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Topic: Ex-S

## Parallel impurity transport measurements using laser ablation seeding of boron and aluminum in a linear $\text{He}^+$ plasma\*

E.M. Hollmann<sup>1</sup>, K. R. Umstadter<sup>1</sup>, R. P. Doerner<sup>1</sup>, J. Munoz<sup>2</sup>, D. Nishijima<sup>1</sup>, and A. Yu.

Pigarov<sup>1</sup>

<sup>1</sup> University of California-San Diego, La Jolla, California 92093, USA

<sup>2</sup> Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

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  $\text{B}^+$  and  $\text{Al}^{2+}$  ions in well-characterized cylindrical  $\text{He}^+$  plasmas. The experiments are performed in the PISCES-A

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  $T_e \approx 5 \text{ eV}$ . The plasmas are weakly ionized, with neutral density  $n_{\text{He}}$  typically at least  $10 \times$  the electron density. Target plasma conditions are varied by varying the helium background fill pressure from  $P_N = 0.8 - 4.3 \text{ mTorr}$ .

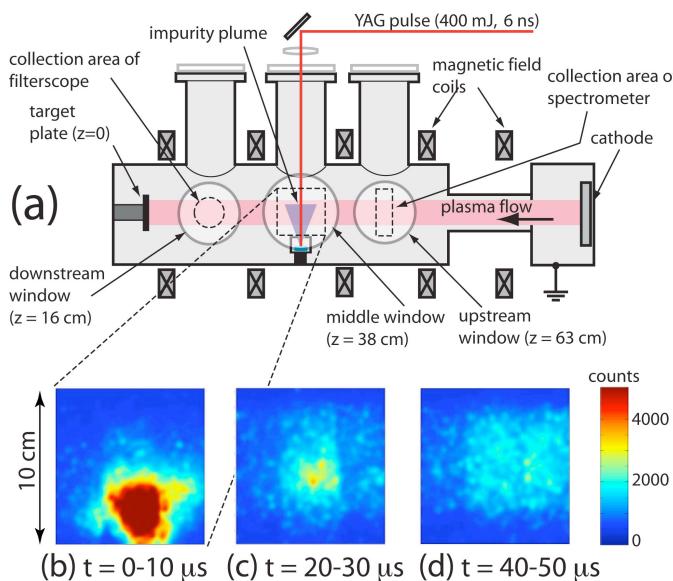


Fig. 1. (a) Experimental setup and (b)-(d) CCD images of  $\text{B}^+$  emission.

Impurities are injected into the middle of the plasma column (middle window), axial location  $z \approx 38$  cm) in a brief ( $\approx 10 \mu\text{s}$  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.

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

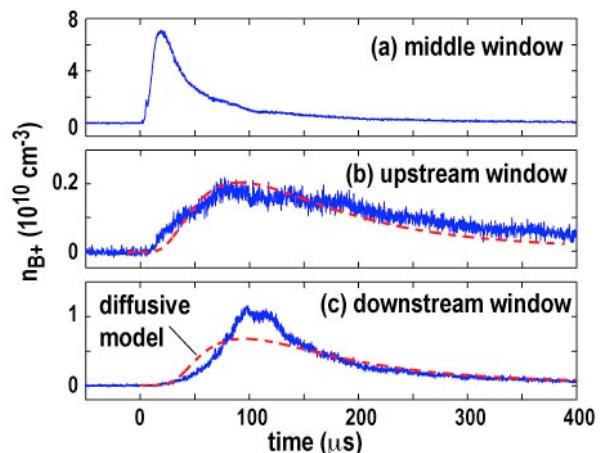


Fig. 2. Time traces of  $B^+$  density,  $n_{B^+}$ , calculated from filterscope data of  $B^+$  brightness in (a) middle window, (b) upstream window, and (c) downstream window

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]:

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

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  $D_{\parallel,j}$ ,  $v_{\parallel,j}$ , 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  $v_{\parallel}$  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  $D_{\parallel}$  and  $D_{\perp}$  from impurity-ion + helium collisions,  $D_{\parallel} \approx \bar{v}_j^2 / \nu_{tot}$  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  $T_i$ ).  $\nu_{tot}$  is the total frequency of collisions of the impurity ion on helium ions and neutrals. Dot-dashed lines in Fig. 3 show

Bohm diffusivity,  $D_B = \left( \frac{cT}{16eB} \right)$ .

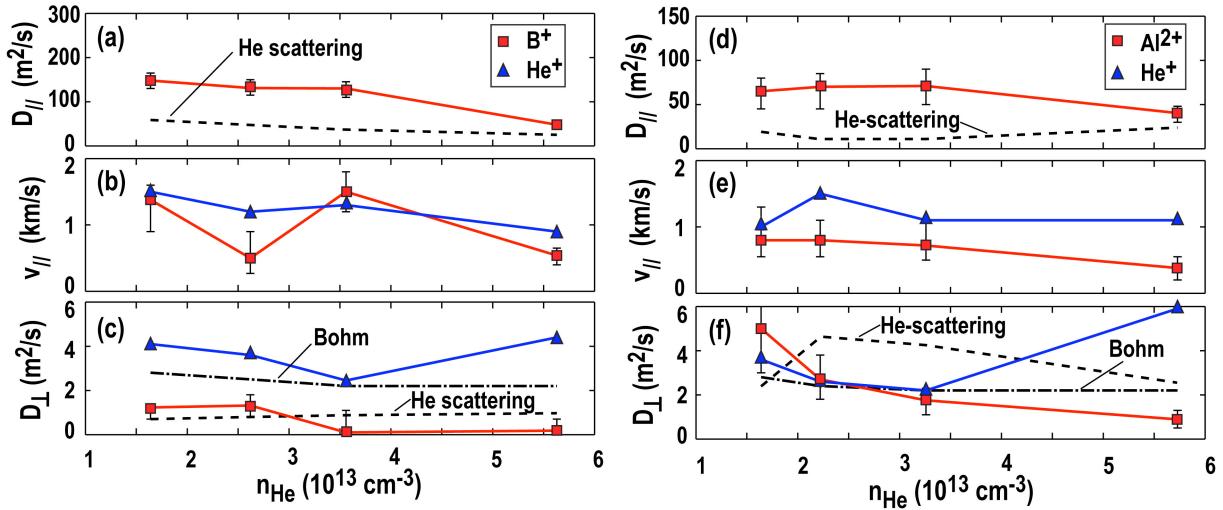


Fig. 3. Transport coefficients estimated from flow experiments for (a)-(c)  $B^+$  and (d)-(f)  $Al^{2+}$ , showing parallel diffusivity  $D_{\parallel}$ , parallel velocity  $v_{\parallel}$ , and perpendicular diffusivity  $D_{\perp}$ .

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×); 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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