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NEUTRAL BEAM PENETRATION CONSIDERATIONS
FOR CIT

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Abstract

Neutral beam injection into CIT is discussed. The beam deposition profile is determined for a wide range of parameters. The effects of the excitation enhanced ionization cross section is studied, both with and without impurities. Monte Carlo methods are used to evaluate available windows of operating density and beam energies. Requirements for low energy beam injection are determined.
I. Introduction

Neutral beam injection is one of the methods used to heat plasma for fusion devices. This heating method injects high energy neutrals into the plasma. The injected neutrals become ionized and trapped in the plasma through charge exchange or ionization collisions and then share their energy via Coulomb scattering. Neutral beam systems are attractive for CIT because of the increased flexibility, allowing heating that is independent of field. In particular, it would allow heating during the start-up phase. Negative-ion-based beams are required because higher beam energy is necessary for penetration into CIT[1]. In this paper we will only address the issues of beam penetration and beam access.

The efficacy of beams is determined by numerous factors including beam penetration, beam induced instabilities, and magnetic field ripple. The beam attenuation is determined by the ionization rate of neutrals by the plasma ions and electrons. It is found that the ionization rate could be substantially increased because of the multistep ionization processes (through excited states).

For the heating purpose of CIT, 10 MW of deposited power is required. In order to minimize the capital costs for beams on CIT, it would be favorable to use the existing power supplies from TFTR. These power supplies are capable of delivering maximum of 150 kV rectified output. If two of these are combined through a common ground (the power supplies cannot be stacked, but they can be reversed), 300 kV will be the maximum operating voltage (for electrostatic acceleration).

The beam energy is set by the need to deposit most of the energy near the magnetic axis. For a given beam energy, penetration determines the maximum allowed plasma density. On the other hand, when the plasma density is low, such as during start-up, the beam shine-through may cause serious damage to the vacuum chamber. The purpose of this paper is to determine the operating window for neutral beams on CIT (1.75 m major radius). Implications for the 2.1 m major radius CIT are made in the conclusions. Some comments about the possibility of tangential injection are also
II. Beam Deposition Model

The computer program used is a modified version of the ORNL neutral beam injection code, NFREYA[2].

The calculation of beam penetration depends on the accuracy of ionization cross section. The cross sections of beam trapping assuming that beam atoms are ionized from the ground state by ionizing collisions or charge exchange with plasma electrons and ions are given by Riviere [3]. However, it has been shown that the beam stopping cross sections could be increased substantially by the influence of multistep processes[4], in which neutral atoms are ionized from excited states. We have modified NFREYA in order to included the effect of enhanced stopping cross sections in our calculations using the numerical fits of Boley[4], which includes collisional ionization due to carbon, oxygen, and iron impurities.

NFREYA computes the ion deposition from the neutral beam injection and the bounce averages over the initial ion orbits by using a Monte Carlo technique. This is done in a poloidal flux surface coordinate system. We have used an MHD equilibrium code, NEQ[5], to obtain the flux equilibria. Figure 1 shows a cross section view of the high-\(\beta\) CIT plasma. The dashed lines are schematic plots of flux surfaces and the dots show the locations where neutrals are ionized. The beam geometry is defined in reference 6 and the beam parameters are given in Table 1.

2.1 Aperture Width and Loss

Due to the compact design of CIT, nearly perpendicular injection has been assumed. The beam injection angle has a significant effect on the aperture width and loss. The aperture width decreases with increasing injection angle. In order to maximize the size of the port width for beam injection, two modifications (shown in figure 2 and figure 3) of the layout have been made. In the first case (figure 2), the walls
of the port are flared to permit a larger angle of injection. In the second case, the vacuum chamber near the port region has been altered to get larger aperture widths.

The relation between injected angle and aperture width is obtained from figure 4 by the following simple equations:

\[ S = d_4 \cos \theta - d_1 \sin \beta, \quad \theta > \alpha \]  
\[ S = d_6 \cos \theta - d_6 \sin \theta, \quad \theta \leq \alpha \]  

where \( d_1, d_4, d_6, \) and \( d_6 \) are shown in figure 4 and \( S \) is the effective aperture width.

