Low-Z impurity transport studies using CXRS at ASDEX Upgrade

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Impurities in fusion plasmas arise from many different sources including the erosion and sputtering of material from plasma facing components, the intentional injection of impurities for divertor cooling and core radiation control, and the production of helium from the fusion process itself. The plasma performance is highly affected by the impurity concentration and, to achieve a stable burning plasma scenario in future reactors, the build up of impurities in the plasma must be controlled. Therefore, a fundamental understanding of impurity transport in fusion plasmas is of great importance. Recent studies have shown discrepancies between theory and experiment [1], which implies that more work on this topic has to be conducted. A simple way of describing the particle transport of an impurity Z is with a radial transport equation, where radial implies the transport perpendicular to the flux surfaces.

$$\frac{\partial n_Z(r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}r\left(D(r)\frac{\partial n_Z(r,t)}{\partial r} - v(r)n_Z(r,t)\right), \quad n_Z(r_{\max},t) = s(t) \tag{1}$$

In equation (1), $n_Z(r,t)$ is the impurity density, $D(r)$ is the diffusion coefficient, $v(r)$ is the drift velocity, and $s(t)$ is the boron density source term at at the edge $r_{\max}$. The process of particle transport can, thus, be described by diffusion and convection. By studying steady-state density profiles only the ratio of D and v can be obtained and previous work using charge exchange recombination spectroscopy (CXRS) at ASDEX Upgrade (AUG) has focused primarily on steady-state profiles [1, 2]. To disentangle v and D, one needs to measure the temporal evolution of the impurity density profiles after a perturbation, e.g. during a modulation of the impurity source at the plasma edge. At AUG, a modulation of the power of the boron- and tungsten-coated ion cyclotron resonance frequency (ICRF) antennae results in a modulation of the boron density in the plasma. This work aims to exploit this result to determine the boron transport coefficient in AUG plasmas. A requirement for the feasibility of this technique is a steady plasma background which means keeping the electron density and the ion and electron temperatures constant such that D and v do not depend on time during the modulation. This places a restriction on the level of the ICRF power that can be modulated. The amplitude of the boron density modulation scales with the ICRH power and, therefore, a compromise between the boron signal and maintaining a constant plasma background has to be found. It has been concluded that a power level of ~ 1 MW of ICRF is sufficient to modulate the boron density up
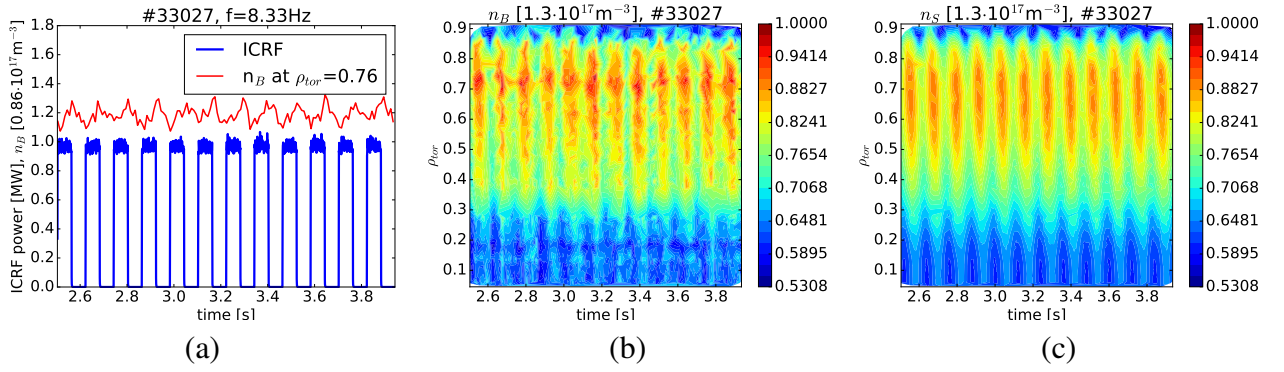
Figure 1: a. Time traces of the modulated ICRF power (blue) and the resultant modulated boron density (red) for one discharge in the database. The frequency f of the modulation is 8.33 Hz. b. Measured boron density n_B. c. Simulated boron density n_S.

to 10% at the edge while keeping the modulation of the ion and electron temperatures to maximally 2-4%. It has also been observed that the boron modulation signal is strongest when the experiments are performed in a freshly boronized machine. This suggests that the ICRF power modulation affects the boron which originates from the boronization and not the boron from the antenna itself. Furthermore, the resultant modulation does not arise from modulated incident heat fluxes to the SOL, since a modulation of the power of the electron cyclotron resonance heating (ECRH) does not result in a modulation of the boron density.

