

Investigation of Fast-Ion Velocity Distribution Functions via Neutron Emission Spectroscopy on EAST



Andong Xu, Peking University

xuandong@pku.edu.cn

Collaborators:

Peking University: A.D. Xu, Y.H. Li, T. Yu, J.Y. Zhang, Z.S. Liu, X.T. Xu, Z.Y. Wang, X.Q. Li, T.S. Fan*

Institute of Plasma Physics, CAS: M.Y. Xu, C.Y. Pan, Y.Q. Zhang, Y.B. Zhang, X.Y. Hong, P. Li, J. Huang, L.Q. Hu, W. Zhang, X.J. Zhang, G.Q. Zhong, B.N. Wan*

Southwestern Institute of Physics: B.L. Hao

University of Milano-Bicocca / ISTP-CNR (Italy): M. Nocente, G. Gorini, M. Tardocchi

Contents

- **EAST–NES System Overview**
- Results from NBI + Third-Harmonic ICRF Heating Discharges
- Results from Discharges with a Record Neutron Rates
- Conclusions and Outlook

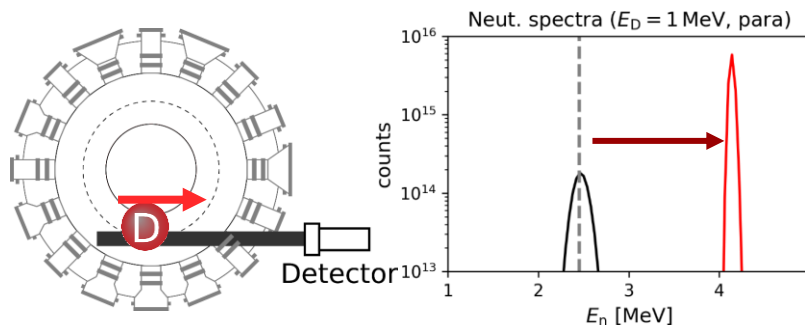
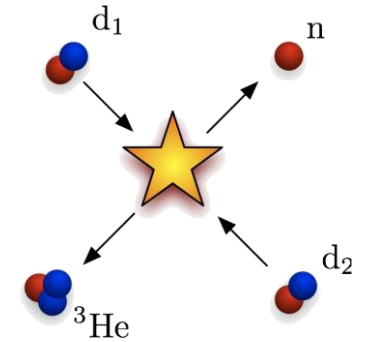
Neutron Spectroscopy for Fast Ion Diagnostics



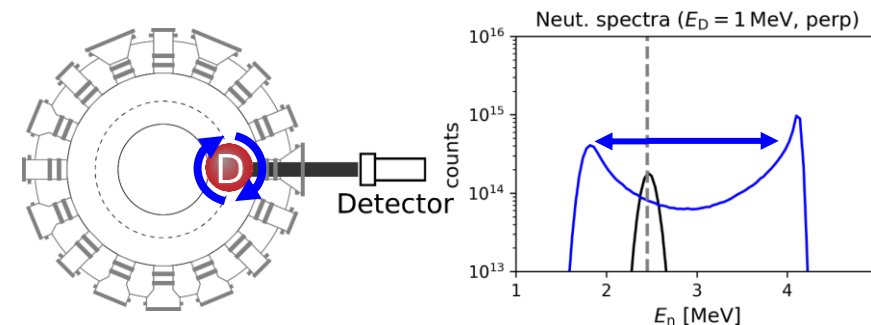
- In DD discharges, beam–thermal reactions dominate neutron emission, with neutron energy depending on fast-ion energy and the measuring angle.

$$E_{n0} = \frac{1}{2}m_n v_{com}^2 + \frac{m_c}{m_n + m_c} (Q + K) + m_n v_{com} \sqrt{\frac{2m_c (Q + K)}{m_n (m_n + m_c)}} \cos \theta'_n$$

- Observations from different angles reveal distinct effects of parallel and perpendicular fast-ion motion on the neutron spectrum.
- Different lines of sight (LOS) have different sensitivities to $v_{\parallel}$ and $v_{\perp}$



$v_{para} \rightarrow$ **Shifted NES**



$v_{perp} \rightarrow$ **Broaden NES**

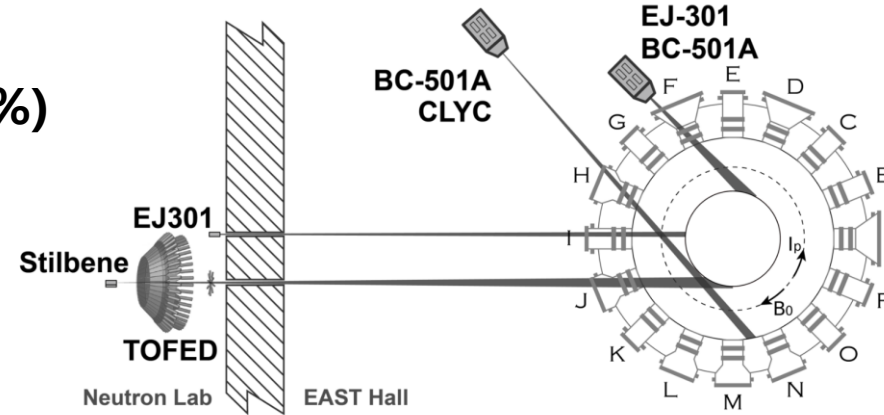
Synergetic multi-sightline NES diagnostics provide constraints on the fast-ion distribution function

EAST Neutron Emission Spectrometry System



Neutron Lab

- Low neutron flux
- Low scattering (20%)
- I-port (Vertical)
- J-port (Ctr.-current)

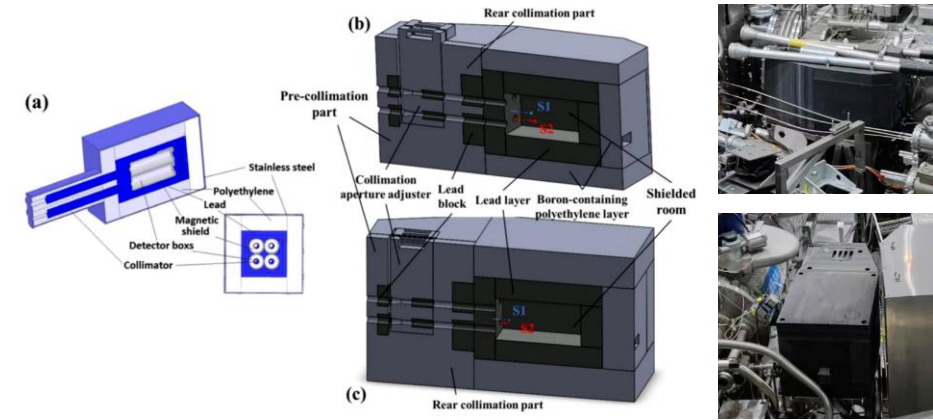


Shielding box

- High neutron flux
- High scattering (80%)
- F-port (Co-current)
- H-port (Ctr.-current)



The neutron lab



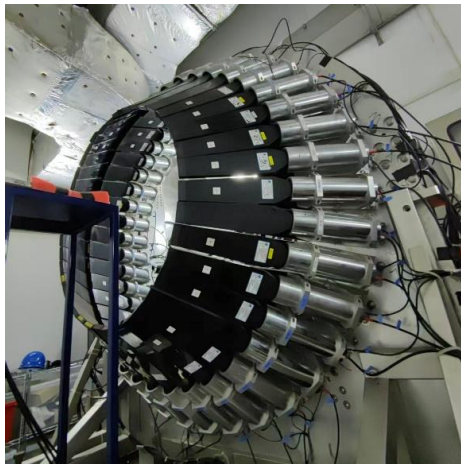
Optimized Radiation Shielding & Collimation

Diagnostic Technique: Time-of-Flight Spectrometer

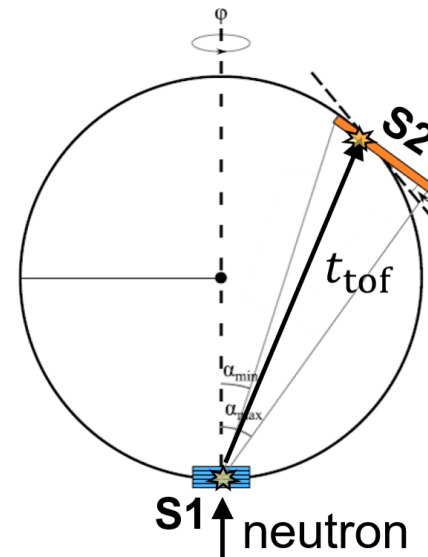


- **TOFED**: Measures neutron energy via flying time between S1 & S2
 - Quasi-Gaussian response, **absolute calibration**
 - Energy resolution: $\sim 6\%$ @ 2.45 MeV
 - Efficiency: 1.8 %

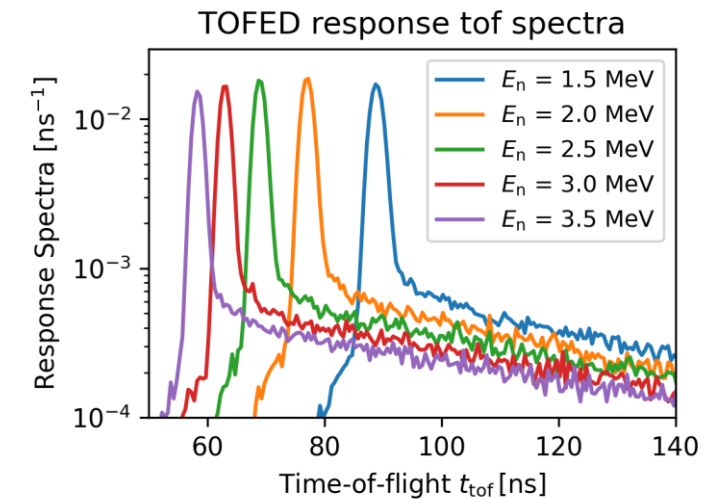
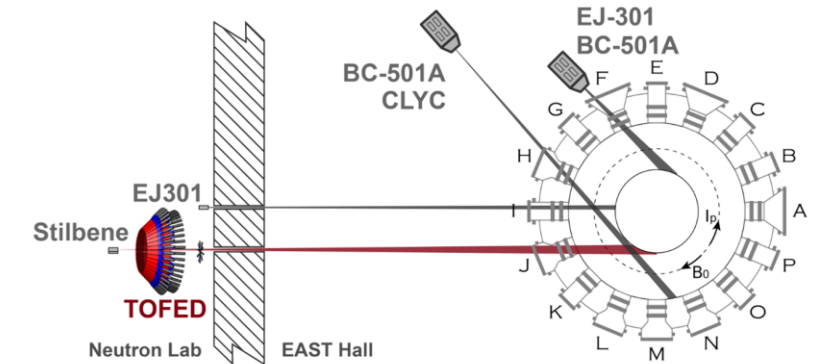
$$E_n = \frac{2mR^2}{t_{\text{tof}}^2}$$



