THE SIMULATION ON BEAM INTERACTION WITH BACKGROUND PARTICLES*

J. L. Wei#, C. D. Hu and L. Z. Liang
Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, Anhui, 230031, China

Abstract

A particle simulation with Monte Carlo was developed to study beam interaction with background particles in neutral beam injector (NBI). The collision processes associated with charge state change and reaction cross-section were analyzed for neutralization and re-ionization. Take the neutralization processes as a reference, for positive arc discharge ion source, there are three different original ion species in the energetic ion beam. In evolution, a fast particle will suffer kinds of collisions decided by the collision cross-section or no impact within the target gas. Classify those collisions and their cross-sections according the change of charge state and momentum. The neutralizer is divided into many extremely short segments averagely. So the gas density quantity at middle point can be regarded as that of each segment. According to the collision cross-section, select a random number to determine the evolution of particle states in each segment. With that particle simulation, the neutralization efficiency is estimated.

INTRODUCTION

A NBI system can produce an energetic neutral beam which is used to heat the plasma in the magnetic confinement fusion device [1]. A sketch of the NBI system is shown in Figure 1 [2]. A high energy ion beam from the ion source will undergo neutralization processes in a gas cell named neutralizer, in which part of the energetic ions turn into energetic neutral particles. And then, the mixed particles beam is separated into ions and neutral particles by the bending magnet. Finally, the energetic neutral particles pass through the drift tube and inject into the fusion device, while the residual ions are dumped into a target (i.e., residual ion dump). However, the produced neutral beam will suffer a re-ionization process, due to the limit of vacuum in the drift tube.

Take neutralization processes for example. In the neutralizer, atomic processes involving charge transfer and dissociation will change particles' charge state and momentum. Thus, these processes will determine the species evolution along the neutralizer downstream and the neutralization efficiency. Numerical calculations of this problem have been reported in [3]. Moreover, the functional forms of variation for all species are discussed later, which offer more detailed information of the species evolution [4]. However, both of the researches base on sets of the differential equations (DE) for each species. Although the same problem is considered here, we adopt Monte Carlo (MC) simulation to research instead.

*Work supported by the National Natural Science Foundation of China under Grant No. 10875146, and the Chinese Academy of Sciences Knowledge Innovation Project: the study and simulation on beam interaction with background particles in neutralization area for NBI.
#jlwei@ipp.ac.cn

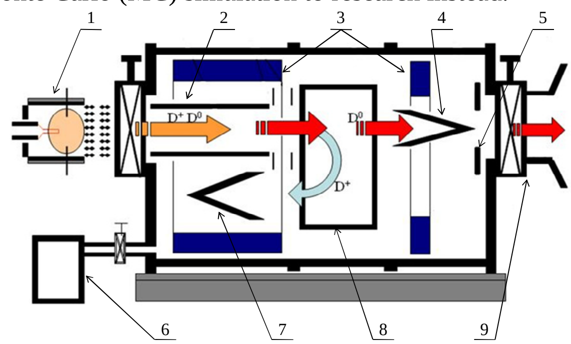

Figure 1: Sketch of NBI beamline: 1. Ion source; 2. Neutralizer; 3. Cryopumps; 4. Calorimeter; 5. Collimator; 6. Pump set; 7. Residual ion dump; 8. Bending magnet; 9. drift tube.

MODEL DESCRIPTION

Collision Processes

For a positive ion source, if the operating gas is deuterium, there are three different original ion species in the energetic ion beam, D^+, D_2^+ and D_3^+ [4]. In evolution these species are independent of each other, so we can analyze the particle species evolution respectively. Enough sample calculations and experiments have been carried out, however, to indicate that D_2 is representative of the better gas neutralizer for D species ion beam [3]. Based on the elementary MC principle, we select the relatively important collision processes between these fast species and slow molecule D and neglect the minute ones, which depend on the values of their corresponding cross sections.

Table 1 lists the various types of collision processes we take into account. From table 1 we can see clearly the close connection of these particles in their various collision processes. Except for the process of secondary D_2^+ production, most of the collisions will change the fast particles' charge state or momentum, which is more concerned for particle species evolution. Particularly, the tiny productions of D^- are considered here to show the rounded system of charge state. Thus, with the number of collisions increasing, the particles species evolution is dominated by inter-conversion between D^+ and D^0 in the neutralizer. Note that, some collision equations are generalized by several collision processes, such as production of fast D from fast D_2, which should be distinguished to avoid repeated calculation. These dates of the cross sections are all taken from [5].

