SPECTROSCOPIC EVIDENCE FOR FLOW REVERSAL AT HIGH DENSITY IN ASDEX UPGRADE DIVERTOR II

J. Gafert, K. Behringer[1], D. Coster[1], A. Kallenbach[1], K. Schmidtmann[1], R. Schneider[1], U. Schumacher and ASDEX Upgrade-Team[1]

Institut für Plasmaforschung, Universität Stuttgart, Pfaffenwaldring 31
D–70569 Stuttgart, Germany
[1] *MPI für Plasmaphysik, EURATOM Association, Boltzmannstr. 2*
D-85748 Garching, Germany

1. Introduction

For an optimized design of the divertor and its operation in future fusion reactors it is essential to study divertor physics in present-day fusion experiments. In order to increase the reliability of extrapolation to ITER, it is most important to validate numerical plasma edge codes by experimental results. One main feature predicted by theory and modelling for a long time is flow reversal [1]. As this effect might lead to a contamination of the main plasma by impurities it has to be understood in order to find and explore methods of controlling it.

After a short description of the toroidal lines of sight used for the determination of particle flows in ASDEX Upgrade, we discuss some theoretical aspects of impurity flow reversal and its detectability. Hereafter, we present spectroscopic evidence for carbon flow reversal in ASDEX Upgrade Divertor II and discuss it in connection with the experimental plasma conditions required for its observation.

2. Experimental Setup

High resolution Doppler spectroscopy is a technique that was demonstrated to be suitable for obtaining flow velocities of ions and atoms [2]. For the ASDEX Upgrade divertor II configuration the spatial resolution is achieved by a fiberoptical system consisting of an overall number of 150 lines of sight. With two sets of chords, aligned perpendicular to the magnetic field lines in a poloidal plane (thin straight lines in Fig. 1), the strike-point regions of the inner and outer divertor are observed. These chords are mainly used to monitor detachment by the temporal evolution of CIII-emission profiles in front of the plates. Furthermore, due to the zero Doppler shift, they supply a reference wavelength. Two other groups are oriented roughly toroidally, one mainly along the magnetic field direction and the other one opposite to it. Owing to the opposite Doppler shifts, they allow for a reliable determination of flow velocities in the divertor. This line of sight arrangement was chosen on the basis of B2-EIRENE [3] predictive calculations and optimized with respect to the possibility of observing flow reversal [4] in the closed Divertor II of ASDEX Upgrade.

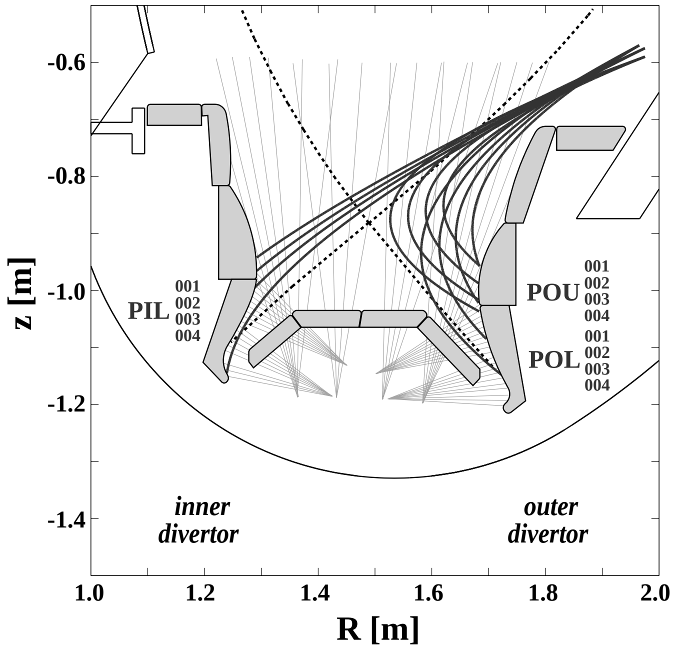

Figure 1. A subset of 12 toroidal lines of sight (thick black lines) in the ASDEX Upgrade Divertor II projected into a poloidal plane; the outer and inner divertor areas are covered to allow for spatially resolved velocity measurements. The poloidal lines of sight (thin grey lines) probe the X-point region and the area in front of the target plates with high spatial resolution.

