Enhancement of the Neutral-Beam Stopping Cross Section in Fusion Plasmas Due to Multistep Collision Processes

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Multistep processes involving excited atomic states are found to produce a substantial increase in the stopping cross section for a neutral hydrogen beam injected into a plasma, and thus to reduce the beam penetration. For typical plasma and beam parameters of current large tokamak experiments, the stopping-cross-sectional enhancement is found to vary from 25% to 50%, depending on the beam energy, plasma density, and impurity level. For neutral hydrogen beams with energies $\gtrsim 500$ keV, envisioned in tokamak and mirror reactor designs, the enhancement can be as large as 80%–90%.

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High-power, high-energy neutral hydrogen beam injection has proved to be a very successful method for heating tokamak plasmas, and is a key element in producing, heating, and confining mirror plasmas.[1] Such beams are used on almost all current large fusion experiments. Calculations of the local time-dependent plasma heating rate from neutral injection, analysis of the ionized-beam-particle confinement, and neutral-beam diagnostic measurements of the plasma rely crucially on the accuracy of the beam stopping cross section.[2] This cross section is usually derived by considering only electron loss from the ground-state beam atoms due to ionizing and charge-exchange collisions with plasma electrons and ions.

Recently it was pointed out by Wiesemann[3] that the neutral-beam stopping cross section is increased by multistep processes, in which beam atoms are first excited by collisions with the plasma and are then ionized. Treating the problem by a two-state model, in which a single effective excited state was used to represent all the discrete excited levels, he found a 5%–15% enhancement of the stopping cross section for beam energies below 100 keV and for plasma densities in the neighborhood of 10^{14} cm^{-3}. The presence of excited states in neutral beams was appreciated early in the mirror program. The Lorentz ionization[4] of excited states arising from the neutralization process was utilized for plasma buildup, and some of the consequences of excitation and deexcitation processes among these states were investigated.[5]

In the present Letter, we consider in detail the influence of multistep processes on the penetration of an energetic hydrogen beam into fusion plasmas. We explicitly include all hydrogenic levels up to the Lorentz ionization limit[6] and employ the presently best available cross sections for collisions with electrons, hydrogen ions, and impurities. We find an enhancement larger than that estimated by Wiesemann and, in fact, sufficiently large to have an important effect on plasma studies related to beam injection and beam-plasma diagnostics. As will be discussed later, this enhancement is important not only for tokamaks, but also for mirror plasma experiments.

In our calculations, the penetrating neutral beam is represented by N separate subbeams, each corresponding to a given principal atomic quantum number n. The normalized intensities $I_n(x)$ of the subbeams, at a distance x, satisfy the system of coupled rate equations

$$v_0 \frac{dI_n(x)}{dx} = -K_n I_n + \sum_{n'<n} [K_{n'n}^{(e)} I_{n'} - (K_{nn'}^{(d)} + A_{nn'}) I_n] - \sum_{n'>n} [K_{nn'}^{(e)} I_n - (K_{n'n}^{(d)} + A_{n'n}) I_{n'}] \equiv \sum_{n'} Q_{nn'} I_{n'}, \quad (1)$$

with K_n the rate for electron loss from state n due to ionization and charge exchange, $K_{nn'}^{(d)}$ the rate for deexcitation from n to n' due to collisions, $K_{nn'}^{(e)}$ the rate for excitation from n to n', $A_{nn'}$ the radiative decay rate, and v_0 the beam speed. Processes inverse to ionization and charge exchange have not been considered, since once ionized, the particle is considered to be lost from the beam. The system (1) is solved numerically subject to the condition that at $x=0$ only the ground state is populated. The normalized beam intensity at any point is, of course, the sum of the individual intensities.

The maximum principal quantum number N of populated states is given by the Lorentz ionization limit, or approximately[6] $N=\frac{1}{2}(\mathcal{E}_0/|\vec{v}\times\vec{B}|)^{1/4}$, where $\mathcal{E}_0$ is the classical electric field of the nucleus evaluated at the first Bohr radius. For a typical condition ($E \simeq 50$ keV, $B \simeq 3$ T), one has $N \simeq 7$. Excitations to levels higher than N are equivalent to ionization; these are taken into account in Eq. (1) by placing a large upper limit on the sum involving $K_{nn'}^{(e)}I_n$. In practice, numerical convergence was achieved with an upper limit of $n' \simeq 80$.

