

# Influence of Charge-Exchange Processes on Effective Beam Energy for Inertial Electrostatic Confinement(IECF) Device

MuHyeop Cha<sup>a</sup>, Taekyoung Kim<sup>a</sup>, Yunho Jung<sup>a</sup>, Heejeong Seo<sup>b</sup>, Y.S. Hwang<sup>a\*</sup>, Kyoung-Jae Chung<sup>a\*</sup>

<sup>a</sup>Department of Nuclear Engineering, Seoul National University, 1, Kwanak-ro, Kwanak-gu, Seoul, Republic of Korea

<sup>b</sup>NIFTEP(Nuclear Research Institute for Future Technology and Policy), Seoul National University, 1, Kwanak-ro, Kwanak-gu, Seoul, Republic of Korea

\*Corresponding author: jkjlsh1@snu.ac.kr

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## 1. Introduction

Electrostatic inertial confinement fusion (IECF) devices are compact neutron sources for rare radioisotope production owing to their structural simplicity and the scalability of its high-voltage drive. However, charge-exchange(CX) reactions in the acceleration region reconstruct the ion energy spectrum and generate fast neutrals, thereby limiting the effective fusion reactivity and the fraction of ions that reach the chamber center. Because increasing the electrode spacing to high-voltage insulation standoff and the pressure to achieve higher plasma current and also elevates CX reaction rates, an optimum operating point is expected to emerge from this trade-off.

In this work, we develop a Monte-Carlo simulation based on two representative CX reactions(D-D, D-D<sub>2</sub>) to predict energy distribution of each deuterium species at the collection plane. The model incorporates CX cross-sections derived from literature fits, as well as pressure-dependent mean free paths, and attribution for the fast neutrals. From these elements we define an effective kinetic energy  $E_{\text{eff}}$  as a function of gap distance and pressure. The results provide for selecting operating pressure and electrode gap to maximize neutron-production efficiency in IECF devices.

## 2. Nuclear Reactions and Cross Sections in IECF

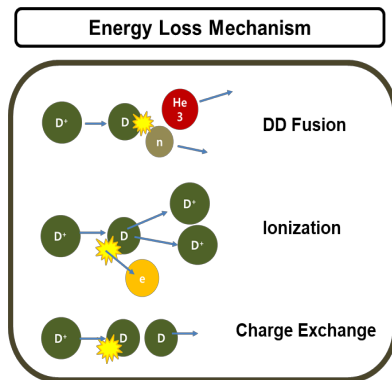


Figure 1: Energy loss mechanisms of accelerated deuterium ions.

Within the IECF, representative reactions that may occur as deuterium ions are accelerated include D-D fusion, ionization, and charge exchange (CX), as

illustrated in Fig. 1. Deuterium ions generated from an external plasma source are accelerated toward the center of the chamber by the electric field structure. Depending on the kinetic energy gained during this acceleration process, the ions may collide with the electrodes or with the background gas inside the chamber. The corresponding cross sections for these reactions are presented in Figures 2 and 3. Note that the reaction cross section in Figure 3 corresponds to hydrogen. Since these collision reactions are governed primarily by the electronic structure rather than the nuclear structure, the cross sections are found to be similar.

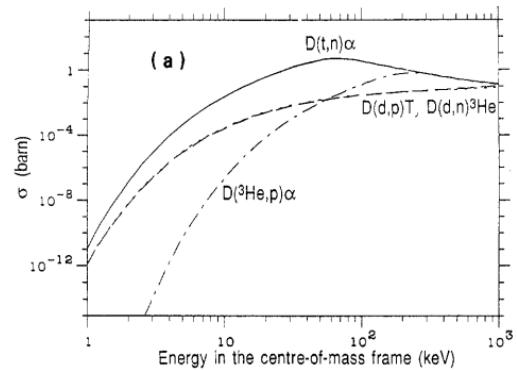


Figure 2: Fusion reaction cross-sections of hydrogen isotopes [1]

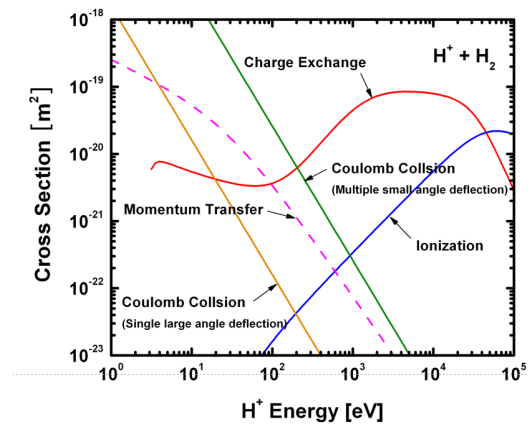


Figure 3: Energy loss mechanisms of accelerated hydrogen ions.

