Modeling process of the neutral beam re-ionization loss*

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Abstract The basic process of re-ionization loss was studied. In the drift duct there are three processes leading to re-ionization loss: the collision of neutral beam particles with the molecules of background gas, similar collisions with released molecules from the inner wall of the drift duct and the ferret-collisions among particles with different energy of the neutral beam. Mathematical models have been developed and taking EAST-NBI parameters as an example, the re-ionization loss was obtained within these models. The result indicated that in the early stage of the neutral beam injector operation the released gas was quite abundant. The amount of re-ionization loss owing to the released gas can be as high as 60%. In the case of a long-time operation of the neutral beam injector, the total re-ionization loss decreases from 13.7% to 5.7%. Then the re-ionization loss originating mainly from the collisions between particles of the neutral beam and the background molecules is dominant, covering about 92% of the total re-ionization loss. The drift duct pressure was the decisive factor for neutral beam re-ionization loss.

Key words Re-ionization loss, background molecule, ferret-collision, excitation outlet, thermal outgassing

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1 Introduction

Neutral beam injection (NBI) is a main method which is envisaged for heating fusion plasma to ignition temperatures. A neutral beam current drive has been observed in most large Tokamaks [1, 2]. Heating with a neutral beam is a complex process. The ions must first be produced and accelerated to the required energy. Then they are neutralized by charge exchange in a gas target and the unwanted residual ions removed. Neutral atoms injected into a plasma travel in straight lines, being unaffected by the magnetic field.

Under neutral beam re-ionization loss one understands the loss of beam power by collisions between particles of the neutral beam and the background gas in the drift duct. Because of the stray magnetic-field of a Tokamak, neutral beam re-ionization loss not only affects the working efficiency of the beam, but also can damage the device to some extend. Therefore the key issue is how to reduce the re-ionization loss of a neutral beam, which is even more important than increasing the energy of its particles.

For the majority of the NBI, it is difficult to measure the re-ionization loss accurately. In this article three of the basic processes of re-ionization loss are discussed and the corresponding mathematical models are developed. Taking a hydrogen neutral beam with the EAST-NBI engineering parameters as an example [3], the re-ionization loss will be derived within these mathematical models.

2 Collisions model for re-ionization

For the neutral beam, energetic atoms constitute a neutral beam. Atoms of a neutral beam impact background molecules, when the neutral beam is passing through the drift duct. Most of the background molecules are molecular hydrogen. It is obvious that the collision in the drift duct is between neutral par-

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ticles. Therefore, the following collision model may be established for collision process.

The collision model includes two particles earmarked by A and B with the radius of R_1, R_2. The mass and speed of the two particles are m_1, m_2, v_1, v_2 respectively, hydrogen atoms have high-speed directional movement and background molecular hydrogen has random thermal motion. Therefore, the following assumption is reasonable, $v_1 = v = \sqrt{\frac{2E_p}{m_1}}$, $v_2 = 0$. Where, E_p is the energy of particles of neutral beam.

After collision, the speed of two particles are v_1', v_2' and the angles with v_1 are α, β respectively. Fig. 1 shows the structure of the collision model. Thus, the collision probability for this process could written as

$$\gamma_{cm} = \frac{\pi(R_1 + R_2)^2}{S} , \quad (1)$$

where, S is the cross section of collision space.

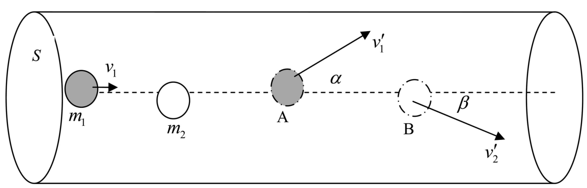

Fig. 1. Structure of collision model.

3 Re-ionization loss resulting from collisions with background molecules

During the working process of a neutral beam, the time sequence of gas input for the neutralizer and the ion source occurs always before the start time of the high voltage. Thus, there are many background molecules when the neutral beam is passing through the drift duct. After the removal of the residual ions the neutral beam is composed of hydrogen atoms with three energy components — full energy, half energy and 1/3 energy [2, 3]. Generally speaking, there is no coulomb effect during the collisions in the drift duct.

