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*A One-and-a-Quarter-Dimensional
Transport Code for Field-Reversed
Configuration Studies*

A User's Guide for CFRX

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A ONE-AND-A-QUARTER-DIMENSIONAL TRANSPORT CODE FOR FIELD-REVERSED CONFIGURATION STUDIES

A User's Guide for CFRX

by

Ming-Yuan Hsiao, Kenneth A. Werley, and Kuok-Mee Ling

ABSTRACT

A one-and-a-quarter-dimensional transport code, which includes radial as well as some two-dimensional effects for field-reversed configurations, is described. The set of transport equations is transformed to a set of new independent and dependent variables and is solved as a coupled initial-boundary value problem. The code simulation includes both the closed and open field regions. The axial effects incorporated include global axial force balance, axial losses in the open field region, and flux surface averaging over the closed field region. Input, output, and structure of the code are described in detail. A typical example of the code results is also given.

I. INTRODUCTION

Field-reversed fusion devices have received considerable attention both theoretically and experimentally in recent years. The significant advantages of higher β ($\beta \equiv$ plasma pressure/magnetic pressure) and longer particle confinement in field-reversed devices (compared with non-field-reversed theta pinch devices) result in higher fusion power density and improved fusion energy gain, and make them strong candidates for commercial fusion reactors. Among the field-reversed devices, the field-reversed configuration (FRC) appears attractive because of encouraging experimental results, compact size, and simple geometry.¹ Figure 1 shows a typical field-reversed configuration.

In recent FRC experiments,¹⁻¹⁰ many encouraging results have been obtained. The FRC lifetimes have been maintained for a significant period of time ($\leq 300\mu s$). The rotational instability has been suppressed and the translation of FRC's has been accomplished. These experimental results have demonstrated some of the attractive

features that could be used in commercial FRC reactor designs. There are, however, still some important issues concerning the fundamental properties of FRC plasmas remaining to be resolved. In particular, the stability of FRC's in reactor-relevant regimes that have a large minor radius relative to the ion cyclotron radius must be demonstrated. Once stability is demonstrated, then the consequences of the anomalous transport must be evaluated. It has been observed that the particle confinement times and trapped flux decay times appear to be shorter than the classical predictions.

Since the transport mechanisms ultimately determine the scaling laws of the FRC approach to controlled nuclear fusion, considerable work has been done on the transport properties of FRC's. Various transport models based on different physical mechanisms have been studied. Auerbach and Condit studied classical diffusion based on magnetohydrodynamics.¹¹ Nguyen and Kammash used a similar approach, but employed a more generalized Ohm's law.¹² Tuszewski and Linford investigated the particle transport induced by the lower-hybrid-drift instability.¹³ Hsiao and Miley studied the velocity-space particle loss, a loss mechanism similar to the loss cone in magnetic mirrors.^{14,15} Steinhauer suggested the possibility of electrostatic confinement on open field lines in FRC's.¹⁶ Krall examined the low-frequency stability of FRC's and suggested that these possible instabilities may be responsible for the anomalous transport.¹⁷ However, a definitive determination of the basic mechanisms that govern transport is not possible at the present time.

To simulate experimental observations and facilitate the parametric study of experimental results such that more detailed physical insight can be extracted, we have implemented the model of Caramana¹⁸ into a two-fluid radial transport code¹⁹ (which includes some axial effects) described herein. The organization of the report is as follows. In Sec. II, the model and the basic governing equations in normal configuration space (i.e., in Eulerian coordinates) are described. In Sec. III, the transformation of the basic equations to a magnetic flux related coordinate system is given. In Sec. IV, the solution method, input, and output of the code are described. A brief description of subroutines is also given. Finally, a brief summary is given in Sec. V. The Appendix contains some algebraic details. The basic formulation of the equations implemented in this code is described in Ref. 18, where it is shown how to reduce the full fluid model to a one-dimensional system appropriate to the FRC and then how that system can be transformed into a flux-coordinate-based representation amenable to numerical solution. An initial study utilizing this code to simulate FRC experiments is given in Ref. 19.

II. MODEL AND GOVERNING EQUATIONS

We start with the set of transport equations, Eqs. (2.1)–(2.4) and (6.23), of Ref. 20. In this report, Gaussian units are used, unless otherwise noted. Assuming quasi-neutrality ($n_i \approx n_e = n$) and ambipolarity ($\vec{\Gamma}_i \equiv n_i \vec{V}_i = \vec{\Gamma}_e \equiv n_e \vec{V}_e = n \vec{V}$), and neglecting inertia and the viscous forces, the set of transport equations can be written as follows:

Continuity Equation

$$\frac{\partial n}{\partial t} + \nabla \cdot (n \vec{V}) = Q_n. \quad (1)$$

Momentum Equation

$$-\nabla P + \frac{1}{c} \vec{j} \times \vec{B} = 0. \quad (2)$$

Energy Equation

$$\frac{n}{\gamma - 1} \left(\frac{\partial}{\partial t} + \vec{V} \cdot \nabla \right) T_s + n T_s \nabla \cdot \vec{V} = Q_{T_s} - \frac{T_s Q_n}{\gamma - 1}, \quad s = i, e. \quad (3)$$

Ohm's Law

$$\vec{E} + \frac{1}{c} \vec{V} \times \vec{B} = \vec{Q}_E + \frac{\vec{j}_{\parallel}}{\sigma_{\parallel}} + \frac{\vec{j}_{\perp}}{\sigma_{\perp}}. \quad (4)$$

Field Equations

$$\frac{\partial \vec{B}}{\partial t} = -c \nabla \times \vec{E} \quad (5)$$

and

$$\nabla \times \vec{B} = \frac{4\pi}{c} \vec{j}. \quad (6)$$

Here, Q_n is the source rate for particles; $P = P_i + P_e = n(T_i + T_e)$; $\gamma =$ adiabatic constant ($= 5/3$ in Ref. 20); subscript s denotes the plasma particle species ($s = e, i$);

$$Q_{T_s} = Q_s - \nabla \cdot \vec{q}_s + \dots \quad (7)$$

represents the source rate for energy, due to an external energy source (Q_s), conduction loss ($-\nabla \cdot \vec{q}_s$, $\vec{q}_s =$ thermal conduction flux), radiation losses, joule heating, electron-ion equilibration of energy, and any other energy sources or losses;

$$\vec{Q}_E = \frac{1}{en} (\nabla P_i + \vec{R}_T) + \dots \quad (8)$$

represents the electric fields generated due to ion pressure gradient, thermal force ($\vec{R}_T$), or any other effects; σ is the plasma electrical conductivity; and all other notations follow the usual conventions.

For an elongated FRC model as depicted in Fig. 1,¹⁹ we assume that, in cylindrical coordinates (r, θ, z) , the vectors:

$$\vec{B} = B_z(r, t)\hat{z}, \quad (9)$$

$$\vec{j} = j_\theta(r, t)\hat{\theta}, \quad (10)$$

$$\vec{V} = V_r(r, t)\hat{r} + f(r, t)z\hat{z}, \quad (11)$$

and the scalars: n, T_i, T_e, Q_n, Q_T , and Q_E are functions of r and t only. The subscripts r, θ , and z refer to the vector components in the r -, θ -, and z -directions, respectively. The variables $\vec{E}$ and $\vec{j}$ are eliminated using Eqs. (4) and (6). The set of equations is, thus, reduced to the following:

Continuity Equation

$$\frac{\partial n}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r}(rnV_r) = Q_n - fn. \quad (12)$$

Momentum Equation

$$n(T_i + T_e) + \frac{B_z^2}{8\pi} = P_o = \text{constant in space.} \quad (13)$$

Temperature Equation

$$\frac{\partial T_s}{\partial t} + V_r \frac{\partial T_s}{\partial r} + (\gamma - 1)T_s \left[\frac{1}{r} \frac{\partial}{\partial r}(rV_r) + f \right] = (\gamma - 1) \frac{Q_{T_s}}{n} - \frac{T}{n} Q_n, \quad s = e, i. \quad (14)$$

Magnetic Field Equation

$$\frac{\partial B_z}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r}(rV_r B_z) = -\frac{c}{r} \frac{\partial}{\partial r}(rQ_{E\theta}) + \frac{c^2}{4\pi} \frac{1}{r} \frac{\partial}{\partial r} \left(\frac{r}{\sigma_\perp} \frac{\partial B_z}{\partial r} \right). \quad (15)$$

It is noted that the terms containing f represent the radial changes (i.e., radial sinks or sources) due to axial expansion or contraction (i.e., due to V_z). Some other axial effects are also included. Global axial force balance, i.e., the average β condition¹, is imposed and is described by

$$\langle \beta \rangle = \frac{2}{r_s^2 P_o} \int_0^{r_s} n(T_e + T_i) r dr = 1 - \frac{r_s^2}{2r_w^2}, \quad (16)$$

where r_s = separatrix radius and r_w = wall radius. In addition, axial particle and energy losses in the open field region due to streaming and thermal conduction are included in the form of effective sinks in the radial transport equations. These effective losses are represented by the terms Q_n and Q_{T_s} .

