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KINETIC AND ELECTROMAGNETIC TRANSPORT PROCESSES IN TOROIDAL DEVICES*

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ABSTRACT

A brief review of transport processes in toroidal devices is presented. Particular attention is given to radial transport of power by the Poynting's vector and kinetic electron flow. This work is primarily focused on the Reversed Field Pinch (RFP) which holds the added complexity of a dynamo process that sustains poloidal current in the edge region, where the toroidal field is reversed. The experimental observation of superthermal unidirectional electrons in the plasma edge of ZT-40M and HBTX1C is noted, and the rapid, nonclassical ion heating in RFPs is taken account of. Radial transport parallel to fluctuating magnetic field lines is deemed a likely candidate for both electromagnetic and kinetic energy transport. Two models are discussed and compared. It is concluded that electromagnetic transport using a local Ohm's law best describes nonclassical ion heating, and the transport of kinetic energy by long mean free path electrons best represents the half-Maxwellian of electrons observed in the edge of several RFPs. A nonlocal Ohm's law is essential for the kinetic electron model.

I. INTRODUCTION

Mass, momentum, and energy transport of charged particles in toroidal devices is achieved by "classical" diffusion perpendicular to

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flux surfaces, convection driven by electrostatic turbulence perpendicular to **B**, or convection along stochastic **B** lines, known as magnetic flutter transport. This paper is directed primarily to magnetic flutter transport. Of particular interest is the role of transport of the electromagnetic field in tandem with the previously mentioned transport of charged particles. The most direct comparison relates the Poynting's vector flow of power across a surface, $\mathbf{E} \times \mathbf{B}$, to the direct transport of kinetic energy by flows of electrons and ions. The sustainment of a reversed field pinch exemplifies the two types of transport. In either case, power is required to sustain a poloidal current at the reversal surface where no poloidal electric field is present to drive it. In the resistive MHD model, power is carried outward by fluctuating electromagnetic fields in a Poynting's vector. In the kinetic dynamo model (KDT) fast electrons carry power directly along stochastic magnetic field lines to the edge region. Correspondingly, the radial flow of electron momentum is related to transport of magnetic helicity, and the relative flow of electrons and ions is governed by the ambipolar electric field parallel to stochastic magnetic field lines. There is experimental evidence for both electromagnetic and kinetic transport. The relative contributions of these two forms of transport are important because they play key and different roles in the ion heating process and the transmission of electron energy to the wall. This paper provides mathematical descriptions of the various types of transport and a discussion of theoretical and experimental efforts to resolve the various models.

II. EXPERIMENTAL OBSERVATIONS

A small electron energy analyzer (EEA) was inserted into the edge plasma of ZT-40M at Los Alamos and HBTX1C at Culham [1]. When the analyzer is accepting electrons moving parallel to the local magnetic field in the same sense as they are accelerated by the toroidal electric field parallel to **B** on the magnetic axis, a strong component of hot electrons is measured. These electrons appear to have a Maxwellian distribution at a temperature T_H, about twice as great as the central plasma temperature, T_o. For typical discharges in ZT-40M, T_H is about 500eV. When the EEA is turned around to accept electrons moving antiparallel to those described above, the measured current drops by a factor of 10 - 20, and the electron temperature is closer to that of the core electrons. Hence, the term "half-Maxwellian" is applied to the hot electrons measured at the edge. Observation of this directed electron flow at the edge suggests that electrons may be accelerated by the toroidal electric field in the plasma core then wander along stochastic orbits to the edge region where they lose kinetic energy and momentum through electron - ion collisions or by striking the wall and limiters.

A Langmuir probe study of the edge plasma measured a bulk electron temperature of ~20ev. Although the hot electron current appears to be capable of driving virtually all of the edge plasma current, the hot electrons make up only about 5% of the total electron density dear the edge.

Another significant observation in RFPs is that ions and electrons are typically heated to comparable temperatures despite the relatively low classical ion thermalization time. The electron, ion and energy confinement times are generally equivalent. This result indicates there may be some form of turbulent ion heating in addition to the classical electron - ion thermalization.

