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Evaluation of a Neutral Beam Injector in the spherical tokamak QUEST

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To support the study of next-generation commercial fusion reactors, **Q**-shu **U**niversity **E**xperiment with **S**teady-State Spherical **T**okamak (**QUEST**) plans to confine high-temperature and high-density plasma in tokamak. It is necessary to install a neutral beam heating system, based on a **D**iagnostic **N**eutral **B**eam Injector (**DNB**) previously used on **C**ompact **H**elical **S**ystem (**CHS**)[1] in NIFS.

This **NB** injector ($E_b < 40\text{keV}, P{\sim}50\text{kW}$) was characterized by the narrower beam and lower power for NIFS **C**ompact **H**elical **S**ystem (**CHS**)[1]. **CHS** was a medium-sized helical device having a major radius of $R = 1m$ and average plasma minor radius $a{\sim}0.2\text{m}$, while **QUEST** has small size but larger poloidal plasma cross-section ($R = 0.64$ m, $a \sim 0.36$ m). Designed for long-term stable operation, $(B_t{\sim}0.25\,T, I_p{\sim}100kA)$ **QUEST** achieved Plasma duration for more than 6 hours[2]. The goal of the numerical simulation of the beam injection process in QUEST is to evaluate the feasibility of conducting heating experiments.

The equilibrium code is an independent code developed at QUEST, which is applicable to the equilibrium calculation of both free-boundaries and fixed-boundaries of general tokamak devices[3]. The QUEST steady-state plasma configuration is calculated by setting the plasma current $I_p = 100$ kA and the toroidal field coils current $TF_{coils} = 100$ kA, and the magnetic pressure grid is obtained. Thus, the normalized magnetic flux is constructed, and the magnetic field distribution can be calculated.

A beam of fast neutral atoms is trapped through the collision with the plasma background particles. The beam attenuation is governed by $I = I_0 e^{(-x/\lambda_b)}$. Where λ_b is beam average free path given by $\lambda = \frac{1}{\sigma n}$. The collision cross-section is denoted by σ, and the background particle density by n. To simplify the calculation, we take $n_e = n_i = n; T_e = T_i$. Thus, the attenuation distribution of the neutral beam along the injection path can be calculated using the given temperature and density distributions.

The Larmor radius of the of the produced fast ion can reach $0.1\,m$ in the low magnetic field of QUEST and it is not negligible compared to the scale length of the magnetic field. Thus, the trajectory calculation based on the guiding center orbit will cause errors. Therefore, the full-orbit calculation is used in this evaluation. This method is obtained by solving the equations of motion $m\frac{dv}{dt} = q(E + v \times B)$, using the fourth order Runge-Kutta-Gill method. Here, m is the ion mass, and v is the ion velocity.

The results show that the attenuation of the beam energy $E_b = 20$ keV is only 63% in the case that $n_e = 2 \times 10^{18}\ \text{m}^{-3}$. Further increasing the beam energy will cause excessive beam energy to penetrate the plasma, leading to losses to the wall of the vacuum vessel. This penetration can be effectively improved by increasing the central electron density of the plasma. It is found that for a plasma with an electron density $n_e = 2 \times 10^{19}\text{m}^{-3}$, the attenuation of the 20 keV beam energy can reach 100%.

And the results of the full-orbit calculations of fast ions show that the confinement for beam ions gradually deteriorates at the high-energy stage. This is mainly due to the larger Larmor radius of ions at high energies. By changing the injection angle to adjust the pitch angle between the ion's velocity and the magnetic field lines, the confinement effect can be effectively improved.

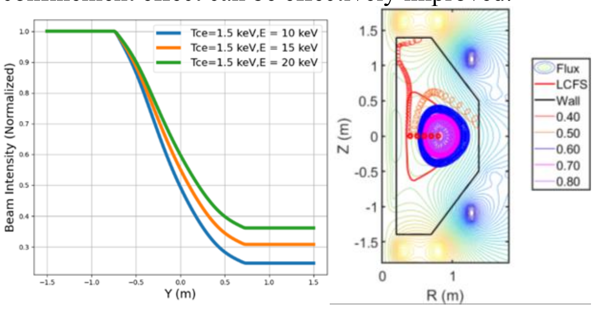

Figure 1. Left-hand side shows the beam intensity for various beam energy injected into the same plasma ($n_e = 2 \times 10^{18}\ m^{-3}; T_e{\sim}1.5keV$). Right-hand side shows the Full-Orbit calculations for 20keV Hydrogen ions in different initial points.

These calculations have been validated against established codes NUBEAM, showing good agreement. In the future, we will further calculate the fast ion slowing-down time to estimate the actual heating power. This work will continue to provide data for the design for QUEST-NBI.

References

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