Use of γ-Ray-Generating ^{6}Li+D Reaction for Verification of Boltzmann-Fokker-Planck Simulation and Knock-on Tail Diagnostics in Neutral-Beam-Injected Plasmas

by

H.Matsuura, M.Nakamura, Y.Nakao

Department of Quantum Physics and Nuclear Engineering,
Kyushu University, Motooka, Fukuoka 819-0395, Japan

e-mail: mat@nucl.kyushu-u.ac.jp
TEL: +81-92-802-3508
FAX: +81-92-802-3508

Presented at ITC16
(December 5-8, 2006, Toki, Japan)

Introduction

It is well known that the nuclear elastic scattering (NES) contributes to a certain extent to the slowing-down of suprathermal ions in fusion plasmas. In conceptual designs of next-generation fusion devices, 3.52-MeV α-particles are continuously produced and use of beam injection with energy more than 1 MeV is also considered. In this case, the NES effects on slowing down of energetic particles may not be negligible compared with those due to Coulomb collisions.

To know the NES effect on reaction rate coefficient and diagnose the plasma parameters in knock-on-tail-created plasmas, the analysis model which can consistently treat the distortion of bulk component of fuel-ion velocity distribution functions is required. We have evaluated the NES effect on burning plasma properties in ITER-like plasmas[1-3] on the basis of the Boltzmann-Fokker-Planck (BFP) model. For forthcoming burning experiments, verification of the BFP model by comparing with measured data in currently existing fusion devices would be meaningful.

In this paper, the BFP calculations are performed assuming 50~250keV proton beam injection into the ^{6}Li containing deuterium plasmas (n_e~10^{19}m^{-3} and T=1~10keV) and knock-on tail formation in deuteron distribution function due to NES by injected proton is examined. Using the obtained deuteron distribution function, the 0.5MeV γ-ray emission rate by ^{6}Li(d,p)^{7}Li*, ^{7}Li*→^{7}Li+γ[4,5] reactions is evaluated for various plasma states.
The experiment to verify the BFP numerical model is proposed.

[1] H.Matsuura, Y.Nakao, K.Kudo, *Nuclear Fusion,* ***39*** , 145 (1999).
[2] H.Matsuura, Y.Nakao, *Physics Plasmas,* ***13*** , 062507 (2006).
[3] H.Matsuura, et al., *(Proc. of ITC-14, Toki Japan, 2004), J. Plasma Fusion Research Series* ***7***, 98 (2006).
[4] V.T.Voronchev, V.I.Kukulin, Y.Nakao, *Phys. Rev. E,* ***63***, 26413-1 (2001).
[5] M.Nakamura, et al., *J. Phys. Soc. Japan,* ***75***, 024801 (2006).

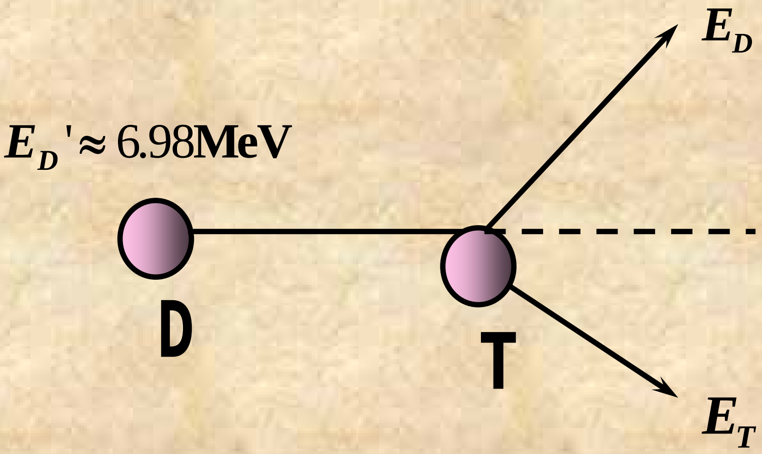
Important Points：

- The NES Effect tends to be significant with decreasing bulk density.
- To look at the knock-on tail effect clearly, it is desirable that the injected-beam specie is different from the background ion species.
- The NES cross-section between proton and deuteron is comparably large compared with deuteron-deuteron one.
- In currently-existing devices, NBI power per unit volume is larger than that in ITER.
- In low temperature plasmas, the ^{6}Li (d,p)^{7}Li reaction rate coefficient is sensitively influenced by energetic (tail) component.

