Modeling Cross-Field Drifts and Current
With the B2 Code for the CIT Divertor

T.D. Rognlien
J.L. Milovich
M.E. Rensink

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MODELING CROSS-FIELD DRIFTS AND CURRENT WITH THE B2 CODE FOR THE CIT DIVERTOR

A Status Report for the CIT Project
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T. D. Rognlien, J. L. Milovich, and M. E. Rensink DE91 004948
Lawrence Livermore National Laboratory
University of California, Livermore, CA 94550

INTRODUCTION

We have modified the B2 edge-plasma code¹ to include the effects of classical fluid drifts across the magnetic field lines and plasma currents. This report presents preliminary results of these effects for the CIT parameter regime.

The basic plasma model described by Braams¹ involves solving the continuity equation, the parallel momentum balance equation, and separate energy balance equations for the ions and the electrons. If multiple ion species are present, they are all assumed to have a common temperature, but their densities and parallel velocities are solved for using additional continuity and parallel momentum balance equations for each species. Momentum and heat transport parallel to the magnetic field, $\mathbf{B}$, are given by the classical collisional theory². On the other hand, transport perpendicular to $\mathbf{B}$ is represented by anomalous diffusion coefficients which are adjusted to agree with experimental measurements. These transport coefficients are generally taken to be constant in radius and poloidal angle, although this is not necessary.

The goal of our work has been to include both the classical cross-field drift terms and the effects of parallel currents in the equations used in the B2 code. The motivation for including the cross-field terms comes from simple model calculations³ which indicate that the classical flows can contribute an important asymmetry which may help explain the transition from L-mode to H-mode confinement. Radial electric fields which arise near the separatrix cause $\mathbf{E} \times \mathbf{B}$ poloidal rotation which may also be related to the L-to-H mode transition through its effect on edge turbulence.^{4,5} Including the parallel currents is done to provide a tool for understanding the biased divertor experiments⁶ on DIII-D at General Atomics. Such biasing may provide an effective means of controlling the asymmetry of the power flow to different divertor plates. Furthermore, even for tokamaks with grounded plates, asymmetries drive parallel currents.

THE MODEL

Toroidal Geometry

Because the cross-field drifts depend on the direction of the magnetic field relative to spatial gradients, care needs to be taken in defining the geometry and coordinate system. The convention used is that in viewing the plasma poloidal cross-section, the

magnetic axis is to the left as shown in Fig. 1. The toroidal unit vector, $\hat{e}_\phi$, is taken into the paper, and the toroidal plasma current is always in this same direction. Thus, the poloidal magnetic field, $B_p \hat{e}_p = \hat{e}_\phi \times \nabla \psi / R$, is directed in the clockwise direction inside the separatrix. Here, ψ is the poloidal flux function, R is the major radius, and we always take B_p to be positive. On the other hand, for the toroidal magnetic field, $B_\phi \hat{e}_\phi$, B_ϕ may be positive or negative. For B_ϕ positive, the toroidal field is into the paper, and the $\mathbf{B} \times \nabla B$ ion drift is directed toward the upper x-point in Fig. 1.

We use a right-handed coordinate system with unit vectors $(\hat{e}_r, \hat{e}_f, \hat{e}_\parallel)$. Here $\hat{e}_\parallel$ is the unit vector along the magnetic field, $\hat{e}_r = \nabla \psi / |\nabla \psi|$ is the radial-like direction, and $\hat{e}_f = \hat{e}_\parallel \times \hat{e}_r$ lies in the flux surface. Note that $\hat{e}_r$ always points to the right at the outer scrap-off layer, but that $\hat{e}_f$ and $\hat{e}_\parallel$ change direction with the sign of B_ϕ . The relationship between the various unit vectors can be summarized as follows:

$$\hat{e}_f = \frac{B_\phi}{B} \hat{e}_p - \frac{B_p}{B} \hat{e}_\phi \quad (1)$$

and

$$\hat{e}_\parallel = \frac{B_p}{B} \hat{e}_p + \frac{B_\phi}{B} \hat{e}_\phi. \quad (2)$$

Here B is the magnitude of $\mathbf{B}$ and is always positive. While, transport in both the $\hat{e}_f$ and $\hat{e}_\parallel$ directions have components in the poloidal and toroidal directions, only the poloidal components will be used explicitly in the equations here because toroidal symmetry is assumed. However, toroidal drifts will be calculated as a diagnostic.

