Full-F gyrofluid modelling of blob-impurity interaction in the tokamak scrape-off layer

E. Reiter[1], M. Held[1], A. Kendl[1], M. Wiesenberger[2]

[1]Universität Innsbruck, Innsbruck, 6020, Austria
[2]Technical University of Denmark, Kongens Lyngby, 2800, Denmark

universität innsbruck

FWF Der Wissenschaftsfonds.

Motivation: Impurity ions alter tokamak plasma evolution.

Impurities denote **ions that are not part of the intended reactor fusion cycle**, but are inevitably present in the plasma: Operating a tokamak involves plasma-wall interaction, intended at strike zones on divertor plates while undesirable anywhere else. Subjected to further ionisation, a significant number of sputtered wall particles will propagate into and severely disturb the plasma [1].

- **Negative effects** on tokamak performance stem from impurity accumulation **at the plasma core**, resulting in increased radiation losses (high mass impurities) and plasma dilution (low mass impurities) [2].
- **Beneficial effects** are expected from heat mitigation via impurity seeding **at the divertor** [3].

Preliminaries: Blobs dominate transport across the plasma edge.

At the edge of magnetised fusion plasmas **radially propagating filaments**, elongated along field-lines, **dominate heat and particle transport**. Fueled by steep pressure gradients at the vicinity of the last closed flux surface these "blobs" are expelled into the scrape-off layer (SOL).

- Particle density amplitudes of such perturbations compared to the background can be well above unity [4], defying any model based on separation of background and fluctuating quantities.
- The strong anisotropy of a tokamak magnetic field decouples perpendicular from parallel blob dynamics and scales (taking the $\boldsymbol{B}$-field orientation as a reference) [5].

Question: Impurities alter blob evolution?

Dependent on their concentrations, masses, charges and temperatures in a magnetised fusion plasma, **how do non-fuel ions, i.e. impurities, modify the dynamics of blobs** propagating through the scrape-off layer?

Common approaches in modelling turbulent impurity ion transport do not provide toolsets suitable for parameter studies on impurity-blob interaction:

- Gyrokinetic simulations [6] remain computationally expansive, whereas
- computationally attractive models most often resort to a "trace-approximation" with impurities as passive test particles not altering plasma evolution.

Result: Impurites slow blob propagation!

A parameter-scan on cold isothermal seeded blob simulations (initial fuel particle densities as Gaussian peaks with constant impurity background) for maximum perpendicular center-off-mass (COM) blob velocities (parameter proportional to heat and particle transport by the filaments) depicts:

- **Increased impurity concentration and/or higher mass-to-charge proportion of non-fuel ions results in slower blob propagation** (fig. 1) and hence less spatial dilation of the filament (compare fig. 2).
- Numerical experiments reproduce the analytical velocity scaling law for the set of full-F multi-species 2d gyrofluid equations.

