Diagnostic scenario for beryllium impurity concentration utilizing modified alpha-particle emission spectrum in DT fusion plasmas

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The alpha-particle emission spectrum in deuterium-tritium (DT) fusion plasmas accompanied with neutral-beam-injection (NBI) heating is evaluated by solving the Boltzmann-Fokker-Planck (BFP) equations for deuteron, triton and α-particle simultaneously. Using the obtained velocity distribution function of α-particle, emission rate of 3.21-MeV γ-ray generated by ^{9}Be($\alpha,n\gamma$)^{12}C reaction is evaluated for various plasma parameters. By comparing the obtained 3.21-MeV γ-ray emission rate with the one experimentally measured, the concentration of ^{9}Be ions could be estimated. The possibility of a diagnostic scenario for beryllium concentration in DT plasmas using ^{9}Be($\alpha,n\gamma$)^{12}C γ-ray emitting reaction is presented.

Keywords: α-particle, emission spectrum, γ-ray, velocity distribution function, concentration of beryllium

1. Introduction

It is well known that in deuterium-tritium (DT) plasmas knock-on tail [1-6] is created in fuel-ion velocity distribution function by nuclear elastic scattering (NES) [7,8] of fusion-produced α-particle. The knock-on tail is also formed by neutral-beam-injection (NBI) heating [4,5] and/or ion cyclotron range of frequency (ICRF) heating [9]. We showed that knock-on tail in fuel-ion distribution function becomes large when NBI heating is applied [4,5]. In such a beam-injected plasma, the α-particle energy spectrum is broadened more widely than that in plasmas without beam injection and energetic α-particle (>3.5 MeV) increases. Using Boltzmann-Fokker-Planck (BFP) model and considering simultaneously the distortion of deuteron, triton and α-particle distribution functions, we evaluated the modified α-particle emission spectrum [10].

For the first protective armor of ITER, beryllium is being considered as the candidate material. In fusion reactors, it is predicted that interactions between plasma and first-wall material cause beryllium sputtering and irruptions into plasmas, and beryllium impurity in plasma induces additional bremsstrahlung loss and/or various nuclear reactions [11]. To use the beryllium as a diagnostic tool [12-14] and clarify the effects of bremsstrahlung loss by beryllium impurity, diagnostics of beryllium concentration in burning plasmas has been required. To diagnose the influx in divertor plasmas and the relative concentration of impurities in core plasma, divertor impurity monitor and ultraviolet spectroscopy have been developed respectively [15].

In this paper, 3.21-MeV γ-ray-emitting ^{9}Be($\alpha,n\gamma$)^{12}C reaction is considered as a diagnostic tool of beryllium impurity concentration in DT plasmas accompanied with injection of a mono-energetic deuterium beam. The 3.21-MeV γ-ray is emitted through the transition from second excited state (7.65MeV) to first excited state (4.44 MeV) of ^{12}C.

$$\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C}^{*}\ [7.65] + \mathrm{n},$$
$$\mathrm{C}^{*}[7.65] \rightarrow {}^{12}\mathrm{C}^{*}[4.44]\ + \gamma\ \ (E_{\gamma} = 3.21\,\mathrm{MeV})$$

The cross section of this process is shown in Fig. 1

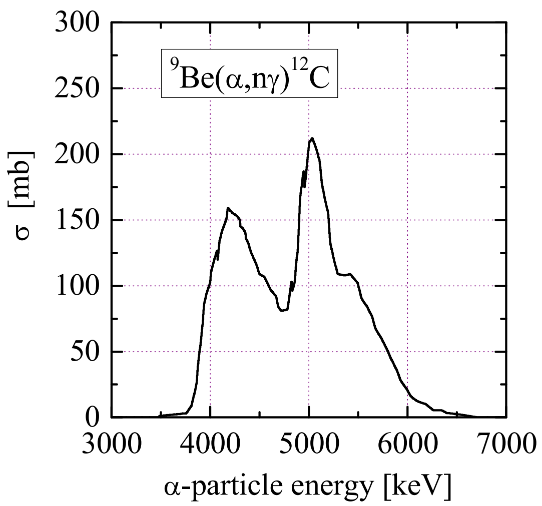

Fig. 1 The cross section of ^{9}Be($\alpha,n\gamma$)^{12}C reaction with 3.21-MeV γ-ray emission [12-14].

