Transport and evolution of ion gyro-scale plasma blobs in perpendicular magnetic fields

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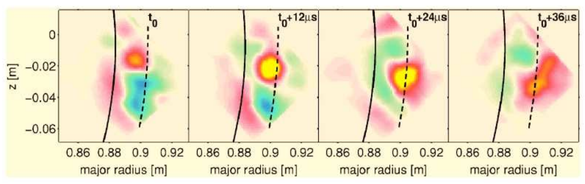
Blobs

The outer regions of tokamak plasmas, near the last closed flux surface, are observed to generate coherent propagating blobs [1], which undergo 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. Models for blob transport and evolution have principally focused on analytical and numerical fluid and multi-fluid descriptions; see, for example, Refs. [2-4]. Here we pursue a hybrid method which combines kinetic ions with fluid electrons. For a recent review of edge plasma physics in tokamaks we refer to Ref. [5].



Blobs imaged in Alcator C-mod [1]. Blobs have also been observed in DIII-D, NSTX, ASDEX Upgrade and MAST.

Hybrid Models

A hybrid model can capture the non-linear interaction between ion gyration and plasma inhomogeneity; capture cross-scale coupling between ion gyro-scale kinetic modes and fluid MHD-like modes; resolve phenomena on much shorter timescales than fluid models; and study inhomogeneities in configuration space and non-Gaussian ion velocity distributions.
The features of our hybrid code are as follows:

- It combines a particle-in-cell (PIC) algorithm for kinetic ions with an electron fluid.
- PIC codes subject weighted pseudo-particles to the Lorentz force in a continuous phase space, with E, B, J fields on a staggered grid.
- The code used is "2D3V" - a 2d simulation plane with 3 field and velocity components, e.g. $B_{x,y,z}(x,y,t)$.

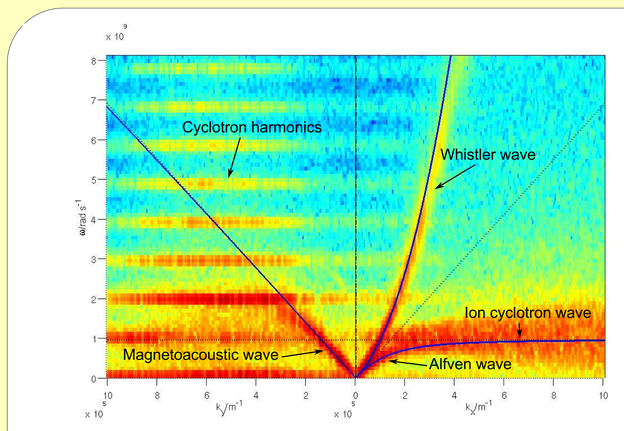
For our model we make the following assumptions:

- Inertia-less electrons, "$m_e = 0$"
- $\nabla \cdot \mathbf{E}$ is negligible on length scales of interest, implying charge neutrality $en_e = q_i n_i$
- Collisionless plasma,
- Ideal, isothermal electron gas, $\nabla \cdot \underline{P_e} = \nabla p = kT_e \nabla n$,
- We take the Darwin limit of Maxwell's equations, neglecting displacement current.

From the electron fluid momentum equation and Ampère's Law, we arrive at the equation used to update the electric field in the code:

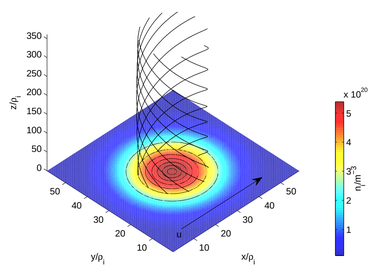
$$\mathbf{E} = -\frac{1}{en}\left(\frac{q_i}{e}kT_e\nabla n + \frac{\nabla B^2}{2\mu_0} - \frac{(\mathbf{B}\cdot\nabla)\,\mathbf{B}}{\mu_0} + \mathbf{J}_i \times \mathbf{B}\right), \qquad (1)$$

Under these assumptions electric fields cannot arise from charge separation; hence electric fields are purely motional in origin. This model allows for the propagation of Alfvén and magnetoacoustic waves, ion cyclotron waves, lower hybrid waves and whistler waves.



