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Injection Heating Scenarios for TNS

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Printed in the United States of America. Available from
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U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$3.50; Microfiche \$3.00

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Contract No. W-7405-eng-26

Fusion Energy Division

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Date Published: July 1977

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ABSTRACT

Neutral beam injection heating is a prime contender for heating TNS. However, injection into a full bore high density plasma during start-up will not give adequate beam penetration even with deuteron energies up to 300 keV and $Z_{\text{eff}} < 1.5$. But low density start-up may be feasible with deuteron energies of ~ 150 keV if advantage is taken of the α -heating and flux surface shifts which occur when β is increased.

1. INTRODUCTION

Neutral beam injection heating is the most technically advanced and experimentally proven form of auxiliary tokamak heating. As such, it is a prime contender for heating TNS (The Next Step). Although existing injection experiments have been uniformly successful, these injected tokamaks are small, low density devices and are not representative of TNS. In TNS, the major problem is a lack of beam penetration. We attempt to scope the problem and outline possible strategies for overcoming it.

A first response to the penetration problem might be to raise the injection energy, but this entails severe penalties in injection efficiency. As the deuteron energy is increased beyond 200 keV, the efficiency of neutralizing the fast ions decreases to below 15%. With such a low efficiency, direct conversion would be necessary in a practical reactor and a large investment in injectors, power supplies, and other hardware would be required. Indeed, one may wonder whether there would be enough physical access on the machine for the requisite number of injectors!

Above 200 keV, negative ion sources have a much higher efficiency and appear attractive. However, this technology is in its infancy and a massive development program would be required if negative ion sources were to be used.

Thus, we would like to obtain an injection scenario that would successfully heat TNS with deuteron beams of less than 200 keV energy.

2. FULL BORE, HIGH DENSITY START-UP

The straightforward approach to heating TNS is to try injection into the full bore, high density TNS plasma. As a base case around which we varied parameters, we used the following values.

$$\begin{array}{ll} R_o = 5 \text{ m} & I = 4.3 \text{ MA (parabolic)} \\ a = 1.25 \text{ m} & n_e = n_p = 3 \times 10^{14} [1 - (r/a)^2]^2 \\ Z_{\text{eff}} = 1 & E_{\text{deuteron}} = 300 \text{ keV} \end{array}$$

Injection angle = 16° from perpendicular (coinjection)

Our present beam deposition code integrates around the actual fast ion orbits but is restricted to circular concentric flux surfaces. Thus, the D-shaped nature of TNS was ignored.

Figure 1 shows the effect of lowering injection energy below 300 keV. The generally accepted criterion of a "flat $H(r)$ profile" for adequate beam penetration would imply that at least 250-keV deuteron energy would be needed. However, a better criterion is that the ratio of the $H(r)$ profile to the density profile should be flat, because it is the energy delivered per particle that counts. This requires an even stronger peaking of $H(r)$ and with this criterion, even 300-keV energies are marginal.

Things deteriorate rapidly when Z_{eff} is increased, as shown in Fig. 2. Although our calculation enhanced only the proton impact ionization cross section by Z_{off} and ignored the enhancement of the charge exchange cross section, it is clear that almost any impurity level is intolerable.

Of course, lowering the plasma density (Fig. 3) improves penetration: $H(r)$ is strongly peaked at a central density of $1 \times 10^{14} \text{ cm}^{-3}$. Penetration is already bad at a density of $4 \times 10^{14} \text{ cm}^{-3}$.

Finally, in Fig. 4 we vary the injection angle because a more nearly perpendicular (smaller) angle decreases the distance to the magnetic axis. This angle can only be decreased to about 12° from perpendicular in order to avoid trapping of the beam ions in the ripples of the toroidal magnetic field. An angle of 16° may not be sufficiently parallel because the particles need only scatter 4° in pitch angle to reach the ripple trapping region. Thus, the largest possible angle should probably be chosen, consistent with coil clearances.

The net result of these brief surveys is dismal: it is very difficult to penetrate a full bore, full density TNS plasma even at an energy of 300 keV.

