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Simulation Study of Energetic Triton Confinement in the D-D Experiment on LHD

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Introduction

Energetic particles in fusion plasmas

- Nuclear fusion reactions

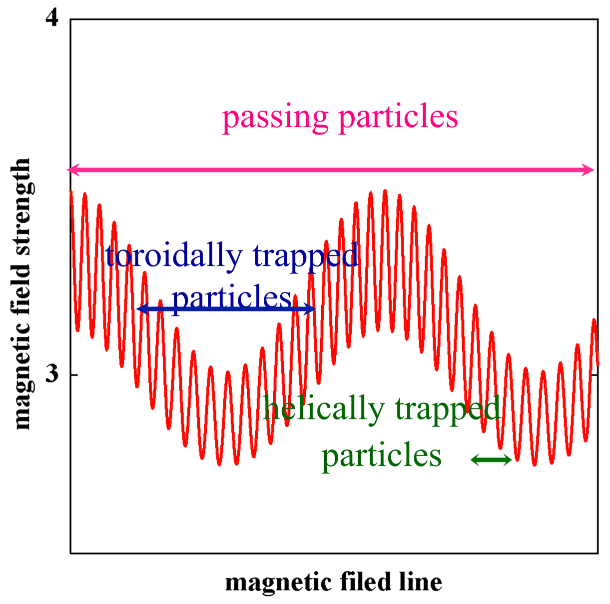
$$\mathrm{D+T} \rightarrow \mathrm{He}^4(3.52\,\mathrm{MeV}) + \mathrm{n}(14.06\,\mathrm{MeV})$$
$$\mathrm{D+D} \rightarrow \mathrm{T}(1.01\,\mathrm{MeV}) + \mathrm{p}(3.03\,\mathrm{MeV})$$

- Energetic particles give their energy to background ions and electrons through Coulomb collisions and heat the plasma.
- Energetic alpha particles produced by D-T fusion reactions heat the plasma, and the high-temperature plasma can be sustained without any additional power input from outside.
- Loss of energetic alpha particles deteriorates the heating of the plasma. Also, it might severely damage the first wall of the reactor.

⇒ Confinement of high-energy alpha particles for a sufficiently long time is of great importance.

Helical fusion reactors

- External coils are applied to induce a toroidal and poloidal magnetic field in order to confine the high-temperature plasma.
- Magnetic field configurations are inherently three-dimensional, and motions of trapped energetic particles are complicated.
  → These motions can lead to a loss of the energetic particles.
- In helical systems, the small modulations generated by the helical coils can be seen in the magnetic field, in addition to the large modulations due to the toroidal modes.



- passing particles ($v_{/\!/} \gg v_\perp$)
- toroidally trapped particles
- helically trapped particles ($v_\perp \gg v_{/\!/}$)

transition particles

The transition between passing and trapped particle orbits can enhance the radial diffusion of the energetic particles.

LHD D-D experiment

- In LHD, experiments using deuterium plasmas are planned to be performed in order to make clear the isotope effect on energy confinement, turbulent transport, and energetic ion confinement.
- The plasma confinement improvement is expected by use of deuterium plasmas.

Results

Simulation conditions

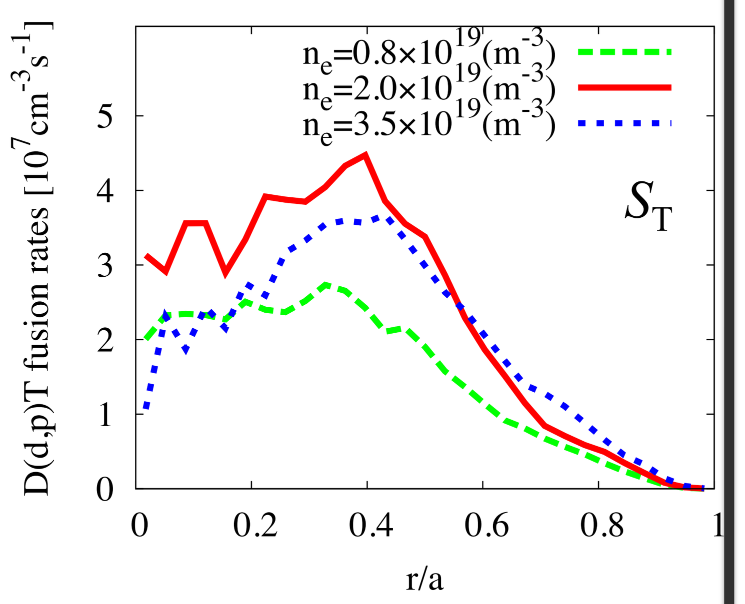
- Confinement of tritons in the D-D experiment on LHD is simulated assuming the typical values for the plasma parameters, as shown in the table.
- The ion temperature is assumed to be equal to the electron temperature. The bulk plasma is assumed to be the hydrogen-deuterium mixed plasma with an equal amount.
- Assuming tangential NBI (with energy E_b = 180 keV), we evaluate the quantities per 1 MW of heat power.

