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Simulation Study of Triton Burn-up in the Deuterium Experiment Plasma on LHD

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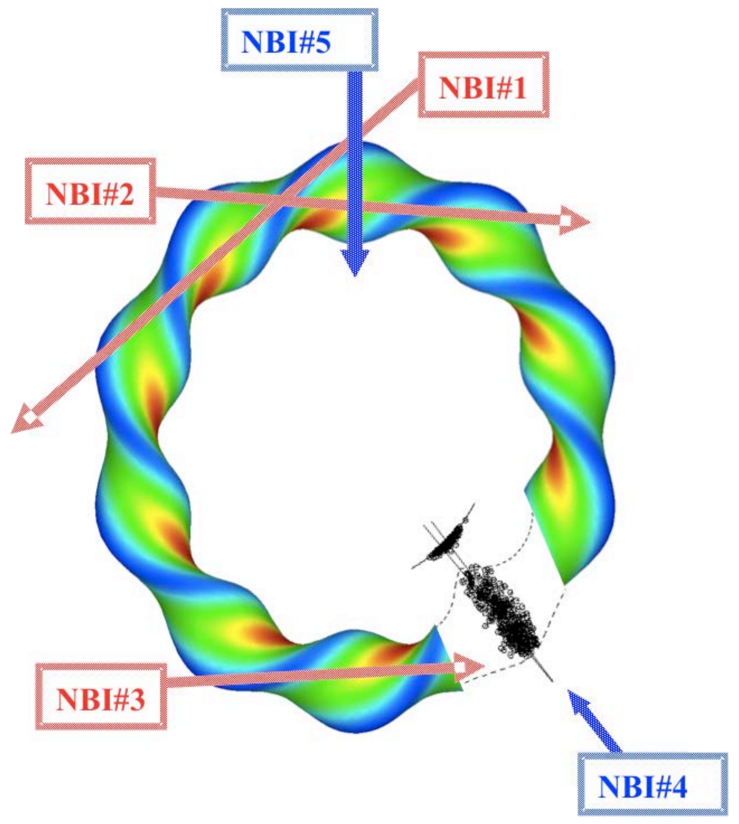
Introduction

LHD D-D experiment and triton burn-up

- In the Large Helical Device (LHD), experiments using deuterium plasmas are planned to clarify the isotope effect on energy confinement or turbulent transport and to understand energetic ion confinement.
- Five NBI (Neutral Beam Injection) heating systems are installed in the LHD: three tangential injection beams (E_b = 180 keV) and two perpendicular beams (E_b = 60-80 keV).
- During the D-D discharges, 1 MeV tritons and 2.5 MeV neutrons are produced mainly through D-D fusion reactions between deuterium NBI beams and deuterium thermal ions, and the confined tritons can undergo D-T fusion reactions emitting 14 MeV neutrons (triton burn-up).



$$\mathrm{D+D} \rightarrow \mathrm{T}(1.01\,\mathrm{MeV}) + \mathrm{p}(3.03\,\mathrm{MeV})$$
$$\mathrm{D+D} \rightarrow \mathrm{He}^3(0.82\,\mathrm{MeV}) + \mathrm{n}(2.45\,\mathrm{MeV})$$
$$\mathrm{D+T} \rightarrow \mathrm{He}^4(3.52\,\mathrm{MeV}) + \mathrm{n}(14.06\,\mathrm{MeV})$$

- Triton burn-up ratio is defined as the 14 to 2.5 MeV neutron production ratio. The confinement and slowing down of energetic tritons can be experimentally investigated by detecting the 14 MeV neutrons and measuring the triton burn-up ratios [1].

Objective of this study

- In this study, we simulate the triton burn-up for the LHD deuterium plasma experiment using the five-dimensional drift kinetic equation solver GNET (Global NEoclassical Transport) and predict the signals of the neutron measurement systems.
- We evaluate the triton production rates due to D-D reactions applying the distribution functions of the NBI deuterons obtained by GNET. Next we investigate the confinement of energetic tritons and calculate the D-T fusion reaction rates using the triton distribution functions.
- It is necessary to estimate the contribution of beam-beam reactions, in which both reacting ions are injected NBI deuterons, for more precise prediction of triton burn-up ratios and neutron production rates.

Results

Simulation conditions

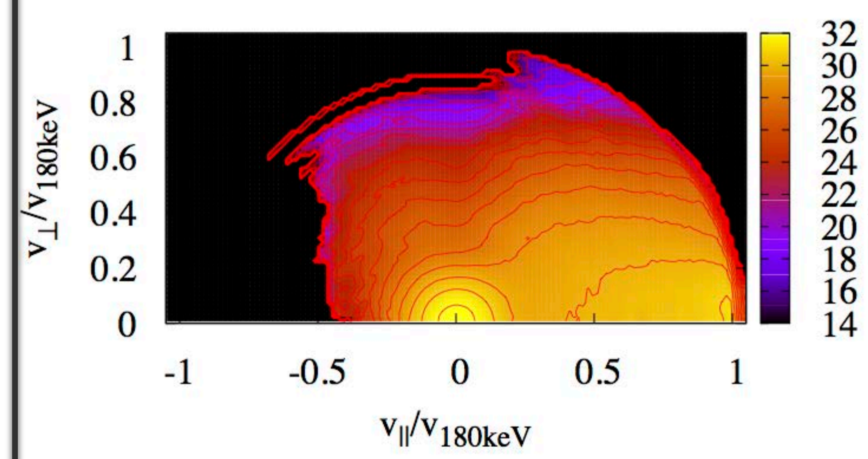
- We evaluate D-D and D-T nuclear fusion rates in the LHD deuterium plasma experiment assuming typical values for the plasma parameters, as shown in the table.
- The bulk plasma is assumed to be a hydrogen-deuterium mixed plasma with the density ratio $n_D / (n_D + n_H) = 0.8$.

