NSTX-U Monday Physics meeting

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Investigation of fast ion distribution and transport in the presence of ICRF and NBI synergetic heating on EAST tokamak

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2023-04-24

Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)

Outline

- Introduction
- ICRF-NBI synergy experiments and simulations
- Fast ion distribution and its parametric dependence
- Fast ion transport and lost on first wall
- Conclusions and outlook

Basic principle of ICRF-NBI synergy

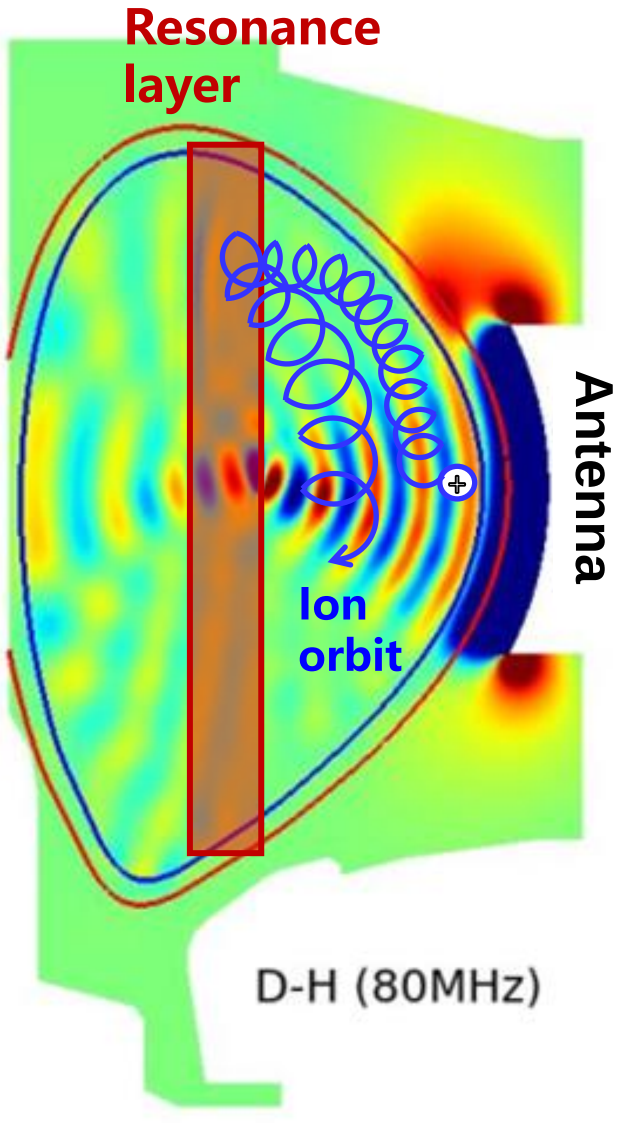
Wave-particle resonance condition:

$$\omega = n\omega_{cj} + k_{\parallel} v_{\parallel j} \ (n = 0, \pm 1, \pm 2, \ldots)$$

- Cyclotron frequency: $\omega_{cj} = q_i B / m_i$
- Resonance position: $R_{res} \approx (n q_i B_0 R_0)/(\omega m_i)$

ICRF heating scenarios on EAST:

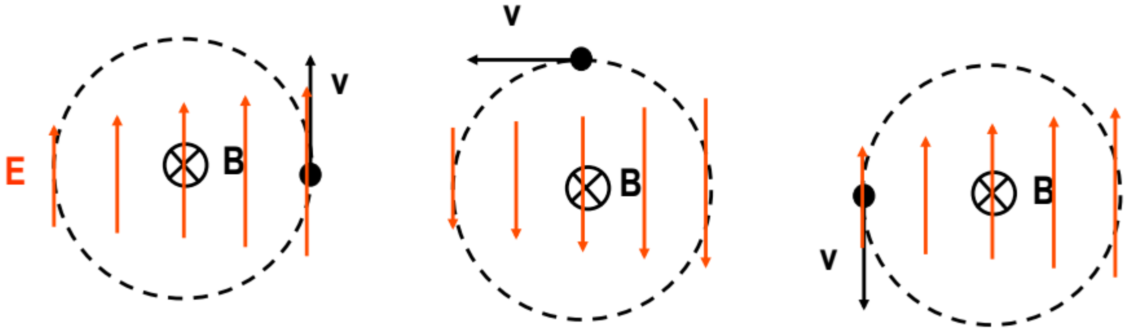
- Minority ion heating (n = 1)
- High harmonic heating (n ≥ 2)
- Landau damping and TTMP (n = 0)



High harmonic heating

- Accelerates ions by the gradient of wave electric field
- Prone to accelerate energetic ions

T = period of the wave



Basic principle of ICRF-NBI synergy

Resonance position: $R_{res} \approx (nq_iB_0R_0)/(\omega m_i)$

To make on-axis heating:

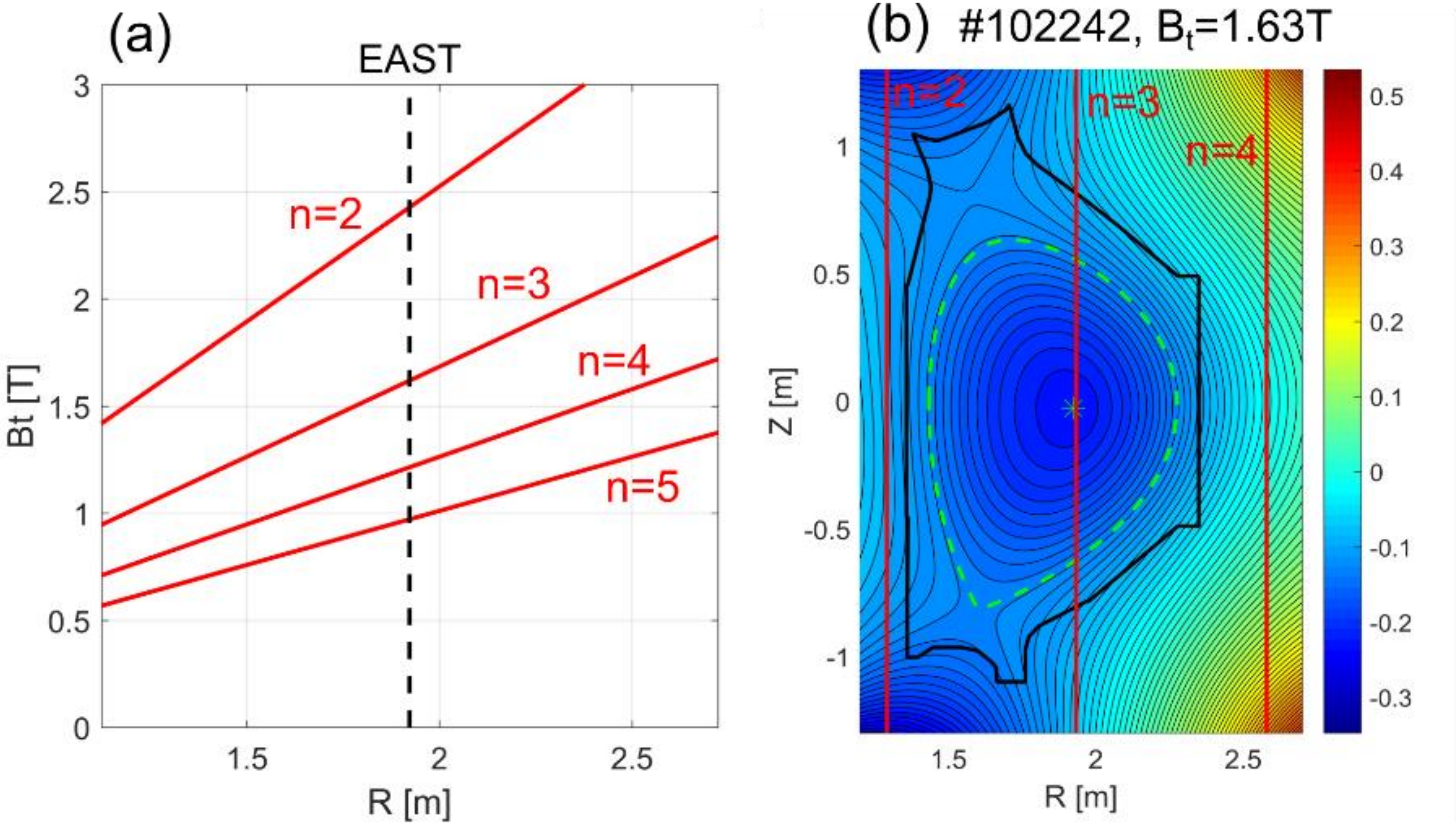
n=2, B_t = 2.43T

n=3, B_t = 1.63T

n=4, B_t = 1.22T

$R_{res} \propto \frac{nq_i}{m_i}$ for fixed B_t:

- ➢ H fundamental and D 2nd harmonic have the same resonance position



Basic principle of ICRF-NBI synergy

Maxwell's equations for the wave field

$$-\nabla\times\nabla\times\mathbf{E}+\frac{\omega^2}{c^2}\left(\mathbf{E}+\frac{i}{\omega\epsilon_0}\mathbf{J}_p\right)=-i\omega\mu_0\mathbf{J}_{\mathrm{ant}},$$

Fokker-Planck equations for fast ion distribution

$$\frac{\partial f_i}{\partial t}=\underset{\substack{\downarrow\\ \text{collision}}}{C(f_i)}+\underset{\substack{\downarrow\\ \text{wave-particle}\\ \text{interaction}}}{Q(f_i)}+\underset{\substack{\downarrow\\ \text{source(NBI)}}}{S(\vec{v})}+\underset{\substack{\downarrow\\ \text{loss}}}{L(\vec{v})}$$

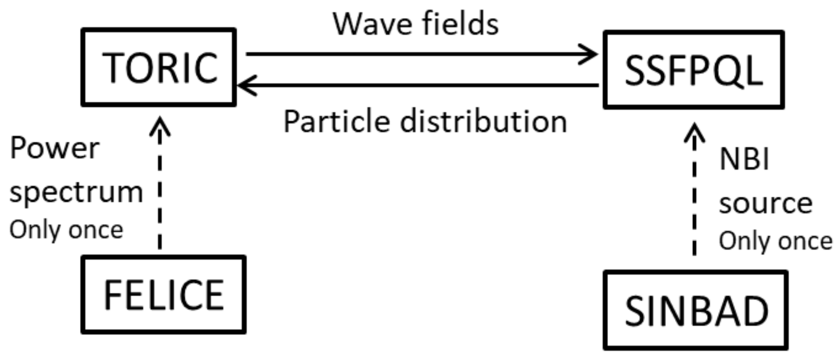
$$Q(f_i)=\frac{1}{2}D_{\mathrm{RF}}v^2\frac{\partial f}{\partial v}.$$

$$D_{\mathrm{RF}}\propto P_\perp\left|\left(\frac{E^+}{E^-}\right)J_{n-1}\left(\frac{k_\perp v_\perp}{\omega_c}\right)+J_{n+1}\left(\frac{k_\perp v_\perp}{\omega_c}\right)\right|^2$$

Basic mechanism:

- NBI beam fast ions accelerated by ICRF high harmonic heating

Example: TORIC+SSFPQL



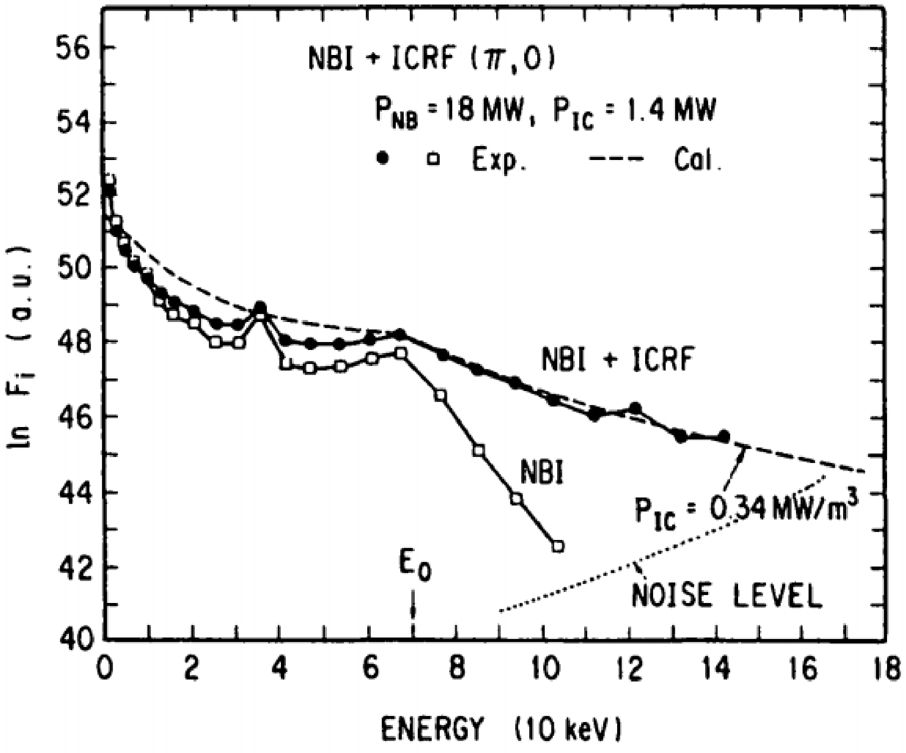
This study: TRANSP

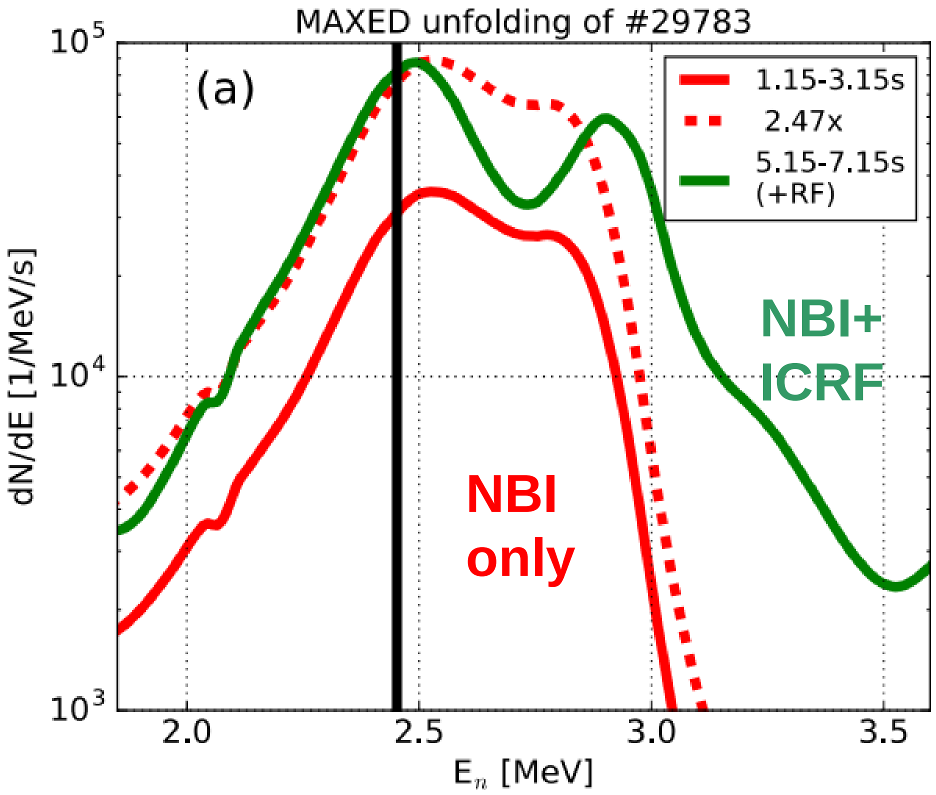
TORIC + XFPPRF
+ NUBEAM (RF-kick operator)

JT-60 and AUG ICRF +NBI synergy

- ICRF+NBI: energy confinement time = 210 ms, three times higher than ICRF only or NBI only
- Due to build-up of the fast ions accelerated by the ICRF wave.

- Deuterium energetic tail up to 500 keV are observed with NBI+ICRF, one order of magnitude higher than NBI only.





