Evaluation of beam-beam fusion reaction rate including local beam profile effect in tokamak plasma

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Introduction

- Many D-D fusion reaction experiments have been performed in tokamaks and helicals.
- D-D fusion reaction rate is used to evaluate energetic particle confinement.
- In many studies ,they use homogenious beam ions distribution to evaluate D-D fusion reaction rate and they dismiss local beam profile. Experimental results are different from simulation results.
- We consider D-D fusion reaction rate between energetic beam ions with local beam profile in tokamak.

Local beam profile effect

- We put energetic particles(deutriums) from NBI into the tokamak perpendicularly for the magnetic field, particles exchange their charges with bulk plasmas(deutriums) and they are locally trapped inside banana orbit by magnetic mirror effect.
- They distributed in a weak magnetic field side on the torus. Because of this, inhomogeneous distribution of D-D reaction rate between beam ions occurs.

Fusion reactivity

- Using Deutrium beam ion velocity distribution from GNET,we evaluate D-D fusion reactivity and neutron generating distribution from (n,^{3}He) reaction.

$$S_{\mathrm{th-th}} = \frac{1}{2} n_{\mathrm{D}}^2 \langle \sigma \nu \rangle_{\mathrm{DD,th-th}}$$

$$S_{\mathrm{b-th}} = n_{\mathrm{b}} n_{\mathrm{D}} \langle \sigma \nu \rangle_{\mathrm{DD,b-th}}$$

$$S_{\mathrm{b-b}} = \begin{cases} n_{\mathrm{bi}} n_{\mathrm{bj}} \langle \sigma \nu \rangle_{\mathrm{DD,b-b}} & (I \neq j) \\ \frac{1}{2} n_{\mathrm{bi}}^2 \langle \sigma \nu \rangle_{\mathrm{DD,b-b}} & (I = j) \end{cases}$$

$$\langle \sigma \nu \rangle_{\mathrm{DD,1-2}} = \int \int f_1(\mathbf{v}_1) f_2(\mathbf{v}_2) \sigma(E) |\mathbf{v}_1 - \mathbf{v}_2| \, \mathrm{d}\mathbf{v}_1 \mathrm{d}\mathbf{v}_2$$

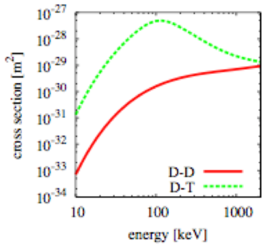
$$f_{\mathrm{D}}(\mathbf{v}_{\mathrm{D}}) = n_{\mathrm{D}} \left(\frac{M_{\mathrm{D}}}{2\pi k T} \right)^{3/2} \exp\left(-\frac{M_{\mathrm{D}} v_{\mathrm{D}}{}^2}{2kT} \right)$$

$$f_{\mathrm{b}}(\mathbf{v}_{\mathrm{b}})$$

$$\sigma(E) = \frac{A_5 + [(A_4 - A_3 E)^2 + 1]^{-1} A_2}{E[\exp(A_1 E^{-1/2}) - 1]}$$

index 1,2 : respectively b(beam ion) or th(thermal ion)
$f_D(v_D)$: thermal ion velocity distribution fuction (assumed Maxwellian distribution)
$f_b(v_b)$: beam ion velocity distribution function (from GNET)
v_b : beam ion velocity[m/s]
v_{th} : thermal ion velocity[m/s]
$\sigma(E)$: fusion reaction cross-section[barn]

A_1 : 46.097
A_2 : 372
A_3 : 4.36E-4
A_4 : 1.220
A_5 : 0



D-Dfusion reaction cross-section

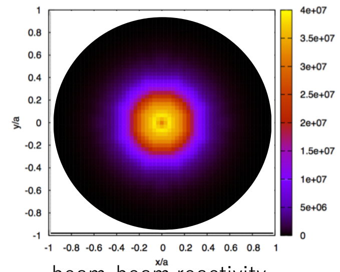
Results

b-b , b-th reactivity and sum of them with local beam profile

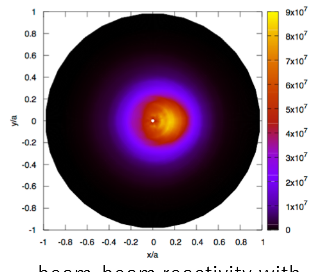
beam-beam reactivity[/s]	1.35E14
beam-thermal reactivity[/s]	2.32E14
Sum of beam-beam and beam-thermal reactivity[/s]	3.67E14

ratio of b-b in sum of b-b and b-th

36.7%



beam-beam reactivity without local beam profile

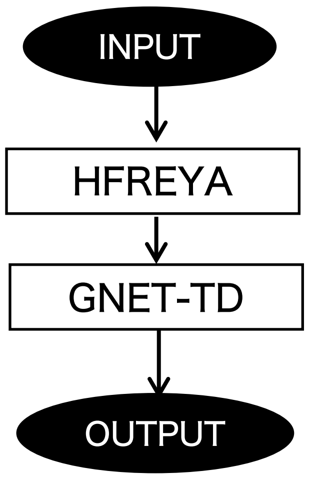


beam-beam reactivity with local beam profile

beam-beam reactivity with local beam profile and w/o that in whole plasma

without local beam profile[/s]	with local beam profile[/s]
5.40E13	14.0E13

Simulation Code



---Evaluate beam source

--- Evaluate slowing down of beam ions in timedevelopment plasma

GNET

- Solving 5 dimension drift kinetic equation shown below with Monte Carlo method ,we evaluate velocity-space deposition of beam ions.

