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Research Article

The Charge State of Protons with 90 and 100 keV Energies Decelerated in Hydrogen Plasma

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Energy loss of protons with 90 and 100 keV energies penetrating through a hydrogen plasma target has been measured, where the electron density of the plasma is about $10^{16}\ cm^{-3}$ and the electron temperature is about 1-2 eV. It is found that the energy loss of protons in the plasma is obviously larger than that in cold gas and the experimental results based on the Bethe model calculations can be demonstrated by the variation of effective charge of protons in the hydrogen plasma. The effective charge remains 1 for 100 keV protons, while the value for 90 keV protons decreases to be about 0.92. Moreover, two empirical formulae are employed to extract the effective charge.

1. Introduction

The energy loss of charged particle in matter has been devoted a large number of investigations, both theoretical and experimental [1–7], in which the interaction of ion beams with cold matter has already obtained a plausible understanding, and theoretical predictions are in a good agreement with the experimental data [8]. Plasma, however, as a fundamental state of matter in our Universe, is only poorly understood and lacks reliable experimental data testing. In plasma physics, the basic problem is the interaction and energy loss of ion beams in the plasma [9–12]. In this subject, the energy loss of kinetic ions in plasma is very important for the development of inertial confinement fusion (ICF) [13, 14], ion-driven fast ignition [15, 16], and high-energy-density physics (HEDP) investigation [17]. Meanwhile, it has many practical applications in medicine, material science, accelerator technology, and so on.

The energy loss of ions in a neutral gas is dominated by the collisions with bound electrons, while the energy loss in plasma is deduced to the collisions with free electrons.. In cold gaseous target, the van der Waals collision is dominating, while in plasma the electrostatic interaction becomes important [18]. A large amount of experimental data for the stopping of ions in cold matter has been accumulated, where the inelastic collision between ions and bound electrons plays a leading role [19]. However, only few experimental data are available for the stopping of ions in plasmas, in which the collision between ions and free electrons is prevailing and the enhancement of the Coulomb energy losses is observed.

In principle, two main terms are found to increase the stopping of ions in plasma: one is the increase of Coulomb logarithm due to high-frequency energy transfer between ions and free electrons, and the other is the increased effective charge of projectiles in the plasma. The charge state of a projectile moving in the plasma is determined by the dynamic equilibrium of ionization and recombination. The charge state is expected to be higher compared to cold gas, and the reason could be deduced from the reduced cross section of direct capture of a free electron compared to that of a bound electron [20–22]. In plasma, the energy loss of ions becomes larger with the increase of charge state. At present, the effective charge theory of energy loss has become a powerful tool to correlate the experimental data [6, 20].

In general, the energy loss of heavy ions can be extrapolated simply from the energy loss of protons in the same material and with the same velocity, in which they can be correlated by the effective charge of ions [23]. Moreover, the energy loss of protons is also very important for nuclear fusion and ion-driven fast ignition. In order to investigate the effective charge state of heavy ions in beam-plasma interaction, the protons can make a comparative measurement of energy loss [24, 25]. Meanwhile, the energy losses of protons can be used as a practical diagnostic method to measure the density of free electrons in plasmas [26]. In application, P-^{11}B reaction provides a new solution for ignition, in which the resonant energy is about the magnitude of hundred keV [27, 28]. Thus, the energy loss of proton with the energy of hundred keV in plasma is an important topic for fusion development. It is proposed that the use of diatomic molecular ions and cluster ion beams of hydrogen may also prove helpful to drive inertial confinement fusion [29]. In addition, collective effect of protons in dense plasma has been investigated, and it is essential for the design of ion-driven fast ignition and inertial confinement fusion [30]. In the low-energy regime, the energy-loss measurement for 100 keV proton in the hydrogen plasma has been presented in our previous work [31], and the energy-loss enhancement effect is attributed to the higher Coulomb logarithm. Nevertheless, the effective charge for protons in the plasma is thought as 1, i.e., the charge-state evolution is not mentioned. In [32], the effective charge for 100 keV proton in the hydrogen plasma has been calculated and discussed again. Moreover, the empirical formulae near the Bragg peak have been used to extract the effective charge [33]. However, the energy loss of ions in plasma for the low-energy regime has not been completely clear yet due to the lack of experiments, and the theoretical predictions also consist of large uncertainties [34, 35].