Kimura H. *et al* 1991 *Nuclear Fusion* **31** 83-92

Tardini G. *et al* 2019 *Nuclear Fusion* **59** 046002

JET ICRF +NBI synergy

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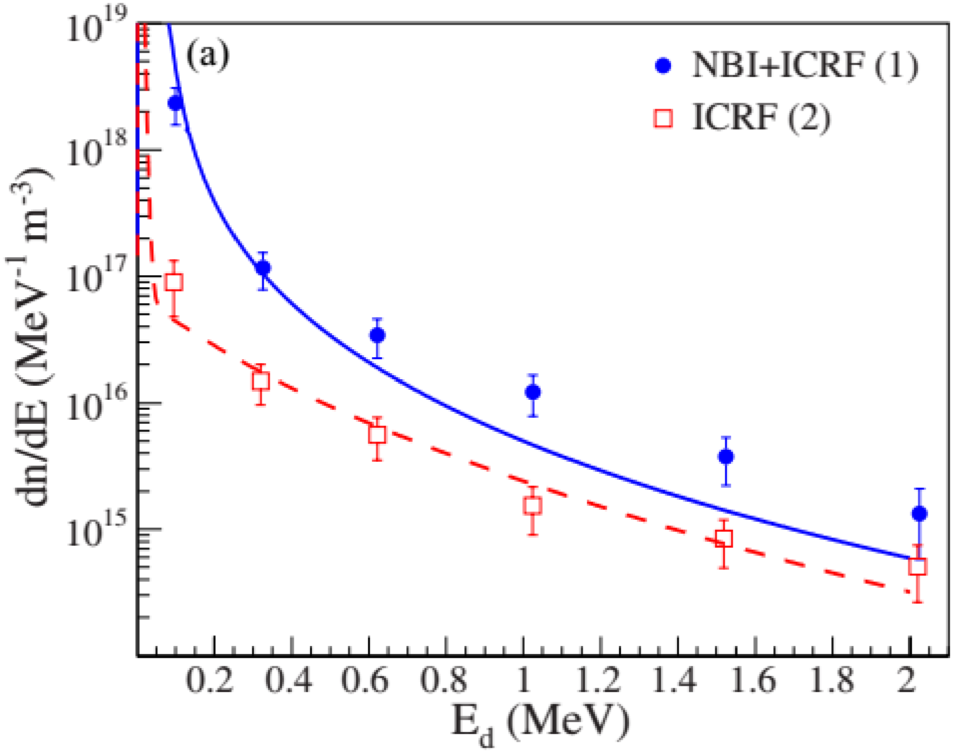
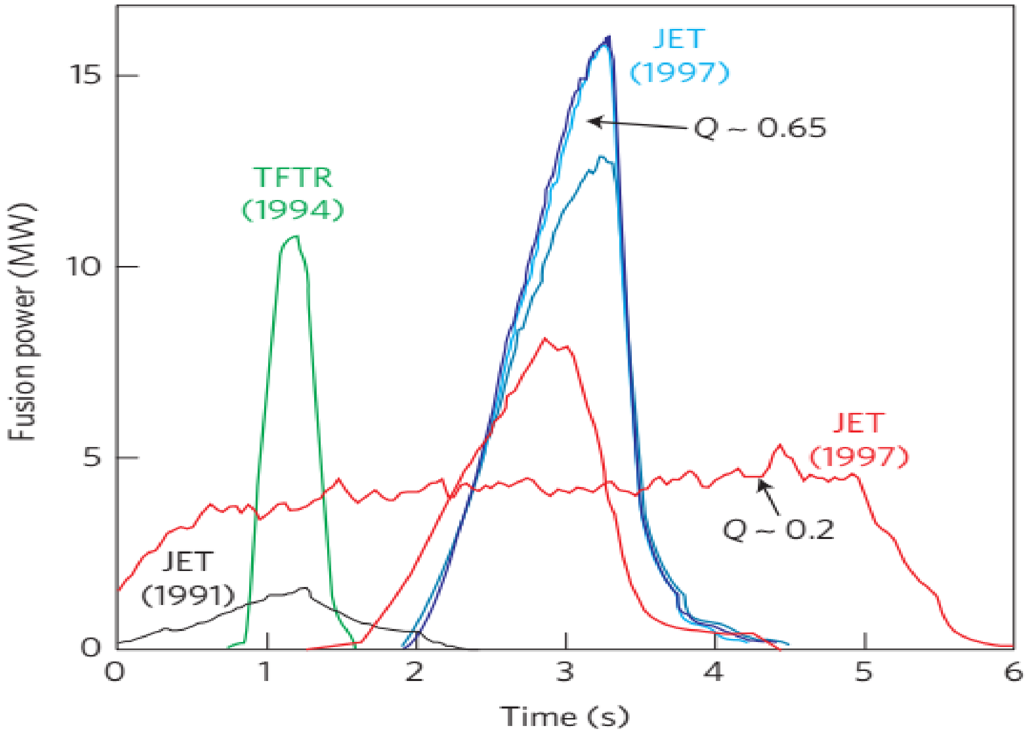
- The measured distributions between 100 and 500keV are elevated by up to 10 times compared to periods with ICRF only.

- ICRF+NBI synergetic heating has been routinely used in JET to achieve high performance plasma



Gallart D. *et al* 2018 *Nuclear Fusion* **58** 106037



Jacquinot J. *et al* 1999 *Plasma Physics and Controlled Fusion* **41** A13-A46

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EAST heating configurations

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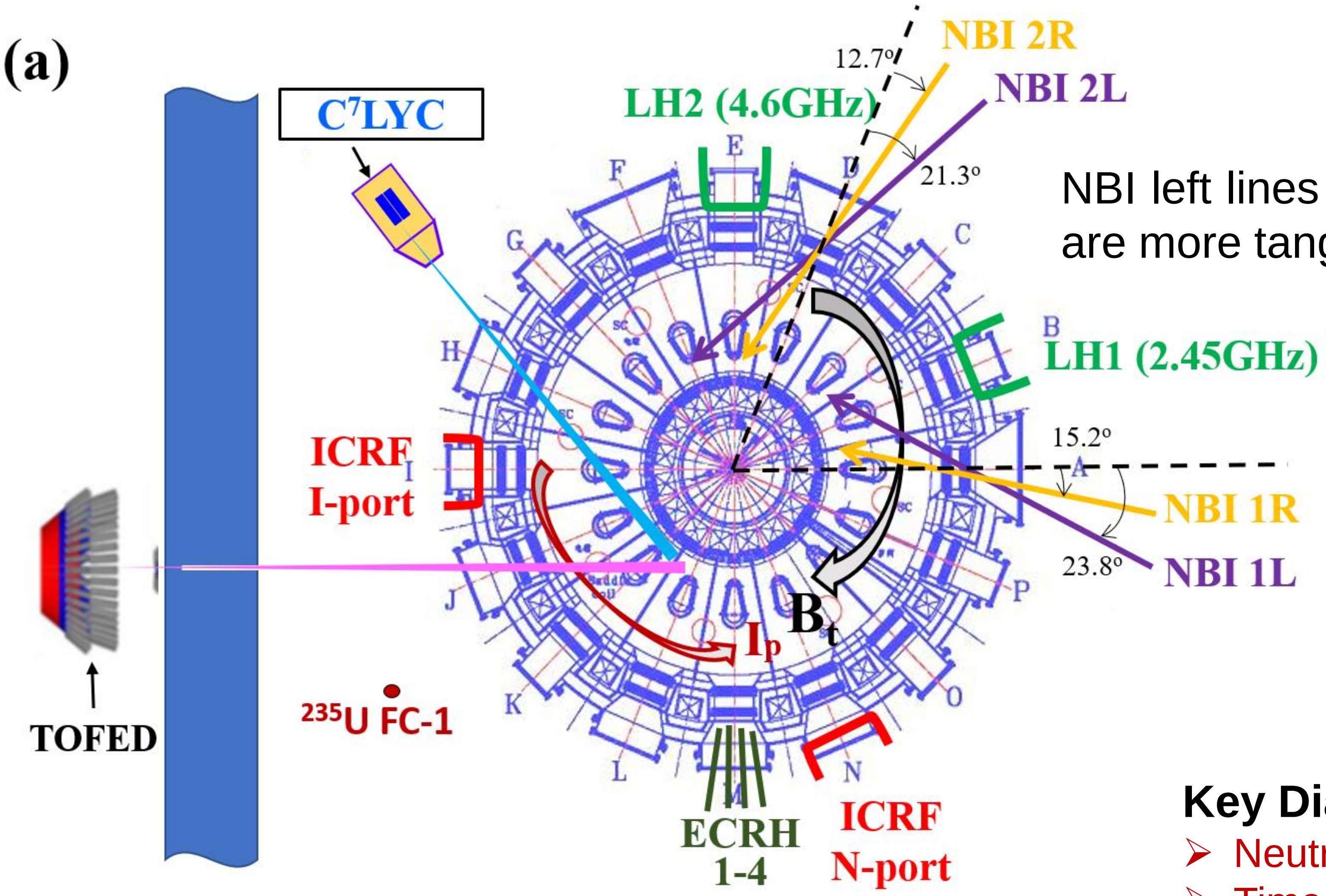
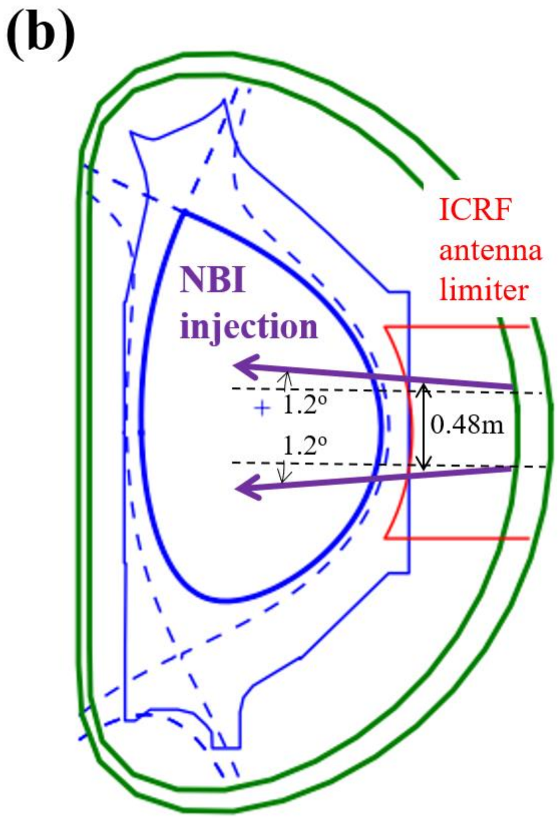


NBI left lines (1L/2L)
are more tangential



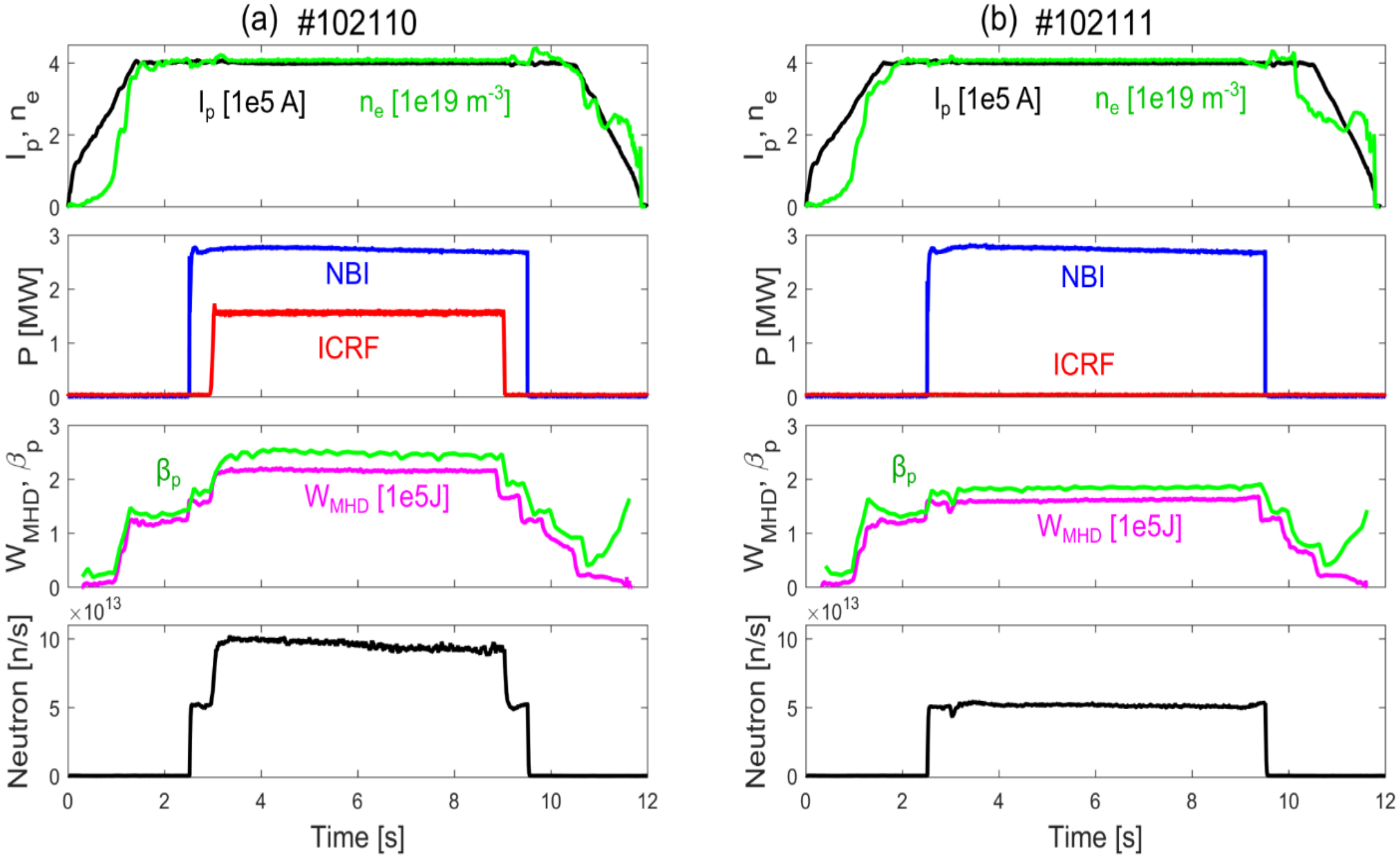
IC~4MW, EC~3MW, LH~4MW, NBI~6MW

Key Diagnostics

- Neutron emission spectroscopy (NES)
- Time of Flight Enhanced Diagnostic (TOFED)
- Neutron yield diagnostics
- Fast-ion Dα spectroscopy (FIDA)

Experiment setups

☐ Significant increase of main plasma parameters



1.5MW ICRF + 2.8MW NBI synergy increases:

β_p by ~36%

W_{MHD} by ~35%

T_i by ~20%

Y_n by ~100%

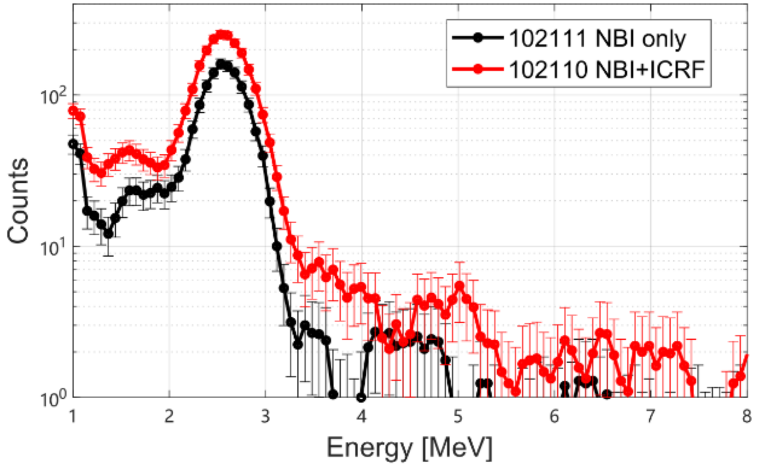
W. Zhang et al 2023 Nuclear Fusion 63 056015

Experimental results

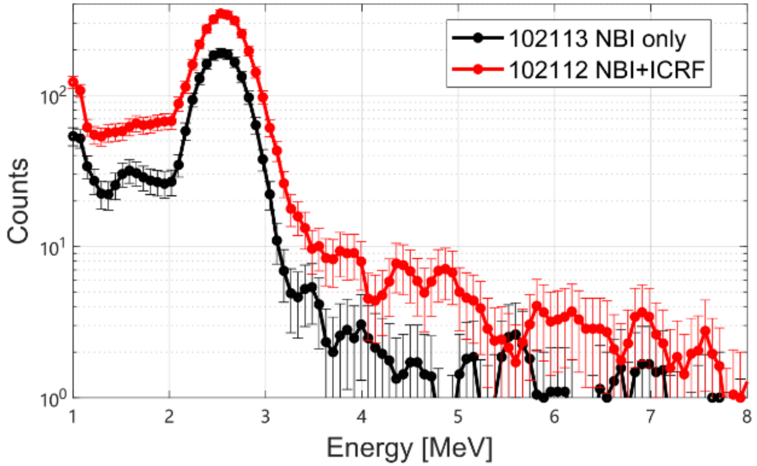
Fast neutron distribution with ICRF+NBI

NES results

(a1) ICRF 1.5MW, NBI 1L+2L (55keV)

