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Topic: Ex-S

Parallel impurity transport measurements using laser ablation seeding of boron and aluminum in a linear He^+ plasma*

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Parallel flow of impurity ions in cold edge plasmas is important for magnetic fusion devices because the resulting redistribution of impurities can affect wall lifetime, core performance, and hydrogenic retention in the wall. Typically, modeling of parallel impurity transport in tokamaks uses classical collisions [1]. Detailed comparisons between this classical model and experiments are scarce, however. The use of divertor simulator plasmas, which have better diagnostic access and simpler geometry than tokamaks, is valuable for studying basic aspects of impurity transport in cold plasmas.

Here, we describe measurements of the parallel transport of B^+ and Al^{2+} ions in well-characterized cylindrical He^+ plasmas. The experiments are performed in the PISCES-A

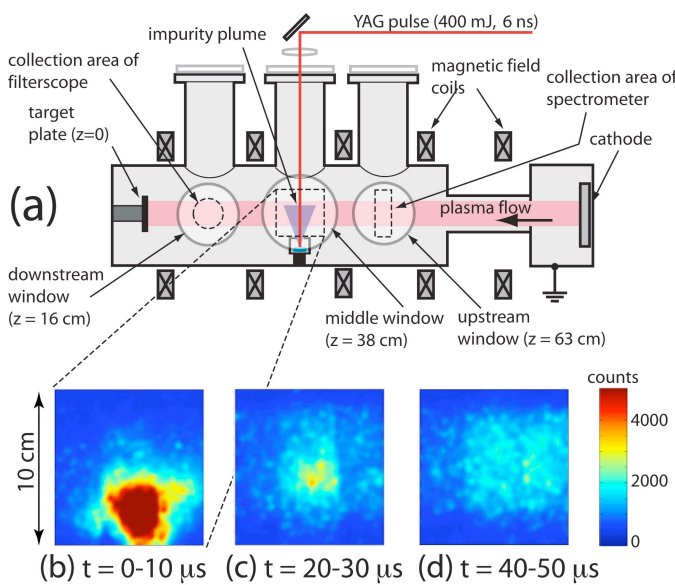


Fig. 1. (a) Experimental setup and (b)-(d) CCD images of B^+ emission.

linear reflex-arc device [2]. A schematic of the basic experiment geometry is shown in Fig. 1(a). Typical parameters are dimension $D \approx 5$ cm, $L \approx 1$ m, electron density $n_e \approx 5 \times 10^{12} \text{ cm}^{-3}$ and electron temperature $T_e \approx 5$ eV. The plasmas are weakly ionized, with neutral density n_{He} typically at least $10 \times$ the electron density. Target plasma conditions are varied by varying the helium background fill pressure from $P_N = 0.8 - 4.3$ mTorr.

Impurities are injected into the middle of the plasma column (middle window), axial location $z \approx 38$ cm) in a brief (≈ 10 μ s long) pulse by use of laser ablation: a 6 ns long Nd:YAG (1064 nm) laser pulse is fired into a sample of boron or aluminum mounted slightly outside the plasma column. Middle window CCD images of B^+ 345 nm emission during boron laser ablation are shown in Figs. 1(b)-(d), showing that the impurity deposition is initially well-localized axially. A laser pulse energy of around 400 mJ was typically used.

Parallel flow of impurity ions is measured using filterscopes (photomultiplier tube + interference filter + collimator lens combinations) at all three main chamber diagnostic windows, labeled upstream, middle, and downstream in Fig. 1(a). Line widths of the interference filters are typically 5 nm, which is sufficiently narrow to isolate the impurity lines from the strongest *He* lines.

An example impurity flow experiment is shown in Fig. 2, where time traces of line-averaged boron ion density n_{B^+} are shown from the three different diagnostic windows. n_{B^+} is calculated from the absolutely-calibrated brightness of B^+ 345 nm line emission. No significant *B* or B^{2+} line emission was seen in these experiments.

In the case of aluminum injection, *Al*, Al^+ , and Al^{2+} are all seen in the middle window, with Al^{2+} dominant; these are monitored by filterscopes at 396, 466, and 570 nm, respectively. In the upstream and downstream window, Al^{2+} is seen only weakly and *Al* and Al^+ signals are essentially zero.

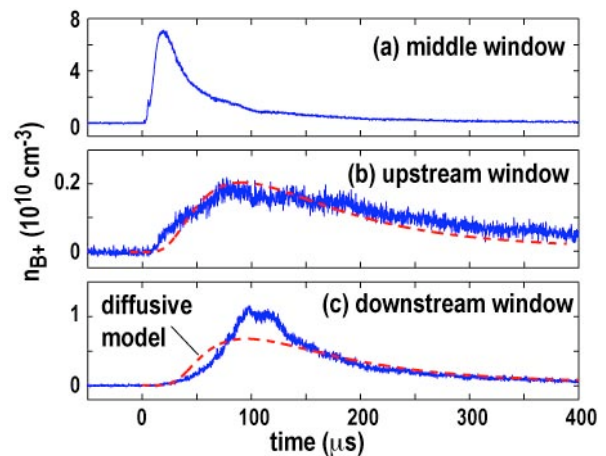


Fig. 2. Time traces of B^+ density, n_{B^+} , calculated from filterscope data of B^+ brightness in (a) middle window, (b) upstream window, and (c) downstream window

Conversion of measured filterscope line brightnesses into line-averaged impurity ion densities is done using ADAS calculations [3] of the expected line brightness as a function of

background plasma n_e and T_e . The view chord line integral $\int dl$ is profile-averaged over the acceptance cone of the filterscope optics. Radial profiles of the background plasma of

background plasma n_e and T_e are obtained at the different window locations using a combination of probe data and absolutely-calibrated He^+ brightnesses [4].

