Recent progress in ICRF experiments on EAST

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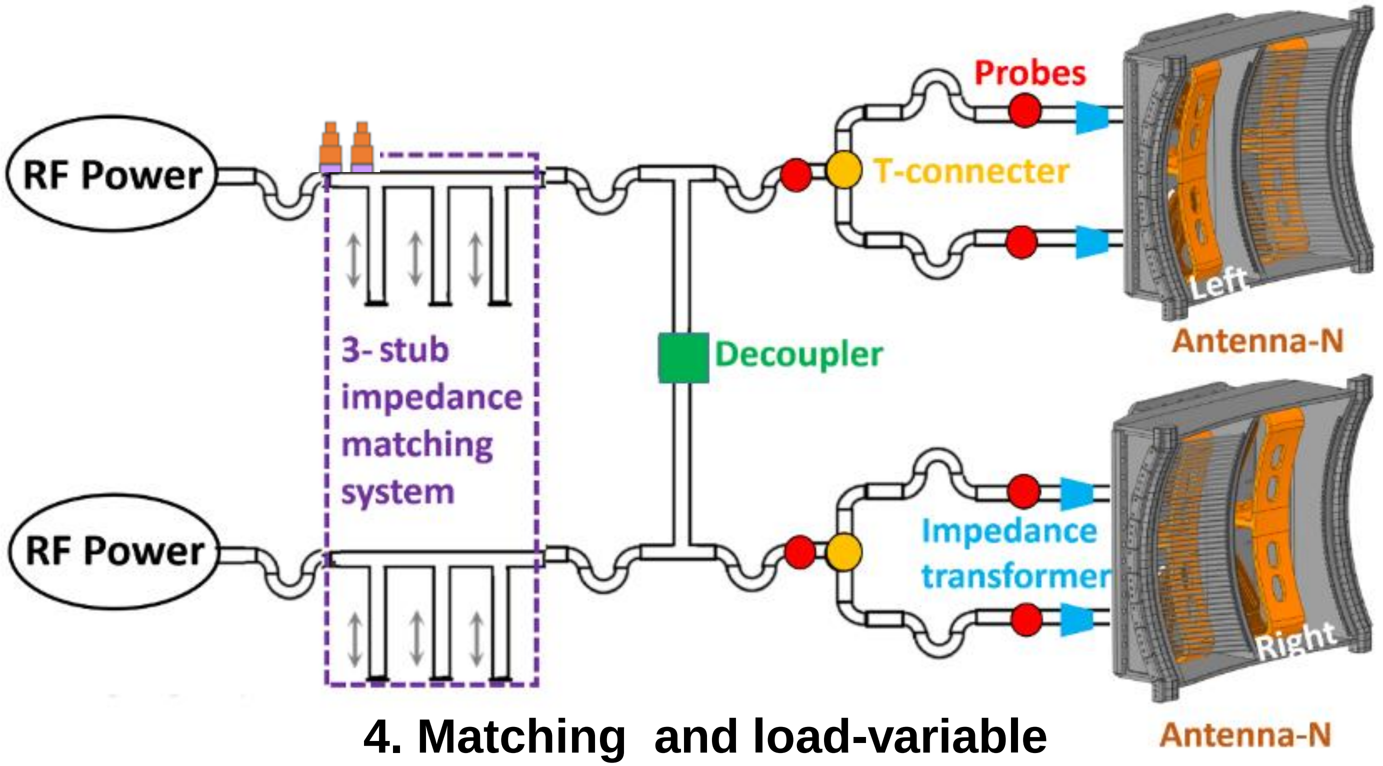
Institute of plasma physics, Chinese Academy of Sciences (ASIPP)

Outline

- **Upgrades of EAST-ICRF system**
- **Increase of ICRF coupling and absorption**
- **ICRF experiments for multi-physics studies**

EAST-ICRF system

1. Better coupling
2. Spectrum control
3. Water cooling
4. Fast impedance matching and load-variation tolerance transmission system



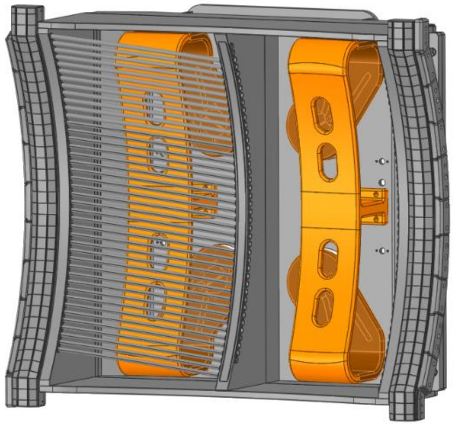
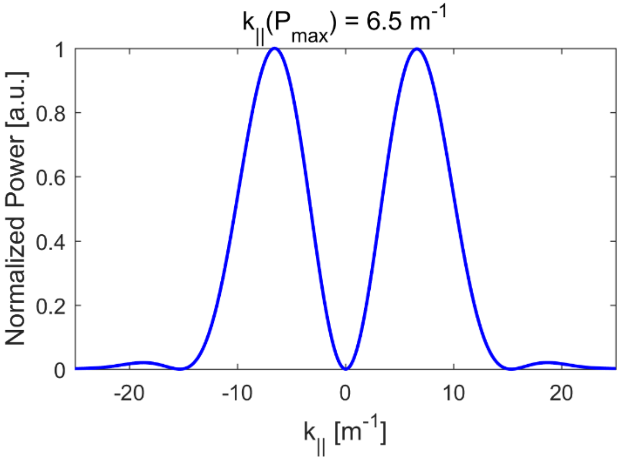
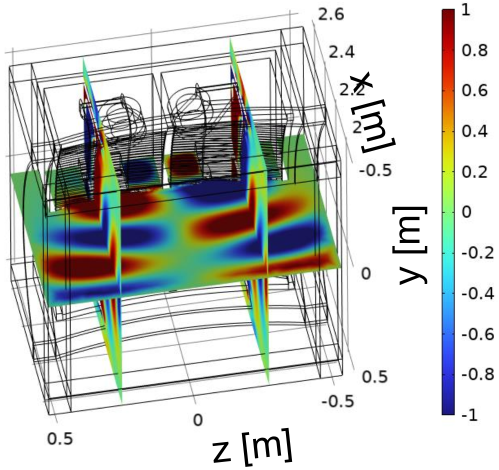
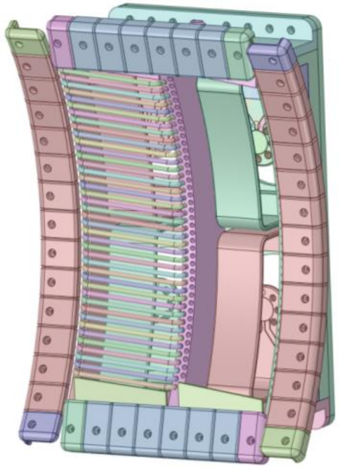
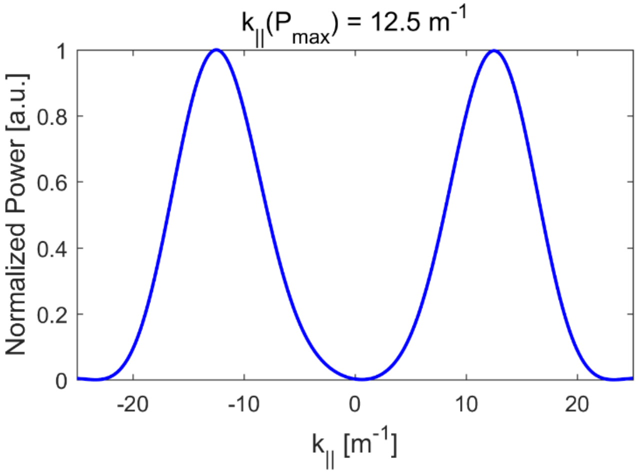
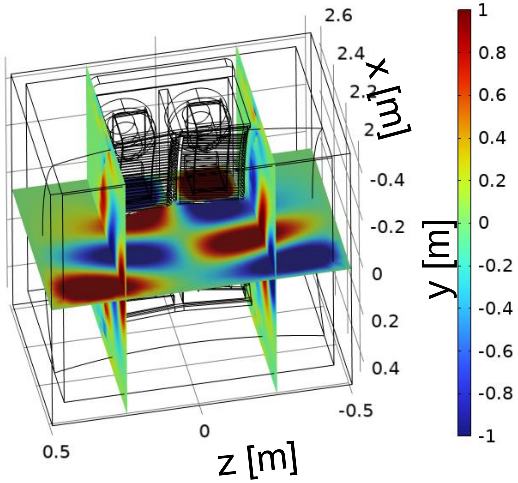
1. ICRF antenna with low $k_{//}$

2. Water cooling of limiter and Faraday screen

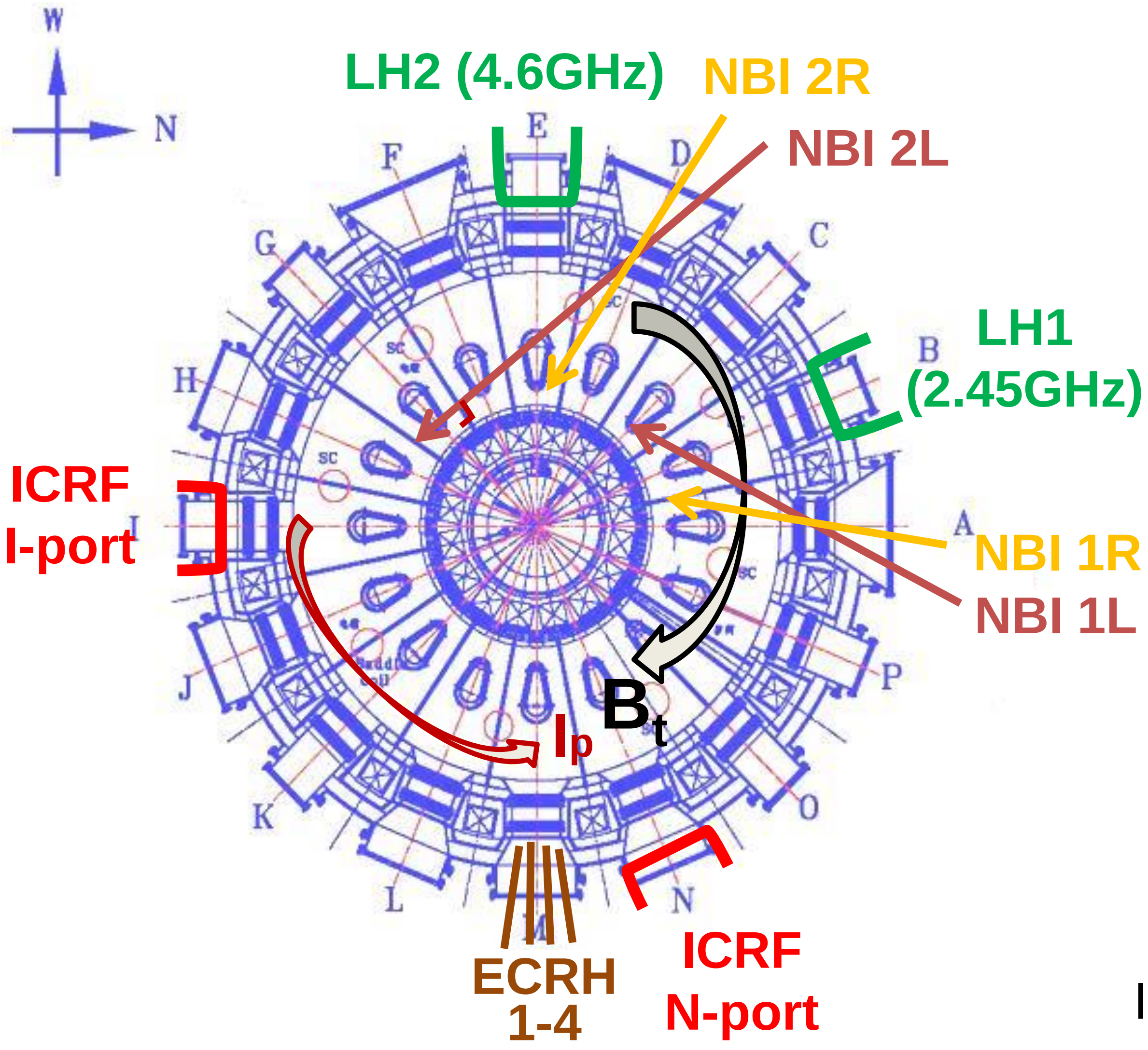
3. Antenna phasing measurement and control

4. Matching and load-variable tolerance transmission system

New 2-strap antennas

	Ant. structure	Power spectrum	E_y [v/m]
New 2-strap antenna			
Old 2-strap antenna			

