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Time dependent neutron rate analysis for neutral-beam-heated deuterium plasmas in a helical system and tokamaks

Kunihiro Ogawa[1, 2], Mitsutaka Isobe[1, 2], Takeo Nishitani[1], Ryosuke Seki[1, 2], Hideo Nuga[1], Sadayoshi Murakami[3], Motoki Nakata[1,2], Neng Pu[2], Masaki Osakabe[1,2], Jungmin Jo[4], MunSeong Cheon[5], Junghee Kim[5], Guoqiang Zhong[6], Min Xiao[6], Liqun Hu[6], and LHD Experiment Group[1]

1) National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, Japan
2) SOKENDAI (The Graduate University for Advanced Studies), Toki, Japan
3) Kyoto University, Kyoto, Japan
4) Seoul National University, Seoul, Republic of Korea
5) National Fusion Research Institute, Daejeon, Republic of Korea
6) Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China

Abstract

A neutron rate analysis code called the FBURN, based on the classical energetic ion confinement assumption with radial diffusion, is developed for the time-dependent analysis of the total neutron emission rate (S_n) in neutral beam (NB) heated deuterium plasmas. The time trend of S_n evaluated by the FBURN shows good agreement with the S_n measured by the neutron flux monitor on the deuterium operation of the Large Helical Device (LHD). The dependence of S_n on line-averaged electron density (n_{e_avg}) has a peak at n_{e_avg} of around 2.5×10^{19} m^{-3} in both experiment and calculation. Here, the absolute value of S_n evaluated by calculation agrees with that obtained in experiments within a factor of two. Time trend analysis of S_n in an electron cyclotron heated plasma with a short pulse neutral beam injection is performed. The analysis shows that the diffusion coefficient of co-going transit beam ions is 0.2 to 0.3 m^2/s. In addition, the diffusion coefficient of helically trapped beam ions decreases from 5 to 3 m^2/s with the inward shift of the magnetic axis position. Time-resolved analysis of the triton burnup experiment shows that the diffusion coefficient of tritons is around 0.15 m^2/s. It is found that the diffusion coefficients of the beam and tritons are of a similar value as obtained in JT-60U. The trend of the triton burnup ratio on the n_{e_avg} calculated by the FBURN agrees with the experiments. The results suggest that the decrease of the triton burnup ratio with the increase of n_{e_avg} is due to the shorter slowing down time of tritons by the decrease of the electron temperature, and the increase of the triton burnup ratio with the increase of n_{e_avg}

is due to the diffusion of tritons. Time trend analysis of S_n in the Korea Superconducting Tokamak Advanced Research (KSTAR) and the Experimental Advanced Superconducting Tokamak (EAST) plasmas with a short pulse NB injection is performed. The time trend of S_n is successfully reproduced by the FBURN.

Keywords:
Neutron rate analysis, deuterium plasma, LHD, KSTAR, EAST

I. Introduction

One of the critical issues for achieving a self-burning plasma is that fusion born energetic alpha particles are sufficiently confined in order to sustain the plasma performance. Therefore, the study on the confinement of energetic particles using neutral beam (NB) injection, ion cyclotron resonance heating, and fusion products has been intensively performed so as to find a way to realize a fusion reactor [1]. In these studies, neutron diagnostics have been intensively used in order to evaluate the energetic-particle confinement because neutrons are mainly created by reactions between energetic particles and a thermal plasma in currently performed deuterium plasma experiments [2]. For example, the total neutron emission rate (S_n), the neutron emission profile, and the neutron energy spectra are measured in order to understand the global confinement property, the radial density profile, and the velocity space distribution of energetic particles [3]. Time-resolved measurement and time-resolved analysis based on the classical confinement of beam ions and fusion born tritons have been performed to understand the global confinement of energetic ions in deuterium plasmas in tokamaks [4-9]. Although the absolute value of DD and DT neutron emissions by these codes are overestimated compared with that obtained by the experiment or with that evaluated by the neutron emission calculation code based on five-dimensional modeling, the code based on the classical beam confinement has an advantage in the low calculation cost (time and memory). In stellarators and heliotrons, a time-resolved global confinement study by means of a comprehensive set of neutron diagnostics was initiated in March 2017 in the Large Helical Device (LHD) and the initial results from the first campaign are reported [10, 11]. This paper describes the time-resolved analysis of DD and secondary DT neutron emission rates in order to study the confinement of beam ions and tritons. Also, time-resolved analysis of S_n for the beam ion confinement study by means of the short pulse NB injection in medium sized tokamaks is reported.

II. FBURN

We developed the FBURN for the time-dependent analysis of DD and DT neutron emission rate in NB heated toroidal plasmas based on classical energetic ion slowing down. The objective of this code is not for precise prediction of the absolute burnup probability, but rather is for the time dependence analysis of DD or DT reactivity in NB heated plasmas using experimental data. The calculation cost such as memory and CPU time is remarkably smaller than that of integration code such as TRANSP [12]. Here, we only include a beam-thermal part for DD reactions because DD neutrons are mainly created by beam-thermal reactions and the DT neutron emission rate is up to ~ 1 % in currently performed NB heated deuterium plasma experiments [2]. Figure 1 shows the block diagram of the FBURN. The plasma was assumed to consist of 100 nested shells. The volume of each shell is given according to the equilibrium reconstructed by the VMEC2000 code [13] based on experimentally obtained plasma parameters such as the temperature and the density profiles for the LHD. The volume of each shell is given by the simple torus approximation for the Korea Superconducting Tokamak Advanced Research (KSTAR) and the Experimental Advanced Superconducting Tokamak (EAST). The deposition profile of beam ions is calculated by the FHREYA code [14] for the LHD, is calculated by the NUBEAM code [15, 16] for the KSTAR, and is assumed to be uniform for the EAST. Here, the time trend of the absorbed beam power and the beam voltage is given according to experimental results. The time-dependent distribution function of energetic ions and the corresponding reactivity in each cell are calculated every 2 ms. Here, energetic ions are assumed to be slowed down according to the classical energy loss theory using the following equation [17]

$$\langle \frac{1}{v}\frac{dW}{dt} \rangle = -\frac{\alpha}{W} - \beta W^{\frac{1}{2}}$$

where

$$\alpha \equiv 1.30 \times 10^{-13} A Z^2 \ln \Lambda \sum_j \frac{n_j Z_j^2}{A_j},$$

$$\beta \equiv 2.28 \times 10^{-15} \frac{Z^2}{A^{1/2}} \frac{n_e \ln \Lambda}{(T_e)^{3/2}},$$

and where W and T_e are in eV. Here, W, lnΛ, and n are the energy of energetic ions, the Coulomb logarithm, and density, respectively. In this equation, A and A_j, Z, and Z_j are the atomic weight of the injected ions, atomic weight of plasma ions, the charge numbers of the injected ions, and the charge numbers of plasma ions, respectively. The radial diffusion of beam ions is considered with the explicit method by assuming that the diffusion coefficient is constant in radius and unchanged in time. The typical width of the time bin in the diffusion calculation is 10 microseconds in order to avoid the divergence of the diffusion calculation. The local emissivity of DD neutrons and tritons are calculated. The reactivity between Maxwellian and the mono energetic ion is given from the equation 6 of Ref. 18 using the fusion cross section fitting by B. H. Duane [19]. Slowing down, radial diffusion, and DT neutron emissivity are performed with the same procedure as for the beam ion calculation.

