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# Dependence of Neutron/Proton Production Rate on Discharged Current in Spherical Inertial Electrostatic Confinement Plasmas

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**Abstract**

The correlation between proton production rate and discharged current in D-$^3$He spherical inertial electrostatic confinement (SIEC) plasmas is studied for various ion/electron distribution functions. In high energy (more than ~50 keV) range, the $^3$He(d,p)$^4$He fusion cross section increases more rapidly than the D(d,n)$^3$He one with increasing relative energy between beam-ion and background gas. It is shown that if electrons have high convergence and energetic component compared with ions, the proton production rate in deuterium-helium-3 gas systems can increase in proportion to more than a power of the discharged current more easily for higher discharged voltage than that in the deuterium-gas systems.

**Keywords:**
IEC, deuterium-helium3 gas system, ion distribution function, fusion reaction rate

## 1. Introduction

The spherical inertial electrostatic confinement (SIEC) is a concept for electrostatically confining high-energy fuel ions in spherical potential well [1-5], where their increased density yields a high fusion reaction rate. The SIEC fusion system has an intrinsic potential for earlier practical use of fusion energy as a compact and economical neutron/proton source [1], and the studies to improve the system performance are now in progress. So far, neutrons (protons) more than $10^8$ n/s produced by D(d,n)$^3$He ($^3$He(d,p)$^4$He) fusion reactions have been observed on several devices [2-5]. By increasing the discharged current and voltage, the world record of the neutron/proton production rate in SIEC devices has been renewed continuously. The combination of higher values of the current and voltage, however, causes the problem of overheating the spherical cathode. To improve further the device performance, it is important to investigate the method not relying on the enormous increment in the current and voltage.

In recent experiment [4,6] using a spherical glow discharge as ion source, an operation mode in which the neutron production rate (by D(d,n)$^3$He fusion reactions in deuterium gas system) increases in proportion to 1.3–2.0th power of the discharged current, *i.e.* so-called "$I^2$-scaling", was observed. The increment in the neutron/proton production rate proportional to more than a power of the discharged current is advantageous to the device scaling. In subsequent theoretical PIC simulation [7], Ohnishi *et al.* evaluated the D(d,n)$^3$He fusion reaction rate between counterflowing ions in deuterium gas system, and revealed that the intermittent peaking of the density in the central region causes the higher neutron production proportional to more than second power of the discharged current. In previous experiments, however, the total neutron production is considered to be produced by the fusion reactions between beam ion and background deuterium gas. We have proposed the mechanism of the $I^2$-scaling, and shown that if electrons have high convergence and energetic component compared with ions, the neutron production rate can increase in proportion to more than a power of the discharged current, even if the neutron production is sustained mainly by the fusion reactions between beam (deuteron) and background (deuterium) gas [8].

In our previous work, it has been shown that the $I^2$-scalling in deuterium gas system is induced as a result of the rapid increment in the D(d,n)$^3$He fusion cross section with increasing relative energy between beam and background gas. It is well known that the $^3$He(d,p)$^4$He fusion cross section more rapidly increases with increasing relative speed compared with the D(d,n)$^3$He one, and thus we can expect the proton production rate by $^3$He(d,p)$^4$He reaction in deuterium-helium3 gas system increases in proportion to more than a power of the discharged current more easily for higher discharged voltage than that in the deuterium-gas systems. In this paper, we consider the deuterium-helium-3 gas system. On the basis of our previously-developed model [9,10], dependence of the

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proton production rate (by $^3$He(d,p)$^4$He reaction in deuterium-helium3 gas system) on the discharged current is examined for various ion/electron distribution functions.