Assuming that the background gas is a uniformly distributed ideal gas of pressure P, one can derive the volume of its molecules from the equation of state:

$$V_{H_2} = \frac{RT}{N_A P} , \quad (2)$$

where, R is the gas constant, T is the temperature of the background gas and N_A is the Avogadro constant. Generally the energy of hydrogen atoms amounts to dozens of keV, which is much higher than the ionization energy. The characteristic dimension of the particle size is not its diameter, but the de Broglie wave length [4–6]. According to the special theory of relativity, a modified quantity can be used instead

$$R_m = \frac{h}{2mv} \times \frac{v}{c} + \left(1 - \frac{v}{c}\right) R_H, \quad (3)$$

where, h is the plank constant, m is the mass of atoms in the neutral beam, v is the speed of the atoms in the neutral beam (determined by the beam energy), c is the speed of light in vacuum and R_H is the radius of the hydrogen atoms. The probability of the collisions between the particles of the neutral beam and the background molecules can be written as follows:

$$\gamma = \frac{\pi\left(\frac{h}{2mv} \times \frac{v}{c} + \left(1 - \frac{v}{c}\right) R_H + R_{H_2}\right)^2}{\left(\sqrt[3]{\frac{RT}{PN_A}}\right)^2} , \quad (4)$$

where, R_{H_2} is the radius of a hydrogen molecule. Thus, if the length of the drift duct is l, the re-ionization loss resulting from collisions with the background gas may be expressed as

$$\gamma_B = \frac{l\pi\left(\frac{h}{2mv} \times \frac{v}{c} + \left(1 - \frac{v}{c}\right) R_H + R_{H_2}\right)^2 PN_A}{RT} . \quad (5)$$

On the assumption that single-charge particles constitute the beam in the accelerator system, the number of electrons gained from re-ionization can approximately be expressed as

$$N_1 = \frac{l\pi\left(\frac{h}{2mv} \times \frac{v}{c} + \left(1 - \frac{v}{c}\right) R_H + R_{H_2}\right)^2 PN_A}{RT} \times \frac{It\eta}{e} , \quad (6)$$

where, I is the beam current, t is the neutral beam pulse length, e is the elementary charge and η is the efficiency of the neutralization process.

4 Re-ionization loss resulting from collisions with released molecules

Under the powerful magnetic field of a Tokamak the ions and electrons resulting from re-ionization strike the wall of the drift duct. Generally the inner wall of the drift duct is covered by metallic oxide. Thus, the excitation outlet and the thermal outgassing occur during the passage of the neutral beam through the drift duct.

The ratio of the cross section of oxide node and the area of the oxide crystal lattice is about 0.04–0.06 and the probability of the interaction between the electron and the oxide node 0.1–0.5 can be taken as the ionization probability. The probability of the interaction between the ions and the oxide node is supposed to be 1 [7]. For stainless steel the coefficient of the excitation outlet by electrons $\gamma_{ex} = 0.004$–0.03, for the ions it is $\gamma_i = 0.04$–0.06. Also during the operation period heat is absorbed by the wall of the drift duct. This thermic energy leads to outgassing. However, since the drift duct is full of hydrogen, molecular hydrogen could be the exclusive gas obtained from the thermal outgassing. The experimental results indicated that the amount of the excitation outlet is ten times that of the thermal outgassing [7].

Take 0.05 as the coefficient of the excitation outlet for stainless steel. Thus, the number of oxygen molecules is given by

$$N_2=\frac{l\pi\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\rm H}+R_{\rm H_2}\right)^2PN_{\rm A}}{RT}\times\frac{It\eta}{20e}. \tag{7}$$

For a given cross section of the drift duct and a short enough time such as to keep all molecular oxygen in the drift duct, the volume of the molecular oxygen is given by:

$$V_{\rm O_2}=\frac{Sl}{\frac{l\pi\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\rm H}+R_{\rm H_2}\right)^2PN_{\rm A}}{RT}\times\frac{It\eta}{20e}}. \tag{8}$$

So, the re-ionization resulting from the collisions between the neutral beam particles and molecular oxygen can be expressed as

$$\gamma_{\rm e}=\frac{\pi^2\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\rm H}+R_{\rm O_2}\right)^2\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\rm H}+R_{\rm H_2}\right)^2lPN_{\rm A}It\eta}{20eSRT}. \tag{9}$$