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	$n_e(0)$	$2.0\times10^{19}\,\mathrm{m}^{-3}$
Electron density at the outermost surface	$n_e(a)$	$0.1\times10^{19}\,\mathrm{m}^{-3}$
Magnetic field strength	B_0	2.75 T
Magnetic axis major radius	R_{ax}	3.60 m
Beta value	β	0.23 %

$$T_e(r) = (T_e(0) - T_e(a))\left[1 - \left(\frac{r}{a}\right)^2\right] + T_e(a)$$
$$n_e(r) = (n_e(0) - n_e(a))\left[1 - \left(\frac{r}{a}\right)^8\right] + n_e(a)$$

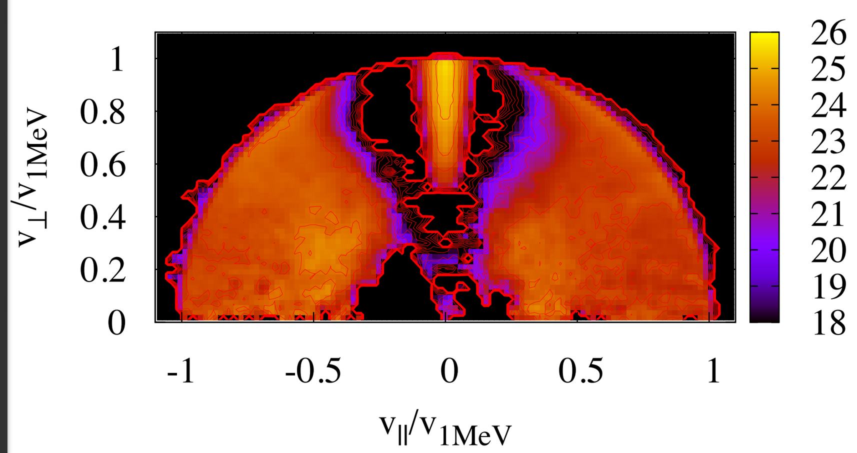
Birth profile of tritons

- The radial birth profile of the 1 MeV tritons is evaluated applying the FIT3D-DD code.
- The population of the beam ions depends on their birth and slowing-down processes. Therefore, the triton production rate does not simply depend on the plasma density.

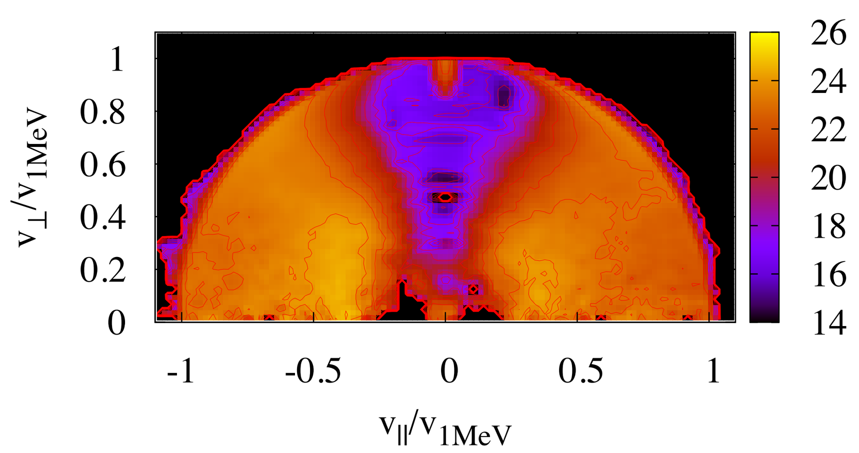


Velocity space distribution ($n_e = 2.0\times10^{19}\,\mathrm{m}^{-3}$)

r/a = 0.2 (near the magnetic axis)