Equations for Cross-Field Flows

We use the fluid equations² to obtain the cross-field plasma flows. First we consider the fluid velocities as obtained from the perpendicular ion momentum equation in which inertia and viscosity are neglected:

$$0 = -\frac{\nabla_\perp p_i}{ne} + \mathbf{E}_\perp + \mathbf{v}_\perp \times \mathbf{B} - \eta_\perp \mathbf{J}_\perp \quad (3)$$

where $\mathbf{E}_\perp$ is the perpendicular electric field, $\mathbf{v}_\perp$ is the perpendicular ion velocity, $p_i = nT_i$ is the ion pressure, n is the density, T_i is the ion temperature, e is the magnitude of the electron charge, $\mathbf{J}_\perp$ is the perpendicular plasma current, and $\eta_\perp$ is the perpendicular resistivity. An anomalous resistivity can be added as we shall mention later. The perpendicular drifts are obtained from Eq. (3) as

$$\mathbf{v}_\perp = \frac{(\mathbf{E}_\perp - \nabla_\perp p_i / ne) \times \mathbf{B}}{B^2} - \eta_\perp \frac{\mathbf{J}_\perp \times \mathbf{B}}{B^2}. \quad (4)$$

The perpendicular currents are found by adding the electron and ion momentum equations with inertia and viscosity terms neglected. This procedure yields the standard relation

$$\mathbf{J}_\perp = \frac{\mathbf{B} \times \nabla_\perp p}{B^2} \quad (5)$$

where $p = p_e + p_i$ is the total plasma pressure. Combining Eqs. (3-4) then gives

$$\mathbf{v} = \frac{(\mathbf{E} - \nabla p_i / ne) \times \mathbf{B}}{B^2} - \eta_{\perp} \frac{\nabla_{\perp} p}{B^2}. \quad (6)$$

The diffusive term that has been used in the B2 code is representative of an anomalous contribution to the last terms in Eq. (6), although it is generally taken to be proportional to ∇n rather than ∇p .

The B2 code solves the fluid equations in the poloidal plane using the coordinates (x, y) to correspond to the $\hat{\mathbf{e}}_p$ and $\hat{\mathbf{e}}_r$ directions, respectively. Using Eqs. (1,2,6), one can write the drift terms explicitly in the (x, y) coordinates as

$$v_x = \frac{B_{\phi}}{B^2} \left(\frac{\partial \phi}{\partial y} + \frac{1}{ne} \frac{\partial p_i}{\partial y} - \eta_{\perp} \frac{B_{\phi}}{B^2} \frac{\partial p}{\partial x} \right) + \frac{B_p}{B} v_{\parallel} \quad (7)$$

and

$$v_y = -\frac{B_{\phi}}{B^2} \left(\frac{\partial \phi}{\partial x} + \frac{1}{ne} \frac{\partial p_i}{\partial x} + \eta_{\perp} \frac{1}{B_{\phi}} \frac{\partial p}{\partial y} \right) - \frac{D_a}{n} \frac{\partial n}{\partial y} + v_a. \quad (8)$$

Here $\mathbf{E} = -\nabla \phi$, and $v_{\parallel}$ is the parallel velocity already calculated in the code. The last two terms in Eq. (8) have been used previously in the code to represent anomalous fluxes; D_a is the anomalous diffusion coefficient, and v_a is the anomalous convective velocity. The values of the D_a and v_a used for tokamak edge plasma modeling are typically sufficient to make the classical terms proportional to $\eta_{\perp}$ unimportant.

It should be mentioned that B2 represents the solution on a grid (x_0, y_0) in which x_0 is the distance along a particular flux surface, and y_0 is radial-like distance normal to the flux surface at a given value of x (we use the midplane, $x=0$). Metric factors (h_x, h_y) are required to translate to the physical location (x, y) . Thus,

$$\frac{\partial}{\partial x} \rightarrow \frac{1}{h_x(x, y)} \frac{\partial}{\partial x_0}$$

and likewise for the y -coordinate.

In addition to ion fluid drifts, we include the cross-field energy flux² for both the ions and the electrons. For the ions, this term has the form

$$q_{cf} = -\frac{5}{2} \frac{n T_i}{e B^2} \mathbf{B} \times \nabla T_i \quad (9)$$

while for electrons, the overall sign changes to a plus. In terms of the (x, y) coordinates, we have

$$q_{cfx} = -\frac{5}{2} \frac{n T_i B_{\phi}}{e B^2} \frac{\partial T_i}{\partial y} \quad (10)$$

and

$$q_{cfy} = \frac{5}{2} \frac{n T_i B_{\phi}}{e B^2} \frac{\partial T_i}{\partial x}, \quad (11)$$

and likewise for the electrons with a sign change.

