TSC Users Manual

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Chapter 1

Introduction

The Tokamak Simulation Code (TSC) is a numerical model of an axisymmetric tokamak plasma and the associated control systems[1]. The code simulates the time evolution of a free boundary plasma by solving the MHD equations on a rectangular computational grid. The MHD equations are coupled to the external circuits (representing poloidal field coils) through the boundary conditions. The code includes provisions for modeling the control system, external heating, and fusion heating. The code was originally written in 1986 as described in [9] and has since been gradually updated and modified.

This manual covers the basic material needed to use the TSC code. A theoretical background of the governing equations and numerical methods is given in Chapter 2. Information on obtaining, compiling and running the code is given in Chapter 3 while vertical stability analysis is discussed in Chapter 4. Two sample input files are listed in Chapter 5 along with some useful notes on each.

Chapter 2

Theoretical Background

The following description of the governing equations and numerical methods closely follows the original paper describing the TSC model written by Jardin, Pomphrey and Delucia in 1986 [9]. A updated theoretical summary of the TSC model is given in a more recent paper by Jardin, Bell and Pomphrey [7].

2.1 Equations

A cylindrical coordinate system with x as the radial coordinate, z as the axial coordinate and ϕ as the toroidal symmetry angle is used in discussing the governing equations.[1] In this geometry, it is useful to express the magnetic field as

$$\vec{B} = \nabla\phi \times \nabla\Psi + g\nabla\phi, \tag{2.1}$$

where Ψ is the poloidal magnetic flux per radian and g is the toroidal field function. To allow separate numerical treatment of the incompressible and compressible parts of the flow field it useful to define the plasma momentum density $\vec{m} = M_i n\vec{v}$ in terms of a stream function A, a toroidal component ω, and a potential Ω

$$\vec{m} = \nabla\phi \times \nabla A + \omega\nabla\phi + \nabla\Omega. \tag{2.2}$$

As shown in Fig. 1, a uniform cartesian spatial mesh is divided into three separate regions : the plasma region, the surrounding vacuum region, and the solid conductors. The interface between the plasma and vacuum regions will change in time as the plasma evolves. The edge of the plasma is

[1] MKS units are used in all equations.

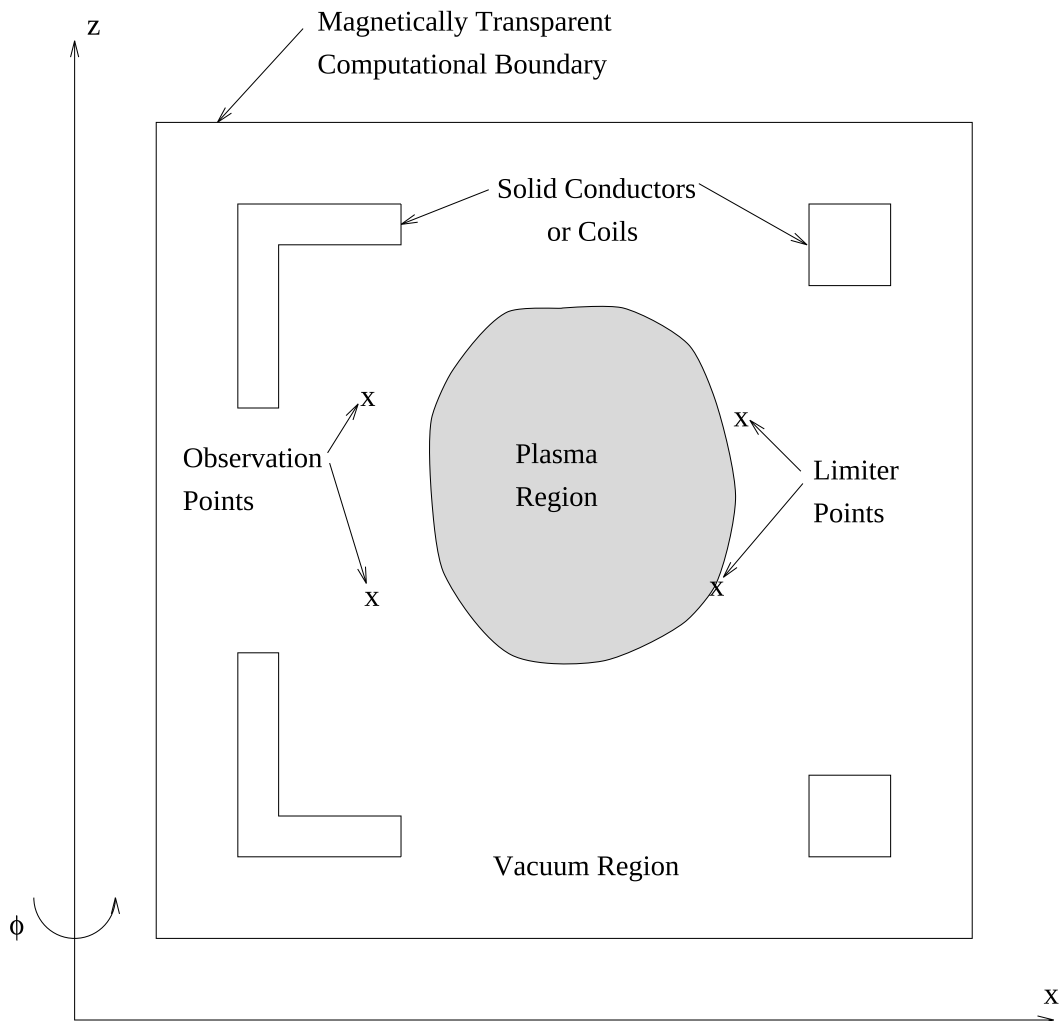

Figure 2.1: Computational domain : Plasma, vacuum and conductor regions inside a magnetically transparent boundary.

defined by the first poloidal flux surface touching a limiter point or containing an x-point. A modified form of the MHD equations are solved in each of the three regions. The modifications involve introducing several continuous parameters into the MHD equations. The three parameters are the enhanced plasma mass density and viscosity and the electrical conductivity of the vacuum region. The equations do not change their type across region boundaries and solutions are continuous. The governing equations in each region are discussed in the following sections.

2.1.1 Plasma Region

The TSC model solves the resistive MHD equations on a time scale governed by resistive dissipation and cross field transport in the plasma and by the rate of change of the currents in the poloidal field circuits. Since the plasma densities and temperatures tend to equilibrate on magnetic flux surfaces on a much shorter time scale, these quantities are modeled as one-dimensional spatial functions uniform on each magnetic surface. The evolution of the magnetic flux surfaces is governed by a momentum transport equation, Faraday's Law and Ohm's Law as discussed in the following section.

Magnetic Flux Surfaces

In the absence of Alfvén time scale (ideal MHD) instabilities, the inertial terms in the plasma force balance are smaller than the magnetic forces by the inverse square of the magnetic Reynolds number

$$S_M = \left(\frac{aB_o}{\eta}\right)\left(\frac{\mu_o}{nM_i}\right)^{1/2}, \tag{2.3}$$

where η is the plasma resistivity and a is the minor radius. Since the magnitude of the true time-averaged inertial terms are small, the TSC model replaces them with a convenient modified term. This is equivalent to enhancing the plasma ion mass, dropping the convective derivative and choosing a form for the viscous force,

$$\vec{F}_v = -\nu_1[\nabla^2\vec{m} - \nabla(\nabla\cdot\vec{m})] - \nu_2\nabla(\nabla\cdot\vec{m}), \tag{2.4}$$

where ν_1 and ν_2 are the compressible and incompressible viscosities. The modified plasma force balance equation is

$$\frac{\partial\vec{m}}{\partial t} + \vec{F}_v(\vec{m}) = \vec{J}\times\vec{B} - \nabla p. \tag{2.5}$$

The left-hand side of Eq. (2.5) must remain small in comparison to the right-hand side for the modified inertial technique to be valid. This is accomplished by carefully choosing the values of the mass enhancement and viscosity parameters and verifying a posteriori that the modified inertial terms are small. The physical results must be independent of the mass and viscosity parameters.

The scalar equations used in the TSC model are obtained by substituting the definitions for $\vec{m}$ and $\vec{F_v}$ into Eq. (2.5) and operating with $\{\nabla\cdot\}$, $\{\nabla\phi\cdot\nabla\times\}$, and $\{\nabla\phi\cdot\}$. The resulting scalar equations are

$$\frac{\partial}{\partial t}\nabla^2\Omega + \nabla\cdot\left[\frac{\Delta^*\Psi}{\mu_o x^2}\nabla\Psi + \frac{g}{\mu_o x^2}\nabla g + \nabla p - \nu_2\nabla(\nabla^2\Omega)\right] = 0, \quad (2.6)$$

$$\frac{\partial}{\partial t}\Delta^* A + x^2\nabla\cdot\left[\frac{\Delta^*\Psi}{\mu_o x^2}\nabla\Psi\times\nabla\phi + \frac{g}{\mu_o x^2}\nabla g\times\nabla\phi - \frac{\nu_1}{x^2}\nabla(\Delta^* A)\right] = 0, \quad (2.7)$$

$$\frac{\partial}{\partial t}\omega + \mu_o^{-1}\nabla\phi\times\nabla g\cdot\nabla\Psi - \nu_1\Delta^*\omega = 0, \quad (2.8)$$

where $\Delta^* = x^2\nabla\cdot x^{-2}\nabla$ is the standard Grad-Shafranov elliptic operator.

Evolution equations for the poloidal flux and toroidal field functions are obtained from Faraday's Law and Ohm's Law. For this model, Ohm's law is expressed as

$$\vec{E} + \vec{\mathrm{v}}\times\vec{B} = \vec{R}, \quad (2.9)$$

where $\vec{R}$ contains the nonideal terms. These evolution equations are

$$\frac{\partial}{\partial t}\Psi + \frac{1}{\rho_o}(\nabla\phi\times\nabla A\cdot\nabla\Psi + \nabla\Omega\cdot\nabla\Psi) = x^2\nabla\phi\cdot\vec{R}, \quad (2.10)$$

$$\frac{\partial}{\partial t}g + x^2\nabla\cdot\left[\frac{g}{\rho_o x^2}(\nabla\phi\times\nabla A + \nabla\Omega) - \frac{\omega}{\rho_o x^2}\nabla\phi\times\nabla\Psi - \nabla\phi\times\vec{R}\right] = 0. \quad (2.11)$$

The constant $\rho_o = n_o M_i$ serves the role of the enhanced mass density. At any time, the solution of Eqs. (2.10) and (2.11) approximates the MHD equilibrium condition $\vec{J}\times\vec{B} = \nabla p$ to within $\epsilon = S_M^{-2}$, where S_M is the magnetic Reynolds number.

Surface-Averaged Transport Equations

The TSC model evolves the surface-averaged thermodynamic variables relative to magnetic coordinate surfaces containing a fixed amount of toroidal flux. The toroidal flux Φ within a constant Ψ surface $\Psi = \Psi_c$ is defined as the integral over the enclosed volume

$$\Phi \equiv \frac{1}{2\pi} \int_{\Psi<\Psi_c} \vec{B} \cdot \nabla\phi \, d\tau = \int_{\Psi<\Psi_c} dx \, dz \, \frac{g(x,z)}{x} \tag{2.12}$$

These surface averaged equations are derived by decomposing the cross-field fluid velocity into two parts

$$\vec{\mathrm{v}} \cdot \nabla\Psi = \vec{\mathrm{v}}_C \cdot \nabla\Psi + \vec{\mathrm{v}}_R \cdot \nabla\Psi, \tag{2.13}$$

where $\vec{\mathrm{v}}_{\mathrm{C}} \cdot \nabla\Psi$ is due to the evolution of the coordinate surfaces and $\vec{\mathrm{v}}_{\mathrm{R}} \cdot \nabla\Psi$ is the fluid flow relative to the magnetic surfaces. Applying Eq. (2.11) to magnetic coordinate surfaces evolving with fixed toroidal flux Φ yields

$$\vec{\mathrm{v}}_R \cdot \nabla\Psi = \frac{x^2}{g} \nabla\phi \times \vec{R} \cdot \nabla\Psi, \tag{2.14}$$

and

$$\frac{\partial}{\partial t}\left(\frac{1}{q}\oint \frac{dl}{B_p}\right) = \frac{\partial}{\partial\Psi}\left(\frac{1}{q}\oint \frac{dl}{B_p}\vec{\mathrm{v}}_C \cdot \nabla\Psi\right), \tag{2.15}$$

where $q \equiv (2\pi)^{-1}\partial\Phi/\partial\Psi$ is the safety factor and B_p is the magnitude of the poloidal magnetic field. The line integrals are around a contour in a poloidal cross section at Ψ = constant. The velocity is eliminated from the mass and energy conservation equations using Eq. (2.13)-(2.15). The resulting one-dimensional evolution equations for the differential number density ($N' = n_e \partial V \partial\Phi$ where V is the volume) and the total and differential electron entropy densities ($\sigma = p(\partial V \partial \Phi)^{5/3}$ and $\sigma_e = p_e(\partial V/\partial\Phi)^{5/3}$) are

$$\frac{\partial}{\partial t}N' = -\frac{\partial}{\partial\Phi}\left(N'\Gamma\right) + S_N, \tag{2.16}$$

$$\frac{\partial}{\partial t}\sigma = \frac{2}{3}\left(\frac{\partial V}{\partial\Phi}\right)^{2/3}\left[V_L\frac{\partial K}{\partial\Phi} - \frac{\partial}{\partial\Phi}(Q_i + Q_e) + \frac{\partial V}{\partial\Phi}(S_e + S_i - R_e)\right], \tag{2.17}$$

$$\frac{\partial}{\partial t}\sigma_e = \frac{2}{3}\left(\frac{\partial V}{\partial\Phi}\right)^{2/3}\left[V_L\frac{\partial K}{\partial\Phi} - \frac{\partial Q_e}{\partial\Phi} + \frac{\partial V}{\partial\Phi}\left(-\Gamma\frac{\partial p_i}{\partial\Phi} + Q_{\Delta e} + S_e - R_e\right)\right]. \tag{2.18}$$

The above transport equations describe the evolution of the thermodynamic variables with respect to magnetic surfaces containing a fixed toroidal flux Φ. The S_N, S_e, S_i are external sources of particles, electron and ion energy and

R_e is energy loss due to radiation. In the above equations, the differential volume is defined as

$$\frac{\partial V}{\partial \Phi} = \frac{\partial}{\partial \Phi} \oint d\tau = \frac{1}{q} \oint \frac{dl}{B_p}, \tag{2.19}$$

the loop voltage as

$$V_L = \frac{2\pi \langle \vec{E} \cdot \vec{B} \rangle}{\langle \vec{B} \cdot \nabla \phi \rangle}, \tag{2.20}$$

where the flux surface average operator is defined as

$$\langle a \rangle = \frac{\oint (dl/B_p) a}{\oint (dl/B_p)}. \tag{2.21}$$

The total toroidal current within a flux surface is defined as

$$K = \oint \vec{B}_p \cdot \vec{dl} = \oint \frac{dl \mid \nabla \Psi \mid}{x}. \tag{2.22}$$

The particle flux and electron and ion heat fluxes are defined as

$$\Gamma = 2\pi q \left[\langle x^2 \vec{R} \cdot \nabla \phi \rangle - \frac{\langle \vec{R} \cdot \vec{B} \rangle}{\langle \vec{B} \cdot \nabla \phi \rangle} \right], \tag{2.23}$$

$$Q_i = \frac{\partial V}{\partial \Phi} \left[\langle \vec{q}_i \cdot \nabla \Phi \rangle + \frac{5}{2} p_i \Gamma \right], \tag{2.24}$$

$$Q_e = \frac{\partial V}{\partial \Phi} \left[\langle \vec{q}_e \cdot \nabla \Phi \rangle + \frac{5}{2} p_e \Gamma \right], \tag{2.25}$$

where $\vec{q}_i$ and $\vec{q}_e$ are the random heat flux vectors.

The plasma is assumed to have two temperatures : T_e for the temperature of the electrons of density n_e and T_i for the temperature of the the bulk ions of charge Z_i, mass M_i and density n_i. The model also assumes a single impurity ion of charge Z_I, mass M_I and density n_I. The temperatures densities and pressures are related according to

$$k_B T_e = p_e / n_e, \tag{2.26}$$

$$k_B T_i = p_i / (n_i + n_I), \tag{2.27}$$

with $k_B = 1.60 \times 10^{-19}$ J/eV. An additional relationship is obtained from charge neutrality

$$n_e = Z_i n_i + Z_I n_I. \tag{2.28}$$

The effective charge $\bar{Z}$ and the equipartition charge $\langle Z \rangle$ are defined as

$$\bar{Z} = (n_i Z_i^2 + n_I Z_I^2)/n_e, \tag{2.29}$$

$$\langle Z \rangle = (n_i Z_i^2/M_i + n_I Z_I^2/M_I)/(n_e/M_p). \tag{2.30}$$

where M_p is the proton mass.

An evolution equation for the normalized rotational transform $\iota \equiv q^{-1}$ is implied by Eq. (2.10) and (2.11),

$$\frac{\partial}{\partial t}\iota = \frac{\partial}{\partial \Phi} V_L. \tag{2.31}$$

In the TSC model, this equation serves as a corrector to the Ψ and g functions evolved through Eq. (2.10) and (2.11). This feature is discussed in section (2.2.2).

The nonideal dissipation vector $\vec{R}$ consists of a classical part $\vec{R}_C$ and an anomalous part $\vec{R}_A$ perpendicular to the magnetic field.

$$\vec{R} = \vec{R}_C + \left(\frac{\vec{B} \times \vec{R}_A \times \vec{B}}{B^2} \right). \tag{2.32}$$

The classical part is modeled as collisonal dissipation

$$\vec{R}_C = \eta_{\parallel} \vec{J}, \tag{2.33}$$

with a resistivity as in Eq. (2.37). In evolving the two-dimensional functions Ψ and g in Eqs. (2.10) and (2.11), it is permissible to take $\vec{R} = \vec{R}_C$ since the anomalous $\vec{R}_A$ is perpendicular to $\vec{B}$.

An explicit equation for the loop voltage in Eq. (2.20) is

$$V_L = \eta_{\parallel} \frac{(2\pi q)^2}{\alpha^2} \frac{\partial}{\partial \Phi} \left(\alpha K \iota \right), \tag{2.34}$$

where α is defined as

$$\alpha \equiv \frac{2\pi q}{g} = \oint \frac{dl}{B_p x^2}. \tag{2.35}$$

Resistivity and Equipartition

The equipartition term in Eq. (2.18) is given [1] by

$$Q_{\Delta e} = \frac{3}{2\tau_{\Delta e}} \left(p_i - \frac{(n_i + n_I)}{n_e} p_e \right), \tag{2.36}$$

where

$$\tau_{\Delta e}^{-1}[\mathrm{s}^{-1}] = 3.1 \times 10^{-11} n_e[\mathrm{m}^{-3}] \eta_C[\Omega \cdot \mathrm{m}] \langle Z \rangle,$$

and η_C is the classical plasma resistivity for a hydrogen plasma(see ref. [1])

$$\eta_C[\Omega \cdot \mathrm{m}] = (1.03 \times 10^{-4}) \ln \Lambda (T_e[\mathrm{eV}])^{-3/2}, \tag{2.37}$$

with the approximation

$$\ln \Lambda = 17.1 - \ln \left\{ (n_e[\mathrm{m}^{-3}])^{1/2} (T_e[\mathrm{eV}])^{-1} \right\}.$$

Neoclassical corrections to the resistivity are used in the TSC model. These are given [4] by

$$\eta_C / \eta_{NC} = \Lambda_E(\bar{Z}) \left(1 - \frac{f_t}{1 + \xi(\bar{Z}) \nu_{*e}} \right) \left(1 - \frac{C_R(\bar{Z}) f_t}{1 + \xi(\bar{Z}) \nu_{*e}} \right), \tag{2.38}$$

where

$$\Lambda_E = \frac{3.40}{\bar{Z}} \left(\frac{1.13 + \bar{Z}}{2.67 + \bar{Z}} \right),$$

$$C_R(\bar{Z}) = \frac{0.56}{\bar{Z}} \left(\frac{3.0 - \bar{Z}}{3.0 + \bar{Z}} \right),$$

$$\xi(\bar{Z}) = 0.58 + 0.20 \bar{Z}.$$

The effective electron collisional frequency is evaluated as

$$\nu_{*e} = (10.2 \times 10^{16})^{-1} R_o[\mathrm{m}] q n_e[\mathrm{m}^{-3}] \Lambda / f_t \delta (T_e[\mathrm{eV}])^2. \tag{2.39}$$

The local inverse aspect ratio is evaluated as $\delta = a/R_o$ with

$$a = \left[V/(2\pi^2 R_o) \right]^{1/2},$$

where V is the volume inside a given magnetic surface and R_o is the radius of the magnetic axis. The trapped particle fraction f_t is evaluated in terms of averages over the magnetic surfaces as follows

$$f_t = 1 + \langle B^2 \rangle \langle B^{-2} \rangle + \frac{3}{2} \langle B^2 \rangle \left\langle \left[B^{-2} (1 - B/B_c)^{1/2} - \frac{1}{3} (1 - B/B_c)^{3/2} \right] \right\rangle, \tag{2.40}$$

where B_c is the maximum value of B on a given flux surface.

In the absence of external current drive, the parallel electric field is the sum of the resistive diffusion term and the bootstrap current drive term as follows

$$\vec{E} \cdot \vec{B} = \eta_{\|} \left[\vec{J} \cdot \vec{B} - \vec{J}_{BS} \cdot \vec{B} \right]. \tag{2.41}$$

Here, the total current density is

$$\vec{J} = \mu_o^{-1} \nabla \times \vec{B}, \tag{2.42}$$

and $\vec{J}_{BS}$ is the bootstrap current density given [3] by

$$\left\langle \vec{J}_{BS} \cdot \vec{B} \right\rangle = -\frac{g p_e}{D} \left\{ N_1 \left[\frac{p_e^{'}}{p_e} + \frac{1}{\bar{Z}} \frac{p_i}{p_e} \left(\frac{p_i^{'}}{p_i} + \alpha_i \frac{T_i^{'}}{T_i} \right) \right] - N_2 \frac{T_e^{'}}{T_e} \right\}, \tag{2.43}$$

with the definitions

$$N_1 = f_x \left(0.754 + 2.21\bar{Z} + \bar{Z}^2 \right) + f_x^2 \left(0.348 + 1.24\bar{Z} + \bar{Z}^2 \right),$$

$$N_2 = f_x \left(0.884 + 2.07\bar{Z} \right),$$

$$D = 1.414\bar{Z} + \bar{Z}^2 + f_x \left(0.754 + 2.657\bar{Z} + 2\bar{Z}^2 \right) + f_x^2 \left(0.348 + 1.234\bar{Z} + \bar{Z}^2 \right),$$

$$\alpha_i = -1.172 / \left(1.0 + 0.462 f_x \right),$$

$$f_x = f_t / (1 - f_t).$$

A modification of the neoclassical resistivity is used in the TSC model to take into account the effect of the sawtooth oscillations on the evolution of the plasma. Unlike some models which attempt to resolve in time the occurrence of each sawtooth event, a time averaged model is used that consists of enhancing the resistivity (and if desired the thermal conductivity) inside the magnetic surface for which $q = 1$. The model uses the parameter a_{120} ($0 < a_{120} \leq 1$), to represent the degree by which the resistivity profile and hence the steady state current profile is flattened inside the sawtooth inversion radius. In terms of this parameter, the sawtooth model is described by

$$\begin{aligned} \eta_{\|} &= \eta_{NC} \qquad \text{for } q \geq 1, \\ \eta_{\|} &= a_{120}\eta_{NC} + (1 - a_{120}) \eta_{NC}|_{q=1} \qquad \text{for } q < 1. \end{aligned} \tag{2.44}$$

A discussion of TSC time averaged model and a comparison with the Kadomtsev reconnection model is given in reference [7].

Thermal Conductivity

In the standard version of TSC, the random heat flux contributions to Q_i and Q_e in Eqs. (2.24) and (2.25) are evaluated using a general geometry formulation of the Coppi-Tang transport model. In this model, the electron and ion heat fluxes depend only on their respective temperature gradients. Thus, the random heat fluxes are of the form

$$\langle \vec{q}_e \cdot \nabla \Phi \rangle = -\chi_e \mid \nabla \Phi \mid^2 n_e \frac{\partial T_e}{\partial \Phi}, \tag{2.45}$$

$$\langle \vec{q}_i \cdot \nabla \Phi \rangle = -\chi_i \mid \nabla \Psi \mid^2 n_i \frac{\partial T_i}{\partial \Phi}. \tag{2.46}$$

The electron and ion thermal conductivities are modeled as (see reference [8])

$$\chi_e = f_m (\chi^2_{\text{TEM}} + \chi^2_{\eta i})^{1/2} F(\Phi) \mid \nabla \Phi \mid^{-2}, \tag{2.47}$$

$$\chi_i = a_{126} \chi_e \tag{2.48}$$

where a_{126} is a constant parameter and $F(\Phi)$ is a profile factor given by

$$F(\Phi) = 8\pi^2 \frac{P(\Phi)}{P(\Phi_b)} \frac{n_e(\Phi_o)}{n_e(\Phi)} \frac{R_o \Phi_b}{(\partial V / \partial \Phi)} \exp\left[\frac{2}{3} \alpha_q \frac{\Phi}{\Phi_b}\right]. \tag{2.49}$$

Here, Φ_b is the toroidal flux at the plasma boundary, Φ_o is the flux at the magnetic axis, $P(\Phi)$ is the total heating power (including Ohmic heating) minus the total radiated power inside the surface Φ, and α_q is taken to be

$$\alpha_q = q_{95} + 0.5, \tag{2.50}$$

where q_{95} is the safety factor at the surface containing 95% of the toroidal flux between the magnetic axis and the plasma edge. The variable α_q is limited to lie between 2.5 and 6.5 in order to avoid unphysical results in regimes where the assumptions underlying the transport model are not valid.