## 2. Analysis model

In SIEC fusion device, we have examined an instantaneous plasma state for various non-equilibrium ion/electron distribution functions. In the moment, we have assumed that the distribution function does not explicitly depend on the radial position. The motion of a charged particle in this system is described by total energy $E = 1/2mv^2 + q\phi$ and angular momentum $L = mrv_\perp$. The ion and electron distribution functions are assumed to be functions of $E$ and $L$ [8-12]. As a model equation, by using dimensionless parameter $\alpha_a$, $\beta_a$ and $\xi_a$, we assume the distribution function in the following form:

$$f_a\,(E,\,L) = c_a \exp\left[-\left(\frac{E-\xi_a|q_a\phi_0|}{\alpha'_a q_a\phi_0}\right)^2 - \left(\frac{L}{\beta_a L_0^a}\right)\right], \quad (1)$$

where subscript a represents particle species, *i.e.* deuteron, helium3 or electron, $\phi_0$ the grid voltage and $L_0^a = r_{cat}\sqrt{2m_a q_a \phi_0}$. By adjusting the $\alpha'_a$, $\beta_a$ and $\xi_a$ values, we can simulate the broadness of the distributions in the energy and angular momentum direction, and the position of energy peak. Throughout the calculations, $\alpha'_a = \alpha_a$ ($E < |q_a\phi_0|$) and $0.1(E \geq |q_a\phi_0|)$ are assumed. The $\alpha'_a$ and $\beta_a$ simulates the broadness of the ion/electron distribution toward energy and angular momentum directions. When $\alpha'_a$ ($\beta_a$) $\rightarrow 0$, the distribution function is close to the $\delta$-function. Small $\beta$ values represent the high-converged ion/electron distribution functions. On the contrary, when When $\alpha'_a$ ($\beta_a$) $\rightarrow \infty$ the ion/electron has uniform distribution in the energy (angular momentum) space. The $\xi_a$ represents the position of the energy peak of the distribution functions. When $\xi_a = 1$, ion/electron has a peak at the same energy as externally discharged potential energy.The $\alpha_a$, $\beta_a$ and $\xi_a$ are parameter with arbitrary values. The coefficient $c_a$ is determined so that the density at the cathode $n_a$ is equal to $n_a^{cat}$. In deuterium-helium-3 gas system, the ratio of hydrogen and a helium-3 at the cathode is assumed by $n_a^{cat} : n_{3He}^{cat} = 1 : \zeta$. In this paper, $\zeta = 1$ is assumed. Following Thorson's treatment [13,14], we relate $n_i^{cat}(= n_d^{cat} + n_{3He}^{cat})$ to the measured cathode current Imeas by

$$n_i^{cat} = \frac{1}{1-\gamma^2}\frac{1}{1+\delta}\frac{I_{meas}}{4\pi q_i r_{cat}^2\sqrt{2q_i\phi_0/m_i}}, \quad (2)$$

where $\gamma$ represents the transparency factor of the inner grid, [2] and $\delta$ is the number of secondary electrons emitted from the grid due to ion impact [14]. We consider the secondary electrons emitted from the cathode with low kinetic energy, $\phi_e = 5eV$. These electrons would pass through the core region only once, thus $n_e^{cat}$ is related to the measured cathode current $I_{meas}$ by

$$n_e^{cat} = \frac{k\delta}{1+\delta}\frac{I_{meas}}{4\pi e r_{cat}^2\sqrt{2e\phi_e/m_e}}, \quad (3)$$

where $k$ represents the rate of secondary electrons drawn inside the cathode, $k = 0.5$. The electrostatic potential structure can be determined by the Poisson equation:

$$\nabla^2\phi(r) = -\frac{q_i n_i(r) - q_e n_e(r)}{\varepsilon_0}. \quad (4)$$

By integrating eq. (1) using the initial potential structure, we obtain the radial profile of ion and electron densities. By substituting the obtained density profiles into eq. (4), we solve the Poisson equation and get the potential structure. This process is repeated until the calculation converges. From $f_a$ ($E$, $L$) and $\phi(r)$, the space-dependent deuteron velocity distribution function can be estimated. Using the velocity distribution function, the D(d,n)$^3$He($^3$He(d,p)$^4$He) fusion reaction rate coefficient is evaluated. Throughout the calculations the background deuterium (deuterium-herium-3) gas is assumed to be Maxwellian at 0.1 eV temperature, and background gas pressure is assumed to be 0.2 Pa.

