# Isotope Mixes in Interchange Driven Plasma filaments

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## Introduction

In magnetic confinement fusion few plasmas contain only a single ion species. Instead most contain a mix of ions either intentionally or unintentionally. The former as e.g burning plasma with a mix of deuterium, tritium and helium or when a wall conditioning is applied [1]. The latter possibly from impurities evaporating out of walls. In this paper we introduce a drift fluid multi-ion species model that is based on the HESEL turbulence model [2]. The multi ion species HESEL model resolves individual ion density and pressure, electron pressure and vorticity equations for an arbitrary number of species. In this work we study the influence of mixes containing two ion species on the radial blob trajectory similar to [3]. The numerical implementation and modelling is carried out within the BOUT++ framework [4].

## MIHESEL-model

The Multi-Ion-Hot-Edge-Sol-ELectrostatic (MIHESEL) model is an extension of the four field drift fluid turbulence HESEL model as derived in [2]. The aim of both models is to investigate interchange driven turbulent behaviour at the outboard mid-plane in a 2D slab configuration. The MIHESEL follows the same derivation, but instead of solving for electron density we solve for the ion densities as there are more than one. To ease the numerical implementation we use a simplified version of the model where we neglect the polarization and viscosity terms in the ion density and pressure equations whilst retaining it in the vorticity. Neglecting all parallel dynamics, we solve for the density $n_\alpha$, potential $\phi$, electron and ion pressure $p_{e/\alpha}$ in a 2D Cartesian system using the gyro-Bohm normalized equations:

$$\frac{d}{dt}\ln(n_\alpha) = -\mathscr{C}(\phi) - \frac{1}{Z_\alpha}\frac{\mathscr{C}(p_\alpha)}{n_\alpha} + \frac{\nabla\cdot(n_\alpha \mathbf{u}_{R\alpha})}{n_\alpha} \tag{1}$$

$$\sum_\alpha a_\alpha \mu_\alpha \nabla\cdot \frac{d^0}{dt}\left(\nabla\phi + \frac{\nabla p_\alpha}{Z_\alpha a_\alpha}\right) = \mathscr{C}\left(\sum_\alpha p_\alpha + p_e\right) + \sum_\alpha \mu_\alpha a_\alpha \sum_\beta D_{\alpha\beta}\nabla^2\nabla^2\left(\phi + \frac{p_\alpha}{Z_\alpha a_\alpha}\right) \tag{2}$$

$$\begin{aligned}\frac{d}{dt}\ln(p_e) &= -\frac{5}{3}\mathscr{C}(\phi) + \frac{5}{3}\mathscr{C}\left[T_e\mathscr{C}\left(\ln(p_e)\right) + \mathscr{C}\left(T_e\right)\right] \\ &+\frac{2}{3}\frac{1}{p_e}\nabla\cdot(p_e\mathbf{u}_{Re}) + \frac{11}{18}\frac{1}{p_e}\sum_\alpha D_{e\alpha}\nabla\cdot(n_e\nabla T_e) - \frac{2}{3}\frac{\mathbf{u}_{Re}}{p_e}\cdot\sum_\alpha \nabla p_\alpha - 2\sum_\alpha \frac{\mu_e}{\mu_\alpha}\nu_{e\alpha}\frac{(T_e - T_\alpha)}{T_e}\end{aligned} \tag{3}$$

$$\frac{d}{dt}\ln(p_\alpha) = -\frac{5}{3}\mathscr{C}(\phi) - \frac{5}{3}\frac{1}{Z_\alpha}\left[T_\alpha\mathscr{C}(\ln(p_\alpha)) + \mathscr{C}(T_\alpha)\right] + \frac{5}{3}\frac{1}{p_\alpha}\nabla\cdot(p_\alpha\mathbf{u}_{R\alpha}) - \frac{2}{3}\mathbf{u}_{R\alpha}\cdot\nabla\ln(p_\alpha)$$
$$+\frac{2}{10}\mu_\alpha a_\alpha D_\alpha\left[(\partial_{xx}(\phi^*_\alpha) - \partial_{yy}(\phi^*_\alpha))^2 + 4(\partial_{xy}(\phi^*_\alpha))^2\right] + \frac{4}{3}\sum_\beta D_{\alpha\beta}\left(\frac{\nabla^2 T_\alpha}{T_\alpha} + \nabla\ln(n_\alpha)\cdot\ln(T_\alpha)\right)$$
$$+2n_e\frac{\mu_e}{\mu_\alpha}\frac{\nu_{e\alpha}}{p_\alpha}(T_e - T_\alpha) + 2\sum_\beta\frac{\nu_{\alpha\beta}\mu_\alpha(T_\beta - T_\alpha)}{(\mu_\alpha + m_\beta)T_\alpha} \quad (4)$$

