Experimental progress in fast-ion-related instabilities and the development of NPA diagnostics on EAST

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OUTLINE

- **Operational Region on EAST**
  - $q \approx 1$ (fishbone) and $q_{min} \approx 2$ (AEs)
  - DTMs instability at $q_{min} \approx 2$
- **RSAEs instability on EAST**
  - RSAEs with micro-instability
  - ITB with RSAEs instability
- **Development of NPA on EAST**
  - Diagnostic of INPA on EAST
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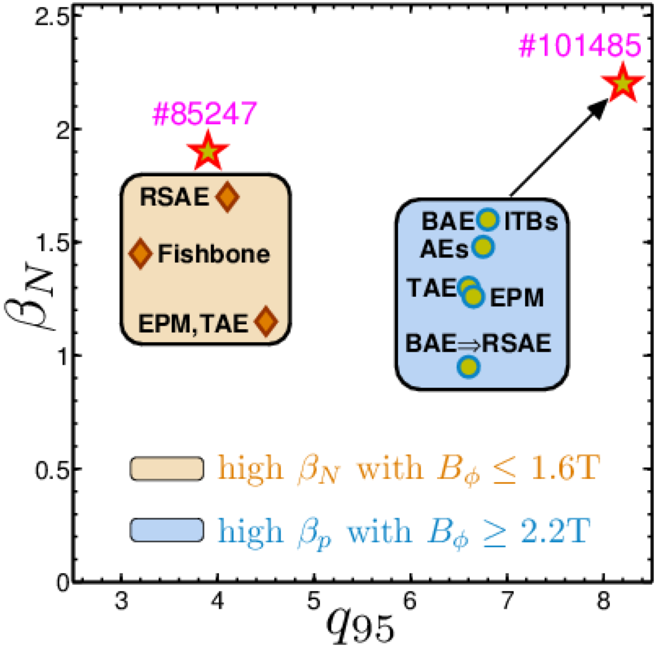
  - Future plan of E//B NPA
- **Conclusion and Discussion**

Two different parameter regions related to fast ions (fishbone, AEs, EPM) instability in EAST