There are also corrections to the electron energy balance equation owing to the presence of the parallel current, $J_{\parallel} = ne(v_{\parallel i} - v_{\parallel e})$, along $\mathbf{B}$. One term is the effect of Joule heating, and is represented by adding a $\mathbf{J} \cdot \mathbf{E}$ source term. The second arises to account for the difference in the electron and ion velocities in the convected heat flux. We use the convention that the parallel velocity used to convect energy in both ion and electron energy balance equations is the ion parallel velocity. Thus, the electron heat flux in the x -direction has a new term given by

$$q_{x e j} = - \left(\frac{5}{2} + \alpha \right) \frac{B_p}{B} \frac{T_e J_{\parallel}}{e} \quad (12)$$

where the term proportional to α ($= 0.71$ for $Z_{eff} = 1$) comes from the thermal force correction. The current modification given by Eq. (12) generally dominates over Joule heating for the cases we have studied. There are also corrections to the perpendicular heat flux from these same effects, but we have neglected them as small for now.

Equations for Electrostatic Potential and Parallel Current

Some of the correction terms we have discussed depend on the electrostatic potential and the parallel current. These quantities are obtained from two equations: the inertialess parallel electron momentum equation written in the form

$$0 = -\frac{1}{ne} \frac{\partial p_e}{\partial x} + \frac{\partial \phi}{\partial x} - \frac{\alpha}{e} \frac{\partial T_e}{\partial x} + \frac{B}{B_p} \eta_{\parallel} J_{\parallel} \quad (13)$$

where $\eta_{\parallel}$ is the parallel resistivity, and the current continuity equation, $\nabla \cdot \mathbf{J} = 0$, written as

$$B_p \frac{\partial}{\partial x} \left(\frac{1}{B} J_{\parallel} \right) = -\nabla_{\perp} \cdot \mathbf{J}_{\perp}. \quad (14)$$

Substituting for $J_{\parallel}$ from Eq. (13) and for $\mathbf{J}_{\perp}$ from Eq. (5) then gives an equation which solve for ϕ in the scrape-off region (SOL) given boundary conditions on the divertor plates. These boundary conditions come from the analysis discussed in Refs. 7 and 8.

The solution of the potential equation in the core region of the plasma is complicated by the need to impose periodic boundary conditions. If we add an anomalous perpendicular current to Eq. (5) proportional to $(\mathbf{E}_{\perp} + \nabla_{\perp} p_e / ne)$ as suggested by B. J. Braams (private communication), the equation for ϕ becomes two-dimensional. We are then able to find a potential in the core region as well. However, the connection of this ansatz to a physical mechanism needs to be determined, so we shall present results where the potential is calculated from Eq. (14) in the SOL, while in the core, the potential is set to the value just across the separatrix in the SOL.

SIMULATION RESULTS

We have modeled two types of configurations to study the effects of with the cross-field terms and parallel current. One is a double-null divertor of the type planned for

CIT as shown in Fig. 1. We have simulated the outer portion of the divertor to study up-down asymmetries arising from the cross-field drifts. Imaginary lines (shown as dots in Fig. 1) are drawn normal to the flux surfaces through the x-points. These lines are taken as reflecting boundaries following previous CIT calculations by Braams and Stotler, who, by symmetry, only consider the lower half of the outer scrape-off layer. The reflecting boundary conditions modify the physics in the vicinity of the x-point, so for this model, we are only partially describing the influence of the cross-field drifts. Nevertheless, the model does give insight into the asymmetries caused by the drifts.

The full problem is to include the inside scrape-off layer as well, and apply periodic boundary conditions in the core region. We have made the first step toward this proper treatment of the x-point region by considering a single-null geometry as shown in Fig. 2, and applying periodic boundary conditions in the core. These calculations model typical DIII-D operation. The calculations show the influence of the periodic boundary conditions and the strong effect that biasing can have on divertor plate asymmetries.

Double-Null Configuration, Outer SOL Only

To model the CIT magnetic field configuration, we use poloidal flux surfaces generated from a conformal mapping procedure by B. J. Braams (private communication, Sept. 1990) for the new $R = 2.6$ m, $B = 9$ T CIT design. The flux surfaces in the outer lower quadrant are shown in Fig. 3. We reflect this configuration vertically, about the midplane to obtain the outer upper quadrant as well. We thus include both the upper and lower divertor plates on the outside, and can study asymmetries. The toroidal field, B_ϕ , is positive, so the $\mathbf{B} \times \nabla B$ ion drift is toward the upper x-point.

