Study on Fast Deuteron Diagnostics Method Using Fast ^{3}He Visible Spectra in the Large Helical Device Deuterium Plasma

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Fast ion diagnostic is one of the most crucial plasma diagnostics for nuclear fusion investigation. A new diagnostic method for fast ions has been proposed using visible spectra of ^{3}He produced by a deuteron-deuteron reaction. This diagnostic method has a better energy resolution than methods using neutron/γ-ray and is superior to conventional spectroscopy in measuring high energy (MeV order) ions. This diagnostic method has been predicted using numerical analysis for ITER, but no verification experiments have been performed yet. In this study, we examined the measurability of this diagnostic method in the large helical device (LHD) deuterium plasma. Although very dependent on the measurement geometry and the spectrometer performance, it may be possible to measure the fast ^{3}He visible spectrum.

Keywords: large helical device, deuterium plasma, velocity distribution function, charge-exchange spectroscopy, visible light spectra

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1. Introduction

Fast ion diagnostics are crucial in plasma diagnostics. This is because fast ions are primarily the cause of plasma heating. Fast ion diagnostics are significant for understanding and forecasting fast ion behavior. Measurement of the velocity distribution function is crucial in fast ion diagnostics. Macroscopic quantities, including temperature and density, are derived by integrating the velocity distribution function. Furthermore, the magnitude and shape of the velocity distribution function are closely related to magnetohydrodynamics instability and fusion power.

There are various types of fast ion diagnostics [1]. An example is a use of fast ion D alpha (FIDA) for fast deuterons in fast ion diagnostics using spectroscopy [2]. In this method, fast deuterons are neutralized by a neutral beam, and the Balmer-α emitted from the neutralized deuterons is measured. The Doppler broadening and Doppler shift of the spectra offer information on the fast deuterons' velocity distribution function. For example, FIDA measurements have been conducted at a large helical device (LHD) [3]. It has been noted that FIDA becomes more challenging to measure as the fast deuteron's energy increases [4]. Diagnostic methods using neutron/γ-ray energy spectra are efficient for such fast deuterons [5, 6]. However, radiation spectrometers have a lower energy resolution than visible light spectrometers. To solve these challenges, a new fast ion diagnostic method using the visible light spectrum of fast ^{3}He produced by the deuteron-deuteron (DD) reaction has been proposed [7, 8]. Since it uses the DD reaction, it is more sensitive to fast ions with energies on the order of MeV than spectroscopy-based diagnostics, including FIDA. This is because the DD reaction's cross-section is large in the high energy region. The proposed method has superior energy resolution compared to one of neutron/γ-ray. The neutron spectrometer measurements' energy resolution is several hundred keV [5]. The proposed method has several good features, but there is bremsstrahlung as a competing process. Thus, this diagnostic becomes challenging under conditions where the electron density is high or where there is not a lot of fast ^{3}He. It is necessary to increase the density of externally injected neutral particles or to design an observing line of sight.

Numerical analysis of this diagnostic method has been performed for ITER, but no empirical tests have been con-

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ducted, to the best of our knowledge. To confirm the efficiency of this diagnostic method, it is crucial to perform demonstration experiments using current equipment and device. To observe fast ^{3}He using spectroscopy, a large amount of fast ^{3}He must be produced by the DD reaction. Because the negative ion source neutral beam (NNB) is installed in the LHD, which has an energy of 180 keV, it is the best option. Even under these conditions, the emissivity of the visible spectrum of fast ^{3}He is not expected to exceed that of device noise, considering that device noise is 100 times larger than bremsstrahlung. This is because a specific percentage of the fast ^{3}He produced by the DD reaction is lost from the LHD plasma. Thus, it is necessary to verify beforehand whether the visible spectrum of fast ^{3}He can be measured with sufficient precision at LHD. There are three possible sources of instrument noise: readout noise, shot noise, and dark shot noise. Increasing the signal level by using a spectrometer with higher optical throughput can effectively reduce the noise.

This study aims to assess the measurability of the validation experiment of the fast ion diagnostics using the visible light spectrum of fast ^{3}He at LHD pure deuterium plasma. Furthermore, an investigation of desirable experimental parameters for the measurement will be conducted using numerical analysis.