Electron temperature at the magnetic axis	$T_e(0)$	3.0 keV
Electron temperature at the outermost surface	$T_e(a)$	0.1 keV
Electron density at the magnetic axis	$n_e(0)$	2.0×10^{19} m^{-3}
Electron density at the outermost surface	$n_e(a)$	0.1×10^{19} m^{-3}
Magnetic field strength	B_0	2.75 T
Magnetic axis major radius	R_{ax}	3.60 m
Beta value	β	0.23 %

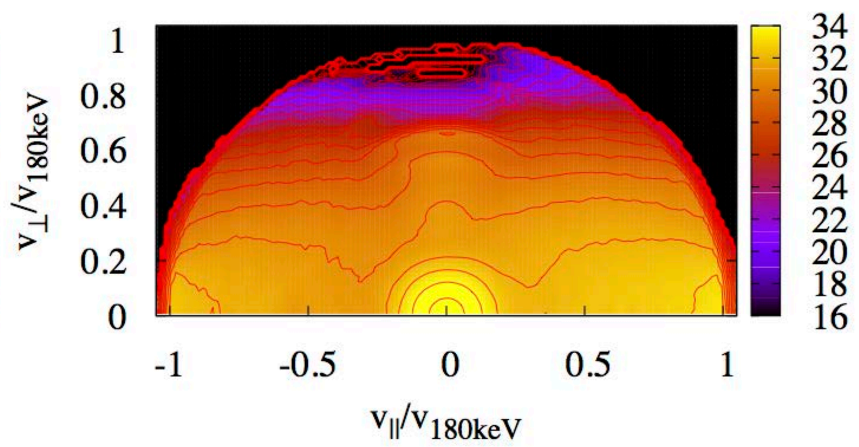
Triton production due to D-D reactions

Velocity distributions of NBI deuterons

NBI #1 (co-tangential)

