LA-UR--90-3512

DE91 001898

TITLE: MAGNETIC TURBULENT ELECTRON TRANSPORT IN A REVERSED FIELD PINCH

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SUBMITTED TO: PHYSICS OF FLUIDS
Int'l School of Plasma Physics
Varenna, Italy
October 15-24, 1990

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Magnetic Turbulent Electron Transport in a Reversed Field Pinch

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Abstract

A model of magnetic turbulent electron transport is presented. The model, based on the thermal conduction theory of Rechester and Rosenbluth, entails a Boltzmann description of electron dynamics in the long mean-free-path limit and quantitatively describes the salient features of superthermal electron measurements in the RFP edge plasma. Included are predictions of the mean superthermal electron energy, current density, and power flux asymmetry. A discussion of the transport model, the assumptions implicit in the model, and the relevance of this work to more general issue of magnetic turbulent transport in toroidal systems is presented.

I. INTRODUCTION

The role of magnetic turbulent transport in toroidal confinement devices is not well understood. Despite the existence of theoretical models that describe particle, momentum, and energy transport due to magnetic field stochasticity, laboratory quantification of magnetic turbulent transport is uncommon. In the tokamak and stellarator edge plasma, where basic turbulence quantities can be measured with insertable probes, the magnetic fluctuations are small ($\tilde{B}/B \leq 10^{-4}$) and electrostatic turbulence is believed to dominate particle and energy transport.¹ However, in the interior of tokamaks and stellarators, the role of magnetic turbulence is uncertain. Here, magnetic fluctuations have been hypothesized as an important anomalous transport contributor.²⁻⁴

In contrast to tokamaks and stellarators, magnetic fluctuations in the Reversed Field Pinch (RFP) are relatively large; typically two to three orders of magnitude larger than those observed in tokamaks or stellarators. As such, magnetic turbulence is hypothesized to play an important role in the transport of momentum and energy.⁵⁻⁷ In this sense, the RFP provides an environment in which to study the fundamental physics of magnetically driven turbulent transport at higher fluctuation levels than achievable on other toroidal confinement devices. In addition, an improved understanding of magnetic turbulent transport is necessary to quantify the confinement performance of present RFP experiments and the expected performance of next generation devices.

Described herein is a model of magnetic flutter driven electron transport that quantitatively predicts the salient features of the RFP experimental observations in the edge plasma. The model, based on test particle diffusion in a stochastic magnetic field, includes quantitative predictions of the mean superthermal electron energy, current density, and power flux asymmetry as a function of the applied electric field and magnetic diffusivity. Following a brief description of the model, quantitative predictions of the superthermal electron transport are compared with data from the ZT-40M experiment in the edge plasma region ($r/a \geq 0.7$). The assumptions used in obtaining these quantitative predictions are also discussed. Finally, we conclude with a brief discussion of this work in the more general context of magnetic turbulent transport in toroidal systems.

II. TRANSPORT MODELING

A. Motivation: The Experimental Observations

Magnetic fluctuations have long been associated with fundamental plasma processes in the RFP.⁸ For example, global energy confinement in the HBTX-1A experiment was consistent with that expected from an electron transport model based on magnetic field stochasticity.⁵ Similar estimates on the ZT-40M experiment⁹ concur with the HBTX-1A results.⁷ Also, the possibility of stochastic electron transport naturally leads to the Kinetic Dynamo Theory (KDT) of RFP sustainment, where magnetic turbulence is hypothesized to drive the transport of field aligned current and concomitantly, the mean magnetic field profiles.⁶