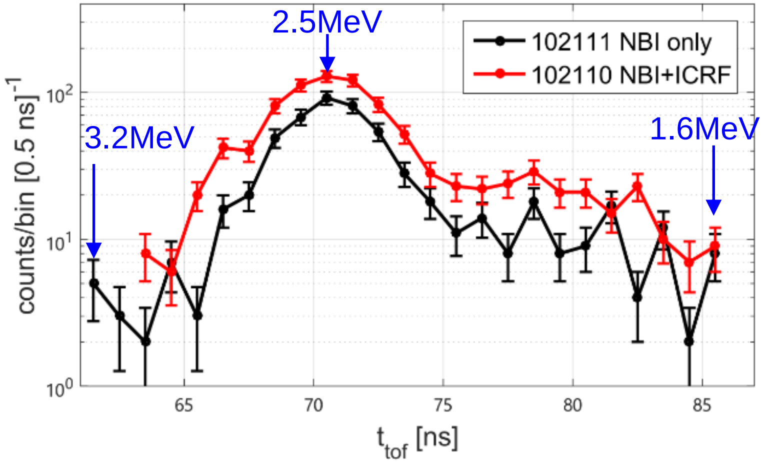


(a2) ICRF 1.5MW, NBI 1L+2L (60keV)

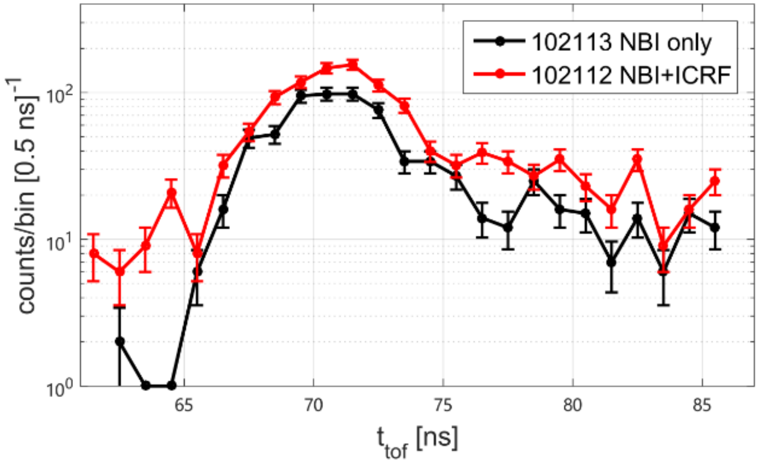


TOFED results

(b1) ICRF 1.5MW, NBI 1L+2L (55keV)



(b2) ICRF 1.5MW, NBI 1L+2L (60keV)



D-D reaction neutrons:

$$\boldsymbol{D} + \boldsymbol{D} \rightarrow {}^{3}\boldsymbol{He}\ (0.82\ MeV) + \boldsymbol{n}\ (2.45\ MeV)$$

Both NES and TOFED show that:

☐ NBI+ICRF synergy leads to

- ➢ More fusion neutrons
- ➢ Larger fast neutron tail

☐ NBI+ICRF synergy is stronger with

- ➢ Larger NBI beam energy

Experimental results

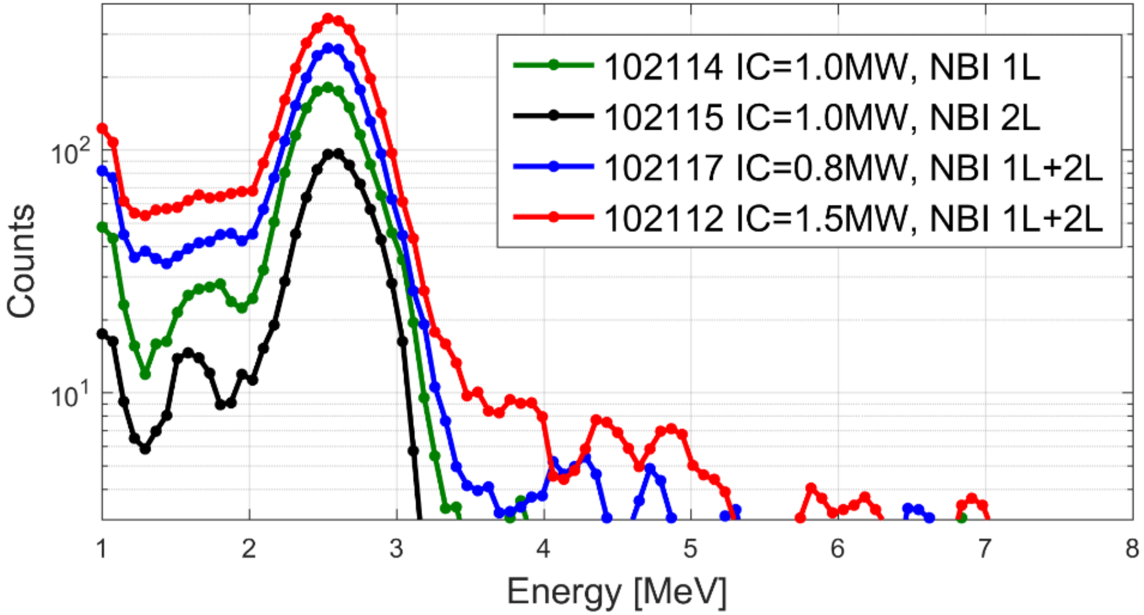
Fast neutron distribution with ICRF+NBI

☐ NBI injection angle
- ➢ Affects the fast neutron/ion distribution

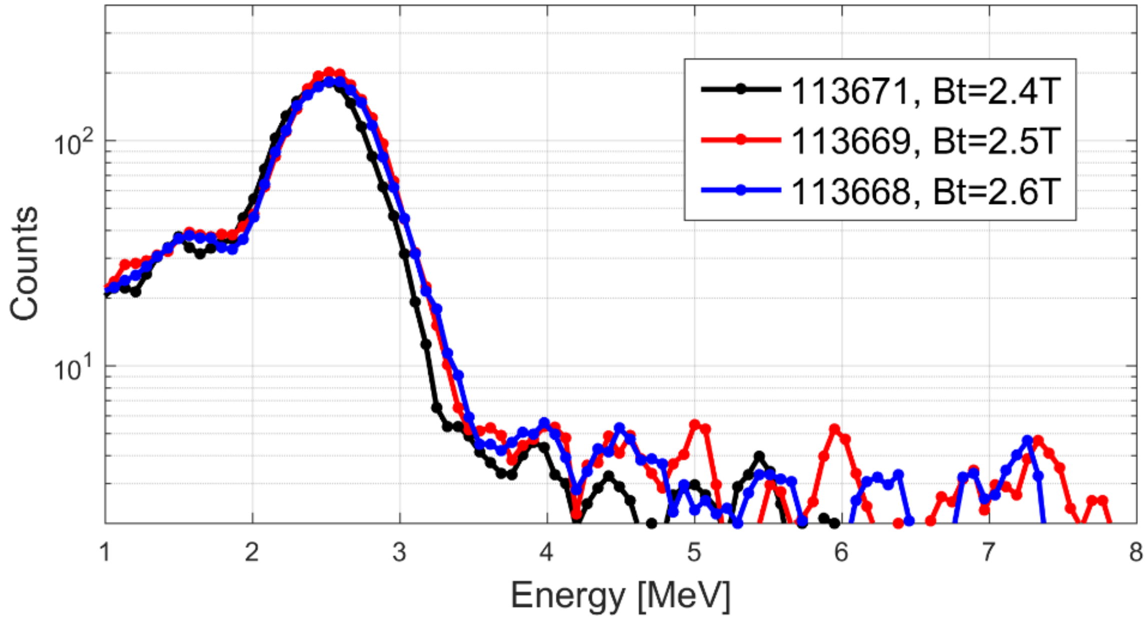
☐ NBI+ICRF synergy is stronger with
- ➢ Larger ICRF power
- ➢ On-axis ICRF heating (B_t=2.5T)

NBI 1L is more tangential than NBI 2L

(a) NBI 1L vs 2L vs 1L+2L (60keV)



(b) ICRF 1.0MW, NBI 1R+2L+2R (50keV)



Experimental results

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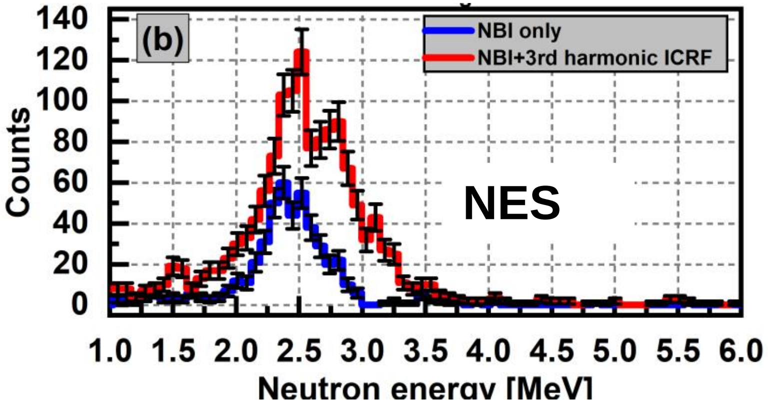
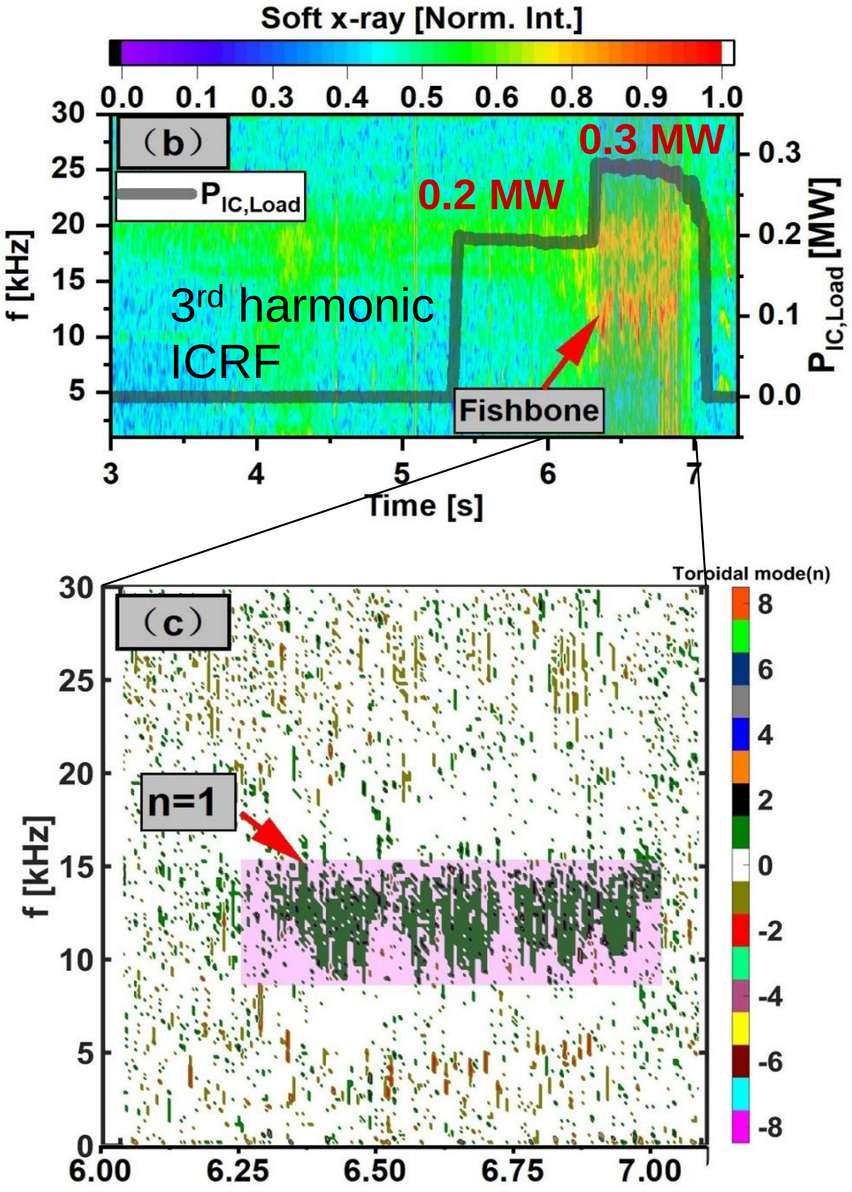
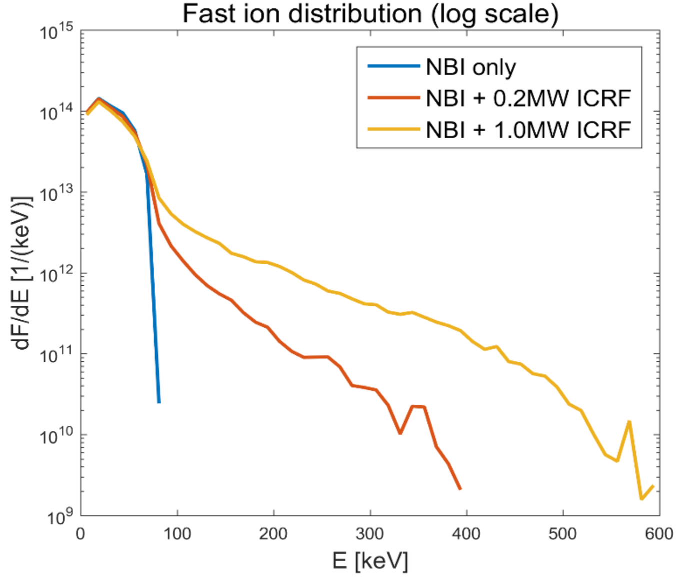
- ☐ 3rd harmonic ICRF+NBI leads to
  - Larger D-D reaction and fast D ion tail
  - Burst of n=1 Fishbone Mode



Possible reason:
More trapped fast ion is generated inside the q=1 surface



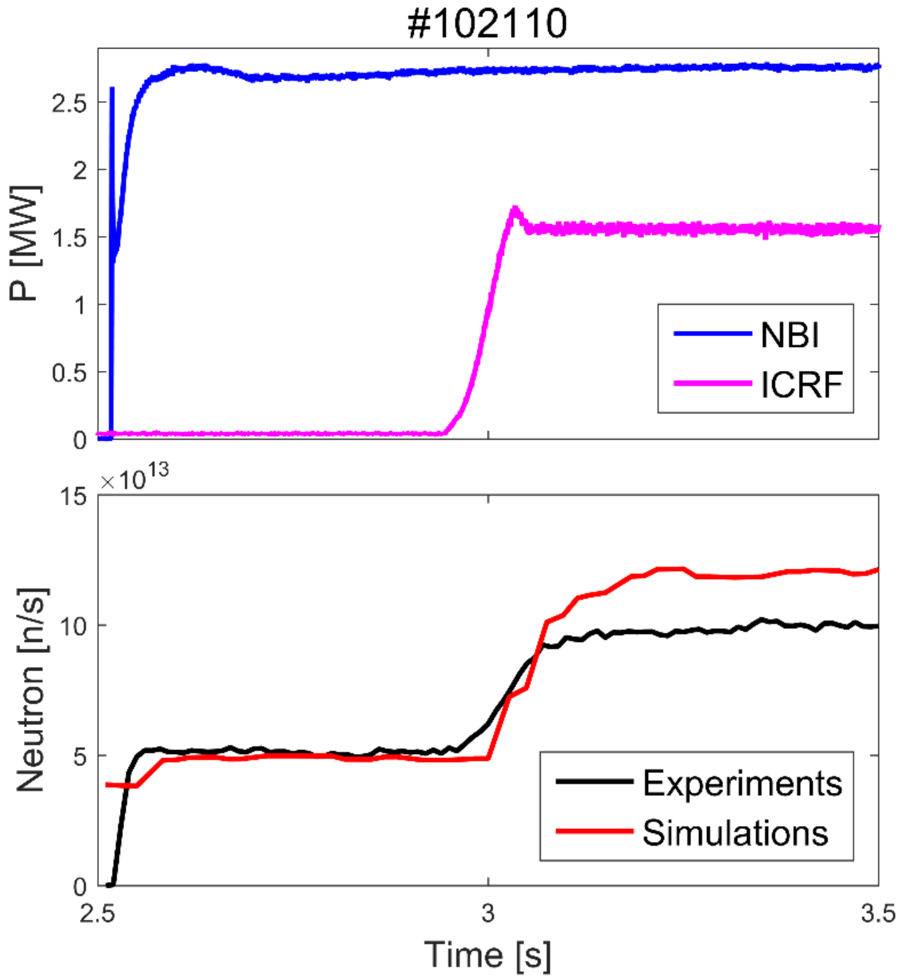


TRANSP simulations
W. Zhang

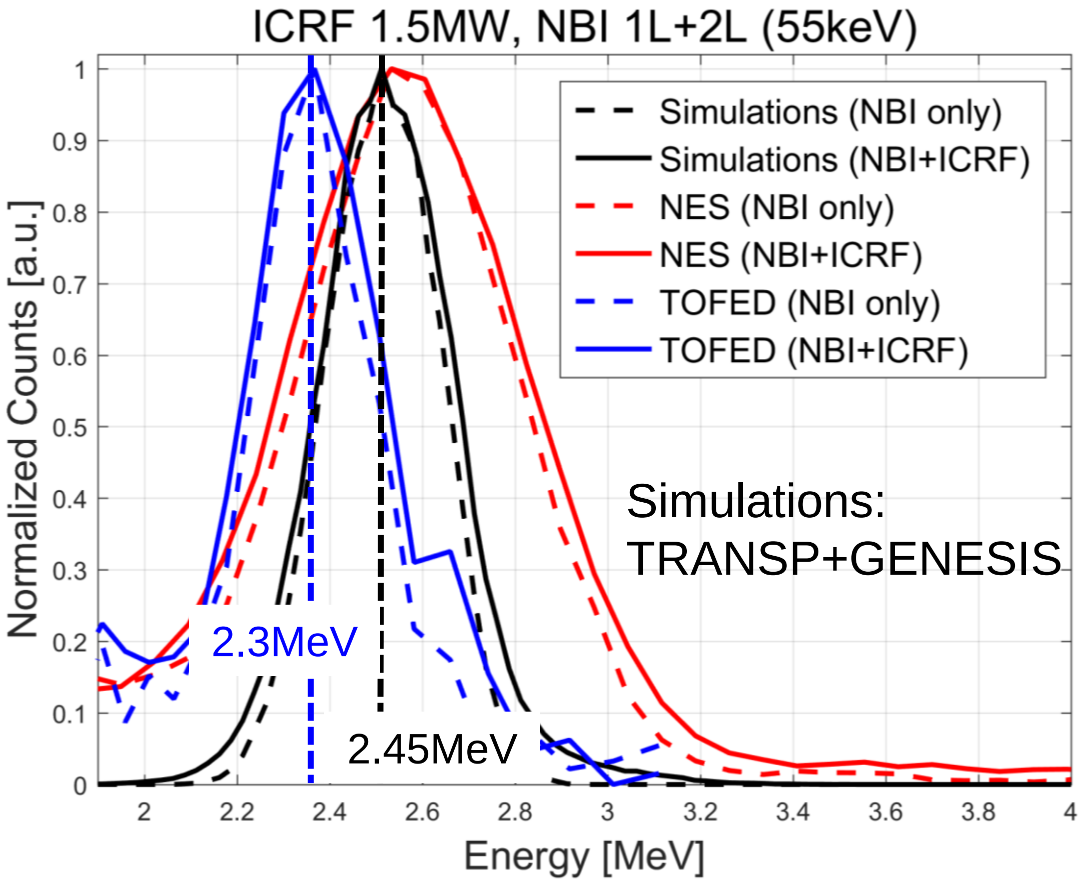
G. Zhu, W. Zhang* et al 2023
Nuclear Fusion 63 036013

