Correlation between Beam Power and Knock-on Effect of Energetic Protons on Slowing-down Deuterons Observed in the Large Helical Device

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ABSTRACT

- Effect of nuclear elastic scattering (**NES**) [1] on slowing-down properties of fast deuterons was observed in the LHD deuterium plasma.
- Numerical simulations on the basis of the Boltzmann-Fokker-Planck (**BFP**) model [2] can explain the observed results with parameters.
- The NES effect would be appreciable in the future reactor-grade plasmas.

BACKGROUND

- Energetic ions knock the thermal ions in higher energy range via NES [1], and create knock-on tails in ion velocity distribution functions.
- A large fraction of the energetic-ion energy is transferred to bulk ions in a single NES event, and the energetic-ion slowing-down properties are influenced by the collisional process (*as well as the Coulomb collision*).

  (i) Owing to the NES effect, fractional energy deposition transferred from energetic ions to bulk ions tends to increase compared with when we only consider Coulomb collision.

  (ii) NES causes distortion of both energetic and bulk distribution functions, and sometimes fusion reaction rate coefficients are changed compared with the values for Maxwellian plasma.
- We have developed the BFP model to understand the NES effect [2]. These phenomena could be appreciable in a thermonuclear plasma and the understanding with experimental validation would be necessary.

CHALLENGES / METHODS / IMPLEMENTATION

EXPERIMENT

On the large helical device (LHD), we attempted to observe the knock-on effect by looking at a decay time of the DD neutrons after deuterium beam was terminated for several beam conditions. We devoted our attention to measure the neutron decay time produced by the DD reactions between the ~60-keV deuterium beam and bulk deuterons. During the decay process the ~180-keV hydrogen beams were continuously injected, and the decay times were compared between several hydrogen beam-injection patterns.

NUMERICAL SIMULATION

Numerical simulations are carried out to understand the observed phenomena on the basis of the Boltzmann-Fokker-Planck model [2].

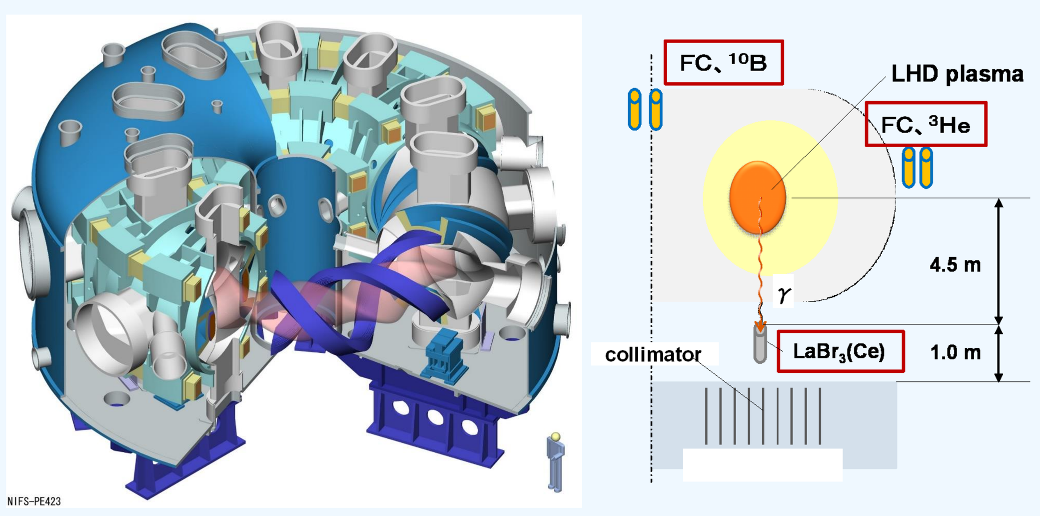

Fig.1 Schematic view of the LHD and the diagnostic systems.