Dispersion relation for a cold, magnetised plasma (blue line) parallel (right) and perpendicular (left) to the background magnetic field, over the FFT of thermal noise in a uniform plasma run of the code.

Simulations



Initial conditions with number density in colour and flux-rope structure of magnetic field lines in black.

Blobs are simulated as Gaussian enhancements in density in combined pressure balance. The background plasma parameters are chosen to be approximately characteristic of edge conditions in a medium-size tokamak such as MAST:

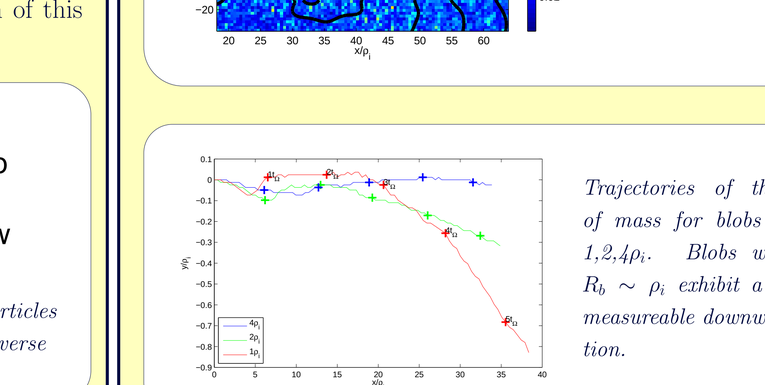
- Number density, $n_0 = 10^{19}\mathrm{m}^{-3}$
  Magnetic field strength, $B_{z,0} = 0.4\mathrm{T}$
- Temperature, $T_0 = 4 \times 10^6\mathrm{K}$
- Thermal gyro-radius, $\rho_i = 8 \times 10^{-3}\mathrm{m}$
- Background flow speed, $u_0 = 0.2v_A$

Results

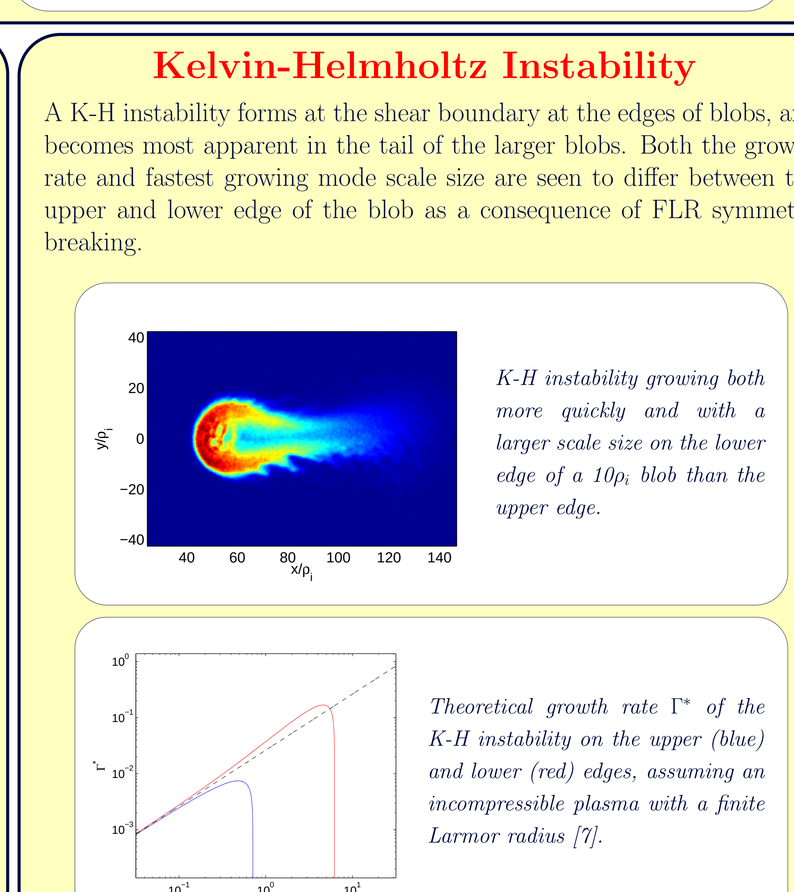
Notable features of the evolution include:

- Structures and gradients forming on the ion gyro-scale,
- Advection of the blow in the flow direction,
- Formation of twin-cell internal vortices,
- Growth of the K-H instability in a tail formed from blob ejecta,
- Asymmetry in all of the above, which becomes more pronounced for the smallest blobs,
- Deflection of smaller blobs perpendicular to the background flow.