2. Analysis Model

In this analysis, two types of neutral beam are assumed to be used: NNB (deuterium beam) for heating and PNB (hydrogen beam) for diagnostics. The 2D velocity distribution function $f(\mathbf{v}, r/a)$ of fast ions (i.e., beam deuteron and fast ^{3}He^{2+}) was assessed by guiding-center orbit computation code DELTA5D [9]. $\mathbf{v}$ is the velocity vector of fast ion, r/a is normalized minor radius of plasma. The velocity distribution function was computed by dividing r/a into twenty parts every 0.05. The equilibrium magnetic field is computed by VMEC code [10]. Profiles of electron temperature $T_e(r/a)$, deuteron temperature $T_d(r/a)$ and electron and deuteron density $n_{e(d)}(r/a)$ are assumed as $T_e(r/a) = T_{e0} \times (1 - (r/a)^2)$, $T_d(r/a) = T_{d0} \times (1 - (r/a)^2)$ and $n_{e(d)}(r/a) = n_{e(d)0} \times (1 - (r/a)^8)$. Z_{eff} is assumed to be 3. The NB deposition and neutral particle density in NB profiles are computed with the FIT3D code [11].

The fast ^{3}He^{2+} emission spectrum produced by the DD reaction is assessed according to Ref. [12]. Using the emission spectra of ^{3}He^{2+}, the orbit computation is conducted again to compute the ^{3}He^{2+} velocity distribution function. The energy and visible spectra of the charge-exchanged ^{3}He$^+$ are obtained based on Ref. [7]. The center wavelength λ_0 of the visible light spectrum of fast ^{3}He$^+$ is 468 nm.

In this study, the velocity distribution function of ^{3}He^{2+} is assumed to be isotropic. This model is unable to determine the precise spectral shape. However, since this study focuses on the spectrum's peak values, the discussion is unaffected. The expected ^{3}He$^+$ visible spectrum is obtained as a line-integrated value over the measurement line of sight. The count rate is the photons' number emitted from ^{3}He$^+$ (or bremsstrahlung) multiplied by the spectrometer's detection efficiency η. η (mm^2 sr s nm) is defined as $\varepsilon QT\Delta\lambda$. ε is etendue, Q is quantum efficiency, T is optical transmission, $\Delta\lambda$ is wavelength resolution. The value of η is 3.8×10^{-13}, which is determined from experimental studies on spectroscopy in LHD [13]. The wavelength resolution $\Delta\lambda$ is 0.5 nm.

In the actual measurement, the visible spectrum of fast ^{3}He$^+$ is measured as a noisy spectrum. The number of count rates' limit of detection (LOD) required for the signal in the visible light spectrum of fast ^{3}He$^+$ to fall within 3σ is represented by n_{LOD}. In this case, n_{LOD} can be written as follows,

$$n_{\mathrm{LOD}} = \frac{3}{2}\left\{\frac{3}{t} + \sqrt{\left(\frac{3}{t}\right)^2 + 4n_b\left(\frac{1}{t} + \frac{1}{t_b}\right)}\right\}, \tag{1}$$

where, $t_{(b)}$ represents the measurement time of ^{3}He$^+$ (background). In this study, $t = t_b$ is assumed. n_b is the background (device noise) count rate.

3. Result and Discussion

To verify the validity of the computational model in this study, a comparison was made with previous investigations on FIDA. In that previous study, experimental results of FIDA measurements at the LHD were reported. Figure 1 shows the FIDA spectra computed by the model in this study and the experimental values of the FIDA spectra of previous investigations [3]. The model in this study assumes that the ^{3}He$^+$ velocity distribution function is isotropic, so the Doppler shift does not occur. However, the spectra's peak values are roughly consistent. The difference of a factor of several is also due to the isotropic assumption.

