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**ZORNOC: A 1½-D Tokamak
Data Analysis Code for
Studying Noncircular
High Beta Plasmas**

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ZORNOC: A $1\frac{1}{2}$ -D TOKAMAK DATA ANALYSIS CODE
FOR STUDYING NONCIRCULAR HIGH BETA PLASMAS

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ABSTRACT

We have developed a new tokamak data analysis code, ZORNOC, to study noncircular, high beta plasmas in the Impurity Study Experiment (ISX-B). These plasmas exhibit significant flux surface shifts and elongation in both ohmically heated and beam-heated discharges. We determine the MHD equilibrium flux surface geometry by solving the Grad-Shafranov equation based on: (1) the shape of the outermost flux surface, deduced from the magnetic loop probes; (2) a pressure profile, deduced by means of Thomson scattering data (electrons), charge exchange data (ions), and a Fokker-Planck model (fast ions); and (3) a safety factor profile, determined from the experimental data using a simple model ($Z_{\text{eff}} = \text{const}$) that is self-consistently altered while the plasma equilibrium is iterated. For beam-heated discharges we determine the beam deposition profile by means of a Monte Carlo scheme and the slowing down of the fast ions by means of an analytical solution of the Fokker-Planck equation. The code also carries out an electron power balance and calculates various confinement parameters. The code is described and examples of its operation are given.

1. INTRODUCTION

For analysis of plasmas in the Impurity Study Experiment (ISX-B), in which high poloidal beta (β_p) produces significant shift and elongation of the flux surfaces, we have developed a static 1½-D tokamak data analysis code to study noncircular high beta plasmas in ohmically heated and beam-heated discharges. The new code is more general than the previous data analysis code, ZORDIC,¹ in that it can study plasmas with nonconcentric flux surfaces, both elliptical and D-shaped, as they are encountered in circular high beta plasmas or in tokamak shaping experiments.

The code starts with the gross plasma parameters ($\bar{n}_e$, I , B_T , V), the Thomson scattering profiles for electron temperature and density [$T_e(r)$, $n_e^{\text{rel}}(r)$], and the charge exchange ion temperature [$T_i(\phi)$]. As in ZORDIC, we ignore any poloidal dependence of the plasma quantities, either using the assumption that they are constant on given poloidal flux surfaces (for such quantities as T_e , T_i , and n_e) or taking flux surface averages for those quantities (such as J and B_θ) that are not poloidally symmetric.

Using a fixed boundary equilibrium code,² we solve the Grad-Shafranov equation based on (1) the shape of the outermost flux surface, deduced from the magnetic loop probes; (2) a pressure profile, deduced by means of Thomson scattering data (electrons), charge exchange data (ions), and a Fokker-Planck model (fast ions); and (3) a safety factor profile deduced from the experimental data using a simple model ($Z_{\text{eff}} = \text{const}$) that is self-consistently altered while the plasma equilibrium is iterated. As an initial guess for the shape of the flux surfaces, we adopt the shape of the outermost surface as deduced from the magnetic loop probes. Later, the flux surface shapes are obtained directly from the poloidal magnetic flux function (ψ) contours obtained from solving for the plasma equilibrium. The ion temperature profiles are assumed to follow the shape of the electron temperature or density, with the central ion temperature obtained directly from the charge exchange data (a value obtained from Artsimovich scaling may be used instead).

We introduce a single impurity species coronal model, the average ion model,³ to take into account the effective Z (Z_{eff}) deduced from conductivity. The code then calculates various confinement parameters (Z_{eff} , $\langle T \rangle$, $\langle n \rangle$, betas, confinement times, etc.) and carries out an electron power balance for ohmically heated and beam-heated discharges. We determine the beam deposition profile, $H(\psi)$, as a function of the poloidal flux function, ψ , using a Monte Carlo code, NFREYA.⁴ The slowing down of the fast ions is studied using the moments code, GEGI.⁵

In Sect. 2 of this report, we describe the flux surface contours. In Sect. 3, we give the methods used to calculate the plasma Z_{eff} and the safety factor (q) profile. Section 4 contains a description of the impurity modeling process, and Sect. 5 gives the formulas used for computing various plasma parameters. Section 6 deals with neutral beam injection, Sect. 7 with the determination of the plasma equilibrium and the current density distribution. In Sect. 8, the method for carrying out the electron power balance is described.

Section 9 describes the data reduction process used to create the input data file for ZORNOC, and Sect. 10 describes the program and gives examples of its results. A listing of the code's command file and a description of each of its common blocks are contained in the Appendix.

2. DESCRIPTION OF THE FLUX SURFACE CONTOURS

We define a rectangular coordinate system (R,Z) with the R axis along the major radius on the midplane and the Z axis along the symmetry axis of the torus (see Fig. 1). The flux surface contours of the plasma can then be described by the parametric equations.

$$Z(\rho) = \epsilon(\rho) a \rho \sin \theta , \quad (1)$$

$$R(\rho) = R_0(\rho) + a \rho \cos [\theta + \delta(\rho) \sin \theta] ,$$

where ρ is the normalized minor radius ($0 \leq \rho \leq 1$), ϵ is the ellipticity ($\epsilon = b/a$), a is the minor radius in the midplane, b is the maximum displacement along the Z axis, θ is the polar angle ($0 \leq \theta \leq 2\pi$), R_0 is the major radius of the flux surface, δ is the triangularity ($\delta = c/a$), and c is the triangularity shift of the major radius along the midplane. When $\delta = 0$, an elliptical cross section results, with the ratio of major and minor axis being ϵ . A value of $\delta > 0$ corresponds roughly to a triangular shape or D-shape pointing outward from the symmetry axis.

