Spectroscopic investigation of main impurity flows under magnetic field reversal in the TCV divertor

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Introduction

Ion flows and temperatures in the Scrape-Off Layer (SOL) play a key role in determining divertor performance, particularly through their contribution to parallel heat convection and target power loads. In attached regimes, the ion heat flux can dominate the total energy flux in the divertor [1]. Magnetic drifts can significantly affect SOL profiles and flow asymmetries. Although fluid codes such as SOLPS-ITER [2] can incorporate magnetic drift effects, experimental validation under well-diagnosed conditions is scarce. To address this, a dedicated experimental campaign was carried out on the TCV tokamak using Ohmic L-mode discharges with a long-leg divertor geometry and attached strike points. By systematically reversing the direction of both the magnetic field and the plasma current, the impact of magnetic drifts on the SOL plasma profiles was isolated and characterised. A key feature of this campaign was the alignment of the outer divertor leg with Thomson Scattering (TS) and the innermost tangency radius of the Tangential Divertor Spectroscopy System (TDSS), to provide simultaneous radial and poloidal profile measurements of electron and ion properties.

Experimental setup

The newly installed Tangential Divertor Spectroscopy System (TDSS) [3] uses high-resolution spectroscopy to analyse visible light emitted by atoms and ions in the divertor. Impurity ion flows, assumed to be mostly aligned with the field lines, are measured by using the difference in Doppler shift of toroidally opposite, and simultaneously recorded, measurement chords, figure 1. The ion temperature is calculated from the Doppler broadening component of the emission line.

Ohmic L-mode discharges with an attached divertor were performed on TCV to highlight any effects of magnetic drifts on SOL profiles. The the divertor leg was precisely aligned with both the Thomson Scattering (TS) measurement chords and the innermost tangency radius of the TDSS Lines of Sight (LOS), figure 2. A leg sweep was executed during the discharge, displacing the outer strike point progressively radially inward whilst maintaining constant upstream conditions. This provided simultaneous acquisition of poloidally and radially resolved profiles of ion and electron parameters. This experiment was repeated for all combinations of the plasma current and toroidal field directions.

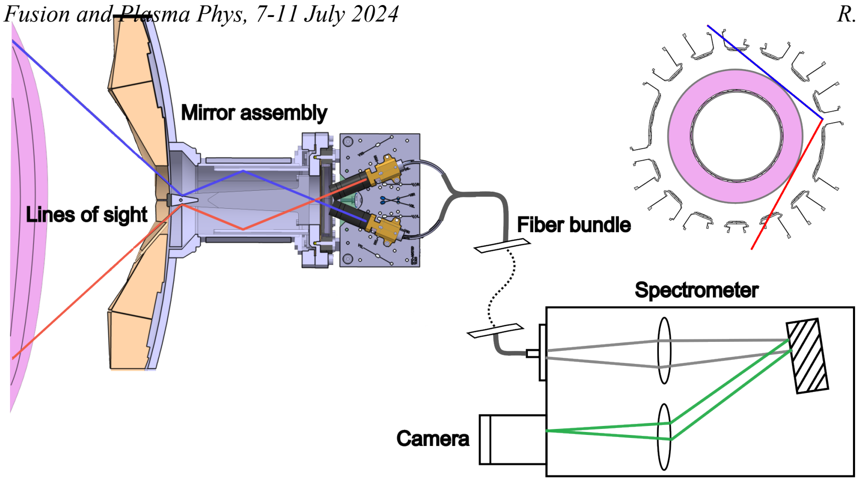


Figure 1: Schematic representation of the TDSS lines of sight, optics, spectrometer and camera setup