TRANSP simulations

- Qualitative agreement between experiments and simulations



High-Z impurities were not considered in simulations
More fast ions are expected to lost in experiments



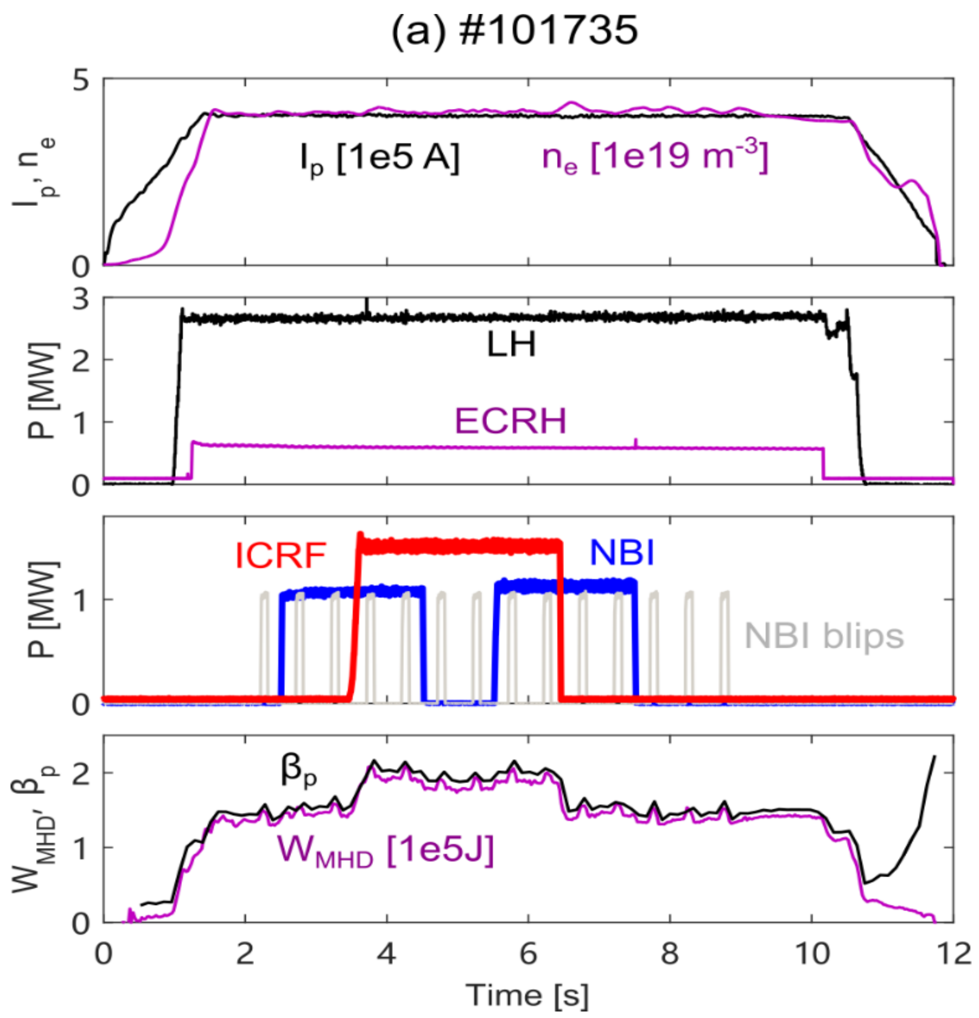
TOFED: co-current view angle → ‘doppler shift’ of distribution
TOFED and simulations match very well if shitted by 0.15MeV

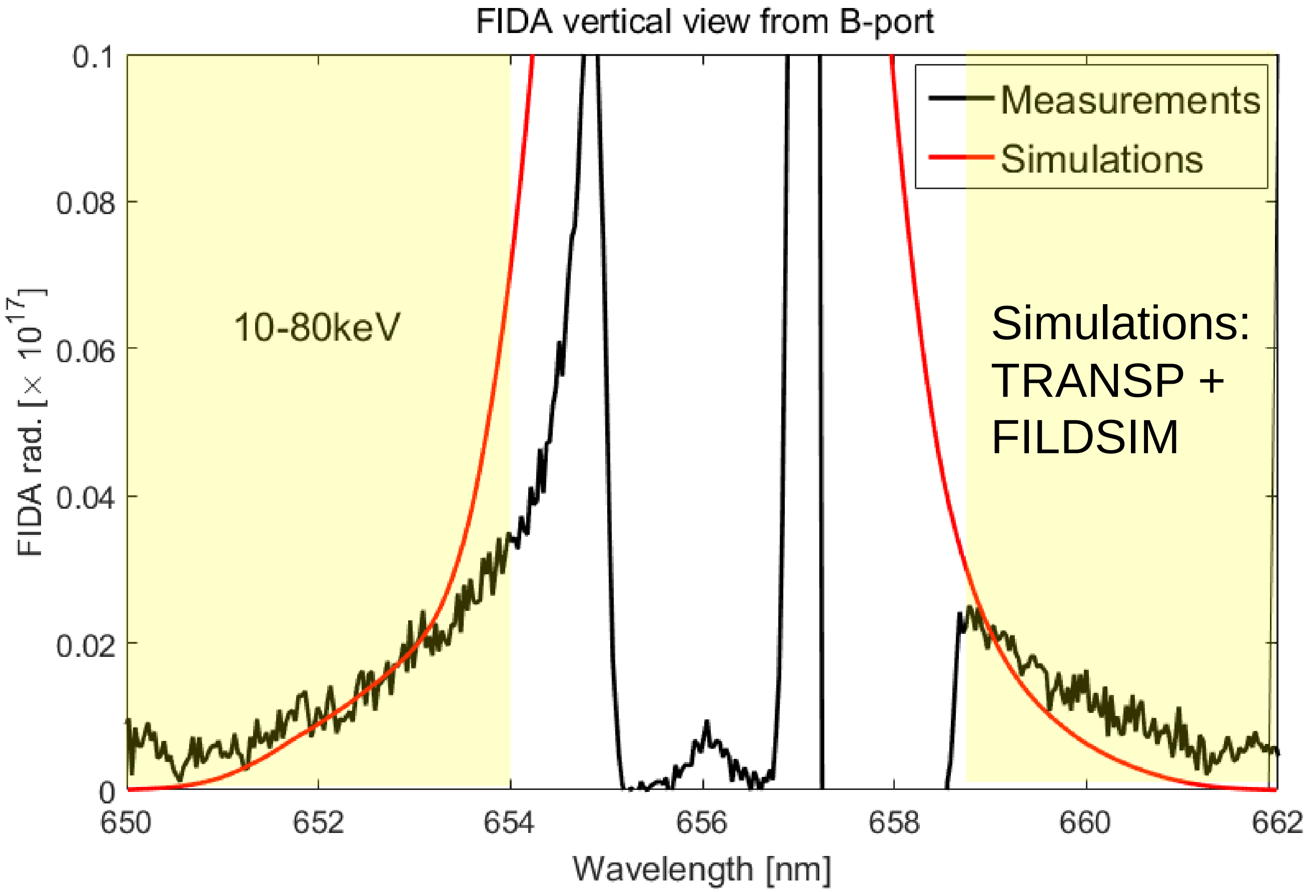
NES: grid resolution → broadening of distribution

TRANSP simulations

- 1.5MW ICRF + 1.0MW NBI synergy increases: β_p~35%, W_{MHD}~33%, T_i~22%, Y_n~80%

- TRANSP + FILDSIM simulations are in qualitative/quantitative agreement with FIDA measurements





Only 10-80keV fast D ions were measured by FIDA

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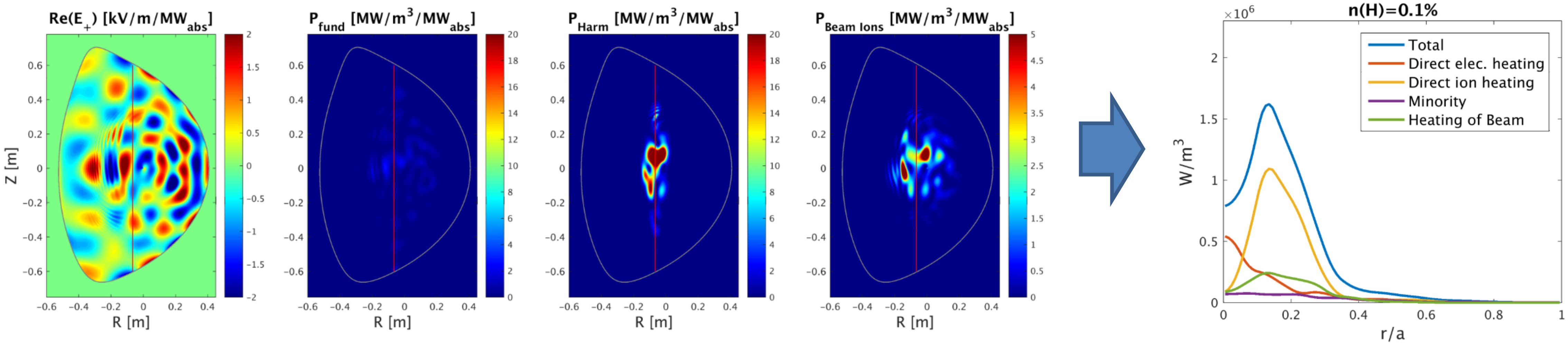
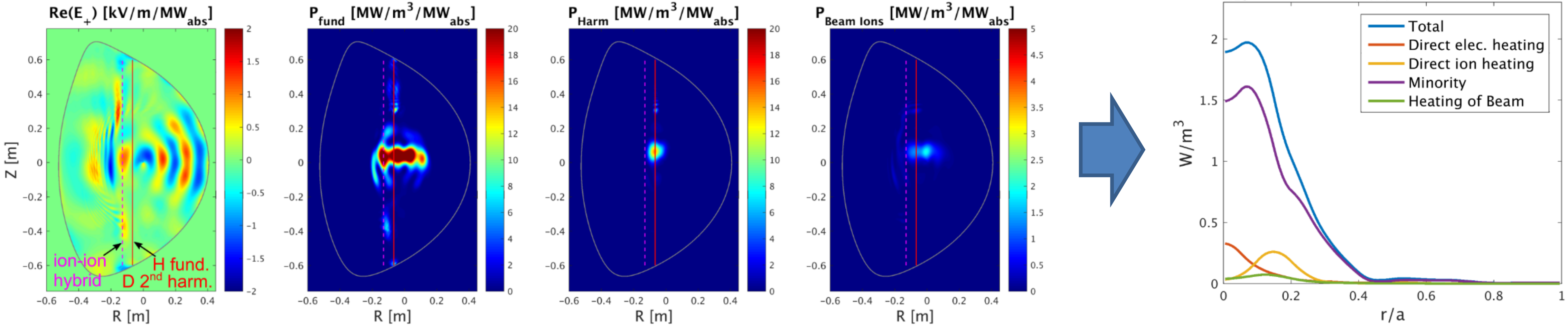
n(H) scan

- Scan of n(H) = 0.1% to 10% is investigated
- Stronger ICRF-NBI synergy and larger RF absorbed by NBI ions when n(H) is lower

(a) n(H)=0.1%

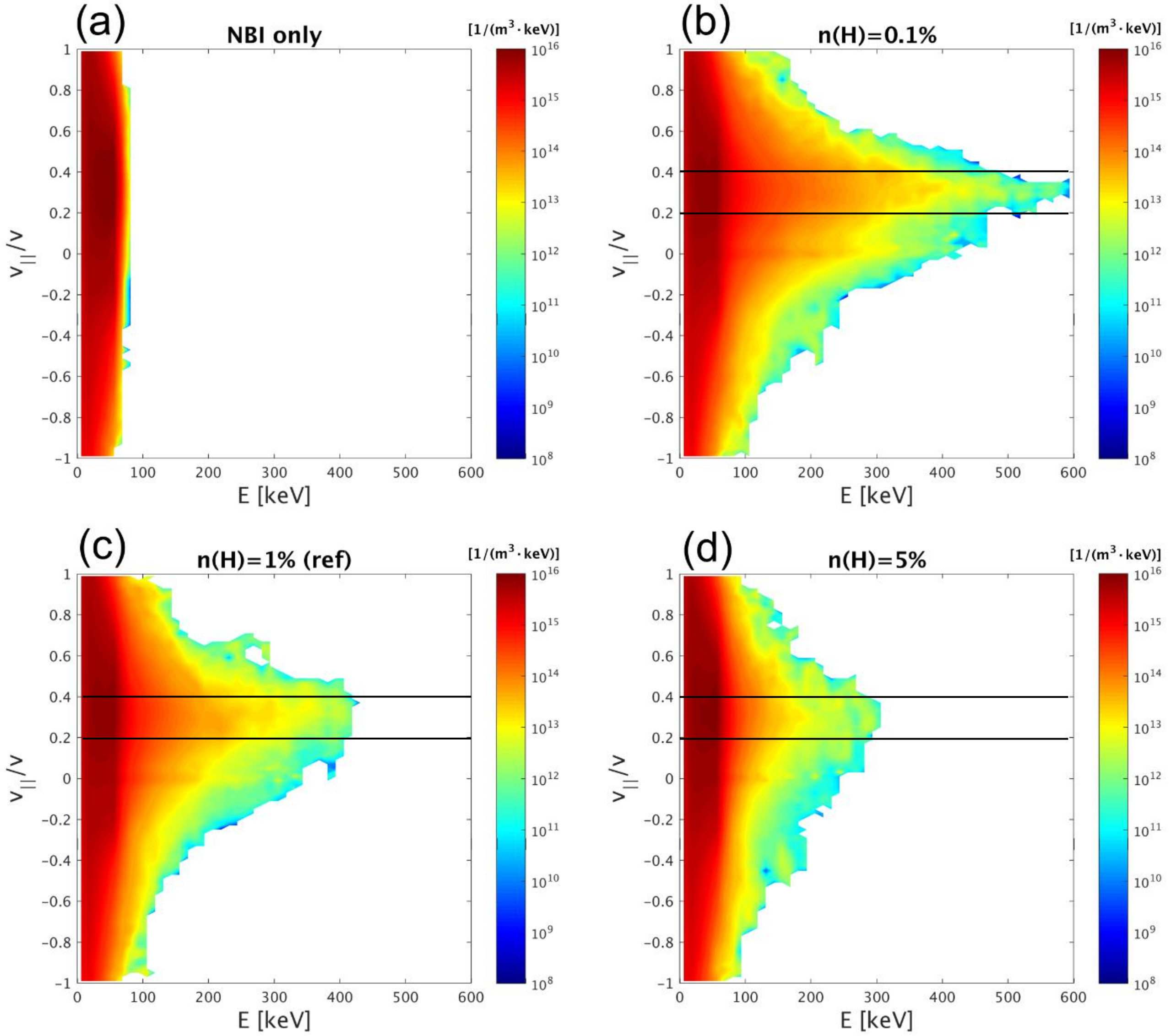


(c) n(H)=5%



n(H) scan

Fast ion distribution df/(dE*dp), p=$v_{||}/v$

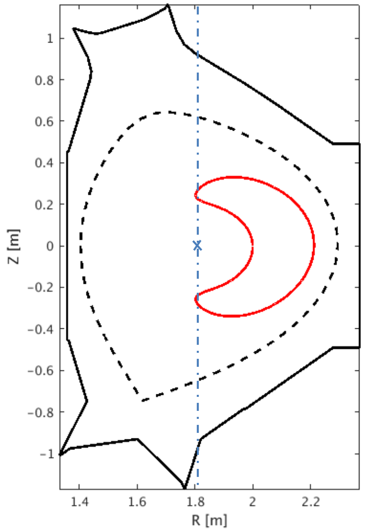


Without ICRF:

- $E_{NBI_max} < 80$keV

With ICRF:

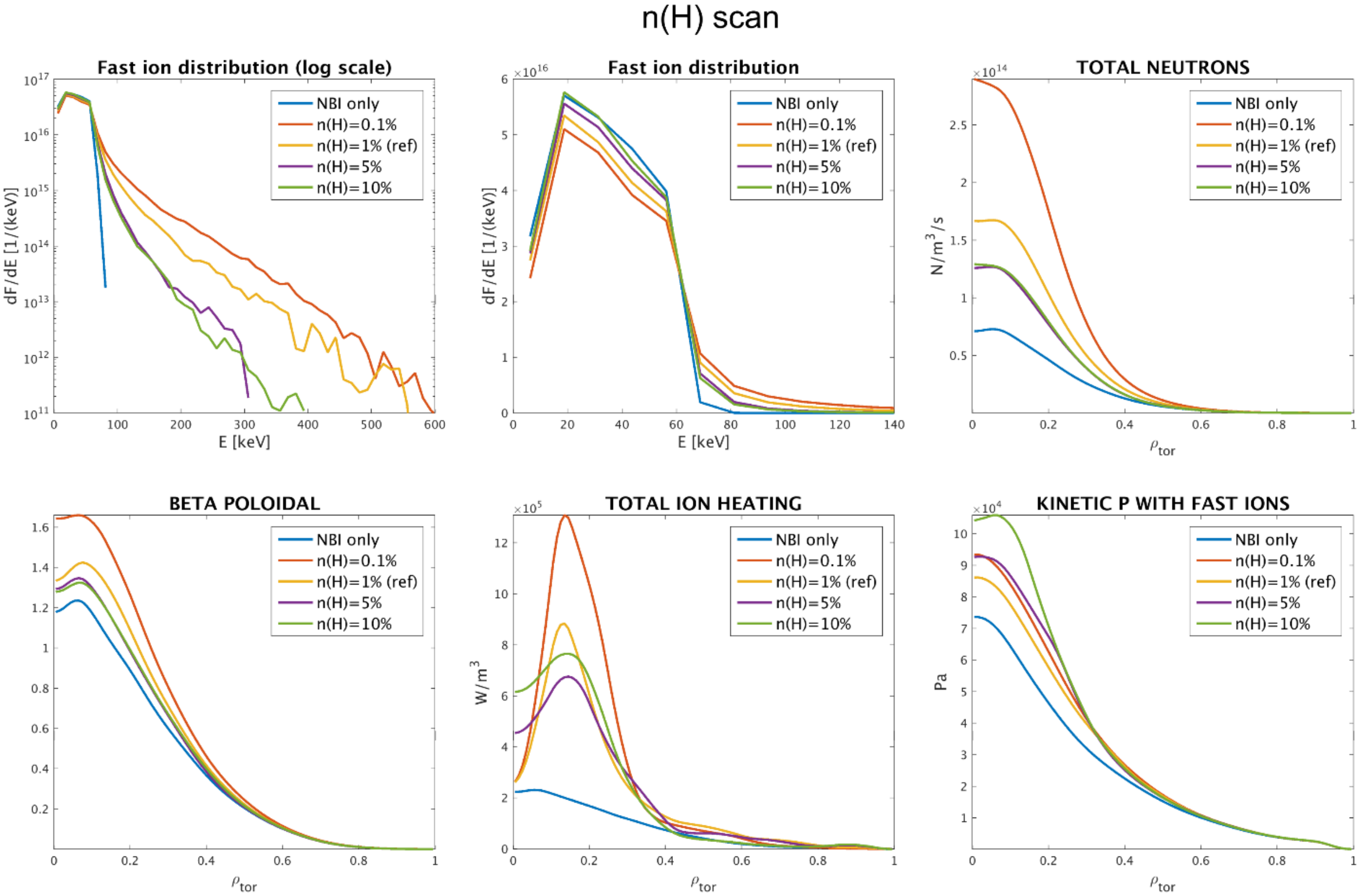
- n(H) = 5%, $E_{NBI_max} = 300$keV
- n(H) = 1%, $E_{NBI_max} = 400$keV
- n(H) = 0.1%, $E_{NBI_max} = 600$keV
- The accelerated NBI ions mainly have $v_{||}/v$ = [0, 0.6]



E=80keV
$v_{||}/v$=0.4

Trapped orbit tips at or close to the resonance position

n(H) scan



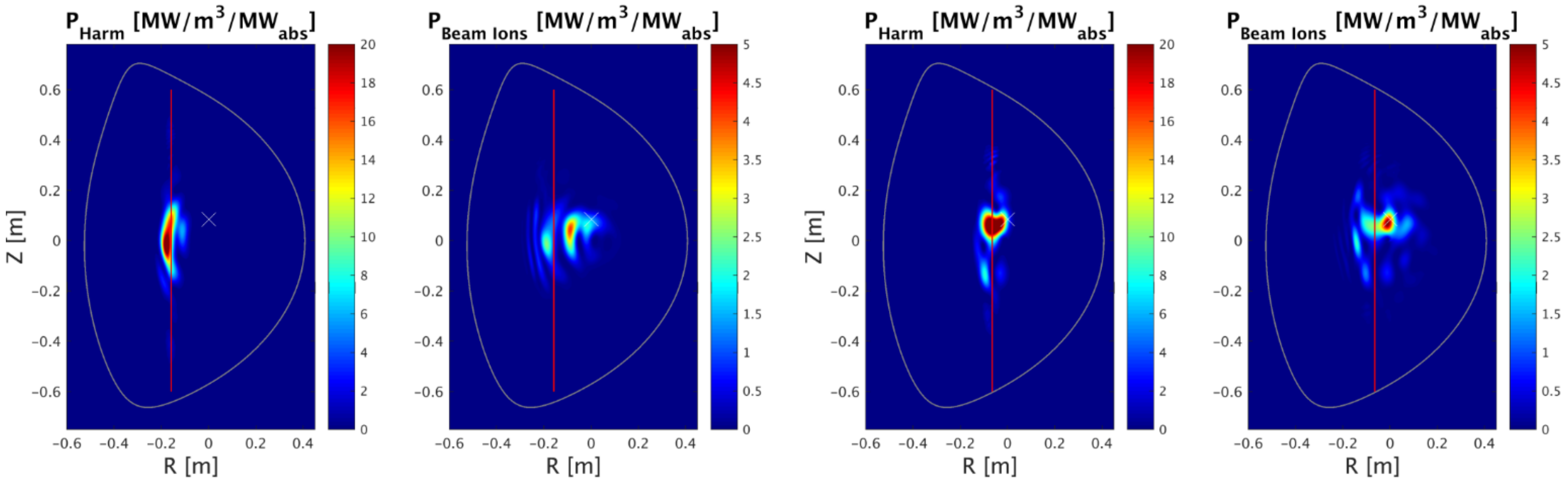
Fast D ion tail is largest when:

- ➢ n(H) is lowest

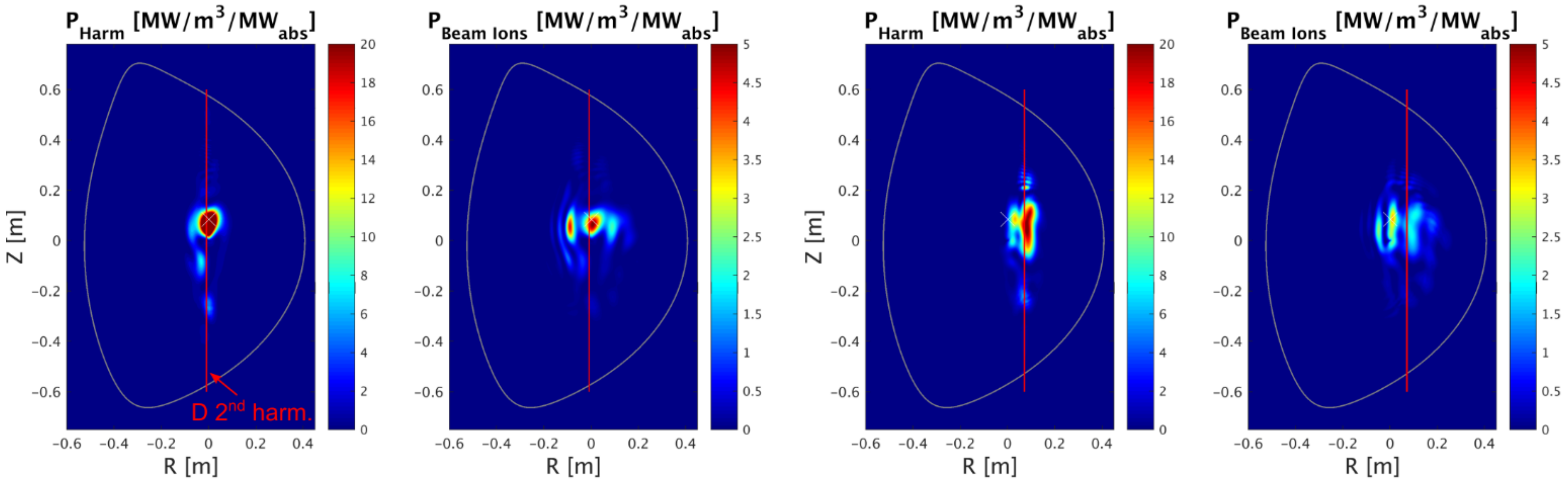
B_t scan

B_t scan: ICRF power absorption

(a) B_t=2.3T (b) B_t=2.4T

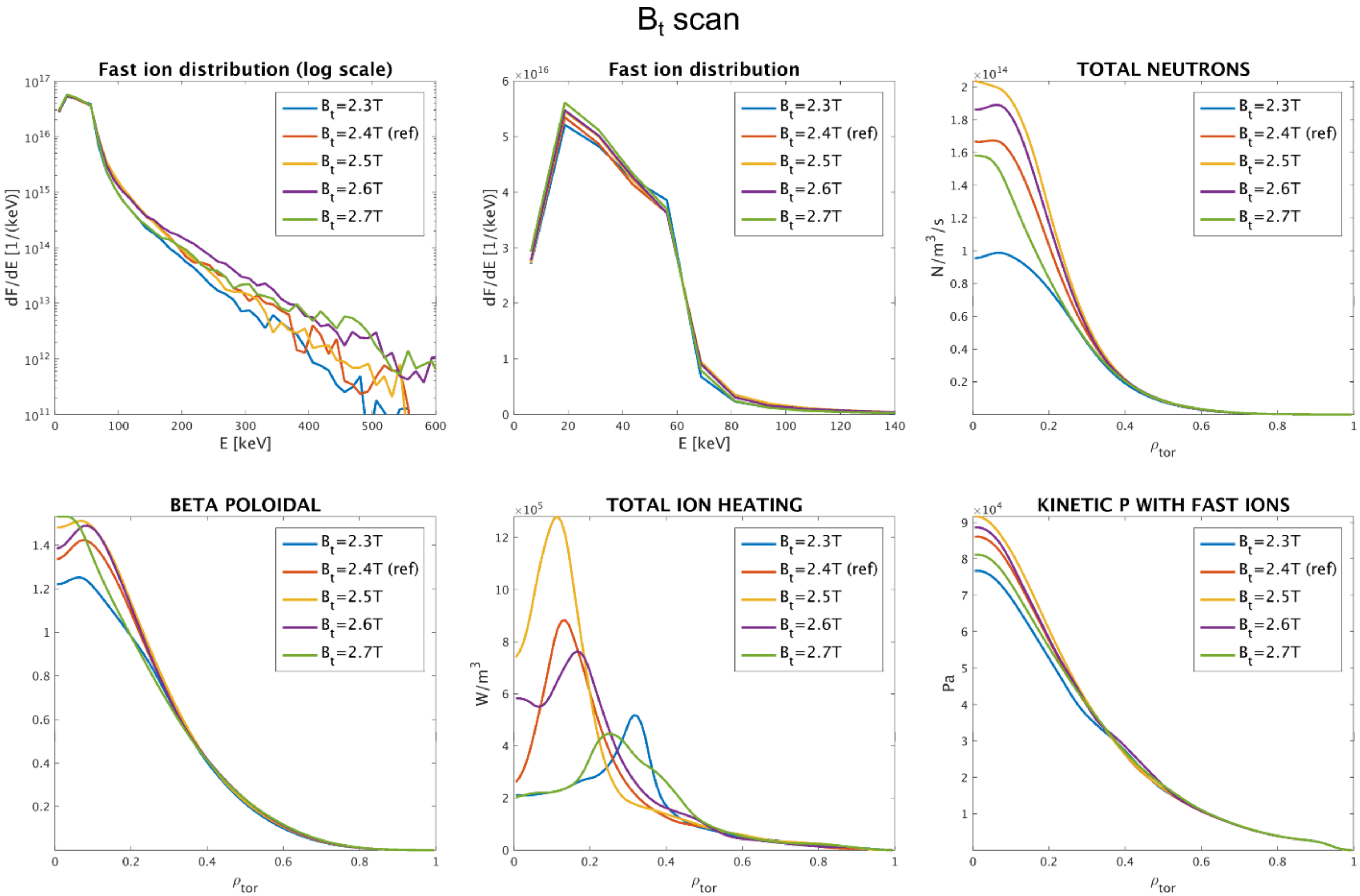


(c) B_t=2.5T (d) B_t=2.6T



- ☐ RF power absorbed by NBI ions is most significant when the resonance position is on-axis
- ☐ Absorption region of D thermal ions is smaller than NBI fast ions

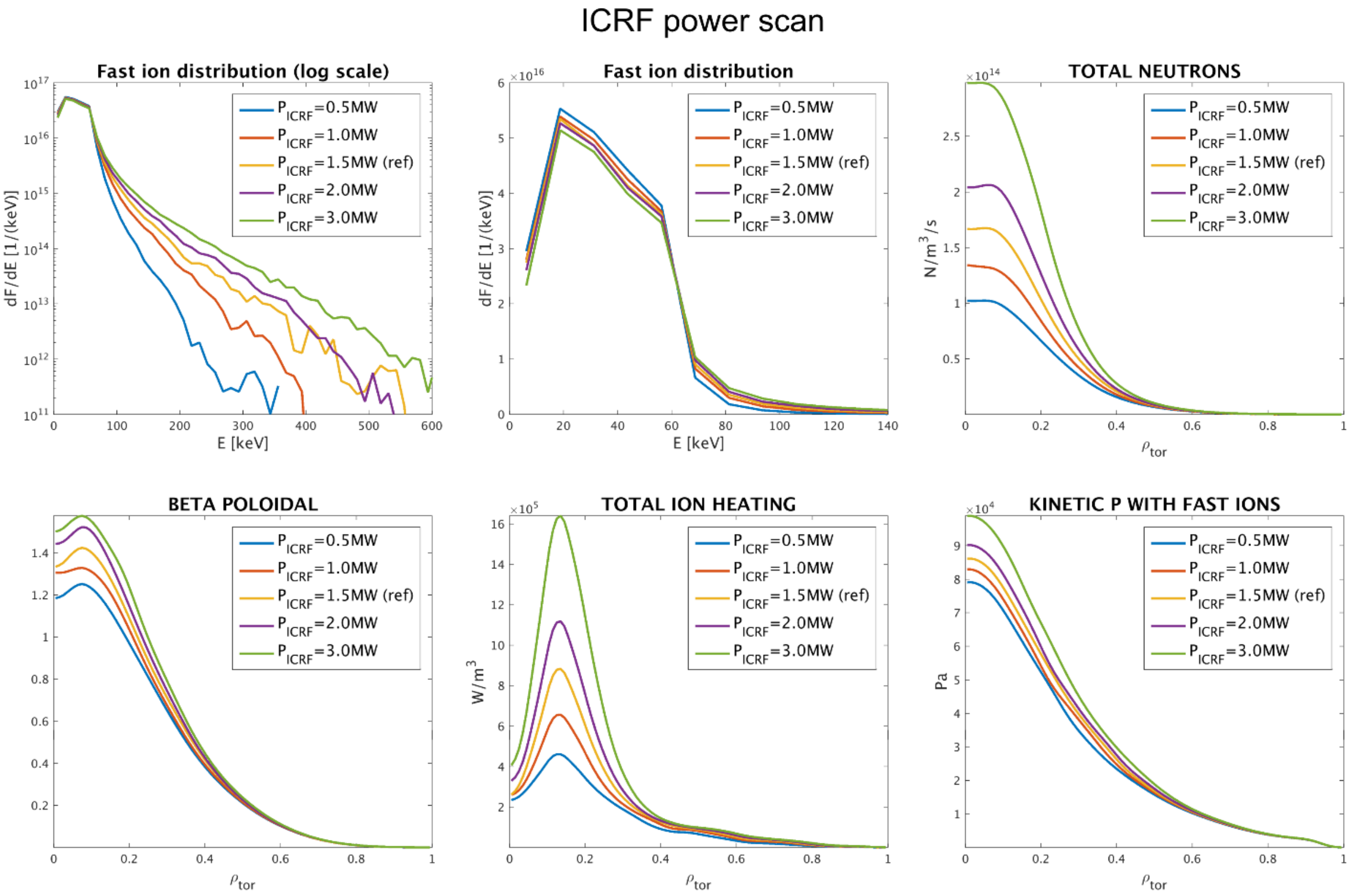
B_t scan



Fast D ion tail is largest when:

- 2nd harmonic resonance position is on the magnetic axis

ICRF power scan

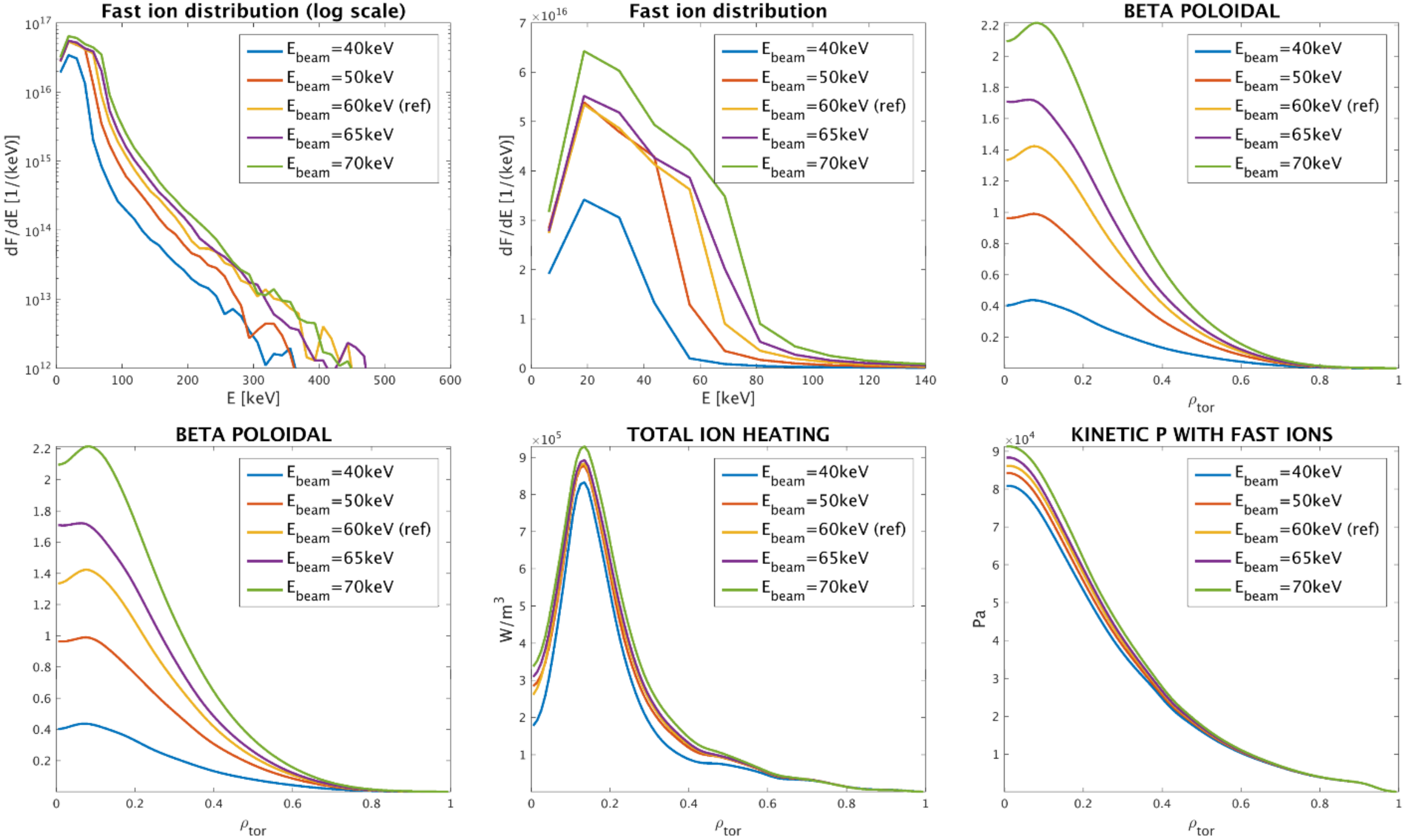

ICRF power scan

Fast D ion tail is largest when:

- ➢ ICRF power is largest

NBI beam energy scan

NBI beam energy scan



Fast D ion tail is largest when:

- ➢ NBI beam energy is largest

NBI beam voltage	NBI beam power
40keV	0.4MW
50keV	0.8MW
60keV	1.0MW
65keV	1.14MW
70keV	1.45MW

NBI beam angle scan

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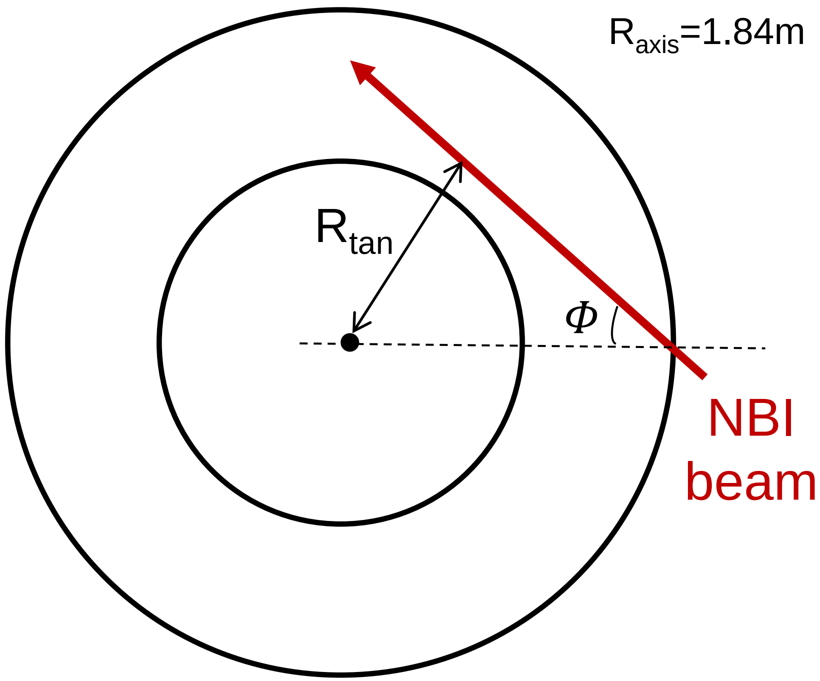
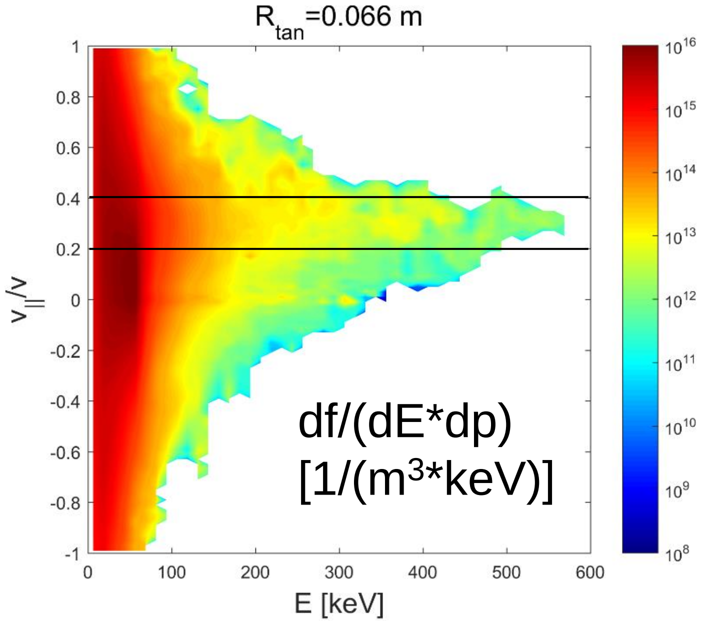
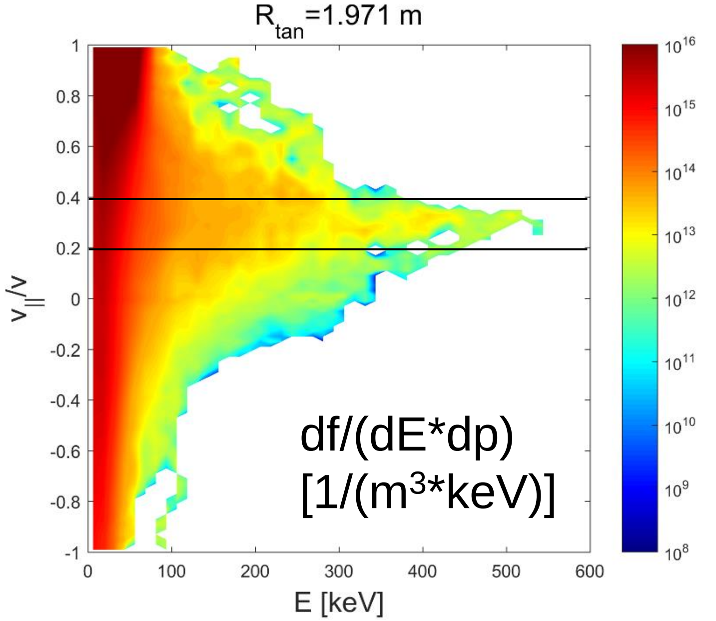
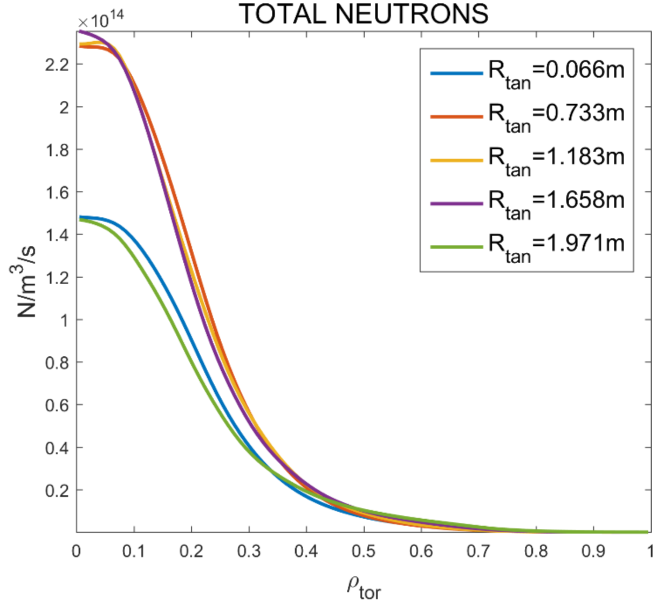
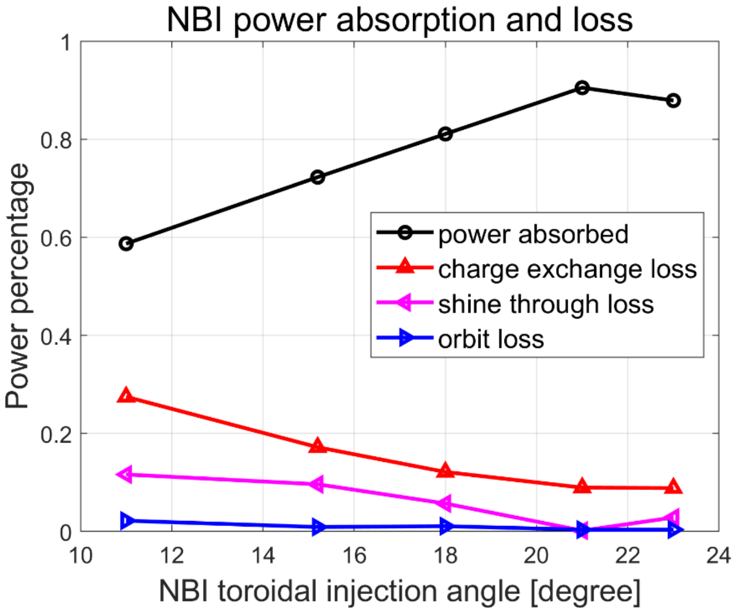
Tangency radius R_{tan}











- ☐ Fast ion tail, neutron yield and β_p are largest when R_{tan}=1.658 m (Φ=21°)
- ☐ Fast D ion tail is centralized at $v_{||}/v$=0.2-0.4

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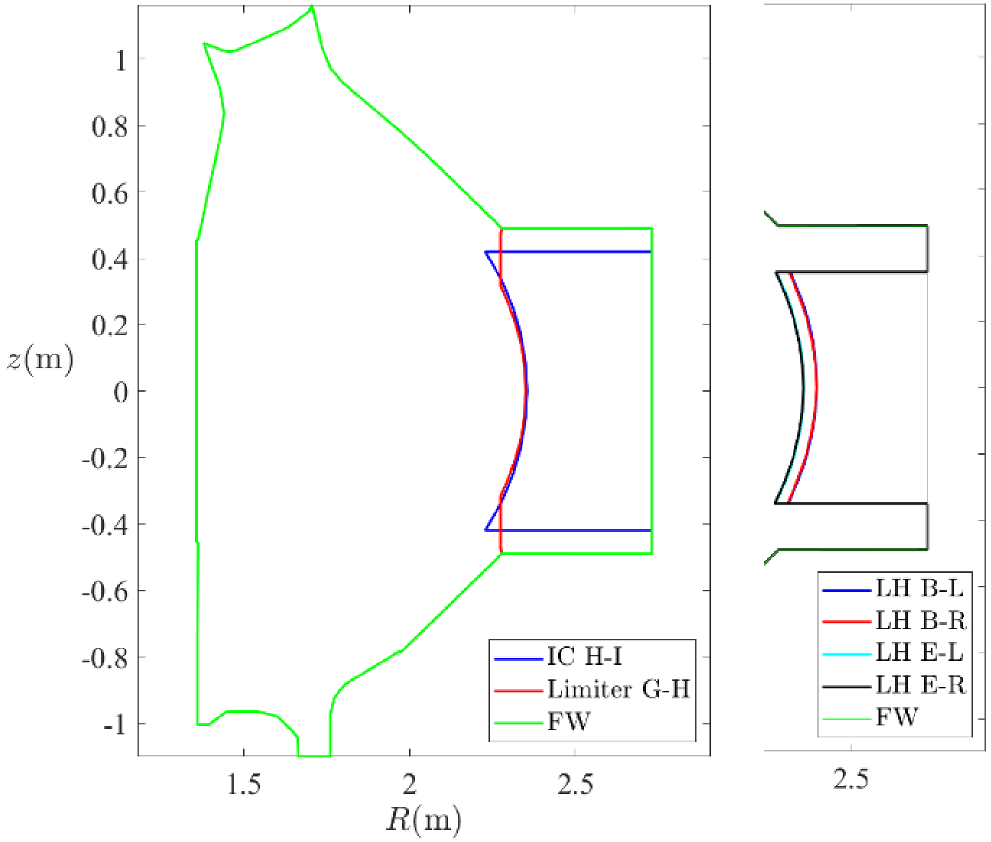
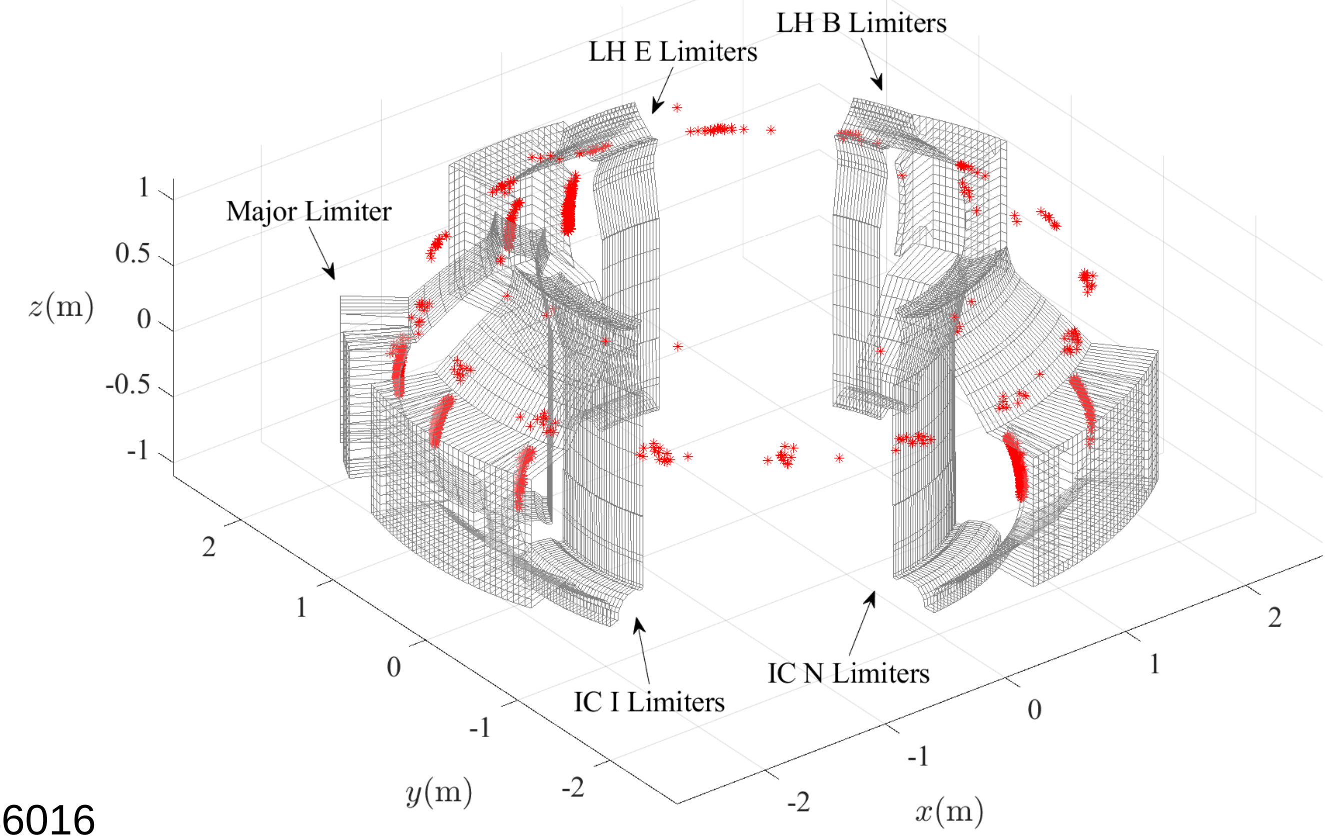
ISSDE simulations with 3D first wall