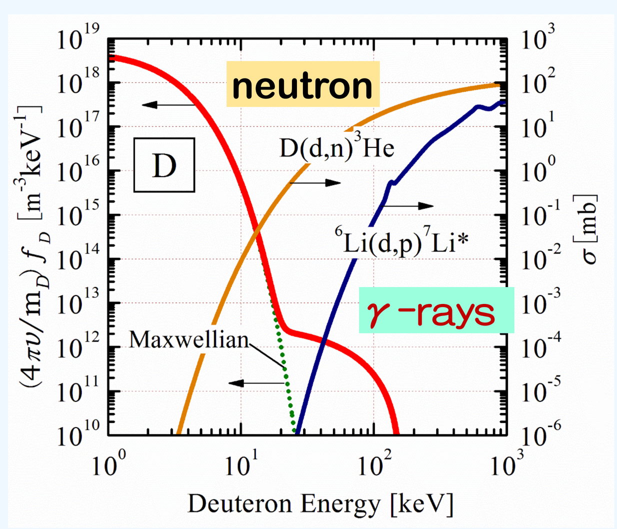

Fig.2 Knock-on tail and cross sections for the neutron/γ-ray generating reactions.

Nuclear elastic scattering [1]

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{NES}} \equiv \left(\frac{d\sigma}{d\Omega}\right)_{\text{Total (measured)}} - \left(\frac{d\sigma}{d\Omega}\right)_{\text{Coulomb}}$$

Large-angle scattering process

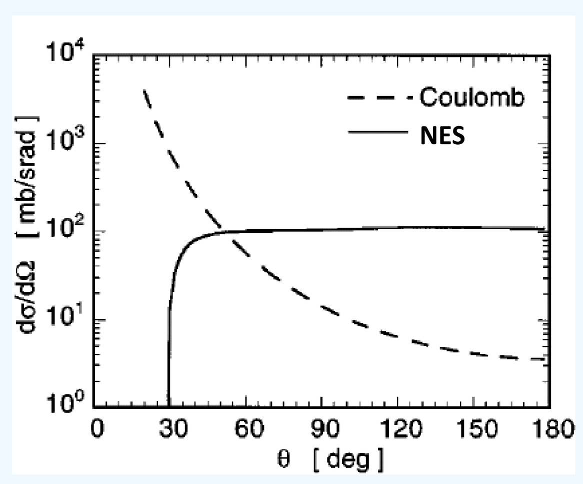

Fig.3 NES differential cross section.
(L. Ballabio, et al., PRE (1997))

Boltzmann-Fokker-Planck Model [2]

$$\left(\frac{\partial f_f}{\partial t}\right)^{C} + \sum_i \left(\frac{\partial f_f}{\partial t}\right)_i^{\text{NES}} + \frac{1}{v^2}\frac{\partial}{\partial v}\left(\frac{v^3 f_f}{2\tau_C^*(v)}\right) + S_f(v) - L_f(v) = 0$$

FP term | NES term | diffusion in velocity space due to thermal conduction | source | particle loss from plasma

$$S_f(v) - L_f(v) = \frac{S_f}{4\pi v^2}\delta(v - v_0) - \frac{f_f(v)}{\tau_p^*(v)}, \quad \tau_{c(p)}^*(v) = \begin{cases} C_{c(P)}\tau_{c(P)} & \text{when } v < v_{th} \\ C_{c(P)}\tau_{c(P)}(v/v_{th})^{\gamma} & \text{when } v \geq v_{th} \end{cases}$$

OUTCOME

OBSERVATION OF NES EFFECT ON FAST-ION SLOWING-DOWN PROPERTIES

We had expected that the neutron decay process would be disturbed by the knock-on effect of energetic protons. We observed that the decay process was actually delayed (decay time increased) with increasing the intensity of the injected hydrogen beam power.

COMPARISON WITH THE BFP SIMULATION

The simulations reproduced the experimentally measured phenomena with several parameters.

