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COMPUTATIONAL STUDIES OF THE TWO-COMPONENT TOROIDAL FUSION
TEST REACTOR

J. Killeen, T. H. Johnson, A. A. Mirin and M. E. Rensink

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COMPUTATIONAL STUDIES OF THE TWO-COMPONENT TOROIDAL

FUSION TEST REACTOR

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ABSTRACT

An extensive study of plasma behavior in the two-component torus is made using a variety of theoretical and computational models.

Using a two-dimensional multi-species Fokker-Planck code we compute the factor Q (the ratio of thermonuclear energy to input energy) for a variety of reactor conditions. In these calculations we vary the DT mixture, the injection energy and electron and tritium temperatures and the effects of impurities. With the Fokker-Planck code, where the time-dependent distributions functions of the ions are functions of energy and pitch angle, we study the effects of energy clamping, fast compression, and decompression on the slowing down and energy multiplication of the injected beam.

The equilibrium of the two-component plasma with its confining magnetic field is studied with a two-dimensional equilibrium code. The target plasma is represented by a pressure, which is a function of ψ . The fast ions are simulated by superparticles whose guiding-center motion is computed and which contribute to the toroidal current. With this code we investigate co- and counter-injection of the beam, varying the injection profile, energy, and current. The aspect ratio, toroidal field, and plasma current are also varied.

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INTRODUCTION

This report of LLL computational studies of the two-energy-component toroidal fusion test reactor consists of two parts. In the first part we present several energy multiplication studies using a new Fokker-Planck code. In the second part we present toroidal equilibria calculations of a two-component plasma where the fast ions are simulated by superparticles.

In Part IA we present the mathematical description of a new two-dimensional, multi-species, Fokker-Planck code; however, we do not discuss the numerical techniques in this report. In IB we describe how the effects of major radius compression are included in the model, and in IC the plasma loss terms for these studies are given. In ID the definition of Q that we use is given. In IE, seven possible TCT scenarios (modes of operation) are described, and in IF the results of energy multiplication studies for these scenarios are given.

In Part IIA we describe the mathematical model of a new toroidal equilibrium code where the plasma current is derived from a fluid description and the beam current is simulated by several thousand superparticles. In IIB we list the classes of problems considered in this report, and in IIC we present some illustrative results of these cases.

The results of our energy multiplication studies indicate that breakeven conditions ($Q = 1$) can be achieved in several modes of operation. By using heating beams fusion beams, fast and slow compression, and decompression in a variety of sequences we demonstrate $Q \geq 1$, even in the presence of impurities.

The beam injection studies indicate that on a short time scale strong counter-injected beams significantly distort the equilibrium plasma due to the mutual repulsion between opposing currents. Beam particle losses may also occur. Co-injected beams do not exhibit this behavior.

I. ENERGY MULTIPLICATION STUDIES

A. Kinetic Equations for a Multi-Species Plasma

In order to calculate the energy transfer among the hot deuterons, tritons, electrons, α -particles, and possible impurity ions we must solve a coupled set of time-dependent Boltzmann equations with Fokker-Planck collision terms. In addition to the energetics of the system we obtain the particle distribution functions in energy and pitch angle which are useful for stability analyses, and an accurate computation of Q , the energy multiplication factor. We do not include spatial dependence in the model so the equations to be solved are

$$\frac{\partial f_a}{\partial t} + \frac{\partial}{\partial \underline{v}} \cdot (\underline{\dot{v}} f_a) = \left(\frac{\partial f_a}{\partial t} \right)_c + S_a, \quad (1)$$

where f_a is the distribution function for particles of type a , S_a is a source term, and $(\partial f_a / \partial t)_c$ is the Fokker-Planck collision term.

We use spherical coordinates (v, θ, ϕ) in velocity space, where $v = |\underline{v}|$, and θ is the angle between the velocity vector and the magnetic field (pitch angle). We assume that the distribution functions are symmetric in ϕ so Eq. (1) becomes

$$\frac{\partial f_a}{\partial t} + \frac{1}{v^2} \frac{\partial}{\partial v} (v^2 \dot{v} f_a) + \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} (\sin \theta \dot{\theta} f_a) = \left(\frac{\partial f_a}{\partial t} \right)_c + S_a. \quad (2)$$

The Fokker-Planck collision term for an inverse-square force was derived by Rosenbluth et al.¹ in the form

$$\frac{1}{f_a} \left(\frac{\partial f_a}{\partial t} \right)_c = - \frac{\partial}{\partial v_i} \left(f_a \frac{\partial h_a}{\partial v_i} \right) + \frac{1}{2} \frac{\partial^2}{\partial v_i \partial v_j} \left(f_a \frac{\partial^2 g_a}{\partial v_i \partial v_j} \right), \quad (3)$$

where $\Gamma_a = 4\pi Z_a^4 e^4 / m_a^2$. In the present work we write the "Rosenbluth potentials"

$$g_a = \sum_b \left(\frac{Z_b}{Z_a} \right)^2 \ln \Lambda_{ab} \int f_b(\underline{v}') |\underline{v} - \underline{v}'| d\underline{v}', \quad (4)$$

$$h_a = \sum_b \frac{m_a + m_b}{m_b} \left(\frac{Z_b}{Z_a} \right)^2 \ln \Lambda_{ab} \int f_b(\underline{v}') |\underline{v} - \underline{v}'|^{-1} d\underline{v}', \quad (5)$$

which differ from those given by Rosenbluth et al. in the dependence of the Coulomb logarithm on both interacting species and its consequent inclusion under the summations. The expression we use is

$$\ln \Lambda_{ab} = \ln \left\{ \left(\frac{m_a m_b}{m_a + m_b} \right) \frac{2\alpha \lambda_D^c}{e^2} \max \left[\left(\frac{2\bar{E}}{m} \right)^{1/2} \right] \right\} - \frac{1}{2}, \quad (6)$$

where α is the fine structure constant, λ_D the Debye length, $\bar{E}$ the mean energy of particles of species a or b, and the other symbols have their usual meanings. The normalization of f_a in Eqs. (1) through (5) is such that the particle density is given by

$$n_a = \int f_a(\underline{v}) d\underline{v}. \quad (7)$$

In v, θ coordinates Eq. (3) becomes

$$\frac{1}{\Gamma_a} \left(\frac{\partial f_a}{\partial t} \right)_c = \frac{1}{v^2} \frac{\partial G_a}{\partial v} + \frac{1}{v^2 \sin \theta} \frac{\partial H_a}{\partial \theta}, \quad (8)$$

where

$$G_a = A_a f_a + B_a \frac{\partial f_a}{\partial v} + C_a \frac{\partial f_a}{\partial \theta}$$

$$H_a = D_a f_a + E_a \frac{\partial f_a}{\partial v} + F_a \frac{\partial f_a}{\partial \theta}$$

and

$$A_a = \frac{v^2}{2} \frac{\partial^3 g_a}{\partial v^3} + v \frac{\partial^2 g_a}{\partial v^2} - \frac{\partial g_a}{\partial v} - v^2 \frac{\partial h_a}{\partial v} - \frac{1}{v} \frac{\partial^2 g_a}{\partial \theta^2} + \frac{1}{2} \frac{\partial^3 g_a}{\partial v \partial \theta^2} - \frac{\cot \theta}{v} \frac{\partial g_a}{\partial \theta} + \frac{\cot \theta}{2} \frac{\partial^2 g_a}{\partial v \partial \theta}$$

$$B_a = \frac{v^2}{2} \frac{\partial^2 g_a}{\partial v^2}$$

$$C_a = -\frac{1}{2v} \frac{\partial g_a}{\partial \theta} + \frac{1}{2} \frac{\partial^2 g_a}{\partial v \partial \theta}$$

$$D_a = \frac{\sin \theta}{2v^2} \frac{\partial^3 g_a}{\partial \theta^3} + \frac{\sin \theta}{2} \frac{\partial^3 g_a}{\partial v^2 \partial \theta} + \frac{\sin \theta}{v} \frac{\partial^2 g_a}{\partial v \partial \theta} - \frac{1}{2v^2 \sin \theta} \frac{\partial g_a}{\partial \theta} + \frac{\cos \theta}{2v^2} \frac{\partial^2 g_a}{\partial \theta^2} - \sin \theta \frac{\partial h_a}{\partial \theta}$$

$$E_a = \sin \theta \left[-\frac{1}{2v} \frac{\partial g_a}{\partial \theta} + \frac{1}{2} \frac{\partial^2 g_a}{\partial v \partial \theta} \right]$$

$$F_a = \frac{\sin \theta}{2v^2} \frac{\partial^2 g_a}{\partial \theta^2} + \frac{\sin \theta}{2v} \frac{\partial g_a}{\partial v}$$

The functions g_a and h_a , defined by Eqs. (4) and (5), can be represented by expansions in Legendre polynomials.¹ For this purpose we let

$$f_a(v, \mu, t) = \sum_{j=0}^{\infty} v_j^a(v, t) P_j(\mu), \quad (9)$$

where $\mu = \cos\theta$, and

$$v_j^a(v, t) = \frac{2j+1}{2} \int_{-1}^{+1} f_a(v, \mu, t) P_j(\mu) d\mu.$$

The expansions for g_a and h_a are

$$g_a(v, \mu, t) = \sum_{j=0}^{\infty} \sum_b \left(\frac{z_b}{z_a} \right)^2 \ln \Lambda_{ab} B_j^b(v, t) P_j(\mu) \quad (10)$$

$$h_a(v, \mu, t) = \sum_{j=0}^{\infty} \sum_b \frac{m_a + m_b}{m_b} \left(\frac{z_b}{z_a} \right)^2 \ln \Lambda_{ab} A_j^b(v, t) P_j(\mu) \quad (11)$$

where

$$A_j^a = \frac{4\pi}{2j+1} \left[\int_0^v \frac{(v')^{j+2}}{v^{j+1}} v_j^a(v', t) dv' + \int_v^{\infty} \frac{v^j}{(v')^{j-1}} v_j^a(v', t) dv' \right] \quad (12)$$

$$B_j^a = - \frac{4\pi}{4j^2 - 1} \left[\int_0^v \frac{(v')^{j+2}}{v^{j-1}} \left(1 - \frac{j - 1/2}{j + 3/2} \frac{(v')^2}{v^2} \right) v_j^a(v') dv' \right. \\ \left. + \int_v^{\infty} \frac{v^j}{(v')^{j-3}} \left(1 - \frac{j - 1/2}{j + 3/2} \frac{v^2}{(v')^2} \right) v_j^a(v') dv' \right]. \quad (13)$$

In the computations we take a finite number (which can be varied) of

terms in the Legendre expansions of g_a and h_a .