The flux surface cross-sectional area defined by Eq. (1) is quite accurately given by the formula⁶

$$S = \pi \epsilon \rho^2 a^2 [J_0(\delta) + J_2(\delta)] ,$$

where J_0 and J_2 are Bessel functions with arguments in the range $0 \leq \delta \leq 1$.

The toroidal plasma volume, V , enclosed by any flux surface can be obtained by rotating the cross section given by Eq. (1) around the symmetry axis and is given by the expression⁶

$$V = 2\pi R_0 S [1 - (0.233 \delta \rho a / R_0)] .$$

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Fig. 1. Definition of flux surface cross-sectional geometric parameters.

3. CALCULATION OF EFFECTIVE Z AND SAFETY FACTOR PROFILE

3.1 CALCULATION OF EFFECTIVE Z

In the present code we have implemented two different methods of calculating the plasma Z_{eff} : (1) the constant Z_{eff} model and (2) the Spitzer model. The first model assumes that Z_{eff} is constant across the plasma, independent of ρ . The second model assumes that the current density distribution is $J \propto T_e^{3/2}$ and allows a determination of the spatial dependence of Z_{eff} through a local application of Ohm's law.

3.1.1 Constant Z_{eff} Model*

The total plasma current is given by

$$I = \int_S \sigma_{\parallel} E \, dS + \Delta I_B, \quad (2)$$

where ΔI_B is the neutral beam-induced current perturbation and $\int_S$ denotes a surface integral over the entire plasma. Assuming the voltage, V_t , is constant across the plasma, the electric field is

$$E = \frac{V_t}{2\pi R_0},$$

and

$$V_t = V_{\ell} - \frac{d}{dt} (LI),$$

where V_{ℓ} is the loop voltage corrected by inductive effects. The neo-classical parallel conductivity, $\sigma_{\parallel}$, is given by⁷

$$\sigma_{\parallel} = \sigma_0 \Lambda_E [1 - f_T / (1 - \xi v_{*e})] [1 - C_R f_T / (1 + \xi v_{*e})].$$

* Temperature is given in electron volts, density in centimeters⁻³, current in amperes, magnetic field in gauss, and mass in units of proton mass.

Here $\sigma_0 \Lambda_E$ is the Spitzer conductivity, where

$$\sigma_0 = 2.817938 \times 10^{-4} n_e \tau_{ee} \text{ mho cm}^{-1} ,$$

$$\tau_{ee} = 3.440742 \times 10^5 T_e^{3/2} / (n_e \ln \Lambda_{ee}) ,$$

and

$$\ln \Lambda_{ee} = \begin{cases} 23.46 + 0.5 \ln [T_e^2 T_i / n_e (T_i / T_e + Z_{eff})] , & T_e \leq 6.67 Z_{eff}^2 (\text{eV}) \\ 24.41 + 0.5 \ln [Z_{eff}^2 T_e T_i / n_e (T_i / T_e + Z_{eff})] , & T_e \geq 6.67 Z_{eff}^2 (\text{eV}) \end{cases}$$

Crume⁷ has obtained for Λ_E the parametrization

$$\Lambda_E(\bar{Z}) = 3.3956 [(0.84598 + \bar{Z}) / (2.1734 + \bar{Z})] / \bar{Z} ,$$

where $\bar{Z}$ as defined in Ref. 7 is approximately Z_{eff} . The collisionality parameter, ν_{*e} , for electrons is given by

$$\nu_{*e} = \frac{6.92 \times 10^{-14} R_0 q n_e \ln \Lambda_{ee}}{T_e^2 \gamma^{3/2}} ,$$

where $\gamma = \rho a / R_0$. The fraction of trapped particles, f_T , is given by

$$f_T(\gamma) = 1 - (1 - \gamma)^2 (1 - \gamma^2)^{-1/2} (1 + 1.46^{1/2})^{-1} .$$

The conductivity reduction, C_R , due to electron-electron collisions, as a function of Z_{eff} , is

$$C_R(\bar{Z}) = 0.56[(3.0 - \bar{Z})/(3.0 + \bar{Z})]/\bar{Z} ,$$

and the parameter ξ is given by $\xi(\bar{Z}) = 0.58 + 0.20 \bar{Z}$.