III. Time-resolved DD neutron emission rate analysis in the LHD

Time-resolved analysis of NB-heated deuterium plasma discharges in the LHD is performed by the FBURN. An overhead view of the LHD and the arrangement of negative-ion-based tangentially injected neutral beams (N-NBs) and positive-ion-based perpendicularly injected neutral beams (P-NBs) is shown in Fig. 2. N-NB injects beam ions having energies of up to 180 keV and a typical pitch angle of 30 degrees, whereas beam ions having energies of up to 60-80 keV and a typical pitch angle of 90 degrees are injected by P-NB. Figure 3 (a) shows the typical waveform of the discharges. The plasma is initiated by N-NB injections assisted by the electron cyclotron resonance heating (ECH). Then, P-NBs are additionally injected. The central electron temperature (T_{e0}) reaches 3 keV and the line averaged density (n_{e_avg}) is rapidly increasing to 2×10^{19} m^{-3}, then is gradually increased due to continuous gas puffing. Here, the typical error bar of the plasma parameter measurement is 10 %. Note that no visible magnetohydrodynamic instability is observed using Mirnov coils in these discharges. S_n increases with N-NB and P-NB injections and decays rapidly after the beam off (Fig. 3(b)). Here, S_n is measured using the absolutely-calibrated neutron flux monitor [20]. Note that the maximum S_n is around the 2×10^{15} n/s at t of 4.0 ~ 4.7 s in this discharge. Figure 3 (c) and (d) show the typical profiles of electron temperature, electron density and the NB deposition in a relatively low density, n_{e_avg} of 2.0×10^{19} m^{-3} and a relatively high density, n_{e_avg}, of 3.8×10^{19} m^{-3}. The profile of fast ion density (n_{fast}) has a relatively peaked profile in the lower density case, whereas in the higher density case n_{fast} has a relatively flat profile. In the FBURN, the equilibrium is reconstructed by VMEC2000 every 50 ms, the beam deposition is calculated by the HFREYA code, the ion temperature profile is assumed to be the same as T_e, and Z_{eff} is set to be two according to the experimental results [21]. Hydrogen to deuterium ratio and hydrogen to helium ratio are specified from Hα, Dα, and He line ratios [22]. Note that the diffusion coefficient for beam ions (D^*_{fast}) is set to be 0 in this calculation. The time trend of S_n is reproduced by the FBURN, whereas the FBURN overestimates S_n by a factor of around two because of the omissions of prompt loss, orbit effect, and transport. The dependence of S_n on n_{e_avg} reported in Ref. 11 is compared with the FBURN. Here, the total injection power of the N-NB is around 6 MW and the total injection power of the P-NB is around 14 MW. In the experiment, the increase of maximum S_n together with n_{e_avg} is observed up to n_{e_avg} of $2.5\times10^{19}m^{-3}$, whereas the decrease of maximum S_n together with n_{e_avg} is obtained starting from n_{e_avg} at $2.5\times10^{19}m^{-3}$ (Fig. 4). The increase of S_n below n_{e_avg} of $2.5\times10^{19}m^{-3}$is mainly due to the improvement of the beam deposition and the decrease of S_n above n_{e_avg} of $2.5\times10^{19}m^{-3}$ is mainly due to the shorter slowing down time due to the decrease of T_e as shown in Fig. 3(c). Note that the radial profile of beam ions and plasma parameter also affects the S_n. The flat n_{fast} profile induces a relatively shorter slowing down time compared with the peaked profile, whereas the hollow n_e profile induces a relatively long slowing down time compared with the peak profile. This tendency is reproduced by the FBURN. Note that the ratio of the absolute value of S_n evaluated by the FBURN and that obtained in experiments is 1.5 to 2 in this magnetic configuration. The effects of drift surface, Larmor radius, and beam ion transport are the candidates for causing this discrepancy. The ratio is almost the same as that evaluated by FIT3D-DD code based on the analytic solution of the Fokker-Planck code [23].

The FBURN is also applied to blip experiments for N-NB and P-NB [24]. In this experiment, N-NB or P-NB with the short pulse length (20 ms to 30 ms) which is much shorter than the Spitzer slowing down time is injected into the ECH plasma having n_{e_avg} of $1.0\times10^{19}m^{-3}$. N-NB blip experiments using NB1 were performed to study the confinement of co-injected transit beam ions. Note that the injection energy and the injection power of the beam are 170 keV and 1.4 MW, respectively. S_n rapidly increases up to 1.5×10^{13} n/s with an N-NB injection, then starts to decay after the N-NB turn off. The decay time of S_n is around 400 ms. Here, typical T_{e0} is 6 keV. The time trend of S_n is compared to that calculated by the FBURN (Fig.5). Note that S_n evaluated by the FBURN is normalized at t of 3.74 s. In each calculation, D^*_{fast} is set to be 0.0 m^2/s, 0.1 m^2/s, 0.2 m^2/s, 0.3 m^2/s, and 0.4 m^2/s. The calculation result shows that the D^*_{fast} of co-going transit beam ions injected by N-NB is 0.2 to 0.3 m^2/s in this discharge. Note that the effect of the diffusion coefficient on the decay of S_n becomes insignificant with the increase of the electron density because the decay time of neutrons is also related to the slowing down of beams. The decay time of neutrons primarily is decided by the diffusion of beams when the characteristic time of the diffusion of beams is much shorter than the Spitzer slowing down time. In this discharge, the diffusion time estimated by the analytic solution $a^2/(5.8D^*_{fast})$ [25] is 0.62 s when D^*_{fast} is 0.1 m^2/s, whereas the Spitzer slowing down time evaluated with $T_{e0}/2$ and n_{e_avg} is 1.2 s. In the higher-density case, n_{e_avg} of $3.0\times10^{19}m^{-3}$, the Spitzer slowing time becomes 0.41 s which is shorter than the diffusion time. The result suggests that the diffusion of energetic particles will not be critical in a high-density fusion reactor where the Spitzer slowing down time of alpha particle is around 0.1 s (n_{e_avg}~10^{20} m^{-3} and T_{e0}~10 keV [26]). P-NB blip experiment using NB4 was performed in order to study the confinement of helically trapped beam ions. In this discharge, P-NB with 30 ms is injected into the ECH plasma. Here, the injection energy and the injection power of the beam are 58 keV and 7.5 MW, respectively. The peak of S_n in R_{ax} of 3.60 m, 3.75 m, and 3.90 m are 3.9×10^{13} n/s, 3.7×10^{13} n/s, and 2.0×10^{13} n/s, respectively. Note that S_n evaluated by the FBURN is normalized at t of 4.95 s. Figure 6 shows that the decay time of S_n becomes shorter in outward shifted configurations. However, the effect of the beam slowing down should be considered, because the electron temperature in the inward shifted configuration tends to be higher compared with the electron temperature in the outward shifted configuration when the injection power of ECH and the plasma density are the same in the LHD. Here, the typical central electron temperature of these discharges in R_{ax} of 3.60 m, 3.75 m, and 3.90 m are 6 keV, 5 keV, and 3 keV, respectively. To remove the beam slowing down effect on the neutron decay time, we applied the FBURN to evaluate the D^*_{fast} in three different R_{ax} configurations in order to compare the confinement of helically trapped ions. In this calculation, we calculate the time evolution of S_n with D^*_{fast} of 3.0, 4.0, and 5.0 m^2/s (Fig. 6). In the R_{ax} of the 3.60 m case, D^*_{fast} in the experiment will be 3.0 to 4.0. The D^*_{fast} becomes around 4.0 for R_{ax} of 3.75 m and around 5.0 in R_{ax} of 3.90 m. We indicate that the confinement of helically trapped beam ions is improved with the inward shift of R_{ax}, as expected by the orbit calculation [27]. Note that although the diffusion coefficient of beam ions injected by P-NB is almost one order larger than that of N-NB ions, the value is similar to the diffusion coefficient of perpendicularly injected beam ions reported in JT-60U [28].