The functional form of the profile factor $F(\Phi)$ given in Eq. (2.49) follows from the insertion of the empirical steady state temperature profile

$$\frac{T_e(\Phi)}{T_e(\Phi_b)} = \exp\left[-\frac{2}{3} \alpha_q \frac{\Phi}{\Phi_b}\right], \tag{2.51}$$

into the steady form of Eq. (2.17) and using the definitions in Eqs. (2.24), (2.25), (2.45) and (2.46) to solve for χ_e and χ_i. It is a generalization to arbitrary geometry of the form first suggested by Coppi [2].

From reference [10], the multipliers for the two confinement regimes are

$$\chi_{\text{TEM}} = a_{122}(1.25 \times 10^{20})\frac{a}{n(\Phi_b)}(xB_T)^{0.3}\bar{Z}^{0.2}(1+\frac{1}{4}\alpha_N)x^{-2.2}q_{95}^{-1.6}, \quad (2.52)$$

$$\chi_{\eta i} = a_{121}(7.5 \times 10^{8})\left[\frac{P(\Phi_b)}{n(\Phi_b)}\right]^{0.6}(xB_Tq_{95})^{-0.8}a^{-0.2}. \quad (2.53)$$

These are combined as shown in Eq. (2.47).

The factor f_m in Eq. (2.47) is used to account for the time averaged effect of the sawtooth instability in causing additional flattening of the temperature profile inside the $q = 1$ surface. Thus, in addition to the prescription given in Eq. (2.44) for modifying the resistivity profile, the sawtooth model is completed by enhancing the thermal conductivity inside the sawtooth inversion radius according to the prescription

$$\begin{aligned} f_m &= 1 \quad \text{for } q > 1 \\ f_m &= a_{124} \quad \text{for } q < 1 \end{aligned} \quad (2.54)$$

Particle Transport

In the standard TSC model,the particle flux Γ appearing in Eqs. (2.16), (2.18), (2.24) and (2.25) is set to zero:

$$\Gamma = 0. \quad (2.55)$$

The density profile is taken to be of the form

$$n_e(\Phi, t) = n_e^0(t)\left[1 - \hat{\Psi}^{\beta_N(t)}\right]^{\alpha_N(t)} + n_b(t), \quad (2.56)$$

where $\hat{\Psi}$ is the normalized poloidal flux which varies between 0 at the magnetic axis and 1 at the plasma boundary and $n_b(t)$ is the density at the plasma boundary. The exponents $\beta_N(t)$ and $\alpha_N(t)$ along with $n_e^0(t)$ and $n_b(t)$ can be adjusted in time to match the experimental data. This approach to modeling the density evolution was adopted for several reasons. A satisfactory dynamic transport model for the density profile does not yet exist and even if such a model did exist it would be difficult to infer the actual source S_N in the presence of both gas fueling and recycling. The user may provide subroutines to describe a particle transport model but one does not currently exist within TSC.

Radiation and Impurities

The dominant radiation procees in the standard model is assumed to be bremsstrahlung emission from fully stripped ions. The surface averaged radiated power density is computed as

$$R_e(\Phi, t) = 1.7 \times 10^{-38} (n_e(\Phi, t)[\mathrm{m}^{-3}])^2 \bar{Z}(t) (T_e(\Phi, t)[\mathrm{eV}])^{1/2}. \tag{2.57}$$

The variation of the effective charge with time, $\bar{Z}(t)$, can be taken to match experimental measurements from visible bremsstrahlung, assuming the radial dependence to be flat.

2.1.2 Vacuum Region

The boundary between the plasma region and the vacuum region is taken to be the first plasma flux surface that makes contact with a limiter. For plasma regions that do not contact the limiter, the plasma boundary surface contains an x-point. The vacuum region is modeled as a low temperature, zero pressure gradient plasma in which currents can exist. Therefore Eqs. (2.6)-(2.11) (with $\nabla p = 0$) are solved in the vacuum region with a classical resistivity as shown in Eq. (2.33) and (2.37). The vacuum temperature is taken as constant in the range of a few eV. In the original TSC code [9], the vacuum temperature and density served as boundary conditions on the surface averaged plasma evolution equations. Modifications to the code now include the provisions to account for the thin boundary layer that exists at the edge of the plasma that is not well described by the transport assumptions of Eqs. (2.16)-(2.18). Since the temperature variation across the layer cannot be resolved by the relatively coarse computational grid, the plasma edge temperature may be specified independently of the vacuum temperature. The details of this option are discussed in section (3.3.6) on page 59. The physical results must be independent of the vacuum temperature. The plasma edge temperature can effect the physical results and must be carefully selected based on experimental information.

The vacuum region extends from the plasma boundary to the boundary of the computational domain (excluding any solid conductor regions). This boundary is modeled as a magnetically transparent boundary by prescribing that the toroidal field strength and the poloidal flux be consistent with the plasma and coil currents. For boundary points $\vec{x}_b$, this requires

$$g(\vec{x}_b, t) = g_o = \frac{\mu_o I_{TF}(t)}{2\pi}, \tag{2.58}$$

$$\Psi(\vec{x}_b, t) = \frac{\mu_o}{2\pi}\int_p G(\vec{x}_b, \vec{x}) J_\phi(\vec{x}, t) d^2\vec{x} + \sum_{i=1}^{N} \frac{\mu_o}{2\pi} G(\vec{x}_b, \vec{x}_i) I_i, \tag{2.59}$$

where I_{TF} is the total current in all toroidal field coils and $G(\vec{x}_b, \vec{x})$ is the analytic exterior Green's function for an axisymmetric filament. The integration is carried out over the plasma volume and the summation is over the discrete poloidal field coils. An approximate method based on analytically expanding the Green's function about the current centroid is used to evaluate the two-dimensional integral in Eq. (2.59). Details and accuracy of the method are discussed in reference [9].

The normal component of the momentum density at the computational boundary, consistent with Eqs. (2.58),(2.59) and (2.6)-(2.11) when the inertial are set to zero, is

$$x\hat{n} \cdot (\nabla\Omega + \nabla\phi \times \nabla A) = \frac{-\rho_o}{B^2 x}\frac{\partial \Psi}{\partial t}\hat{n} \cdot \nabla\Psi \equiv N(\vec{x}_b, t). \tag{2.60}$$

Thus the boundary conditions on the stream function and potential are

$$\frac{\partial A}{\partial l} = N(\vec{x}_b, t) - \bar{N}(t), \tag{2.61}$$

$$x\frac{\partial \Omega}{\partial n} = \bar{N}(t), \tag{2.62}$$

where $\hat{n}$ and $\hat{l} = \hat{n} \times \hat{\phi}$ are the directions normal and tangential to the boundary and $\bar{N}(t)$ is the average value of $N(\vec{x}_b, t)$ on the boundary

$$\bar{N}(t) \equiv \frac{\oint N(\vec{x}_b, t) dl}{\oint dl}. \tag{2.63}$$

2.1.3 Solid Conductors

The material velocity in the solid conductor regions is zero. The poloidal flux evolution equation is

$$\frac{\partial \Psi}{\partial t} = \frac{\eta \Delta^* \Psi}{\mu_o} + \frac{V(t)}{2\pi}, \tag{2.64}$$

where $V(t)$ is an applied voltage from an external circuit connection. This equation is directly analogous to a discrete circuit equation. This can be shown by treating a single isolated mesh point (x,z) as a solid conductor with resistance $r_{i,j}$ and and current $I_{i,j}$. The poloidal flux at the mesh point is due to a self-inductance and a mutual inductance part

$$-2\pi\Psi_{i,j} = L_{i,j}I_{i,j} + \sum_{i',j'} M_{i,j;i',j'}I_{i',j'}, \tag{2.65}$$

where the sum is over all other currents. The discrete form of Eq. (2.64) is then

$$\frac{d}{dt}\left(L_{i,j}I_{i,j} + \sum_{i',j'} M_{i,j;i',j'}I_{i',j'}\right) + r_{i,j}I_{i,j} + V(t) = 0. \tag{2.66}$$

In the TSC model, the continuous form is used for conductors inside the computational grid while the discrete form is used for conductors outside the grid.

The TSC model includes a provision to model conductors with toroidal gaps or toroidally localized regions of high resistance, such as vacuum vessels with toroidal breaks. For a group of N poloidal field conductors connected by a small gap(area of high resistance), the generalization to Eq. (2.64) is

$$\frac{\partial\Psi_n}{\partial t} = \frac{\eta_n \Delta^*\Psi_n}{\mu_o} + \frac{[V_n(t) + r_G I_G]}{2\pi}, \tag{2.67}$$

where r_G is the gap resistance and I_G is the gap current

$$I_G = \sum_{n=1}^{N} I_n = \Delta x \Delta z \sum_{n=1}^{N} \frac{\Delta^* \Psi_n}{\mu_o x_n}, \tag{2.68}$$

and $\Delta x\Delta z$ is the associated area.

The appropriate boundary conditions on the variables A and Ω for the interface between the conductors and the vacuum region are also given by Eqs. (2.61) and (2.62). The TSC model does not use these directly because imposing internal boundary conditions would make the computational domain multiply connected and would prevent the use of fast elliptic solvers for Ω and A. Instead, the TSC model specifies $\nabla^2\Omega$ and $\Delta^* A$ inside the conductor region as

$$\nabla^2\Omega = \nabla\cdot\left(-\frac{\rho_o}{B^2x^2}\frac{\partial\Psi}{\partial t}\nabla\Psi\right), \tag{2.69}$$

$$\Delta^* A = x^2\nabla\cdot\left(-\frac{\rho_o}{B^2x^2}\frac{\partial\Psi}{\partial t}\nabla\Psi\times\nabla\phi\right). \tag{2.70}$$

Outside the conductors, this appears equivalent to specifying the boundary conditions in Eqs. (2.61) and (2.62).

2.1.4 Control System

There are currently two methods of modeling the TSC control system. The variable IDATA on card 01 is used to select the control scheme. The first method was developed in the original TSC code [9]. This method assumes that the current in each of the poloidal field coils is the sum of a preprogrammed current and a much smaller correction current. The plasma shape as a function of time is obtained as part of the solution. The preprogrammed currents are obtained from a sequence of MHD equilibria or are inferred from a previous discharge. The correction currents are computed during the simulation to adjust the position and shape of the plasma. This is accomplished by letting the feedback current in each coil group be proportional to a flux difference between two observation points $(\vec{x}_1, \vec{x}_2)$. The observation points are the coordinates at which the flux is measured for the feedback system. The location of these points is dependent on what the feedback system is to control (vertical position,radial position, shape, etc.) and can vary in time. Thus, the current in each coil group is computed by

$$I_W^k(t) = I_o^k(t) + I_{FB}^k(T) = I_o^k(t) + \alpha_p^k(\Psi(\vec{x_1}) - \Psi(\vec{x_2})), \tag{2.71}$$

where I_W^k is the desired current, I_o^k is the preprogrammed current,I_{FB}^k is the feedback current, α_p^k is the proportional gain, and the superscript denotes the coil group. Additional terms can be included in the above equation that are proportional to the time rate of change of the flux difference or a time integral of the flux difference. The feedback current can also be proportional to other quantities such as the difference between the plasma current and a preprogrammed value or magnetic axis location and a preprogrammed value. The voltage applied to the coil group to produce the desired current change is computed using a second level of feedback as follows

$$V_{FB}^k = \beta_p^k(\Delta I^k) + \beta_d^k\left(\frac{d\Delta I^k}{dt}\right) + \beta_I^k\left(\int \Delta I^k dt\right), \tag{2.72}$$

where $\Delta I^k = I_W^k - I_o^k$ and $\beta_p^k, \beta_d^k, \beta_i^k$ are the proportional, derivative and integral gains. The second level of feedback is required for coils internal to the computational grid and is optional for coils external to the grid (include only if interested in coil voltages). The TSC model has the option of using a modified form of Eq. (2.72). This modification is obtained by multiplying the right hand side of Eq. (2.72) by a mutual inductance matrix $M_{k,j}$

$$V_{FB}^j = \left[\beta_p^k(\Delta I^k) + \beta_d^k\left(\frac{d\Delta I^k}{dt}\right) + \beta_I^k\left(\int \Delta I^k dt\right)\right] \cdot M_{k,j}. \tag{2.73}$$

This effectively decouples the coil groups and allows one to change the coil current in a coil group independently by applying appropriate voltages to all the groups. The above method of controlling the plasma has one major shortcoming. If the plasma parameters of the actual simulation turn out to be very different from those assumed in computing the preprogrammed currents (e.g. with an MHD equilibrium code), the correction currents can become large and the plasma shape suffers. A trial and error procedure must then be used to improve the preprogrammed currents.

The second method of modeling the TSC control system was developed by Hofmann and Jardin in 1990 [5] and avoids some these difficulties. In the Hofmann control scheme, the shape of the plasma is a preprogrammed function of time while the coil currents are computed during the simulation. Only the initial equilibrium coil currents need to be specified. The basic idea of the method is to control the poloidal flux at a number of points along the plasma boundary. The coordinates of these points are preprogrammed functions of time and define the desired plasma shape evolution. The flux errors at the boundary points are computed by reconstructing the plasma current distribution in the form of a finite element matrix. From these flux errors, the Hofmann control model calculates the poloidal field coil currents at each instant in time that minimize the error between the preprogrammed shape and the actual shape, while minimizing a cost functional. As shown in Fig. 2.1.4, the algorithm consists of four basic elements. The matrix A converts the vector of measurements (coil currents, flux loops, magnetic field probes, etc.) into a vector of error signals. The preprogrammed evolution of the plasma (plasma current, shape, etc) is needed to calculate this matrix. The error signals are then fed to the PID controllers where they are mixed with their own time derivatives and integrals. The third element (matrix M^{-1}) calculates the rate of change of the poloidal field coil currents to minimize the errors. This is achieved by minimizing a cost functional of the form

$$C = \sum_i \gamma_i \epsilon_i^2 + D \sum_j \lambda_j I_j^2, \tag{2.74}$$

where ϵ_i are the error signals, I_j are the coil currents and γ_i, λ_j are weighting coefficients. The γ_i's are usually assumed to be unity while the λ_j's are chosen such that the second term on the r.h.s of Eq. (2.74) becomes proportional to the total power dissipation in the poloidal field coils. The parameter D controls the trade-off between the shape accuracy and power dissipation. The fourth element of the control algorithm (matrix L) computes the coil voltages which are necessary to produce the desired rate of change of the coil currents. This is done using the circuit equations for the

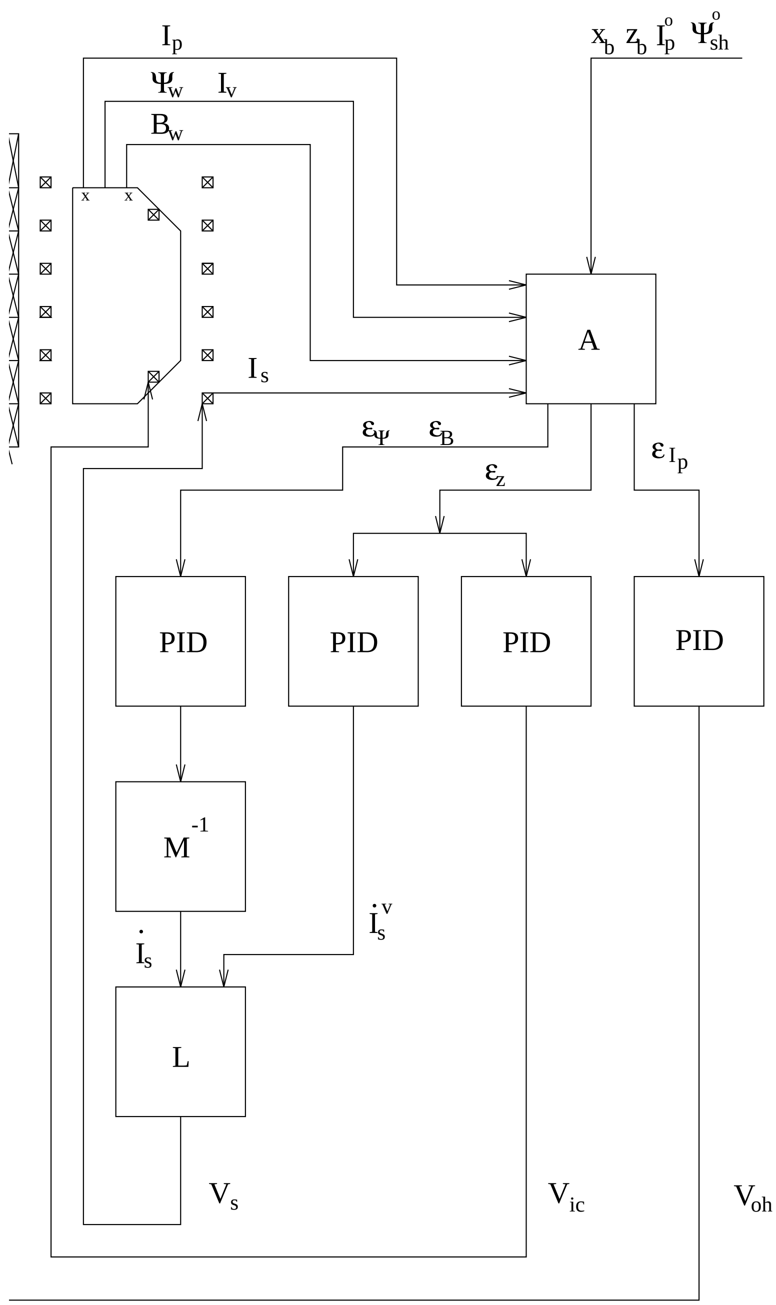

Figure 2.2: Schematic representation of Hofmann control algorithm.

poloidal field coils. The advantage of the Hofmann control scheme is that the plasma shape and position evolve according to a preprogrammed scenario, irrespective of changes in the plasma parameters, and no preprogrammed coil currents are used. Due to this, it is considered the preferred method for most simulations.

2.1.5 Summary of Equations

Variable	Description	Evolution Equation	Boundary Condition
Ω	potential	Eq. 2.6	Eq. 2.62
A	stream function	Eq. 2.7	Eq. 2.61
ω	toroidal momentum density	Eq. 2.8	ω=0
Ψ	poloidal flux	Eq. 2.10	Eq. 2.59
g	toroidal field function	Eq. 2.11	Eq. 2.58
N	differential number density	Eq. 2.56	Not needed
σ	total differential entropy density	Eq. 2.17	$(T_{edge})_e$ p. 59
σ_e	differential electron entropy density	Eq. 2.18	$(T_{edge})_i$ p. 59

2.2 Numerical Methods

2.2.1 Two-Dimensional Variables

In the TSC model, finite difference methods are used to solve the two-dimensional partial differential equations discussed in section (2.1). The variables are defined at staggered locations on a uniform Cartesian grid inside a rectangular domain. The variables Ψ, A, and $\Delta^* A$ are defined to lie on grid line intersections, while the variables g, ω, Ω and $\nabla^2\Omega$ lie on cell centers. This staggering leads to a scheme consistent with the imposition of accurate boundary conditions and minimizes the number of coupled grid points. The method of artificially enhancing the plasma mass (discussed in section (2.1.1)) greatly reduces the frequencies of the Alfvèn wave oscillations. Unfortunately, there remain disparate time scales in the equations due to the differences in the propagation speeds of the compressible and transverse Alfvèn waves and due to the differences between the resistivity in the hot plasma and in the cold vacuum region. The TSC model uses the technique of subcycling to account for this time scale disparity. The diffusive and fast wave terms are evaluated N times (typically N=10-80) during each time step used by the rest of the problem. The subcycling method is implemented by introducing a variable U for the divergence of the velocity, $U = \nabla^2\Omega$. The forms of the Eqs. (2.6),(2.10),(2.11) appropriate to apply subcycling are

$$\frac{\partial U}{\partial t} + \frac{g_o}{\mu_o}\nabla \cdot \frac{1}{x^2}\nabla g + Q = \nabla \cdot \nu_2 \nabla U, \tag{2.75}$$

$$\frac{\partial \Psi}{\partial t} + S = \frac{\eta_\parallel}{\mu_o}\Delta^*\Psi, \tag{2.76}$$

$$\frac{\partial g}{\partial t} + \frac{g_o U}{\rho_o} + T = \frac{x^2}{\mu_o}\nabla \cdot \frac{\eta_\parallel}{x^2}\nabla g, \tag{2.77}$$

where g_o/x is the toroidal field strength outside the plasma (as in Eq. (2.58)). The slowly varying variables Q, S and T are defined as

$$Q = \nabla \cdot \left(\frac{\Delta^*\Psi}{\mu_o x^2}\nabla\Psi + \frac{g - g_o}{\mu x^2}\nabla g + \nabla p \right), \tag{2.78}$$

$$S = \rho_o^{-1}\left(\nabla\phi \times \nabla A \cdot \nabla\Psi + \nabla\Omega \cdot \nabla\Psi\right), \tag{2.79}$$

$$T = x^2\nabla\cdot\left(\frac{g}{\rho_o x^2}\nabla\phi \times \nabla A + \frac{g - g_o}{\rho_o x^2}\nabla\Omega - \frac{\omega}{\rho_o x^2}\nabla\phi \times \nabla\Psi \right) + g_o x^2 \nabla\Omega \cdot \nabla \frac{1}{\rho_o x^2}. \tag{2.80}$$

For each major time-step Δt, the variables U, Ψ, and g are updated N times using Eqs. (2.75)-(2.77) with a time step $\delta t = \Delta t/\mathrm{N}$. The variables Q, S and T are evaluated from Eqs. (2.78)-(2.80) while $\Delta^* A$ and ω are updated from Eqs. (2.7) and (2.8). The surface averaged equations for N', σ, and σ_e are advanced and the elliptic equations for A and Ω are inverted. The finite difference method utilizes an explicit time advancement scheme in which the wave and convection terms are differenced by using the leapfrog method and the diffusive terms by using a mix of a forward-time centered-space method and the method of Dufort and Frankel. Details of this method and resulting stability restrictions on the time steps are discussed in reference [9].

2.2.2 Surface-Averaged Variables

The one-dimensional surface-averaged Eqs. (2.16), (2.17) ,(2.18) and (2.31) for N', σ, σ_e, and ι are integrated in time simultaneously with the two-dimensional equations as described in Section 3 of reference [6]. The transport quantities Γ, Q_e, Q_i, and V_L are allowed to be linear combinations of any functions multiplying the gradients of n, p, p_e, or q^{-1}. The quantities N', σ, σ_e and ι are adiabatic variables so that if $\Gamma = Q_e = Q_i = V_L = 0$

and if all sources vanish $S_N = S_e = S_i = 0$ and $Q_{\Delta e} = 0$ these variables are exactly conserved. The finite difference method used in the TSC model preserves this property.

Using the definitions in Eqs. (2.19), (2.22) and (2.35), the surface averaged quantities $\partial V/\partial\Phi$, K and α are evaluated every few time steps by performing integrals on Ψ=constant surfaces. The contour integrals are evaluated at N_c points equally spaced in toroidal flux, $\Delta\Phi = 2\pi q\Delta\Psi$. The number of points N_c is allowed to change during the simulation to accommodate a growing or shrinking plasma region $0 < \Phi < \Phi_p$, with the increments $\Delta\Phi$ remaining fixed.

The surface averaged variables N', σ, σ_e and ι are defined at cell centers to allow accurate treatment of the boundary and the magnetic axis. An implicit Crank-Nicolson finite difference scheme is used to advance the variables forward in time. Details are discussed in reference [9].

As the simulation proceeds, the transform $\iota(\Phi)$ obtained from integrating Eq. (2.31) will differ with that obtained from integrating Eqs. (2.10) and (2.11). The difference is due to the differences in the finite-grid truncation error. To avoid accumulating error, the toroidal field function g is corrected from its calculated value as follows

$$\tilde{g}_{i,j}^{n+1} = g_{i,j}^{n+1} + \frac{\Delta t}{\tau}\left(\frac{2\pi}{\alpha_{i,j}\iota_{i,j}^{n+1}} - g_{i,j}^{n+1}\right), \tag{2.81}$$

where τ is a relaxation time (typically $\tau = 10\Delta t$).

Chapter 3

TSC Usage

3.1 Preliminaries

The system dependent details of this section apply to the NERSC system running UNICOS operating system. The code runs on the Cray-2 and C-90 machines at NERSC. The TSC code is written in FORTRAN and consist of four main files :

unx9.06m.f	: The main program and some subroutines.
unxsubs.f	: Large block of subroutines.
unxmiss.f	: Used to determine if any subroutines are missing.
subs.f	: Additional subroutines.

In addition, there are a number of include files used for setting parameters and specifying common blocks. The most important of these for the end user is **param.i** which is used to set the array sizes for the computational grid, poloidal field coils, etc. The default settings for these parameters are quite large. Setting these parameters closer to the actual values of the model in question will result in a smaller executable file.