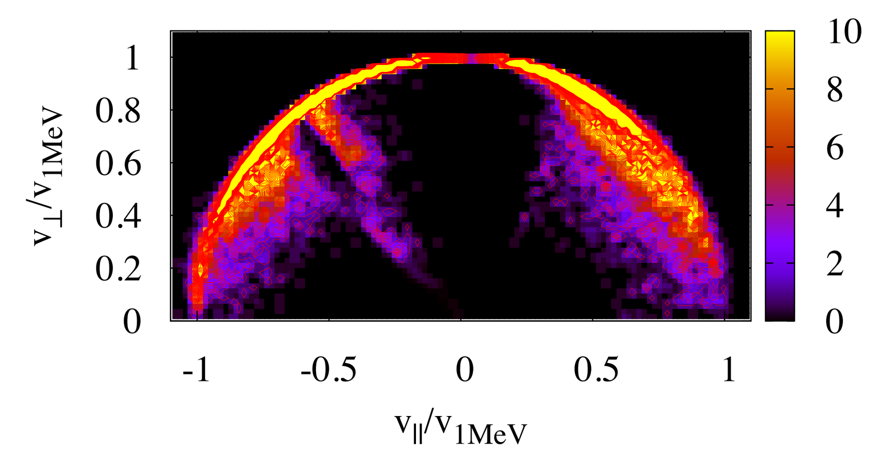


r/a = 0.5



Loss of the tritons

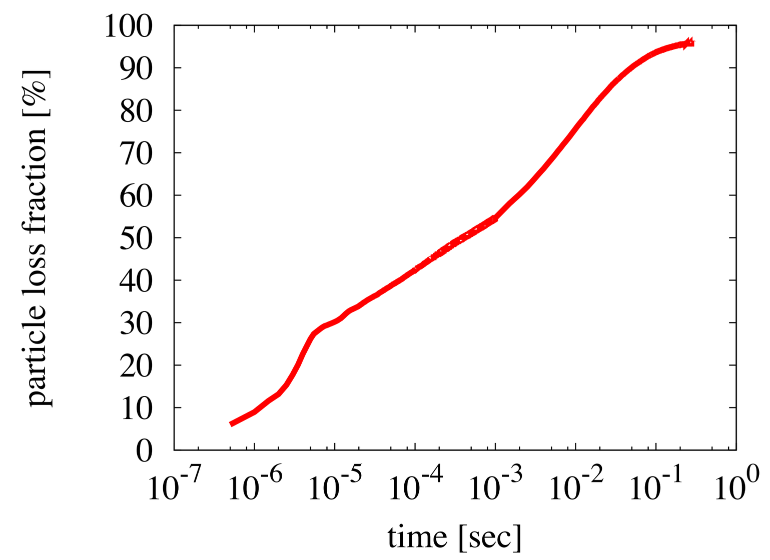
lost particle



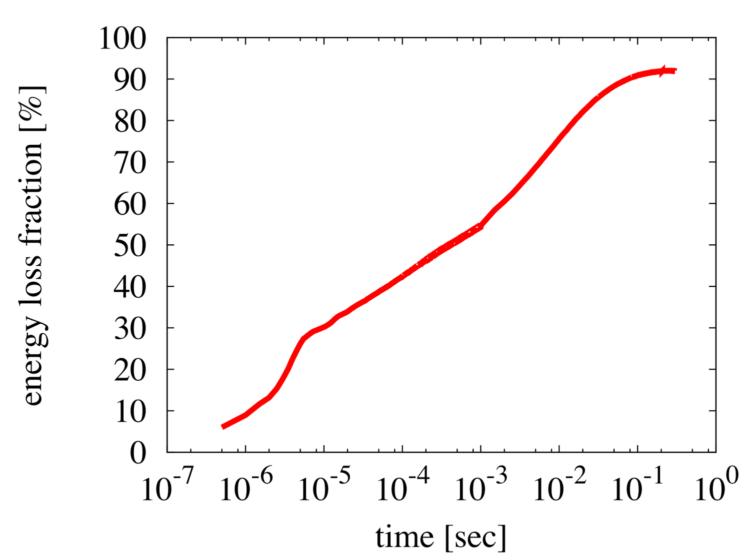
- A lot of tritons escape with nearly the initial energy 1 MeV. This is the prompt orbit loss due to the drift motion immediately after their birth.
- In the passing region ($v_{/\!/} > v_\perp$), we can see the tritons which get partially thermalized before reaching the LCFS. This is because the passing particles moving near the LCFS undergo pitch-angle scatterings due to the collisions with the bulk ions.
- In the region with a pitch angle θ ~ 120°, a large number of lost particles can be seen regardless of their energy. This tendency results from the stochastic diffusion of the transition particles.