IV. Time-resolved DT neutron rate analysis in the LHD

Time-resolved triton burnup experiments have been performed in the LHD by means of a scintillation fiber detector (Fig. 7 (a)) [29]. In this discharge, plasma is initiated by N-NB and ECH, and N-NB is then turned off at t of 5.3 s. T_{e0} is around 4 to 5 keV during the discharge and n_{e_avg} is around 1×10^{19}m^{-3}. A rapid increase of S_n is observed with N-NB and ECH injections, then S_n decays after then N-NB turn off. There are two components in the decay of S_n. The first component corresponds to the decay of the DD neutron emission rate (S_{n_DD}) due to the slowing down of beam ions, whereas the second component corresponds to the decay of the DT neutron emission rate (S_{n_DT}) due to the slowing down of 1 MeV tritons created by d(d,p)t reactions. Note that the time evolution of S_{n_DT} measured by a scintillating fiber detector matched with the second decay component of S_n. We compared the time evolution of S_{n_DT} with the FBURN including the radial diffusion of tritons. The time evolution of S_{n_DT} measured in the experiment and calculated by the FBURN with a radial diffusion coefficient of triton D^*_T of 0.00 m^2/s, 0.05 m^2/s, 0.10 m^2/s, 0.15 m^2/s, and 0.20 m^2/s are shown in Fig. 7 (b). Note that the absolute value of S_{n_DT} is normalized at t of 5.3 s. It shows that D^*_T is between 0.15 m^2/s to 0.20 m^2/s. We also compared the shot integrated triton burnup ratio obtained by the experiment with the triton burnup ratio evaluated by the FBURN (Fig. 8). In this calculation, the triton burnup ratio with D^*_T of 0.00 m^2/s and 0.15 m^2/s are calculated. Here, the total injection power of N-NB is around 6 MW and the total injection power of P-NB is around 14 MW in these discharges. The triton burnup ratio has a peak at around n_{e_avg} of 3×10^{19} m^{-3}. Without including the diffusion case, the triton burnup ratio evaluated by the FBURN monotonically decreases with the increase of n_{e_avg} because of the shorter Spitzer slowing down time due to the decrease of T_{e0} and increase of n_{e_avg}. On the other hand, in the triton burnup ratio with D^*_T of 0.15 m^2/s case, the triton burnup ratio has a peak at around n_{e_avg} of 3×10^{19} m^{-3}, as obtained in experiments. The result suggests that the decrease of the triton burnup ratio with increasing n_{e_avg} is the result of the shorter slowing down time and the increase of the triton burnup ratio with the increase in n_{e_avg} is due to the effect of the radial diffusion. Hence, the triton burnup ratio has a peak due to the effects of the slowing down and the diffusion of tritons.

V. Neutron emission rate analysis in medium sized tokamaks

Time-resolved analysis of DD neutron emission rate is conducted using the FBURN in neutral beam injected deuterium plasma experiments in medium sized tokamaks. In the KSTAR, a fast neutron scintillation detector consisting of an EJ410 scintillator coupled with a 2-inch photomultiplier (R878, Hamamatsu Photonics) is installed in order to obtain S_n with fine time resolution through the collaboration between the National Institute for Fusion Science, National Fusion Research Institute, and Seoul National University. The time trend of S_n measured by the fast neutron scintillation detector in the NB blip experiment is compared with the FBURN (Fig. 9). In this experiment, B_t, I_p, n_{e_avg}, and T_{e0} are 2.4 T, 690 kA, 2×10^{19} m^{-3}, and 1.3 keV, respectively. Here, n_{e_avg} and T_{e0} are measured by the millimeter wave interferometer and the electron cyclotron emission diagnostics, respectively. The pulse width of an NB injection is 20 ms in this discharge. In calculation, the plasma volume in each cell is evaluated by a simple torus approximation, and the beam ion deposition profile is calculated by the NUBEAM code. Note that the oscillation of the fast neutron scintillation detector signal is mainly due to the electrical noise and the statistical error. The decay time of S_n around 21 ms matches in both experiment and the FBURN. It is found that D^*_{fast} is 0.0 to 0.2 m^2/s, which is the same order with that of N-NB in the LHD. Note that the effect of diffusion on the decay of S_n is not so clear compared with the result obtained in the LHD because the diffusion time estimated by the analytic solution at D^*_{fast} of 0.2 m^2/s is 170 ms, whereas the Spitzer slowing down time evaluated by $T_{e0}/2$ and n_{e_avg} is 76 ms. In the EAST, NB injection to the lower-hybrid-wave heated plasma with the relatively long NB pulse length (50 ms) is performed. In this discharge, the simple analysis applied to blip experiment is not suitable because the injection period of NB is so long that the distribution function of NB ion is no longer treated as a delta function [30]. The time trend of S_n measured by the neutron flux monitor [31] is compared with the FBURN (Fig. 10). In this experiment, B_t, I_p, n_{e_avg}, and T_{e0} are 2.4 T, 300 kA, 2×10^{19} m^{-3}, and 1.5 keV, respectively. Here, n_{e_avg} and T_{e0} are measured by the HCN interferometer and the Thomson scattering diagnostics, respectively. In this calculation, the plasma volume in each cell is evaluated by the simple torus approximation, and the radial beam ion density is assumed to be uniform. The decay time of S_n, 15 ms, matches in both experiment and the FBURN. It is found that the diffusion coefficient D^*_{fast} is 0.0 to 0.2 m^2/s which is the same order with that on N-NB in the LHD. Note that the fluctuation of S_n at t of around 3.26 s may be due to magnetohydrodynamic (MHD) instabilities such as tearing modes.

VI. Summary

The time-resolved analysis by means of the FBURN are performed for understanding energetic ion confinement in deuterium operations of toroidal plasma experiments. The FBURN calculates DD and secondary DT neutron emission rates based on the classical confinement of energetic ions with radial diffusion. The time trend of S_n evaluated by the FBURN matches with the experimental result in the LHD. The absolute value of S_n agrees with experiments within a factor of two. The NB blip experiments show that the radial diffusion coefficient of tangentially injected N-NB is 0.2 to 0.3 m^2/s, whereas the diffusion coefficient of perpendicularly injected P-NB is one order higher than that of N-NB. However, it is indicated that the diffusion coefficient becomes lower with the inward shift of R_{ax}. The time trend of S_{n_DT} evaluated by the FBURN agrees with the time trend obtained in experiments in the LHD. The analysis shows that the diffusion coefficient of triton is 0.15 m^2/s which is the same order as the diffusion coefficient obtained in the JT-60U. Time-resolved analysis of S_n in the NB blip experiments the KSTAR and the EAST are performed. Time trends of normalized S_n are successfully reproduced by the FBURN. The diffusion coefficient of beam ions in the KSTAR and the EAST is the same order as that of the co-going transit beam ions in the LHD.