The source code is located in the public directory /u/p11/u431/tsc. The code can be compiled using the makefile *maketsy* located in the this public directory. The user should simply copy the makefile to the desired directory on the users account and then run the makefile by typing *make -f maketsy gotsy* from the unix prompt. This will return an executable file named *gotsy*. If modification of the source code is necessary (to change array size or add auxiliary file for Hofmann control, etc.), one must copy all of the source files in the directory /u/p11/u431/tsc to a directory on the users account and then make the desired changes in the source code. The makefile *maketsy* must then be modified to refer to this new directory. The following input files are required:

inputa : The main input file decribed in the following section.
sprsina: A restart file needed if IRST1=1 (rename output file **sprsoua**)
enina : Special experimental data file (needed only for IDATA $\neq$ 0)
eqflina : Equilibrium file (needed only for IRST1=2)
wirera : Needed when IRST=1 and IWAYNE=1 (rename output file **wirefa**)

The code produces the following output files:

eqfloua : equilibrium file
outputa: main output file
tsc.cgm: graphics output (in cgm format)
sprsoua: restart file produced if IRST2=1
0167AA: special data file produced if IDATA=1
eqfloua : equilibrium file
eqdska : pest mapping file produced if IPEST=1
jaypha : disruption plasma current history produced if IWAYNE=1
wirefa : disruption wire file produced if IWAYNE=1
divhisa : divertor history file produced when type 32 cards are used
lhcdoua: lower hybrid heating data file produced if ILHCD>0

The code can be run directly from the unix prompt by typing the name of the executable file. The preferred method of submitting large jobs is through the use of a batch file and the *qsub* command. A simple batch file for running a TSC model is shown below. Information about the history of the run and the amount of computer time used is output to the file *1001a*.

```
#Batch script to run TSC
#QSUB -s /bin/csh
#QSUB -eo
#QSUB -o 1001a
#QSUB -lT 9:00
#QSUB -lM 5.5Mw
cd ** put working directory here **
set echo
```

```
set timestamp
ja ja.out
tsc
ja -cst ja.out
#End of batch script
```

3.2 Units and Scaling

All TSC input and output quantities are in MKS units unless otherwise specified. MKS is referred to as "standard" units or "s". The standard unit for temperature is the electron volt. Internal to the code, another system of dimensionless units (referred to by "d") are used. A scaling and units transformation is necessary to get physically meaningfull results and at the same time increase the ion mass by the factor FFAC^2 to compensate for the disparate time scales between Alfvèn wave and transport phenomena. A number of scaling factors are defined each time step (Δt in section 2.2.1) to aid in the scaling of the variables. These scaling factors and their mneumonics are defined as follows:

Quanity	From Internal to MKS	From MKS to Internal
time	UDST	USDT
resistivity	UDSR	USDR
pressure	UDSP	USDP
density	UDSD	USDD
heat	UDSH	USDH
current	UDSI	USDI
voltage	UDSV	USDV

These can be remembered as UDST "Units from Dimensionless to Standard Time", etc. Note that UDST = 1/USDT. The lengths, magnetic field strengths and magnetic fluxes are not scaled internally. The standard unit of temperature T_e(eV) from the internal dimensionless pressure p_e and number density n_e is

$$T_e = (\mathrm{UDSH} * p_e)/(\mathrm{UDSD} * n_e). \tag{3.1}$$

A quantity with dimensions of power is scaled from standard (watts) to internal units by

$$\mathrm{Power(internal)} = \mathrm{Power(watts)} * \mathrm{USDH/USDT}, \tag{3.2}$$

and vice versa.

3.3 Description of Input

The main input file for TSC is **inputa**. It contains nearly all the information needed to describe a job. The input file must be a plain text file. The first line of the input file is reserved for a title, while all other lines have the same input format (I2,8X,10E10). The first two columns specify the card type and the other input fields specify options for the card. The character "c" in the first column causes the entire line to be ignored, to allow comments in the input file. All numbers, except for the card type, must contain a decimal point. After the title, the next line in the file must be the type 00 card. The rest of the cards can be entered in any order but the last card must be a type 99. This card is simply a flag marking the end of the input file. The input file contains a large number of cryptic variables which can be confusing to remember. An alphabetical listing of all input variables and associated card types along with a brief description of each is included in Appendix A. This appendix also includes a complete format listing of the input file. A complete description of every input card is presented in section (3.3.6). The following sections presents the basic information needed to describe a model in terms of descriptive categories.

3.3.1 Program Control

There are a large number of switches and control parameters spread throughout the input file. Careful reading of section (3.3.6) is needed to be fully aware of all options currently available in the TSC model. The main control variables are listed in card 00. They determine how to start a run, how often to generate output, the type of graphical output, and what output files to create . The time point at which the simulation starts is determined by the type 14 card. The time at which the run is stopped is determined by either the last cycle specified on card 00 or by the stopping time specified on card 11 ACOEF(29). The option to suppress regular energy and density transport modeling is on card 02 while the option for selecting a transport model is on card 04. Additional contour and vector plots are requested using type 22 and type 23 cards, while default plots are suppressed using type 40 cards.

3.3.2 Geometry

The physical layout of a TSC model is specified by the following geometric information:

Computational Domain - All information regarding the computational grid is provided on a type 01 card. This information must include the radial extent of the inside and outside computational boundaries as well as the height of the computational domain. In addition, the number of zones in each coordinate direction must be specified. The TSC model has the option of specifying symmetry about the midplane by setting the variable ISYM=1 on card 01. When this option is selected, the computational grid only covers the upper half plane and symmetry conditions are used at the midplane.

External Coils - The poloidal field coils and conductors which are external to the computational domain are specified using the cards 09 and 39. Information regarding the coil location, resistance, inductance and group number is specified on type 09 cards. Coils belonging to the same coil group are connected in series for feedback and control purposes. The resistance and inductance given on type 09 cards is overwritten if a type 39 card is included. This card provides information on the radial and vertical thickness of the coil as well as the physical makeup of the coil in terms of copper and stainless steel. Each coil requires a type 09 card. A type 39 card is optional for each coil.

Internal Coils - The poloidal field coils and conductors which are internal to the computational domain are specified using the type 10 cards. Information concerning the location, resistance, number of turns, and group number must be provided.

Limiter - The limiter is defined on type 05 cards by specifying the coordinates of a set of points. Up to 3 points can be defined on each card. When the symmetry option is specified on the type 01 card, only limiter points in the upper half plane need to be defined (points with $z<0$ will be ignored).

Divertor - The geometry of the divertor is defined using type 32 cards. Up to 3 points can be defined on each card. This card can also be used to define the geometry of the first wall (if interested in the heat flux on first wall).

3.3.3 Control System

As discussed in section (2.1.4), there are two control methods in the TSC model. In the original control scheme, the currents in the poloidal field coils are the sum of a preprogrammed current and a feedback current. The preprogrammed currents are specified on type 15 cards for each coil group. The coordinates of the observation pairs used in the feedback scheme (see Eq. (2.71)) are specified using type 08 cards. Information linking coil groups to feedback systems and observation points is provided on type 19 cards. In addition, the proportional and integral gains and the flux offset are specified on type 19 cards. The derivative feedback gain is specified on type 20 cards along with the time when the feedback system is turned on and off and information on which flux to use from the observation coils. To insure stability in the feedback model, the proportional, differential and integral gains must be set appropriately. This is accomplished as follows:

1. Make an initial guess for the dimensional feedback gains in the input file and then run TSC with NCYCLE=-1 on card 01. This will perform a check on the input file without running the model.

2. Using a text editor examine the output file **outputa** (search for the string "gain"). This file contains a section of information on the dimensionless gains (calculated from the dimensional gains in 1) as a function of time for each feedback system. To insure stability of the feedback system, the dimensionless gains corresponding to the proportional feedback coefficient FBFAC must be of order -1 for the entire range of times. Normally, for a vertical feedback system, the dimensionless gains corresponding to FBFAC should be between -1 and -2. For a radial feedback system, they should be between -2 and -10. The integral and derivative feedback gains corresponding to FBFACI and FBFACD have units of $(\text{sec})^{-1}$ and (sec) respectively. Normally, if these are used, and if multiplied or divided by the natural L/R time of the conducting structure in the problem, a negative number with magnitude less than -1 should result.

3. If the gains listed in **outputa** are not of order -1, rescale the gains in the input file in a linear fashion. For example, if the dimensionless gain in the **outputa** file is 20, the gain guessed in step 1 must be multiplied by -0.05.

4. Run TSC with NCYCLE=-1 and recheck the file **outputa** to make sure that the dimensionless gains are all of order -1.

The second level of feedback on the voltage (see Eq. (2.72) and (2.73)) is specified using the ACOEF array on card 11. This is optional for external coils but is required for internal coils. The required information in the array is between ACOEF(130) and ACOEF(300). The index numbers of the input is dependent on the number of coils used as described on pages 53-54 under card 11.

With the Hofmann control scheme, discussed in section (2.1.4), the input cards 8, 19 and 20 are not used. Instead, the control model is defined using the ACOEF array on card 11 and with an auxiliary data file created by the user. This file must take the form of a subroutine and is called by the subroutine **tcv1** located in the file **unxsubs.f**. The new subroutine contains input variables describing the number and location of flux loops and magnetic field probes as shown below:

nshac	Number of coil groups used for feedback control of plasma shape.
nshap	Number of coil groups whose current is taken into account in computation of flux errors. Normally nshap=nshac
nvvel	Passive plates and vacuum vessel are represented by nvvel elements
nluup	Number of flux loops
xf(n) , zf(n)	Coordinates of flux loop positions
nprob	Number of magnetic field probes
xb(n), zb(n)	Coordinates of probe positions. Probes must be numbered consecutively
isvf(k)	For k≤nshap, index of first coil in k-th coil group For k>nshap, index of first wire in k-th passive element
isvl(k)	For k≤nshap, index of last coil in k-th coil group For k>nshap, index of last wire in k-th passive element
dddd(k)	Resistance of k-th coil group, scaled such that the maximum value of dddd array is of order unity

The code must be recompiled when this file is added or changed. An additional line must be added to the subroutine **tcv1** to call on the auxiliary subroutine containing the data. This line should have the same form as the other call statements at the very beginning of the subroutine (see the first few lines of **tcv1**. The choice of which auxiliary file to read is specified using ACOEF(317) on card 11. Several auxiliary data files are already included in the code (for example BPX, SSAT). A new auxiliary file should be patterned after one of these. The rest of the information needed for the Hofmann control model is specified with ACOEF(300)-(560), ACOEF(2000)-ACOEF(3000) (see card 11 description in section 3.3.6 for details)

3.3.4 Initial Equilibrium

The initial plasma equilibrium is calculated by assigning values to the initial plasma and coil currents, the initial toroidal field, the initial safety factor, and the initial pressure. The initial plasma current is taken from the first time point specified on the type 16 cards. The initial coil currents are specified using the first time point in type 15 cards, The initial toroidal field is specified by the first time point of the type 27 cards supplemented by a choice of functional form on card 13. The safety factor on the magnetic axis is also specified by the type 13 card. The initial pressure is specified using the first time point of the type 17 card and choosing a functional form on the type 02 card. The exponent in the functional form of the pressure is specified on card 13. A guess for the initial location of the magnetic axis is given on card 13.

3.3.5 Plasma Evolution

Using the original TSC control scheme, the programming of the plasma and coil current along with the density and heating power are allowed. The plasma shape is not preprogrammed but is calculated during the simulation. With the Hofmann control scheme discussed in section (2.1.4), independent programming of the plasma current, density, heating power, shape and position are allowed. The coil currents are not preprogrammed but are calculated during the simulation. Specifying the above time varying quantities is accomplished by giving the desired value of each quantity at a number of time points. Intermediate values found using linear or cubic interpolation (see ICUBE switch). The time points used in this scheme are specified using type 18 cards. The respective preprogrammed quantities for each time point are specified as follows :

Coil current - The preprogrammed coil currents are only needed for the original TSC control model. The Hofmann control scheme only uses the values from the first time point to calculate an initial equilibrium. The coil currents are specified on type 15 cards.

Density - If the density transport model is turned off (IDENS=1), the normalized central density for each time point is specified on type 24 cards.

In addition, the density exponents in the specified density function Eq. (3.5) are specified as functions of time on cards 47 and 48.

Heating Power - The amplitude of a neutral beam source (MW) for each time point is specified on type 23 cards. The deposition profile is given by type 25 cards. Fusion heating from D-T reactions is specified using IALPHA=1 on card 12. Lower hybrid RF heating is specified using cards 38,46,51-58.

Plasma Current - The programmed plasma current (kA) for each time point is specified on type 16 cards.

Plasma Shape and Position - The shape and position of the plasma as a function of time is determined by the trajectory of a preselected number of boundary points in the control algorithm (see section (2.1.4)). These boundary points are determined by one of two methods. If the switch ACOEF(309)=0, the boundary points are specified explicitly in the ACOEF array at a number of time points. If the switch ACOEF(309)=1, the boundary points are generated analytically from the major radius R_o, minor radius a, ellipticity κ and triangularity δ as follows

$$x = R_o + a\cos(\theta + \delta\sin(\theta)), \tag{3.3}$$

$$z = a\kappa\sin(\theta). \tag{3.4}$$

The major radius, minor radius, ellipticity and triangularity for each time point are specified using cards 42, 43, 44 and 45 respectively. The Eqs. (3.3) and (3.4) define a plasma shape which is inherently symmetric about the midplane. Therefore, this option for specifying the shape is useless for an asymmetric plasma (ISYM=0 on card 01).

Toroidal Field - The toroidal magnetic field produced by the toroidal field coils for each time point is specified using type 27 cards. The variable GZERO in the functional forms discussed under card 13 is specified at each time point.

3.3.6 Detailed Description of Input Cards

Card 00 - Control

11	21	31	41	51	61	71
IRST1	IRST2	IPEST	NCYCLE	NSKIPR	NSKIPL	IMOVIE

IRST1	= 0.0	Start run beginning at time t=TPRO(ISTART)
	= 1.0	Restart run which reads the file SPRSINA. A restart job normally requires only 3 input cards: title, type 00, and type 99. Cards which specify the evolution of parameters in time can also be included in a restart job. However, only the fields corresponding to future time points should be changed.
	= 2.0	Start run which reads initial equilibrium from the file EQFLINA
IRST2	= 0.0	Don't write a restart file
	= 1.0	Do write a restart file. Restart files are updated every NSKIPL cycles and at the times specified on the type 29 card and at the end of the run.
IPEST	= 0.0	Don't write PEST file
	= 1.0	Do write PEST file EQDSKA at times specified on type 29 cards and at the end of the run. This file can then be read by J-SOLVER code with IFUNC2=4.
NCYCLE		Last cycle to be computed. If NCYCLE=0, only the initial equilibrium is computed. Use NCYCLE=-1 to check dimensionless gain for original TSC control model as described in section (3.3.3).
NSKIPR		Number of cycles between print cycles and between times when profile information is plotted
NSKIPL		Number of cycles between plot cycles. Restart files are also written every NSKIPL cycles.
IMOVIE	= 0.0	Regular graphics
	= 1.0	b/w movie with plasma currents plotted
	= 3.0	Color movie with plasma currents plotted
	= 6.0	Color movie of poloidal flux contours and plasma current with fixed flux increments. For this option, the data statement in the subroutine CPLOT must be changed: PSISMAL-(minimum value) PSINCR-(increment) YMAX & YMIN at end of CPLOT (now PCUR(12))

= 7.0	Color movie of heat flux distribution on the divertor plate
= 8.0	Special disruption plots

Note : All jobs write a equilibrium file EQFLOUA upon termination. A start job with IRST1=2 can have ISYM=0 (type 01 card) even if the job which created the equilibrium file had ISYM=1, as long as the zone *size* (dimension of grid spacing) is the same.

Card 01 - Dimensions

11	21	31	41	51	61	71
NX	NZ	ALX	ALZ	ISYM	CCON	IDATA

NX		Number of zone vertices in the x direction,(NX-1) zones. Must have NX$\leq$ PNX-2 (see param.i) (46)
NZ		Number of zone vertices in the z direction,(NZ-1) zones. This should be an odd number if ISYM = 0. Must have NZ$\leq$ PNZ-2 (see param.i) (16)
ALX		Major radius of outside computational grid boundary in meters (3.0)
ALZ		One half the height of the computational grid boundary in meters (1.0)
ISYM	= 0.0	No symmetry about the midplane
	= 1.0	Symmetry about the midplane
CCON		Major radius of inside computational grid boundary (meters)
IDATA	= 0.0	Regular run
	= 1.0	Reads from PBX data tape file ENINA
	= 2.0	Reads from TFTR data tape file ENINA
	= 3.0	Reads from D-III-D data tape file ENINA
	= 4.0	Reads from PBX-M data tape file ENINA
	= 5.0	Reads from PBX-M data tape file ENINA (New format)
	= 6.0	FEDTSC
	= 7.0	TCV - Hofmann control algorithm
	= 8.0	ASDEX-U

Note : A problem with ISYM=0 and NZ=NZ0 will have the same zone size as a problem with ISYM=1 and NZ=(NZ0-1)/2 +1.

Card 02 - Time step and switches

11	21	31	41	51	61	71
DTMINS	DTMAXS	DTFAC	LRSWTCH	IDENS	IPRES	IFUNC

DTMINS		Minimum time step allowed (μsec). Initial time step is 2*DTMINS (0.001)
DTMAXS		Maximum time step allowed (μsec) (1.0)
DTFAC		Time step safety factor. The time step used is the maximum value that is theoretically stable multiplied by DTFAC with the additional constraint that δt increase by at most 20% every 10 cycles and be less than DTMAXS (0.5)
LRSWTCH	= 0.0	Normal run
	= N.0	Special test run for coils without plasma where coil currents in group N are initialized to :

CCOILS(N)=SGN[ZCOIL(N)]*ACOEF(12)/RSWIRES(N)

To use this option TEVV must be positive, turn off all feedback and set IRST=0.0

IDENS	= 0.0	Regular calculation of density transport Particle diffusion and pinch coefficients are input via acoef(851) and (852). Particle source terms provided by Neutral Beams [cards 25 and 23] and the boundary conditions are provided by acoef(881) and the type 24 cards.
	= 1.0	Forces the density to have profile given by

$$R(\Psi, t) = \text{UDSD} * \text{RNORM(t)}* \left[1 - \left(\frac{\Psi - \Psi_{min}}{\Psi_{lim} - \Psi_{min}}\right)^{\text{BETAR}}\right]^{\text{ALPHAR}} \tag{3.5}$$

where ALPHAR and BETAR are input on type 04 or type 47,48 cards. The above density profile is the same as Eq. (2.56) in section 2.1.1

IPRES	= 0.0	Regular calculation of energy transport
	= 1.0	Forces the pressure to equal one of the following analytical forms :

For IFUNC=1,3,4,5 :

$$P(\Psi,t) = P0(t)\left[\frac{\Psi_{lim}-\Psi}{\Psi_{lim}-\Psi_{min}}\right]^{\text{ALPHAP}} \tag{3.6}$$

$$+ \quad \text{ACOEF}(110) * \left(\frac{\text{ALPHAP}}{\text{ALPHAP}+1}\right) * \left[\frac{\Psi_{lim}-\Psi}{\Psi_{lim}-\Psi_{min}}\right]^{\text{ALPHA+1}} \tag{3.7}$$

For IFUNC=2

$$\frac{dP}{d\Psi} = P0\left[\frac{e^{-(\text{ALPHAP})\hat{\Psi}} - e^{-(\text{ALPHAP})}}{e^{-(\text{ALPHAP})}-1}\right]. \tag{3.8}$$

where $\hat{\Psi} = (\Psi - \Psi_{min})/(\Psi_{lim} - \Psi_{min})$ and ALPHAP is input on type 13 card. P0(t) is determined by card type 17. The ratio of electron to ion pressure is given by ACOEF(2). Pressure equilibration time is given by EQRATE,ACOEF(4).

IFUNC — Switch to choose the functional forms to use for pressure and toroidal field functions as described above and on type 13 card.

= 1.0	tokamak profiles (Princeton)
= 2.0	tokamak profiles (ORNL)
= 3.0	RFP profiles (LANL)
= 4.0	spheromak profiles (Princeton)
= 5.0	"ohmic" profiles stationary on resistive time scale
= 6.0	Calls special subroutine **splinfit**

Card 03 - Numerical

11	21	31	41	51	61	71
XLIM	ZLIM	XLIM2	FFAC	NDIV	ICIRC	ISVD

XLIM		An internal boundary is defined inside the computational grid so that the plasma can only occupy the rectangular region defined by : XLIM $<$ X $<$ XLIM2 ,and $\mid$ Z $\mid<$ ZLIM. The region outside this is always treated as vacuum. (i.e. , no plasma can exist there)
ZLIM		See XLIM
XLIM2		See XLIM
FFAC		Factor by which Alfvén waves are artificially slowed down. Ion mass is increased by FFAC^2. The time steps for the fast wave and the Alfvén wave are proportional to this. If negative, uses the absolute value to initialize and adjusts FFAC according to ACOEF (801)-(805) to keep AMACH constant. (1.0)
NDIV		Number of sub-cycles in diffusion part of poloidal flux equation and in the fast wave equation. The time step for fast wave and resistive diffusion are inversely proportional to this, as discussed in section (2.2.2) (1.0)
ICIRC	= 0.0	Don't solve circuit equations for the external coils
	= 1.0	Do solve circuit equations for the external coils
ISVD	= 0.0	Don't perform SVD analysis to obtain x-point
	= 1.0	Do perform SVD analysis to obtain x-point

Card 04 - Surface Averaging

11	21	31	41	51	61	71
ISURF	NPSI	NSKIPSF	TFMULT	ALPHAR	BETAR	ITRMOD

ISURF	= 0.0	No surface averaging (default)
	= 1.0	Use surface averaged transport equations
NPSI		Number of PSI surfaces (Φ surfaces) for one-dimensional transport calculation (always must be NPSIT < NPSI)
NSKIPSF		Number of cycles skipped between each surface average calculation (20.)
TFMULT		Multiplier defining the toroidal flux domain used in surface average calculation. The initial NPSIT will be NPSI/TFMULT. NPSIT will increase as the plasma grows, but if NPSIT ever exceeds NPSI the program will terminate.
ALPHAR		Exponent for the prescribed density function (see type 02 card) Will be overwritten if type 47 card is included. (0.5)
BETAR		Exponent for the prescribed density function (see type 02 card). Will be overwritten if type 48 card is included. (2.0)
ITRMOD		Switch selecting transport model
	= 1.0	The neo-ALCATOR model, where

χ_e = ACOEF(35) $\times 10.^{19}/n_e$ (mks)
χ_i = ACOEF(37) $\times 10.^{19}/n_e$ (mks)
d = ACOEF(39)

If ACOEF(107) is greater than zero, these coefficients are enhanced according to the Kaye-Goldston formula

$$\mathrm{ACOEF(35)} = \sqrt{\mathrm{ACOEF(35)}^2 + \mathrm{CHIAUXS}}$$

where

$$\mathrm{CHIAUXS} = [(\mathrm{ACOEF(107)*NE(0)*300.})/\mathrm{I_p}]^2\mathrm{*PTOT}$$

where $\mathrm{I_p}$ is the plasma current in amps and PTOT is the total power in watts.

= 2.0 Coppi/Tang transport model

Need to input the following on type 11 cards :

ACOEF(121) - 0.05	Auxiliary heated transport coefficient (see Eq. 2.53)
ACOEF(122) - 1.0	Ohmic heated transport coefficient (see Eq. 2.52)
ACOEF(123) - 0.5	Constant in form factor
ACOEF(126) - 2.0	Ratio of χ_i to χ_e (see Eq. 2.48)

Card 05 - Limiter Points

11	21	31	41	51	61	71
I	XLIMA(I)	ZLIMA(I)	XLIMA(I+1)	ZLIMA(I+1)	XLIMA(I+2)	ZLIMA(I+2)

XLIMA(I)	The x coordinate of limiter I. If XLIMA(I)=0 for any I, that field and the rest of the cards are ignored.
ZLIMA(I)	The z coordinate of limiter I.

Up to 3 limiter points can be defined on each type 5 card. The minimum value of the poloidal flux amongst all limiter points, PSILIM, defines the plasma boundary PSI=PSILIM

Note : If ISYM=1 and ZLIMA(I)<0 for some I, this limiter point will be automatically discarded and the remaining points will be renumbered to be consecutive.

Card 06 - Divertor

11	21	31	41	51	61	71
IDIV	PSIRAT	X1SEP	X2SEP	Z1SEP	Z2SEP	NSEPMAX

IDIV	= 0.0	Code does not check for magnetic divertor
	= 1.0	Code will attempt to locate magnetic separatrix and use this as the limiter if the value of PSI at the separatrix is less than PSILIM from the limiter points.
PSIRAT		Actual value of PSI used to limit plasma from separatrix is PSILIM = PSIRAT*(PSISEP-PSIMIN)+PSIMIN where PSISEP is the actual poloidal flux at the separatrix and PSIMIN is the flux at the magnetic axis. The normal value is PSIRAT = 0.999.
X1SEP		The separatrix is only searched for in the region : X1SEP<X2SEP
X2SEP		See X1SEP
Z1SEP		The separatrix is only searched for in the region : Z1SEP< Z2SEP
Z2SEP		See Z1SEP
NSEPMAX		The maximum number of separatrices that will be searched for. (2.)