Equation (8) is used for each ion species present. For electrons we assume that the distribution function is isotropic, so Eq. (3) becomes

$$\frac{1}{\Gamma_e} \left(\frac{\partial f_e}{\partial t} \right)_c = \frac{1}{v^2} \frac{\partial G_e}{\partial v} \quad (14)$$

where

$$G_e = A_e f_e + B_e \frac{\partial f_e}{\partial v}$$

and

$$A_e = 4\pi \sum_b \left[\left(\frac{Z_b}{Z_e} \right)^2 \frac{m_e}{m_b} \ln \Lambda_{eb} \int_0^v V_0^b(v', t) v'^2 dv' \right]$$

$$B_e = 4\pi \sum_b \left\{ \left(\frac{Z_b}{Z_e} \right)^2 \ln \Lambda_{eb} \left[\frac{1}{3v} \int_0^v V_0^b(v', t) v'^4 dv' \right. \right. \\ \left. \left. + \frac{v^2}{3} \int_v^\infty V_0^b(v', t) v' dv' \right] \right\}$$

B. Adiabatic Compression

In the TCT studies presented in this report we have included the effects of major radius compression of the plasma. This means that we have a time varying force in the second term on the LHS of Eq. (1).

We assume that the magnetic moment of a particle is conserved during compression, so

$$\frac{v^2 \sin^2 \theta}{B} = \text{constant} \quad (15)$$

or

$$\frac{2\dot{v}}{v} + 2 \frac{\cos\theta}{\sin\theta} \dot{\theta} - \frac{\dot{B}}{B} = 0 \quad (16)$$

where B is the magnitude of the field. In major radius compression

$$\frac{\dot{B}}{B} = - \frac{\dot{R}}{R} \quad (17)$$

so

$$2 \frac{\dot{v}}{v} + 2 \frac{\cos\theta}{\sin\theta} \dot{\theta} + \frac{\dot{R}}{R} = 0. \quad (18)$$

We need an additional equation which is the constant canonical angular momentum condition

$$P_{\theta} \equiv mv_{\parallel}R + \frac{q}{c} RA_{\theta} = \text{constant}, \quad (19)$$

where A_{θ} is the vector potential and $B_z = (1/R)(\partial/\partial R)RA_{\theta}$ is the vertical field. If we take $B_z \sim R^{-2}$, as in ATC, then

$$Rv \cos\theta = \text{constant} \quad (20)$$

or

$$\frac{\dot{v}}{v} - \frac{\sin\theta}{\cos\theta} \dot{\theta} + \frac{\dot{R}}{R} = 0. \quad (21)$$

Solving Eqs. (18) and (21) we have

$$\dot{v} = -v \frac{\dot{R}}{R} \left(1 - \frac{1}{2} \sin^2\theta\right) \quad (22)$$

$$\dot{\theta} = \frac{1}{2} \frac{\dot{R}}{R} \sin\theta \cos\theta. \quad (23)$$

During major radius compression the density should scale inversely with R^2 , so

$$\frac{\dot{n}}{n} = -2 \frac{\dot{R}}{R} . \quad (24)$$

This behavior can be modeled by adding a term of the form

$$-2 \frac{\dot{R}}{R} f_a(v, \theta, t)$$

to the RHS of Eq. (2). If we substitute the expressions for $\dot{v}$ and $\dot{\theta}$ from Eqs. (22) and (23) into the LHS of Eq. (2), we have

$$\frac{\partial f_a}{\partial t} + \frac{\dot{R}}{R} \left[-\left(1 - \frac{1}{2} \sin^2 \theta\right) v \frac{\partial f_a}{\partial v} + \frac{1}{2} \sin \theta \cos \theta \frac{\partial f_a}{\partial \theta} \right] = \left(\frac{\partial f_a}{\partial t} \right)_c + S_a, \quad (25)$$

where $(\partial f_a / \partial t)_c$ is given by Eq. (8). For electrons we have

$$\frac{\partial f_e}{\partial t} + \frac{\dot{R}}{R} \left[-\frac{2v}{3} \frac{\partial f_e}{\partial v} \right] = \left(\frac{\partial f_e}{\partial t} \right)_c + S_e, \quad (26)$$

where $(\partial f_e / \partial t)_c$ is given by Eq. (14). Equation (25) for each ion species, coupled with Eq. (26), are solved in a two-dimensional, multi-species Fokker-Planck code called HYBRID II.

C. Plasma Losses

The effects of finite particle and energy confinement times are incorporated into the Fokker-Planck code by adding terms of the form

$$\frac{\partial f_a}{\partial t} = \dots - \frac{f_a}{\tau_p} + \frac{1}{v^2} \frac{\partial}{\partial v} \left[\left(\frac{1}{\tau_E} - \frac{1}{\tau_p} \right) \frac{v^3 f_a}{2} \right].$$

Taking moments, we find

$$\frac{\partial n_a}{\partial t} = -\frac{n_a}{\tau_p}$$

and

$$\frac{\partial}{\partial t} (n_a \bar{E}_a) = - \frac{(n_a \bar{E}_a)}{\tau_E},$$

where τ_p and τ_E are the particle and energy confinement times, respectively. These are read into the code as input parameters.

D. Energy Gain Factor

The overall energy gain factor for the system is defined by

$$Q = \frac{\text{Fusion Energy Out}}{\text{Net Input Energy}}$$

where

$$\text{Fusion Energy Out} = \int_0^t dt V(t) n_D(t) n_T(t) \bar{\sigma v}(t) E_F$$

$n_{D,T}$ = number density

$E_F = 17.6 \text{ MeV}$

$\bar{\sigma v}$ = velocity-averaged fusion cross section²

$V(t) = V(0)/C^2(t)$ = plasma volume

$C(t)$ = major radius compression factor

Net Input Energy = Total System Energy at time t

- Total System Energy at $t = 0$

+ System Energy Loss

$$\text{Total System Energy} = V(t) \sum_a n_a(t) \bar{E}_a(t)$$

$\bar{E}_a$ = mean energy of species "a"

$$\text{System Energy Loss} = (\tau_E)^{-1} \int_0^t dt V(t) \sum_a n_a(t) \bar{E}_a(t)$$

E. Fokker-Planck Scenarios

The Fokker-Planck investigations have been set up to study several possible scenarios for TCT operation. These scenarios are defined to illustrate combinations of neutral beam heating and major radius compressional heating which might profitably be employed in a two-component toroidal reactor. The effects of various types and concentrations of impurities are also illustrated.

Scenario I

- (a) Injection of 150 keV fusion beams into an appropriately prepared target plasma;
- (b) Thermalization of fusion beams and target plasma--breakeven experiment.

Scenario II

- (a) Injection of 80 keV fusion beams into a pre-compression target plasma;
- (b) Fast compression to boost the fusion beam and target plasma energy;
- (c) Thermalization of fusion beams and target plasma--breakeven experiment.

Scenario III

- (a) Injection of 80 keV heating beams into a target plasma;
- (b) Thermalization of heating beams and target;
- (c) Fast compression to further boost the target energy;
- (d) Injection of 150 keV fusion beams--breakeven experiment.

Scenario IV

- (a) Injection of 80 keV heating beams into a target plasma;

- (b) Thermalization of heating beams and target;
- (c) Injection of 80 keV fusion beams;
- (d) Fast compression to boost the fusion beam and target plasma energy;
- (e) Thermalization of fusion beams and target plasma--breakeven experiment.

Scenario V

- (a) Injection of 110 keV fusion beams into a target plasma;
- (b) Slow compression to maintain the fusion beam energy--energy clamping;
- (c) Thermalization of fusion beams and target plasma.

Scenario VI

- (a) Injection of 110 keV fusion beams into a target plasma;
- (b) Slow compression to maintain the fusion beam energy--beam clamping;
- (c) Fast de-compression to recover energy from fusion beams and target plasma;
- (d) Thermalization of fusion beams and target plasma.

Scenario VII

- (a) Injection of 50 keV fusion beams into a target plasma;
- (b) Fast compression to boost the fusion beam and target plasma energy;
- (c) Slow compression to maintain the fusion beam energy--energy clamping;
- (d) Fast de-compression to recover energy from fusion beams and target plasma;
- (e) Thermalization of fusion beams and target plasma.

F. Fokker-Planck Results

A series of runs illustrates the various scenarios outlined in the previous section. No extensive parameter surveys have been done for these runs, so the results are not necessarily optimum. More detailed studies will obviously be required as the TCT design becomes finalized.

The output information available from each of the Fokker-Planck runs includes, for each particle species,

- (1) the distribution function, $f(v, \theta, t)$,
- (2) the density, in particles/cc,
- (3) the mean energy, in keV,
- (4) the perpendicular pressure of each species, as a fraction of the total perpendicular pressure

In addition, certain overall energy diagnostics are computed:

- (1) total system energy, in keV/cc,
- (2) cumulative fusion reaction energy, in keV/cc,
- (3) cumulative plasma energy loss, in keV/cc,
- (4) overall system Q, from time $t = 0$, as defined in a previous section.