$$\frac{\partial f_f}{\partial t} + (v_\parallel + v_d) \cdot \nabla f_f + \dot{v} \cdot \nabla_v f_f = C(f_f) + L_{\mathrm{particle}}(f_f) + S_{\mathrm{beam}}$$

f_f : velocity distribution function
v_d : drift velocity
C : collision term

$v_\parallel$: parallel velocity to magnetic field
$L_{particle}$:loss term
S_{beam} : source term

HFREYA

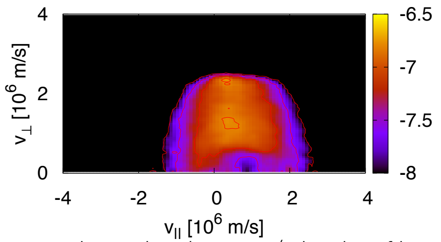
- Tracking neutral particles injected from NBI heating device, with Montecarlo method, we evaluate process of ionization based on assumed ionization cross-section.

Plasma parameters

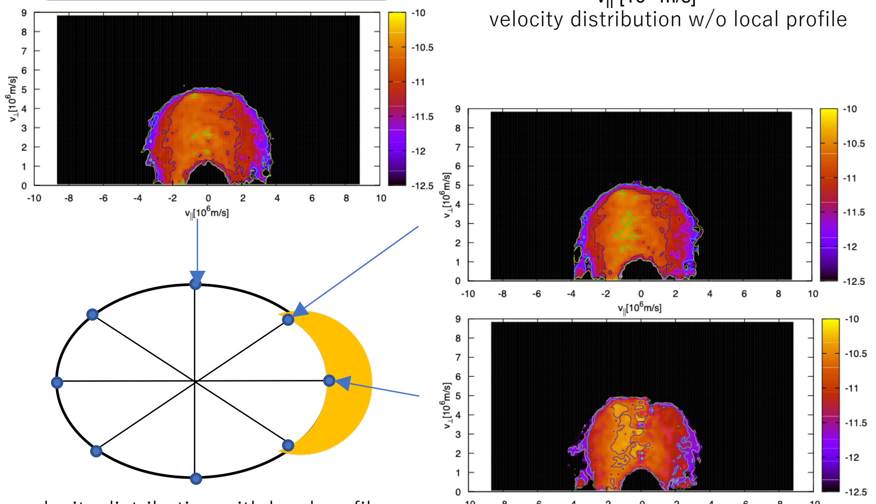
Plasma temperature(T_i, T_e)	3.0 keV
Plasma density(n_i, n_e)	3.0×10^{19} m^{-3}
Magnetic field strength	3 T
Magnetic axis position	4.07 m

Results

- The velocity space distribution of beam-ion depends on poloidal angle especially in the banana orbit.

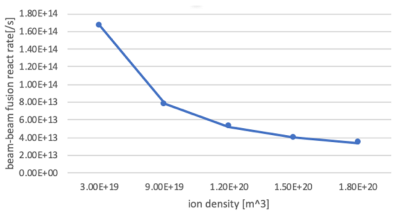


velocity distribution w/o local profile

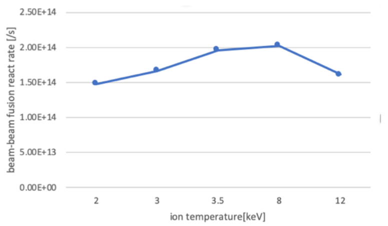


velocity distribution with local profile

- Beam-Beam reactivity distribution is shifted to outside of the torus.
- Particles are injected into plasma perpendicularly and $v_\perp$ is greater than $v_{/\!/}$ that meet trapped condition



beam-beam reactivity dependence on plasma density



beam-beam reactivity dependence on plasma temperature

- beam-beam reactivity is 36.7% of the whole reactivity, and with local beam profile effect beam-beam reactivity increase upto 2.6 times of beam-beam reactivity without local beam profile
- beam-beam reactivity for plasma temperature is not monotonic increase

SUMMARY

- **We have studied the D-D fusion reaction rate using GNET, HFREYA code.**
- **The local beam distribution has been evaluated and the beam-beam fusion reaction rates estimated using the local distribution function.**
- **We have obtained the significant effect of the local distribution function.**
- **The plasma density and temperature dependencies have been evaluated.**