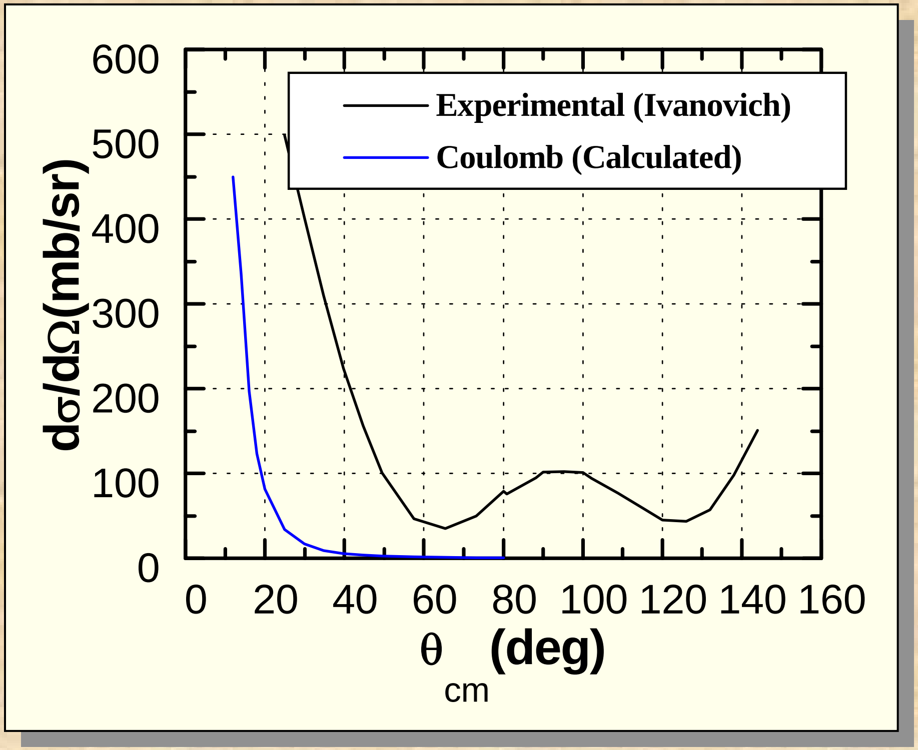
Idea：

- **We consider 50~250keV proton beam injection into the ^{6}Li containing low density and low temperature plasmas.**
- **By measuring the 0.5MeV γ-ray emission rate from ^{6}Li(d,p)^{7}Li*, ^{7}Li*→^{7}Li+γ reaction, we can estimate the energy range and intensity of the knock-on tail. Comparing the measured date with the ones obtained from BFP simulations, we can verify the BFP model.**

Nuclear Elastic Scattering (NES)



M.Ivanovich, et al., Nucl. Phys. A110 (1986) 441.



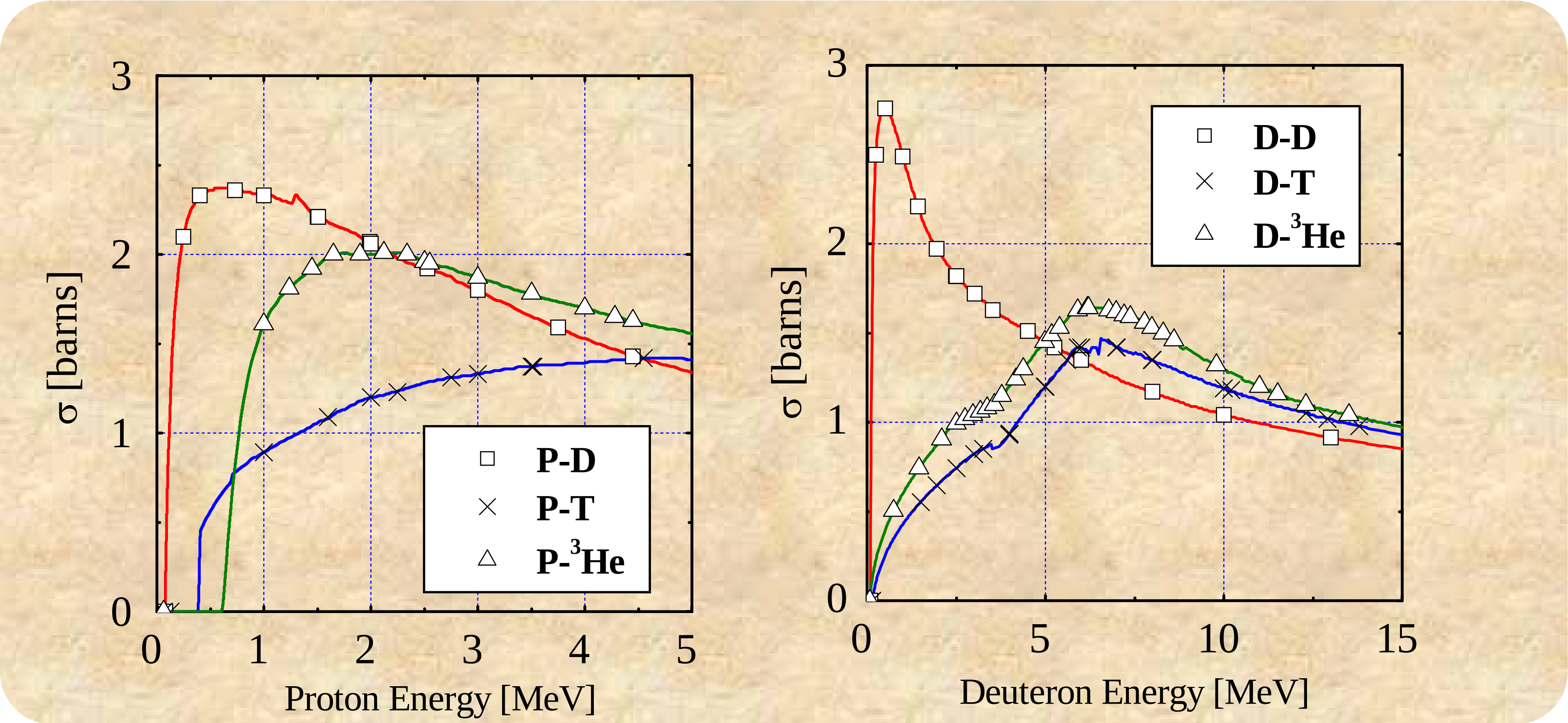
- **Definition of NES cross sections**

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

⇨

$$\sigma_{\text{NES}}(E) = 2\pi\int\left(\frac{d\sigma}{d\Omega}\right)_{\text{NES}} d\mu$$

NES cross sections



Large-angle scattering

Large fraction of the fast ion energy is transferred in a single event. (LET effect)

(Coulomb scattering process is characterized by many small energy transfer event.)