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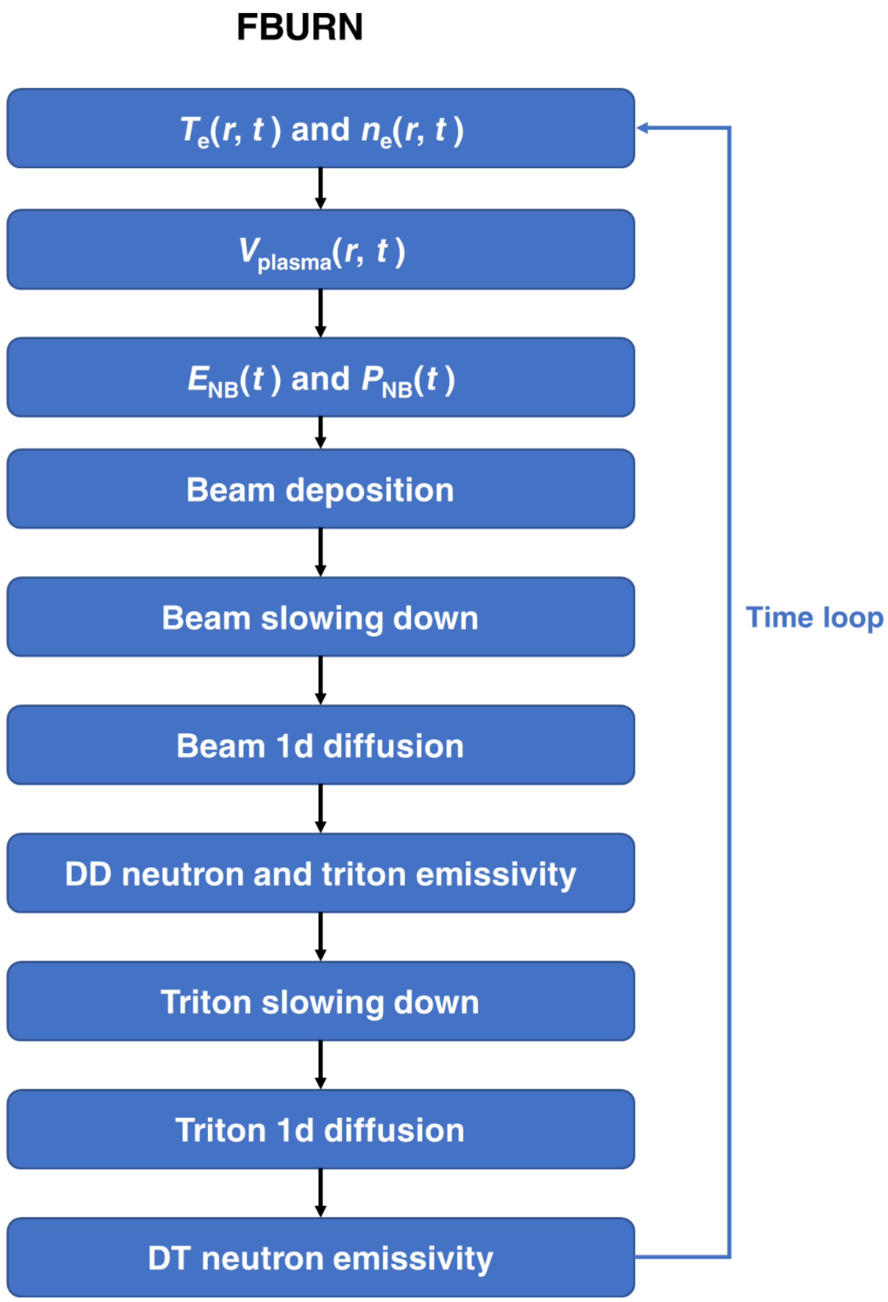

T_e: Electron temperature, n_e: Electron density, V_{plasma}: Plasma volume
E_{NB}: Beam voltage, P_{NB}: Beam power, r : Minor radius, t : Time

Fig.1 Block diagram of the FBURN.

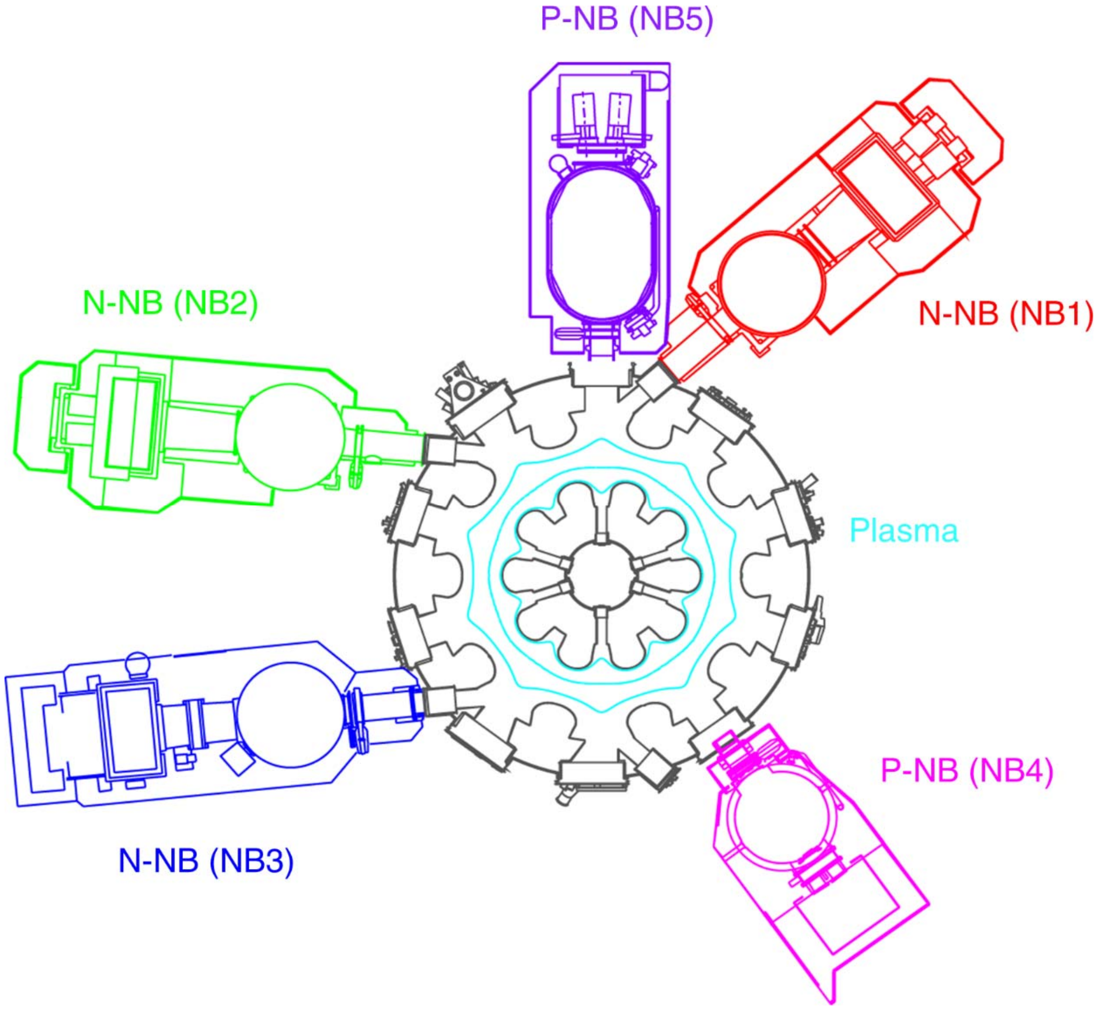

Fig. 2 An overhead view of the LHD and the NBs.