Table 1: Margin Specifications

Particle	Process	New product
D	$D + D_2 \rightarrow D^+ + D_2 + e$	D^+, e
	$D + D_2 \rightarrow D^- + D_2^+$	D , D_2^+
	$D + D_2 \rightarrow D + D_2^+ + e$	D_2^+ , e
D^+	$D^+ + D_2 \rightarrow D + D_2^+$	D , D_2^+
	$D^+ + D_2 \rightarrow D^- + 2D^+$	D^-, D^+
	$D^+ + D_2 \rightarrow D^+ + D_2^+ + e$	D_2^+ , e
D^-	$D^- + D_2 \rightarrow D + D_2 + e$	D , e
	$D^- + D_2 \rightarrow D^+ + D_2 + 2e$	D , e
D_2	$D_2 + D_2 \rightarrow \sum D$ (fast, total)[a]	D
	$D_2 + D_2 \rightarrow \sum D^+$(fast, total)[a]	D^+
	$D_2 + D_2 \rightarrow \sum D_2^+$ (fast, total)[a]	D_2^+
	$D_2 + D_2 \rightarrow$ (destruction of D_2)[b]	
D_2^+	$D_2^+ + D_2 \rightarrow \sum D$ [a]	D
	$D_2^+ + D_2 \rightarrow \sum D^+$ [a]	D^+
	$D_2^+ + D_2 \rightarrow D_2 + D_2^+$	D_2 , D_2^+
	$D_2^+ + D_2 \rightarrow D + D^+$	D , D^+
D_3^+	$D_3^+ + D_2 \rightarrow$ (destruction of D_3^+)[b]	
	$D_3^+ + D_2 \rightarrow \sum D^+$ [a]	D
	$D_3^+ + D_2 \rightarrow \sum D_2$ [a]	D^+
	$D_3^+ + D_2 \rightarrow \sum D_2^+$ [a]	D_2
	$D_{3\,f}^+ + D_{2s} \rightarrow \sum D_{2\,f}^+$ [a]	D_2^+

[a] X (fast, total) indicates the sum of all processes leading to the creation of a fast species X.

[b] (Destruction of X) indicates the sum of all processes leading to the destruction of species X.

Physical Model

We will consider the idealized NBI system. We assume that (1) a monoenergetic ion beam is extracted and accelerated from the source in the x direction; (2) the ion beam is perfectly collimated, and the beam divergence is neglected; finally, (3) most of the collisions occur at large impact parameter, hence the fast particles hardly changing the direction and decelerate.

Under these hypotheses, we can create the following physical model. Consider the distribution of target gas density along the neutralizer is in an arbitrary form (shown in figure 2). Divide the neutralizer into k segments averagely, and ensure that the length of each segment Δl is less than $\lambda/20$, where λ is mean free path. If Δl is short enough, we can regard the gas density quantity n_i at middle point as that of each section. Furthermore, we postulate that every particle impacts with the target gas molecules no more than once in each segment. Thus, the probability of specific collision process in each segment is give by:

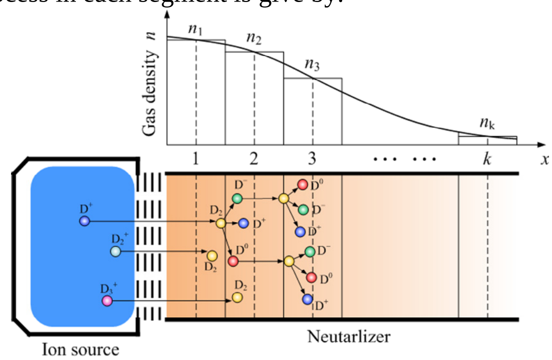

Figure 2: Sketch of neutralization processes.

$$P_{cd}^{ab} = \sigma_{cd}^{ab} \cdot n_i \cdot \Delta l \quad (1),$$

where σ_{cd}^{ab} is the reaction cross-section involving a mass change from a to b and a charge state change from c to d for fast particle.

Monte Carlo Simulation

According to the above analysis, we adopt Monte Carlo method to simulate the particle species evolution in the neutralizer. The collision type is stochastic, so we can use a random number to ascertain which processes the incident particle undergoes: construct an interval sequence $[0, z_1)$, $[z_1, z_2)$, … , $[z_{m-1}, z_m]$, $[z_m, 1]$, where $z_1 = P_1$, $z_2 - z_1 = P_2$, $z_{m-1} - z_m = P_m$. Obviously, each interval represents a corresponding collision type, and the interval $[z_m, 1]$ indicates a collisionless process. Afterwards, judge a random number (distributing uniformly between 0 and 1) yielded by computer, find out which interval it belongs to and fix on the collision process. Thus, we can learn what process the incident particle undergoes after traversing the first segment of the neutralizer, and the property of emergent particle. At the same time, the emergent particle for the first segment is just the incident particle for the second segment. Consequently, we can use the same method step by step to research this particle evolution in the following segments. Note that the possible collision types may be different for diverse incident particle. Finally, we accomplish the simulation on particle species evolution in the neutralizer of one ion injecting.