$q \approx 1$

Featured by the fishbone instability



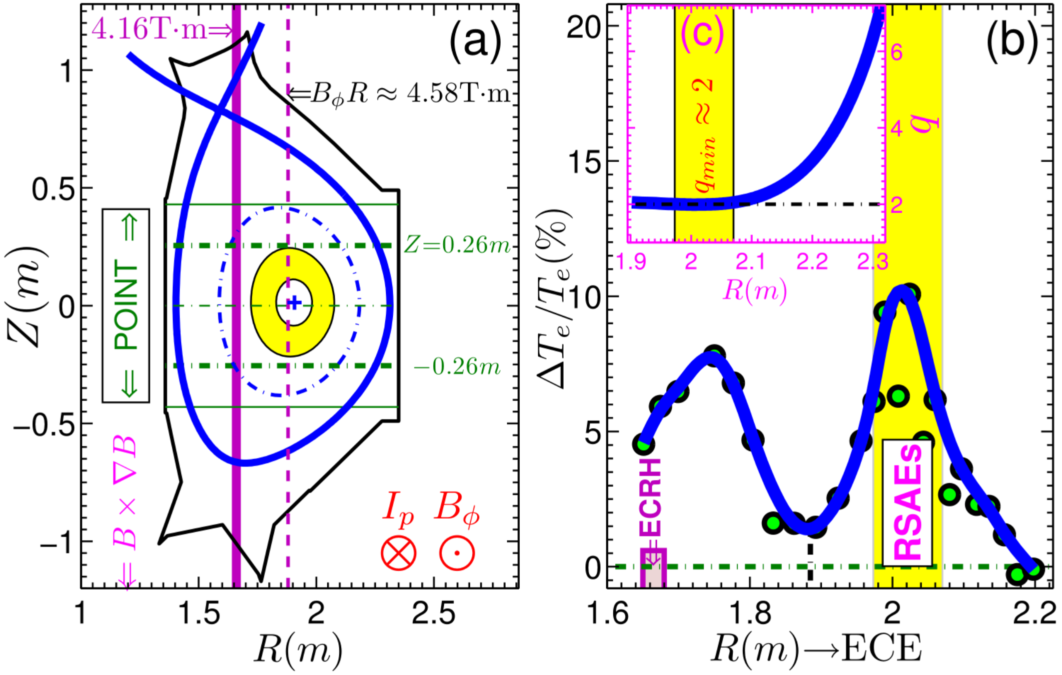
$q_{min} \approx 2$

Alfven waves and EPM instabilities

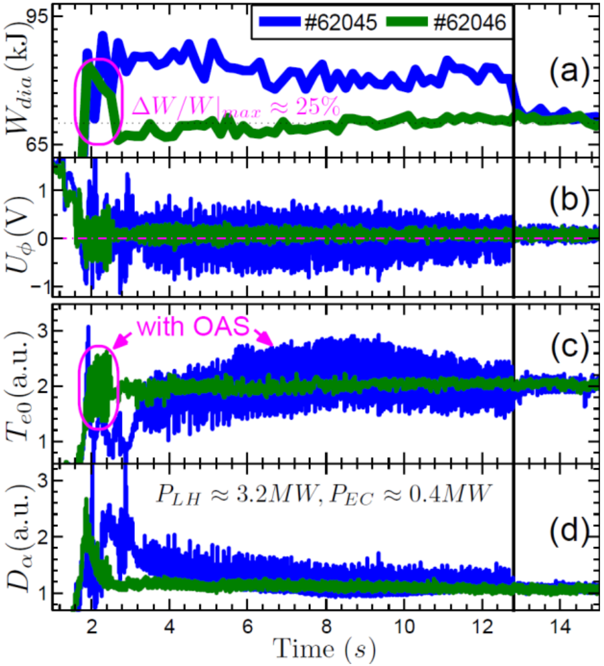
- High-β_N scenario (yellow): **fishbone**, EPM, TAE, etc
- High- β_p scenario (blue): BAE, **RSAE**, EPM, etc

Establishment of reversed shear q-profile with $q_{min} \approx 2$ by the synergy of LHCD+ECRH

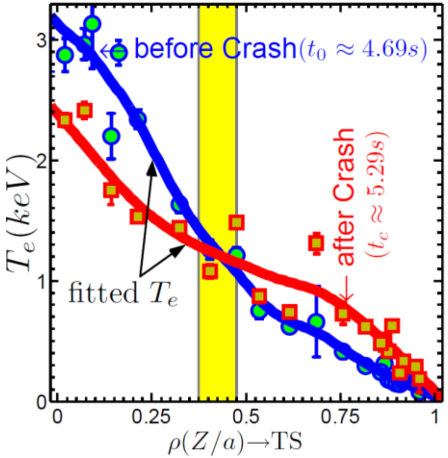
- **The reversed q-profile is established by synergy of LHCD + ECRH:**
  - Full driven **LHCD** ($U_\phi \approx 0$);
  - Off-axis **ECRH** in (a).
- **Other indirect evidences:**
  - **DTMs** (m/n=2/1);
  - LFMs (4/2, 6/3, …);
  - RSAEs: $0.2 \leq \rho \leq 0.4$;
  - $\Delta T_e/T_e$ caused by ECRH: $0.2 \leq \rho \leq 0.4$ (b).

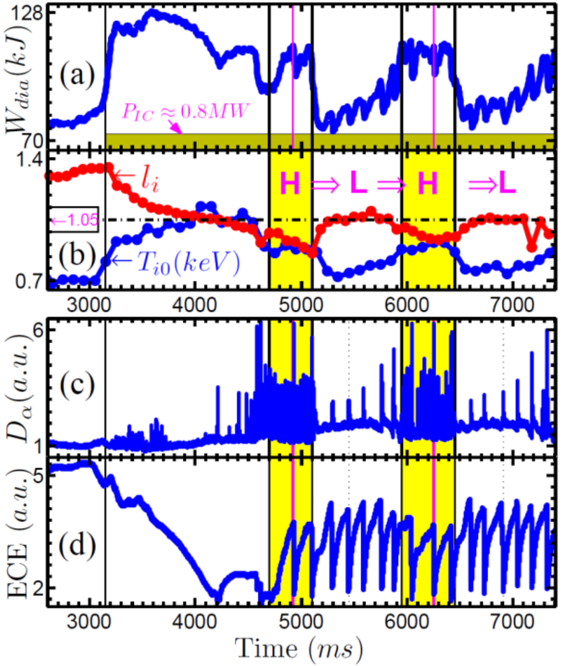


The existence of DTRC is beneficial for the L-mode while harmful for the H-mode plasmas



