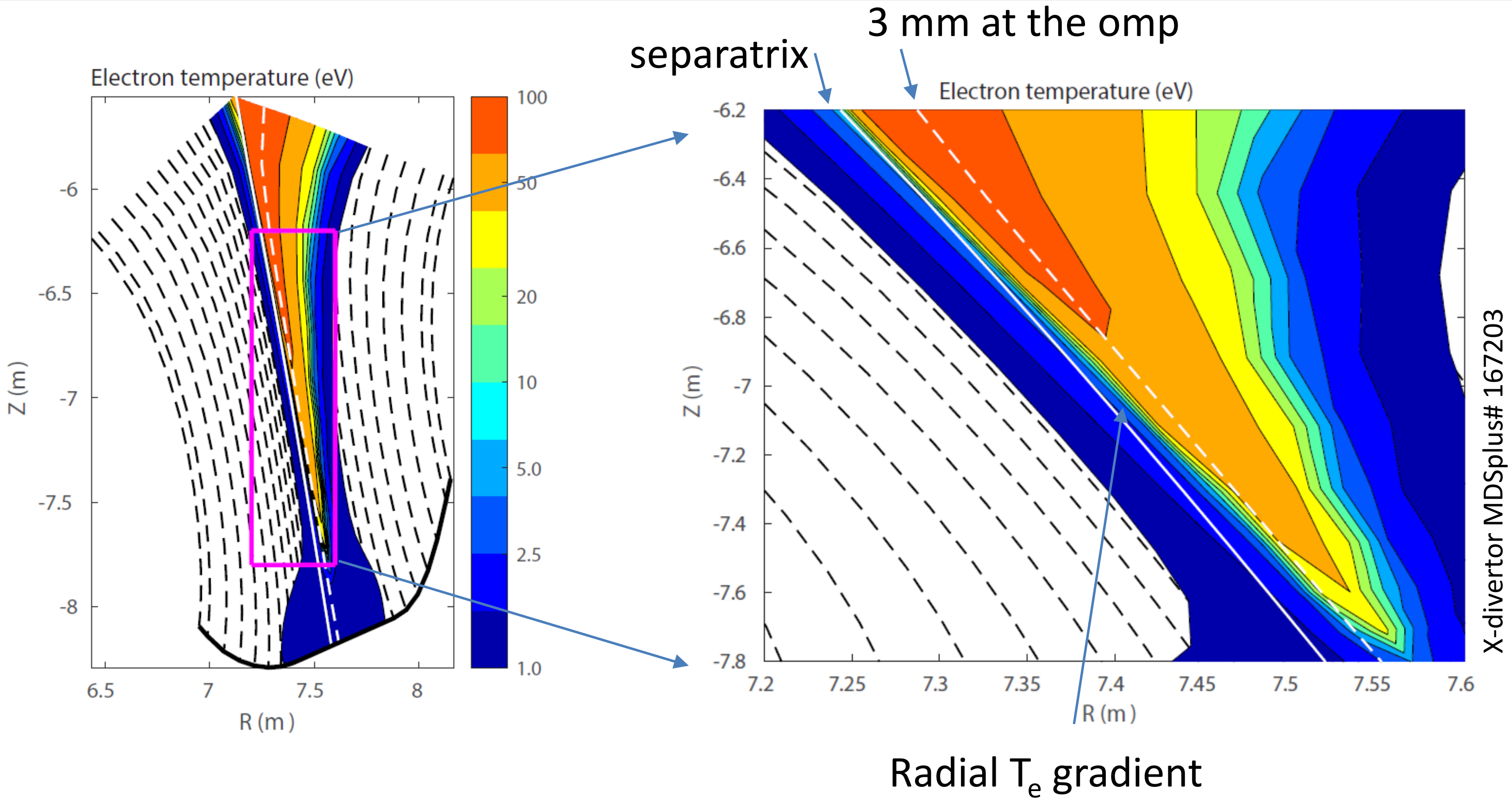
- **Even with non-equilibrium cooling rates, Lengyel model underpredicts the total radiation in T_e between 5 – 11 eV, because the spatial extent of these T_e values is negligible in Lengyel model predictions**
- Due to the 3-fluid bundling scheme, the Ar rates represent equilibrium in these SOLPS-ITER simulations