Particle and energy loss fraction

particle loss fraction



energy loss fraction



- The prompt orbit loss normally occurs before a particle has completed its typical orbit in the poloidal direction. → until $t \sim 10^{-5}$ s.
- After that, the diffusive loss becomes dominant.
- The particle and energy loss fraction obtained in this calculation can be more or less overestimated because re-entering particles [5] are not taken into account in the GNET code.

	(I) $t = 1\times10^{-5}$ s (prompt orbit loss)	(II) t = 0.3 s (orbit + diffusive loss)
Particle loss fraction	30 %	96 %
Energy loss fraction	30 %	92 %

- During the D-D discharges, 1 MeV tritons are produced by fusion reactions between deuterium NBI (Neutral Beam Injection) beams and deuterium thermal ions.
- Confinement and slowing down of the energetic tritons can be experimentally investigated by detecting 14 MeV neutrons generated by D-T reactions between the tritons and deuterium plasmas [1].

Objective of this study

- The 1 MeV tritons have similar kinetic properties to those of D-T produced 3.5 MeV alpha particles. Thus, to clarify the behavior of the energetic tritons would make it possible to experimentally verify the alpha particle confinement in D-T plasmas, which is of great importance for sustaining high temperature burning plasmas.
- In this study, we investigate the confinement of energetic tritons by the five-dimensional drift kinetic equation solver GNET assuming the LHD deuterium plasmas and predict the measurement in the upcoming D-D experiment.
- Energetic particle confinement in helical systems can be verified comparing the simulation results obtained in this study with the experimental ones.

Simulation Model

GNET code [2,3]

- 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 the tritons.
- The test particle orbits is followed with high accuracy using the sixth-order Runge-Kutta method.
- In the GNET code, a particle is regarded as lost when it has reached the last closed flux surface (LCFS).

$$\frac{\partial f}{\partial t} + (\boldsymbol{v}_{\parallel} + \boldsymbol{v}_{\mathrm{dr}}) \cdot \boldsymbol{\nabla} f + \dot{\boldsymbol{v}} \cdot \boldsymbol{\nabla}_{\boldsymbol{v}} f = C^{\mathrm{coll}}(f) + L^{\mathrm{particle}} + S_{\mathrm{T}}$$