For D–D fusion, the cross section is on the order of a few mbarns[1], which is significantly smaller compared to other reactions. Geant4 simulations indicate that in the energy range below 100 keV, approximately 1-2 fusion events are expected out of  $\sim 10^9$  incident particles, making observation of the D–D reaction negligible. In the low-energy regime, energy loss due to Coulomb collisions is the dominant process, and particles that acquire sufficient energy subsequently undergo CX reactions as the primary interaction within the IECF chamber. To demonstrate that these reactions are negligible compared to the energy distribution caused by CX, a Geant4 toolkit simulation was conducted for taking account into the stopping power due to Coulomb collisions and ionization. The results showed that at pressures below 100 mTorr, the energy loss was less than 2% in the high energy regimes over 100 keV.

### 3. Simulation Method

To calculate the energy distribution and effective energy obtained from CX reactions, the following algorithm was applied in 1-D plane geometry. First, the linear potential structure in the diode geometry is defined, and  $D^+$  ions are accelerated accordingly. The accelerated ions undergo a Monte Carlo decision process to determine whether a CX reaction occurs, based on the given reaction cross-section. Ions that do not undergo any reaction until they reach the opposite electrode are directly collected in the energy distribution, and in this case, their energy corresponds to the given potential.

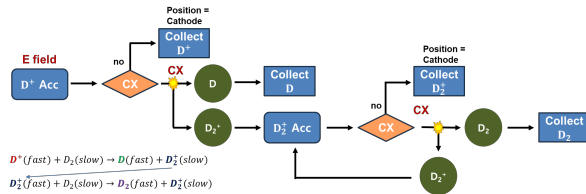


Figure 4: Monte-Carlo simulation algorithm flowchart.

On the other hand, if a CX reaction occurs, the previously accelerated  $D^+$  ion becomes a neutral deuterium and is no longer accelerated. The energy of this neutral deuterium is also incorporated into the energy distribution, after which the newly formed  $D_2^+$  ion proceeds in the simulation cycle. In the case of a  $D_2^+$  ion, when a charge exchange reaction occurs, there is no need to kill the existing  $D_2$  ion; instead, it is re-generated from the kill position with initial energy. The remaining neutral  $D_2$  species are also incorporated in the energy distribution, and if they reach the opposite electrode, their energy is recorded as well. A schematic diagram of this algorithm is shown in Figure 4.

Meanwhile, to calculate the CX reaction, an analytic curve based on a Chebyshev polynomial was used so that the reaction cross section could be smoothly

interpolated according to the energy at each position. This fitting method is not only applied to charge exchange but also widely used to represent various fusion reactions, and many fitting coefficients have been proposed based on experimental results [2,3]. Among these, the fitting results of Wang et al. were adopted, and the corresponding energy-dependent mean free path of CX is shown in Figure 5. From this, it can be inferred that at a pressure of about 0.1 mTorr, CX can be neglected in most chambers size.

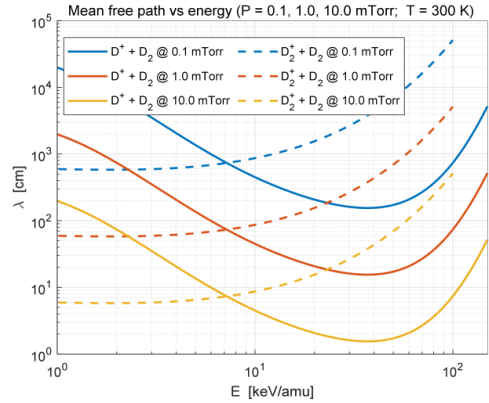


Figure 5: Mean free path expectation value vs. incident deuterium ion energy depending on operating pressure

### 4. Results and Discussion

The simulation was carried out with a potential of 100 kV, electrode gaps of 10–30 mm, and pressures ranging from 0.1 to 10 mTorr. Figure 6 shows the following for a diode structure with a 15 mm gap and 30,000 incident  $D^+$  particles, as a function of pressure: (a) the average number of CX reactions for  $D^+$  ions, (b) the average number of CX reactions for newly generated  $D_2^+$  ions, (c) the energy distribution of neutral D particles, and (d) the energy distribution of neutral  $D_2$  molecules.

Figure 6 (a) demonstrates that once the pressure reaches 5 mTorr, more than 95% of the particles undergo at least one CX reaction, thereby halting acceleration. In particular, unlike Deuterons, which can undergo only a single CX reaction,  $D_2$  particles can experience multiple charge exchange reactions, as shown in Figure 6 (b). Since the probability of charge exchange for  $D_2$  ions increases at lower energies, this phenomenon becomes more pronounced. Therefore, under pressure conditions where CX reactions occur, it is expected that most particles contributing to fusion with effective energy will be  $D^+$  ions. This tendency is also evident in the neutral particle distributions. While fast neutral deuterons exhibit a bell-shaped distribution, neutral deuterium  $D_2$  molecules predominantly show a low-energy distribution with a right-tailed shape, as illustrated in Figures 6(c) and 6(d). As the pressure increases, both distributions become increasingly skewed to the left.