TOFED on EAST



principle

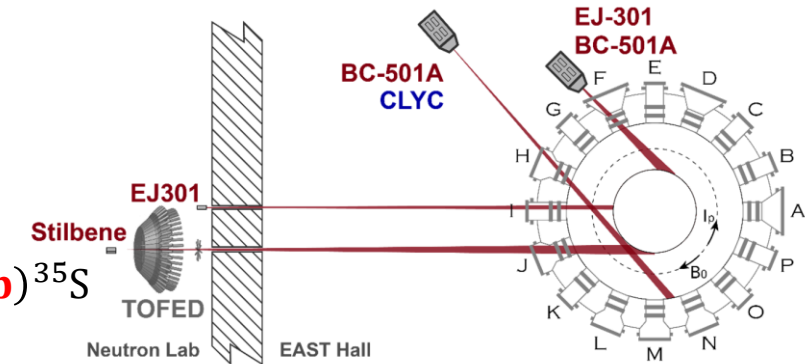


response

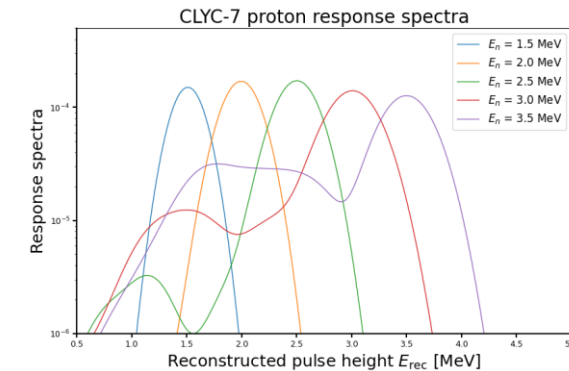
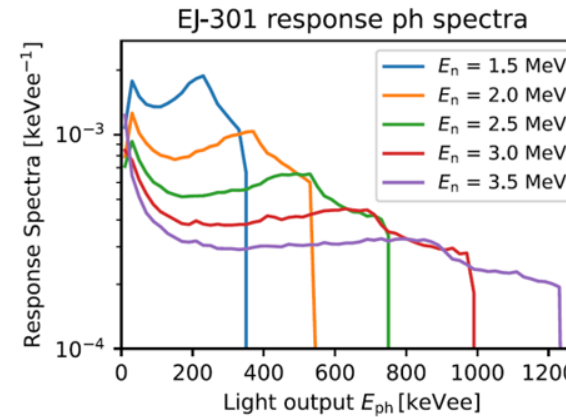
Diagnostic Technique: Compact Scintillators



- **Organic Scintillators:** Measures recoil proton energy of $p(n, n')p'$
 - Quasi-rectangular response
 - Energy resolution: $\sim 10\%$ @ 2.45 MeV
 - Efficiency: $\sim 10\%$
- **Inorganic Scintillators (C⁷LYC):** Measures product energy of $^{35}\text{Cl}(n, p)^{35}\text{S}$
 - Quasi-Gaussian response
 - Energy resolution: $\sim 10\%$ @ 2.45 MeV



Organic/ Inorganic scintillators on EAST



response

- [1] X. Yuan *et al* 2013 *JINST* **8** 07016
- [2] L.Y. Liao *et al* 2021 *RSI* **92** 043506
- [3] M.Y. Xu 2024 *FED* **204** 114490

Systematic Trade-offs in NES Diagnostic



□ LOS & shielding method

Neutron Flux



Scatter Shielding

□ Detectors

Detection Efficiency



Energy Resolution

Detector Type	Response Shape	Detection Efficiency	Energy Resolution (at 2.45 MeV)
Time-of-Flight (TOFED)	Quasi-Gaussian (Peak) Direct interpretation	~ 1.8 %	Excellent (~ 6%)
Organic Scintillators (Stilbene / EJ-301)	Quasi-Rectangular (Edge) Complex unfolding needed	~ 10 %	Moderate (~ 10%)
Inorganic Scintillators (C ⁷ LYC)	Peak-like (Full-energy Peak) Direct interpretation	~ 1 %	Moderate (~ 10%)

Multi-sightline and multi-detector integration enables cross-validation and provides a comprehensive view of the fast-ion phase space.

Contents

- EAST–NES System Overview
- **Results from NBI + Third-Harmonic ICRF Heating Discharges**
- Results from Discharges with a Record Neutron Rates
- Conclusions and Outlook

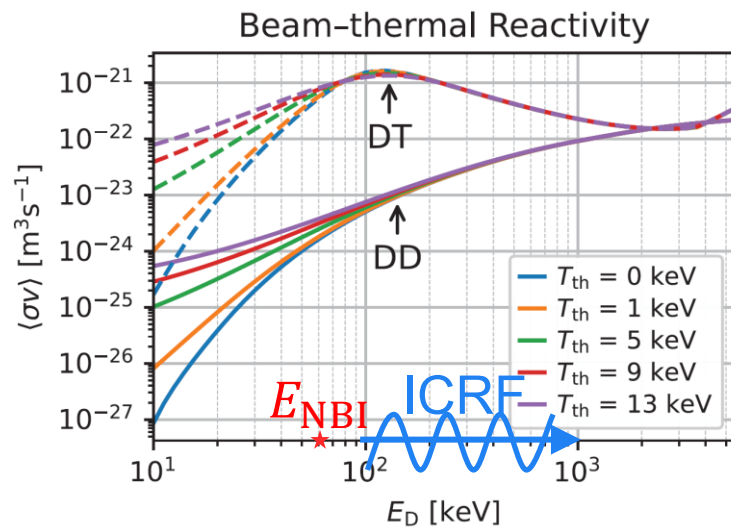
Reference: A.D. Xu *et al* 2026 *NF* **66** 066024

NBI – 3rd harmonic ICRF synergy heating

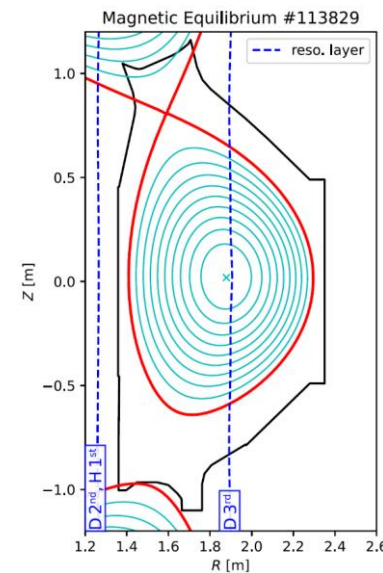


□ EAST #113829

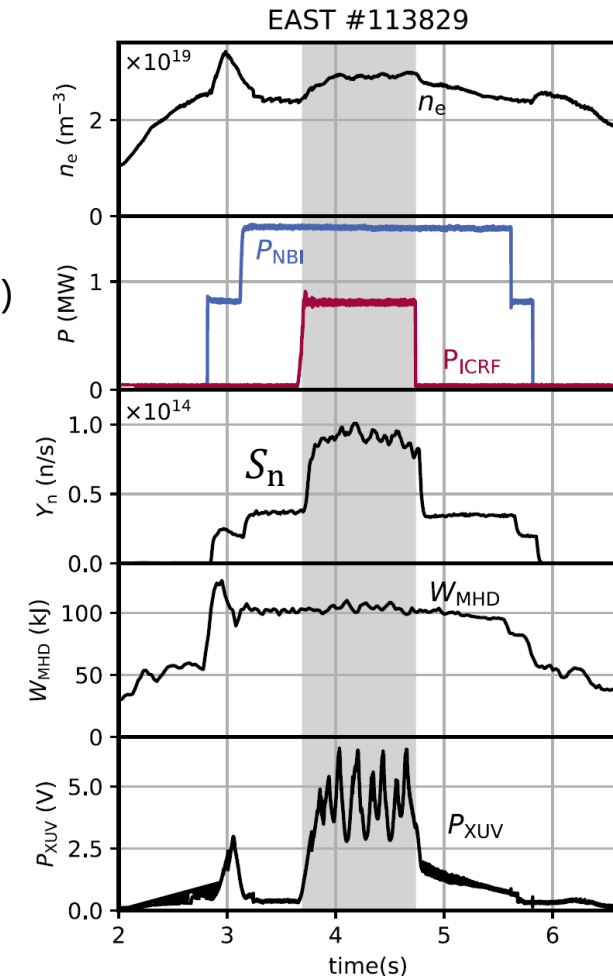
- Scenario: Low field ($B_T = 1.65$ T), $I_p = 500$ kA, $\bar{n}_e = 2.8 \times 10^{19} \text{ m}^{-3}$.
- Heating: 1.5 MW NBI + 0.8 MW ICRF (3rd harm. of D) + 1.2 MW LHW.
- During the synergistic phases (shaded area):
 - Stored energy (W_{MHD}) remained stagnant: ~ 110 kJ. (enhanced impurity radiation)
 - Neutron rate (S_n) increased by nearly three-fold: $3.7 \rightarrow 9.1 \times 10^{13} \text{ s}^{-1}$.