New 2-strap antennas



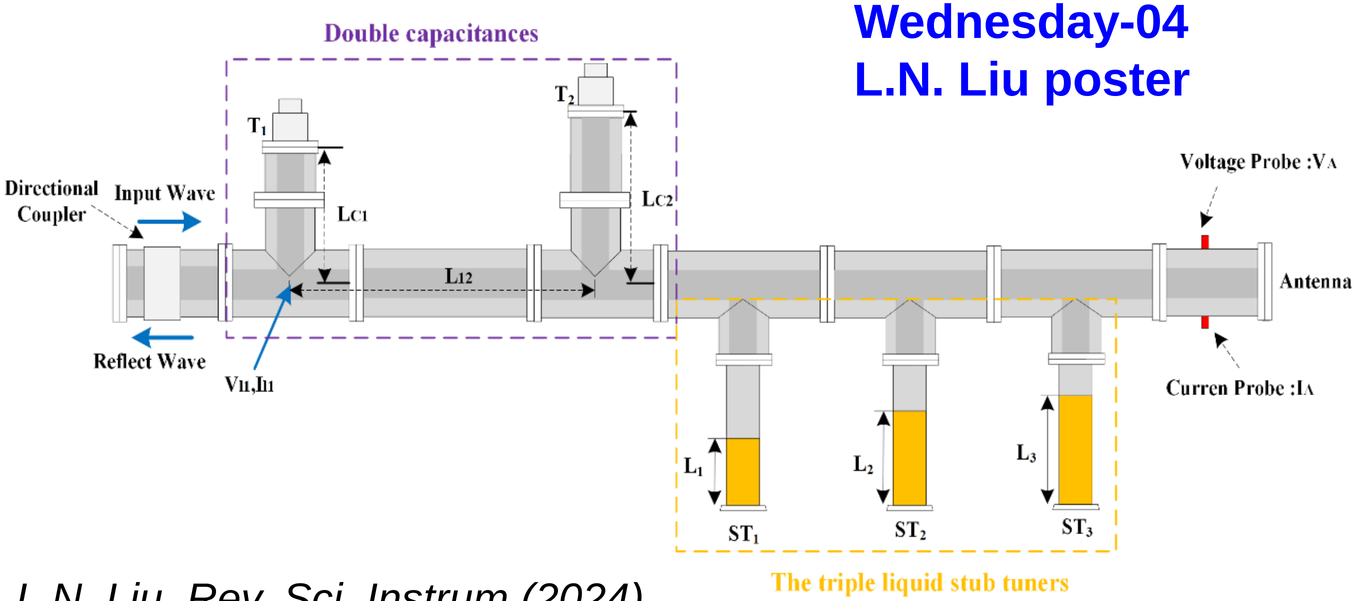
2MW per ICRF-antenna

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

Real-time matching

Real-time impedance matching of ICRF system:

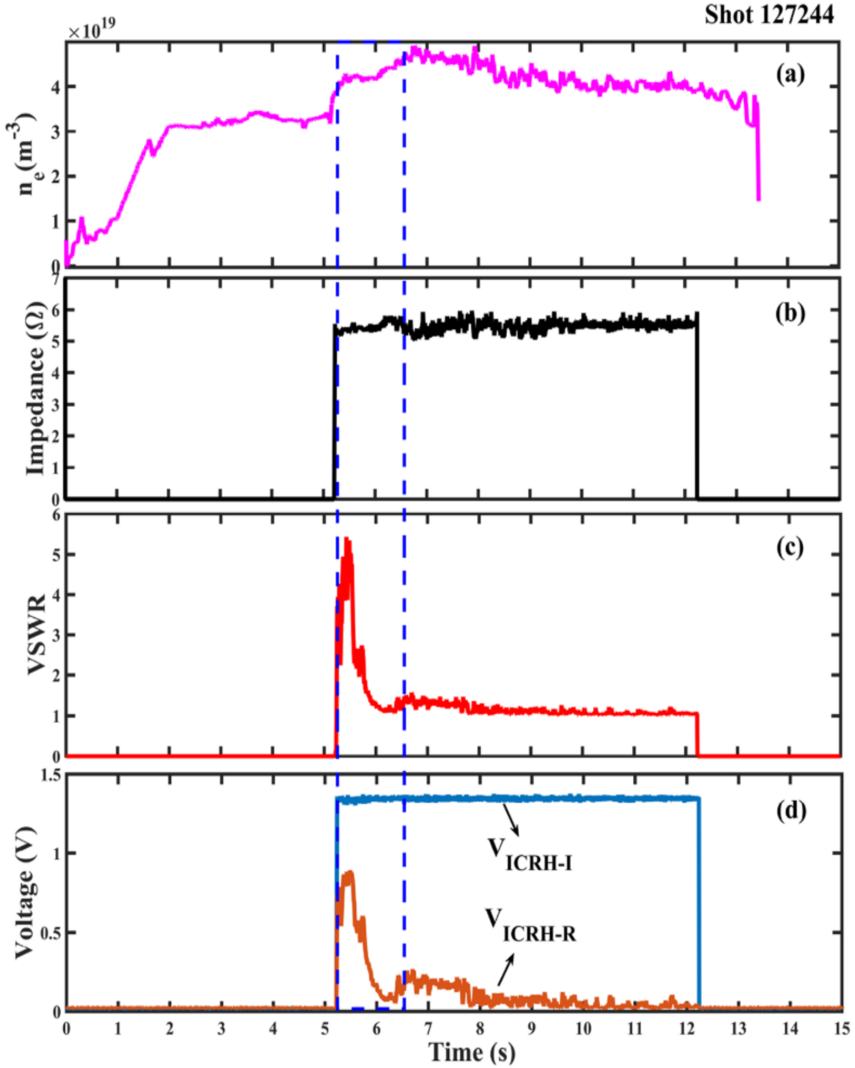
- Impedance measurement, motor controlling;
- Both vacuum and plasma situation
- matching achieved within 1 second;



Wednesday-04
L.N. Liu poster

L.N. Liu, Rev. Sci. Instrum (2024)

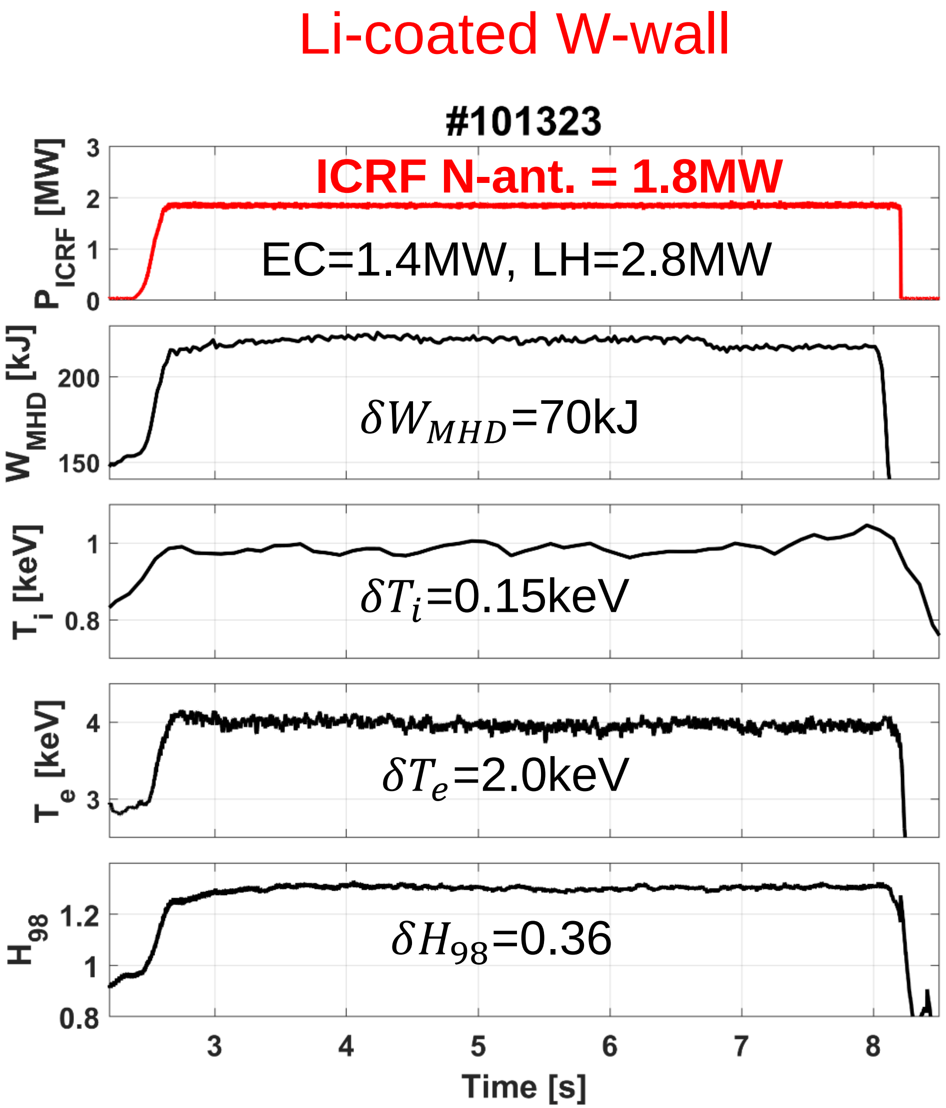
Example

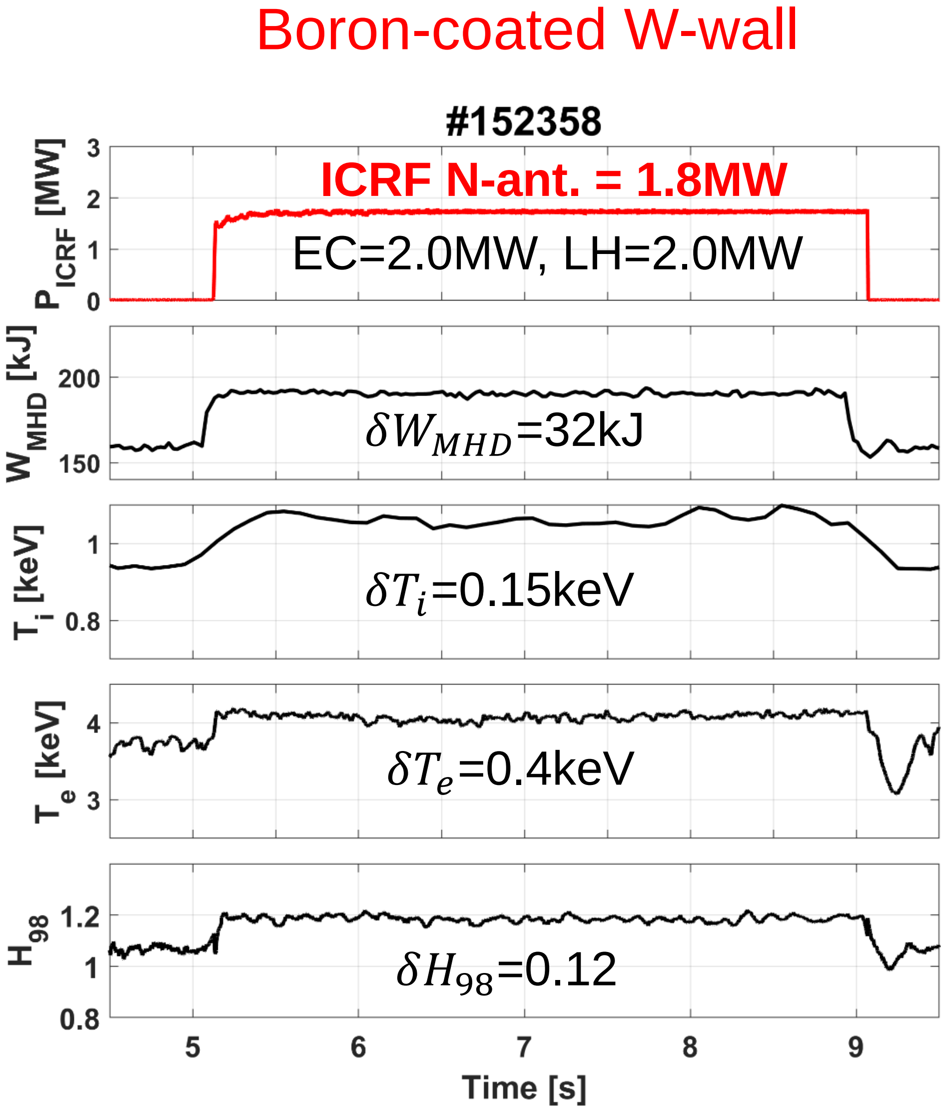


ICRF heating with Li/Boron-coated wall

Same B_t, I_p, n_e, q_{95}

Wednesday-14
H. Yang Poster





Diagnostics near antenna

Strap current probes
→ ICRF phasing

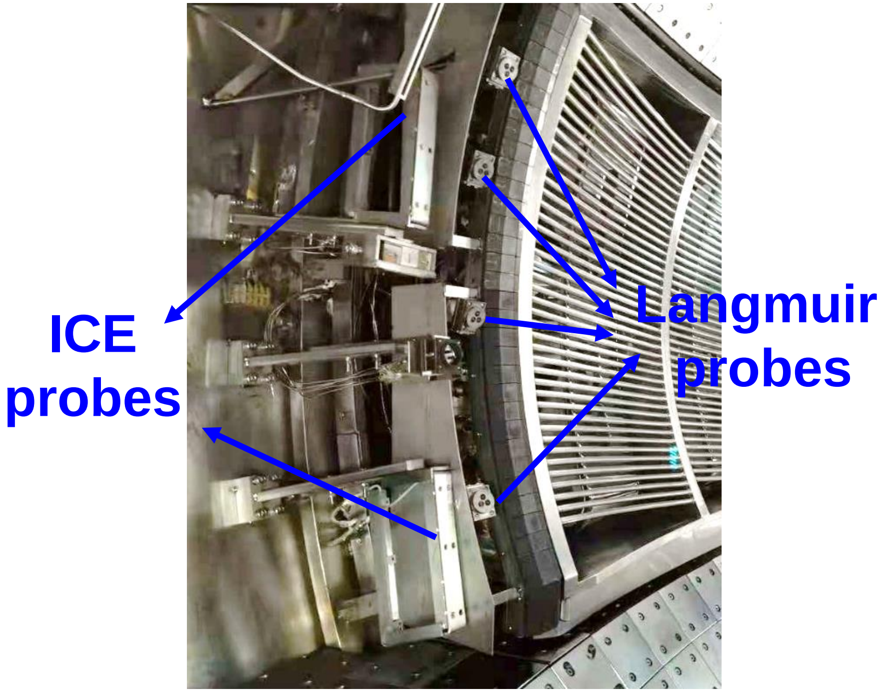
Transmission voltage probes
→ ICRF coupling

