Modeling of aluminum impurity entrainment **the** in PISCES-A He^+ plasma

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Abstract

A 1D theoretical model describing transport of Al impurities in a low temperature He^+ plasma is discussed. The model adopts a kinetic approach to describe impurity entrainment in a steady state He^+ plasma flow. Results of a 1D Monte Carlo simulation supporting this model are presented and compared to experimental data collected from PISCES-A linear experiment. Both simulation and experimental results confirm that impurities are quickly entrained by the background plasma and quickly acquire its flowing velocity. However, a major discrepancy is observed in the temporal width when comparing the simulation to the experimental Al^{2+} density profiles downstream. Consideration of several potential effects suggests that background plasma velocity shear is the most likely cause for this discrepancy.

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I. Introduction

Understanding impurity transport is of major importance for the magnetic fusion community because of their crucial role in both core and edge plasma performance. Released from the plasma facing material or intentionally injected into the divertor plasma, impurities enter the plasma where they get ionized in the SOL. Some even enter deeper into the core and accumulate there, increasing the radiative power losses, contaminating the plasma and reducing its efficiency. Investigating impurity transport, mainly in the SOL region, is therefore essential to achieve a better plasma performance.

In order to study parallel entrainment of Aluminum impurities, a recent experiment was carried out in PISCES-A machine [1], a cylinder of length $L=1\text{m}$ and diameter $d=5\text{cm}$ (Fig.1). The plasma is dominated by singly ionized He^+ ions and characterized by an average electron density $n_e=5\times 10^{12}/\text{cm}^3$ and average electron and ion temperatures $T_e=5\text{eV}$ and $T_i=1\text{eV}$. The axial magnetic field was $B_z=1.4\text{kG}$ and the plasma flow velocity as measured at the mid window level was $u=2\times 10^5\text{cm/s}$ and the Helium neutral density was reported to be at least 10 times that of the electrons in this weakly ionized plasma. Al neutrals, created by laser ablation of an Aluminum substrate, collide with plasma electrons and get ionized into Al^+ and Al^{2+} ions that get entrained by the plasma. Spectroscopic measurements of Al^+ and Al^{2+} optical radiation signals were performed at three different locations as shown in Fig.1 (downstream, mid and upstream window). Temporal and spatial variations of impurity density n_I of both Al^+ and Al^{2+} were then interpreted with an *ad hoc* convective-diffusive model:

$$\frac{\partial n_I}{\partial t} = D_{\parallel} \frac{\partial^2 n_I}{\partial z^2} + v_{\parallel} \frac{\partial n_I}{\partial z} - 5.8 n_I \frac{D_{\perp}}{R^2} + \left(\frac{\delta n_I}{\delta t} \right)_{source} - \left(\frac{\delta n_I}{\delta t} \right)_{sink} \quad (1)$$

where $R=2.5$ cm is the plasma column radius, $5.8 = (2.405)^2 = \text{square of the first root of Bessel function}$, $D_{//}, D_{\perp}, v_{//}$ are free parameters varied to get a best fit of the experimental profile and the last two terms correspond to impurity sources and sinks.

Usually when describing impurity transport, two approaches can be adopted; the fluid approximation [2-4] or the kinetic one [5, 6]. The fluid approximation remains valid for a time scale longer than the impurity-ion collision time and a collision mean free path shorter than the plasma system characteristic length. It provides a theoretical basis for many numerical code packages used to model impurity transport in fusion devices such as B2 [7], SOLPS [8] and UEDGE [9]. However, close to positions where impurities are injected and are still in their low ionization states, this approximation is questionable. The kinetic approximation may be more appropriate to describe the SOL transport. Code packages like DIVIMP [10] and DORIS [11] use this approach for kinetic modeling of impurity transport.

We present a kinetic description of the Aluminum entrainment experiment discussed above. A kinetic approximation accounting for impurity ionization and losses as well as Coulomb collisions is implemented in a 1D Monte Carlo code developed for this purpose. In section II of this paper, a description of impurity-plasma as well as impurity-neutral interactions is presented, along with the appropriate collision frequencies. In section III, simulation results are compared to experimental data of Ref. [1]. Aluminum impurities are found to be entrained by the background plasma flow, their velocity quickly reaching the plasma flow velocity. However, a major width discrepancy is found when comparing experimental and modeling time evolution of Al^{2+} detected at the downstream window. Possibilities to reconcile experimental and modeling results are then presented. Final conclusions are summarized in section IV.

