A Simple Neoclassical Point Model for Transport and Scaling in EBT

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TRANSPORT AND SCALING IN EBT

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ABSTRACT

A simple neoclassical point model is presented for the ELMO Bumpy Torus experiment. Solutions for steady state are derived. Comparison with experimental observations is made and reasonable agreement is obtained.

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I. INTRODUCTION

Here we consider a simple neoclassical point model for transport and scaling in the ELMO Bumpy Torus (EBT). Steady-state solutions are found which are in reasonable accord with experimental observations. Several modes of operation are observed in EBT and this model is only meant to apply to the most interesting regime of operation. Thus we begin by summarizing the pertinent features of the experimental results.¹

The EBT is a plasma confinement device consisting of a set of magnetic mirror sections linked in a torus. A central element of the EBT concept is the presence of a hot electron annulus in each mirror section, of sufficient density and temperature that diamagnetic plasma currents produce a minimum in the magnetic field. Without such a minimum, theory would predict macroscopic instability. Experimentally a rather cold and noisy mode of operation is observed when insufficient microwave power is supplied to produce substantial annular beta (ratio of plasma pressure to magnetic pressure). A rather abrupt transition from the cold or C-mode of operation to a quiet state is observed when the annular beta exceeds a critical value (5% to 15%). This value of beta corresponds to theoretical estimates of the beta necessary to produce a well defined minimum in the magnetic field. This quiet

mode of operation has a substantial toroidal plasma and is termed the T-mode. The model presented here is for the T-mode.

The T-mode is a steady-state plasma, with neutral particles entering the torus and being ionized at the same rate at which plasma is lost by diffusion. As the neutral particle density is lowered, a second abrupt transition occurs, from the T-mode to the M-mode. In the mirror or M-mode, the individual sectors (or bumps) of the torus behave rather like disconnected simple mirror machines. The hot electron annular beta becomes quite large and the toroidal plasma all but vanishes.

Both theoretically and experimentally a radial ambipolar electric field arises to equalize electron and ion diffusion losses. This radial field, E_r , in the T-mode is such that $e\phi/T_i$ is of order unity. Thus the bulk of the ions have energies below a few times the ambipolar potential energy. This has important consequences on single particle drift motion and hence upon neoclassical losses. The motion of particles with energies below the ambipolar potential energy are dominated by $E \times B$ drifts. The drift motion of high energy particles is dominated by gradient B and curvature drifts (proportional to particle energy).

There are two important neoclassical particle loss mechanisms associated with drift orbits. The first of these is particles drifting directly to the walls due to the toroidal curvature drifts of particles, which because of their location in velocity space, do not sample the entire EBT geometry (unconfined orbits). The electric field can affect this loss mechanism by moving the "loss zone" to higher energy portions of velocity space which are sparsely populated. The second mechanism is neoclassical diffusion. This mechanism depends upon scattering in velocity space and dispersion in the particle drift orbits. Since much of the distribution has its motion dominated by the $E \times B$ drift, this loss mechanism is also affected.

Experimentally the electric field appears to be strongest in the vicinity of the annulus so that the following picture emerges. Exterior to the annuli, the losses are dominated by particles moving directly to the walls. Interior to the annuli, diffusive transport losses dominate. It is for this central toroidal core that our model applies.

Within the toroidal core the ions are reasonably approximated by a fluid description in which Coulomb collisions provide the scattering mechanism. The electrons' behavior on the other hand, may be more complex. One reason for this is that the hot-electron annulus overlaps this central region. Thus we have a mirror confined, high energy tail on the distribution which could alter the usual neoclassical transport coefficients calculated for a Maxwell distribution. Also the microwave

electric field may provide a significant source of scattering in velocity space in addition to Coulomb collisions, although a rigorous theory of this process is presently lacking. In this paper, we ignore these complexities, assume that the dominant electron losses are neoclassical and equate the theoretical expressions for the ion and electron loss rates. The electric field is then calculated and used to determine a single, self-consistent neoclassical, ambipolar loss rate. The success of this fully neoclassical model in predicting energy balance consistent with observation indicates the validity of our assumption.

II. EBT MODEL EQUATIONS

In this section we present the equations for the plasma density, n , and the toroidal core ion and electron temperatures, T_i and T_e . The spatial dependence is eliminated by replacing all plasma gradients by characteristic scale lengths equal to the plasma minor radius, $a = -(d/dx)^{-1}$. Since all transport coefficients have the same functional form we define a single confinement time taken to be the particle ambipolar diffusion time.