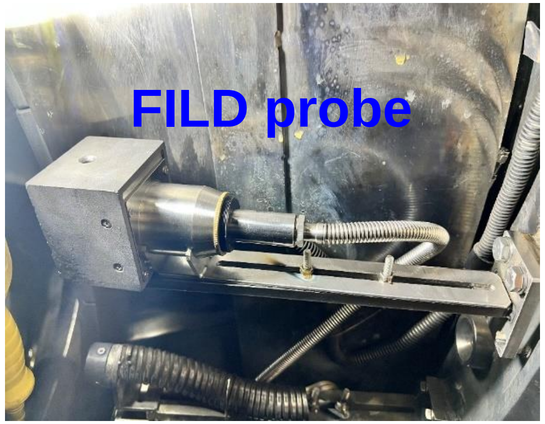
Langmuir probes
→ n_e in front of antenna

Magnetic probe array
→ ICE instabilities

FILD probe
→ Fast ion lost near antenna

Doppler backscattering system
→ Core/edge turbulence





Outline

- Upgrades of EAST-ICRF system
- **Increase of ICRF coupling and absorption**
- ICRF experiments for multi-physics studies

ICRF coupling: decrease $k_{||}$

Coupling improved by decreasing antenna $k_{||}$

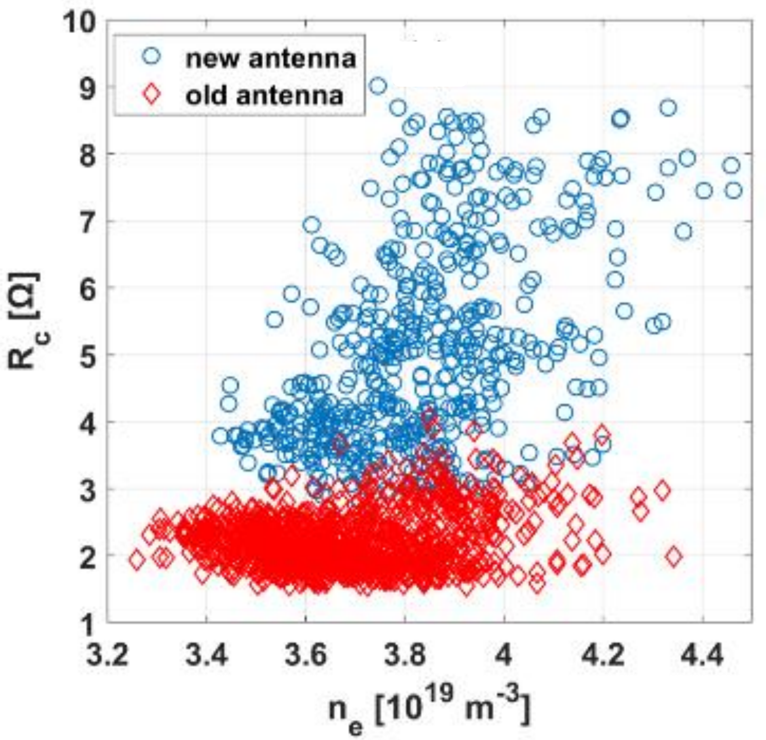
New 2-strap antenna with low-$\boldsymbol{k_{||}}$:

→ increases strap-distance from 0.225 m to 0.425 m

→ decreases $k_{||}$ from 13-14 m^{-1} to 7.5 m^{-1}

→ decreases cut-off density from 8× 10^{18} m^{-3} to 2.8× 10^{18} m^{-3}

→ increases coupling resistance by a factor of 2



ICRF coupling: strike-point optimization

ASIPP

Coupling improved by decreasing d_{evan}

- **New method**:

Shifting striking point to increase coupling

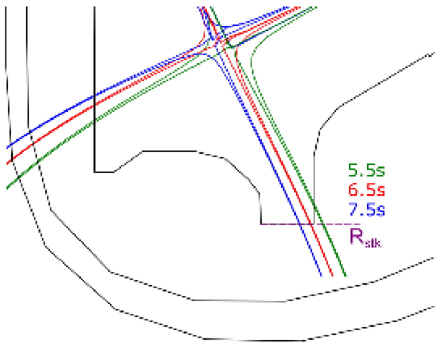
- **Mechanism:**

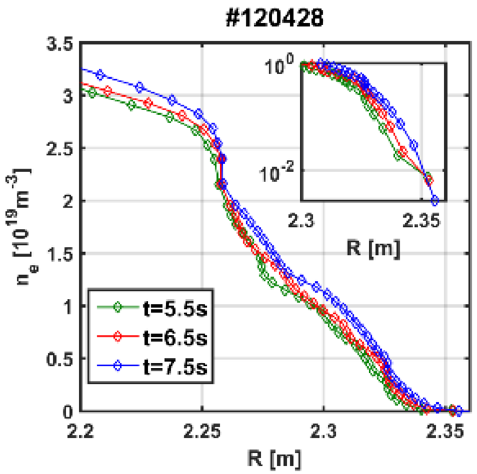
Interplay between divertor closure and drifts

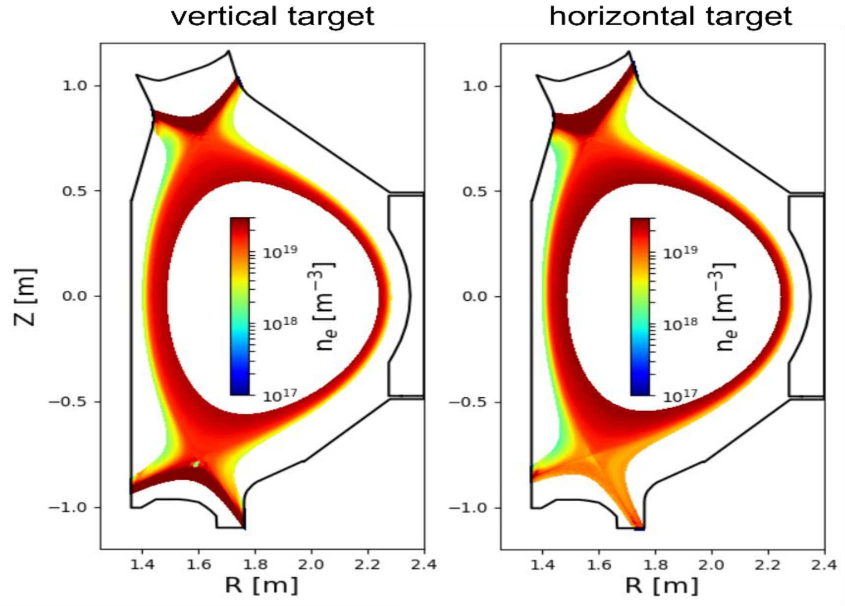
→ More particles trapped between separatrix and vertical divertor wall

→ Divertor recycling increase

→ SOL density increase





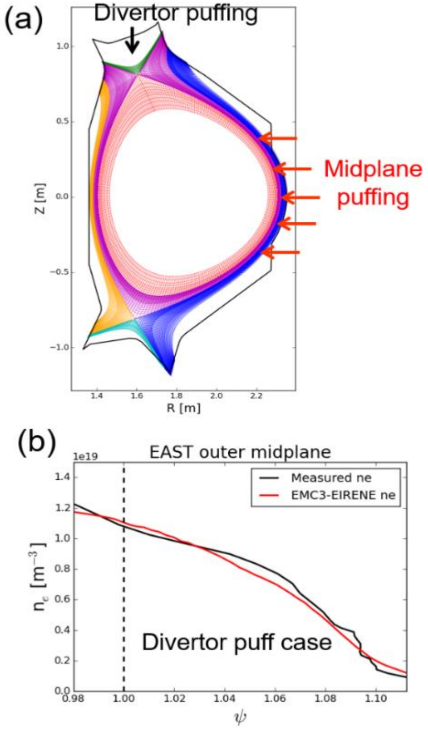


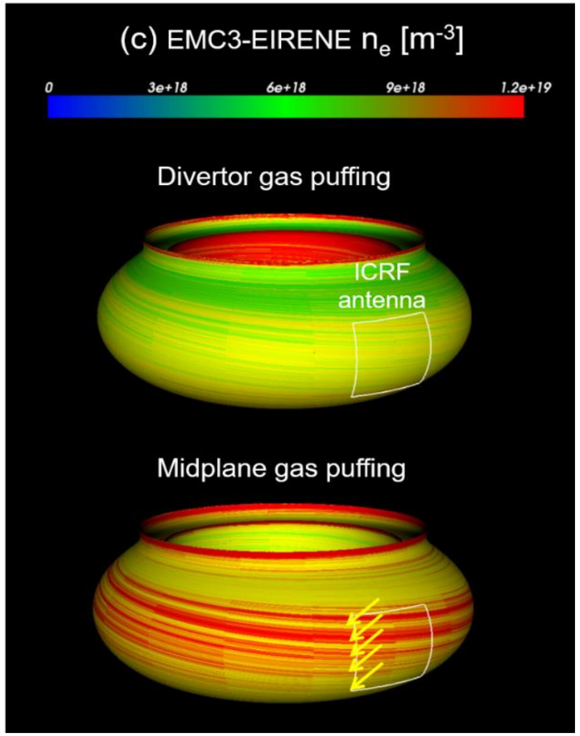
ICRF coupling: local gas puffing

Coupling improved by decreasing d_{evan}

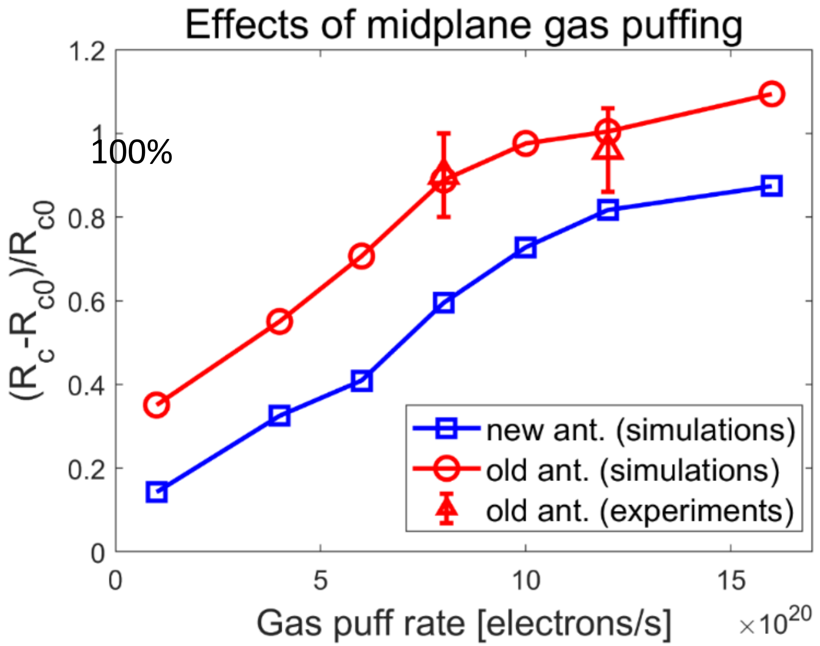
- Coupling resistance increased by midplane local gas puffing (~12e22 el/s) by a factor of 2
- EMC3-EIRENE + RAPLICASOL simulation results in good agreement with experiments

3D SOL density simulation





Coupling resistance



ICRF coupling: other methods

Coupling improved by decreasing $\boldsymbol{d_{evan}}$

(a) Decrease SOL width

(δR_c ~ 34%)

