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Kinetic Modelling of Parallel Transport in Tokamak Scrape-Off Layer

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1. Introduction

1.1 Tokamak

- Tokamaks are toroidal magnetically confined fusion devices.
- Inside, exists confined plasma which divides into two regions:

1. The "core", where the magnetic field lines are closed and lie on toroidal surfaces
2. The scape-off layer (SOL), beyond the core, where the lines are open and spiral onto the walls.

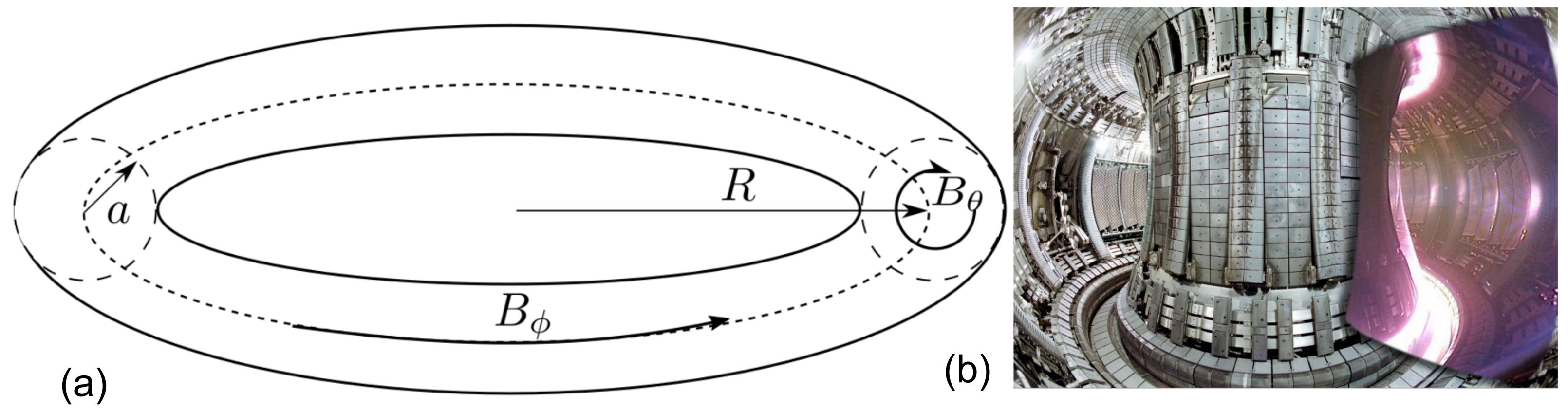


Figure 1 – (a) Schematic of magnetic fields in a tokamak. Toroidal B_φ and poloidal B_θ fields together confine the plasma. The minor and major radii of the tokamak, a and R respectively, are shown. [1] (b) JET tokamak both during (right) and after operation [7]

1.2 Divertor configuration

- Modern tokamaks operate in a poloidal divertor configuration, the divertor extracts heat and ash produced by the reaction
- Plasma in from the core which diffuses across the last closed flux surface (LCFS), will be on open flux surfaces which connect directly to the solid surface (divertor targets)