SIMULATION RESULTS

The required amount of target gas in the neutralizer (i.e., target thickness) varies with beam energy and species, and in turn affects the requirement of gas feeding system and large vacuum system. See the figure 3, multiplying the density values n_i by Δl , we get the gas line density for each section. And then, target thickness π of the neutralizer turns out to be:

$$\pi = \int_0^L n(x) \cdot dx = \sum_k n_i \cdot \Delta l \ . \ (2)$$

If the target gas density n is uniform along the neutralizer, the particles traversing each segment in sequence is the same as particle species evolution in linear target thickness. So this MC method can be used to calculate the variation of the fraction of particle species with the target thickness as the DE method does. In the DE methods, the solutions to the relevant differential equations of each beam are given in [4], but we get the solutions by Runge-Kutta method here.

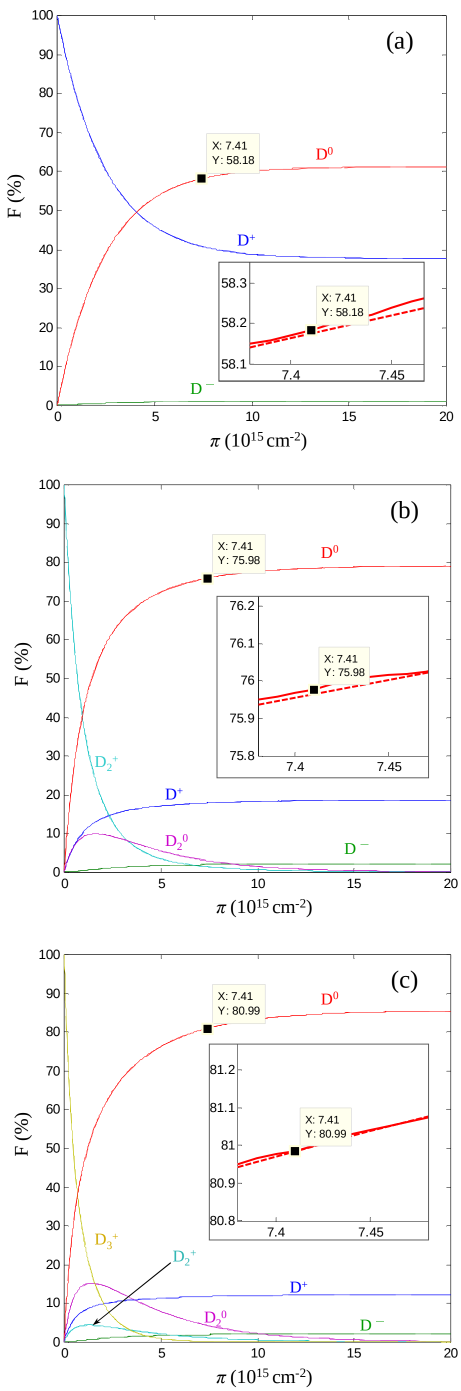

Figure 3: Fraction of particle species as a function of target thickness for (*a*) 80 keV D_3^+ beam, (*b*) 80 keV D_3^+ beam and (*c*) 80 keV D_3^+ beam (or 40 keV H^+, H_2^+ and H_3^+ beam) traversing D_2 (or H_2): (—) results of MC simulation; (- - -) results of DE simulation.

With two methods, the fraction of particle species vs. D_2 neutralizer target thickness for D^+, D_2^+ and D_3^+ beam at the energy 80 keV are shown respectively in figure 3. In those figures, the solid curves are the results of MC method, and the dash ones are given by DE method. We can see that, each pair of data curves are all fitting close with the target thickness increasing, and we cannot tell the difference in common dimension. To distinguish the two sorts of lines, the regions around the same value of target thickness for D^0 curve are zoomed in 100 times.

Particularly, the curve of D^0 for D^+ beam is just the variation of neutralization efficiency η with target thickness π. As target thickness increasing, the neutralization efficiency doesn't have a significant maximum but tends to equilibrium. The target thickness is usually set less than the equilibrium target thickness in a NBI system since the fraction of neutrals is slightly increasing near the equilibrium, and the excessive gas flowing to the drift tube will lead to more neutrals re-ionization losses [16]. We define optimum neutralizer thickness π_{opt}, which is the value of π required to achieve 95% of the equilibrium η. Acronyms should be defined the first time they appear.

CONCLUSION

The collision processes have been selected and classified in the beamline of the NBI system precisely, according to their collision cross sections and significance. Based on the relationships among responsible collision processes, a Monte Carlo simulation model is developed to analysis beam interaction with background particles in the neutralization processes, which are more complicated. The fractions of the major particles as a function of target thickness is given for 80 keV compared with the results of the differential equations method, which are fitting closely.

REFERENCES

[1] Wang J, Wu B and Hu C 2010 Plasma Sci. Technol. 12 289.
[2] Wesson J 2004 Tokamaks 3rd Ed. (Oxford, UK: Clarendon).
[3] Berkner D H, Plye R V and Stearns J W 1975 Nucl. Fusion 15 249.
[4] Kim J and Haselton H H 1979 J. Appl. Phys. 50 3802
[5] Barnett C F 1990 ORNL Technical Reports No. ORNL-6086.