(b) Increase core density

(δR_c ~ 44%)

(c) Change strike point position

(δR_c ~ 70%)

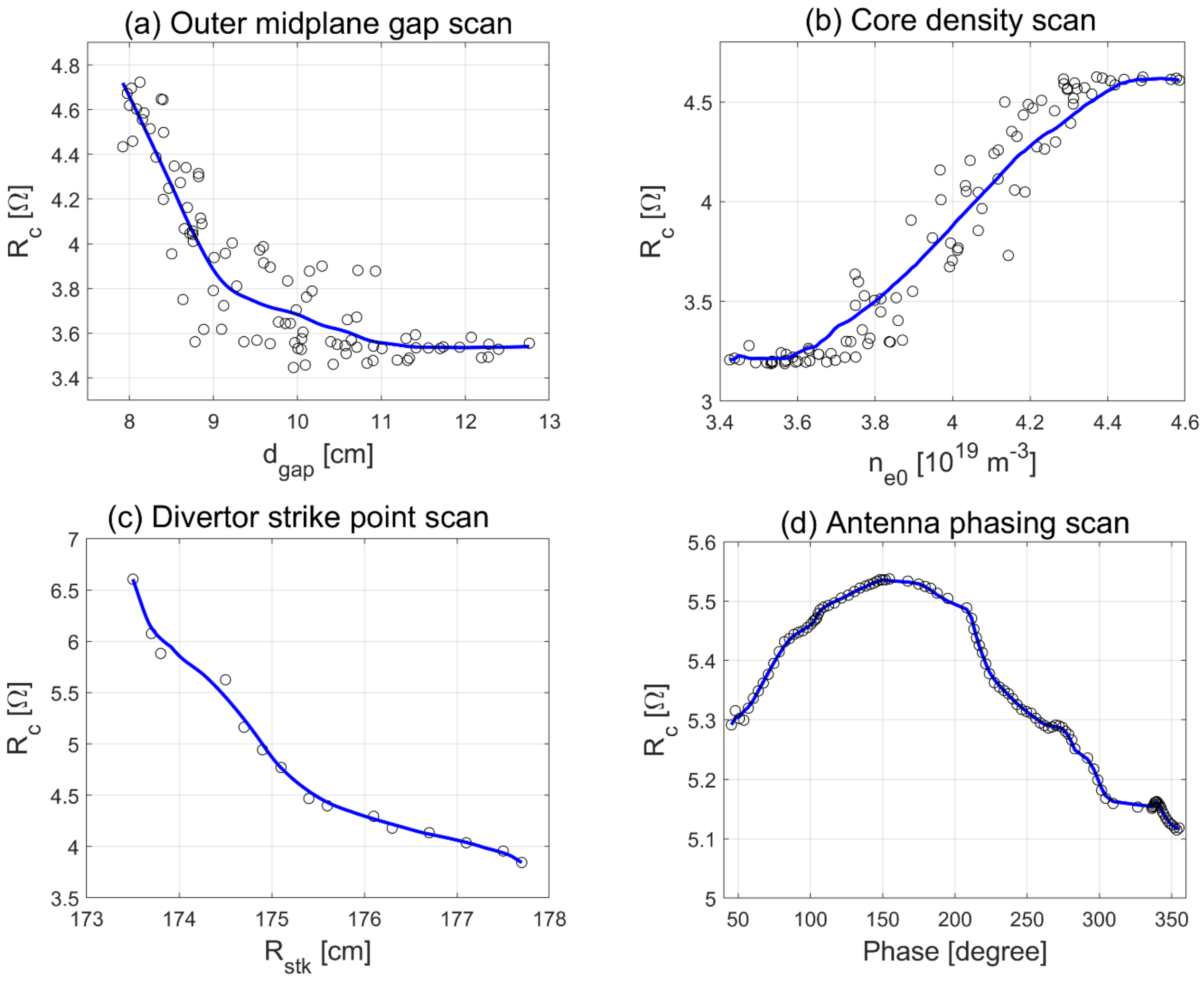
(d) Optimize antenna phasing

(δR_c ~ 10%)

W. Zhang, Nuclear Fusion (2024)

Relative increase of coupling resistance:

$$\delta R_c = (R_c - R_{c0})/R_{c0}$$

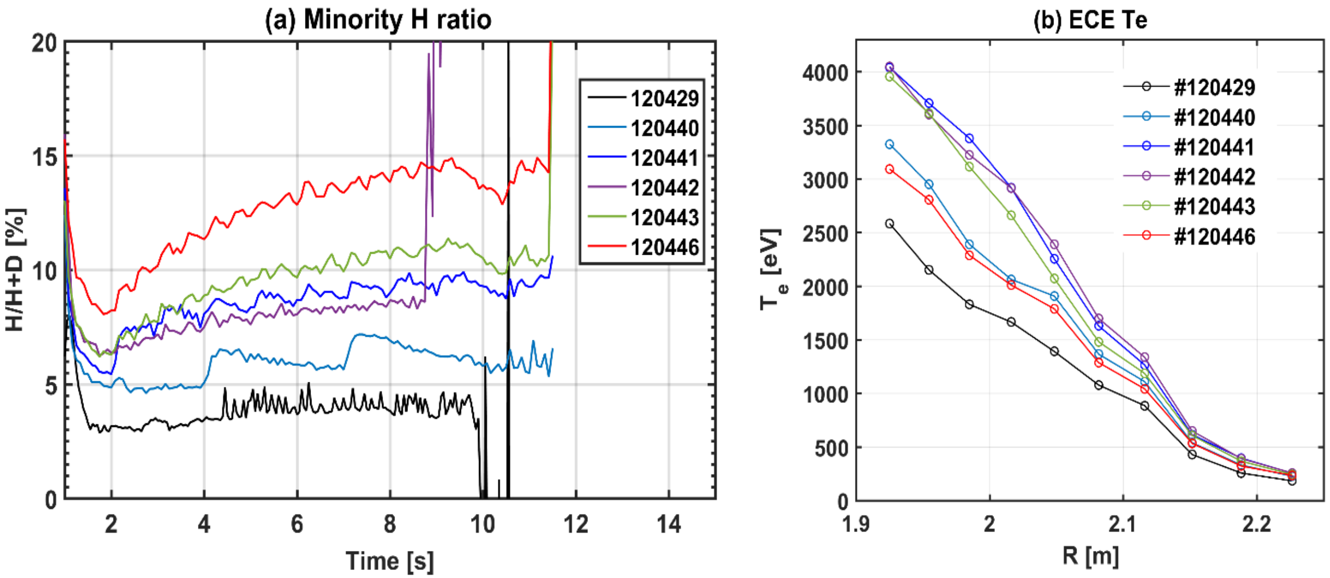


D(H) minority: B_t and X(H) optimization

Good ICRF absorption when

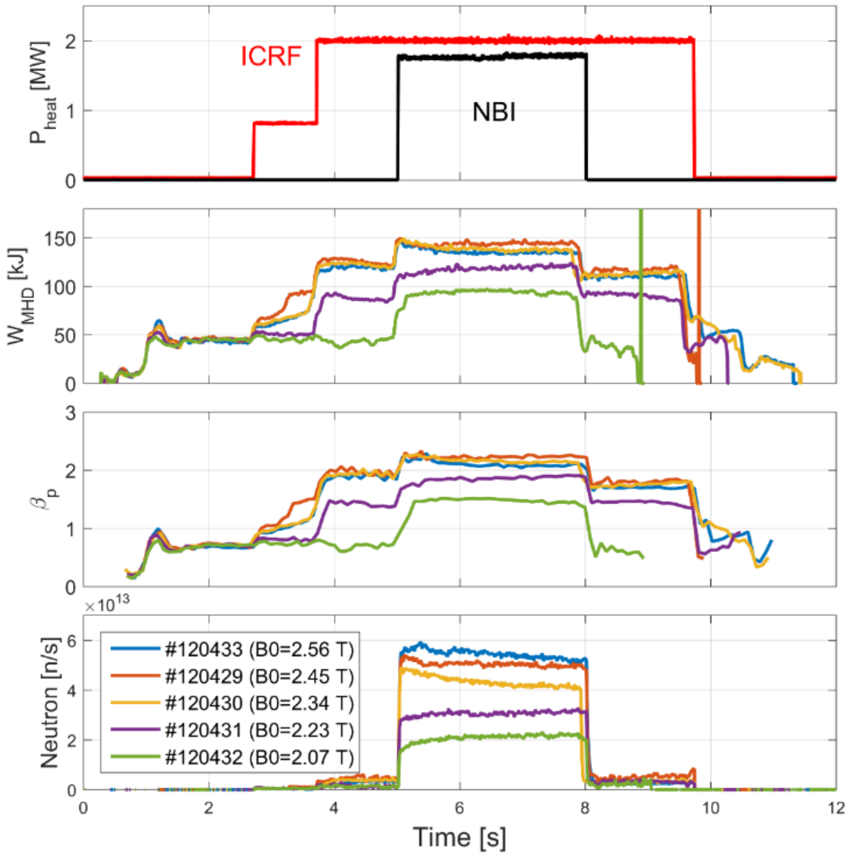
- **core** X(H)=5%-10% and **edge** X(H)~10%
- B_t=2.45-2.50T (on-axis heating)