This result is consistent between the three investigated divertor configurations

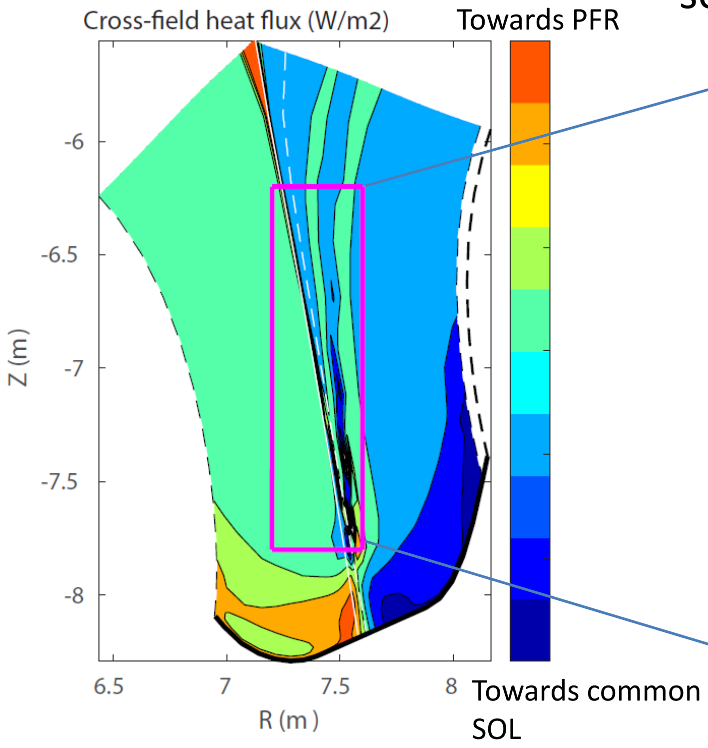


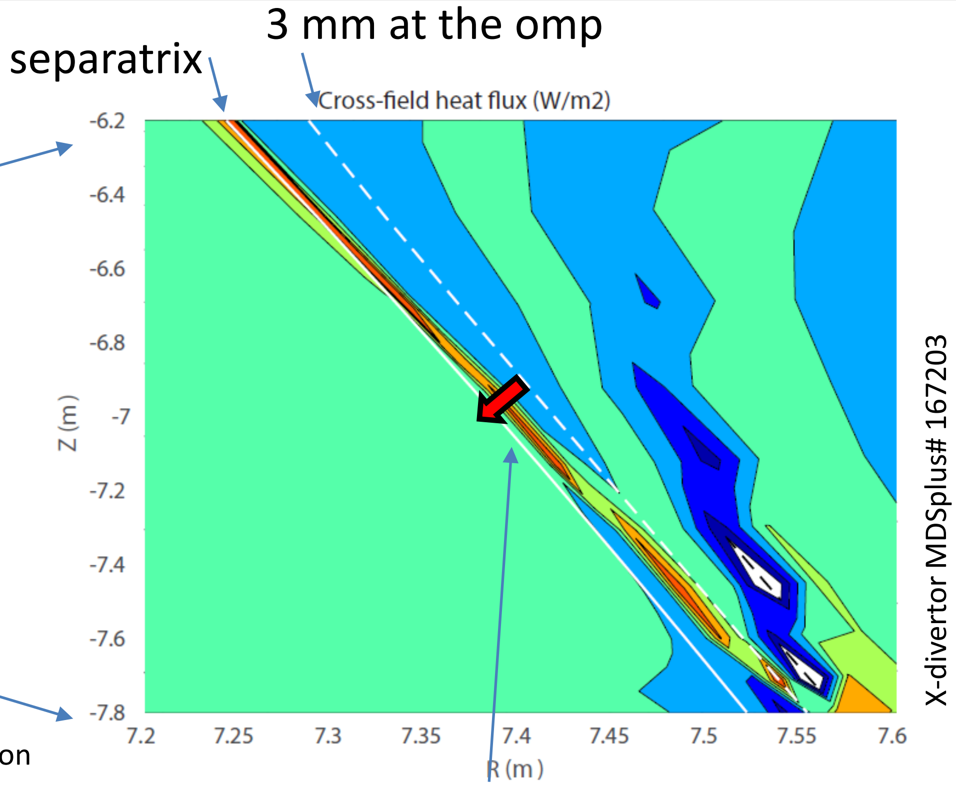
*Reserve slide for database wide figures