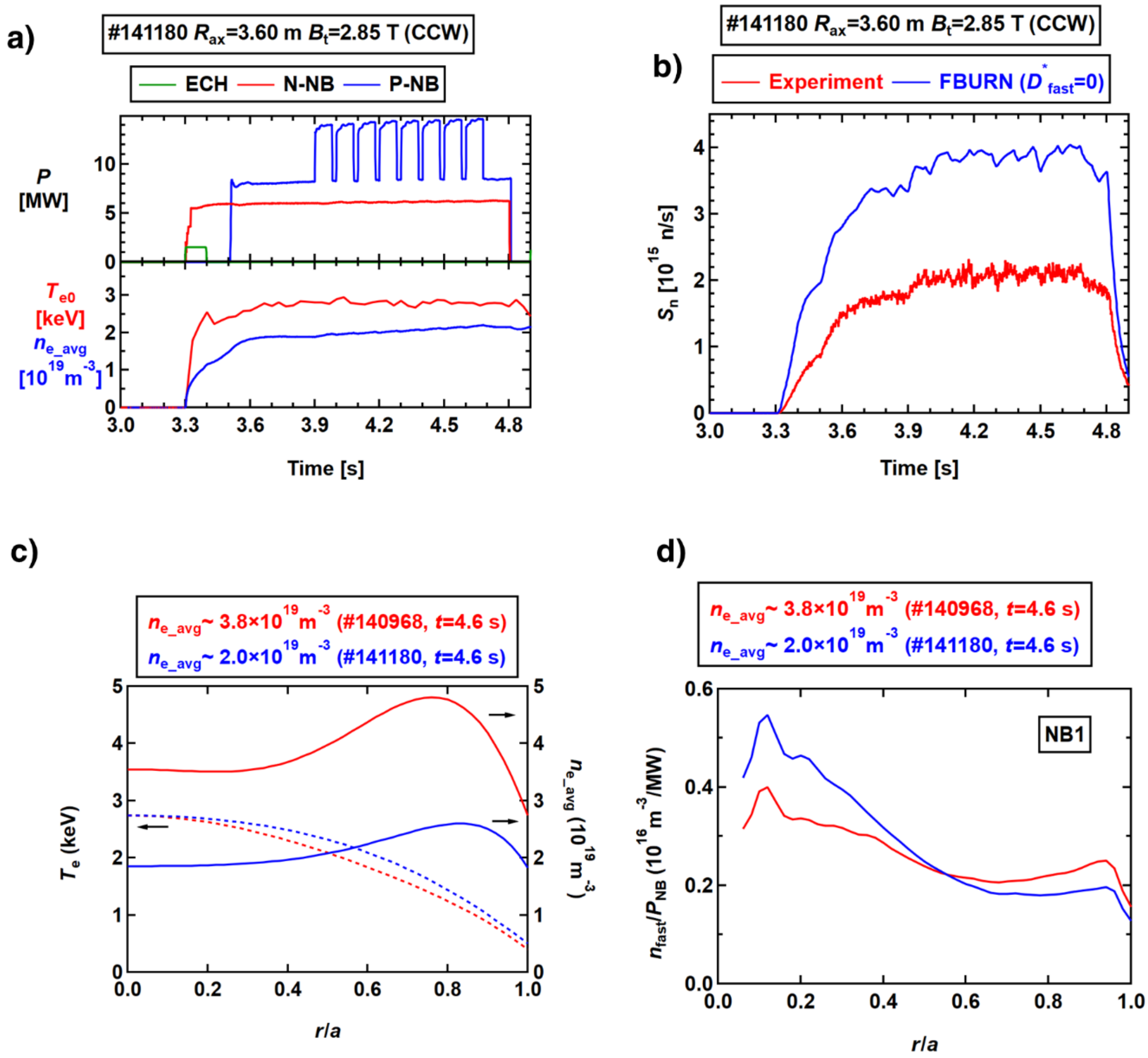

Fig.3 (a) Typical time trace of the heating pattern and plasma parameters of the discharge. (b) Time evolution of total neutron emission rate measured in experiment and evaluated by FBURN without energetic ion diffusion. Although the absolute neutron emission rate requires a normalization factor of around two to match experimental measurements, the time evolution is reproduced accurately. (c) Typical radial profiles of electron temperature and density. (d) Typical beam ion density profile of NB1 ions. The deposition profile becomes flat in the higher density case compared with the lower density case.