Where the advective derivatives are $\frac{d}{dt} = \frac{\partial}{\partial t} + B^{-1}\{\phi,\cdot\}$, $\frac{d^0}{dt} = \frac{\partial}{\partial t} + \{\phi,\cdot\}$ with $\{\phi,\cdot\}$ being the poisson brackets and $B$ the magnetic field. The modified potential is defined as $\phi^*_\alpha = \phi + \frac{p_\alpha}{q_\alpha n_{\alpha 0}}$ and constants $\mu_\alpha = \frac{m_\alpha}{m_{Deu}}$, $a_\alpha = \frac{n_{\alpha 0}}{n_{e0}}$, $\tau_\alpha = \frac{T_{\alpha 0}}{T_{e0}}$ and $D_{**}$ a diffusion coefficient. To derive the vorticity equation we use quasi-neutrality $n_e = \sum_\alpha Z_\alpha n_\alpha$. Finally the resistive terms are:

$$\mathbf{u}_{Re} = -\sum_\alpha D_{e\alpha}\left(\nabla\ln(n_e) + \frac{\tau_\alpha}{Z_\alpha}\nabla\ln(n_\alpha)\right) \quad (5)$$

$$\mathbf{u}_{Re\to\alpha} = -\frac{D_{e\alpha}}{Z_\alpha}\frac{n_e}{n_\alpha}\left(\nabla_\perp\ln(n_e) + \frac{\tau_\alpha}{Z_\alpha}\nabla_\perp\ln(n_\alpha)\right) \quad (6)$$

$$\mathbf{u}_{R,i\to\alpha} = -\sum_\beta D_{\alpha\beta}\left[\nabla_\perp\ln(n_\alpha) - \frac{Z_{\alpha 0}\tau_{\beta 0}}{Z_{\beta 0}\tau_{\alpha 0}}\nabla_\perp\ln(n_\beta)\right] \quad (7)$$

The total resistive drift on an ion is then $\mathbf{u}_{R_\alpha} = \mathbf{u}_{Re\to\alpha} + \mathbf{u}_{R,i\to\alpha}$.

**Seeded blobs**

The dynamics of seeded blobs has been studied extensively, e.g. with the HESEL model in ref [5]. In this work we investigate different ion mixes and the inlfuence it has on blob-propagation. We initialize the blob with a uniform temperature and Gaussian density perturbation:

$$n(x,y,0) = n_0 + n_b\exp\left(-\frac{x^2+y^2}{2\sigma^2}\right) \quad (8)$$

For the electrons we have $n_0 = 10^{19}m^{-3}$, $n_b = n_0$ and blob width of $\sigma = 5\rho_s = 5\sqrt{\frac{T_{e0}}{m_D\Omega^2_{D0}}}$. We initialize both ions equally with the same magnitude of perturbation compared to their respective background meaning that the initial ratio between ion densities is uniform.

**Mass Dependence**

A commonly used velocity scaling can be found in [5] and states that:

$$V_\perp \propto c_s \propto \sqrt{m_{ion}^{-1}} \quad (9)$$

From this we see that for heavier species the blob should move slower. The results for these runs are seen in Figure 1 where we see both a real mix of DT and the same runs in a one fluid simulation with effective mass instead, with it being defined as

$$m_{eff} = \frac{\sum_\alpha n_\alpha m_\alpha}{\sum_\alpha n_\alpha} \quad (10)$$

It is evident that the more tritium the mix contains the heavier the average ion in the blob is.

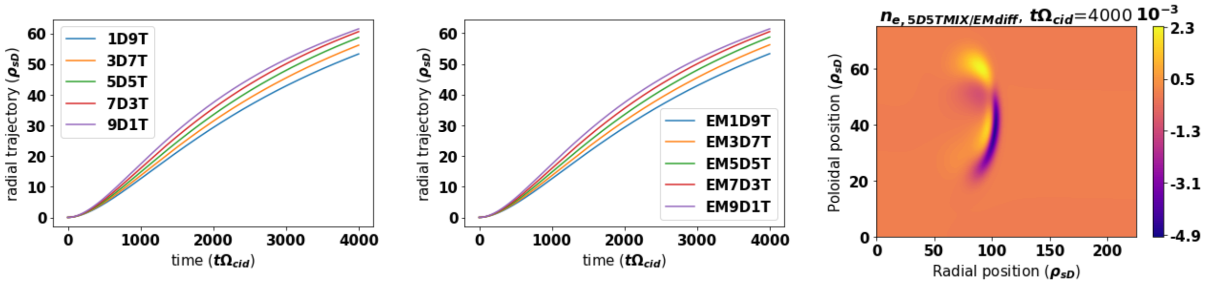


*Figure 1: Left: Five runs with different ion mix where e.g. 1D9T means 10% of electron are supplied from deuterium and 90% from tritium. Middle: Five runs similar to the ones in left but with one species with effective mass. Right: Electron density difference for isotope mix and effective mass for 50% D and 50% T.*

