A Plan for a Fast-Ion D-Alpha (FIDA) Measurement for JT-60SA*)

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A new fast-ion diagnostic based on the spectroscopy of the Doppler shifted Balmer-alpha line of Deuterium is considered for JT-60SA. Two sight lines, one tangential and the other perpendicular, are examined as candidates. It was found that the tangential one has better sensitivity than the perpendicular one. A trial of the FIDA measurement was performed on JT-60U. Signals due to the tangential-NB injection were obtained. It was found that about the one third of the signal would be due to the active FIDA signal, which was produced by fast-ions and a probe beam, while the remainder would be due to passive signal. The results indicate the FIDA measurement on JT-60SA would be possible with proper background measurements.

Keywords: fast-ion diagnostic, JT-60SA, FIDA

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1. Introduction

Confinement of fast-ions is one of the important issues for realizing fusion reactors since its degradation might cause; (1) fatal damage on the surface of in-vessel components due to the heat load by the lost fast-ions, (2) degradation of heating efficiency of fusion-born alpha particles, and (3) degradation of current drive efficiency by externally introduced fast-ions, such as neutral beams.

To investigate fast-ion confinement properties, we are considering the application of a new fast-ion diagnostic, named Fast-Ion D-Alpha (FIDA), on JT-60SA. This measurement was originally developed by W.W. Heidbrink, *et al.* [1], on D-IIID and was applied at various devices such as NSTX [2], TEXTOR [3] and LHD [4]. In the method, the Doppler shifted deuterium Balmer-alpha light (D_α), which is created as a result of the Charge eXchange Recombination (CXR) processes between fast-ions and injected Neutral Beams (NB), are utilized as the signals of fast-ions. Compared to the conventional fast-ion diagnostics, e.g. neutron diagnostics and fast neutral particle diagnostics, this method has an advantage in obtaining the spatial information of the fast-ion energy spectra. Since the energy spectra of fast-ions are strongly affected by their confinement properties, this method will provide us with the detailed information of fast-ion confinement in plasmas. On the other hand, the measurement is expected to be very difficult since the intensity of the FIDA light is usually weak compared to other emission from the plasmas around its wavelength, i.e., the direct Beam Emission Spectral (BES) light from NB, D_α-lights from the plasma periphery and the continuum spectra of bremsstrahlung radiation. Moreover, the shape of its Doppler shifted spectra is very sensitive to the observation geometry. Thus, it is better to investigate the property of observation geometry for various cases for the FIDA measurement on JT-60SA. One possible implementation of FIDA measurement on JT-60SA is to share the optics with the CXR Spectroscopy (CXRS) for ion-temperature measurement. If we can share the optics with CXRS in JT-60SA, the geometrical relation among NBI, Line-Of-Sight (LOS), and the toroidal field in JT-60SA is similar to that in JT-60U. Thus, the evaluation of the CXRS-LOS on JT-60U for FIDA measurement is a good first step in the evaluation.

In this paper, the sensitivity of the intensities of FIDA signals for various observation geometries are examined and optimum observation geometries are described in Section 2. In Section 3, a result of the FIDA trial measurement on JT-60U is presented in Section 3. Section 4 is a summary.

2. Evaluation of the Properties of Sightlines for FIDA Measurement on JT-60SA

The principle of the measurement is shown in Fig. 1 (a). As shown in the figure, the ion in magnetically confined devices undergoes Larmour-motion and it stays a longer time in the LOS when it moves tangentially to the sight lines of the measurement. Therefore, the Doppler shifted D_α light from the Deuterium neutral, which was created by the Charge eXchange (CX) process between the circulating Deuterium ions and the Deuterium neutrals introduced by the injected NB, show twin peaks in its spec-

