Prediction of Neutron Emission Rate in Deuterium Neutral Beam Heated CFQS Plasmas Using FIT3D-DD Code*)

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FIT3D-DD code, which is a neutron emission and heating efficiency evaluation code based on a simple analytical solution of the Fokker-Planck equation, was applied to deuterium Chinese first quasi-axisymmetric stellarator (CFQS) plasmas heated by a deuterium neutral beam injector. A database of the neutron emission rate due to the beam-bulk D-D fusion reaction in the CFQS was created with the electron temperature and density, which were evaluated from the energy confinement time using ISS04 scaling. The neutron emission rate increases monotonically with the increase in the electron temperature and density. The neutron emission rate is expected to be up to $\sim 2.7 \times 10^{12}$ [n/s] for an electron density of less than 4×10^{19} m^{-3}.

Keywords: quasi-axisymmetric stellarator, CFQS, prediction of neutron emission rate, a simple Fokker-Planck code, FIT3D-DD

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1. Introduction

The construction of the Chinese first quasi-axisymmetric stellarator (CFQS), which is a quasi-axisymmetric stellarator, has progressed with the collaboration between the National Institute for Fusion Science and Southwest Jiaotong University [1]. To obtain high plasma parameters and to study the fast ion confinement in the quasi-axisymmetric configuration, the installation of a neutral beam injector (NBI) is planned in the CFQS [2, 3]. A feasibility study of the hydrogen NBI of the CFQS was reported by means of the beam deposition calculation code and guiding center orbit-following code [4].

In the CFQS, deuterium plasma experiments will be one of the strategic options to investigate the isotope effects and/or physics-related energetic particles. In deuterium experiments, 2.45 MeV neutrons are generated by nuclear fusion reactions between thermal, beam deuteron-thermal deuteron, and beam deuterons. In NBI-heated CFQS plasmas, the neutron emission due to the beam-thermal reaction is expected to be the main component because the injection energy of the NBI is much higher than the expected ion temperature and only one tangential NBI is planned. Thus, the neutron emission rate reflects the global confinement of beam ions. Thus, the global beam ion confinement can be experimentally studied by comparing the experimentally determined neutron emission rate and that calculated by the analytical Fokker-Planck code, as performed in the Large Helical Device (LHD) [5]. Additionally, the prediction of the neutron emission rate is important for radiation management for deuterium plasmas. Therefore, a neutron emission rate database should be created to plan for the deuterium experiment.

In this study, FIT3D-DD code [5,6], which is based on the simple analytical solution of the Fokker-Planck equation, was applied to evaluate the neutron emission rate and the heating efficiency in deuterium CFQS plasmas at various temperature and density ranges. A neutron emission rate database for the CFQS was constructed, and the maximum neutron emission rate was predicted.

2. Neutron Emission Rate Evaluation Code: FIT3D-DD

A neutron emission evaluation code, FIT3D-DD, was developed from FIT3D code. FIT3D-DD was implemented to evaluate the neutron emission rate in LHD experiments. The FIT3D code [6] is the heating power profile and beam-ion pressure evaluation code according to the simple analytical solution of the Fokker-Planck equation. The code was constructed using the combination of

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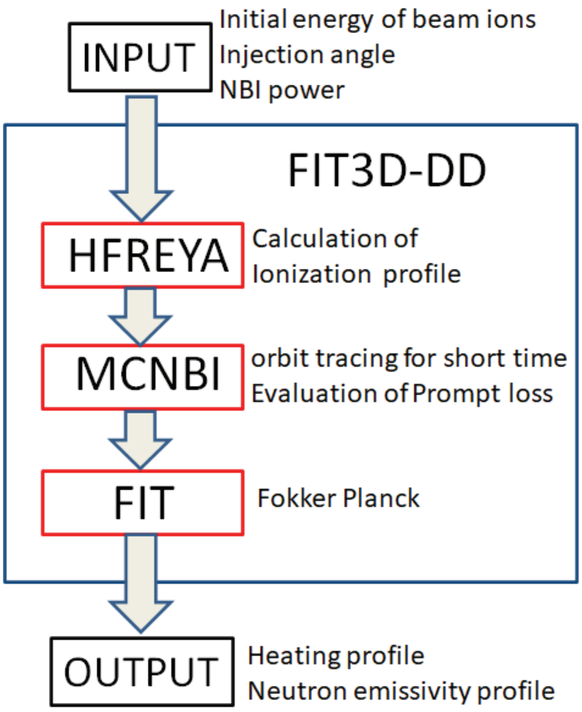

Fig. 1 Flowchart of the FIT3D-DD code.

the HFREYA, MCNBI, and FIT codes (Fig. 1).

The HFREYA code calculates the ionization profile of the NBI using the Monte Carlo method. In the HFREYA code, the position and simple shape of the ion source of NBIs and the focus position of the beam lines are considered. The large number of fast neutral particles are traced from the ion source to the vacuum vessel by using a random number and the cross section of beam ionization, including charge exchange, ion stripping, and electron stripping reactions. As a result, the ionization points of the beam-ions can be calculated. The cross section fit by Suzuki *et al.* [7] was introduced into the HFREYA code by P. Vincenzi for application to LHD deuterium experiments [8].