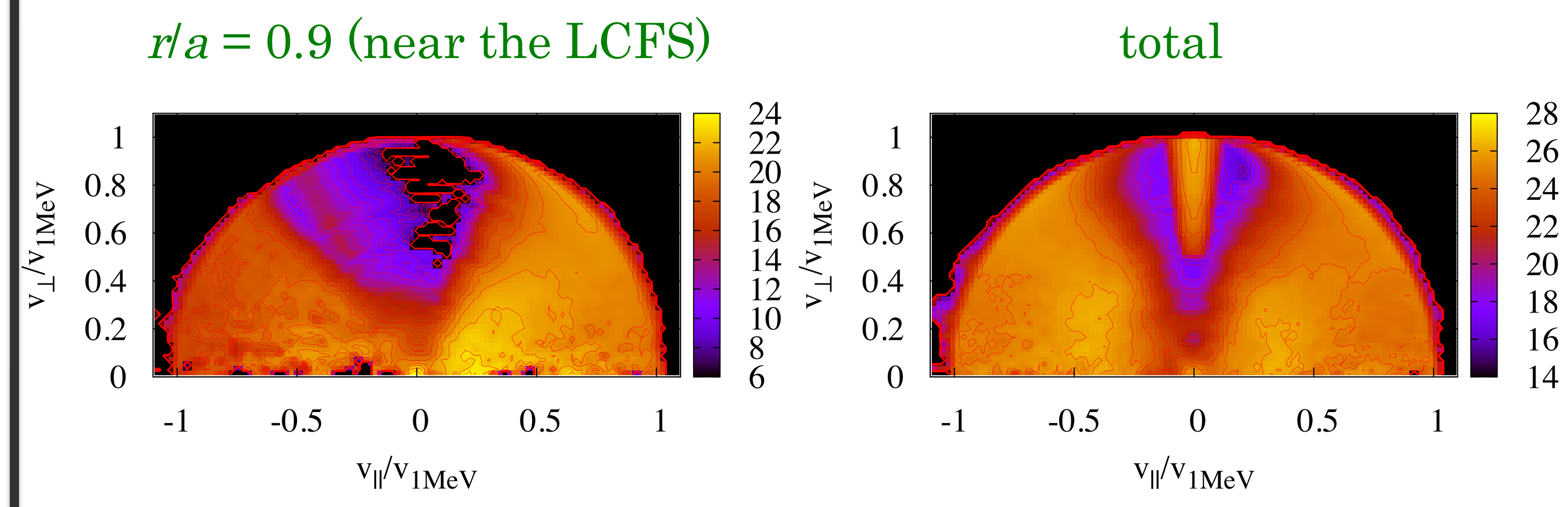
f : the distribution function of the tritons
$\boldsymbol{v}_{\mathrm{dr}}$: the drift velocity
L^{particle} : the particle loss term
$\boldsymbol{v}_{/\!/}$: the parallel velocity to the field line
C^{coll} : the linear Coulomb collision operator
S_{T} : the source term of the tritons

FIT3D-DD code

- The heat-deposition profiles of electrons and ions due to NBI are evaluated.
- Using the cross section below [4], we calculate the D(d,p)T fusion reaction rates between deuterium beams and deuterium thermal ions and evaluate the source profile of tritons.