We follow an iterative procedure to obtain the value of Z_{eff} that satisfies Eq. (2), starting with $Z_{\text{eff}} = 1$, $\ln \Lambda_{ee} = 17$, and $v_{*e} = 1$. Once we know Z_{eff} (and thus $\sigma_{\parallel}$), we initially approximate the current density by $J = \sigma_{\parallel} E$ (assumed constant on each flux surface) and the integrated current by

$$I(\rho) = \int_{S_{\rho}} J \, dS .$$

3.1.2 Spitzer Model

In this model we assume the current density to be given by

$$J = C \frac{T_e^{3/2}}{R_o} ,$$

where C is a constant determined by the condition

$$I = \int_{S'} J \, dS .$$

Knowing the current density and applying Ohm's law on each flux surface, we can follow an iterative procedure similar to the previous one to determine Z_{eff} as a function of ρ .

3.2 CALCULATION OF SAFETY FACTOR PROFILE

In the general case of a noncircular plasma, the safety factor, q , is given by the expression⁸

$$q = \frac{d\phi}{d\psi} , \quad (3)$$

where ϕ , the toroidal magnetic flux function, is given by

$$\phi = (2\pi)^{-1} \int_{S_1} B_T dS ,$$

and ψ , the poloidal magnetic flux function, is given by

$$\psi = (2\pi)^{-1} \int_{S_2} B_\theta dS ,$$

and S_1 and S_2 are surfaces normal to the toroidal and poloidal magnetic fields, B_T and B_θ respectively. Expression (3) reduces to

$$q(\rho) = \frac{B_T \left(\oint_{\ell_\rho} d\ell \right)^2}{2\pi R_o(\rho) \mu_o \left(\int_{S_\rho} J dS \right)} ,$$

where the line integral is the contour length, ℓ_ρ , of a flux surface, ρ . A more simplified expression with the units we are using is

$$q(\rho) = \frac{0.126 B_T \ell_\rho^2}{R_o(\rho) I(\rho)} .$$

Here we have assumed the introduction of an average poloidal field, given by

$$\overline{B}_\theta(\rho) = 1.2566 \frac{I(\rho)}{\ell_\rho} .$$

4. IMPURITY MODELING

We use a single impurity species model to take into account the plasma Z_{eff} deduced from conductivity. Any one of three different impurity species can be selected: carbon, oxygen, or iron. To deal with the particular impurity selected, we apply a simple coronal model, the average ion model.³ In this way we can easily determine the average charge state of the impurity, Z_{avg} , and the power radiated per electron and impurity ion. Both are a function of the electron temperature alone.

From the definition of Z_{eff} and the charge neutrality equation,

$$Z_{\text{eff}} = \frac{n_i + Z_{\text{avg}}^2 n_z}{n_e}$$

and

$$n_i + n_b + Z_{\text{avg}} n_z = n_e ,$$

we can determine the proton density, n_i , and the impurity density, n_z , as a function of the electron temperature and density; n_b is the fast ion density.

Once we know Q_R , the radiation power loss per unit volume (as for Z_{avg} , we have analytical expressions with tabulated coefficients), we can calculate the integrated radiation power loss, P_R :

$$P_R = \int_{V_\rho} Q_R dV ,$$

within the volume, V_ρ , enclosed by the flux surface ρ .

5. CALCULATION OF PLASMA PARAMETERS

We calculate the various confinement parameters of theoretical and experimental interest that can be deduced from the experimental data. We give here a useful set of formulas for computing these parameters as they have been implemented in the ZORNOC code.

(1) Density-averaged temperatures, $\langle T \rangle$:

$$\langle T \rangle = \int_{V'} nT \, dV / \int_{V'} n \, dV \quad (\text{eV}) .$$

(2) Volume-averaged densities, $\langle n \rangle$:

$$\langle n \rangle = \int_{V'} n \, dV / V' \quad (\text{cm}^{-3}) .$$

(3) Plasma kinetic pressure, p :

$$p = 1.6 \times 10^{-12} (n_e T_e + n_i T_i) \quad (\text{D/cm}^2) .$$

(4) Volume-averaged plasma pressure, $\langle p \rangle$:

$$\langle p \rangle = \int_{V'} p \, dV / V' \quad (\text{D/cm}^2) .$$

(5) Internal plasma inductance per unit of length, ℓ_i :

$$\ell_i = \int_{S'} B_\theta^2 \, dS / (S' \bar{B}_\theta'^2) .$$

(6) Averaged current density, $\langle J \rangle$:

$$\langle J \rangle = \int_{S'} J \, dS / S' .$$

(7) Ratio of electron drift velocity to electron thermal velocity, ξ :

$$\xi = \langle J \rangle \sqrt{m_e / 2 \langle T_e \rangle} / (1.2658 \times 10^{-6} \langle n_e \rangle) .$$

(8) Poloidal flux function, ψ_ρ :

$$\psi_\rho = \int_{S_\rho} \frac{B_T dS}{2\pi q} .$$

(9) Various plasma betas:

$$\langle \beta_p \rangle \equiv 2\mu_o \langle p \rangle / \overline{B_\theta'}^2 ,$$

$$\langle \beta_T \rangle \equiv 2\mu_o \langle p \rangle / B_T^2 ,$$

$$\beta^* \equiv 2\mu_o (\langle p \rangle^2)^{1/2} / B_T^2 ,$$

$$\beta_J \equiv 2 \langle p \rangle / (I / \oint d\ell)^2 ,$$

$$\beta_I \equiv 8\pi \langle p \rangle / \mu_o I^2 ,$$

$$\beta_T(0) = 4.03 \times 10^{-9} [n_e(0)T_e(0) + n_i(0)T_i(0)] / B_T^2 .$$

See Ref. 9 for a discussion of β_I .