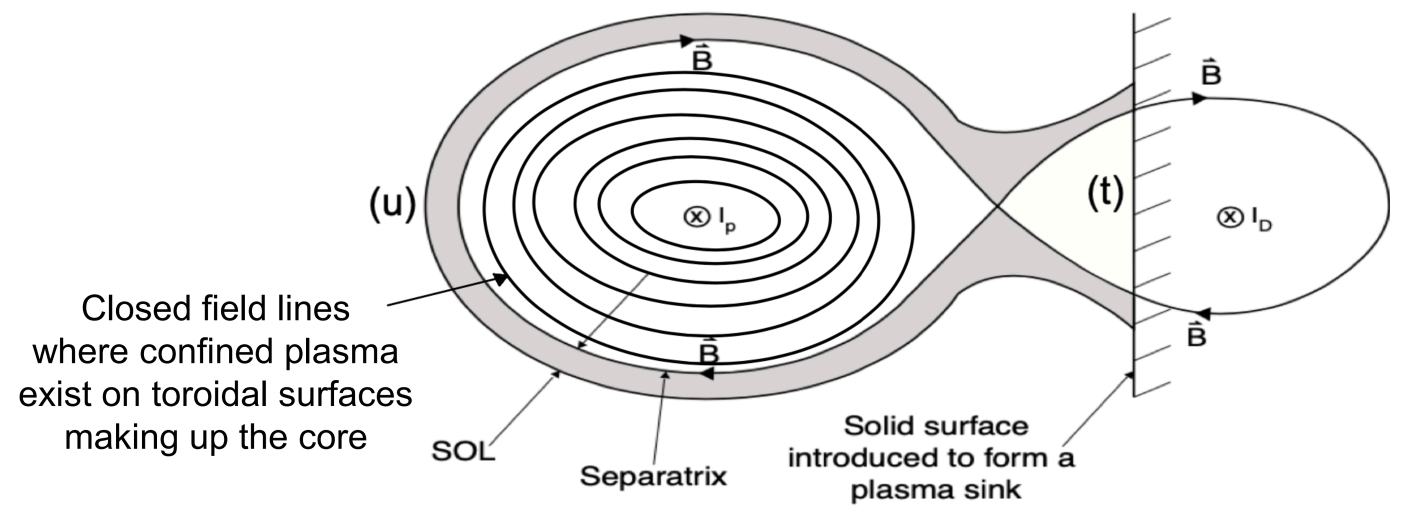


Figure 2. External conductors carrying current I_D and I_P create magnetic field lines in a figure-of-eight shape with targets at a significant distance from core to reduce contamination and dilution of fuel (adapted from [2])

2. Research Questions and Motivation

- Divertor targets are susceptible to heat-induced damage
- Routinely, fluid models are used when simulating energy transport in the SOL, however the predictions these models make are inconsistent with experimental data [1,3]
- We aim to introduce kinetic/non-local effects on parallel transport, to determine steady-state radial plasma density and temperature profiles and compare with published data from JET tokamak runs

3. Method

3.1 The two-point model (2PM)

- Although the kinetic model provides a more accurate representation of the transport of plasma in the SOL [3,4], it is computationally taxing to be including the full plasma picture and so a simpler model is required
- To achieve this, the SOL is straightened out along the field line and the system is viewed with reference to two points of interest, the upstream (u) and target (t)[1], Figure 3.

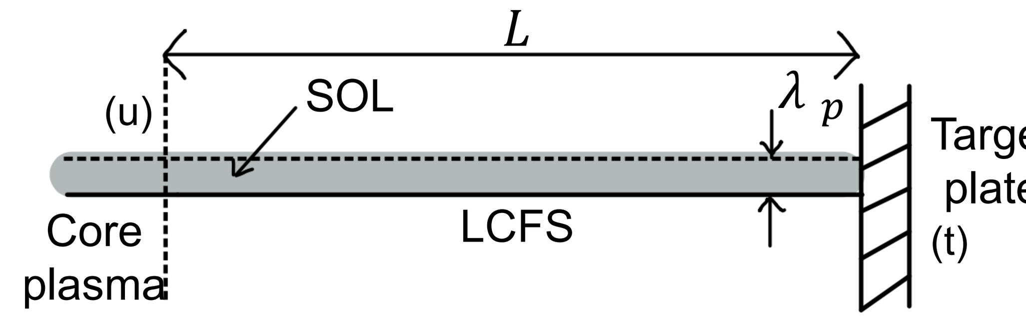


Figure 3. simplified schematic of SOL after stretching out into 1D system of length L