3. FULL BORE, LOW DENSITY START-UP

The scenario of Sect. 2 is unrealistic because a tokamak the size of TNS will not operate at such a high density without injection, at least if the scaling law $n_e \sim B_T/R_0$ can be believed. Thus, TNS will have to start at much lower densities, i.e., $n_e(0) \sim 2 \times 10^{13} \text{ cm}^{-3}$. Because the density is lower, we may also consider a lower energy beam and still be assured of penetration.

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Fig. 1. The effect of deuteron energy on penetration for near perpendicular injection.

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Fig. 2. The effect of impurities on beam penetration for near perpendicular injection.

For example, in Fig. 5(a), we show that a 150-keV deuteron beam can easily penetrate a $5 \times 10^{13} \text{ cm}^{-3}$ full bore TNS plasma and deposit most of its energy in the central region. Thus, we consider injecting into such a low β , low density plasma. As the plasma heats up, we increase the density by gas puffing and/or by pellet injection. Simultaneously, β is increasing in a flux conserving manner. As this occurs, the flux surfaces shift outward so that the penetration distance to the magnetic axis decreases. As β approaches 3%, fusion reactions begin to occur near the magnetic axis with the resulting α -particles heating the central core of the plasma. This is an important effect because by now the density has increased to a point where beam penetration is becoming marginal and most beam heating occurs away from the core region.

In the final state, $\beta \rightarrow 15\%$, $n_e(0) \approx 4 \times 10^{14} \text{ cm}^{-3}$, and the magnetic axis has shifted outward to 560 cm. Figure 5(b) shows beam deposition in this case where we have assumed a circular plasma with $R_0 = 560 \text{ cm}$ and $a = 65 \text{ cm}$. The actual $H(r)$ would be lower than this because the actual D-shaped volume is greater than we assumed.

Thus, it appears that utilizing a low density start-up and taking advantage of α -particle heating and flux surface shifts will allow 150-keV deuteron beams to have adequate penetration. Also, since the slowing down time is shorter for lower energy beams, the plasma will be heated more quickly and will be able to conserve flux more easily.

4. INTEGRATED SCENARIO

To test the plausibility of the above scenario, we employed a simplified one-dimensional flux coordinate transport code together with the flux conserving tokamak (FCT) equilibrium solver to see what would happen in a self-consistent manner. We assumed empirical scaling and arbitrarily increased the density as time progressed. A net heating of 50 MW from 150-keV deuteron injectors was used to start the heating process.

Figure 6 shows the temperature and density profiles along the equator as β is increased. The initially symmetric profiles become progressively shifted outwards. In Fig. 7, the α -particle heating profiles are shown

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Fig. 5. The flux surface shifts which accompany the high β equilibria allow penetration with deuteron energies of $\sim 150 \text{ keV}$.

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Fig. 6. Temperature and density profiles along the equator as β is increased.

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Fig. 7. Increase of α -particle heating profiles as β increases.

to increase as β increases. Meanwhile, the required injection heating decreases in the center and the profiles can move outward (Fig. 8). These $H(r)$ profiles were obtained by subtracting the α -heating profile from the total required power profile, while assuming that the pressure profile, $p(\psi)$, stays unchanged.

When $\bar{\beta} \sim 2\%$, the α -heating in the center begins to exceed the required beam power. At $\bar{\beta} \sim 3.5\%$, the central core of the plasma has ignited and beam deposition in that region is not needed. Indeed, if we wish to maintain the $p(\psi)$ profile, we should discontinue any beam heating in this region.

5. CONCLUSIONS

We have shown that heating of TNS must be started at low densities to allow beam penetration. As the plasma is heated and as the density is increased, α -heating and flux surface shifts seem to allow adequate penetration with 150-keV deuterons. A simple one-dimensional transport code shows that this model is plausible and that at $\bar{\beta} \sim 3.5\%$, the α -heating power density has locally exceeded the original beam heating power density and local ignition has occurred.

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Fig. 8. $H(r)$ profiles showing decrease in required injection heating.

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