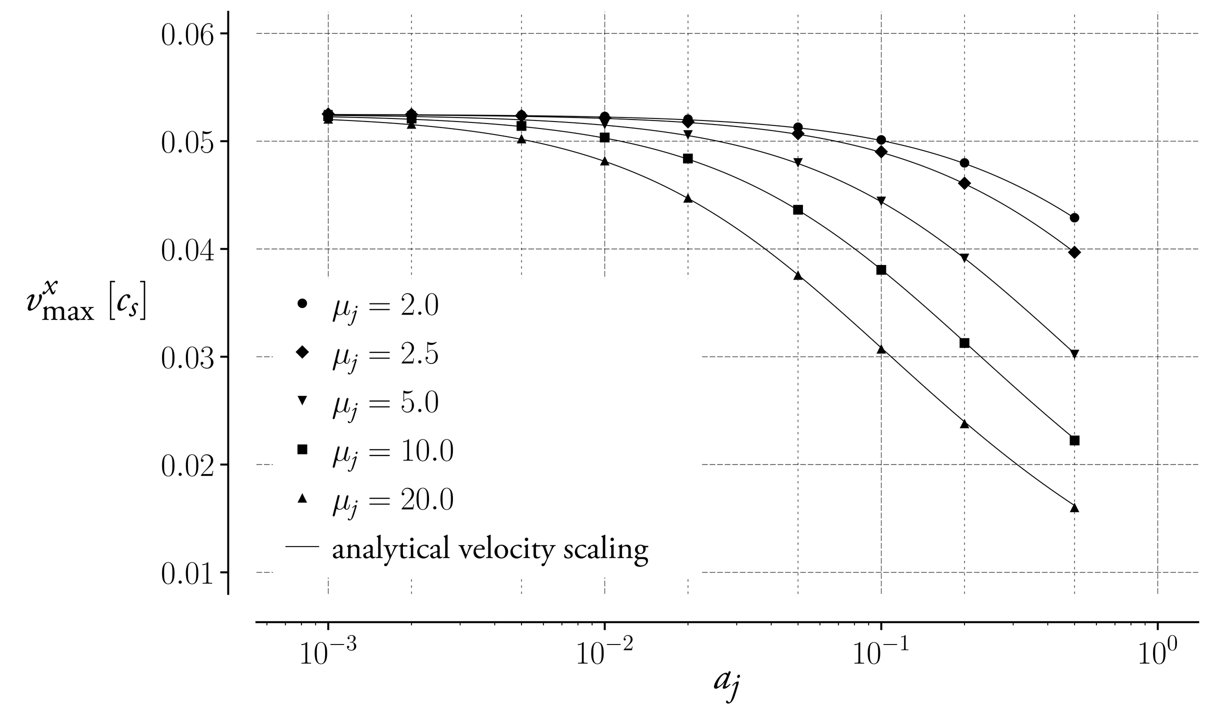


Fig. 1: Maximum perpendicular COM blob velocity $v^x_{\max}$ (physical parameters resemble ASDEX-U low field side) dependent on impurity concentration a_j for different mass/charge proportions μ_j.