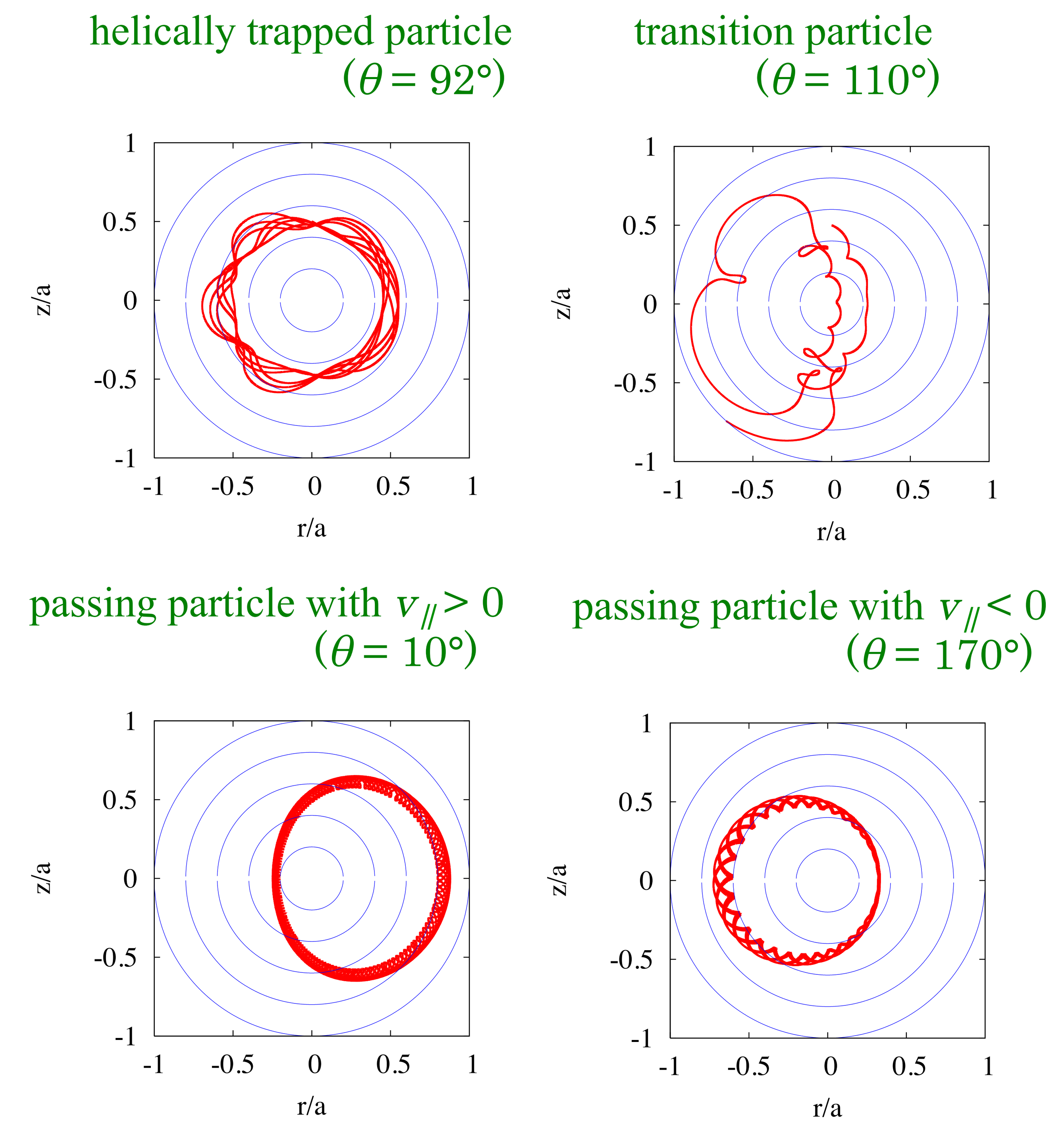
$$\langle \sigma v \rangle = \iint f_{\mathrm{D}}^{\mathrm{beam}}(v_{\mathrm{D}}^{\mathrm{beam}}) f_{\mathrm{D}}^{\mathrm{th}}(v_{\mathrm{D}}^{\mathrm{th}}) \sigma_{\mathrm{DD}}(E) \left| v_{\mathrm{D}}^{\mathrm{beam}} - v_{\mathrm{D}}^{\mathrm{th}} \right| \mathrm{d}v_{\mathrm{D}}^{\mathrm{beam}} \mathrm{d}v_{\mathrm{D}}^{\mathrm{th}}$$

$$\sigma_{\mathrm{DD}}(E) = \frac{\left[\left(1.220 - 4.36 \times 10^{-4} E\right)^2 + 1\right]^{-1} \times 372}{E\left[\exp\left(46.097 E^{-\frac{1}{2}}\right) - 1\right]} \ (\mathrm{barn}), \quad E = \frac{1}{2} M_{\mathrm{D}} \left| v_{\mathrm{D}}^{\mathrm{beam}} - v_{\mathrm{D}}^{\mathrm{th}} \right|^2$$



- A relatively large number of tritons can be seen in the region of $v_{\perp} \gg v_{/\!/}$. They are the deeply trapped particles, whose orbits are stable along the helical ripples.
- However, the distribution is reduced in its neighboring region ($v_{\perp} > v_{/\!/}$). Particles in this region make a transition between passing and trapped particle orbits and behaves as stochastic particles. The stochastic behavior of the transition particles would enhance the radial diffusion of the energetic particles.
- At minor radii r/a = 0.5 and r/a = 0.9, a small distribution of deeply trapped particles can be observed. This is because in these radial positions, the helically trapped particles drift into the region close to the plasma edge and would be easily lost due to orbit loss.

