Gyrofluid Simulations of Tokamak Edge Plasmas

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Initial progress with gyrofluid filament simulations is presented in this work. The gyrofluid model used in this study is briefly introduced [1] and initial progress towards solving it using BOUT++ [2, 3] is presented. The focus of these simulations is on filament dynamics as modified by finite Larmor radius (FLR) effects. Of particular interest are filament-background interactions and filament propagation near the SOL.

Introduction

Filaments are field aligned structures that are known to form in the scrape-off-layer (SOL) in tokamaks. These structures are composed of hot electrons and ions. They can constitute a non-negligible thermal and particle flux on the first wall. As such the propagation of these structures to the first wall is problematic. All unnecessary heat loading of structural components must be avoided to prolong the lifetime of a fusion device. In order to arrive at an optimal design for a next-generation machine it is advantageous to predict wall fluxes so that thermal loading and tritium retention can be modelled. One approach to predicting such fluxes in plasmas is to rely on simulation. However depending on which kinetic equation, closure and approximations are used some physics can be lost. For instance, finite Larmor radius *FLR* effects are often lost. The approach described herein is to use a gyrofluid model.

When attempting to capture finite Larmor radius effects to high order without incurring a large computational cost a gyrofluid code is a natural choice. There are two main types of gyrofluid models, those that are *delta-f* and those that are *full-f*. Delta-f models are derived with the assumption that fluctuations of state variables are small compared their background values. Full-f models typically make no such assumption, however collsion operators are much more difficult to implement while maintaining energetic consistency in full-f models [4]

GEM

The model used in this work is GEM [1, 5], a six-moment, n-fluid, delta-f, electromagnetic gyrofluid code. The dissipation free part of the moments being evolved is shown below where z is the species label. $[\phi_G,]$ and $[\Omega_G,]$ are advective terms, terms of the form $\nabla_\parallel$ are linear parallel gradient and magnetic pumping terms, S is a particle source and terms of the form $[\chi_G,]$ are FLR correction terms. $\Gamma_{1|2}$ are gyroaverage operators and $\mathscr{K}$ is a curvature operator. ϕ and $A_\parallel$ are the electrostatic and parallel electromagnetic potentials respectively. τ_z and μ_z

are signed temperature and mass ratios. To these expressions dissipative terms are added. It is largely because of GEM's ability to handle collisional and dissipative terms in a straightforward manner that it was chosen for this application. Collisions are expected to be important in the edge, therefore so too is having correct collisional terms.

$$\frac{\partial n_z}{\partial t} = -\left[\phi_G, n_z\right] - \left[\Omega_G, T_{z\perp}\right] - B\nabla_{\parallel}\frac{u_{z\parallel}}{B} + \beta_e\left[\chi_G, q_{z\perp}\right] + \mathscr{K}\left(\tau_z\frac{p_{z\parallel}+p_{z\perp}}{2} + \phi_G + \frac{\Omega_G}{2}\right) + S$$

$$\beta_e\frac{\partial A_G}{\partial t} + \mu_z\frac{\partial u_{z\parallel}}{\partial dt} = -\mu\left[\phi_G, u_{z\parallel}\right] - \mu_Z\left[\Omega_G, q_{z\perp}\right] - \nabla_{\parallel}(\phi_G + \tau_z p_{z\parallel}) + \beta_e\left[\chi_G, (\Omega_G + \tau_z T_{z\perp})\right]$$
$$- \left(\Omega_G + \tau_z T_{z\perp} - \tau_z T_{z\parallel}\right)\nabla_{\parallel}\log(B) + \tau_z\mu_z\mathscr{K}\left(\frac{4u_{z\parallel}+2q_{z\parallel}+q_{z\perp}}{2}\right) - \mu\frac{Su_{z\parallel}}{n_z}$$

$$\nabla_{\parallel} = b\cdot\nabla - \beta_e\left[A_G,\right], \quad \phi_G = \Gamma_1\phi, \quad \Omega_G = \Gamma_2\phi, \quad A_G = \Gamma_1 A_{\parallel}, \quad \chi_G = \Gamma_2 A_{\parallel}$$

Implementation

Initially a 2D version of GEM was implemented and used to carry out seeded filament simulations. The filaments were initialised Gaussian profiles in the perpendicular plane. Simulations using the 2D version overestimated the peak filament velocity compared to fluid models. It is now believed that applying better parallel closures may have yielded more realistic results.

In order to evolve the parallel velocity a global, 3D version of GEM was implemented in BOUT++. Initially the code was implemented using co-located grids however checker-boarding due to pressure-velocity decoupling introduced significant noise in the parallel direction. To remedy this problem staggered grids were adopted. This meant that flux like variables and the electromagnetic potential were defined on the lower cell face in the parallel direction while the state variables remained defined at cell centres. Interpolation routines are used where combinations of state and flux variables are required. This procedure effectively eliminates the checker-boarding problem.

To further stabilise the code $\ln n$ is evolved instead of n, this is trivially implemented since $\frac{\partial \ln n}{\partial t} = \frac{1}{n}\frac{\partial n}{\partial t}$. This is observed to have a strong stabilising effect on the stability of the code.