III. THE RFP DYNAMO

In the context of a local Ohm's law, $\mathbf{E} + \mathbf{u}\times\mathbf{B} = \eta\mathbf{J}$, power that is injected locally into the plasma by $\mathbf{E}\cdot\mathbf{J}$ is dissipated in the same place by $\eta(\langle \mathbf{J}\rangle^2 + \langle \tilde{\mathbf{J}}^2\rangle)$, except for the term driving plasma motion, $\mathbf{u}\times\mathbf{B}\cdot\mathbf{J}$. The mean toroidal electric field, $\langle \mathbf{E}\rangle = E_o\hat{\mathbf{z}}$, couples to the mean toroidal current as follows, $\langle \mathbf{E}\rangle\cdot\langle \mathbf{J}\rangle = E_o \langle J_z\rangle$. Discounting $\mathbf{u}\times\mathbf{B}\cdot\mathbf{J}$ and recognizing that the toroidal edge current is small and perhaps negative, it is very unlikely that $\langle \mathbf{E}\rangle$ alone can drive the full local current in the RFP edge,

$$\eta(\langle \mathbf{J}\rangle^2 + \langle \tilde{\mathbf{J}}^2\rangle) \gg E_o \langle J_z\rangle. \quad (1)$$

This is an indication that the poloidal edge current must be driven by power from a source other than local toroidal electric field and current coupling.

IV. POYNTING'S THEOREM

Radial power flow attributable directly to electromagnetic fields is given by the Poynting's vector,

$$\Gamma_E \equiv \frac{1}{\mu_o} \int \mathbf{E} \times \mathbf{B} \cdot d\mathbf{s}.$$

E can then be separated into steady and fluctuating parts,

$$\mathbf{E} = \langle \mathbf{E} \rangle + \tilde{\mathbf{E}}$$

where < > indicates averaging over a surface of constant radius and over a time short compared to the discharge length but long compared to plasma turbulent motion timescales. $\tilde{\mathbf{E}}$ is the part of the electric field that is fluctuating both in time and space. $\mathbf{E}$ may be reduced further as follows,

$$\mathbf{E} = E_o \hat{\mathbf{z}} - \nabla \phi - \frac{\partial \tilde{\mathbf{A}}}{\partial t}.$$

The scalar potential represents both a steady state ambipolar radial electric field and the fluctuating electrostatic field, while $\frac{\partial \tilde{\mathbf{A}}}{\partial t}$ accounts for the fluctuating inductive electric field.

Steady state inward power flow across a surface of constant r is given by $\Gamma_{ES} = \frac{1}{\mu_o} E_o \langle B_\theta \rangle$ where S is the total surface area. Meanwhile, the outward power flux due to fluctuations is

$$\Gamma_{EF} = -\frac{1}{\mu_o}\iint\left(\nabla\phi + \frac{\partial\tilde{\mathbf{A}}}{\partial t}\right)\times\tilde{\mathbf{B}}\cdot d\mathbf{s}$$

$$= \int\phi\mathbf{J}\cdot d\mathbf{s} - \frac{1}{\mu_o}\int\frac{\partial\tilde{\mathbf{A}}}{\partial t}\times\tilde{\mathbf{B}}\cdot d\mathbf{s} \qquad (2)$$

Eq. (2) is central to the discussion of electromagnetic transport. First it should be noted that unless there is a net outward current, a steady radial ambipolar field will not enter into Eq. (2). However, when considering a net loss of electrons, the radial ambipolar field is the instrument by which quasineutrality is maintained.

To further understand the induction term, it is expressed in a Fourier expansion on a surface of constant r. In cylindrical coordinates define

$$\nabla_S \equiv \hat{\theta}\frac{1\partial}{r\partial\theta} + \hat{\mathbf{z}}\frac{\partial}{\partial z}.$$

To chose a gauge where only induction through the surface is represented, one must set $\nabla_S\cdot\tilde{\mathbf{A}} \equiv 0$. $\tilde{\mathbf{A}}$ can the be represented by the following expansion set,

$$\mathbf{k} = k_\theta\hat{\theta} + k_z\hat{\mathbf{z}}, \qquad \mathbf{x}_S = r\theta\hat{\theta} + z\,\hat{\mathbf{z}}$$

and

$$\tilde{\mathbf{A}}_{sk} \equiv \mathbf{A}_k \exp[i(\mathbf{k}\cdot\mathbf{x}_S - \omega t)].$$

