1 Introduction

Blob are annoying account for much transport Why are PIC codes nice?

2 Stating the physical problem and expectations

Basic idea Purpose is to test blob dynamics and verify fluid scaling based on interchange motion. Furthermore, as the FLR effects are an inherent part of the gyromotion they are expected to occur naturally.

In this paper blobs are modelled as Gaussian perturbation in the density and some in the temperature on a uniform background:

$$n(t=0) = n_0 + n_b \exp\left(-\frac{(\mathbf{x}-\mathbf{x}_c)^2}{2\sigma^2}\right) \tag{1}$$

The blob is placed in a static inhomogeneous magnetic field given by:

$$\mathbf{B} = -\frac{B_0 R_0}{R_0 + x}\hat{\mathbf{z}} \tag{2}$$

Here B_0 is the magnetic field at R_0 which is the distance of the blob from the center???????!!!!!! The gradient arising from this field leads to a grad-B drift of the ions and electrons causing a polarization of the blob in turn creating an electric field The problem has been analysed thoroughly using fluid theory and a velocity scaling for the radial propagation of the blob can be found from dimensional analysis of:

$$V_\perp \propto \gamma\sigma = c_s\sqrt{\frac{\sigma\Delta n}{R n_0}} \tag{3}$$

Where $\gamma = \sqrt{\frac{c_s \Delta n}{\sigma R n}}$ is the interchange rate and $c_s = \sqrt{P/\rho_m}$ is the ion sound speed with P the plasma pressure and ρ_m the plasma mass density.

A typical assumption in the fluid picture is that the plasma is quasineutral, i.e. $|n_i - n_e| \ll 1$. For the code in question this is explicitly met for the system in its entirety but not necessarily on the appropriate length scales. Therefore the definition of quasi neutrality from [cite] is used as a measure:

$$\frac{\Delta n}{n} \leqslant \frac{\lambda_d^2}{L^2} \ll 1 \tag{4}$$

Where λ_d is the Debye length and L is some characteristic length scale which in this case is the Larmor radius. This effectively means that the Debye screening is large within a region of L^2.

FLR effects [MAKE SURE LARMOR RADIUS IS DEFINED BEFORE HAND]: Due to the mass dependency on the Larmor orbits, ions will have a larger radius than the electron at the same temperature. In the case of the blob perturbation this means that an ion will transverse a larger part of the blob than the electron. As the electric field varies on a scale comparable to the blob width, the field felt by the ions change significantly compared to the field felt by an electron over the course of an orbit. As such the electron experiences an almost homogeneous electric field. The effects arising from this is what is known as finite Larmor radius (FLR) effects. In [madsen, held] an attempt has been made at quantifying effect and numerical results show a secondary drift of the blob in the ion grad-B direction. In this paper we will not do so, but simple give a measure of the FLR effects on the poloidal propagation for comparing different scenarios:

$$\Phi = \frac{x}{y} \sim \frac{v_x}{v_y} \tag{5}$$

3 Numerics and simulation system

In this paper the goal is to investigate blob dynamics using a first principle, fully kinetec approach. This means that individual particle motion for both ions and electrons is resolved and so that all physics are inherently resolved in particular the gyromotion and the effects arising from this. This type of simulation is particularly useful when it comes to transport and turbulence simulations as all dynamics are present. This is in contrast to fluid models where a number of moments are taken of the boltzmann equation, and certain approximations are included to give a coherent picture.

To model this first principles approach an electrostatic Particle-In-Cell code modified from the Photon-Plasma code is used []. This modified version solves the Vlasov equation:

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\boldsymbol{\nabla}_{\boldsymbol{x}} f + \frac{q}{m}\left(\mathbf{E} + \mathbf{v}\times\mathbf{B}\right)\cdot\boldsymbol{\nabla}_{\boldsymbol{v}} f = 0 \tag{6}$$

Where $f(\mathbf{x}, \mathbf{v}, t)$ is the distribution function for a single particle. The charge of the particles are interpolated onto a spatial grid using cubic spline interpolation. This gives rise to a charge density on the grid which in turn can be used to find the electrical fields. Note that the system is assumed collision-less expect for interactions through the particle-grid interpolation. The magnetic field is assumed to be constant and the electric potential is solved for using the Poisson equation:

$$\rho = -\frac{\Delta\phi}{\varepsilon_0} \tag{7}$$

Where ρ is the charge density and ϕ the electric potential. From this the electrical field is found as:

$$\mathbf{E} = -\boldsymbol{\nabla}\phi \tag{8}$$

The grid is staggered in such a way that the electric field is shifted wrt. the density field. And the potential solver is of 6th order.

In the simulations the background density is set to be $n_0 = 10^{17} m^{-3}$ with a background magnetic field $B_0 = 1T$. Note that the density is some orders of magnitude smaller than typical densities found in fluid simulations and real worlds problems [cite?]. The reason for this is the computational constraints imposed by stability criteria of PIC codes where both the plasma frequency and the Debye length have to be resolved.