Figure 5 shows the effective port width as a function of \( \theta \). Substantially larger apertures are obtained in our second modification. It is found that the optimum value of \( \theta \) is around 10°. Beyond 10° the aperture width dramatically decreases.

The aperture losses of neutral atoms for our second modification are shown in figure 6. This figure assumes 0.6° beam divergence, and 10 m between the source and the plasma (i.e., a very compact beam line, which is necessary in order to fit in the test cell). As anticipated, the aperture losses increase rapidly for \( \theta > 10^\circ \) because of the dramatic decrease in aperture width. For the parameters in Table 1, the aperture loss of neutral atoms is around 14 % when \( \theta = 10^\circ \).

The definition of the injection angle is different from \( \theta \), which is defined as the angle between the optical line of the beam and the plane of symmetry of the port (see Figure 4). \( \theta = 10^\circ \) corresponds to 13° off-perpendicular injection as defined on the plasma magnetic axis. In what follows, it is assumed that the injection angle is 13° (\( \theta = 10^\circ \)).

2.2 Shine-Through

Shine-through is the fraction of neutrals that pass through the plasma and strike the wall. The attenuation of a beam of neutral atoms passing through a plasma is determined by the probability of interaction per unit distance and the distance
traversed; that is

\[ dI = -\Sigma I \, dx \quad (3) \]

where \( \Sigma \) is the probability per unit distance that a neutral atom will undergo some sort of interaction. Then, the beam attenuation is governed by

\[ I = I_0 e^{-\int \Sigma \, dx} \quad (4) \]

In order to obtain the total effect for all the collisions, all the cross sections due to different processes are added up.

III. Numerical Results

The allowable density for neutral beam heating in CIT is determined in this section. The lower limit of plasma density is when 10% of the beam shines through resulting in \( \sim 400 \) W/cm\(^2\). The upper limit is fixed by the condition of flat beam deposition profiles (i.e., hollow deposition profiles are to be avoided). Since the multistep processes and impurities seriously affect the beam deposition, these effects on beam penetration are discussed.

3.1 Deuterium Beam Injection Considerations

The percentage of the beam that shines through as a function of plasma density for deuterium beam is shown in figure 7. Case 1 does not include the multistep collision processes; whereas case 2 includes them with 2% carbon impurity. For \( n \sim 1 \times 10^{14} \) cm\(^{-3}\), the shine-through is decreased by as much as a factor of 2 when multistep processes are included.

Figure 8 shows how multistep processes affect the deposition profile of 300 keV deuterium beam. The solid curve is for the case when only simple impact collisions are considered while the dashed curve includes the multistep processes. The central plasma density is \( 6 \times 10^{14} \) cm\(^{-3}\). It is found that at the highest densities of CIT, 300 keV deuterium beams result in edge heating. A peaked deposition profile can
be obtained by increasing deuteron energy to 700 keV (the solid curve in figure 9) at the same plasma density. A comparison between figures 8 and 9 shows that when multistep processes are included for deuterium beams, 700 keV instead of 300 keV is needed to achieve the same penetration condition.

The presence of plasma impurities further increases the required beam energy. Figure 10 shows the effect of the presence of impurity carbon ions. The central plasma density is $6 \times 10^{14}$ cm$^{-3}$ and deuterium beam energy is 700 KeV. The solid curve is the case without carbon contamination. A hollow profile is formed when the effective charge, $Z_{\text{eff}}$, is larger than 2.5. The definition of $Z_{\text{eff}}$ is given by,

$$
Z_{\text{eff}} = \frac{\sum n_i Z_i^2}{\sum n_i Z_i}
$$

where $n_i$ is the ion density and $Z_i$ is the charge state of ion $i$ inside the plasma. For impurity carbon, $Z_{\text{eff}} = 2.5$ corresponds to a 5% carbon contamination. $Z_{\text{eff}} = 1.6$ (2% carbon ions) results in a flat deposition profile shown in the second line. Figure 11 also shows the effect caused by impurities when the deuterium beam energy is 300 keV.