Card 07 - Impurities

11	21	31	41	51	61	71
IIMP	ILTE	IMPBND	IMPPRL	AMGAS	ZGAS	NTHE

IIMP	= 0.0	No impurity line radiation (but Eq. (2.57) is still used)
	= 1.0	Impurity constant fraction of background density
	= 2.0	Impurity transport
ILTE	= 0.0	Local thermodynamic equilibrium assumed
	= 1.0	Local thermodyanmic equilibrium not assumed
IMPBND	= 0.0	non-flow boundary condition for impurities
	= 1.0	pedistal boundary condition for impurities
IMPPEL	= 0.0	impurity pellet is deuterium
	= 1.0	impurity pellet is oxygen(not available)
	= 2.0	impurity pellet is carbon(not available)
	= 3.0	impurity pellet is iron(not available)
	= 4.0	impurity pellet is beryllium(not available)
	= 5.0	impurity pellet is neon
	= 6.0	impurity pellet is krypton
AMGAS		Mass of primary ion species in amu (1.0 for hydrogen, 2.0 for deuterium, etc) (1.0)
ZGAS		Charge of primary ion species (1.0 for hydrogen, 2.0 for helium, etc) (1.0)
NTHE		Number of theta zones used in contouring plasma for parallel impurity diffusion, and also in ballooning mode calculation (100.)

Note : For IIMP>0, at least one of the fractions FRACOX or FRACCA must be greater than zero. For IIMP=2, these values are used to initialize the impurity transport calculation.

Card 08 - Observation Pairs

11	21	31	41	51	61	71
J	XOBS(2J-1)	ZOBS(2J-1)	XOBS(2J)	ZOBS(2J)	NPLOTOBS	

J		Number of observation pairs where poloidal flux difference is to be recorded (and plotted optionally), and possibly used for feedback control (type 19 cards)
XOBS(2J-1)		x coordinate of first point in pair
ZOBS(2J-1)		z coordinate of first point in pair
XOBS(2J)		x coordinate of second point in pair
ZOBS(2J)		z coordinate of second point in pair
NPLOTOBS	= 0.0	Don't plot time histories
	= 1.0	Do plot time history of fluxes and flux difference at observation pair

Note : If ISYM=1 and ZOBS(J)<0 for some J, this observation point will be automatically discarded and the remaining observation points will be renumbered to be consecutive. The values of NFEEDO on the type 19 cards will automatically be changed also to reflect this renumbering.

Card 09 - External Coils

11	21	31	41	51	61	71
N	XCOIL(N)	ZCOIL(N)	IGROUPC(N)	ATURNSC(N)	RSCOILS(N)	AINDC(N)

Each type 09 card defines the properties of a single coil *external* to the computational grid.

N	External coil number (this must be a unique identifying number between 1 and PNCOIL)
XCOIL(N)	The x coordinate of the center of the external coil. (Must be outside the computational grid)
ZCOIL(N)	The z coordinate of the center of the external coil. (Must lie outside the computational grid)
IGROUPC(N)	Group number of coil N. Refers to type 15 card with the same group number.
ATURNSC(N)	Number of turns for coil N. This is a positive or negative number, not necessarily an integer. The preprogrammed current for coil N will be the product of ATURNSC(N) and the current in IGROUPC(N) as specified by the appropriate type 15 card
RSCOILS(N)	Resistance of coil N (ohms). For multiturn coils, this is the one-turn equivalent resistance.
AINDC(N)	Self inductance of coil N, assuming a single turn. If a type 39 card is included, this will be overwritten with an inductance calculated from the geometry.

Note 1 : If ISYM=1 AND ZCOIL(N)<0 for some N, this coil will be automatically discarded and the remaining coils will be renumbered to be consecutive.

Note 2 : An external coil can belong to more than one coil group for the feedback systems. To specify the second group, follow the type 09 card with another type 09 card of the form:

09 10NN. ATURN(N,1) ATURN(N,2)...ATURN(N,6)

This will cause coil N to also belong to coil group NN with variable number of turns ATURN(N,I) at time TPRO(I) as specified by the type 18 card. Up to four additional systems can be specified by using 10NN., 20NN.,30NN.,40NN., in the first field.

Card 10 - Internal Coils

11	21	31	41	51	61	71
M	XWIRE(M)	ZWIRE(M)	IGROUPW(M)	ATURNSW(M)	RSWIRES(M)	CWICS(M)

Each type 10 card defines the properties of a single coil *internal* to the computational grid, denoted a *wire*.

M	Wire number (this must be a unique identifying number between 1 and PNCOIL)
XWIRE(M)	The x coordinate of the center of the wire. (coordinate must lie inside the grid)
ZWIRE(M)	The z coordinate of the center of the wire. (coordinate must lie inside the grid)
IGROUPW(M)	The absolute value |IGROUPW(M)| is the group number. Refers to type 15 card with the same group number. If IGROUPW(M)<0, this is a switch indicating that the wire is to occupy four adjacent cells (rather than 1) and to have the relative number of turns in the four cell area weighted so that the current centroid will be at [XWIRE(M),ZWIRE(M)].
ATURNSW(M)	The number of turns for wire M. This is a positive or negative number, not necessarily an integer. The pre-programmed current for wire M will be the product of ATURNSW(M) and the current in IGROUPW(M) as specified by the appropriate type 15 card.
RSWIRES(M)	The resistance of wire M (ohms). If negative, resistance is major radius XWIRE(M) times the absolute value of RSWIRES(M). For a multiturn coil, this is a one turn equivalent resistance.
CWICS(M)	Initial induced current in wire M. (kA)

Note 1 : If ISYM=1 AND ZWIRE(M)<0 for some M, this wire will be automatically discarded and the remaining wires will be renumbered to be consecutive.

Note 2 : An internal coil can belong to more than one coil group for feedback systems. To specify the second group, follow the type 10 card with another type 10 card of the form:

10 10NN. ATURN(M,1) (M,2) (M,3) (M,4) (M,5) ATURN(M,6)

This will cause coil M to also belong to coil group NN with variable number of turns ATURN(M,I) at time TPRO(I) as specified by type 18 card. Up to four additional systems can be specified by using 10NN.,20NN.,30NN.,40NN., in the first field.

Note 3 : If IGROUPW(M)$<$0, three new coils will be generated and the parameter PNCOIL must be large enough to accommodate these.

Note 4 : Resistivity of copper : $1.724\times10^{-8}\Omega \cdot \mathrm{m}$
Resistivity of Aluminum : $2.824\times10^{-8}\Omega \cdot \mathrm{m}$

Card 11 - ACOEF Array

11	21	31	41	51	61	71
ICO	NCO	ACOEF(ICO)	...(ICO+1)	...(ICO+2)	...(ICO+3)	ACOEF(ICO+4)

ICO	First index of ACOEF array specified on this card
NCO	The number of elements on this card. (1≤NCO≤5)
ACOEF(I)	The value of ACOEF(I). The following ACOEF array elements are presently defined (default values in parentheses):
ACOEF(1)	If 1.0,special run for PBX, if 2.0, special run for BPX, if 3.0 special run for ASDEX-U. If 4.0 or 5.0, special for ITER(0.)
ACOEF(2)	Ratio of initial electron to total pressure (0.5)
(3)	Time interval over which feedback systems are turned on. (0.0)
(4)	Relaxation factor for pressure when IPRES=1 (100).
(5)	If 1.0, time history plots start new at restart time. (0.0)
(6)	Parallel diffusion multiplier for ISURF=0, IPRES=0 (10.)
(7)	Mix between Dufort Frankel and FTCS in flux diffusion (0.5)
(8)	Implicit parameter for surface averaged time advancement (1.0)
(9)	Numerical viscosity coefficient (40.)
(10)	Ratio of incompressible to compressible viscosity (0.5)
(11)	Proportionality constant in plasma current feedback (0.5)
(12)	Initial voltage in wires for LRSWTCH>0 (1.0)
(13)	IFLUX switch for poloidal flux boundary condition (see Eq. (2.59). The options are : 0.0 constant, 1.0 first order, 2.0 second order, 3.0 full integral, 4.0 Von-Hagenow's virtual casing method. (default is 4.0)
(14)	Maximum scale for SURFVOLT plot (10.0)
(15)	Minimum OH loop voltage (-100.0)
(16)	Maximum OH loop voltage (100.0)
(17)	ICUBE switch for cubic time point interpolation. IF ICUBE=0.0 linear interpolation is used and for ICUBE=1.0 cubic interpolation is used. (0.0)
(18)	Multiplier in front of PSIDOT on boundary (0.0)
(19)	Not used
(20)	Switch for UCOR (0.0)
(21)	Error criterion for AMACH (1.0)
(22)	Error criterion for EKIN (100.)
(23)	EPSIMIN...convergence criterion on PSI for equilibrium(10^{-7})
(24)	EZCURF...convergence criterion on Z for equilibrium(10^{-6})

(25) DELG...equilibrium parameter used for IFUNC=3 (1.0)
(26) GRPRFP...equilibrium parameter used for IFUNC=3 (1.0)
(27) BETAJ...equilibrium parameter used for IFUNC=3 (1.0)
(28) Bypass initial filament growth rate calculation if nonzero (0.0)
(29) Time in seconds at which calculation stops (1000.)
(30) IWAYNE...switch to write special disruption file and produce voltage plots at flux loops (0.0)
(31) TJPHI...time when to start writing (0.0)
(32) DTJPHI...time increment for writing (0.0)
(33) TMOVIE (0.0)
(34) DTMOVIE (0.0)
(35),(37),(39) Anomalous transport coefficients CHIE,CHII,D (1.0,1.0,0.2)
(40) If 1.0, U not zeroed in vacuum (0.0)
(41) RESGAP...coefficient of resistivity for gap in conductors (0.5). Set to 0.0 for no gap. The effect of the gap is to constrain zero net current in coil groups with IGROUP<0 on type 15 cards. If equal to 0.0 no current is allowed to flow across gap, if nonzero then current can flow across the gap.
(42) Minimum x for profile plots (0.)
(43) Maximum x for profile plots (0.)
(44) IRFP...set to 1.0 for reversed field pinch (0.0)
(45) Number of zones to search over for x-point (2.0)
(46) Maximum for τ_e plot (sec) (2.0)
(47) Maximum power for problem with burn control (used to regulate heating) ($1. \times 10^{12}$)
(48),(49) The number of contours drawn in plasma and vacuum (20.,20.)
(50),(51) Relaxation factors for initial equilibrium calculation (0.5,0.5)
(52) Vacuum vessel poloidal inductance (0.0)
(53) Vacuum vessel poloidal resistance (0.0)
(54) Current feedback coefficient for burn control (0.0)
(55) Reflectivity coefficient for cyclotron radiation (0.9)
(56) HYPER heating multiplier (0.0)
(57) t-begin for HYPER (0.0)
(58) t-end for HYPER ($1. \times 10^{6}$)
(59) EPSHYP...convergence criteria in HYPER ($1. \times 10^{-6}$)
(60) NLOOPM...maximum iterations in HYPER (4000.)
(61) If nonzero, ZMAG time history plotted even for ISYM=1 (0.0)
(62) Ratio of toroidal to compressible viscosity (1.0)
(63) Affects LSAW for ISURF=0 (0.667)
(64) Hyperresistivity coefficient (0.0)

(65) Hyperresistivity fraction (0.1)
(66) Hyperresistivity exponent (4.0)
(67) Hyperresistivity iteration damping-factor (1.2)
(68) Hyperresistivity iteration safety factor (1.0)
(70) Relaxation for resistivity when LRSWTCH≠0 ($1. \times 10^{-4}$)
(71) Maximum temperature for resistivity calculation ($1. \times 10^{6}$)
(72) Bypass writing input on plot file if ACOEF(72)>0 (0.0)
(74) Special limiter adjustment switch (0.0)
(75) Number of cycles coil resistivity is enhanced to let perturbation in(0.0)
(76) Switch for setting FBFAC(I1) to FBFAC(I2) to zero after equilibrium calculation (0.0)
(77) I1 - see ACOEF(76) (0.0)
(78) I2 - see ACOEF(76) (0.0)
(80) Group number of superimposed oscillation (0.0)
(81) Amplitude of oscillation (kA) (0.0)
(82) Period of oscillation (seconds) (0.0)
(83) 2nd group number (0.0)
(84) 2nd amplitude number (0.0)
(85) 3rd group number (0.0)
(86) 3rd amplitude number (0.0)
(87) 4th group number (0.0)
(88) 4th amplitude number (0.0)
(90) Drag terms in equation of motion (0.2)
(91) Drag terms in equation of motion (0.2)
(92) Drag terms in equation of motion (0.2)
(93) Confinement time for He-ash (1.0)
(95) TDISRUPT…time at which disruption occurs and QSAW changes ($1. \times 10^{6}$)
(96) QSAW2…value of QSAW after disruption (2.0)
(97) Fraction of flux in plasma that halo extends beyond - a halo width. (overwritten if type 61 card is included) (0.0)
(98) Temperature of halo in eV (overwritten if type 60 card is included) (1.0)
(101) IDTEST…see note below (0.0)
(102) VTEST…see note below (0.0)

Note : Program will terminate normally if :

IDTEST =	-1	AND	$I_p(a)$	$<$	VTEST
"	1	"	"	$>$	"
"	-2	"	Z_{MA}	$<$	"
"	2	"	"	$>$	"
"	-3	"	$\dot{I}_p(A/S)$	$<$	"
"	3	"	"	$>$	"
"	-4	"	$X_{MA}(m)$	$<$	"
"	4	"	"	$>$	"
"	-5	"	q_{95}	$<$	"
"	5	"	"	$>$	"
"	-6	"	κ	$<$	"
"	6	"	"	$<$	"
"	-7	"	δ	$<$	"
"	7	"	"	$>$	"
"	-8	"	PTOT(MW)	$<$	"
"	8	"	"	$>$	"

(106)	Multiplier of AJLH for lower hybrid (1.0)
(107)	Anomalous auxiliary heating transport coefficient (1.0)
(109)	No trapped particles when ACOEF(109)=1.0 (0.0)
(110)	Coefficient in pressure function (0.0) (see type 02 card)
(111)	Feedback constant for plasma density when IDATA=1 (0.0)
(112)	Feedback constant for ZEFF when IDATA=1 (0.0)
(113)	relative fraction of tritium for alpha heating calculation (0.49)
(114)	Stored energy wanted for feedback on D-T mix(0.0)
(115)	Derivative gain for control of feedback on DT mix(0.0)
(120)	Fraction of ETA (LSAW) to use in sawtooth model. Note: 0 gives maximum flattening, 1 gives no flattening.(0.5)
(121)	Auxiliary heated transport coefficient for ITR=2 (see Eq. 2.53) (0.08)
(122)	Ohmic transport coefficient for ITR=2 (see Eq. 2.52) (0.42)
(123)	Factor added to q_{cylin} for ITR=2 (0.5)
(124)	χ enhancement inside q=1 surface (see Eq. 2.54) (2.0)
(125)	Feedback constant for χ when IDATA=1 (0.0)
(126)	Ratio of χ_i to χ_e (see Eq. 2.48) (2.0) If negative, then ACOEF(126) is χ_i in m^2/sec (spatial constant)
(127)	Feedback coefficient for χ time derivative term (0.0)
(128)	Minimum value for FBCHI (IDATA=1) (0.5)
(129)	Maximum value for FBCHI (IDATA=1) (2.0)
(130)-(298)	Special coefficients for thyristor voltage source model

Special coefficients for current feedback:

Coils inside grid:

ACOEF(290)	= 1.0 Lausanne feedback model
	= 2.0 Standard PID-model

PID-model :

ACOEF(291)	NSTART : first coefficient for feedback
ACOEF(292)	NFB : total number of feedback systems
ACOEF(293)	NWPRINT : print cycle (coil currents and voltages)

Having specified NSTART and NFB, the subsequent coefficients have to be specified according to:

ACOEF(J)	IGROUPW:	NSTART	<	J	<	NSTART+NFB-1
	VGAINP:	NSTART+NFB	<	J	<	NSTART+2*NFB-1
	VGAIND:	NSTART+2*NFB	<	J	<	NSTART+3*NFB-1
	VGAINI:	NSTART+3*NFB	<	J	<	NSTART+4*NFB-1
	TFBON:	NSTART+4*NFB	<	J	<	NSTART+5*NFB-1
	TFBOFF:	NSTART+5*NFB	<	J	<	NSTART+6*NFB-1
	VOLTMAX:	NSTART+6*NFB	<	J	<	NSTART+7*NFB-1
	TRAMP:	NSTART+7*NFB	<	J	<	NSTART+8*NFB-1

where:

IGROUP :	coil group for feedback
VGAINP :	proportional feedback constants (V/A)
VGAIND :	differential (Vs/A)
VGAINI :	integral (V/As)
TFBON :	time when feedback system is switched on (s)
TFBOFF :	time when feedback system is switched off (s)
VOLTMAX :	maximum voltage (V)(one turn equiv. voltage)
TRAMP :	ramp time (s)

Coils outside grid :

Feedback on external coil group currents is applied, if :

ICIRC=1 and ACOEF(294)>129

ACOEF(294)	NSTART : first coefficient for feedback					
ACOEF(295)	NFB : total number of coil groups for feedback					
ACOEF(296)	= 0.0	Use inductance matrix in voltage feedback model :				

$$V_{FB}^{j} = \left[\beta_p^k(\Delta I^k) + \beta_d^k\left(\frac{d\Delta I^k}{dt}\right) + \beta_I^k\left(\int \Delta I^k dt\right)\right] \cdot M_{k,j}.$$

where β_p^k, β_d^k, β_I^k are the proportional and derivative and integral gains, ΔI is the difference between the actual current and the desire current and $M_{k,j}$ is the mutual inductance matrix

= 1.0 Standard PID-model :

$$V_{FB}^{k} = \left(\beta_p^k(\Delta I^k) + \beta_d^k\left(\frac{d\Delta I^k}{dt}\right) + \beta_I^k\left(\int \Delta I^k dt\right)\right) \cdot \delta_{k,j},$$

where $\delta_{k,j}$ is the identity matrix.

= 2.0 Special for ZT-H

= 3.0 Use the following voltage feedback model:

$$V_{FB}^{k} = \left(R_j I_j + \beta_p^k(\Delta I^k) + \beta_d^k\left(\frac{d\Delta I^k}{dt}\right) + \beta_I^k\left(\int \Delta I^k dt\right)\right) \cdot \delta_{k,j},$$

= 4.0 ASDEX upgrade

= 5.0 call missionc

= 6.0 call volt

ACOEF(J)	IGROUPC :	NSTART	<	J	<	NSTART+NFB-1
	GAINPEG :	NSTART+NFB	<	J	<	NSTART+2*NFB-1
	GAINDEG :	NSTART+2*NFB	<	J	<	NSTART+3*NFB-1
	GAINIEG :	NSTART+3*NFB	<	J	<	NSTART+4*NFB-1
	TONEG :	NSTART+4*NFB	<	J	<	NSTART+5*NFB-1
	TOFFEG :	NSTART+5*NFB	<	J	<	NSTART+6*NFB-1
	VMINEG :	NSTART+6*NFB	<	J	<	NSTART+7*NFB-1
	VMAXEG :	NSTART+7*NFB	<	J	<	NSTART+8*NFB-1

where:

IGROUPC :	external coil group for feedback
GAINPEG :	proportional feedback constants (V/A) (else:(mu/s))
GAINDEG :	differential (Vs/A) (else: (mu))
GAINIEG :	integral (V/As) (else: (mu/s**2)

TONEG :	time when feedback system is switched on (s)
TOFFEG :	time when feedback system is switched off (s)
VMINEG :	minimum voltage (kV)/turn
VMAXED :	maximum voltage (kV)/turn

The following information is used by the shape control subroutine **tcv1**, when IDATA=7 on card 01. The default values for ACOEF(300) to ACOEF(560) are all equal to zero.

(300)		If ACOEF(307)=0, the number of plasma current elements is equal to 2*ACOEF(300)
(301)		If ACOEF(307)=0 AND ACOEF(319)=1, the plasma current elements cover the rectangular area defined by : ACOEF(302) $< x <$ ACOEF(302) ACOEF(303) $< z <$ ACOEF(304)
(302)		See (301)
(303)		See (301)
(304)		See (301)
(305)		Not used
(306)		Not used
(307)	= 0.0	fixed plasma current elements
	= 1.0	current elements are periodically adapted to the preprogrammed plasma shape
(308)		Overall shape control gain, expressed as a time constant (in seconds) for the action of the control algorithm
(309)	= 0.0	boundary points are specified in the ACOEF array
	= 1.0	boundary points are generated analytically using the variables RZERV, AZERV, EZERV, DZERV on type 42, 43, 44 and 45 cards
(310)		Not used
(311)		Shape control proportional feedback gain
(312)		Shape control derivative feedback gain
(313)		Not used
(314)		Not used
(315)		Exit time in seconds for program diagnostics
(316)		Feedback coefficient for plasma current control by acting on flux at reference point. Only used when ACOEF(318)=2.
(317)	= 1.0	TCV
	= 2.0	BPX
	= 3.0	SSAT

	= N.0	User supplied subroutine containing the information discussed in section (3.3.3). This information is required for the Hofmann control scheme.
(318)	= 0.0	Plasma current is feedback controlled by applying an OH moment. OH group currents are defined in ACOEF(401) through ACOEF(450). Feedback gain is ACOEF(332)
	= 1.0	Plasma current is feedback controlled by acting on the boundary flux. The gain is ACOEF(329) and the weight is preprogrammed (see ACOEF(2093) , ACOEF(2193) etc)
	= 2.0	Plasma current is feedback controlled by acting on flux at reference point. Trajectory of reference point is preprogrammed (see ACOEF(2091),ACOEF(2092),ACOEF(2191),ACOEF(2192), etc). The gain is ACOEF(316) and the weight is preprogrammed as under 1 above.
	= 3.0	Plasma current is not feedback controlled, but the total volt-sec at reference point (same reference point as under 2 above) is feedback controlled to follow a given time evolution, as defined in ACOEF(2095), ACOEF(2195), etc. Gain is ACOEF(333), weight is preprogrammed as under 1 above.
(319)		Ratio of maximum to minimum width of finite element matrix.
(320)		Vertical position control proportional feedback gain. If ACOEF(320)≠0 group currents for a radial field moment must be given in ACOEF(451), ACOEF(452), etc.
(321)		Not used
(322)		Ellipticity control proportional feedback gain. If ACOEF(322)≠0, group currents producing a quadrupole moment must be specified in ACOEF(501), ACOEF(502) etc. This is not recommended!
(323)		Ellipticity control derivative feedback gain. If ACOEF(323)≠0, group currents producing a quadrupole moment must be specified in ACOEF(501), ACOEF(502) etc. This is not recommended!
(324)		Control cycle time (in seconds). This is the time interval for applying the control algorithm
(325)	= 0.0	For plasma current to be calculated from flux loops using finite elements
	= 1.0	For the TSC plasma current to be used in shape subroutines.
(326)		Not used
(327)		Number of control cycles between successive element changes

(328)		If ACOEF(328)=1, the shape evolution between two given shapes can be modified by using the type 44 card. In this case FRAC=EZERW (see subroutine tcvshap).
(329)		Feedback gain for plasma current control by acting on the flux at the plasma boundary. Used when ACOEF(318)=1.
(330)	= 0.0	Measurements are taken from psi-matrix using the subroutine **grap**.
	= 1.0	Measurements are computed using the subroutines **gf** and **gradgf**.
(331)		Damping coefficient for control algorithm (normally = 0.5)
(332)		Feedback coefficient for plasma current control by applying an OH current moment (see ACOEF(401)...). Only used when ACOEF(318)=0.
(333)		Feedback coefficient for volt-sec preprogramming. Only used when ACOEF(318)=3.
(334)	= 0.0	Vessel currents are equal to sum of the wire currents
	= 1.0	Vessel currents are computed from time derivative of flux
(340)		Number of plasma shapes specified using the ACOEF array
(341)		If equal to 1, weight of the top boundary point is preprogrammed.
(342)		If equal to 1, weight of the bottom boundary point is preprogrammed.
(380)		Number of preprogrammed boundary points (should be approximately 2×(Number of poloidal field coil groups))
(401)-(450)		Group currents which produce a perfect OH field. Used only when ACOEF(318)=0. Currents should be scaled such that the sum of all OH currents is of the order 10 kA-turns
(451)-(500)		Group currents which produce a pure radial field. Only used when ACOEF(320)≠0 or ACOEF(2096)≠0. Currents should be scaled as above
(510)		factor for determining the regularization parameter for feedback with type 62,63 cards
(540)		Number of preprogrammed BSUBR=0 points
(560)		Number of preprogrammed BSUBZ=0 points

Note : Additional information for the Hofmann shape control algorithm is provided on ACOEF(2000)-ACOEF(3000)

(700)	NSLHRT : number of cycles skipped between ray tracing in LSC (50.)
(701)	NSLHPC : number of cycles skipped between power and current calls to LSC (10.). Note that NSLHPC < NSLHRT

Note : 700-704 also are used to define divertor plots
These coefficients are needed for IFFAC=1 (neg FFAC on type 03) to control automatic adjustment of FFAC.