The equations are:

$$\frac{dn}{dt} = n \left(n_0 \langle \sigma v \rangle_{\text{ioniz}} - \tau^{-1} \right) \quad (1)$$

$$\frac{d}{dt} \left(\frac{3}{2} n T_i \right) = P_{ei} - \frac{3}{2} n T_i \left(n_0 \langle \sigma v \rangle_{\text{cx}} + \tau^{-1} \right) \quad (2)$$

$$\frac{d}{dt} \left(\frac{3}{2} n T_e \right) = P_{\mu} - P_{ei} - \frac{3}{2} n T_e \tau^{-1} \quad (3)$$

Here n_0 is the neutral particle density and $n_0 \langle \sigma v \rangle_{\text{ioniz}}$ and $n_0 \langle \sigma v \rangle_{\text{cx}}$ are the ionization and charge exchange rates. The neo-classical particle diffusion rates, based on the work of Kovrizhnikh² and Harris,³ are taken to be

$$\tau_{\alpha}^{-1} = \left(4 D_{\alpha} / a^2 \right) \left(1 + q_{\alpha} a E T_{\alpha} \right) \quad (4)$$

$$D_{\alpha} = \frac{a^2}{3} \left(\frac{Rc}{R_T} \right)^2 \frac{\nu_{\alpha}}{y_{\alpha}^2} \frac{1}{\left(1 + \nu_{\alpha}^2 / y_{\alpha}^2 \Omega_{\alpha}^2 \right)} \quad (5)$$

where $\alpha = e, i$ refers to electrons, ions. The collision frequencies are

$$\nu_i = C_1 n / T_i^{\frac{3}{2}} ; \quad C_1 = \left(\frac{e^2}{\epsilon_0} \right)^2 \frac{\ln \Lambda}{25.8 \sqrt{\pi M_i}} \quad (6)$$

$$\nu_e = \left(T_i / T_e \right)^{\frac{3}{2}} \left(M_i / m_e \right)^{\frac{1}{2}} \nu_i$$

and the average poloidal curvature drift frequencies are given by

$$\Omega_{o\alpha} = \left(\frac{T_\alpha}{q_\alpha B R_c a} \right) \quad (7)$$

and

$$y_\alpha = 1 + \frac{q_\alpha E R_c}{T_\alpha} \quad (8)$$

Notice that Ω_{oy} incorporates the gradient-B and curvature drifts through the mirror radius of curvature, R_c , and the $E \times B$ drift through the parameter y . R_T is the toroidal or major radius of the plasma. The $E \times B$ drift from a positive electric field increases the ion poloidal drift frequency and decreases it for the electrons.

The transfer of energy from electrons to ions via Coulomb collisions is given by

$$P_{ei} = C_2 \frac{n^2}{T_e^{\frac{3}{2}}} \left(1 - \frac{T_i}{T_e} \right); \quad C_2 = \left(\frac{e^2}{\epsilon_0} \right)^2 \frac{\sqrt{m_e}}{M_i} \frac{\ln \Lambda}{(2\pi)^{\frac{3}{2}}} \quad (9)$$

The microwave power per unit volume absorbed by the toroidal core electrons is denoted by P_μ , and we will find it convenient to define a reactivity

$$S_{cx} \equiv 1 + \langle \sigma v \rangle_{cx} / \langle \sigma v \rangle_{ioniz} \quad (10)$$

III. STEADY-STATE SOLUTIONS

We now set the time derivatives to zero in Eqs. (1) - (3) to obtain the steady-state solutions. The time dependent equations can properly be regarded as equations for n , T_i and T_e in terms of the independent variables n_0 and P_μ . The solution of the (algebraic) steady-state equations is facilitated by interchanging the role of dependent and independent variables. In particular we regard n_0 as a dependent variable and introduce a new independent variable

$$X = T_e / T_i \quad (11)$$

Setting the time derivative to zero in Eq. (1) yields

$$n_o = 1/(\tau \langle \sigma v \rangle_{\text{ioniz}}) \quad (12)$$

Using this expression to eliminate the neutral density from Eq. (2) and setting the time derivatives to zero in Eqs. (2) and (3) gives the following power balance

$$P_{ei} = \frac{3}{2} \frac{nT_i}{\tau} S_{cx} \quad (13)$$

$$P_\mu = P_{ei} + \frac{3}{2} \frac{nT_e}{\tau} \quad (14)$$

Using Eq. (9) for P_{ei} , Eq. (13) becomes

$$\tau = \left(\frac{3}{2} \frac{S_{cx}}{C_2} \right) \frac{T_e^{\frac{3}{2}}}{n(X-1)} \quad (15)$$