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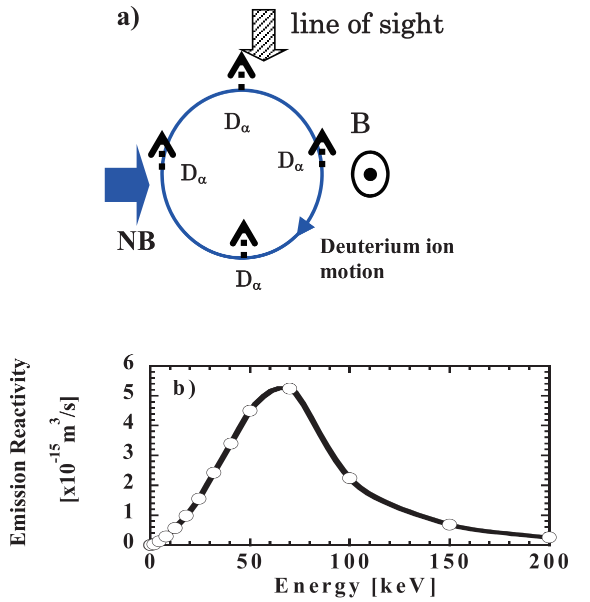

Fig. 1 (a) A Schematic drawing of the principle of FIDA measurement. (b) Reaction rate for D_α light from charge exchange process between a Deuterium ion and neutral.

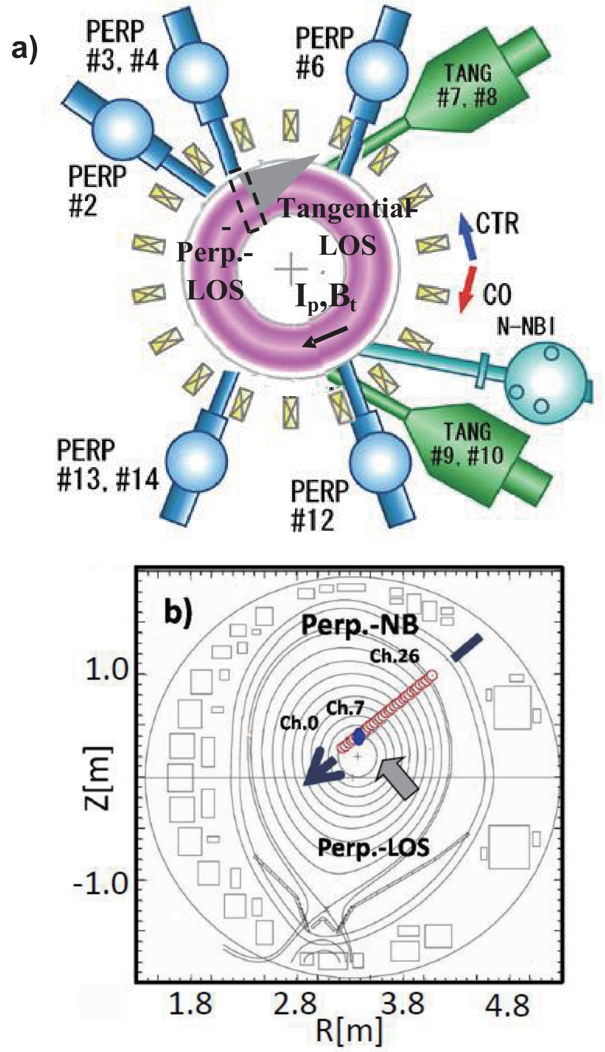

Fig. 2 (a) Schematic tangential (indicated by a gray triangle) and perpendicular (indicated by a dashed rectangle) observation LOS in JT-60U. (b) Poloidal cross section of the planned measurement location where the open circles are the measurement points of the tangential LOS. The direction of the perpendicular-LOS is indicated by a gray arrow, while the center line of the diagnostic-NB is indicated by a dashed line.

tra when the LOS is chosen perpendicular to the magnetic field lines. Since the peak can be considered as a delta-function, it was expected that the Doppler shifted spectra show the fast-ion velocity distribution functions in plasmas. But, the spectral shape becomes different when the reaction rate of the emission process is taken into account. As shown in Fig. 1 (b), the reaction rate reaches its maximum value when the relative energy between the Deuterium ion and neutral is around 75 keV. In the case of 80 keV Deuterium NB injection, the relative energy can be changed from 0 to 160 keV when the NB is injected perpendicular to the magnetic field lines. Thus, the spectra can be significantly affected by the energy dependence of the reaction rate. Therefore, the observation geometry must be chosen carefully.