6. NEUTRAL BEAM INJECTION

6.1 BEAM DEPOSITION PROFILE

The beam deposition profile, $H(\psi)$, is an injection shape factor whose volume average represents the percentage of the fast neutrals that are absorbed by the plasma. We compute $H(\psi)$ with a Monte Carlo deposition code, NFREYA,⁴ which was designed for noncircular tokamak plasmas with displaced flux surfaces. The birth locations of the fast ions are calculated by following the neutral beam particles from the injector source along straight paths until they are ionized or suffer charge-exchange collisions. The code can be used with or without bounce averaging. With bounce averaging, it bounce averages $H(\psi)$ over the initial ion orbits and weights the deposition profile by the fraction of the bounce time the ion spends in each interval of ψ .

6.2 PLASMA PARAMETERS RELATED TO BEAM INJECTION

In ZORNOC we calculate the parameters related to neutral beam injection with the expressions given in Ref. 10. The fast ion birth rate is

$$\dot{n}_f(\psi) = \frac{I_o/e}{V'} H(\psi) \quad (\text{sec}^{-1} \text{cm}^{-3}) ,$$

where I_o is the neutral beam equivalent current. The stored fast ion density is

$$n_f(\psi) = \dot{n}_f(\psi) \tau_s N \quad (\text{cm}^{-3}) ,$$

where

$$N \cong 1 - \exp(-\tau_f/\tau_{cx}) \tau_{cx}/\tau_s , \text{ and}$$

τ_f , τ_{cx} , and τ_s are the ion lifetime, charge-exchange lifetime, and the Spitzer slowing-down time, respectively. Expressions for calculating these parameters are given in Ref. 10. The fast ion energy density is

$$W_b(\psi) = \dot{n}_f(\psi) \tau_s E_o \frac{G_e(\psi)}{2} \quad (\text{eV}) ,$$

where E_o is the beam energy (eV) and $G_e(\psi)$ is the energy fraction transferred from the fast ions to the plasma electrons while slowing down. The fast ion pressure is

$$p_b(\psi) = 1.6 \times 10^{-12} (2/3) W_b(\psi) \quad (\text{D/cm}^2) .$$

Knowing the fast ion pressure profile, we can calculate the beam contribution to the plasma betas. Power density transferred from the beam to the electrons (Q_{Be}) and to the ions (Q_{Bi}) is given by the expressions

$$Q_{Be}(\psi) = \dot{n}_f(\psi) E_o G_e(\psi) \quad (\text{eV sec}^{-1} \text{ cm}^{-3}) ,$$

$$Q_{Bi}(\psi) = \dot{n}_f(\psi) E_o G_i(\psi) \quad (\text{eV sec}^{-1} \text{ cm}^{-3}) .$$

G_e and G_i are calculated in ZORNOC by means of the moments code, GEGI, which uses an approximate analytical solution of the Fokker-Planck equation in which the distribution function is expanded in a series of Legendre polynomials and only the zeroth order term is retained.

7. PLASMA EQUILIBRIUM AND CURRENT DENSITY DISTRIBUTION

We use a fixed boundary equilibrium code² to determine, consistent with the plasma equilibrium, (1) the shapes of the inner flux surfaces, (2) their displacements or shifts, and (3) the current density distribution. This code solves the Grad-Shafranov equation,

$$\begin{aligned}\Delta^*\psi(R,Z) &\equiv R \frac{\partial}{\partial R} \left(\frac{1}{R} \frac{\partial \psi}{\partial R} \right) + \frac{\partial^2 \psi}{\partial Z^2} \\ &= -4\pi R^2 p' - FF',\end{aligned}$$

where F is the toroidal flux function ($F = RB_T$) and p' and F' are derivatives with respect to ψ . The code has as its input (1) the shape of the outermost flux surface, deduced from the magnetic loop probes, (2) a plasma pressure profile, $p(\psi)$, and (3) a safety factor profile, $q(\psi)$.

The toroidal current density distribution is then given by

$$J(R,Z) = c \frac{\Delta^*\psi}{4\pi K},$$

where c is the velocity of light.

8. ELECTRON POWER BALANCE

In an ohmically heated discharge the electrons are heated by the Joule heating effect. Since we already know the spatial distribution of the current, we can determine the radial dependence of the ohmic heating power input to the electrons. The ohmic heating power density, Q_{OH} , is given by

$$Q_{OH}(\rho) = \frac{V_t J(\rho) \Delta S}{\Delta V},$$

where ΔS is the area between two contiguous contours and ΔV is the differential volume between two contiguous flux surfaces.