All such information is available at arbitrary times throughout each run. A selected small fraction of this information is included in the description of results for the TCT scenarios.

The following special conditions have been used in all of the TCT scenarios, although these are not essential features of the Fokker-Planck code:

- (1) All beams are assumed to be injected tangentially with a

gaussian velocity distribution (see, for example, Fig. 1).

(2) All initial plasmas are 100% tritium with $T_e = T_i$ and isotropic Maxwellian velocity distributions.

(3) Although the energy confinement time for each species is usually taken to be 200 msec, the particle confinement time is assumed to be infinite.

(4) Alpha particles are not included as a separate species for these runs, so alpha heating is not taken into account.

It should be noted that the results quoted for particle energies refer to average energies, $\bar{E}$, rather than temperatures, T . For an isotropic Maxwellian velocity distribution these are related by $\bar{E} = 3/2 T$.

Scenario I--Simple Injection

The simplest model of the two-component concept is the injection of a pulse of energetic deuterons into a tritium target plasma. The initial target plasma parameters for this run were

$$n = 7 \times 10^{13} \text{ cm}^{-3}$$

$$\bar{E} = 9 \text{ keV}$$

$$\tau_E = 200 \text{ msec.}$$

A 30 msec pulse of 150 keV deuterons was injected starting at time $t = 0$. The current was chosen so as to yield $\Gamma \sim 1$ at the end of the injection period. The evolution of the tangentially injected deuteron distribution function is shown in Figs. 1-3. Figure 1 gives the injected deuteron distribution as a function of the magnitude of the velocity, v , and the angle, θ , of the velocity vector relative to the

magnetic field (defined as $\theta = 0$). As time goes on, this distribution spreads in angle and the peak of the distribution moves to lower velocities as the deuterons slow down in the target plasma. By the end of this run the deuteron distribution has become an isotropic Maxwellian. The tritium and electron distributions remain approximately Maxwellian throughout the run. The time history of the density and mean energy of each species in the system is shown in Figs. 4-6. The overall Q of the system as time proceeds is shown in Fig. 7 along with the total system energy. The final value of Q was 1.123.

Scenario II--Fast Compression

If efficient high-current neutral beams at energies ≥ 150 keV are not available, one can use a lower energy beam, say 80 keV, in combination with major radius compression to produce essentially the same results. In this scenario the injected 80 keV fusion beam can, in principle, be boosted to an energy of 135 keV with major radius compression factor $C = 1.3$ (recall $\bar{E} = \bar{E}_0 C^2$ for tangentially injected particles). Scattering and energy transfer to the background plasma reduce the effectiveness of the compression, as shown in the following results. The injection and compression sequence are shown schematically below. The initial plasma parameters are

$$n = 4.7 \times 10^{13} \text{ cm}^{-3}$$

$$\bar{E} = 6.3 \text{ keV}$$

$$\tau_E = 200 \text{ msec.}$$

The injection current was chosen so as to yield $\bar{\Gamma} \sim 1$ after compression. The results for the mean energy and density as a function of time are

given in Figs. 8-10 for the electrons, deuterons, and tritons. The deuteron distribution function before and after compression is shown in Figs. 11 and 12. The electron and triton distributions remained essentially isotropic and Maxwellian. The final Q for the system was $Q = 0.780$. The compression was not strong enough to raise the deuteron energy to the desired 135 keV. Alternatively, a higher deuteron source energy would also produce a higher Q .

Scenario III--Neutral Injection Heating, Compression, 150 keV Fusion Beams

This scenario is suggested by preliminary results from the Princeton/Westinghouse TCT study: Ohmic heating is assumed to produce plasma temperatures of about 1 keV, neutral injection heating raises this to about 4 keV, and by major radius compression ($C = 1.25$) the final temperature of the target plasma reaches 6 keV. The 150 keV fusion beam is then injected with sufficient current to sustain the plasma temperature at 6 keV. This final stage constitutes the "breakeven experiment". For this particular Fokker-Planck run, the initial plasma parameters were:

$$n = 4.5 \times 10^{13} \text{ cm}^{-3}$$

$$\bar{E} = 1.35 \text{ keV}$$

$$\tau_E = 200 \text{ msec.}$$

The injection and compression sequence are shown schematically below:

The mean energy and density for electrons, deuterons (heating + fusion), and tritons are shown in Figs. 13-15 as a function of time. At the beginning of the 150 keV injection phase ($t = .120$) a mean plasma energy $\bar{E} = 9$ keV is desired. The low observed values ($\bar{E}_e = 5.121$, $\bar{E}_T = 7.764$) are a consequence of the heating beam source current being too small in this run. Consequently, during the "breakeven experiment" the fusion beam deuterons are slowed down too rapidly and the Q of the system is lower than expected. The overall system Q at the end of this run is 0.571. Additional runs are being made to find sets of parameters which produce larger Q values.

Scenario IV--Neutral Injection Heating, 80 keV Fusion Beams,

Fast Compression

This scenario is suggested by preliminary results from the Princeton/Westinghouse TCT study, assuming that efficient high-current neutral beams are available only at energies less than about 80 keV. The scenario starts with a relatively low-energy tritium plasma produced by ohmic heating. The relevant parameters for the Fokker-Planck runs are

$$n = 4.7 \times 10^{13} \text{ cm}^{-3}$$

$$\bar{E} = 1.35 \text{ keV}$$

$$\tau_E = 200 \text{ msec.}$$

Deuterons at 80 keV are injected in a 30 msec pulse with sufficient current to raise the plasma energy to 6.3 keV after thermalization (in this case, about 60 msec). The 80 keV fusion beam is then injected and the system is compressed to raise the fusion beam energy to about 120 keV. The "breakeven experiment" is then defined to occur during the subsequent thermalization of the fusion beam and plasma when the plasma energy is being maintained by input from the hot deuterons.

The injection and compression sequence are shown schematically below.

The density and mean energy of the electrons, deuterons (heating + fusion beams), and tritons is shown in Figs. 16-18 as a function of time. The overall Q of the system at the end of the run is $Q = 0.618$ and the "breakeven" energy gain factor Q_b is

$$Q_b = \frac{\text{fusion energy out during breakeven experiment}}{\text{fusion beam energy at beginning of breakeven experiment}}$$

$$Q_b = 0.690.$$

The low value for Q_b can be partially attributed to the fact that the fusion beam energy did not reach the desired 120 keV after compression (the fusion deuterons only reached about 95 keV). The timing and magnitude of the injection currents could be changed to yield higher Q values. Such a parameter study is now being conducted. Also, the Q could be increased by using a larger compression factor (1.5 instead of 1.3). This is consistent with the Princeton/Westinghouse preliminary study results and would raise the fusion beam energy after compression from the present value of 95 keV to the desired 120 keV.

Scenario V--Energy Clamping

The maximum fusion probability per unit time for an energetic deuteron in a tritium target plasma occurs at about 110-120 keV. By suitably programming the major radius compression cycle one can arrange to keep the injected deuteron energy fixed at the optimum value, thus maximizing the fusion reaction rate. The results shown in Figs. 19-25 illustrate the technique for a particular set of system parameters. The initial plasma conditions are given by

$$n = 3 \times 10^{13} \text{ cm}^{-3}$$

$$\bar{E} = 6 \text{ keV}$$

$$\tau_E = 200 \text{ msec.}$$

A 30 msec pulse of 125 keV deuterons is injected starting at time $t = 0$. The source current is chosen so as to yield $\Gamma \sim 1$. At the end of the injection period, the compression cycle begins and lasts for 150 msec. At the end of this time the major radius has been compressed by a factor of 1.5. The system is then allowed to thermalize. The sequence is shown schematically below. The evolution of the tangentially injected deuteron distribution function is shown in Figs. 19-21 (after injection, after clamping, and after thermalization).

The density and mean energy of the electrons, deuterons, and tritons are shown as a function of time in Figs. 22-24. The overall system Q is given in Fig. 25. One sees that in this particular case the deuteron energy was not held precisely constant because the programming of the major radius compression was not optimal. The analytic form used for $C(t)$ (or $\dot{R}/R$) was based on a sharply peaked tangential deuteron

distribution, but from Fig. 20 one sees that the distribution has spread considerably by the end of the clamping period.

Scenario VI--Energy Clamping + Decompression

When large compression factors are used, as would be the case for energy clamping over an extended period of time, it may be advantageous to perform an adiabatic decompression of the system at the end of the clamping stage. Energy is then extracted from the plasma and returned to the vertical field coils (just the reverse of the compression cycle). The results shown in Figs. 26-28 give an example of such a scenario. The injection and compression sequence is shown schematically below.

The initial plasma parameters are:

$$n = 3 \times 10^{13} \text{ cm}^{-3}$$

$$\bar{E} = 6 \text{ keV}$$

$$\tau_E = 200 \text{ msec.}$$

The injection current is chosen so as to yield $\Gamma \sim 1$ during the clamping stage. The density and mean energy of the electrons, deuterons, and tritons are shown as a function of time in Figs. 26-28. The overall Q of the system at the end of 400 msec was 0.695.

Scenario VII--Compression, Clamping, Decompression, Impurities

This series of runs illustrates the use of the major radius compression facility for heating, energy clamping, and energy recovery. The first run in this series contains no impurities, but in subsequent runs either oxygen or iron is added as a separate fully ionized species in an amount sufficient to yield $Z_{\text{eff}} = 2, 3$ where

$$Z_{\text{eff}} \equiv \frac{\sum_i n_i Z_i^2}{n_e}$$

All of these runs use the same injection and compression time sequence shown schematically below.