**Fast-ion tail enhances
the neutron rate**



Magnetic equilibrium

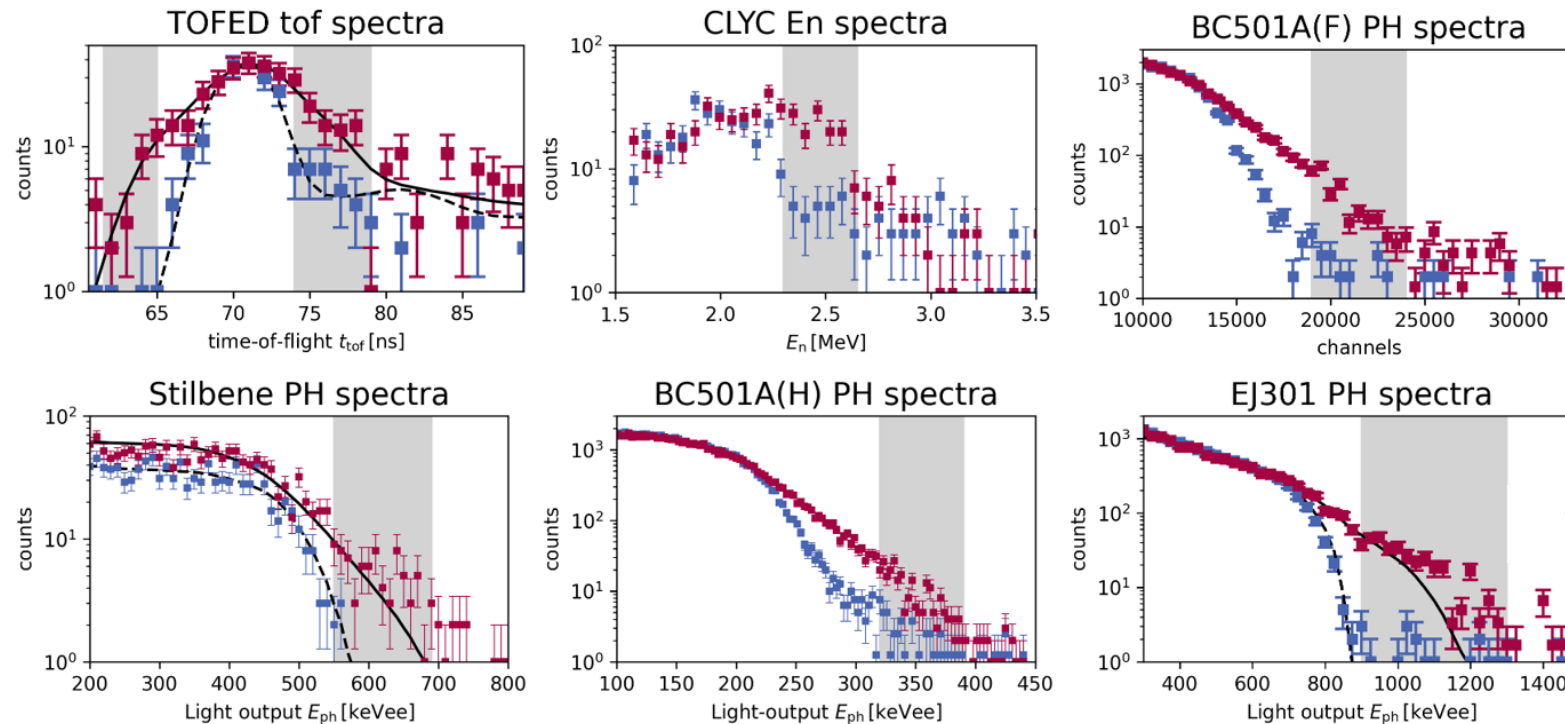


Time traces

Experimental Spectrum Broadening



- TOFED: Broadens at both low & high TOF $\rightarrow$ higher & lower energy neutrons.
- Scintillators: Broadens at high-energy side only (low-energy broadening buried by scattering).

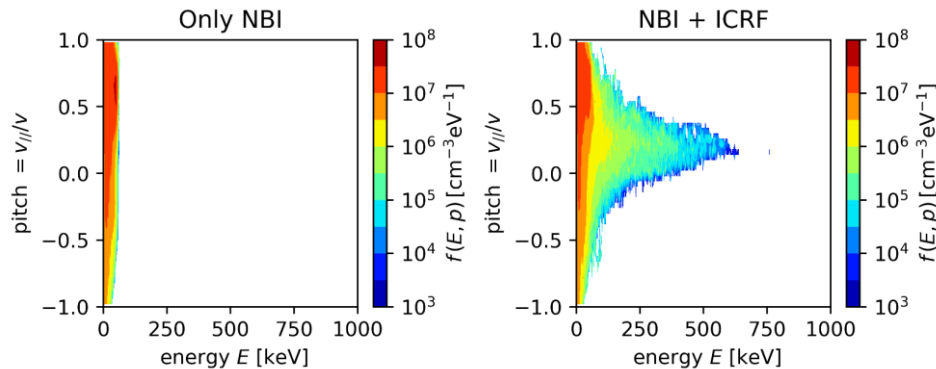


Direct evidence of ICRF accelerating ions above E_{NBI}

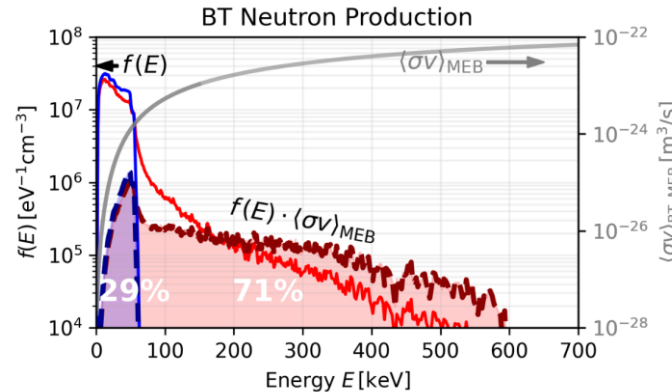
Forward Analysis

□ Fast-Ion Distribution (TRANSP)

- NUBEAM + TORIC + RF-kick
- Energy Tail: ICRF accelerates beam ions up to ~ 600 keV, with strongly pitch-asymmetric at **positive pitches** (co-Ip, not the same as JET which is pitch-symmetric)
- The tail concentrate $\sim 71\%$ of the total neutron emission

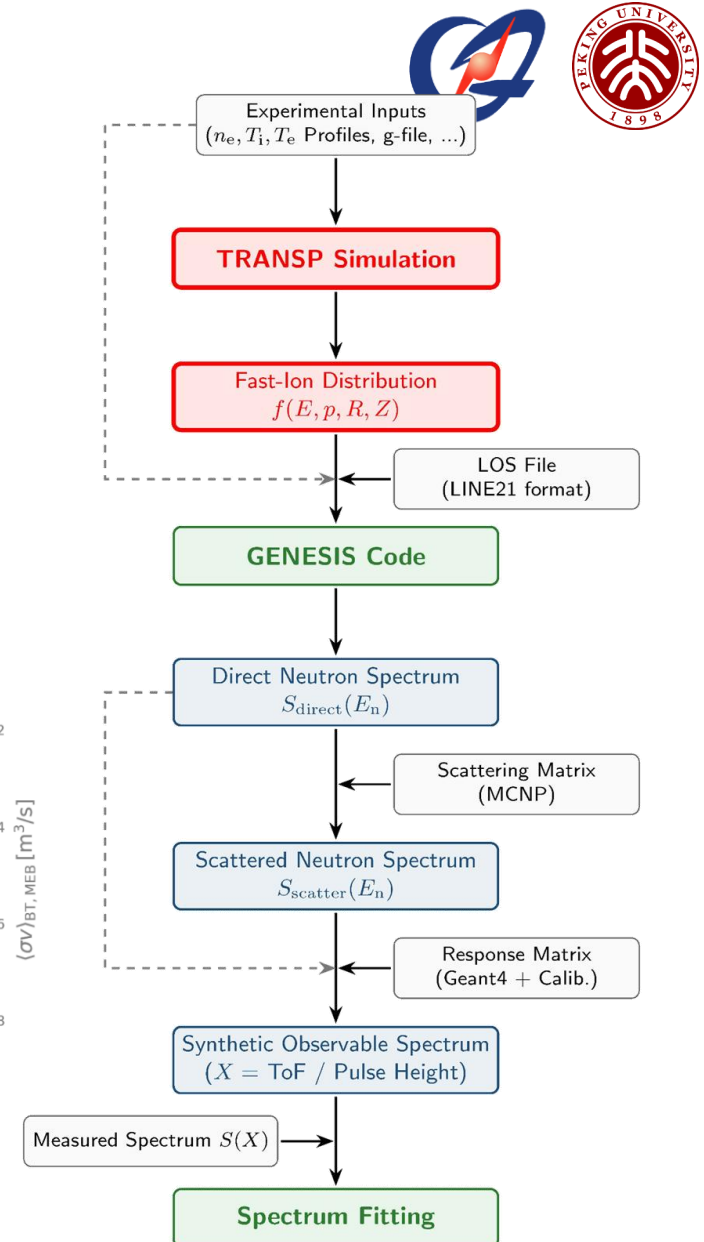


Fast ion distribution function
Asymmetric in pitch under 3rd ICRF (co-Ip)



FIDF

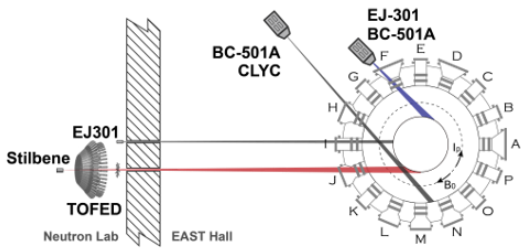
$$R_{n,BT} = n_D n_{fi} \langle \sigma v \rangle_{BT} = n_D \int_0^\infty \langle \sigma v \rangle_{MEB} (T_i, E) f_{fi}(E) dE$$



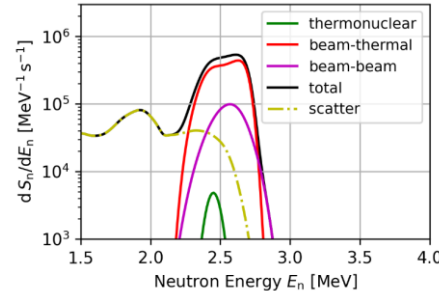
Forward Analysis

□ Neutron spectra broadening (GENESIS + MCNP)

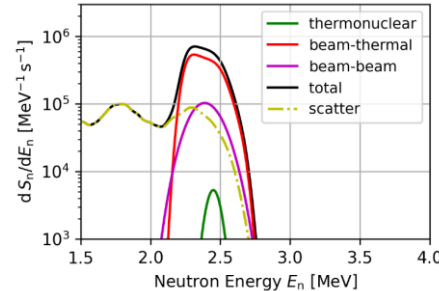
- Both lines of sight show broadening at both the high- and low-energy ends.
 - F – LOS (co-lp): more pronounced high-energy broadening
 - J – LOS (ctr.-lp): more pronounced low-energy broadening
- Due to scattering, only the high-energy broadening is dominated by direct neutrons and can be resolved reliably.



