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NEUTRAL BEAM SHINETHROUGH IN TBR-E

Antonio Montes

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A. Montes
Laboratório Associado de Plasma
Instituto Nacional de Pesquisas Espaciais

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We discuss the absorption of tangentially injected neutral beams in TBR–E. Injection roughly tangent to the magnetic axis (tangential injection) is generally preferred because this leads to maximum beam-plasma interaction length and consequently beam absorption. The geometry for tangential injection is illustrated in Fig. . In the first part of this note we discuss briefly the relevant atomic processes and, in the following, we discuss the absorption of a pencil beam caused by these processes. The discussion is based on Rome el al.[1]

The dominant collision processes of energetic neutrals with tokamak plasmas are charge exchange, electron ionization and proton ionization. The cross-section for these processes in the energy range of interest have been reviewed by Riviere.[2] Since only the electron ionization cross-section depends on the plasma temperature (and only weakly), the total ionization cross-section is only very weakly dependent on the plasma temperature and this variation will be ignored. Hence the absorption mean free path depends only on the local plasma density.

If we define $N_B(s)$ as the number of beam particles per second in a pencil beam at a point along the beam path, then the equation governing N_B is given by

$$\frac{dN_B}{ds} = -\frac{N_B}{\lambda(s)}, \tag{1}$$

where $\lambda(s)$ is the mean free path of a neutral beam particle at point s. The solution of this equation is

$$N_B(s) = N_B(-\infty)\exp\left[-\int_{-\infty}^{s}\frac{ds'}{\lambda(s')}\right]. \tag{2}$$

Since the total absorption cross-section is only very weakly dependent on the plasma properties, we can express the mean free path as

$$\lambda(s) = \frac{1}{n_p(s)\sigma_T} = \frac{n_0\lambda_0}{n_p(s)}, \tag{3}$$

where $\lambda_0 = 1/n_0\sigma_T$ is the absorption mean free path at the maximum plasma density n_0.

The experimental values for the cross-section for ionization of atomic hydrogen by electrons σ_1, reviewed by Tawara et al.,[3] is quite well fitted by the analytic expression derived by Grizinski from a classical theory,[4]

$$\sigma_1 = \frac{6.513 \times 10^{-14}}{E_i^2} g(x) \quad \text{cm}^2 , \tag{4}$$

where

$$g(x) = \frac{1}{x}\left(\frac{x-1}{x+1}\right)^{3/2}\left[1 + \frac{2}{3}\left(1 - \frac{1}{2x}\right)\ln\left(2.7 + \sqrt{x-1}\right)\right] , \tag{5}$$

and x is the ratio of the electron energy to the ionization potential E_i (= 13.605 eV). It should be noted that the experimental and theoretical values calculated from the above expression are two orders of magnitude smaller than the values obtained by Rome et al.[1]

The cross-section for ionization by protons is fitted by the expression

$$\log_{10}\sigma_2 = -0.8712(\log_{10} E)^2 + 8.156\log_{10} E - 34.833 \tag{6}$$

for proton energies $E < 150\,\text{keV}$ and by

$$\sigma_2 = 3.6 \times 10^{12} E^{-1}\log_{10}(0.1666E) \tag{7}$$

for $E \geq 150\,\text{keV}$.

The cross-section for charge exchange by protons in atomic hydrogen are reasonably well represented by the expression

$$\sigma_3 = \frac{0.6937 \times 10^{-14}(1 - 0.155\log_{10} E)^2}{1 + 0.1112 \times 10^{-14} E^{3.3}} . \tag{8}$$

A proper treatment would require the cross-section to be averaged over the energy distribution of the plasma electrons and ions. This is not done here and the temperature dependency is neglected. The total cross-section, σ_T in Eq. 3, is $\sigma_T = \sigma_1 + \sigma_2 + \sigma_3$.

Therefore, given the beam energy, we can calculate the total ionization cross-section and use its value to integrate Eq. 2 along the beam trajectory. This is done numerically in order to take into account a more realistic model for the density profile. In the present calculations, the density profile is given by

$$n_p(s) = (1 - \psi(s))^\alpha , \tag{9}$$

where $\psi(s)$ is the poloidal magnetic flux function and we take $\alpha = 1$. We assume that the ψ-function is well modelled by the Solove'v equilibrium

$$\psi = \frac{1}{4\epsilon^2}\left[\left(1 + \frac{R}{R_0}\right)^2 - \left(1 + \epsilon^2\right)\right]^2 + \left[G_1\left(1 + \frac{R}{R_0}\right) - G_2\right]\frac{Z^2}{R_0^2} , \tag{10}$$

where G_1 and G_2 are functions of the inverse aspect ratio ϵ, the elongation κ and the triangularity δ.[5]

