ANALYSIS OF FAST ION DISTRIBUTIONS USING NEUTRON EMISSION SPECTROSCOPY IN NBI-ICRF SYNERGISTIC HEATING PLASMA ON EAST

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ABSTRACT

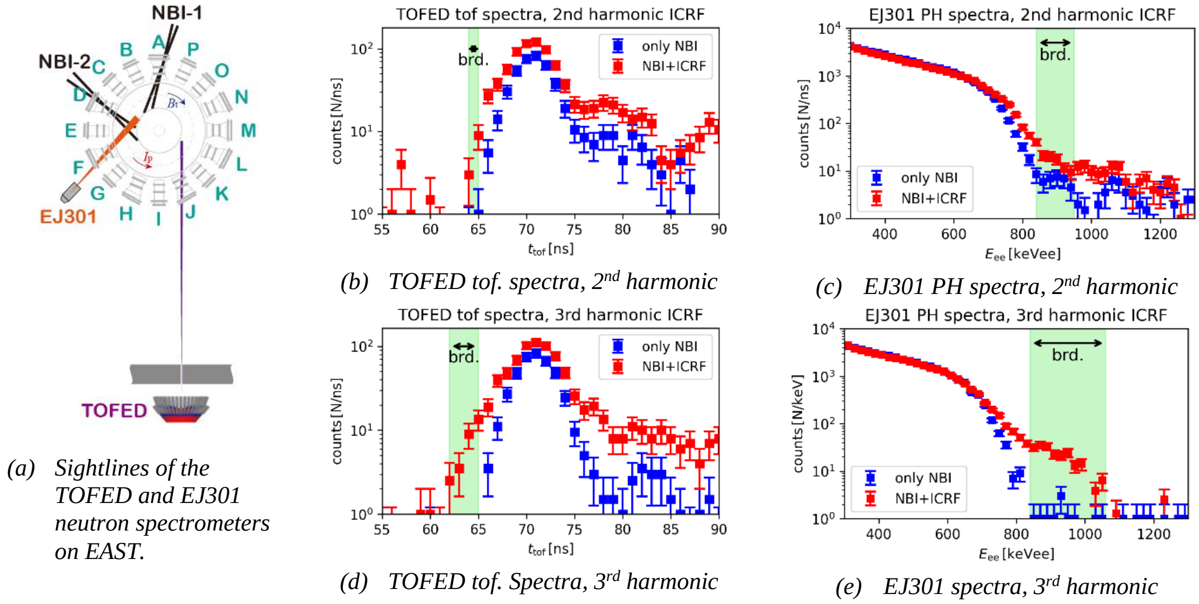
This study reports the diagnosis of fast-ion velocity distribution under NBI-ICRF synergistic heating on EAST's Deuterium discharge, using multi-view neutron energy spectrometers. A new data processing method is developed, and for the first time on EAST, neutron diagnostics provide direct experimental evidence of 100 keV fast Deuterium ion generation in the plasma core under NBI-ICRF synergistic heating. We observe an asymmetry in the pitch angle of the fast ion tail, which is confirmed by TRANSP simulations, presumed to be related to the fast ion orbit loss based on further orbit calculations. This study demonstrates the capability of neutron emission spectroscopy for diagnosing fast ion distribution functions on EAST, providing a foundation for distribution function tomography and fast-ion research for future fusion reactors.

1. INTRODUCTION

In Tokamaks' Deuterium discharge, synergistic heating via Ion Cyclotron Resonance Heating (ICRH) and Neutral Beam Injection (NBI) is an effective method for generating fast ions with energies exceeding 100 keV. This typically results in an increase and broadening of neutron emission energy. Neutron Emission Spectroscopy (NES) diagnostics can directly study the distribution of high-energy fast-ion tails. We have developed a new integrated data analysis method, which, by establishing the spectrometer's weight function and performing joint analysis of data from different lines of sight, enables the extraction of information on the fast-ion tail distribution.

2. EXPERIMENTAL SETUP

An EJ301 liquid scintillator neutron spectrometer and a TOFED neutron spectrometer are used, with their lines of sight shown in Fig. 1(a). The parameters for second- and third-harmonic heating shots are listed in Table 1. Fig. 1(b)–(e) illustrate the broadening of the TOFED time-of-flight and EJ301 pulse-height spectra under 2nd and 3rd harmonic heating. Despite the lower power, third-harmonic heating caused more pronounced spectral broadening in both diagnostics.



(a) Sightlines of the TOFED and EJ301 neutron spectrometers on EAST.