II. Kinetic modeling

A kinetic model that describes impurity parallel entrainment in plasmas is implemented in a 1D Monte Carlo code. An appropriate collision operator that takes into account impurity interactions with neutral *He* atoms, charged plasma particles and other impurities is used. In our simulations, *Al* is injected in small quantities so it is safe to neglect impurity-impurity interactions.

We start first by estimating the collision frequency of *Al* interactions with both neutral *He* and other charged plasma particles. The cross section of the collision between *Al* ions of charge Z_I and *He* atoms is given by the semi-classical Massey-Mohr formula [12]: $\sigma = 2.2 \times \pi \times (Z_I^2 e^2 \alpha / \mu v_r^2)^{1/2}$ where e is the elementary charge, μ is the reduced mass of the two particles system, v_r is the relative velocity between interacting particles and $\alpha = 1.35 a_0^3 = 2 \times 10^{-25} \text{ cm}^3$ is the *He* atom polarizability where a_0 is Bohr radius. The collision frequency would be: $\nu = n_{He} \times \sigma \times v_r$.

On the other hand, neglecting the impurity-electron collision frequency if compared to the impurity-ion one (because of the electrons low mass and relatively high temperature with respect to that of ions), the resulting Coulomb collision frequency is [13]:

$$\nu_I = \nu_{ii} = \frac{4\sqrt{2}\pi e^4 \ln \Lambda}{3} \cdot \frac{Z_I^2 n_i \sqrt{m_i}}{M_I T_i^{3/2}} \quad (2)$$

where $\ln \Lambda$ is plasma coulomb logarithm, M_I is the impurity mass, m_i , n_i and T_i are the plasma ion mass, density and temperature.

For the plasma parameters of the experiment, the characteristic ionization time of Al^+ ions is $3\mu\text{s}$ and $300\mu\text{s}$ for Al^{2+} ions. One can therefore consider that injected *Al* gets almost instantaneously ionized into Al^{2+} as it is shown in Fig.3 of Ref. [1] that densities of Al^{2+}

detected in the injection window are significantly higher than those of Al^+ . For this, one is mainly interested in Al^{2+} ion transport.

For a neutral Helium density $n_{He}=5\times 10^{13}/\text{cm}^3$ and a plasma ion temperature $T_i=1\text{eV}$ the corresponding collision frequencies are $\nu_{Al^{2+}/He} = 6.3\times 10^4/\text{s}$ and $\nu_{Al^{2+}/He} = 1.2\times 10^6/\text{s}$. Comparing both frequencies, it is reasonable to neglect any impurity-neutral interaction and solely consider Coulomb interactions, mainly impurity-plasma ions collisions.

III. Simulation model, results and interpretations

A 1D Monte Carlo model similar to that of Ref.[10] was developed in an attempt to simulate parallel transport of Al impurities in He^+ plasma as described in Ref. [1]. Al^+ impurities, injected according to a time dependent profile, at the mid-level window (at $z_0=38\text{cm}$ along the magnetic field axis) with an initial velocity v_0 taken from a prescribed distribution in velocity space, are followed in a background plasma characterized by $n_e=5\times 10^{12}/\text{cm}^3$, $T_e=5\text{eV}$, $T_i=1\text{eV}$ and a flow velocity $u=2\times 10^5\text{cm/s}$ measured at the injection window level. The model allows for impurity ionization into Al^{2+} state, as well as for impurity radial loss at a time rate τ_{loss} . Time dependent concentration profiles of Al^{2+} are recovered upstream and downstream the plasma flow at $z=16\text{cm}$ and $z=63\text{cm}$ respectively and plotted as function of time in Fig.2 and Fig.3.

Simulations show an absence of impurities upstream the plasma flow (Fig. 2), Al ions being accelerated in the other direction. A comparison of these simulations with experimental data supports this conclusion as minor traces of Al^{2+} are present in the experimental data.

As for the downstream window, simulation results show that a time $t=120\mu\text{s}$ is required by the majority of impurities to reach the downstream detection window. The separation distance between the injection and the detection window being $\Delta z=22\text{cm}$, the impurity velocity is approximately $v_i \approx 2\times 10^5\text{cm/s}$, a value equal to the input background plasma

velocity. However the time width of Al^{2+} signal found in simulation is much smaller than that seen in the experiment.