As is described in the introduction, the CXRS-LOS on JT-60U was chosen as the first evaluation LOS for FIDA on JT-60SA. In Fig. 2, the observation geometry which was used for CXRS on JT-60U is shown. The perpendicularly injected NB is chosen as an active source of neutrals for the diagnostic since it is expected to provide better spatial resolution and wider measurement range in space compared to a tangential NB. Two measurement directions were examined as FIDA sight lines. One observes the perpendicular-NB tangentially to the magnetic field lines and the other observes the same NB perpendicularly to the field lines. In this evaluation, the NB#4 was chosen as a probe beam. In Fig. 2 (b), the measurement points are shown by open circles with the flux surfaces of JT-60U.

In Fig. 3, the expected FIDA spectra for mono-energetic Deuterium ions are shown for tangential- and perpendicular-LOSs. The pitch angles of the particles are scanned in the figure. As is expected, the Doppler shift becomes larger as the direction of the particle motion becomes parallel to the magnetic field lines in the case of tangential-LOS, while the Doppler broadening becomes wider as the pitch angle becomes closer to 90-deg. in the case of perp.-LOS. It must be noted that the intensities for tangential LOS are about 10 times larger than those for perp.-LOS. This is because the broadening of the spectra due to the Larmour-motion becomes larger in the perp.-LOS than in the tangential-LOS. This estimation suggests that for the FIDA measurement in JT-60SA it would be better to start with the tangential-LOS and then try the perp.-LOS.

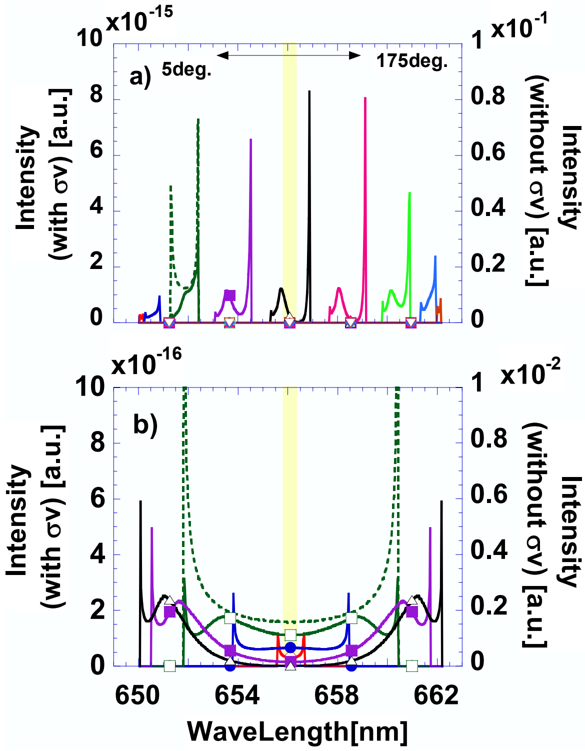

Fig. 3 Expected FIDA spectra of (a) tangential- and (b) perp.-LOSs for mono-energetic particles of 80 keV. The particles of having pitch angles of 5(○), 22.5(●), 45(□), 67.5(■), 90(△), 112.5(▲), 135(◇), 157.5(◆), and 175 deg.(▽) are shown. For the particle with a 45 degree pitch angle, the spectra without considering the effect of emission reactivity are shown by dashed curves. Yellow shaded area shows the expected region where cold D_α spectra can be observed.