The MCNBI code is an orbit tracing code with a guiding center equation in the Boozer coordinates. In the MCNBI code, many beam ions are traced from the ionization points for a short time (20 µs) without considering the Coulomb collision or the charge exchange reaction. As a result of the short orbit tracing, the deposition profile, including the prompt loss and the initial orbit width is obtained.

The FIT code evaluates the heating power profile and the beam ion pressure by using the simple analytical solution of the Fokker-Planck equation. In the FIT3D-DD, the neutron emission rate in the plasma volume (ΔV) can be evaluated with the power density of the beam ions (w_{dep}) as follows.

$$\Delta R_{neut} = \Delta V \frac{w_{dep}\tau_s}{E_0} \int_{v_{th}}^{v_{f0}} \int \sigma_{dd} |v_{i\_th} - v_f| \times n_d f_{Maxwell}(v_{i\_th}) \mathrm{d}v_{i\_th} \frac{v_f^2}{v_f^3 + v_c^3} \mathrm{d}v_f. \quad (1)$$

Here, σ_{dd} is the cross section of the D-D fusion reaction described in Ref. [9]. Additionally, E_0 is the initial energy of the beam ions. v_{f0} and v_{th} are the initial velocities of the beam ions and the velocity of the thermal ions, respectively. $v_c = \sqrt{2E_c/m_f}$, E_c is the critical energy, and m_f is the mass of the beam ions. The critical energy can be calculated by

$$E_c\,[\mathrm{keV}] = T_e\,[\mathrm{keV}] \left(\frac{9\pi}{16}\frac{m_f}{me}\right)^{1/3} \left(\frac{m_f}{m_p} Z_1\right)^{2/3}, \quad (2)$$

and

$$Z_1 = \sum_i \frac{z_i^2 n_i}{A_i n_e}, \quad (3)$$

where m_e and m_p represent the masses of the electrons and protons, respectively. T_e is the electron temperature, and n_e and n_i are electron and ion densities. Z_i and A_i denote the ion charge and mass number, respectively. The slowing down time is expressed by

$$\tau_s = 0.12 \frac{T_e\,[\mathrm{keV}]^{3/2}}{z_f^2 n_e [10^{19}\,\mathrm{m}^{-3}]} \frac{m_f}{m_p}, \quad (4)$$

where Z_f is the charge of fast ions. In the FIT3D-DD, the cross section is calculated with the relative speed between bulk deuteron and beam deuteron.

3. Prediction of the Neutron Emission Rate by Using FIT3D-DD

A tangential NBI will be installed in the CFQS. In the prediction calculation of the neutron emission rate, the injection angle of the tangential NBI, which is shown in Fig. 2, was set to be 48 degrees which was shown to be a more favorable injection angle regarding deposition and beam ion confinement in a feasibility study of hydrogen NBI [4]. The injection energy of the D-NBI was set to 30 keV, which is the same as the injection energy of the H-NBI planned in the CFQS. The injection power (P_{inj}) was 0.9 MW.

Figure 3 shows the neutron emission rate database for the CFQS plasma. In this database, the vacuum magnetic field, whose major radius and minor radius are 1.0 m and 0.25 m, respectively, is used. The vacuum field is the same as that in Ref. [4]. In the magnetic configuration, the field strength was set to be 1.0 T. Pure deuterium plasma is assumed. The temperature and density profiles are given by

$$T_e = T_0(1 - \rho^2), [T_0 = 0.25, \cdots, 4\,\mathrm{keV}], \quad (5)$$

and

$$n_{e,i} = n_0(1 - \rho^2), [n_0 = 0.25, \cdots, 4 \times 10^{19}\,\mathrm{m}^{-3}]. \quad (6)$$

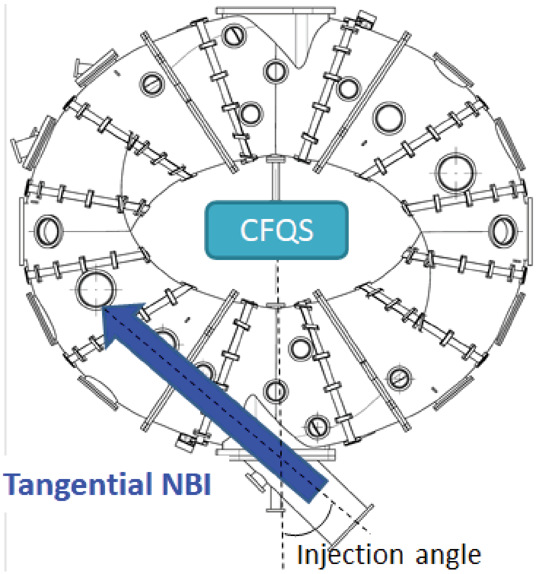

Fig. 2 Top view of CFQS and injection angle of tangential NBI.