(760) pellet run if 1.0
(761) VXPEL...initial R velocity of pellet (note...normally negative)
(762) VZPEL...initial Z velocity of pellet
(763) XPEL....initial R position of pellet
(764) ZPEL....initial Z position of pellet
(765) RADPEL..initial radius of pellet (assumed spherical)
(766) time pellet gets injected
(767) fraction of impurity in pellet

(770) second pellet if 1.0
(771) VXPEL...initial R velocity of second pellet (note...normally negative)
(772) VZPEL...initial Z velocity of second pellet
(773) XPEL....initial R position of second pellet
(774) ZPEL....initial Z position of second pellet
(775) RADPEL..initial radius of second pellet (assumed spherical)
(776) time second pellet gets injected
(777) fraction of impurity in second pellet

(778) time between subsequent pellets
(779) final time

(790)	= 0.0	original calculation of pellet density
	= 1.0	average pellet density source over trail
(791)	= 0.0	original calculation of density integration for plots
	= 1.0	start density integration at restart time

(801) maximum AMACH (0.005)
(802) minimum FFAC decrease (0.9)
(803) maximum FFAC increase (1.1)
(804) maximum FFAC (1000.)
(805) minimum FFAC (1.0)
(806) Boundary relaxation factor (1.0)

(810) multiplies η (1.0)
(811) QLIM : plasma will be limited by surface where q$\geq$QLIM (0.0)
(815) in missionc

These coefficients are needed for subroutine ITERATE

(821)	PHI2 (1.75) for	ITYPE=1	poloidal flux
(822)	SF (1.4)	"	
(823)	FACCONV ($1. \times 10^{-8}$)	"	
(824)	NIMAX (4000.)	"	
(831)	PHI2 (1.85) for	ITYPE=2	velocity stream function
(832)	SF (1.4)	"	
(833)	FACCONV ($1. \times 10^{-8}$)	"	
(834)	NIMAX (2000.)	"	
(841)	PHI2 (1.62) for	ITYPE=3	velocity potential
(842)	SF (1.38)	"	
(843)	FACCONV ($1. \times 10^{-8}$)	"	
(844)	NIMAX (4000.)	"	

(850) Initial voltage for equilibrium calculation (0.0)
(851) Particle diffusion coefficient (m^2/s) (0.0)
(852) Exponential decay factor for the steady state particle radial density profile (0.0)
(853) Flux of impurities crossing outermost flux surface (#/s) (0.0)
(854) Oxygen (0.0)
(855) Carbon (0.0)
(856) Iron (0.0)
(857) Berillium (0.0)
(858) Neon (0.0)
(859) Krypton (0.0)
(860) VT : transfer voltage(kV) for ZTH circuit when IRFP=1 and ACOEF(296)=2; when $V_T \leq$ACOEF(860), OH power supply comes on. (0.0)
(870) α for Ohm's law (0.0) : $\vec{E} + \vec{v} \times \vec{B} = \eta \left(\vec{J} - \alpha \vec{B}/\mu_o \right)$
(880) T_{edge} (eV) for transport calculations. (0.0)

Note : The electron and ion edge temperatures are deterined as follows :

For ACOEF(880)=0.0 : $(T_{edge})_e$ = TEVV unless THALO is specified by ACOEF(98) or by the type 60 card, then $(T_{edge})_e$ = THALO

For ACOEF(880)>0.0 : $(T_{edge})_e$ =ACOEF(880)

In all cases : $(T_{edge})_i$ = (ACOEF(882)-1.)$(T_{edge})_e$

(881) Fraction of n_o for edge density (0.1)
(882) Ratio of total pressure to electron pressure at edge (2.0)
(890) Heat conduction multiplier (1.0)
(891) Heat conduction denominator used in temperature equilibration (100.)
(895) Let x-point exist in structure
(896) Set to 1.0 for velocity chopping
(901) equilibrium shape control parameter

1.0	only shape points are used
2.0	shape points + flux linkage (acoef(902)) at xplas,zplas
3.0	shape points, + x-point (r_x=acoef(903),z_x=acoef(904))
4.0	shape points + flux linkage + x-point

(905) specifies max number of coil group currents to calculate (actually set this equal to the total number of groups. To fix any coil current, set the desired value in gcur(2) and set the corresponding gcur(3) value to 1.0)
(906) is the relative error tolorance...[1.e-3]
(907) is the iteration number when shape feedback starts
(908) is the iteration number when type 19 feedback ends
(909) is the relaxation factor for equilibrium shape feedback
(910) is number of iterations between resetting sigmax and relaxation factors
(911) is number of iterations to full implementation of vsec constraint

The following is additional information for the Hofmann control scheme :

(2000)	Time when the first plasma shape is specified (seconds)
(2001-2030)	The x coordinates of the boundary points
(2031-2060)	The z coordinates of boundary points
(2061)	Weight of top boundary point
(2062)	Weight of bottom boundary point
(2071,2072,2073)	x, z, weight of first BR=0 point
(2074,2075,2076)	x, z, weight of the second BR=0 point
(2081,2082,2083)	x, z, weight of first BZ=0 point
(2084,2085,2086)	x, z, weight of second BZ=0 point
(2091,2092)	x, z for preprogrammed volt seconds

(2093)	Weight of flux control, used when ACOEF(318)=1, 2, or 3.
(2094)	D-matrix scaling factor
(2095)	Preprogrammed volt seconds, used when ACOEF(318)=3.
(2096)	Derivative gain for vertical position control. If ACOEF(2096)$\neq$0, group currents for a radial field moment must be given in ACOEF(451), ACOEF(452) etc.
(2100)-(2195)	Same as above for second plasma shape
(2200)-(2295)	Same as above for third plasma shape
(etc)	Continue in same fashion for all plasma shapes

Note : In order to use the Hofmann control scheme, the additional information described in section (3.3.3) must be provided through a subroutine.

Card 12 - Transport

11	21	31	41	51	61	71
TEVV	DCGS	QSAW	ZEFF	IALPHA	IBALSW	ITEMP

TEVV		Temperature of the vacuum region for use in resistivity calculation. If TEVV is negative, (-TEVV) is used initially then TEVV is adjusted to give the maximum value which is numerically stable. If type 34 card is included, this overrides value specified here. (1.0)
DCGS		Reference number density in units of $10^{19}/\text{m}^3$ The actual density for IDENS=1 is the product of DCGS and RNORM on type 24 card.
QSAW		The resistivity is enhanced in the center of the plasma if ISURF=1 and the local safety factor satisfies q<QSAW. (1.0)
ZEFF		The effective Z used in the resistivity calculation. (1.0)
IALPHA		Switch for α-particle heating. If IALPHA=1, the α-particle heating corresponding to a 50:50 D/T mixture is included in the energy equation. (0.0)
IBALSW		Switch for ballooning calculation (0.0)
	= 0.0	No ballooning calculation
	= 1.0	Ballooning calculation performed every NSKIPSF cycles on every flux surface. Results are presented as a stability plot at the end of the calculation. *WARNING :* may be expensive for time dependent calculations
	= 2.0	Same as 1.0, with the addition that the thermal conductivity is increased by a factor of 10 on all surfaces found to be unstable.
ITEMP		If ITEMP=1.0, the temperature in the external coils will be calculated as a function of time. In this case, type 39 cards must be included to provide additional coil information.

Card 13 - Initial Conditions

11	21	31	41	51	61	71
ALPHAG	ALPHAP	NEQMAX	XPLAS	ZPLAS	GZERO	QZERO

ALPHAG The initial toroidal field is given by $g\nabla\phi$ where

For IFUNC =1:

$gg^{'}$ = [GP1*FF1(Ψ)+GP2*FF2(Ψ)]

where

$\mathrm{FF1}(\hat{\Psi}) = -\hat{\Psi}^{\mathrm{ALPHAG}}$
$\mathrm{FF2}(\hat{\Psi}) = -4.0\hat{\Psi}^{\mathrm{ALPHAG}}[1-\hat{\Psi}]$
$\hat{\Psi}$=$(\Psi_{lim}-\Psi)/(\Psi_{lim}-\Psi_{min})$

And GP1 and GP2 are determined so that the central q value is QZERO and the total plasma current is PCUR(ISTART).

For IFUNC=2:

$$\frac{1}{2}\frac{dg^2}{d\Psi} = (\mathrm{XPLAS}^2 * \mathrm{PO} * (1/\mathrm{BETAJ} - 1) * \left[\frac{e^{-(\mathrm{ALPHAG})\hat{\Psi}} - e^{-(\mathrm{ALPHAG})}}{e^{-(\mathrm{ALPHAG})} - 1}\right]$$

where $\hat{\Psi} = (\Psi - \Psi_{min})/(\Psi_{lim} - \Psi_{min})$, BETAJ=ACOEF(27), and PO above and in the pressure equation are initialized by the type 17 card, but are iterated (renormalized) so the total plasma current is PCUR(ISTART) and g=GZERO at $\Psi = \Psi_{lim}$.

For IFUNC=3:

if (DELG>0) g=GZERO + (const) $\hat{\Psi}^{\mathrm{ALPHAG}}$
where (const) is chosen to make plasma current come out right
if (DELG<0) g=GRPFP*(1+(DELG-1)$\hat{\Psi}^{\mathrm{ALPHAG}}$)

where DELG=ACOEF(25) and GRPFP=ACOEF(26) is iterated (renormalized) so the total plasma current is PCUR(ISTART)

For IFUNC=4:

$g^2 = \text{GZERO}^2 + 2 * \text{GP1} * \text{FF1}(\Psi)$

and GP1 is determined so the total plasma current is GCUR(1)

For IFUNC=5:

$$-\frac{1}{2}\frac{dg^2}{d\Psi} = \frac{\text{GP1}/2\pi\eta + (p^{'} + \langle J_{CD}\rangle)/\langle R^{-2}\rangle}{\langle B^2\rangle/\langle B_T^2\rangle}$$

ALPHAP	Pressure exponent for equilibrium calculation (see type 02 card)
NEQMAX	Maximum number of equilibrium iterations allows. Normal value is 200. If NEQMAX is negative, the absolute value is used and the error flag is skipped if convergence is not obtained in ABS(NEQMAX) iterations.
XPLAS	Initial guess for the x coordinate of the magnetic axis
ZPLAS	Initial guess for the z coordinate of the magnetic axis
GZERO	Vacuum toroidal field given by GZERO $\nabla\phi$. This can be specified as a function of time on the type 27 card.
QZERO	Initial value of the safety factor at the magnetic axis for IFUNC=1

Card 14 - Initial Conditions 2

11	21	31	41	51
ISTART	XZERIC	AXIC	ZZERIC	BZIC

ISTART	This indicates at which time point TPRO(I) as specified on the type 18 card the calculation is to begin. The normal value is 1.
XZERIC	If this is nonzero, the initial equilibrium iteration will be initialized with the plasma current distributed over a rectangular region centered at XZERIC and ZZERIC and with half width AXIC and half height BZIC. If these variables are specified, then the initial plasma position XPLAS and ZPLAS on the type 13 card are overwritten.
AXIC	See above
ZZERIC	See above
BZIC	See above

Card 15 - Coil Group Current

11	21	31	41	51	61	71
IGROUP	GCUR(1)	GCUR(2)	GCUR(3)	GCUR(4)	GCUR(5)	GCUR(6)

IGROUP The group number used to identify the coil. It is specified on type 9 and 10 cards for the external and internal coils. If IGROUP<0, then ABS(IGROUP) is used and this coil group has zero net current constraint applied if ACOEF(41)>0. If RESGS(IGROUP) is non-zero, then this resistance is used for the group resistance.

GCUR(I) The programmed coil current (kA) for the coil group IGROUP at time TPRO(I). When using the Hofmann control scheme only the initial coil currents are needed.

Card 16 - Plasma Current

11	21	31	41	51	61	71
-	PCUR(1)	PCUR(2)	PCUR(3)	PCUR(4)	PCUR(5)	PCUR(6)

PCUR(I) The programmed plasma current (kA) at the time TPRO(I)

Card 17 - Plasma Pressure

11	21	31	41	51	61	71
-	PPRES(1)	PPRES(2)	PPRES(3)	PPRES(4)	PPRES(5)	PPRES(6)

PPRES(I) The programmed plasma pressure (mks) at the time TPRO(I). For IPRES=0, only the initial value is needed. For IPRES=1, all values are used.

Card 18 - Time

11	21	31	41	51	61	71
-	TPRO(1)	TPRO(2)	TPRO(3)	TPRO(4)	TPRO(5)	TPRO(6)

TPRO(I) Time (in seconds) corresponding to GCUR(I),PCUR(I), etc. The intermediate values are linearly interpolated for ICUBE=0, cubic interpolation is used for ICUBE=1 (set by ACOEF(17)). Note that while most time dependent quantities are interpolated between time points, auxiliary heating system powers specified on type 23 (Neutral Beam) and 46 (Lower Hybrid) cards come on abruptly at these times and stay at the fixed level during each time interval.

Card 19 - Feedback 1

11	21	31	41	51	61	71
L	NRFB(L)	NFEEDO(L)	FBFAC(L)	FBCON(L)	IDELAY(L)	FBFACI(L)

L	Number of feedback system
NRFB(L)	If NRFB(L)>0, indicates coil group number for feedback If NRFB(L)=0, indicates feedback on plasma current
NFEEDO(L)	Observation pair number (type 8) used in feedback system
FBFAC(L)	This is a proportionality factor between the coil group current and the desired flux difference. Units are (amps/weber/radian) For external coils, this current is changed instantaneously. For internal coils, a voltage is applied (proportional to the wire resistivity) so that the desired current will be obtained after the coil L/R time. If IPEXT(L)=4 on corresponding type 20 card, FBFAC(L) is the proportionality factor between coil group current desired and difference between plasma current and plasma current desired.
FBCON(L)	Flux offset, FBFAC(L) multiplies : (PSI1-PSI2-FBCON(L)*FAC)
IDELAY(L)	If this is greater than zero, a time delay of IDELAY(L) time steps is introduced into the calculations. Note that the parameter PDELAY must be greater than the maximum IDELAY(L).
FBFACI(L)	This is the time integral feedback proportionality term. It is the same as FBFAC(L) except it multiplies the time integral of the flux or current difference. May be superimposed with FBFAC.

Note : If the first field on the type 19 card is equal to 1000.0, this card defines time varying observation points for the feedback system defined by the preceding type 19 card. The format is similar to that of the type [15,16,17,18,23,24] cards:

11	21	31	41	51	61	71
1000.0	NFEEDV(1,L)	(2,L)	(3,L)	(4,L)	(5,L)	(6,L)

NFEEDV(I,L)	Observation pair number (type 08) used in feedback system L at time point I (type 18). Multiple cards can be included to define more than 6 points

Card 20 - Feedback 2

11	21	31	41	51	61	71
L	TFBONS(L)	TFBOFS(L)	FBFAC1(L)	FBFACD(L)	IPEXT(L)	

L		Number of feedback system (same as that on corresponding type 19 card)
TFBONS(L)		Time when feedback system L is turned on (sec)
TFBOFS(L)		Time when feedback system L is turned off (sec)
FBFAC1(L)		If >0, factor multiplying FBCON is proportional to the (plasma current)/(final current)
FBFACD(L)		This is the time derivative feedback proportionality term. It is the same as FBFAC(L) and FBFACI(L) except it multiplies the time derivative of the flux or current difference. It may be superimposed with FBFAC and FBFACI
IPEXT(L)		Signifies which flux to used from the observation coils
	= 1.0	Total flux per radian
	= 2.0	Flux from coils only (not presently available)
	= 3.0	Flux from plasma only (not presently available)
	= 4.0	Feedback signal is proportional to plasma current minus preprogrammed value. For this option , FBFAC is dimensionless
	= 5.0	Feedback signal is proportional to (XMAG-XMAGO(t)). where XMAGO(t) is defined on type 30 card...see note 4
	= 6.0	Feedback signal is proportional to (ZMAG-ZMAGO(t)). where ZMAGO(t) is defined on type 31 card...see note 4
	= 7-10	Feedback is proportional to EPS1C-EPS4C
	= 10NN	Feedback is proportional to current in wire NN
	= 21-24	Special option for RFP, proportional to $\cos(\theta) - \cos(4\theta)$
	= 25	Special shape control using acoef(510) and cards 62-63

Note 1 : If TFBONS or TFBOFS are negative, then their absolute value refers to the cycle number for which the feedback is turned on or off.

Note 2 : If controlling plasma current by using IPEXT(L)=4, the automatic plasma current control should be turned off by setting ACOEF(11)=0.

Note 3 : If IPEXT(L) = 7,8,9,10, the switch ISVD must be set to 1.0

on type 03 card

Note 4 : Feedback signal multiplied by $(I_p/1\,\mathrm{MA})$ for IPEXT(5) or IPEXT(6)

Card 21 - Contour Plots

11	21	31	41	51	61	71
ICPLET	ICPLGF	ICPLWF	ICPLPR	ICPLBV	ICPLUV	ICPLXP

If any of these switches are set to 1.0, the following contour plots are produced every NSKIPL cycles.

ICPLET	Resistivity array ETAY
	If (IRFP=1) ETA*J
ICPLGF	Toroidal field function g
ICPLWF	Toroidal velocity W
	If (IRFP=1) ($\vec{J} \cdot \vec{B}/B^2$)
ICPLPR	Pressure p
ICPLBV	Curl of the velocity field B $\equiv \Delta^* A$
	If (IRFP=1) HYPER/J
ICPLUV	Divergence of velocity field U$\equiv \nabla^2 \Omega$
	If (IRFP=1) (ETA*J+HYPER)/(ETA*J)
ICPLXP	Close-up of poloidal flux near x-point region

Card 22 - Vector Plots

11	21	31	41	51	61	71
IVPLBP	IVPLVI	IVPLFR	IVPLJP	IVPLVC	IVPLVT	-

If any of these switches are set to 1.0, the following vector plots are produced every NSKIPL cycles.

IVPLBP	Poloidal magnetic field
IVPLVI	Incompressible velocity field
IVPLFR	Forces
IVPLJP	Poloidal current
IVPLVC	Compressible velocity field
IVPLVT	Total velocity field

Card 23 - Neutral Beam

11	21	31	41	51	61	71
-	BEAMP(1)	BEAMP(2)	BEAMP(3)	BEAMP(4)	BEAMP(5)	BEAMP(6)

BEAMP(I) The amplitude of the neutral beam source (MW) at time TPRO(I). The deposition profile is given on the type 25 card.

Card 24 - Plasma Density

11	21	31	41	51	61	71
-	RNORM(1)	RNORM(2)	RNORM(3)	RNORM(4)	RNORM(5)	RNORM(6)

RNORM(I) The normalized central density for IDENS=1 at time TPRO(I). The actual density is RNORM(I)*DCGS.

Card 25 - Neutral Beam Deposition Profile

11	21	31	41	51	61	71
ABEAM	DBEAM	NEBEAM	EBEAMKEV	AMBEAM	FRACPAR	IBOOTST

ABEAM — This variable along with DBEAM and NEBEAM specify the spatial external heat source deposition profile which is multiplied by the beam amplitude parameter on the type 23 card. (0.25) The spatial form factor is

FF=F1*F2/SUM

$F1=DBEAM^2/[(\hat{\Psi}-ABEAM)^2+DBEAM^2]$

$F2=(1-\hat{\Psi}^2)^{NEBEAM}$

with $\hat{\Psi}=(\Psi-\Psi_{min})/(\Psi_{lim}-\Psi_{min})$ and SUM is the normalization factor.

DBEAM — See ABEAM above. (0.1)

NEBEAM — See ABEAM above. (1.0)

EBEAMKEV — Energy of the neutral beam ions in keV. (80.)

AMBEAM — Mass of the neutral beam particles in amu. (1.0)

FRACPAR — Fraction of beam particles which are oriented parallel to the plasma current (0.0). -1< FRACPAR < 1. This can be input as a function of plasma current on the type 50 card.

IBOOTST — If IBOOTST≠0, the bootstrap current is included in the calculation. If IBOOTST=1, the collisionless Hirshman model is used and if IBOOTST=2 the collisional Harris model is used

Card 26 - Anomalous Transport

11	21	31	41	51	61	71
-	FBCHIA(1)	FBCHIA(2)	FBCHIA(3)	FBCHIA(4)	FBCHIA(5)	FBCHIA(6)

FBCHIA(I) Factor by which thermal conductivity is enhanced at time TPRO(I)

Card 27 - Toroidal Field

11	21	31	41	51	61	71
-	GZEROV(1)	...(2)	...(3)	...(4)	...(5)	GZEROV(6)

GZEROV(I) Vacuum toroidal field function GZERO at time TPRO(I)

Card 28 - Loop Voltage

11	21	31	41	51	61	71
-	VLOOPV(1)	...(2)	...(3)	...(4)	...(5)	VLOOPV(6)

VLOOPV(I) Programmed loop voltage for OH system at time TPRO(I). In general, a loop voltage determined by feedback will be superimposed on VLOOPV(I). The "automatic" plasma current control feedback is proportional to ACOEF(11). The maximum and minimum loop voltages (sum of preprogrammed and feedback) are limited by ACOEF(15)(min) and ACOEF(16)(max). Currents in passive conductors are initialized when VLOOPV(ISTART)>0 and ACOEF(41)=0.

Card 29 - PEST Output

11	21	31	41	51	61	71
-	TPEST(1)	TPEST(2)	TPEST(3)	TPEST(4)	TPEST(5)	TPEST(6)

TPEST(I) The specified times at which PEST output is to be written onto file EQDSKA for IPEST=1. Plots and a restart file are also written at these times.

Cards 30 and 31 - Magnetic Axis

11	21	31	41	51	61	71
-	XMAGO(1)	XMAGO(2)	XMAGO(3)	XMAGO(4)	XMAGO(5)	XMAGO(6)
-	ZMAGO(1)	ZMAGO(2)	ZMAGO(3)	ZMAGO(4)	ZMAGO(5)	ZMAGO(6)

XMAGO(I) The x-magnetic axis position corresponding to time TPRO(I) for use in feedback system (type 19,20) with IPEXT=5

ZMAGO(I) The z-magnetic axis position corresponding to time TPRO(I) for use in feedback system (type 19,20) with IPEXT=6

Card 32 - Divertor Plate

11	21	31	41	51	61	71
N	XLPLATE(N)	ZL...(N)	XR...(N)	ZR...(N)	FPLATE(N,1)	FPLATE(N,2)

N	Number of divertor plate
XLPLATE(N)	The x-coordinate of leftmost side of divertor plate N.
ZLPLATE(N)	The z-coordinate of leftmost side of divertor plate N.
XRPLATE(N)	The x-coordinate of rightmost side of divertor plate N.
ZRPLATE(N)	The z-coordinate of rightmost side of divertor plate N.
FPLATE(N,1)	Fraction of charged particle heat flux deposited on divertor plate N. Outside strike point is 1, inside is 2
FPLATE(N,2)	See FPLATE(N,1)

The plate will be divided into PNSEG bins, and the heat flux in each bin will be calculated and plotted. One sided exponential distributions are used, based on midplane scrapeoff distance of 0.6 cm.

Note : The default divertor shape follows a straight line between the coordinates specified here. If this card is followed by additional type 32 cards with option 1000 in the second field, additional defining points are added. The individual PNSEG+1 x-z coordinates are input 3 per card as follows

Note : Acoef(700)-(704) must be defined for divertor plots

32	10000.	X(I)	Z(I)	X(I+1)	Z(I+1)	X(I+2)	Z(I+2)

Card 33 - Gap Resistance

11	21
IGROUP	RESGS(IGROUP)

IGROUP Group number of coil (same as type 15 card).

RESGS The resistance of gap in coil. This will override the gap resistance computed from ACOEF(41) when IGROUP is negative.

Card 34 - Vacuum Temperature

11	21	31	41	51	61	71
-	TEVVO(1)	TEVVO(2)	TEVVO(3)	TEVVO(4)	TEVVO(5)	TEVVO(6)

TEVVO(I) Vacuum temperature TEVV at time point I. This card overrides the value specified on card 12

Card 35 - Mass Enhancement

11	21	31	41	51	61	71
-	FFACO(1)	FFACO(2)	FFACO(3)	TEVVO(4)	FFACO(5)	FFACO(6)

FFACO(I) Mass enhancement FFAC at time point I. Inclusion of of this card will override the value specified on card 3.

Card 36 - Resistivity Enhancement

11	21	31	41	51	61	71
-	ZEFFV(1)	ZEFFV(2)	ZEFFV(3)	ZEFFV(4)	ZEFFV(5)	ZEFFV(6)

ZEFFV(I) Resistivity enhancement ZEFF at time point I. Inclusion of this card will override the value specified on card 12

Card 37 - Voltage Group

11	21	31	41	51	61	71
IGROUP	GVOLT(1)	GVOLT(2)	GVOLT(3)	GVOLT(4)	GVOLT(5)	GVOLT(6)

GVOLT(I) The preprogrammed voltage (kV) for coil group IGROUP at time TPRO. This is the equivalent one turn voltage.