- Three main assumptions for the 2PM, *particle balance*, *pressure balance* and *power balance* lead to three simultaneous equations with three unknowns
- Where n_t is target density, T_u and T_t are upstream and target temperature respectively; with controlled variables $q_\parallel$ (parallel conductive heat flux) and upstream density n_u

$$2n_t T_t = n_u T_u \quad (3.1)$$

$$T_u^{7/2} = T_t^{7/2} + \frac{7}{2}\frac{q_\parallel L}{\kappa_{0e}} \quad (3.2)$$

$$q_\parallel = \gamma n_t k T_t c_{st} \quad (3.3)$$

Where k_{0e} is the electron conductivity, γ is the sheath heat transmission coefficient and C_{st} is the ion sound speed [2]

3.2 2PM relations

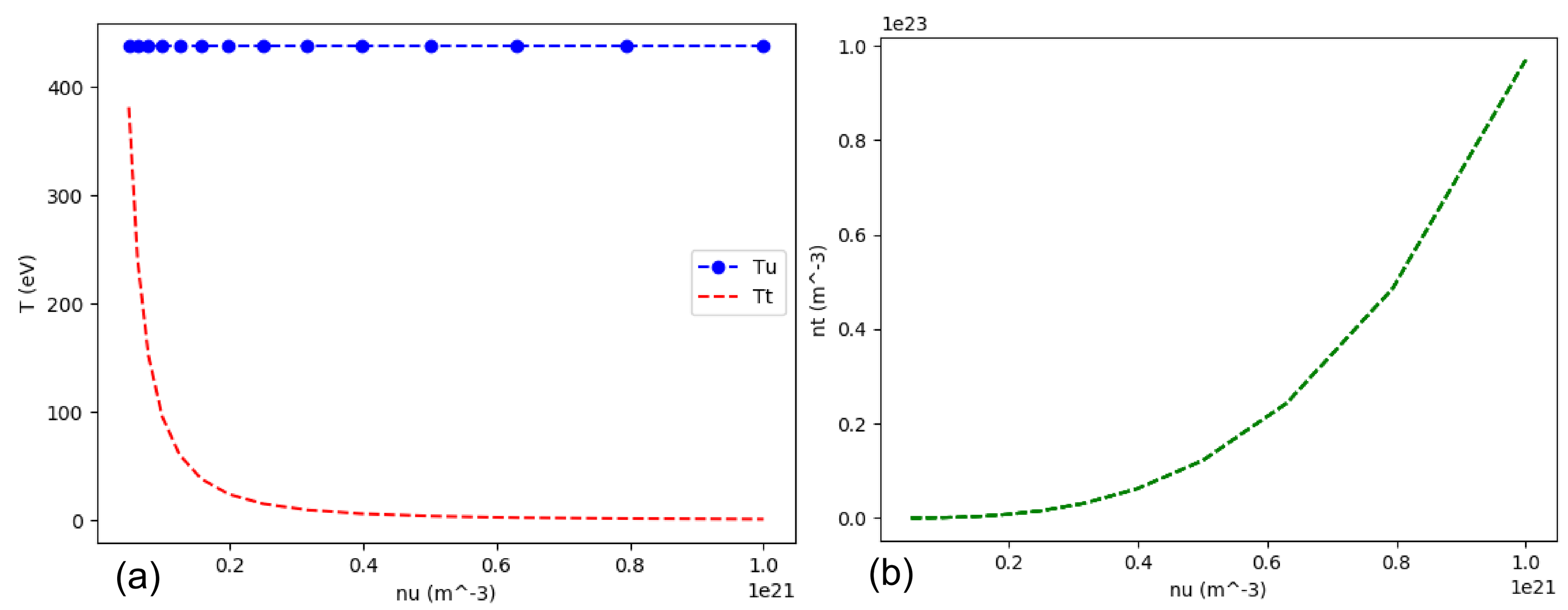


Figure 4. Solutions for upstream and target temperatures T_u and T_t and target density n_t as a function of upstream density n_u calculated for 1D system described by eqns (3.1), (3.2) and (3.3). With $q = 1000MWm^{-2}$, $L = 50m$, $\gamma = 10$

- Both n_t and T_t are highly sensitive to the input parameters
- T_u is insensitive to all parameters [2]