Similarly, the molecular hydrogen from the thermal outgassing will lead to the re-ionization loss

$$\gamma_{\rm h}=\frac{\pi^2\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\rm H}+R_{\rm H_2}\right)^4lPN_{\rm A}It\eta}{200eSRT}. \tag{10}$$

5 Re-ionization loss resulting from ferret-collisions

For a neutral hydrogen beam, after the residual ions have been removed by the bending system, the energy of the atoms in the neutral beam is divided into three groups — full energy, one half and one third of the full energy. So, as some particles with the half energy pull up to the particles with the third energy, the ferret-collision will happen. Similarly, the ferret-collision happens to the particle with the full energy and the particle with the half energy, the particle with the full energy and the particle with the third energy. In the case of a uniformity distribution, the volume occupied by the particles with different energy is given by

$$V_i=\frac{S_{\rm B}v_it}{n}=\frac{S_{\rm B}t\sqrt{\frac{2E_{\rm p}}{m}}}{\frac{It}{e}\gamma_i}=\sqrt{\frac{2E_{\rm p}}{m}}\frac{S_{\rm B}e}{I\gamma_i}, \tag{11}$$

where, $S_{\rm B}$ is the cross section of the neutral beam; $i=1,2,3$ denotes the particles belonging to the groups with full energy, half energy and one third energy respectively, γ_i is the corresponding fraction of the particles and n is the number of the particles.

According to the above analysis, the rate of ferret-collisions moving particles from group 2 to 3 is given by

$$\gamma'_{23}=\frac{\pi\left[\frac{h}{2mv_3}\times\frac{v_3}{c}+\left(1-\frac{v_3}{c}\right)R_{\rm H}+\frac{h}{2mv_2}\times\frac{v_2}{c}+\left(1-\frac{v_2}{c}\right)R_{\rm H}\right]^2l}{\sqrt{\frac{2E}{m}}\frac{S_{\rm B}e}{I\gamma_3}}. \tag{12}$$

Thus, the re-ionization loss resulting from the corresponding ferret-collision can be expressed as

$$\gamma_{23}=\frac{\pi\left[\frac{h}{2mv_3}\times\frac{v_3}{c}+\left(1-\frac{v_3}{c}\right)R_{\rm H}+\frac{h}{2mv_2}\times\frac{v_2}{c}+\left(1-\frac{v_2}{c}\right)R_{\rm H}\right]^2l}{\sqrt{\frac{2E}{m}}\frac{S_{\rm B}e}{I\gamma_3}}\gamma_2. \tag{13}$$

Similarly, the other two re-ionization losses resulting from the ferret-collision are given by

$$\gamma_{12}=\frac{\pi\left[\frac{h}{2mv_1}\times\frac{v_1}{c}+\left(1-\frac{v_1}{c}\right)R_{\mathrm{H}}+\frac{h}{2mv_2}\times\frac{v_2}{c}+\left(1-\frac{v_2}{c}\right)R_{\mathrm{H}}\right]^2 l}{\sqrt{\frac{2E}{m}}\frac{S_{\mathrm{B}}e}{I\gamma_2}}\gamma_1\ , \tag{14}$$

$$\gamma_{13}=\frac{\pi\left[\frac{h}{2mv_1}\times\frac{v_1}{c}+\left(1-\frac{v_1}{c}\right)R_{\mathrm{H}}+\frac{h}{2mv_3}\times\frac{v_3}{c}+\left(1-\frac{v_3}{c}\right)R_{\mathrm{H}}\right]^2 l}{\sqrt{\frac{2E}{m}}\frac{S_{\mathrm{B}}e}{I\gamma_3}}\gamma_1\ . \tag{15}$$

