The Transition from Interchange to Boltzmann Dynamics in a 3D SOL Filament

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Introduction

Filaments are field aligned structures which remain highly localised in the plane perpendicular to the magnetic field. They are ubiquitous to magnetically confined plasmas [1]. They provide a strong source of non-local particle transport into the SOL (Scrape Off Layer) and consequently can play a crucial role in determining SOL parameters. As a consequence the subject of filament dynamics has received considerable attention from the theoretical ([2] and references therein) and experimental ([1] and references therein) communities in recent years. In this paper the term filament will refer to the full 3D structure of the object, and the term blob will refer to the 2D structure of the object in the perpendicular plane.

The interchange mechanism, which is the dominant dynamic mechanism underlying filament propagation, is a polarization of charge by drift motion induced by forces directed perpendicular to the magnetic field [3]. In the SOL of a tokamak a centrifugal force is produced by the curvature of magnetic field lines which leads to charge polarization. The filament is then advected outwards by **E**x**B** motion due to the dipolar potential. Commonly closure schemes are employed to account for charge dissipation along the magnetic field line. Recently however Angus *et. al*. have shown that accounting for 3D effects in plasma filaments can cause a departure from standard 2D dynamics[4]. If the filament is homogeneous along the field line small perturbations in the parallel direction can drive unstable resistive drift-waves which form on the filament front and cause it to disperse. If macroscopic, sustained parallel gradients occur then the filament can adopt a Boltzmann potential which spins it, preventing radial propagation. In this paper we investigate the transition from interchange dynamics to Boltzmann dynamics in a realistic MAST SOL geometry.

Model

The model employed to perform the filament simulations presented herein is a very simple two-fluid model consisting of (in SI units) continuity of electron density

$$\frac{d}{dt}n = 2c_s\rho_s\boldsymbol{\xi}\cdot\nabla n + \nabla_{||}\frac{J_{||}}{e} \quad (1)$$

and current ($\nabla\cdot\boldsymbol{J} = 0$)

$$\rho_s^2 n\frac{d}{dt}\Omega = 2c_s\rho_s\boldsymbol{\xi}\cdot\nabla n + \nabla_{||}\frac{J_{||}}{e} \quad (2)$$

with the vorticity

$$\Omega = \nabla_\perp^2 \phi \tag{3}$$

and parallel current density

$$J_{||} = \sigma_{||} T_e \left(\nabla_{||} \mathrm{Ln}(n) - \nabla_{||} \phi \right) \tag{4}$$

solved as auxiliary equations. Here n is electron density, ϕ is electrostatic potential normalized to the electron temperature T_e (in eV). $\boldsymbol{\xi} = \boldsymbol{b} \times \boldsymbol{\kappa}$ is the polarization vector where $\boldsymbol{b}$ is the magnetic field tangency vector and $\boldsymbol{\kappa}$ is the magnetic curvature vector. c_s and ρ_s are the Bohm sound speed and Bohm gyro-radius whilst $\sigma_{||}$ is the parallel conductivity (see [5] for details). The simulation geometry is based in a field aligned coordinate system [5,6]. y points along the magnetic field line whilst z points toroidally and x points in the direction of $\nabla\psi$ at the midplane (where all the results within this paper will be taken from, unless otherwise stated). The boundary conditions are zero gradient Neumann conditions for all variables on the x and y boundaries except the parallel current which is matched to the sheath current at the y boundary. The z domain (which is in the toroidal direction) is assumed to be axisymmetric and is periodic with a period of 15. The simulation domain is based around a MAST SOL flux tube where magnetic parameters are allowed to vary along the length of the simulation grid (ie in the y coordinate). Figure 1 shows the magnetic field line chosen for the simulation grid, along with the magnetic field strength and curvature strength along y. The effect of allowing variation in magnetic parameters along the field line is that the interchange mechanism becomes driven at different rates along the filament. This is through curvature variation, and also through flux expansion which arises due to the varying magnitude of the magnetic field. As such a filament undergoing interchange motion will naturally develop parallel gradients in both density and potential [5], which can become subject to the Boltzmann response in certain parameter ranges. In the next section results of simulations conducting in the MAST SOL flux tube geometry using the BOUT++ fluid modelling framework [6] are presented.