- X(H) scan

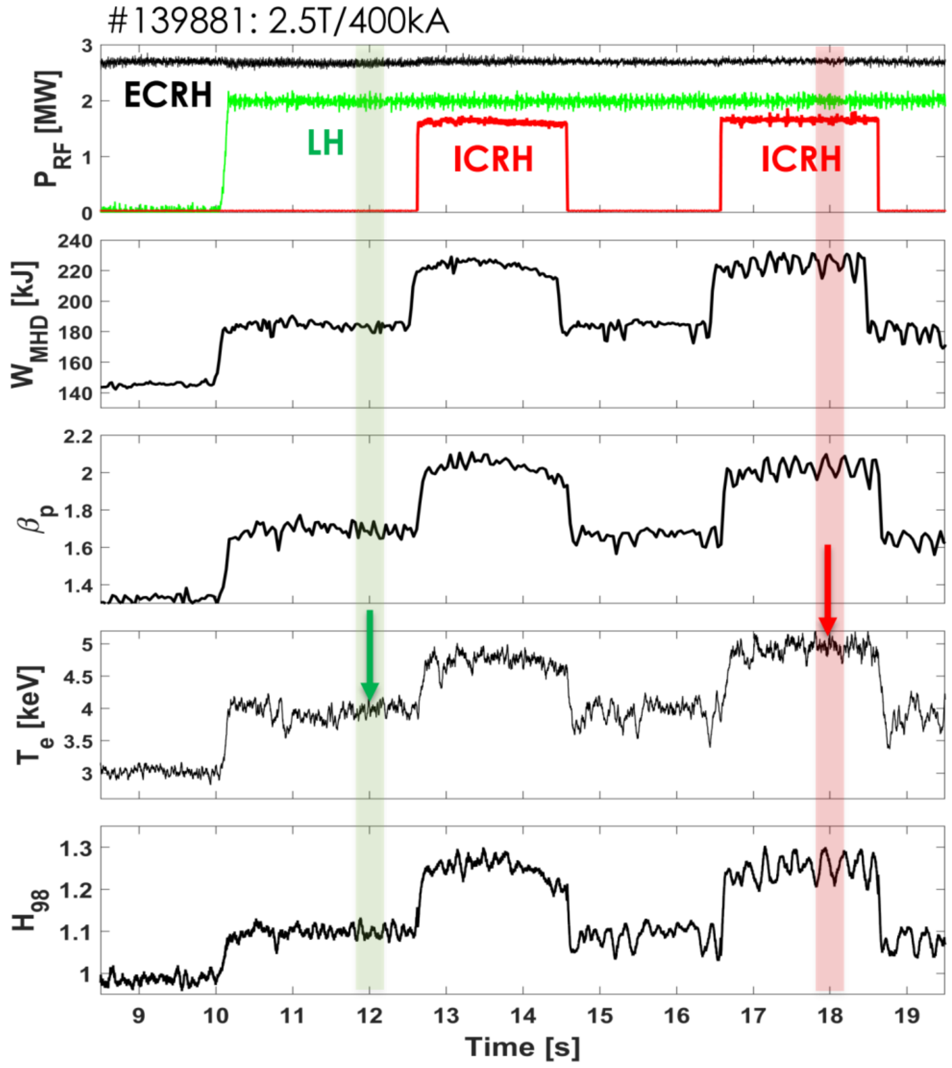


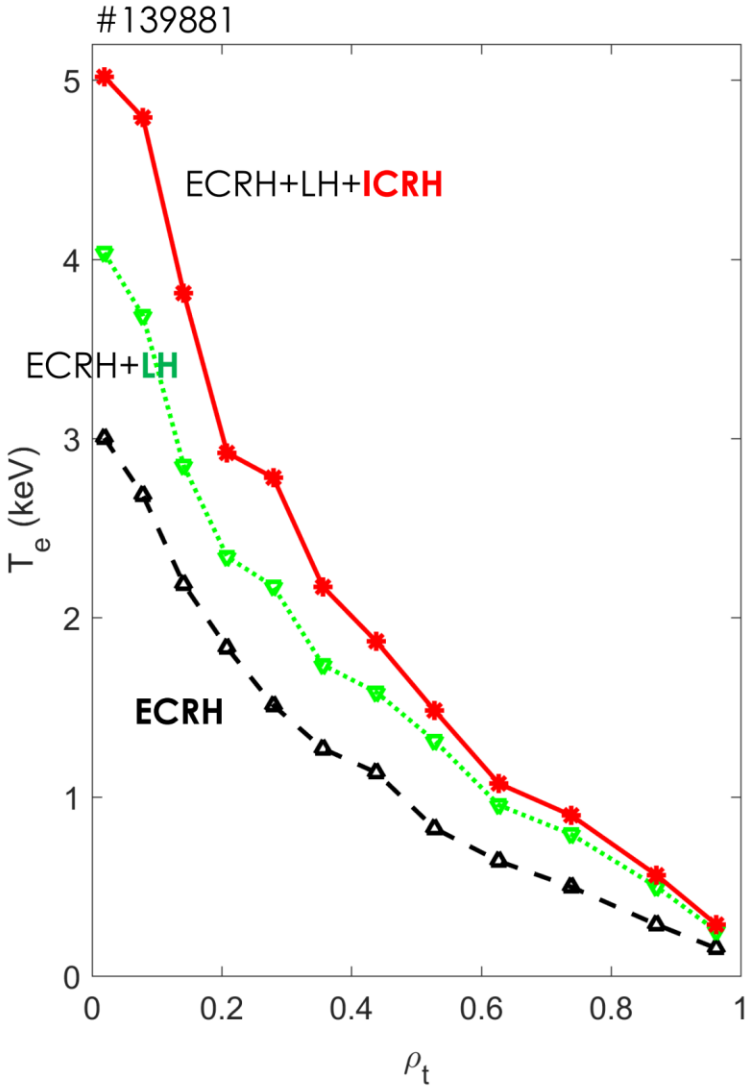
- B_t scan

B_t > 2.45T: low-field side
B_t = 2.45T: on-axis heating
B_t < 2.45T: high-field side



D(H) minority heating: ITER-relevant scenario





Heating mix	T_{e0} (keV)
ECRH	~3.0keV
ECRH + LH	~4.0keV
ECRH + LH + ICRH	~5.0keV

- Work with Y. Kazakov and J. Ongena

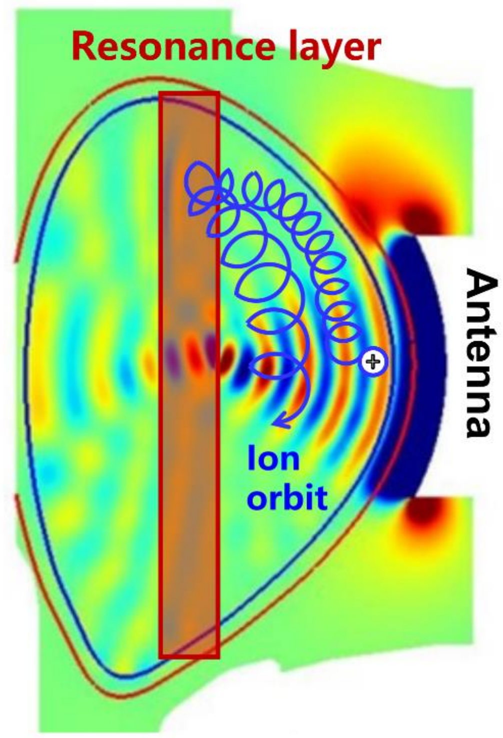
ICRF-NBI synergetic heating

ICRF-NBI synergetic heating

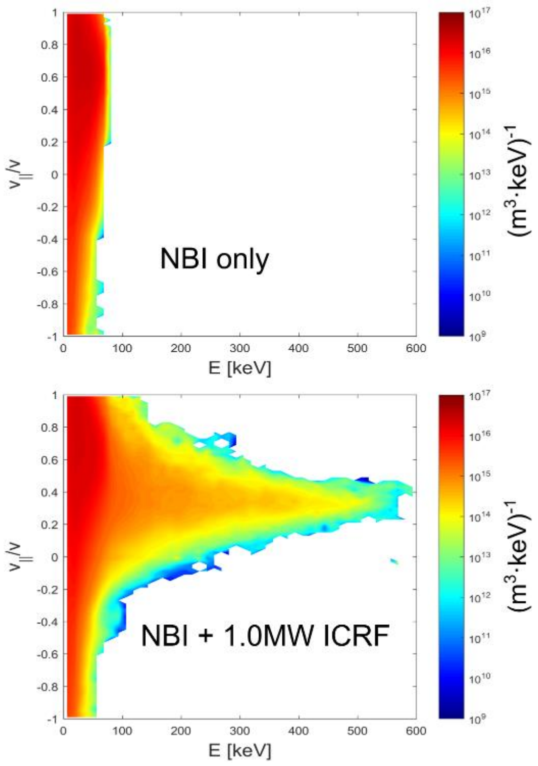
1.5 MW ICRF + 2.8 MW NBI synergetic heating increases:

- β_p ~36%, W_{MHD} ~35%, T_i ~20%, Y_n ~100%
- Tail of fast ion distribution

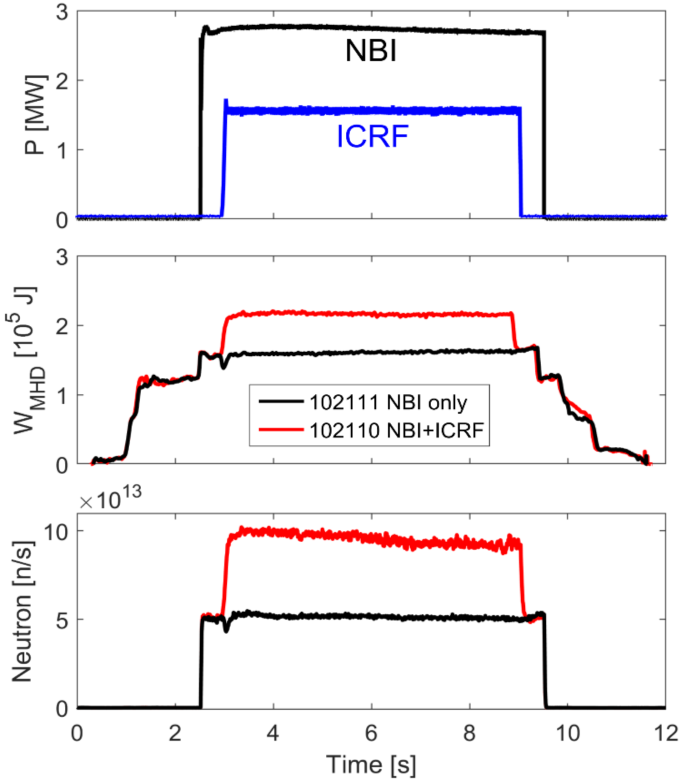
(a) Resonance heating



(b) Fast ion distribution

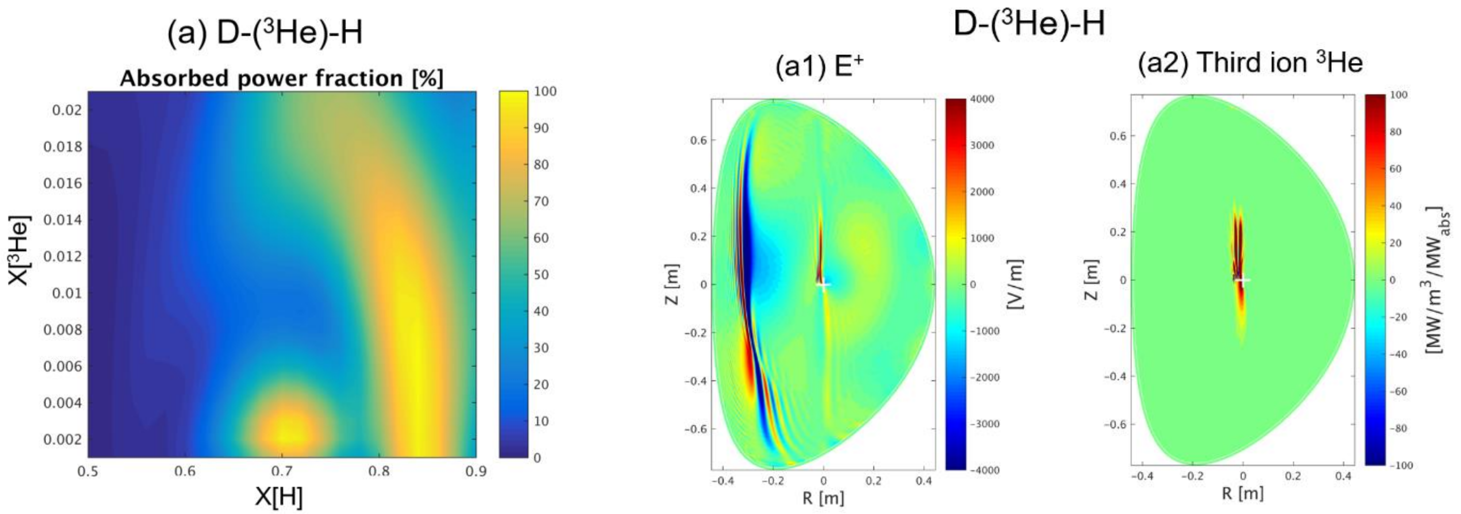


(c) Fusion neutron yield

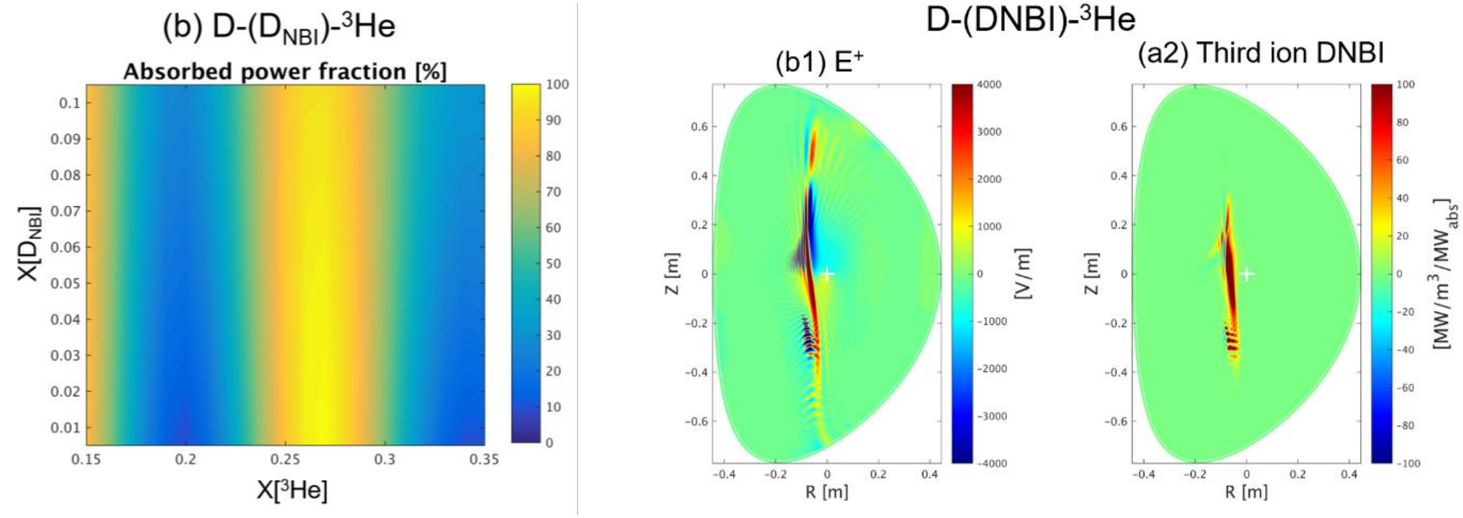


3-ion heating schemes

Scenario #1: D-(^{3}He)-H
H=85%, D = 13%,
^{3}He=1%



Scenario #2: D-(D_{NBI})-^{3}He
^{3}He = 28%, D = 41%,
D_{NBI} = 3% (40-65 keV)