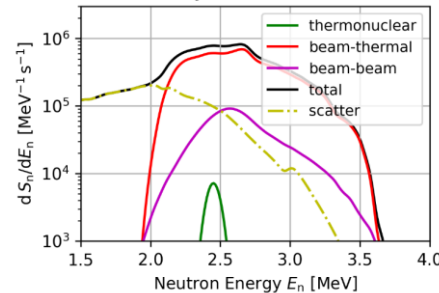
w/o ICRF NES of EJ301 LOS: 13829C06



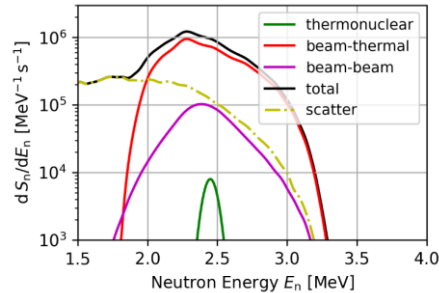
NES of TOFED LOS: 13829C06



NBI + ICRF NES of EJ301 LOS: 13829C23

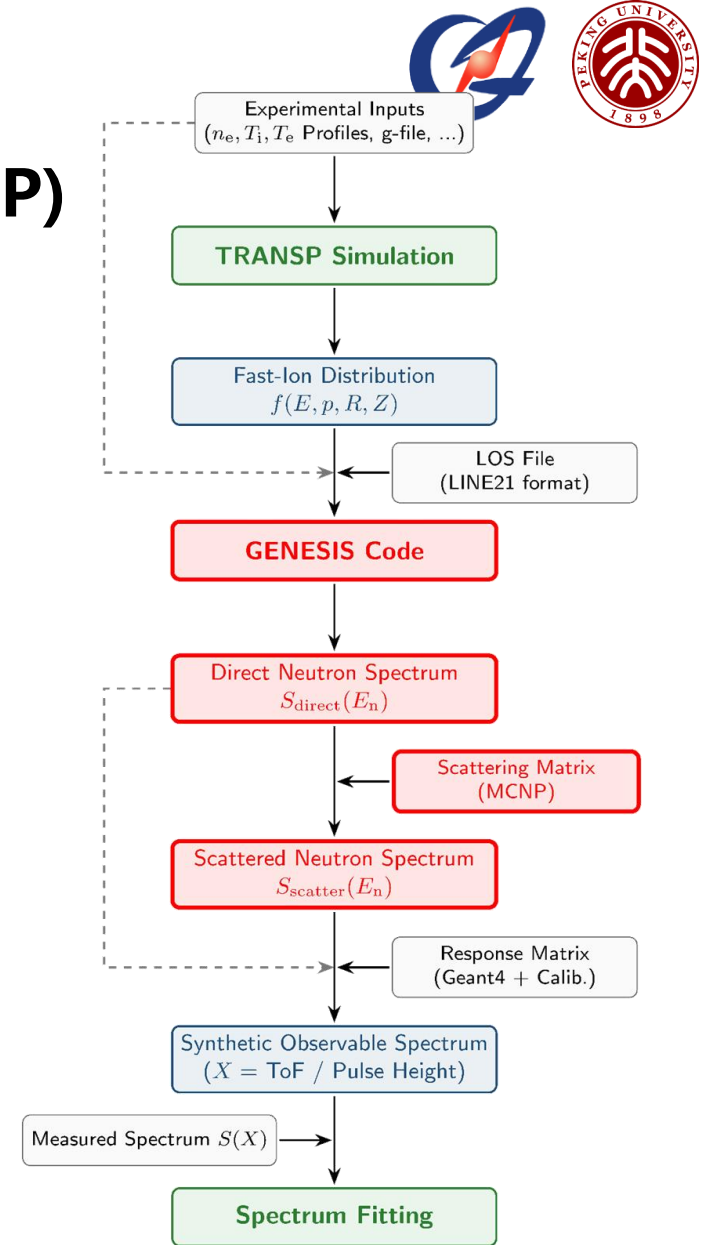


NES of TOFED LOS: 13829C23



F – LOS (co-lp)

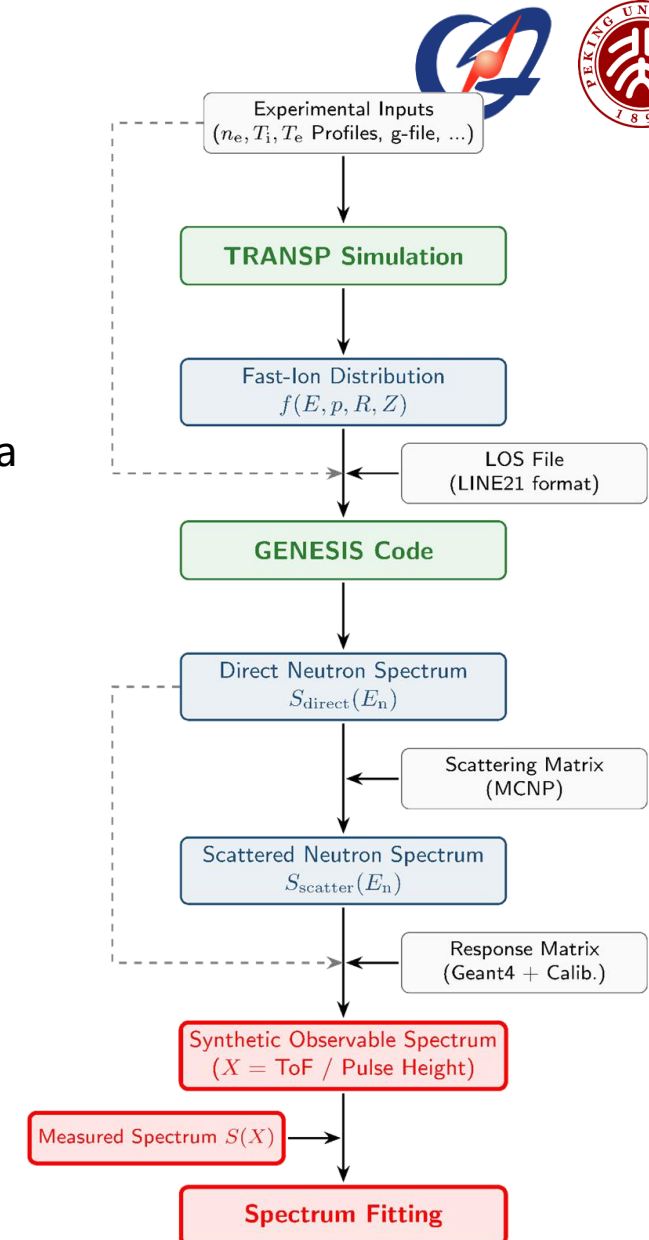
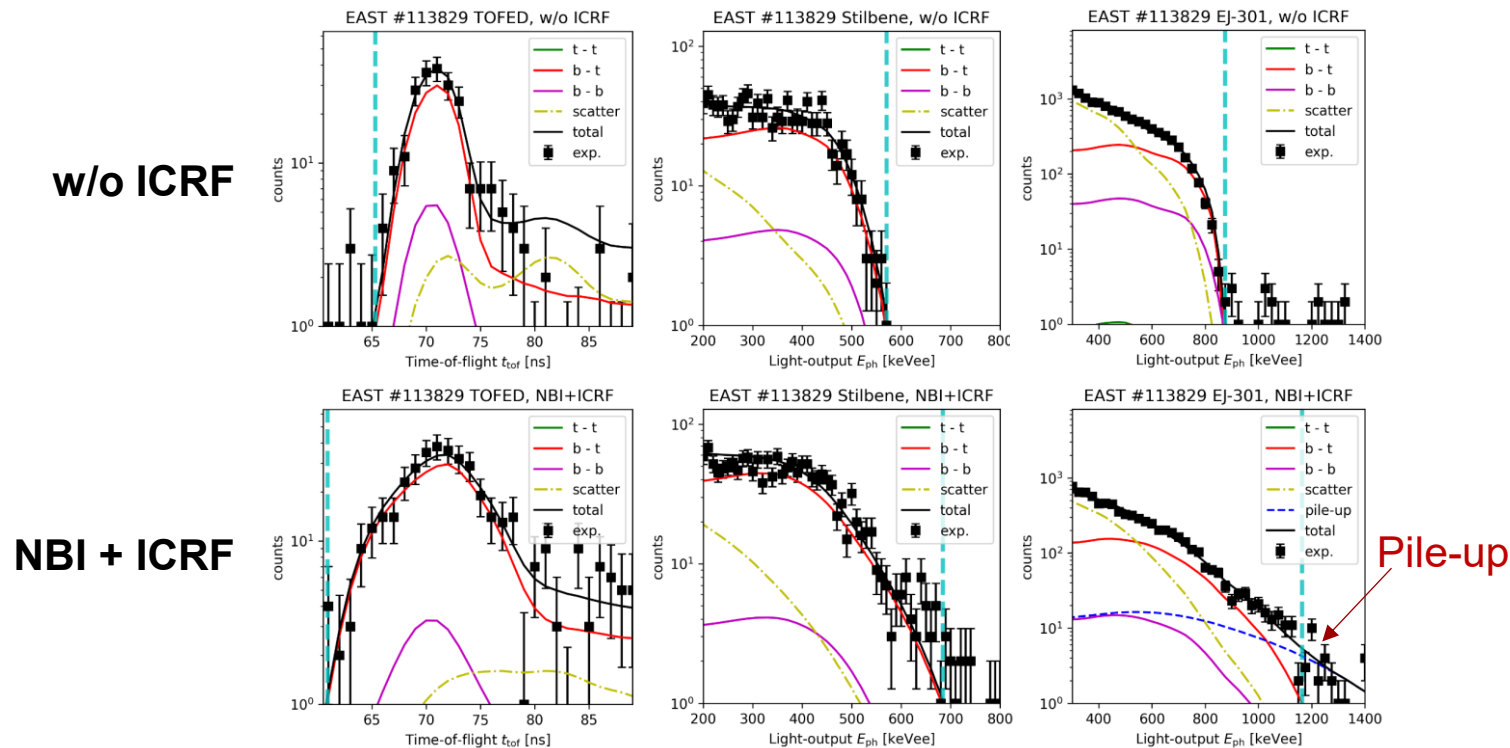
J – LOS (ctr.-lp)