At AUG three core CXRS systems can measure the boron content in the plasma. In total these systems have 72 lines-of-sight (LOS) and a typical integration time of 10 ms [3, 4]. Figure 1 (a) shows a time trace of the modulated ICRF power, with a frequency of 8.33 Hz, in blue and the resultant boron density in red from one channel at ρ_{tor}=0.76 from one of these CXRS systems.

To assess the transport coefficients the experimental data is modelled by solving an inverse problem, where n_B is the measured boron density and n_S is the simulated one.

$$\min_{D,v,s} \frac{1}{2}\|n_S - n_B\|^2_{L^2([r_{\min},r_{\max}]\times[t_{\min},t_{\max}])} \quad \text{w.r.t equation (1)} \tag{2}$$

Problem (2) is solved by a quasi-Newton method yielding the simulated density n_S by solving equation (1) for various D and v profiles as well as the source term s. A robust ansatz for the simulated density n_S is used when this inverse problem is solved:

$$n_S(r,t) = n_0(r) + a(r)cos(\omega t) + b(r)sin(\omega t)$$
$$s(t) = s_0 + a_0 cos(\omega t) + b_0 sin(\omega t). \tag{3}$$

In equation (3), n_0 is the steady-state density and $\omega = 2\pi f$, where f is the frequency of the modulation. The boron source term $s(t)$ is assumed to have the same shape as the density n_S. This ansatz suits the used method particularly well, since the measured boron signal has a sinusoidal shape, which clearly can be seen in figure 1 (a). The model is thus reduced to the steady-state and the modulation at the frequency ω, which corresponds to a Fourier transform
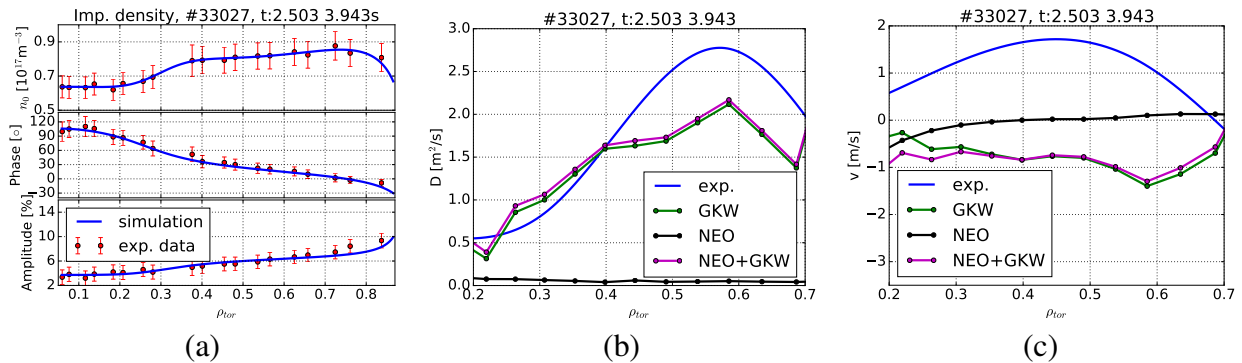
(a) (b) (c)

Figure 2: a. Steady-state density, phase, and amplitude profiles. b (c). Comparison between experimental, neoclassical, and turbulent D (v).

in time at the modulation frequency. Thus, no time discretization is necessary. The singularity in equation (1) at $r = 0$ is resolved by natural Neumann boundary conditions at the axis. D and v are represented with arbitrary degree B-splines and second order finite differences are used for solving the transport equation. The complete problem can readily be set up and solved using the Scipy minimization toolbox in Python. Figure 1 (b) and (c) show an example of the measured and simulated boron densities, respectively. As one already can see by eye, the agreement is very good but this becomes even clearer if one looks at the phase and amplitude profiles. The resulting steady-state density as well as the phase and amplitude of the modulation are depicted in figure 2 (a). The red points represent these quantities as obtained from the measured boron density profiles and the blue lines are B-spline representations of these quantities from the simulated density. In this particular case, the steady-state boron profile is hollow. The phase shift indicates how fast the modulation propagates into the core. The amplitude modulation is strongest at the edge where the source is located. Looking at this plot it becomes more evident that the agreement with experiment is very good. The analysis region is between ρ_{tor}=0.2-0.7, as sawteeth are present in the center and there are too few data points outside ρ_{tor}=0.7 to capture the edge gradient properly. Several discharges exploiting this technique have been performed at plasma currents of 0.6 and 0.8 MA. The applied heating powers vary between 0.5-2.4 MW of ECRH and 2.5-10 MW of NBI. The ICRF has a modulation frequency of either 8.33 or 10 Hz in all of these discharges. The measured boron density profiles in the database collected so far range from slightly hollow to peaked ones.