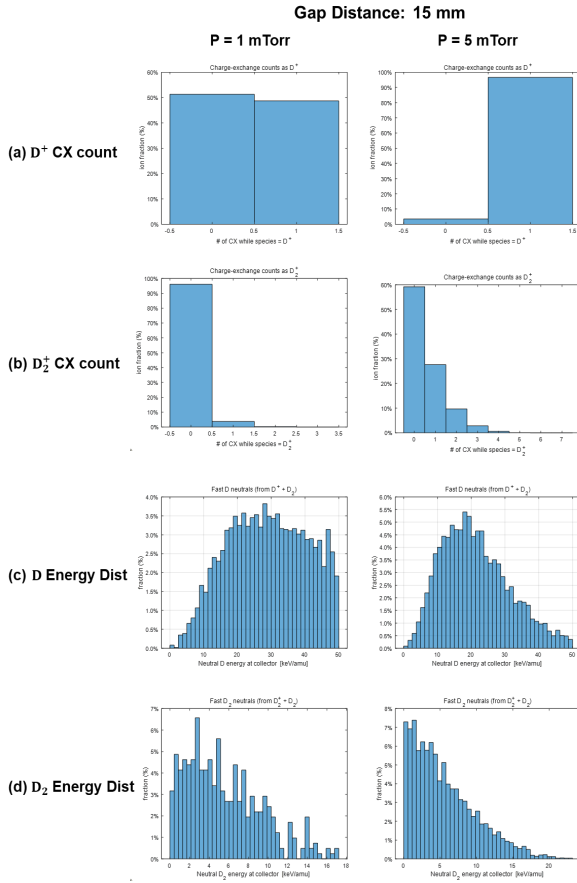


Figure 6. The number of charge exchange reactions occurring during incidence of (a)  $D^+$  ions and (b)  $D_2^+$  ions, and the energy distribution of neutral (c) deuterons and (d) deuterium molecules.

Since the energy distributions of D and  $D_2$  ions and neutrals are provided through the Monte Carlo simulation, the effective energy contributing to fusion can be calculated using Eq. (1), by applying the fact that the D–D fusion reaction in the 10–150 keV range is approximately proportional to the square of the energy.  $E_i$  and  $p_i$  in Eq. (1) means energy and number proportion of each species. The effective energy calculated in this manner is shown in Figure 7 as a function of gap spacing and pressure.

$$E_{\text{eff}} = \sqrt{\sum_{D, D^+, D_2, D_2^+} E_i^2 p_i} \quad (1)$$

It should be noted that this effective energy calculation assumes that the generated neutral species participate in fusion without considering time or loss effects; therefore, it represents the upper limit of the actual effective energy. From this, it can be inferred that at sufficiently low pressures around 0.1 mTorr, the IECF chamber size has little influence, allowing sufficient insulation distance to be secured. However, at lower pressures, the extracted plasma current may also decrease.

Because plasma current and effective energy scale linearly with pressure, while the fusion reaction scales with the square of the energy, reducing pressure appears to be a favorable strategy, even though the extractable plasma beam current decreases.

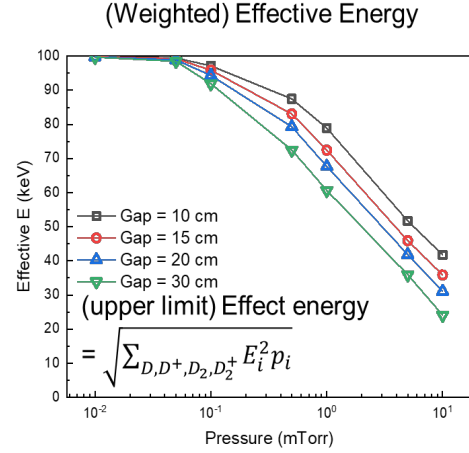


Figure 7: Effective beam energy of 100 keV incident particles in respect to gap distance and gas pressure.

## 5. Conclusions

Using Monte Carlo simulations, the effect of charge exchange (CX) reactions was investigated, as predicted to be the main energy loss process in IECF. As the operating pressure decreases, the effective energy rapidly converges to the incident beam energy. In particular, in the high-vacuum regime below 0.1 mTorr, the influence of chamber size becomes negligible. Therefore, for incident beam energies below 150 keV, the chamber size only needs to satisfy the minimum insulation requirement, while the operating condition can be primarily determined by the pressure. These results highlight that accounting for CX reactions is essential for selecting the optimal operating pressure in IECF systems, and that the chamber size can be designed independently.

## ACKNOWLEDGEMENT

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## REFERENCES

- [1] Bosch, H-S., and Gerald M. Hale. Improved formulas for fusion cross-sections and thermal reactivities. *Nuclear fusion* 32.4 (1992): 611.
- [2] Wang, J.G., and P.C. Stancil. Hydrogen ion-molecule isotopomer collisions: Charge transfer and rearrangement. *Physica Scripta*, 2002(T96) (2002):72.
- [3] Emmert, Gilbert A., and John F. Santarius. "Atomic and molecular effects on spherically convergent ion flow. II. Multiple molecular species." *Physics of Plasmas* 17.1 (2010)