The initial plasma for each of these runs is defined by

$$n_0 = 2 \times 10^{13} \text{ cm}^{-3}$$

$$\bar{E}_0 = 2.25 \text{ keV}$$

$$\tau_E = 300 \text{ msec.}$$

The density and mean energy of electrons ($k = 0$), deuterons ($k = 1$), and tritons ($k = 2$) are shown as a function of time in Figs. 29-31 for the run with no impurities. The results for the other runs are qualitatively similar. The energy clamping of the deuterons works very effectively in this case as seen in Fig. 30. The overall Q of the system with no impurities is shown in Fig. 32. The effect of impurities on the final value of Q for the other runs is given in the table. One sees that the Q is more seriously degraded by the lower Z_i impurities.

Z_{eff}	Impurity type	Q
1	none	1.189
2	oxygen	0.955
2	iron	1.167
3	oxygen	0.855
3	iron	1.058

II. TOROIDAL EQUILIBRIUM OF A TWO-COMPONENT PLASMA

A. The GUIDON Code

GUIDON represents a torus in two-dimensional cylindrical coordinates as shown, where the circle is a cross section of the torus and θ is the coordinate of symmetry measuring rotation about the z-axis

$R = R_0$ is the torus's major radius.

Operations are performed within a rectangular grid (presently 64×64 , but any power of 2 in the z -direction will suffice; the r -direction is not limited). First, all three coordinates of the magnetic field (B_r, B_θ, B_z) due to vacuum sources are computed at all mesh points by integration of the Biot-Savart law; these vacuum components of the field are stored permanently. Three kinds of vacuum sources are permitted: (1) a straight wire in the $\pm z$ -direction at $R = 0$, giving rise to the toroidal field; (2) any number of arbitrarily-placed coils whose only current component is j_θ , giving rise to a poloidal field; and (3) a vertical field in the $\pm z$ -direction applied

to center the plasma current.

Within this framework, two components of plasma are represented by different means and permitted to interact through self-consistent magnetic fields. The first, which is referred to as the plasma current, models the background plasma (tritium in the case of the TCT) as a fluid; the second, referred to as the beam current, models the injected deuterium beam in the TCT with an arbitrary number of macro-particles.

1. Plasma Current Model

The fluid model for the plasma is based upon balancing the pressure force against the Lorentz force to maintain the plasma in equilibrium. Thus

$$\nabla p = \frac{1}{c} \underline{j} \times \underline{B} \quad (27)$$

If we further define a flux function

$$\psi \equiv r A_{\theta} \quad (28)$$

then from the definition $\underline{B} = \nabla \times \underline{A}$ we can find r- and z-components of the magnetic field as

$$B_r = - \frac{\partial A_{\theta}}{\partial z} = - \frac{1}{r} \frac{\partial \psi}{\partial z} \quad (29a)$$

and

$$B_z = \frac{1}{r} \frac{\partial}{\partial r} (r A_{\theta}) = \frac{1}{r} \frac{\partial \psi}{\partial r} . \quad (29b)$$

This definition of ψ allows us to obtain from (27)

$$j_{\theta} = - c r \frac{\partial p}{\partial \psi} , \quad (30)$$

the source term for use in Ampere's law.

We are left with a choice for the ψ -dependence of p . Following refs. (3) and (4), we define

$$p = \bar{c}(\psi - \psi_0)^m \quad \text{for } \psi \geq \psi_0; \quad p = 0 \text{ otherwise} \quad (31)$$

where $\bar{c}$ and m are arbitrary constants and ψ_0 is a reference flux defining the boundary of the plasma. For a given $\bar{c}$, each integral value of $m > 0$ will produce an equilibrium solution. Using (31) in (30) the source term becomes

$$j_\theta = -c\bar{c}m(\psi - \psi_0)^{m-1} \quad (32)$$

so that $\bar{c}$ controls the total amount of current present in the problem (for fixed ψ_0). Using (28), Ampere's law becomes

$$\nabla^* \psi = + \frac{1}{r} \frac{\partial^2 \psi}{\partial z^2} + \frac{\partial}{\partial r} \left(\frac{1}{r} \frac{\partial \psi}{\partial r} \right) = \frac{4\pi}{c} j_\theta. \quad (33)$$

It is significant to note that the flux ψ consists of vacuum as well as plasma generated components, so that the total flux is actually

$$\psi_{\text{total}} = \psi_{\text{plasma}} + \psi_{\text{vacuum}}$$

where ψ_{vacuum} includes the vertical centering (B_z) field and those due to any other coils in the problem. The form of (33) being

$$\nabla^* \psi = f(\psi),$$

the correct equation to solve is

$$\nabla^* \psi_{\text{plasma}} = f(\psi_{\text{total}}) \quad (34)$$

since $\nabla^* \psi_{\text{vacuum}} = 0$.

The principal method of solution for the equilibrium of the plasma in GUIDON uses the following procedure: the code receives as input the location of the center of the plasma, the total current flowing, the radius of the plasma, and the value of the parameter m . Given these, the code generates a set of trial fluxes using the Biot-Savart law, then calculates $\bar{c}$ to produce the correct total current. With these as initial conditions, (34) can be solved for ψ_{plasma} . The current maximum moves as a result of this process; ψ_0 is reassigned, $\bar{c}$ recalculated, and (34) solved again. This basic cycle is performed a number of times ($\sim 10-15$), after which several cycles (~ 5) are calculated without reassigning ψ_0 to allow the plasma to achieve a correct equilibrium radius.

This procedure has been compared with the mathematically more precise one of Ref. 5 and shown to give identical results; it is several times faster.

After this initial equilibrium has been found the beam is injected; thereafter the location of the plasma current is calculated self-consistently at each timestep, viz,

$$\psi_{\text{total}} = \psi_{\text{plasma}} + \psi_{\text{vacuum}} + \psi_{\text{beam}} \quad (35a)$$

$$j_{\theta} = j_{\text{plasma}} + j_{\text{beam}} \quad (35b)$$

$$\text{and} \quad \nabla^*(\psi_{\text{plasma}} + \psi_{\text{beam}}) = \frac{4\pi}{c} j_{\theta} \quad (35c)$$

is solved instead of Eq. (34). The value of ψ_0 is fixed throughout the problem and $\bar{c}$ is recalculated at each timestep to keep the total

plasma current constant.

Provision is also made in the code for some amount of the plasma current to flow in the poloidal direction, giving rise to toroidal B. For the pressure as defined in (31), the form of the adjustment is

$$B_{\theta} = \frac{B_{\theta 0}}{1 + bp} \quad (36)$$

where B_{θ} is the new toroidal field, $B_{\theta 0} = 0.2I_z/r$ is the vacuum toroidal field, and b is the arbitrary constant (input) specifying the fraction of plasma current flowing in the poloidal direction. To allow for the degradation of toroidal current, Eq. (32) is rewritten as

$$j_{\text{plasma}} = \left[1 - \frac{bk^2}{(1 + bp)^3} \right] \text{crmc}(\psi - \psi_0)^{m-1} \quad (37)$$

where $k \equiv 0.2I_z$. This form is convenient since inputting $b = 0$ will recover the original equation.

2. Beam Current Model

Macroparticles can be injected into the torus at any given angle ϕ from the tangential, or may have their injection angles randomized over some angle. The beam energy is also specified (and may be randomized over a given range). The beam is presumed to be circular but may be located anywhere in the poloidal cross section, may have any radius, and may have any profile of particle density as a function of beam radius.

Currents due to the macroparticles are defined on a grid (offset $\Delta R/2$ and $\Delta z/2$ from the B-field grid) by area-weighting the charges of

each of the particles among their four neighboring points and defining the local current density as

$$j = eQ \frac{d\theta}{dt} . \quad (38)$$

Since each of the particles actually represents a ring of charge in the θ -direction,

$$Q \equiv \frac{Q_{\text{ring}}}{2\pi e} \frac{1}{\Delta R \Delta z} . \quad (39)$$

The geometrical factor is included to make j a current density; the quantity $Q_{\text{ring}}/2\pi e \equiv N$, the total number of charged particles in each macroparticle. This particular set of definitions is chosen in order to guarantee conservation of the total charge present in the problem. Using this prescription for the local values of j_{plasma} , (35c) can be solved as indicated before for the self-consistent magnetic fields. Note that as a result of (38) the poloidal currents arising in the beam are ignored; B_θ is not adjusted to allow for these.

The guiding center motion of the particles must now be calculated. The following assumptions are made:

(1) Effective microscopic neutralization of all particles of one species by a fixed background of particles of the other. Electrostatic interactions among the macroparticles are not included in the code at present.

(2) Invariance of the magnetic moment

$$\gamma\mu \equiv - \frac{1}{2} \frac{\gamma^2 m_0 v_G^2}{B} \quad (40)$$

(v_G is the velocity of the particles around their guiding centers). Each particle's magnetic moment is calculated as a function of its initial velocity and stored. Actually, for particles which execute banana orbits the magnetic moments are adjusted at their mirror points for specious nonadiabatic effects arising from purely computational difficulties; such adjustments are necessary to calculate correct trajectories near the mirror points but rarely amount to as much as 1% of the particle's total magnetic moment. They can be justified as representing real deviations from adiabaticity.

(3) Conservation of kinetic energy. An exception is that energy may be supplied to or removed from (according to their motion) the particles by an externally applied voltage which for obvious reasons is assumed constant around the torus. Physically the particles would be the secondary coil of a transformer and hence this E-field would be the result of an applied variable B, but this additional field is not represented in the code. Thus the electric potential (V) is input in constant volts/turn and energy supplied to the particles at each cycle as a function of their θ -coordinates.

$$E = -qrV(\Delta\theta). \quad (41)$$

Thus, although the code is essentially 2-D, θ -coordinates (as well as v_θ , used in current calculations) are calculated and saved for each particle; but no useful information about the 3-D distribution of particles is actually generated. The framework is also included for consideration of the effects of induced toroidal electric fields upon the motion of the particles; such effects on the plasma current are

not, however, considered at present.