In addition to affecting global confinement, magnetic turbulence can also strongly influence the electron distribution function due to the dependence of the radial particle diffusivity on electron velocity parallel to $\mathbf{B}$. Hence a further motivation for investigating magnetic turbulent transport in the RFP derives from the observation of superthermal electrons in the edge plasma.¹⁰ On ZT-40M, retarding potential measurements with an electron energy analyzer (EEA) and a calorimeter Langmuir probe (CLP) indicate that the superthermal electrons have a characteristic energy greatly exceeding the local edge plasma temperature, and comparable to the central temperature. The data show that the superthermal electron tail is well characterized by an exponential dependence on energy, but their flow is unidirectional along $\mathbf{B}$. Furthermore, superthermal electron flow in the edge plasma (exterior to the reversal surface) is opposed to the applied electric field force which suggests a generation mechanism in the plasma interior.¹⁰

The existence of unidirectionally flowing superthermal electrons in the edge plasma leads to a substantial asymmetric power flow along $\mathbf{B}$.^{11-15,10} The most striking evidence of this asymmetry is in the damage patterns on limiters and walls. For example, in ZT-40M, the power flux from the electron drift direction is four times that from the ion drift direction, and has been measured at 25 to 75 kw/cm². The observed properties of the superthermal electrons responsible for this power flux suggests a particle transport mechanism that is energy dependent. Quantification of this transport mechanism is crucial for devising techniques to mitigate wall loading and power flux peaking in next generation RFP devices.

B. The Model

The quantification of superthermal electron transport derives from a kinetic description of the electron dynamics. In this model,^{6,16} electrons are accelerated by the applied parallel electric field ($E_{\parallel} \equiv \mathbf{E} \cdot \mathbf{B}/B$) in the core region of the discharge where $E_{\parallel}$ is maximized. A low level of magnetic field stochasticity, driven by magnetic field fluctuations, provides the mechanism that allows the superthermal electrons to transport across the mean magnetic fields. We note that this transport model, like most magnetic flutter transport models, is not totally self-consistent in that the effect of the transport on the plasma dynamics is not considered. In this sense, the transport description is "test-particle" like. Nevertheless, as discussed in

Section II, this “test-particle” description appears to embody the salient properties of superthermal electron dynamics in the RFP.

We adopt a drift kinetic equation (DKE) for electrons that is based on the work of numerous authors.^{17,6,18-20} In cylindrical coordinates, the DKE is given by²⁰:

$$\frac{\partial f}{\partial t} - eE_{\parallel}(r)\frac{\partial f}{\partial \varepsilon} = \frac{\partial f}{\partial t}|_{\text{collision}} + \frac{\partial f}{\partial t}|_{\text{stochastic}}. \quad (1)$$

where f denotes the mean electron distribution function averaged over a constant radius. The first term on the RHS of equation 1 is the electron-electron and electron-ion collision operator, whereas the second term defines the diffusion operator due to the magnetic field stochasticity.

In general, when considering the contribution of field line stochasticity to particle diffusion, the two approximate constants of motion are the magnetic moment $\mu \equiv \frac{1}{2}m_e v_{\perp}^2/B$ and the total energy $\varepsilon \equiv \frac{1}{2}m_e v_{\parallel}^2 + \mu B - e\phi_A$. Here, $v_{\parallel}$ and $v_{\perp}$ denotes the electron velocity parallel and perpendicular to the local mean magnetic field, respectively and ϕ_A is the electrostatic ambipolar potential. It follows that in equation 1, f is an explicit function of r, ε , and μ .

We adopt from earlier work^{21,20} the stochastic diffusion operator in the collisionless (long-mean-free-path) limit:

$$\frac{\partial f}{\partial t}|_{\text{stochastic}} = \frac{|v_{\parallel}|}{r} \frac{\partial}{\partial r} (r D_F \frac{\partial f}{\partial r}), \quad (2)$$

where D_F , the magnetic field diffusivity, quantifies the diffusion of magnetic field lines due to stochasticity. For the case of weak turbulence, D_F may be expressed in the quasi-linear limit as:²²

$$D_F \equiv \int_0^{\infty} \langle b_r(0)b_r(z) \rangle dz = L_0 \langle b_r(0)^2 \rangle, \quad (3)$$

where L_0 , the parallel autocorrelation length of the radial magnetic field fluctuations, is defined as:²²

$$L_0 \equiv \frac{\pi}{\Delta k_{\parallel}}, \quad (4)$$

and where $b_r = \tilde{B}_r/|\mathbf{B}|$, $\tilde{B}_r$ is the fluctuating radial component of $\mathbf{B}$, $\Delta k_{\parallel}$ is the spectral width of the magnetic turbulence parallel to $\mathbf{B}$, and the path integration is along the unperturbed magnetic field line trajectory.