(b) TOFED tof. spectra, 2nd harmonic

(c) EJ301 PH spectra, 2nd harmonic

(d) TOFED tof. Spectra, 3rd harmonic

(e) EJ301 spectra, 3rd harmonic

Fig. 1: Diagnostic Sightlines and Results of EJ301 Pulse Height(PH) and TOFED Time-Of-Flight(tof.) Spectra on EAST

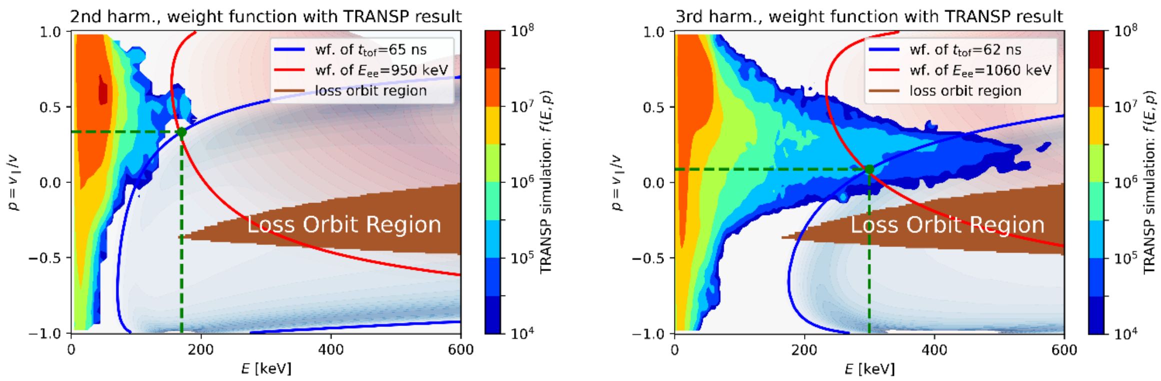
Table 1: Experimental Setup. 2nd Harmonic is from EAST Shots #102110, #102111; 3rd Harmonic is from EAST Shots #113829, #113829, #113845, #113846. "Brd." Means Broadening of Time-Of-Flight or Phase-Height Spectra Here.

Harm.	$n_e(10^{13}\mathrm{cm}^{-3})$	$B_\mathrm{t}(\mathrm{T})$	$V_\mathrm{NBI}(\mathrm{kV})$	$P_\mathrm{NBI}(\mathrm{MW})$	$P_\mathrm{IC}(\mathrm{MW})$	$n_\mathrm{H}/n_\mathrm{D}$	t_tof brd.	E_ee brd.
2nd	4.1	2.4	55	3.0	1.5	4%	1 ns	10^2 keV
3rd	2.8	1.65	55	2.3	0.2-0.8	35%	3 ns	2×10^2 keV

3. WEIGHT FUNCTION ANALYSIS

The weight function $w(E,p,x)$ ($x = t_\mathrm{tof}$ or E_ee) of the neutron spectrometer describes the response of the spectra $s(x)$ to the fast ion distribution function $f(E,p)$. The weight functions for the EJ301 and TOFED spectrometers were calculated using the GENESIS code, assuming the spectrum originates entirely from core-emitted beam-thermal neutrons with $T_\mathrm{i} = 1.5$ keV. Inspired by the "null measurement" method in distribution tomography[1], we developed a fast approach using dual-view NES diagnostics to estimate the fast-ion tail position. The boundary of the weight function at the spectrum's cutoff position is plotted in (E,p) space for each spectrometer, and their intersection gives the approximate location of the fast-ion tail.

The analysis results are shown in Fig. 2, along with the $f(E,p)$ calculated by TRANSP code. The fast-ion tail energies and pitches obtained from the above analysis are (0.2 MeV, 0.3) and (0.3 MeV, 0.1) (green points in Fig. 2) for 2nd and 3rd, respectively. The fast-ion tail energy of 3rd harmonic heating is higher, and the pitch angle is closer to 0, which is qualitatively consistent with the TRANSP results. The tail under 3rd harmonic heating shows discrepancies compared to TRANSP calculations, which are preliminarily attributed to the RF coupling efficiency. Despite the lower ICRF power during the 3rd harmonic discharge, the conclusion that a higher-energy fast-ion tail is produced is reliable, as the influence of minority hydrogen ions has been excluded.



(a) NBI – 2nd ICRF heating. The weight functions corresponding to the cutoff in Figure 1(b) and (c)

(b) NBI – 3rd ICRF heating. The weight functions corresponding to the cutoff in Figure 1(b) and (c)

Fig. 2: Weight Function Analysis, TRANSP-Simulated Fast Ion Velocity Distribution, and Core($R_\mathrm{m} = 1.9$ m) Fast Ion Orbit Loss Region Calculated by OWCF.

In both experiments and TRANSP simulations, the fast-ion tail is mainly observed in the p>0 region. The reason of the asymmetries are: (1) NBI injection direction, favoring p>0 (Fig. 1(a)) (2) the orbit loss. A calculation by the Orbit Weight Computational Framework (OWCF)[2] shows a high-energy, negative-pitch loss orbit region (brown regions in Fig. 2(a), (b)). Fast-ion losses may introduce additional thermal loads and degrade confinement, posing a challenge for high-power NBI-ICRF synergistic heating on EAST.

4. CONCLUSION

This study establishes the diagnostic potential of multi-view neutron spectrometers for characterizing the fast-ion tail distribution function under NBI-ICRF synergistic heating, laying a solid foundation for future tomography efforts. Moving forward, we aim to integrate high-energy (NES) and low-energy (Fast Ion D_α or FIDA) fast-ion diagnostics on EAST to pursue the inversion of the fast-ion velocity distribution function across the full energy range (20 keV - 1 MeV). This will provide crucial insights into ICRF physics and offer critical information for the optimization and control of synergistic heating experiments.

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