## 3. Results and discussion

First, we calculate the proton (neutron) production rate by assuming that electrons have almost the same (or lower) convergence as (than) ions. In Fig. 1, the proton (neutron) production rate by $^3$He(d,p)$^4$He (D(d,n)$^3$He) fusion reactions in deuterium-helium-3 gas system is shown as a function of discharged voltage. The circles show the experimental data [15]. Here, $\alpha_i = \alpha_e = 0.1$, $\beta_i = \beta_e = 0.1$, $\xi_i = \xi_e = 1.0$ are assumed. The proton production rates in the experiment are about two times larger than the calculations in high voltage range. In the experiment, it has been reported that almost 50 % of protons are produced by fusion reactions between deuteron and grid-embedded herium-3 [16]; the calculation roughly agreed with the experiment. If we aim at more accurate comparison of the absolute values of the proton (neutron) production rate, more detailed information on the

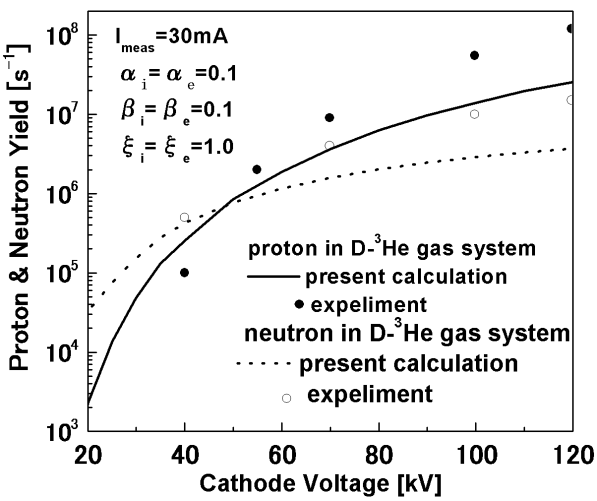


Fig. 1 The total proton (neutron) production rate by $^3$He(d,p)$^4$He fusion reactions for several $\gamma$ values, as a function of voltage.

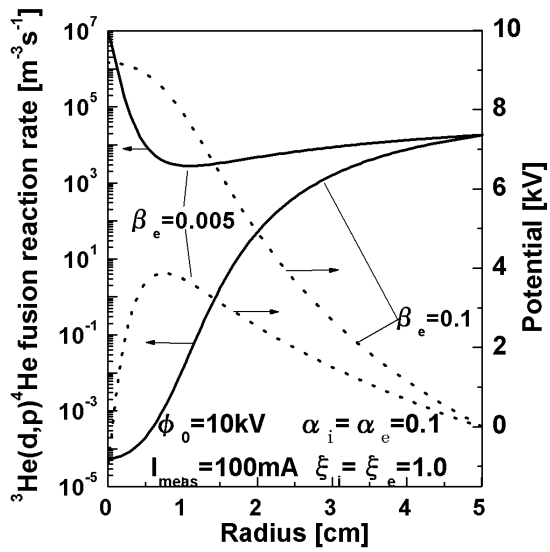


Fig. 2 Radial profile of potential and $^3$He(d,p)$^4$He fusion reactivity($\beta_e$ = 0.1 and 0.005).

device should be incorporated.

In Fig. 2, the radial profile of electrostatic potential and $^3$He(d,p)$^4$He fusion reaction rate in deuterium-helium-3 gas system are shown. The results when ion and electron have almost the same convergence ($\beta_i = \beta_e = 0.1$), and electron has higher convergence than ion ($\beta_i = 0.1$, $\beta_e = 0.005$) are presented. The grid voltage is taken as $\phi_0 = 10$ kV, the cathode current is $I_{meas} = 100$ mA. Here, $\alpha_i = \alpha_e = 0.1$, $\xi_i = \xi_e = 1.0$ are assumed. When the electrons convergence is higher than (same as) ions, the potential decreases (increases) in the central core region. In this case, ions are accelerated (slowed down), and the proton/neutron production rate from the central core region increases (decreases). In this case, a contribution of the protons/neutrons produced in the central core region to the total proton/neutron production rate becomes large (small).