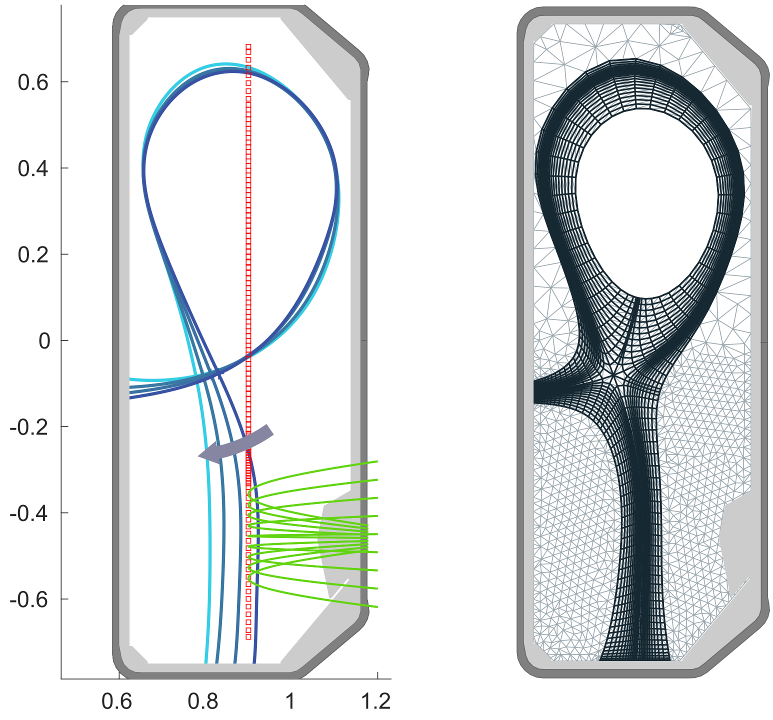
SOLPS-ITER setup

A long-leg simulation grid, figure 2, was used in a simulation with Carbon impurities and magnetic drifts. The Carbon chemical sputtering yield was set to 3.5% for ionic species, but removed for neutral species to match the Carbon emissivity measured by the MANTIS [4] diagnostic in the divertor [5]. The ion conductivity heat flux limiter was set higher than one, unlike previous studies [6] [7].

Experimental measurements and comparison to simulations

Figure 3 shows the radial profiles of electron temperature, ion temperature, electron density, and parallel ion velocity for two magnetic configurations: $B \times \nabla B$ towards the X-point (**F**orward **F**ield, blue) and $B \times \nabla B$ away from the X-point (**R**eversed **F**ield, red). The experiments with opposite plasma current direction are not shown as they yielded similar results to those shown. The profiles are shown with experimental data from TS and TDSS overlaid upon values obtained from SOLPS-ITER simulation results.

In the electron temperature profiles, Fig. 3 a), for the RF case, the temperature peaks at over 25 eV near the separatrix and falls sharply in the SOL. For the FF case, the peak is reduced ($\sim$ 20 eV). The ion temperature profiles, Fig. 3 b), follow a similar trend. TDSS data for the RF case shows a higher Ti peaking just outside the separatrix. Comparison with SOLPS-ITER simulations reveals good qualitative agreement in terms of profile shape and peak location, whereas the simulation tends to have a higher Ti peak. The electron density profiles, Fig. 3 c), show a pronounced difference in both shape and magnitude between the two magnetic drift directions. For the FF case, the density peaks at $\rho = 0.99$ and remains elevated across the SOL, whereas with RF, the peak density is lower and at $\rho = 1.02$. These observations are consistent with the transport of particles radially outwards due to the E $\times$ B drift [7]. Surprisingly, the parallel ion flow velocity profiles Fig.3 d) displayed a strong drift dependence. The TDSS data in RF shows that the flow velocity is peaked near $\rho = 1.02$, exceeding 15 km/s. In contrast, the FF configuration exhibits a flatter profile, though the radial extent of the experimental profile is



(a) **(b)**

Figure 2: a) TDSS LOS together with the TS observation volumes (red squares) in the long-leg scan experiment. b) SOLPS-ITER computational grid for the corresponding simulation.

limited to $\rho > 1.01$ due to the line-integrated nature of the measurement, thus potentially missing the peak flow velocity, located at the separatrix in the SOLPS-ITER simulation. Overall, the SOLPS-ITER simulations reproduce the broad trends observed in the experiments, especially the drift-induced asymmetries in density and ion flow. However, discrepancies remain in the absolute magnitudes—particularly for ion temperature and flow velocity—and in the radial fall-off lengths of temperature. The inclusion of magnetic drifts and a higher ion conductivity heat flux limiter allowed for improved agreement in density and temperature profiles compared to previous studies. Further refinements to cross-field models and impurity source distributions may be needed to resolve the remaining mismatches.

Conclusion

The effect of magnetic drifts on divertor SOL profiles was investigated by reversing the direction of the magnetic field in experiments on TCV. To measure ion and electron radial and poloidal profiles, the outer divertor leg was aligned with the Thomson Scattering and Tangential Divertor Spectroscopy System lines of sight. SOLPS-ITER simulations were run with optimised input parameters to match experimental upstream temperature and density. The simulation results are not only able to qualitatively match the experimental profiles, but also show similar trends to experiments where the magnetic field direction is inverted. Both the experiments and the simulations showed that the electron density, ion temperature and ion flow velocity are strongly affected by the change in magnetic field direction. This validation process helps understand