Card 38 - ILHCD

11	21	31	41	51	61	71
ILHCD	VILIM	FREQLH	AION	ZION	CPROF	IFK

ILHCD	= 0.0	No LHCD calculation and no hot plasma conductivity correction
	= 1.0	LHCD calculation and hot plasma conductivity contribution are included
VILIM		Lower velocity limit for the LHCD spectrum normalized to local thermal velocity. (typical value 2 to 3)
FREQLH		Frequency in GHz of the LH wave(3.7 for instance)
AION		Ratio of masses m_i/M_p for the dominant ion species (1 for hydrogen)
ZION		Atomic number of the dominant ion species
CPROF		Option to calculate the RF current profile
	= 0.0	RF current profile is calculated from the Fisch formula (depends on power)
	= 1.0	RF current profile is calculated independently of power, from cards 54-88 according to

$$\frac{d_c^2 r^{a_{c_1}} (1-r)^{a_{c_2}}}{(r-a_c)^2 + d_c^2}$$

IFK	= 1.0	Read data file TSCOUTA
	= 2.0	Call LSC

Card 39 - External Coils 2

11	21	31	41	51	61	71
ICO	DXCOIL	DZCOIL	FCU	FSS	TEMPC	CCICS

ICO	External coil number (same as on type 09 card)
DXCOIL	Radial thickness of coil in meters
DZCOIL	Vertical thickness of coil in meters
FCU	Fraction of coil volume which is copper (see note below)
FSS	Fraction of coil volume which is stainless steel
TEMPC	Initial temperature of coil in °K
CCICS	Initial induced current in coil (kA)

Note: If FCU(N)>1, the truncated integer refers to the alloy type, while the decimal fraction refers to the fraction

Note: For superconducting coils, set ITEMP=-1 (type 12), FCU=0, RSCOILS=1.e-12

0.000<FCU<0.999 OFHC Copper
1.000<FCU<1.999 AL25 (Glidcop)
2.000<FCU<2.999 Berylium Copper

Card 40 - Output Reduction

11	21	31	41	51	61	71
NOPLOT(1)	...(2)	...(3)	...(4)	...(5)	...(6)	NOPLOT(7)

Plots are suppressed if the following numbers are assigned to the NOPLOT array on type(40) cards.

NOPLOT	Description
1	Grid, coils and limiters
2	Switch and time step information
3	Filament growth rate model
4	Initial coil and wire information
5	Coil currents,cycle=#
6	Current and flux
7	Special for spheromak formation
8	Special x-point plot
9	Heat flux, plate # cycle #
10	Profile plots(eg: q-prof vs poloidal flux, etc.)
11	Surface profiles, cycle=#
12	Summary plot
13	Flux measurements of observation pairs
14	Special divertor plots
15	Group number current and voltage
16	Current groups
17	Group voltage
18	Group power
19	Group energy
20	Total power and energy
21	Coil temperature
22	Currents(kA)
23	Timing information
51	AMACH and EKIN vs time
52	IPLIM and ZMAG vs time, XMAG vs TIME and ZMAG
53	XMAG and CUR vs time
54	DELP.TPI and PMIN.TPI vs time
55	DIAMAG and SURFVOLT vs time
56	QZERO and QEDGE vs time
57	DT and BETA vs TIME
58	$\langle N \rangle$/NMUR vs time and 1/q nr/B

	Density and INT ENER vs time
59	LI/2 vs time and LI vs q
60	TAUE-KG and TAU(MS) vs time
61	TI(0) and TE/TE-AV vs time
62	CHIOHMS and HFLUX-MW vs time
63	RO and MINORRAD vs time
64	DELT-TRI and ELLIP vs time
65	XSEP and ZSEP vs time
66	RESV-SEC and VSEC-TOT vs time
67	LOOPV-OH and VSEC-OH vs time
68	PTOT(MW) and PSEPCAL vs time
	Power flow in system
	FFAC and TEVV vs time
	NPSIT and RESID vs time
69	Nullapole and dipole vs time
70	Quadrupole and hexapole vs time
71	Octapole and decapole vs time

Note : To cancel the suppression of a certain plot, restart the job and input a negative number (eg: -9)

Example:

10. 2. +23. -9. 15. 12. 7.

Card 41 - TF Ripple

11	21	31	41	51	61	71
IRIPPL	NTFCOIL	RIPMAX	RTFCOIL	NPITCH	RIPMULT	IRIPMOD

IRIPPLE = 0.0 Does not calculate ripple losses
= 1.0 Does calculate ripple losses. *WARNING* : may be expensive for time dependent calculation
NTFCOIL Number of TF coils
RIPMAX Ripple magnitude at radius of TF coil
RTFCOIL Radius of TF coil
NPITCH Number of pitch angles for integration
RIPMULT Ripple multiplier
IRIPMOD= 1.0 CIT 2.1 meter design (U. Christenson)
= 2.0 TFTR model
= 3.0 Model RIPMAX*(R/RTFCOIL)$^{\mathrm{NTFCOIL}}$

Card 42 - Major Radius

11	21	31	41	51	61	71
-	RZERV(1)	RZERV(2)	RZERV(3)	RZERV(4)	RZERV(5)	RZERV(6)

RZERV(I) The preprogrammed major radius at time TPRO(I) for use in the plasma shape control algorithm.

Card 43 - Minor Radius

11	21	31	41	51	61	71
-	AZERV(1)	AZERV(2)	AZERV(3)	AZERV(4)	AZERV(5)	AZERV(6)

AZERV(I) The preprogrammed minor radius at time TPRO(I) for use in the plasma shape control algorithm.

Card 44 - Ellipticity

11	21	31	41	51	61	71
-	EZERV(1)	EZERV(2)	EZERV(3)	EZERV(4)	EZERV(5)	EZERV(6)

EZERV(I) The preprogrammed ellipticity at time TPRO(I) for use in the plasma shape control algorithm.

Card 45 - Triangularity

11	21	31	41	51	61	71
-	DZERV(1)	DZERV(2)	DZERV(3)	DZERV(4)	DZERV(5)	DZERV(6)

DZERV(I) The preprogrammed triangularity at time TPRO(I) for use in the plasma shape control algorithm.

Card 46 - Lower Hybrid Heating

11	21	31	41	51	61	71
-	PLHAMP(1)...(2)		...(3)	...(4)	...(5)	PLHAMP(6)

PLHAMP(I) The lower hybrid heating power (MW) at time TPRO(I)

Card 47 - Density Exponent 1

11	21	31	41	51	61	71
-	ALPHARV(1)	...(2)	...(3)	...(4)	...(5)	ALPHARV(6)

ALPHARV(I) The density exponent ALPHAR (see Eq. (2.56)) at time TPRO(I) (0.5). If included, this overwrites the value on the type 04 card.

Card 48 - Density Exponent 2

11	21	31	41	51	61	71
-	BETARV(1)	...(2)	...(3)	...(4)	...(5)	BETARV(6)

BETARV(I) The density exponent BETAR (see Eq. (2.56)) at time TPRO(I) (2.0). If included, this overwrites the value on the type 04 card.

Card 49 - Multipolar Moments

11	21	31	41	51	61	71
N	MULTN(N)	ROMULT(N)	IGROUPM(N)	ATURNSM(N)		

N		Multipole coil number (this must be a unique identifying number between 1 and PNCOIL
MULTN(N)		Multipole field type :
	= 0.0	Even nullapole
	= 1.0	Odd nullapole
	= 2.0	Even dipole
	= 3.0	Odd dipole
	= 4.0	Even quadrupole
	= 5.0	Odd quadrupole
	= 6.0	Even hexapole
	= 7.0	Odd hexapole
	= 8.0	Even Octapole
	= 9.0	Odd Octapole
	= 10.0	Even decapole
ROMULT(N)		Major radius about which multipole fields are expanded
IGROUPM(N)		Group number of multipole coil N. Refers to type 15 card with the same number.
ATURNSM(N)		Number of turns for multipole coil N. This is a positive or negative number, not necessarily an integer. The preprogrammed current for multipole coil N will be the product of ATURNSC(N) and the current in IGROUPC(N) as specified by the appropriate type 15 card.

Card 50 - Neutral Beam Fraction

11	21	31	41	51	61	71
-	FRACPAR(1)	...(2)	...(3)	...(4)	...(5)	FRACPAR(6)

FRACPAR(I) The fraction of neutral beams oriented tangentially at time TPRO(I). If included, this overwrites the value on the type 25 card.

Cards 51-54 Input Power Profile (LH)

11	21	31	41	51	61	71
-	A(1)	A(2)	A(3)	A(4)	A(5)	A(6)
-	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)
-	A1(1)	A1(2)	A1(3)	A1(4)	A1(5)	A1(6)
-	A2(1)	A2(2)	A2(3)	A2(4)	A2(5)	A2(6)

The above cards specify the input power profile for lower hybrid waves at time TPRO according to

$$S_{LH}(\hat{\Psi}) = \frac{d^2 \hat{\Psi}^{a_1} (1 - \hat{\Psi})^{a_2}}{(\hat{\Psi} - a)^2 + d^2}, \tag{3.9}$$

where $\hat{\Psi} = (\Psi - \Psi_{min})/(\Psi_{lim} - \Psi_{min})$. Normalization is such that the total power in MW is given on the type 38 card.

Cards 55-58 Current Profile (LH)

11	21	31	41	51	61	71
-	AC(1)	AC(2)	AC(3)	AC(4)	AC(5)	AC(6)
-	DC(1)	DC(2)	DC(3)	DC(4)	DC(5)	DC(6)
-	AC1(1)	AC1(2)	AC1(3)	AC1(4)	AC1(5)	AC1(6)
-	AC2(1)	AC2(2)	AC2(3)	AC2(4)	AC2(5)	AC2(6)

The above cards specify the current profile for lower hybrid waves evolving independently in time from the power according to according to

$$J_{LH}(\hat{\Psi}) = \frac{d_c^2 \hat{\Psi}^{a_{c1}} (1 - \hat{\Psi})^{a_{c2}}}{(\hat{\Psi} - a_c)^2 + d_c^2}. \tag{3.10}$$

Linear interpolation is used between different time values. Normalization is such that the total current is given by the Fisch formula.

Card 59 - ICRH Power

11	21	31	41	51	61	71
-	PICRH(1)	...(2)	...(3)	...(4)	...(5)	PICRH(6)

PICRH(I) The amplitude of the ICRH source(MW) at time TPRO(I). The deposition profile is given on the TYPE 65-68 cards.

Cards 62 and 63 - Control Points

11	21	31	41	51	61	71
-	XCON0(1)	XCON0(2)	XCON0(3)	XCON0(4)	XCON0(5)	XCON0(6)
-	ZCON0(1)	ZCON0(2)	ZCON0(3)	ZCON0(4)	ZCON0(5)	ZCON0(6)

XCON0(I) The x-shape point corresponding to time TPRO(I) for use in equilibrium iteration when acoef(901)¿0

ZCON0(I) The z-shape point corresponding to time TPRO(I) for use in equilibrium iteration when acoef(901)¿0

Card 64 - ICRH Fast Wave Current

11	21	31	41	51	61	71
-	FWCD(1)	...(2)	...(3)	...(4)	...(5)	FWCD(6)

FWCD(I) The total toroidal current(MA) driven by fast wave current drive at time TPRO(I). The deposition profile is given on the TYPE 69-72 cards.

Cards 65-68 Input Power Profile(ICRH)

11	21	31	41	51	61	71
-	A(1)	A(2)	A(3)	A(4)	A(5)	A(6)
-	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)
-	A1(1)	A1(2)	A1(3)	A1(4)	A1(5)	A1(6)
-	A2(1)	A2(2)	A2(3)	A2(4)	A2(5)	A2(6)

The above cards specify the input power profile for ICRH heating. The power density from fast wave at time t is given by:

$$S_{ICRH}(\hat{\Psi}, t) = \alpha_N(t) \frac{d^2 \hat{\Psi}^{a_1} (1 - \hat{\Psi})^{a_2}}{(\hat{\Psi} - a)^2 + d^2}. \tag{3.11}$$

where $\hat{\Psi} = (\Psi - \Psi_{min})/(\Psi_{lim} - \Psi_{min})$. The normalization parameter $\alpha_N(t)$ is chosen such that the total power from fast waves in MA is given on the type 59 card.

Cards 69-72 Current Profile (FW)

11	21	31	41	51	61	71
-	A(1)	A(2)	A(3)	A(4)	A(5)	A(6)
-	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)
-	A1(1)	A1(2)	A1(3)	A1(4)	A1(5)	A1(6)
-	A2(1)	A2(2)	A2(3)	A2(4)	A2(5)	A2(6)

The above cards specify the input current density profile for fast wave current drive. The current density from fast wave at time t is given by:

$$\vec{J_{FW}} = \alpha_N(t) f(\hat{\Psi}, t)\vec{B} \tag{3.12}$$

where

$$f(\hat{\Psi}, t) = \frac{d^2\hat{\Psi}^{a_1}(1-\hat{\Psi})^{a_2}}{(\hat{\Psi}-a)^2+d^2}. \tag{3.13}$$

where $\hat{\Psi} = (\Psi - \Psi_{min})/(\Psi_{lim} - \Psi_{min})$. The normalization parameter $\alpha_N(t)$ is chosen such that the total current driven by fast waves in MA is given on the type 64 card.

3.4 Description of Output

The numerical results from TSC simulations are contained in the files **outputa** and **tsc.cgm**. The file **outputa** is a text file which contains a wealth of information. The following is a partial listing :

1. A mirror of the input file *inputa*
2. Coordinates of the computational grid (see variables *xary* and *zary*)
3. A summary of geometry parameters and switches
4. Time step information
5. Actual Limiter coordinates (see *xlima* and *zlima*)
6. Complete listing of time preprogrammed quantities
7. Complete listing of ACOEF array
8. Multipole decomposition of coil groups

9. Dimensionless gains for feedback systems

10. Convergence information for the initial equilibrium

11. State of the system at every NKSIPR cycles

12. Listing of any errors encountered during the simulation

13. A listing of plots produced in the file **tsc.cgm**

The file **tsc.cgm** contains all the output plots produced during the simulation in the Computer Graphics Metafile format. The plots in this file can be viewed or converted to a form for printing using a metafile translator. The translator available at NERSC is called *ctrans* (the interactive version is *ictrans*). The very last portion of the file **outputa** contains a useful listing of each frame in the graphics file. This information can be used to view the desired plot immediately without paging through all the plots.

Chapter 4

Vertical Stability Analysis

The vertical stability of elongated plasmas can be examined with TSC by allowing the plasma to move freely within the surrounding conductors. Since the equations of motion for the plasma are modified by an artificial mass enhancement and viscosity to make the computational time reasonable, a convergence study must be done to obtain the actual, nearly massless, plasma behavior. The method for determining the growth time τ_g (reciprocal of the growth rate γ_g) for the vertical motion of the plasma is fundamentally different from a standard linear perturbation stability analysis. Rather than perform a perturbation analysis about the equilibrium, TSC solves the full nonlinear dynamics of the plasma as it evolves from the initial equilibrium and moves vertically. For TSC to find the linear growth rate, the plasma must spend some amount of time in a linear growth phase. By linear growth phase, we mean that the plasma vertical position can be described by an exponential with a single fixed time constant,

$$z(t) = z_o \exp\left(\gamma_g t\right). \tag{4.1}$$

If the plasma is evolving in a nonlinear phase, the time constant is a function of the position $\gamma_g = \gamma_g(z)$. This is in fact observed with TSC and there is a phase where the growth time becomes constant as the the plasma moves vertically. If the simulation is continued the growth time will start to change and continue to vary with the plasma's vertical motion. In order to make the plasma vertically unstable so that it will drift freely, one must *push* it from the equilibrium position. This introduces transients due to the conducting structure surrounding the plasma. The plasma vertical position is then described by

$$z(t) = z_o \sum_n a_n \exp\left(\gamma_n t\right) \qquad (\gamma_n = \text{constant}) \tag{4.2}$$

The linear growth time desired is the longest lived mode. The simulation must run long enough to allow the shorter lived modes to decay away. Thus to simulate the vertical motion of the plasma to obtain a linear growth time for the vertical instability, one must move the plasma away from its initial equilibrium position and allow it to drift long enough for the shorter lived modes to decay and then examine the growth time over some period to be certain that it remains nearly constant.

The linear growth time is determined in TSC by tracking the poloidal flux difference between several pairs of flux loops located symmetrically above and below the plasma midplane. A typical distribution of flux pairs is shown in Fig. 4, where loop U1 is paired with L1, etc., and the plasma boundary is shown.

When the instability is in a linear phase, the time rates of change of these flux differences should have approximately the same value. One should keep these flux loops away from x-points and conducting structures as much as possible. The average obtained from these flux loops then gives the growth time. These times are given in the graphics output under "observation pair". The growth time is also given for the vertical position of the magnetic axis. However, this can be misleading since the plasma can deform as it moves (even in the linear approximation), so that the magnetic axis may move at a different rate than other parts of the plasma. The flux loop growth rate times are the most reliable. In addition, there are two flux calculations of the growth time : one involving flux derivatives and the other flux differences. The flux differences are more reliable since the derivative calculation can be too sensitive. The procedure for a vertical stability calculation is described by the following steps.

1. Generate the equilibrium configuration of interest

2. Set up a vertical position feedback control system

    (a) Generate a coil pair near the midplane but not too close to the plasma and give them high resistances (type 10 cards).

    (b) Set up a feedback system to control the plasma vertical position (type 19 and type 20 cards)

    (c) Feedback on the flux (IPEXT=1 on type 20).

    (d) Set a flux offset (type 19 card)

    (e) Set the turn off time to a very small value (1×10^{-5}) (on card 20).

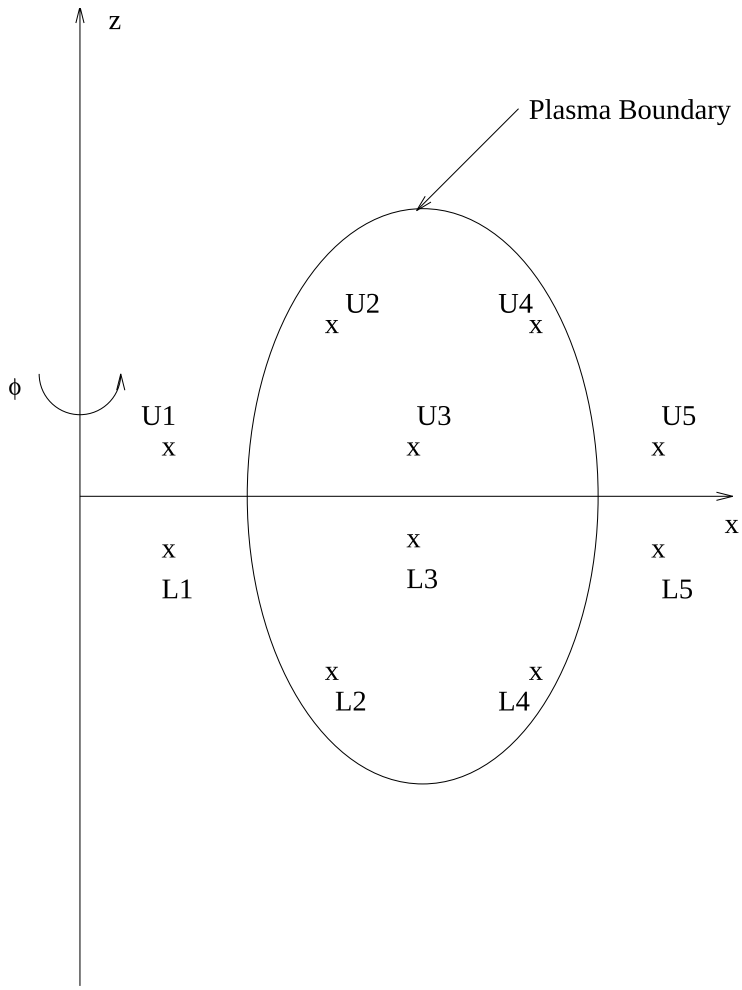

Figure 4.1: Typical distribution of flux loop pairs

3. Re-calculate the equilibrium. The plasma should be displaced slightly from the midplane ($z_{\rm mag}$ ∼1% of half-height).

4. This equilibrium is then the beginning of the dynamic simulation (set IRST=1.0 and NCYCLE>0).

5. Since TSC evolves the plasma pressure, the equilibrium in general will have a changing β_p and ℓ_i, which is undesirable. This is eliminated by setting IPRES=1.0 (type 02 card) and putting the equilibrium pressure from step 1 on the type 17 card. In addition, the current profile is frozen in by setting ACOEF(810)=1.0×10^{-4}.

6. Run the simulation to various displacements from the midplane by using ACOEF(101) and (102) (say 2, 4, 6, and 8 cm). From this, determine over what distance the plasma growth time remains constant and fix this value on the ACOEF(101) and (102) cards.

7. With the input file set up as described, run simulations with decreasing FFAC (type 3 card) values (say 2000., 1000., 500., and 250.). The actual γ_g can be determined from Eq. (4.3) below. This is the convergence analysis mentioned earlier.

8. Convergence can also be done with the viscosity by varying ACOEF(9) and ACOEF(90)-(92) (say 20., 10., and 5. for ACOEF(9) and 0.1, 0.05, and 0.025 for ACOEF(90)-(92)). *This is not recommended.* It is preferable to keep the default values of ACOEF(9) and ACOEF(90)-(92) and do the convergence with FFAC.

There is a theoretical expression relating the actual growth time (FFAC=1.0) to the simulated growth time with FFAC>1.0. This is in terms of the growth rate γ as follows

$$\frac{1}{\gamma_o} = \frac{1}{\gamma}\left[1 + c_1 \nu f \gamma + c_2 f^2 \gamma^2\right], \tag{4.3}$$

where γ is the calculated growth rate, f = FFAC^2 is the mass enhancement factor, ν is the artificial viscosity (ν=ACOEF(9)), and γ_o is the actual growth rate. With three or more simulated growth times, this equation can be solved using a least squares regression to give c_1, c_2 and γ_o.

