# Hybrid code investigation of the physics of multi-species plasma blobs in magnetic fields

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## Abstract

Strongly localised concentrations or depressions of plasma density and temperature ("blobs") together with magnetic field density are ubiquitous in fusion experiments and in space. For example, the outward flux of energy and particles in the edge region of tokamaks often incorporates a substantial population of moving blobs. In many of these contexts, the ratio of characteristic blob lengthscales to ion orbit lengthscales is not large enough for the approximations underlying fluid or guiding centre models of plasmas to be relied upon. In the cases examined in this paper, for example, the ion Larmor radius can be comparable to the size of a plasma blob and can exceed the lengthscales which characterise the gradients of density, temperature, or magnetic field near the boundary of a blob. First principles understanding of the evolving internal and external structure of plasma blobs, and of the interplay between internal and external forces and blob dynamics, is desirable. Here we address these questions using a hybrid code in two spatial dimensions perpendicular to the magnetic field **B**. The code couples fluid equations for the plasma electrons to a fully kinetic, particle-in-cell treatment of the ions.

## Introduction

Plasma in the outer regions of a tokamak, near the last closed flux surface, can generate coherent propagating blobs. These undergo radial transport, and can break free of the confinement region. Blobs with sufficient radial velocity can strike the walls of the tokamak, increasing local particle and energy fluxes, reducing divertor efficiency, and increasing impurity levels [1][2][3][4]. Polarising curvature drifts of ions and electrons, giving rise to an electric field that may not be shorted out by parallel motion under tokamak edge conditions, gives rise in the classic picture [5] to $\mathbf{E} \times \mathbf{B}$ radial blob motion. This requires the blob to cohere on ion gyroscales, a question inviting kinetic treatment, complementing existing single- and multi-fluid treatments [6][7].

We simulate blobs using the hybrid code, which treats ions using a particle-in-cell description coupled to electron fluid equations, and self-consistently evolves the electric and magnetic fields. We assume: inertia-less electrons; $\nabla \cdot \mathbf{E}$ is negligible on length scales of inter-

est, implying charge neutrality; collisionless plasma; and an ideal, isothermal electron gas, $\nabla \cdot \underline{\underline{P_e}} = \nabla p = kT_e \nabla n$. We take the low frequency limit, allowing us to neglect displacement current.

Combining the electron fluid momentum equation,

$$n_e m_e \frac{d\mathbf{v}_e}{dt} = -en_e(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \nabla \cdot \underline{\underline{P_e}}, \tag{1}$$

with Ampère's Law yields the equation to update the electric field:

$$\mathbf{E} = \frac{1}{qn}\left(kT_e\nabla n + \frac{\nabla B^2}{2\mu_0} - \frac{(\mathbf{B} \cdot \nabla)\mathbf{B}}{\mu_0} + \mathbf{J}_i \times \mathbf{B}\right) \tag{2}$$

The current in the final term is the ion current only. The other terms arise from conventional single fluid MHD forces: pressure gradient, magnetic pressure and magnetic tension.

We initialise blobs as flux ropes of enhanced density and depressed magnetic field strength (Fig 1) in combined pressure equilibrium with the background plasma, which is initialised flowing transversely to a magnetic field at speed $\mathbf{u}$, with $u = 0.2v_A$ where $v_a$ denotes the Alfvén velocity. Conversely in the rest frame of the background plasma, the blob moves transversely to $\mathbf{B}$ at $0.2v_a$. Importantly there is no electrical charge separation, and electrical fields are motional in origin: Eqs. 1 and 2. The blob may have been launched by the mechanism of Ref. [5], and is now in a ballstic phase [7]; here we address the physical implications of such hypotheses for ion scale blob dynamics.
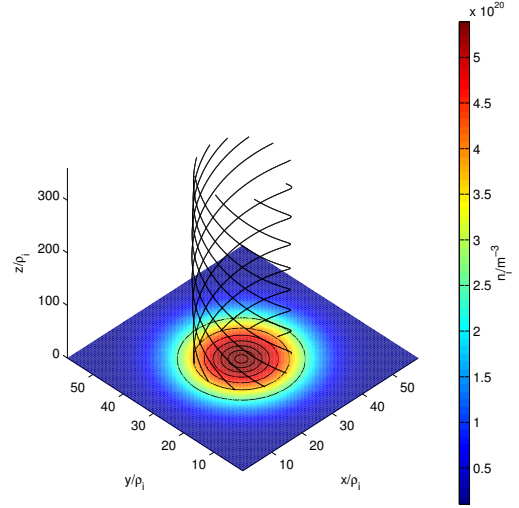