The explicit forms for Q_n , Q_{T_e} , $Q_{E\theta}$, and f in Eqs. (12)–(15) used in the present code are given as follows:

$$Q_n = -\frac{n}{\tau_{fs}}. \quad (17)$$

$$Q_{T_i} = \frac{3m_e}{m_i} \frac{n(T_e - T_i)}{\tau_e} + f_i \frac{j_\theta^2}{\sigma_{an}} + \frac{1}{r} \frac{\partial}{\partial r} r K_{\perp i} \frac{\partial T_i}{\partial r} - \frac{8K_{\parallel i} T_i}{7\ell(\ell_w - \ell/2)} - \frac{nT_i}{(\gamma - 1)\tau_{fs}}. \quad (18)$$

$$Q_{T_e} = \frac{-3m_e}{m_i} \frac{n(T_e - T_i)}{\tau_e} + \left[\frac{1}{\sigma_{cl}} + \frac{(1 - f_i)}{\sigma_{an}} \right] j_\theta^2 - \frac{8}{7} \frac{K_{\parallel e} T_e}{\ell(\ell_w - \ell/2)} - \frac{nT_e}{(\gamma - 1)\tau_{fs}} + \frac{1}{r} \frac{\partial}{\partial r} \left[r K_{\perp e} \frac{\partial T_e}{\partial r} \mp r \beta_{\perp}^{TU} \frac{j_\theta}{ne} \right] \mp \frac{j_\theta}{en} \beta_{\perp}^{UT} \frac{\partial T_e}{\partial r}. \quad (19)$$

$$Q_{E\theta} = \mp \frac{1}{en} \beta_{\perp}^{UT} \frac{\partial T_e}{\partial r}. \quad (20)$$

$$f = \begin{cases} \frac{2V_{z0}}{\ell} & \text{for } r \leq r_s, \\ 0 & \text{for } r > r_s, \end{cases} \quad (21)$$

where $V_{z0}(t)$ is the axial velocity of the FRC ends, i.e., at $z = \ell/2$, $\ell = \text{FRC plasma axial length}$ (see Fig. 2). In Eqs. (19) and (20), the upper and lower signs apply to the regions of $r > r_0$ and $r < r_0$, respectively, and r_0 is the field null radius. In the above source terms, τ_{fs} is the characteristic ion free streaming time in the open field region; τ_e is the electron-ion collision time; σ_{an} is the anomalous electrical conductivity; σ_{cl} is the classical perpendicular electrical conductivity; $K_{\perp}$ is the perpendicular thermal conductivity; $K_{\parallel}$ is the parallel thermal conductivity; ℓ_w is the axial wall length (see Fig. 2); $j_\theta = -(c/4\pi)(\partial B_z/\partial r)$; $\beta_{\perp}^{UT}$ and $\beta_{\perp}^{TU}$ are related to the thermal force; and f_i is the fraction of anomalous heating deposited to the ion species. In Eqs. (18) and (19), the terms involving ℓ_w are the effective sink terms due to thermal conduction loss in the open field region (for derivation, see Appendix A of Ref. 19). Furthermore, to allow for convenient parametric studies, a multiplicative factor is placed in front of each transport coefficient, as given in Table I.

In summary, Eqs. (12)–(16) describe the radial equilibrium and transport of an FRC: Eqs. (13) and (16) determine the FRC equilibrium; Eqs. (12) and (14) determine the time evolution of number density, electron temperature, and ion temperature; and Eq. (15) determines the magnetic field evolution. The approximate FRC model geometry described by this set of equations is shown in Fig. 2.

Furthermore, n , T_e , and T_i are assumed to be functions of magnetic flux only, i.e., n , T_e , and T_i are constant on a magnetic flux surface. Therefore, for the closed field region, we only need to average over the inner and outer flux surface prior to solving the equations.

To completely determine the initial-boundary value problem, boundary conditions need to be specified. In the present code, it is possible to run either with or without plasma in the open field region. The closed field region simulation requires three boundary conditions at the field null and three at the separatrix since n , T_e , and T_i are assumed to be functions of magnetic flux $\psi (\equiv \int_0^r 2\pi r' B_z(r', t) dr')$ only. The boundary conditions at the field null are $\partial n / \partial r = \partial T_i / \partial r = \partial T_e / \partial r = 0$, while at the separatrix either the values of n , T_i , and T_e or the gradient scale lengths of the adiabatic variables associated with n , T_i , and T_e (see Sec. III) can be specified. If both the closed field and the open field regions are simulated, we have a two-region problem. The three inner boundary conditions at the field null are the same, while the three outer boundary conditions are applied at the wall. In addition, there are six continuity conditions at the separatrix, i.e., n , T_i , T_e , and their particle and energy fluxes must be continuous at the separatrix. At present, the code only enforces continuity of the fluxes at the separatrix. It is also noted that the present version of the code, CFRX, contains the full model described above. However, terms related to the thermal force, i.e., those containing either $\beta_\wedge^{UT}$ or $\beta_\wedge^{TU}$, have not been debugged yet.

III. TRANSFORMED EQUATIONS

For numerical convenience and facilitating the analytical treatment, the set of governing equations, Eqs. (12)–(16), is transformed to a new set of independent and dependent variables. A general description of the transformation can be found in Ref. 18; a typical example of the derivation is given in the Appendix. Here, we only summarize the results.

A. Closed Field Region

The independent variable r is transformed to the magnetic flux related variable η .

$$\eta \equiv -(1 - \psi_n)^{1/2} \quad (22)$$

where

$$\psi_n \equiv \frac{1}{\psi_0} \int_0^r B_z 2\pi r' dr' \quad (23)$$

and

$$\psi_0 \equiv \int_0^{r_0} B_z 2\pi r' dr'. \quad (24)$$

The dependent variables n , T_i , and T_e are transformed to U , W_i , and W_e according to

$$n = \frac{2U}{\frac{\partial y}{\partial \eta}}, \quad (25)$$

$$T_{i,e} = \left(\frac{2W_{i,e}}{\frac{\partial y}{\partial \eta}} \right)^{\gamma-1}, \quad (26)$$

where

$$y = \frac{r^2}{2}. \quad (27)$$

In terms of the new set of variables, the basic equations are transformed and the flux surface averages are performed analytically. The results for the inner closed field region ($r < r_0$) are as follows:

Density Equation:

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial \eta} U < V > + \frac{1}{2} \frac{\partial y}{\partial \eta} < Q_n > - < f > U. \quad (28)$$

Momentum Equation

$$\frac{2\gamma U (W_i^{\gamma-1} + W_e^{\gamma-1})}{\left(\frac{\partial y}{\partial \eta} \right)^\gamma} + \frac{1}{8\pi} \left(\frac{\eta \psi_0}{\pi \frac{\partial y}{\partial \eta}} \right)^2 = P_0. \quad (29)$$

Temperature Equation

$$\begin{aligned} \frac{\partial W_{i,e}}{\partial t} = \frac{\partial}{\partial \eta} W_{i,e} < V > + \left(\frac{1}{2} \frac{\partial y}{\partial \eta} \right)^\gamma \frac{< Q_{T_{i,e}} >}{U W_{i,e}^{\gamma-2}} - \frac{W_{i,e}}{(\gamma-1)U} \frac{1}{2} \frac{\partial y}{\partial \eta} < Q_n > \\ - < f > W_{i,e}. \end{aligned} \quad (30)$$

Field Equation

$$\frac{\partial \psi_0}{\partial t} = \frac{-c^2 y_0 \psi_0}{\pi \sigma_{\perp 0} \left(\frac{\partial y}{\partial \eta} \right)_0^2}. \quad (31)$$

Average β Condition

$$4y_w \left[\frac{\psi_0(y_w - 2y_0)}{\psi'_0 y_0} \right]^2 \int_{-1}^0 \frac{\eta^2}{\frac{\partial y}{\partial \eta}} d\eta = 1. \quad (32)$$

Here,

$$< V > = \frac{(\eta^2 - 1)}{2\eta \psi_0} \frac{\partial \psi_0}{\partial t} - \frac{c^2}{2\pi \sigma} \frac{y_0}{\left(\frac{\partial y}{\partial \eta} \right)^3} \left(\frac{1}{\eta} \frac{\partial y}{\partial \eta} - \frac{\partial^2 y}{\partial \eta^2} \right)$$

$$-\frac{2^{\gamma-1}\pi C\beta_{\wedge}^{UT}}{e\psi_0}\frac{y_0}{\eta U}\frac{\partial}{\partial\eta}\left(\frac{W_e}{\frac{\partial y}{\partial\eta}}\right)^{\gamma-1}, \quad (33)$$

$$\frac{\partial^2 y}{\partial\eta^2} = \frac{\frac{\eta\psi_0^2}{4\pi^3}\frac{\partial y}{\partial\eta} + 2^\gamma\left(\frac{\partial y}{\partial\eta}\right)^{3-\gamma}\frac{\partial}{\partial\eta}\left[U(W_i^{\gamma-1} + W_e^{\gamma-1})\right]}{\gamma P_0\left(\frac{\partial y}{\partial\eta}\right)^2 + (2-\gamma)\frac{\eta^2\psi_0^2}{8\pi^3}}, \quad (34)$$

$$\langle Q_n \rangle = 0 \quad \text{if there is no particle source,} \quad (35)$$