In this work, we present a new experimental data of energy losses of 90 keV and 100 keV protons penetrating through the hydrogen plasma, and the effective charge state in the low-energy regime is discussed through the empirical formula calculations.

2. Experimental Setup

The experiment was performed at the 320 kV high-voltage experimental platform at the Institute of Modern Physics, Chinese Academy of Sciences (IMP, CAS), Lanzhou [36, 37]. Proton beams were extracted from the electron cyclotron resonance (ECR) ion source and selected by two 90° bending magnets. The protons were accelerated to 90 and 100 keV, respectively, and then introduced into a special experimental terminal for ions and plasma interaction investigation. The experimental system has been fully described in the previous work [31]. In brief, the proton beams with a spot size of about φ1 mm penetrated through the hydrogen plasma target. After through the plasma, a 0.5 m radius bending magnet with a deflection of 45° and a coupled time-resolved position-sensitive detector were used to measure the position of protons. The remained energy of the proton can be obtained from the position shift which is a function of the velocity of protons and magnetic field intensity. If the protons lose a certain amount of energy (dE) in the plasma, the position of the outgoing beam at the detector shifts by dx correspondingly. The range of the delay time (after the ignition of the discharge) of the detector is about 200 ns–20 ms, and the width of the detection time is from 10 ns up to infinity. The spatial resolution was about 70 μm. A good spatial resolution detector and the very stable magnetic field of the bending magnet were employed. The size of the proton beam was only 1 mm which is corresponding to 1 keV energy difference. In the experiment, the shift distance of the beam is about 0.5 mm. So the resolution of energy loss on the detector system is about 0.5 keV.

The plasma target based on a linear electric discharge in Z-pinch geometry was applied to study the energy loss of charged particles in ionized matter. The plasma will exist in about 8 μs and the temperature is about 1-2 eV. A Rogowski coil is used to measure the temporal discharge current (see Figure 3 in [31]) and the start pulse signal for triggering the detector is derived from the rising edge when the voltage is higher than 0.89 V. The higher discharge voltage produced larger current intensity and higher ionization degree, and free-electron density becomes larger. The maximum of the free-electron density is at about 3 μs (relative to the ignition) for the different discharge voltages. The plasma linear electron density has been determined by the laser interferometry techniques [38]. The length of the gas column in the target is limited to about 220 mm. The vacuum system of the beam line is protected from the gas load of the target by means of differential pumping. For the initial pressure of the hydrogen gas ranging 1~9 mbar, the free-electron density of 10^{16-17} cm^{-3} can be created in such a discharge.

3. Results and Discussion

A typical energy-loss measurement spectrum of 100 keV proton penetrating through the hydrogen plasma at different discharging time (the initial gas pressure was about 0.81 mbar, and the voltage was 3 kV) is shown in Figure 1. Figures 1(a) and 1(b) show the measured positions of ions in the detector at 0 μs and 3 μs time, respectively. The systematical energy loss can be obtained by measuring the position shift at different discharging time. Here, that energy loss increases by 4.07 keV comparing to the cold gas can be found in Figure 1.

The plasma state has been diagnosed by Kuznetsov, and in our experiment, the plasma state can be determined by the initial gas pressure and discharge voltage based on the results presented in [38]. The initial energy loss ΔE for 100 and 90 keV protons was measured to be 5.02 and 7.73 keV before discharge. The gas pressure is determined to be 0.81 mbar and 1.25 mbar according to the measured ΔE (see [Zhang et al., 2020]. for details). With the discharge voltage of 3 kV, the linear free-electron density n_f and average ionization

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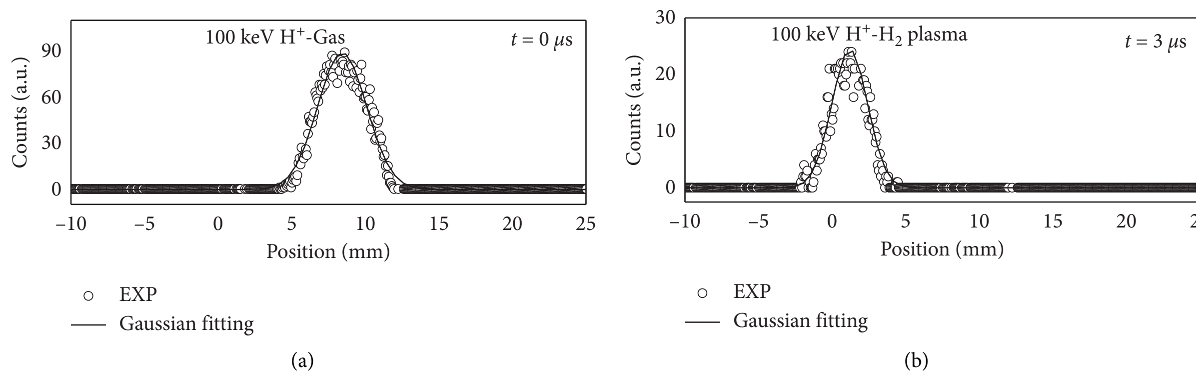