Figure 1: Initial conditions of the simulated blobs. Field lines are given in black, with the number density in color. The initial number density rises from $10^{19}m^{-3}$ in the background to $5 \times 10^{20}m^{-3}$ in the centre of the blob. The z-component of the $\mathbf{B}$ field rises from 0.08T in the centre of the blob, to 0.4T in the background.

**Simulation Results**

Snapshots of the blob as it evolves in time are given in Figure 2.

The incorporation of ion gyroscale physics enables, first, the resolution of internal blob structures, and associated gradients, in Fig. 2, that could not be captured in the fluid ion limit. This approach yields, second, external boundary structures in the same category, notably the ion gyroscale Kelvin-Helmholtz features visible at later times in Fig. 2. Third, the up-down asymmetry in Fig 2 is explicable in terms of finite ion gyroscale effects at the kinetic level of description.
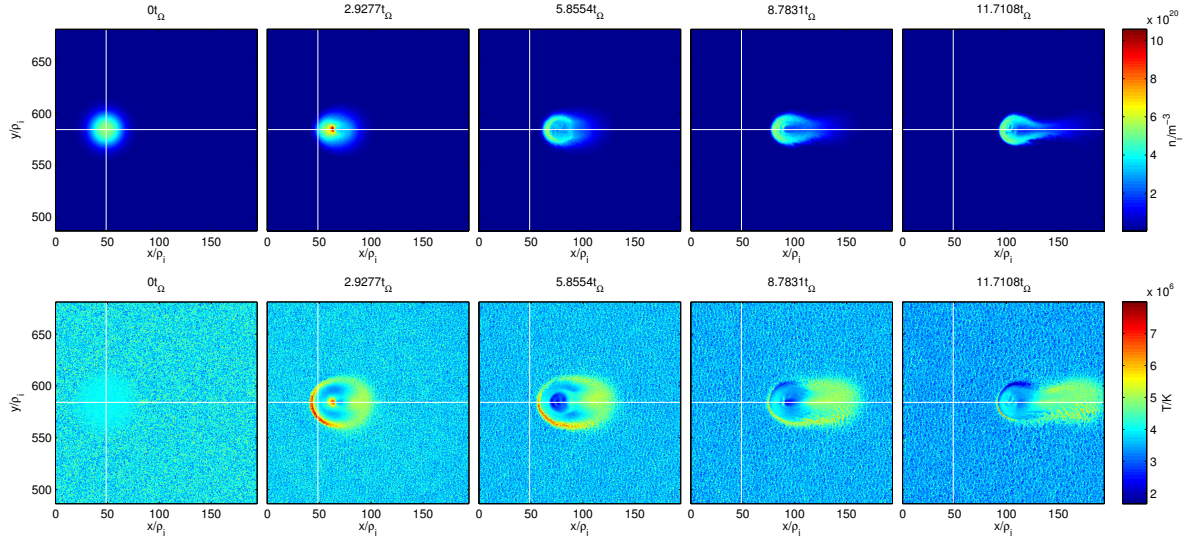
Figure 2: Number density (top) and ion temperature (bottom) color maps for the evolution of a blob in a background flow of $0.2v_A$, with background magnetic field perpendicular to the plane of the page. The ion temperature, calculated as $T = \frac{m}{3k} \left\langle v^2 - u^2 \right\rangle$ where $v$ are particle velocities and $u$ is the bulk flow, is initially constant at $4 \times 10^6$ K. The white crosshair marks the starting position of the blob. The blob is advected to the right, along the direction of the background flow, and subject to a growing Kelvin-Helmholtz instability at the boundary between the flow and blob plasmas. An asymmetry in the growth of the K-H instability is visible between the upper and lower edges of the blob, caused by finite Larmor radius effects as discussed below.