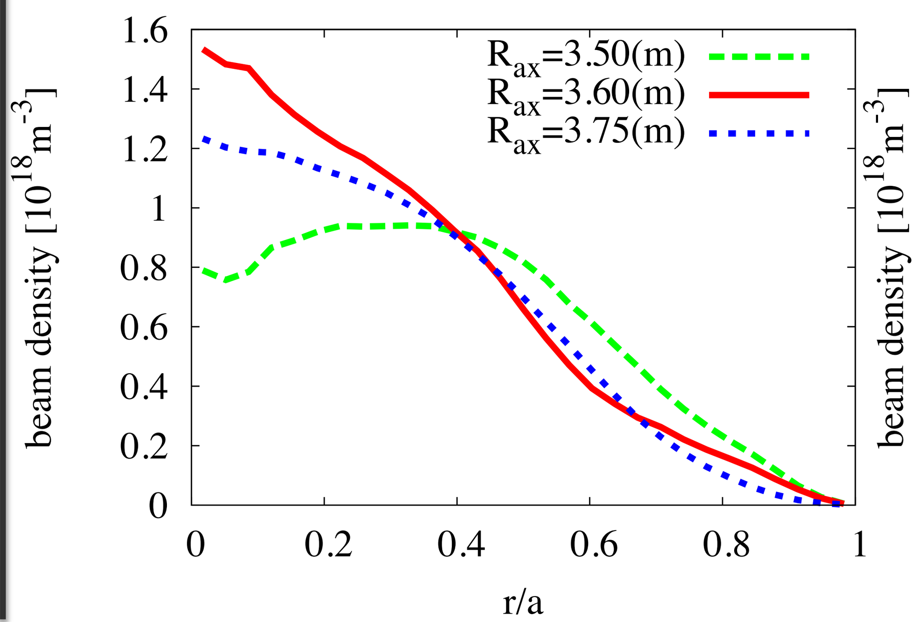


Sum of NBI #1 - #5

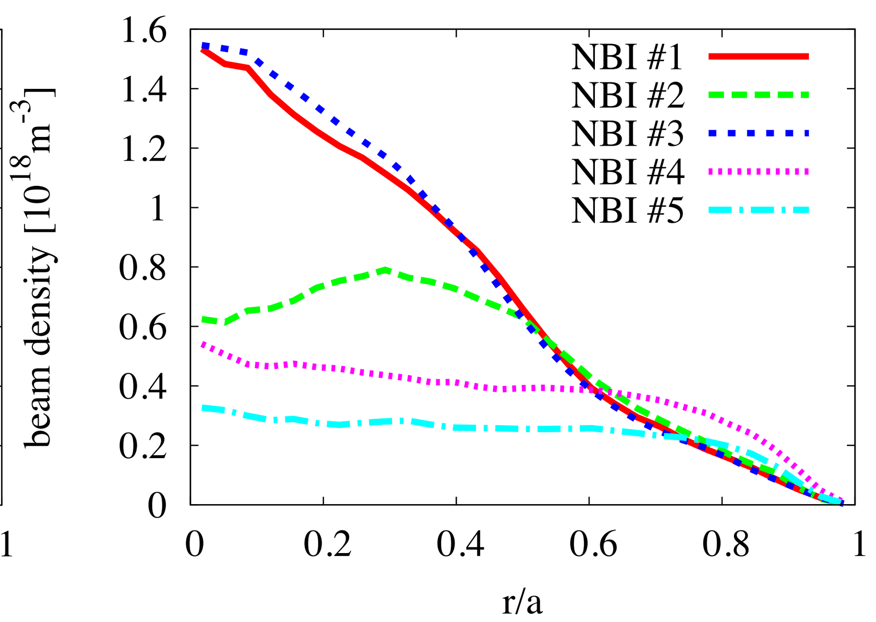


NBI deuteron density profile

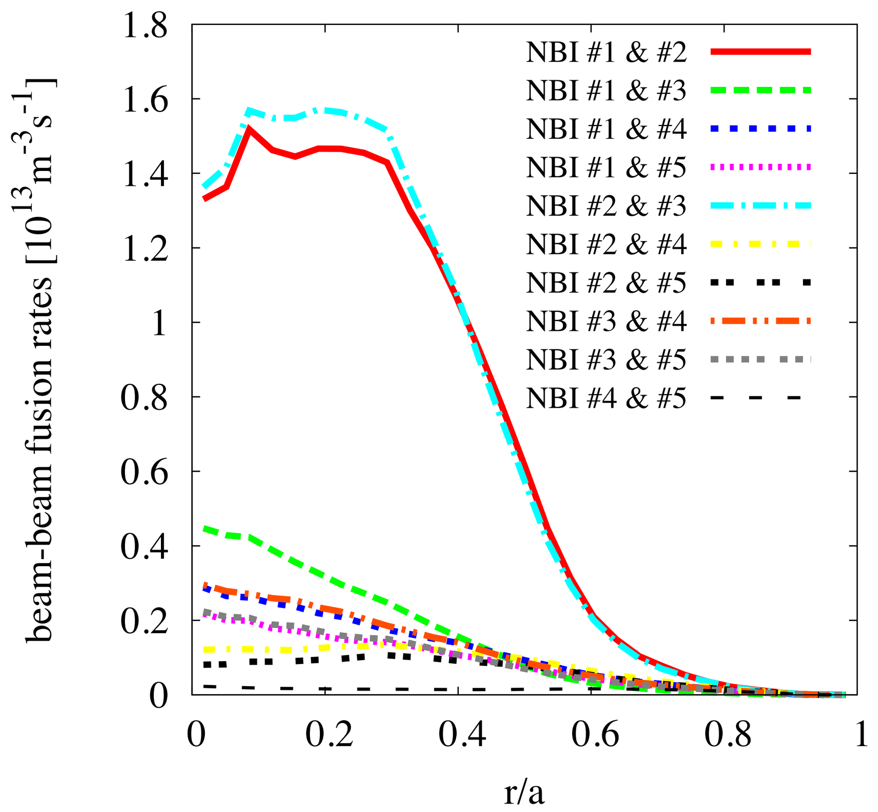
R_{ax} dependence (NBI #1)



NBI #1 - #5



NBI #1-#5 (different beamlines)

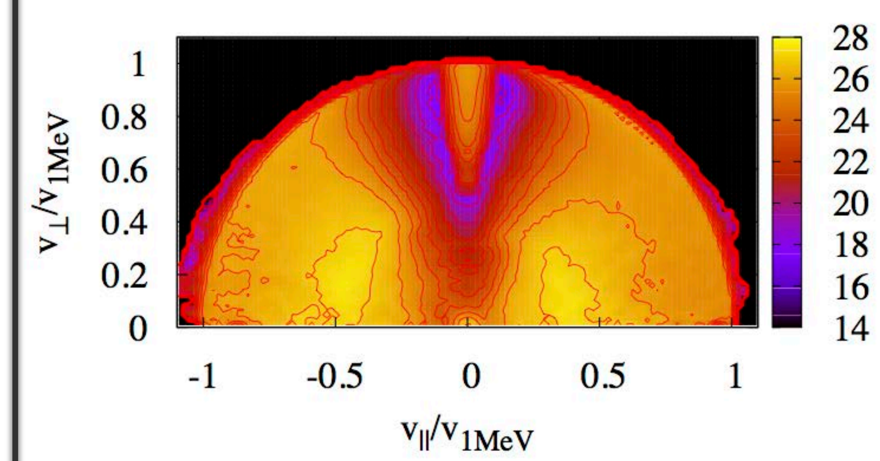


- When both of co- (NBI #1) and counter- (NBI #2) beamlines are injected simultaneously, the synergetic beam-beam fusion rates can be about 7.6 times of the sum of each beamline contribution alone resulting from the increase of the relative velocity.
- The total neutron production rate due to thermal-thermal, beam-thermal, and beam-beam reactions is calculated to be 2.1×10^{16} s^{-1} in the 1MW case.