Forward Analysis: Spectrum Fitting



- Convolve calculated spectra with response matrices → synthetic data, fit experimental data with direct / scatter fraction as a free parameter
- Synthetic spectra match measurements in both NBI and NBI+ICRF phases, validating the TRANSP results
- For EJ-301, pile-up occurs at high count rates under synergistic heating; we used a forward-calculation method [1] to calculate and remove the pile-up events



Backward Analysis

□ Weight Function Framework

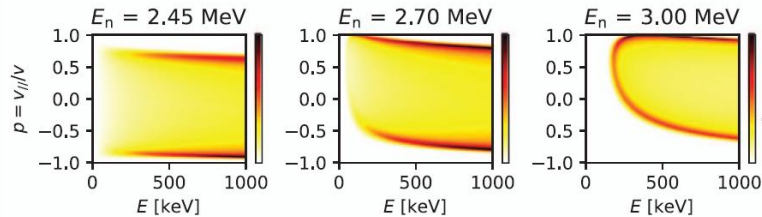
- $w(E, p, X)$ represents the contribution of velocity space (E, p) to diagnostic signal X .

$$s(X) = \iint w(E, p, X) f(E, p) dE dp$$

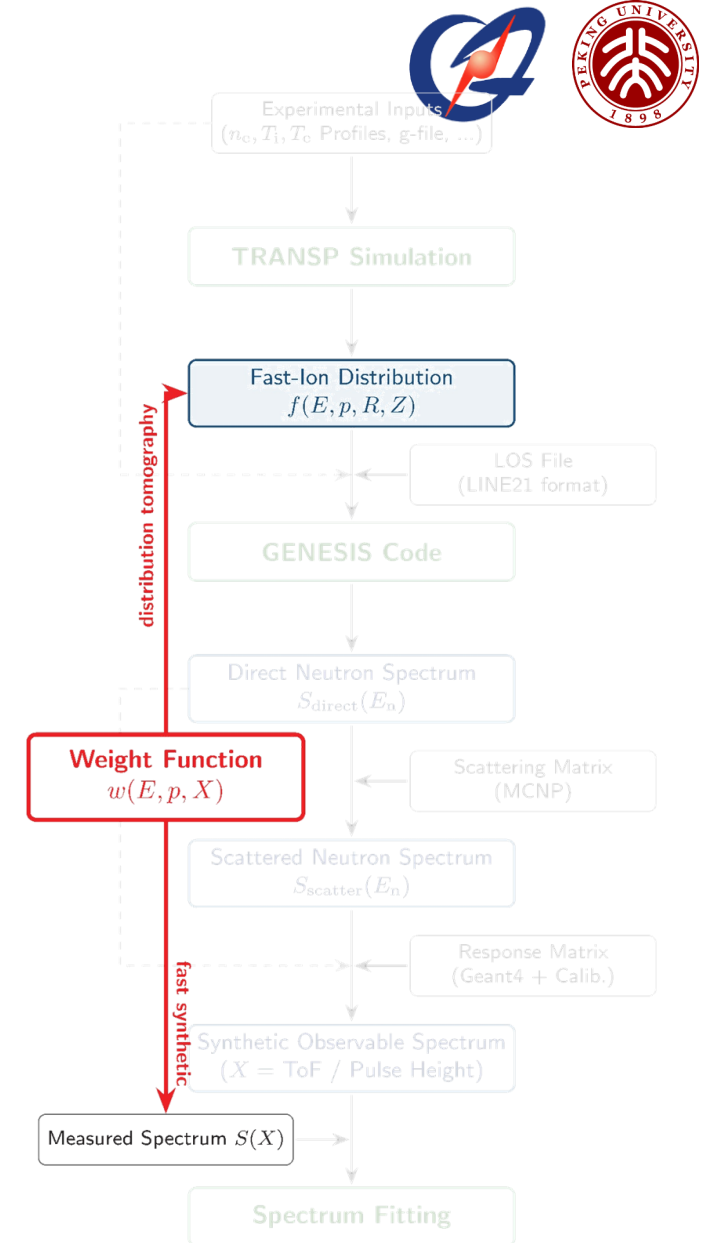
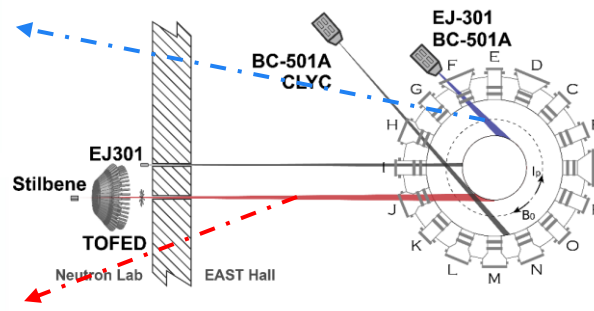
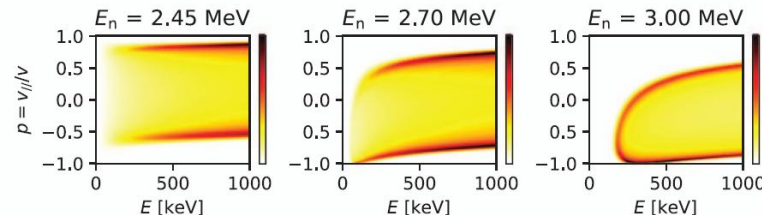
• NES:

- Highly sensitive to $E > 100$ keV (ideal for ICRF tails).
- Different lines of sight are sensitive to different pitch-angle ranges of the fast ions.

**F-LOS
(co-lp)**



**J-LOS
(ctr-lp)**

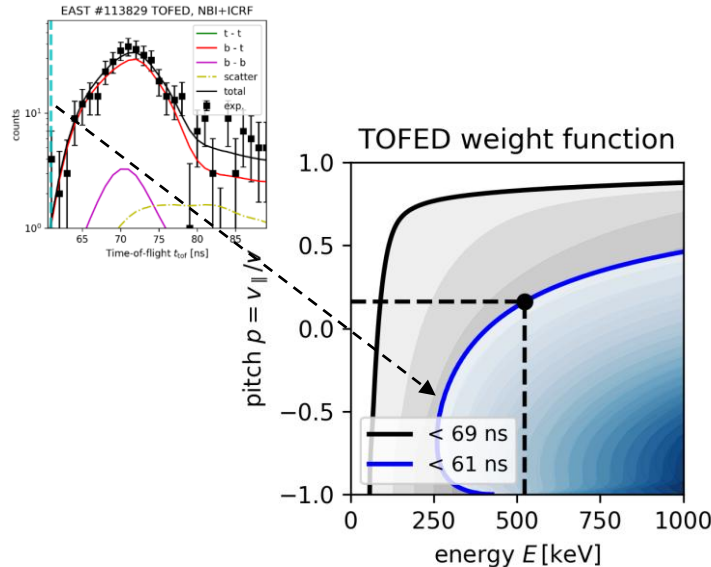


Backward Analysis: Tail "Tip" Determination

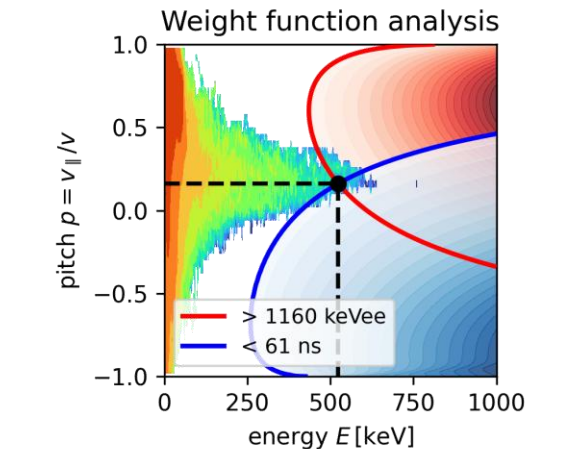
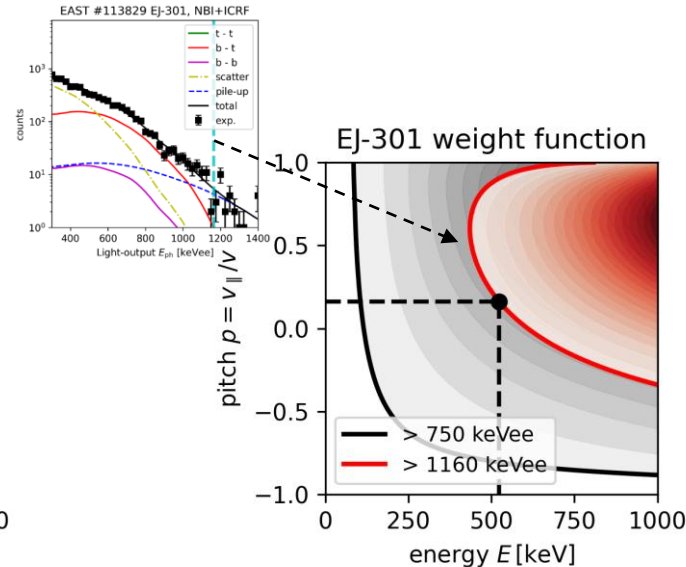


□ Null-Measurement Method

- Signal beyond cutoff where $s(X) = 0$, $\Rightarrow f(E, p) = 0$ in weight function coverage $w(E, p, X) \neq 0$
- Identifying the high-energy cutoff bins in both TOFED and EJ-301 and intersecting their respective null-measurement region boundary, we pinpoint the tail 'tip' at the intersection point.
- Intersection pinpoints the fast-ion tail "tip" at $E \approx 520$ keV, $p \approx 0.2$, matching TRANSP result.



Colored : sum of the null-measurement regions



Comparison with TRANSP

Two LOS NES can Determine the maximum "tip" of the fast-ion tail.