Now substituting for P_{ei} in Eq. (14) and using Eq. (15), we obtain a relation between n , T_e , P_μ , and X which can be written as:

$$T_e = Q^2 n^4 / P_\mu^2 \quad (16)$$

where

$$Q \equiv \left(\frac{C_2}{S_{cx}} \right) \frac{(X-1)(X+S_{cx})}{X} \quad (17)$$

Equation (16) may now be used to eliminate T_e from Eq. (15) with the result

$$\tau = \left(\frac{3}{2} \frac{S_{cx}}{C_2} \right) \frac{Q^3}{X-1} \frac{n^5}{p_\mu^3} \quad (18)$$

We now make our first use of the explicit expressions for the neoclassical lifetimes, Eq. (4). As discussed in the introduction, neoclassical theory is used to calculate both electron and ion loss rates, and the ambipolar field is calculated from the condition that these rates be equal.

The following interesting relationships follow from ambipolarity

$$E = \frac{T_e}{ea} \left(\frac{D_e - D_i}{D_e + XD_i} \right) \quad (19)$$

$$\tau^{-1} = \frac{4(1+X)}{a^2} \left(\frac{D_i}{1 + X \frac{D_i}{D_e}} \right) \quad (20)$$

$$D_i/D_e = \left(1 - eEa/T_e \right) / \left(1 + eEa/T_i \right) \quad (21)$$

These formal relationships are similar to those obtained in the problem of classical diffusion in weakly ionized gases, but here the diffusion coefficients themselves depend on the electric field. From Eq. (21) and the definition of D_α (D_α is positive definite) we see that the ambipolar electric field is bounded as

$$-T_i < eEa < T_e \quad (22)$$

In addition we see from Eqs. (19) and (20) that for highly mobile electrons, i.e., $D_e \gg X D_i$, the electric field is approximately

$$E \simeq \frac{T_e}{ea} \quad (23)$$

and the containment time is determined by the ion diffusion rate in this field.

$$\tau^{-1} \simeq \frac{4(1+X)}{a^2} D_i (E \simeq T_e/ea) \quad (24)$$

Experimentally measured electric fields at the plasma periphery¹ in T-mode operation are of the same sign and comparable magnitude to that in Eq. (23). Note that $D_e > D_i$ is required for positive E . It is shown below using numerical solutions of the exact equations that this ($D_e > X D_i$) branch of the multivalued equilibrium corresponds to experimental observation. Other branches have negative E or $T_e \gg T_i$. Thus before proceeding to a more exact analysis of the ambipolar equilibrium, it is instructive to examine the equilibrium predicted by Eqs. (23), (24). Substituting Eq. (24) into Eq. (13) and using Eqs. (5), (6), (8) and (9), we find

$$\frac{(X-1)}{X^{\frac{3}{2}}} \frac{\left(1 + X \frac{R_c}{a}\right)^2}{(1+X)} = 0.69 \left(M_i/m_e\right)^{\frac{1}{2}} \frac{\left(R_c/R_T\right)^2 S_{cx}}{\left[1 + \frac{\nu_i}{\Omega_{oi}} \left(1 + X \frac{R_c}{a}\right)^{-2}\right]} \quad (25)$$

Thus collisionless operation, which is actually the limit in which Eq. (23) is the approximate ambipolar field, determines X for a given aspect ratio. Equation (16) and (18) can then be used to determine T_e and τ for a given density and P_μ , and $T_i = T_e/X$ completes the explicit analytic solution of the power balance equations in this limit. Note the favorable scaling $T_e \sim n^4$, $\tau \sim n^5$ for fixed X . For present EBT, Eq. (25) predicts $X \simeq 1.3$, if the collisionless ion limit were attained, assuming $S_{cx} = 2$. Further if we assume $P_\mu = 5 \times 10^{-3} \text{ W/cm}^3$ (about $\frac{1}{5}$ the total power input) then at $n = 3 \times 10^{12} \text{ cm}^{-3}$, $\tau = 27 \text{ msec}$, $T_i = 60 \text{ eV}$, $T_e = 80 \text{ eV}$. This is consistent with present experimental estimates of density, ion temperature and containment time but is too low for the electron temperature. As we shall see, a more accurate numerical treatment brings the neoclassical point model into better overall agreement with experiment.