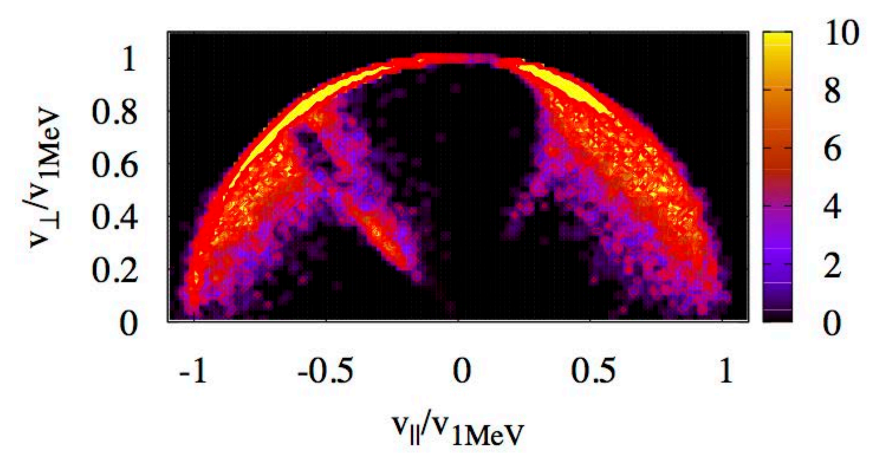
Triton confinement and D-T reactions

Velocity distributions of tritons

Confined tritons



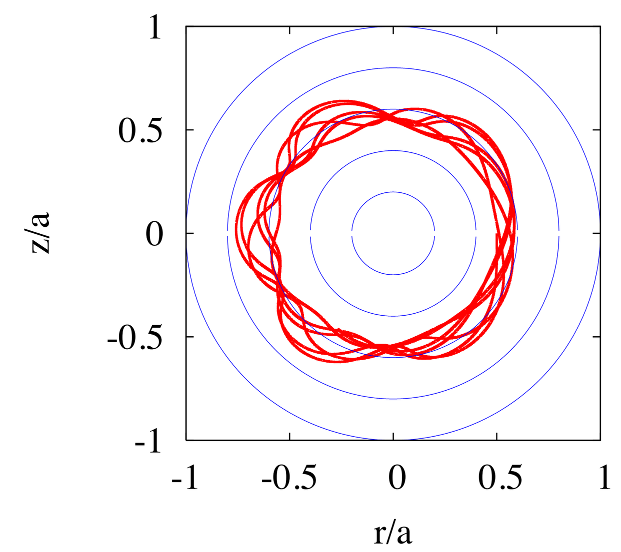
Lost tritons



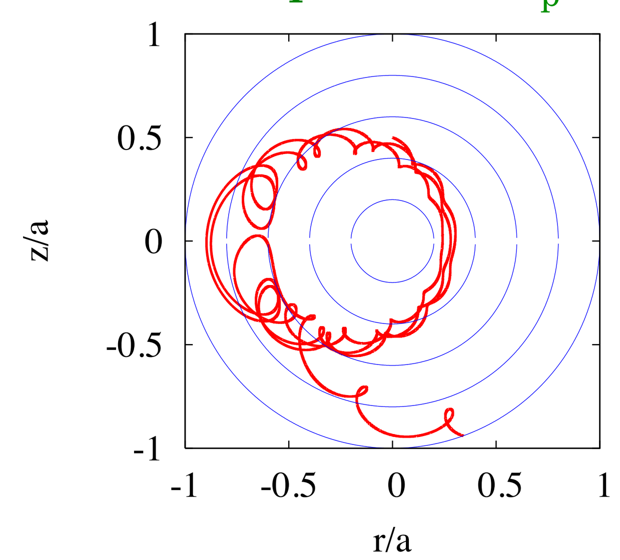
- A relatively large number of deeply helically trapped particles, whose orbits are stable along helical ripples, are seen in the region where $|v_\perp| \gg |v_{/\!/}|$.
- The stochastic behavior of the transition particles would enhance the radial diffusion of energetic particles.
- A lot of tritons escape with almost all of their initial energy of 1 MeV due to prompt orbit loss.

Typical orbits of energetic tritons

Helically trapped particle (θ_p = 91°)



Transition particle (θ_p = 120°)



Simulation Model

GNET code [2]

- The drift kinetic equation below is solved in five-dimensional phase space based on Monte Carlo methods in order to obtain the distribution function of test particles.
- The test particle orbits are followed with high accuracy by the sixth-order Runge-Kutta method.

$$\frac{\partial f_s}{\partial t} + (\boldsymbol{v}_\parallel + \boldsymbol{v}_{\rm dr}) \cdot \frac{\partial f_s}{\partial \boldsymbol{x}} + \dot{\boldsymbol{v}} \cdot \frac{\partial f_s}{\partial \boldsymbol{v}} = C^{\rm coll}(f_s) + L^{\rm particle}(f_s) + S_s$$

f_s : the distribution function of test particles
$\boldsymbol{v}_{\rm dr}$: the drift velocity
$L^{\rm particle}$: the particle loss term
$\boldsymbol{v}_{/\!/}$: the parallel velocity to the field line
$C^{\rm coll}$: the linear Coulomb collision operator
S_s : the source term of test particles

1. We solve the drift kinetic equation for NBI deuterons by GNET and obtain the deuteron beam distribution functions. The birth profile of NBI deuterons is calculated by the HFREYA code [3].
2. Using the calculated distribution function and the D-D fusion cross section [4], we evaluate the triton production rates due to thermal-thermal, beam-thermal, and beam-beam reactions.
3. Applying the source profile of tritons, we solve the drift kinetic equation for energetic tritons by GNET and obtain the triton distribution functions.
4. Using the calculated distribution function and the D-T fusion cross section [4], we evaluate the D-T neutron production rates due to D-T reactions between fast tritons and Maxwellian thermal deuterons.