6 Calculations and discussion

From experiments it is known that there is a dynamic pressure in the drift duct when the neutral beam passes through. The duct pressure shows a slow, almost linear, rise with time during the heating injection [8]. If the pressure in the duct is increased to p_2 from p_1, the length of the drift duct is l. So, γ_{B}, γ_{h}, γ_{e} would be modified by an integral as shown below

$$\gamma_{\mathrm{Bm}}=\frac{\pi\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\mathrm{H}}+R_{\mathrm{H_2}}\right)^2 N_{\mathrm{A}}}{RT}\int_0^l\left(p_1+\frac{p_2-p_1}{l}l'\right)\mathrm{d}l', \tag{16}$$

$$\gamma_{\mathrm{hm}}=\frac{\pi^2\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\mathrm{H}}+R_{\mathrm{H_2}}\right)^4 N_{\mathrm{A}}It\eta}{200eSRT}\int_0^l\left(p_1+\frac{p_2-p_1}{l}l'\right)\mathrm{d}l', \tag{17}$$

$$\gamma_{\mathrm{em}}=\frac{\pi^2\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\mathrm{H}}+R_{\mathrm{O_2}}\right)^2\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\mathrm{H}}+R_{\mathrm{H_2}}\right)^2 N_{\mathrm{A}}It\eta}{20eSRT}\int_0^l\left(p_1+\frac{p_2-p_1}{l}l'\right)\mathrm{d}l'\ . \tag{18}$$

For a long pulse or an enduring NBI the molecules will be pumped out in a time τ, which is much shorter than the pulse length. We define this as the characteristic time of the pump. In this case only part of the molecules will contribute to the re-ionization and our equations have to be adjusted accordingly.

$$\gamma_{\mathrm{em}}=\begin{cases}\frac{\pi^2\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\mathrm{H}}+R_{\mathrm{O_2}}\right)^2\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\mathrm{H}}+R_{\mathrm{H_2}}\right)^2 N_{\mathrm{A}}It\eta}{20eSRT}\int_0^l\left(p_1+\frac{p_2-p_1}{l}l'\right)\mathrm{d}l' & (t<\tau),\\ \frac{\pi^2\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\mathrm{H}}+R_{\mathrm{O_2}}\right)^2\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\mathrm{H}}+R_{\mathrm{H_2}}\right)^2 N_{\mathrm{A}}I\tau\eta}{20eSRT}\int_0^l\left(p_1+\frac{p_2-p_1}{l}l'\right)\mathrm{d}l' & (t>\tau);\end{cases} \tag{19}$$

$$\gamma_{\mathrm{hm}}=\begin{cases}\frac{\pi^2\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\mathrm{H}}+R_{\mathrm{H_2}}\right)^4 N_{\mathrm{A}}It\eta}{200eSRT}\int_0^l\left(p_1+\frac{p_2-p_1}{l}l'\right)\mathrm{d}l' & (t<\tau),\\ \frac{\pi^2\left(\frac{h}{2mv}\times\frac{v}{c}+\left(1-\frac{v}{c}\right)R_{\mathrm{H}}+R_{\mathrm{H_2}}\right)^4 N_{\mathrm{A}}I\tau\eta}{200eSRT}\int_0^l\left(p_1+\frac{p_2-p_1}{l}l'\right)\mathrm{d}l' & (t>\tau).\end{cases} \tag{20}$$

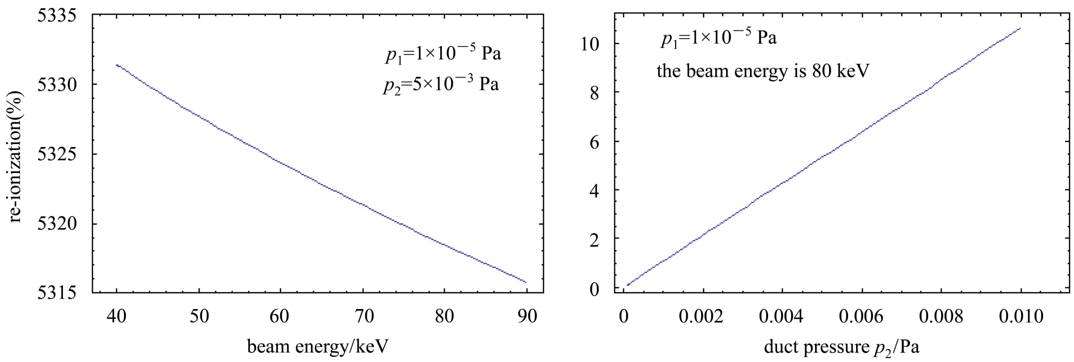

Fig. 2. The change of re-ionization with the beam energy and the duct pressure p_2.

