Feasibility Study of Deuterium-Deuterium Fusion Profile Diagnostics Using Fusion Born 3 MeV Proton for CFQS*)

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A feasibility study for measuring a deuterium-deuterium (D-D) fusion reaction radial profile by promptly lost D-D fusion born 3 MeV protons, whose energy Larmor radius is the same as the minor radius of CFQS, was performed. The Lorentz orbit code was utilized to estimate the predicted signals of collimated proton detectors using the D-D fusion radial profile calculated by the analytical Fokker-Planck code for steady-state plasma FIT3D-DD code. The inversion of the D-D fusion profile using the estimated signals was performed using a linear matrix solution library. The coarse agreement between input and inverted profiles shows the possibility of D-D fusion profile diagnostics by a 3 MeV proton in CFQS.

Keywords: CFQS, fusion product diagnostics, fusion emission profile, deuterium plasma, energetic ion

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1. Introduction

The study of energetic ion transport/losses due to magnetic field ripples and fast-ion-driven magnetohydrodynamic instabilities is an important research subject in understanding deuterium-tritium fusion-born 3.5 MeV alpha particle transport/losses in a future fusion reactor [1]. Measurement of energetic ion distribution in the plasma core region is crucial in understanding energetic ion transport and excitation of magnetohydrodynamic instabilities. Under a joint project of the National Institute for Fusion Science and the Southwest Jiaotong University [2], construction of the world's first quasi-axisymmetric stellarator CFQS has begun, based on physics [3–7] and engineering design [8–13]. Energetic particle confinement experiments in a quasi-axisymmetric configuration will be possible using beam ions created by a tangential neutral beam injector in CFQS [14]. In the deuterium plasma experiment, which is one of the strategy candidates in CFQS, 3 MeV protons originate from deuterium-deuterium (D-D) reactions, primarily due to a so-called beam-plasma reaction. Therefore, 3 MeV proton emissivity reflects the information of beam deuterons confined in a plasma core region. The energy Larmor radius of the 3 MeV proton at a toroidal magnetic field strength B_t of CFQS 1 T is 0.25 m, the same as the minor radius a of a CFQS plasma. Therefore, the 3 MeV protons born in the plasma core region can be promptly lost on the vacuum vessel before a full gyro motion. Therefore, the inverse transformation of the D-D fusion profile is feasible, using the collimated proton detector array located on the vacuum vessel. The feasibility study of the D-D fusion profile using a collimated particle detector array was performed in NSTX (B_t = 0.3 T and $a \sim 0.68$ m) [15, 16]. Then the D-D fusion profile measurement was reported in MAST (B_t = 0.55 T and $a \sim 0.6$ m) [17]. These studies showed that the measurement is feasible where the Larmor radius is comparable with the minor radius of the plasma. In this study, the candidate location for a 3 MeV proton detector array suitable for inverse transformation of the D-D fusion profile is investigated in CFQS.

2. Setups for Calculation

For a feasibility study of the D-D profile measurement, e.g., the possibility of D-D fusion profile inversion by 3 MeV protons, was performed. Three-dimensional plasma equilibrium was reconstructed by the VMEC2000 code [18] with the fixed boundary mode. The analytical Fokker-Planck code for a steady-state plasma FIT3D-DD code [19, 20] was utilized to calculate the D-D fusion profile. In the FIT3D-DD calculation, a tangential deuterium

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beam was injected into pure deuterium plasma, e.g., the effective charge was set to be 1. The injection energy and the power of the neutral beam were set to be 30 keV and 1 MW, respectively. The plasma temperature and density were assumed to be a parabolic profile with a central electron temperature of 2 keV, a central deuteron temperature of 500 eV, and a central electron density of 10^{19} m^{-3}. The collisionless Larmor orbit following simulation in the Cartesian coordinates LORBIT code [21] was utilized to calculate 3 MeV proton orbits. In the LORBIT code, the equation of motion of a proton was solved using the sixth order Runge-Kutta method, using the magnetic field in a vacuum. The electrical field was excluded because the proton energy 3 MeV was significantly higher than the electrical potential formed inside a plasma ~ keV order. The toroidal magnetic field was directed to be counterclockwise from the top view. Figure 1 shows the candidate position of the 3 MeV proton detector array considered in this study. The detector location was set to be the lower side from the equatorial plane based on the Larmor motion of a proton. The location of the detector was selected to be (x, y, z) of (1.46 m, 0.05 m, −0.34 m). The detector axis was located on the x-y plane. A time-reversed collisionless Lorentz orbit of 3 MeV protons was calculated from the detector position. Therefore, the orbit trace of the proton inside the plasma could be found. Note that the time step was set to be 0.1 ns. The calculation was terminated when the proton hit the vacuum vessel. Finally, inversion of the D-D fusion profile was conducted by solving the linear matrix equation $\mathbf{b} = \mathbf{A}\mathbf{x}$, where $\mathbf{b}$, $\mathbf{A}$, and $\mathbf{x}$ represent the signal of the detector array, weight function, and D-D fusion profile, respectively.