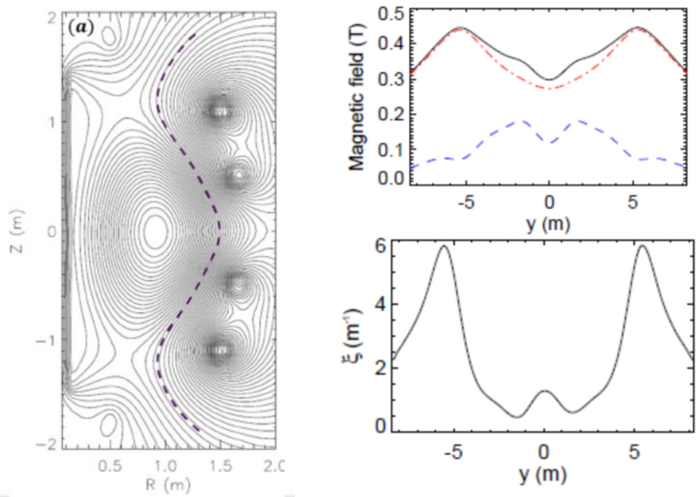


Figure 1. Magnetic field line in the MAST SOL selected as the basis for the simulation grid (left). The magnetic field strength (right, upper; black is total, red is toroidal and blue is poloidal) and magnetic curvature (right, lower) along the length of the field line

Results

A series of simulations have been conducted with varying electron temperature, background density and radius. The most notable change in the filament dynamics occurs with electron temperature. Figure 2 shows a series of midplane cross-section in the x,z plane of a filament simulation conducted with an electron temperature of 1eV. At this temperature the filament undergoes interchange motion, as indicated by the classic mushrooming structure that develops. The lower panels in figure 2 show $\nabla_{||}\mathrm{Ln}(n)$ in colour and $\nabla_{||}\phi$ as contours. When the filament undergoes interchange motion the parallel gradients of density and potential that develop as a result of the magnetic geometry are not in phase. When electron temperature increases the left hand side of (4) can be neglected and $\nabla_{||}\mathrm{Ln}(n)\sim\nabla_{||}\phi$ which is the definition of the Boltzmann response. Figure 3 shows a filament simulation at 20eV. Two

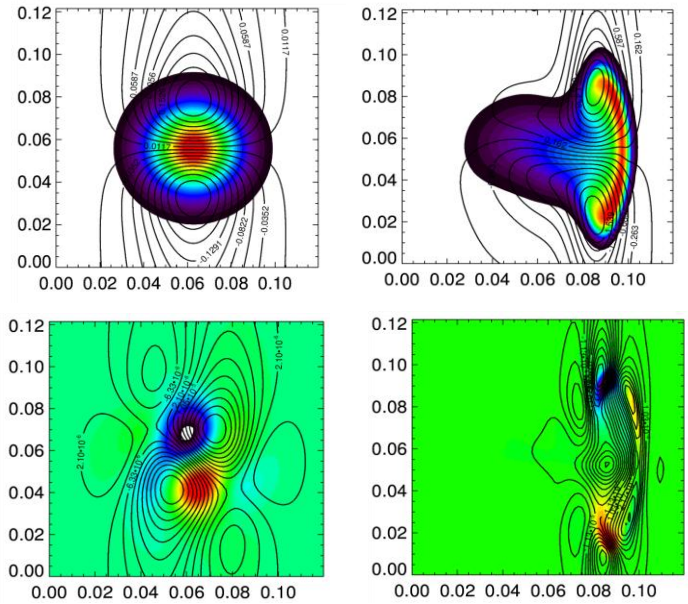


Figure 2. Upper; Filament cross-sections taken at the midplane at 20 and 400μs left to right at 1eV. Color is density and contours are potential. The filament was initialised with $\frac{\delta n}{n_0} = 1$, $n_0 = 5 \times 10^{18} m^{-3}$. Lower; Parallel density gradient (colour) and potential gradients (contour) taken at the same cross-section as in the upper frames . x and z axis are in meters.