$$\begin{aligned} \langle Q_{T_e} \rangle = & \frac{-3m_e}{m_i\tau_e}\left(\frac{2}{\frac{\partial y}{\partial\eta}}\right)^\gamma U(W_e^{\gamma-1} - W_i^{\gamma-1}) + \frac{2^\gamma y_0}{\frac{\partial y}{\partial\eta}}\frac{\partial}{\partial\eta}\left[\frac{K_{\perp e}}{\frac{\partial y}{\partial\eta}}\frac{\partial}{\partial\eta}\left(\frac{W_e}{\frac{\partial y}{\partial\eta}}\right)^{\gamma-1}\right] \\ & + \left[\frac{1}{\sigma_{cl}} + \frac{1-f_i}{\sigma_{an}}\right]\left[\frac{c^2\psi_0^2}{8\pi^4}\right]\frac{y_0}{\left(\frac{\partial y}{\partial\eta}\right)^6}\left[\frac{\partial y}{\partial\eta} - \eta\frac{\partial^2 y}{\partial\eta^2}\right]^2 \\ & - \frac{c\psi_0}{4\pi^2 e}\frac{y_0}{\left(\frac{\partial y}{\partial\eta}\right)}\frac{\partial}{\partial\eta}\frac{\beta_{\wedge}^{TU}}{U\left(\frac{\partial y}{\partial\eta}\right)^2}\left(\frac{\partial y}{\partial\eta} - \eta\frac{\partial^2 y}{\partial\eta^2}\right) \\ & - \frac{2^{\gamma-3}c\psi_0}{\pi^2 e}\frac{y_0\beta_{\wedge}^{UT}}{U\left(\frac{\partial y}{\partial\eta}\right)^3}\left(\frac{\partial y}{\partial\eta} - \eta\frac{\partial^2 y}{\partial\eta^2}\right)\frac{\partial}{\partial\eta}\left(\frac{W_e}{\frac{\partial y}{\partial\eta}}\right)^{\gamma-1} \\ & - \frac{2^{\gamma+2}K_{\parallel e}}{7\ell(\ell_w - \ell/2)}\left(\frac{W_e}{\frac{\partial y}{\partial\eta}}\right)^{\gamma-1} - \left(\frac{2}{\frac{\partial y}{\partial\eta}}\right)^\gamma \frac{UW_i^{\gamma-1}}{(\gamma-1)\tau_{fs}}, \end{aligned} \quad (36)$$

$$\begin{aligned} \langle Q_{T_i} \rangle = & \frac{3m_e}{m_i\tau_e}\left(\frac{2}{\frac{\partial y}{\partial\eta}}\right)^\gamma U(W_e^{\gamma-1} - W_i^{\gamma-1}) + \frac{2^\gamma y_0}{\frac{\partial y}{\partial\eta}}\frac{\partial}{\partial\eta}\left[\frac{K_{\perp i}}{\frac{\partial y}{\partial\eta}}\frac{\partial}{\partial\eta}\left(\frac{W_i}{\frac{\partial y}{\partial\eta}}\right)^{\gamma-1}\right] \\ & + \frac{f_i}{\sigma_{an}}\frac{c^2\psi_0^2}{8\pi^4}\frac{y_0}{\left(\frac{\partial y}{\partial\eta}\right)^6}\left[\frac{\partial y}{\partial\eta} - \eta\frac{\partial^2 y}{\partial\eta^2}\right]^2 \\ & - \frac{2^{\gamma+2}K_{\parallel i}}{7\ell(\ell_w - \ell/2)}\left(\frac{W_i}{\frac{\partial y}{\partial\eta}}\right)^{\gamma-1} - \left(\frac{2}{\frac{\partial y}{\partial\eta}}\right)^\gamma \frac{UW_i^{\gamma-1}}{(\gamma-1)\tau_{fs}}. \end{aligned} \quad (37)$$

The subscript 0 refers to the value at the field null $r = r_0$ and $\langle \rangle$ denotes the average over the inner ($0 \leq r \leq r_0$) and outer ($r_0 \leq r \leq r_s$) part of a ψ surface to account for the physical connection in the FRC.

B. Open Field Region

Similarly, transformations are done for the open field region. Without the presence of a field null, the independent variable r is transformed to normalized magnetic flux ψ^* ,

$$\psi^* = \frac{1}{\psi_v} \int_{r_s}^r B_z 2\pi r' dr' \quad (38)$$

where

$$\psi_v = \int_{r_s}^{r_w} B_z 2\pi r' dr'. \quad (39)$$

The dependent variables, n , T_i , and T_e , in this region are transformed to N , Z_i , and Z_e , respectively, according to

$$n = \frac{N}{\frac{\partial q}{\partial \psi^*}}, \quad (40)$$

$$T_{i,e} = \left(\frac{Z_{i,e}}{\frac{\partial q}{\partial \psi^*}} \right)^{\gamma-1}, \quad (41)$$

where

$$q = \frac{r^2}{2}. \quad (42)$$

The transformed equations are given as follows:

Density Equation

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial \psi^*} NV = \frac{\partial q}{\partial \psi^*} Q_n. \quad (43)$$

Momentum Equation

$$\frac{N(Z_i^{\gamma-1} + Z_e^{\gamma-1})}{\left(\frac{\partial q}{\partial \psi^*} \right)^\gamma} + \frac{1}{8\pi} \left(\frac{\psi_v}{2\pi \frac{\partial q}{\partial \psi^*}} \right)^2 = P_0. \quad (44)$$

Temperature Equation

$$\frac{\partial Z_{i,e}}{\partial t} + \frac{\partial}{\partial \psi^*} Z_{i,e} V = \left(\frac{\partial q}{\partial \psi^*} \right)^\gamma \frac{Q_{T_{i,e}}}{N Z_{i,e}^{\gamma-2}} - \frac{Z_{i,e}}{(\gamma-1)N} \frac{\partial q}{\partial \psi^*} Q_n. \quad (45)$$

Here,

$$V = -\frac{\psi^*}{\psi_v} \frac{\partial \psi_v}{\partial t} - \frac{c^2}{4\pi\sigma} \frac{2q}{\left(\frac{\partial q}{\partial \psi^*} \right)^3} \frac{\partial^2 q}{\partial \psi^{*2}}, \quad (46)$$

$$Q_n = 0 \quad \text{if there is no particle source,} \quad (47)$$

$$P_o \equiv \frac{[\psi'_v]^2}{32\pi^3(q_w - 2q_0)^2}, \quad (48)$$

$$\psi'_v = \psi_v \int_0^1 \left(\frac{32\pi^3 N(Z_i^{\gamma-1} + Z_e^{\gamma-1})}{\psi_v^2} \left(\frac{\partial q}{\partial \psi^*} \right)^{2-\gamma} + 1 \right)^{1/2} d\psi^*, \quad (49)$$

and

$$\frac{\partial^2 q}{\partial \psi^{*2}} = \frac{\frac{\partial q}{\partial \psi^*} \frac{\partial}{\partial \psi^*} \left[N \left(Z_i^{\gamma-1} + Z_e^{\gamma-1} \right) \right]}{\frac{\psi_v^2}{16\pi^3} \left(\frac{\partial q}{\partial \psi^*} \right)^{\gamma-2} + \gamma N \left(Z_i^{\gamma-1} + Z_e^{\gamma-1} \right)}. \quad (50)$$

Some properties of the transformed equations may be worth mentioning here.

- (1) Although r_w and r_s can be functions of time, we have fixed boundaries for the new independent variable, η or ψ^* ($-1 \leq \eta \leq 0$ for $0 \leq r \leq r_s$, $0 \leq \psi^* \leq 1$ for $r_s \leq r \leq r_w$).
- (2) The equations describing time evolution of n, T_i , and T_e (i.e., U, W_i , and W_e for the closed field region, and N, Z_i , and Z_e for the open field region) are in conservative form.
- (3) Particle transport due to motion of flux surfaces has been incorporated into the resultant equations through the velocity term. The B_z profile is determined by equilibrium conditions; the rate of change of magnetic flux is constrained by Eq. (31) and boundary condition on ψ_v . Therefore, there is no need to directly solve the equation for $\partial B_z / \partial t$.
- (4) Terms containing f in the equation for the closed field region are particle or energy sources or sinks due to axial contraction or expansion.

IV. CODE DESCRIPTION

A. Solution Method

The transformed equations given in Sec. IV are solved numerically by a finite-difference method. The code is named CFRX. The equations are solved as a coupled initial-boundary value problem.