In this paper, we seek the solution for equation (1) in steady state ($\frac{\partial}{\partial t} \rightarrow 0$). We also limit the solution to the case where the superthermal electrons are collisionless. For this case, the stochastic diffusion operator dominates that for classical electron-electron and electron-ion collisions, and equation 1 becomes

$$\underbrace{-e E_{\parallel}(r) v_{\parallel} \frac{\partial f}{\partial \varepsilon}}_{\text{applied field drive}} = \underbrace{\frac{|v_{\parallel}|}{r} \frac{\partial}{\partial r} (r D_F \frac{\partial f}{\partial r})}_{\text{stochastic diffusion}}. \quad (5)$$

Equation 5 describes a relevant limit of superthermal electron dynamics where, in steady state, the distribution function is set by a balance between the applied electric field drive and stochastic diffusion. We note that this limit is insufficient to model the full kinetic behavior of all plasma electrons. For example, Eq. 5 neglects drifts associated with density gradients, field line curvature, ∇B , and $v_E = \mathbf{E}_0 \times \mathbf{B}/B^2$. The effect of drifts on turbulent transport has been discussed by several authors.^{23,2} In essence, drifts can mitigate stochastic diffusion by particle trapping or by the decorrelation of particle motion from the turbulent field when the radial excursion of a drift orbit from the mode rational surface exceeds the radial correlation length of the turbulence. In the RFP, for the superthermal electrons of interest in this paper, the magnitude of these effects on the stochastic diffusion operator are small. However, drifts and associated effects can have a large effect on the transport of the low energy, bulk plasma electrons. This is particularly relevant to the $\mathbf{E} \times \mathbf{B}$ drift which can drive a non-trivial inward particle pinch.

Equation 5 also neglects the effects due to electron-electron and electron-ion collisions. Previous work has shown that effects such as enhanced plasma resistivity due to edge electron momentum absorption requires the inclusion of both operators in Eq. 1.¹⁶ In addition, a proper determination of the source or background distribution function, which is necessary to calibrate the absolute density

of the superthermal electrons, requires the inclusion of the collision operator.²⁰ Nevertheless, equation 5 can provide important insights into electron distribution evolution in the presence of magnetic field diffusivity and high magnetic shear as the ratio of applied to critical electric field becomes large ($E_\phi/E_{critical} \rightarrow 1$).

With these assumptions, the application of separation of variables to Eq. 5 leads to a solution of the form:

$$\begin{aligned} f(r, \epsilon) &= \sum_n A_n F_n(r) e^{-\frac{\epsilon}{T_n}} & \text{for } (v_{||} > 0) \\ &= 0 & \text{for } (v_{||} < 0) \end{aligned} \quad (6)$$

where $F_n(r)$ is the n^{th} radial eigenmode with amplitude A_n . The n^{th} “temperature” harmonic is defined as

$$T_n = T_0/\lambda_n^2, \quad (7)$$

where $T_0 = eE_0 a^2/D_F$, E_0 is the applied electric field on axis, and λ_n is the eigenvalue of mode n set by the boundary condition that $F_n = 0$ at the plasma edge ($r=a$).