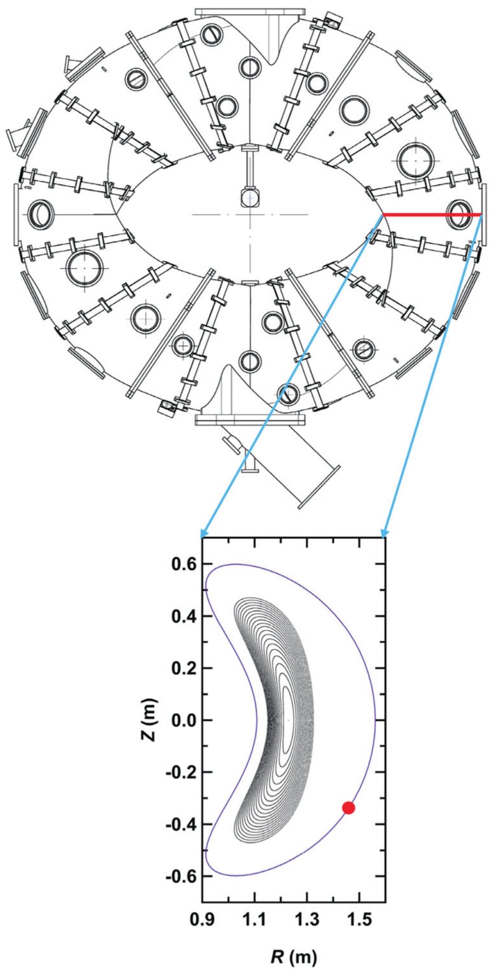

Fig. 1 (top) Top view of CFQS. (bottom) Poloidal cross section of CFQS. Purple line shows vacuum vessel. Red point shows candicate position of collimated proton detector array. Detector position located below midplane because proton Larmor motion directed counterclockwise.

3. Orbit Simulation Results

Figure 2 shows the 3 MeV proton emissivity calculated by the FIT3D-DD code. The total 3 MeV proton emission rate, almost the same as the 2.45 MeV neutron emission rate, is calculated to be 1.2×10^{12} s^{-1} [22]. The proton emission emissivity has a peaked profile with a central value of ~3.0×10^{11} m^{-3}s^{-1}. The proton emissivity becomes negligibly small at the plasma edge normalized minor radius $r/a > 0.8$. The peaked profile is formed because of the slowing down time (proportional to $T_e^{3/2}/n_e$) due to the parabolic electron temperature. The proton emissivity profile was fitted with a polynomial function of r/a in order to evaluate the signal in each proton detector.

In this study, the detector direction changes from 10 degrees to 50 degrees with five degree steps. Here, the angle starts from the negative x-axis. We assumed that the length of the collimator was long enough, e.g., the initial velocity of the proton was set to be parallel to the detector axis. The broadening of the proton velocity affects the fineness of the inverted D-D fusion profile. Therefore, the inverted D-D fusion profile shown in this study is expected in the ideal case. The broadening effect will be evaluated in the actual design phase. Figure 3 shows time-reversed orbits calculated by the LORBIT code. The initial pitch

