

CONFERENCE PRE-PRINT

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

¹A.D. Xu, ¹Y.H. Li, ¹J.Y. Zhang, ¹T. Yu, ²M.Y. Xu, ³B.L. Hao, ²Y.B. Zhang, ²Y.Q. Zhang, ²C.Y. Pan, ¹Z.S. Liu, ¹X.T. Xu, ¹X.Q. Li, ²J. Huang, ²L.Q. Hu, ⁴, ⁵G. Gorini, ⁵M. Nocente, ⁴M. Tardocchi, ²G.Q. Zhong, ^{1, 2, *}T.S. Fan, ^{2, *}B.N. Wan and ²the EAST Team

¹ School of Physics, Peking University, Beijing, China

² Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China

³ Southwestern Institute of Physics, Chengdu, China

⁴ Institute for Plasma Science and Technology, Milan, Italy

⁵ University of Milano Bicocca, Milan, Italy

Email of the poster presenter: xuandong@pku.edu.cn

* Email of the corresponding author: tsfan@pku.edu.cn, bnwan@ipp.ac.cn

Abstract

Multi-line-of-sight measurements of fusion neutron spectra were obtained during NBI-ICRF third-harmonic synergistic heating on EAST using the TOFED spectrometer and four compact organic scintillators. Compared with pure NBI heating, during NBI-ICRF synergistic heating, the neutron spectra broadened at the high-energy end, indicating fast ions in the plasma core exceeding NBI energies. TRANSP simulations show the fast ion tail reaches about 600 keV, primarily in the co-current direction. Synthetic diagnostic data generated with GENESIS and spectrometer response matrices reproduce the observed broadening. Analysis using spectrometer weight functions and cut-off energies confirms the fast ion tail energy-pitch distribution. Orbit calculations reveal core-loss orbits that cause pitch-angle asymmetry. These results demonstrate that EAST's multi-line-of-sight neutron spectrometers have the ability to resolve fast ion (E, p) information, providing essential diagnostic capability for MeV fast ion studies in burning plasmas.

INTRODUCTION

Understanding fast-ion behavior is essential for achieving high performance in burning plasma experiments. In deuterium plasmas, fast ions are mainly generated by neutral beam injection (NBI) and ion cyclotron resonance heating (ICRF). During NBI-ICRF synergistic heating, harmonic ICRF accelerates beam ions, producing high-energy tails in the distribution that reach hundreds of keV to MeV[1]. Neutron spectrometry diagnoses the energy spectrum of fusion neutrons[2], providing information on the fast ion velocity distribution and is particularly suitable for studying fast ions in this energy range[3].

On EAST, NBI-3rd harmonic ICRF synergistic heating discharges has recently been reported[4]. This work presents measurements from five neutron spectrometers during the discharge. Pronounced spectral broadening was observed along all sightlines. TRANSP simulations combined with GENESIS and forward modeling reproduce the observed neutron spectra and reveal a pitch-angle asymmetry in the fast ion tail, consistent with fast ion orbit effects. These results provide a foundation for tomographic reconstruction of fast ion velocity distributions and support diagnostics relevant to burning plasma studies.

1. EXPERIMENTS

1.1. Experimental Setup

A representative EAST discharge (#113829) was studied with NBI and third-harmonic ICRF heating, where the resonance layer was located in the plasma core. The line-averaged density was about $2.8 \times 10^{13} \text{cm}^{-3}$, the plasma current 0.50 MA, and the toroidal field 1.65 T. Two neutral beams delivered 1.3 MW (55 kV) and 1.1 MW (50 kV), while the I and N port ICRF antennas each provided 0.4 MW.

After ICRF injection, the stored energy remained near 110 kJ, but impurity radiation increased and electron/ion temperatures dropped slightly ($T_{e0} \sim 1.6 \text{ keV}$, $T_{i0} \sim 1.5 \text{ keV}$). The neutron yield rose significantly from $0.62 \times 10^{14} \text{ N/s}$ to $1.01 \times 10^{14} \text{ N/s}$ (62% increase).

Neutron spectroscopy was performed using:

- TOFED time-of-flight spectrometer (J port)
- Compact stilbene crystal spectrometer (CSCNS, J port)
- EJ301 liquid scintillator spectrometer (F port)
- BC501A liquid scintillator spectrometers (F and H ports)

The lines of sight of the neutron spectrometers are shown in Fig. 1a, the evolution of the discharge in Fig. 1b, and typical plasma profiles in Fig. 1c and 1d.