For a subset of the database the experimental data is compared to theoretical predictions. In this study the code NEO [5, 6] was used for simulating the neoclassical transport coefficients. The modelling of the turbulent transport was performed with the gyrokinetic code GKW [7]. The data shown in this paper was achieved through quasi linear GKW simulations. Turbulent and neoclassical transport components are summed under the assumption that the turbulent transport heat conductivity matches the anomalous part of the power balance heat conductivity, which is computed with TRANSP, see Ref. [8] for more details. An example comparison between experimental and theoretical D and v for one discharge in the database is depicted in
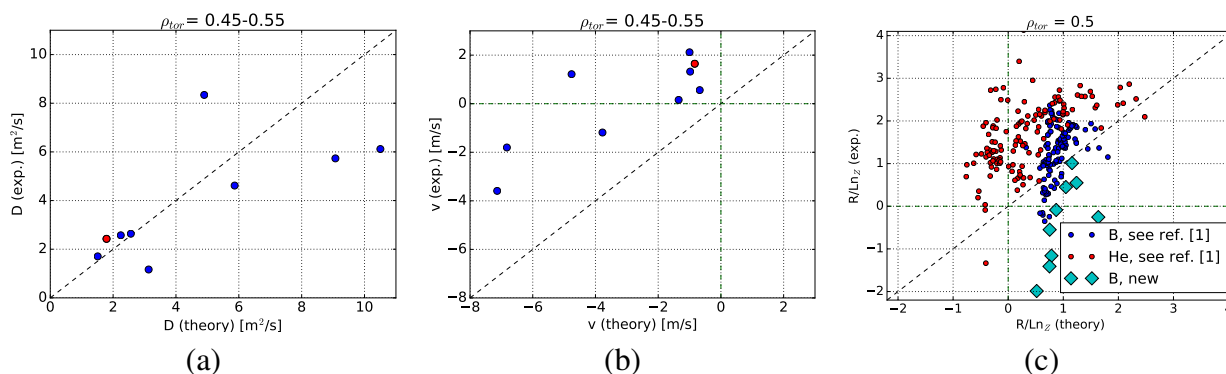
Figure 3: a (b). Total theoretical D (v) plotted against experimental D (v) averaged over a ρ_{tor} interval of 0.45 to 0.55. The red point represents the data shown in previous figures. c. Experimental and theoretical values of the normalized gradient at ρ_{tor}=0.5.

figures 2 (b) and (c). Neoclassical diffusion (black line) is, as expected, much smaller than the measured values. The turbulence driven transport (green), however, is of the correct order of magnitude. In this case the total theoretical D (magenta) agrees quantitatively with the experimental one, whereas the total theoretical v is in the opposite direction. It should be noted that there are cases in which the D profile shows poorer agreement, see figure 3 (a) overall, however, it trends quite well with the experiment. In all cases the predicted v from GKW is significantly more negative, which is shown in figure 3 (b), and this suggest much more peaked profiles than what is seen in the experiment. This is consistent with earlier work at AUG looking at the steady-state profiles, see figure 3 (c), in which the normalized gradient R/L_{n_B} from the boron modulation database collected so far, cyan diamonds, is compared to previously conducted steady-state transport experiments, red and blue points [1], at ρ_{tor}=0.5. It can be concluded that the new data is able to reproduce the prior experiments.

In summary, the ICRF modulation technique has been exploited at AUG for obtaining time-dependent boron density signals. A database of transport coefficients at different heating scenarios have been collected and compared to theory. The first comparison shows that the diffusion predicted by GKW is of the correct order of magnitude and tends well with the experimental data. The predicted convections, on the other hand, are significantly more negative (inward) than seen in the experiment.

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