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[12-14]. Since the cross section of this reaction rapidly increases in the energy range above ~3.8 MeV, the emission rate of 3.21-MeV γ-ray from ^{9}Be(*α,nγ*)^{12}C reaction would sensitively respond to the modification of the α-particle emission spectrum which is broadened toward high energy region by NBI heating.

We accurately evaluate the energetic (>3.8 MeV) component of the α-particle velocity distribution function considering the modification of α-particle emission spectrum on the basis of BFP model. Using the obtained α-particle distribution function, the 3.21-MeV γ-ray emission rate by ^{9}Be(*α,nγ*)^{12}C reaction is evaluated. By comparing the obtained 3.21-MeV γ-ray emission rate with the one experimentally measured, the concentration of ^{9}Be ions could be estimated. A scenario to diagnose the concentration of ^{9}Be using ^{9}Be(*α,nγ*)^{12}C γ-ray emitting reaction is presented.

2. Analysis model

The velocity distribution function for ion species *a* (*a*= D, T and α-particle) are evaluated by solving the following BFP equation.

$$\sum_j \left(\frac{\partial f_a}{\partial t}\right)^C + \sum_i \left(\frac{\partial f_a}{\partial t}\right)_i^{NES} + \frac{1}{\upsilon^2}\frac{\partial}{\partial \upsilon}\left(\frac{\upsilon^3 f_a}{2\tau_c^*(\upsilon)}\right) + S_a(\upsilon) - L_a(\upsilon) = 0\ , \quad (1)$$

where $f_a(\upsilon)$ is the velocity distribution function of the species *a*. For simplifications, plasma is assumed to be spatially uniform. The first term in the left-hand side of Eq.(1) represents the effect of the Coulomb collisions. The summation is taken over all back ground species, i.e. *j*=D, T, α-particle and electron. The collision term is hence non-linear, retaining collisions between ions of the same species. The second term accounts for the NES of species *a* by back ground ions. We consider NES between α-particle and D, and between α and T, i.e., (*a*,*i*) = (D,α), (T,α), (α,D) and (α,T). The NES cross-sections are taken from the work of Perkins and Cullen [8].

The third term in the left-hand side of Eq.(1) represents the diffusion in velocity space due to thermal conduction. To incorporate the unknown loss mechanism of energetic ions into the analysis, we simulate the velocity-dependence of the energy-loss due to thermal conduction and the particle-loss time (see Ref.4-6).

The source [$S_a(\upsilon)$] and loss [$L_a(\upsilon)$] terms take different form for every ion species. For deuteron, the source and loss terms are described so that the fueling, beam-injection, transport loss and the loss due to T(*d,n*)^{4}He reaction are balancing each other. The NBI rate per unit volume S_{NBI} is expressed using the beam energy E_{NBI} and injection power P_{NBI}, i.e., $S_{NBI} = P_{NBI}/(E_{NBI}V)$. Here *V* represents the plasma volume and V = 800 m^3 is assumed. For triton the NBI injection term has not been included, and the source and loss terms are described so that fueling rate, transport loss, and the loss due to T(*d,n*)^{4}He reaction are balancing.

For α-particle, the source term due to T(*d,n*)^{4}He reaction is written as

$$S_a(\upsilon) = \frac{(dE/dv)}{4\pi\upsilon^2}\frac{dN_a}{dE}. \quad (2)$$

Here N_a represents the α-particle generation rate. Its energy spectrum is described as

$$\frac{dN_\alpha}{dE}(E) = \iiint f_D\left(\left|\vec{\upsilon}_D\right|\right) f_T\left(\left|\vec{\upsilon}_T\right|\right)\frac{d\sigma}{d\Omega} \times \delta(E - E_\alpha)\left|\vec{\upsilon}_D - \vec{\upsilon}_T\right| d\vec{\upsilon}_D d\vec{\upsilon}_T d\Omega\ , \quad (3)$$

where *dσ/dΩ* is the differential cross section of T(*d,n*)^{4}He reaction and E_α represents the α-particle energy in laboratory system :

$$E_\alpha = \frac{1}{2}m_\alpha V_c^2 + \frac{m_n}{m_\alpha + m_n}(Q + E_r) + V_c \cos\theta_c \sqrt{\frac{2m_\alpha m_n}{m_\alpha + m_n}(Q + E_r)}\ , \quad (4)$$

where $m_{\alpha(n)}$ is the α-particle (neutron) mass, V_c is the center- of-mass velocity of the colliding particles, θ_c is the angle between the center-of-mass velocity and the α-particle velocity in the center-of-mass frame. The E_r represents the relative energy :

$$E_r = \frac{1}{2}\frac{m_D m_T}{m_D + m_T}\left|\vec{\upsilon}_D - \vec{\upsilon}_T\right|^2 . \quad (5)$$

The cross section of T(*d,n*)^{4}He reaction is taken from the work of Drosg [16] and Bosch [17].