The results for the conditions of TBR-E are shown in Figs. and . Fig. shows the variation of N_B along the beam path for a plasma with $R_0 = 0.39\,\mathrm{m}$, $\epsilon = 1/1.5$, $\kappa = 1.7$ and $\delta = 0$. The different curves are for different peak densities. In all cases the beam axis is tangent to the torus with a radius of tangency $R_B = (1 - \epsilon/2)R_0$, that is midway between the plasma center and the inboard plasma edge, for which the absorption is largest. The shinethrough for a plasma with $R_0 = 0.50\,\mathrm{m}$ is shown in Fig. . The other parameters are $\epsilon = 1/2.0$, $\kappa = 1.5$ and $\delta = 0$. In both cases, we see large shinethrough at low densities ($\sim 50\%$ for $n_0 = 1 \times 10^{19}\,\mathrm{m}^{-3}$) and total absorption at high densities.

References

[1] J. A. Rome, J. D. Callen, J. F. Clarke. Nuclear Fusion, 14, 141, 1974.

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[4] M. Grizinski in *Atomic Collision Processes* (McDowell, M. R. C., Ed.), North-Holland Publ. Co., Amsterdam, 226, 1964.

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Figure Caption

Fig. 1 Geometry of neutral beam injection into a torus. Top view showing a pencil beam.

Fig. 2 Neutral beam density along the beam path for $R_0 = 0.39\,\mathrm{m}$ with various peak densities n_p.

Fig. 3 Neutral beam density along the beam path for $R_0 = 0.50\,\mathrm{m}$ with various peak densities n_p.