The cross sections for excitation from $n=1$ to $n=2$ and ground-state ionization, due to both electron impact and proton impact, were taken from Born-type extrapolations of experimental data.[7] For the electron-impact excitation/deexcitation and ionization processes involving excited states we used the semiempirical formulas of Vriens and Smeets.[8] The proton- and impurity-ion–impact excitation and deexcitation processes (except for $n=1$ and $n=2$ in the proton case) were taken from a calculation based on a two-state close-coupling method with a dipole ion-atom interaction.[9] The cross section for the proton charge-exchange reaction with the ground-state hydrogen atom was taken from experiment,[7] while for the sum of the cross sections for ionization and charge exchange with excited ($n \geq 2$) atoms due to collisions with protons or impurity ions (the electron loss cross section), we used a recently derived scaling relation.[10] For processes involving the ground state, the typical error of the cross sections is about 10%, while for other processes the typical error may be as high as 50%. The reaction rates $\langle \sigma v \rangle$ for the above processes were computed from the cross sections with standard numerical integration techniques. The oscillator strengths for spontaneous radiative decay rates were taken from a standard approximation.[11,12]

We have characterized the results of our calculations by the fractional beam-stopping increment

$$\delta = (\lambda_0 - \lambda)/\lambda, \qquad (2)$$

where λ is the mean free path including excitation effects and λ_0 is the mean free path of the beam calculated with the ground-state atoms only. Thus δ is the fractional increase in the beam stopping cross section defined as $\sigma = (n_e\lambda)^{-1}$. Figure 1 illustrates the dependence of δ on beam energy and plasma density. The enhancement of the beam stopping is small (~10%–20%) at low

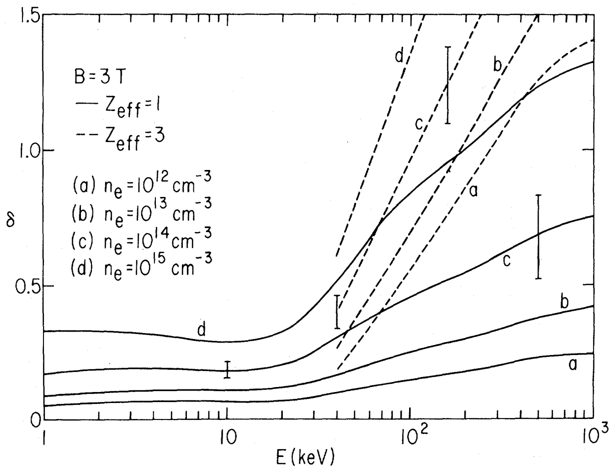

FIG. 1. Enhancement of the beam stopping cross section due to excitations, calculated for four electron densities as a function of beam energy. The electron and ion temperatures are taken as $E/10$ for $E < 100$ keV and as 10 keV for $E > 100$ keV. The solid curves are for $Z_{eff}=1$, and the dashed curves are for $Z_{eff}=3$ produced by carbon, oxygen, and iron in the ion density ratio 10:10:1. The error bars indicate the variation when the cross sections for excitation and deexcitation are increased and decreased by 10% (50% for processes not involving the ground state).

beam energies ($E \lesssim 30$ keV), but becomes quite significant in the 50-keV range and above. In the low-energy range (1–30 keV), electron-impact collisions dominate the excitation and ionization rates, and charge exchange is the dominant electron-loss mechanism. At energies above ~40 keV, proton collisions become dominant for excitation and ionization, and the ion-impact ionization rate exceeds the charge-exchange rate. As expected, the effect of multistep collision processes on the beam penetration also increases with plasma density. As Fig. 1 indicates, the presence of impurities in the plasma leads to a substantial increase in δ. At fixed plasma temperature, electron density, and beam energy δ increases in a practically linear fashion with the effective charge (Fig. 2). One contribution to δ (dashed curves in Fig. 2) is due to impurity-impact electron loss from the ground state,[13] in which case the dependence on Z_{eff} is easily shown to be linear. The major contribution to δ, however, arises from excitation effects. As the figures show, impurities have the largest effect on δ for the higher beam energies.

The error bars in Fig. 1 give an idea of the sensitivity of the results to uncertainties in the cross sections. The greatest sensitivity arises

