

# Monte-Carlo Simulation of Dissipation Processes in Ion Beam Plasma<sup>\*)</sup>

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This study particularly focuses on the dissipation processes of trapped ion beams such as deceleration and diffusion, which are caused by Coulomb binary collisions. It demonstrated that collisions in ions or low-temperature electrons have major influences on ion beams. Beam convergence was improved by applying a magnetic field. To assess the medical applicability of our neutron source, a combined Monte-Carlo simulation with Diffusion-Reaction model was employed to evaluate the available neutron yield for the Boron Neutron Capture Therapy (BNCT) neutron source under the beam diffusion conditions. The paper found that the proposed electrostatic trap of deuterium beam ions could provide sufficient neutron generation for the therapy.

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## 1. Introduction

Momota *et al.* [1] suggested an idea that ion sources are opposed to each other and the extraction electrode is used as an electrostatic trap. Here deuterium ions are withdrawn at a voltage of about 30 kV and electrostatically trapped in the reaction vessel by the solenoid magnetic field and the potential gap. If the confinement time of the deuterium beam reciprocating between the potentials is sufficiently long, then, the beam ion density in the reaction vessel will gradually increase and the D-D fusion reaction rate can be improved. The idea is to apply 2.45 MeV neutrons to Boron Neutron Capture Therapy (BNCT) [2] for use in advanced cancer radiotherapy.

There are several issues to examine in the development of electrostatic traps. The first is the stability of the beam plasma in the trap. Since a plasma consists of opposing beams, the occurrence of two stream instability causes the beam component to disappear [3], with a consequentially significant reduction in the nuclear reaction rate. Moreover, since the beam plasma is a linear plasma, its macroscopic structural change [4] needs to be investigated.

The second issue is on the attenuation and diffusion of the beam plasma due to Coulomb collision aside from pulling out and confining the beam in the electrostatic trapping reaction vessel, it must also be supplied with electrons to satisfy the electrical neutrality condition. When the electron temperature is low, a large frictional force acts with the beam ions causing them to decelerate significantly

and instigate a decline in the nuclear fusion reaction rate. In addition, Coulomb collision between the beam ions may cause the beam to diffuse radially to the reaction vessel and suffer a trajectory loss.

This research aims to clarify the influence of Coulomb collision on the beam ions confined in the solenoid coil, through the Monte-Carlo numerical simulation. We employed the Diffusion-Reaction model to Monte-Carlo method to demonstrate the availability of BNCT concept as an initial step.

## 2. Methods

The Monte-Carlo collision simulation approach microscopically calculates the interaction among the deuterium ion beam and the background particles. Relatively, the Diffusion-Reaction model macroscopically computes neutron yield from the neutron source reactor by taking into account a D-D reaction cross-section.

### 2.1 Collision model

The reaction vessel of the proposed BNCT neutron source is cylindrical in structure. We injected reciprocating deuterium ion beams from both sides of the reactor with 30-keV beam energy. The solenoid coil, whose location is assumed outside of the device, generates magnetic fields in the reactor to improve beam convergence. Inside the reactor, a Coulomb binary collision interactively occurs between an injected deuterium ion beam and the background ions or electrons, as shown in Fig. 1. From the figure, the simulation only considers a unidirectional beam with a uniformly distributed external magnetic field along

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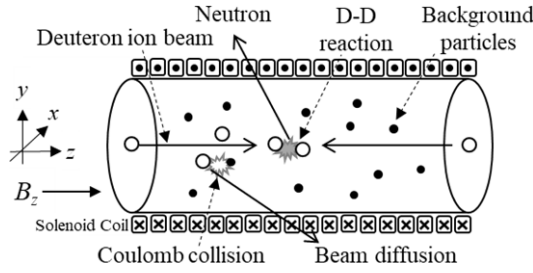


Fig. 1 Schematic diagram of beam collisions in the proposed reaction vessel.

the  $z$ -direction.

At the initial stage of the simulation, we employed the collision model to calculate the trajectory of a deuterium ion and an electron under the external magnetic field with the Adams-Bashforth method:

$$\frac{d\mathbf{v}}{dt} = \frac{q}{m}(\mathbf{v} \times \mathbf{B}), \quad (1)$$

where  $m$ ,  $q$ , and  $\mathbf{v}$  are the mass, charge, and velocity of ions or electrons and  $\mathbf{B}$  is the magnetic field. We did not include electric field computations at this stage yet.