In the transport phase, the time-dependent governing equations, Eqs. (28), (30), (31), (43), and (45), are advanced in time to obtain the values of U, W_i, W_e, N, Z_i, Z_e , and ψ_0 at the new time step. In the equilibrium phase (equivalently, taking $Q_n = Q_{T_i} = 0, \sigma_\perp = \infty$, and $\psi_0 = \text{constant}$ in the governing equations), the equilibrium magnetic configuration described by $y(\eta)$ and $q(\psi^*)$ is found by solving the equilibrium equations, Eqs. (29), (32), and (44) for given total trapped flux ψ_0 and profiles of U, W_i, W_e, N, Z_i , and Z_e . It was found that the solution of the equilibrium equations consumed most of the computational time. Hence, significant effort was made to optimize the solution method. This was accomplished via a double Newton iteration to simultaneously converge both the separatrix radius and axial length, with an inner iteration to get the proper radial spacing of the flux

coordinate mesh in the closed field line region. After the inside solution is converged, radial pressure balance is used to estimate the radial mesh spacing (assuming the plasma pressure in the open field region is small enough that the actual open field flux can be estimated from ψ_* with only one iteration of the detailed plasma profiles) for the open field region as a function of the previous mesh spacing. This completes the adiabatic phase. Simulation proceeds by alternating between the adiabatic and the non-adiabatic phases. In the non-adiabatic phase, the transport terms, i.e., all the terms related to Q_n, Q_{T_i}, Q_{T_e} , and $\sigma_\perp$, are first solved on a uniform mesh in η and ψ_* . Then, the transformation required to relate these results back to real space is accomplished by using the equilibrium obtained in the adiabatic phase, i.e., $y(\eta)$ and $q(\psi_*)$. The transport equations, i.e., the density and temperature equations, form a set of three, second-order partial differential equations which are implicitly differenced to ensure numerical stability. These difference equations are written and solved in a block tridiagonal matrix form with 3×3 blocks.

A logic diagram for the code is given in Fig. 3. First, the initial conditions are set up and the equilibrium solver is called to ensure equilibrium. Then the time-advance loop is begun. Internal to this is the predictor-corrector loop, which is necessary to converge the implicit nature of the solution technique to a final answer. This loop begins by setting up the boundary conditions and then calculating new coefficients and constructing the matrix elements associated with the transport (non-adiabatic) problem. The matrix problem is then solved, and the result is fed into the equilibrium via the (adiabatic) equilibrium constraint equations, which determine the radial position of the mesh points. This loop repeats until the solution converges. After the solution is obtained, global energy balance is checked to measure error buildup. Then the solution is transformed back to physical variables in laboratory coordinates so that the data can be outputted in a useful form. Finally, the timestep is adjusted so that the maximum rate of change of the dependent variables is less than a prescribed maximum percent change (to preserve accuracy of the implicit description) and is greater than a prescribed minimum percent change (for efficient use of computer time). This completes one pass through the time-advance loop, which is repeated until some desired simulation time is attained.

It may be worth mentioning that the code uses normalized variables. The units for normalization of variables are defined in the subroutine INITL and summarized in Table II as well.

B. Input Description

Input data for the code are specified through **NAMelist** and **PARAMETER** statements. The **NAMelist** input is read in from the input file, which is named **IFRXO**, in the **CALL**

LINK statement. If any of the **NAMelist** input variables are not read in from **IFRX0**, then the default values (given in Table IV) will be used. The **PARAMETER** input is specified in the beginning of **CLICHE TRP1** in the source program.

First, we describe the **NAMelist** input. Figure 4 shows a sample input file; the explanations of variables are given in Table III and the default values are given in Table IV. Next, we describe the **PARAMETER** input. These input variables are specified in the **PARAMETER** statements (in **CLICHE TRP1**) in the beginning of the program and are explained in Table V. Note that **Xs** is not an input variable; its value comes out of the calculations.

C. Output Description

After the input file **IFRX0** is prepared, to run the code, use

RCFT P = CFRX LIB = (T', P6BLD) L = 0.

The controllee obtained after this will be named **XCFRX**. As noted above, the **TV80L1B** (abbreviated as **T'**) and **P6BLD** libraries must be available. Then,

XCFRX

will start running the simulation.

There are three types of output from the code. First, the following brief information is output on the terminal:

$N = ? \quad < n > = ? \quad Xs = ? \quad Rs = ?$
 $Pl = ? \quad Rw = ? \quad R0 = ? \quad Sbar = ?$
 $time = ? \quad \text{seconds}$

The meanings of the above variables are explained in Table VI. Second, a summary of important data during various times, as specified by the input parameter **NPRNT**, is output to a text file **OFRX0**. Third, various radial profiles and time evolution of certain important quantities are plotted in a graphic file **F3????0X**. (The name of the graphic output file is self-generated by the graphics routine **TV80**.)

To view the plots, use

NETPLOT F3????0X.

All output plots are self-explanatory. Figures 5–9 show the initial profiles of a sample run. Figures 10-14 contain sample graphic output for the final time step ($t = 80\mu s$) in the file F3????0X. Figures 15–19, which are the last 5 plots in the graphic output file, show the time evolution of key quantities regarding the FRC.

To print out text file OFRX0, use

NETOUT OFRX0.

Figure 20 shows the information regarding one time step printed in the file OFRX0. Particular attention should be paid to the variables regarding the result of the energy balance check. In particular, the values of WERR, DWERR, WERROF, and DWERROF tell how well the various energy conservation laws are preserved; normally, their values should be less than 10%. If these values are too high, say $> 10\%$, the simulation results become questionable. Figure 21 shows some additional output information. It is noted that the input parameter IWRS specifies how much information will be printed out. The explanation of the output variables is given in Table VI. (All output variables are in Gaussian units, except temperature T in eV.)

D. Subroutine Description

The subroutines are described briefly in Table VII.

V. SUMMARY

A computer code for FRC equilibrium and transport calculations is described. The code is one-dimensional (radial) but has incorporated some axial effects. The analytic treatment of the governing equations brings both numerical and physics conveniences. The code runs fast, about 1.5 seconds of cpu time on the CRAY-1 per time step with 101 mesh points in the closed field region and 81 mesh points in the open field region, including both equilibrium and transport phases. This allows the simulation to calculate and iterate on the equilibrium in every time step, whereas usually in $1\frac{1}{2}$ -dimensional simulation, the equilibrium is calculated only once for several tens of time steps due to the constraint on the computer time. In addition, in most experiments, the FRCs are very elongated; hence, the model used in the code is expected to be a realistic approximation to the actual FRC geometry. Therefore, this code should be a useful tool for theoretical FRC studies, especially in the parametric studies of relevant experimental quantities. For example, empirical scaling laws may be obtained from parametric studies and give indications or directions for future experiments. At the present time, there are certain experimental observations not understood, yet doing parametric studies to reproduce the experimental

observations will give useful guidance to the understanding of the FRC physics. It is noted that this report summarizes the current version of the code. Since the code is under continuing development, further improvements and modifications of the model and the code are expected.

Appendix

DERIVATION OF A TYPICAL TERM IN THE TRANSFORMED EQUATIONS

To demonstrate the transformations explicitly, let us consider, say, the thermal conduction term in the governing equations. This term in the usual (r, θ, z) cylindrical coordinates is given by

$$\frac{1}{r} \frac{\partial}{\partial r} r K_{\perp} \frac{\partial T(r, t)}{\partial r} \equiv Q_{T,k}, \quad (A-1)$$

and appears in the Eqs. (18) and (19).

Using Eq. (27), it can be easily shown that for a function $F(r, t)$,

$$\frac{\partial F(r, t)}{\partial r} = \frac{\sqrt{2y}}{(\frac{\partial y}{\partial \eta})} \frac{\partial F(\eta, t)}{\partial \eta}. \quad (A-2)$$

This equation relates $\partial/\partial r$ to $\partial/\partial \eta$. Using Eq. (A-2), we transform Eq. (A-1) to

$$Q_{T,k} = \frac{1}{(\frac{\partial y}{\partial \eta})} \frac{\partial}{\partial \eta} \left[\frac{2y K_{\perp}}{(\frac{\partial y}{\partial \eta})} \frac{\partial T}{\partial \eta} \right]. \quad (A-3)$$

Furthermore, we transform the dependent variable T to W according to Eq. (26). The result is

$$Q_{T,k} = \frac{2^{\gamma}}{(\frac{\partial y}{\partial \eta})} \frac{\partial}{\partial \eta} \left\{ \frac{y K_{\perp}}{(\frac{\partial y}{\partial \eta})} \frac{\partial}{\partial \eta} \left[\frac{W}{(\frac{\partial y}{\partial \eta})} \right]^{\gamma-1} \right\}, \quad (A-4)$$

and

$$\begin{aligned} \langle Q_{T,k} \rangle = & \frac{1}{2} \left\{ \frac{2^{\gamma}}{(\frac{\partial y}{\partial \eta})_{out}} \frac{\partial}{\partial \eta} \frac{y_{out} K_{\perp}}{(\frac{\partial y}{\partial \eta})_{out}} \frac{\partial}{\partial \eta} \left[\frac{W}{(\frac{\partial y}{\partial \eta})_{out}} \right]^{\gamma-1} \right. \\ & \left. + \frac{2^{\gamma}}{(\frac{\partial y}{\partial \eta})_{in}} \frac{\partial}{\partial \eta} \frac{y_{in} K_{\perp}}{(\frac{\partial y}{\partial \eta})_{in}} \frac{\partial}{\partial \eta} \left[\frac{W}{(\frac{\partial y}{\partial \eta})_{in}} \right]^{\gamma-1} \right\}, \end{aligned} \quad (A-5)$$

where $\langle \rangle$ denotes the flux-surface averaged quantity and subscripts “out” and “in” refer to the values in the outer and the inner flux surfaces with the same ψ value, respectively. Realizing the relationships,

$$y_{out} + y_{in} = 2y_0, \quad (A-6)$$

$$\left(\frac{\partial y}{\partial \eta} \right)_{out} = - \left(\frac{\partial y}{\partial \eta} \right)_{in}, \quad (A-7)$$

and

$$W_{out} = -W_{in}, \quad (A-8)$$

we can reduce Eq. (A-15) to

$$\langle Q_{T,k} \rangle = \frac{2^\gamma y_0}{\left(\frac{\partial y}{\partial \eta} \right)} \frac{\partial}{\partial \eta} \frac{K_\perp}{\left(\frac{\partial y}{\partial \eta} \right)} \frac{\partial}{\partial \eta} \left[\frac{W}{\left(\frac{\partial y}{\partial \eta} \right)} \right]^{-1}, \quad (A-9)$$

which is the thermal conduction term in Eqs. (36) and (37).