The integrated ohmic heating power, P_{OH} , is given by

$$P_{OH}(\rho) = \int_V Q_{OH}(\rho) dV.$$

The electrons heat the ions by Coulomb collisions, and the power density transferred by this mechanism is given by¹¹

$$Q_{ei} = 1.26 \times 10^{-19} \frac{[Z] n_e^2 (T_e - T_i)}{m_i T_e^{3/2}} \quad (\text{W/cm}^3),$$

where $[Z]$ is the effective Z for energy transfer, which is usually very close to 1, given by

$$[Z] = \sum_{j \neq e} \frac{n_j m_i Z_j^2}{n_e m_j}.$$

Here m_i is the plasma ion mass. The energy content of the electrons, W_e , and ions, W_i can be determined from the experimental density and temperature profiles with the expressions

$$W_e(\rho) = \int_{V_\rho} \frac{3}{2} n_e T_e dV$$

$$W_i(\rho) = \int_{V_\rho} \frac{3}{2} n_i T_i dV .$$

The total energy of the plasma is

$$W(\rho) = W_e(\rho) + W_i(\rho) .$$

From these results we can deduce the confinement times, assuming $\dot{W} = 0$.
The gross electron energy confinement time is given by

$$\tau_{Ee}(\rho) = \frac{W_e(\rho)}{P_{OH}(\rho) + P_{Be}(\rho) - P_{ei}(\rho)} ,$$

the ion energy confinement time by

$$\tau_{Ei}(\rho) = \frac{W_i(\rho)}{P_{ei}(\rho) + P_{Bi}(\rho)} ,$$

and the gross energy confinement time by

$$\tau_E(\rho) = \frac{W(\rho)}{P_{OH}(\rho) + P_{BT}(\rho)} ,$$

where P_{Be} , P_{Bi} , and P_{BT} are the power transferred from the beam to the electrons, power transferred from the beam to the ions, and total power transferred, respectively, and P_{ei} is the integrated electron-ion transfer power.

9. DATA REDUCTION

The data reduction of the experimental electron temperature and density profiles and the creation of the input data file for running ZORNOC are performed by an independent program, DARED. We have implemented in it a data reduction procedure that is especially oriented to deal with the data provided by the present Thomson scattering system. This diagnostic can provide electron temperatures and relative densities along the midplane of the tokamak at discrete radial positions between $R = 87$ cm and 117 cm (usually all points are separated by 3 cm). Using either an analytical fitting or a smoothing and interpolation algorithm, we can obtain values of T_e and n_e at any value of the reduced minor radius ρ . Our practice is to choose an equidistant radial grid of 25 points. We determine the magnetic axis position from the peak of the pressure profile, and from the points of this profile we deduce the major radius, $R_0(\rho)$, for each flux surface ρ . To simplify the input data file we parametrize the value of $R_0(\rho)$ by the expression

$$R_0(\rho) = a\rho^2 + b\rho + c .$$

The coefficients a , b , and c are obtained for a least squares fit to the data and stored in the ZORNOC input data file. The position and shape of the outermost flux surface are chosen to be consistent with the Thomson scattering profile, the data provided by the magnetic loop probes, and the flux surface shifts calculated with the equilibrium code. The intersections of the flux surfaces with the equatorial axis take place for radial positions given by

$$R_i^{\pm} = R_0(\rho) \pm a\rho_i ,$$

where a is the equatorial plasma radius.

10. PROGRAM DESCRIPTION

10.1 SUBPROGRAMS

ZORNOC runs on the Fusion Energy Division's PDP-10. The program is written in single-precision FORTRAN IV and the graphics are written in the Display Integrated Software System and Plotting Language (DISSPLA). The subprograms and brief summaries of their functions are listed in Table 1.

Table 1. ZORNOC subprograms

ZORNOC	Main program, drives other subroutines
NONCIN	Calculates areas and volumes enclosed by a discrete set of flux surfaces, as well as contour lengths
MODEL C	Calculates Z_{eff} according to the $Z_{\text{eff}} = \text{const}$ model, current densities, q profile, and collisionality parameter for electrons
MODEL J	Similar to MODEL C, but implements the Spitzer model to calculate Z_{eff}
CLEAN	Calculates impurity concentration, proton deficiency, and radiation power losses with an impurity corona model
PLASMA	Calculates various confinement parameters
PBALAN	Calculates the ohmic heating power balance for electrons
NFREY	Couples and drives the Monte Carlo beam deposition code
NFREYA	Monte Carlo deposition code
BEAMS	Drives the Fokker-Planck moments code and calculates the plasma parameters related to the beam injection
GEFI	Fokker-Planck moments code
EQUI	Couples and drives the fixed boundary equilibrium code
RSTEQ	Fixed boundary equilibrium code
IMPRES	Prints code outputs
PLOT	Plots code outputs

10.2 INPUT

The input data file for ZORNOC is described in Table 2. This file is created by an independent program in which we implement the data

reduction procedure explained in Sect. 9. The user must specify, on executing ZORNOC, the name of the input data file (that is the same as the laser sequence), the kind of plasma ions, the Z_{eff} model to be used, and the type of ion temperature profile.