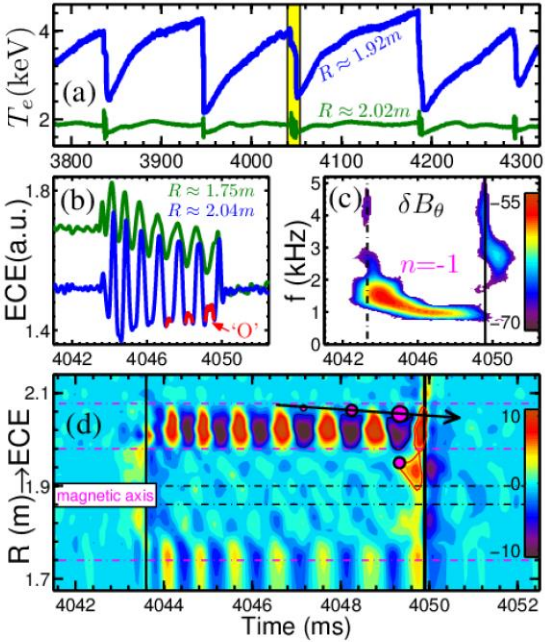
Redistribution of T_e-profile caused by the reconnection of DTM

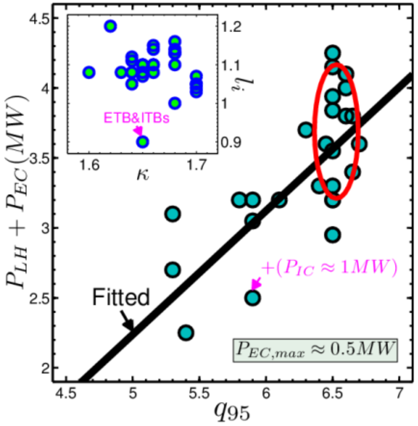




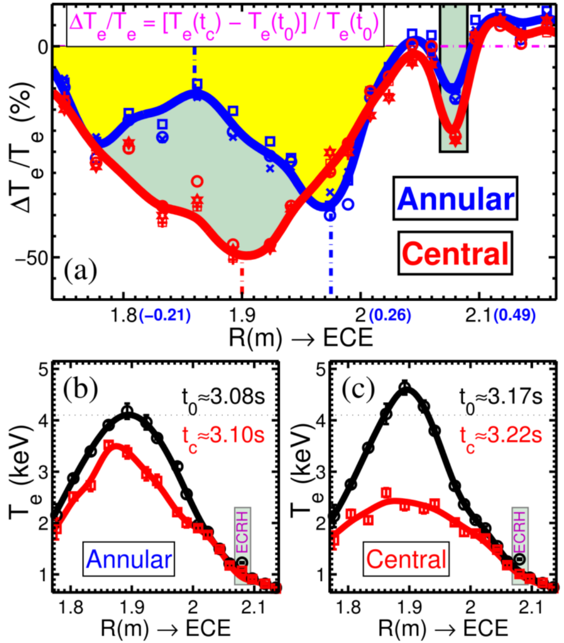
- ➢ (Left): The plasma confinement (W_{dia}) increases dramatically for the excitation of DTM instability in the L-mode plasmas;
- ➢ (Right): the existence of DTM is degenerated of W_{dia} in the H-mode plasmas.

Basic characteristics of DTMs/DTRC at $q_{min} \approx 2$ are summarized in EAST





[1] Ming Xu et al **NF** 61 106008 (2021);
[2] Ming Xu et al **Acta Physica Sinica** 72 215204 (2023);



- ➢ Characteristics: mode number ($m/n = 2/1$) with position of $1.98 \le R \le 2.07m$ ($0.2 \le \rho \le 0.4$);
- ➢ Classification: **Annular**/**Central** Collapse, and **No-reconnection** crash events are observed;
- ➢ Statistics: LHCD + ECRH ($q_{95} \approx 6.5, l_i \approx 1.1, 1.6 \le \kappa \le 1.7$);