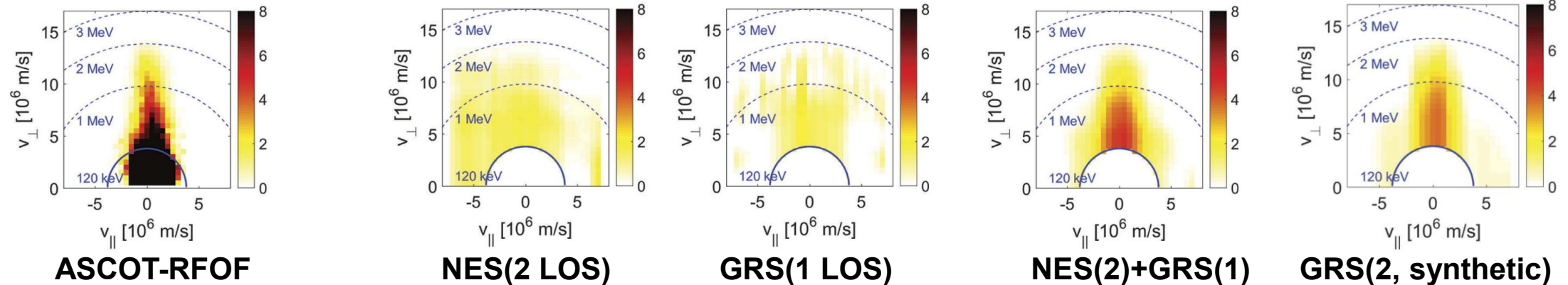
Tomography: Lessons from JET



□ JET: Artifact elimination requires 2 NES + 1 GRS [2]

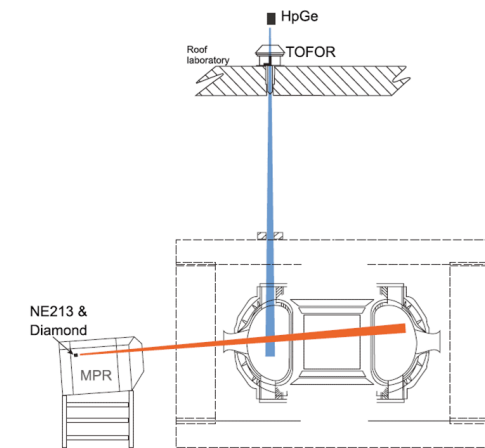
- 2 NES views or only one 1 GRS view (as seen in these plots) leaves significant artifacts

All from [2]



• Comparison of EAST to JET

- Lower neutron rate ($< 4 \times 10^{14} \text{ s}^{-1}$ for EAST, $\sim 10^{-2}$ of JET) $\rightarrow$ Sparse data statistics
- Lack of usable GRS peaks for fast-ion analysis
- More NES lines-of-sight



JET NES&GRS lines-of-sight 16

[1] M. Salewski *et al* 2017 *NF* **57** 056001

[2] M. Salewski *et al* 2018 *FST* **74** 23-26

Tomography Capability of the EAST 4-View NES System

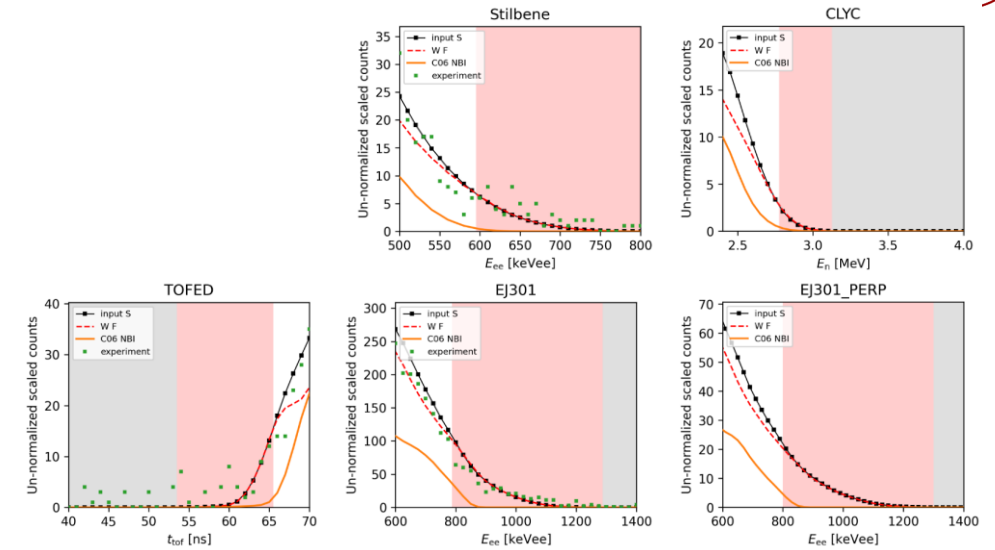


- Data Source: Synthetic spectra generated via weight functions and normalized to actual experimental count rates.
- Signal Selection: Focus on the high-energy tail region ($E > E_{\text{NBI}}$) highlighted in red.

• Methodology:

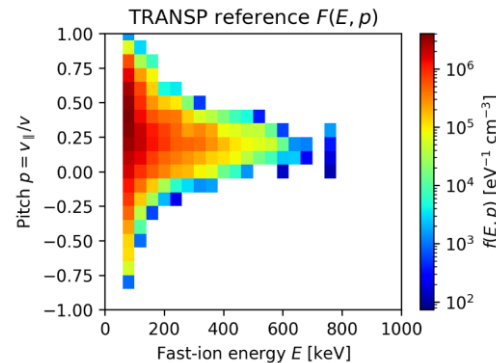
$$\min \left\| \begin{pmatrix} W \\ \lambda L \end{pmatrix} F - \begin{pmatrix} S \\ 0 \end{pmatrix} \right\|_2, \quad \text{s.t. } F \geq 0$$

- 1st-order Tikhonov regularization
- Null-measurement constraints (gray regions)
- NNLS (non-negative least square) method.

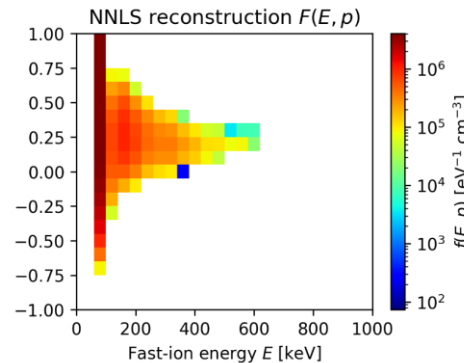


recovers the main features of the TRANSP reference

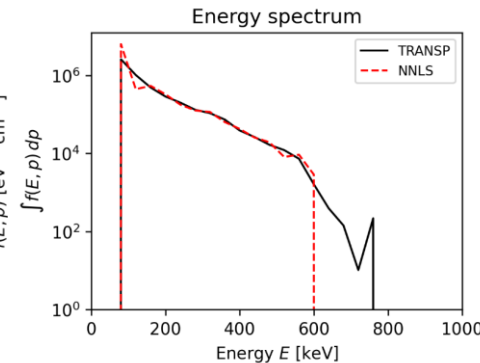
Synthetic spectra



TRANSP Ref.



Reconstruction



Comparison

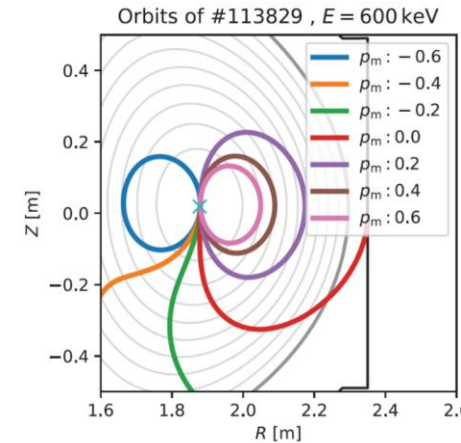
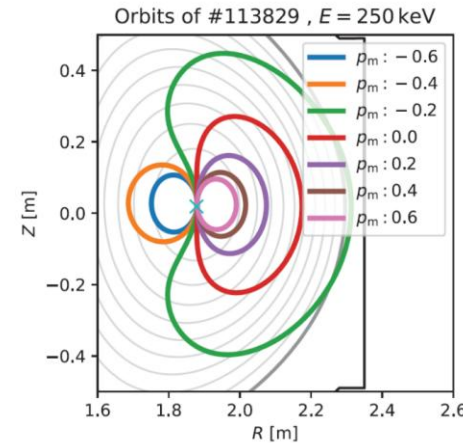
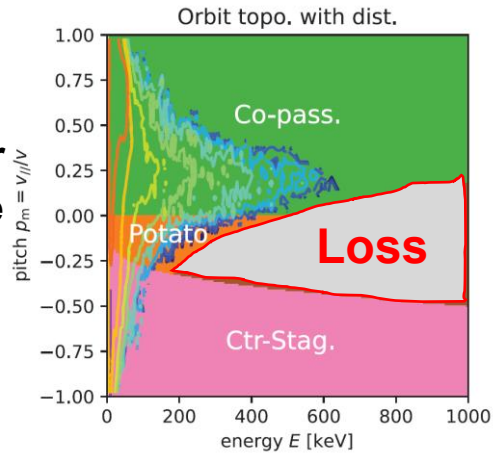
The 4-view NES system is capable of reconstructing the ICRF fast-ion tail distribution under current experimental conditions.

Origin of Pitch Asymmetry: Orbit Losses

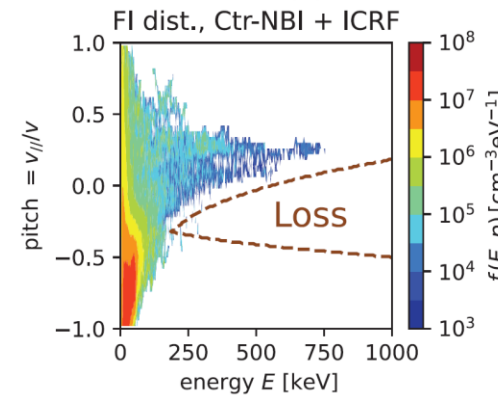
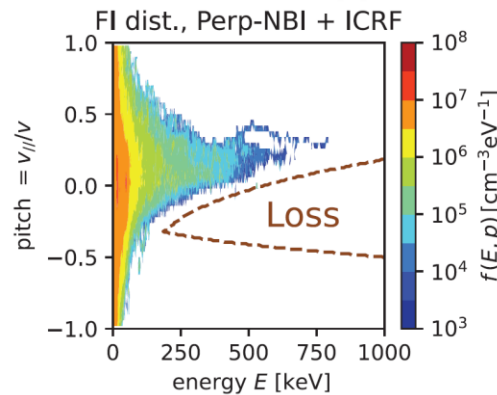
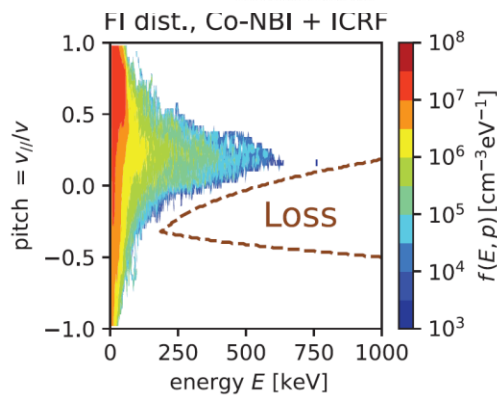


- OWCF (Orbit Weight Computational Framework[1]) calculation shows prompt losses dominate at negative pitches
- The velocity distribution coincides with the loss region boundary. Loss boundaries reshape the ICRF-driven tail into a pitch-asymmetric distribution favoring co- I_p .