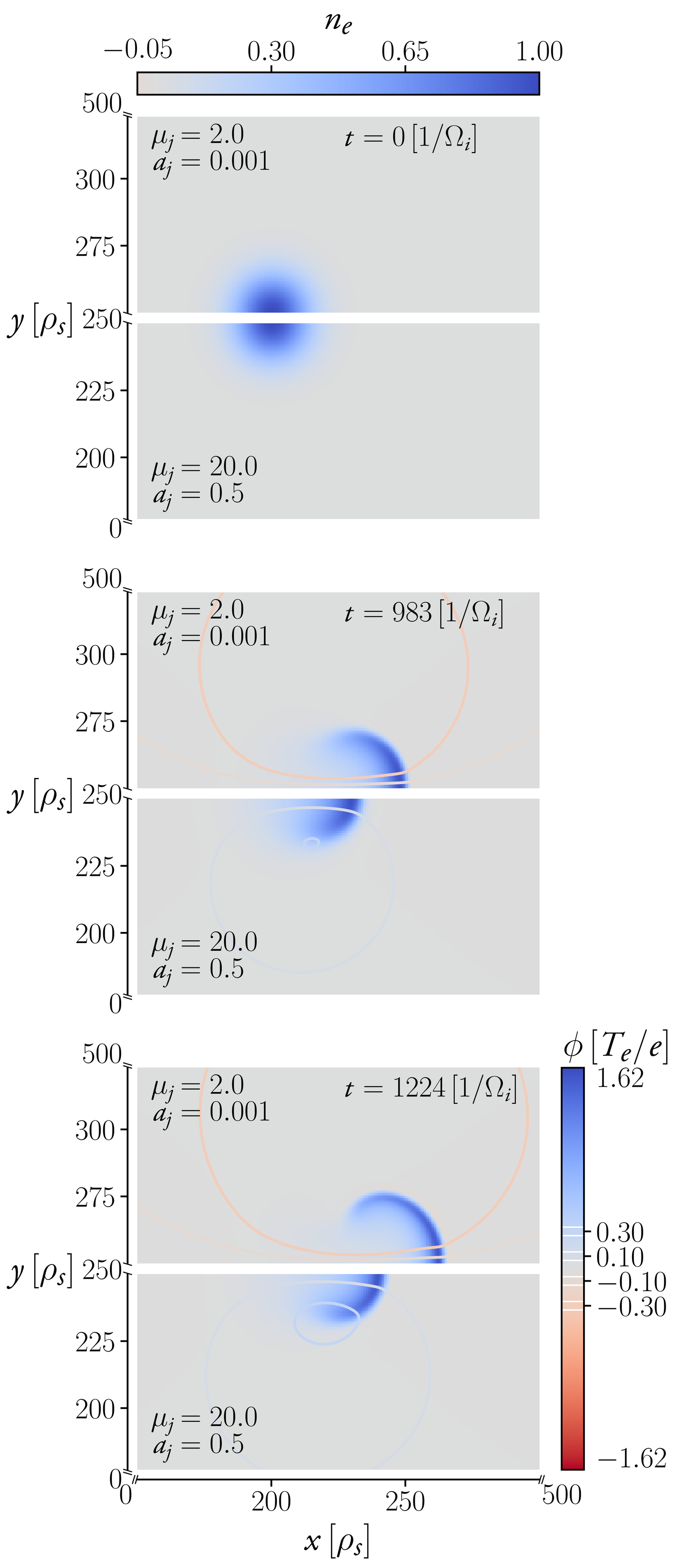


Fig. 2: Seeded cold fuel ion blob simulation with constant impurity background: Electron density n_e and electric potential ϕ. Physical parameters resemble the SOL on the low field side of the ASDEX Upgrade tokamak (simulation parameters: Initial gaussian density distribution of fuel ions with amplitude $\Delta n_i/n_i = 1$ and $\sigma = 10$, for $\kappa = 0.000457$ and Reynolds number chosen to $\mathcal{R}a = 10^5$).

Model: Full-F multi-species 2d gyrofluid equations

The evolution of electron particle density n_e and ion gyrocenter densities N_s of fuel respectively impurity ions ($s = i, j$) in a quasi-neutral, isothermal and electrostatic plasma is described via a full-F multi-species gyrofluid model. No distinction is made between dynamical background and fluctuations.

By gyro-Bohm normalisation (referencing ion gyrofrequency $\Omega_i = eB_0/m_i$, drift scale $\rho_s = \sqrt{m_i T_e}/(eB_0)$ and cold ion acoustic speed $c_s = \rho_s \Omega_i$) dimensionless equations are derived in an orthonormal 2D slab geometry. Dynamics parallel to $\hat{\boldsymbol{z}}$ direction are neglected, the magnetic field strength B varies radially alongside $\hat{\boldsymbol{x}}$ via $1/B = (1 + x/R)/B_0$, with R the major tokamak radius:

$$\partial_t n_e + \frac{1}{B}\{\phi, n_e\} - n_e \kappa \partial_y \phi + \kappa \partial_y n_e = -\nu \nabla_\perp^4 n_e$$

$$\partial_t N_s + \frac{1}{B}\{\psi_s, N_s\} - N_s \kappa \partial_y \psi_s - \tau_s \kappa \partial_y N_s = -\nu \nabla_\perp^4 N_s$$

$$\sum_s \left[\nabla \cdot \left(\frac{a_s \mu_s N_s}{B^2} \nabla_\perp \phi\right) - n_e + a_s \Gamma_s N_s\right] = 0$$

$$\Gamma_s = \left(1 - \frac{1}{2}\tau_s \mu_s \nabla_\perp^2\right)^{-1} \quad \text{... Padé approximation of gyroaveraging operator}$$

$$\psi_s = \Gamma_s \phi - \frac{1}{2}\mu_s \left(\frac{\nabla_\perp \phi}{B}\right)^2 \quad \text{... FLR corrected electric potential}$$

With reference to fuel ion mass m_i and electron temperature T_e a set of three dimensionless parameters:

$$\mu_s = \frac{m_s}{Z_s m_i}, \quad \tau_s = \frac{T_s}{Z_s T_e} \quad \text{and} \quad a_s = \frac{Z_s n_{s,0}}{n_{e,0}}$$

accounts for charge numbers Z_s, masses m_s, temperatures T_s and concentrations of different ion species.