The impurity flow time traces such as shown in Fig. 2 are fit with a diffusive model [5]:

$$\frac{\partial n_j}{\partial t} = D_{||,j} \frac{\partial^2 n_j}{\partial z^2} + v_{||,j} \frac{\partial n_j}{\partial z} - \left(\frac{\partial n_j}{\partial t} \right)_{ion} - 5.8 n_j \frac{D_{\perp,j}}{R_p^2} + \left(\frac{\partial n_j}{\partial t} \right)_{source}, \quad (1)$$

where n_j is the impurity ion density (B^+ or Al^{2+} ; we ignore other charge states since their densities are low) and $R_p \approx 2$ cm is the plasma radius. $\left(\frac{\partial n_j}{\partial t} \right)_{ion}$ is the loss to higher charge states due to ionization, estimated from the n_e , T_e profiles. $\left(\frac{\partial n_j}{\partial t} \right)_{source}$ is the source term due

to the impurity injection; this is assumed to be localized only to the middle window and is varied to match the middle window measurement, e.g. Fig. 2(a). The free parameters $D_{||,j}$, $v_{||,j}$, and $D_{\perp,j}$ are varied to give a best match to the measured time traces in upstream and downstream windows. Sample fits are shown with dashed lines in Figs. 2(b) and 2(c).

A similar model to Eq. (1) was fit to the background helium plasma. In this case, the term $\frac{\partial n_j}{\partial t}$ is 0 (steady state), the parallel flow velocity $v_{||}$ is measured and the source term $\left(\frac{\partial n_i}{\partial t} \right)_{source}$ is due to neutral gas ionization; this term can be obtained from neutral He line brightnesses using ionization/photon (S/XB) factors from ADAS.

Transport coefficients for boron injection experiments are shown in Fig. 3. The horizontal axis is profile-averaged neutral density in the middle window for each case. The dashed lines in Fig. 3 show simple estimates of $D_{||}$ and D_{\perp} from impurity-ion + helium collisions, $D_{||} \approx \bar{v}_j^2 / \nu_{tot}$ and $D_{\perp} \approx \nu_{tot} r_j^2$, where \bar{v}_j is the impurity thermal velocity (impurity ions are assumed to be at the same temperature as the equilibrium T_i). ν_{tot} is the total frequency of collisions of the impurity ion on helium ions and neutrals. Dot-dashed lines in Fig. 3 show Bohm diffusivity, $D_B = \left(\frac{cT}{16eB} \right)$.

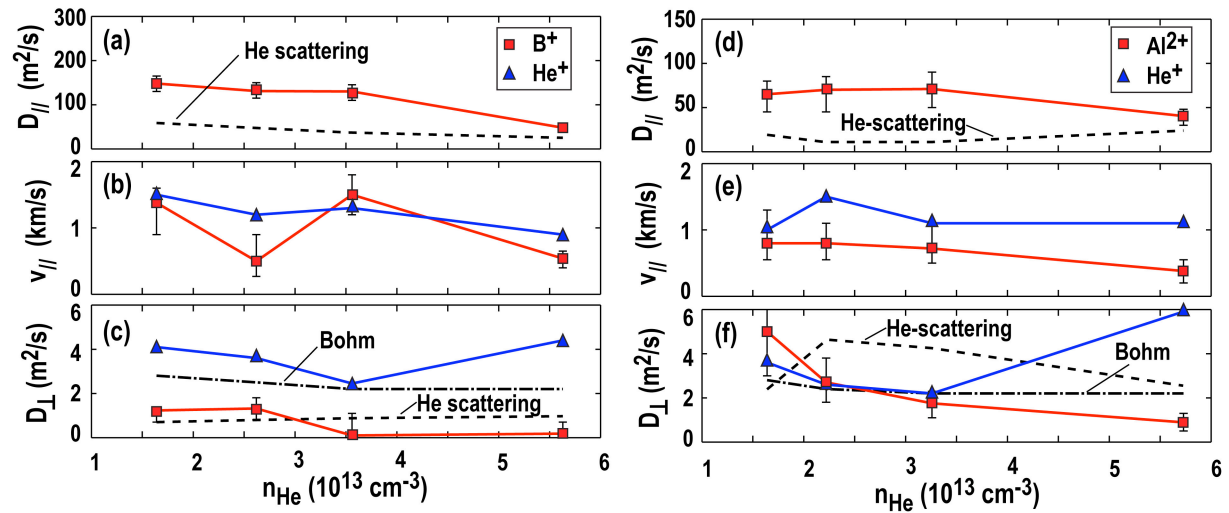


Fig. 3. Transport coefficients estimated from flow experiments for (a)-(c) B^+ and (d)-(f) Al^{2+} , showing parallel diffusivity $D_{||}$, parallel velocity $v_{||}$, and perpendicular diffusivity D_{\perp} .

Overall, we see evidence of entrainment, with B^+ flowing at about the He^+ parallel flow velocity, Fig. 3(b), and Al^{2+} at about half the He^+ flow velocity, Fig. 3(e). Parallel diffusion appears to be faster than expected from impurity-He collisions (by perhaps $2-5\times$); this might suggest that the ion-ion collision rate is being underestimated here. The simple diffusive analysis done here neglects many potentially important terms, such as parallel electric field forces, parallel gradient in the parallel diffusion coefficient, and temperature gradient forces. Future work will attempt to use fluid flow codes such as UEDGE or OEDGE to model these results.

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