The magnetic moment μ does not explicitly appear in the differential operators of Eq. 5 or in the functional form of Eq. 6. In the collisionless limit with no particle drifts, explicit μ dependence can be included in Eq. 6 by means of a multiplicative function $G(\mu)$. That is, $f(r, \epsilon, \mu) = f(r, \epsilon)G(\mu)$. The function $G(\mu)$ is set by the initial conditions in the electron source function $f(r, \epsilon_0, \mu)$, where $\epsilon_0 = \mu B - e\phi_A$. Specific forms for $G(\mu)$ will be developed and discussed within the context of comparing the model solutions with experimental measurements in Section C.

The radial eigenmodes, F_n , satisfy the equation

$$\frac{\partial^2 F_n}{\partial r^2} + \frac{1}{r} \frac{\partial F_n}{\partial r} + \frac{E_{||}(r)}{E_0} \left(\frac{\lambda_n}{a} \right)^2 F_n = 0. \quad (8)$$

For $E_{\parallel}$ independent of radius, the eigenmodes are described by Bessel functions of order zero, and hence equation 8 has the well known Fourier-Bessel solution. However, in the RFP, the spatial behavior of $E_{\parallel}(r)$ necessitates a numerical solution. The behavior of $E_{\parallel}(r)$ is calculated by first using a model to calculate the mean magnetic fields. In this model, called the Modified Bessel Function Model (MBFM), the RFP is assumed to evolve through a series of quasi-relaxed states determined by the modified force free equation $\nabla \times \mathbf{B} = \Lambda(r)\mathbf{B}$, where $\Lambda(r)$ is a function of the minor radius and specifies the parallel current density profile ($\Lambda(r) = \mu_o \mathbf{J} \cdot \mathbf{B} / B^2$).²⁴ For a given discharge, $\Lambda(r)$ is chosen such that the calculated MBFM mean fields are consistent with the measured values of the edge poloidal and toroidal magnetic fields ($B_{\theta}(a), B_{\phi}$) and the toroidal magnetic flux ($\pi a^2 < B_{\phi} >$). This force free formalism provides a good approximation to RFP mean field behavior even with finite beta.²⁵

Once the mean fields are obtained, the steady-state $E_{\parallel}(r)$ is calculated by the relation:

$$E_{\parallel}(r) = E_0 \frac{< B_{\phi}(r) >}{\sqrt{< B_{\phi}(r) >^2 + < B_{\theta}(r) >^2}} \quad (9)$$

where $< B_{\phi}(r) >$ and $< B_{\theta}(r) >$ denote the mean toroidal and poloidal magnetic fields, respectively. With $E_{\parallel}(r)$ determined, Equation 8 is numerically solved for the first five radial eigenmodes using a fourth order Runge-Kutta algorithm.²⁶ Equation 6 is then inverted using a least-squares algorithm to solve for the eigenmode amplitudes. This numerical algorithm was benchmarked by solving the Fourier-Bessel equation and comparing the numerically derived solutions with the analytic Fourier-Bessel solutions. For this comparison, the numerical and analytic solutions agreed to better than one part in a thousand.

C. Comparisons with Experiment

The most extensive published survey of edge plasma conditions in the RFP, to date, have been made on the ZT-40M experiment.¹⁰ Of principal interest is the use of an electrostatic energy analyzer (EEA) to measure the tail of the electron energy distribution function in the edge plasma. The primary result of the EEA measurement is the observation of an intense, superthermal electron tail that moves

with a nearly unidirectional flow along $\mathbf{B}$ in a toroidal sense consistent with an acceleration by the applied electric field force in the plasma core (inside the reversal surface). The distribution of energy in the tail electrons is well characterized by an exponential dependence with a characteristic energy several times the central electron temperature (roughly 350 eV for the 60 kA discharges studied). This is in contrast to the background plasma temperature of ≈ 20 eV. The superthermal electrons have a density of 2% to 3% of the bulk edge plasma, and they are highly collisionless in that their mean free path typically exceeds 100 meters.