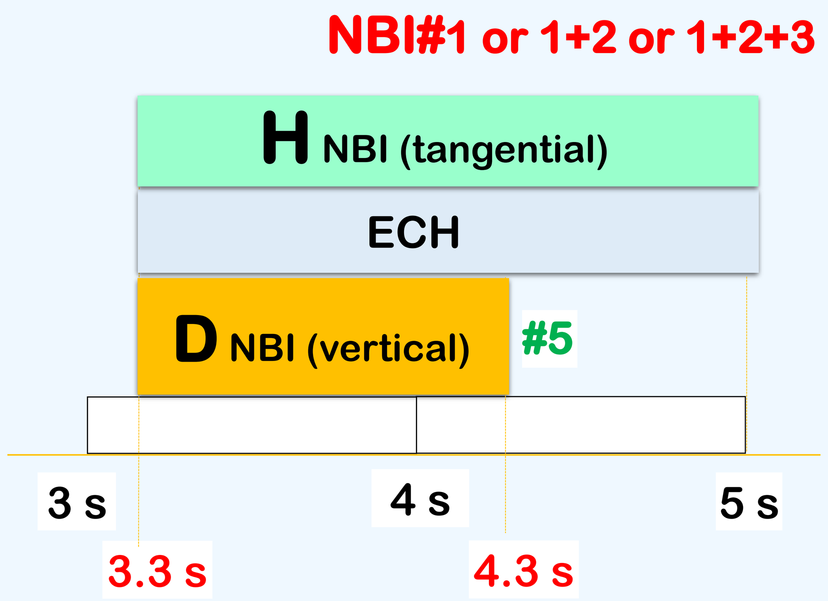

Fig.4 Beam injection and plasma heating pattern.

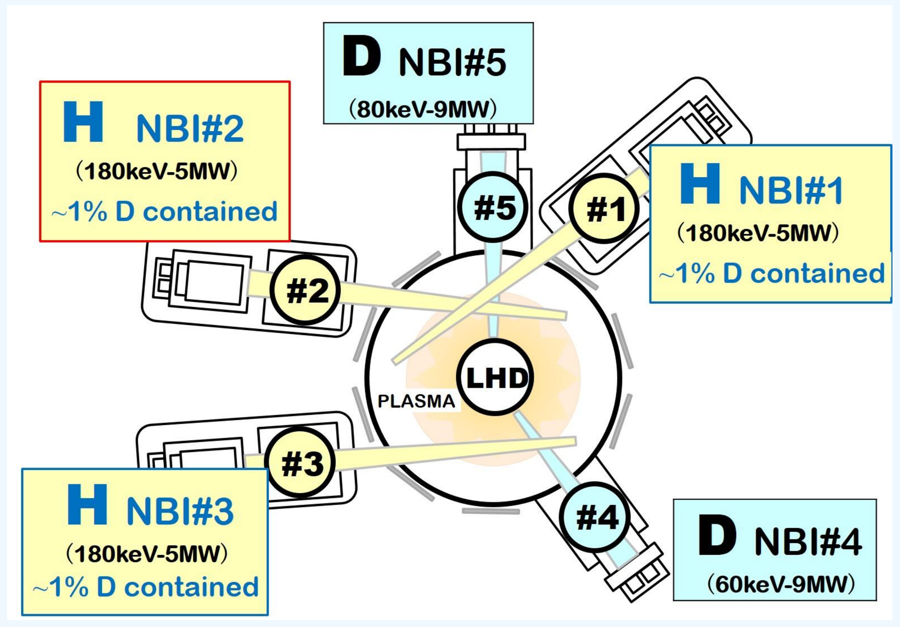

Fig.5 NBI systems in the LHD.