3. Theoretical Aspects of Flow Reversal

Considering flow reversal it has to be distinguished basically between the backflow of the plasma ions (H, D) themselves and that of impurities. In this paper we only focus on impurity flow reversal driven by thermal forces. If the temperature gradient created by the background plasma is large enough so that the resulting thermal forces acting on the impurities are able to overcome the usual forces (electric field, pressure, friction) directed towards the target flow reversal is expected to occur. This situation will be given, when the local Mach number becomes smaller than the ratio of the ion mean free path to the temperature gradient length, i.e. when the coupling due to collisions is sufficiently reduced. These conditions are likely to occur in the course of detachment when the divertor density is increased. A further increase might again switch off the flow reversal due to a flattening of the temperature gradient. Accordingly, thermal force driven flow reversal is expected to exist only in a limited density range.

To be able to detect flow reversal spectroscopically the spatial overlap of the respective regions of emission and flow reversal has to be large enough. B2-EIRENE simulations for different densities predict that the CIII-emission in the respective flow reversal zone should be sufficient to be measured under the partially detached conditions described above. It turns out that this required overlap is only given [5] for chord POU004 (comp. Fig. 1). Accordingly, the resulting CIII-spectrum in this toroidal line of sight should be composed of a "normally" (e.g. blue) Doppler shifted component and an oppositely shifted (e.g. red) one, which is due to the ions flowing back.

4. Spectroscopic Evidence for C^{2+}-Flow Reversal during Detachment

In order to verify these expectations an L-Mode density ramp was performed at ASDEX Upgrade by gas puffing and successive increase of the NBI-power. Fig. 2a and b show the CIII-spectra (toroidal chord POU004) obtained in this discharge (# 9761) for attached (a, t = 2.8 s) and

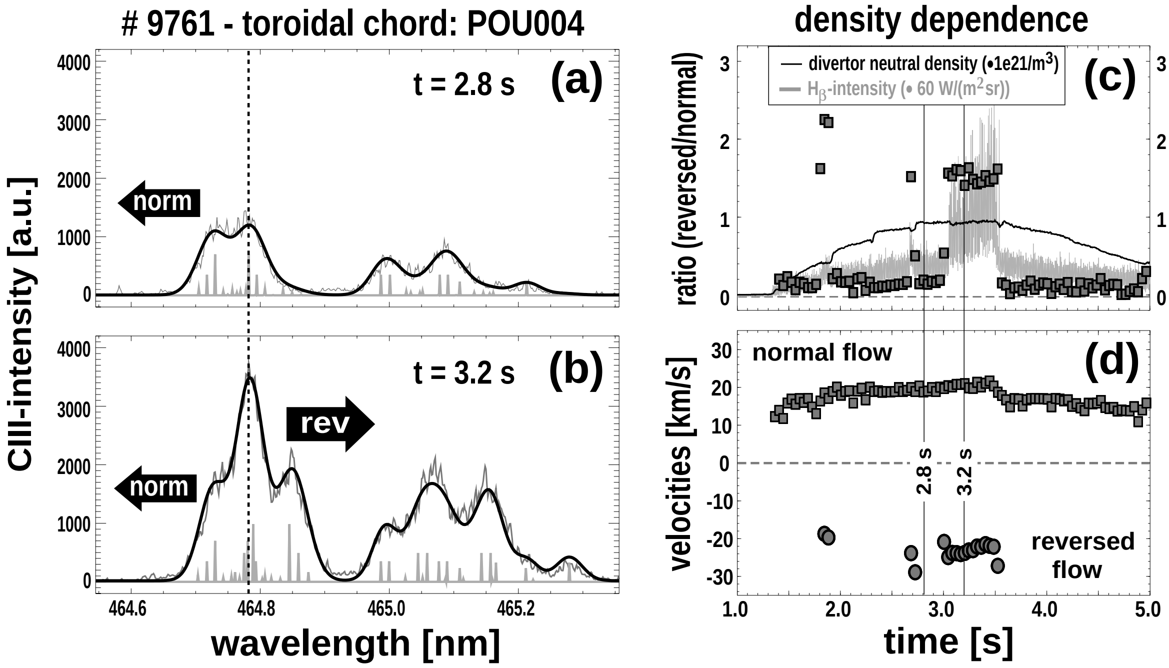

Figure 2. Spectroscopic observation of C^{2+}-flow-reversal in toroidal chord POU004 (near separatrix; comp. Fig. 1b) in an L-Mode density ramp: (a) blue-shifted CIII-spectrum (t = 2.8 s; attached), (b) superposition of additional red-shifted CIII-component (reversed flow) onto blue-shifted one (t = 3.2 s; detached), (c) ratio (reversed/normal), divertor neutral density and H_β-emission (outer separatrix) as detachment monitor and (d) resulting C^{2+}-flow-velocities