In the LFS divertor leg near SOL, the field line close to the separatrix cools first, leading to a radial T_e gradient in near SOL



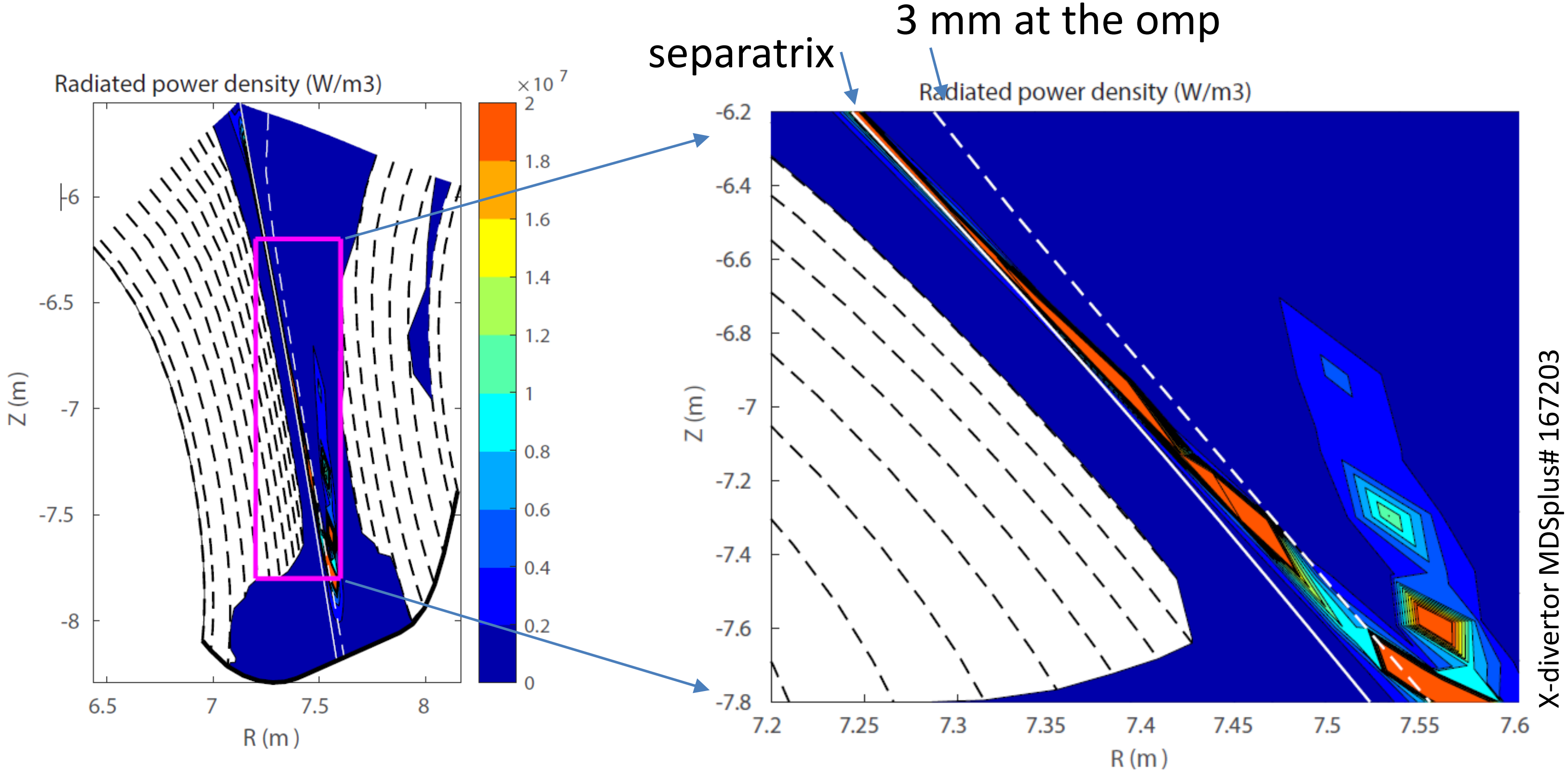
The radial T_e gradient in near SOL leads to radial transport of heat from common SOL towards the field lines near the separatrix