Coulomb collision is numerically computed through the Monte-Carlo binary collision model proposed by T. Takizuka and H. Abe in 1977 [5]. This model makes use of randomly chosen particle pairs to cause binary collision. The scattering angle is sampled randomly with a Gaussian random variable to set post-collisional velocities. Wall interaction and reflection are ignored.

At the next stage, we evaluated the dissipation processes of the deuterium beam. The above-mentioned methods calculate beam diffusion causing the interaction of the deuterium ion beam and the background particles in the reactor. We examined the effect of suppressing loss ion beam processes by the axial magnetic field  $B_z$  to determine the diffusion coefficient [6]. Here, we employed the three-dimensional (3D) Cartesian coordinates, and used two types of background particles, deuterium ions that cause an ion-ion collision and electrons that cause an ion-electron collision. Table 1 lists some parameters used for the simulation.

## 2.2 Diffusion-Reaction model

As discussed in the preceding section, we obtained the diffusion coefficient values of the deuterium ion beams through the combination of the Monte-Carlo collision model and trajectory and binary collision calculations. We applied these values in the Diffusion-Reaction model to comprehensively estimate the relationship between beam dissipations and neutron generation from the reactor. Hence, we used the diffusion equation of the deuterium ions:

$$\frac{dn_i}{dt} = D\nabla^2 n_i + S - L, \quad (2)$$

Table 1 Collision model parameters.

Calculation region	$X = -0.25$ to $0.25$ [m] $Y = -0.25$ to $0.25$ [m] $Z = -1.0$ to $1.0$ [m]
Deuteron ion beam energy	30 [keV]
Number of beam ions	500
Number of background particles	500
Temperature of background particles	100 [eV]
Axial magnetic fields	$B_z = 0.1, 0.5, 1.0, 5.0$ [T]

where  $n_i$  is deuterium ion density,  $D$  is the diffusion coefficient from the collision model,  $S$  is supplies per unit time, and  $L$  is loss per unit time. In the reaction vessel,  $S$  consists of the injected deuterium ion beam and  $L$  is the loss from the D-D fusion reaction.  $S$  and  $L$  are expressed as:

$$S = \frac{I}{4\pi e \ell \sigma_b^2} \exp\left(-\frac{r^2}{2\sigma_b^2}\right), \quad (3)$$

$$L = \frac{1}{2} \sigma_{D-D} v_i n_i^2, \quad (4)$$

where  $r$  is the distance from the center of the beam,  $I$  is the beam current,  $\sigma_b$  is the beam variance,  $\ell$  is the half-length of the confinement vessel, and  $e$  is the elementary charge. The 30-keV opposed deuterium ion beams inside the reactor cause a D-D fusion reaction. The beam has a radially symmetrical Gaussian distribution, which is small enough for the device radius. Thus, it is possible to use  $\sigma_{D-D}$  (60 [keV]) as the fusion cross-section when assuming a head-on collision and a homogeneous particle. The expression  $v_i$  in Eq. (4) is the average velocity of ions calculated as relative velocity using

$$v_i = 2\sqrt{\frac{2E}{m_i}}, \quad (5)$$

where  $E = 30$  [keV] is the beam energy and  $m_i$  is the mass of a deuterium ion.

Figure 2 gives the layout of the model's circular calculation area, which is the mid-plane of the reactor. The model uses 3D cylindrical coordinates system assuming symmetry in both axial and circumferential directions. The Successive Over-Relaxation (SOR) method is used to solve the equations.

To obtain the steady state when the beam supply and the loss components are balanced, we assumed

$$\frac{dn_i}{dt} = 0, \quad (6)$$

on the equation, and then computed the proper deuterium

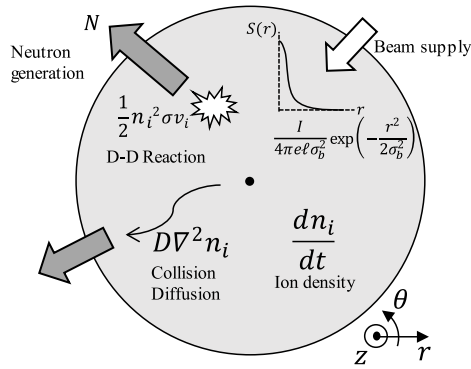


Fig. 2 Schematic diagram supply-loss balance inside the reactor.