Boundary condition. The boundary condition for the y-direction are periodic while for the x-direction a Neumann boundary for the electric potential is used and the particles are reflected according to [cite the one with boundary]. The magnetic field on the boundary is as prescribed above. Since the code is a 6th order code in the fields, a number of ghost points are needed outside the domain. The magnetic field is known beforehand due to it being constant. The charge density is handled as mirror charges, making it possible to find the potential which is also mirrored. From this the electric field, the x-component is found with the ghost points being antisymmetric around zero wrt. the inside field. The y-component is simply reflected [IS THIS TOO DETAILED? PROBABLY].

In the code, the grid is resolved s.t. $\Delta x \approx \lambda_d \approx 5\rho_s$ where $\rho_s = \sqrt{T_e/m_i}/\omega_{ci}$ is the Larmor radius and λ_d is the Debye length.

A number of different simulation are carried out to test the different scaling parameters. A common setup is such that the perturbation amplitude is $n_b = n_0$ with a temperature of $T_i = T_e = 20eV$, radius of $R_0 = 500\rho_s$ and blob width of $\sigma = 5\rho_s$. To test the various scaling parameters, one parameters is varied while the others are fixed with the above quantities. The used values are; for radius of $R_0/\rho_s = 250, 500, 1000, 2000$; for perturbation $n_b/n_0 = 0.5, 1, 2, 4$; for width $\sigma/\rho_s = 2.5, 5, 10, 20$.

The default grid is such that $x_{min} = -20\rho_S$, $x_{max} = 80\rho_S$ and $-y_{min} = y_{max} = 50\rho_s$, with a total of 512×512 grid points. With this the blob is positioned at $\mathbf{x}_c = 0, 0$ so that the magnetic field at the center of the blob is B_0. Furthermore to alleviate computational requirements the mass ratio between the ions and electrons is $m_i/m_e = 100$. The charge of the particles are $q_i = q_e$

4 Numerical Results

Checking the driving mechanism - potential and electric field - the blob moves - how does it scale - what about FLR effects.

To test scaling the scaling of the radial motion the blob seen in equation [insert eq.] several runs with varying perturbation amplitude, blob width, major radius and ion temperature. The ion temperature dependence is through the sound speed $c_s \propto \sqrt{1+\tau}$ where $\tau = Ti/T_e$.

Snapshots of the density evolution of blob simulation with the default values stated above is seen in fig... As seen the seeded blob moves radially outwards and starts forming a plume like structure. This is similar to results seen in e.g. [jens, held etc.] and corresponds with what is expected for density inhomogeneities in an inhomogeneous magnetic field such as this.

The radial driving mechanism is thought to be an initial dipole creation from the gradient in the magnetic field followed by an radial electrical drift. I.e. an overall effect of individual charged particle motion in the inhomogeneous magnetic field. Looking at the gyro-averaged potential of the blob it is seen that a dipole has en indeed appeared at the position of the blob. This in turn results in an electric field as seen in fig [figure with E-field]. The strengh of the electric field within the blob corresponds well with the radial velocity of the blob.

Furthermore, as the blob moves outwards we see a break in the poloidal symmetry of the blob with a movement in the $\nabla \mathbf{B} \times \mathbf{B}$-direction (-y-direction). Note that this is in the opposite direction of what is seen in fluid simulations while consistent with results seen in [Hasegawa] and [Gingell?]. This symmetry breaking has been described in detail in [jens] and is in large part attributed to finite Larmor radius effects as discussed earlier.

Before we dive into the scaling dependence we look at the basis for the scaling we saw earlier, namely the quasi-neutrality condition. As mentioned, this is not fulfilled at every point in the domain, se particles are 'free' to move around. Instead we introduced a measure to estimate the level of quasi-neutrality.

5 Discussion

We see good scaling results - FLR effects in the y-dir - not the same as all fluid papers.

6 Conclusion

Awesome new code to show awesome results.

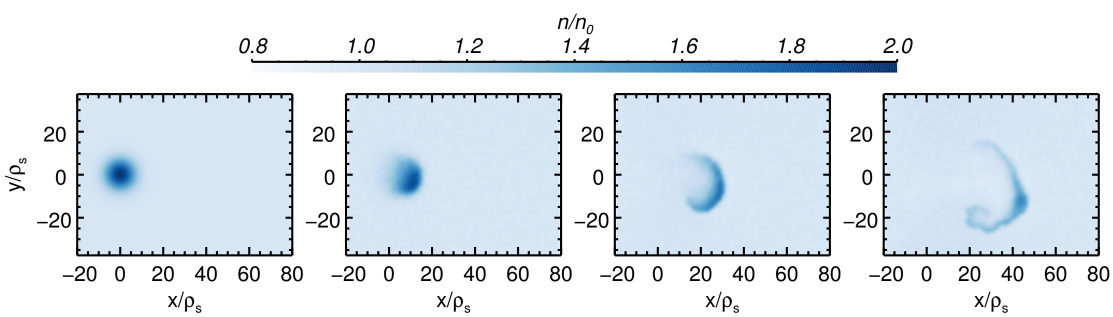

Figure 1: This is a tiger.