At each time step, knowing the particle's location and the local value of B , its guiding-center velocity can be calculated from the definition of μ above. Using its energy (also a function of position), the velocity parallel to the magnetic field can be calculated from

$$\gamma \equiv \left(1 - \frac{v^2}{c^2}\right)^{-1/2} \approx \left(1 - \frac{v_{\parallel}^2 + v_G^2}{c^2}\right)^{-1/2}.$$

We have

$$\frac{1}{\gamma^2} = \frac{m_0 v_G^2}{2\mu B} \approx 1 - \frac{v_{\parallel}^2}{c^2} - \frac{v_G^2}{c^2}$$

$$\text{hence } v_{\parallel}^2 = c^2 - v_G^2 \left(1 + \frac{m_0 c^2}{2\mu B}\right). \quad (42)$$

Finally, using the resulting $v_{\parallel}$ and appropriate derivatives of B at the particle's position, the components of its guiding-center's drift velocity, v_D , can be calculated using

$$\bar{v}_D = \frac{\bar{b}}{B} \times \left(-\bar{E} + \frac{\mu c}{\gamma e} \nabla B\right) + \frac{\gamma m_0 v_{\parallel}^2}{eB} \left[\bar{b} \times (\bar{b} \cdot \nabla) \bar{b}\right] \quad (43)$$

where $\bar{b} \equiv \bar{B}/B$ and $B \equiv |\bar{B}|$. The total velocity in each direction is the sum of the $\bar{v}_{\parallel}$ and $\bar{v}_D$ components in that direction.

The positions of all particles are updated using a leap-frog-corrector technique to solve $d\bar{r}/dt = \bar{v}$:

$$\text{Step 1} \quad (\bar{r}^{n+1})^* = \bar{r}^{n-1} + 2\Delta t \bar{v}^n$$

$$\text{Step 2} \quad (\bar{r}^{n+1})^* \rightarrow \left(\begin{array}{c} \text{guiding center} \\ \text{formalism above} \end{array}\right) \rightarrow (\bar{v}^{n+1})^*$$

$$\text{Step 3} \quad \bar{r}^{n+1} = r^n + \frac{1}{2} \Delta t \left[(\bar{v}^{n+1})^* + \bar{v}^n \right].$$

When the particles have been moved to new positions, their currents and the plasma current are recalculated, giving rise to new B-fields. Thus the most basic assumption involved in the code is one of quasi-steady evolution over the short time scales on which the particles are moved. Since this is typically a small fraction of a microsecond, the approximation is quite good. In earlier versions of the code an intermediate relaxation cycle, in which j and B were updated once again without moving the particles, was included, but it was found to be unnecessary.

Graphic outputs of the code include plots of surfaces of constant $|B|$ and ψ , locations of all particles in configuration space and v_r , v_z velocity space, plasma and beam current profiles, and distribution functions of velocity and energy. In addition, the complete orbit of a sample particle is plotted so that details of typical orbits may be studied. Virtually all the physical quantities mentioned are available in printed output as desired.

Details of the plasma equilibrium solution method have been compared with results of other methods and B-fields expected from chosen currents. The orbits of single particles have been checked and shown to conserve canonical angular momentum

$$P_\theta = mrv_\theta + \frac{e}{c} rA_\theta$$

better than 1 part in 10^6 and longitudinal adiabatic invariant (for trapped particles)

$$J \equiv \int m v_{\parallel} ds = m_0 \int \gamma v_{\parallel} ds$$

better than 1 part in 10^4 . When large fluctuating beam currents are flowing p_0 is conserved to within 2%; conservation of J then varies between 1% and 5%, depending upon the problem.

B. GUIDON Studies of TCT

The GUIDON code is used to study three classes of TCT problems:

(1) ideal MHD equilibrium of the bulk plasma, (2) single particle orbits of hot deuterons injected into the bulk plasma, and (3) injection of pulsed neutral beams into the bulk plasma, including self-fields of the beam particles and modifications of the bulk plasma equilibrium state. The energetic neutral beam injection problems are further broken down into three specific types:

- (1) Injection of 80 keV heating beams into an ohmic-heated target plasma;
- (2) Injection of 80 keV fusion beams into a heated precompression target plasma;
- (3) Injection of 150 keV fusion beams into a heated postcompression target plasma.

The appropriate target plasma equilibria for these and other TCT situations are computed. From the equilibrium calculations one obtains the vertical magnetic field necessary to position the plasma at the desired major radius. Details of the flux surface configuration and current and pressure profiles are also given. The neutral beams are assumed to be both co-injected and counter-injected relative to the plasma current. Several different beam deposition profiles have been used. Tangential injection is assumed in all cases.

GUIDON Results:

The results presented here use parameters from TCT scenarios suggested by preliminary Princeton/Westinghouse studies, but they are illustrative of the more general problems of energetic neutral beam injection. The two scenarios considered here are also discussed in the section on Fokker-Planck results:

Scenario III

- (a) Injection of 80 keV heating beams into a target plasma;
- (b) Thermalization of heating beams and target;
- (c) Fast compression to further boost the target energy;
- (d) Injection of 150 keV fusion beams — breakeven experiment.

Scenario IV

- (a) Injection of 80 keV heating beams into a target plasma;
- (b) Thermalization of heating beams and target;
- (c) Injection of 80 keV fusion beams;
- (d) Fast compression to boost the fusion beam and target plasma energy;
- (e) Thermalization of fusion beams and target plasma — breakeven experiment.

EQUILIBRIA

For scenario III the equilibria of interest are the ohmic-heated plasma target for the heating beams and the compressed plasma target for the 150 keV fusion beams.

For scenario IV the equilibria of interest are the ohmic-heated plasma target for the heating beams, the heated plasma target for the fusion beams, and the compressed plasma at the beginning of the "breakeven experiment".

In computing these equilibria only toroidal currents are taken into account. The equilibrium code is set up to handle both toroidal and poloidal currents but for simplicity the poloidal currents are assumed to be negligible in these scenarios.

A. Equilibrium Target for Heating Beams:

The ohmic-heated plasma target for the heating beams in a two-component torus is represented by the scalar pressure model

$$\begin{aligned} p(\psi) &= \bar{c}(\psi - \psi_0) & \psi > \psi_0 \\ &= 0 & \text{otherwise} \end{aligned}$$

which yields an approximately uniform toroidal current density

$$J_\theta = -\bar{c}R \quad \psi > \psi_0$$

A set of relevant plasma parameters (from preliminary Princeton/Westinghouse TCT studies) is:

$$\begin{aligned} I &= 0.77 \text{ MA} \\ R_0 &= 325 \text{ cm} \\ a &= 64 \text{ cm} \\ B_T &= 37.5 \text{ kG} \end{aligned}$$

The self-consistent plasma equilibrium results for these parameters are given in Figures 33 - 35. The poloidal flux surfaces in the (R,Z) domain are shown in Figure 33, including the effect of a uniform vertical field, $B_v = -350 \text{ G}$, needed to position the plasma at R_0 . The plasma boundary is indicated by the solid line in this figure. For other values of the vertical field strength the major radius of the plasma varies as in Figure 34. The perfectly conducting walls of the computational domain are responsible for limiting the

radial excursions of the plasma as $B_v \rightarrow 0, \infty$. The toroidal plasma current density as a function of radius is shown in Figure 35. The radial pressure profile (not shown) has a peak value of $p_* = 4.08 \times 10^5$ dynes/cm² which is consistent with a density and temperature given by

$$n_* = 10^{14} \text{ cm}^{-3}$$

$$T_* = 1 \text{ keV}$$

B. Equilibrium Compressed Target for Fusion Beams:

The beam-heated compressed plasma target for the 150 keV fusion beams is represented by the scalar pressure model

$$\begin{aligned} p(\psi) &= \bar{c}(\psi - \psi_0)^2 & \psi > \psi_0 \\ &= 0 & \text{otherwise} \end{aligned}$$

which yields a roughly parabolic toroidal current density profile. The relevant plasma parameters used here are:

$$I = 1.0 \text{ MA}$$

$$R_0 = 260 \text{ cm}$$

$$a = 58 \text{ cm}$$

$$B_T = 46.8 \text{ kG}$$

The poloidal flux surfaces for this equilibrium plasma are shown in Figure 36. The plasma boundary is indicated by the solid line. The vertical field required to position the plasma at R_0 was $B_v = -600$ gauss. The toroidal plasma current density as a function of radius is shown in Figure 37. The radial pressure profile (not shown) has a peak value $p_* = 1.629 \times 10^6$ dynes/cm²

which is consistent with a density and temperature given by

$$n_* = 10^{14} \text{ cm}^{-3}$$

$$T_* = 5 \text{ keV}$$

C. Equilibrium Heated Target for Fusion Beams:

The beam-heated uncompressed plasma target for the 80 keV fusion beams is represented by the parabolic pressure model (see B above). The relevant plasma parameters are:

$$I = .77 \text{ MA}$$

$$R_o = 325 \text{ cm}$$

$$a = 64 \text{ cm}$$

$$B_T = 37.5 \text{ kG}$$

The poloidal flux surfaces and plasma boundary (solid line) are shown in Figure 38. The vertical field was $B_v = -425$ gauss. The toroidal plasma current density as a function of radius is shown in Figure 39. The radial pressure profile (not shown) has a peak value $p_* = 8.36 \times 10^5 \text{ dynes/cm}^2$ which is consistent with a density and temperature

$$n_* = 10^{14} \text{ cm}^{-3}$$

$$T_* = 3 \text{ keV}$$

D. Equilibrium Compressed Plasma for Breakeven Experiment:

After the 80 keV fusion beams have been injected and the system is compressed, the equilibrium tritium plasma has parameters:

$$I = 1.0 \text{ MA}$$

$$R_o = 250 \text{ cm}$$

$$a = 56 \text{ cm}$$

$$B_T = 46.8 \text{ kG}$$

The poloidal flux surfaces and plasma boundary (assuming no net current due to the fusion beams) are given in Figure 40. The vertical field was $B_v = -800$ gauss. The toroidal plasma current density as a function of radius is shown in Figure 41. The radial pressure profile (not shown) has a peak value $p_* = 1.647 \times 10^6$ dynes/cm² which is consistent with

$$n_* = 10^{14} \text{ cm}^{-3}$$

$$T_* = 5 \text{ keV}$$

SINGLE-PARTICLE ORBITS

The guiding-center orbits of individual particles in both vacuum and plasma fields have been checked against approximate, analytically calculable orbits and the agreement is very good. Stagnation points for co-injected and counter-injected particles are observed and agree well with theoretical predictions for simple current models. Trapped particle orbits have also been verified.