First wall in poloidal cross-sections with different types of limiters



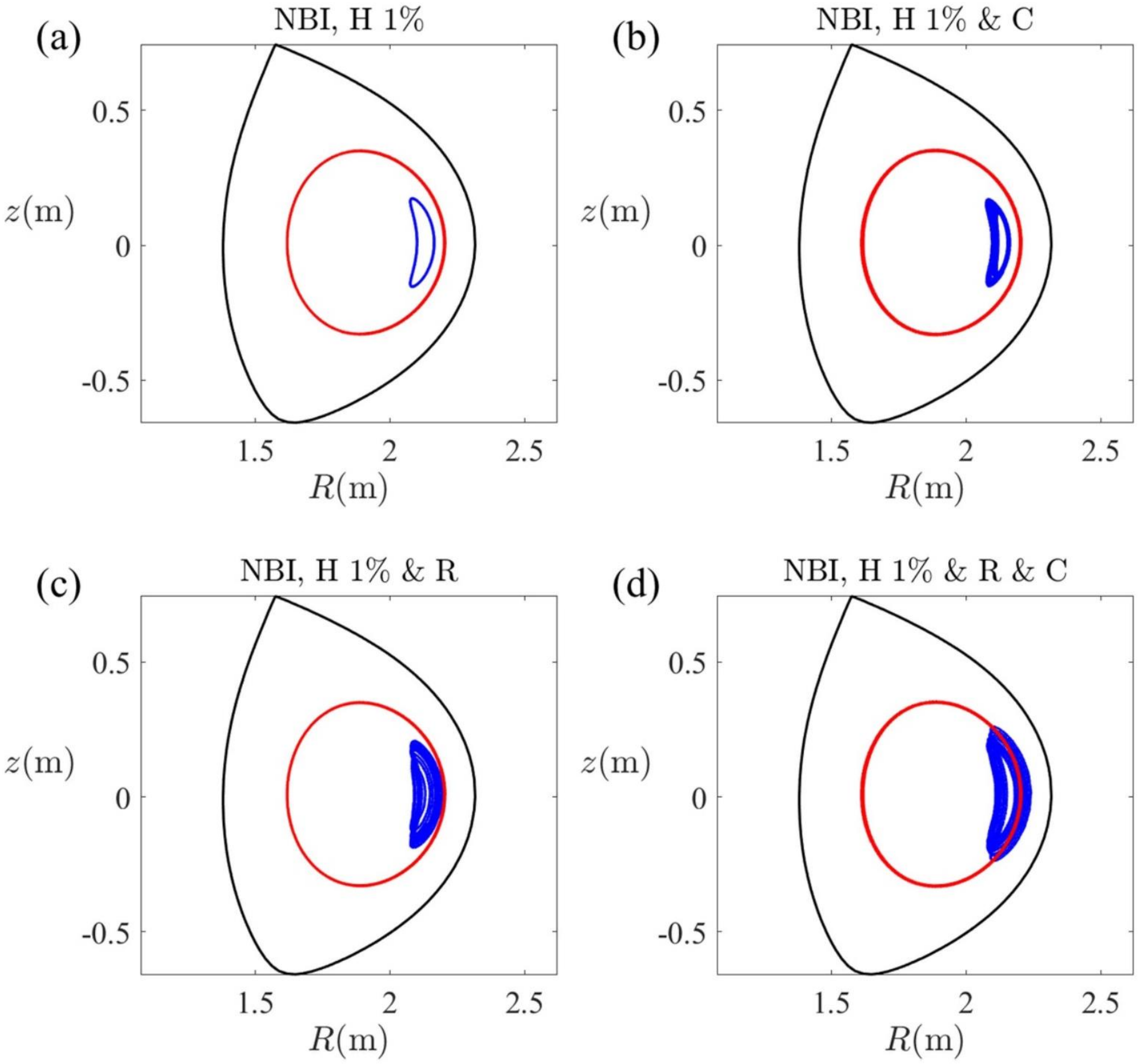
- ☐ Deuterium fast ions calculated by TRANSP are used as inputs in ISSDE
- ☐ All 3D plasma facing components are included
- ☐ Loss mechanism: direct orbit loss, Ripple, Collisions



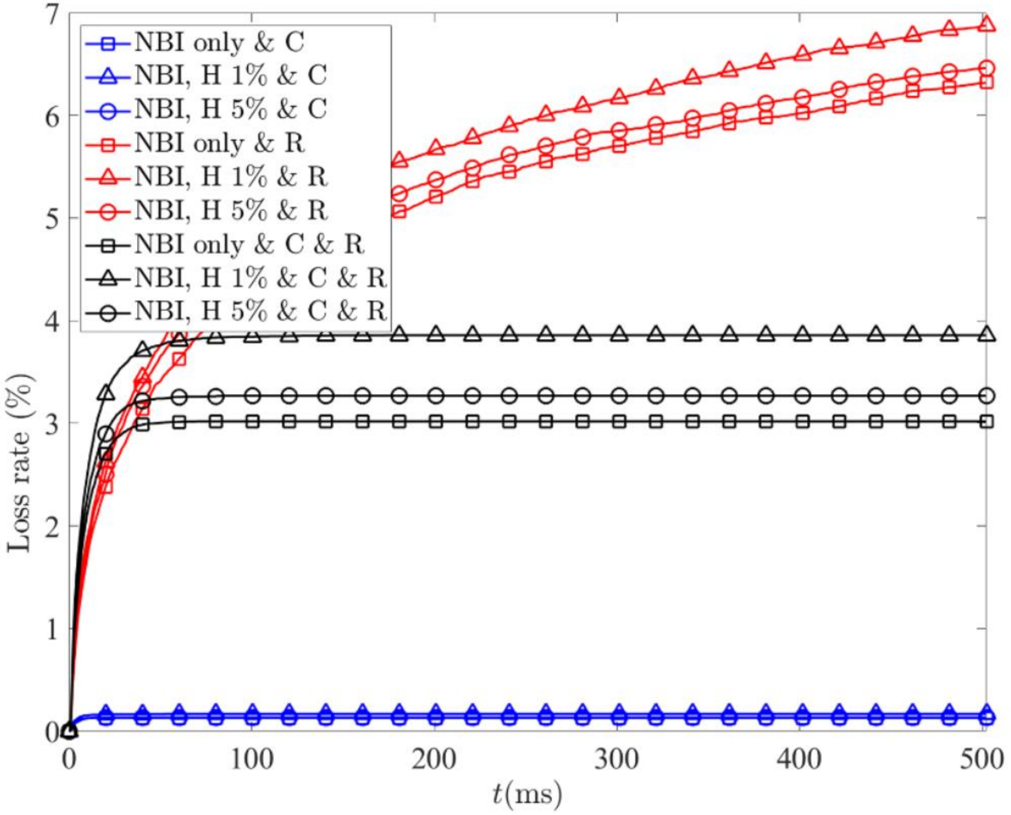
Y.F. Zheng, W. Zhang* et al, 2023 Nuclear Fusion 63 046016

Fast ion orbit and loss

C: Collision R: Ripple



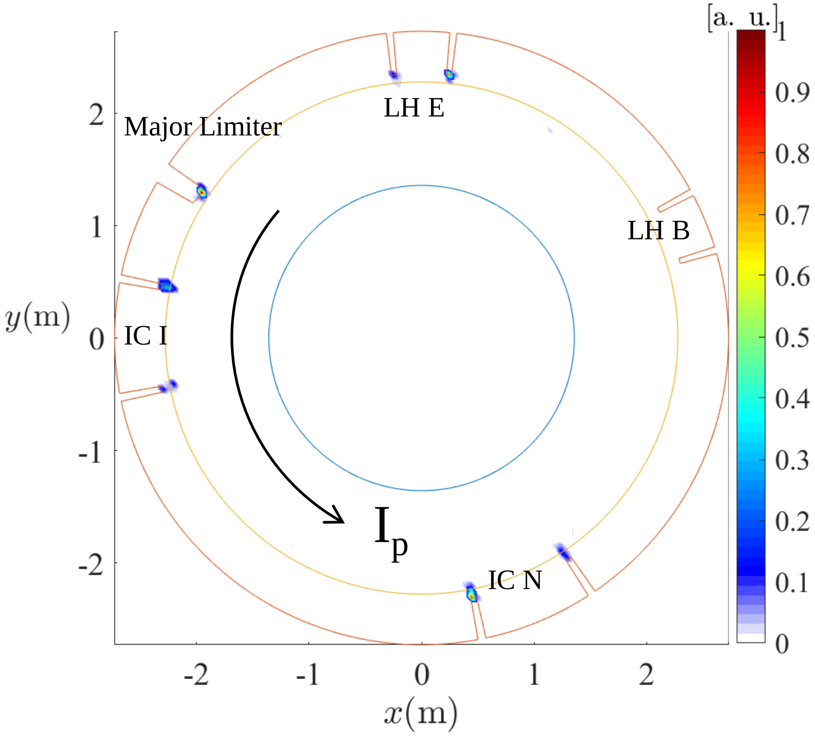
- The NBI+ICRF(1% H) generates most fast ions, but also has the largest losses

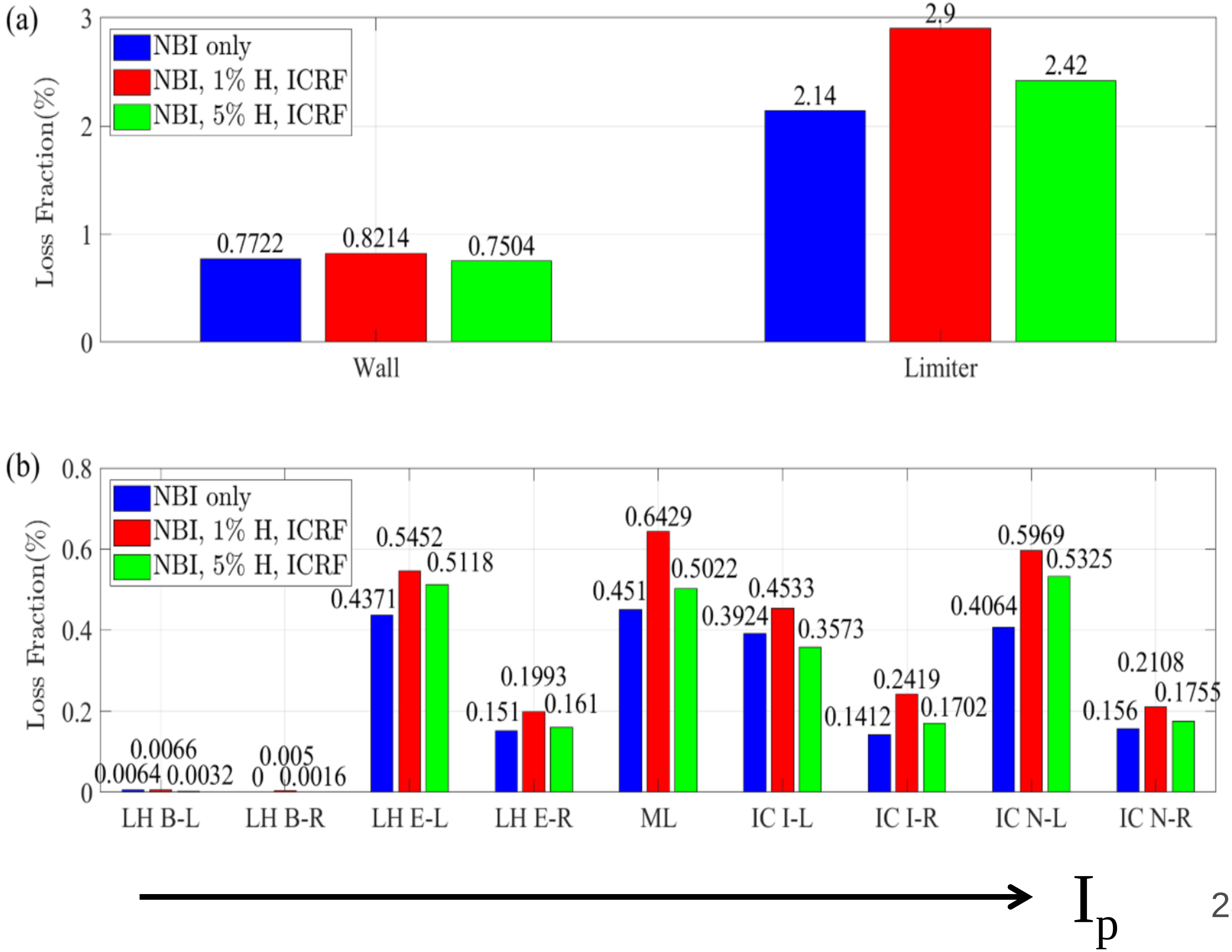


Fast ion loss on limiters

- ☐ Most fast D ions are lost on the limiters
- ☐ Different radial positions of the limiters → different fast ion lost fraction
- ☐ The NBI+ICRF(1% H) generates most fast ions, but also has the largest losses