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TABLE I. TRANSPORT COEFFICIENTS IN CODE

Definitions:

cl = classical Braginskii formulation

B = Bohm

f = factor

electrical conductivity:

$$\frac{1}{\sigma_{\perp}} = \frac{(f_{cl_1} + f_{cl_2}\eta^2)}{\sigma_{\perp_{cl}}} + \frac{f_B}{\sigma_B}$$

$$\frac{1}{\sigma_{\perp_{cl}}} = \frac{m_e}{ne^2\tau_e}$$

$$\frac{1}{\sigma_B} = \left| \frac{B}{16cne} \right|$$

cross-field thermal conductivity:

$$K_{\perp} = f_K K_{\perp_{cl}}$$

along-field thermal conductivity:

$$K_{\parallel} = f_{K_p} K_{\parallel_{cl}}$$

free streaming time:

$$\tau_{fs} = \frac{1}{f_{fs}} \frac{\ell}{2} \left(\frac{m_i}{T_i} \right)^{1/2}$$

TABLE II. UNITS USED FOR INTERNAL NORMALIZATION

Variable Name	Normalization Unit
y	$[r_w(t=0)]^2 \equiv YU$
T	$T_e(r=r_0, t=0) \equiv \text{TEMPU}$
B	$B_{ext}(t=0) \equiv \text{external } B \text{ field at } t=0 \equiv BU$
σ	$(\text{TEMPU}/\text{BETA3}) * * 1.5 \equiv \text{SIGMAU}$ where $\text{BETA3} = [(4/3)(2\pi m_e)^{1/2} e^2 Z \ell_n \wedge]^{2/3}$
P	$(\psi_v^2/8\pi^3 r_w^4)_{t=0} \equiv \text{PRU}$
ψ	$ \psi_0(t=0) \equiv \text{PSIU}$
U	$0.5 * \text{PRU} * YU / \text{TEMPU} \equiv \text{UU}$
W	$(0.5 * YU * \text{TEMPU})^{\frac{1}{(\gamma-1)}} \equiv \text{WU}$
t	$2\pi * \text{SIGMAU} * YU/c^2 \equiv \text{TU}$
r	$YU * 0.5 \equiv \text{RU}$
ℓ	$\ell(t=0) \equiv \text{PLU}$
$4\pi r_w^2 \ell =$ volume of closed field region	$4\pi * \text{PLU} * YU$

TABLE III. INPUT VARIABLE DESCRIPTION

Variable Name	Description
RW	Initial wall radius(cm) = $r_w(0)$ in Eq. (65)
PL	Initial separatrix length (cm)
WL	Initial axial wall length (cm)
DTIN	Dimensionless initial time step, in units of the initial resistive diffusion time
DTMAX	Dimensionless maximum time step allowed
TMAX	Simulation time (s)
IDENCF	=1: Use the following analytic formula Eq. (51) for the initial density profile in the closed field region inside the null radius. =2: Use Eq. (52) for the initial density profile in the closed field region inside the null radius. $n(x) = \text{DENOA} + (\text{DENNUL} - \text{DENOA}) * x ** \text{X1D} * (1. + \text{X5D} - x ** (\text{X1D} * \text{X5D}))/\text{X5D}, \quad (51)$ $n(x) = \text{DENOA} + (\text{DENNUL} - \text{DENOA}) * x ** \text{X1D} * (2. - x ** 2) ** \text{X5D}, \quad (52)$ where $x = r/r_0 \leq 1$.
DENOA	Initial number density at the separatrix (cm^{-3})
DENNUL	Initial density at the field null (cm^{-3})
X1D,X5D	Parameters in Eq. (51) or (52) specifying the initial density profile in the closed field region inside the null radius. They are dimensionless exponents.
ITICF	=1: Use the following analytic formula Eq. (53) for the initial ion temperature profile in the closed field region inside the null radius. =2: Use Eq. (54) for the initial ion temperature profile in the closed field region inside the null radius. $T_i(x) = \text{TIOA} + (\text{TINUL} - \text{TIOA}) * x ** \text{X1TI} * (1 + \text{X5TI} - x ** (\text{X1TI} * \text{X5TI}))/\text{X5TI}, \quad (53)$ $T_i(x) = \text{TIOA} + (\text{TINUL} - \text{TIOA}) * x ** \text{X1TI} * (2 - x ** 2) ** \text{X5TI}, \quad (54)$ where $x = r/r_0 \leq 1$.

TABLE III (CONT)

Variable Name	Description
TIOA	Initial ion temperature at the separatrix (eV)
TINUL	Initial ion temperature at the field null (eV)
X1TI, X5TI	Parameters in Eq. (53) or (54) specifying the initial ion temperature profile in the closed field region inside the null radius. They are dimensionless exponents.
ITECF	<p>= 1: Use the following analytic formula Eq. (55) for the initial electron temperature profile in the closed field region inside the null radius.</p> <p>= 2: Use Eq. (56) for the initial electron temperature profile in the closed field region inside the null radius.</p> $T_e(x) = TEOA + (TENUL - TEOA) * x ** X1TE * (1 + X5TE - x ** (X1TE * X5TE))/X5TE, \quad (55)$ $T_e(x) = TEOA + (TENUL - TEOA) * x ** X1TE * (2 - x ** 2) ** X5TE, \quad (56)$ <p>where $x = r/r_0 \leq 1$.</p>
TEOA	Initial electron temperature at the separatrix (eV)
TENUL	Initial electron temperature at the field null (eV)
X1TE, X5TE	Parameters in Eq. (55) or (56) specifying the initial electron temperature profile in the closed field region inside the null radius. They are dimensionless exponents.
IDENOF	<p>= 1: Use Eq. (57) for the initial number density profile in the open field region.</p> <p>= 2: Use Eq. (58), instead of Eq. (57).</p> $n(y) = DENOA * y ** CXDNOF \quad (57)$ $n(y) = DENOA * EXP (-3 * (y ** 2 - 1)) \quad (58)$ <p>where $y = r/r_s$.</p>
CXDNOF	Parameter in Eq. (57) specifying the initial density profile in the open field region; a dimensionless exponent
ITIOF	<p>= 1: Use Eq. (59) for the initial ion temperature profile in the open field region.</p> <p>= 2: Use Eq. (60), instead of Eq. (59).</p> $T_i(y) = TIOA * y ** CXTIOF \quad (59)$ $T_i(y) = TIOA * EXP (-3 * (y ** 2 - 1)) \quad (60)$ <p>where $y = r/r_s$.</p>

TABLE III (CONT)

Variable Name	Description
CXIIOF	Parameter in Eq. (59) specifying the initial ion temperature profile in the open field region; a dimensionless exponent
ITEOF	<p>= 1: Use Eq. (61) for the initial electron temperature profile in the open field region.</p> <p>= 2: Use Eq. (62), instead of Eq. (61).</p> $T_e(y) = TE0A * y ** CXTEOF \quad (61)$ $T_e(y) = TE0A * EXP ** (-3 * (y ** 2 - 1)) \quad (62)$ <p>where $y = r/r_s$.</p>
CXTEOF	Parameter in Eq. (61) specifying the initial electron temperature profile in the open field region; a dimensionless exponent
IBC	<p>= 2: Specify pedestal boundary conditions on n, T_i, and T_e at the outer boundary (at $r = r_s$ if only closed field region is simulated; at $r = r_w$ if both closed field and open field regions are simulated.)</p> <p>= 3: Specify convective boundary conditions at the separatrix, i.e.,</p> $\frac{dX}{d\eta} + hX = 0 \text{ at the separatrix,} \quad (63)$ <p>where $X = U, W_i$, and W_e, and the value of h is from the initial condition and is held constant in time. This option can only be used with no open field plasma, i.e., only when $NSWOF = 0$.</p>
FLX1, FLX2	Parameters specifying the change of vacuum magnetic flux $\psi_v(t)$ according to
TTU	$\psi_v(t) = \psi_v(0) * (1 + FLX1 * t/TTU + FLX2 * (t/TTU)**2), \quad (64)$ <p>where t and TTU are in seconds.</p>
DRWDT	<p>Parameter specifying the change of wall radius $r_w(t)$ according to</p> $r_w(t) = r_w(0) * (1 + DRWDT * t/TTU), \quad (65)$ <p>where t and TTU are in seconds. For example, if the wall radius decreases to 50% of the initial value in $20\mu s$, we then should set $DRWDT = 0.5$ and $TTU = 2.0 \text{ e-5}$.</p>

TABLE III (CONT)