Asymmetries are visible in both the trajectories of individual ions, and the evolution of bulk properties such as number density:



Ion trajectories in the $10\rho_i$ (left) and $2\rho_i$ (right) blobs.



Number density evolution for 1, 4 and $10\rho_i$ blobs (left to right).

Finite Larmor Radius Symmetry Breaking

The chirality of ion gyration can break the symmetry of the evolution of an otherwise symmetric blob. The asymmetry can be described mathematically using the ion momentum equation [6]:

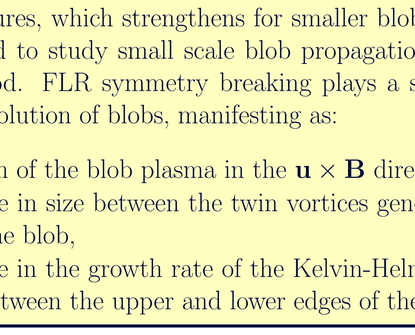
$$m_\alpha n_\alpha \frac{D\mathbf{v}_\alpha}{Dt} = en_\alpha\left(\mathbf{v}_\alpha - \frac{1}{n}\sum_{\alpha'} n_{\alpha'}\mathbf{v}_{\alpha'}\right) \times \mathbf{B} + \frac{n_\alpha}{n}(\mathbf{J}\times\mathbf{B} - \nabla p_e) - \nabla p_\alpha \qquad (2)$$

The first term on the RHS represents an asymmetry present in plasmas with distinct ion populations in velocity space. The form of this asymmetry is as follows:

Blob particles (blue) feel the $E = -u \times B$ electric field of the flow particles (red), causing them to move up as they begin to gyrate, while the reverse happens for the flow particles.

Bulk Asymmetries

The difference in flow speeds on the upper and lower edges caused by FLR symmetry breaking leads to the following bulk asymmetries:

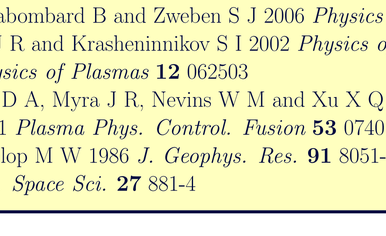


Streamlines (black) over bulk velocity (colour) for a $4\rho_i$ blob. The vorticity cells on the upper and lower edges grow asymmetrically.

Trajectories of the centres of mass for blobs of radius 1,2,4ρ_i. Blobs with radius $R_b \sim \rho_i$ exhibit a small but measureable downward deflection.

Kelvin-Helmholtz Instability

A K-H instability forms at the shear boundary at the edges of blobs, and becomes most apparent in the tail of the larger blobs. Both the growth rate and fastest growing mode scale size are seen to differ between the upper and lower edge of the blob as a consequence of FLR symmetry breaking.



K-H instability growing both more quickly and with a larger scale size on the lower edge of a $10\rho_i$ blob than the upper edge.

Theoretical growth rate Γ^* of the K-H instability on the upper (blue) and lower (red) edges, assuming an incompressible plasma with a finite Larmor radius [7].

Conclusions

The preceding results demonstrate how the hybrid model (fluid electrons and fully kinetic ions) embodied in the code captures key elements of the plasma dynamics and the evolution of the fields in ion gyro-scale blobs. Many of the phenomena described above are common to a purely fluid approach to blob simulation, including:

- Advection in the direction of the background flow
- Development of a twin-celled internal vortex pattern
- Growth of a Kelvin-Helmholtz instability in the tail of the blob

The substantial asymmetry which we find develops in these evolving features, which strengthens for smaller blobs, underlines the need to study small scale blob propagation using a hybrid method. FLR symmetry breaking plays a significant role in the evolution of blobs, manifesting as:

- A deflection of the blob plasma in the $\mathbf{u} \times \mathbf{B}$ direction,
- A difference in size between the twin vortices generated internal to the blob,
- A difference in the growth rate of the Kelvin-Helmholtz instability between the upper and lower edges of the blob.

Acknowledgements

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