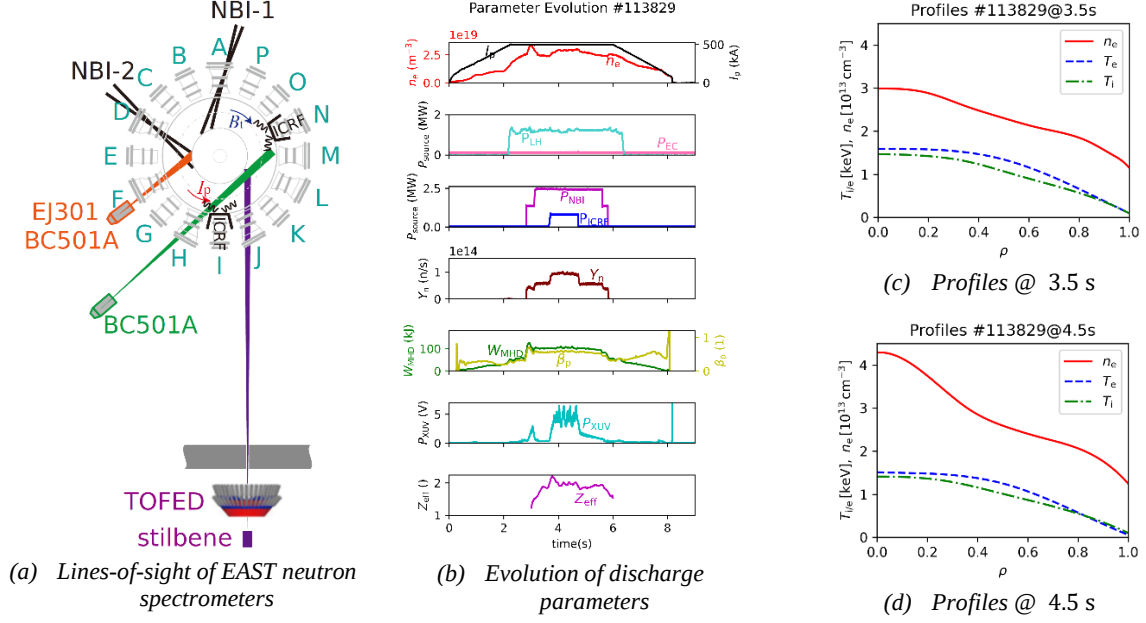


Fig. 1: Overview of EAST neutron spectrometer diagnostics and discharge evolution

1.2. Results of Neutron Spectrometers

Neutron spectra of discharge #113829 were obtained from TOFED, Stilbene, EJ301, and BC501A detectors. Two conditions were compared: NBI only and NBI with ICRF. The results are shown in Fig. 2.

TOFED shows clear spectral broadening at both high and low energies during ICRF heating, while organic scintillators mainly reveal broadening on the high-energy side, with the low-energy part obscured by scattered neutrons. These results indicate that third-harmonic ICRF heating enhances the production of higher-energy neutrons and modifies the fast ion distribution.

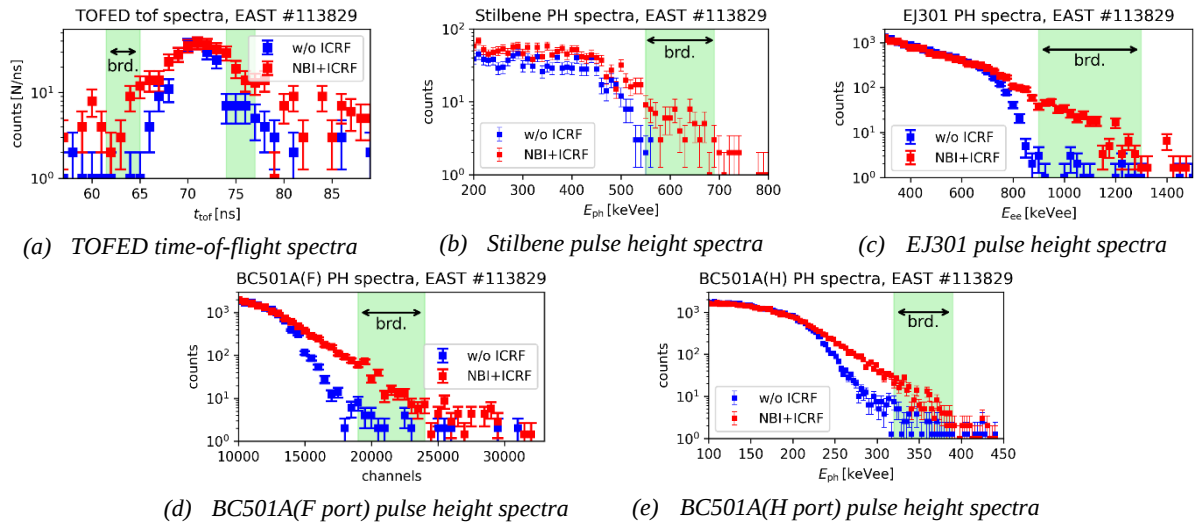


Fig. 2: Comparison of neutron spectrometer measurements for EAST discharge #113829 under full-power NBI and NBI+ICRF synergistic heating.