An important comparison with the experimental data is afforded by modeling the spatially dependent superthermal electron current collected by the EEA, called (I_{EEA}), as a function of the retarding bias potential, V_B . In general, this current is related to the electron distribution function $f(r, \varepsilon, \mu)$ by the expression

$$I_{EEA}(r, V_B) \propto \int_{v_B}^{\infty} \int_0^{\infty} f(r, \varepsilon, \mu) v_{\perp} dv_{\perp} v_{\parallel} dv_{\parallel} \quad (10)$$

where $v_B = \sqrt{2eV_B/m_e}$ and, as previously discussed, $f(r, \varepsilon, \mu) = f(r, \varepsilon)G(\mu)$. For quantitatively comparing the model predictions with experimental data, the constants of proportionality in Eq.10, $G(\mu)$, as well as an absolute calibration of the EEA must be determined. In general, this is a difficult process due to systematic uncertainties in the measurements and a lack of information on the source distribution function $f(r, \varepsilon_0, \mu)$. However, for a known $G(\mu)$, the proportionality constants can be estimated by performing a least-squares fit to the experimental data as a function of bias potential at one spatial position. The remaining data can then be directly compared with the model predictions at other radial positions.

Two extreme cases were used to estimate the effect of $G(\mu)$ on the calculation of I_{EEA} . The first case assumed $T_{\perp} \ll T_{\parallel}$ and $G(\mu) = e^{-\mu/T_{\perp}}$, where $T_{\perp}$ and $T_{\parallel}$ denote the effective superthermal temperature perpendicular and parallel to $\mathbf{B}$, respectively. The second case assumed $T_{\perp} \approx T_{\parallel}$ which gives $G(\mu) \approx 1$. It was found for these cases that the effect of $G(\mu)$ on I_{EEA} was weak; less than 20%. As such, and for simplicity, the $G(\mu) = 1$ approximation is used.

For $G(\mu) = 1$, the model predicted analyzer current is given in terms of $f(r, \varepsilon)$ by the expression²⁷

$$I_{EEA}(r, V_B) \propto \int_{eV_B}^{\infty} f(r, \varepsilon) \varepsilon \left(1 - \frac{eV_B}{\varepsilon}\right) d\varepsilon. \quad (11)$$

We note that the EEA collects current for electrons with parallel kinetic energy ($\frac{1}{2}m_e v_{\parallel}^2$) in excess of the bias potential eV_B , where V_B is referenced to the plasma vacuum vessel wall. The vacuum vessel wall is also the $\phi_A = 0$ reference in Eq. 5. Consequently, the measured electron energy can be directly related to ε in Eq. 11 without specific knowledge of $\phi_A(r)$.

Figure 1 compares the measured and calculated $I_{EEA}(r, V_B)$ for a series of 60 kA discharges on ZT-40M. The measurements were all obtained at 3 ms into the discharge, and during a current flat-top. For these discharges, the EEA was inserted into the edge plasma at r/a values of 0.95, 0.85, and 0.75, respectively.¹⁰ Fig 1a shows the least-squares fit to the data at $r/a = 0.95$. The measured and calculated behavior of $I_{EEA}(r, V_B)$ at $r/a = 0.85$ and 0.75 are shown in Figs. 1b and 1c, respectively. Insertion further into the plasma or insertion in discharges with currents exceeding 60 kA was contraindicated due to EEA damage that resulted from superthermal electron bombardment. As a point of reference, the reversal surface for this discharge series was estimated at $r/a \approx 0.8$.

The Fig. 1 comparisons show significant agreement between the model predictions and the experimental data. The model predicts a spatially uniform superthermal electron “temperature” in the exterior plasma region. This spatial uniformity derives from the collisionless nature of the transport, coupled with an acceleration process that is dominant in the plasma interior where $E_{\parallel}$ is maximized. In addition, the model predicts both the unidirectionality of I_{EEA} along $\mathbf{B}$ and the monotonically increasing behavior of $I_{EEA}(r, V_B)$ as a function of EEA insertion. The unidirectional, exponential behavior of I_{EEA} derives from the velocity dependence of the stochastic diffusion operator, and its symmetry with respect to the direction of $v_{\parallel}$ in Eq. 5.