Orbit Topology for fast ions originate from plasma core



Typical fast ion orbit of 250 keV and 600 keV



Change the NBI direction, the fast ion remains positive-pitched

Contents

- EAST–NES System Overview
- Results from NBI + Third-Harmonic ICRF Heating Discharges
- **Results from Discharges with a Record Neutron Rates**
- Conclusions and Outlook

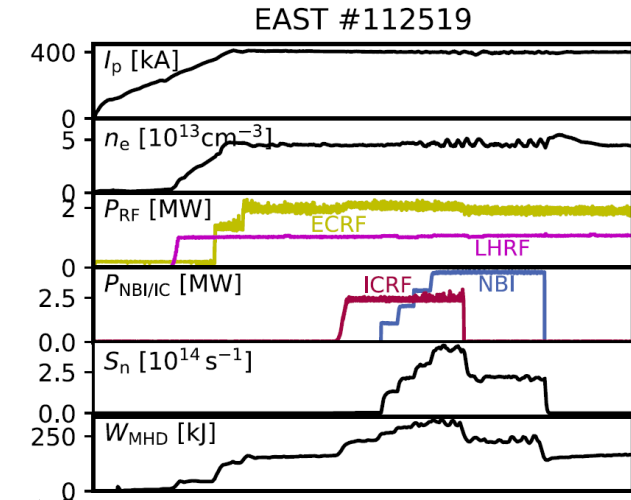
Reference: A.D. Xu *et al* 2026 *NF* **66** 126011

A record neutron rate of EAST

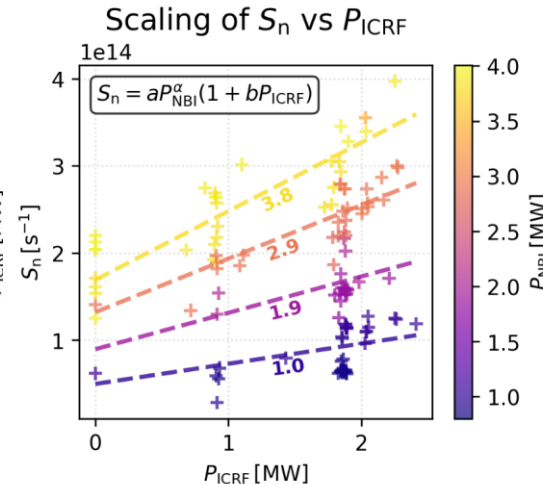
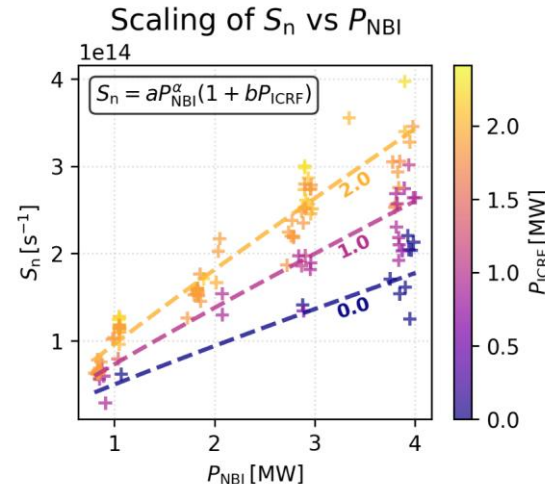
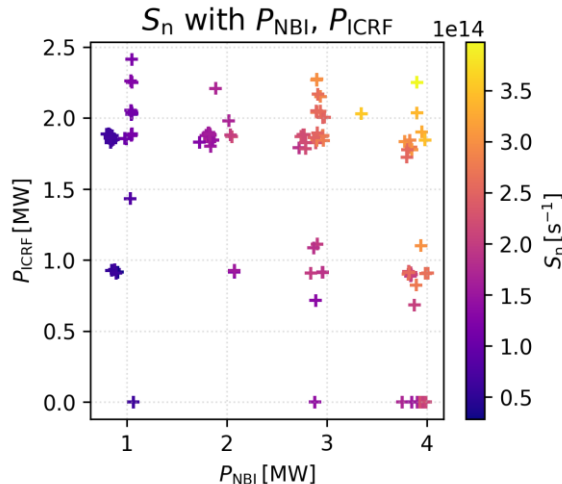


#112519 ($S_n = 3.9 \times 10^{14} \text{ s}^{-1}$)

- Basic parameters: 400 kA, 2.43 T, $4.6 \times 10^{13} \text{ cm}^{-3}$; $\beta_p = 2.8$
- Heating:
 - NBI: 4 MW (sequentially increased)
 - ICRF: 2.3 MW via I & N ports, (D 2nd harm. + H minority fund.)
 - ECRF (2.1 MW) + LHW (1.0 MW)



Scaling: Statistical analysis of 40 discharges with NBI+ICRF synergy (EAST #112494 - #112601).



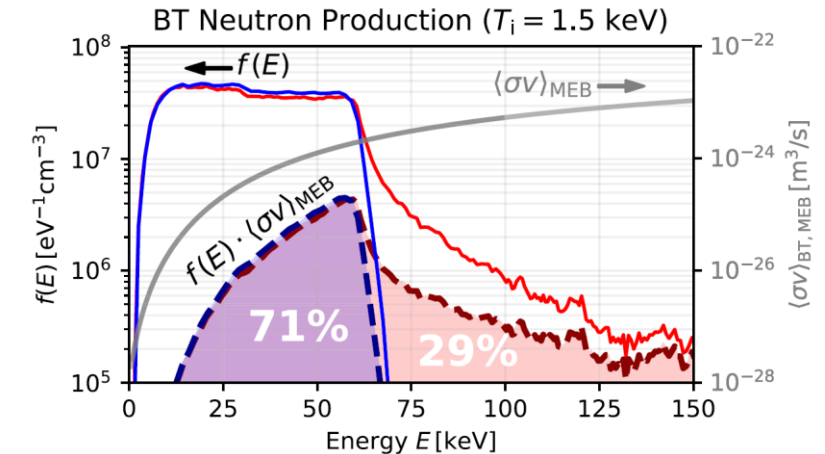
Scaling:

$$S_n \propto P_{\text{NBI}}^{0.92} (1 + 0.47 P_{\text{ICRF}})$$

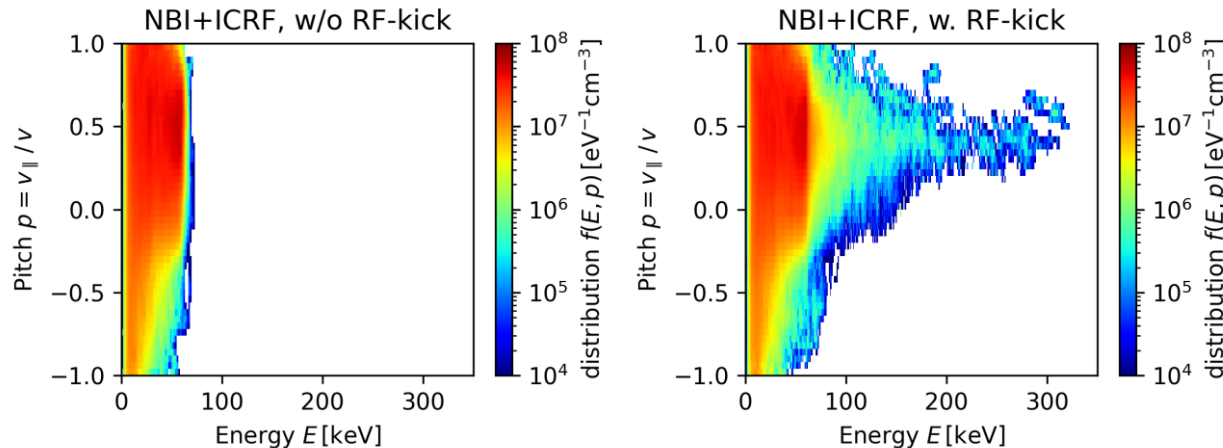
Synthetic effect contributes 29% of the neutron yield



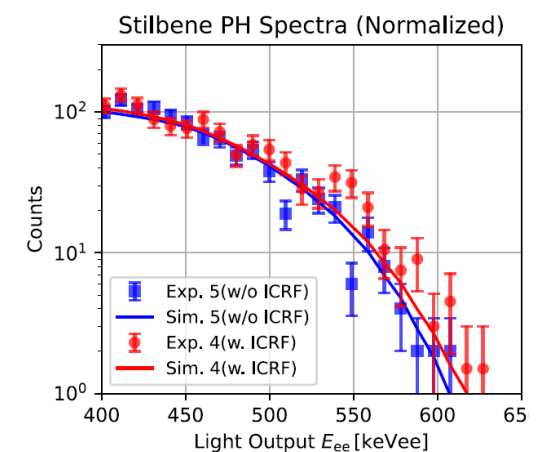
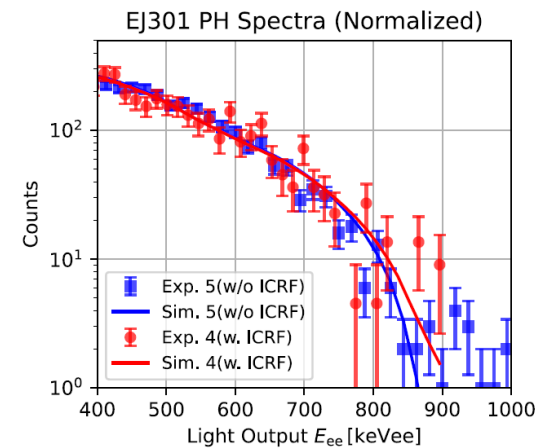
- TRANSP (NUBEAM) simulations decouple the direct synergy (tail formation) from indirect profile effects (dilution, temperature variation).
- Synergistic tail ($E > E_{\text{NBI}}$) contributes **~29%** to the total neutron
- Validation: Multi-sightline NES (Stilbene & EJ301) confirms the high-energy tail generation.