Figure 1: A typical energy-loss measurement spectrum of 100 keV proton penetrating through hydrogen gas discharging plasma at different discharging time (a) was at 0 μs time and (b) was at about 3 μs time (the initial gas pressure was about 0.81 mbar, and the voltage was 3 kV).

degree of the plasma are found to be $3.35*10^{17}\,\mathrm{cm}^{-2}$ and $3.75*10^{17}\,\mathrm{cm}^{-2}$, and 0.76 and 0.44, respectively, at the peak stage of discharge (around 3 μs). The linear free- and bound-electron density can be obtained by ref [38]. Figure 2 shows the free- and bound-electron density (the initial gas pressure was about 0.81 mbar, and the voltage was 3 kV), where n_b and n_f denote the linear bound- and free-electron density, respectively. n_f gradually rises up until the onset of the discharge peak stage. Then, it gradually decreases with the discharge time. Meanwhile, n_b evolves in the opposite tendency.

The energy-loss change in the whole plasma lifetime was recorded as a function of time after the discharge, which is shown in Figure 3 where the theoretical prediction is also shown for comparison. In our experiment, the total uncertainly of the energy loss is about 10% mainly from the broadening of the ion beam spot and the detector itself. Figures 3(a) and 3(b) represent energy losses of 100 keV and 90 keV protons in plasma (the discharging voltage was 3 kV), respectively. The initial gas pressures were estimated to be 0.81 mbar for 100 keV proton incident and 1.25 mbar for 90 keV proton incident. It should be noted that a similar trend of the change of discharge current, free-electron density, and energy loss of protons as a function of time can be observed in [31]. Both the discharging current and energy loss are mainly dependent on the free-electron density in the plasma, and for the first 1 microsecond, the discharge current and energy loss are not very stable (see ref. [31] for details), which is probably due to the fast changing of the electromagnetic field in the beginning. It results in decrease of energy loss at the beginning of discharge (0-1 μs). The phenomena, however, have not been clear yet, and a similar case is also found in refs. [39, 40]. When the discharging current reaches the maximum at around 3 μs after discharging, the temporal gradients of the electromagnetic field and the plasma parameters are minimum. Thus, the energy loss reaches the maximum at around 3 μs where the plasma reaches its most stable state. We choose the experimental

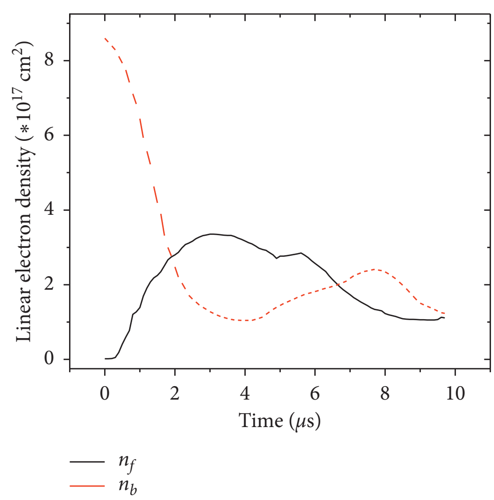

Figure 2: Linear free-electron (solid line) and bound-electron densities in plasma as a function of discharge time (the initial gas pressure was about 0.81 mbar, and the voltage was 3 kV).

data from the relatively stable plasma state from 2 to 4 μs to carry out the discussion below.