Figure 2 shows the beam deuteron velocity distribution function for each r/a. As computation conditions, we assumed, $T_{e0} = 8$ keV, $T_{d0} = 1$ keV, $n_{e0} = n_{d0} = 10^{19}$ m^{-3}, $E^{\mathrm{D}}_{\mathrm{NNB}} = 180$ keV, $P^{\mathrm{D}}_{\mathrm{NNB}} = 9$ MW, and $Z_{\mathrm{eff}} = 3$. In this figure, the bulk component is added to the fast component obtained from the orbit computation. Since the NNB is a tangential injection, the beam tail is largest at the plasma center. As the beam power is lowered (i.e., the number of NNBs injected is reduced), the beam tail's size is reduced proportionally. Thus, only the 9 MW case is denoted here.

The emission spectrum of fast ^{3}He^{2+} produced by the DD reaction was computed from the velocity distribution function of deuterons obtained using orbital computations. Figure 3 shows the fast ^{3}He^{2+} emission spectra for each r/a. A certain amount of fast ^{3}He^{2+} with energies >0.8 MeV, the production energy in the quiescent state, is produced. Near the plasma center (r/a < 0.2), fast ^{3}He^{2+} with energy of 1.5 MeV is produced in large quan-

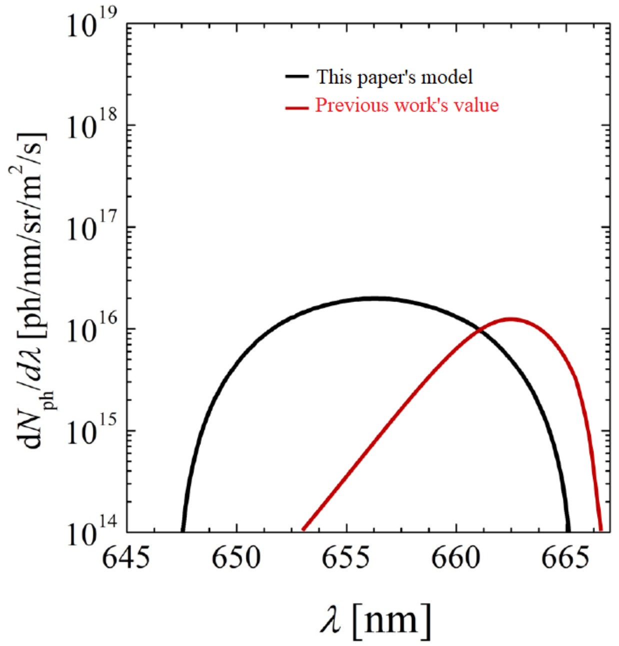

Fig. 1 The FIDA spectra calculated by the model in this paper and the experimental values of the FIDA spectra of previous studies.

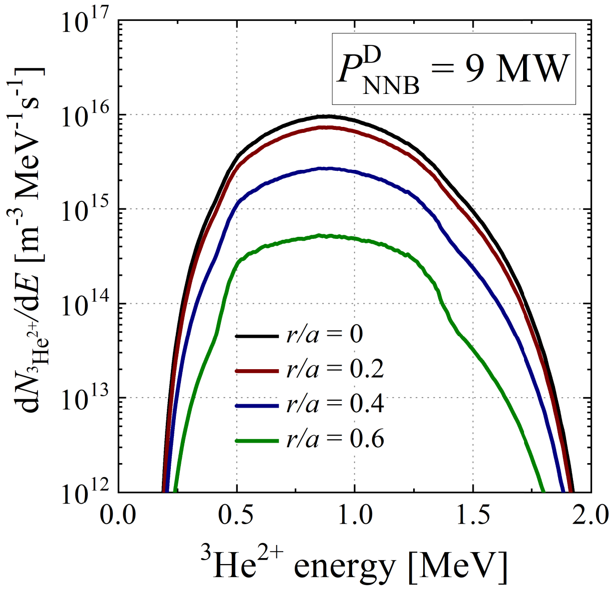

Fig. 3 The emission spectrum of fast $^3He^{2+}$ produced by the DD reaction for each r/a when $T_{e0} = 8$ keV, $T_{d0} = 1$ keV, $n_{e0} = n_{d0} = 10^{19}$ m^{-3}, $E^D_{NNB} = 180$ keV, $P^D_{NNB} = 9$ MW, $Z_{eff} = 3$.