The slope of I_{EEA} , hereafter called the temperature, is strongly dependent on the first temperature harmonic, T_1 . Recalling $T_1 = T_0/\lambda_1^2 = eE_0 a^2/(D_F \lambda_1^2)$, it follows that the observed superthermal electron temperature (T_S) is primarily determined by the applied parallel electric field on axis (E_0), the behavior of $E_{\parallel}$ as a function of radius (due to mean magnetic field shear), and the magnetic field

diffusivity. Thus, by knowing E_0 , D_F and $E_{||}(r)$ for a given discharge, the mean superthermal electron energy is quantifiable. Conversely, Eq. 7 can be used to calculate the mean or globally averaged D_F from the known or measured values of T_S , E_0 , λ_n , and minor radius (a). A test of model accuracy can then be made by comparing the calculated mean diffusivity to that inferred from the measured properties of the magnetic turbulence.

On ZT-40M, magnetic turbulence has been characterized for 60 kA discharges with conditions similar to those used for obtaining the superthermal electron current data. The measurements, made with a four fingered $\tilde{\mathbf{B}}$ probe array inserted 1 cm into the edge plasma,²⁸ indicate that the magnetic turbulence is dominated by $m=1$, $n=15 \pm 25$ fluctuations resonant in the plasma interior. These interior modes are believed to originate from current driven MHD activity; the so called MHD dynamo modes. Owing to the global nature of the modes, the spectral properties of the turbulence in the edge plasma can be extrapolated into the plasma interior by utilizing an RFP stability model.²⁹ In this way, the measured $\tilde{\mathbf{B}}$ cross-power spectrum is radially resolved in terms of a poloidal (m) and toroidal (n) eigenmode spectrum ($b_{mn}(r)$). The radial eigenmodes can then be used to infer D_F using Eq. 4.

Figure 2 plots D_F as calculated from the edge $\tilde{\mathbf{B}}$ measurements for the 60 kA discharge series..²⁸ In comparison, the model predictions for the 60 kA edge electron measurements have $T_1 = 317.5$ eV, $E_0 = 7$ V/m, $a = 0.2$ m, and λ_1 , in which is quantified the $E_{||}(r)$ contribution, is 2.8. Using Eq. 7 yields a normalized mean magnetic diffusivity of $D_F/a = 6 \cdot 10^{-4}$ which is consistent with the range of fluctuation based magnetic diffusivity values shown in Figure 2.

As an alternate check, we note from the measured $\tilde{\mathbf{B}}$ spectrum that $\Delta k_{||} \leq \frac{1}{a}$ which gives (from Eq. 4) $L_0 \leq \pi a$. From Eq. 7, a D_F of $6 \cdot 10^{-4}$ yields a lower limit on the rms radial magnetic fluctuations $b_{r|rms}$ of $\sqrt{\frac{1}{\pi} \frac{D_F}{a}}$ or 1.4 %. Again, this value is consistent with the 1 to 2 % values of $b_{r|rms}$ observed for the 60 kA conditions in ZT-40M.

Finally, a corroborative check on the premise of cross-field magnetic turbulent transport is possible by noting that in the quasi-linear limit, the radial superthermal electron flux is given by $\Gamma_{r\mathbf{B}} = \frac{-1}{eB} < \tilde{j}_{||} \tilde{B}_r >$ where $\tilde{j}_{||} = -e \int_{-\infty}^{\infty} v_{||} \tilde{f} dv$ is the fluctuation in the superthermal electron current.³⁰ In essence, $\tilde{j}_{||}$ is proportional

to $\tilde{I}_{EEA}$, so that $\Gamma_{rB} \propto \langle \tilde{I}_{EEA} \tilde{B}_r \rangle$. Experimental measurements of $\langle \tilde{I}_{EEA} \tilde{B}_r \rangle$ is displayed in Fig. 3 and shows an experimentally significant correlation which is consistent with an outward particle flux driven by magnetic fluctuations.³¹