Beam-thermal neutron production



TRANSP simulation



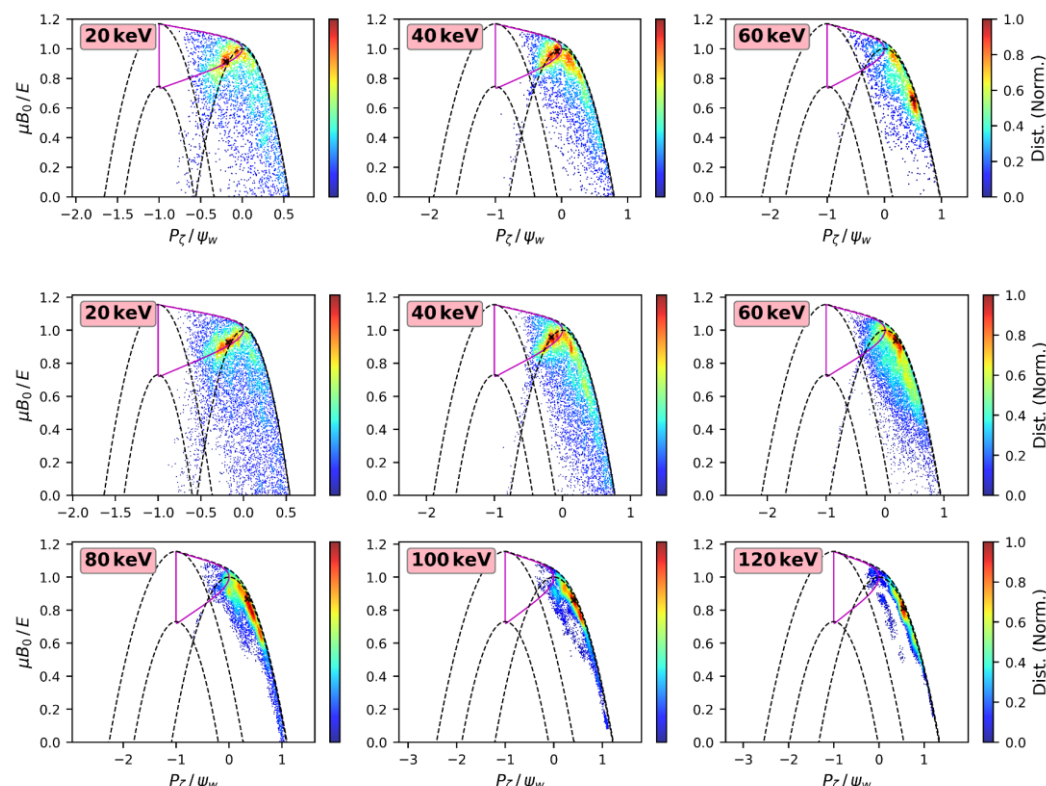
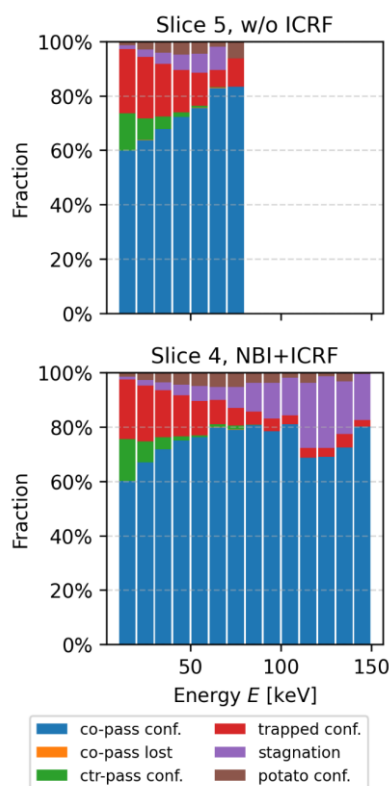
NES spectra and fitting

Orbit Topology & Neutron Emission Profile



□ Fast-Ion Orbit Topology in COM Space

- ORBIT code: Project the fast-ion distribution function onto the constant-of-motion orbit space.
- Orbit fraction shift: Synergistic heating drives ions into co-passing and stagnation orbits as energy increases.
- Resonant acceleration bands identified for different $k_{||}$ components.



w/o ICRF

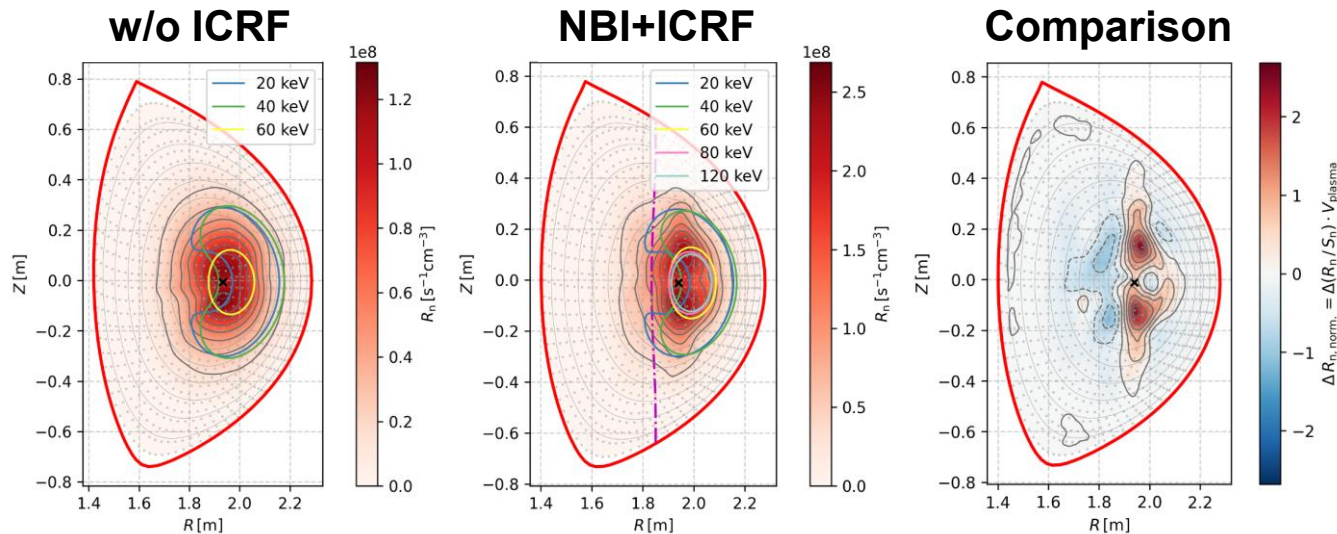
NBI+ICRF

Orbit Topology & Neutron Emission Profile

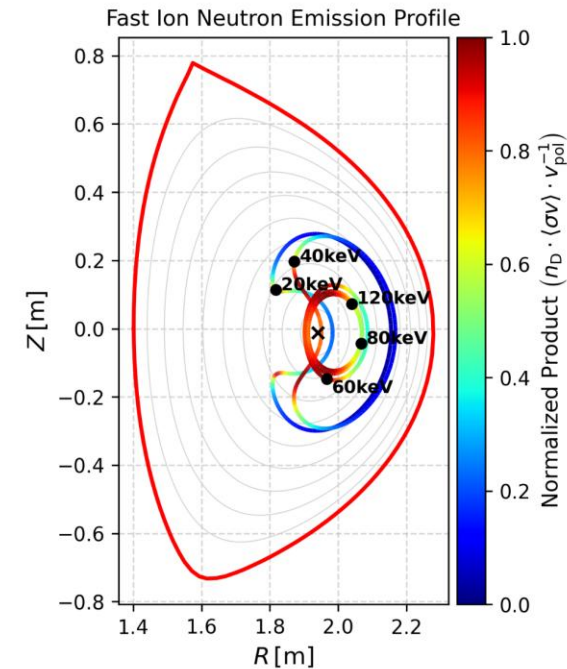


□ Spatial Reshaping of Neutron Emissivity under ICRF

- Synergistic heating leads to a more centrally peaked emissivity with a double-peak structure.
- Geometric alignment: High-energy tail orbits (60-120 keV) traverse the peak emissivity regions
- Neutron emission along a single orbit is non-uniform — maximum at the turning points.



Neutron Emission (TRANSP) with typical fast ion orbit (ORBIT)



$$w_{R_n}^{\text{CoM}}(R, Z; E, \mu, P_\phi) = n_D(R, Z) \cdot \langle \sigma v \rangle_{\text{MEB}}(T_i(R, Z), E) \cdot \frac{\Delta \tau \cdot \Delta \phi}{\Delta V}$$

Poloidal profile of neutron emission for typical fast ion orbits

Neutron spectroscopy + camera : fast-ion effects on neutron emission in CoM space

Contents

- EAST–NES System Overview
- Results from NBI + Third-Harmonic ICRF Heating Discharges
- Results from Discharges with a Record Neutron Rates
- **Conclusions and Outlook**

Conclusions and Outlook



- A 4-view NES system with complementary detector technologies was established on EAST to provide comprehensive fast-ion phase-space information.
- Forward and backward analyses of NBI – ICRF 3rd harmonic heating confirm that the system is capable for reconstructing fast-ion velocity distributions above 100 keV.
- In high- β_p discharges with NBI – ICRF 2nd harmonic heating, EAST achieved a record neutron rate of $3.9 \times 10^{14} \text{ s}^{-1}$, with direct NBI–ICRF synergy contributing 29 % via a NES-verified energetic tail.
- Orbit analysis reveals that ICRF synergy reshapes the spatial neutron emissivity profile, making integrated NES and neutron camera studies a primary next step.
- A newly upgraded DAQ system now enables simultaneous DD and 14 MeV DT neutron measurements to investigate 1 MeV triton confinement from D(D, p)T burnup.

Thank you for your attention



Andong Xu, Peking University
xuandong@pku.edu.cn