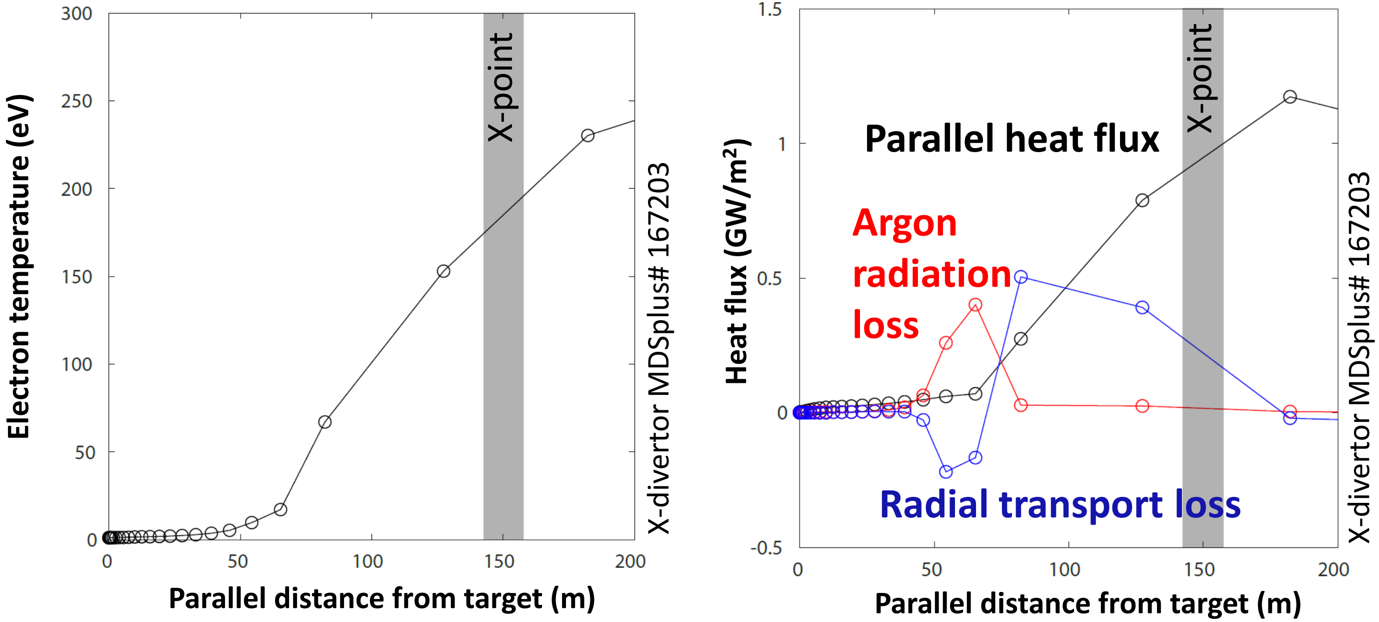


Radial heat flux

This is the same region where most of the divertor argon radiation takes place



The end result is strong argon radiation in relatively low T_e regions, without a Lengyel model like collapse of T_e



- The basic assumption of **heat conduction dominated power flow** to the radiation front **is just not consistent** with these SOLPS-ITER simulations

Strong convective flows (parallel & E×B) have also been observed in present-day tokamaks

