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.

$$\frac{\partial n_Z(r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r \left(D(r)\frac{\partial n_Z(r,t)}{\partial r} - v(r) n_Z(r,t) \right) + Q_Z(r,t) \quad (1)$$

A simple way of describing the particle transport of an impurity Z is with a radial transport equation, see equation (1). Radial implies the transport perpendicular to the flux surfaces. In equation (1), $n_Z(r,t)$ is the impurity density, $D(r,t)$ is the diffusion coefficient, $v(r,t)$ is the drift velocity, and $Q_Z(r,t)$ is the source and sink term. 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 [2]. To disentangle v and D from one another, 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 it has been discovered that 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 method and obtain a clear time dependent signal of the boron density, from which the individual transport coefficients can be extracted. 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. However, a performed feasibility study showed that the amplitude of the boron density modulation scales with the ICRH power, see Figure 1. Therefore, a compromise between the boron signal and maintaining a constant plasma background has to be found. From the study it was concluded that a power level of ~ 1 MW of ICRF is sufficient to modulate the boron density up 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 the strongest when the experiments are performed when the machine is freshly boronized. This suggests that the ICRF power modulation affects the boron which originates from the boronization and not the boron from the antenna itself. This hypothesis is further strengthened by the fact that a strong modulation signal is also achieved when only modulating the tungsten-coated ICRF antennae. 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 intensity.

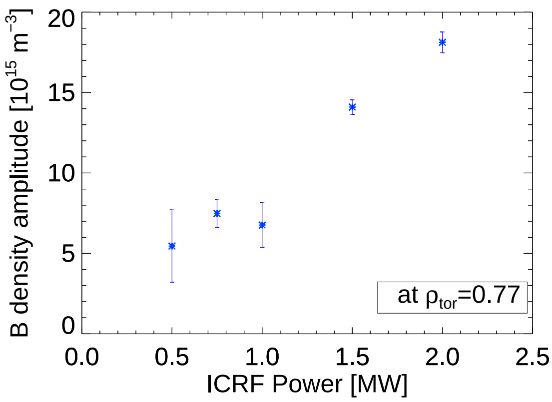

Figure 1: Amplitude of the boron density modulation at different ICRF power levels.

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]. The CXRS diagnostics measure the line intensity of the impurity, ion temperature, and plasma rotation. From the line intensities $I_{CX,Z}$ the impurity density n_Z can be calculated with equation (2).

$$n_{\mathrm{Z}} = \frac{4\pi}{h\nu} \frac{I_{\mathrm{CX,Z}}(\lambda)}{\int_{LOS} \sum_i \sum_j \langle \sigma v \rangle_{i,j} n_{0,i,j} dl}, \tag{2}$$

where $\langle \sigma v \rangle_{i,j}$ is the effective CX emission rate coefficient for a given spectral line with the neutral ions from the beam $n_{0,i,j}$ for a given energy component i and a given excited state j of the beam. Figure 2 shows time traces of the modulated ICRF power, with a frequency of 8.33 Hz, in blue and the resultant boron density in red for discharge 33413, which aimed to test the feasibility of the technique described above. The data is taken from one of the CXRS core systems.

The plasma movement is taken into account by fitting the density profiles and performing the analysis in normalized flux units. The radial phase and amplitude profiles of the resultant boron density modulation are then calculated in two different ways. The first method Fourier transforms the signal in time to obtain the frequency spectrum. The ICRF signal is used for a phase reference. The radially dependent phase and amplitude of the Fourier mode at the modulation frequency is then retrieved. In the second method a sum of a sine and cosine at the modulation

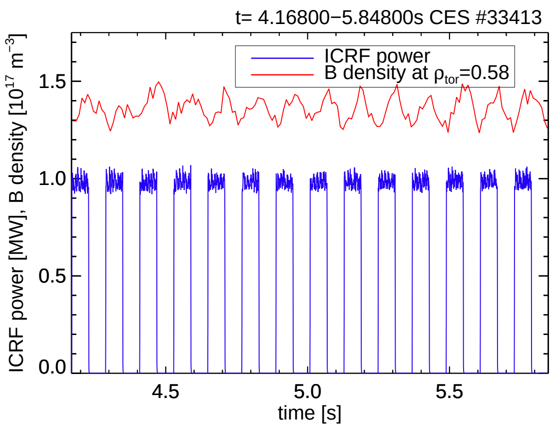

Figure 2: Time traces of the modulated ICRF power (blue) and the resultant modulated boron density (red) for discharge 33413. The frequency of the modulation is 8.33 Hz.

frequency is fitted to the signal, which gives the phase and amplitude information directly. The results of both methods agree well with each other. Figure 3 displays the amplitude (left) and phase (right) profiles for the same discharge and time interval shown in Figure 2. The amplitude of the modulation is peaked at the edge where the source is located. The phase shows how fast the modulation propagates into the core and in this particular case there is a phase shift of $\sim 70^\circ$ or 23 ms from edge to core.