3. Trial of FIDA Measurement at JT-60U

To examine the possibility of the FIDA measurement at JT-60SA, trial measurements were performed on JT-60U by using its CXRS system for ion temperature measurement during the last few days before it was shutdown. In Fig. 4, a typical FIDA spectra obtained during the trial was shown. The LOS of the measurement is the same as that shown in Fig. 2. The NB#4 is used as a probe-NB to supply active neutrals for the measurement. The modulation of NB#4 was not performed during the experiment. Thus, the obtained spectra could contain the charge exchange component between fast-ions and neutrals penetrated from the periphery (peripheral neutrals) of the plasma. To avoid the contamination of the measured spectra by BES light from NB#7 and #8 on its LOS, the measured spectral range was set between 649 and 653 nm. The D_α-light from the bulk-plasma components (656.1 nm) are out of the range and are not shown in the figure. The intense peaks at 650 nm correspond to the characteristic-lines from the oxygen impurity (650.04 nm). The small peaks at around 651.5- and 652.8-nm might also be impurities, but the species are

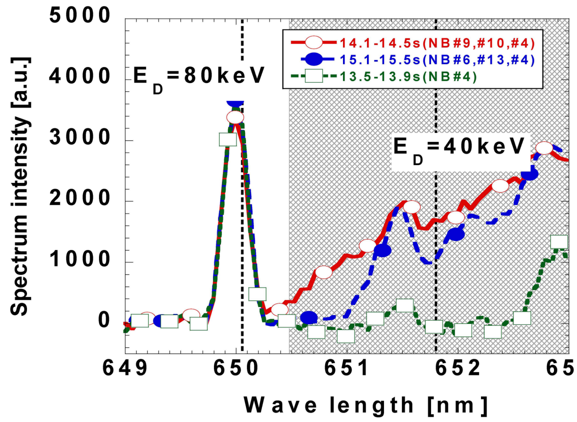

Fig. 4 Typical FIDA spectra measured on JT60U (at R = 3.4 m) for tangential-NB plus probe-NB injection(○), perp.-NB plus probe-NB injection(●), and probe-NB only injection(□) are shown.

not yet identified. Vertical dashed lines indicate the expected wavelengths for Doppler shifted D_α-light from 80 and 40 keV deuterium neutrals, which are flying toward the view-port of the measurement. Since the blue shifted D_α spectra are chosen to be measured, the signals by lower energy or higher pitch angle ions appear in the longer wavelength region in the figure and their wavelength approaches 656.1-nm as the energy of the ion decreases or the pitch angle of the ion approaches 90 deg. In Fig. 4, the spectrum shown by dashed-lines with open squares is obtained only during the probe beam injection (NB#4). In the figure, the spectrum shown by the solid-lines with open circles is for the additional co-directed tangential-NB (#9 and #10) injection, while the lines with closed circles show that for the additional perpendicular-NB (#6 and #13) injection. As shown in this figure, significant changes of the spectra are observed in the wavelengths above 650.5 nm with the injections of additional tangential-NB injections and above 651.5 nm with perp.-NB injection. Since these NBs were not injected on the sight lines, these spectra are considered to be FIDA signals due to the fast-ions produced by these NBs.

To examine the property of observed spectra, FIDA spectra were estimated. To simplify the problem, we concentrate our analysis on the FIDA-spectra in the region where the largest Doppler shift was expected. Thus, the calculation of the spectra for initial fast-ion distributions, which were calculated from the NB birth profiles and from orbit calculations without a slowing-down process, would be enough. In Fig. 5 (a), the initial pitch-angle distributions along the LOS of FIDA channel No.7 are shown by contours for fast-ions produced by a tangential-NB injection, while those for a perp.-NB injection are shown in Fig. 5 (e). In these figures, the x-axes indicate the distance of the point of interest from the observation port and the dashed lines show the pitch-angles of the LOS. The vertical dashed lines shown in Figs. 5 (a)-