detached (b, t = 3.2 s) conditions, respectively. While the first spectrum (Fig. 2a) is blue-shifted (relative to the dashed line indicating zero-shift), the latter one (Fig. 2b) obviously shows a significantly changed line shape that is brought about by the additional red-shifted component which is created by flow reversal of C^{2+}-ions. The numerical fit yields a larger magnetic field (Zeeman splitting $\rightarrow \approx 2.7\,T$) for the reversed component which is in accordance with the expectation that the — spectroscopically detectable — flow reversal zones are located at somewhat smaller radii ($R \approx 1.54\,m$ and $1.65\,m$) than the region of "usual" flow ($R \approx 1.68\,m$) directed towards the plates ($\rightarrow \approx 2.5\,T$; see [5]).

Fig. 2c and d summarize the results on C^{2+}-flows for this discharge (# 9761): Fig. 2c contains the time evolution of divertor neutral density and the resulting H_β-intensity (at the separatrix) which is to be used as detachment indicator: Detachment is related to enhanced volume recombination and, therefore, to a steep increase of neutral hydrogen emission. The squares represent the ratio of the reversed to the normal CIII-component obtained from the numerical fit to the spectra. This ratio is used to discriminate the reversed flow velocities that are reliable by setting a detection threshold. In Fig. 2d the resulting velocities are plotted: While the normal flow can be seen during the whole discharge, the reversed flow is only detectable if the ratio (squares in Fig. 2c) is high enough. This is obviously only the case if the plasma is detached enough (increased H_β in Fig. 2c) to provide the required CIII-emission in the flow reversal zone located more upstream. As soon as the plasma attaches again the reversed

CIII-component vanishes. However, this does not necessarily mean that the flow reversal itself disappears, because the emission zone just might shift out of the flow reversal zone. The reversed flow velocity lies between 20 km/s and 30 km/s and is in good agreement with the respective 2D-code results: For this L-mode density ramp a detailed B2-EIRENE modelling was especially performed for the experimental conditions. In order to compare experiment and modelling we selected a run that fits with the actual discharge according to the power into the SOL (4 MW), SOL-density ($2.5 \cdot 10^{19}\,\mathrm{m}^{-3}$), carbon- and hydrogen radiation and the respective distributions in the divertor. For these conditions where we observed flow reversal of C^{2+}, B2-EIRENE yields a (chord averaged) "forward" velocity of about 20 km/s and a reversed velocity of (15 – 20) km/s. The measured values (Fig. 2d) are about 21 km/s and (22 – 25) km/s, respectively. Hence, B2-EIRENE predictions have not only been validated qualitatively by the spectroscopic observation of impurity flow reversal, but there is also good quantitative agreement.

Further support for modelling comes from recent ASDEX Upgrade discharges with the line averaged electron density being ramped up to $1.1 \cdot 10^{20}\,\mathrm{m}^{-3}$. This upper value corresponds to a SOL-density of $3.6 \cdot 10^{19}\,\mathrm{m}^{-3}$. The respective spectroscopic data confirm the expectation discussed above that flow reversal should only be detectable in a limited density range where the thermal forces as well as the required overlap of emission and flow reversal zone are sufficent: Flow reversal of C^{2+} first appeared and then disappeared again before the density had reached its maximum value.

5. Summary and Discussion

The B2-EIRENE code has been validated in the important subject of flow reversal by these spectroscopic measurements.

No significant increase of Z_{eff} in the core was observed in the respective time range of detectable flow reversal. The reason for this might be that due to the existence of radial transport one gets the formation of large-scale convective cells and, consequently, an effective global mixing in the whole divertor. In regions where flow reversal appears the Mach number is rather low (below 0.05). Accordingly, the radial transport brings the impurities, during their backflow, into regions where they experience again forces directed towards the target plates. Therefore, it seems that flow reversal mainly leads to a redistribution of impurities in the divertor with the retention capability not being affected severely even at the high densities needed for (partial) detachment.

References

[1] J. Neuhauser et al.: J. Nucl. Mater. **121**, 194–198 (1984).

[2] J. Gafert et al.: Plasma Phys. Control. Fusion **39**, 1981–1995 (1997).

[3] D. Reiter: J. Nucl. Mater. **80**, 196–198 (1992).

[4] J. Gafert et al.: Europhys. Conf. Abstr. **21A**, Part IV, 1397–1400 (1997).

[5] J. Gafert et al.: J. Nucl. Mat., *Proc. of 13th PSI-Conf.*, San Diego, 1998.