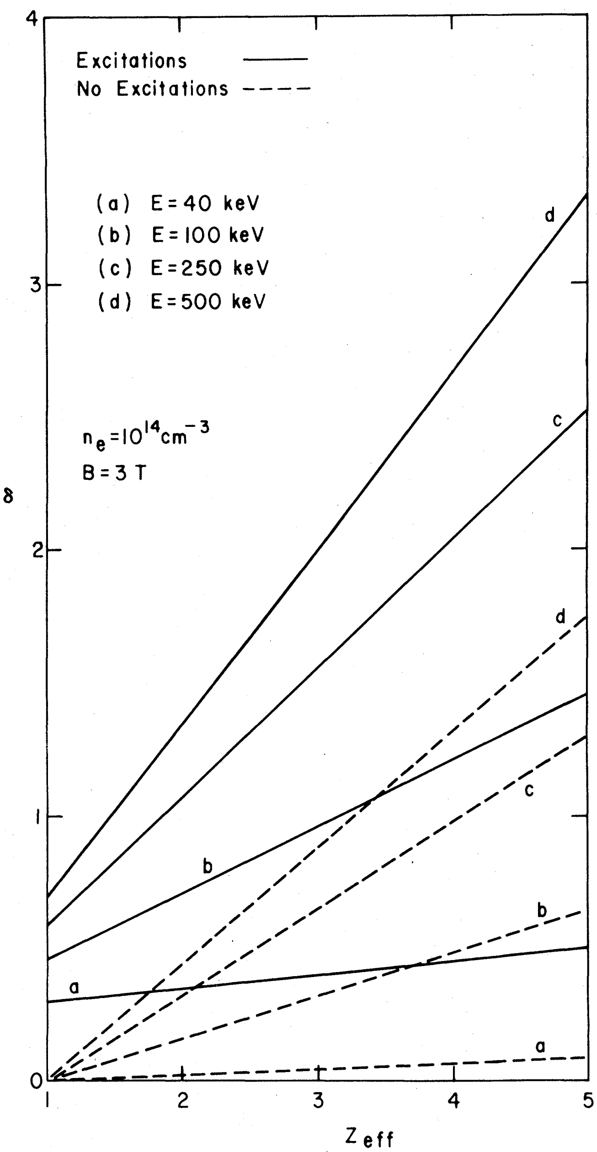

FIG. 2. The beam-stopping-cross-section enhancement as a function of Z_{eff} for carbon, oxygen, and iron impurities in the ion density ratio 10:10:1, at four beam energies. The solid lines include the effects of excitations, while the dashed lines include only the effects of electron loss from the ground state.

from variations in the excitation and deexcitation cross sections. (Of course, the cross sections for these processes are related by detailed balance.) The upper (lower) limits indicate the change when all excitation and deexcitation cross sections are increased (decreased) to the extreme values consistent with the accuracies previously stated.

The dependence of δ on the magnetic field strength was also examined and found to be very small for $2\ T \leq B \leq 15\ T$, as would be expected from the weak dependence of the Lorentz ionization limit N on the magnetic field.

The results of the present investigation have important implications for neutral-beam-heated plasma experiments. The analysis and predictions of the performance of plasmas heated by neutral beams (local heating rate, beam-particle confinement, etc.) are highly sensitive to the beam attenuation which, in turn, depends exponentially on the beam stopping cross section.

For example, the usual criterion that neutral-beam heating provide adequate penetration is that $a/\lambda \sim 2$ to 4, where a is the plasma minor radius and λ is the mean free path.[14] With such a requirement, the central heating rate would scale approximately as $(1+\delta)\exp(-\delta a/\lambda_0)$. For a beam system designed for a given a/λ_0, a value of $\delta = 0.5$ would decrease the central heating by 45% to 80%. This would imply that tokamaks with high-energy beam systems would have to operate at a much reduced density to achieve the designed central-heating rate. Analyses of the radial profile of the energy confinement would also be in substantial error since the local heating rate would be calculated with a systematic error.

Interpretations of experimental data on different particle density profiles obtained by active beam diagnostic methods also depend critically on an accurate knowledge of the beam stopping cross section. Considerable effort has been devoted in the past to determine the effects of impurities on beam penetration.[13] As Fig. 2 shows, the influence of multistep processes on beam penetration (and plasma properties related to it) is even more important than the effects of impurities in the absence of excitations. The 80%–100% increase of the beam stopping at energies above 500 keV implies that the beam energy has to be increased by the same percentage in order to achieve a given penetration depth. The results thus have serious consequences for the design and operation of negative-ion-based systems, which are designed to operate in the range of 100–500 keV/u. At beam energies above 40 keV/u, both the ground-state and excited-state stopping cross sections scale as $1/E$. Since $\lambda \sim E/n_e$, compensation of a decrease in λ due to excitation effects requires either raising the beam energy E or decreasing the plasma density n_e.

On the other hand, the enhancement of the beam stopping power due to multistep processes has beneficial effects on the large mirror plasma experiments. In many current designs of such experiments, the beam energy is limited by the requirement that at least 20% or so of this energy (typically 300–500 keV) be stopped in the mirror plasma.[15] If the stopping cross section is increased by 60%–100%, then either the beam energy can be increased or the beam current can be reduced (by the above percentage) to obtain the same level of performance.

In summary, our calculations have shown that the enhancement of the stopping cross section of energetic neutral hydrogen beams injected into fusion plasmas may be as large as 25%–50% for experiments such as TFTR and JET, which have beam energies of 60–80 keV/u, and as large as 80%–90% for the very-high-energy (300–500-keV) beams proposed for the large tokamak and mirror experiments.

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