2. SIMULATIONS

The fast ion velocity distributions during discharge #113829 were simulated using TRANSP[5] with the NUBEAM Monte Carlo module and the TORIC ICRF solver. The synergistic effect of ICRF on beam ions is included through the RF-kick operator, which models quasilinear diffusion as velocity changes when ions cross the resonance layer.

As shown in Fig. 3, TRANSP calculation results shows that ICRF accelerates NBI-injected ions and produces a high-energy tail extending to about 500 keV. The effect is most pronounced at positive pitch angles ($0 < p < 0.4$).

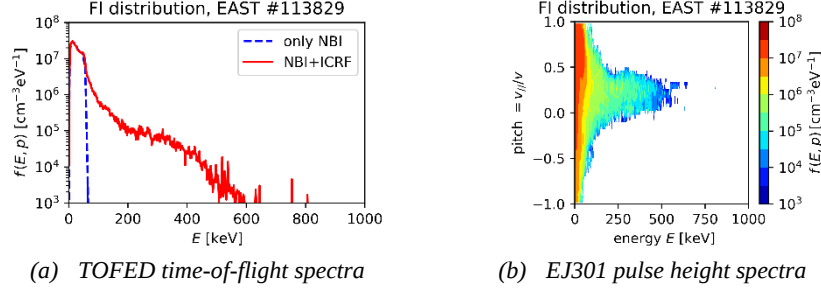


Fig. 3: TRANSP simulation results.

Neutron spectra were calculated using GENESIS[6], with the intensities of direct and scattered components fitted using the Cash statistic. The synthetic spectra show good agreement with the measurements under pure NBI heating, as Fig. 4. During NBI-ICRF synergistic heating, the simulations reproduce the spectral broadening observed in TOFED and Stilbene, while for EJ301(Fig. 4f), agreement is good below ~ 900 keVee, with the higher-energy tail in the measurements attributed to pile-up effects.