Table 2. Input data file

FORTRAN name	Definition
FNAM	Identification name of the laser sequence
ISHOT	First shot of the laser sequence
FSHOT	Last shot of the laser sequence
V	Loop voltage (V)
PC	Plasma current (kA)
BT	Toroidal field (kG)
ENM1	Equatorial line-averaged density (cm^{-3})
ENM2	Vertical line-averaged density (cm^{-3})
TI $\emptyset$	Central ion temperature (eV)
TIML	Time of laser shot profile (ms)
EP	Ellipticity of the outermost flux surface
DEL	Triangularity of the outermost flux surface
R $\emptyset$	Major radius of the outermost flux surface (cm)
APLAS	Equatorial plasma radius (cm)
ALIM	Limiter radius (cm)
AC(I)	Fitting coefficients
TE(I)	Flux surface electron temperature (eV)
ENE(I)	Relative electron density (eV)

The only NAMELIST file used by ZORNOC is stored in the file FOR07.DAT. It contains the data about the injectors and neutral beam used by the Monte Carlo code NFREYA and is read in the subroutine NFREYA. This set of variables is described in Table 3.

Table 3. Namelist input

FORTTRAN name	Definition
NPART	Total number of neutral atoms to be followed into plasma
NPSKP	Number of particles followed into plasma per source particle (that is, only every NPSKP th particle is generated at the injector source)
MB	Number of injectors
AWB	Atomic weight of beam particles
BAMP(I)	Current for neutral beam I (A)
EFRACT(I,J)	Fraction of beam current I at energy E_0/J ; J = 1, 2, or 3
EBKEV(I)	Energy, E_0 , of beam I (keV)
BHGHT(I)	Height of beam I (cm)
BWDTH(I)	Width of beam I (cm)
BLENGT(I)	Distance from injector source to pivot point (cm)
NSHAP(I)	Specifies shape of beam I. NSHAP(I) = 1 for a circular beam with diameter BWDTH(I); NSHAP(I) $\neq$ 1 for a rectangular beam of width BWDTH(I) and height BHGHT(I)
APHGHT(I)	Aperture height of beam I when NPSHAP(I) $\neq$ 1 (cm)
APWDTH(I)	Aperture diameter for beam I when NPSHAP(I) = 1; otherwise APWDTH(I) is the width of aperture I (cm)
NPSHAP(I)	Determines geometry of the aperture for beam I. NPSHAP = 1 for a circular aperture; otherwise NPSHAP $\neq$ 1 for a rectangular aperture
BHZFPC(I)	Horizontal focal length of beam I (cm)
BVTFOC(I)	Vertical focal length of beam I (cm)
BDVGHZ(I)	Vertical divergence of beam I (deg)
BDVGVT(I)	Horizontal divergence of beam I (deg)
ANGLE1(I)	Angle between the pivot radius and toroidal plane for beam I (deg)
ANGLE2(I)	Angle between the optical axis of injector and toroidal plane for beam I (deg)
ANGLE3(I)	Angle between the optical axis of injector and the plane containing the pivot point and toroidal center line for beam I (deg)

Table 3 (Cont'd)

FORTRAN name	Definition
ANGLE4(I)	Orientation of the injector face relative to the cross section plane of the torus (deg)
RPIVOT(I)	Distance of the pivot point from the toroidal center as defined by RMJPVT(I) for beam I (cm)
RMJPVT(I)	The major radius defining the toroidal center for the location of the pivot point of beam I (cm)
ANO	Plasma density at the magnetic axis (cm^{-3})
RO	Major radius of magnetic axis, used only for plotting (cm)
RBORE	Plasma radius, used only for plotting (cm)
R1CHAB	Inside major radius for vacuum vessel (cm)
R2CHAB	Outside major radius for vacuum vessel (cm)
ZCHAB	Height of vacuum vessel (cm)
IBOUCE	If IBOUCE = 1, bounce averages over the initial ion orbits are done; otherwise, no bounce averaging

10.3 OUTPUT

If execution of ZORNOC is successful, four output data files (three if the injection calculation is omitted) are generated. These will be named FOR30.DAT (main output), FOR08.DAT (NFREYA results), FOR10.DAT (equilibrium code results), and FOR24.VEC (plotting file).

10.4 APPLICATIONS

In order to illustrate the ZORNOC analysis capabilities, we include here some results obtained from three particular discharges:

- (1) a tokamak shaping experiment plasma with only ohmic heating (ISX-B, Seq. 031591.DXX-3),
- (2) a high poloidal beta plasma with neutral beam injection (ISX-B, Seq. 042291.DHX-2), and
- (3) a noncircular plasma with neutral beam injection (ISX-B, Seq. 051191.DHX-2).

In Fig. 2 we show, for sequences (1) and (2), the flux surface contours obtained by solving the plasma equilibrium. The shape of the outermost flux surface was deduced from the magnetic loop probes. In Table 4, we show the values of various confinement parameters obtained by ZORNOC for sequence (3).

The analysis of sequence (1) was carried out assuming both a circular and a noncircular plasma to show the effects of noncircularity on the calculation of plasma parameters. Some results are shown in Table 5.

In Table 6, we present the values of various confinement parameters obtained by analyzing sequence (2).

Fig. 2. Flux surface contours for (a) a noncircular plasma and (b) a high β_p plasma.