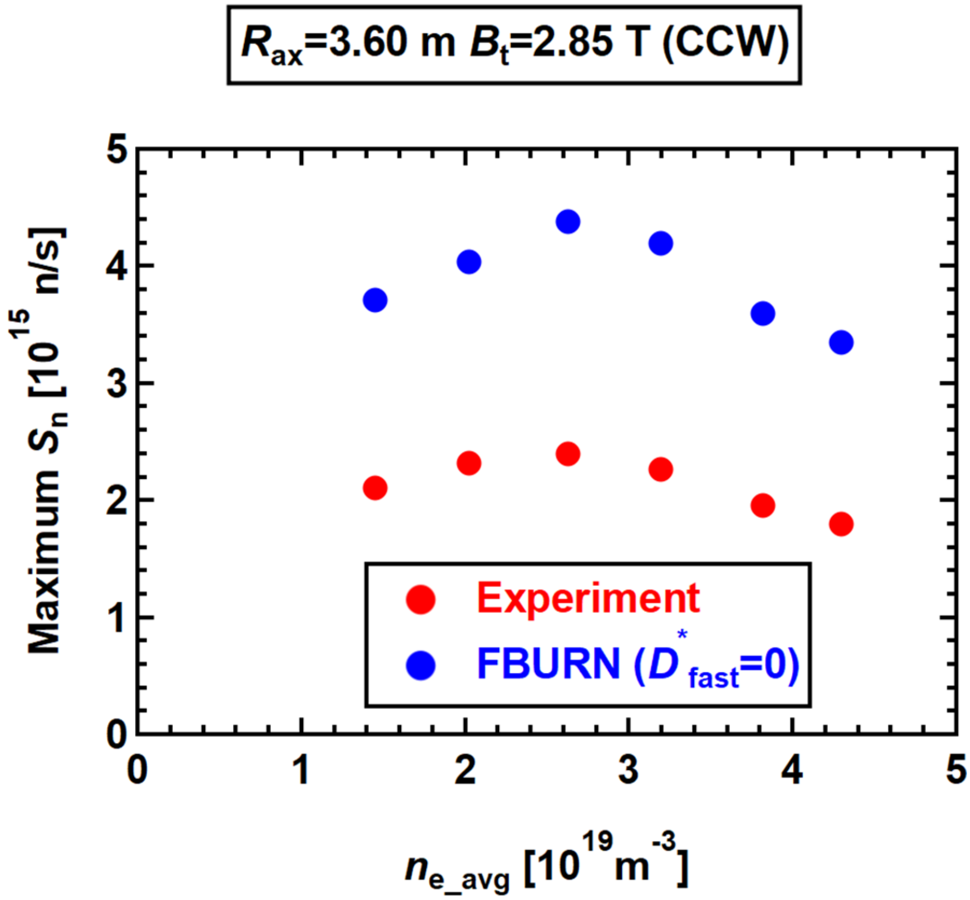

Fig4. Maximum total neutron emission rate obtained in one shot as a function of line averaged electron density. Here, six shots having same NB injection patterns are analyzed. Note that the range of T_{e0} is from 2.6 keV to 2.9 keV. The total neutron emission rate has a peak at the density of 2×10^{19} to 3×10^{19} m^{-3} in both experiments and calculation.

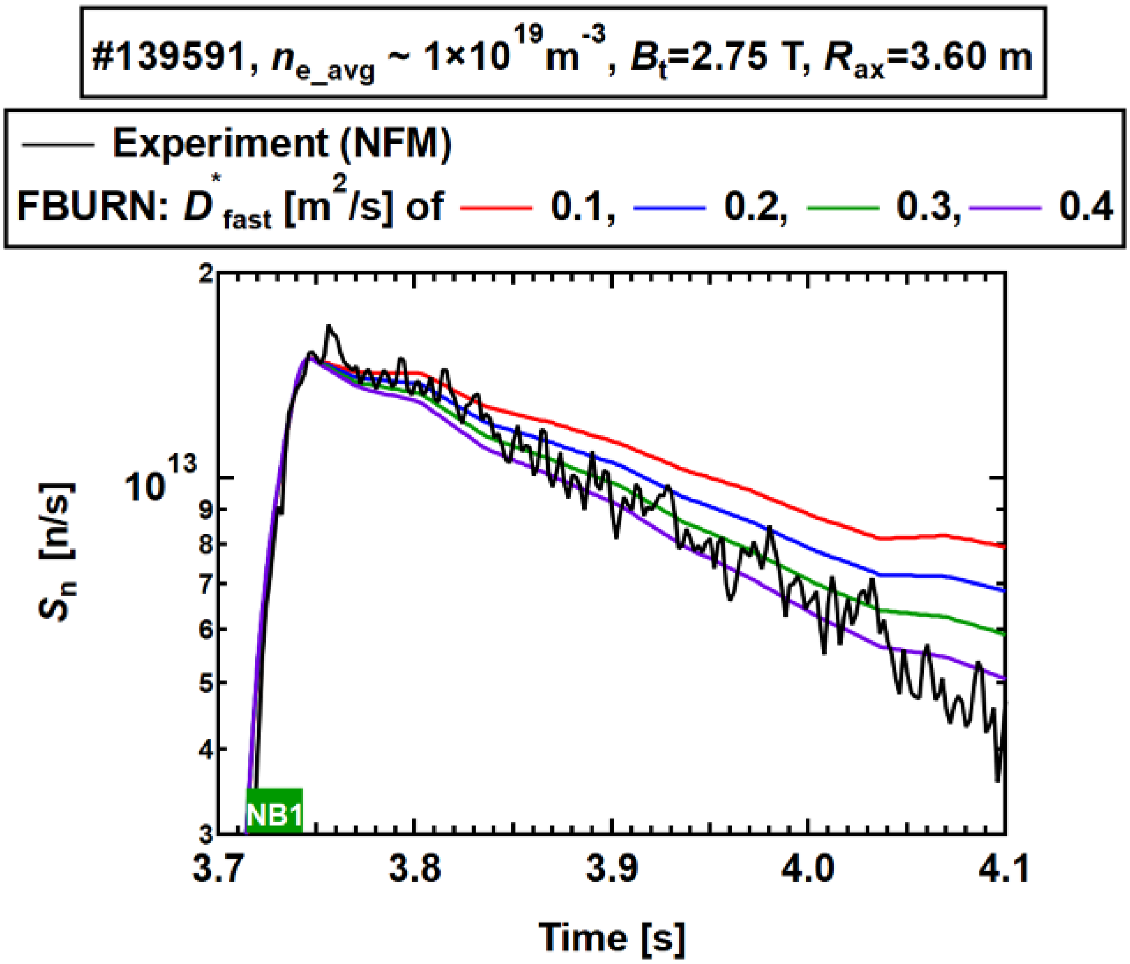

Fig.5 Time evolution of total neutron emission rate in N-NB blip experiment. S_n evaluated by FBURN is normalized at *t* of 3.74 s. The graph shows that the diffusion coefficient of co-going transit energetic ions is between 0.2 to 0.3 m^2/s.