In conclusion, magnetic turbulent transport plays an important role in the superthermal electron dynamics of the RFP. Even in the collisionless limit, the RFP does not exhibit canonical run-away electrons due to the presence of moderate magnetic diffusivity and a strong monotonic decrease in $E_{||}$ as a function of radius. This is in sharp contrast to the tokamak, where runaway electrons can achieve very high energy.² The described transport model, based on quasi-linear test particle diffusion due to magnetic field stochasticity in the collisionless limit, quantitatively predicts the observed temperature and spatial dependence of superthermal electrons in the edge plasma. The importance of magnetic turbulent driven transport is further supported by experimental estimates of Γ_{rB} and the evaluation that superthermal electrons convect roughly six times more thermal energy in the edge plasma than convected or conducted by electrostatic turbulence.²⁸

III. DISCUSSION

One can not discuss the role of magnetic turbulent transport in confinement systems without briefly acknowledging the fundamental difficulties associated with quantifying this physical process. The difficulties arise from several issues. For one, unlike electrostatic turbulence, magnetic turbulent transport is intrinsically non-ambipolar. Thus an important element of a self-consistent transport solution is the inclusion of all relevant particle transport mechanisms. Another important self-consistency issue is the effect of induced transport on the driving turbulence. This includes the association between electrostatic and magnetic turbulent transport in a given system, and the justification for using a simple quasi-linear description of the transport dynamics.

In the preceeding discussion, we have hypothesized that a quasi-linear test particle diffusion model embodies physics that is relevant to understanding magnetic turbulent transport in the RFP. While not immune from all difficulties, a fundamental premise of test particle transport seeks to decouple cause from effect and as such, simplifies the resulting analysis. As an example, recent work by Terry and Diamond³² has shown that within the context of a collisionless model

with thermal particle distributions, a self-consistent treatment of magnetic turbulent transport results in a reduction of order $\frac{m_e}{m_i}$ in the radial transport when compared with quasi-linear estimates. However, the constraints imposed by self-consistency are not applicable to particles that are non-resonant with the turbulent fields ($v_{\parallel} > \omega^*/k_{\parallel}$). Thus it is most likely that the superthermal electrons discussed in this paper are not subject to these constraints.

The question remains as to the applicability of the quasi-linear formalism to problems of general interest to the plasma science community. For the case of the RFP, where magnetic turbulence is relatively large, the quasi-linear formalism shows applicability. However, the proper quantification of magnetic turbulent transport for other confinement devices remains an open question and an active area for further research.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge input to this work by Guthrie Miller, Chuck Ingraham, Paul Weber and Stewart Prager. This work was performed under the auspices of the U.S.D.O.E.

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Figure 1: Experimental vs. model comparison of collected electron energy analyzer current (I_{EEA}) as a function of retarding bias potential (V_B) and radial position for 60 kA discharges in ZT-40M. The EEA data is shown as points. The solid line shows the model predictions. The EEA data and model predictions are normalized at $r/a = 0.95$. a) $r/a=0.95$, b) $r/a=0.85$, c) $r/a=0.75$

Figure 2: The normalized magnetic diffusivity $\frac{D_F}{a}$, based on extrapolations of edge magnetic turbulence measurements, is given by the solid curve. The dotted curve shows the model calculated value of $\frac{D_F}{a}$ necessary to predict the measured superthermal electron temperature in ZT-40M.

Figure 3: Experimental measurement of the the normalized cross-power spectrum or coherence defined as $\gamma = \langle \tilde{I}_{EEA} \tilde{B}_r \rangle / \sqrt{\langle \tilde{I}_{EEA}^2 \rangle \langle \tilde{B}_r^2 \rangle}$, made by the electron energy analyzer and insertable magnetic probes in ZT-40M³¹. The experimentally significant coherence is consistent with the radial transport of superthermal electrons by magnetic turbulence.

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