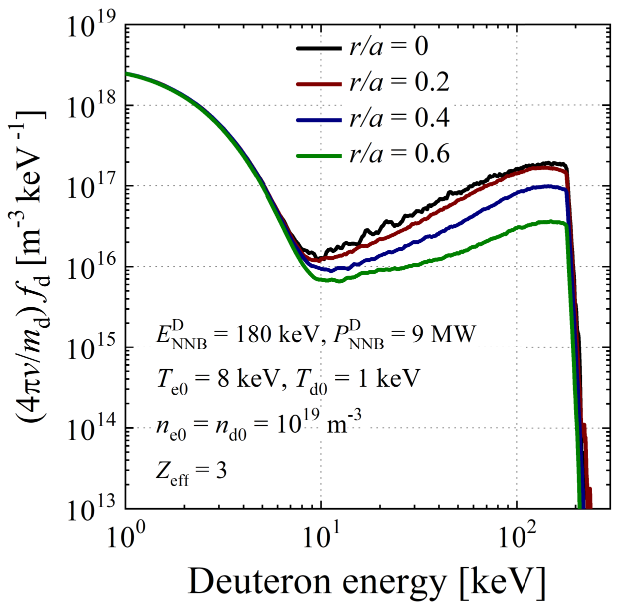

Fig. 2 The beam deuteron velocity distribution function for each r/a when $T_{e0} = 8$ keV, $T_{d0} = 1$ keV, $n_{e0} = n_{d0} = 10^{19}$ m^{-3}, $E^D_{NNB} = 180$ keV, $P^D_{NNB} = 9$ MW, $Z_{eff} = 3$.

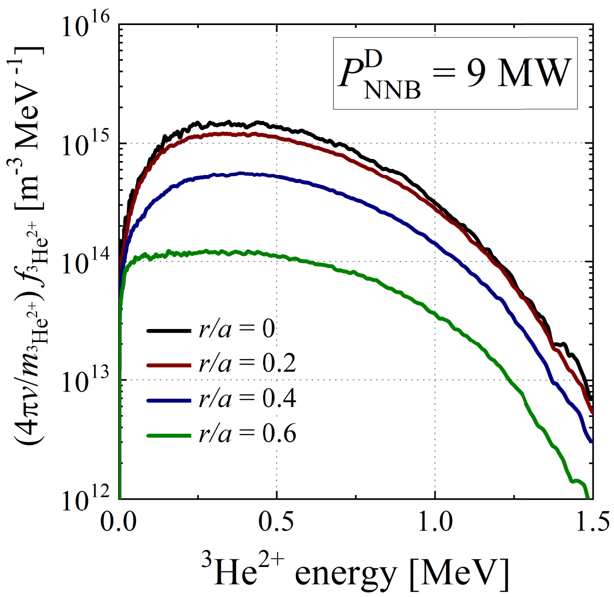

Fig. 4 The fast $^3He^{2+}$ velocity distribution function for each r/a when $T_{e0} = 8$ keV, $T_{d0} = 1$ keV, $n_{e0} = n_{d0} = 10^{19}$ m^{-3}, $E^D_{NNB} = 180$ keV, $P^D_{NNB} = 9$ MW, $Z_{eff} = 3$.

tities. The emission spectrum of $^3He^{2+}$ for each r/a was used as the initial condition for the test particles in the orbit computation, and the $^3He^{2+}$'s velocity distribution function was computed. Figure 4 shows the velocity distribution function of fast $^3He^{2+}$ for each r/a. Fast $^3He^{2+}$ with energies above 0.8 MeV existed in the plasma at about 1/10 of the peak value. Unlike tritons that have similar mass, the charge is 2, so confinement is better than for tritons. Thus, measuring the visible spectra of fast $^3He^+$ at LHD is more feasible than at triton. The fact that $^3He^{2+}$ above 1 MeV is produced in large quantities at the plasma center is also a factor in better confinement. Since there is a 10-fold difference in the density of fast $^3He^{2+}$ between the plasma center and $r/a = 0.6$, it is crucial to prepare a more central line of sight. Furthermore, it is crucial to verify the density