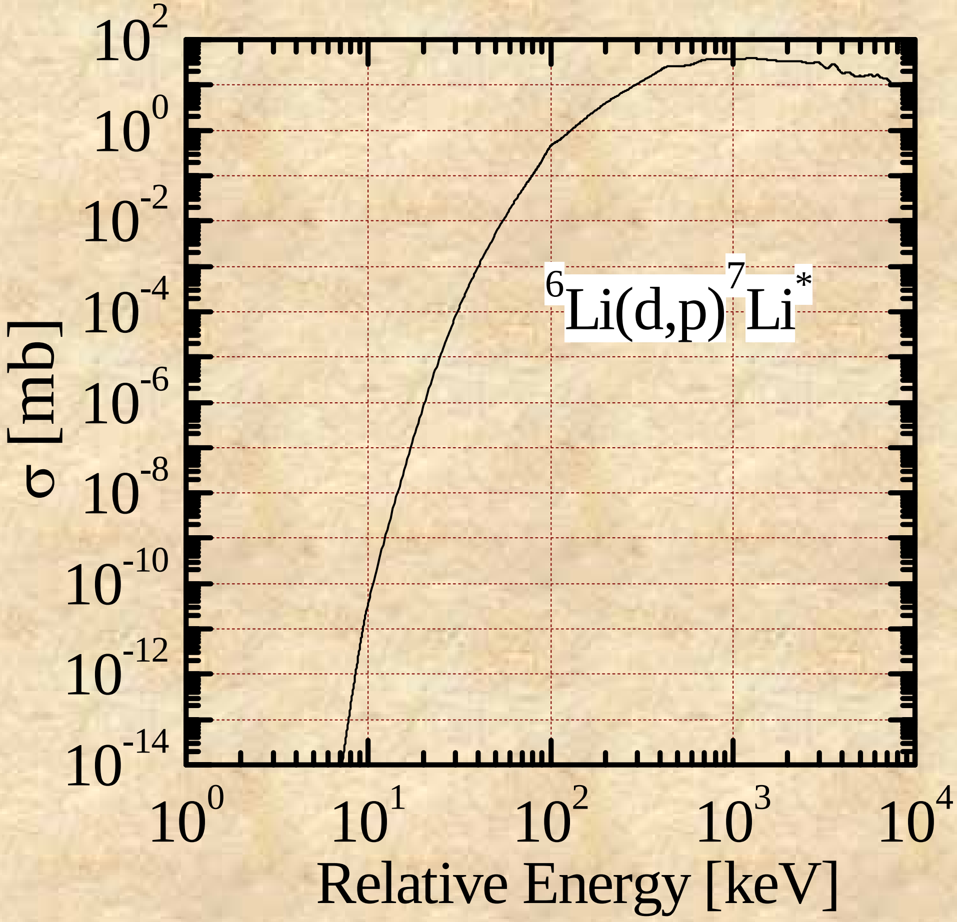
Discrete energy transfer

Continuous slowing-down (CSD) model can not be adopted.

The NES cross-sections data are taken from the work of Perkins and Cullen.

S. T. PERKINS and D. E. CULLEN, "*Elastic Nuclear Plus Interference Cross Sections for Light-Charged Particles*", *Nucl. Sci. Eng.*, 20, 77 (1981).

^{6}Li(d,p)^{7}Li* cross sections



The ^{6}Li(d,p)^{7}Li cross-sections data are taken from the work of Voronchev.
V. T. Voronchev, et al., Mem. Fac. Eng. Kyushu Univ., 51, 63 (1991).

Analysis Model

0 Assumptions

- NES is isotropic in the CM system
- Electron and ^{6}Li are assumed to be Maxwellian.

1 Boltzmann-Fokker-Planck (BFP) Equation

$$\left(\frac{\partial f_a}{\partial t}\right)^{\mathrm{C}} + \sum_i \left(\frac{\partial f_a}{\partial t}\right)_i^{\mathrm{NES}} + \frac{1}{v^2}\frac{\partial}{\partial v}\left(\frac{v^3 f_a}{2\tau_C^*(v)}\right) + S_a(v) - L_a(v) = 0$$

f_a … deuteron and ^{6}Li velocity distribution function

First term in left-hand site	･･･ effect of Coulomb collision
Second term 〃	･･･ effect of NES
Third term 〃	･･･ diffusion in velocity space due to thermal conduction
5th and 6th terms 〃	･･･ source and loss of beam-ions from plasma

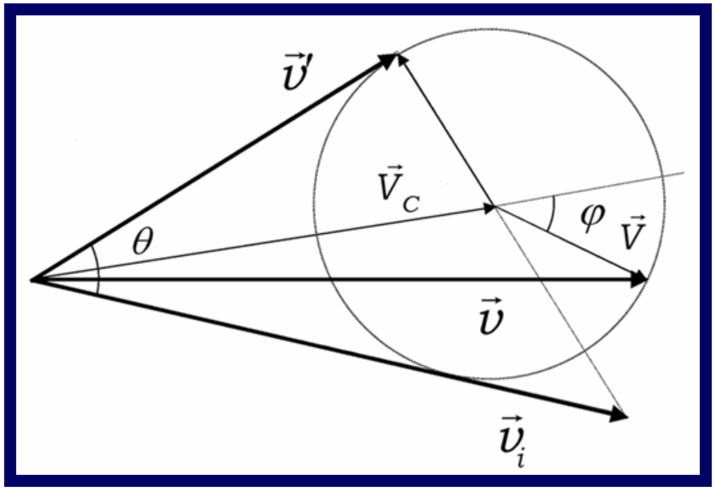
NES Term

$$\left(\frac{\partial f_a}{\partial t}\right)_i^{\text{NES}} = \frac{2\pi}{v^2}\int_0^\infty v' f_a(v')\int_0^\infty v_i f_i(v_i)\mathrm{P}(v' \to v\,|\,v_i)\int_{|v'-v_i|}^{v'+v_i} v_r'^2 \sigma_{\text{NES}}(v_r')\,dv_r'\,dv_i\,dv'$$

$$-\sum_i \frac{2\pi}{v} f_a(v)\int_0^\infty v_i f_i(v_i)\int_{|v-v_i|}^{v+v_i} v_v^2 \sigma_{\text{NES}}(v_r)\,dv_r\,dv_i \qquad i = D, p$$

Probability Distribution Function

$\Big($ probability that the injected beam ion which has the speed v' is scattered into the speed region v owing to the NES with background ion, i.e. deuteron or triton, which has speed v_i $\Big)$



$$P(v' \to v|v_i)dv = \begin{cases} \dfrac{|\vec{v}|}{2|\vec{V}_C||\vec{V}|}dv & ,\text{for } \ |\vec{V}_C - \vec{V}| \le v \le |\vec{V}_C + \vec{V}| \\ 0 & ,\text{otherwise} \end{cases}$$

Suppose the scattering event of ion species a which has the velocity $\vec{v}'$ by ion species i which has the velocity $\vec{v}_i$. Here $\vec{v}$ and $\vec{V}$ represent the velocities of ion species a after the scattering in the laboratory and the center of mass (CM) systems respectively, $\vec{V}_C$ the velocity of center of mass and φ the angle between $\vec{V}_C$ and $\vec{V}$.