In an attempt to reconcile experimental and modeling results, we explore the following possibilities: i) Increase the ion temperature T_i . ii) Launch the impurities with an initial injection temperature T_I prescribed from a specific velocity distribution. iii) Assess the effect of the background plasma pressure excess created by the ionization process on the impurity dynamics iv) Investigate the radial shear of the plasma background velocity.

i) Increase the plasma ion temperature: This leads to an impurity-ion collision frequency decrease which allows for a wider range of impurity velocities, therefore a wider time interval for impurities to reach the detection window. To verify this, a simulation corresponding to the same plasma parameters and a higher ion temperature $T_i=7\text{eV}$ was run. The corresponding Al^{2+} profile was again generated as function of time and plotted in [Fig. 3](#). The peak again occurs at $t=120\mu\text{s}$, corresponding to $v_I = 2 \times 10^5 \text{ cm/s}$, equal to the plasma flow velocity, however the Al^{2+} profile width is much more compatible with the experimental one.

For further verification, we compare the impurity diffusion coefficient obtained in Ref. [1] to that calculated from the impurity momentum equation:

$$M_I n_I \frac{dv_I}{dt} = -\nabla p_I - n_I M_I \nu_{Ie} (v_I - v_e) - n_I M_{Iv_{ii}} (v_I - v_i) \quad (3)$$

For a steady state and a constant temperature T_I , neglecting the electron-impurity collision frequency as compared to the ion-impurity collision frequency, assuming a Maxwellian distribution of colliding particles, the impurity flux is $\Gamma_I = -n_I (v_I - v_i) = -D_{//} \nabla n_I$ where the impurity parallel diffusion coefficient is:

$$D_{//} = \frac{3}{4\sqrt{2\pi}e^4 \ln \Lambda} \cdot \frac{T_I T_i^{3/2} \sqrt{m_i}}{M_I Z_I^2 n_i} \quad (4)$$

For sufficient impurity-plasma collisions to assume $T_i=T_I$, Al^{2+} diffusion coefficients are $D_{//}=0.5m^2/s$ at $T_i=1eV$ and $D_{//}=66m^2/s$ at $T_i=7eV$. Comparing the results with those obtained from the convective-diffusive model, at $T_i=1eV$ the Al^{2+} diffusion coefficient $D_{//}=0.5m^2/s$ is much less than $D_{//}=70m^2/s$ found in Ref. [1]. For $T_i=7eV$, a much more compatible value of $D_{//}=66m^2/s$ is obtained. This temperature ($T_i=7eV$) however seems higher than the $T_e=5eV$ value measured within the error bars in Ref. [1].

ii) Inject the impurities with an initial temperature: We inspected next how the impurity injection temperature T_I affects the broadening of the detected Al^{2+} signal. Fig.4 shows simulations at different injection temperatures. As T_I increases, impurities spread faster and the width of Al^{2+} profile gets wider. The simulation Al^{2+} profile corresponding to $T_I=7keV$ fits the experimental profile obtained when using a collimated beam of Aluminum impurities. Spectroscopic measurements however showed a much lower impurity temperature, T_I less than 5eV for a collimated Aluminum beam, and T_I less than 10eV for a broader beam of Aluminum impurities [14]. These experimental temperatures are three orders of magnitude smaller than the 7keV value found in the simulation, leaving the impurity injection temperature hypothesis unrealistic.

iii) Impurity acceleration due to pressure increase: Plasma momentum equations are:

$$m_\alpha n_\alpha \frac{dv_\alpha}{dt} = n_\alpha q_\alpha E - T_\alpha \frac{\partial n_\alpha}{\partial z} - \sum_\beta m_\alpha n_\alpha v_{\alpha\beta} (v_\alpha - v_\beta) \quad (5)$$

We will assume next that T_i and $T_I \ll T_e$. The electron temperature gradient resulting from the injection process is immediately eliminated because of the electrons high parallel heat conductivity. In fact an estimate of the rate of this dissipation is obtained from the electrons heat equation [15]:

$$\frac{3}{2} n_e \frac{\partial T_e}{\partial t} = \frac{\partial}{\partial z} \left(3.2 \frac{n_e T_e \tau_e}{m_e} \cdot \frac{\partial T_e}{\partial z} \right) \quad (6)$$

The time needed for the temperature gradient to reach the end of the plasma column is $t = m_e \times L^2 / 8 \times \tau_e \times T_e \approx 10^{-6} \text{ s}$.