Poisson-Brackets $\{\ ,\ \}$ are used in denoting $\boldsymbol{E} \times \boldsymbol{B}$ advection, $\nabla_\perp$ abbreviates application of $-\hat{\boldsymbol{z}} \times (\hat{\boldsymbol{z}} \times \nabla)$ and $\kappa = 1/R$. Fourth order hyperdiffusion $-\nu \nabla_\perp^4$ ensures numerical stability.

Model: Energy conservation

$$\partial_t \int d\Omega \left[n_e \ln n_e + \sum_s a_s \tau_s N_s \ln N_s + \frac{1}{2}\sum_s a_s \mu_s N_s \left(\frac{\nabla_\perp \phi}{B^2}\right)\right] =$$
$$\nu \int d\Omega \left[\nabla_\perp^4 n_e (1 + \ln n_e - \phi) + \sum_s a_s \nabla_\perp^4 N_s (\tau_s + \tau_s \ln N_s - \psi_s)\right]$$

Model: Velocity scaling

Scaling analysis of the vorticity equation provides an equation for the growth rate γ and hence for the maximum perpendicular velocity of a σ-sized blob with amplitude A:

$$v^x_{\max} := \gamma\sigma \propto \sqrt{\frac{A\kappa\sigma\,(1 + \sum_s a_s \tau_s)}{\sum_s a_s \mu_s}}$$

Model: Derivation

particle $\mathcal{H}$ dynamics $\longleftrightarrow$ **Vlasov-Maxwell (VM) equations**

average: gyration of particles in equilibrium B-field

guiding-center (gi) $\mathcal{H}$ dynamics

average: gi gyromotion in perturbed field

gyro-center (gy) $\mathcal{H}$ dynamics $\longleftrightarrow$ **gyrokinetic VM equations**

take moments, apply closure

gyrofluid equations

Method: FELTOR numerical library

The multi-species 2d gyrofluid equation set is integrated using the FELTOR C++ numerical library [7]:

- Discontinous Galerkin spatial discretisation,
- semi-implicit multistep time integrator (Karniadakis),

both access a preconditioned conjugate gradient solver.

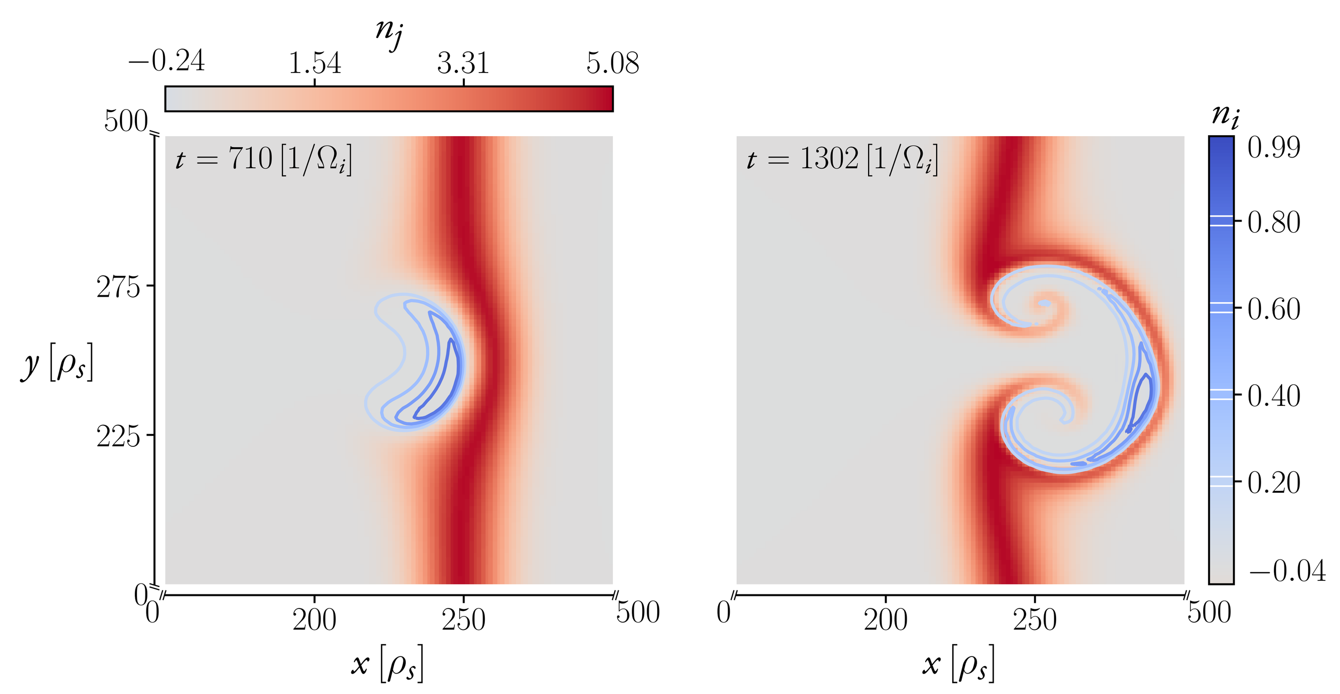
Calculations scale on distributed as well as on shared memory systems, efficiently executable on CPUs and GPUs (NVIDIA) as well as on accelerators (Intel Xeon Phi: Knights Landing).