From the obtained velocity distribution function of α-particle, emission rate of 3.21-MeV γ-ray from ^{9}Be(*α,n*)^{12}C reaction can be evaluated;

$$Y_{\gamma(3.21)} = 8\pi^2 V \int d\upsilon_\alpha \upsilon_\alpha f_\alpha(\upsilon_\alpha) \times \int d\upsilon_{^9Be}\upsilon_{^9Be} f_{^9Be}(\upsilon_{^9Be}) \times \left[\int_{|\upsilon_\alpha - \upsilon_{^9Be}|}^{\upsilon_\alpha + \upsilon_{^9Be}} d\upsilon_r \upsilon_r^2 \sigma_{^9Be(\alpha,n)^{12}C}(\upsilon_r)\right] \quad (6)$$

where υ_r is relative velocity between ^{9}Be and α-particle. The velocity distribution function of beryllium is assumed to be Maxwellian at the temperature same as bulk ion temperature. Because the mass of ^{9}Be is larger than fuel

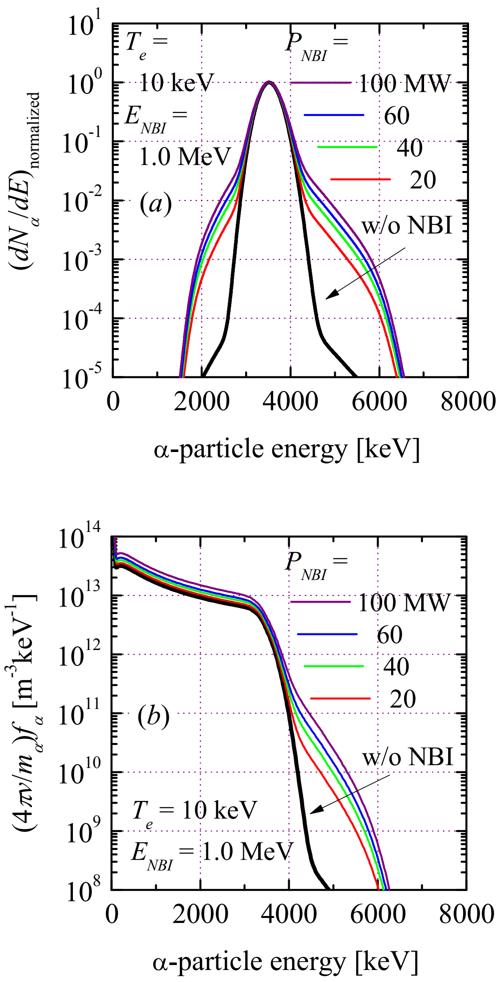

Fig. 2 (a) α-particle emission spectrums and (b) α-particle distribution functions for several NBI powers at T_e =10 keV.

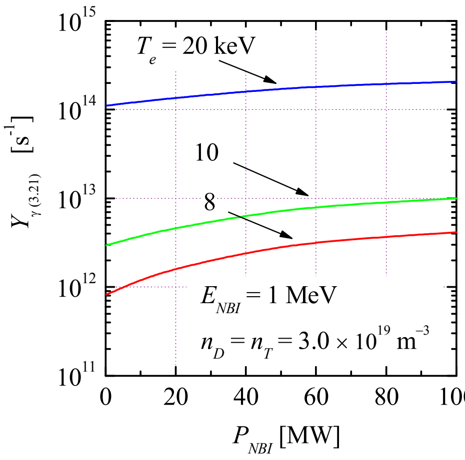

Fig. 3 Emission rate of 3.21-MeV γ-ray from ^{9}Be($\alpha,n\gamma$)^{12}C reaction as functions of P_{NBI} for several T_e.

ions, distortion of velocity distribution function, e.g. due to NES, would be negligible.