If one puts together all the individual contributions, one gets the total re-ionization loss of the neutral beam as

$$\gamma_{\rm T}=\gamma_{\rm Bm}+\gamma_{\rm hm}+\gamma_{\rm em}+\gamma_{12}+\gamma_{13}+\gamma_{23}. \tag{21}$$

As an example we consider a neutral beam of 70 A with a cross section of 0.12 m × 0.48 m, a cross section of the drift duct of 0.5 m×0.5 m, a temperature of background gas of 300 K, and the full energy shall be 80 keV. For a duct pressure of 0.00001–0.005 Pa, the characteristic time of the pump is 100 ms. Taking for the fraction of the particles with full energy $\gamma_1=0.8$ and correspondingly $\gamma_2=0.14$ and $\gamma_3=0.06$.

Re-ionization loss resulting from collisions with the background molecule is about 5.31%; re-ionization loss resulting from collisions with the excitation outlet particle is about 5.54%; re-ionization loss resulting from collisions with the thermal outgassing particle is about 2.86%; re-ionization loss resulting from the ferret-collision is about 0.001%. The total neutral beam re-ionization loss is about 13.71%. It is clear that the gas resulting from the excitation outlet and the thermal outgassing are the dominating cause for the re-ionization loss of the neutral beam, about 60%. Generally the coefficient of the excitation outlet is not affected by the kind of material and the energy of the particles in a high vacuum environment. But, the coefficient of the excitation outlet and the coefficient of the thermal outgassing show a strong dependence on the vacuum environment. The experimental results indicated that the coefficients of the excitation outlet and the thermal outgassing reduce to the original 0.1–0.01 [7]. Take 0.05 as the coefficients, the re-ionization loss can be modified as

$$\gamma_{\rm T}=\gamma_{\rm Bm}+0.05\gamma_{\rm hm}+0.05\gamma_{\rm em}+\gamma_{12}+\gamma_{13}+\gamma_{23}. \tag{22}$$

Thus, the total re-ionization loss of the neutral beam is 5.739% and in agreement with the experimental results [8–10]. 92.67% of re-ionization loss results from collisions with background molecules; and the re-ionization loss caused by released gas is about 7.32%. The re-ionization loss caused by ferret-collisions is less than 0.01%, and can therefore be ignored.

From Eq. (16), we see that the re-ionization caused by the collisions of the neutral beam particles with the molecules of the background gas is determined by the beam energy, the duct pressure p_1 and p_2 and the length of the drift duct. Generally speaking, for a neutral beam injector the length of the drift duct is a certain given numerical value. The duct pressure is dominantly determined by the gas supply in the ion source and neutralizer and the cryopanel working as the high speed vacuum pump. Therefore, the duct pressure p_1 usually has a certain given constant value. Fig. 2 shows the change of re-ionization with the beam energy and the duct pressure p_2. In this calculation, the length of drift duct is 1m, the drift duct pressure p_1 is 1×10^{-5} Pa. As we can see, the re-ionization loss becomes lower with the increase of beam energy. But the change of the re-ionization loss is very small, just about 0.01% for the energy increase from 40 keV to 90 keV. On the other hand is the increase of re-ionization loss with the duct pressure p_2 remarkable.

7 Conclusion

During neutral beam injection background gas, released gas and ferret-collisions cause re-ionization loss. In the early stage of the neutral beam injector operation, the released gas is abundant with about 60% of the total re-ionization loss coming from the released gas. As the experiment went on, the released gas reduced to its original value of 0.1–0.01. Thus, the background gas is the dominating factor for re-ionization loss, about 92% of the total re-ionization loss results from the collisions of neutral beam particles with the molecules of the background gas.

The re-ionization loss depends on the parameters and performance of the device, the parameters of the neutral beam and so on. Above all, the decisive factor is the drift duct pressure p_2. The effect of the beam energy on re-ionization loss is marginal. Decreasing the drift duct pressure p_2 is a useful method for reducing the neutral beam re-ionization loss.

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