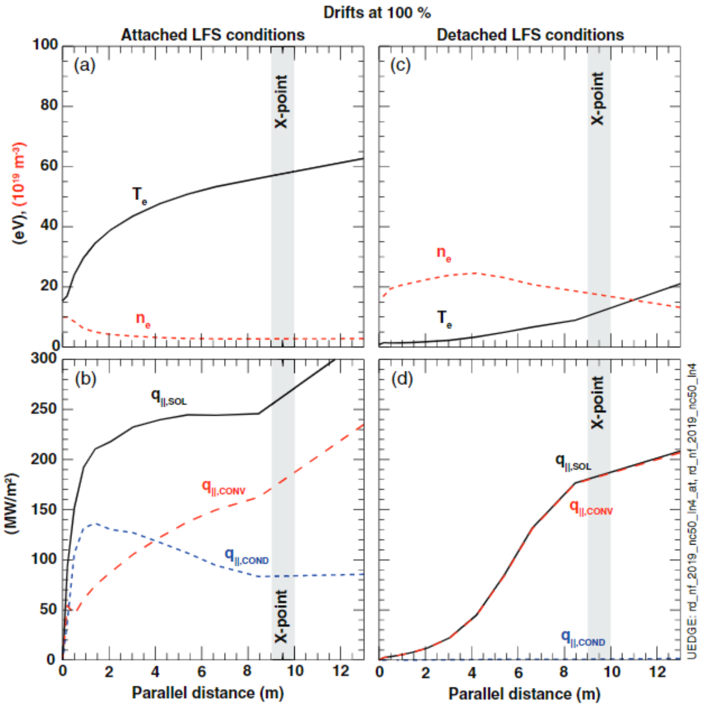


FIGURE 2 Same profiles as in Figure 1 for UEDGE simulations with full drifts. Predicted low field side (LFS) divertor plasma electron temperature (black solid line) and density (red dashed line) in attached (a) and detached (c) LFS conditions with full drifts, as well as predicted total (black solid line), conducted (blue dashed line), and convected (red dashed line) heat fluxes along the separatrix in LFS divertor in attached (b) and detached (d) LFS conditions. The *x*-axis represents parallel distance near the separatrix from the LFS target. The grey-shaded area illustrates the poloidal location of the X-point

CPP 2019

https://doi.org/10.1002/ctpp.201900111

A. Leonard Poster on Tuesday

VOLUME 78, NUMBER 25 PHYSICAL REVIEW LETTERS 23 JUNE 1997

Distributed Divertor Radiation through Convection in DIII-D

A. W. Leonard, M. A. Mahdavi, S. L. Allen,* N. H. Brooks, M. E. Fenstermacher,* D. N. Hill,* C. J. Lasnier,* R. Maingi,† G. D. Porter,* T. W. Petrie, J. G. Watkins,‡ and W. P. West
General Atomics, P.O. Box 85608, San Diego, California 92186-5608
(Received 24 February 1997)

The radiative dissipation of divertor target heat flux on DIII-D is shown to greatly exceed the limitations of energy transport dominated by electron thermal conduction parallel to the magnetic field. More than 80% of the power flowing into the outboard divertor is dissipated through radiation with a broad poloidal profile. It is shown that energy transport dominated by convection over a large region of the divertor is consistent with the data. [S0031-9007(97)03465-0]

PACS numbers: 52.55.Fa

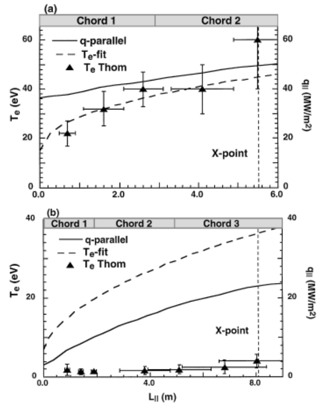


FIG. 2. The outboard divertor energy flux analysis for (a) standard ELMing H mode and (b) radiative divertor through deuterium puffing. Shown are the energy flux profile, $q_\|$, the fitted T_e profile for conduction dominated transport, and measurements of T_e from divertor Thomson scattering measurements. Shown at the top of the graphs are the approximate view locations of the horizontal viewing bolometer chords.