Diffusion in velocity space due to thermal conduction :

$$\frac{1}{v^2}\frac{\partial}{\partial v}\left(\frac{v^3 f_a}{2\tau_C^*(v)}\right)$$

where

$$\tau_C^*(v) = C_C \tau_C \mathrm{Max}[1, v/v_0]^{\gamma} \ .$$

the coefficient C_C is determined so that the velocity-integrated energy loss rate becomes $(3/2)nT/\tau_C$

Particle source and loss term

$$S_D(v) - L_D(v) = \frac{S_0}{4\pi v^2}\delta(v - v_0) - \frac{f_D(v)}{\tau_D^*(v)}$$

$$S_p(v) - L_p(v) = \frac{S_{NBI}}{4\pi v^2}\delta(v - v_{\mathrm{NBI}}) - \frac{f_p(v)}{\tau_P^*(v)}$$

$$\frac{1}{\tau_E} = \frac{1}{\tau_P} + \frac{1}{\tau_C}$$

where $S_{\mathrm{NBI}} = P_{\mathrm{NBI}}/(VolE_{\mathrm{NBI}})$, $v_{\mathrm{NBI}} = \sqrt{\frac{2E_{\mathrm{NBI}}}{m_p}}$, $S_0 = n_{\mathrm{D}}/\tau_p$, $v_0 \approx 0$,

$$\tau_P^*(v) = C_P \tau_P \mathrm{Max}[1, v/v_0]^{\gamma} \ .$$

the coefficient C_P is determined so that the velocity-integrated energy loss rate becomes n/τ_P

Reaction rate coefficient :

$$\langle \sigma v \rangle_{^{6}\mathrm{Li(d,p)}^{7}\mathrm{Li}} = \sqrt{8\pi}\left(\frac{m_{Li}}{T}\right)^{3/2} \int dv_{\mathrm{D}} v_{\mathrm{D}} f_{D} \int dv_{\mathrm{Li}} v_{\mathrm{Li}} \exp\left(-\frac{m_{Li}}{2T} v_{Li}^{2}\right) \left[\int_{|v_{\mathrm{D}}-v_{\mathrm{Li}}|}^{v_{\mathrm{D}}+v_{\mathrm{Li}}} dv_{r} v_{r}^{2} \sigma_{^{6}\mathrm{Li(d,p)}^{7}\mathrm{Li}}(v_{r}) \right]$$

The ^{6}Li(d,p)^{7}Li cross-sections data are taken from the work of Voronchev.
V. T. Voronchev, et al., Mem. Fac. Eng. Kyushu Univ., 51, 63 (1991).

Reactivity enhancement parameter η :

$$\eta = \left(\frac{\langle \sigma v \rangle_{^{6}\mathrm{Li(d,p)}^{7}\mathrm{Li}}}{\langle \sigma v \rangle^{\mathrm{Maxwell}}_{^{6}\mathrm{Li(d,p)}^{7}\mathrm{Li}}} - 1 \right) \times 100\,[\%]$$

We estimate the deuteron temperature T_{eff} when knock-on tail is created by comparing thermal component of the obtained distribution function with Maxwellian by mean of method of least squares.

$\langle \sigma v \rangle^{\mathrm{Maxwelli}}_{^{6}\mathrm{Li(d,p)}^{7}\mathrm{Li}}$ · · · · reactivity when both deuteron and triton are assumed to be Maxwellian at temperature T_{eff}

Deuteron distribution function

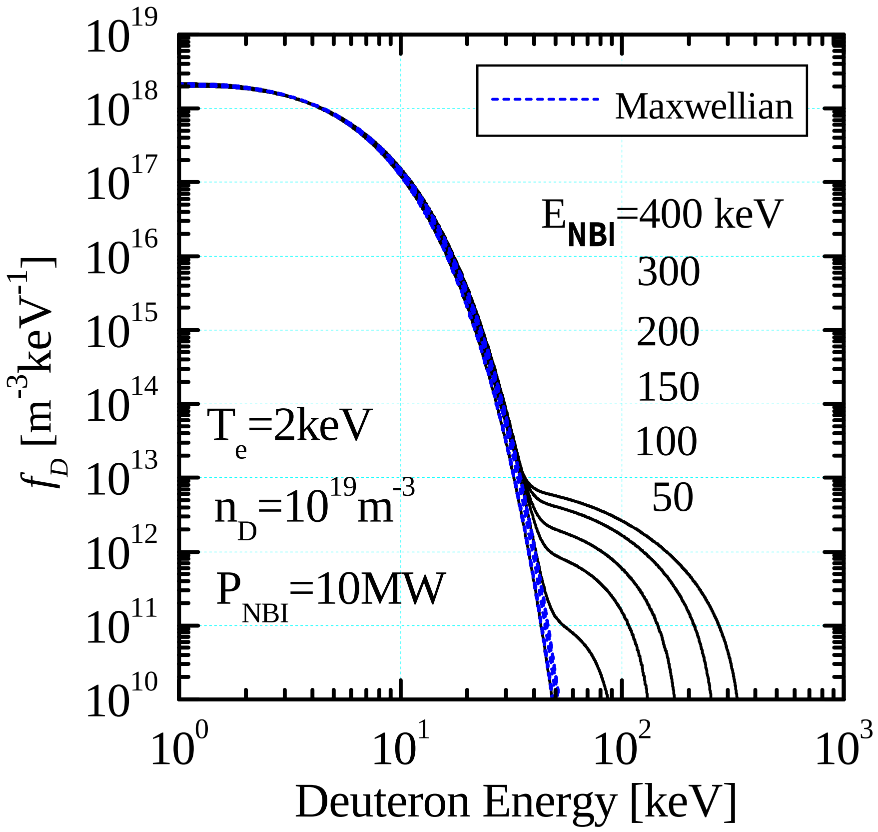
Calculation condition:

$$n_D = n_e = 10^{19} m^{-3}$$

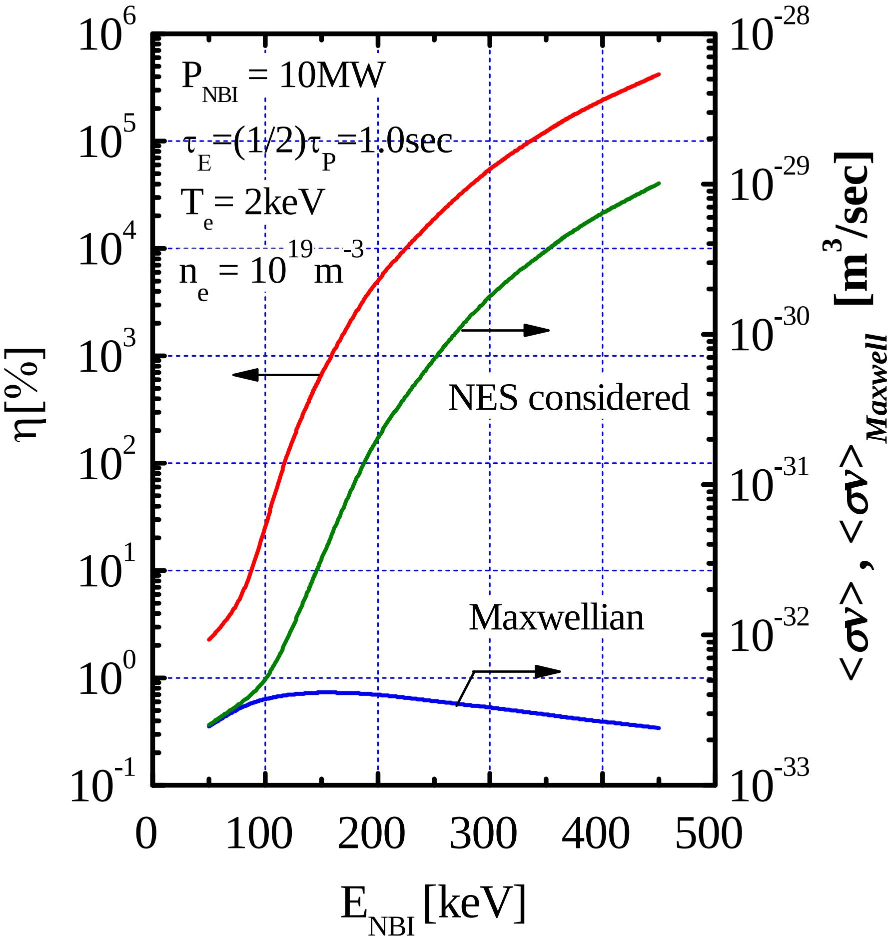
$$\tau_E = (1/2)\tau_p = 1\sec$$

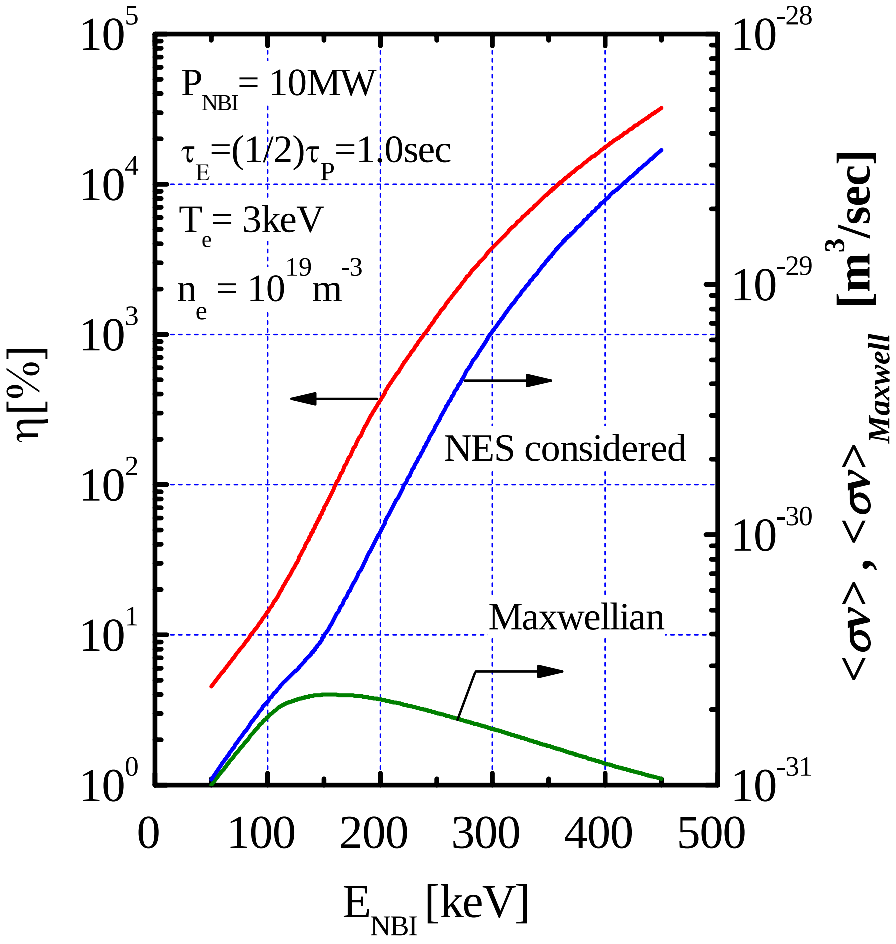
$$P_{NBI} = 10\text{MW}$$

$$V = 100\text{m}^3$$

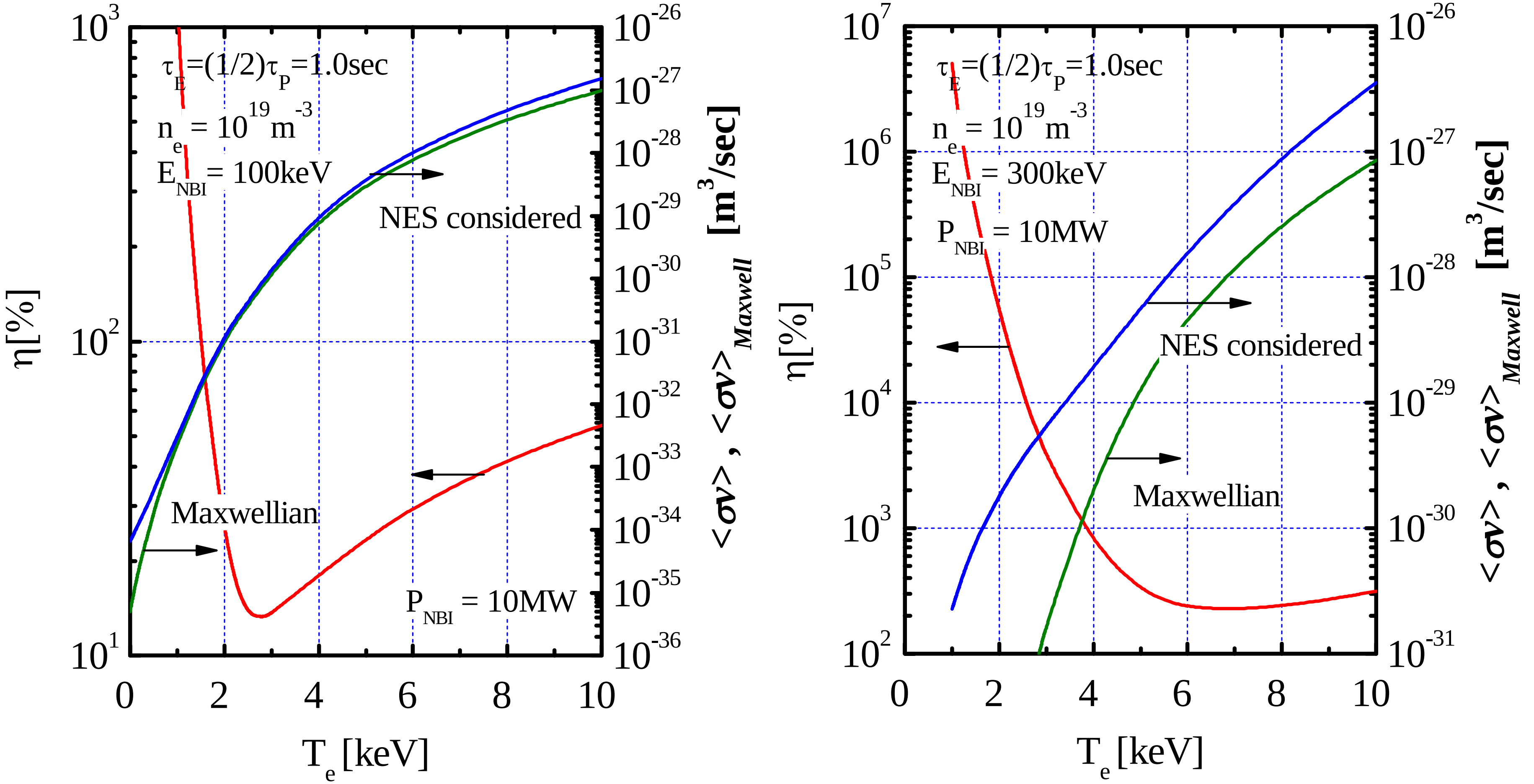


^{6}Li(D,p)^{7}Li reaction rate coefficient and η parameter