$$S_{\rm T} = S_{\text{th-th}} + S_{\text{b-th}} + S_{\text{b-b}}$$

$$S_{\text{th-th}} = \frac{1}{2} n_{\rm D}^2 \langle \sigma v \rangle_{\text{DD,th-th}} \qquad S_{\text{b-b}} = \begin{cases} n_{{\rm b}_i} n_{{\rm b}_j} \langle \sigma v \rangle_{\text{DD,b-b}} & (i \neq j) \\ \frac{1}{2} n_{{\rm b}_i}^2 \langle \sigma v \rangle_{\text{DD,b-b}} & (i = j) \end{cases}$$

$$S_{\text{b-th}} = n_{\rm b} n_{\rm D} \langle \sigma v \rangle_{\text{DD,b-th}}$$

$$S_{\text{n:14 MeV}} = n_{\rm D} n_{\rm T} \langle \sigma v \rangle_{\rm DT}$$

$$\text{reactivity:} \quad \langle \sigma v \rangle_{\text{1-2}} = \iint f_1(\boldsymbol{v}_1) f_2(\boldsymbol{v}_2) \sigma(E) |\boldsymbol{v}_1 - \boldsymbol{v}_2| {\rm d}\boldsymbol{v}_1 {\rm d}\boldsymbol{v}_2$$

- We compute the integral as a limit of the Riemann sum below.

$$\langle \sigma v \rangle_{\text{1-2}} = \frac{1}{(2\pi)^2} \int_{-V_1}^{V_1} \int_0^{V_1} \int_0^{2\pi} \int_{-V_2}^{V_2} \int_0^{V_2} \int_0^{2\pi} f_1(v_{1\parallel}, v_{1\perp}) f_2(v_{2\parallel}, v_{2\perp})$$
$$\times \sigma(v_{1\parallel}, v_{1\perp}, v_{2\parallel}, v_{2\perp}) U_{\rm rel}(v_{1\parallel}, v_{1\perp}, \varphi_1, v_{2\parallel}, v_{2\perp}, \varphi_2)$$
$$\times 2\pi v_{1\perp} {\rm d}v_{1\parallel} {\rm d}v_{1\perp} {\rm d}\varphi_1 2\pi v_{2\perp} {\rm d}v_{2\parallel} {\rm d}v_{2\perp} {\rm d}\varphi_2$$
$$= \sum_{i=1}^{2N_v} \sum_{j=1}^{N_v} \sum_{k=1}^{N_\varphi} \sum_{l=1}^{2N_v} \sum_{m=1}^{N_v} \sum_{n=1}^{N_\varphi} \Big[f_1(v_{1\parallel i}, v_{1\perp j}) f_2(v_{2\parallel l}, v_{2\perp m})$$
$$\times \sigma(v_{1\parallel i}, v_{1\perp j}, v_{2\parallel l}, v_{2\perp m}) U_{\rm rel}(v_{1\parallel i}, v_{1\perp j}, \varphi_{1k}, v_{2\parallel l}, v_{2\perp m}, \varphi_{2n})$$
$$\times v_{1\perp j} v_{2\perp m} \Delta v_{1\parallel} \Delta v_{1\perp} \Delta \varphi_1 \Delta v_{2\parallel} \Delta v_{2\perp} \Delta \varphi_2 \Big]$$

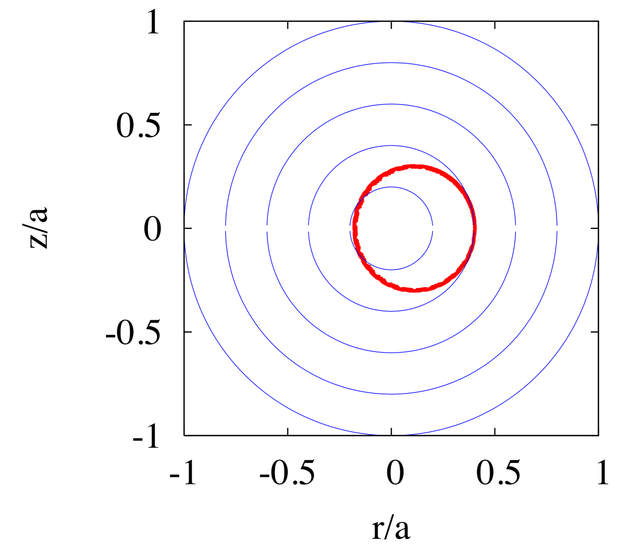
$$U_{\rm rel}(v_{1\parallel i}, v_{1\perp j}, \varphi_{1k}, v_{2\parallel l}, v_{2\perp m}, \varphi_{2n}) = \Big[(v_{1\parallel i} - v_{2\parallel l})^2$$
$$+ (v_{1\perp j} \cos\varphi_{1k} - v_{2\perp m} \cos\varphi_{2n})^2 + (v_{1\perp j} \sin\varphi_{1k} - v_{2\perp m} \sin\varphi_{2n})^2 \Big]^{1/2}$$

