# 3. WORKING GROUP REPORTS ON REQUIRED AND RECOMMENDED DATA

## 3.1. Working Group Report on the required atomic database for neutral hydrogen beam penetration in large tokamaks

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### 1. Introduction. Multistep beam ionization

Injection of energetic neutral hydrogen beams is one of the major methods for plasma heating in the present-day large tokamaks (JET, TFTR, JT-60, DIII-D, ASDEX, etc.) and is envisaged to play a similar role in the next-generation fusion (such as NET, TIBER-II, FER, ITER, etc.), where this method should also provide a large contribution to the non-inductive current drive in the central part of the discharge. The efficiency of the neutral beam injection (NBI) method for heating and current drive of large tokamak plasmas relies on the deposition of beam energy and momentum in the central (near axis) plasma region, i.e. on a correct determination of the required beam energy which ensures such deposition. The attenuation of the neutral hydrogen beam penetrating a plasma depends exclusively on the atomic collision processes. These processes lead to beam-atom ionization, after which the motion of ionized beam particles is determined by the tokamak magnetic field, and their energy is dissipated in Coulomb collisions with the charged plasma particles.

The standard beam penetration and beam energy deposition codes are designed on the asumption that beam particles are all in the ground state and that beam atom ionization occurs due to ground state-continuum transitions in collisions with plasma electrons, protons and impurities, and due to the electron capture from the ground state by plasma protons and impurity ions. This approximation is valid as long as the beam velocity and plasma density are such that the collision time is much longer than the radiative lifetime of excited atomic states. However, for beam energies above 200 keV/u and plasma densities above $\sim 5\times10^{19} m^{-3}$, the radiative and collision times of excited beam atoms become comparable, and the beam-plasma system is in a radiative-collisional regime. Inclusion of the collision processes of excited beam atoms in the beam attenuation kinetics becomes necessary, and this leads to an enhancement of the effective beam attenuation (or "stopping") cross section [1].

The effects of multistep processes on the beam attenuation (or, the multistep beam ionization) became recently an important issue in the design of beam heating and current drive systems for the next-step, reactor level fusion devices (ITER, NET, etc). The required NBI heating power in these devices is of the order of ~ 100 MW, with beam energies around ~ 1 MeV, and operating plasma densities around $10^{20} m^{-3}$. The estimated beam stopping enhancement due to multistep processes for beam-plasma parameters in this range is between 50% and 100%, [1-3] depending on the accuracy of the atomic database used in the calculations. This uncertainty is reflected in the requirements for the beam energy value and the associated beam technology, with obvious economical consequences. Therefore, an accurate determination of the required atomic database for the beam stopping calculations is necessary for resolving this important issue.

## 2. The required atomic database

The following processes are involved in the beam attenuation kinetics, when multistep processes are included (H stands for D or T):

### 2.1. Electron impact processes

1) $$e + H(n) \rightleftarrows e + H(m) \quad , \quad 1 \le n < m \le N \tag{1}$$

2) $$e + H(n) \rightarrow e + H^+ + e \quad , \quad 1 \le n \le N \tag{2}$$

(N is defined by Eq.(8) below)

### 2.2. Proton impact processes

1) $$H^+ + H(n) \rightleftarrows H^+ + H(m) \quad , \quad 1 \le n < m \le N \tag{3}$$

2) $$H^+ + H(n) \rightarrow H^+ + H^+ + e \quad , \quad n \ge 1 \tag{4a}$$

$$H(m) + H^+ \qquad (m \simeq n) \tag{4b}$$

2.3. Impurity-ion impact processes

$$1)\quad A^{q+} + H(n) \rightleftarrows A^{q+} + H(m)\ ,\ 1 \leq n < m \leq N \tag{5}$$

$$2)\quad A^{q+} + H(n) \rightarrow A^{q+} + H^{+} + e\ ,\quad n \geq 1 \tag{6a}$$

$$\rightarrow A^{(q-1)+}(m) + H^{+}\ ,\quad (m \simeq n) \tag{6b}$$

$A^{q+} = He^{2+}$, $(Be^{4+})$, $C^{6+}$, $O^{8+}$, $Fe^{24-26+}$, $W^{n+}$ ,

2.4. Radiative processes

$$H(m) \rightarrow H(n) + h\nu\ ,\quad 1 \leq n < m \leq N \tag{7}$$

2.5. Lorentz field ionization

$$H(m) + F_L \rightarrow H^{+} + e\ ,\quad m \geq N = \frac{1}{2F_L^{1/4}} \tag{8}$$

where $F_L = |\vec{V}_o \times \vec{B}|$ , $V_o$ and B are the neutral beam velocity and strength of magnetic field, respectively. For neutral beam energies $E_o$ of about 10 keV/u and magnetic fields of $B \simeq 3$ T, $N \simeq 7$, while for $E_o \simeq 1-2$ MeV/u and $B \simeq 10$ T, $N \simeq 4$.