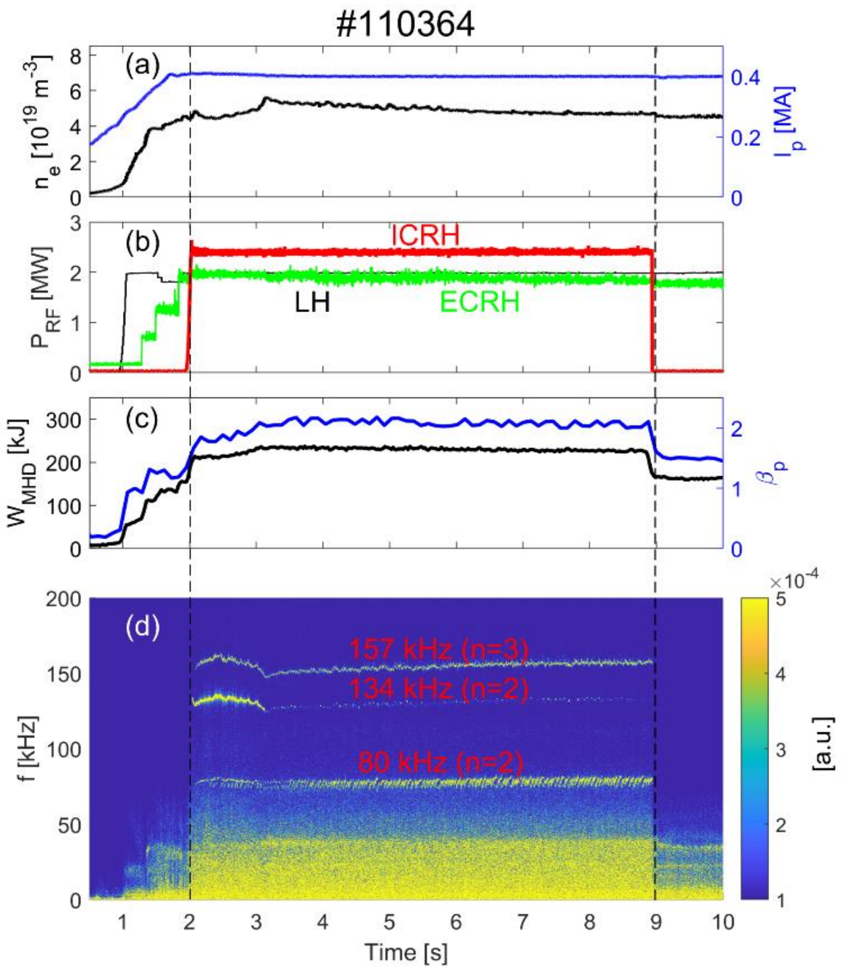
Experiments scheduled in June-July 2025

Outline

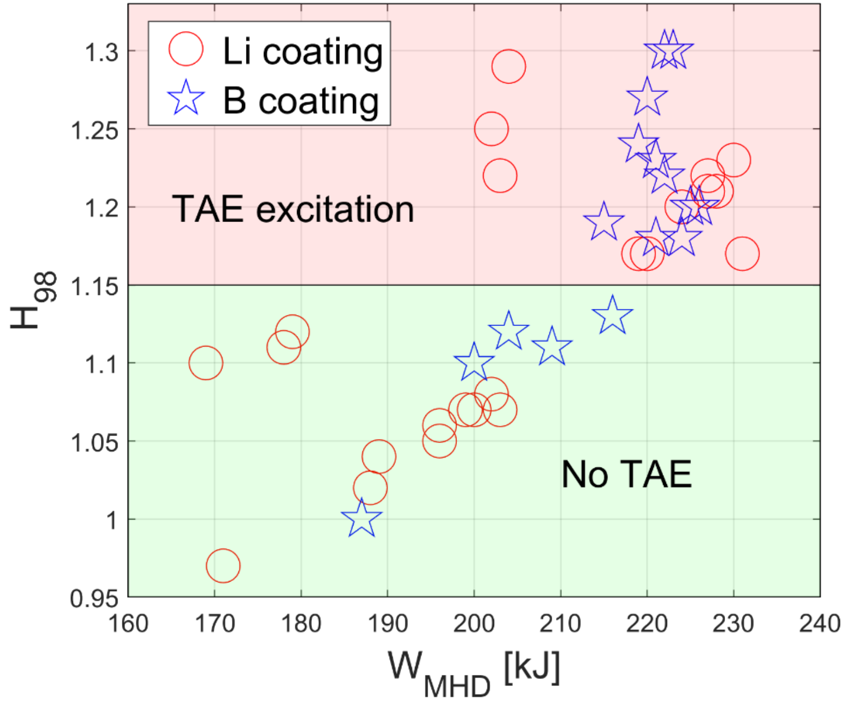
- ➢ Upgrades of EAST-ICRF system
- ➢ Increase of ICRF coupling and absorption
- ➢ **ICRF experiments for multi-physics studies**
  - Various Alfvén instabilities
  - Sawtooth control
  - Turbulence suppression
  - ICWC in ITER relevant conditions

Alfvén instability: experimental observation

- Alfven Eigenmode (AE) excited by ~2.4MW ICRH



- f = 80 kHz (n = 2) is BAE: depends on T_e; independent of n_e
- 134 kHz (n = 2) and 157 kHz (n = 3) are TAE: $f_0 \propto v_A \propto B/\sqrt{\mu_0 n_e}$
- TAEs exhibit a strong dependence on H_{98} factor and can only be excited when it is larger than 1.15

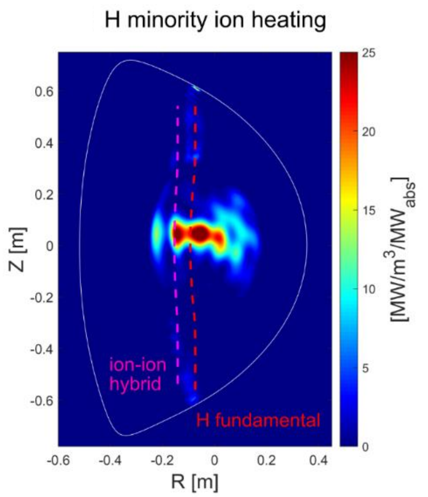


Alfvén instability: integrated simulations

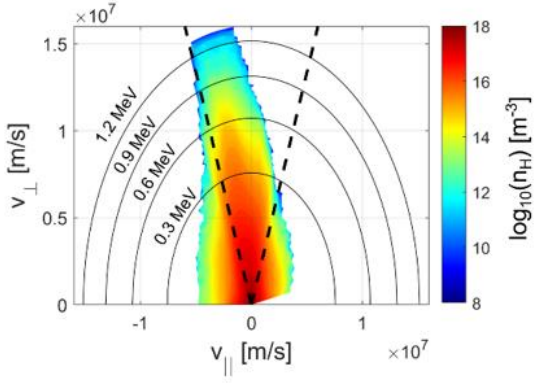
Simulation codes: TRANSP/TORIC+ASCOT+NOVA-C/GTC

- Most fast ions are banana orbits with bouncing tips near cyclotron resonance
- TAEs exist in plasma core and edge
- **f=134 kHz (n=2)** is in good agreement with simulations
- The driving originated from the spatial gradient of the fast H-ion distribution

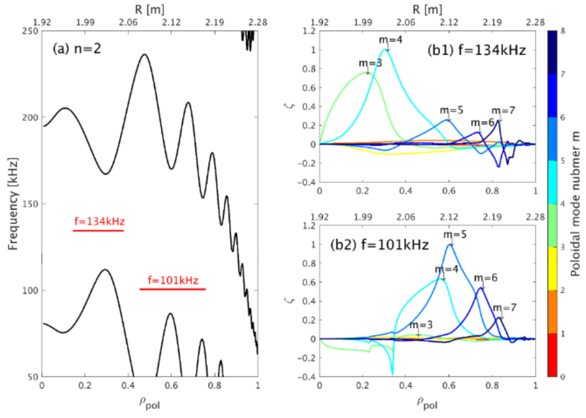
TORIC



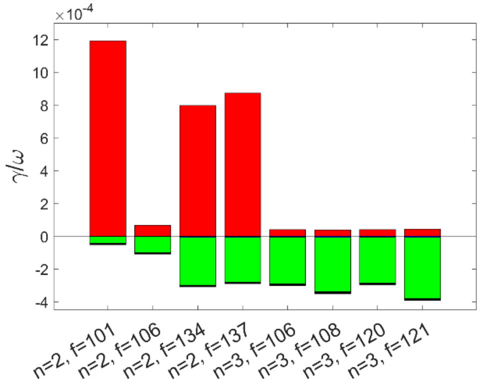
ASCOT



NOVA



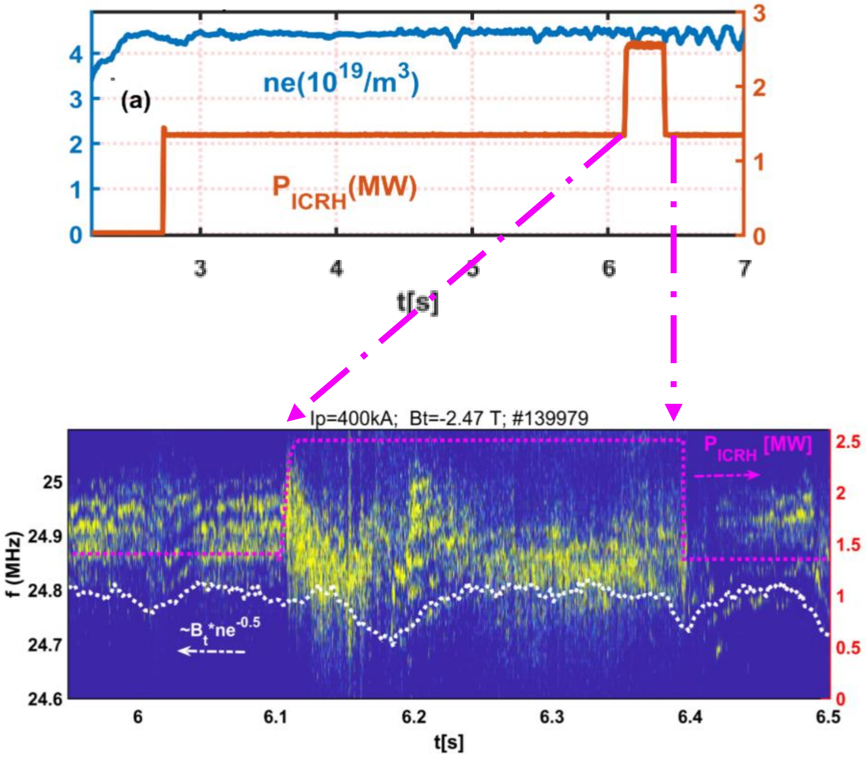
NOVA-C/GTC



Alfvén instability: high frequency AE and ICE

- **High frequency AE excited during minority heating**

#139979

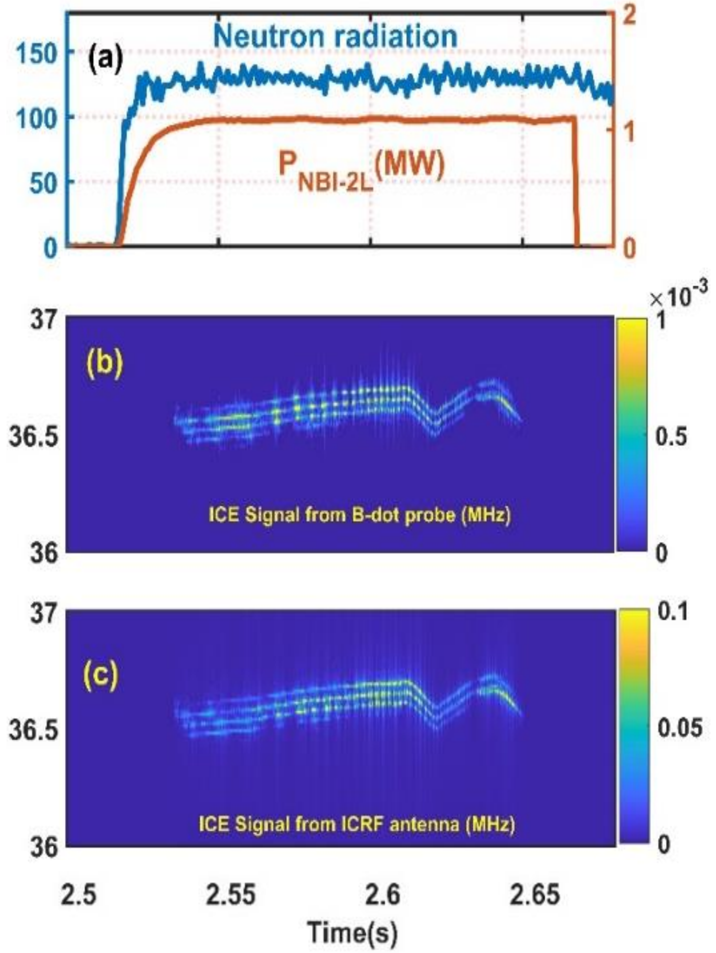


No NBI used in this discharge

L.N. Liu, Nuclear Fusion (2024)