Setting $\tau_i = \tau_e$ using Eq. (4) we obtain the following cubic equation for E

$$\left[\left(1 + \frac{eR_c E}{T_i} \right)^2 + \frac{\nu_i^2}{\Omega_{oi}^2} \right] \left(\frac{eaE}{T_e} - 1 \right) + \left[\left(1 - \frac{eR_c E}{T_e} \right)^2 + \frac{\nu_e^2}{\Omega_{oe}^2} \right] \cdot \delta^{\frac{1}{2}} X^{\frac{3}{2}} \left(\frac{eEa}{T_i} + 1 \right) = 0 \quad (26)$$

where $\delta \equiv m_e/m_i$. For possible future reference we note that in deriving Eq. (26) no use has been made of the steady state limit ($d/dt = 0$) of Eqs. (1) - (3). Thus these four equations can be used to study the time evolution of EBT, although this is not done in the present paper. We notice that Eq. (26) does indeed have the approximate solution Eq. (23) in the (collisionless) limit $(\nu_e^2/\Omega_{oe}^2) \delta^{\frac{1}{2}} X^{\frac{3}{2}} \ll 1$. Equations (26), (13) - (15) are a coupled set of equations for n , T_e , T_i , E . It is convenient to solve them by using Eq. (15) with $\tau = \tau_i$, with Eq. (26) guaranteeing that $\tau_i = \tau_e$, to generate an independent quadratic equation for E .

$$\left(1 + \frac{eR_c E}{T_i} \right)^2 + \frac{\nu_i^2}{\Omega_{oi}^2} = \left(1 + \frac{eaE}{T_i} \right)^2 S_{cx} \frac{C_1}{C_2} \left(\frac{R_c}{R_T} \right)^2 \frac{X^{\frac{3}{2}}}{(X-1)} \quad (27)$$

Solving Eq. (27) for ν_i^2/Ω_{oi}^2 and noting from Eqs. (6) and (7) that

$$-\frac{\nu_e}{\Omega_{oe}} = \frac{\nu_i}{\Omega_{oi}} \frac{1}{\sqrt{\delta X^5}}$$

we may substitute into Eq. (26) to obtain an equation for E/T_i in terms of X . Note the occurrence of the common factor $(1 + eEa/T_i)$ when we do this. We neglect this negative root as unphysical. The remaining roots for E/T_i satisfy

$$\begin{aligned} & \left(1 + \frac{eR_c E}{T_i}\right)^2 - \delta X^5 \left(1 - \frac{eR_c E}{T_e}\right)^2 - 2 S_{cx} \frac{C_1}{C_2} \left(\frac{R_c}{R_T}\right)^2 \frac{X^{\frac{3}{2}}}{(X-1)} \\ & \bullet \left[1 + \frac{eEa}{T_i} + \delta^{\frac{1}{2}} X^{\frac{7}{2}} \left(\frac{eEa}{T_e} - 1 \right) \right] = 0 \end{aligned} \tag{28}$$

Finally we utilize Eqs. (6), (7) and (16) to write

$$\frac{\nu_i}{\Omega_{oi}} = \frac{C_1 e B R_c a P_\mu^5}{Q^5} \frac{X^{5/2}}{n^9}$$

Substituting this expression into Eq. (27) we obtain:

$$n^{18} = P_\mu^{10} \frac{(C_1 e B R_c a)^2}{Q^{10}} X^5 \cdot \left\{ 2 S_{cx} \frac{C_1}{C_2} \left(\frac{R_c}{R_T} \right)^2 \frac{X^{3/2}}{X-1} \left(1 + \frac{e E a}{T_i} \right) - \left(1 + \frac{e R_c E}{T_i} \right)^2 \right\}^{-1} \quad (29)$$

We now have expressions for all the relevant quantities as functions of X . The procedure is to solve Eq. (28) for E/T_i as a function of X . From Eq. (29) we then obtain the density. From Eq. (16) we obtain T_e and hence T_i from $T_i = T_e / X$. The lifetime is obtained from Eq. (18) and the neutral density from Eq. (12).

The density in EBT appears to be limited by microwave cutoff. Thus in the next section we cross-plot the results versus density. We, also restrict our attention to positive electric fields as inferred from measurement at the plasma periphery.¹

IV. COMPARISON WITH EXPERIMENTAL RESULTS

In this section we present numerical results for comparison with experiment. For all the calculations presented here we have taken:

$$B = 0.65 \text{ Tesla}$$

$$R_T = 1.5 \text{ m}$$

$$R_c = 0.188 \text{ m}$$

$$a = 0.1 \text{ m}$$

$$\ln \Lambda = 17$$

$$\langle \sigma v \rangle_{\text{ioniz}} = \langle \sigma v \rangle_{\text{cx}} = 3.5 \times 10^{-14} \text{ m}^3/\text{sec}$$