The computer codes for beam attenuation calculations solve the system of coupled equations

$$V_o \frac{dI_n}{dx} = \sum_{n'=1}^{N} Q_{nn'} I_{n'}(x)\ ,\quad n = 1 \ldots\ldots N\ , \tag{9}$$

$$I_n(o) = \delta_{n1}\ , \tag{10}$$

where $I_n(x)$ is the fraction of the beam in the n-th quantum state at the distance x from the point where the beam enters the plasma (x=o). The reaction matrix $Q_{nn'}$ includes the reaction rate coefficients for all the processes 2.1 - 2.4.

The stopping cross section is defined as $\sigma_s = 1/(n_e\lambda)$, where $\lambda$ is the e-folding beam intensity decay distance, and $n_e$ is the plasma density. The relative enhancement of $\sigma_s$ due to multistep processes is $\delta = (\sigma_s-\sigma_s^o)/\sigma_s^o$, where $\sigma_s^o$ is the stopping cross section for ground state processes only.

Previous calculations of $\sigma_s$ have shown [1] that for plasma densities $n_e \leq 10^{21}m^{-3}$ and beam energies $E \leq 30$ keV/u, the effect of excitations on $\sigma_s$ is only about 10-15%. The relative enhancement $\delta$ starts to increase considerably for $E \gtrsim 150$-200 keV/u, even at moderately low densities ($n_e \sim 5x10^{19}m^{-3}$). As function of $E_o$, $n_e$, and $Z_{eff}$, $\delta$ shows the following dependences (in the ranges 10 keV/u $\leq E_o \leq$ 10 MeV/u, $10^{19}m^{-3} \leq n_e \leq 10^{21}m^{-3}$, $1 \leq Z_e \leq 10$): logarithmic increase with $E_o$, almost linear increase with $n_e$, and linear increase with $Z_{eff}$.

The standard beam penetration codes calculate the beam heating rates and current-drive profiles on the base of a single-state (ground-state) beam model and local beam stopping cross sctions. With the necessity of inclusion of multistep processes, the question arises whether the codes require a full multi-state description of the beam. From heating calculations for TFTR, it appears that one can still employ a single-state model but with an appropriately enhanced beam stopping cross section. It would seem prudent, however, to check whether this remains true for the parameters of the next-step devices. As a representative example one could take the design parameters for the physics and technology phase of ITER: $n_e = (0.7 - 2) \times 10^{20}m^{-3}$, $E_o = 1 \pm 0.3$ MeV, $T_e \sim 18$-30 keV, $Z_{eff} \approx$ 1.5-2.5 ($Z_{eff} = 2.3$ for the technology phase, with an impurity mix of He : C : O : Fe = 5 : 1.5 : 0.5 : 0.05).

Having in mind the above range of $E_o$, and that the relevant interaction energy parameter is $E_o/q$ ($q \lesssim 25$ for metallic impurities), one defines the region of $E_o/q \gtrsim 20$ keV/u for which data for the heavy-particle collisions are required for the next-step fusion devices. In order to incorporate the data needs also for the presently operating tokamak devices ($E_o \gtrsim 60$ keV/u), one would have data for $E_o/q \gtrsim 1$ keV/u. As well known, the region of $E/q \sim 25$ keV/u is a critical one for the theoretical description of heavy-particle collision processes.

The required electron impact data, however, all lie in the region where the Born approximation is applicable.

## 3. Required data accuracies

Ideally, the total beam stopping cross section needs to be known to an accuracy of ~ 10%. It is fortunate that the cross sections for the most important, electron-removal processes involving the ground state are experimentally known to an accuracy better than 10% (as documented by the Working Group Reports of this Meeting). A rough sensitivity analysis for the beam energies and plasma densities of interest, and for penetration into a uniform plasma has shown that:

- The contribution of all electron processes to the total beam stopping cross section is of the order of 15-20%, so that the required accuracy for their cross sections would be about 50%;
- The contribution of all impurity impact excitations to $\sigma_s$ is about 20% (although this fraction increases with the beam energy) and the required accuracy for the corresponding cross sections is about 50%. This is only for the most important $1 \rightarrow n$ excitations; for the less important $n \rightarrow m$ ($n \geq 2$) transition (which contribute only 5% to $\sigma_s$), the required accuracy is a factor of 2 to 3, only;
- The proton impact excitation and electron removal processes contribute about 30-40% in the beam stopping enhancement. The required accuracy of the corresponding cross sections is estimated to about 20-30% for the excitations from the ground state, and 30-50% for the electron removal.

## References

1. C.D. Boley, R.K. Janev, D.E. Post, Phys. Rev. Letts. 52, 534 (1984);
2. A.S. Schlachter, J.W. Stearns, W.S. Cooper, R.E. Olson, "Penetration of an energetic $D^o$ beam in an ETR plasma. Current Drive for ITER", Report LBL-25369; presented at the ITER Workshop on Heating and Current Drive, June 13-17, 1988, Garching, FRG;
3. V.A. Abramov, A. Yu. Pigarov, V. Pistunovich, Report presented at the ITER Workshop on Heating and Current Drive, June 13-17, 1988, Garching, FRG.