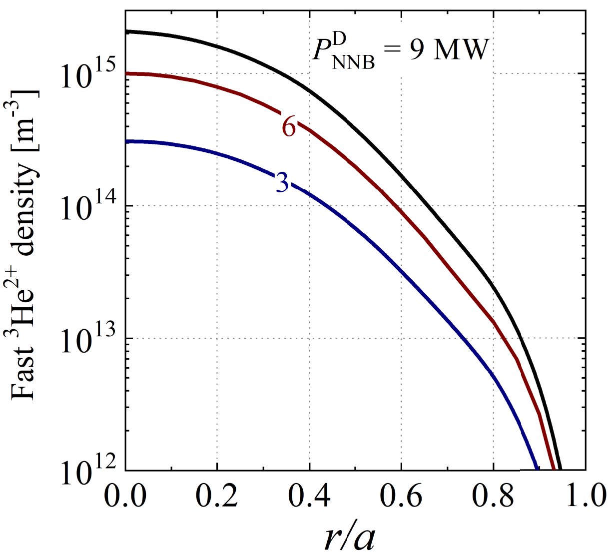

Fig. 5 The fast $^3He^{2+}$ density profile when $T_{e0} = 8\,keV$, $T_{d0} = 1\,keV$, $n_{e0} = n_{d0} = 10^{19}\,m^{-3}$, $E^{D}_{NNB} = 180\,keV$, $Z_{eff} = 3$.

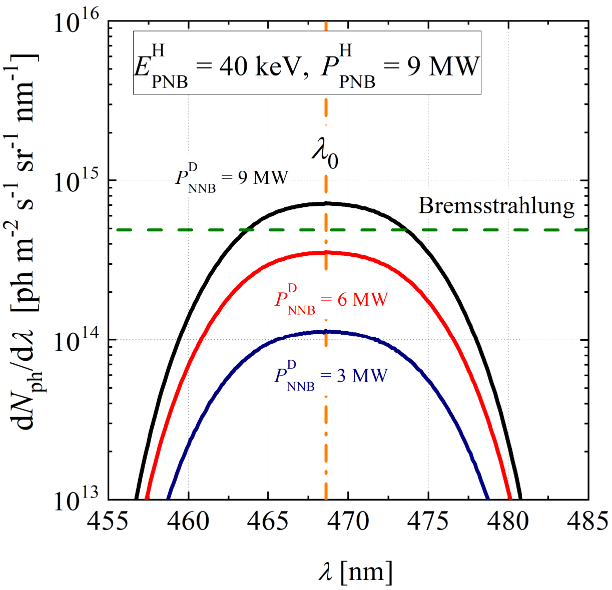

Fig. 6 Visible spectra (solid line) from $^3He^+$ for NNB power dependences when $T_{e0} = 8\,keV$, $T_{d0} = 1\,keV$, $n_{e0} = n_{d0} = 10^{19}\,m^{-3}$, $E^{D}_{NNB} = 180\,keV$, $E^{H}_{PNB} = 40\,keV$, $P^{H}_{PNB} = 9\,MW$, $Z_{eff} = 3$.

of fast $^3He^{2+}$ in the plasma in more detail. Figure 5 thus shows the fast $^3He^{2+}$'s density distribution with deuterium beam power as a parameter. For $P^{D}_{NNB} = 3\,MW$, the fast $^3He^{2+}$'s density surpasses $10^{14}\,m^{-3}$ at $r/a < 0.5$. However, at $r/a > 0.5$, the density of fast $^3He^{2+}$ is 10^{12} - $10^{13}\,m^{-3}$. If P^{D}_{NNB} is increased, the density of fast $^3He^{2+}$ surpasses $10^{14}\,m^{-3}$ at $r/a = 0.6$.