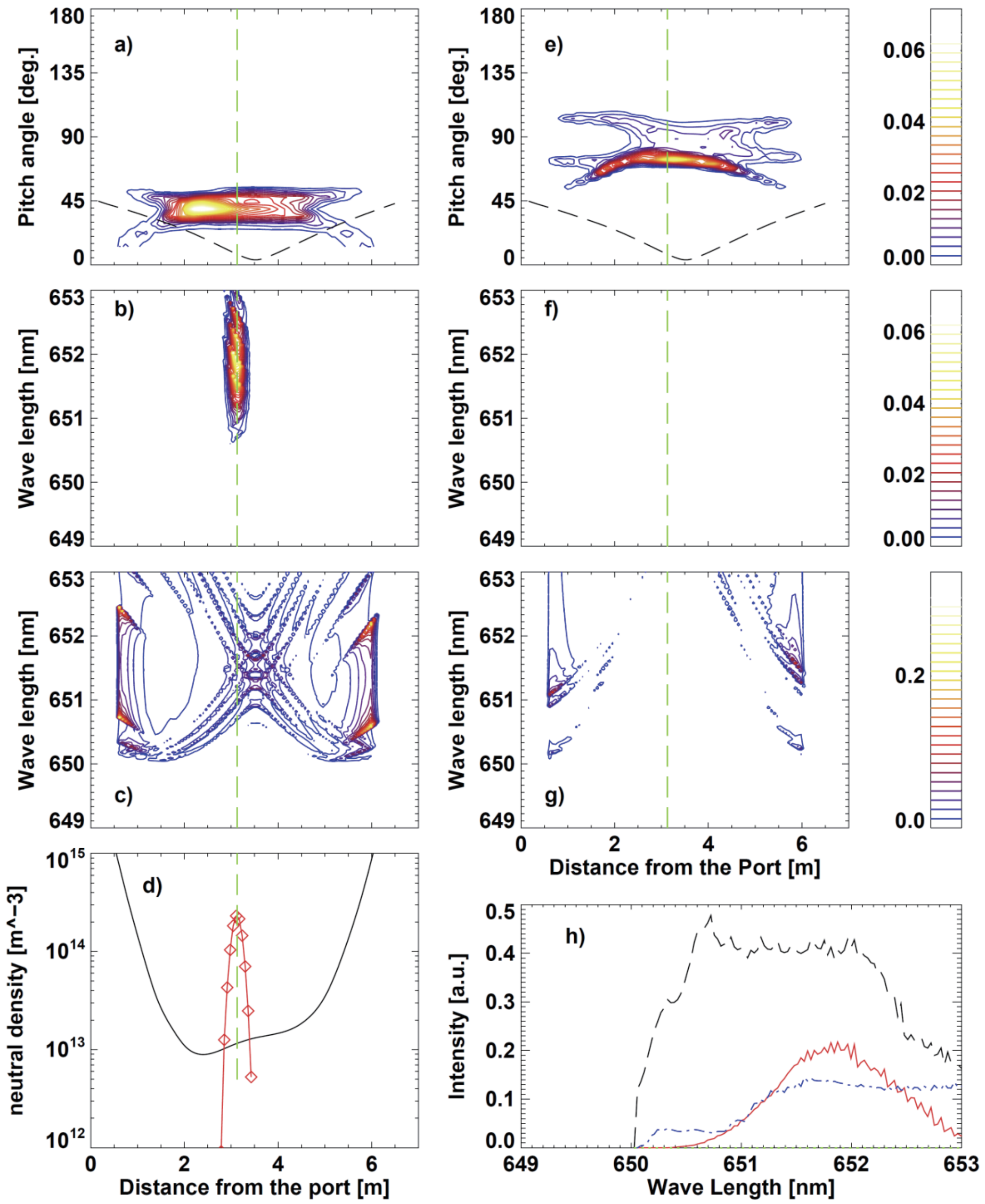

Fig. 5 (a) Initial pitch-angle distributions for fast-ions produced by tangential-NB on the LOS of FIDA channel 7 are shown by contours. The expected FIDA spectra for these fast-ions in the measured spectral range of Fig. 4 are also shown by contours in (b) and (c), where the former is for the active-component and the latter is for the passive-component. Similar figures to (a), (b) and (c) are shown for fast-ions produced by perpendicular-NB in (e), (f) and (g), respectively. In (f), none of active FIDA spectra can be found since the Doppler shift was too small in this case. The neutral density distribution along the LOS is shown in (d), where solid lines indicate the neutrals penetrating from the periphery and was evaluated by AURORA-code [5]. In the figure, the lines with squares indicate neutral by probe-NB. The line integrated FIDA spectra on the LOS are shown in (h), where active and passive components for tangential-NB injection are shown by solid lines and dashed lines, respectively. That of the passive component for perp.-NB injection is shown by dotted and dashed lines. Active-component for the perp.-NB case is also shown in the figure, but is aligned on the *x*-axis.

(g) indicate the locations of the center of the probe-NB. The density profile of peripheral neutrals and that of the probe beam are shown in Fig. 5 (d). Using these neutral densities and pitch-angle distributions, the expected FIDA spectra were reconstructed. In Figs. 5 (b) and (c), the active- and passive-FIDA spectra on the LOS in the region between 649 and 653 nm are shown by contours for tangential-NB injection, respectively. Here, “active” means the CX-process between fast-ions and neutrals injected by the probe-beam, while “passive” means that between fast-ions and peripheral neutrals. The active- and passive-FIDA spectra for perp.-NB injection are also plotted by contours in Figs. 5 (f) and (g). But, none of the spectra are shown in Fig. 5 (f) since the expected Doppler-shift of active-FIDA lights are too small for the perp.-NB injection case. As shown in Figs. 5 (d) and (e), the active neutral source by the probe-beam was localized at around 3.1-m and the pitch-angles of fast-ions for the perp.