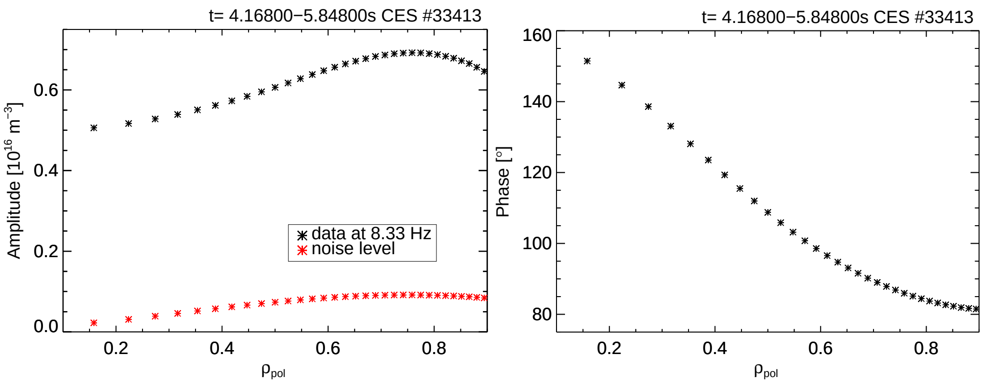

Figure 3: Radial amplitude and phase profiles. The amplitude modulation is strongest at the edge where the source is located. The phase shift indicates how fast the modulation propagates into the core.

D and v are extracted with two different methods. One is to simulate the measured phase and amplitude profiles. This is done with STRAHL [5], which solves equation (1) for the sought impurity. A sinusoidal function with the same frequency as the modulation of the ICRF power is given to STRAHL as a source term. The ratio of v and D can be obtained from the measured steady-state profiles and this is also given to STRAHL as a constraint. D is then changed until the simulated phase and amplitude profiles match the experimental ones. The other method is to use analytical expressions for D and v. By solving equation (1) with the ansatz $n(r,t) = n_0(r) + A(r)e^{i(\omega t - \Phi(r))}$, analytical expressions for D and v can be obtained:

$$D(r) = -\frac{\omega}{rA(r)}\left(\frac{\partial\Phi(r)}{\partial r}\right)^{-1}\int_0^r A(\tilde{r})\cos\left(\Phi(\tilde{r})-\Phi(r)\right)\tilde{r}\,\mathrm{d}\tilde{r} \quad (3)$$

$$v(r) = -\frac{\omega}{rA(r)}\int_0^r A(\tilde{r})\sin\left(\Phi(\tilde{r})-\Phi(r)\right)\tilde{r}\,\mathrm{d}\tilde{r} + D(r)\frac{\frac{\partial A(r)}{\partial r}}{A(r)} \quad (4)$$

In equation (3) and (4), ω is the frequency, A the amplitude, and Φ the phase of the modulation. By performing a harmonic analysis on the measured data and using equation (3) and (4) D and v profiles can be obtained.

Figure 4 displays the first preliminary D and v profiles for discharge 33413 simulated with STRAHL. A linear D profile was given to STRAHL as a first guess. v/D is constrained by measured steady-state profiles.

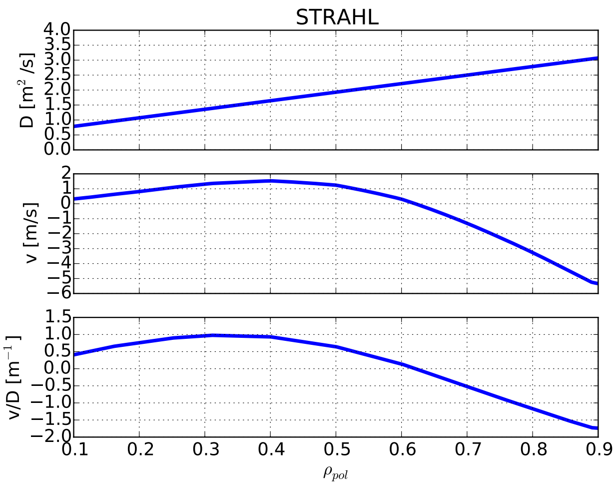

Figure 4: D and v profiles for discharge 33413 simulated with STRAHL.

In summary, a feasibility study performed demonstrates the viability of the technique. So far, a database of clear phase and amplitude profiles for several discharges have been collected. D and v profiles can be obtained from analytical expressions or by simulations. The next steps are to implement the analytical method, perform a proper error analysis on the measured phase and amplitude profiles, to extract v and D for these profiles, and to incorporate all CXRS systems in the analysis.

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