Since the primary purpose of this computer code is to simultaneously follow the self-consistent orbits of many particles, and since many other people have previously studied single-particle orbits in Tokomaks, no results on this aspect of the code are deemed necessary. It should be noted, however, that during the course of a beam injection run involving some 2500 particles, the orbit of a single tracer-particle (chosen at random from the originally injected particles) is followed in time. This acts as check or monitor on the behavior of individual particles in the time-varying fields of the beam and plasma.

BEAM INJECTION

There are two primary beam injection problems associated with TCT scenarios III and IV as previously outlined:

(a) injection of the 80 keV heating beams into a 1 keV target plasma, and (b) injection of either 80 keV or 150 keV fusion beams into a hot target plasma for the "breakeven experiment". For each of these situations the appropriate equilibrium target plasma model is the starting point for the beam injection run.

Each of the 2500 "macro-particles" injected into this equilibrium system represents a very large number of deuterons (typically $\sim 10^{15}$) uniformly distributed around the torus in a real system. In the model, all 2500 particles are injected simultaneously at the initial time-step. However, the toroidal current associated with each particle is initially set equal to zero and is defined to increase linearly with time over some finite interval, τ_b . This has the effect of modelling the decay of the induced plasma current due to an instantaneously injected beam. At time $t=0$ the induced current is assumed to exactly cancel the beam particle current.

The particles are initially injected into the system with random spatial coordinates, subject to some assumed beam deposition profile, $n_b(r)$, where r is the distance from the centroid of the beam. Typically, a peaked distribution of the form

$$n_b(r) \sim \left(\frac{1}{r} - \frac{1}{r_0} \right)$$

is used. Here r_0 is the minor radius of the beam distribution. Other profiles have also been used, but the results are similar. In all of the cases described here, the particle velocities were assumed to be tangential to the torus at time $t=0$, i.e. $v_R = v_Z = 0$, the sign of v_θ could correspond

to either co-injection or counter-injection.

As the beam particles move on guiding-center orbits during the course of a run, the self-consistent poloidal magnetic field changes. The target plasma pressure and current density profile are also changing. At each time-step the plasma is assumed to be represented by a fixed functional form for $p(\psi)$ and $j_\theta(\psi)$. However, ψ itself is changing — it is given by the self-consistent solution to Ampere's law, including both particle and plasma currents. The parameters $\bar{c}$ and ψ_0 in the functional form, $p(\psi) = \bar{c}(\psi - \psi_0)^m$, are adjusted at each time-step so as to yield the same total plasma current as at time $t=0$. In practice, ψ_0 is fixed and only $\bar{c}$ is adjusted.

Finally, it should be noted that the time-scales for the computer runs are typically on the order of 100 microseconds whereas the actual beam injection time in TCT is likely to be on the order of 100 milliseconds. At present it is not feasible to simulate the real injection times or decay times for induced plasma currents. However, by choosing the beam current build-up time, τ_b , long compared to the time for the guiding centers to circulate around the torus, a somewhat realistic qualitative picture of the true situation should be obtained.

A. 80 keV Heating Beams

The injection of 80 keV heating beams is examined for the case of neutral beam sources supplying a total of 442 amperes in a 30 msec. pulse. These deuterons are assumed to be injected into the ohmic-heated plasma, Equilibrium "A", described previously. The magnitude of the source current is chosen large enough to yield a plasma temperature of 4 keV after thermalization of the heating beam. The mean radius of injection is 325 cm with a peaked beam deposition profile having a minor radius $r_0 = 50$ cm. Three cases

were run:

- (1) both co- and counter-injected beams are used (one-half of the total current in each direction); the particle current build-up time is $\tau_b = 25$ microseconds.
- (2) same as (1) above, except $\tau_b = 150$ microseconds.
- (3) only co-injection is used; $\tau_b = 150$ microseconds.

The results for case (1) are shown in Figures 42-47. The toroidal particle current flowing in each direction after full build-up is about 0.90 MA whereas the plasma current is 0.77 MA. The initial spatial distribution of the beam particles is shown in Figure 42 and the flux surfaces and plasma boundary (solid line) are shown in Figure 43. After 10 μ sec, when the beam currents are about ± 0.36 MA, the situation is as shown in Figure 44 and 45. On the particle position plot one sees a slight concentration of particles to the upper right of center and this is verified in the flux surface plot. The flux surface deformation one sees is due to the counter-injected beam particles. The plasma boundary flux surface has not yet been disturbed. At 16.5 μ sec., however, the distortions have become more obvious. In Figure 46 two concentrations of particles can be identified as the co- and counter-injected beams, now spatially separated by a few centimeters. The corresponding flux plots reveal that the plasma has been pushed toward the upper-right of the domain and its surface is no longer circular. What is apparently happening is that the co-injected and counter-injected beams are repelling one another. Any small transverse perturbation is sufficient to start this process. Meanwhile, the plasma tends to stay near the co-injected beam (parallel currents attract). As time proceeds, the gross motion of the system in the R-Z domain is basically an orbital motion of the oppositely directed currents about one another. The time scale for this orbital motion is observed to be less than or of the order of one microsecond in this run.

The results for case (2) are shown in Figures 48-51. In this instance the beam particle current was allowed to build up more slowly than in (1); $\tau_b = 150 \mu\text{sec}$. Initial distributions are the same as case (1); see Figures 48 and 49. After 36 μsec , when the beam current in each direction has built up to 0.22 MA, the particles and flux surfaces are as shown in Figures 50 and 51. Although gross distortions are not yet evident, the longer build-up time has allowed some of the counter-injected particles to drift outside the plasma boundary and eventually be lost on the limiter. By observing this case for a longer time interval one should be able to determine whether the beam separation observed in case (1) is eliminated or merely delayed. Results are not yet available.

The results for case (3) are shown in Figures 52-55. To avoid the possible undesirable effects associated with a counter-injected beam, only co-injection is used. The particle current build-up time was 150 μsec . Initial positions of particles and flux surfaces are shown in Figures 52 and 53. After 40 μsec , with the circulating beam current at 0.470 MA, the situation is as shown in Figures 54 and 55. There are no noticeable changes in the spatial distribution of the beam particles since injection, and the plasma surface has expanded only slightly (solid line in Figure 55).

B. 80 keV Fusion Beams

Neutral beam sources are assumed to produce 60 amperes of 80 keV deuterons in a 30 msec. pulse. This source current is injected into Equilibrium "C", described previously, at a mean radius of 325 cm with a peaked beam deposition profile having a minor radius $r_0 = 50 \text{ cm}$. Half of the source particles are assumed to be co-injected; the other half counter-injected. The toroidal

particle current flowing in each direction is ultimately about 0.125 MA while the equilibrium plasma current is 0.77 MA. The build-up time for the particle current in this run is taken as 25 microseconds. The initial spatial distribution of the beam particles is shown in Figure 56 and the flux surfaces and plasma boundary are shown in Figure 57. After 25 μ sec, when the particle currents have assumed their full value, the situation is as shown in Figures 58 and 59. A few particles (most likely counter-injected) have begun to separate from the main beam. The plasma remains relatively undisturbed. After 50, 100 and 150 μ sec the beam particle distribution and flux surfaces are as shown in Figures 60-65, respectively. A significant number of counter-injected particles appears to be leaving the plasma and main beam, and would probably be lost on the limiter. The plasma has remained essentially undisturbed throughout this run. This is not unexpected since the toroidal particle currents are only a small fraction of the plasma current.

C. 150 keV Fusion Beams

The 150 keV deuterons are assumed to be injected continuously for 160 msec during the "breakeven" experiment in Scenario III, described earlier. An injection current of 60 amperes is sufficient to maintain a constant plasma energy during the experiment if the energy confinement time is 200 msec. The appropriate equilibrium plasma for this injection problem is Equilibrium "B", described previously. The mean radius of injection for the particles is 260 cm with a peaked beam deposition profile having a minor radius $r_0 = 50$ cm.

Results in this case are similar to case A (heating beam injection) since the total circulating beam current after build-up is comparable to the plasma current.

With both co- and counter-injected beams (one-half of the total current in each direction) and a build-up time of 25 μ sec, the results after 14 μ sec

are as shown in Figures 66 and 67. The opposing beams are well-separated in space and the plasma has been pushed toward the domain boundary. A few particles from the counter-injected beam have been lost at the upper edge of the domain. A limiter near the original plasma boundary would have increased the number of lost particles.