φ : the gyro-phase of test particles

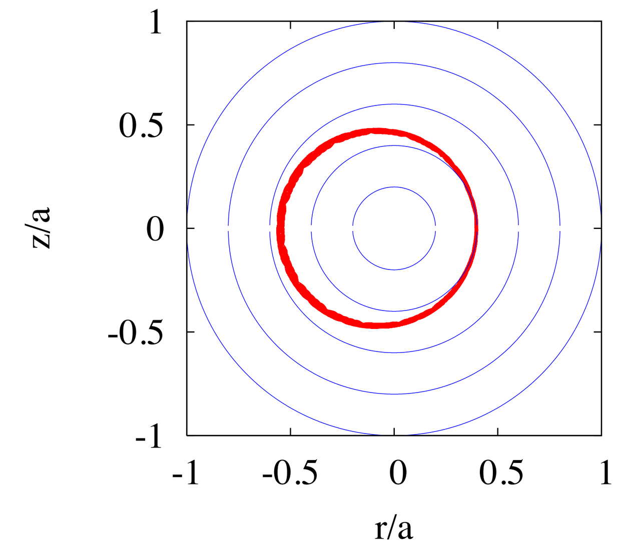
- The core beam density is lower in the $R_{\rm ax}$= 3.50 m case because the NBI system is designed so as to effectively heat the core plasma in the outward shifted configuration.
- In the perpendicular injection (NBI #4 and #5), the beam deuterons tend to become helically trapped particles and are relatively easily lost by orbit loss.

Typical orbits of passing NBI deuterons

Co-passing (NBI #1)



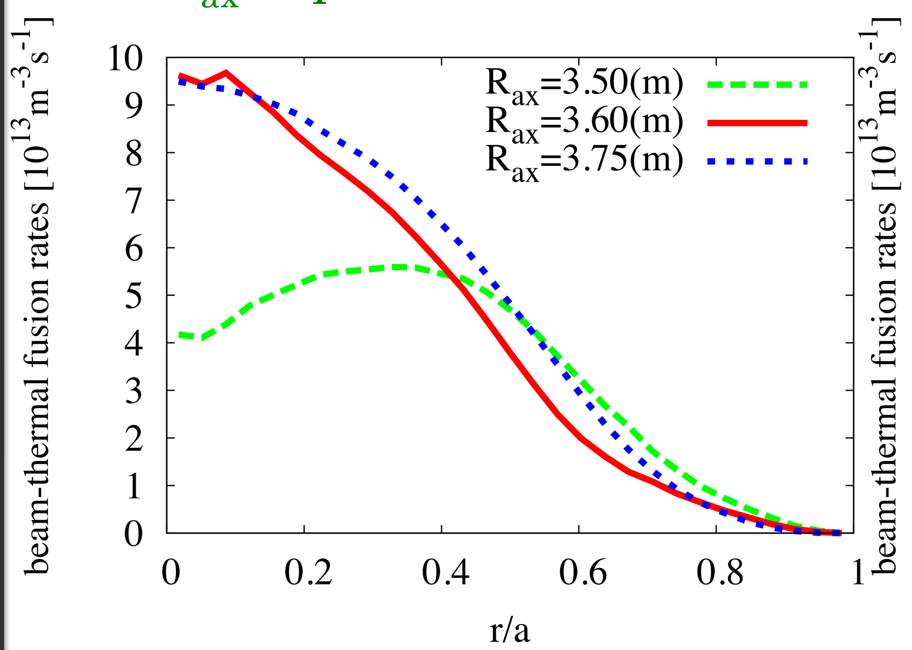
Counter-passing (NBI #2)



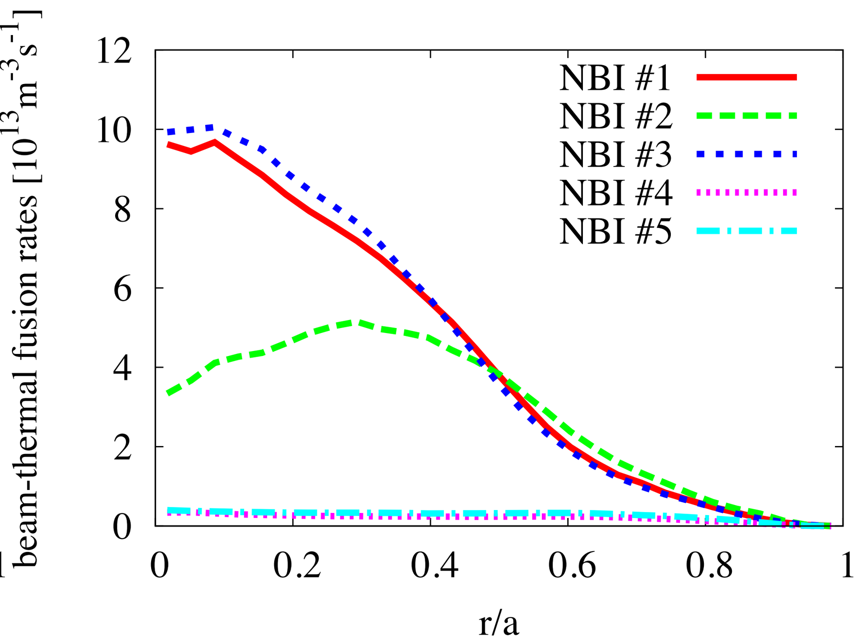
- The poloidal drift motion is in opposite direction for co- and counter-passing particles. Hence, the orbits of deuterons from the NBI #2 tend to deviate from the center region.