With these definitions, the vector potential and magnetic field normal to the surface are related as follows,

$$\tilde{\mathbf{A}}_{sk} \equiv i\,\mathbf{k}\times\tilde{\mathbf{B}}_{kn}/k^2 \qquad (3)$$

Eq. (2) is now rewritten in more physically recognizable expressions,

$$\Gamma_{EF} \equiv \int \phi J_n \mathrm{ds} \qquad \text{Current}$$

$$- \frac{1}{2\mu_o} Re \int \sum_k \frac{\omega}{k^2} (\mathbf{k}\cdot\mathbf{B}_{ks}) B_{kn}{}^* \mathrm{ds} \qquad \text{Induction} \qquad (4)$$

$$- \frac{1}{2\mu_o} Re \int \mathbf{E}_{00} \times \mathbf{B}_{00}{}^* \cdot \mathrm{ds} \qquad \text{Induction}, \quad m = n = 0$$

The current and induction terms in Eq. (4) are profoundly different. The current term must have **J** normal to the surface to transmit power radially, while the first inductive term can only contribute when there is a radial magnetic field component oscillating in time. The 00 inductive component has no radial field but must act uniformly over the entire surface. The steady state form of the 00 term represents the transformer coupling to the plasma already mentioned above. The oscillatory 00 term is the mathematical expression of oscillating field current drive (OFCD).

The inductive terms are of considerable interest, especially in the context of OFCD. Since this paper is directed more toward power loss from the core plasma, the inductive terms are less relevant here. For instance, the largest value for the ω/k term would probably be approximately the Alfven speed. Assuming magnetic field fluctuations ~ 1% of the background field, the waves would have to be nearly perfectly in phase to transmit significant power. It is difficult to imagine how oscillating inductive transport could carry power part way through the plasma then use it to accelerate electrons into unidirectional flow at the edge. Consequently current transport is treated as the dominant constituent of the Poynting's vector in the remainder of the paper.

V. KINETIC ELECTRON TRANSPORT

Radial power flux across a surface of constant r is given by

$$\Gamma_K \equiv \int \frac{1}{2} m v^2 f \mathbf{v} \cdot d\mathbf{s}.$$

where f is the electron distribution function. The velocity may be reduced to

$\mathbf{v}_{\parallel}$ - motion $\parallel$ **B**

$\mathbf{v}_{\perp}$ - motion $\perp$ **B**

$\mathbf{v}_d$ - drift velocity.

This leads to an approximate radial flux of

$$\Gamma_K \equiv \frac{1}{2} m \int [(2 v_{\perp}^2 + v_{\parallel}^2) v_{dn} + (v_{\perp}^2 + v_{\parallel}^2) v_{\parallel n}] d^3 v ds \qquad (5)$$

The relative contributions of terms involving the drift velocity versus those driven by parallel transport, $v_{\parallel n}$, are a source of considerable debate. It is generally acknowledged that plasma drifts play a key role in particle transport in both tokamaks and RFPs [2]. If drifts accounted for most of the electron energy transport in the RFP, it would be difficult to reconcile that assumption with the fast electron results mentioned earlier. If, for example, v_{dn} were driven by $\mathbf{E} \times \mathbf{B}$, all of the bulk plasma would drift at the same speed. Since $20 eV$ electrons outnumber hot electrons, $500 eV$, in the edge by 20 to 1, one might expect the electron energy confinement time to be ~ 10% of the particle confinement time. As mentioned before, the two confinement times are generally comparable. Therefore, one might believe that parallel transport plays a stronger role than perpendicular drifts in electron energy loss. This is by no means a definitive proof, but we will direct our attention to parallel electron transport for the rest of the paper.