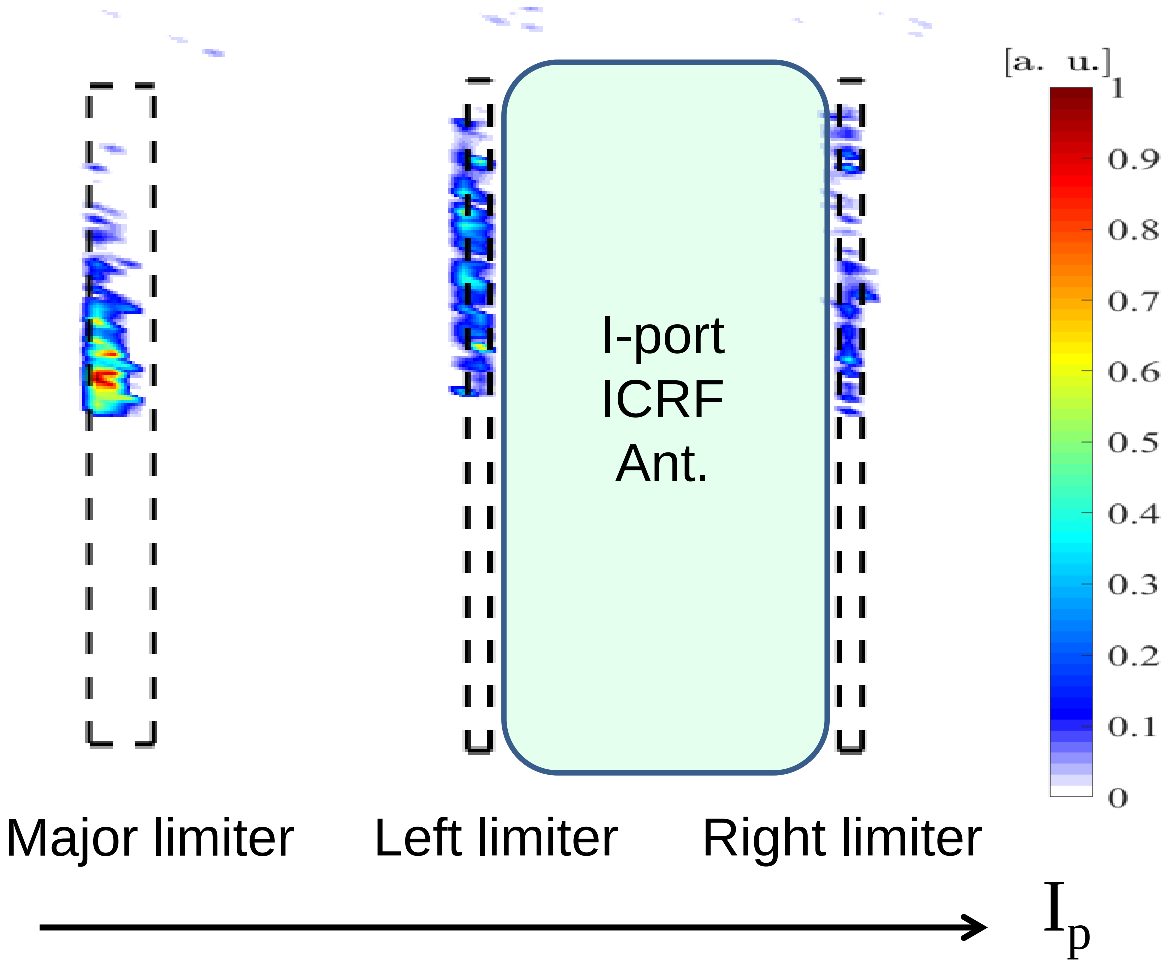
Power deposition in the midplane wall



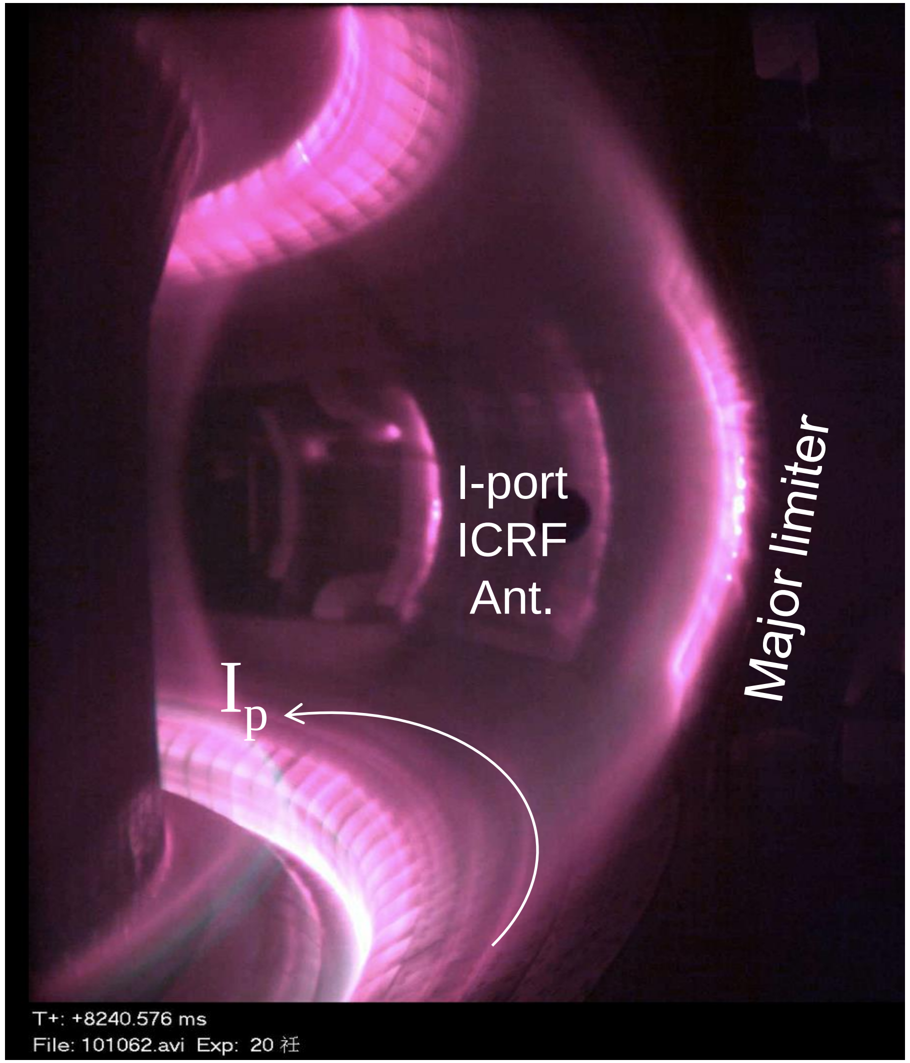


Power deposition on limiters

- The simulated power deposition appears to be in agreement with experiments
- More quantitative simulations are needed



EAST experimental results

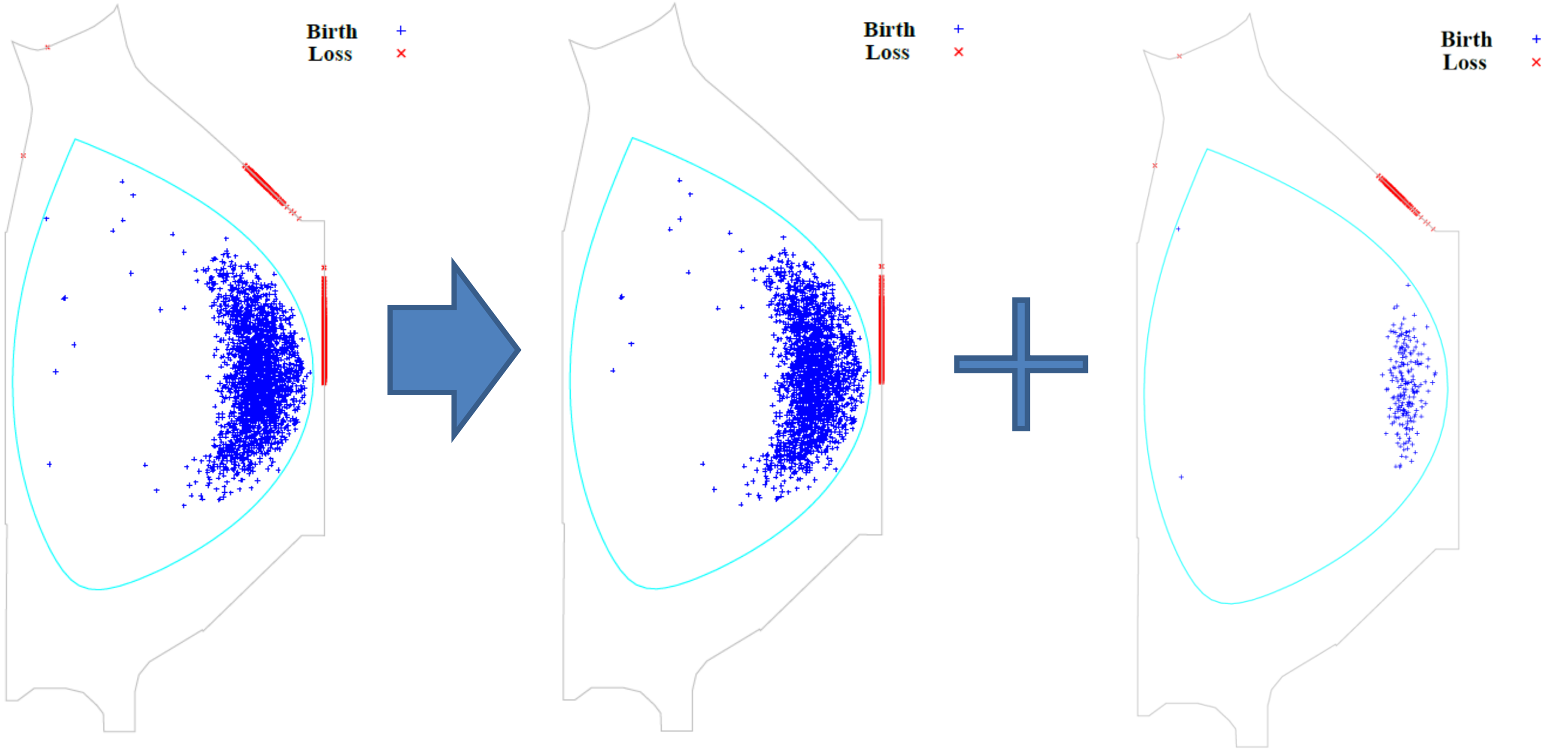


Orbital type of lost fast ions

3D ISSDE and 2D SOFT simulations are in agreement. They indicate:

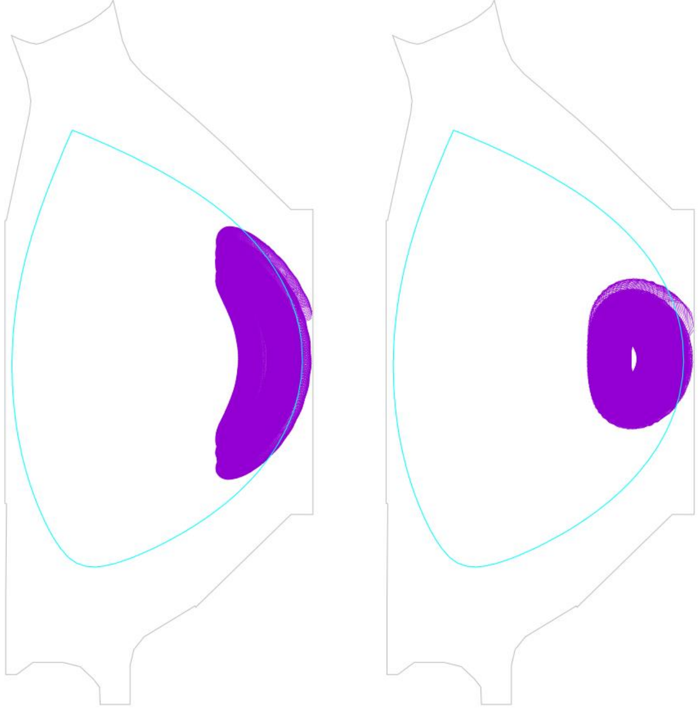
- Fast D ions mainly lost on the midplane wall
- Lost ions are mainly trapped orbits, initially on the low field side
- Fast ions with large energy are lost more easily

SOFT code: K.Y. He et al, 2021
Nuclear Fusion 61 016009



E=50keV
v/v||=0.28

E=500keV
v/v||=0.28



Outline

ASIPP

- Introduction
- ICRF-NBI synergy experiments and simulations
- Fast ion distribution and its parametric dependence
- Fast ion transport and lost on first wall
- Conclusions and outlook

Conclusions

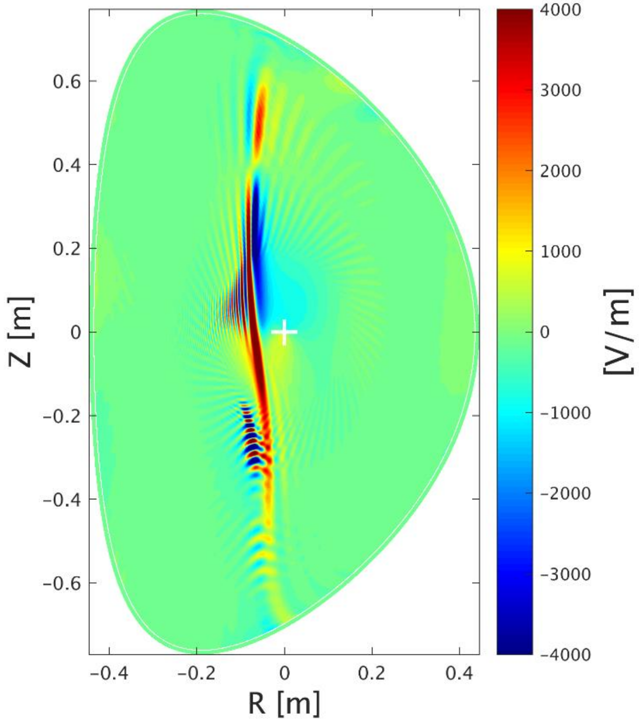
- TRANSP simulations are in qualitative/quantitative agreement with the experiments
- ICRF-NBI synergy significantly increases the number of fast neutrons (by a factor of 2) and fast neutron tail with energy >3 MeV
- ICRF-NBI synergy increases NBI fast ions from ~60keV to 300-600keV, depending on n(H) and P_{ICRF}
- The ICRF-NBI synergy and fast ion tail can be enhanced by optimizing the minority ion concentration, harmonic resonance position, ICRF/NBI power and NBI injection angle
- The fast ions mainly lost on the midplane of the limiters/first wall. The dominant lost fast ions are trapped orbits, and their initial positions are on the low field side

Outlook

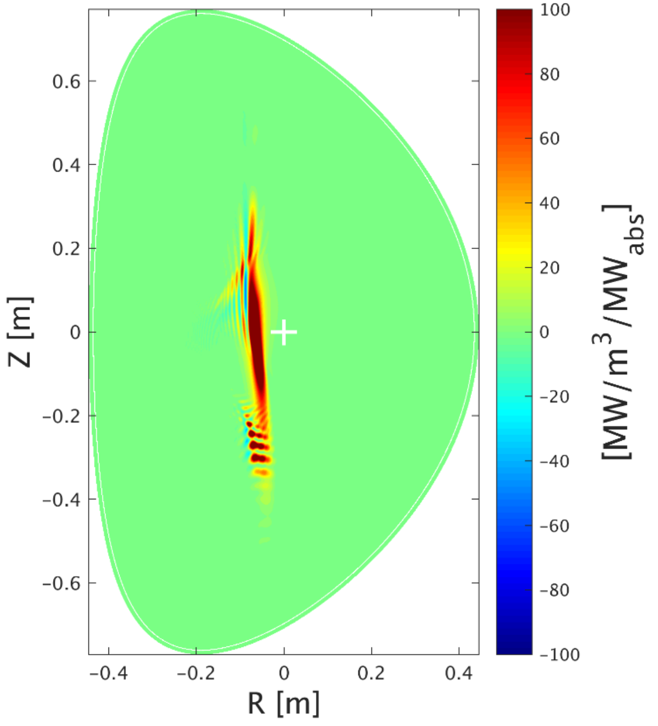
☐ ICRF-NBI synergy with D-(DNBI)-He3 and D-(3He)-H planned on EAST:
- in cooperation with Y. Kazakov and J. Ongena (KMS-ERM)

Preliminary TORIC simulations for D-(DNBI)-He3 with B_t=3.0T and f=27MHz:

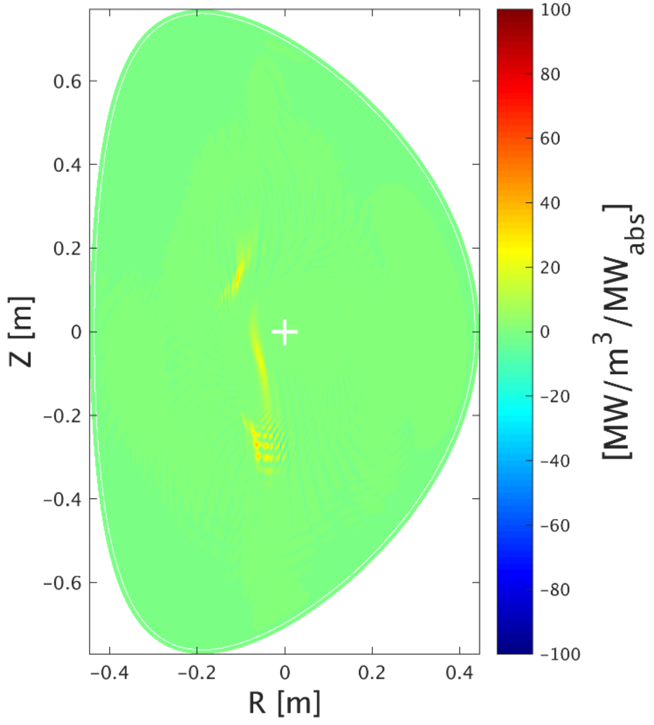
Re(E+)



Third ion DNBI



Electrons



Power absorption: 76.06 % 18.20 %

Outlook

- We have manufactured ICRF antennas for ASDEX-U, WEST, DIII-D
- Now building RF generators for AUG, RF windows for ITER
- Looking forward for cooperations on :

  - Energetic particle physics

  - ICRF physics and engineering
- Please contact me and visit ASIPP

  email: wei.zhang@ipp.ac.cn

ASDEX-U ICRF antenna