Variable Name	Description
AMU	Mass of the ion species, in unit of proton mass
Z	Charge state of the ion species, in unit of elementary charge
GAMMAN, GAMMAD	Parameters to specify the adiabatic constant $\gamma \equiv \text{GAMMAN}/\text{GAMMAD}$
AFIT	= 2.: Linearly extrapolate to $\eta = 0$. = 8.: Parabolically extrapolate to $\eta = 0$.
EPSDY	Accuracy requirement for $dy/d\eta$
EPSB	Accuracy requirement for the average β condition
EPSU	Accuracy requirement for $\bar{U}$, W_i , and W_e
EPSTMX	Maximum allowed change of U , W_i , and W_e in one time steps
EPSTMN	Minimum allowed change of U , W_i , and W_e in one time step
MASDY	Maximum number of iterations for $dy/d\eta$ convergence
MAXYO	Maximum number of iterations for y_o convergence
MAXP	Maximum number of iterations for pressure convergence
MAXDT	Maximum number of iterations in adjusting time step
MAXNPC	Maximum number of iterations in the convergence of prediction-correction DO loop
NTIME	Number of time steps allowed in the simulation
NPRNT	Parameter specifying how often to print out information as time step advances. Always print out the first and the last time step; in between, printout every NPRNT step.
MSHPRT, NOUT	Print out closed field variables at mesh points ($I = 1$, NOUT, MSHPRT) in η mesh.
AKIFC	Multiplying factor that adjusts the perpendicular ion thermal conductivity, i.e., $K_{\perp i} \equiv$ perpendicular ion thermal conductivity used in the code = AKIFC * $K_{\perp i, cl}$, (66) where $K_{\perp i, cl} \equiv$ classical perpendicular ion thermal conductivity
AKEFC	Multiplying factor for perpendicular electron thermal conduc- tivity, i.e., $K_{\perp e}$ (in codes) = AKEFC * $K_{\perp e, cl}$
AKIPFC	Multiplying factor for parallel ion thermal conductivity, i.e., $K_{\parallel i} = \text{AKIPFC} * K_{\parallel i, cl}$
AKEPFC	Multiplying factor for parallel electron thermal conductivity, i.e., $K_{\parallel e} = \text{AKEPFC} * K_{\parallel e, cl}$

TABLE III (CONT)

Variable Name	Description
RSTCFC, RSTCF2, RSTBFC	<p>Multiplying factors for electrical conductivity. The actual electrical conductivity used in the code, σ, is given by</p> $\frac{1}{\sigma} = \frac{RSTCFC + RSTCF2 \cdot \eta^2}{\sigma_{\perp cl}} + \frac{RSTBFC}{\sigma_B} \quad (67-1)$ <p>in the closed field region, and</p> $\frac{1}{\sigma} = \frac{(RSTCFC + RSTCF2)}{\sigma_{\perp cl}} + \frac{RSTBFC}{\sigma_B} \quad (67-2)$ <p>in the the open field region, where $\sigma_{\perp cl}$ is the classical perpendicular electrical conductivity, σ_B the Bohm electrical conductivity, and η the flux related coordinate defined before.</p>
SWOH	Switch to turn on (SWOH = 1.) or off (SWOH = 0.) the ohmic heating (i.e., the term involving j_θ^2 in Eq. (19) in the transport calculation
OH2IFC	Fraction of Ohmic heating deposited to ion species due to anomalous electrical conductivity, i.e., the f_i in Eq. (18) or (19)
FSTREM	<p>Multiplying factor for ion streaming loss in the open field region, in Eq. (18), i.e.,</p> $\tau_{fs} = \frac{1}{FSTREM} \frac{\ell}{2} \left(\frac{m_i}{T_i} \right)^{1/2} \quad (68)$
SWEQ	Switch to turn on (SWEQ = 1.) or off (SWEQ = 0.) the electron-ion equilibration (i.e., the first term in Eq. (18) or (19))
SWVN	Switch to turn on (SWVN = -1.) or off (SWVN = 0.) the density flux source to the open field region. (Usually for debugging purposes.)
SWQQI	Similar to the switch SWVN, but for ion energy flux
SWQQE	Similar to the switch SWVN, but for electron energy flux
SWEQM	<p>= 1.1: Simulate adiabatic phase (i.e., equilibrium calculation) only; no transport.</p> <p>= any other positive value: Include both equilibrium and transport calculations.</p> <p>< 0.0: Run transport calculations only; no equilibrium.</p>
SWU	Switch to turn on (SWU = 1.) or off (SWU = 0.) the transport evolution of U (i.e., the $\partial U / \partial t$ equation)
SWI	Similar to the switch SWU, but for W_i
SWE	Similar to the switch SWU, but for W_e

TABLE III (CONT)

Variable Name	Description
BC1	Plotting limit for normalized profile plots
NSWOF	Switch to include (NSWOF = 1) or not to include (NSWOF = 0) the open field region in the calculations
NOUTOF	Similar to NOUT, but for the open field region. Namely, print out the open field variables at mesh points ($I = 1$, NOUTOF, MSHPR) in ψ^* mesh.
IWRS	Parameter specifying how much information will be printed out in the text output file OFRC. = 0: Print out all the input values only. = 1: Print out the input values and the basic information on the FRC, including r_s, x_s , etc., at the time steps specified (by NPRNT). = 2: Print out the input values, the basic information, and the results of energy balance check. = 3: Print out the location where maximum change occurs during time advancing and comparison of separatrix variables of closed field and open field meshes, in addition to the case of IWRS = 2. = 4: Print out various time and length scales in the open field region, in addition to the case of IWRS = 3. ≥ 5 : Print out the default values of the input variables and various radial profiles at the locations specified by NOUT, NOUTOF, and MSHPR.

TABLE IV. DEFAULT VALUES OF THE NAMELIST INPUT VARIABLES

rw	= 35.	afit	= 8.
pl	= 160.	epsdy	= 1.e-08
wl	= 500.	epsb	= 1.0 e-08
dtin	= 1.e-08	epsu	= 1.0e-06
dtmax	= 1.e-05	epstmx	= 9.e-02
tmax	= 3.e-05	epstmn	= 4.e-02
idencf	= 1	maxdy	= 19
den0a	= 1.e11	maxy0	= 31
dennu1	= 2.e+15	maxp	= 21
x1d	= 0.45	maxdt	= 11
x5d	= 0.225	maxnpc	= 20
iticf	= 1	ntime	= 250
ti0a	= 90.	nprnt	= 18
tinul	= 125.	mshprt	= 1
x1ti	= 0.3	nout	= 1
x5ti	= 0.15	akifc	= 1.
itecf	= 1	akefc	= 1.
te0a	= 90.	akipfc	= 1.
tenul	= 125.	akepfc	= 1.
x1te	= 0.3	rstcfc	= 1.
x5te	= 0.15	rstcf2	= 0.
idenof	= 1	rstbfc	= 0.
cxdnof	= -8.	swoh	= 1.
itiof	= 1	oh2ifc	= 0.
cxtiof	= -8.	fstrem	= 1.0
iteof	= 1	sweq	= 1.
cxteof	= -8.	swvn	= 1.
ibc	= 2	swqqi	= 1.
flx1	= -0.72	swqqe	= 1.
flx2	= 0.	sweqm	= 1.2
ttu	= 2.0e-5	swu	= 1.
drwdt	= -0.5	swi	= 1.
amu	= 2.	swe	= 1.
z	= 1.	bc1	= 1.5
gamman	= 5.	nswof	= 1
gammad	= 3.	noutof	= 5
	=	iwrs	= 1

TABLE V. INPUT VARIABLES IN PARAMETER STATEMENTS

Variable Name	Description
NETA	Number of mesh points in η .
NPSI	Number of mesh points in ψ^* ; need to have NPSI < NETA ; if NPSI $\geq$ NETA , replace NETA2 by NP2 in COMMON BLOCK VAR6 .
IPTS	Number of mesh points in r/r_0 . This is used to convert the initial profiles from functions of (r/r_0) to functions of η .
MAXN	Dimension of arrays of time-dependent variables. Hence, need to have MAXN $\geq$ NTIME .