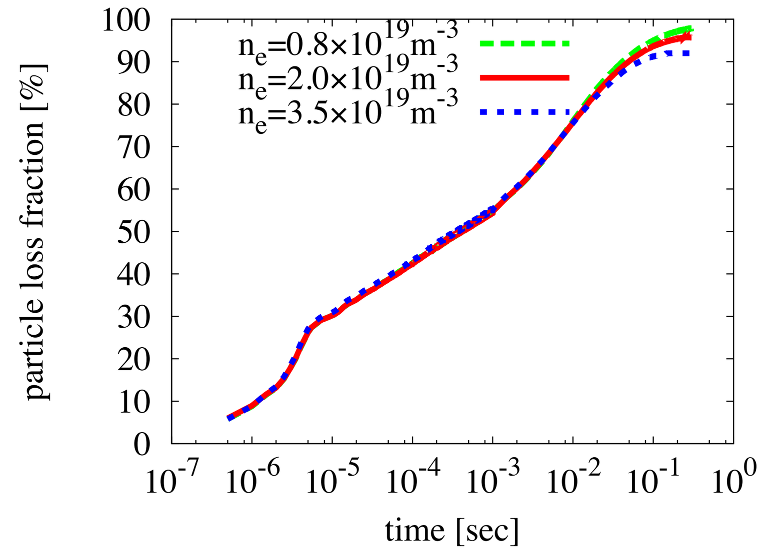
Typical orbits of energetic tritons



- The orbits of the energetic tritons in the poloidal cross section at various pitch angles are illustrated above.
- The stable motion of the deeply trapped particles and the stochastic behavior of the transition particles can be seen.
- Due to the poloidal drift motion, the orbit of the passing particle with $v_{/\!/} > 0$ is shifted outward, while that with $v_{/\!/} < 0$ is shifted inward. This is the reason for the asymmetry of the velocity distributions at r/a = 0.2 and at r/a = 0.9.

Parameter Dependences

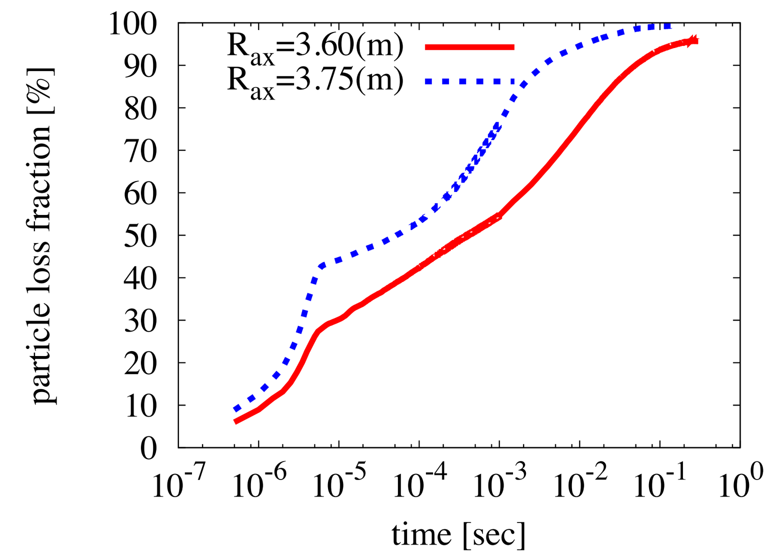
On the plasma density



- The prompt orbit loss fraction does not depend on the plasma density.
- In the case of n_e= 3.5×10^{19}m^{-3}, the diffusive loss fraction is about 7% lower than that in the case of n_e= 0.8×10^{19}m^{-3} because of the shorter slowing-down time.

	(I) t = 1 × 10^{-5} s (prompt orbit loss)	(II) t = 0.3 s (orbit + diffusive loss)
n_e= 0.8×10^{19} m^{-3}	30 %	98 %
n_e= 2.0×10^{19} m^{-3}	30 %	96 %
n_e= 3.5×10^{19} m^{-3}	31 %	92 %

On the magnetic configurations



	(I) t=10^{-5}s	(II) t=0.3s
R_{ax} = 3.60 m	30 %	96 %
R_{ax} = 3.75 m	44 %	100 %

- When the magnetic axis is shifted outward, the particle orbit greatly deviates from the flux surface and the prompt orbit loss fraction increases.

Summary

- We have evaluated the velocity distribution of the tritons by the GNET code and analyzed the loss mechanisms of the energetic tritons (the prompt orbit loss and the diffusive loss). Furthermore, we have calculated the particle and energy loss fractions and investigated the dependencies on the plasma parameters.
- In the D-D experiment, 14 MeV neutrons are produced by the D-T fusion reactions between tritons and deuterium plasmas. It is necessary to simulate the triton burn-up and predict the signals of the neutron measurement systems in the deuterium experiments of LHD.

References

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