The $^3He^{2+}$ is recombined by PNB to become $^3He^+$. Then, photons are emitted, which are measured as visible spectra. We assumed, $T_{e0} = 8\,keV$, $T_{d0} = 1\,keV$, $n_{e0} = n_{d0} = 10^{19}\,m^{-3}$, $E^{D}_{NNB} = 180\,keV$, $E^{H}_{PNB} = 40\,keV$, $P^{H}_{PNB} = 9\,MW$, and $Z_{eff} = 3$. Figure 6 shows $^3He^+$'s visible spectra plotted with the NNB power as a parameter. The orange line is the central wavelength, and the green line is the bremsstrahlung. Device noise is difficult to estimate accurately due to a combination of factors. The values of the device noise were determined with reference to the experimental values presented in the FIDA experiment [3]. The noise line in the observed FIDA spectrum that appears to be noise is 100 times larger than the estimated value of the bremsstrahlung. Therefore, the device noise was estimated to be about 100 times higher than the bremsstrahlung. The magnitude of the spectrum of $^3He^+$ is not proportional to the beam power. This is due to the presence of some contribution from beam–beam reactions. The reaction rate of a beam–beam reaction is proportional to the beam power's square. The larger contribution from the beam–beam reaction appears to be near the plasma center, where the beam tail's size is larger. The energy resolution is estimated from the calculation results in Fig. 6. For a wavelength bin of 0.01 nm, the energy resolution of the visible light spectrometer around $\lambda = 468\,nm$ is approximately 0.1 meV.

The measurement time needed for the verification experiment is calculated from the peak value of the obtained visible spectrum of $^3He^+$. For this purpose, we clarified the relationship between the ratio of the fast $^3He^+$ signal n_s and the minimum count rate n_{LOD} needed for the verification experiment and the measurement time. Figure 7 (a) shows the results with the detection efficiency as a parameter, while (b) shows the results with the NNB power as a parameter. Under $P^{D}_{NNB} = 9\,MW$ and $\eta = 3.8 \times 10^{-13}$ ($\Delta\lambda = 0.5\,nm$) [13], the ^3He visible spectrum measurement accuracy is 3σ after about 10 s of measurement time. Additionally, if the wavelength resolution is reduced to 1/10 to measure the visible spectral shape in detail, a measurement time of >100 seconds is required. Because these required measurement times are minimum, it is preferable to take n_s/n_{LOD} of at least 3 for actual measurements. This is because this ratio is for the spectrum's peak value, and a longer measurement time would be required to measure the entire spectrum. At $\Delta\lambda = 0.5\,nm$, a measurement time of approximately 100 s is required. The required measurement time increases as the power of the NNBs diminishes (i.e., the number of injected NBs is reduced). At $P^{D}_{NNB} = 6\,MW$, $n_s/n_{LOD} = 1$ requires 40 s and $n_s/n_{LOD} = 3$ requires 300 s. At 3 MW, $n_s/n_{LOD} = 1$ requires 300 s, so at least two NBs (6 MW) are needed.

These results indicate that the measurement time for the verification experiment requires tens to hundreds of seconds. This is impossible to execute in a single shot since the LHD's discharge time is only a few seconds. However, this measurement time can be attained by adding up the results of numerous discharges. Thus, the number of shots required is in the tens or hundreds. For this reason, it is feasible to perform verification experiments at LHD.