The results are summarized in Figs. 1 and 2. In Fig. 1 we have taken $P_\mu = 5 \times 10^{-3} \text{ watts/cm}^3$ (roughly one fifth the microwave power density in EBT). Figure 1a shows the electron and ion temperatures and their ratio versus density and Fig. 1b shows the confinement time and normalized ambipolar field versus density. Figure 2 shows the same curves assuming that $P_\mu = 10^{-2} \text{ W/cm}^3$. These curves predict the existence of equilibria in reasonable agreement with experimental observations

$$n \approx 4 \times 10^{12} \text{ cm}^{-3}$$

$$50 \text{ eV} \approx T_i \approx 90 \text{ eV}$$

$$150 \text{ eV} \approx T_e \approx 300 \text{ eV}$$

and τ a few tens of milliseconds. The higher microwave power absorption gives somewhat better agreement. There is some experimental evidence that $e\phi/T = 0$ (1), which is also consistent with these results. The upper bound on density is presumably due to microwave cutoff.

There are no acceptable equilibria corresponding to the lower density portion of the scales shown. It is interesting to speculate that this might be related to the observed sharp transition between the relatively high density quiescent T-mode and the low density highly fluctuating M-mode as the fill density is decreased.

Note that the electron and ion temperatures increase with density and that the electric field and temperature ratio tend towards the collisionless limit of Eqs. (23) and (25). It appears from these calculations that present EBT operation is in a transitional regime to collisionless operation.

VI. SUMMARY

We have presented a simple neoclassical point model which is in reasonable agreement with experimental observations of power balance. We assumed that the dominant electron losses are neoclassical, and equated the neoclassical expressions for τ_i and τ_e to determine a self-consistent, ambipolar field which is then used to calculate power balance. An encouraging feature of the numerical results is that the temperatures and confinement times increase with density indicating an approach to a collisionless regime. If this regime can be reached the analysis predicts the very favorable density scaling $T_e \sim n^4$, $\tau \sim n^5$.

Finally we emphasize that scaling arguments based on $\tau(T_e, T_i, n)$ are consequences of neoclassical loss rates, and would be expected to be valid only in the absence of substantial plasma turbulence. Scaling arguments based on the relation between T_e, T_i and the microwave power input P_μ are peculiar to the particle heating scheme employed in EBT which channels the total energy input through the electrons. Other heating schemes, e. g. ion beam heating, will follow different scaling laws.

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FIGURE CAPTIONS

Figure 1. (a) Electron and ion temperatures and their ratio (T_e/T_i) versus density assuming $P_\mu = 5 \times 10^{-3} \text{ W/cm}^3$.
(b) Ambipolar confinement time and normalized electric field versus density.

Figure 2. Same as Figure 1 but with $P_\mu = 10^{-2} \text{ W/cm}^3$.

Figure 1a

Figure 1b

Figure 2a

Figure 2b

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70. CTR Reading Room, c/o Prof. C. S. Liu, Dept. of Physics and Astronomy, Univ. of Maryland, College, MD 20742
71. CTR Reading Room, c/o Prof. T. Kammash, 103 Research Admin. Bldg., N. Campus, Univ. of Michigan, Ann Arbor, MI 48105
72. CTR Reading Room, c/o Dr. Ravi N. Sudan, Phillips Hall, Cornell Univ., Ithaca, NY 14850
73. Prof. Marshall N. Rosenbluth, Institute for Advanced Study, Princeton, NJ 08540
74. CTR Reading Room, c/o Prof. R. Gross, Plasma Research Lab., Columbia Univ., New York, NY 10027
75. CTR Reading Room, c/o Prof. Roy Gould, California Inst. of Tech., M.S. 116-81, Pasadena, CA 91125
76. Dr. Nicholas A. Krall, Science Applications, Inc., P.O. Box 2354, 1200 Prospect St., La Jolla, CA 92037
77. CTR Reading Room, c/o Dr. Jay P. Boris, Plasma Physics, Naval Research Laboratory, Washington, DC 20390
78. Professor A. Simon, Dept. of Mechanical & Aerospace Sciences, University of Rochester, Rochester, NY 14627
79. CTR Library, c/o Dr. Alan F. Haught, United Technologies Research Labs, East Hartford, CT 06108
80. Dr. H. K. Forsen, Exxon Nuclear Co., Inc. 777-106th Avenue, NE, C-000777, Bellevue, WA 98009
81. Dr. George Vahala, Physics Dept., College of William & Mary, Williamsburg, VA 23185
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