Outlook: Hot ions & impurity inhomogeneity

Model and method include multiple impurity species, finite ion temperatures and arbitrary initial impurity distributions (examples depicted in fig. 3). Further simulations will examine:

- temperature effects on impurity-blob interaction,
- Blob propagation/multi-species impurity transport with inhomogeneous particle distributions.

Comparison with gyrokinetic calculations for impurity transport by blobs and holes [6] will provide a useful benchmark.



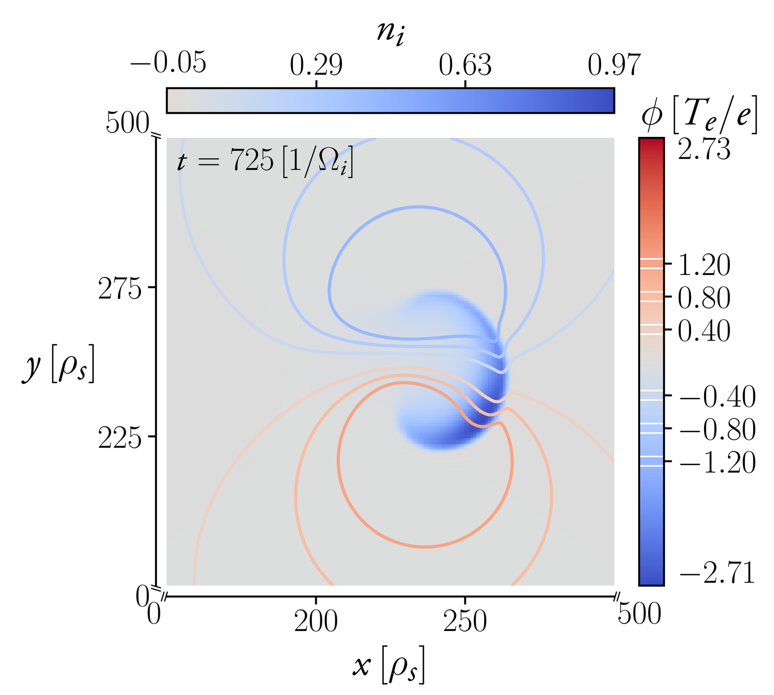


Fig. 3: *(top)* Seeded hot blob simulation; Impurity wall: Impurity density n_j and fuel ion density n_i.
Simulation parameters as for fig. 2, with wall amplitude $\Delta n_j/n_j = 1$ and wall width $\sigma_{\text{wall}} = 10$, temperatures are chosen to result in $\tau_i = \tau_j = 1$).
(right) -; Constant impurity background: Fuel ion density n_i and electric potential ϕ.
Simulation parameters as for fig. 2, with temperatures chosen to accord to $\tau_i = \tau_j = 2$ and concentration $a_j = 0.01$).

Data & licence

Sourcecode, scripts and parameters to reproduce simulations, results and this poster, available at:

https://www.uibk.ac.at/ionen-angewandte-physik/compsys/eftc17/eftc17.html

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