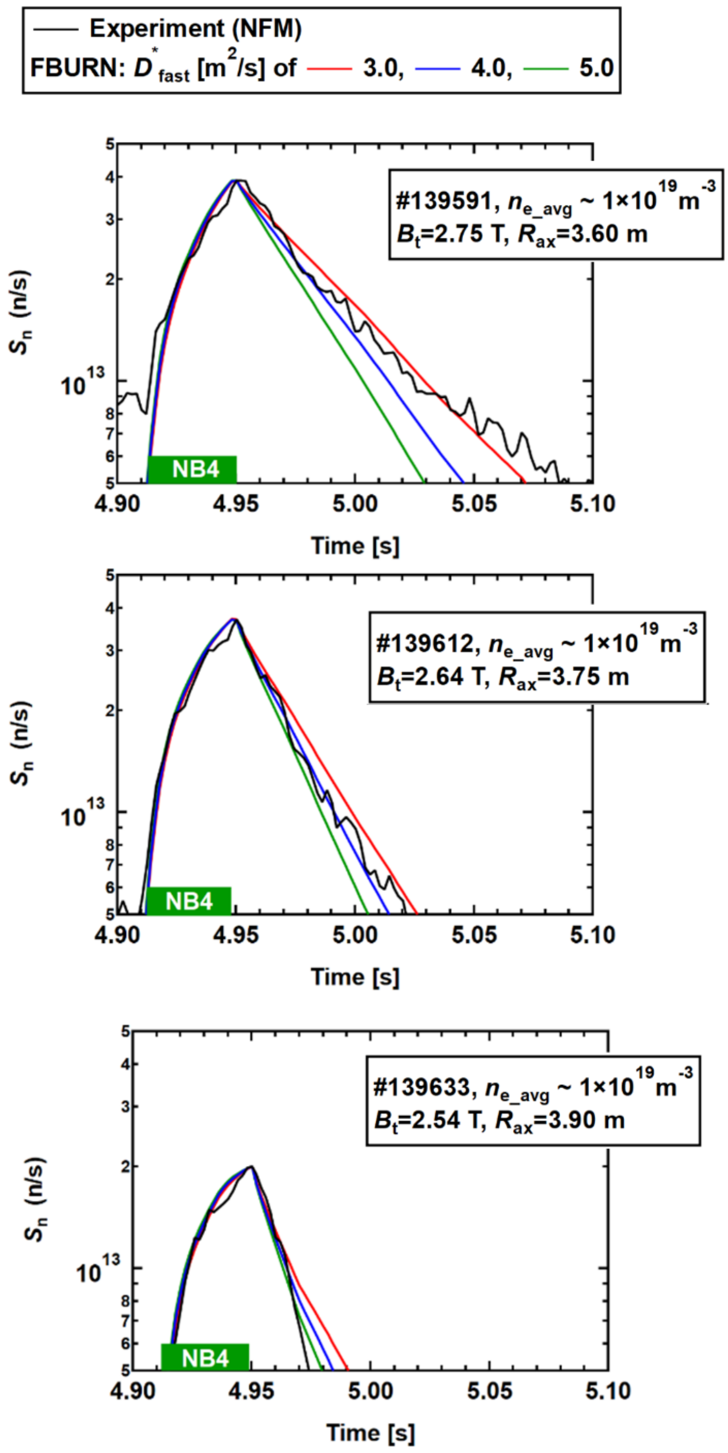

Fig.6 Time evolution of total neutron emission in P-NB blip experiments on the magnetic axis position of (a) 3.60 m, (b) 3.75 m, and (c) 3.90 m. S_n evaluated by FBURN is normalized at t of 4.95 s. The diffusion coefficient of helically trapped energetic ions decreases as R_{ax} shifts inward.

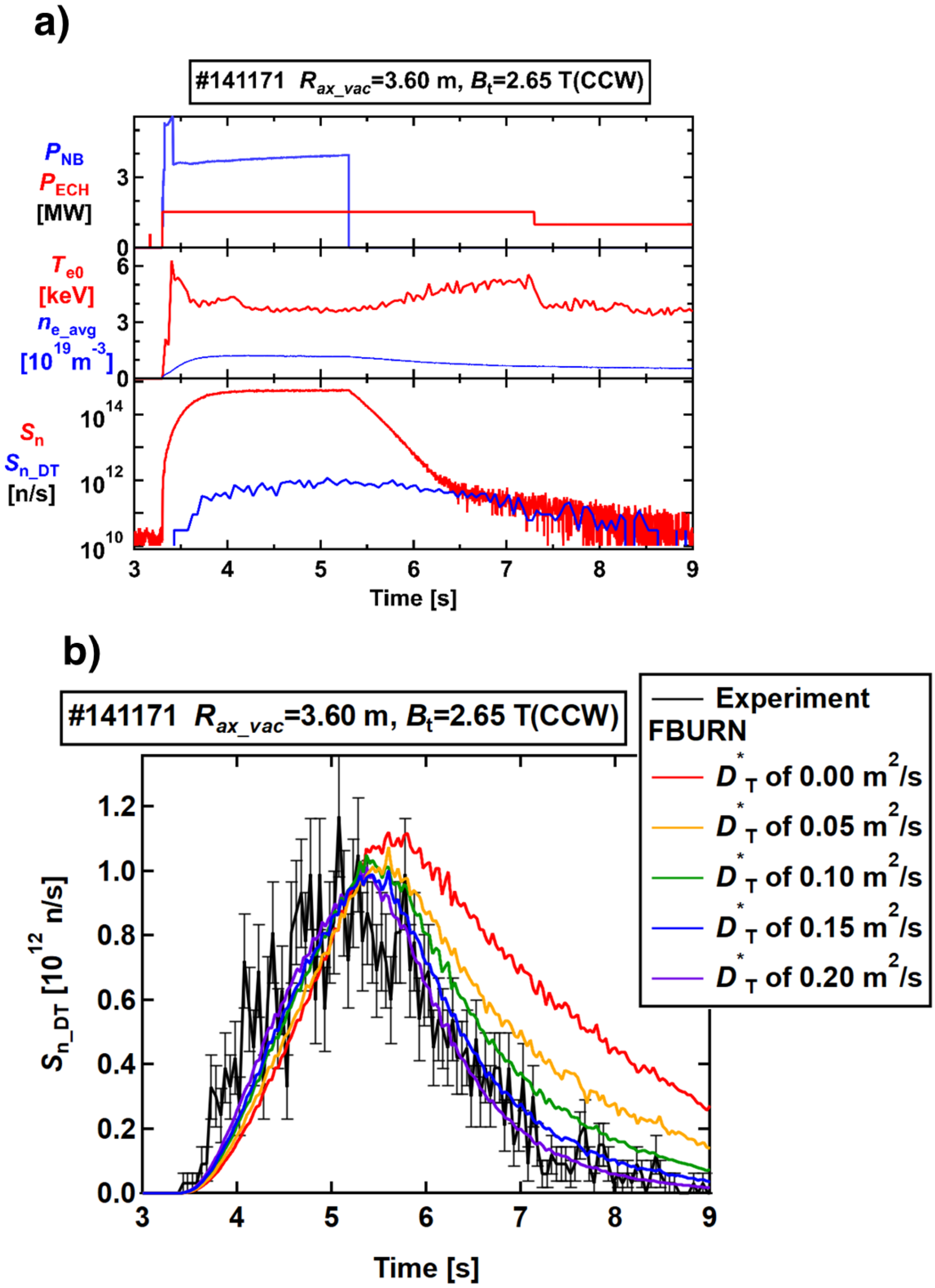

Fig.7 (a) Time trace of the heating power, plasma parameters, and total and DT neutron emission rate on the triton burnup experiment. (b) Time evolution of the DT neutron emission rate obtained in the experiment and evaluated by the FBURN. S_{n_DT} evaluated by FBURN is normalized at t of 5.3 s. The diffusion coefficient of triton is approximately 0.15 m^2/s.