By increasing the build-up time to $\tau_b = 150 \mu\text{sec}$, the distortion of the plasma by the beams appears to be less severe. The situation after 50 μsec is as shown in Figures 68 and 69. The longer build-up time has allowed some of the counter-injected beam particles to drift outside the plasma and eventually be lost on a limiter. However, the number of such particles is small. (This run is being continued for a longer time to see if the particle losses saturate before a significant fraction of the beam is lost. Results will be available later.)

If only co-injected beams are used, and the build-up time is $\tau_b = 150 \mu\text{sec}$, the results are as shown in Figures 70 and 71 after 65 μsec . At this time the toroidal beam current is 0.917 MA. The beam particles have not spread appreciably. A possible disadvantage of this mode of injection is illustrated by the fact that the plasma surface has expanded from its original minor radius of 58 cm to 85 cm.

SPECIES NO 1 TIME= 3.000000E-32

DEUTERONS

FIGURE 1

SPECIES NO 1 TIME= 8.000000E-02

DEUTERONS

FIGURE 2

SPECIES NO 1 TIME= 1.500000E-01

DEUTERONS

FIGURE 3

DENSITY

TIME →

ELECTRONS

DENSITY= 7.839883E+13

ENERGY= 4.523305E+00

TIME= 2.000000E-01

PPERP= 4.290001E-01

FIGURE 4

DENSITY

TIME →

DEUTERONS

K = 1 ENERGY

DENSITY= 9.822440E+12 ENERGY= 6.036982E+00
 TIME= 2.000000E-01 PPERP= 6.436746E-02

FIGURE 5

K= 2 ENERGY

DENSITY

TRITONS

DENSITY= 6.994680E+13

ENERGY= 5.987419E+00

TIME= 2.000000E-01

PPERP= 5.066324E-01

Figure 6

EL. VOLT FACTOR = 1.122559E+00 TOTAL SYSTEM ENERGY = 8.267012E+14

TIME= 2.000000E-01

FIGURE 7

DENSITY

ELECTRONS

K= 0 ENERGY

DENSITY= 9.158838E+13 ENERGY= 8.339338E+00
TIME= 4.000000E-02 PPERP= 4.490734E-01

FIGURE 8A

DENSITY

ELECTRONS

K= 0 ENERGY

DENSITY= 9.15829E+13

ENERGY= 8.20423E+00

TIME= 8.00000E-02

PPERP= 4.00496E-01

FIGURE 8 B

DENSITY

ELECTRONS

DENSITY= 9.157959E+13

ENERGY= 7.440448E+00

TIME= 1.200000E-01

PPERP= 4.058100E-01

FIGURE 8C

DENSITY

ELECTRONS

K=0 ENERGY

TIME →

DENSITY= 9.157917E+13

ENERGY= 6.725924E+00

TIME= 1.500000E-01

PPERP= 4.241418E-01

FIGURE 8D

K= 1 ENERGY

DEUTERONS

DENSITY

DENSITY= 1.213759E+13

ENERGY= 9.505341E+01

TIME= 4.000000E-12

PPERP= 1.417350E-11

FIGURE 9 A

K= 1 ENERGY

DEUTERONS

DENSITY

DENSITY= 1.207867E+13 ENERGY= 4.573994E+01
TIME= 8.000000E-02 PPERP= 1.664371E-01

FIGURE 9 B

DENSITY

TIME →

K= 1. ENERGY

DEUTERONS

DENSITY= 1.210931E+13 ENERGY= 1.924570E+01
 TIME= 1.200000E-01 PPERP= 1.189663E-01

FIGURE 9 C

DENSITY

DEUTERONS

K= 1 ENERGY

DENSITY= 1.211737E+13 ENERGY= 1.102010E+01
 TIME= 1.500000E-01 PPERP= 8.896825E-02

FIGURE 9 D

DENSITY

TRITONS

K= 2 ENERGY

DENSITY= 7.932741E+13 ENERGY= 9.124548E+00
 TIME= 4.000000E-02 PPERP= 4.091916E-01

FIGURE 10 A

K= 2 ENERGY

TRITONS

DENSITY

DENSITY= 7.929143E+13 ENERGY= 1.022662E+01
TIME= 8.000000E-02 PPERP= 4.330659E-01

FIGURE 10 B

DENSITY

K= 2 ENERGY

TRITONS

DENSITY= 7.929376E+13

ENERGY= 1.002614E+01

TIME= 1.200000E-01

PPERP= 4.743237E-01

FIGURE 10 C

K= 2 ENERGY

DENSITY

TRITONS

DENSITY= 7.923363E+13 ENERGY= 8.920615E+00
TIME= 1.500000E-01 PPERP= 4.868899E-01

FIGURE 10 D

SPECIES NO 1 TIME= 3.000000E-02

DEUTERONS

FIGURE 11

SPECIES NO 1 TIME= 4.000000E-02

DEUTERONS

FIGURE 12

DENSITY

ELECTRONS

DENSITY= 5.300466E+13 ENERGY= 2.780920E+00
 TIME= 2.000000E-02 PPERP= 4.902856E-01

FIGURE 13 A

DENSITY

K=0 ENERGY

ELECTRONS

DENSITY= 5.700728E+13

ENERGY= 4.178974E+00

TIME= 7.500000E-02

PPERP= 3.567845E-01

FIGURE 13 B

DENSITY

TIME →

ELECTRONS

K= 0 ENERGY

DENSITY= 8.986796E+13 ENERGY= 5.043535E+00
 TIME= 1.300000E-01 PPERP= 4.080529E-01

FIGURE 13 C

DENSITY

TIME →

ELECTRONS

K= 0 ENERGY

DENSITY= 9.070836E+13

ENERGY= 4.951859E+00

TIME= 1.500000E-01

PPERP= 4.289557E-01

FIGURE 13 D

K= 0. ENERGY

ELECTRONS

DENSITY

DENSITY= 9.491016E+13 ENERGY= 4.006046E+00
TIME= 2.500000E-01 PPERP= 4.312108E-01

FIGURE 13 E

K= 0 ENERGY

ELECTRONS

DENSITY

DENSITY= 9.911194E+13

ENERGY= 3.336148E+00

TIME= 3.500000E-01

PPERP= 4.372593E-01

FIGURE 13 F

DENSITY

ELECTRONS

DENSITY= 1.012128E+14

ENERGY= 3.041881E+00

TIME= 4.000000E-01

PPERP= 4.410864E-01

FIGURE 13 6

DENSITY

K= 1 ENERGY

DEUTERONS

DENSITY= 8.085484E+12 ENERGY= 0.203009E+01
 TIME= 2.000000E-02 PPERP= 2.091796E-01

FIGURE 14 A

DENSITY

K= 1 ENERGY

DEUTERONS

DENSITY= 1.213079E+13

ENERGY= 1.930957E+01

TIME= 7.500000E-02

PPERP= 2.327823E-01

FIGURE 14 B

K= 1 ENERGY

DEUTERONS

DENSITY

DENSITY= 1.947540E+13

ENERGY= 1.059327E+01

TIME= 1.300000E-01

PPERP= 1.334714E-01

FIGURE 14 C

DENSITY

K= 1 ENERGY

DEUTERONS

DENSITY= 2.032600E+13 ENERGY= 1.317840E+01

TIME= 1.500000E-01 PPERP= 1.363074E-01

FIGURE 14 D

DENSITY

K= 1 ENERGY

DEUTERONS

DENSITY= 2.455264E+13

ENERGY= 1.231002E+01

TIME= 2.500000E-01

PPERP= 1.902584E-01

FIGURE 14 E

K = 1 ENERGY

DEUTERONS

DENSITY

DENSITY= 2.875928E+13

ENERGY= 9.194083E+00

TIME= 3.500000E-01

PPERP= 1.915093E-01

FIGURE 14 F

K= 1 ENERGY

DEUTERONS

DENSITY

DENSITY= 3.035816E+13 ENERGY= 7.964503E+00
 TIME= 4.000000E-01 PPERP= 1.963878E-01

FIGURE 14 9

K= 2 ENERGY

TRITONS

DENSITY

DENSITY= 4.496528E+13 ENERGY= 1.975637E+00
TIME= 2.000000E-02 PPERP= 3.005346E-01

FIGURE IS A

K= 2 ENERGY

TRITONS

DENSITY= 4.489068E+13

ENERGY= 6.097315E+00

TIME= 7.500000E-02

PPERP= 4.104331E-01

FIGURE 15 B

K= 2 ENERGY

TRITONS

DENSITY

DENSITY= 7.036863E+13

ENERGY= 7.299326E+00

TIME= 1.300000E-01

PPERP= 4.584757E-01

FIGURE 15 C

K= 2 ENERGY

TRITONS

DENSITY

DENSITY= 7.036635E+13

ENERGY= 6.463152E+00

TIME= 1.500000E-01

PPERP= 4.347369E-01

FIGURE 15 D

K= 2 ENERGY

TRITONS

DENSITY

DENSITY= 7.033924E+13

ENERGY= 4.860255E+00

TIME= 2.500000E-01

PPERP= 3.885309E-01

FIGURE 15 E

DENSITY

TRITONS

K= 2 ENERGY

DENSITY= 7.030670E+13 ENERGY= 3.985932E+00
 TIME= 3.500000E-01 PPERP= 3.712314E-01

FIGURE 15 F

K= 2 ENERGY

TRITONS

DENSITY

DENSITY= 7.029044E+13