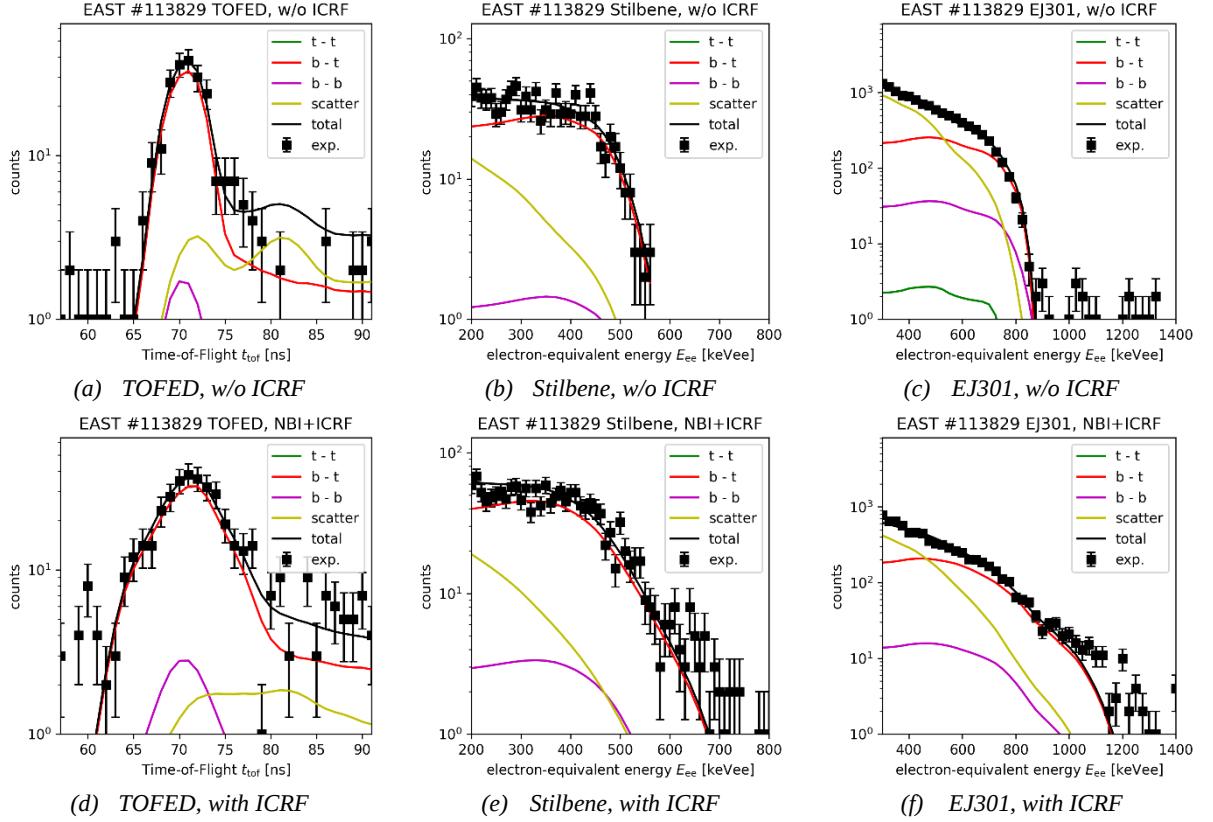


Fig. 4: Comparison of measured and forward-modeled neutron spectra for EAST discharge #113829 under full-power NBI and NBI-ICRF synergistic heating.

3. WEIGHT FUNCTION AND ORBIT ANALYSIS

Building on previous work[7-8], the GENESIS code was used to calculate TOFED and EJ301 weight functions for the current lines of sight, assuming that all neutrons are emitted from the plasma core, and extending the fast ion energy range up to 1 MeV.

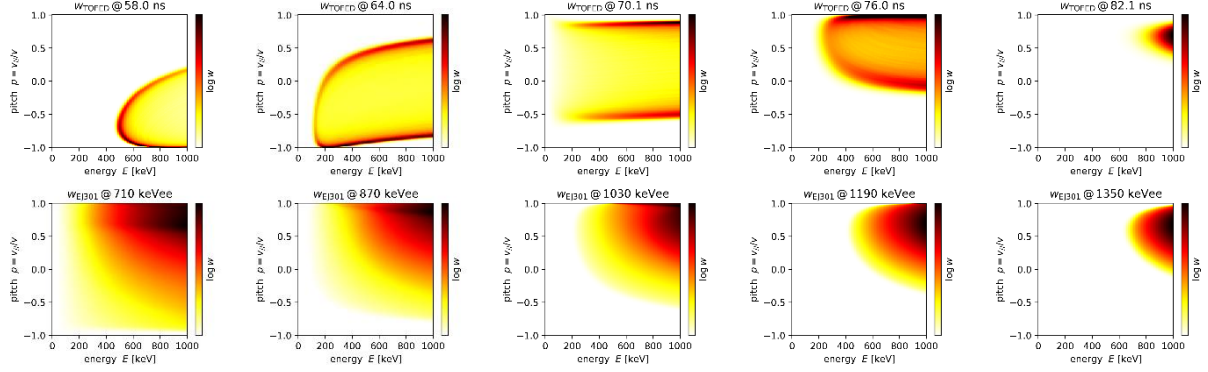
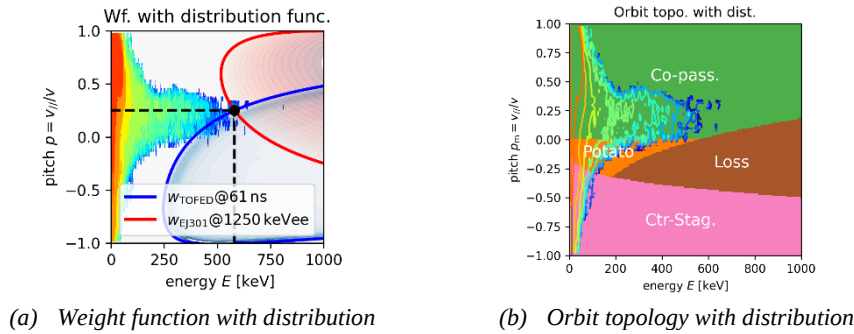


Fig. 5: Typical weight functions of TOFED and EJ301

Inspired by the “null measurement” method in distribution tomography[9], Using spectral cutoffs from TOFED and EJ301, the location of the fast ion tail in energy–pitch space can be estimated. As shown in Fig. 6a, The analysis indicates a tail energy of approximately 0.6 MeV at positive pitch angles, consistent with TRANSP simulations. This approach provides a simple yet effective diagnostic method, revealing that NBI–ICRF third-harmonic heating in EAST produces fast ion tails with clear pitch-angle asymmetry, unlike the more symmetric distributions observed in other devices.