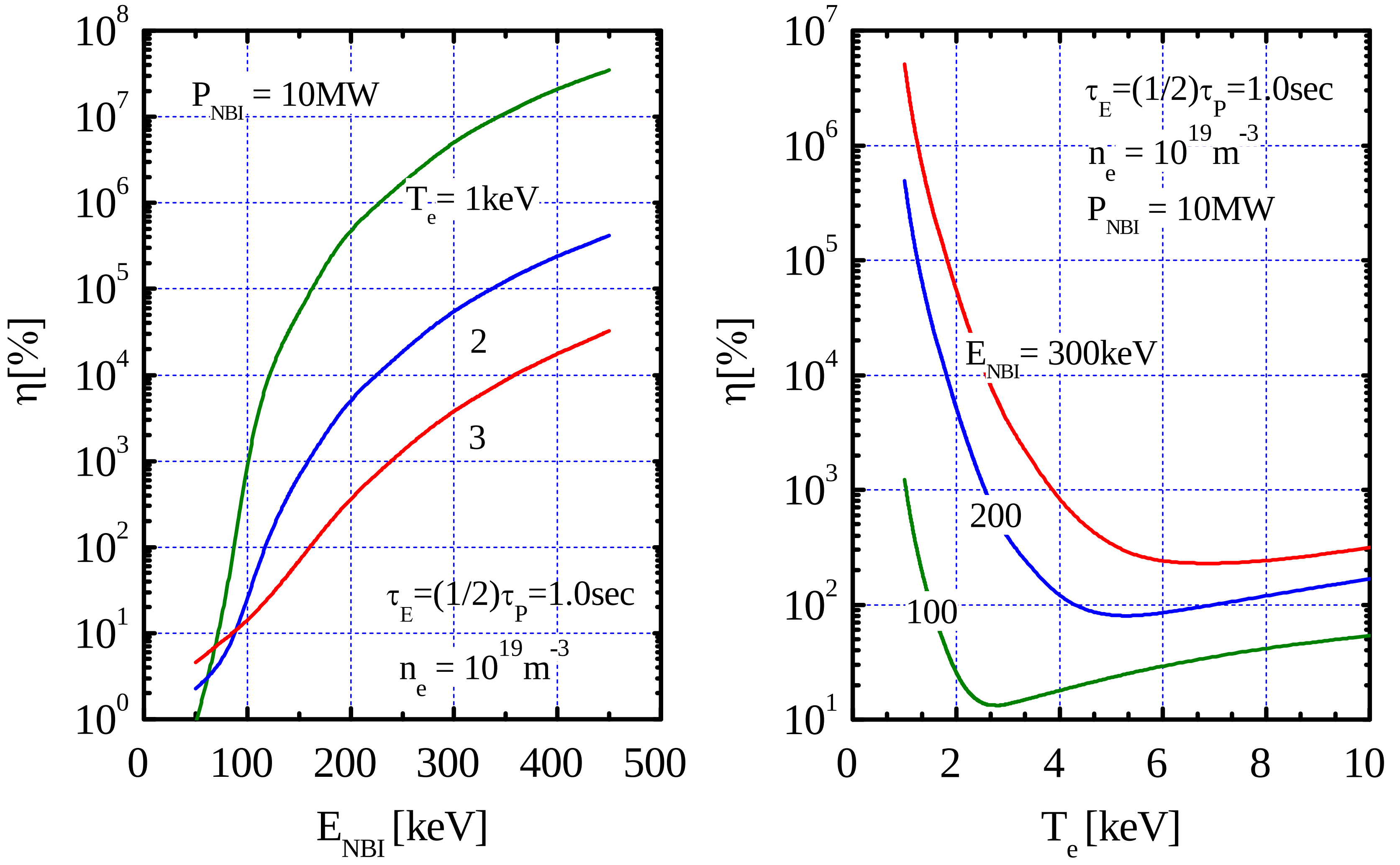




^{6}Li(D,p)^{7}Li reaction rate coefficient and η parameter



^{6}Li(D,p)^{7}Li reaction rate coefficient and η parameter



Summary

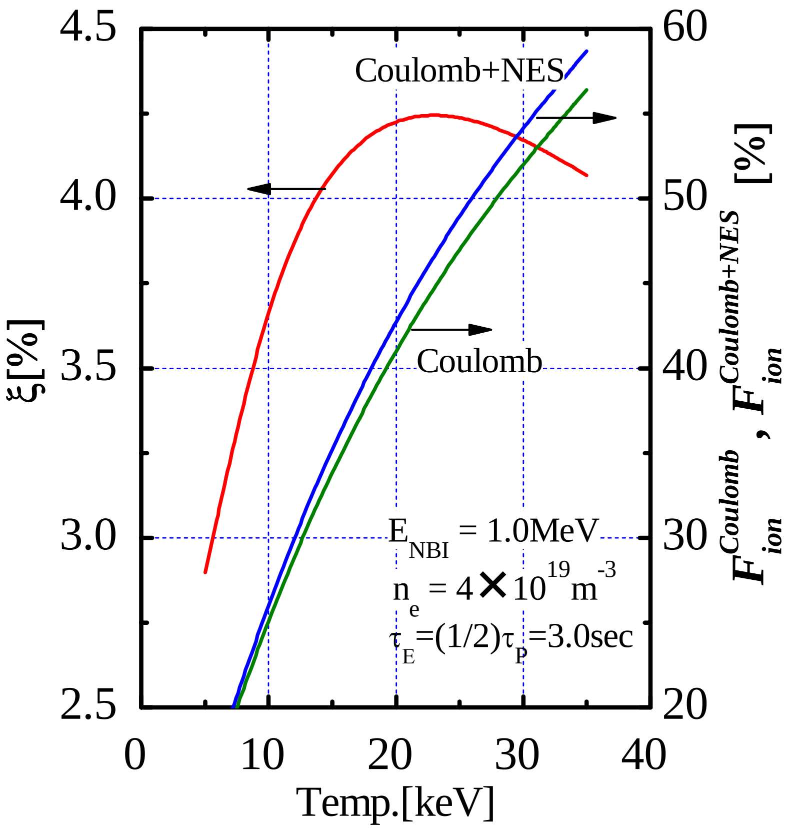
- On the basis of the BFP model, the enhancement of the ^{6}Li(d,p)^{7}Li* reaction rate coefficient due to knock-on