This then means that the more tritium, the slower it moves which is also seen unambiguously in the left (and middle) plot. I.e. qualitatively, the blobs evolve as we would expect from the velocity scaling mass dependency. Similarly we see that if we instead use a single species with an effective mass, which is defined as: the same result appears. In fact, the two cases look very similar which is also evidenced the in right plot where we see the difference between the electron density for a mix and an effective mass in the 50%-50% DT case. Here the difference is so small compared to the initial perturbation that to leading order the two cases are the same.

**Charge Dependence**

Plasmas containing ions with different charge is another point of interest and to look into this question we use a $He^+$ and $He^{2+}$ mixture as they have the same mass but different charge. We initialize the two species such that they each contribute the same amount of electrons to the electron density, hence the notation is again such that $5He^+5He^{2+}$ means 50% of electron are supplied by each species respectively. The reason for this choice of notation is because we fix the electron density. Again five runs are made with varying mixtures with the results shown in fig 2. Due to the $1/Z$ dependency in the diamagnetic drift, which initializes the blob polarization and leads to $\mathbf{E}\times\mathbf{B}$-drift, we expect the blob to move slower for higher ionization number. Here we see in the left plot that as expected, the mix with lower ionization number moves faster radially. At the same time, an effective charge has been tested which shows very similar behaviour. The effective charge is calculated such that the overall ion electron collision frequency stays the same which gives the effective charge (see [6]):

$$Z_{eff} = \frac{\sum_\alpha n_\alpha Z_\alpha^2}{\sum_\alpha n_\alpha Z_\alpha} \tag{11}$$

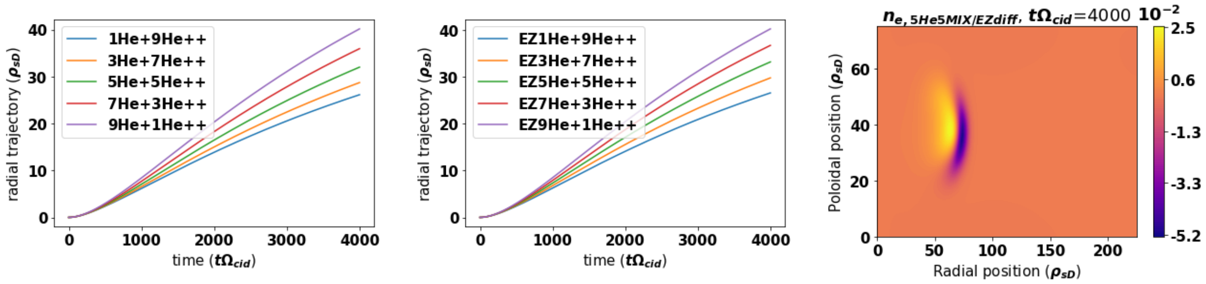


*Figure 2: Left: Five runs with different ion mix where e.g.* $1He^{+}9He^{2+}$ *means 10% of electron are supplied from* $He^{+}$ *and 90% from* $He^{2+}$*. Middle: Five runs similar to the ones in left but with one species with effective charge. Right: Electron density difference for isotope mix and effective charge for* $5He^{+}5He^{2+}$.

Likewise we see in the right plot that the difference between real mix and difference is somewhat small, although not as small as for effective mass. This together with the comparing the middle and left plot shows that in this ideal case, the effective charge is a decent approximation.

## Conclusion

In this contribution we have seen the use of a multispecies code to study seeded blobs with different mixes of ions with different masses and charges. We saw that the behaviour is qualitatively as we expect with blob movement correlated to ion mass and charge number. Furthermore, we found that an effective mass and charge were reasonable approximations as they showed very similar radial behaviour. In this regard, further studies should be done into whether the approximations still hold when there is a non-uniform ratio. For example when we inject a species into a different mix, e.g. lithium into a pure deuterium plasma and so an overall effective mass would not be suitable. One main strength of our model, which will be investigated later, is the ability to influence individual species such as heating mainly one ion species, or isotope dependent initial pressure and density conditions.

## References

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