The observed pitch-angle asymmetry of the fast ion tail is explained by orbit losses in EAST. Orbit topology calculations using Orbit Weight Computational Framework(OWCF)[10-11], illustrated in Fig. 6b, show that lost orbits predominantly occupy the negative pitch region, with the loss region widening at higher energies. For energies above 500 keV, even particles with zero pitch can be lost. While ICRF accelerates ions and reduces their absolute pitch, fast ions with near-zero or negative pitch in the hundred-keV range are preferentially lost. This selective loss shapes the fast ion tail at positive pitch angles, consistent with the boundaries of the lost-orbit region.



(a) Weight function with distribution

(b) Orbit topology with distribution

Fig. 6: Analysis of weight functions and fast ion orbit topology

4. CONCLUSION

Multi-view neutron spectrometers were used to diagnose NBI-ICRF third-harmonic synergistic heating on EAST. All five spectrometers observed broadening of the fusion neutron spectrum at the high-energy end, indicating the generation of fast ions up to about 580 keV at positive pitch. Weight functions for TOFED and EJ301 reproduce the measurements and confirm the fast ion tail location, consistent with TRANSP simulations. The pitch-angle asymmetry of the tail is attributed to orbit losses. These results demonstrate that multi-view neutron spectrometry can resolve two-dimensional fast ion energy–pitch information under synergistic heating.

Future work will extend weight function calibration to other spectrometers to obtain more complete phase-space coverage, and combine neutron spectrometry with complementary diagnostics such as FIDA for tomographic of

fast ion velocity distributions from tens of keV to MeV. Such measurements are critical for evaluating fast ion behavior and heating performance in future burning plasma devices like BEST, SPARC, ITER and CFETR.

ACKNOWLEDGEMENTS

This work is supported by the National Magnetic Confinement Fusion Energy R&D Program of China (Grant No.2019YFE03040000 and No. 2024YFE03170001) and the National Nature Science Foundation of China (Grant No. 12575216). The numerical calculations of TRANSP in this paper were performed on the ShenMa High Performance Computing Cluster in Institute of Plasma Physics, Chinese Academy of Sciences. The authors also acknowledge Henrik Järleblad and colleagues at the Technical University of Denmark for releasing the OWCF code on GitHub, which provided important tools for this study.

REFERENCES

- [1] C. Hellesen, M. Gatu Johnson, E. Andersson Sundén, et al., “Fast-ion distributions from third harmonic ICRF heating studied with neutron emission spectroscopy,” *Nuclear Fusion*, 53(11), 2013.
- [2] J. Eriksson, C. Hellesen, F. Binda, et al., “Measuring fast ions in fusion plasmas with neutron diagnostics at JET,” *Plasma Physics and Controlled Fusion*, 61(1), 2019.
- [3] M. Salewski, M. Nocente, A. S. Jacobsen, et al., “MeV-range velocity-space tomography from gamma-ray and neutron emission spectrometry measurements at JET,” *Nuclear Fusion*, 57(5), 2017.
- [4] G. Zhu, W. Zhang, X. Zhang, et al., “First results from third harmonic ion cyclotron acceleration of deuterium beams in EAST ion heating studies experiments,” *Nuclear Fusion*, 63(3), 2023.
- [5] J. Breslau, M. Gorelenkova, F. Poli, et al., *TRANSP*, 2018.
- [6] M. Nocente, et al., “Neutron and gamma-ray emission spectroscopy as fast ion diagnostics in fusion plasmas,” PhD thesis, 2012.
- [7] L. J. Ge, Z. M. Hu, Y. M. Zhang, et al., “Velocity-space sensitivity of time-of-flight neutron spectrometer at EAST in deuterium plasma,” *Review of Scientific Instruments*, 89(10), 2018.
- [8] Y. M. Zhang, L. J. Ge, J. Q. Sun, et al., “Velocity-space sensitivity of the compact neutron emission spectrometers at EAST,” *Rev. Sci. Instrum.*, 89(10):10I141, 2018.
- [9] M. Salewski, B. Geiger, A. S. Jacobsen, et al., “High-definition velocity-space tomography of fast-ion dynamics,” *Nuclear Fusion*, 56(10), 2016, 106024.
- [10] H. Järleblad, L. Stagner, M. Salewski, et al., “A framework for synthetic diagnostics using energetic-particle orbits in tokamaks,” *Computer Physics Communications*, 294, 108930, 2024.
- [11] H. Järleblad, *JuliaFusion/OWCF: A framework for synthetic diagnostics using energetic-particle orbits in tokamaks*, GitHub repository, Version v1.3.0, Apache-2.0 license, 2024, <https://github.com/JuliaFusion/OWCF>.