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慣性静電閉じ込め核融合装置のモンテカルロ数値解析
Monte-Carlo Numerical Analysis of an Inertial Electrostatic Confinement Fusion Device

長谷川純，板垣智信，田端真之介，堀田栄喜，高倉啓
Jun HASEGAWA, Tomonobu ITAGAKI, Shinnosuke TABATA, Eiki HOTTA, Kei TAKAKURA

東工大先導原子力研
LANE Tokyo Tech

In the inertial electrostatic confinement (IEC) fusion device, deuterium ions produced by glow discharge are accelerated toward a high-voltage cathode and electrostatically confined in a negative potential well. The recirculating motion of the deuterium ions is expected to enhance fusion reaction rate between deuterons, thus making the IEC device an attractive candidate for compact neutron generators. The behaviors of deuterium particles in the IEC device are very complicated because of huge amount of collisions between the particles. Particularly, interactions between fast particles (D, D^+, D_2, D_2^+, and D_3^+) and background gas molecules (D_2) determines the velocity distributions of the deuterium particles causing D-D fusion reactions.

The purpose of this study is to develop a Monte-Carlo numerical simulation model including various collisions and reactions between fast ions/atoms and background neutral molecules, and to investigate the dependence of the fusion reaction rate on the discharge parameters.

Figure 1 shows a cross-sectional view of the linear IEC device developed in this study. The overall structure of the device is axisymmetric. A hollow cathode and two facing anodes made of stainless steel are arranged coaxially on the center axis with gap lengths of 115 mm. The cathode has an inner diameter of 60 mm and a length of 100 mm. The side walls are 8-mm-thick glass tubes having an inner diameter of 134 mm. Fuel gas is supplied from one end of the device through a solenoid valve and evacuated by a turbo molecular pump from the other end of the device. The gas pressure is maintained to be ~1 Pa by controlling the solenoid valve with a feedback signal from a diaphragm pressure gauge.

In the present study, the cathode was negatively biased up to –30 kV by a regulated high-voltage power supply to induce high-voltage glow discharge in hydrogen gas. The power supply was operated in a constant current mode and the discharge voltage was indirectly controlled by changing the hydrogen gas pressure.

A 1D numerical model based on the Monte Carlo (MC) method was developed to predict the distribution functions of fast particles $f_i(x, v)$ in the linear IEC device. Here, x and v are, respectively, the position and velocity of hydrogen atoms when they cause Hα emission after charge-exchange reactions with background deuterium or hydrogen molecules. The electrostatic potential calculated in advance by COMSOL Multiphysics® was imported to the MC code. By accumulating 10^7 trials and analyzing the particle record, we obtained distribution functions related to specific events such as Hα emission and D-D fusion reaction.

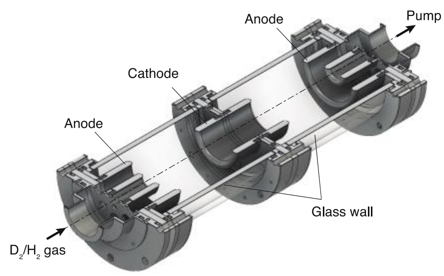

Fig. 1. A cross-sectional view of the developed linear IEC device.

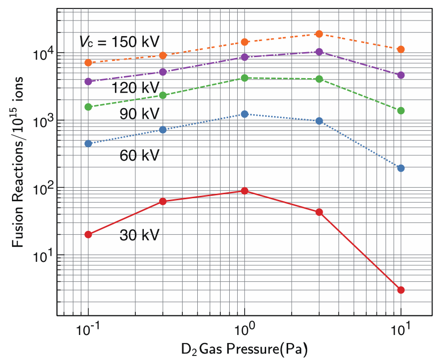

Fig. 2. Dependencies of the number of D-D fusion reactions on discharge voltage and background gas pressure.

We also performed a spectroscopic measurement of hydrogen Balmer series emission from the discharge plasma using a 50-cm monochromator combined with a high-resolution EMCCD camera. The Doppler-shift components of Hα were precisely observed and compared with the MC calculations to check the validity of the calculation model.

Figure 2 shows the dependencies of the number of fusion reactions on the discharge voltage and the background deuterium gas pressure. One can see that the number of the D-D fusion reactions drastically increases with increasing the discharge voltage. Meanwhile, there is an optimal gas pressure that maximizes the fusion reactions in each discharge condition with fixed cathode voltage. The optimal gas pressure slightly increases from 1 Pa to 3 Pa with increasing discharge voltages from 30 kV to 150 kV, indicating that smaller gap distances are more preferable when we operate the IEC device with higher discharge voltage.