TABLE VI. OUTPUT VARIABLE DESCRIPTION

Variable Name	Description
n	Number density, n (cm^{-3})
$T_i(T_e)$	Ion (electron) temperature, $T_i, (T_e)$
PSI*	ψ^*
TAUi(TAUe)	$\tau_i(\tau_e)$
TAUfsi (TAUfse)	$\tau_{fsi}(\tau_{fse})$
WTAUi (WTAUe)	$\omega_{ci}\tau_i$ ($\omega_{ce}\tau_e$) where ω_c is cyclotron frequency
RHOi (RHOe)	Ion (electron) Larmor radius $\rho_i(\rho_e)$
GSCLN, GSCLTi, GSCLTe	Scale lengths for ∇n , ∇T_i , and ∇T_e , respectively
DFSLi(DFSLe)	n_i/τ_{fsi} (n_e/τ_{fse})
TFSLi (TFSLe)	$1.5 T_i/\tau_{fsi}$ ($1.5 n_e/\tau_{fse}$)
QK11i (QK11e)	Ion (electron) parallel thermal conduction flux
EQBRAT	Electron-ion thermal equilibration time
N	Number of time step in the simulation
T(N)	Real time in the simulation
P ℓ	FRC plasma length, ℓ
Rw	Wall radius, r_w
RO	Field null radius, r_0
S $\bar{s}$ ar	$\bar{s} \equiv \frac{1}{r_s} \int_{r_0}^{r_s} \frac{r}{\rho_i} dr$, where $\rho_i = m_i v_{\perp} c / q_i B$ and $v_{\perp} = (2T_i/m_i)^{1/2}$
< n >	Average number density
Volume	Volume of the FRC, $\pi r_s^2 \ell$
Xs	$x_s \equiv r_s / r_w$
BETAs	Plasma β at separatrix, β_s
TAUpsi	Instantaneous flux confinement time, $\tau_{\phi} \equiv -\psi_0 / (\partial \psi_0 / \partial t)$
TAUen	Instantaneous energy confinement time, $\tau_E \equiv -$ (total plasma energy)/(total energy loss rate), of the closed field region
TAUeni	Instantaneous ion energy confinement time, $\tau_{Ei} \equiv -$ (ion energy)/(ion energy loss rate), of the closed field region
TAUene	Instantaneous electron energy confinement time; similar to TAUeni
TAUeki	Instantaneous ion energy confinement time due to thermal conduction, $\tau_{Eki} \equiv -$ (total ion energy)/(ion thermal conduction loss rate)

TABLE VI (CONT)

Variable Name	Description
TAUeke	Similar to TAUeki, but for electrons
PSIO	Trapped magnetic flux, ψ_0
PSIV	Vacuum magnetic flux, ψ_v
R_s	Separatrix radius, r_s
B_z	Magnetic Field, B_z
OHCF	Ohmic heating rate in the entire closed field region
RSTV (bhm/cl)	Bohm resistivity/classical resistivity, σ_{cl}/σ_B
U	Adiabatic variable associated with the number density in the closed field region, U (Dimensionless)
$W_i(W_e)$	Adiabatic variable associated with the ion (electron) temperature in the closed field region, W_i (W_e) (Dimensionless)
S	$s \equiv U(W_i^{\gamma-1} + W_e^{\gamma-1})$
PR	Plasma pressure, $p = n_i T_i + n_e T_e$
r	Radial position r
DD	Adiabatic variable associated with the number density in the open field region, N in Sec. III (Dimensionless)
$Z_i(Z_e)$	Adiabatic variable associated with the ion (electron) temperature in the open field region, $Z_i(Z_e)$ in Sec. III (Dimensionless)
dq	$\partial q / \partial \psi^*$ in Sec. III
dy	$\partial y / \partial \eta$ in Sec. III
Jthin	Poloidal-current density, j_θ
rJ/sig	j_e / σ
BX2/BW1	$(P(r_o, t) / P(r_o, 0))^{1/2}$ where P is total plasma pressure
n2/n1	$n(r_o, t) / n(r_o, 0)$
T2/T1	$(T_i(r_o, t) + T_e(r_o, t)) / (T_i(r_o, 0) + T_e(r_o, 0))$
WWP(WWPOF)	Total plasma energy in closed (open) field region (Dimensionless)
WWB(WWBOF)	Total magnetic field energy in closed (open) field region (Dimensionless)
WP1(WPWOF)	Plasma energy density at separatrix (wall) (Dimensionless)
WB1(WBWOF)	Magnetic field energy density at separatrix (wall) (Dimensionless)

TABLE VI (CONT)

Variable Name	Description
WACT(WACTOF)	Actual total energy existing in the closed (open) field region at the time when this is printed, $WACT = WWP + WWB$ ($WACTOF = WWPOF + WWBOF$) (Dimensionless)
WWNEW(WWNEWOF)	Total energy in the closed (open) field region calculated by tracing all the losses from and sources to the region up to the time when this is printed (Dimensionless)
WERR(WERROF)	Cumulative relative change of the total energy in the closed (open) field region up to the present time step (Dimensionless)
DWACT(DWACTOF)	Change of WACT (WACTOF) in the present time step (Dimensionless)
DELTA W(DELTA WOF)	Change of WWNEW (WWNEWOF) in the present time step (Dimensionless)
DWERR (DWERROF)	Relative difference between DWACT (DWACTOF) and DELTA W (DELTA WOF) in the present time step (Dimensionless)
MAXIMUM AHANGE	Absolute value of maximum relative change of U , W_i , and W_e in the present time step
J,X1,X2,X3,X5	J is the location of the η mesh point where the MAXIMUM CHANGE occurs; X1,X2,X3, and X5 are the absolute relative changes of U , W_i , W_e , and y at $\eta(J)$, respectively.
TAUpsi,av	Least-square-fit average confinement times for trapped flux, average number density, total plasma energy, $T_i(r_0) + T_e(r_0)$, and $T_i(r_s) + T_e(r_s)$, respectively, over the simulation time period
TAUp,av	
TAUen,av	
TAU ϕ ,av	
TAUTs,av	
SERRpsi, SERRp, SERRen, SERR ϕ SEPRts	Square errors of the least-square-fit for TAUpsi,av, TAUp,av, TAUen,av, TAU ϕ ,av, and TAUTs,av, respectively

TABLE VII. SUBROUTINE DESCRIPTION

Subroutine Name	Description
COEF	Calculate various transport coefficients and plasma related parameters.
DENIC	Specify the initial density profile in the closed field region as a function of normalized radius, r/r_0 .
DNOFIC	Specify the initial density profile in the open field region as a function of r/r_s .
ENBAL	Check the overall energy balance.
EQUIL	Equilibrium solver.
INITL	Set up the initial conditions and define the dimensionless units.
LINEFIT	Do linear least-square fit in calculating various average confinement times.
MAXINV	Do matrix inversion.
MAXMLT	Do matrix multiplication.
PHYSCK	Calculate various characteristic lengths and times in the open field region for checking the validity of assumptions.
PLOT	Plot the time evolution of various quantities.
SEPBC	Specify the boundary conditions.
SETMAT	Set up the matrix elements for the transport calculations in the closed field region.
SETMOF	Set up the matrix elements for the transport calculations in the open field region.
TEIC	Specify the initial electron temperature profile in the closed field region as a function of r/r_0 .
TEOFIC	Specify the initial electron temperature profile in the open field region as a function of r/r_s .
TIIC	Similar to TEIC, but for ion species.
TIOFIC	Specify the initial ion temperature profile in the open field region as a function of r/r_s .
TRIMAX	Solve the 3×3 tridiagonal matrix equation for the transport in the close field region.
TRIMOF	Similar to TRIMAX, but for the open field region.

TABLE VII (CONT)

Subroutine Name	Description
WRS1	Print out the values of N and $T(N)$ to the output file <code>OFRX0</code> , where N = the time step and $T(N)$ = the real time in seconds at the time step N .
WRS2	Print out information to the output file <code>OFRX</code> and to the terminal; also plot various radial profiles at specified time steps.
WRS3	Print out information regarding energy balance check to the output file <code>OFRX0</code> .

Fig. 1. A typical field-reversed configuration.¹⁹

Fig. 2. The approximate FRC model geometry used in the present work.¹⁸

FLOW DIAGRAM

Fig. 3. The logic diagram for the code.¹⁹

```

rw=25.          pl=146.4      wl=200.
dtin=1.0e-8     dtmax=2.0e-5  tmax=8.0e-5
idencf=1        den0a=3.77e15 dennul=5.20e15  x1d=1.5      x5d=0.6666667
iticf=1         ti0a=100.     tinul=110.   xlti=1.5     x5ti=0.6666667
itecf=1         te0a=100.     tenul=110.   xlte=1.1     x5te=0.40
idenof=1        cxdnof=-8.    itiof=1     cxtiof=-8.
iteof=1         cxteof=-8.
ibc=2           flx1=-.062     flx2=0.     ttu=2.0e-5   drwdt=-0.
amu=2.          z=1.          gamman=5.   gammad=3.    afit=2.
epsdy=1.0e-8    epsb=1.0e-6   epsu=1.0e-4 epstmx=9.0e-2 epstmn=4.e-2
maxdy=19        maxy0=31     maxp=21     maxdt=11     maxnpc=20
ntime=1000      nprnt=10     mshprt=1    nout=5
akifc=1.        akefc=5.6     akipfc=1.0  akepf=1.
rstcf=5.6       rstcf2=-3.1   rstbfc=0.   sweq=1.
swoh=1.         oh2ifc=0.5    fstrem=0.3
swvn=-1.        swqqi=-1.    swqqe=-1.
sweqm=1.3       swu=1.        swi=1.      swe=1.
bcl=1.5         nswof=1       noutof=5    iwrs=5
$end of namelist input

```

Fig. 4. A sample input file.

Fig. 5. Initial radial profiles of number density, ion temperature, electron temperature, and plasma pressure.

TIME = 0 sec

Fig. 6. Initial radial profiles of total resistivity used in the code, classical resistivity, and Bohm resistivity, i.e., σ , $\sigma_{\perp cl}$, and σ_B in Table I, respectively, shown for both closed and open field regions.

TIME = 0 sec

Fig. 7. Initial radial profiles of total resistivity, classical resistivity, and Bohm resistivity for the closed field region, i.e., σ , $\sigma_{\perp cl}$, and σ_B in Table I, respectively.