tail formation in deuteron distribution function when proton beam in injected 6Li containing plasma has been evaluated.

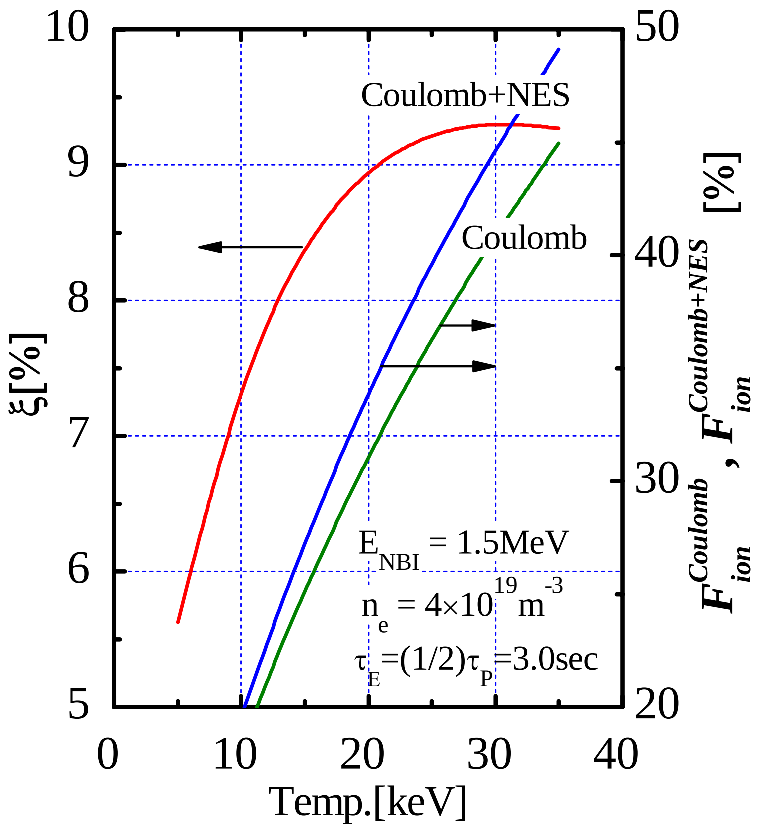
  For T=2keV, E_{NBI}=230keV, n_e=10^{19}m^3, τ_E=(1/2)τ_P=1sec, the enhancement in the ^{6}Li(d,p)^{7}Li reaction rate coefficient reaches almost ~10^4.