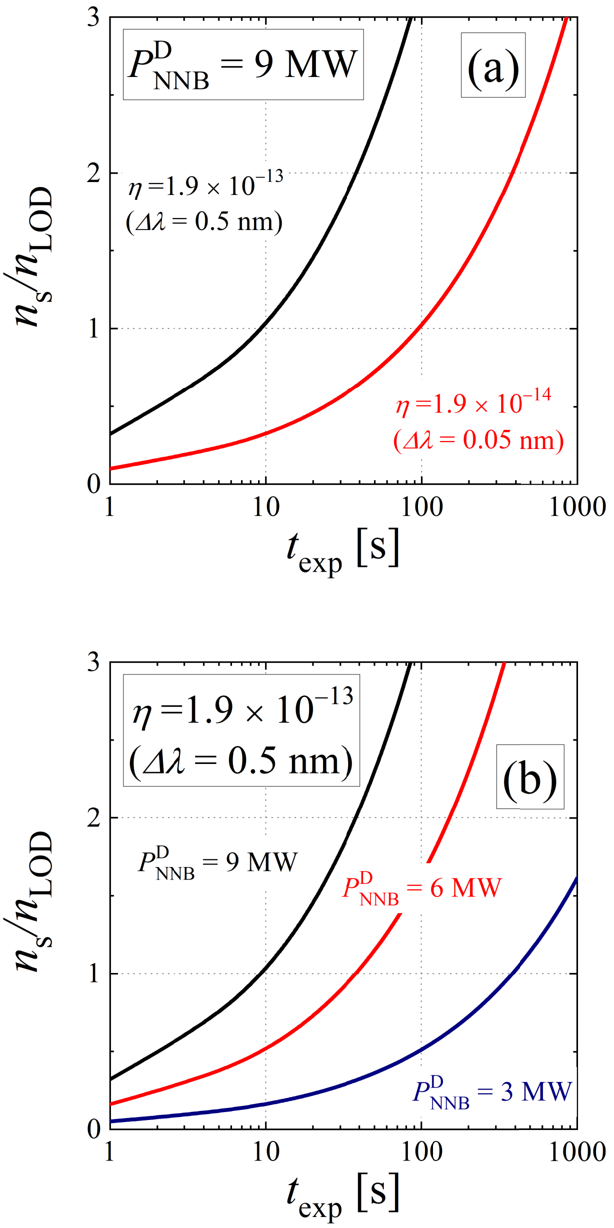

Fig. 7 The ratio of the fast ^{3}He$^+$ signal n_s and the minimum count rate n_{LOD} required for the verification experiment and the measurement time: (a) detection efficiency dependences, (b) NNB power dependences.

4. Conclusion

This study assessed the measurability of the validation experiment of the fast deuteron diagnostic method using the visible spectrum of fast ^{3}He produced by the DD reaction at LHD. Under typical experimental conditions (P^{D}_{NNB} = 9 MW and η = 3.8 × 10^{-13}), the device noise was assumed 100 times that of bremsstrahlung [3]. The ^{3}He visible spectrum's measurement accuracy is <3σ after about 10 seconds of measurement time. Under similar conditions (P^{D}_{NNB} = 9 MW and η = 3.8 × 10^{-14}), if the wavelength bin is increased by a factor of 10, the required measurement time is 100 s. Next, we assess the measurability using the deuterium beam's power as a parameter. The measurement time is 30 s when two of the NBIs are injected (P^{D}_{NNB} = 6 MW and η = 3.8 × 10^{-13}), and 300 s when only one of the NBIs is injected (P^{D}_{NNB} = 3 MW and η = 3.8 × 10^{-13}), respectively. The LHD discharge time is a few seconds, but this measurement time can be achieved by adding up the results of numerous discharges. These results vary substantially depending on the measurement geometry and the spectrometer performance.

[1] D. Moseev *et al.*, Rev. Mod. Plasma Phys. **2**, 7 (2018).
[2] W.W. Heidbrink *et al.*, Plasma Phys. Control. Fusion **46**, 1855 (2004).
[3] Y. Fujiwara *et al.*, Nucl. Fusion **60**, 112014 (2020).
[4] C.M. Muscatello *et al.*, Rev. Sci. Instrum. **90**, 073504 (2019).
[5] C. Hellesen *et al.*, Nucl. Fusion **53**, 113009 (2013).
[6] Y. Kawamoto and H. Matsuura, Fusion Eng. Des. **144**, 62 (2019).
[7] K. Kimura *et al.*, Rev. Sci. Instrum. **92**, 053524 (2021).
[8] K. Kimura *et al.*, IEEE Trans. Plasma Sci. **9**, 3142 (2021).
[9] D.A. Spong, Phys. Plasmas **18**, 056109 (2011).
[10] S.P. Hirschman and J.C. Whitson, Phys. Fluids **26**, 3553 (1983).
[11] S. Murakami *et al.*, Trans. Fusion Technol. **27**, 256 (1995).
[12] H. Brysk, Plasma Phys. **15**, 611 (1973).
[13] H. Zhou *et al.*, J. Appl. Phys. **9**, 106103 (2010).