Table 4. Values of various confinement parameters for
a noncircular beam-heated plasma (sequence 3)

<u>Plasma conditions</u> at $t = 160$ ms		<u>Outermost flux surface shape</u>	
$I_p = 108$ kA		$\epsilon = 1.21$	$\delta = 0.16$
$B_T = 11.1$ kG		<u>Beam power</u>	
$\bar{n}_e = 3.16 \times 10^{13} \text{ cm}^{-3}$		$\cong 850$ kW	
$V = 0.57$ V			
$T_i(0) = 800$ eV			
$T_c(0) = 1120$ eV			
<u>Plasma parameters</u>		<u>Main code results</u>	
$n_e(0)$		$4.55 \times 10^{13} \text{ cm}^{-3}$	
$\langle n_e \rangle$		$2.34 \times 10^{13} \text{ cm}^{-3}$	
$\langle T_e \rangle$		481 eV	
$\langle T_i \rangle$		562 eV	
Z_{eff}		2.1	
ℓ_1		1.18	
q_0		1.25	
q_a		4.90	
$\langle J \rangle$		38.9 A/cm ²	
τ_{EE}		4.2 ms	
τ_E		11.5 ms	
$\langle \beta_p \rangle_{p+b}$		1.7 + 0.8	
$\langle \beta_T \rangle_{p+b}$		0.71 + 0.3%	
$\beta_T(0)_{p+b}$		2.66 + 2.4%	
β_{p+b}^*		1.82%	
P_{Be}		514 kW	
P_{Bi}		157 kw	

Table 5. Effects of noncircularity on the calculation of plasma parameters (sequence 1)

<u>Plasma conditions</u>		<u>Outermost flux surface shape</u>	
$I_p = 97.37 \text{ kA}$		$\epsilon = 1.36$	$\delta = 0.24$
$B_T = 11.55 \text{ kG}$			
$\bar{n}_e = 1.66 \times 10^{13} \text{ cm}^{-3}$			
$V = 1.32 \text{ V}$			
$T_i(0) = 270 \text{ eV}$			
$T_e(0) = 542 \text{ eV}$			
<u>Main code results</u>			
<u>Plasma parameters</u>	<u>Circular</u>	<u>Noncircular</u>	
$\langle T_e \rangle$	222 eV	211 eV	
$\langle T_i \rangle$	124 eV	119 eV	
Z_{eff}	1.25	1.66	
ℓ_i	1.35	1.42	
q_o	0.76	1.01	
q_a	4.67	6.56	
$\langle \beta_p \rangle$	0.28	0.34	
$\langle \beta_T \rangle$	0.11%	0.09%	
β^*	0.19%	0.17%	
τ_{EE}	5.9 ms	7 ms	
τ_E	9 ms	10.6 ms	
$P_R(\text{oxygen})$	4 kW	15 kW	

Table 6. Analysis of a beam-heated high poloidal
beta plasma (sequence 2)

<u>Plasma conditions</u> at $t = 140$ ms		<u>Outermost flux surface shape</u>	
$I_p = 112$ kA		$\epsilon = 1.13$	$\delta = 0.08$
$B_T = 11.2$ kA			
$\bar{n}_e = 5.04 \times 10^{13}$ cm $^{-3}$		<u>Beam power</u>	
$V = 0.57$ V		$\cong 750$ kW	
$T_i(0) = 940$ eV			
$T_e(0) = 1516$ eV			
<u>Plasma parameters</u>		<u>Main code results</u>	
$n_e(0)$		7.9×10^{13} cm $^{-3}$	
$\langle n_e \rangle$		3.5×10^{13} cm $^{-3}$	
$\langle T_e \rangle$		736 eV	
$\langle T_i \rangle$		678 eV	
Z_{cff}		2.84	
ℓ_i		1.05	
q_0		0.94	
I_a		3.90	
$\langle J \rangle$		50.3 A/cm 2	
τ_{EE}		15.0 ms	
τ_E		20.0 ms	
$\langle \beta_p \rangle_{p+b}$		$2.68 + 0.6$	
$\langle \beta_T \rangle_{p+b}$		$1.5 + 0.36\%$	
$\langle \beta^* \rangle_{p+b}$		3.0%	
$\beta(0)_{p+b}$		$6.0 + 2.6\%$	
P_{Be}		$\cong 450$ kW	
P_{Bi}		$\cong 187$ kW	

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APPENDIX

CODE COMMAND FILE AND COMMON BLOCK DESCRIPTION

To execute the code on the PDP-10 one simply types, under MONITOR control, EX @ZORNOC. In this Appendix, we include a listing of the code command file and descriptions of each of the main common blocks of the code.