In a partially ionized plasma target, the incident ions lose their energy through cascade collisions with free electrons and/or bound electrons. Considering the homogeneity of the plasma target and the (nearly zero) slope of the stopping power function at this energy regime, a stepwise integration is not necessary and the total energy loss ΔE can be expressed as follows:

$$\Delta E = \left(\left[\frac{\mathrm{d}E}{\mathrm{d}x} \right]_{\mathrm{free}} + \left[\frac{\mathrm{d}E}{\mathrm{d}x} \right]_{\mathrm{bound}} \right) \times L, \tag{1}$$

where $L = 15.6$ cm is the plasma target length and $[\mathrm{d}E/\mathrm{d}x]_{\mathrm{free}}$ and $[\mathrm{d}E/\mathrm{d}x]_{\mathrm{bound}}$ represents the stopping power of the free electrons and bound electrons, respectively.

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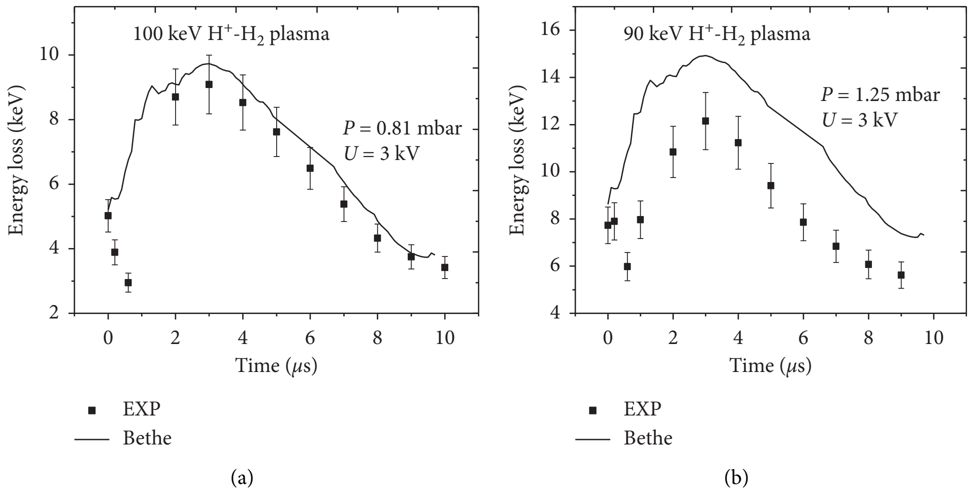

FIGURE 3: Energy losses of protons penetrating through hydrogen gas discharging plasma. (a) 100 keV proton in plasma (the initial gas pressure was about 0.81 mbar, and the voltage was 3 kV); (b) 90 keV proton in plasma (the initial gas pressure was about 1.25 mbar, and the voltage was 3 kV). The symbols represent experimental data. The solid line represents the theoretical predictions of the Bethe model with $Z_{\text{eff}} = 1$.

According to the Bethe model, the stopping power from the aspects of free electrons and bound electrons can be represented as follows:

$$\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\text{free}} = -\frac{Z_{eff}^2 e^2 \omega_p^2}{v_p^2} \ln\left(\frac{2m_e v_p^2}{\hbar\omega_p}\right),$$
$$\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\text{bound}} = -\frac{4\pi Z_{eff}^2 e^4 n_{be}}{m_e v_p^2} \ln\left(\frac{2m_e v_p^2}{I}\right), \tag{2}$$

where $\omega_p = \sqrt{4\pi n_{fe} e^2/m}$ is the plasma frequency, Z_{eff} is the projectile effective charge state, v_p denotes the projectile velocity, m_e and e are the electronic mass and charge, and n_{be} and n_{fe} are the density of free electrons and bound electrons, respectively, in which the degree of ionization has been considered. $I = \hbar\varpi$ is the average excitation energy of target atoms, which is 15 eV for hydrogen atom [41].

In the present work, when Z_{eff} is chosen as 1, the experimental data for 100 keV proton incident can be well reproduced by Bethe theoretical predictions, which is consistent with our previous results [31]. However, for 90 keV proton incident, the theoretical calculations obviously overestimate the experimental data by a factor of about 2, which may be attributed to the charge-state evolution of protons in the plasma [42].