Table 2 Diffusion-Reaction model parameters.

Calculation region	$r = 0.0$ to $0.25$ [m]
D-D cross section	$\sigma_{D-D} = 4.0 \times 10^{-30}$ [m <sup>2</sup> ]
Beam currents	$I = 10^{-6}$ to $10^0$ [A]
Beam variance	$\sigma_b = 5.0 \times 10^{-3}$ [m]
Diffusion coefficients	$D = 10^{-2}$ to $10^1$ [m <sup>2</sup> s <sup>-1</sup> ]

ion beam current and the neutron yield. Table 2 lists the detailed calculation parameters.

### 3. Results and Discussion

#### 3.1 Collision model

The collision model simulates for 1,000 time steps which is equivalent to  $20.9 \mu\text{s}$  in real time. Figure 3 indicates the appearance of the diffusion at 1,000 step in  $B_z = 1.0$  [T] in case of an ion-ion collision and an ion-electron collision. The initial beam position is  $(x, y) = (0, 0)$  at 0 step. From Fig. 3, the diffusion for an ion-ion collision is larger than for the ion-electron collision. This implies that the opposite ion beams, residual ions, and neutral gases in the reactor have non-negligible influence on beam convergence, consequently leading to a performance decrement of the neutron yield.

Figure 4 plots the dependence of the diffusion coefficients ( $D$ ) of the beam as a function of the axial magnetic field. From the figure, the  $D$  for the ion-ion collision is higher than for the ion-electron collision. Furthermore,  $D$  decreases with increasing magnetic field. Our results indicate that  $D$  is almost proportional to  $B_z^{-2}$ , which agrees with the theoretical estimation [6].

Figure 5 plots the relaxation of the beam velocity, calculated at  $B_z = 1.0$  [T]. The quantity  $v_0$  is the initial deuterium ion beam velocity at 30 keV. An ion-electron collision

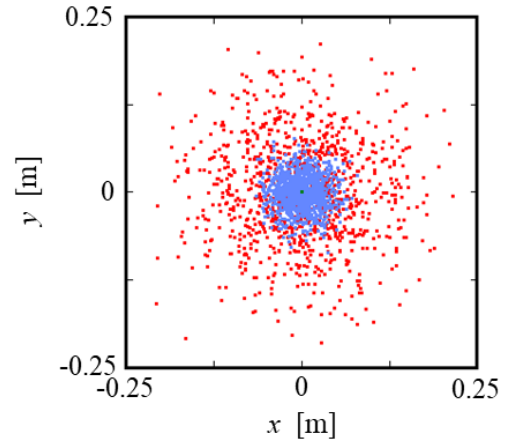


Fig. 3 Beam diffusions (Red points: ion-ion collision, Blue points: ion-electron collision).

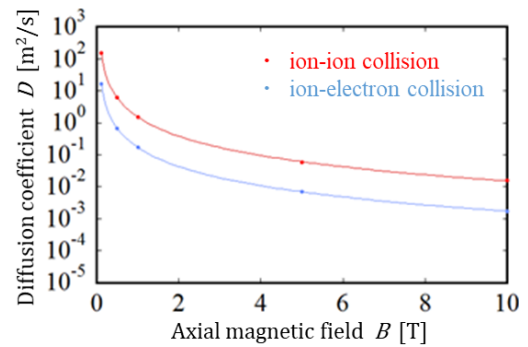


Fig. 4 Diffusion coefficient in magnetic fields.

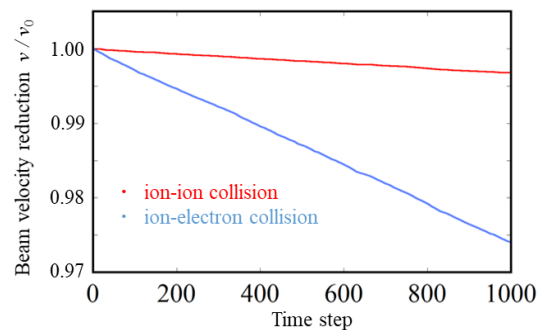


Fig. 5 Beam velocity relaxations.

sion has a large impact on the beam speed than an ion-ion collision does. The resulting beam deceleration prevents D-D fusion reaction. Thus, it is suggested that electrons heating in the reaction vessel is necessary to suppress their interplays.

