THEORY AND SIMULATION OF TURBULENCE IN TOROIDAL MAGNETIZED PLASMAS II

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1. Introduction

In some plasma discharges anomalous cross-field currents influence the turbulence as well as the formation of equilibria in magnetically confined plasmas [1]. Such plasma discharges are the Blåmann device at the University of Tromsø, the ACT-1 device at Princeton, the BETA device in Gandhinagar and the Thorello device in Milan among others. In these devices a weakly ionized plasma is produced by a hot-cathode filament discharge. The injection of electrons by the filament produces a potential well with the potential minimum in the area where the filament is situated. The injected charge must be compensated in order for the plasma to stay quasi-neutral. Thus, the cross-field currents are essential for these discharge plasma devices, and therefore determine the type of equilibrium that can exist in such devices.

The hot electrons injected by the filament ionize the neutral gas, and thus form a source for plasma mass as well. However, both experiments and simulations show that the equilibrium is dominated by the charge source. Therefore it is the filament as a charge source that determine the turbulence. Consequently, the cross-field current, and not the mass transport, determine the equilibrium and turbulent properties.

Another important aspect of these devices is the simple magnetic geometry. First of all the plasma is a low-β plasma. And secondly the magnetic field is often only toroidal without any rotational transform.

In this paper we present fluid simulations of a model for a low-β toroidal plasma. The simulations show that the cross-field currents determine the essential features of the plasma equilibrium. The simulations also show that the feature of the plasma equilibrium depends on the type of cross-field current that dominates. In the model we have included three different currents; the diamagnetic current, the current due to the ion-polarization drift and the current due to ion-neutral collisions.

For low densities the current due to the ion-polarization drift dominates. In this case the radial transport of charge as well as mass is associated with a large, coherent dipole vortex rotating poloidally with the mean plasma flow where the density and potential are in anti-phase. In this regime the potential well is of the order of 100V.

When the simulations are done with a higher density the diamagnetic current dominates. In this case the coherent structures are short lived and the density and potential are no longer in anti-phase. In this case the simulations show that almost all kind of phase relations between density and potential are possible. In this regime the potential well is typically 10V or less.

If we include the current due to ion-neutral collisions, we find that for some value of the collision frequency this current is important.

2. The model and Numerical Results

The model is based on the single-fluid equations for plasmas. The magnetic field is given as $\mathbf{B} = (B_0 R_0/R)\mathbf{b}$, where R is the major radius of the torus and $\mathbf{b}$ is the unit vector in the toroidal direction. A plasma source S_m in the mass continuity equation is introduced to give

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{v}) = S_m \ . \tag{1}$$

We use the the drift approximation in the momentum equation and it then becomes

$$\rho_m \frac{d\mathbf{v}_E}{dt} = \mathbf{j} \times \mathbf{B} - \nabla p - S_m \mathbf{v}_E - \nu \rho_m \mathbf{v}_E \ ,$$

where $\mathbf{v}_E$ is the $\mathbf{E}\times\mathbf{B}$-velocity . A friction force $\nu\rho_m\mathbf{v}_E$ due to ion-neutral collisions is included along with a force due to the source S_m. There are four different currents in our model and we find that they can be written as $\mathbf{j} = \mathbf{j}_m + \mathbf{j}_p + \mathbf{j}_s + \mathbf{j}_\nu$, where

$$\mathbf{j}_m = \frac{\rho_m}{B^2}\frac{d}{dt}\mathbf{E} \ , \ \mathbf{j}_p = -\frac{1}{B}\mathbf{b} \times \nabla p \ , \ \mathbf{j}_s = \frac{1}{B^2} S_m \mathbf{E} \ and \, \mathbf{j}_\nu = \frac{1}{B^2}\nu\rho_m\mathbf{E} \ .$$

The model consist of the mass continuity equation (1) and the equation $\nabla \cdot \mathbf{j} = S_q$, where S_q is a charge source. We assume the plasma to be electrostatic and write $\mathbf{E} = -\nabla\phi$. And we also assume the plasma to be isothermal and write $p = (T/m_i)\rho_m$. The model consists therefore of two equations in the two variables ρ_m and ϕ

In the simulations we have used the geometry, boundary conditions, sources and sinks that corresponds to the Blåmann device. In Table 1 and 2, and we show tables that give an overview of the results for a number of numerical simulations. The simulations show that for the high densities the current is mainly due to the diamagnetic current. For lower densities the current due to ion-polarization drift becomes important. In the tables we have given the average value of the cross correlation. The definition of the normalized cross correlation is motivated from the definition of the cross helicity in the local simulation, and is defined as

$$V = \frac{\int \rho_m \varrho \, dV}{\left(\int \rho_m \, dV\right)^{1/2} \left(\int \varrho \, dV\right)^{1/2}} \ ,$$