Figure 12 shows the sensitivity of the deposition profile against different value of $\beta$. The central plasma density and deuterium beam energy assumed in figure 12 are $6 \times 10^{14}$ cm$^{-3}$ and 700 keV, respectively. From figure 12, it can be concluded that variable $\beta$ has little effect on neutral beam penetration. The available operating window of deuterium beam is listed in tables 2 and 3.

The maximum injection energy is determined by shine-through at the highest density in CIT ($6 \times 10^{14}$ cm$^{-3}$). For near perpendicular injection, 2000 keV deuterium beams and $Z_{\text{eff}} = 1.6$, the fractional shine-through is $\sim 5%$.

### 3.2 Hydrogen Beam Injection Considerations

Figure 13 shows results for 300 keV hydrogen injection under different considerations. A flat profile is found at $Z_{\text{eff}} = 2.5$ and $n = 6 \times 10^{14}$ cm$^{-3}$. Thus 300 keV
hydrogen beams penetrate successfully (penetration is equivalent to that of 600 keV deuterium).

With hydrogen injection, it is necessary to consider the problem of plasma dilution. With 5 seconds injection pulse and assuming that none of the hydrogen leaves the plasma during this time, we find that \( \frac{n_H}{n_{total}} \sim 13\% \). Hydrogen dilution seems not to have a large effect on the fusion reactivity.

3.3 Tangential injection

Due to the relative large size of the ports in CIT, it is possible to have access for tangential injection. The effective aperture size, however, is severely limited, with a effective width of \( \sim 8.5 \text{ cm} \) (for the 1.75 m CIT). The minimum beam energy required is about 600 keV, i.e., twice the value needed for near perpendicular injection. For 2 MeV deuterium beams the minimum density is \( \sim 1.8 \times 10^{14} \text{ cm}^{-3} \). Due to the smaller aperture size better optics are required to reduce the losses in the port aperture.
Conclusion

The allowable operating window for neutral beam heating in CIT has been evaluated. Due to access limitations, the optimum injection angle is $\sim 13^\circ$-off perpendicular. The minimum allowable density is $1 \times 10^{14}$ cm$^{-3}$ for 300 keV deuterium beams and $1.8 \times 10^{14}$ cm$^{-3}$ for 700 keV beams. On the other hand, the highest allowable density is $\sim 4 \times 10^{14}$ cm$^{-3}$ for 300 keV deuterium beams and $6 \times 10^{14}$ cm$^{-3}$ for 700 KeV beams. At $6 \times 10^{14}$ cm$^{-3}$ - 2000 keV deuterium beams result in $\sim 5\%$ of shine-through.

In order to be able to use the TFTR power supplies (300 kV maximum), it is necessary to inject hydrogen beams. The effect of hydrogen dilution of a D-T plasma does not seem to be substantial.

The results, although derived for the 1.75 m CIT, can be directly applied to the 2.1 m (with a larger plasma radius but smaller density).

We have not discussed other physics aspects that need to be considered if neutral beam injection is to become a heating alternative for CIT. They include beam induced instabilities (Alfven and fishbones) and ripple induced losses. Further work is this area is needed.

Acknowledgement

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References


Table 1: Beam Parameters Used in This Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic weight of beam particles</td>
<td>1.2</td>
</tr>
<tr>
<td>Height of beam (cm)</td>
<td>80</td>
</tr>
<tr>
<td>Width of beam (cm)</td>
<td>30</td>
</tr>
<tr>
<td>Distance from injector source to pivot point (cm)</td>
<td>1000</td>
</tr>
<tr>
<td>Angle between the optical axis of injector and the plane containing the pivot point and toroidal center line (degrees)</td>
<td>10</td>
</tr>
<tr>
<td>Angle between the optical axis of injector and port vertical symmetry plane (degrees)</td>
<td>13</td>
</tr>
<tr>
<td>Port height (cm)</td>
<td>100</td>
</tr>
<tr>
<td>Effective port width (cm)</td>
<td>34.4</td>
</tr>
<tr>
<td>Vertical divergence of beam (mrad)</td>
<td>10.</td>
</tr>
<tr>
<td>Horizontal divergence of beam (mrad)</td>
<td>10.</td>
</tr>
<tr>
<td>Beam energy (keV)</td>
<td>300 - 700</td>
</tr>
<tr>
<td>Plasma density (cm$^{-3}$)</td>
<td>$1 \times 10^{13}$ - $7 \times 10^{14}$</td>
</tr>
<tr>
<td>Major radius of magnetic axis (cm)</td>
<td>175.3</td>
</tr>
<tr>
<td>Minor radius (cm)</td>
<td>54.9</td>
</tr>
</tbody>
</table>
Table 2: Lower Limits of Plasma Density