However, Moulton et al. study for the ITER SOLPS4.3 database indicated that the Lengyel model can provide a remarkably good *scaling* for c_z

- **When the factor of 4.3 overprediction by Lengyel model was calibrated out, the scaling for c_Z was remarkably good**
- **Is this consistent with what is presented in this talk?**
- **I would argue that it is. Two main reasons:**
  1. **The radiator in those simulations is neon, for which enhanced volumes in T_e ~ 5 – 10 eV do not make as big difference as for other radiators, such as Ar**
  2. **The study focuses only on the flux tube of highest target heat flux (3rd SOL flux tube) and it is quite likely that the role of the cross-field transport on the T_e profile is not as significant as on average flux tube within ~ λ_q**

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Comparison between SOLPS-4.3 and the Lengyel Model for ITER baseline neon-seeded plasmas

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CrossMark

Abstract

If correct, the Lengyel model offers a simple and powerful tool to predict the conditions required for detachment onset in future fusion reactors. We assess its validity against a comprehensive SOLPS-4.3 simulation database of ITER baseline ($Q = 10$) neon-seeded plasmas (Pacher *et al* 2015 *J. Nucl. Mater.* **463** 591). In absolute terms, the Lengyel Model is found to significantly overpredict the simulated impurity concentration required in the ITER outer divertor for outer target ion flux rollover (by a factor ~4.3 in this particular case). Importantly though, at detachment onset, and even beyond onset, the Lengyel model does give a remarkably accurate prediction of the *scaling* interdependencies between the electron density at the outer divertor entrance, the parallel energy flux density at the outer divertor entrance, and the impurity concentration in the outer divertor. However, the generalisation of these two key results to other machines, and in the presence of additional physics not included in these simulations, requires further studies. The analysis techniques described here provide a framework for such studies. Regarding the factor ~4.3 overprediction of the simulated outer

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It is possible for the Lengyel model to work quite well in certain circumstances.

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

- SOLPS-ITER simulations indicate that Ar radiation contribution is reduced by x2 – 4 in the LFS near-SOL due to other dissipation processes, e.g. cross-field heat transport

  - ➢ This discrepancy could still be partially resolved by calibrating Lengyel model with SOLPS-ITER simulations, **if Lengyel model would give a reasonable scaling for Ar radiation → However, this does not seem to be the case**

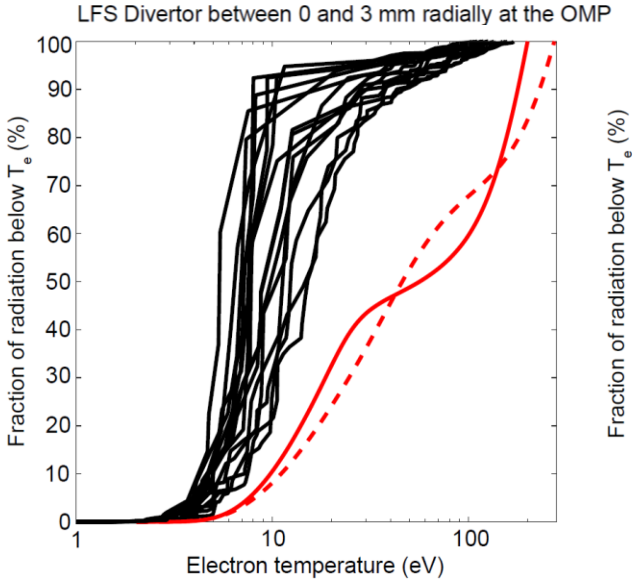
- **The simulations indicate that the assumption of the radiative front powered only through parallel heat conduction can be highly inaccurate and lead to a significant underprediction of the extent of radiating region and total Ar radiation**

The research on simple dissipation model development should critically evalute the assumption of heat conduction dominated transport in the radiation front. Research should focus on finding methods to go beyond this assumption.

