TOKAMAK TWO-FLUID CODE: EFFECTS OF

NEUTRAL BEAM HEATING, RADIATION LOSS, AND CHARGE EXCHANGE*

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Abstract: Requirements for heating a large Tokamak device with energetic neutral beams are considered. Even in a pessimistic treatment we find that ≈ 10 MW of supplemental injected power would produce plasma of true thermonuclear interest. Losses from radiation, plasma thermal conduction, mass transport, ionization, and charge exchange are included.

Energetic neutral beam injection is one of the most natural ideas for heating Tokamak plasmas.⁽¹⁾ Rapid progress in the production of significant current at high energy justifies careful studies of the effect of injection on the energy balance of higher temperature systems. We solve the following equations in the cylindrical, (r,t) , approximation

$$\frac{\partial}{\partial t} N = - \frac{1}{r} \frac{\partial}{\partial r} (rNV) + S_{\text{ionization}} \quad (1)$$

$$\begin{aligned} \frac{3}{2} \frac{\partial}{\partial t} (NT_e) = & - \frac{1}{r} (rQ_e) + Q_{e-i} + Q_{e-\alpha} + Q_{e-\text{injection}} + E \cdot J \\ & + Q_{\text{compression}} - L_{\text{bremsstrahlung}} - L_{\text{synchrotron}} - L_{\text{ionization}} \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{3}{2} \frac{\partial}{\partial t} (NT_i) = & - \frac{1}{r} \frac{\partial}{\partial r} (rQ_i) - Q_{e-i} + Q_{i-\alpha} + Q_{i-\text{injection}} - Q_{\text{compression}} \\ & - L_{\text{ionization}} - L_{\text{charge exchange}} \end{aligned} \quad (3)$$

and Maxwell field equations. The cold (non-injected) neutral population in the plasma is calculated self-consistently from the kinetic equation. A flux of cold neutral H_2^0 incident uniformly around the torus is ionized

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and undergoes resonance dissociation yielding 2 H^0 with a mean energy of 3 ev. Consideration of higher energy particles from the limiter would require a three-dimensional calculation, similar to that in (2), and this is yet to be done. Spatial profiles of density and mean energy for the neutrals are shown in Fig. 1. Here we give the ratio of neutral density to density of incident Franck-Condots, the neutral temperature and the ion temperature for a T3 case with $N(r) = 5 \times 10^{13} \times (1 - r^2/a^2)$. (Charge exchange energy spectra are computed and agree with data from T3 and ST.)

The importance of radiation at higher temperatures is illustrated when losses from bremsstrahlung and synchrotron radiation are added, the latter including the effects of line broadening due to toroidal field⁽³⁾ inhomogeneities. Here we make the pessimistic assumption that none of the radiation is reflected and reabsorbed in the plasma. We assume that heating from thermonuclear alpha particles goes mainly to the electrons. The ions are a D-T mixture treated as one type with effective atomic mass 2.5.

Injection of beams roughly parallel and anti-parallel to the field gives a power deposition peaked toward the outside of the plasma (Fig. 2). For pinched plasma density distributions, central peaking would occur and lead to a greatly enhanced efficiency. Injection heating is divided by electrons and ions, if the energy is chosen appropriately.

Figure 3 gives results for two typical cases. The plasma has a 50 cm minor radius, 300 cm major radius, and a 55 kG toroidal field. The total current is assumed constant at 1.2 MA and initial temperatures are chosen to be high. Ohmic heating supplies the bulk of the power required to reach the 5 keV state. We then follow the evolution to learn the power requirements for increased plasma heating and conditions for thermal stability. Case (a), at low density and low injected power levels, shows some skin

formation even though the initial profile was peaked at the center.

(Maximum plasma density is $5 \times 10^{13} \text{ cm}^{-3}$ with 0.5 MW of injected power).

The energy at a later time, for example, at 1 sec, has decreased. A clear break point occurs at densities near $1-2 \times 10^{14}$, and the second case in Fig. 3 shows a higher density plasma ($N_{\text{Max}} = 1. \times 10^{14} \text{ cm}^{-3}$) with 5 Mw of supplemental injection. Higher density and losses from synchrotron radiation prevent large excursions in T_e and provide thermal stability.

A summary of these time dependent calculations is given in Fig. 4 for a plasma with $N_{\text{Max}} = 1. \times 10^{14} \text{ cm}^{-3}$. Maximum values of T_e and T_i (whose spatial profiles are typified in Fig. 3) are given at 1 sec with the injected power level and the Ohmic heating power for comparison. The decrease of the latter is a natural consequence of the increase in T_e . Less than 10 volt seconds are expended in the evolution, for start up and constant current phase, and extension to longer times seems feasible.

In present experiments, plasma diffusion losses are much more significant. We have as expressions for the fluxes:

$$Q_e = \frac{5}{2} NVT_e + \sum_{\alpha} L_{\alpha}^{(1)} F_{\alpha} ; \{F_{\alpha}\} = \left(\frac{\partial T_e}{\partial r} \frac{\partial T_i}{\partial r} \frac{\partial N}{\partial r}, E \right) \quad (4)$$

$$V = \sum_{\alpha} L_{\alpha}^{(3)} F_{\alpha} ; Q_i = y NVT_i + \sum_{\alpha} L_{\alpha}^{(2)} F_{\alpha} ; E = \eta \left\{ J + \sum_{\alpha} L_{\alpha}^{(4)} F_{\alpha} \right\} \quad (5)$$

and the code readily allows comparison with a burgeoning number of simulations⁽⁴⁻⁷⁾. We have concentrated on the neo-classical equations derived in Ref. (8) with appropriate plateau corrections for the region of the magnetic axis⁽⁶⁾. For the high energy cases discussed above we have used the diagonal form for the fluxes with the empirical scaling⁽⁹⁾ modified for higher densities⁽¹⁰⁾.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

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1. G. G. Kelley, et. al., CRNL TM-3076 (1970), Nucl. Fusion 12 (1972) 169
2. R. J. Colchin, Nucl. Fusion 11 (1971) 329
3. M. N. Rosenbluth, Nucl. Fusion 10 (1970) 340
4. Y. N. Dnestrovsky, et. al., Moscow University Press, Moscow (1971)
5. C. Mercier, et. al., 4th Intl. Conf. on Cont. Fusion, Madison, (1971)
6. F. L. Hinton (Private Communication)
7. D. F. Duchs, et. al., 4th Intl. Conf. on Cont. Fusion, Madison (1971)
8. M. N. Rosenbluth, et. al., Physics of Fluids 15 (1972) 116
9. L. A. Artsimovich, Nucl. Fusion 12 (1972) 215
10. R. A. Dory, et. al., Kiev Conf. on Theo. Physics, Kiev, (1971)