$n_0(\mathrm{m}^{-3})$	$\langle V \rangle$	$\langle \phi_{min} \rangle$	$\langle I_m \rangle / I_0$	$\langle I_p \rangle / I_0$	$\langle \Gamma_E \rangle / S_m$	$\langle \Gamma_o \rangle / S_m$
$1.0 \cdot 10^{17}$	-0.47	$-397\mathrm{V}$	0.78	0.22	1.22	-0.22
$2.0 \cdot 10^{17}$	-0.45	$-263\mathrm{V}$	0.63	0.37	1.18	-0.18
$4.0 \cdot 10^{17}$	-0.22	$-49\mathrm{V}$	0.21	0.79	1.12	-0.12
$6.0 \cdot 10^{17}$	-0.16	$-28\mathrm{V}$	0.06	0.94	1.09	-0.09
$8.0 \cdot 10^{17}$	-0.14	$-16\mathrm{V}$	0.04	0.96	1.06	-0.06
$1.0 \cdot 10^{18}$	-0.15	$-6\mathrm{V}$	0.06	0.94	0.94	0.06

Table 1. The table shows values for simulations with $B_0 = 0.16$T, $T = 4$eV, $\nu = 0$ and the discharge current $I_0 = 1$A . n_0 is the initial density, $\langle V \rangle$ is the average normalized cross correlation, $\langle \phi_{min} \rangle$ is the average potential minimum, $\langle I_m \rangle$ is the average current due to the ion-polarization drift, $\langle I_p \rangle$ is the average diamagnetic current, $\langle \Gamma_E \rangle$ is the average mass flux $\rho_m \mathbf{v}_E$ due to the $\mathbf{E} \times \mathbf{B}$-convection, $\langle \Gamma_o \rangle$ is the average mass flux due to other drifts and S_m is the mass source.

$n_0(\mathrm{m}^{-3})$	$\langle V \rangle$	$\langle \phi_{min} \rangle$	$\langle I_m \rangle / I_0$	$\langle I_p \rangle / I_0$	$\langle I_\nu \rangle / I_0$	$\langle \Gamma_E \rangle / S_m$	$\langle \Gamma_o \rangle / S_m$
$1.0 \cdot 10^{17}$	-0.57	$-87\mathrm{V}$	0.17	0.36	0.47	1.26	-0.26
$2.0 \cdot 10^{17}$	-0.22	$-37\mathrm{V}$	0.05	0.64	0.31	1.18	-0.18
$4.0 \cdot 10^{17}$	-0.25	$-12\mathrm{V}$	0.03	0.77	0.20	1.05	-0.05
$6.0 \cdot 10^{17}$	-0.25	$-6\mathrm{V}$	0.04	0.80	0.16	0.99	0.01
$8.0 \cdot 10^{17}$	-0.26	$-4\mathrm{V}$	0.06	0.80	0.14	0.97	0.03
$1.0 \cdot 10^{18}$	-0.29	$-3\mathrm{V}$	0.06	0.78	0.16	0.96	0.04

Table 2. The table shows values for simulations with $B_0 = 0.16$T, $T = 4$eV, $\nu = 10^4$s^{-1} and the discharge current $I_0 = 1$A . n_0 is the initial density, $\langle V \rangle$ is the average normalized cross correlation, $\langle \phi_{min} \rangle$ is the average potential minimum, $\langle I_m \rangle$ is the average current due to the ion-polarization drift, $\langle I_p \rangle$ is the average diamagnetic current, $\langle I_\nu \rangle$ is the average current due to ion-neutral collisions, $\langle \Gamma_E \rangle$ is the average mass flux $\rho_m \mathbf{v}_E$ due to the $\mathbf{E} \times \mathbf{B}$-convection, $\langle \Gamma_o \rangle$ is the average mass flux due to other drifts and S_m is the mass source.

where ρ_m is the mass density and ϱ is the charge density. When the cross correlation is negative the density and potential are in anti-phase, and the cross correlation is positive when they are in phase. Notice that the normalized cross correlation increases with increasing density. It also increases when the current due to ion-neutral collisions is included in the simulations. The simulations show that the mass transport is anomalous due to the high value of Γ_E in all the simulations.

3. Conclusions

In a paper by K. Rypdal and others [2] it was postulated that classical charge transport was not sufficient for the plasma to get rid of the charge injected by the filament. In the paper they concluded that both charge and mass transport had to be anomalous. The simulations show that the mass and charge transport are anomalous.

From the simulations we find that if we use the density observed in the experiments in the simulations, we do not get an agreement between the simulations and the experiments. If we increase the density we get a good agreement between simulations and experiments. And it seems that it is the collision regime with density $n_0 = 2 \cdot 10^{17}\mathrm{m}^{-3}$ and $\nu = 10^4\mathrm{s}^{-1}$ that gives the best agreement between the simulations and the experiments. It has been argued that the method used for measuring the density in the Blåmann device might underestimate the density by a factor of 5-10. The value of the collision frequency is also important in order to compare the simulations with the experiments. And to estimate the frequency one needs measurements of the neutral pressure and the ion temperature. It is therefore essential to get reliable measurements of the density, neutral pressure and ion temperature in order to compare the simulations with the experiments.

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References

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