In [42], the classical trajectory calculations were used to predict the charge-transfer and impact-ionization cross sections for collisions of H^+-H in the velocity range of $2–7 \times 10^8$ cm/sec, which is equivalent to the ion velocity in our experiment. Here, the charge-exchange cross section corresponds to a capture into any of the bound states of the ions, that is, a total capture cross section rather than a capture into the ground state only. The projectile charge state is determined by the total electron-loss cross sections (sum of charge exchange and impact ionization). One can clearly see that impact-ionization cross sections for 100 keV and above 100 keV H^+-H collisions are dominated. This means that, in this case, the charge-transfer cross sections can be ignored, in which the cross sections decrease with the increase of incident energy, while for below 100 keV H^+-H collisions, the total electron-loss cross sections are determined by both the charge-transfer cross sections and the impact-ionization cross sections. Therefore, the charge-state evolution effect needs to be taken into account for below 100 keV H^+-H collisions. Based on the discussion above, when Z_{eff} is equal to 1, the theoretical predictions for 90 keV proton incident overestimate the experimental data, which can be explained by the charge-state evolution effect. The experimental phenomenon concerned with the variation of the effective charge of protons in the plasma has not been reported so far. In our experiment, for the low-energy regime, when the incident energy is 100 keV, the effective charge of protons is equal to 1. While for 90 keV proton incident, the charge-state evolution needs to be considered, Z_{eff} should be less than 1 [42].

In the present work, the effective charge of 90 keV protons in the hydrogen plasma can be calculated through some empirical formulae. Kreussler et al. [43] suggested that the equilibrium charge state of projectile ions can be used to estimate the energy loss. The equilibrium charge state relies on the relative velocity of the projectile v to the electrons of the target v_e, in which all the possible orientations of vector $v - v_e$ are considered, which is given by

$$v_r = \left|v - v_e\right| = \frac{v_e^2}{6v}\left[\left(\frac{v}{v_e} + 1\right)^3 - \left|\frac{v}{v_e} - 1\right|^3\right]. \tag{3}$$

In the case of plasma, the electron velocity is determined by its corresponding Fermi velocity and the thermal velocity of free electrons:

$$v_e = \left(2 \cdot \frac{3}{5} E_{\text{F}} + 3k_{\text{B}}T\right)^{1/2}, \tag{4}$$

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where T is the plasma temperature, E_F is Fermi energy, and k_B is the Boltzman constant. The effective charge state is then calculated by

$$Z_{\text{eff}} = Z - Ze^{-\nu_r/Z^{2/3}\nu_0}, \tag{5}$$

where Z is the projectile atomic number.

Moreover, Gus'kov et al. [23] proposed a similar model, in which the effective charge is defined by the following relationship:

$$Z_{\text{eff}} = Z * \gamma. \tag{6}$$

Here, the typical parameter is given by

$$\gamma = 1 - \exp\left[-0.92 * Z^{-2/3} * \langle|\nu - \nu_e|\rangle\right]. \tag{7}$$

In the Kreussler model, Z_{eff} is equal to 0.861. In the Gus'kov model, the value of Z_{eff} is 0.832. Figure 4 shows the theoretical calculations from two empirical models, in which they all underestimate the experimental data. The main reason is that the parameters of only incident ions in two empirical formulae are considered, while target properties are ignored. In our experiment, the plasma is partially ionized, and ionization degree should be taken into account [32].

Compared to neutral matter, plasmas have different components (atoms, ions, and electrons), and the component density depends on plasma temperature and density. In order to describe the interaction between incident ions and plasma, the rate constants of the processes are employed, i.e., $N\ \langle \upsilon\sigma \rangle\ (\text{s}^{-1})$ [44]. The constant quantities averaged over a Maxwellian distribution of particle velocities v; here, N is the particle density of the plasma. Therefore, in the present work, the ionization degree of plasma needs to be considered for the calculation of the effective charge of the projectile. Moreover, for the empirical formulae, it is necessary that the mean values of the relative velocity and fluctuations of the quantities also need to be taken into account [23].

In this work, the value of Z_{eff} is found to be about 0.92, and the theoretical predictions give a good description with the experimental data, as shown in Figure 4. In [45, 46], to achieve better agreement with the experimental data, various typical parameters of expression (5) have been used. Here, expression (5) can be modified as follows:

$$\gamma = 1 - \exp\left[-1.31 * Z^{-2/3} * \langle|\nu - \nu_e|\rangle\right]. \tag{8}$$

Thus, our experimental results can be reproduced by the theoretical predictions.