Figure 3 shows the associated electric field, with flow streamlines inferred from $\nabla \cdot \mathbf{u} = 0$, where $\mathbf{u}$ is the local plasma ion flow velocity in the simulation.

A clear effect seen in our simulations is the formation of a Kelvin-Helmholtz (K-H) instability on the upper and lower edges of the blob, due to the sheared flow between the blob and background plasmas. This instability allows momentum transfer between the two sheared fluids, contributing to the internal convection pattern as shown in Figure 3. At late times in Figure 2, we see the blob evolves asymmetrically, with a faster flow, and hence stronger K-H instability, on the lower edge. This asymmetry, which develops as a result of finite ion Larmor radius (e.g. [8]), leads to momentum transfer from background flow to blob ions in the $\mathbf{u} \times \mathbf{B}$ direction.

**Conclusions**

The preceding results show that the hybrid description (fluid electrons and fully kinetic ions) embodied in this code captures key elements of plasma dynamics and field evolution in blobs, that would be difficult to access using a multi-fluid approach. In particular, structures and gradients emerge on ion gyro lengthscales, both internal to the blob and at the boundary between the blob and the external flowing plasma. This level of ion gyro-scale physics resolution deepens understanding of the mechanisms for momentum transport into and within the evolving
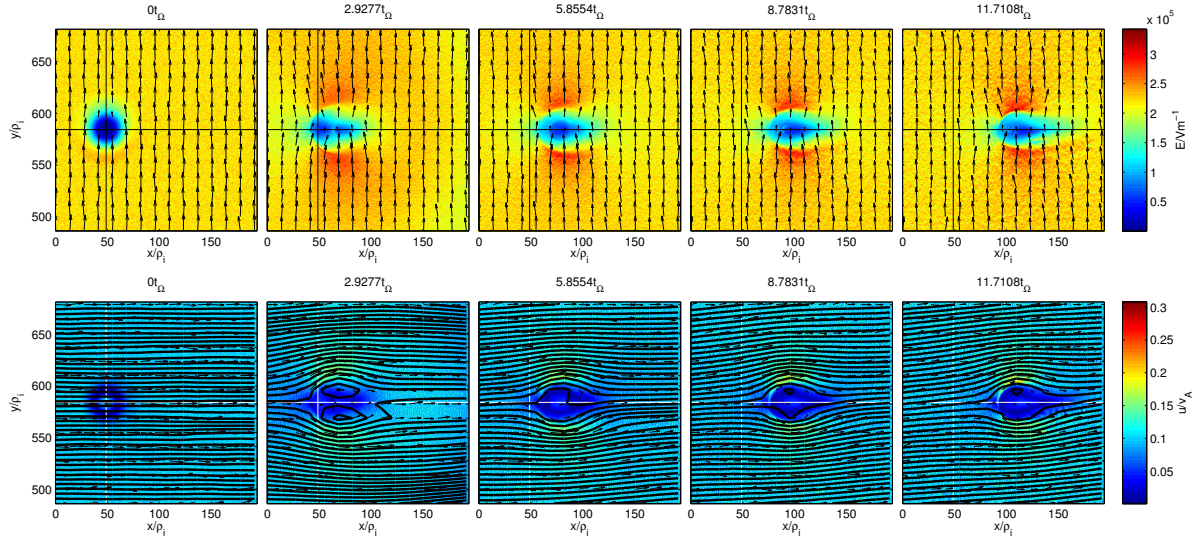
Figure 3: Electric field components in the x,y-plane (top), with directional arrows and magnitude in color, and approximate streamlines (bottom) calculated under the assumption $\nabla \cdot \mathbf{u} = 0$. Streamlines are plotted in the rest frame of the blob, with the magnitude of the velocity also given in colour. Though we do not in fact have incompressible flow, these streamlines with the accompanying electric field plots are suitable to illustrate the two convection cells formed on the upper and lower sides of the blob by momentum transfer which may be due to the Kelvin-Helmholtz instability.

blob, for example in terms of motional electric fields and of the nonlinear phase of fluid-type instabilities such as Kelvin-Helmholtz.

## Acknowledgements

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