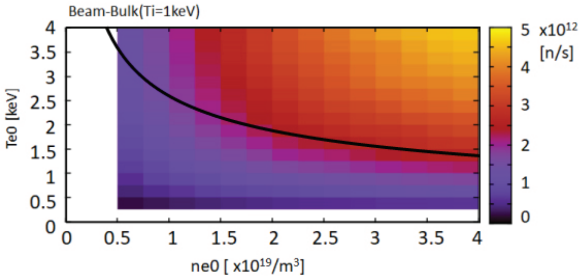

Fig. 3 Database of the neutron emission rate in the CFQS plasma. The horizontal axis shows the central electron density, and the vertical axis represents the central electron temperature. The colors represent the different neutron emission rates. The solid line represents the electron temperature and density evaluated from ISS04 scaling [10] of the energy confinement with the improved factor of 1.5.

As shown in Fig. 3, the neutron emission rate of beam-bulk D-D fusion increased with an increase in the electron temperature and density. The neutron emission rate was ~5×10^{12} [n/s] when the electron density was 4×10^{19} m^{-3} and the electron temperature was 4 keV.

Then, we roughly evaluated the neutron emission rate in the CFQS plasma by using ISS04 scaling [10] of the energy confinement time (τ_{iss04}), which is the international stellarator confinement database, and an assumption of the energy balance ($P_{\mathrm{inj}} = \int 3nT\mathrm{d}V/\tau_{\mathrm{iss04}}$). Because P_{inj} is the injection power of the NBI, the temperature evaluated by ISS04 was overestimated. On the line of the electron temperature and density that was evaluated from ISS04 scaling of the energy confinement with the improved factor of 1.5, the neutron emission rate becomes larger with a higher electron density. The neutron emission rate was up to ~2.7×10^{12} [n/s] in the database.

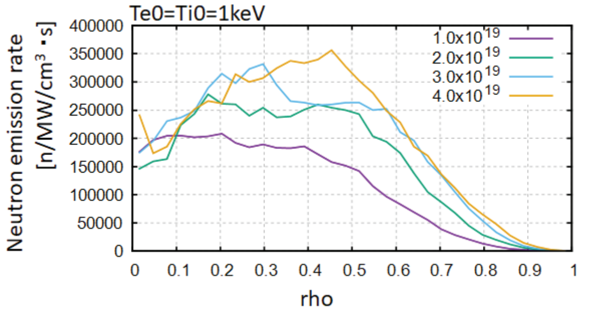

Fig. 4 Density dependence of the neutron emissivity profile when the center electron and ion temperatures were 1 keV. The purple, green, blue, and yellow lines correspond to central electron densities of 1.0, 2.0, 3.0, and 4.0×10^{19} m^{-3}, respectively.

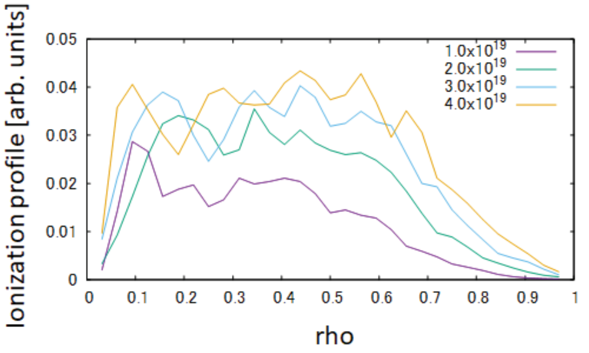

Fig. 5 Density dependence of the ionization profile when the center electron and ion temperatures were 1 keV. The purple, green, blue, and yellow lines correspond to central electron densities of 1.0, 2.0, 3.0, and 4.0×10^{19} m^{-3}, respectively.

Figure 4 shows the neutron emissivity profile with a change in the electron density when the center electron and ion temperatures were at 1 keV. As shown in Fig. 4, in the case of 1.0×10^{19} m^{-3}, the neutron emissivity has a peak near the plasma center. By increasing the density, the peak of neutron emissivity shifted to the outer region because the fast neutral particles injected by NBI tend to be ionized near the last closed flux surface when the density is higher (Fig. 5). When the electron density was 4×10^{19} m^{-3}, the neutron emission rate showed a peak at rho ~0.5.

4. Summary

The deuterium plasma experiment by using the deuterium-NBI will be one of the strategic options for the CFQS. FIT3D-DD code, which is a neutron emission and heating efficiency evaluation code based on the simple analytical solution of the Fokker-Planck equation, was applied to evaluate the neutron emission rate of the beam-bulk D-D fusion reaction in deuterium CFQS plasmas.

The neutron emission rate database for CFQS shows that the neutron emission rate of beam-bulk D-D fusion reaction increased with increases in the electron temperature and density. The peak of the neutron emission rate profile shifted to the outer region by increasing the density. The neutron emission rate was up to $\sim 2.7 \times 10^{12}$ [n/s] in the range of the electron temperature and density evaluated from the ISS04 scaling of energy confinement in the database.

Acknowledgments

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