- **Core ICE excited by D ions**

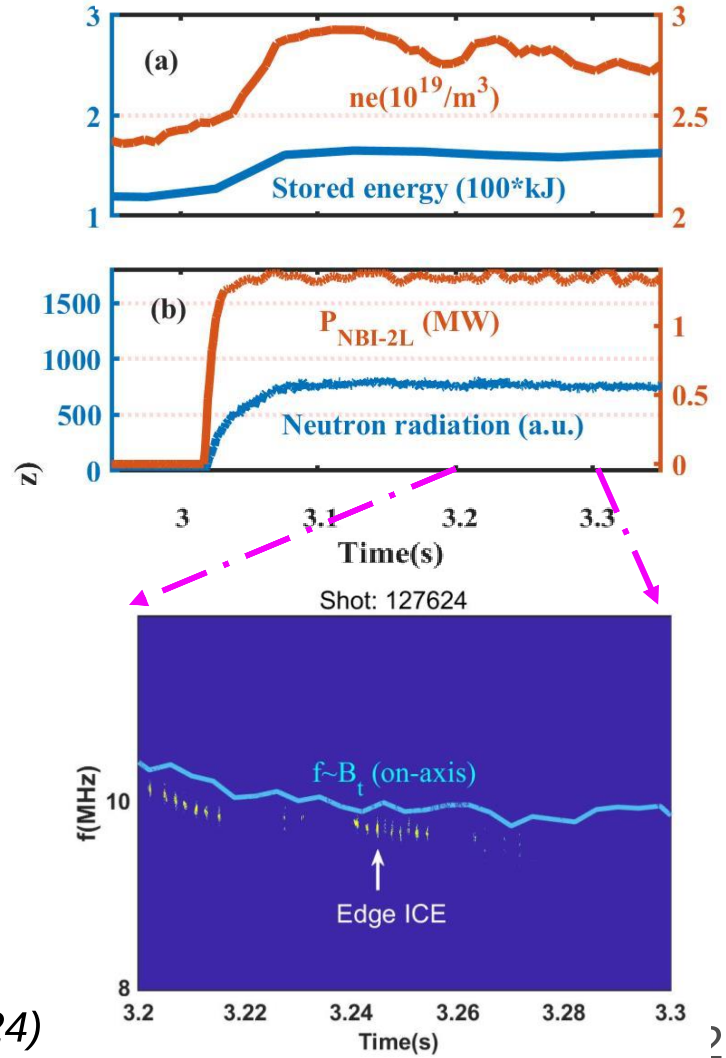
#127012



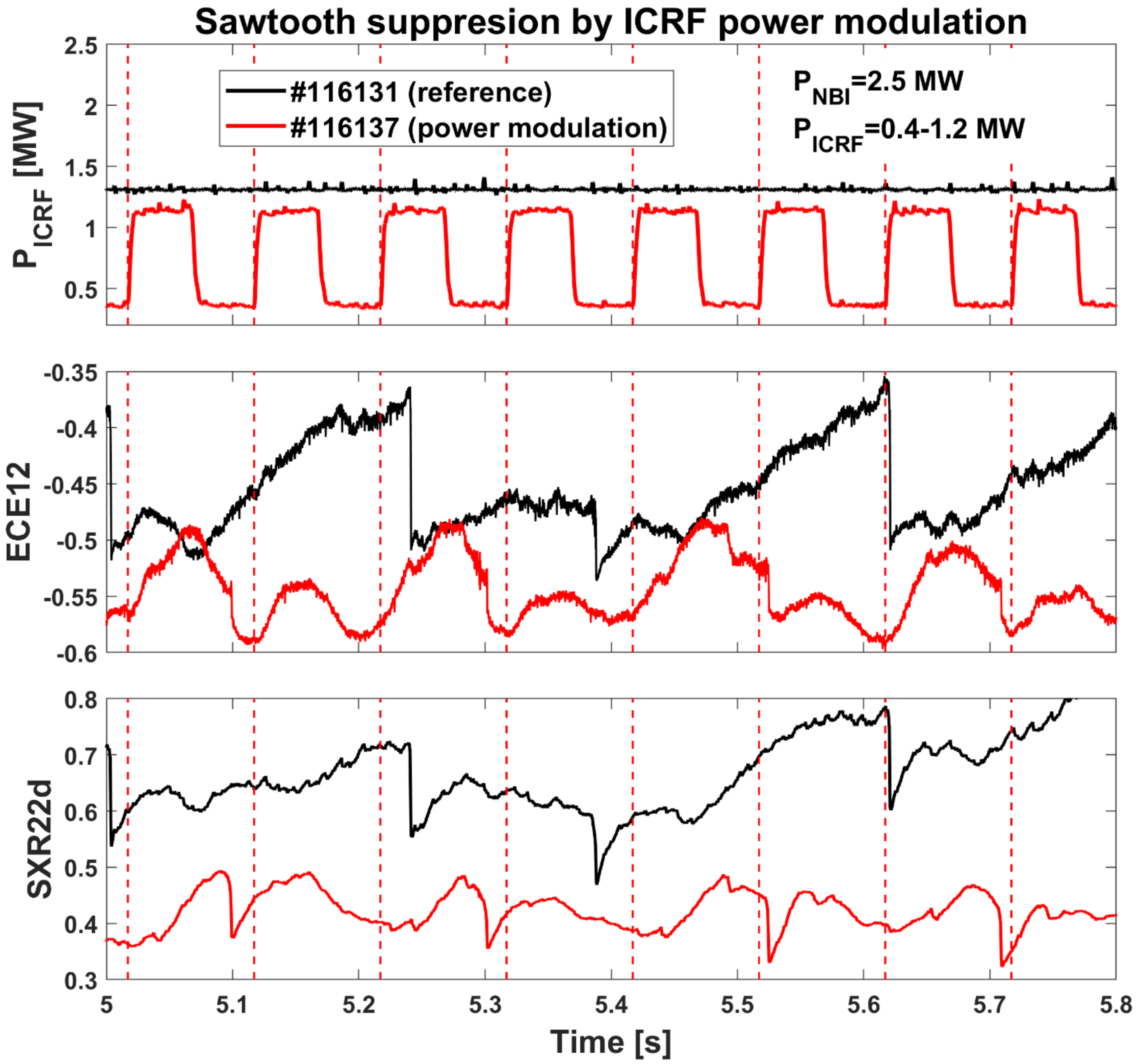
H.P. Zhang, Nuclear Fusion (2024)

- **Edge ICE excited by T ions**

#127624



Sawtooth control: ICRF power modulation



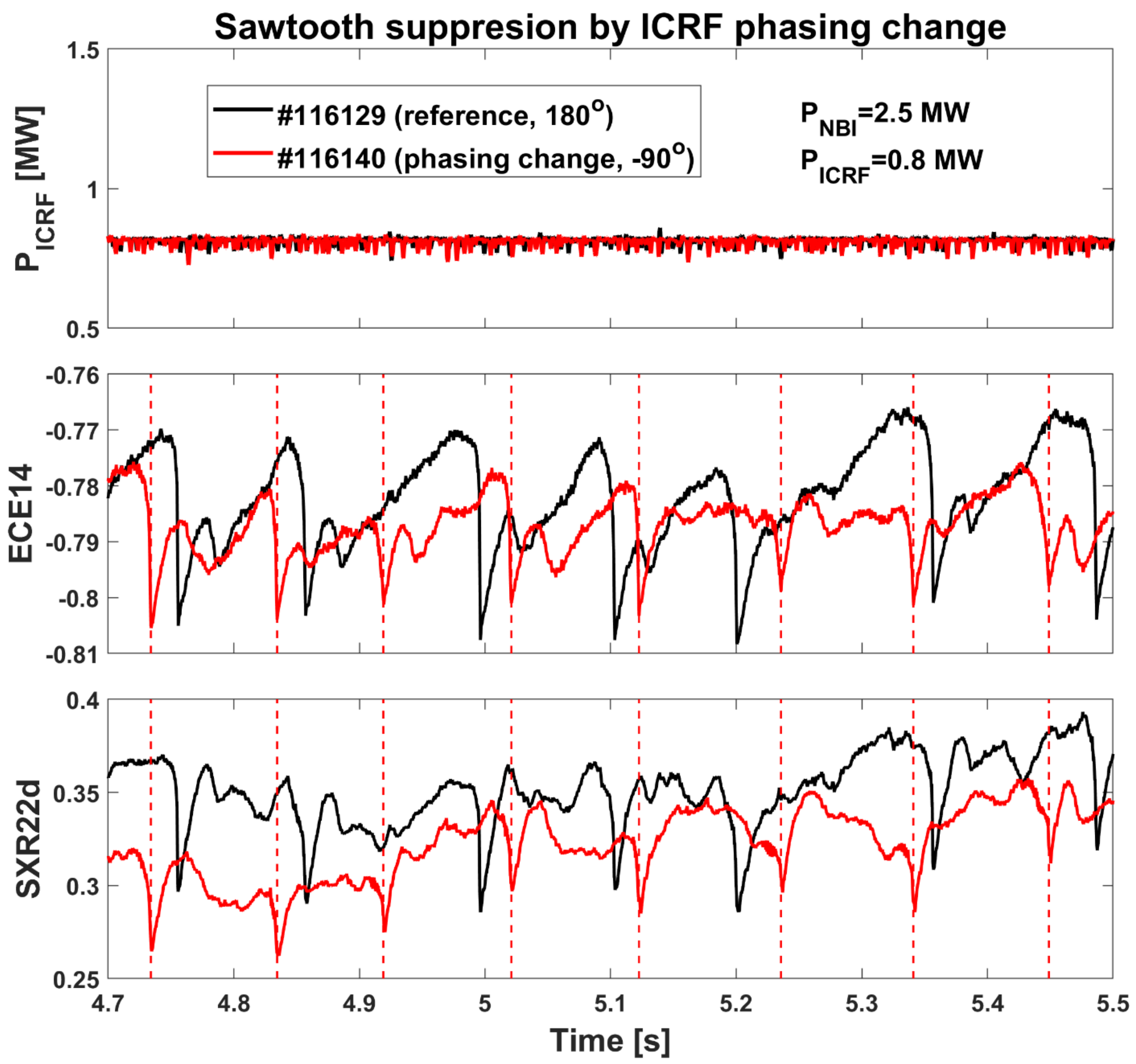
#116131 (reference case) :
Constant power P_{IC} ~1.3 MW

#116137 (power modulation) :
P_{ICRF} ~0.4-1.2 MW

- Sawtooth period decreased from T = 0.24s to 0.1s
- Mechanism: change of fast ion beta inside q=1 surface

TRANSP & M3D-K simulations ongoing
— PhD student Z. Wang

Sawtooth control: ICRF phasing change



#116129 (reference) :
Phasing: Φ=180º

#116140 (phasing change) :
Phasing Φ=-90°

- Sawtooth period decreased from T = 0.14s to 0.1s
- Mechanism: change of passing fast ion distributions

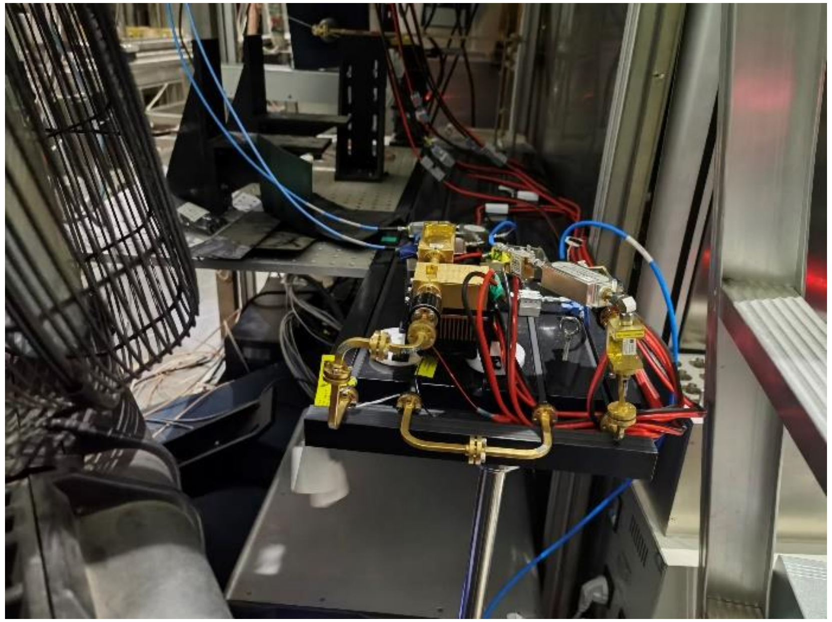
TRANSP & M3D-K simulations ongoing
— PhD student Z. Wang

