Contribution of Beam-Driven Fusion in Pure Deuterium Plasma

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1. Introduction

The urgent and ultimate goal of the fusion research is to accomplish a fusion reactor functioning practically. Though the first fusion reactor is expected to use a DT fuel, most fusion researchers have studied H or D plasmas instead of DT plasma because of radioactivity and resource problems. DD plasma experiments, now a usual trend, can give useful information on the fusion plasma physics, tritium retention, alpha particle transport, neutronics, and so on at a safe controlled radiation level.

The KSTAR tokamak, all-superconductor world level fusion research device, has been operated with pure deuterium plasmas since the 2010 campaign, however, the thermal fusion reaction rate is still far below significant because of low plasma temperature.

The NBI system equipped on the KSTAR tokamak can deliver more than 1.5 MW input power of deuterium neutral beam at 100 keV with one ion source, which have contributed to making H-mode plasmas for several seconds. The next goal of the NBI input power at the 2012 campaign is 3.5 MW with two ion sources. Hot ions generated from the deuterium neutral beam injected into the D plasma can produce beam-driven fusion reactions at a much more notable level than thermal ones. Contribution of deuterium neutral beam injection on the fusion reactions in a D plasma is preliminarily assessed here

2. Simulation of Beam-driven Fusion

2.1 Beam-Target Fusion Reactivity

Various fusion reactions, in addition to DD, may occur even in a pure D plasma. There are five probable fusion reactions coming into existence in the pure deuterium experiment;

$D+D \rightarrow n(0.82)+{}^3He(2.45)$,
$D+D \rightarrow P(1.01)+T(3.03)$,
${}^3He+D \rightarrow P(3.67)+{}^4He(14.68)$,
$D+T \rightarrow n(3.5)+{}^4He(14.1)$,
$T+T \rightarrow 2n+{}^4He+11.34$.

All fusion cross-sections used in this simulation are expressed as formulas parameterized by Bosch[1] and Peres[2]. The beam-target reactivity $<\sigma v>_b$ is obtained as follows assuming a Maxwellian plasma and a mono-energetic beam [3], where v_b is the beam particle velocity and v_{th} is the thermal ion velocity.

$$\langle\sigma v\rangle_b = \frac{1}{v_b v_{th}\sqrt{\pi}}\int_0^\infty \sigma(v)v^2\left(e^{\frac{(v-v_b)^2}{v_{th}^2}} - e^{\frac{(v+v_b)^2}{v_{th}^2}}\right)dv$$

Fig. 1 is the graph of five major fusion cross-sections as a function of the beam energy, and Fig. 2 is the calculated beam-target fusion reactivity as a function of the plasma ion temperature at the beam energy of 120 keV.

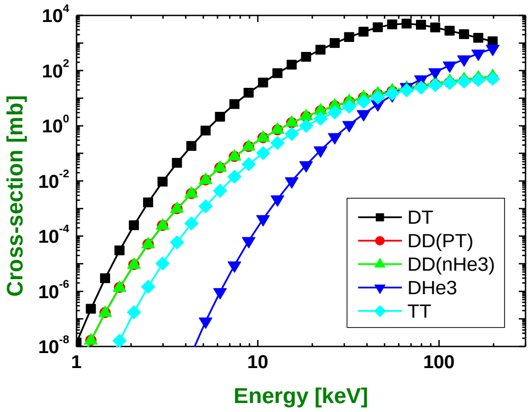

Fig. 1. Major fusion reaction cross-sections as a function of the beam energy, where the target is fixed.

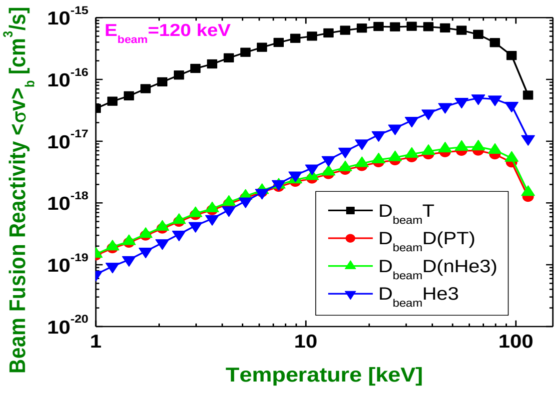

Fig. 2. The beam-target fusion reactivity as a function of the plasma ion (target) temperature at the fast ion (beam) energy of 120 keV.