TIME = 0 sec

Fig. 8. Initial radial profiles of B_z and normalized flux ψ^* ; profiles of $N_1(\psi^*) \equiv \int_0^{r(\psi^*)} 2\pi r' \ell n(r') dr'$ where $0 \leq r \leq r_0$ and $P(\psi^*)$.

TIME = 0 sec

Fig. 9. Initial profile of $N_2(\psi^*) \equiv \int_{r(\psi^*)}^{r_0} 2\pi r' \ell n(r') dr'$.

TIME = 80 μ seconds

Fig. 10. Final radial profiles of number density, ion temperature, electron temperature, and plasma pressure.

TIME = 80 μ seconds

Fig. 11. Final radial profiles of total resistivity used in the code, classical resistivity, and Bohm resistivity, i.e., σ , $\sigma_{\perp cl}$, and σ_B in Table I, respectively, shown for both closed and open field regions.

TIME = 80 μ seconds

Fig. 12. Final radial profiles of total resistivity, classical resistivity, and Bohm resistivity for the closed field region, i.e., σ , $\sigma_{\perp cl}$, and σ_B in Table I, respectively.

TIME = 80 μ seconds

Fig. 13. Final radial profiles of B_z and normalized flux ψ^* ; profiles of $N_1(\psi^*) \equiv \int_0^{r(\psi^*)} 2\pi r' \ell n(r') dr'$ where $0 \leq r \leq r_0$ and $P(\psi^*)$.

Fig. 14. Final profile of $N_2(\psi^*) \equiv \int_{r(\psi^*)}^{r_s} 2\pi r' (n(r')) dr'$.

Fig. 15. Time evolutions of r_0 , ℓ , ψ_0 , and $(\pi r_0^2 \ell)$.

Fig. 16. Time evolutions of $\bar{s}$, x_s , ψ_v , and r_w .

Fig. 17. Time evolutions of separatrix beta (β_s), total temperature at field null, average number density ($\langle n \rangle$), and magnetic (w_b), plasma (w_p), and total energy ($w_t = w_b + w_p$), of the closed field region (w_b —the lower solid line, w_p —the dotted line, w_t —the upper solid line).

Fig. 18. Time evolutions of $T_e + T_i$ at the separatrix and B_z at wall.

Fig. 19. Time evolutions of ψ_0 , $\langle n_e \rangle$, and w_p (solid lines), and the corresponding least-square exponential fits (dotted lines).

N= 151 T(N)= 0.8012e-04 seconds

P1= 0.1616e+03 Rw= 0.2500e+02 RO= 0.6273e+01 Sbar= 0.1814e+01
 <n>= 0.3724e+16 Volume= 0.3995e+05 Xs= 0.3548e+00 BETAs= 0.7462e+00
 TAUpsi= 0.76e-04 TAUen= 0.60e-04 TAUeni= 0.70e-04 TAUeki= 0.29e-03 TAUene= 0.53e-04 TAUeke= 0.11e-03 TAUpe= 0.15e-03
 PSIO= -0.2038e+05 PSIV= 0.1321e+07 Rs= 0.8871e+01
 NULL: n = 0.39488e+16 Ti= 0.76854e+02 Te= 0.75876e+02
 WALL: n = 0.25614e+13 Ti= 0.68010e-01 Te= 0.68010e-01 Bz= 0.49270e+04
 OHCF= 0.43974e+23 RSTV(bhm/cl)@sep= 0.

RADIAL PROFILES :

U(I)	n(I)	W(I)	Ti(I)	We(I)	Te(I)	S(I)	PR(I)	r(I)
0.11359e-01	0.30871e+16	0.15108e-01	0.76070e+02	0.13253e-01	0.69708e+02	0.18841e-01	0.72105e+06	0.
0.11454e-01	0.31012e+16	0.15172e-01	0.76093e+02	0.13354e-01	0.69886e+02	0.18980e-01	0.72534e+06	0.40764e+00
0.11640e-01	0.31287e+16	0.15297e-01	0.76136e+02	0.13549e-01	0.70221e+02	0.19251e-01	0.73365e+06	0.70736e+00
0.11823e-01	0.31551e+16	0.15419e-01	0.76176e+02	0.13738e-01	0.70535e+02	0.19515e-01	0.74163e+06	0.91487e+00
0.12001e-01	0.31805e+16	0.15538e-01	0.76213e+02	0.13921e-01	0.70831e+02	0.19773e-01	0.74930e+06	0.10844e+01
DD(I)	n(I)	Zi(I)	Ti(I)	Ze(I)	Te(I)	dq(I)	PR(I)	r(I)
0.72821e+00	0.30871e+16	0.99004e+00	0.76070e+02	0.84638e+00	0.69708e+02	0.84730e+00	0.72105e+06	0.88710e+01
0.58948e+00	0.28125e+16	0.87485e+00	0.76907e+02	0.71125e+00	0.66992e+02	0.74825e+00	0.64843e+06	0.92199e+01
0.31201e+00	0.19548e+16	0.64447e+00	0.75222e+02	0.44100e+00	0.58411e+02	0.56983e+00	0.41853e+06	0.97690e+01
0.18486e+00	0.13174e+16	0.53374e+00	0.72286e+02	0.30535e+00	0.49815e+02	0.50097e+00	0.25772e+06	0.10193e+02
0.11433e+00	0.87273e+15	0.45232e+00	0.67771e+02	0.21951e+00	0.41852e+02	0.46767e+00	0.15329e+06	0.10563e+02
dy(I)	Bz(I)	Jthin(I)	rJ/sig(I)	r(I)				
0.26272e-01	-0.24821e+04	0.	0.50578e+04	0.				
0.26371e-01	-0.24603e+04	0.98820e+17	0.50234e+04	0.40764e+00				
0.26565e-01	-0.24175e+04	0.16639e+18	0.49581e+04	0.70736e+00				
0.26756e-01	-0.23757e+04	0.20892e+18	0.48942e+04	0.91487e+00				
0.26942e-01	-0.23348e+04	0.24043e+18	0.48300e+04	0.10844e+01				

BX2/BW1= 0.7298e+00 n2/n1= 0.7622e+00 T2/T1= 0.6988e+00
 WVP,WVB,WPI,WBI= 0.37499727e-01 0.16788975e-02 0.85950469e+00 0.19480122e+00
 WACT,WNEW,WERR= 0.3918e-01 0.3534e-01 0.9793e-01
 DVACT,DELTA,V,DWERR= -0.3722e-03 -0.4098e-03 -0.1010e+00
 WVPWF,WVBOF,WVVOF,WVVOF= 0.50495638e-01 0.12994146e+01 0.21124703e-05 0.30702314e+01
 VACTOF,WVNEWOF,WVVEROF= 0.1350e+01 0.1350e+01 0.2202e-03
 DVACTOF,DELTA,V,DVVEROF= -0.8934e-02 -0.8909e-02 0.2794e-02
 MAXIMUM CHANGE= 0.3071e-01 J,X1,X2,X3,X5= 1 0.6196e-03 0.3071e-01 0.2663e-02 0.4176e-02

Fig. 20. Information printed in the text output file OFRX0 regarding one time step.

THE AVERAGE CONFINEMENT TIMES & LEAST SQUARE ERRORS ARE :

TAUpsi,av = 0.1208e-03 SERRpsi = 0.7116e-01 TAU,av = 0.3015e-03 SERRp = 0.1568e-01
 TAUen,av = 0.1088e-03 SERRen = 0.1111e-01 TAU0,av = 0.2278e-03 SERRt0 = 0.7575e-03
 TAUts,av = 0.3200e-03 SERRts = 0.5999e-01

CHECK VARIOUS TIME AND LENGTH SCALES IN THE OPEN FIELD REGION :

AT PSI*= PSI*(2) :
 TAUi= 0.6685e-06 TAUe= 0.6342e-08 TAUfsi= 0.1206e-04 TAUfse= 0.2132e-06
 WTAUi= 0.9031e+01 WTAUe= 0.3146e+03 RHoi= 0.6353e+00 RHOe= 0.9785e-02
 GSCLN= -0.1622e+01 GSCLTi= -0.2988e+02 GSCLTe= -0.3970e+01 DFSLi= 0.2332e+21 DFSLe= 0.1319e+23
 TFSLi= 0.4310e+11 TFSLe= 0.2123e+13 QK1li= 0.4872e+10 QK1le= 0.1039e+12
 EQBRAT= 0.5756e+10

CHECK VARIOUS TIME AND LENGTH SCALES IN THE OPEN FIELD REGION :

AT PSI*= PSI*(80) :
 TAUi= 0.6733e-06 TAUe= 0.7111e-08 TAUfsi= 0.1806e-03 TAUfse= 0.3080e-05
 WTAUi= 0.1587e+02 WTAUe= 0.6154e+03 RHoi= 0.2433e-01 RHOe= 0.3884e-03
 GSCLN= -0.2510e-01 GSCLTi= -0.1545e+00 GSCLTe= -0.1429e+00 DFSLi= 0.4609e+16 DFSLe= 0.2702e+18
 TFSLi= 0.3801e+04 TFSLe= 0.2085e+06 QK1li= 0.2891e+02 QK1le= 0.7918e+03
 EQBRAT= 0.3378e+04

cpu time= 0.30e+03 seconds

Fig. 21. Additional information printed in the text output file OFRX0.