A.1 ZORNOC.CMD

ZORNOC	IMPRES
READ	PLOT
NONCIN	CONTA2
MODEL C	NAVARR
MODEL J	GRIDS
CLEAN	AJPO
IMPUR	DETE
PLASMA	INTDER
PBALAN	DER
NFREY	SPLINE
NFREYA	INT
BEAMS	INTEGB
GEGL	ANGL
SIGMAV	LIASDE
EQUI	@PUB:DISVEC
RSTEQ	@PUB:IMSL

A.2 DESCRIPTIONS OF COMMON BLOCKS

A.2.1 COMMON/GEDA/RAD(25), RO(25), EP(I), DEL(I), ALIM, RØ, APLAS

RAD(I) Major radius of the flux surfaces
 RO(I) Reduced minor radius of the flux surfaces
 EP(I) Flux surface ellipticities
 DEL(I) Flux surface triangularities

ALIM Limiter radius
 RØ Major radius of the outermost flux surface
 APLAS Equatorial plasma radius

A.2.2 COMMON/CURE/ZEFF(25), AJ(25), CU(25), Q(25), ETA(25), ANUE(25),
 ZEFAV, RES

ZEFF(I) Z_{eff}
 AJ(I) Current density
 CU(I) Integrated current
 Q(I) Safety factor
 ETA(I) Plasma resistivity
 ANUE(I) Collisionality parameter for electrons
 ZEFAV Volume-averaged Z_{eff}
 RES Plasma resistance

A.2.3 COMMON/BETA/EBP, AVBP, BETAI, AVBT, PKBETA, RMSB, TEV, TIV,
 PIND, AJV, VDT

EBP Volume-averaged electron poloidal beta
 AVBP Volume-averaged poloidal beta
 BETAI β_I
 AVBT Volume-averaged toroidal beta (%)
 PKBETA Maximum toroidal beta (%)
 RMSB Root mean square beta (%)
 TEV Density-averaged electron temperature
 TIV Density-averaged ion temperature
 PIND Internal plasma inductance per unit of length
 AJV Surface-averaged current density
 VDT Ratio of electron drift to thermal velocity

A.2.4 COMMON/OPTION/IION, ITI, IZM, IIMP, IEQ, INJ

IION Switch to select the kind of plasma ions:
 1 = hydrogen
 2 = deuterium

ITI Switch to choose the type of ion temperature profile and central value:
 0 = charge-exchange value and T_i profile like n_e
 1 = charge-exchange value and T_i profile like T_e
 2 = Artsimovich scaling and T_i profile like n_e
 3 = Artsimovich scaling and T_i profile like T_e

IZM Switch to select Z_{eff} model:
 0 = Spitzer model
 1 = $Z_{eff} = \text{const}$ model

IIMP Switch to select kind of impurity:
 6 = carbon
 8 = oxygen
 26 = iron

IEQ Equilibrium iteration counter

INJ Injection on/off switch

A.2.5 COMMON/GEO/ALENG(25), S(25), VO(25)

ALENG(I) Contour lengths
 S(I) Cross-sectional areas
 VO(I) Volumes enclosed by the flux surfaces

A.2.6 COMMON/CONTI/TAUEE(25), TAUEI(25), TAUE(I)

TAUEE(I) Electron energy confinement time
 TAUEI(I) Ion energy confinement time
 TAUE(I) Total energy confinement time

A.2.7 COMMON/EBAL/WE(25), WI(25), W(25), POH(25), PEI(25), QOH(25),
QEI(25), ZENN(25)

WE(I) Integrated electron energy content
 WI(I) Integrated ion energy content
 W(I) Integrated total energy content
 POH(I) Integrated ohmic heating power
 PEI(I) Integrated electron-ion power transfer
 QOH(I) Ohmic heating power density
 QEI(I) Electron-ion power density transfer
 ZENN(I) Effective Z for energy transfer

A.2.8 COMMON/FREYA/CURB(3), HENERG(3), BMTOT(3), ORLOSS(3), APLOS(3),
AMISS(3), PASSED(3), BMDEP(3), HRLOSE(3), H(3,25)

CURB(I) Current of each neutral beam component
 HENERG(I) Energy of each neutral beam component
 BMTOT(I) Number of particles used in Monte Carlo simulation
 ORLOSS(I) Number of particles lost in orbit
 APLOS(I) Number of particles lost at aperture
 AMISS(I) Number of particles missing the chamber
 PASSED(I) Number of particles passing through
 BMDEP(I) Number of particles deposited in the plasma
 HRLOSE(I) Fraction lost
 H(I,J) Beam deposition profile (I is beam component, J is
flux surface index)

A.2.9 COMMON/CBEAM/FBE(25,3), FBI(25,3), QBE(25), QBI(25), PBE(25),
PBI(25), GE(25), GI(25), TAUS(25), TF(11), TCX(11), TAVE(11),
EC(11), AVBPB, AVBTB, RMSBB, PKBETB, BPRES(25)

FBE(I,J) Energy to electrons
 FBI(I,J) Energy to ions
 QBE(I) Power density transferred from the beam to the plasma
electrons
 QBI(I) Power density transferred from the beam to the plasma
ions

PBE(I)	Integrated power transferred to the electrons
PBI(I)	Integrated power transferred to the ions
TAUS(I)	Slowing-down time on electrons
TFC(I)	Fast ion lifetime
TCXC(I)	Charge-exchange lifetime
TAVEC(I)	Average lifetime
EC(I)	Critical energy
AVBPB	Beam poloidal beta
AVBTB	Beam toroidal beta (%)
RMSBB	Root mean square beta (plasma + beam) (%)
PKBETB	Beam peak toroidal beta (%)
BPRES(I)	Fast ion pressure

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