ENERGY= 3.594347E+00

TIME= 4.000000E-01

PPERP= 3.625258E-01

FIGURE IS 6

DENSITY

ELECTRONS

K= 0 ENERGY

DENSITY= 5.500466E+13 ENERGY= 2.747252E+00
 TIME= 2.000000E-02 PPERP= 4.878211E-01

FIGURE 16 A

DENSITY

K= 0 ENERGY

ELECTRONS

DENSITY= 5.900734E+13

ENERGY= 4.292357E+00

TIME= 6.000000E-02

PPERP= 3.712740E-01

FIGURE 16 B

DENSITY= 6.140865E+13 ENERGY= 4.309689E+00
 TIME= 1.000000E-01 PPERP= 3.907931E-01

FIGURE 16 C

DENSITY

ELECTRONS

K= 0 ENERGY

DENSITY= 6.621140E+13 ENERGY= 4.795174E+00
 TIME= 1.200000E-01 PPERP= 3.985315E-01

FIGURE 16 D

K= 0 ENERGY

ELECTRONS

DENSITY

DENSITY= 1.119696E+14 ENERGY= 5.078079E+00
 TIME= 2.500000E-01 PPERP= 4.429652E-01

FIGURE 16 E

K= 1 ENERGY

DENSITY

DEUTERONS

DENSITY= 8.083000E+12 ENERGY= 6.121413E+01
TIME= 2.000000E-02 PPERP= 2.069970E-01

FIGURE 17 A

DENSITY= . 1.209921E+13 ENERGY= 2.651802E+01
 TIME= 6.000000E-02 PPERP= 2.576469E-01

FIGURE 17 B

DENSITY

K= : ENERGY

DEUTERONS

DENSITY= 1.456599E+13 ENERGY= 2.042389E+01
 TIME= 1.000000E-01 PPERP= 1.743124E-01

FIGURE 17 C

K= 1 ENERGY

DENSITY

DEUTERONS

DENSITY= 1.938035E+13

ENERGY= 2.796397E+01

TIME= 1.200000E-01

PPERP= 2.166209E-01

FIGURE 17 D

DENSITY

K= 1 ENERGY

DEUTERONS

DENSITY= 3.259675E+13

ENERGY= 6.351362E+00

TIME= 2.500000E-01

PPERP= 1.612724E-01

FIGURE 17 E

K= 2 ENERGY

DENSITY

TRITONS

DENSITY= 4.696394E+13 ENERGY= 1.980596E+00
TIME= 2.000000E-02 PPERP= 3.051819E-01

FIGURE 18 A

K= 2 ENERGY

DENSITY

TRITONS

DENSITY= 4.689426E+13 ENERGY= 5.362814E+00

TIME= 5.000000E-02 DDDDD= 2.710771E-01

K= 2 ENERGY

TRITONS

DENSITY= 4.588390E+13

ENERGY= 6.271745E+00

TIME= 1.000000E-01

PPERP= 4.348945E-01

FIGURE 18 C

DENSITY

K= 2 ENERGY

TRITONS

DENSITY= 4.687277E+13 ENERGY= 6.486585E+00
 TIME= 1.200000E-01 PPERP= 3.848476E-01

FIGURE 18 D

K= 2 ENERGY

TRITONS

DENSITY

DENSITY= 7.914352E+13

ENERGY= 6.418777E+00

TIME= 2.500000E-01

PPERP= 3.957624E-01

FIGURE 18 E

SPECIES NO : TIME= 3.000000E-02

DEUTERONS

FIGURE 19

SPECIES NO : TIME= 1.800000E-01

DEUTERONS

FIGURE 20

SPECIES NO : TIME= 3.60000E-01

DEUTERONS

FIGURE 21

DENSITY

ELECTRONS

K = : ENERGY

DENSITY= 7.473041E+13

ENERGY= 2.610497E+00

TIME= 5.800000E-01

FIGURE 22

DENSITY

K = ENERGY

DEUTERONS

DENSITY= 6.820299E+12 ENERGY= 3.419352E+00
 TIME= 3.800000E-01

FIGURE 23

DENSITY

TRITONS

K= 2 ENERGY

DENSITY= 6.783194E+13 ENERGY= 3.369153E+00
 TIME= 3.800000E-01

FIGURE 24

CO-2013-1000 = 1.05187E+00

ρ

TIME= 3.600000E-01

FIGURE 25

DENSITY

K= 0 ENERGY
ELECTRONS

DENSITY= 3.200106E+13 ENERGY= 5.468910E+00
TIME= 2.000000E-02 PPERP= 4.915006E-01

FIGURE 26 A

K= 0 ENERGY

ELECTRONS

DENSITY

DENSITY= 4.206319E+13 ENERGY= 5.914950E+00
TIME= 8.000000E-02 PPERP= 4.397407E-01

FIGURE 26 B

K= 0 ENERGY

ELECTRONS

DENSITY

DENSITY= 7.470579E+13 ENERGY= 6.423969E+00
TIME= 1.800000E-01 PPERP= 4.210347E-01

FIGURE 26 C

DENSITY= 3.322737E+13 ENERGY= 2.457113E+00
 TIME= 2.800000E-01 HPERP= 4.563396E-01

FIGURE 26 D

K= 0 ENERGY

DENSITY

ELECTRONS

DENSITY= 3.322716E+13 ENERGY= 1.513232E+00
 TIME= 3.000000E-01 PPERP= 4.818443E-01

FIGURE 26 E

DENSITY

K= : ENERGY
DEUTERONS

DENSITY= 2.033742E+12 ENERGY= 1.080073E+02
 TIME= 2.000000E-02 PPERP= 3.898649E-02

FIGURE 27 A

DENSITY

K= 1 ENERGY

DEUTERONS

DENSITY= 3.882743E+12 ENERGY= 7.290180E+01
 TIME= 8.000000E-02 PPERP= 1.475239E-01

FIGURE 27 B

K= 1 ENERGY

DENSITY

DEUTERONS

DENSITY= 6.920941E+12 ENERGY= 1.935862E+01
TIME= 1.800000E-01 PPERP= 9.393796E-02

FIGURE 27 C

K= 1 ENERGY

DEUTERONS

DENSITY

DENSITY= 3.066945E+12 ENERGY= 2.907781E+00
TIME= 2.800000E-01 PPERP= 4.989817E-02

FIGURE 27 D

K = 1 ENERGY

DENSITY

DEUTERONS

DENSITY= 3.067080E+12 ENERGY= 1.616947E+00
 TIME= 3.800000E-01 PPERP= 4.752558E-02

FIGURE 27 E

DENSITY

K= 2 ENERGY

TRITONS

DENSITY= 2.999818E+13 ENERGY= 5.547366E+00
 TIME= 2.000000E-02 PPERP= 4.695129E-01

FIGURE 28 A

K= 2 ENERGY

TRITONS

DENSITY

DENSITY= 3.822814E+13 ENERGY= 6.106051E+00
TIME= 8.000000E-02 PPERP= 4.127353E-01

K= 2 ENERGY

TRITONS

DENSITY

DENSITY= 6.779731E+13 ENERGY= 8.232576E+00
TIME= 1.800000E-01 PPERP= 4.850274E-01

FIGURE 28 C

K= 2 ENERGY

TRITONS

DENSITY

DENSITY= 3.006214E+13 ENERGY= 2.934023E+00
 TIME= 2.900000E-01 PPERP= 4.937622E-01

K= 2 ENERGY

TRITONS

DENSITY

DENSITY= 3.006625E+13

ENERGY= 1.633405E+00

TIME= 3.800000E-01

PPERP= 4.706301E-01

FIGURE 28 E

DENSITY

K=0 ENERGY

ELECTRONS

DENSITY= 2.165110E+13 ENERGY= 1.568352E+00
 TIME= 2.000000E-01

DENSITY

K=1 ENERGY

DEUTERONS

DENSITY= 9.054544E+11 ENERGY= 2.144571E+00
TIME= 2.000000E-01

FIGURE 30

DENSITY

K= 2 ENERGY

TRITONS

DENSITY= 2.036175E+13 ENERGY= 1.873831E+00

TIME= 2.000000E-01

FIGURE 31

EN MULT FACTOR = 1.169255E+00

Q

TIME= 2.000000E-01

FIGURE 32

FIGURE 33

FIGURE 34

MAJOR RADIUS VS. VERTICAL FIELD

PLASMA CURRENT DENSITY VERSUS RADIUS

FIGURE 36

FIGURE 37

FIGURE 38

PLASMA CURRENT DENSITY VERSUS RADIUS

FIGURE 40

PLASMA CURRENT DENSITY VERSUS RADIUS

FIGURE 42

FIGURE 43

TIME = 1.0515E+01 MAGNETIC FIELD MAX = 6.0957E+04 MIN = 2.7327E+04 CUR

FIGURE 44

FIGURE 45

FIGURE 46

FLUX MAX= 6.0498E+07 MIN= -3.5067E+07

FIGURE 47

TIME = 6.0000E-02 MAGNETIC FIELD MAX = 6.0958E+04 MIN = 2.7327E+04 CUR

FIGURE 48

FIGURE 49

FIGURE 50

Figure 51

FIGURE 52

FIGURE 53

TIME = 4.0515E+01 MAGNETIC FIELD MAX = 6.0984E+04 MIN = 2.7328E+04 CUR

FIGURE 54

FIGURE 55

FIGURE 56

FIGURE 57

FIGURE 58

FLUX MAX= $5.4480\text{E}+07$ MIN= $-4.2555\text{E}+07$

FIGURE 59

FIGURE 60

FIGURE 61

FIGURE 62

FLUX MAX= $5.9944\text{E}+07$ MIN= $-4.2541\text{E}+07$

FIGURE 63

FIGURE 64

TIME = 1.5002E+02 MAGNETIC FIELD MAX = 6.0948E+04 MIN = 2.7329E+04 CUR

FLUX MAX= $6.0546\text{E}+07$ MIN= $-4.2541\text{E}+07$

FIGURE 65

FIGURE 66

FIGURE 67

TIME = 4.9620E+01 MAGNETIC FIELD MAX = 9.3686E+04 MIN = 3.3289E+04 CUR

Figure 68

FIGURE 69

FIGURE 70

FIGURE 71

ACKNOWLEDGEMENT

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