#### 3.2 Diffusion-Reaction model

Figures 6 and 7 plot the results of the Diffusion-Reaction model. Diffusion coefficients are adopted from Table 2 in consideration of Fig. 4. Figure 6 presents the

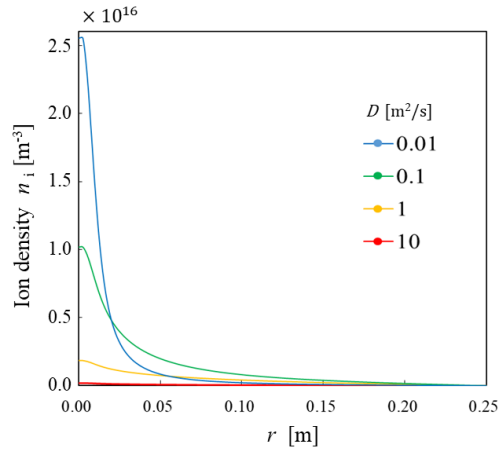
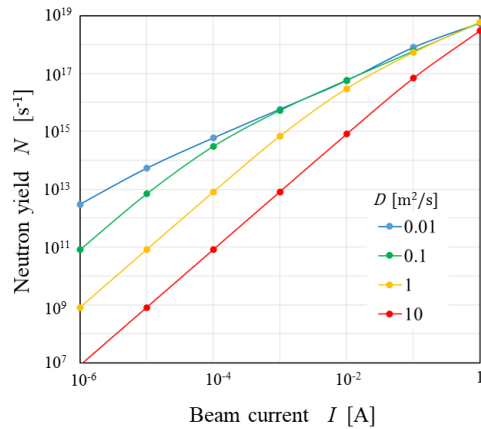

 Fig. 6 Ion density in diffusions at  $I = 1.0$  [mA].


Fig. 7 Neutron generation rate for beam current.

deuterium ion density along the radial direction at the steady state when beam current is 1.0 mA. An increase in beam diffusion causes the decrease in ion density near the center. Simultaneously, beam dissipation and ion flow into the reactor wall are massive, which could cause serious damage to the reactor wall.

Figure 7 plots the neutron yield per unit time from the whole reactor. Neutron yield  $N$  is calculated from the volume integral of the loss term  $L$ :

$$N = \int_V \frac{1}{2} n_i^2 \sigma_{D-D} v_i dV. \quad (7)$$

The impact of beam diffusion on neutron generation expands when beam current is low. Thus, beam dissipation control is very important when improving neutron yield for relatively small beam current.

A neutron flux of  $10^9 \text{ cm}^{-2} \text{ s}^{-1}$  at the patient position is said to be a requirement for the therapy [7]. Although

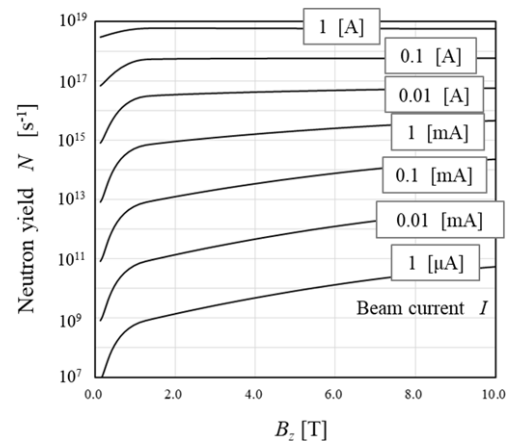


Fig. 8 Neutron generation rate for the axial magnetic field.

our system emits neutrons isotropically, once its external mechanism collects them or irradiates part of them to the patient, it is possible to obtain the available neutron amount at a beam current of approximately over 1.0 mA.

In other words, there is a possibility that the neutron source is usable for the BNCT by the deuterium ion beam of 30-keV energy and a current in the order milli-ampere. In addition, from Fig. 8, the axial magnetic field will have little influence on the neutron yield when its value goes over 2.0 T.

Thus, external magnetic fields should be adequately applied to obtain as much neutron as necessary, aside from its use in reactor wall protection and suppression of other beam plasma instabilities. Moreover, to understand the configurations of the beam plasma it is necessary for the simulation model to calculate the collision and reaction of each particle in detail.

## 4. Summary

We have validated the feasibility of the proposed nuclear-fusion-reaction neutron source for BNCT by a conventional ion source. We have also clarified the importance of electron temperature and external magnetic field in the process of improving the efficiency of the neutron generation.

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