In the previous PIC simulation [7], it has been revealed that the potential frequently oscillates, and in the oscillation deep potential well appears at the center of the sphere, which implies existence of the energetic and highly-converged electrons. To reproduce such a potential structure, we assume shape of the distribution function by using the parameters $\beta_e > \beta_i$, $\xi_i = 0.5$, $\xi_e = 1.5$. In Fig. 3, the proton production rates in deuterium-helium-3 gas system are plotted as a function of the discharged current for several $\beta_e$ values. For small $\beta_e$ values, the electrons strongly concentrate in the central core region, and the potential decreases. The $^3$He(d,p)$^4$He fusion cross section rapidly increases with increasing relative energy. If a deep potential well is formed at the center core region, the proton production rate can increase proportional to more than a power of the discharged current even if the fusion between beam-ion and background gas.

In Fig. 4, the dependence of the proton/neutron production rates on discharged current are compared between D-$^3$He and D-gas systems. In the calculation, same parameters as Fig. 3 are assumed. It is found that when the external voltage $\phi_0$ increases, the $I^2$-scaling becomes small. This is because in high energy region, degree of the increment in the $^3$He(d,p)$^4$He/D(d,n)$^3$He fusion cross-section with increasing relative velocity becomes small. It is also well known that in high energy range the $^3$He(d,p)$^4$He fusion cross section increases more rapidly than the D(d,n)$^3$He one with increasing relative speed. The proton production rate in D-$^3$He-gas systems can hence increase in proportion to more than a power of the discharged current more easily for higher discharged voltage than that in the D-gas systems.

In this paper, the ion/electron distribution function is

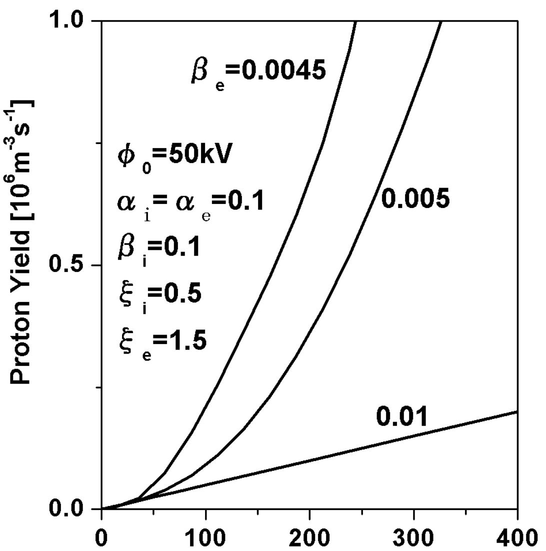


Fig. 3 The total proton production rate as a function of the discharged current for several $\beta_e$

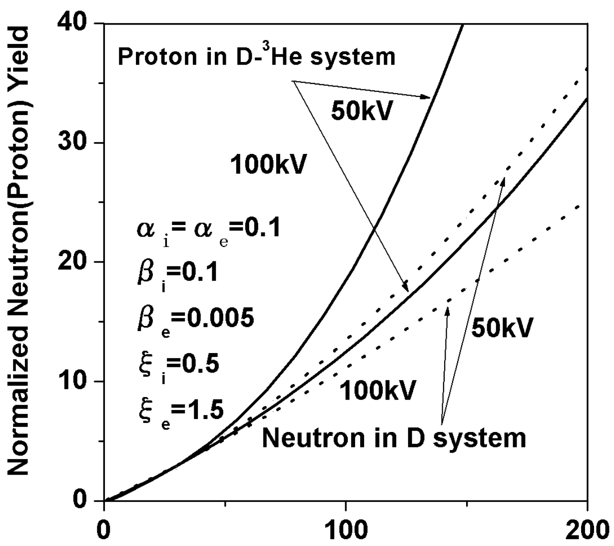


Fig. 4 The proton (neutron) production rate normalized with the value of $I_{meas}$ = 10 mA for $\phi_0$ = 50 kV and 100 kV

given by using arbitrary parameters, *i.e.* $\alpha_a$, $\beta_a$, $\xi_a$ and, the $I^2$-scaling of proton/neutron production rate is examined for various ion/electron distribution function. In order to know how the fuel-ion distribution function in laboratory SIEC devices is influenced by the device parameters, grid current and grid voltage, the Fokker-Plank analysis would be an effective numerical approach. By coupling the present treatment with the kinetic simulation considering the interaction between ions and electrons via variation of the electrostatic potential, more detailed dynamics of SIEC plasmas can be clarified.

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