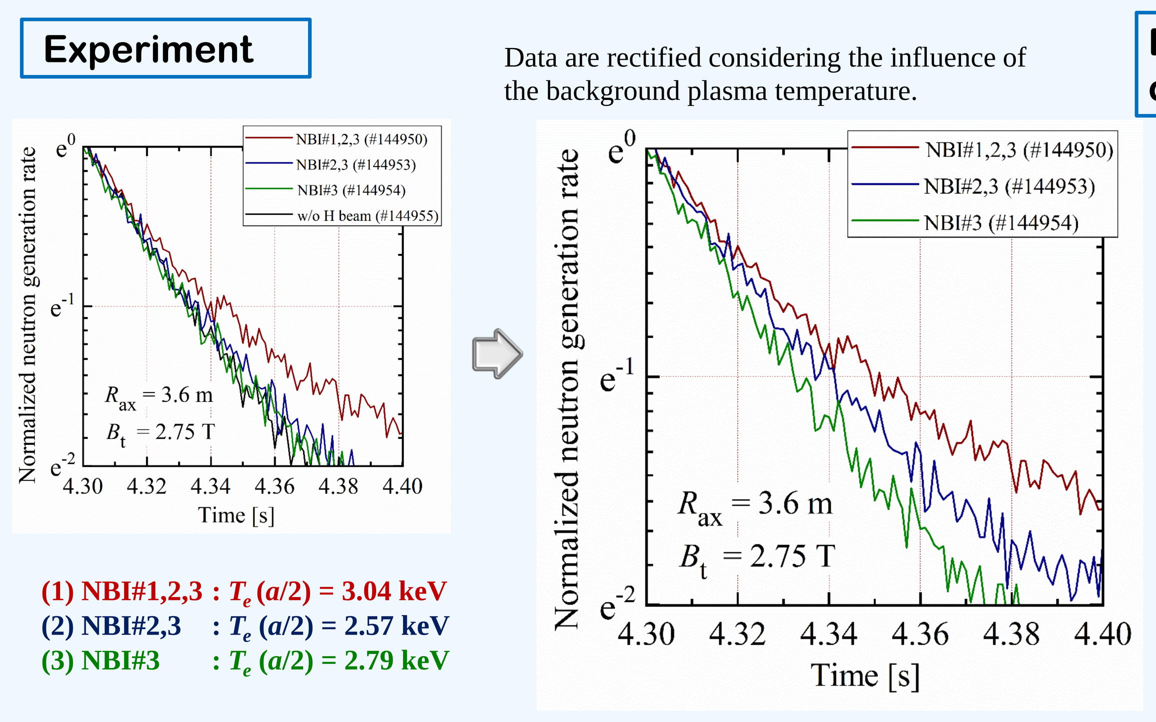

Fig.6 Observed decay process of DD neutron generation rates after terminating the NBI#5.

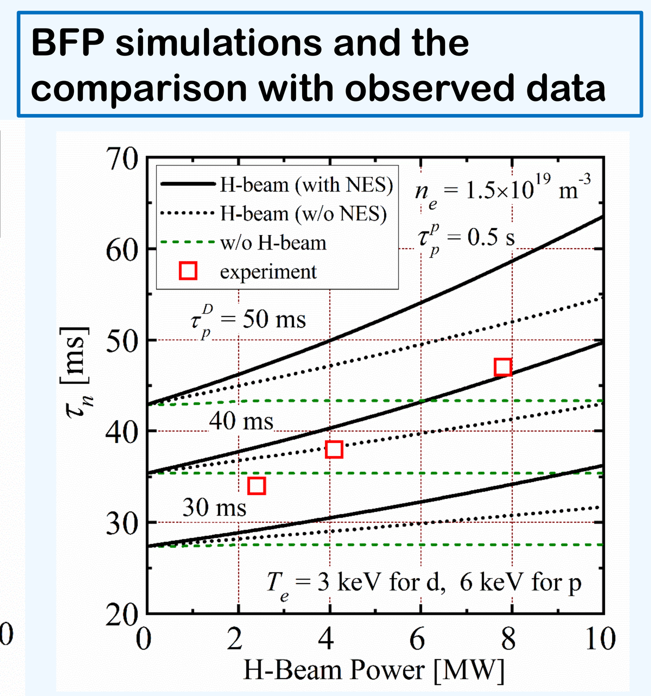

Fig.7 Decay times of DD neutrons as a function of H-beam injection power.