2.2 Estimation of Neutron Generation Rate

The fusion reaction rate of deuterium neutral beams in the deuterium plasma can be approximately given by integrating the beam-target reactivity divided by the beam energy loss rate in the plasma over the fast ion energy from the initial injection energy to the thermalized one[4,5], where, n_F is the fuel particle density in the plasma.

$$R[\#/s\cdot cm^3] = (I_{NB}/eV_{plasma})n_F\int_{E_{b0}}^{E_{therm}}\langle\sigma v\rangle_b/(dE_b/dt)dE_b$$

Densities of fuel ion species are calculated by solving zero-D simultaneous particle balance equations. (refer to Fig. 3) Finally, the fusion reaction rate and the neutron generation rate per plasma volume for thermal and beam-target mechanisms are given.

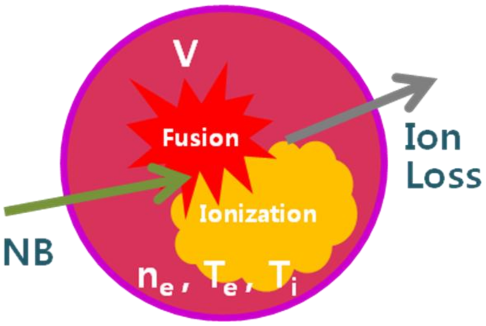

Fig. 3. Zero-D model for simulating beam-driven fusion reaction.

Fig. 4 shows the neutron generation rate obtained at 4 different beam and plasma conditions. The portion of the beam-driven fusion is higher than 99.9% and the neutron generation rate is in the 10^{14}/s/m^3 range when assuming the plasma temperature of 1~2 keV and the plasma density of 3~5x10^{13}/cm^3. For the case of a DT plasma and D beams at the same plasma condition, the neutron generation steps up about 100 times. If the plasma temperature increases to the 10 keV range, the portion of the thermal fusion becomes considerable even in the pure deuterium plasma. (refer to Fig. 4)

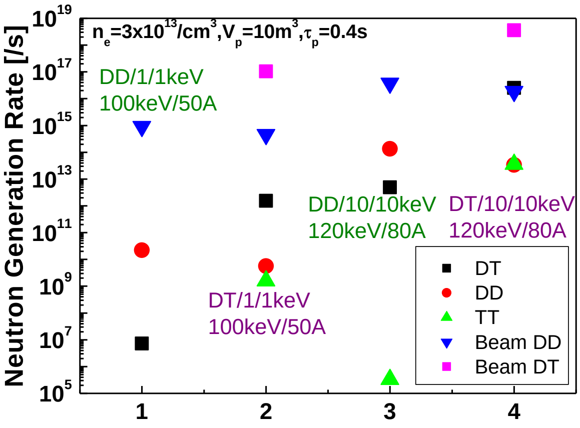

Fig. 4. The neutron generation rates from thermal and beam-driven fusion at different plasma conditions. Numerals on the x-axis represent case number.

3. Conclusions

An NBI system is equipped on the KSTAR tokamak to heat the plasma and drive the toroidal current. The NBI input power at the 2012 campaign is to be 3.5 MW at the beam energy of 100 keV with two ion sources. Hot ions generated from the deuterium neutral beam injected into the D plasma can produce beam-driven fusion reactions at a much higher level than thermal ones. More than 99.9% of the fusion reaction and neutron generation rates (10^{14}/s/m^3 range) are originated from the beam-driven fusion when assuming the plasma temperature of 1~2 keV and the plasma density of 3~5x10^{13}/cm^3.

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