  If we consider a deuteron plasma containing 1 percent of ^{6}Li to deuteron, the 0.5MeV γ-ray emissin rate is roughly estimated as ~5×10^7cps.

- A possible experiment to verify the BFP simulation on currently-existing fusion devices, i.e. observation of the 0.5MeV γ-ray emission rate from ^{6}Li(d,p)^{7}Li*, ^{7}Li*→^{7}Li+γ reaction, is presented.

Appendix Ⅰ : NES effect in DT Thermonuclear Plasmas
(Enhancement of fractional NBI-power deposition to ions)



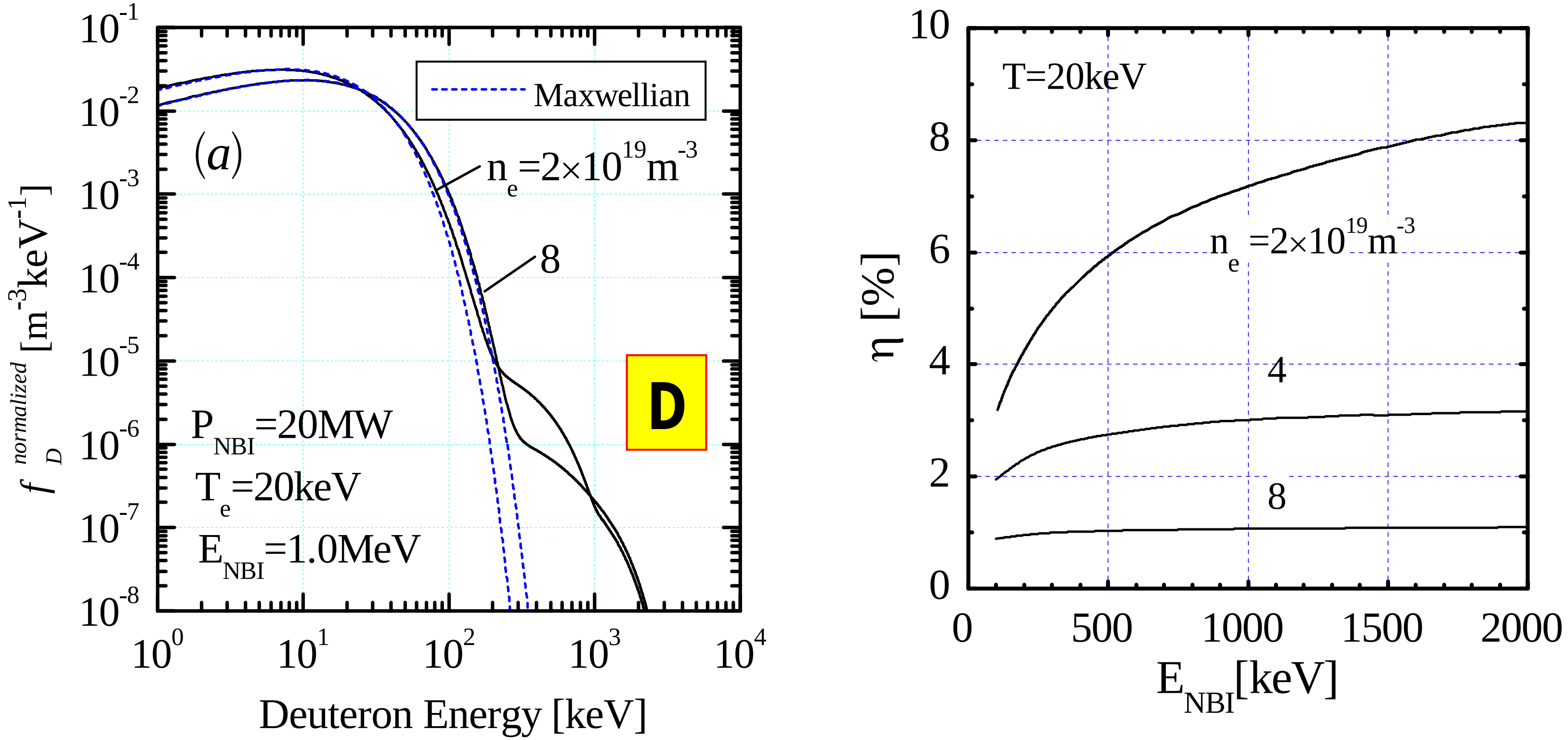


- **The enhancement in the fraction becomes appreciable in 10-30keV temperature range.**
- **In low-temperature range the slowing down of energetic ions is intensified, thus the high-energy component in beam-ion distribution functions becomes relatively small. On the other hand, in high-temperature range, relative velocity between beam and background ions becomes small, and contribution of NES is reduced compared with Coulomb ones.**

[H.Matsuura, Y.Nakao, *Physics Plasmas*, ***13*** , 062507 (2006).]

Appendix II : NES effect in DT Thermonuclear Plasmas

(① Deuteron distribution function when 1MeV deuterium beam is injected
② $T(d,n)^4He$ reactivity enhancement)



The reactivity is compared between solid lines (present calculations) and dotted lines (Maxwellian of temperature T_{bulk}). The temperature T_{bulk} is estimated by comparing thermal component of the obtained distribution function with Maxwellian by mean of method of least squares.

- Tail (non-Maxwell component) is created in several hundreds-keV energy range of fuel-ion distribution functions owing to NES by high-energy beam ions.
- For small beam-injection energy, the enhancement is small. This is because the NES cross-sections are small in this energy range.