Chapter 5

Sample Input Files

5.1 TPX

The following input file was used to model the current ramp and flat top phase of the proposed TPX experiment. The current was ramped linearly in time from 100 kA at $t = 0$ to 2.0 MA at $t = 4.0$ sec at a fixed toroidal field of B_T=4T. The Hofmann control algorithm was used to specify the shape evolution. This model has 7 external coil groups, assumes symmetry about the midplane and includes auxiliary heating. The geometry is shown in Fig. 5.1 at the end of the input file.

```
c..Title card
TPX DN 4.0sec RAMPUP:100kA->2.00MA+heating phase (331)=0.1 after t=4 sec
c
c         IRST1     IRST2     IPEST     NCYCLE    NSKIPR    NSKIPL     IMOVIE
00        0.0       1.0       0.0       100000.   005000.   005000.    0.0
c
c..Grid = 5cm x 5cm, symmetry switch=on, use Hofmann control
c         NX        NZ        ALX       ALZ       ISYM      CCON      IDATA
01        28.       30.       3.375     2.175     1.0       1.35      7.0
c
c         DTMINS    DTMAXS    DTFAC     LRSWTCH   IDENS     IPRES     IFUNC
02        1.0       6000.     .40       0.        1.        0.        1.
c
c         XLIM      ZLIM      XLIM2     FFAC      NDIV      ICIRC     ISVD
03        1.542     1.50      2.95      500.      40.       1.        0.
c
c         ISURF     NPSI      NSKIPSF   TFMULT    ALPHAR    BETAR     ITRMOD
04        1.        100.      10.0      16.       0.5       1.        2.
c
c..Inboard limiter on midplane
c         I         XLIMA(I)  ZLIMA(I)  X..(I+1)  Z..(I+1)  X..(I+2)  Z..(I+2)
05        1.0       2.800     0.00      1.542     0.00
c
```

```
c         IDIV      PSIRAT    X1SEP     X2SEP     Z1SEP     Z2SEP     NSEPMAX
06        1.        .999      1.542     2.75      0.0       1.50      3.0
c
c..PF coils from Bulmer 92047
c         N         XCOIL     ZCOIL     IGROUPC   ATURNSC   RSCOILS   AINDC(N)
09 pf1u   1.        0.90      +0.17     1.0       1.0       -1.
09 pf2u   2.        0.90      +0.52     2.0       1.0       -1.
09 pf3u   3.        0.90      +0.87     3.0       1.0       -1.
09 pf4u   4.        0.90      +1.22     4.0       1.0       -1.
09 pf5u   5.        1.50      +2.20     5.0       1.0       -1.
09 pf6u   6.        3.57      +2.08     6.0       1.0       -1.
09 pf7u   7.        4.33      +1.12     7.0       1.0       -1.
c
c..control cards for Hofmann shape and current feedback
c-------------------------------------------------------------------------------
c         ICO       NCO       ACOEF(ICO)..(ICO+1) ..(ICO+2) ..(ICO+3) ACOEF(ICO+4)
11        305.      5.0                           1.00      0.030     0.00
11        310.      5.0                 +0.50                         4.0
11        315.      5.0       999.0               3.0       1.0       3.00
11        320.      5.0                                               0.001
11        325.      5.0       0.0                 50.0                1.0
11        330.      5.0       0.0       0.50
11        340.      5.0       4.0       1.0       1.0
11        380.      1.0       18.0
11        540.      1.0       2.0
11        560.      1.0       2.0
c
c         outboard limited circle a=0.4 at t=0.0
c
11        2000.     1.0       0.0
11        2001.     4.0       2.400     2.553     2.683     2.770
11        2005.     4.0       2.800     2.770     2.683     2.553
11        2009.     5.0       2.400     2.322     2.247     2.117     2.030
11        2014.     5.0       2.000     2.030     2.117     2.247     2.332
11        2031.     4.0       0.400     0.370     0.283     0.153
11        2035.     4.0       0.000     -0.153    -0.283    -0.370
11        2039.     5.0       -0.400    -0.392    -0.370    -0.283    -0.153
11        2044.     5.0       0.000     0.153     0.283     0.370     0.392
11        2061.     2.0       1.0       1.0
11        2071.     3.0       1.85      1.20      0.001
11        2074.     3.0       1.85      -1.20     0.001
11        2081.     3.0       1.85      1.20      0.001
11        2084.     3.0       1.85      -1.20     0.001
11        2094.     3.0       1.0e-4
c
c         double-null dee with kx=2.0 at t=4.0 sec
c
11        2100.     1.0       4.00
11        2101.     4.0       2.134     2.386     2.582     2.707
```

```
11        2105.     4.0       2.750     2.707     2.582     2.386
11        2109.     5.0       2.134     1.850     1.806     1.775     1.756
11        2114.     5.0       1.750     1.756     1.775     1.806     1.850
11        2131.     4.0       0.927     0.775     0.556     0.291
11        2135.     4.0       0.000     -0.291    -0.556    -0.775
11        2139.     5.0       -0.927    -1.000    -0.752    -0.503    -0.252
11        2144.     5.0       0.000     0.252     0.503     0.752     1.000
11        2161.     2.0       1.5       1.5
11        2171.     3.0       1.85      1.00      1.0
11        2174.     3.0       1.85      -1.00     1.0
11        2181.     3.0       1.85      1.00      1.0
11        2184.     3.0        1.85      -1.00    1.0
11        2194.     3.0       1.0e-4
c
c         double-null dee with kx=2.0 at t=14.0 sec
c
11        2200.     1.0       14.0
11        2201.     4.0       2.134     2.386     2.582     2.707
11        2205.     4.0       2.750     2.707     2.582     2.386
11        2209.     5.0       2.134     1.850     1.806     1.775     1.756
11        2214.     5.0       1.750     1.756     1.775     1.806     1.850
11        2231.     4.0       0.927     0.775     0.556     0.291
11        2235.     4.0       0.000     -0.291    -0.556    -0.775
11        2239.     5.0       -0.927    -1.000    -0.752    -0.503    -0.252
11        2244.     5.0       0.000     0.252     0.503     0.752     1.000
11        2261.     2.0       1.5       1.5
11        2271.     3.0       1.85      1.00      1.0
11        2274.     3.0       1.85      -1.00     1.0
11        2281.     3.0       1.85      1.00      1.0
11        2284.     3.0        1.85      -1.00    1.0
11        2294.     3.0       1.0e-4
c
c         outboard limited circle a=0.4 at t=18.0
c
11        2300.     1.0       18.0
11        2301.     4.0       2.400     2.553     2.683     2.770
11        2305.     4.0       2.800     2.770     2.683     2.553
11        2309.     5.0       2.400     2.322     2.247     2.117     2.030
11        2314.     5.0       2.000     2.030     2.117     2.247     2.332
11        2331.     4.0       0.400     0.370     0.283     0.153
11        2335.     4.0       0.000     -0.153    -0.283    -0.370
11        2339.     5.0       -0.400    -0.392    -0.370    -0.283    -0.153
11        2344.     5.0       0.000     0.153     0.283     0.370     0.392
11        2361.     2.0       1.0       1.0
11        2371.     3.0       1.85      1.20      0.001
11        2374.     3.0       1.85      -1.20     0.001
11        2381.     3.0       1.85      1.20      0.001
11        2384.     3.0       1.85      -1.20     0.001
11        2394.     3.0       1.0e-4
```

```
c..end of control cards for Hofmann shape and current feedback
c-----------------------------------------------------------------------
c
c..Time to end the simulation (seconds)
11        29.       1.        14.0
c...turn off automatic oh feedback
11        11.       1.        0.0
c...number of contours in plasma and vacuum
11        48.       2.0       11.0      16.0
c...Aux heated transport coeff.
11        121.      1.        .038
c...Use standard feedback subroutines
11        290.      1.0       2.0
c
c         TEVV      DCGS      QSAW      ZEFF      IALPHA    IBALSW    ITEMP
12        -0.2      18.0      1.0       4.0       0.        0.        1.
c
c         ALPHAG    ALPHAP    NEQMAX    XPLAS     ZPLAS     GZERO     QZERO
13        +1.00     +2.00     +800.     2.2500    0.        9.0000    2.5
c
c         ISTART    XZERIC    AXIC      ZZERIC     BZIC
14        1.0       2.400     0.40      0.00      +.40
c
c..initial coil current (following for bias -10vsec)
c         IGROUP    GCUR(1)
15 pf1u   1.        +870.4
15 pf2u   2.        +1340.7
15 pf3u   3.        +1659.0
15 pf4u   4.        +1578.8
15 pf5u   5.        +1694.4
15 pf6u   6.        +472.5
15 pf7u   7.        -65.0
c
c..plasma current as a function of time (multiple cards are used)
c
c         -         PCUR(1)   PCUR(2)   PCUR(3)   PCUR(4)   PCUR(5)   PCUR(6)
16                  100.0     108.0     122.0     145.0     223.9     322.6
16                  369.0     509.0     646.0     845.0     1200.0    1408.0
16                  1605.3    1802.7    2000.0    2000.0    2000.0    2000.0
16                  2000.0    2000.0    2000.0    2000.0    2000.0    2000.0
16                  2000.0    2000.0    2000.0    2000.0    2000.0    2000.0
c
c..initial plasma pressure
c
c         -         PPRES(1)
17                  1200.
c..timing
c         -         TPRO(1)   TPRO(2)   TPRO(3)   TPRO(4)   TPRO(5)   TPRO(6)
18                  0.0       0.04      0.12      0.24      0.40      0.60
```

```
18                0.80     1.20     1.60     2.00     2.40     2.80
18                3.20     3.60     4.00     14.0     14.4     14.8
18                15.2     15.6     16.0     16.4     16.8     17.2
18                17.4     17.6     17.7     17.8     17.9     18.0
c
c..aux heating(t)
c        -        BEAMP(1) BEAMP(2) BEAMP(3) BEAMP(4) BEAMP(5) BEAMP(6)
23                0.       0.       0.       0.       0.       0.
23                0.       0.       0.       0.       0.       0.
23                0.       0.       29.5     29.5     0.       0.
23                0.       0.       0.       0.       0.       0.
23                0.       0.       0.       0.       0.       0.
c
c..density(t)
c        -        RNORM(1) RNORM(2) RNORM(3) RNORM(4) RNORM(5) RNORM(6)
24                .100     .100     .100     .100     .100     .150
24                .200     .300     .400     .500     .600     .700
24                .800     .900     1.00     1.00     1.00     1.00
24                1.00     1.00     1.00     1.00     1.00     1.00
24                1.00     1.00     1.00     1.00     1.00     1.00
c
c..heating profile
c        ABEAM    DBEAM    NEBEAM   EBEAMKEV AMBEAM   FRACPAR  IBOOTST
25       0.0      0.80     1.00                                1.0
c
c FFAC(t) (overrides the value on card 03)
c
c        -        FFACO(1) FFACO(2) FFACO(3) FFACO(4) FFACO(5) FFACO(6)
35                0500.    1000.    1500.    2000.    04000.   08000.
35                08000.   09000.   10000.   11000.   12000.   13000.
35                14000.   15000.   16000.   16000.   16000.   16000.
35                16000.   16000.   16000.   16000.   16000.   16000.
35                32000.   32000.   32000.   32000.   32000.   32000.
c
c ZEFF(t) (overrides the value on card 12)
c
c        -        ZEFFV(1) ZEFFV(2) ZEFFV(3) ZEFFV(4) ZEFFV(5) ZEFFV(6)
36                4.0      3.444    2.6      2.0      2.0      2.0
36                2.0      2.0      2.0      2.0      2.0      2.0
36                2.0      2.0      2.0      2.0      2.0      2.0
36                2.0      2.0      2.0      2.0      2.0      2.0
36                2.0      2.0      2.0      2.0      2.0      2.0
c
c..coil dimensions, packing fractions
c
c        ICO      DXCOIL   DZCOIL   FCU      FSS      TEMPC    CCICS
39       1.       .14      .30      .8       0.       90.
39       2.       .14      .30      .8       0.       90.
39       3.       .14      .30      .8       0.       90.
```

```
39        4.        .14       .30       .8        0.        90.
39        5.        .20       .20       .8        0.        90.
39        6.        .20       .20       .8        0.        90.
39        7.        .25       .25       .8        0.        90.
c
c..End of input file
99
```

Notes :

1. The grid input on the type 01 card is relatively coarse ($\Delta x = \Delta z$ =5 cm). To resolve gradients in the pressure and current density a minimum of 5 grid points across the minor radius is needed at all times to avoid numerical instabilities. This can be used as a guide to determine how coarse a grid to use for a simulation.

2. The variable IDATA=7 on the type 01 card means the Hofmann control algorithm is used (see sections (2.1.4) and (3.3.3)).

3. ACOEF(317)=3 implies the user must supply an additional subroutine for the Hofmann control algorithm as described in section (3.3.3)

4. The variable FFAC is entered once on card 03 and as a function of time on type 35. The value on type 35 overrides the value on type 3. This is a general feature of the program for variables which can be specified in a time-dependent and time-independent manner (i.e., ZEFF, ALPHAR, BETAR).

5. The plasma shape was defined by setting ACOEF(309)=0 and giving the boundary points in ACOEF(2001)-(2018), ACOEF(2031)-(2043), etc. An alternate method of defining the plasma shape is to set ACOEF(309)=1 and generate the boundary points analytically from the shape parameters R_o, a, κ, and δ on the type 42-45 cards. The functional form of this shape profile is shown in Eqs. (3.3) and (3.4) on page 33.

6. The variable NPSI on the type 04 card is set to 100, which is a fairly typical value. The code evolves the surface averaged quantities on a toroidal flux grid. For accounting reasons, the total number of toroidal flux zones NPSIT (i.e. grid intervals) must never exceed NPSI. However, during a current and/or B_T ramp, NPSIT will increase as a function of time and it is possible that NPSIT will exceed NPSI. The code will then crash with an error message stating that the TFMULT

is too small. In such a case, one must start over from $t = 0$ with a larger value of TFMULT. By looking at the time history plot of NPSIT in **tsc.cgm**, one should be able to estimate the final value of NPSIT at the end of the run and adjust TFMULT accordingly. Alternatively, one may increase NPSI to allow for the larger number of toroidal flux zones.

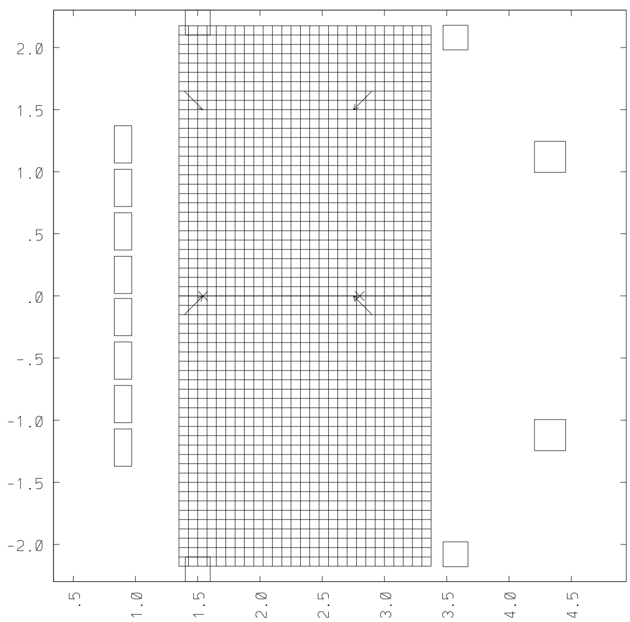

Figure 5.1: The computational grid, coils and limiter points for TPX.

5.2 ITER

The following input file is for a current ramp up and flat top of the proposed ITER experiment. The model does not assume symmetry about the midplane. The original TSC control algorithm is used with two feedback systems to control the radial and vertical position of the plasma. There is no feedback on the plasma shape in this model. The model includes 33 coils external to the computational boundary and no external heating. The geometry is shown in Fig. 5.2 at the end of the input file.

```
RUN 02 --ITER STARTUP          ---  18 time points ...no shape control
c
c          IRST1      IRST2      IPEST      NCYCLE     NSKIPR     NSKIPL     IMOVIE
00         0.0        0.0        0.0        0.         5000.      5000.      0.0
c
c          NX         NZ         ALX        ALZ        ISYM       CCON       IDATA
01         63.        109.       12.8       8.1        0.0        3.5
c
c          DTMINS     DTMAXS     DTFAC      LRSWTCH    IDENS      IPRES      IFUNC
02         .01        5000.      0.40       0.0        1.0        0.0        1.0
c
c          XLIM       ZLIM       XLIM2      FFAC       NDIV       ICIRC      ISVD
03         4.4        6.50       11.9       1000.      60.        0.0        0.0
c
c          ISURF      NPSI       NSKIPSF    TFMULT     ALPHAR     BETAR      ITRMOD
04         1.0        400.       50.        90.        0.5        1.0        2.0
c
c          I          XLIMA(I)   ZLIMA(I)   X..(I+1)   Z..(I+1)   X..(I+2)   Z..(I+2)
05         1.0        10.        -2.        10.2       -1.7       10.4       -1.3
05         4.0        10.6       -1.0       10.8       -.75       11.0       -0.5
05         7.0        11.1       -.1        11.2       0.2        11.3       0.55
05         10.        11.35      0.9        11.4       1.25       11.45      1.75
05         13.        11.4       2.1        11.35      2.4        11.25      2.8
05         16.        11.2       3.2        11.0       3.5
c
c          IDIV       PSIRAT     X1SEP      X2SEP      Z1SEP      Z2SEP      NSEPMAX
06         1.0        0.99       5.0        13.5       0.0        6.5        3.
c
c          IIMP       ILTE       FRACOX     FRACCA     AMGAS      ZGAS       NTHE
07         0.
c
c..Observation pairs
c
c          J          XOBS(2J-1)ZOBS(2J-1)XOBS(2J)   ZOBS(2J)   NPLOTOBS
08         1.00       1.014E+01 5.000E-01 1.130E+01 5.000E-01
08         2.00       9.763E+00 5.033E-01 1.130E+01 5.033E-01
08         3.00       9.477E+00 5.067E-01 1.130E+01 5.067E-01
08         4.00       9.242E+00 5.100E-01 1.130E+01 5.100E-01
08         5.00       9.039E+00 5.133E-01 1.130E+01 5.133E-01
```

```
08        6.00      8.860E+00 5.167E-01 1.130E+01 5.167E-01
08        7.00      8.178E+00 5.333E-01 1.130E+01 5.333E-01
08        8.00      7.315E+00 5.667E-01 1.130E+01 5.667E-01
08        9.00      6.750E+00 6.000E-01 1.130E+01 6.000E-01
08        10.00     5.790E+00 7.000E-01 1.130E+01 7.000E-01
08        11.00     5.260E+00 8.333E-01 1.130E+01 8.333E-01
08        12.00     5.260E+00 1.000E+00 1.130E+01 1.000E+00
08        13.00     5.260E+00 1.167E+00 1.130E+01 1.167E+00
08        14.00     5.220E+00 1.333E+00 1.127E+01 1.333E+00
08        15.00     5.180E+00 1.500E+00 1.123E+01 1.500E+00
08        16.00     5.180E+00 1.500E+00 1.123E+01 1.500E+00
08        17.00     5.180E+00 1.500E+00 1.123E+01 1.500E+00
08        18.00     5.180E+00 1.500E+00 1.123E+01 1.500E+00
08        19.00     1.072E+01 1.000E+00 1.072E+01 0.000E+00
08        20.00     1.053E+01 1.003E+00 1.053E+01 3.333E-03
08        21.00     1.039E+01 1.007E+00 1.039E+01 6.667E-03
08        22.00     1.027E+01 1.010E+00 1.027E+01 1.000E-02
08        23.00     1.017E+01 1.013E+00 1.017E+01 1.333E-02
08        24.00     1.008E+01 1.017E+00 1.008E+01 1.667E-02
08        25.00     9.739E+00 1.033E+00 9.739E+00 3.333E-02
08        26.00     9.308E+00 1.067E+00 9.308E+00 6.667E-02
08        27.00     9.025E+00 1.100E+00 9.025E+00 1.000E-01
08        28.00     8.545E+00 1.200E+00 8.545E+00 2.000E-01
08        29.00     8.280E+00 1.333E+00 8.280E+00 3.333E-01
08        30.00     8.280E+00 1.500E+00 8.280E+00 5.000E-01
08        31.00     8.280E+00 1.667E+00 8.280E+00 6.667E-01
08        32.00     8.243E+00 1.833E+00 8.243E+00 8.333E-01
08        33.00     8.205E+00 2.000E+00 8.205E+00 1.000E+00
08        34.00     8.205E+00 2.000E+00 8.205E+00 1.000E+00
08        35.00     8.205E+00 2.000E+00 8.205E+00 1.000E+00
08        36.00     8.205E+00 2.000E+00 8.205E+00 1.000E+00
c
c..external coils
c------------------------------------------------------------------------------
c         N         XCOIL     ZCOIL     IGROUPC   ATURNSC   RSCOILS   AINDC(N)
09        2.0       5.947      9.981    2.0       1.0       0.01
09        3.0       13.017     7.197    3.0       1.0       0.01
09        4.0       15.193    -2.445    4.0       1.0       0.01
09        5.0       15.193    -5.745    5.0       1.0       0.01
09        6.0       9.650     -9.635    6.0       1.0       0.01
09        7.0       5.184     -9.485    7.0       1.0       0.01
09        8.0       2.016      1.300    8.0       1.0       0.01
c..define coil number 9 in group 9 to belong also to group 10
09        9.0       16.        8.0      9.0       1.0       0.01
09        1010.     1.0        1.0      1.0       1.0       1.0       1.0
09        1010.     1.0        1.0      1.0       1.0       1.0       1.0
09        1010.     1.0        1.0      1.0       1.0       1.0       1.0
c..define coil number 10 in group 9 to belong to coil group 10
09        10.       16.        -8.      9.0       -1.       0.01
```

```
09        1010.     1.0        1.0      1.0       1.0       1.0       1.0
09        1010.     1.0        1.0      1.0       1.0       1.0       1.0
09        1010.     1.0        1.0      1.0       1.0       1.0       1.0
c
c         N         XCOIL     ZCOIL     IGROUPC   ATURNSC   RSCOILS   AINDC(N)
09        11.       2.290     -0.5      1.0       0.03382   0.01
09        12.       2.290      0.5      1.0       0.03382   0.01
09        13.       2.290     -1.5      1.0       0.03382   0.01
09        14.       2.290      1.5      1.0       0.03382   0.01
09        15.       2.290     -2.5      1.0       0.03382   0.01
09        16.       2.290      2.5      1.0       0.03382   0.01
09        17.       2.290     -3.5      1.0       0.03382   0.01
09        18.       2.290      3.5      1.0       0.03382   0.01
09        19.       2.290     -4.5      1.0       0.03382   0.01
09        20.       2.290      4.5      1.0       0.03382   0.01
09        21.       2.290     -5.5      1.0       0.03382   0.01
09        22.       2.290      5.5      1.0       0.03382   0.01
09        23.       2.669     -0.5      1.0       0.049500  0.01
09        24.       2.669      0.5      1.0       0.049500  0.01
09        25.       2.669     -1.5      1.0       0.049500  0.01
09        26.       2.669      1.5      1.0       0.049500  0.01
09        27.       2.669     -2.5      1.0       0.049500  0.01
09        28.       2.669      2.5      1.0       0.049500  0.01
09        29.       2.669     -3.5      1.0       0.049500  0.01
09        30.       2.669      3.5      1.0       0.049500  0.01
09        31.       2.669     -4.5      1.0       0.049500  0.01
09        32.       2.669      4.5      1.0       0.049500  0.01
09        33.       2.669     -5.5      1.0       0.049500  0.01
09        34.       2.669      5.5      1.0       0.049500  0.01
c-----------------------------------------------------------------------------
c..relaxation on equilibrium and equilibrium feedback
c         ICO       NCO       ACOEF(ICO)..(ICO+1) ..(ICO+2) ..(ICO+3) ACOEF(ICO+4)
11        2.0       1.0       0.70
11        50.       2.0       0.20      0.4
11        29.       1.0       42.
c
c         TEVV      DCGS      QSAW      ZEFF      IALPHA    IBALSW    ITEMP
12        -0.1       10.        0.8     1.5       1.0       0.0       1.0
c
c         ALPHAG    ALPHAP    NEQMAX    XPLAS     ZPLAS     GZERO     QZERO
13        1.5       1.5       -900.0     11.0      0.0       48.35     2.0
c
c         ISTART    XZERIC    AXIC      ZZERIC     BZIC
14        1.0       11.0      0.2       +0.5       0.2
c
c..preprogrammed coil currents
c
c         IGROUP    GCUR(1)   GCUR(2)   GCUR(3)   GCUR(4)   GCUR(5)   GCUR(6)
15        1.00      1.281E+05 1.274E+05 1.267E+05 1.260E+05 1.253E+05 1.246E+05
```

```
15        1.00      1.212E+05 1.143E+05 1.074E+05 8.674E+04 5.919E+04 2.477E+04
15        1.00      -9.663E+03-4.409E+04-7.852E+04-7.852E+04-7.852E+04-7.852E+04
c
15        2.00      1.963E+04 1.956E+04 1.949E+04 1.943E+04 1.936E+04 1.929E+04
15        2.00      1.895E+04 1.827E+04 1.760E+04 1.556E+04 1.285E+04 9.465E+03
15        2.00      6.077E+03 2.688E+03 -7.000E+02-7.000E+02-7.000E+02-7.000E+02
c
15        3.00      7.500E+02 7.218E+02 6.936E+02 6.654E+02 6.372E+02 6.090E+02
15        3.00      4.680E+02 1.860E+02 -9.600E+01-9.420E+02-2.070E+03-3.480E+03
15        3.00      -4.890E+03-6.300E+03-7.710E+03-7.710E+03-7.710E+03-7.710E+03
c
15        4.00      1.230E+03 1.216E+03 1.201E+03 1.187E+03 1.173E+03 1.158E+03
15        4.00      1.086E+03 9.427E+02 7.990E+02 3.680E+02 -2.067E+02-9.250E+02
15        4.00      -1.643E+03-2.362E+03-3.080E+03-3.080E+03-3.080E+03-3.080E+03
c
15        5.00      -1.020E+03-1.071E+03-1.123E+03-1.174E+03-1.225E+03-1.277E+03
15        5.00      -1.533E+03-2.047E+03-2.560E+03-4.100E+03-6.153E+03-8.720E+03
15        5.00      -1.129E+04-1.385E+04-1.642E+04-1.642E+04-1.642E+04-1.642E+04
c
15        6.00      2.640E+03 2.648E+03 2.656E+03 2.664E+03 2.672E+03 2.680E+03
15        6.00      2.719E+03 2.799E+03 2.878E+03 3.116E+03 3.433E+03 3.830E+03
15        6.00      4.227E+03 4.623E+03 5.020E+03 5.020E+03 5.020E+03 5.020E+03
c
15        7.00      1.939E+04 1.940E+04 1.941E+04 1.942E+04 1.943E+04 1.944E+04
15        7.00      1.948E+04 1.958E+04 1.967E+04 1.995E+04 2.032E+04 2.079E+04
15        7.00      2.125E+04 2.172E+04 2.218E+04 2.218E+04 2.218E+04 2.218E+04
c
15        8.00      0.000E+00 -3.237E+01-6.473E+01-9.710E+01-1.295E+02-1.618E+02
15        8.00      -3.237E+02-6.473E+02-9.710E+02-1.942E+03-3.237E+03-4.855E+03
15        8.00      -6.473E+03-8.092E+03-9.710E+03-9.710E+03-9.710E+03-9.710E+03
c
c..plasma current
c         -         PCUR(1)   PCUR(2)   PCUR(3)   PCUR(4)   PCUR(5)   PCUR(6)
16                  1.000E+02 1.830E+02 2.660E+02 3.490E+02 4.320E+02 5.150E+02
16                  9.300E+02 1.760E+03 2.590E+03 5.080E+03 8.400E+03 1.255E+04
16                  1.670E+04 2.085E+04 2.500E+04 2.500E+04 2.500E+04 2.500E+04
c
c..plasma pressure
c         -         PPRES(1)  PPRES(2)  PPRES(3)  PPRES(4)  PPRES(5)  PPRES(6)
17                  1.000E+03 1.030E+02 1.060E+02 1.090E+02 1.120E+02 1.150E+02
17                  1.300E+02 1.600E+02 1.900E+02 2.800E+02 4.000E+02 5.500E+02
17                  7.000E+02 8.500E+02 1.000E+03 1.000E+03 1.000E+03 1.000E+03
c
c..timing
c         -         TPRO(1)   TPRO(2)   TPRO(3)   TPRO(4)   TPRO(5)   TPRO(6)
18                  0.000E+00 1.000E-01 2.000E-01 3.000E-01 4.000E-01 5.000E-01
18                  1.000E+00 2.000E+00 3.000E+00 6.000E+00 1.000E+01 1.500E+01
18                  2.000E+01 2.500E+01 3.000E+01 3.500E+01 4.000E+01 4.500E+01
c
```

```
c..density
c        -         RNORM(1)  RNORM(2)  RNORM(3)  RNORM(4)  RNORM(5)  RNORM(6)
24                 1.000E-01 1.330E-01 1.660E-01 1.990E-01 2.320E-01 2.650E-01
24                 4.300E-01 7.600E-01 1.090E+00 2.080E+00 3.400E+00 5.050E+00
24                 6.700E+00 8.350E+00 1.000E+01 1.000E+01 1.000E+01 1.000E+01
c
c..feedback systems
c-----------------------------------------------------------------------------
c..radial control
c        L         NRFB(L)   NFEEDO(L) FBFAC(L)  FBCON(L)  IDELAY(L) FBFACI(L)
19       1.0       10.       1.0       -2.0e6                        -0.0e6
19       1000.     1.0       2.0       3.0       4.0       5.0       6.0
19       1000.     7.0       8.0       9.0       10.       11.       12.
19       1000.     13.       14.       15.       16.       17.       18.
c..vertical control
19       2.0       9.0       19.       1.e7
19       1000.     19.       20.       21.       22.       23.       24.
19       1000.     25.       26.       27.       28.       29.       30.
19       1000.     31.       32.       33.       34.       35.       36.
c..time on, time off, feedback signal
c        L         TFBONS(L) TFBOFS(L) FBFAC1(L) FBFACD(L) IPEXT(L)
20       1.0       0.0       100.                          1.0
20       2.0       0.0       100.                          1.0
c------------------------------------------------------------------------------
c
c..mass enhancement
c        -         FFACO(1)  FFACO(2)  FFACO(3)  FFACO(4)  FFACO(5)  FFACO(6)
35                 2.000E+03 2.660E+03 3.320E+03 3.980E+03 4.640E+03 5.300E+03
35                 8.600E+03 1.520E+04 2.180E+04 4.160E+04 6.800E+04 1.010E+05
35                 1.340E+05 1.670E+05 2.000E+05 2.000E+05 2.000E+05 2.000E+05
c
c..coil dimensions, packing fractions
c        ICO       DXCOIL    DZCOIL    FCU       FSS       TEMPC     CCICS
39       2.0       0.865     0.865     1.0       0.0       2.0       0.0
39       3.0       0.585     1.170     1.0       0.0       2.0       0.0
39       4.0       0.805     1.170     1.0       0.0       2.0       0.0
39       5.0       0.805     1.170     1.0       0.0       2.0       0.0
39       6.0       1.080     1.170     1.0       0.0       2.0       0.0
39       7.0       1.080     1.170     1.0       0.0       2.0       0.0
39       8.0       0.188     5.000     1.0       0.0       2.0       0.0
39       9.0       1.080     1.170     1.0       0.0       2.0       0.0
39       10.       1.080     1.170     1.0       0.0       2.0       0.0
39       11.       0.339     1.0       1.0       0.0       2.0       0.0
39       12.       0.339     1.0       1.0       0.0       2.0       0.0
39       13.       0.339     1.0       1.0       0.0       2.0       0.0
39       14.       0.339     1.0       1.0       0.0       2.0       0.0
39       15.       0.339     1.0       1.0       0.0       2.0       0.0
39       16.       0.339     1.0       1.0       0.0       2.0       0.0
39       17.       0.339     1.0       1.0       0.0       2.0       0.0
```

```
39        18.       0.339     1.0       1.0       0.0       2.0       0.0
39        19.       0.339     1.0       1.0       0.0       2.0       0.0
39        20.       0.339     1.0       1.0       0.0       2.0       0.0
39        21.       0.339     1.0       1.0       0.0       2.0       0.0
39        22.       0.339     1.0       1.0       0.0       2.0       0.0
39        23.       0.413     1.0       1.0       0.0       2.0       0.0
39        24.       0.413     1.0       1.0       0.0       2.0       0.0
39        25.       0.413     1.0       1.0       0.0       2.0       0.0
39        26.       0.413     1.0       1.0       0.0       2.0       0.0
39        27.       0.413     1.0       1.0       0.0       2.0       0.0
39        28.       0.413     1.0       1.0       0.0       2.0       0.0
39        29.       0.413     1.0       1.0       0.0       2.0       0.0
39        30.       0.413     1.0       1.0       0.0       2.0       0.0
39        31.       0.413     1.0       1.0       0.0       2.0       0.0
39        32.       0.413     1.0       1.0       0.0       2.0       0.0
39        33.       0.413     1.0       1.0       0.0       2.0       0.0
39        34.       0.413     1.0       1.0       0.0       2.0       0.0
c
c..End of input file
99
```