Similar calculations for 100 keV protons are also applied. Basing on the Gus'kov and Kreussler models, the values of Z_{eff} are 0.846 and 0.864, respectively. They all underestimated the experimental data, as shown in Figure 5. The effective charge calculated by the modified empirical model is equal to 0.93. The value is consistent with the result presented in [32], in which electrons are all assumed to be captured into the projectile ground state. Figure 5 represents the theoretical predictions from the modified empirical model, which are in agreement with the experimental data in the range of errors. It implied that the effective charge for

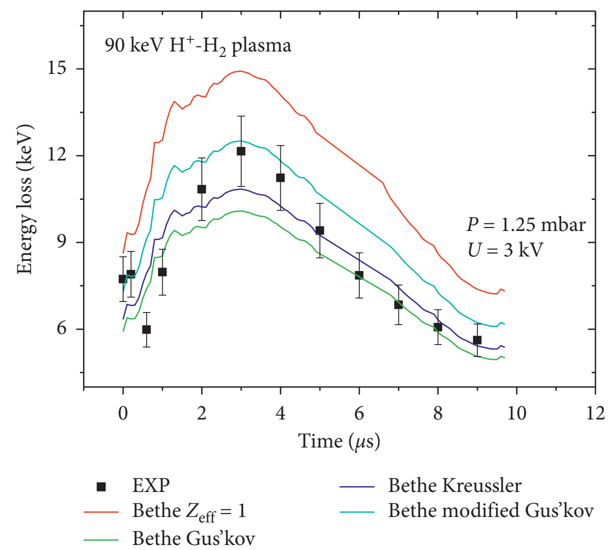

Figure 4: Energy losses of 90 keV protons in hydrogen gas discharging plasma. Theoretical model calculations are also shown for comparison.

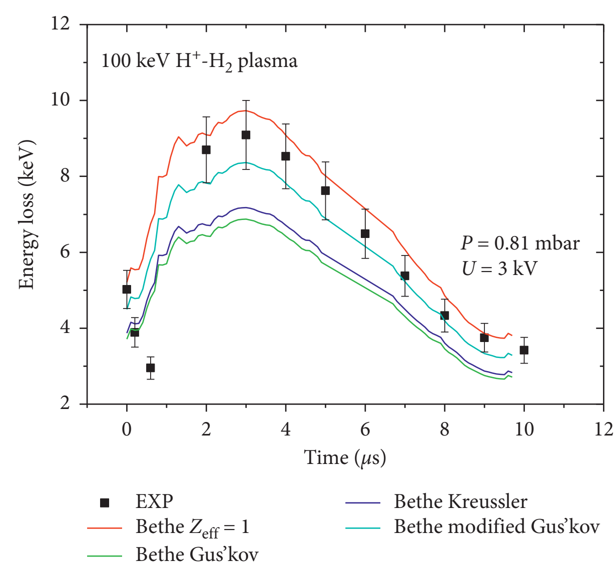

Figure 5: Energy losses of 100 keV protons in hydrogen gas discharging plasma. Theoretical model calculations are also shown for comparison.

100 keV protons in plasmas also needs to be considered, as described in [32]. It is not in accord with the case of neutral matter in [42]. Meanwhile, in our previous work, that the effective charge for 100 keV protons is chosen as 1 is arbitrary. However, the detailed and further experimental measurements are necessary, and how the target properties are added in the empirical formulae still needs further theoretical investigation.

4. Summary

The energy losses of protons with the initial energy of 90 keV and 100 keV penetrating through the hydrogen plasma have

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been measured. The enhancement of energy loss in plasma compared to cold gas is introduced, which is consistent with our previous work. In our investigation, however, when $Z_{\text{eff}} = 1$, the experimental data for 100 keV protons can be described by the theoretical predictions of the Bethe model, while it fails for 90 keV case, in which the theoretical calculations overestimate the experimental data. We apply the charge-state evolution to discuss our experimental results, and in the low-energy regime, the charge state remains 1 for larger than 100 keV protons, whereas the charge-state evolution needs to be considered with the decrease of incident energy. In order to reproduce the experimental results, the two empirical formulae are used to extract the effective charge. In the present work, the theoretical calculations from the effective charge extracted by two empirical formulae all underestimate the experimental data, which is mainly ascribed not to be referred to ionization degree of plasma in the empirical formulae. Based on our experimental results, a modification of the empirical formula is proposed, and the experimental data can be well reproduced. Moreover, the systematical measurement on energy loss and charge-state distribution for protons will be carried out in the future.

Data Availability

Data can be available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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