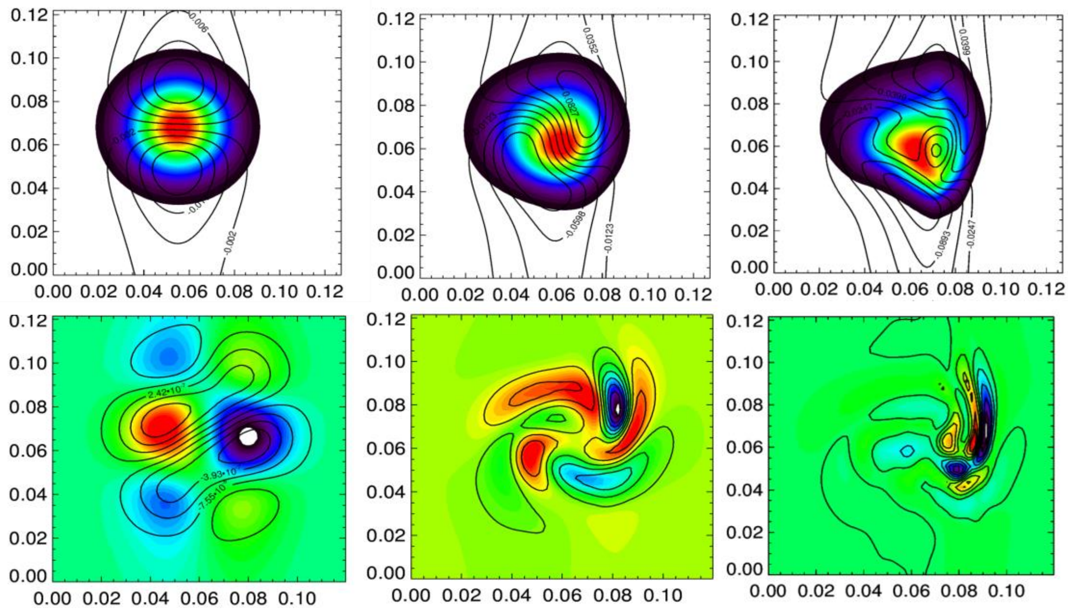
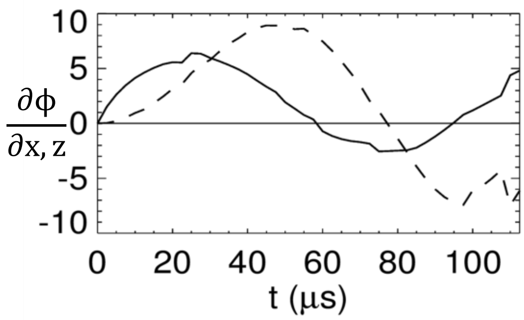


Figure 3. Filament evolution in the Boltzmann regime. From left to right cross-sections are taken at 2.5, 50 and 100 μs which is approximately 30% of the parallel streaming time, as in figure 2.) Upper; Following a period of pole rotation the potential (contours) and density (colour) begin to match phases, causing the blob core to rotate and halting radial propagation. Lower; Pole rotation results in the alignment of parallel gradients in density (colour) and potential (contours) confirming that the Boltzmann response is the dominant mechanism. x and z axis are in meters.

stages of the filament motion are evident. First the parallel gradients in density and potential that occur as the filament is initially interchange driven must realign to satisfy the Boltzmann relation. This is achieved by a rotation of the poles of the potential. When the Boltzmann relation is satisfied and the gradients have aligned, a phase matching between the density and potential begins to occur. This is shown in the latter panel of Figure 3. In the Boltzmann regime higher temperatures increase the conductivity along the filament. As such the filament can no longer sustain a large charge polarization across its core since the charge is quickly conducted away. As a result the spinning motion induced by the Boltzmann response is comparable to the radial propagation due to charge separation. Figure 4 shows the spinning nature of the filament. Notably some net radial motion occurs since the gradient of potential in z is slightly offset from zero however the resulting velocity is comparable to the Boltzmann spinning, so the filament cannot be ejected into the far SOL.



Potential gradient in x (dashed) and z (solid) calculated at the filament core in the Boltzmann regime.

Discussion and Conclusions

Simulations of filaments in a magnetic geometry based on the SOL of the MAST tokamak show a transition with temperature between filaments dominated by purely interchange motion and filaments which are augmented by the Boltzmann response. Parallel gradients develop in the filaments as a consequence of the magnetic geometry. When the temperature increases the filament adopts a Boltzmann relation between parallel density and potential gradients which causes a rotation of the potential poles before a phase matching between density and potential. Charge conduction along the filament then acts to reduce the radial velocity and the filament spins.

Filaments in experiment are commonly found in the far SOL region. However filaments are non-local and should inherit the parameters from the separatrix region, which are often above the temperature range predicted here to result in the Boltzmann regime. We hypothesise therefore that some cooling must take place to facilitate a transition from the Boltzmann to the interchange regime and allow the filaments to propagate into the far SOL.

References

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