A Comprehensive Study of Energetic Particle Transport Due to Energetic Particle Driven MHD Instabilities in LHD Deuterium Plasmas

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• DT fusion born $\alpha$ particle confinement is one of the issues for realizing a fusion reactor.
• Energetic $\alpha$ particle transport due to MHD instabilities has been studied.


Neutron (14 MeV): tritium bleeding, electricity generation
$\alpha$ particle (3.5 MeV) : self heating
Energetic confinement study in deuterium experiments in the Large Helical Device (LHD)

- To understand $\alpha$ confinement in a fusion reactor, energetic particle behavior has been studied in LHD.
- Confinement of short-pulsed beam ions in MHD quiescent plasmas can be described as a neoclassical theory.
- Confinement capability of fusion born 1 MeV tritons is comparable with tokamaks having a similar minor radius.

• An energetic confinement study has been performed using intensive neutral beam injectors and comprehensive neutron diagnostics.

Fusion reactions in deuterium plasmas

Primary reaction
• D+D -> \(^{3}\text{He} (0.8 \text{ MeV}) + \text{n} (2.5 \text{ MeV})\)
• D+D -> \(^{3}\text{T} (1 \text{ MeV}) + \text{p} (3 \text{ MeV})\)

Secondary reaction
T+D -> \(^{4}\text{He} (3.5 \text{ MeV}) + \text{n} (14 \text{ MeV})\)

1 mm Φ Sci-Fi

14 MeV n Recoil proton

Scintillation light

Detection efficiency

Number of Sci-Fis

91  LANL Sci-Fi
   Used in TFTR and JT-60U discontinued

109  NIFS Sci-Fi
     Strong against magnetic field

144  Toyama Sci-Fi
     High-counting rate capability

456  Middle Sci-Fi

Poincaré plot of beam ion and triton orbits

- Passing-transit and helically-trapped ions exist in LHD.
- Helically-trapped ion has a poloidal structure.
- 1 MeV triton has large Larmor radius and large orbit deviation from the flux surface.

\( R_{ax} = 3.60 \, \text{m}, \, B_t = 2.75 \, \text{T} \)
Energetic ion driven resistive interchange mode (EIC) excited in a deuterium plasma discharge

- EIC is excited in relatively low-density plasma with intense P-NB injections.
  - Helically-trapped ions created by P-NB excite EIC.
  - The termination of the high-$T_i$ state in LHD.
- Deuterium N-NBs and deuterium P-NBs were injected into a deuterium plasma.
  - $T_{e0} \sim 3$ keV and $n_{e\text{ avg}} \sim 10^{19}$ m$^{-3}$
  - EIC having $\sim 10^{-3}$ T was observed with a magnetic probe located on the vacuum vessel.
  - $S_n$ reflects global confinement of N-NB and P-NB ions.

EIC: X. D. Du et al., Nucl. Fusion (2016).
Beam ion transport due to EIC

- Drop of $S_n$ due to an EIC burst shows that EIC induces beam ion transport.
  - 90% of $S_n$: plasma-N-NB ion reactions. 10% of $S_n$: plasma-P-NB ion reactions.
- Drop rate of $S_n$ linearly increases with $b_{\theta_{EIC}}$ and reaches ~13%.
To determine the EIC effect on N-NB and P-NB ions separately, additional experiments were performed.

- Hydrogen N-NBs and deuterium P-NBs were injected into a deuterium plasma.
- $T_{e0} \sim 3$ keV and $n_{e\_avg} \sim 10^{19}$ m$^{-3}$.
- The intensity of EIC is almost same as that in a full deuterium NB condition.
- $S_n$ reflects the global confinement of P-NB ions.
Helically-trapped beam ion transport due to EIC

- $S_n$ drops significantly due to an EIC burst.
- Drop rate of $S_n$ reaches $\sim 60\%$. $\Rightarrow$ EIC induces up to 60% of P-NB ion losses.
  - P-NB ions are the driving source of EIC.

- In full-D beam cases: $-dS_n/S_n$ reached 13% with $S_{n\_N-NB} \sim 90\%$ and $S_{n\_P-NB} \sim 10\%$. $\Rightarrow$ $\sim 8\%$ of N-NB ions are lost due to EIC.
• High triton confinement capability is realized in high-$B_t$ and inward shift of $R_{ax}$.
• A study of 1 MeV triton transport induced by energetic-particle-driven MHD instabilities was performed under high triton confinement condition.
S_{n,DT} drops rapidly and significantly due to EIC.
Drop rate of S_{n,DT} increases substantially with b_{0,EIC}.
  • Loss of tritons reaches ~30% at b_{0,EIC} ~ 10^{-3} T.
  • 1 MeV tritons are largely transported because the tritons are barely confined.
• Beam ion and DD fusion born triton transport due to energetic-particle-driven MHD instabilities is simultaneously studied in LHD to understand $\alpha$ particle confinement in a fusion burning plasma.
  • The neutron flux monitor is used for beam ion confinement study. A high sensitivity scintillating fiber detector is developed for measuring time-resolved triton confinement.

• Enhanced transport of beam ions and DD fusion born tritons due to EIC burst is observed using neutron diagnostics.

• Experiments in full D and H/D beam conditions shows that EIC induces up to 8% of passing transit beam ion losses and up to 60% of helically-trapped beam ion losses.

• Drop rate of $S_{n\_DT}$ increases with $b_{\theta\_EIC}^3$ and reaches up to 30% due to EIC. 1 MeV tritons barely confined in LHD are rapidly and significantly lost due to EIC.