Because no particle or energy flux is allowed to flow across the boundaries through the x-point, there is a problem with the cross-field fluxes which depend on gradients along the boundary rather than normal to it as for the other fluxes. Consequently, we have multiplied the cross-field fluxes by a function which goes to zero smoothly over the last few grid points before the reflecting boundary. The other choice is to let the normal fluxes become nonzero at the boundary to cancel the cross-field fluxes. While both are clearly unphysical, the former method allows convergent solutions while the latter is more problematic.

We have performed a set of simulations with the cross-field fluxes present to determine the asymmetries that result. The B2 code is run using boundary conditions on the innermost core flux surface of constant density and temperature; the density is always set at $5 \times 10^{19} \text{ m}^{-3}$ while the temperature is varied between 250 eV and 500 eV. For the divertor plates, the parallel velocity is set equal to the local sound speed, and the energy transmission factors for the ions and electrons are set to 2.5 and 4, respectively. The particle recycling coefficient on the plates is taken as 0.97. On all other boundaries, zero particle flux boundary conditions are used, and the ion and electron temperatures are equal to 2 eV. The anomalous density diffusion coefficient is $D_a = 1 \text{ m}^2/\text{s}$, and a small convective velocity of $v_a = -10 \text{ m/s}$ is used. If we set $v_a = 0$, the code has difficulty with convergence. However, doubling v_a to -20 m/s does not change the calculated profiles by more than $\approx 20\%$ except very near the wall ($y = y_{\max}$). For

the anomalous energy diffusion coefficients in the y -direction, $\chi_{yi} = \chi_{ye} = 2 \text{ m}^2/\text{s}$ are used. The (x, y) grid is taken to have (96,24) cells. The distance between the x-point and the plate, D_{xp} , is 28 cm.

In Fig. 4, we show the results of the total power on the upper and lower divertor plates on the outside for a range of core temperatures. The asymmetry shown here increases with temperature because the cross-field terms increase with temperature and because the gradients become steeper. The higher power on the upper plate can be understood by the fact that the poloidal cross-field energy flux for the electrons [Eq. (10) with a minus sign] is directed toward the upper plate. The corresponding ion flux is in the opposite direction, but it does not cancel the electron term because the electron temperature gradient in the y -direction is larger than that for the ions.

The profile of the power striking the upper and lower plates for $T_c = 500 \text{ eV}$ is shown in Fig. 5a. Note that the electron flux (long-dashed line) is particularly enhanced on the upper plate. The width of the profile is about 3 cm on the upper plate and 4.5 cm on the bottom. Also, the profile for the ion flux on the lower plate lower plate has a irregularity on it that indicates the grid resolution is not yet sufficient. If we increase T_c even further, the gradients become too steep, and the code does not converge. For comparison, the power flux for the $T_c = 500 \text{ eV}$ symmetric case with no cross-field drifts is shown Fig. 5b. Here each plate receives 31.1 MW.

In order to estimate the expected power to the outer plates for CIT, we use the following: For 500 MW of fusions power, there is 100 MW of alpha-particle power, of which 75% is assumed to go to the outer SOL. Splitting this power between the upper and lower plates gives 37.5 MW per plate, neglecting any loss from radiation. Thus, the $T_c = 500 \text{ eV}$ case is in the required range.

Figure 6 shows the radial profiles at the midplane for the $T_c = 500 \text{ eV}$ case. The temperatures and potential are given in Fig. 6a. Note that the potential is not calculated in the core region. The electron temperature falls more rapidly because of the large electron conductivity along $\mathbf{B}$; the ion temperature follows T_e because of collisional coupling. The density profile in Fig. 6b shows a characteristic slower decay. Changing v_a to -20 m/s decreases the magnitude of the density scale length at the separatrix by $\approx 20\%$, but the density at the wall ($y_0 = 0.072 \text{ m}$) decreases from $5 \times 10^{18} \text{ m}^{-3}$ to $2 \times 10^{18} \text{ m}^{-3}$.