Beam-thermal reaction rates (per 1 MW)

$R_{\rm ax}$ dependence (NBI #1)



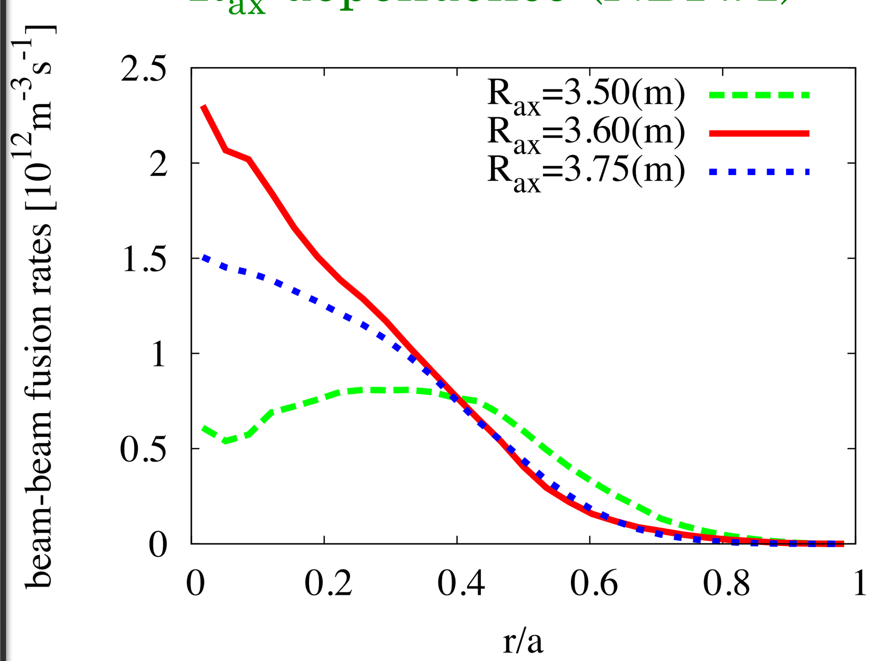
NBI #1 - #5



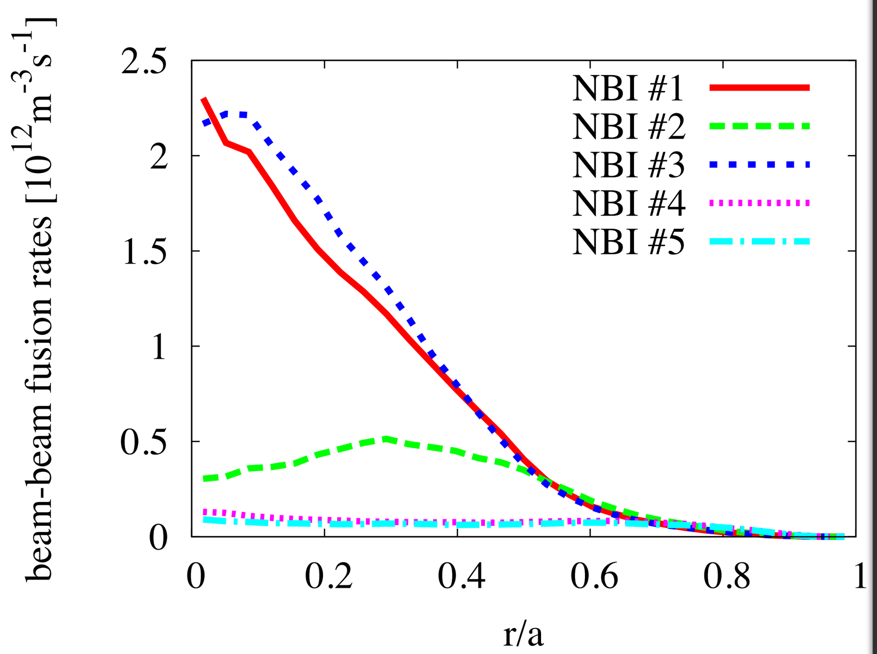
- The triton production rate depends on the beam ion birth and slowing-down process in addition to the injection energy.

Beam-beam reaction rates (per 1 MW)

$R_{\rm ax}$ dependence (NBI #1)

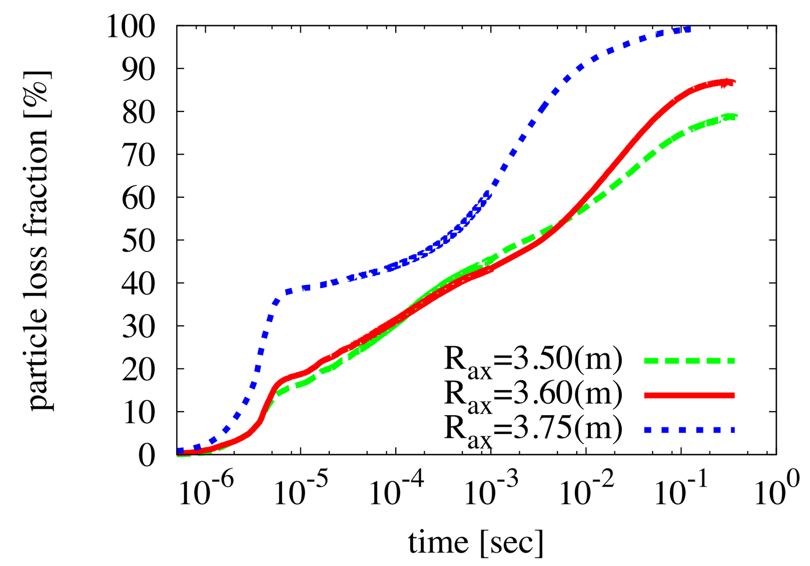


NBI #1-#5 (identical beamlines)