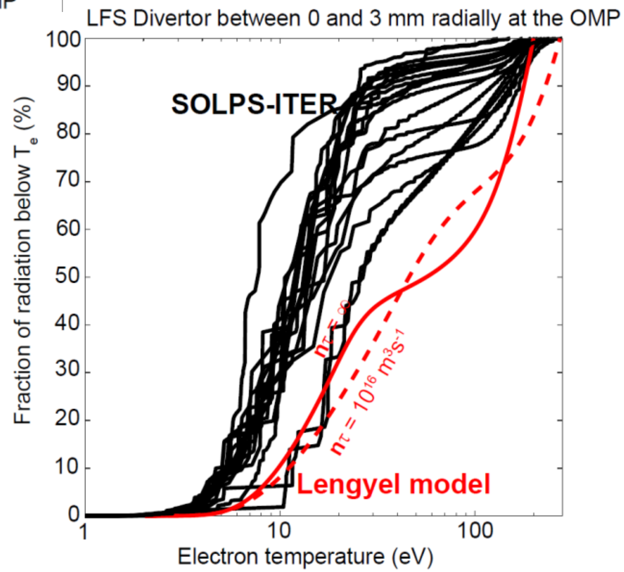
Having said that, we need scaling for c_Z. Calibrated Lengyel model is still better than no scaling. Sometimes this can even work quite well.

Throughout the investigated database, SOLPS-ITER predicts significantly stronger Ar radiation contributions in T_e < 11 eV than the Lengyel model

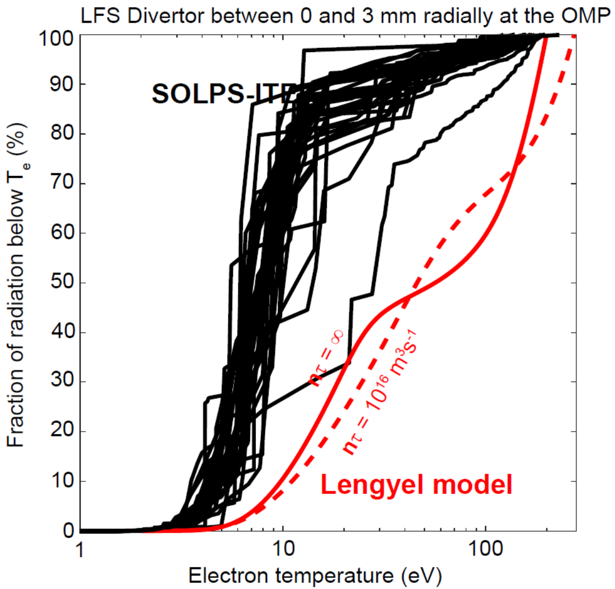
SN



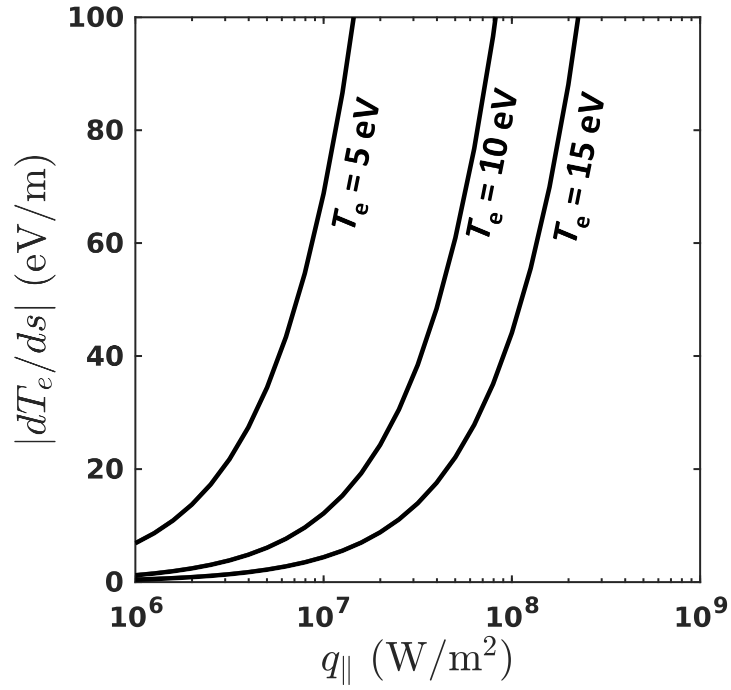
SX



XD



Due to the $T_e^{5/2}$-dependence, at T_e < 15 eV, dT_e/ds increases quickly to several 10 eV/m with increasing $q_{||}$ if heat conduction is assumed to dominate