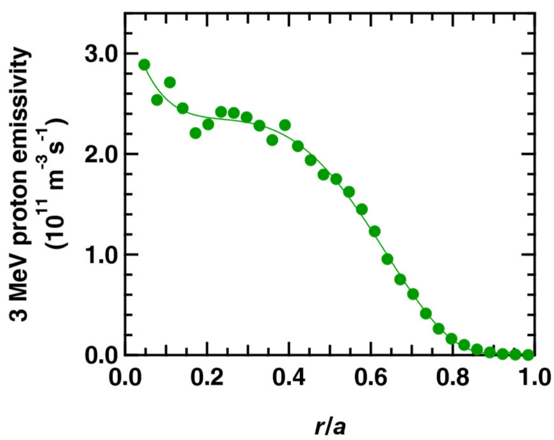

Fig. 2 3 MeV proton orbit emissivity calculated by FIT3D-DD code.

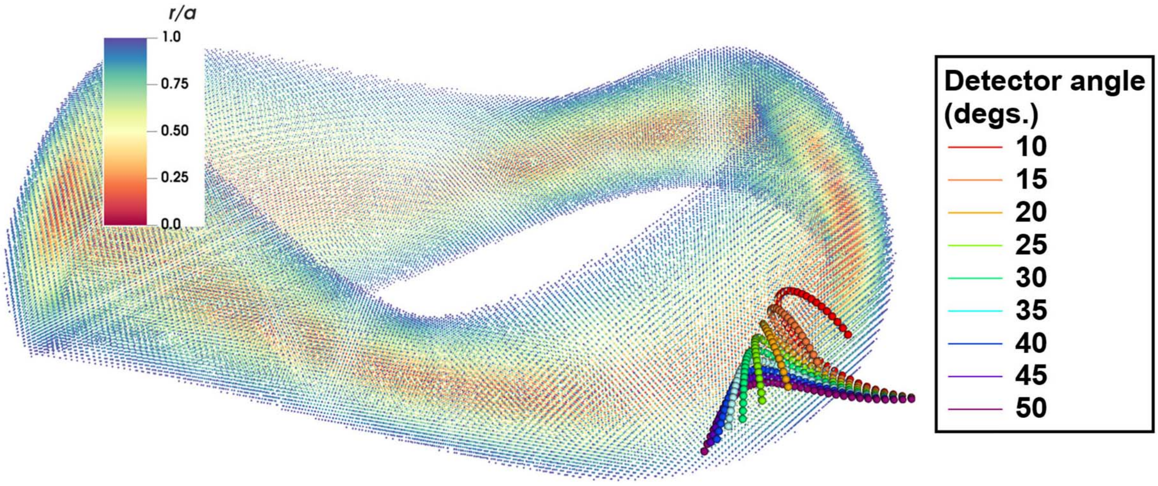

Fig. 3 Time-reversed 3 MeV proton orbits from detector position.

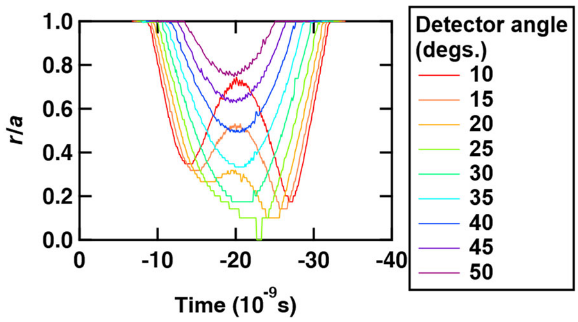

Fig. 4 Time trace of normalized minor radius position of 3 MeV protons. Points located at r/a less than one plotted.

angles at the detector angle of 10, 15, 20, 25, 30, 35, 40, 45, and 50 degrees are 73, 68, 64, 60, 57, 53, 51, 48, and 46 degrees, respectively. The sphere points represent the orbit and the color of dots forming the plasma shape corresponds to the r/a value. The endpoint of the sphere corresponds to the hit position on the vacuum vessel. All protons reach the vacuum vessel before one gyromotion. Figure 4 shows r/a along the proton orbit. Here points located at r/a less than one, e.g. inside the plasma boundary, are plotted. Time equal to zero corresponds to the detector position. 3 MeV protons escape from the plasma within 40 ns. The orbits with a detector angle greater than or equal to 25 degrees have a single peak, whereas the orbits with detector angles smaller than 25 degrees have two peaks. The reason for having two peaks is that the orbit goes into the inboard side of the plasma.