3.3 Extensions to basic 2PM

- Correction factors can be introduced for more accurate modelling [2]
- Power loss due to radiation and charge exchange loss
- Momentum loss due to volume recombination, viscous forces and frictional collisions with neutrals
- Conduction contribution to parallel heat transfer

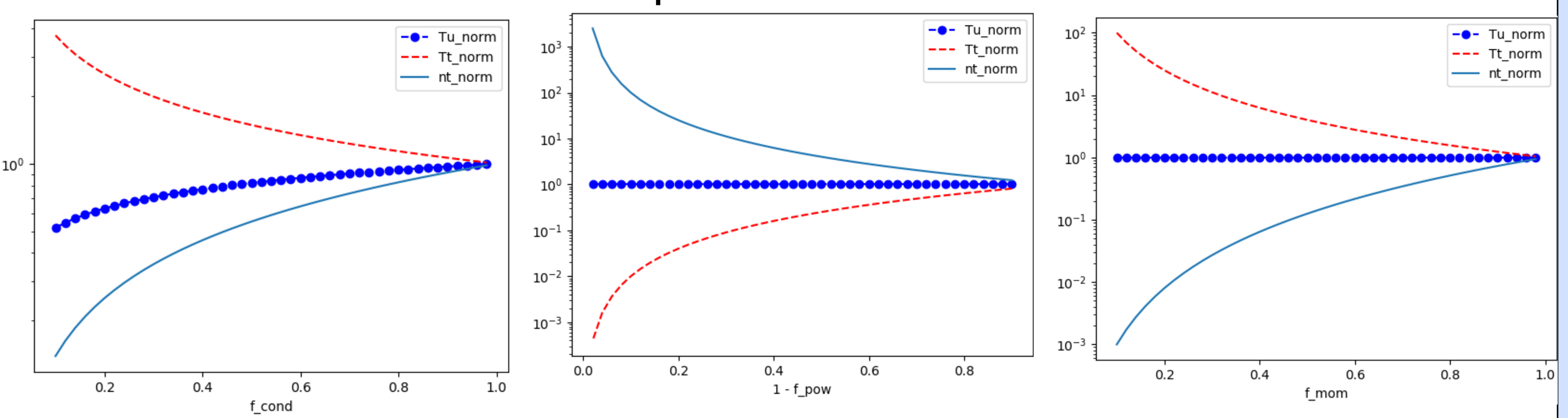


Figure 5. The effect of the two-point model 'correction factors', f_{cond}, f_{mom}, f_{pow}. With T_u, T_t and n_t values normalized to their values for f_{cond} = f_{mom} = 1 – f_{pow} = 1 (reproduced from [2])

- Target quantities extremely sensitive to correction factors
- Large T-gradients occur when there are volumetric power losses [2]