<table>
<thead>
<tr>
<th>Case 1: no multistep processes</th>
<th>300 keV</th>
<th>700 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2: with multistep processes and impurity ($Z_{\text{eff}} \approx 1.6$)</td>
<td>$2 \times 10^{14}$ cm$^{-3}$</td>
<td>$3.6 \times 10^{14}$ cm$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$1 \times 10^{14}$ cm$^{-3}$</td>
<td>$1.8 \times 10^{14}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>

Table 3: Upper Limit of Plasma Density

<table>
<thead>
<tr>
<th>Case 1: no multistep processes</th>
<th>300 keV</th>
<th>700 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2: with multistep processes and impurity ($Z_{\text{eff}} \approx 1.6$)</td>
<td>$&gt; 1 \times 10^{15}$ cm$^{-3}$</td>
<td>$&gt; 1 \times 10^{15}$ cm$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$\sim 6 \times 10^{14}$ cm$^{-3}$</td>
<td>$\sim 9 \times 10^{14}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>
Figure 1. Magnetic flux surfaces and beam deposition for a high $\beta$ CIT plasma.

- $E_0 = 300.0$ keV
- $B_0 = 10.00$ T
- $\beta = 0.025$
- $n_{e0} = 1.00 \times 10^{11}$
- $R_0 = 175.0$ cm
Figure 2. Simple modification of beam aperture to permit larger injection angles (walls of port flared); case 1.
Figure 3. Additional modification of beam aperture to permit larger injection angles (walls of port flared, plus modified first wall); case 2.
\[ \beta = \theta - \alpha \]

Figure 4. Schematic diagram of aperture width and beam injected angle.
Figure 5. Effective port width as a function of injected angle for the geometries of cases 1 and 2 (shown in Figures 2 and 3).
Figure 6. Aperture loss as a function of injected angle for case 2 geometry (figure 3)
Figure 7. Shine-through fraction for near perpendicular injection (10°) as a function of the plasma density, both with and without the multiple-step processes.
Figure 8. $h(r)$ as a function of poloidal flux $\psi^{1/2} \sim r$ with and without the multiple step ionization processes. (Deuterium injection, $N_p = 6 \times 10^{14} \text{ cm}^{-3}$, $E_b = 300 \text{ keV}$, no impurities).
Figure 9. $h(r)$ as a function of $\psi^{1/2}$ for 300 and 700 keV deuterium beams, multiple step ionization processes included. ($N_p = 6 \times 10^{14}$ cm$^{-3}$, no impurities).
Figure 10. $h(r)$ as a function of $\psi^{1/2}$ for 700 keV deuterium beams, multiple step ionization processes included. ($N_p = 6 \times 10^{14} \text{ cm}^{-3}$, $Z_{eff} = 1, 1.6, 2.5$).
Figure 11. $h(r)$ as a function of $\psi^{1/2}$ for 300 keV deuterium beams, multiple step ionization processes included. ($N_p = 6 \times 10^{14}$ cm$^{-3}$, $Z_{\text{eff}} = 1, 1.6, 2.5$).
Figure 12. Effect of $\beta$ on the beam deposition profile. (700 keV deuterium beams, $N_p = 4 \times 10^{14} \text{ cm}^{-3}$).
Figure 13. $h(r)$ as a function of $\psi^{1/2}$ for 300 keV hydrogen beams, multiple step ionization processes included. ($N_p = 6 \times 10^{14} \text{ cm}^{-3}$, $Z_{eff} = 1, 1.6, 2.5$).