-NB case ranges from 67 to 105 degree, while that of the LOS is about 7 degree in the region. Thus, the Doppler shift of the D_α-lights is 3.0 nm at the maximum in the blue region. Therefore, none of the spectra can be found in the region between 649 and 653 nm. Line integrated spectra of them are shown in Fig. 5 (h). As shown in these figure, most of the spectra in the wavelengths between 650 and 651 nm were due to the passive-FIDA component for tangential-NB injection. Even in the region between 651.5 and 652 nm for the tangential-NB case, the intensity of the passive components become as large as double that of the active components due the line integration effect. Since the sum of them was observed in the experiment and they are estimated by calculation to be comparable, this indicates that the FIDA measurement for tangential-NB injection would be possible on JT-60SA with a proper background measurement. On the other hand, none of the active-FIDA components were found for perp.-NB injection in the wavelength range between 649 and 653 nm. Thus, all of the signals observed in the experiment for the perp.-NB injection were due to the passive-FIDA components. A contribution of passive-FIDA spectra comparable to the active one implies another application of the FIDA measurement. It might be possible to use it for peripheral neutral density evaluation since the difference between these two FIDA spectra comes mainly from the difference of neutral distributions between a probe-beam and peripheral neutrals and the neutral density by the beam can be easily evaluated by calculation.

4. Summary

A new fast-ion diagnostic based on the spectroscopic measurement of Doppler shifted Balmer-alpha light from Deuterium is considered for application to JT-60SA. Two sight lines, one is tangential and the other is perpendicular, are examined as candidates. It was found that the tangential one has better sensitivity than the perpendicular one. In the FIDA trial measurements at JT-60U, a significant amount of passive FIDA components were observed. It is expected that the active-components would be about half of the passive components in the range of 651.5 and 652 nm. It is suggested that the FIDA-measurement for a tangential-NB injection is possible at JT-60SA with a proper measurement of the background, such as by NB-modulation. Another use of the FIDA measurement for peripheral neutrals was implied through the comparison of passive- and active-FIDA measurements.

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