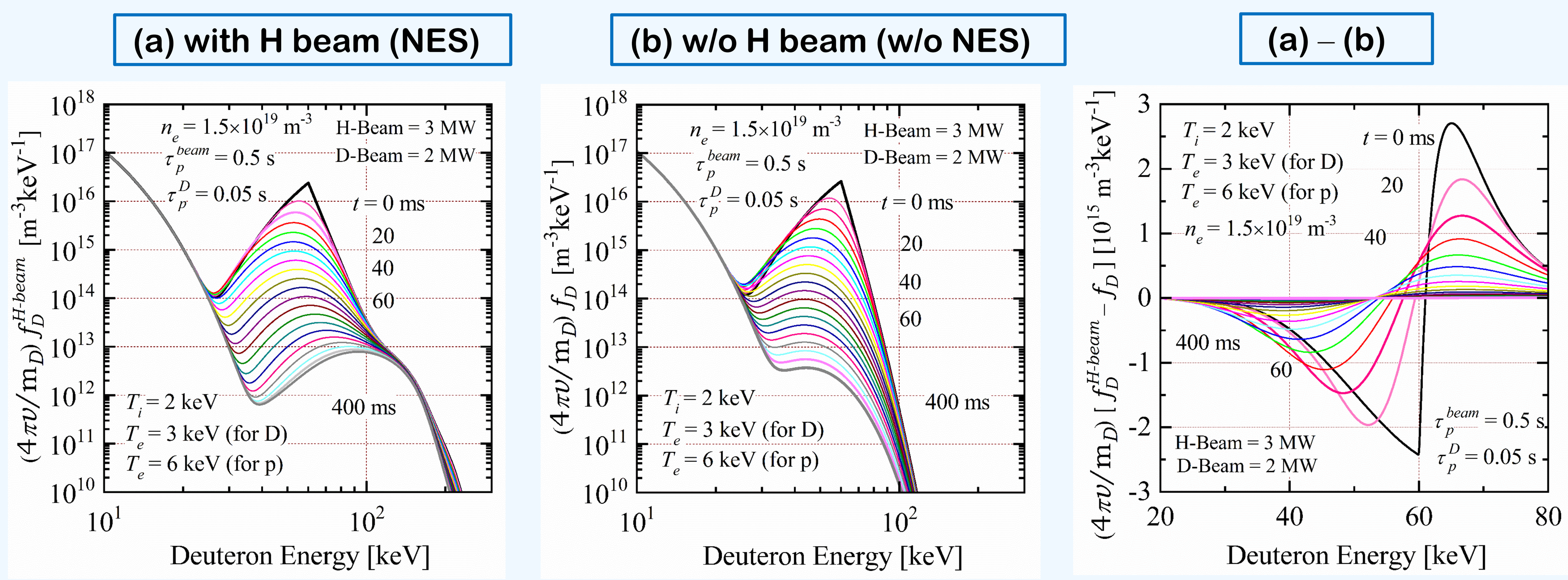

Fig.8 Time evolutions of deuteron distribution functions with/without H-beam injection.

CONCLUSION

- In the LHD plasma, it was observed that the DD neutron decay time was delayed by the fast H-beam injection. The decay time depended on the H-beam injection power.
- The experimental result was analyzed by using the BFP model assuming several plasma parameters.
- The results can be explained by considering the NES effect in addition to the heating via Coulomb collisions.
- The NES effect becomes more influential as beam-injection energy increases. The effect will be important in reactor-grade plasmas.

ACKNOWLEDGEMENTS / REFERENCES

- The authors would like to thank the cooperative program of NIFS 17KLPH029 and the LHD experimental team for their contributions.

[1] J. J. Devaney and M. L. Stein, Nucl. Sci. Eng., **46** (1971) 323.
[2] H. Matsuura, et al., Plasma Phys. Contr. Fusion, **53** (2011) 035023.