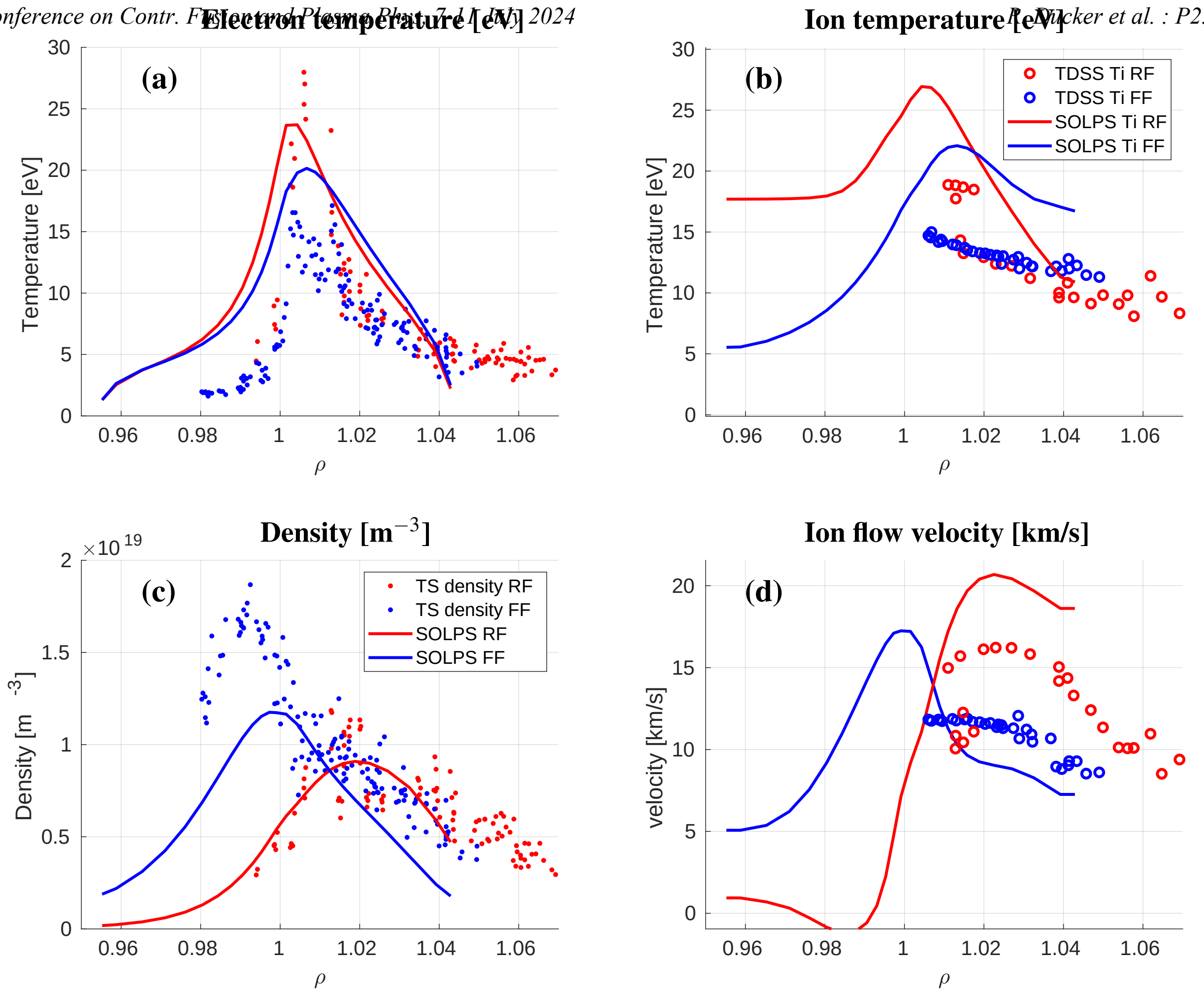


Figure 3: Experimental and simulated radial profiles of a) electron temperature, b) C^{2+} temperature, c) electron density, d) C^{2+} flow velocity at Z=-0.45m in the outer divertor leg in reversed field (RF) and forward field (FF) as a function of normalised minor radius $\rho = \frac{\sqrt{\psi-\psi_0}}{\sqrt{\psi_{edge}-\psi_0}}$ where ψ is the poloidal flux, .

how magnetic drifts influence divertor physics by modifying the energy distribution between ions and electrons, ultimately affecting the balance between conductive and convective heat transport to the targets.

References

1. Järvinen, A. E. *et al.* Role of Poloidal $\mathbf{E}\times\mathbf{B}$ Drift in Divertor Heat Transport in DIII-D. *Contributions to Plasma Physics* **60.** arXiv:1909.09190 [physics], e201900111. ISSN: 0863-1042, 1521-3986 (June 2020).
2. BONNIN, X. *et al.* Presentation of the New SOLPS-ITER Code Package for Tokamak Plasma Edge Modelling. *Plasma and Fusion Research* **11,** 1403102–1403102 (2016).
3. Ducker et al, R. High-resolution visible spectroscopy for ion temperature and velocity measurements of the TCV divertor plasma. *Review of Scientific Insturments* (in preparation).

4. Perek, A. *et al.* MANTIS: A real-time quantitative multispectral imaging system for fusion plasmas. *Rev. Sci. Instrum.* `https://doi.org/10.1063/1.5115569` (1 December 2019).
5. Tonello, E. *36th ITPA-DivSol meeting* in (Paper in preparation).
6. Wensing, M. *et al.* Experimental verification of X-point potential well formation in unfavorable magnetic field direction. *Nuclear Materials and Energy* **25,** 100839. ISSN: 2352-1791 (2020).
7. Colandrea, C. *Investigation of scrape-off layer and divertor transport using infrared thermography and SOLPS-ITER simulations* PhD thesis (EPFL, 2024).