Turbulence suppression: core plasma

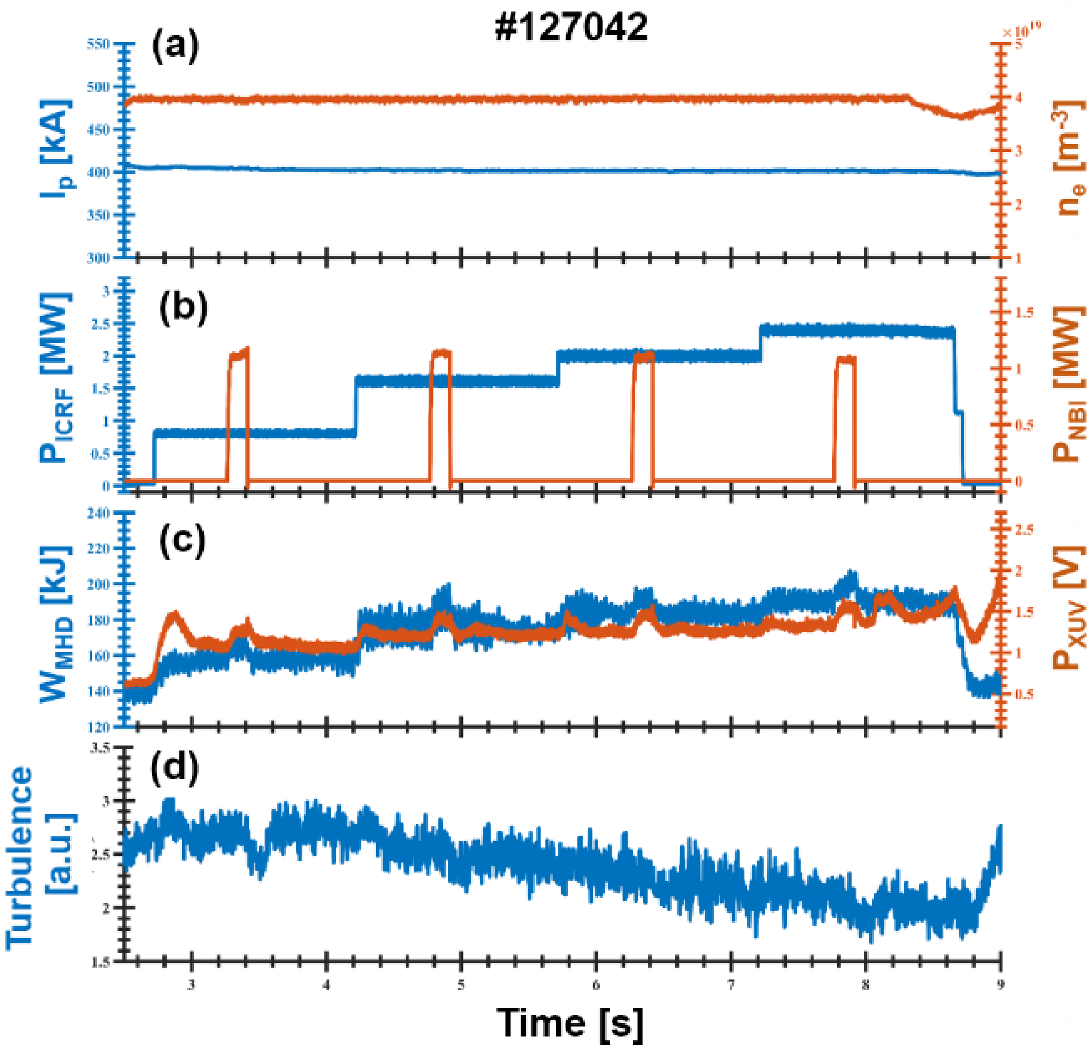
During ICRF power modulation:

- Excitation of TEM by Tungsten impurity
- Stabilization of turbulence by fast ions

New V-band DBS system
— PhD student S.C. Qiu

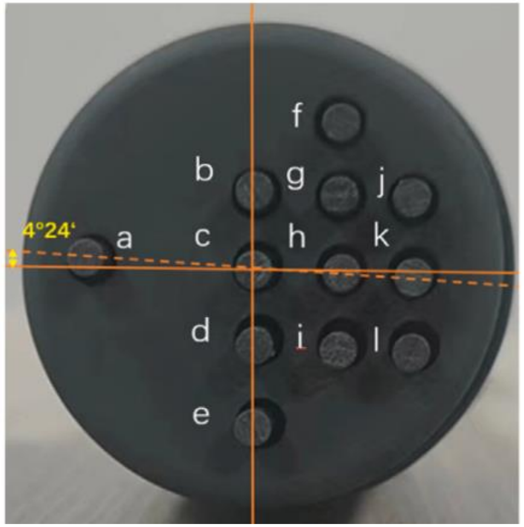


Turbulence decreases during ICRF power ramping up



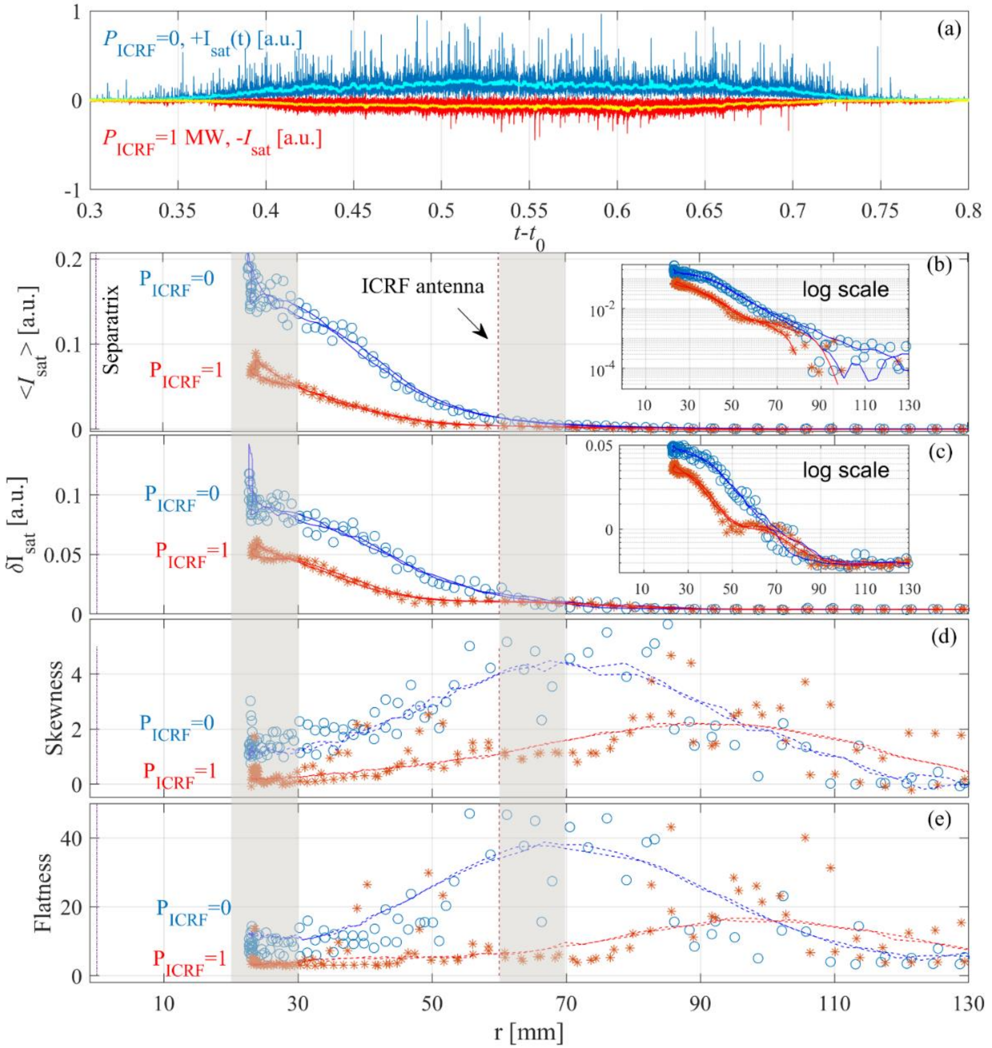
Turbulence suppression: edge plasma

New reciprocating probe — PhD student L.X. Li



g, i, j, l → V_f
a, b, c, d, e, h, k → I_{sat}

#107111



W. Zhang, Physics of Plasmas (2024)

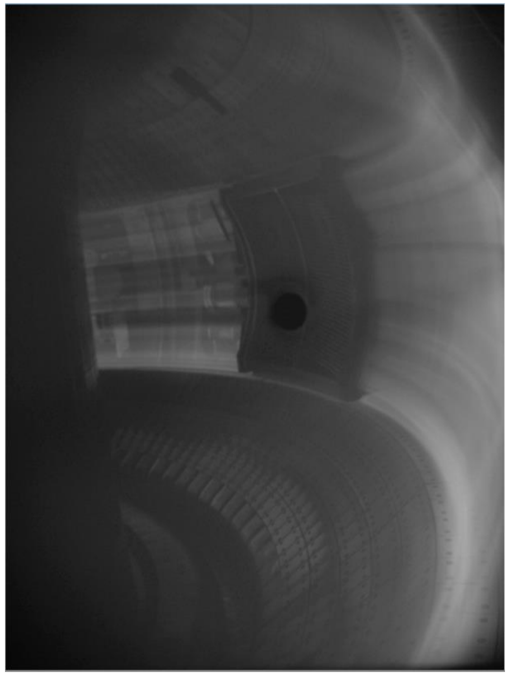
- Effect of ICRF on turbulence at different radial locations were measured
- Large-scale, low-frequency turbulence are reduced by ICRF
- Poloidal shear flow in the edge is measured: possible mechanism

ICWC in ITER relevant conditions

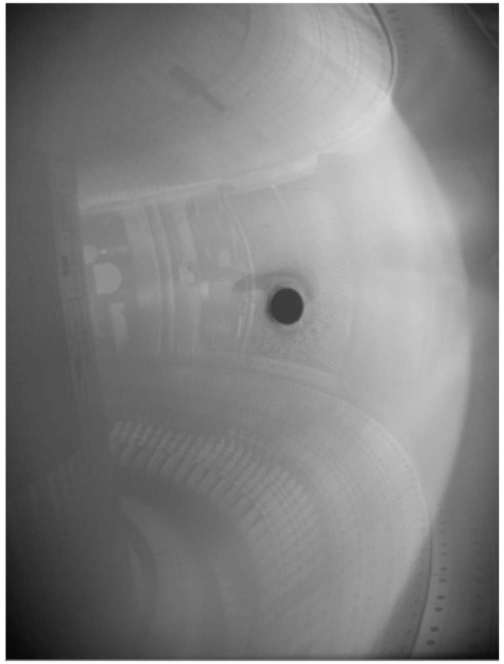
- Plasma is more brightness with heating antenna ICWC than that with cleaning antenna
- D-ICWC is sensitive to working gas pressure and heating power, and needs 100kW to build plasma; normal working power is larger than 200kW

- Work with T. Wauters

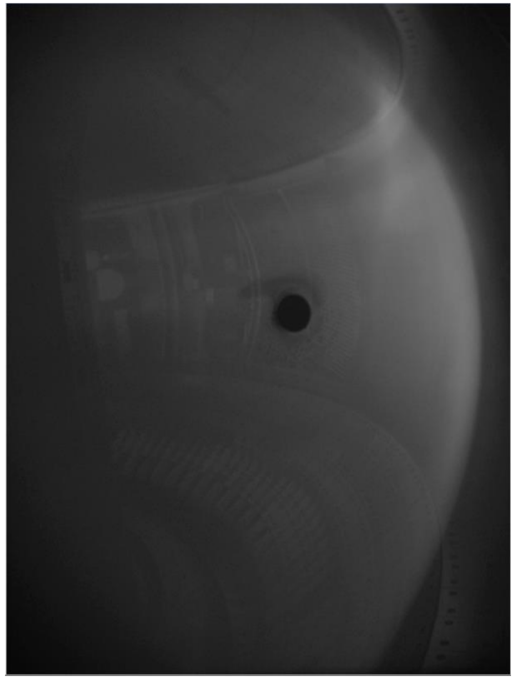
- **cleaning antenna:**
  27 MHz, 45 kW, B_t ~2.5 T



- **heating antenna:**
  37MHz, 200 kW, B_t ~0.95 T



- **heating antenna:**
  37 MHz, 200 kW, B_t~2.5 T



Conclusions

EAST-ICRF system and heating

EAST-ICRF system

- Two 2-strap antenna with low $k_{||}$ installed, with a total heating power up to 4MW
- Capacitances installed in addition to liquid stub-tuners, allowing real-time fast impedance matching

ICRF edge coupling and core absorption

- ICRF coupling improved by local gas puffing, optimization of gap-out distance, core density, divertor strike-point position, antenna phasing etc.
- Power absorption increased by optimization of B_t, X(H) and ICRF-NBI synergetic heating

Conclusions

ICRF multi-physics studies

Alfvén instability

- Various AEs and ICEs observed in plasmas with Lithium or Boron-coated wall
- Low-frequency TAE driven by radial gradient of fast ion distribution

Sawtooth control

- Sawtooth suppression by ICRF power modulation and ICRF phasing change
- Due to change of fast ion beta and fast ion distribution

Turbulence suppression

- Core: stabilization of turbulence by fast ions, possibly due to changes in ITG/TEM
- Edge: decrease of low-frequency turbulence, possibly due to poloidal shear flow

ICWC

- First time to use heating antenna for ICWC on EAST, obtained more brightness plasma