Once numerical issues were minimised equilibrium fields were calculated for each state and flux variable. Sheath boundary conditions were applied at one end of the domain with midplane boundary conditions applied on the other. A flux tube geometry was adopted which reduces the equilibrium calculation problem to 1D. A generalised Ohm's law is used to calculate the equilibrium potential. Once the 1D simulations converge the equilibrium solutions are used as initial conditions for 3D simulations. A filament is added to the background fields prior to running. The electromagnetic potential calculation required an inversion of a polarisation equation involving gyroaverage operators. However the GMRES method [6] has been applied successfully to the problem.

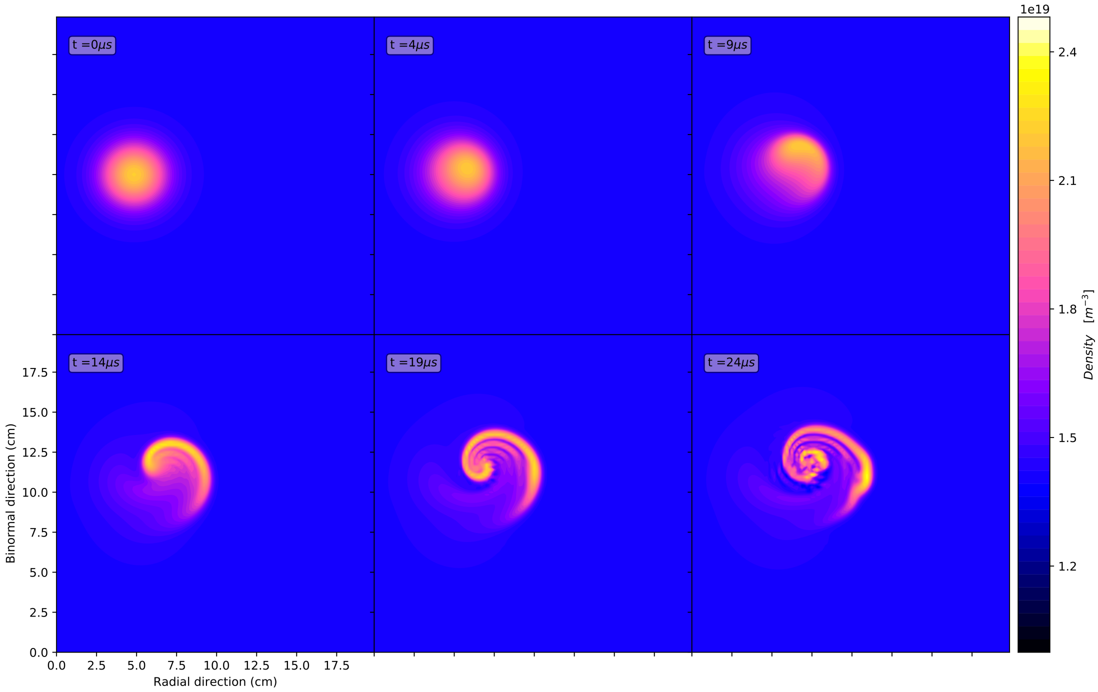

Figure 1: Midplane density

Results

Typical filament dynamics have been qualitatively captured in the edge and are shown in fig.1. The dipole potential that is know to form in filaments due to plasma curvature effects is observed which leads to a radial acceleration of the filament. The peak velocity reached of $2km \cdot s^{-1}$ (seen in fig.2) is within the range of results from well established fluid models [7]. This is in contrast to the previously mentioned 2D simulations in which the peak radial velocity overestimated. The radial velocity peaking early in the simulation is also quite typical of filament simulations.

Only preliminary simulations have been carried out to date. Further simulations are required as well as simulations on finer grids. A parameter scan of filament radius will be carried out to ascertain what impact, if any, FLR effects have on filament velocity scaling laws.

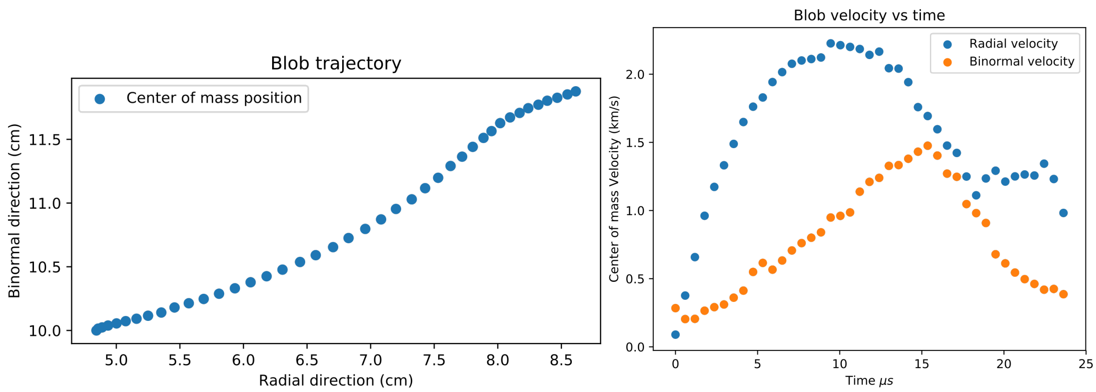

Figure 2: Centre of mass trajectory and velocity profile

Summary

A global version of GEM has been implemented in BOUT++ with sheath boundary conditions in order to simulate filament dynamics. Preliminary 3D filament simulations have been performed with sheath boundary conditions in a flux tube geometry. These preliminary simulations agree qualitatively with fluid models and further studies are planned where filament scaling laws will be investigated. A more detailed comparison to fluid models will also be carried out.

References

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