Notes :

1. There is no coil number 1 in this model. TSC simply renumbers the existing coils.
2. Since the Hofmann control algorithm is not used, the shape is calculated as the simulation proceeds.
3. A second level of feedback on the coil voltages was not included in this model. This second level of feedback is only required for coils internal to the computational boundary, otherwise it only needs to be included when the coil voltages are desired.

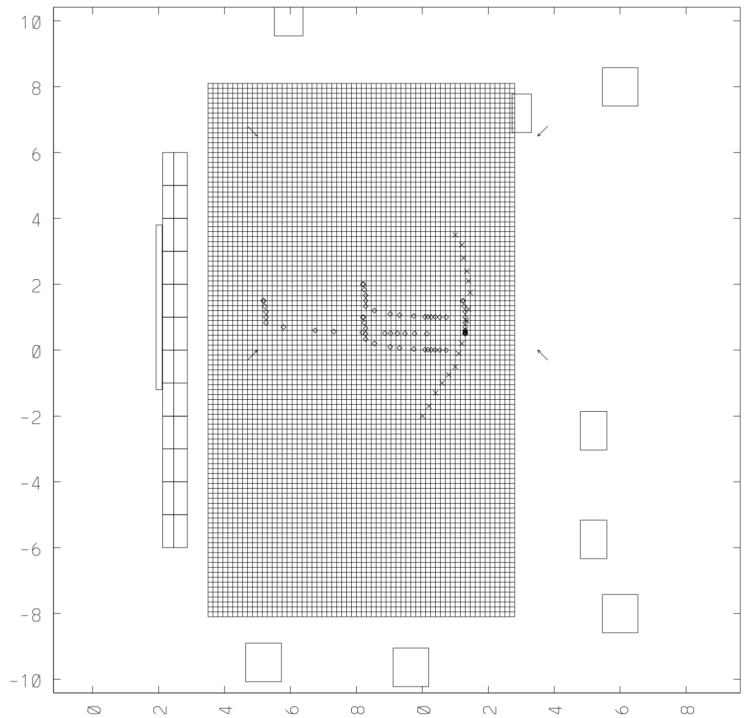

Figure 5.2: The computational grid, coils and observation points for ITER.

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Appendix A

Mathematical Notation

A	=	stream function
a	=	minor radius
$\vec{B}$	=	magnetic field
B_p	=	poloidal magnetic field
$\vec{F}_v$	=	viscous term in force balance
$\vec{E}$	=	Electric field
g	=	toroidal field function
G	=	Green's function for an axisymmetric filament
I_{TF}	=	total current in all toroidal field coils
$\vec{J}$	=	current density
K	=	total toroidal current within a flux surface
K_B	=	Boltzman's constant
$\vec{m}$	=	momentum density
n	=	particle density
N'	=	differential number density $= n\frac{\partial V}{\partial \Phi}$
$\vec{R}$	=	nonideal dissipation vector
q	=	safety factor $= \frac{1}{2\pi}\left(\frac{\partial \Phi}{\partial \Psi}\right)$
$\vec{q}_i, \vec{q}_e$	=	random heat flux vectors
Q_i	=	ion heat flux
Q_e	=	electron heat flux
p	=	plasma pressure
$\vec{v}$	=	velocity vector
$\vec{v}_c$	=	velocity of coordinate flux surface
$\vec{v}_R$	=	velocity of fluid relative to coordinate flux surface
V_L	=	loop voltage $= \frac{2\pi\langle \vec{E}\cdot\vec{B}\rangle}{\langle \vec{B}\cdot\nabla\phi\rangle}$

S_N = external source of particles
S_e, S_i = external sources of electron and ion energy
ω = toroidal component of momentum density
Ω = velocity potential
Φ = toroidal flux $= \frac{1}{2\pi} \int_{\Psi<\Psi_c} d\tau \, \vec{B} \cdot \nabla\phi$
ϕ = toroidal symmetry angle
Ψ = poloidal flux per radian
$\hat{\Psi}$ = Normalized poloidal flux $= (\Psi - \Psi_{min})/(\Psi_{lim} - \Psi_{min})$
$\eta_\perp, \eta_\parallel$ = perpendicular and parallel resistivity
σ_e = differential electron entropy density $= p_e \left(\frac{\partial V}{\partial \Phi}\right)^{5/3}$
σ = total entropy density $= p \left(\frac{\partial V}{\partial \Phi}\right)^{5/3}$
Γ = particle flux
ν_1, ν_2 = compressible and incompressible viscosity

Subscripts

e = electron
i = bulk ion
I = impurity ion
p = proton

Appendix B

Input Variables

B.0.1 Alphabetical Listing of Input Variables

Variable	Description	Card
ABEAM	- Spatial external heat source deposition profile	25
ACOEF()	- A large input array	11
AINDC()	- Self inductance of coil N	09
AION	- Ratio of masses m_i/m_p for dominant ion species.	38
ALPHAG	- Specifies initial toroidal field.	13
ALPHAP	- Pressure exponent for equilibrium calculation	13
ALPHAR	- Exponent for prescribed density function	04
ALPHARV()	- Density exponent as a function of time	47
ALX	- Major radius of outside computational boundary	01
AMBEAM	- Mass of neutral beam particles (amu)	25
AMGAS	- Mass of primary ion species in AMU	07
ATURNSC()	- Number of turns for coil N	09
ATURNSM()	- Number of turns for multipolar coil	49
ATURNSW()	- Number of turns for wire M	10
AXIC	- The half width of an initial plasma current	14
AZERV()	- Preprogrammed minor radius	43
BEAMP(I)	- Power of neutral beam source as a function of time	23
BETAR	- Exponent for prescribed plasma density function	04
BETARV()	- Plasma density exponent as a function of time	48
BZIC	- The half height of an initial plasma current rectangle	14
CCICS	- Initial induced current in coil (kA)	39
CCON	- Major radius of inside computational boundary	01
CPROF	- Option to calculate RF current profile	38

CWICS()	- Initial induced current in wire M (kA)	10
DBEAM	- Spatial external heat source deposition profile	25
DCGS	- Reference number density (10^{19} /m^3)	12
DTFAC	- Time step safety factor	02
DTMAXS	- Maximum time step allowed (μsec)	02
DTMINS	- Minimum time step allowed (μsec)	02
DXCOIL	- Radial thickness of coil in meters	39
DZCOIL	- Vertical thickness of coil in meters	39
DZERV()	- Preprogrammed triangularity	45
EBEAMKEV	- Energy of neutral beam ions (keV)	25
EZERV()	- Preprogrammed ellipticity	44
FBCHIA(I)	- Enhancement factor for thermal conductivity as a function of time	26
FBCON(L)	- Flux offset	19
FBFAC(L)	- Proportionality factor between desired coil current and flux difference	19
FBFAC1(L)	- Gives additional control over FBCON	20
FBFACD(L)	- The time derivative feedback proportionality term	20
FBFACI(L)	- Time integral feedback proportionality term	19
FCU	- Fraction of coil volume which is copper	39
FFAC	- Mass enhancement factor	03
FFACO()	- Mass enhancement as a function of time	35
FPLATE()	- Faction of charged particle heat flux deposited on divertor plate	32
FRACCA	- Fraction of carbon for IIMP=2, initial fraction for IIMP=2	07
FRACOX	- Faction of oxygen for IIMP=1, initial fraction for IIMP=2	07
FRACPAR	- Fraction of neutral beam particles oriented parallel to toroidal field	25
FRACPAR()	- Fraction of neutral beams oriented tangential as a function of time.	50
FREQLH	- Frequency of LH wave (GHz)	38
FSS	- Faction of coil volume which is stainless steel	39
GCUR(I)	- Preprogrammed current in a specified coil (kA)	15
GVOLT()	- Preprogrammed voltage in specified coil group (kV)	37
GZERO	- Specifies vacuum toroidal field as GZERO $\nabla\phi$	13
GZEROV(I)	- Vacuum toroidal field function as a function of time	27
IALPHA	- Switch for α particle heating	12
IBALSW	- Switch for ballooning calculation	12
IBOOTST	- Switch to include bootstrap current in calculation	25

ICIRC	- Control over solving circuit equations for external coils	03
ICO	- External coil number (same as on type 09 card)	39
ICPLBV	- Switch to produce contour plots for the curl of the velocity field	21
ICPLET	- Switch to produce contour plots for the resistivity array	21
ICPLGF	- Switch to produce contour plots for the toroidal field function	21
ICPLPR	- Switch to produce contour plots for the pressure	21
ICPLUV	- Switch to produce contour plots for the divergence of the velocity field	21
ICPLWF	- Switch to produce contour plots for the toroidal velocity	21
ICPLXP	- Switch to produce contour plots of poloidal flux near x-point region	21
ICUBE	- Switch for cubic time point interpolation	11
IDATA	- Choice on data tapes used	01
IDELAY(L)	- Introduces a time delay into feedback calculations	19
IDENS	- Control of density transport calculation	02
IDIV	- Switch to check for magnetic divertor	06
IFUNC	- Control functional form to use for pressure and toroidal field function	02
IGROUPC()	- Group number of coil N	09
IGROUPM()	- Group number of multipole coil	49
IGROUPW()	- Group number of wire M and special switch	10
IIMP	- Control of modeling of impurities	07
ILHCD	- Switch on LHCD calculation	38
ILTE	- Control over local and non local thermal equilibrium	07
IMOVIE	- Graphical output option	00
IPEST	- Control of writing PEST file	00
IPEXT(L)	- Signifies which flux to use from the observation coils	20
IPRES	- Control of energy transport calculation	02
IRIPMOD	- Control of ripple loss model	41
IRIPPLE	- Switch to calculate ripple losses	41
IRST1	- Control of starting time condition	00
IRST2	- Control of writing restart file	00
ISTART	- Starting time point for the calculation to begin	14
ISURF	- Control over using surface averaging	04
ISVD	- Control over performing SVD analysis to obtain x-point	03

ISYM	- Control of symmetry about the midplane	01
ITEMP	- Switch to calculate coil temperature in time	12
ITRMOD	- Switch selecting transport model	04
IVPLBP	- Switch to produce vector plots of the poloidal magnetic field	22
IVPLFR	- Switch to produce vector plots of the forces	22
IVPLJP	- Switch to produce vector plots of the poloidal current	22
IVPLVC	- Switch to produce vector plots of the compressible velocity field	22
IVPLVI	- Switch to produce vector plots of the incompressible velocity field	22
IVPLVT	- Switch to produce vector plots of the total velocity field	22
LRSWTCH	- Choice of normal run or coil test run	02
M	- The index number of a wire (internal coil)	10
MULTN()	- Multipole field type	49
N	- The index number for external coils	09
NCYLE	- Last cycle to be computed.	00
NDIV	- Number of subcyles for short time scale equations	03
NEBEAM	- Specifies the spatial external heat source deposition profile	25
NEQMAX	- Maximum number of equilibrium iterations allowed	13
NFEEDO(L)	- Observation pair number used in feedback system	19
NOPLOT()	- Suppresses specified plots during output	40
NPITCH	- Number of pitch angles for integration in ripple calculation	41
NPLOTOBS	- Control over plotting time history of observation point	08
NPSI	- Number of PSI surfaces for transport calculation	04
NRFB(L)	- Switch for feedback on coils and plasma current	19
NSEPMAX	- Maximum number of separatrices that will be found	06
NSKIPL	- Number of cycles between plot cycles	00
NSKIPSF	- Number of cycles skipped between surface average calculation	04
NTFCOIL	- Number of TF coils	41
NTHE	- Number of theta zones used in impurity diffusion calculation	07
NX	- Number of grid points in x direction of computational domain	01
NZ	- Number of grid points in z direction of computational domain	01
PCUR(I)	- Preprogrammed plasma current (kA)	16

PLHAMP()	- Lower hybrid heat power as a function of time	46
PPRES(I)	- Preprogrammed pressure for IPRES=1. (mks)	17
PSIRAT	- Specifies value of PSI used to limit plasma from separatrix	06
QSAW	- Restriction on q for resistivity enhancement to take effect	12
QZERO	- Initial value of safety factor at magnetic axis for IFUNC=1	13
RESGS()	- Resistance of gap in coil	33
RIPMAX	- Ripple magnitude at radius of TF coil	41
RIPMULT	- Ripple multiplier	41
RNORM(I)	- Normalized central density as a function of time for IDENS=1	24
ROMULT()	- Major radius about which multipolar fields are expanded	49
RSCOILS()	- Resistance of coil N (ohms)	09
RSWIRES()	- Resistance of wire M (ohms)	10
RTFCOIL	- Radius of TF coil	41
RZERV()	- Preprogrammed major radius	42
TEMPC	- Initial temperature of coil (Kelvin)	39
TEVV	- Temperature of the vacuum region	12
TEVVO()	- Vacuum temperature as a function of time	34
TFBOFS(L)	- Time when feedback system L is turned off (sec)	20
TFBONS(L)	- Time when feedback system L is turned on (sec)	20
TFMULT	- Multiplier for toroidal flux domain	04
TPEST(I)	- Time at which PEST output is to written	29
TPRO(I)	- Time corresponding to GCUR(I),PCUR(I),etc (seconds)	18
VILIM	- Lower velocity limit for the LHCD spectrum	38
VLOOP(I)	- Preprogrammed loop voltage for OH system	28
X1SEP	- Lower radial bound for separatrix search	06
X2SEP	- Upper radial bound for separatrix search	06
XCOIL()	- The x coordinate of the center of an external coil	09
XLIM	- Lower bound on radial region plasma can occupy	03
XLIM2	- Upper bound on radial region plasma can occupy	03
XLIMA()	- The x coordinates of the limiter surface	05
XLPLATE()	- The x coordinate of inner side of divertor plate	32
XMAGO(I)	- The x coordinate of the magnetic axis position in time.	30
XOBS()	- The x coordinate of an observation point	08
XPLAS	- Initial guess for x coordinate of magnetic axis	13

XRPLATE()	- The x coordinate of rightmost side of divertor plate	32
XWIRE()	- The x coordinate of the center of a wire	10
XZERIC	- The x coordinate of the center of an initial plasma	14
Z1SEP	- Lower z bound for separatrix search	06
Z2SEP	- Upper z bound for separatrix search	06
ZCOIL()	- The z coordinate of the center of an external coil	09
ZEFF	- The resistivity enhancement factor	12
ZEFFV()	- Resistivity enhancement as a function of time	36
ZGAS	- Charge of primary ion species	07
ZION	- Atomic number of the dominant ion species	38
ZLIM	- Bound on axial region plasma can occupy	03
ZLIMA()	- The z coordinates of the limiter surface	05
ZLPLATE()	- The z coordinate of inner side of divertor plate	32
ZMAGO(I)	- The z coordinate of the magnetic axis position in time	31
ZOBS()	- The z coordinate of an observation point	08
ZPLAS	- Initial guess for z coordinate of magnetic axis	13
ZRPLATE()	- The z coordinate of rightmost side of divertor plate	32
ZWIRE()	- The z coordinate of the center of a wire	10
ZZERIC	- The z coordinate of the center of an initial plasma current rectangle	14

B.0.2 Format of Input File

NAME CARD		11	21	31	41	51	61	71
00	Control	IRST1	IRST2	IPEST	NCYCLE	NSKIPR	NSKIPL	IMOVIE
01	Dimensions	NX	NZ	ALX	ALZ	ISYM	CCON	IDATA
02	Time step	DTMINS	DTMAXS	DTFAC	LRSWTCH	IDENS	IPRES	IFUNC
03	Numerical	XLIM	ZLIM	XLIM2	FFAC	NDIV	ICIRC	ISVD
04	Surf. Ave.	ISURF	NPSI	NSKIPSF	TFMULT	ALPHAR	BETAR	ITRMOD
05	Limiter	I	XLIMA(I)	ZLIMA(I)	XLIMA(I+1)	ZLIMA(I+1)	XLIMA(I+2)	ZLIM(I+2)
06	Divertor	IDIV	PSIRAT	X1SEP	X2SEP	Z1SEP	Z2SEP	NSEPMAX
07	Impurities	IIMP	ILTE	FRACOX	FRACCA	AMGAS	ZGAS	NTHE
08	Obs. pairs	J	XOBS(2J-1)	ZOBS(2J-1)	XOBS(2J)	ZOBS(2J)	NPLOTOBS	
09	Ext. coils	N	XCOIL(N)	ZCOIL(N)	IGROUPC(N)	ATURNSC(N)	RSCOILS(N)	AINDC(N)
10	Int. coils	M	XWIRE(M)	ZWIRE(M)	IGROUPW(M)	ATURNSW(M)	RSWIRES(M)	CWICS(M)
11	ACOEF	ICO	NCO	ACOEF(ICO)	...(ICO+1)	...	...	...(ICO+4)
12	Tranport	TEVV	DCGS	QSAW	ZEFF	IALPHA	IBALSW	ITEMP
13	Init. cond-1	ALPHAG	ALPHAP	NEQMAX	XPLAS	ZPLAS	GZERO	QZERO
14	Init. cond-2	ISTART	XZERIC	AXIC	ZZERIC	BZIC		
15	Coil groups	IGROUP	GCUR(1)	...	...	...	...	GCUR(6)
16	Plasma curr.	-	PCUR(1)	...	...	...	...	PCUR(6)
17	Plasma press.	-	PPRES(1)	...	...	...	...	PPRES(6)
18	Timing	-	TPRO(1)	...	...	...	...	TPRO(6)
19	Feedback-1	L	NRFB(L)	NFEEDO(L)	FBFAC(L)	FBCON(L)	IDELAY(L)	FBFACI(L)
20	Feedback-2	L	TFBONS(L)	TFBOFS(L)	FBFAC1(L)	FBFACD(L)	IPEXT(L)	
21	Contour plot	ICPLET	ICPLGF	ICPLWF	ICPLPR	ICPLBV	ICPLUV	ICPLXP
22	Vector plot	IVPLBP	IVPLVI	IVPLFR	IVPLJP	IVPLVC	IVPLVT	-
23	Aux. heat	-	BEAMP(1)	...	...	...	...	BEAMP(6)
24	Density	-	RNORM(1)	...	...	...	...	RNORM(6)
25	Dep. prof.	ABEAM	DBEAM	NEBEAM	EBEAMKEV	AMBEAM	FRACPAR	IBOOTST
26	Anom. trans.	-	FBCHIA(1)	...	...	...	...	FBCHIA(6)
27	Tor. field	-	GZEROV(1)	...	...	...	...	GZEROV(6)
28	Loop volt.	-	VLOOPV(1)	...	...	...	...	VLOOPV(6)
29	PEST output	-	TPEST(1)	...	...	...	...	TPEST(6)
30	Mag. Axis(x)	-	XMAGO(1)	...	...	...	...	XMAGO(6)
31	Mag. Axis(z)	-	ZMAGO(1)	...	...	...	...	ZMAGO(6)
32	Divertor	N	XLPLATE(N)	ZLPLATE(N)	XRPLATE(N)	ZRPLATE(N)	FPLATE(N,1)	FPLATE(N,2)
33	Coil grp-2	IGROUP	RESGS( )					
34	TEVV(t)	-	TEVVO(1)	...	...	...	...	TEVVO(6)
35	FFAC(t)	-	FFACO(1)	...	...	...	...	FFACO(6)
36	ZEFF(t)	-	ZEFFV(1)	...	...	...	...	ZEFFV(6)
37	Volt group	IGROUP	GVOLT(1)	...	...	...	...	GVOLT(6)
38	LHDEP	ILHCD	VILIM	FREQLH	AION	ZION	CPROF	IFK
39	Ext. coil-2	N	DXCOIL(N)	DZCOIL(N)	FCU(N)	FSS(N)	TEMPC(N)	CCICS(N)
40	Noplot	NOPLOT(1)	...	...	...	...	...	NOPLOT(7)
41	Ripple	IRIPPL	NTFCOIL	RIPMAX	RTFCOIL	NPITCH	RIPMULT	IRIPMOD
42	Major rad.	-	RZERV(1)	...	...	...	...	RZERV(6)
43	Minor rad.	-	AZERV(1)	...	...	...	...	AZERV(6)
44	Ellipticity	-	EZERV(1)	...	...	...	...	EZERV(6)
45	Triangularity	-	DZERV(1)	...	...	...	...	DZERV(6)
46	LH heating	-	PLHAMP(1)	...	...	...	...	PLHAMP(6)
47	Dens. exp-1	-	ALPHARV(1)	...	...	...	...	ALPHARV(6)
48	Dens. exp-2	-	BETARV(1)	...	...	...	...	BETARV(6)
49	Multipole	N	MULTN(N)	ROMULT(N)	IGROUPM(N)	ATURNSM(N)		
50	CD	-	FRACPAR(1)	...	...	...	...	FRACPAR(6)
51	alh	-	A(1)	...	...	...	...	A(6)
52	dlh	-	D(1)	...	...	...	...	D(6)
53	a1lh	-	A1(1)	...	...	...	...	A1(6)
54	a2lh	-	A2(1)	...	...	...	...	A2(6)
55	ac	-	AC(1)	...	...	...	...	AC(6)
56	dc	-	DC(1)	...	...	...	...	DC(6)
57	ac1	-	AC1(1)	...	...	...	...	AC1(6)
58	ac2	-	AC2(1)	...	...	...	...	AC2(6)
59	ICRH	-	RHAMP(1)	...	...	...	...	RHAMP(6)
60	Halo Temp	-	TH(1)	...	...	...	...	TH(6)
61	Halo Width	-	AH(1)	...	...	...	...	AH(6)
99								

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