4. Inversion of DD Fusion Profile

The signal vector **b** having nine components was calculated by integrating the 3 MeV proton emissivity along the proton orbit. Figure 5 top shows the expected relative signal intensity of each detector. A peaked profile was obtained. The relatively intense signal is expected in a 20 degree case, whereas almost no signal is expected in

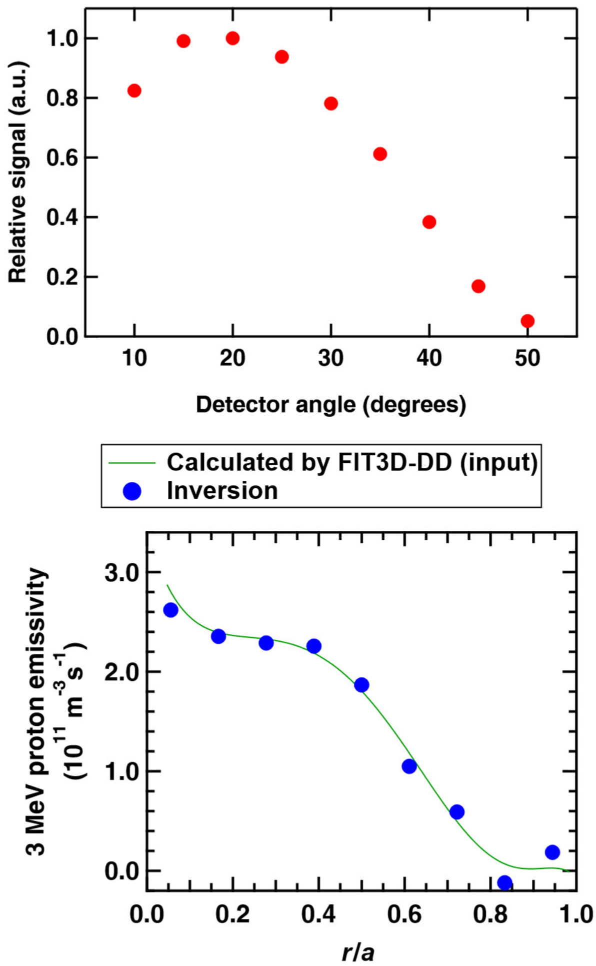

Fig. 5 (top) Signal intensity profile for proton detector array. (bottom) 3 MeV proton emissivity calculated by FIT3D-DD code (input) and inversed profile from calculated detector signals. Inverted profile almost agrees with input profile.

a 50 degree case. The weight function **A** was calculated by making a histogram of dwell time in each r/a. Here, for the radial grid, r/a from 0.1 to 1.0 is divided into nine regions. Therefore, the weight function **A** is a 9×9 matrix. An inversion of the D-D fusion profile was performed. The linear matrix equation $\mathbf{b} = \mathbf{Ax}$ was solved using the NumPy linear matrix solution library (linalg.solve 1.0.4) with python3.8.2. Figure 5 bottom shows the comparison of inversed D-D fusion profile to the input D-D profile. It is found that the inversed profile almost matches with the input profile, except for the edge region of the plasma, e.g. $r/a > 0.8$. One of the possibilities for the discrepancy of the profile at the edge region is that the 3 MeV proton emissivity there is at least one order smaller than the emissivity at the core region, e.g. $r/a < 0.4$. The limiting condition for the **x** value or the precision setting for solving the linear matrix equation is needed to obtain a better agreement of the profile inversion.

5. Summary

To understand energetic particle confinement in the quasi-axisymmetric configuration, a feasibility study of D-D fusion profile diagnostics, using fusion-born 3 MeV protons for CFQS, was performed using the Lorentz orbit code. Here, we consider using D-D born 3 MeV protons. The energy Larmor radius of the proton is comparable to the minor radius of the plasma. Therefore, the 3 MeV proton has a prompt loss orbit before one gyro motion. The feasibility study of a D-D fusion profile inversion, using 3 MeV detector signals, is performed by solving the linear matrix equation. The inversed profile almost matches the input profile, except for the plasma edge region. This study shows that D-D fusion profile measurement, which is the key for an energetic ion confinement study, is possible in CFQS.

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