VI. COMBINED TRANSPORT MODEL

The electromagnetic and kinetic electron parallel transport expressions can be combined into one equation,

$$\Gamma W_{\|} \equiv \int [\tfrac{1}{2} m (v_{\perp}^2 + v_{\|}^2) - e\phi] v_{\|} n f \, d^3 v ds \quad (6)$$

$$= \int \varepsilon v_{\|} n f \, d^3 v \, d s$$

where

$$\varepsilon \equiv \tfrac{1}{2} m (v_{\perp}^2 + v_{\|}^2) - e\phi.$$

Electron potential and kinetic energy appear to be almost interchangeable in parallel transport. The two extremes of transport model are resistive MHD based on a local Ohm's law [3-6] and the kinetic dynamo theory [7,10]. Various characteristics that distinguish the two forms of power transport will be discussed in the context of these two models.

VII. RESISTIVE MHD

Numerical modeling of the RFP dynamo was pioneered by Sykes and Wesson [3]. A more conceptual treatment of the concept, based on flux tube stochasticity in the plasma, was developed by Rusbridge [4]. A major achievement came when Caramana, Nebel and Schnack [5], using a 2D single helicity code, predicted sawtooth behavior in RFPs prior to its experimental observation on several machines. 3D MHD modeling of the RFP has been developed to show a high degree of consistency among codes authored by a number of different people [6].

In a model based on a local Ohm's law, electrons lose to collisions as much parallel momentum as is gained from $\mathbf{E}_{\|}$ in any volume element. When there is no net radial current, there is no radial kinetic energy transport derived from the Ohm's law. Power transport in Eq. (6) is driven entirely by the electrostatic field term, $e\phi$.

The model clearly demonstrates the dynamo sustainment of field reversal [3-6]. When the power dissipation term involving plasma motion, $\mathbf{u}\times\mathbf{B}\cdot\mathbf{J}$, is also included in the MHD model, it may be possible to describe nonclassical ion heating [11,13]. The understanding of ion heating is far less developed than that of the RFP dynamo. However, by distinguishing the apparent plasma resistivity based on magnetic helicity transport from that based on energy transport it becomes clear that there is sufficient energy of relaxation available in a RFP to drive the observed nonclassical ion heating [11].

Another feature of MHD modeling is that it is claimed to account for observed toroidal loop voltage enhancement associated with current interruption in the plasma edge [15]. This too is based on a comparison of magnetic helicity transport with energy transport.

The observed half-Maxwellian of hot electrons in the edge plasma [1] is not well accounted for by resistive MHD alone. The fact that 500 eV electrons appear to drive most of the current in a bulk plasma at 20 eV is difficult to explain in the context of a local Ohm's law. There is a strong indication that the hot electrons are not accelerated to such a velocity in the edge plasma. The observed electron distribution is not consistent with classical resistivity modeling. These hot electrons probably arise by having electrons that move over diverse radii of the plasma in one mean free path.

VIII KINETIC DYNAMO

What has become known as the "kinetic dynamo theory" [10]] has its roots in a number of papers [7-10]. Key assumptions of the model are: a low level of magnetic field line stochasticity, uniform toroidal and radial ambipolar electric fields, time dependent magnetic fluctuations and spatial electrostatic fluctuations are not considered, and cross field currents are implicitly present.

The above assumptions lead to a model whereby electrons that are at the upper end of the thermal distribution in the plasma core have relatively long mean free paths, ~ 10 - 100 m. They could now slide away from the thermal distribution in the strong toroidal electric field of the RFP. As this begins to happen, they wander along stochastic magnetic field lines toward the edge region. There the mean field turns into the poloidal direction reducing, and ultimately reversing, the electron acceleration parallel to **B**. The fast electrons have still carried momentum parallel to **B** to the edge region. Some of this momentum is dissipated in electron-ion collisions, some is lost by electrons that go as far as the wall [16] and some move back to the core uninterrupted. It is the objective of the KDT to formalize the statistics of this electron flow.

The KDT does indeed model RFP field reversal with realistic plasma parameters [10]. It also explains the observed loop voltage enhancement correlated with edge current interruption [16]. Recent work using the KDT model has accounted for the half-Maxwellian electron distribution in the edge plasma. This work is especially interesting because the field line diffusivity, D_f, needed to model the dynamo is consistent with that needed to quantify the temperature of the hot electrons at the edge [17].