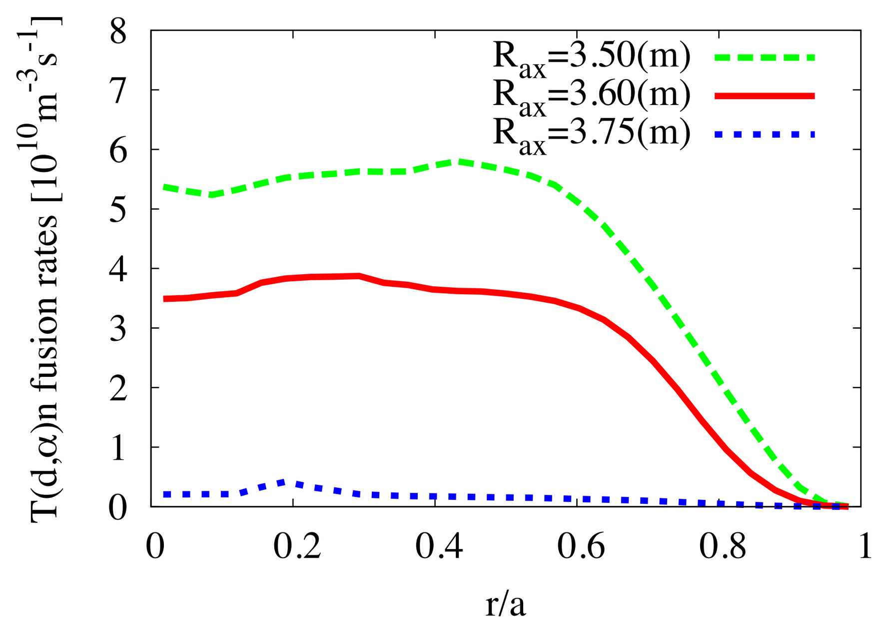
- The beam-beam fusion rate varies as the heating power squared, while the beam-thermal one is linearly proportional to the power.
- The ratio of the beam-beam contribution to the total triton production rate is approximately 1.3% in the case of 1 MW NBI power.

Temporal history of triton loss fraction

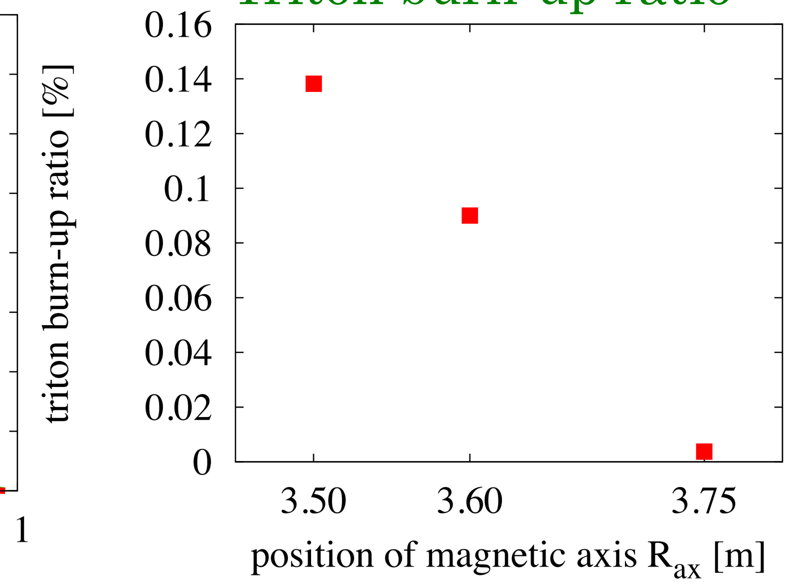


- Prompt orbit loss normally occurs before a particle has completed its first orbit in the poloidal direction. → before $t \sim 10^{-5}$ s
- After that, the collisionless diffusive loss ($10^{-5}<t<10^{-2}$) and the collisional diffusive loss ($t>10^{-2}$) become dominant.
- When the magnetic axis is shifted outward, the particle orbit greatly deviates from the flux surface and the prompt orbit loss increases.

D-T fusion reaction rates (per 1 MW)



Triton burn-up ratio



- Neutron production rate increases as the magnetic axis is shifted inward because the confinement of energetic tritons is improved.
- It is found that the fusion rates peak near r/a = 0.2 because of the presence of well-confined trapped particles in these radial positions.

Summary

- We have simulated the triton burn-up in the deuterium experiment plasma on LHD. In order to calculate the fusion rates, we have applied the velocity distribution functions of energetic particles obtained by the GNET code.
- We have calculated the production rates of tritons and D-D neutrons due to beam-thermal and beam-beam reactions.
- We have evaluated the velocity distribution of the tritons and analyzed the loss mechanisms of the energetic tritons. Finally, we have estimated the amount of 14 MeV neutrons produced through the D-T fusion reactions.
- The triton burn-up ratio has been calculated to be approximately 0.14% in the inward shifted configuration.

References

[1] T. Nishitani *et al.*, Plasma Phys. Control. Fusion **38**, 355 (1996).
[2] S. Murakami *et al.*, Nucl. Fusion **40**, 693 (2000).
[3] S. Murakami, Trans. Fusion Technology **27**, 256 (1995).
[4] J. D. Huba, *NRL Plasma Formulary* (Naval Research Laboratory, 2002).