Writing the electron, impurity ion and plasma ion momentum equations explicitly, considering a zero electric current value, the expression of electrons velocity v_e is obtained in terms of v_i and v_I . In the electron momentum equation, we neglect the electrons inertia and solve for the induced electric field E . Replacing v_e and E by their expressions in impurity and plasma ion equations we obtain:

$$m_i n_i \frac{dv_i}{dt} = -T_e \frac{n_i}{n_e} \cdot \frac{\partial n_e}{\partial z} - n_i m_i v_{it} (v_i - v_I) \quad (7)$$

$$M_I n_I \frac{dv_I}{dt} = -T_e \frac{Z_I n_I}{n_e} \cdot \frac{\partial n_e}{\partial z} + n_i m_i v_{it} (v_i - v_I) \quad (8)$$

Next we expand these equations for a small impurity density perturbation $\tilde{n}_I$. The friction term is neglected, this one being of second order since the collision frequency ν_{it} depends on $\tilde{n}_I$ and is furthermore multiplied by $\tilde{v}_I$ or $\tilde{v}_i$. Al^{2+} ions being heavier than He^+ ones, their motion is neglected so that $\tilde{v}_I = 0$. In the impurity continuity equation, this corresponds to a zero time dependence of so that the impurity density perturbation profile does not change as function of time: $\tilde{n}_I(z, t) = \tilde{n}_I(z, 0)$ and remains stationary in the injection region.

As for plasma ions, expanding both momentum and continuity equations, after considering the appropriate time and space derivative, recasting all in a single non homogeneous wave equation:

$$m_i \frac{\partial^2 \tilde{n}_i}{\partial t^2} - T_e \frac{n_e}{n_i} \frac{\partial^2 \tilde{n}_i}{\partial z^2} = Z_I T_e \frac{n_i}{n_e} \frac{\partial^2 \tilde{n}_I(Z, 0)}{\partial Z^2} \quad (9)$$

For the initial conditions $\tilde{n}_i(z, 0) = \tilde{v}_i(z, 0) = 0$, neglecting the impurity perturbation density if compared to the ions one, we get:

$$\tilde{n}_i(z, t) = \frac{Z_I}{2} [\tilde{n}_I(z - C_s t) + \tilde{n}_I(z + C_s t)] - Z_I \tilde{n}_I(z, 0) \quad (10)$$

Where $Z_I=2$ for Al^{2+} . The resulting plasma ion perturbation propagates left and right at sound speed $C_s^2 = T_e / m_i$ with amplitude equal to that of the impurity perturbation.

Thus the electron density profile remains unperturbed as it was initially before the impurity injection. The impurity perturbation remains unchanged as time passes and located at the injection region while the background plasma ions react by spreading away from it. However this approach does not explain the source of the observed discrepancy between simulation and experimental data.

iv) Plasma shear effect on impurity diffusion: Given a radially dependent plasma flow velocity, impurities injected at different radii reach the detection window at different times. The time delay Δt , measured experimentally as the temporal width of Al^{2+} profile:

$$\frac{\Delta t}{t_{average}} = \frac{\Delta u}{u_{average}} \quad (11)$$

Numerically $\Delta t = 80\mu s$, $t_{average} = 120\mu s$ and $\Delta u/u_{average} = 2/3$. A velocity variation of the same order of magnitude as suggests that a radial background plasma shear velocity is mostly responsible of the observed broadening in the experimental data, a feature confirmed experimentally by the radial dependence of the plasma parallel velocity (Fig.4c of Ref.[1]).

IV. Conclusions

After comparing simulation results to experimental data, we conclude that impurity transport occurs at a velocity equal to the background plasma flow velocity. The main disagreement between the two sets of data was in the Al^{2+} profile temporal width. We could only fit the experimental profile, obtained at an ion temperature $T_i = 1eV$, with simulation results corresponding to a higher ion temperature $T_i = 7eV$ which seems unrealistic in an experiment where the electrons temperature is $T_e = 5eV$. The other possible way to recover the same experimental profile was to inject impurities with an initial temperature $T_I = 7keV$, a value too high to be conserved during collisions. After investigating the effect of the

Aluminum perturbation on the plasma species, it was found that heavy impurities remain at the injection region while lighter plasma ions spread away. Electrons simply provide a constant background pressure. As a conclusion we can finally say that the plasma shear velocity is responsible of the observed discrepancy, a shear induced by the flow velocity radial dependence, a feature that cannot be detected by a 1D simulation.

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Figure captions

Fig.1: Schematic of PISCES-A.

Fig.2: Experimental and simulation Al^{2+} profiles detected upstream the plasma flow.

Fig.3: Experimental and simulation Al^{2+} profiles at $T_{\text{He}^+}=1\text{eV}$ and 7eV detected downstream the plasma flow.

Fig.4. Experimental and simulation Al^{2+} profiles at different impurity injection temperatures detected downstream the plasma flow.

Fig. 1.

Fig.2

Fig.3

Fig.4