A second effect of the cross-field drifts is that a significant toroidal velocity develops while the poloidal velocity remains small. The $\mathbf{E} \times \mathbf{B}$ and diamagnetic drifts from Eq. (5) both give an ion velocity directed toward the upper plate, in the $-\hat{\mathbf{e}}_f$ direction. However, a substantial parallel velocity develops which results in a poloidal velocity which is roughly an order of magnitude smaller than the cross-field velocities. If we let v_{fc} stand for the cross-field velocity in the $\hat{\mathbf{e}}_f$ direction, then from Eqs. (1-2), the poloidal velocity, v_p , is

$$v_p = v_{fc} \frac{B_\phi}{B} + v_{\parallel} \frac{B_p}{B}. \quad (15)$$

What happens is that a positive $v_{\parallel}$ develops to nearly balance the term from v_{fc} . The poloidal velocity needs to stay small because it is a measure of the particle flux into the plate, which changes little. Since the parallel direction is mostly along the toroidal

direction, a toroidal drift results, given by

$$v_{tor} = -v_{fc} \frac{B_p}{B} + v_{\parallel} \frac{B_{\phi}}{B} \quad (16).$$

Figure 7 shows contour plots of the various velocities in the regions between the x-points; the abscissa is the poloidal-like coordinate x_0 and the ordinate is the radial-like coordinate y_0 . The separatrix is located at $y_0 = 0$. For reference, the ion-acoustic velocity at 100 eV for deuterium is about 10^5 m/s, and the toroidal velocity near the separatrix is about 10% – 20% of that.

These results indicate that the cross-field drifts do not result in a large power asymmetry on the plates, but before firm conclusions can be stated, parameter variations need to be made and the treatment of the x-point region improved to allow flow through this region. The asymmetries that do exist will drive parallel plasma currents; we are just beginning to look at this effect. The potential needs to be calculated in the core region which also may influence the conclusions.

Single-Null Configuration with Bias Voltage

For the single-null configuration shown in Fig. 2, we have removed the artificial boundary in B2 that passed through the x-point, which prevented flow near the x-point in the poloidal direction; the core now has periodic boundary conditions and the private flux region is continuous. We shall show the strong effect that divertor plate biasing⁶ can have on controlling the distribution of power between the inner and outer plates.

For this study, we use a DIII-D configuration with the following input parameters:

$$\begin{array}{ll} D_a = 2 \text{ m}^2/\text{s} & v_a = -40 \text{ m/s} \\ \chi_{ye} = 4 \text{ m}^2/\text{s} & \chi_{yi} = 0.2 \text{ m}^2/\text{s} \\ T_{e,core} = 100 \text{ eV} & T_{i,core} = 100 \text{ eV} \\ n_{core} = 2 \times 10^{19} \text{ m}^{-3} & \Gamma_{recycle} = 0.97 \end{array}$$

These parameters result in a total power of ~ 1 MW striking the divertor plates.. The (x, y) grid has (32,16) cells, which is somewhat coarse but useful for initial computational efficiency.

The poloidal current is plotted versus the bias voltage in Fig. 8. Note the rather sensitive behavior at small voltages. This curve is similar to the $I \propto \tanh(-e\phi/\tau T)$ characteristic for a double probe. However, here the situation is more complicated as the temperatures at the two ends change strongly with ϕ_b . The current in Fig. 8 at about 50% of the saturation current for both $\phi_b = \pm 50$ V. We tried running the code for $\phi_b = 100$ V, but it did not converge.

A more striking result is shown in Fig. 9 where the power to each plate is given, together with that provided from the bias supply. The power to each plate can be varied by a factor of 4, and the power ratio by a factor of 16. Note that a very modest bias supply power is needed except at the largest voltages.

The power asymmetry can be explained by the large electron convective heat flux that arises in response to the bias potential. This additional heat flux can be written

in the form given by Eq. (12) if one adopts the convention of using the ion velocity for the remaining electron convective heat flow, $(5/2)n_e T_e v_i$. In terms of the poloidal current density, J_x , the additional heat flux is,

$$q_{xej} = 3.2 J_x T_e / e \quad (17)$$

where $\alpha = 0.7$ has been used. The total power associated with this flow can be estimated as $-3.2 I_x T_e / e$, where I_x is the poloidal current in Fig. 8. Thus, for $\phi_b = -5$ V, $I_x \approx 2$ kA, and for an average value of $T_e = 50$ eV, the extra electron convected power is -0.3 MW. The minus sign means this power is directed toward the inner plate. By considering Fig. 9, one can see that this power is of sufficient size, and of the proper sign, to account for the shift of power to the inner divertor plate for $\phi_b = -5$ V.