$$\left|\frac{dT_e}{ds}\right| = \frac{q_{||}}{\kappa_0 T_e^{5/2}}$$

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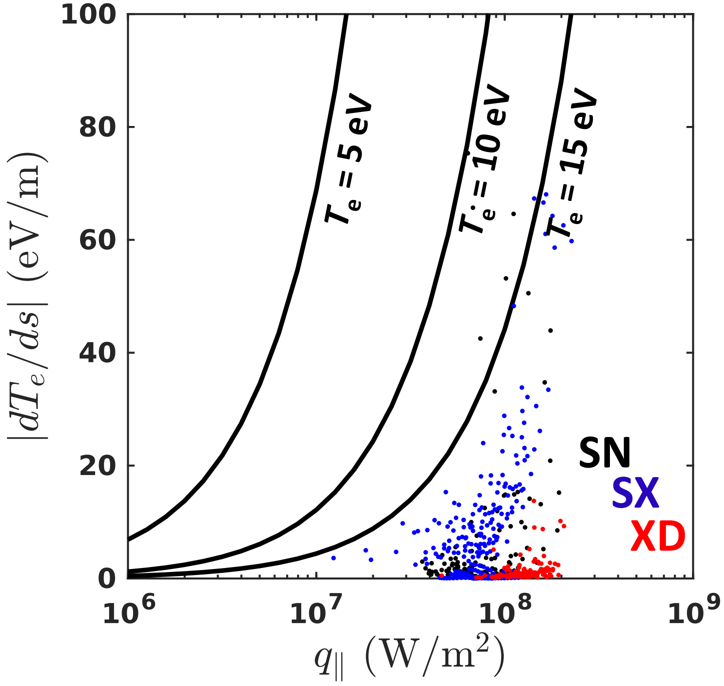

$$\left|\frac{dT_e}{ds}\right| = \frac{q_{||}}{\kappa_0 T_e^{5/2}}$$

- SOLPS-ITER shows significantly shallower gradients in T_e of 5 to 15 eV:
  - Mean for SN 3.9 eV/m
  - Mean for SX 20.9 eV/m
  - Mean for XD 1.3 eV/m

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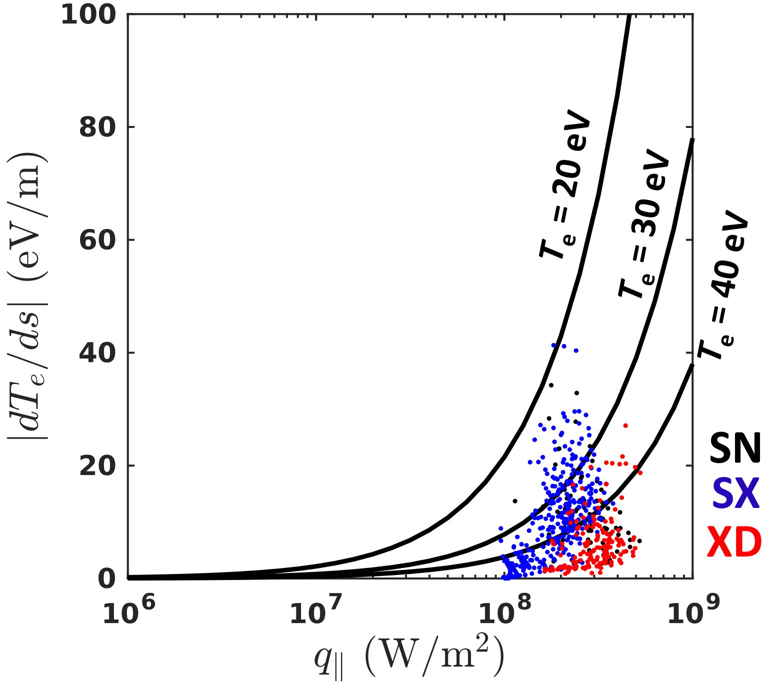

$$\left|\frac{dT_e}{ds}\right| = \frac{q_{||}}{\kappa_0 T_e^{5/2}}$$

- At T_e of 20 to 40 eV, the SOLPS-ITER values are not too far from
  - Mean for SN 10.4 eV/m
  - Mean for SX 12.0 eV/m
  - Mean for XD 6.2 eV/m

This is the same region where most of the divertor argon radiation takes place