3. Results and Discussion

In Fig. 2, we show (a) the α-particle emission spectrums and (b) the α-particle distribution functions when 20, 40, 60 and 100 MW NBI heating is applied. In this calculation, electron temperature T_e =10 keV, ion densities n_D = n_T = 3×10^{19} m^{-3}, energy and particle confinement times τ_E = (1/2)τ_p = 3 sec and beam-injection energy E_{NBI} = 1 MeV are assumed. It is found that the α-particle energy spectrum is broadened to high energy region by NBI heating and that energetic components (> 3.8 MeV) are formed in α-particle distribution functions. The bold line represents the distribution function in the case without NBI heating. It is found that the energetic (>3.8 MeV) components are formed owing to the NES of fusion-produced α-particle [1] even if the beam is not injected. The broadness of the emission spectrum (as well as the relative concentration of the energetic (>3.8 MeV) α-particle component) becomes larger with increasing beam injection powers. In Fig. 3, the 3.21-MeV γ-ray emission rate from ^{9}Be(α,n)^{12}C reaction is shown as a function of beam-injection power P_{NBI} for several electron temperatures. The calculation parameters except temperature and beam-injection power are same as those in Fig. 2. The concentration of beryllium is assumed to be $n_{^9Be} = 0.005\times(n_D+n_T) = 3.0\times10^{17}\ m^{-3}$. The emission rate of 3.21-MeV γ-ray becomes larger with increasing P_{NBI} and T_e.

We next show (a) the α-particle emission spectrums and (b) the α-particle distribution functions for several deuterium (tritium) densities in Fig. 4. In this calculation, electron temperature T_e =10 keV, energy and particle confinement times τ_E = (1/2)τ_p = 3 sec, beam-injection power P_{NBI} = 40 MW and beam-injection energy E_{NBI} = 1MeV are assumed. It is found that the α-particle energy spectrum is broadened to high energy region and the energetic components of α-particle distribution function become larger with decreasing deuteron density. This is because the slowing–down of fast beam-ion is weakened for low background density [4]; the non-Maxwellian tail in deuteron distribution function created by NBI heating becomes large and the α-particle emission spectrum is further broadened toward high energy region.

In Fig. 5, we show the 3.21-MeV γ-ray emission rate as a function of fuel ion density for several electron temperatures. The calculation parameters except temperature and deuterium density are same as those in Fig. 4. The concentration of beryllium is assumed to be $n_{^9Be} = 3.0\times10^{17}\ m^{-3}$. In the low density region, the generation of α-particle from DT reaction decreases and the γ-ray emission rate from ^{9}Be(α,nγ)^{12}C tends to be

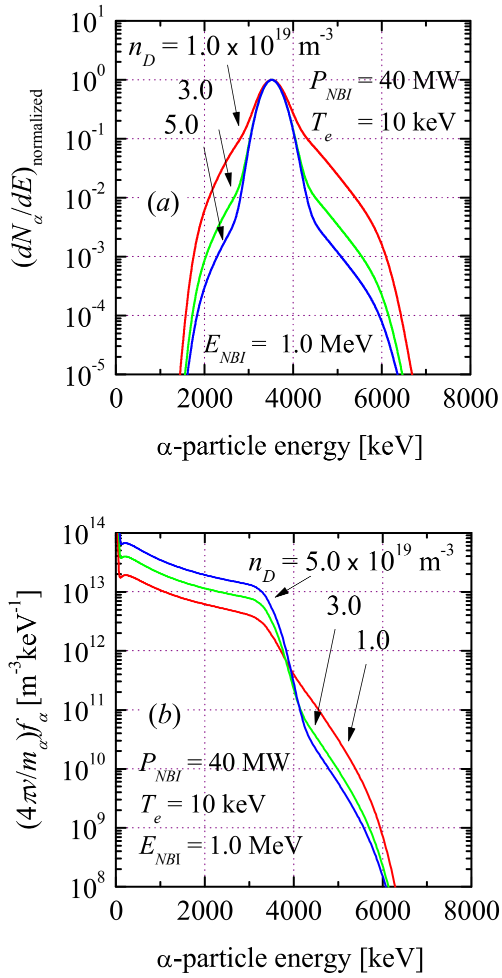

Fig. 4 (*a*) α-particle emission spectrums and (*b*) α-particle distribution functions for several deuterium (tritium) density at T_e =10 keV.