Finally, we note that the cross-field drifts were left off for the DIII-D cases discussed above. If we turn on the diamagnetic particle and energy fluxes given in Eqs. (7-8,10-11), we calculate only $\sim 10\%$ difference in the results. Presently, the code has trouble operating with the $\mathbf{E} \times \mathbf{B}$ velocities on, so we cannot make specific statements about that. Part of the problem concerns the resulting drifts near the x-point and how to extend them smoothly into the core region. We are presently working on this difficulty.

SUMMARY

We summarize our work to date by the following points:

1. Initial results indicate that cross-field drifts give asymmetries of $\sim 30\%$ for CIT parameters assuming 500 MW of fusion power. The asymmetries increase with power to the divertor plates.
2. The results may be affected by the treatment of the x-point region for double-null configurations which needs to be upgraded by removing the artificial reflecting boundary as we have done for the single null. We will work on that this year.
3. The cross-field drifts do result in a toroidal rotation velocity in the SOL of $\sim 0.1C_s$, while the poloidal velocity is constrained to a lower value.
4. We have demonstrated that a small bias-supply power can control the distribution of a large divertor power between inner and outer plates for the single null DIII-D parameter regime.
5. Dominant effect for power control is the *additional* electron parallel convective heat flux proportional to $J_{||}$.
6. Power distribution control should also be possible for higher power, double null configurations like ITER or CIT, but simulations are yet to be done. This mechanism would provide a powerful technique for correcting asymmetries that arise from cross-field drifts and unbalanced MHD equilibria.

7. Calculation of the potential in the core region to give proper $\mathbf{E} \times \mathbf{B}$ drifts remains to be done.

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REFERENCES

1. B. J. Braams, "A Multi-Fluid Code for Simulation of the Edge Plasma in Tokamaks", NET Report, Nr. 68, January, 1987.
2. For example, S. I. Braginskii, in *Reviews of Plasma Physics*, edited by M. A. Leontovich (Consultants Bureau, New York, 1965), Vol. I, p. 205.
3. F. L. Hinton and G. M. Staebler, "Collisional Transport near a Separatrix and the H-Mode," Nucl. Fusion **29**, 405 (1989).
4. K. C. Shaing and E. C. Crume, Jr., "Bifurcation Theory of Poloidal Rotation in Tokamaks: A Model for the L-H Transition," Phys. Rev. Lett **63**, 2369 (1989).
5. Y. B. Kim, P. H. Diamond, H. Biglari, and P. W. Terry, "Theory of Resistivity-Gradient-Driven Turbulence in a Differentially Rotating Plasma," Phys. Fluids B2, 2143 (1990).
6. R. D. Stambaugh, M. Ali Mahdavi, and M. Shimada, "Electrical Biasing of the Divertor Plate in Tokamaks," Bull. Am. Phys. Soc. **31**, 1535 (1986).
7. G. M. Staebler and F. L. Hinton, "Currents in the Scrape-Off Layer of Diverted Tokamaks," Nucl. Fusion **29**, 1820 (1989).
8. P. C. Stangeby, "Comment on Paper by Staebler and Hinton," Nucl. Fusion **30**, 1153 (1990).

FIGURE CAPTIONS

Fig. 1. Poloidal cross section of a tokamak like CIT with double-null divertor (four plates). The directions of various unit vectors are illustrated.

Fig. 2. Poloidal cross section of the DIII-D tokamak with a single-null divertor (two plates).

Fig. 3. Poloidal flux surfaces from a conformal mapping by B. J. Braams used to model the $R = 2.6$ m, $B = 9$ T CIT configuration. We rotate these surfaces about the midplane to obtain the symmetric upper half region as well.

Fig. 4. Total power incident on the outer upper and lower divertor plates for CIT versus the assumed temperature on the core boundary just inside the separatrix. The asymmetry is caused by the presence of cross-field fluxes.

Fig. 5. Energy fluxes (total, ion, and electron) versus distance along the divertor plate for (a), the upper and lower divertor plates with $T_c = 500$ eV with cross-field fluxes, and (b), the same case without cross-field terms.

Fig. 6. Midplane profiles of (a), potential, and ion and electron temperatures, and in (b), the density.

Fig. 7. Contour plots of various velocities in the core-SOL region showing a large toroidal velocity compared to the poloidal velocity for the $T_c = 500$ eV case.

Fig. 8. The poloidal current versus bias voltage of the single null DIII-D case with the core temperature $T_c = 100$ eV.

Fig. 9. The power to the inner and outer divertor plates versus bias voltage, and the external power required from the bias supply.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 8

Fig. 9

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