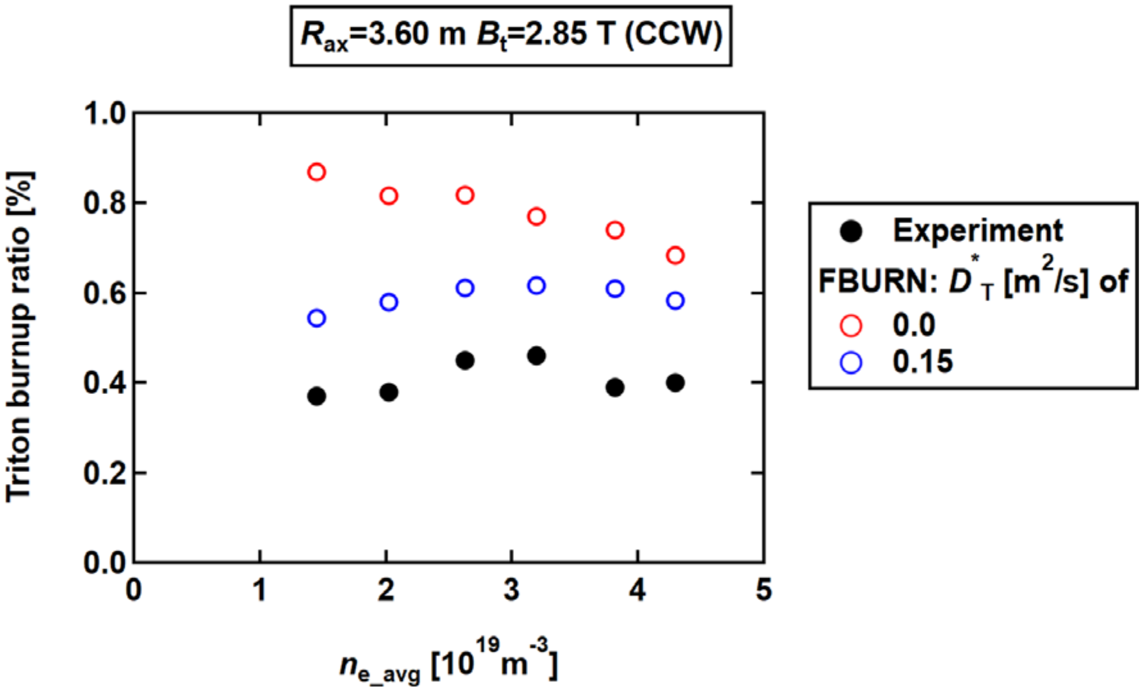

Fig.8 The triton burnup ratio as a function of the line averaged electron density. The triton burnup ratio has a peak around the electron density of 3×10^{19} m^{-3} in experiment and calculation by the FBURN with the diffusion coefficient of tritons of 0.15 m^2/s.

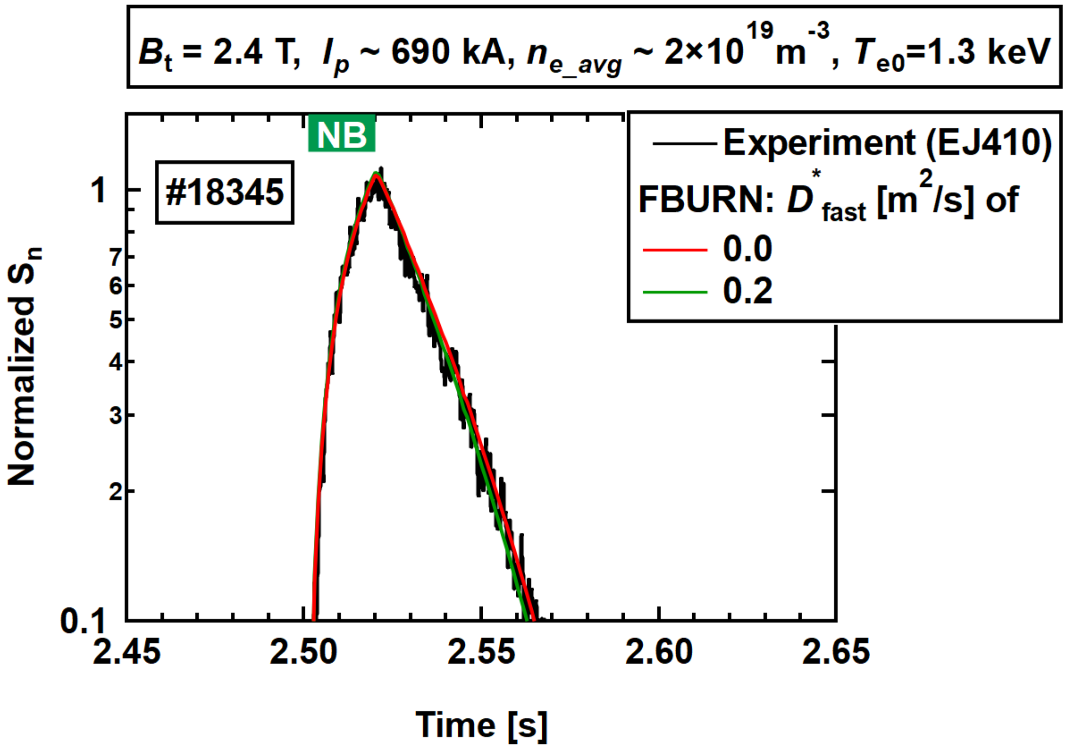

Fig.9 Time evolution of the total neutron emission rate in the NB blip experiment in the KSTAR. The analysis shows that the diffusion coefficient of energetic ions is 0.0-0.2 m^2/s.

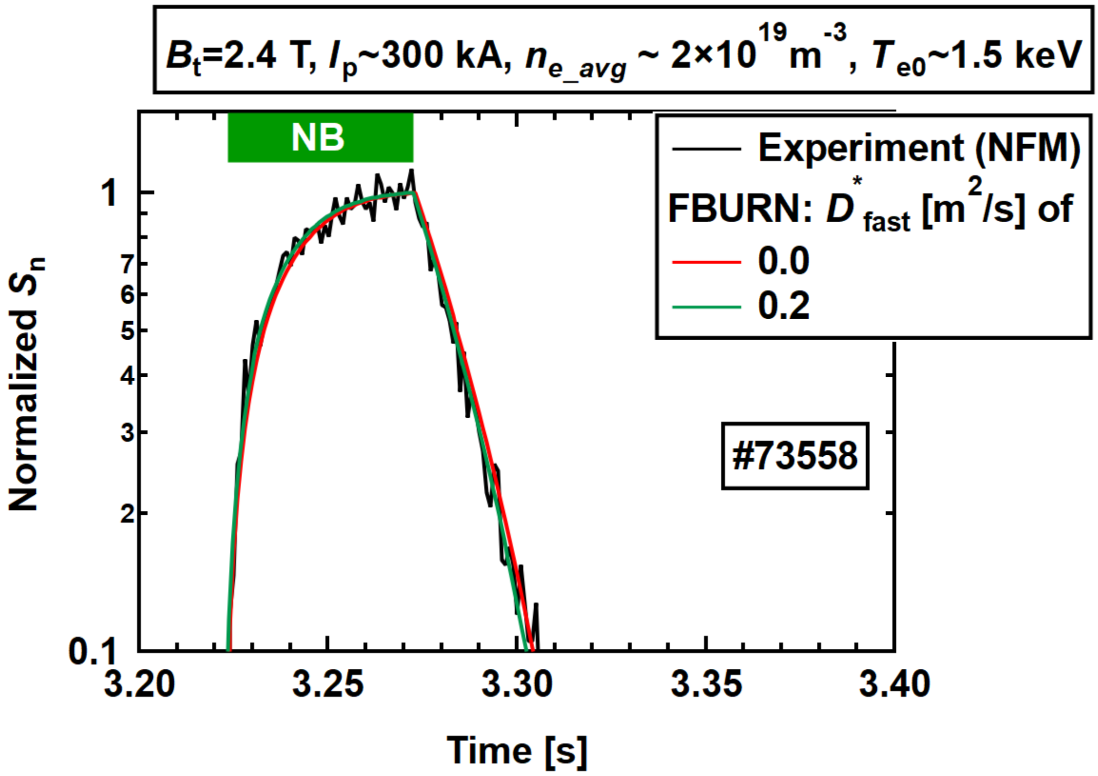

Fig.10 Time evolution of the total neutron emission rate in the NB blip experiment in the EAST. The graph shows that the diffusion coefficient of energetic ions is 0.0-0.2 m^2/s.