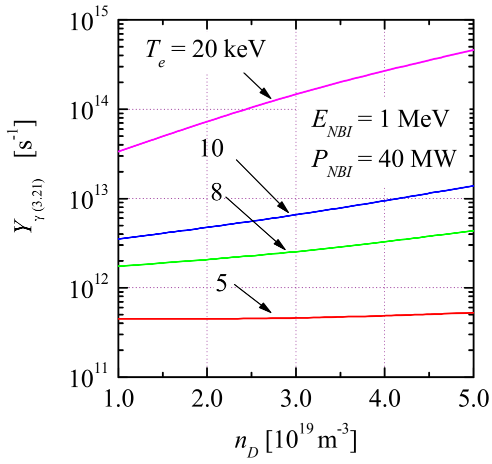

Fig. 5 Emission rate of 3.21-MeV γ-ray from ^{9}Be($\alpha,n\gamma$)^{12}C reaction as a function of deuterium (tritium) density and T_e.

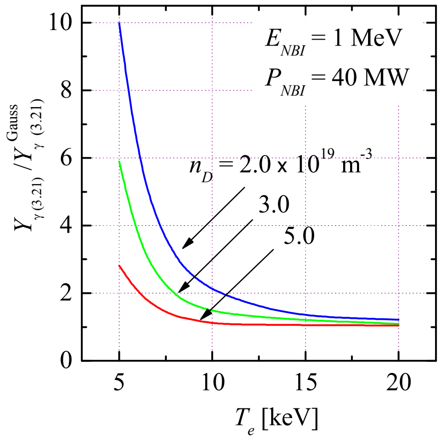

Fig. 6 Enhancement of 3.21-MeV γ-ray emission rate due to the modification of α-particle emission spectrum as a function of T_e for several deuterium (tritium) density.

small. As was shown in Fig. 4 (*b*), however, the energetic (>3.8 MeV) component in the α-particle distribution function increases with decreasing density. The γ-ray emission rate is consequently kept nearly constant especially in low-temperature range even if deuteron density decreases.

In Fig. 6, the enhancement of the 3.21-MeV γ-ray emission rate due to the α-particle emission spectrum modification, i.e., $Y_{\gamma(3.21)}/Y^{Gauss}_{\gamma(3.21)}$, from the value when Gaussian spectrum is assumed ($Y^{Gauss}_{\gamma(3.21)}$) is presented as a function of electron temperature for several deuteron densities. The calculation parameters except temperature and deuterium density are same as those in Fig. 5. In low temperature (and low density) range, the enhancement becomes significant. On the other hand, in high temperature range, the degree of the enhancement rapidly reduces, e.g. at T_e = 20 keV and n_D = 5.0×10^{19}, $Y_{\gamma(3.21)}/Y^{Gauss}_{\gamma(3.21)}$ ~1.04. In such a case, the 3.21-MeV γ-ray emission rate could be evaluated by assuming Gaussian distribution.

Finally we summarize the correlation between ^{9}Be concentration and γ-ray emission rate for several (*a*) beam-injection power P_{NBI}, (*b*) deuteron density n_D and (*c*) electron temperature T_e in Fig. 7. When the velocity distribution function of ^{9}Be is assumed to be Maxwellian, the 3.21-MeV γ-ray emission rate is proportional to the beryllium concentration. The correlation between ^{9}Be concentration and γ-ray emission rate is determined as a function of P_{NBI}, n_D and T_e. If we could measure the spatial distribution of n_D and T_e and accurately evaluate the energetic (>3.8 MeV) component of the α-particle distribution, by comparing the 3.21-MeV γ-ray emission rate evaluated with the experimentally measured one, the concentration of beryllium could be estimated.