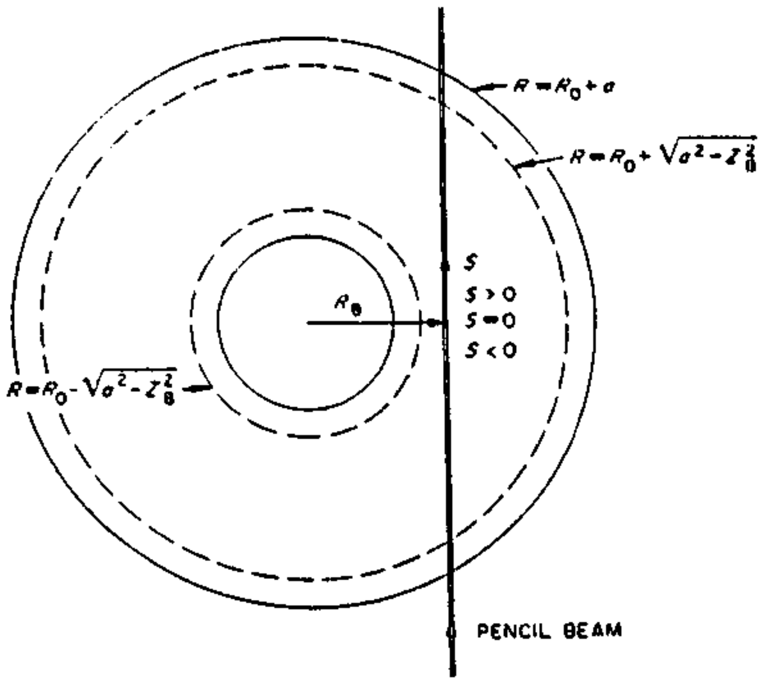
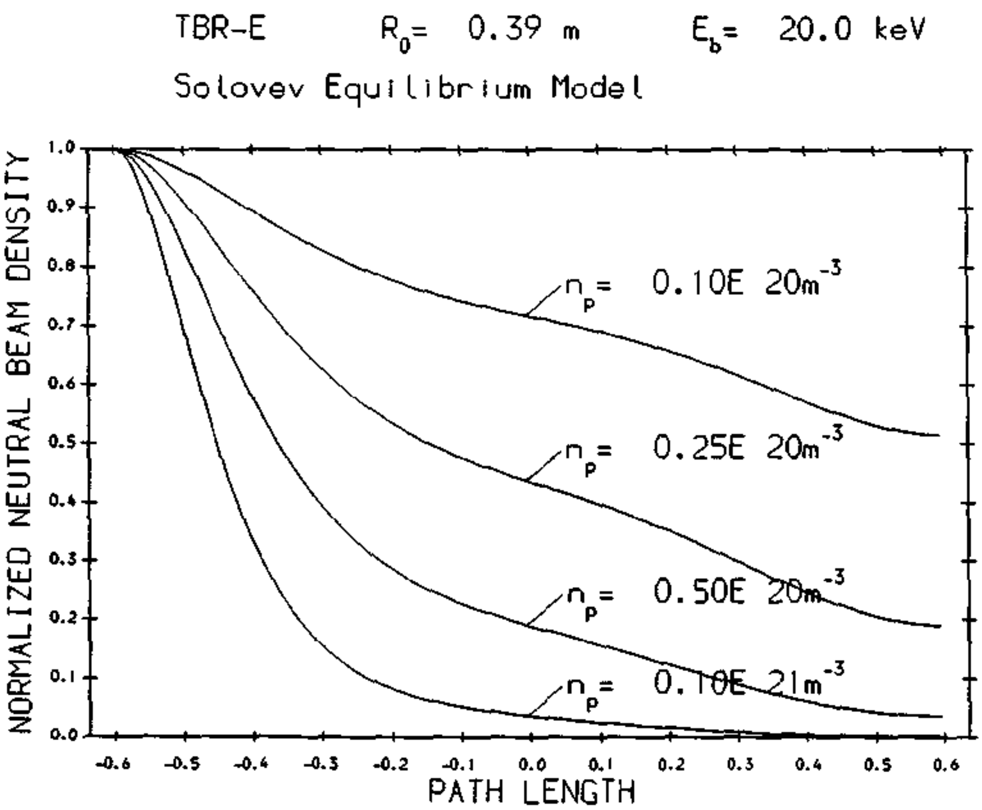
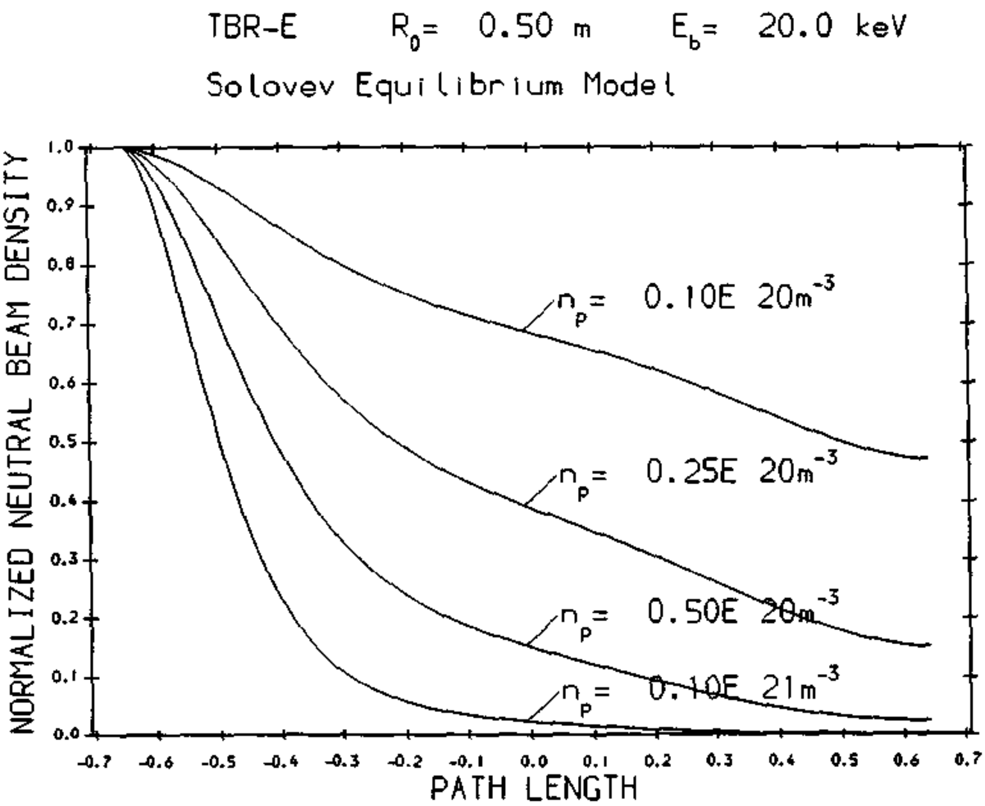


Fig. 1



TBR-E R_0= 0.39 m E_b= 20.0 keV
Solovev Equilibrium Model
NORMALIZED NEUTRAL BEAM DENSITY
PATH LENGTH
n_p= 0.10E 20m^{-3}
n_p= 0.25E 20m^{-3}
n_p= 0.50E 20m^{-3}
n_p= 0.10E 21m^{-3}
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6

Fig. 2



TBR-E R$_0$= 0.50 m E$_b$= 20.0 keV
Solovev Equilibrium Model
NORMALIZED NEUTRAL BEAM DENSITY
PATH LENGTH
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n$_p$= 0.50E 20m^{-3}
n$_p$= 0.10E 21m^{-3}
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0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Fig. 3

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AUTOR

Antonio Montes

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