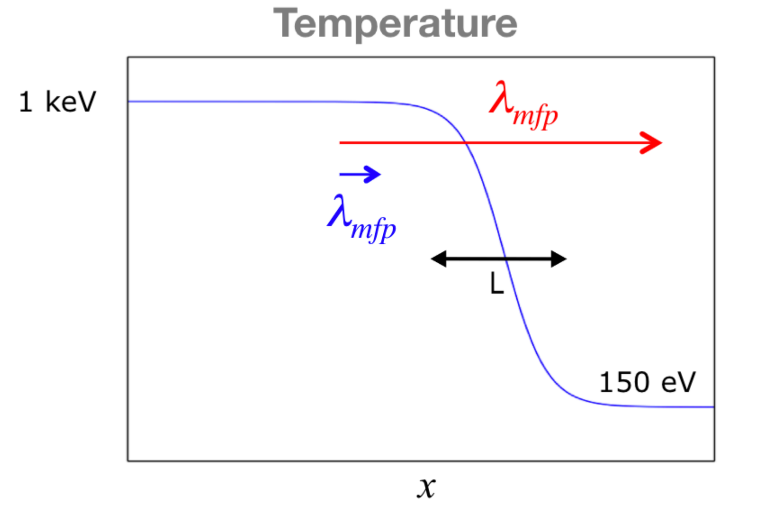
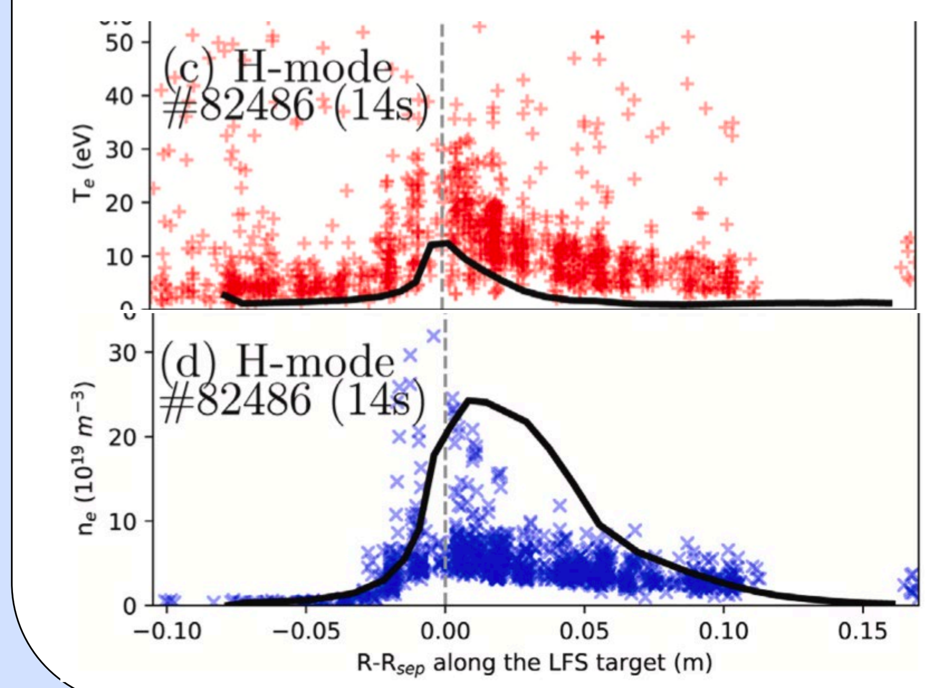


Figure 6. Schematic showing non-local implications of large T-gradients [5]

- Preheating – when mean-free-path (λ_{mfp}) of plasma is much larger than plasma length scale (L) [5]
- Heat flow is non-local as hot plasma has a large area of effect which impedes on cold region
- Non-Maxwellian distributions [1]

3.4 Upcoming work

- We have modelled simple 2PM employing local heat transport mechanisms and introduced correction factors



- We will employ a convolution to the heat-flow model to include kinetic effects and compare simulations with tokamak data from JET runs [6], Figure 7.

Figure 7. Experimental electron density (blue) and temperature profiles (red) from Langmuir probe measurements in high-confinement mode, with predicted profiles (solid lines) [6]

[1] Mijin, Stefan. "Modelling of Kinetic Effects in Parallel Transport in the Tokamak Scrape-off Layer." (2020). Web
[2] P. Stangeby, The Plasma Boundary of Magnetic Fusion Devices. CRC Press, 2000
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[4] Robson, Robert & Nicoletopoulos, P & Li, Bo & White, Ron. (2008). Kinetic theoretical and fluid modelling of plasmas and swarms: The big picture. Plasma Sources Science and Technology. 17. 024020. 10.1088/0963-0252/17/2/024020
[5] Kingham, R., 2016. *Non-local Transport: A Primer.*
[6] H.A. Kumpulainen, M. Groth, G. Corrigan, D. Harting, F. Koechl, A.E. Jaervinen, B. Lomanowski, A.G. Meigs, M. Sertoli,Validation of EDGE2D-EIRENE and DIVIMP for W SOL transport in JET, Nuclear Materials and Energy, Volume 25, 2020
[7] ITER. 2021. *Capturing the energy*. [online] Available at: <https://www.iter.org/sci/MakingitWork> [Accessed 5 March 2021].