The KDT alone does not have a mechanism to compute the source of field line stochasticity. This presently is assumed to have its origin in different physics. For example, MHD processes must be functioning simultaneously with the kinetic electron physics of this model. The MHD based plasma relaxation is assumed to generate the field line stochasticity that enables the KDT model. Correspondingly the KDT has no mechanism to account for ion heating. Terry and Diamond [18] have called into question the whole issue of magnetic flutter transport by kinetic electrons on the basis of turbulent drift wave modeling. This issue will be critiqued briefly in the next section.

IX NONLOCAL OHM'S LAW

To consider a nonlocal Ohm's law, one must first examine the linearized Boltzmann equation in the context of a local model. In uniform parallel **E** and **B** fields, the fundamental relations are:

$$-\frac{e}{m}E_{\parallel}\frac{\partial f^{(0)}}{\partial v_{\parallel}} = -\frac{v}{2\lambda}f^{(1)}$$

$$f^{(0)} = f_o \exp(-v^2/v_o^2)$$

$$\lambda = \lambda_o(v/v_o)^4$$

$$v_o \equiv \sqrt{2kT_e/m}$$

$$f^{(1)} \propto E_{\parallel}\left(\frac{v}{v_o}\right)^4 \frac{v_{\parallel}}{v} f^{(0)} \tag{7}$$

$$J_{\parallel} = -\int e v_{\parallel} f^{(1)} d^3v = \sigma_{Spitzer} E_{\parallel} \tag{8}$$

The Ohm's law relating $E_{\parallel}$ and $J_{\parallel}$ is very specific to $f^{(1)}$. The fourth power on v/v_o in Eq. (7) places considerable weight on faster electrons to carry the current indicated in Eq. (8). The primary current carrying electrons are at the speed $2v_o$. One then asks the question: what happens if cross field currents introduce a different $f^{(1)}$?

Consider current flow along a flux tube, $x_{\parallel}$. Quasineutrality requires the net divergence to be zero,

$$\nabla \cdot \mathbf{J} = \nabla \cdot \mathbf{J}_{\perp} + \frac{\partial J_{\parallel}}{\partial x_{\parallel}} = 0.$$

Although parallel currents are dominated by "collisionless" electrons, Cross field currents that drive viscous plasma motion are dominated by "collisional" electrons. For example the relation $\sigma_{Spitzer\perp} \sim \frac{1}{2}\sigma_{Spitzer\parallel}$. may be taken as an indication of the greater importance of collisional electrons attached to perpendicular transport. It is conjectured here that when cross field currents enter a flux tube, they decrease the apparent conductivity by $\Sigma\, \delta J_{\parallel}$ where

$$\Sigma \equiv \frac{\partial J_{\|}/\partial x_{\|}}{\partial E_{\|}/\partial x_{\|}}. \tag{9}$$

Heuristically, one may estimate $\Sigma \sim \frac{1}{2}\sigma_{\text{Spitzer}}$. A simplified calculation using the appropriate Boltzmann equation indicates that the altered conductivity stays in effect for a distance between the mfp of the thermal and that of the "hot" electrons measured by the EEA, 10-100m. Consequently an increase of $J_{\|}$ will disproportionately increase $E_{\|}$. More interestingly, a decrease of $J_{\|}$ could actually reverse the sign of $E_{\|}$ without changing the sign of $J_{\|}$! This accounts for the possibility of having $E_{\|}$ negative in the edge region of an RFP as described in the KDT. It is the belief of the present authors that Terry and Diamond [18] have not found this effect in their model because they have not accounted for alteration of the distribution function describing parallel electron flow caused by the cross field current of collisional electrons.

X DISCUSSION

This paper has briefly explored magnetic flutter transport in the context of a local Ohm's law and in the context a separate model based on directed transport of fast electrons. Each model can describe some experimentally observed phenomena better than the other. For example, nonclassical ion heating is best described in the context of electromagnetic energy transport, while fast directed electrons at the edge are easier to understand in the context of a kinetic electron transport model.

An heuristic explanation has been given for how the parallel electric field can change sign along a flux tube when the parallel current does not change sign. This tends to justify consideration of a nonlocal Ohm's law.

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