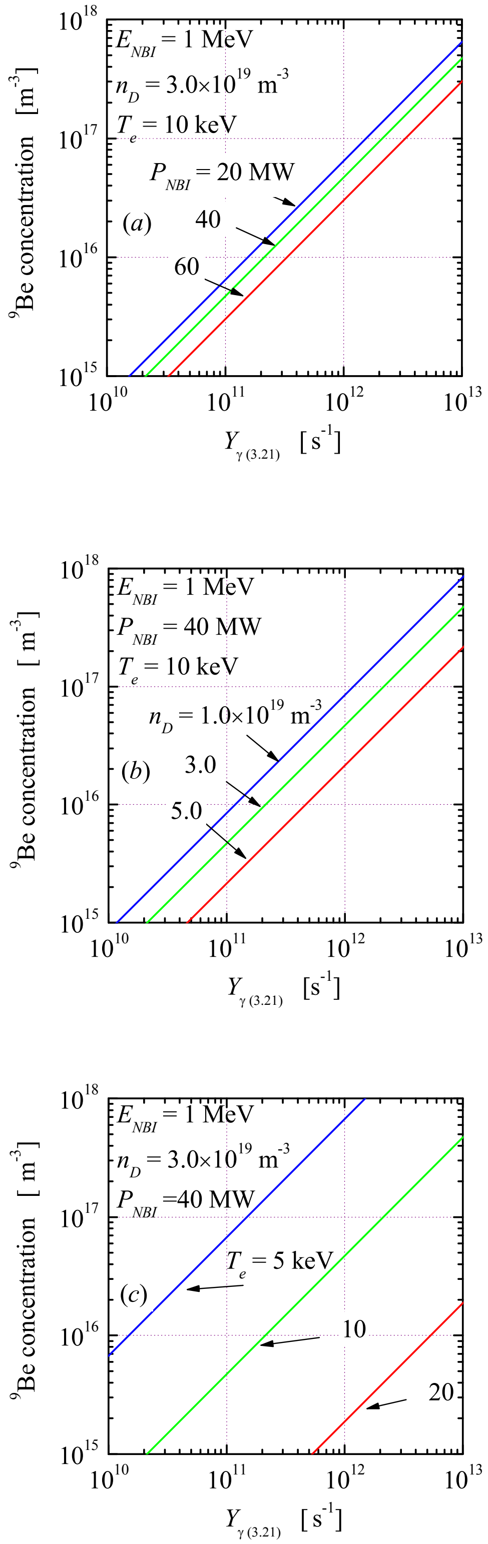

Fig. 7 Correlation between ^{9}Be concentration and γ-ray emission rate for several (*a*) P_{NBI}, (*b*) n_D and (c) T_e.

The 3.21-MeV γ-ray emission rate also depends on beam-injection energy E_{NBI}. In this paper, beam-injection energy E_{NBI} = 1MeV is assumed. When E_{NBI} exceeds 1 MeV, the α-particle emission spectrum is furthermore broadened toward low and high energy range and γ-ray emission rate would increase [10]. In such a case, the lines shown in Fig. 7 shift toward right-hand side to some extent. When E_{NBI} exceeds 1.2 MeV, the energetic α-particles (>6MeV) mainly increase and shift of the lines comes to the end because the cross section of ^{9}Be($\alpha,n\gamma$)^{12}C reaction rapidly decreases in the energy range above ~6 MeV. In the experimental reactor, line-integrated γ-ray emission rate is measured. If the spatial distribution of the γ-ray emission source could be assessed using the techniques like tomography [11], the γ-ray emission rate from arbitrary point in plasma could be estimated.

4. References

[1] L. Ballabio, G. Gorini, and J. Källne, Phys. Rev. E, **55**, 3358 (1997).

[2] J. Källne, et al., Phys. Rev. Let, **85**, 1246 (2000)

[3] A. A. Korotkov, A. Gondhalekar, and R. J. Akers, Phys. Plasmas, **7**, 957 (2000).

[4] H. Matsuura and Y. Nakao, Phys. Plasmas, **13**, 062507 (2006).

[5] H. Matsuura and Y. Nakao, Phys. Plasmas, **14**, 054504 (2007).

[6] M, Nakamura, et al., J. Phy. Soc. Jpn. **75**, 024801 (2006).

[7] J. J. Devaney and M. L. Stein, Nucl. Sci. Eng. **46**, 323 (1971).

[8] S. T. Perkins and D. E. Cullen, Nucl. Sci. Eng., **20**, 77 (1981).

[9] F. S. Zaitsev, et al., Plasma Phys. Control. Fusion **49**, 1747 (2007).

[10] H.Matsuura and Y. Nakao, Phys. Plasmas, **16**, 042507 (2009).

[11] G. Federici, et al., Nucl. Fusion **41**, 1967 (2001).

[12] V. G. Kiptily, et al., Phys. Rev. Let, **93**, 115001 (2004).

[13] V. G. Kiptily, Fusion Technol., **18**, 583 (1990).

[14] V. G. Kiptily, F. F. Cecil, and S. S. Medley, Plasma Phys. Control. Fusion, **48**, R59 (2006).

[15] T. Sugie, et al., J. Plasma Fusion Res., **79**, 1051 (2003).

[16] M. Drosg and O. Schwerer, Handbook of Nuclear Activation Data, IAEA, Vienna, STI/DOC/10/273, 83 (1987).

[17] H. –S. Bosch and G. Hale, Nucl. Fusion **32**, 611 (1992).