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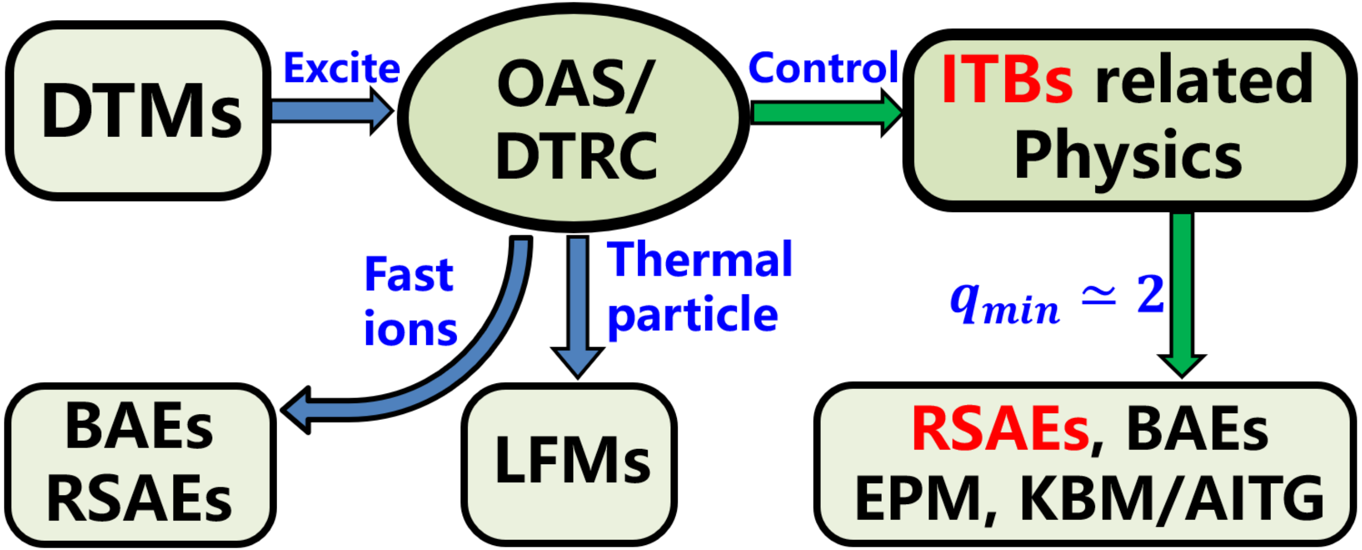
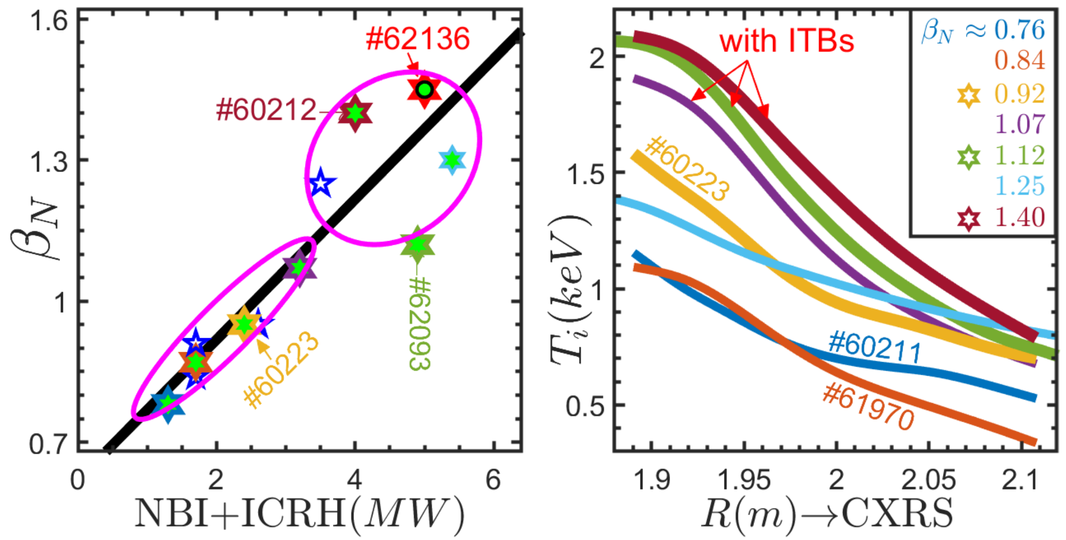
Framework Diagram of MHD and fast-ions instabilities related to ITB with $q_{min} \approx 2$



[1] Ming Xu et al submitting to NF;
[2] Ming Xu et al **Acta Physica Sinica** 72 215204 (2023);
[3] Ming Xu et al **NF** 62 126041 (2022); [4] Ming Xu et al **NF** 61 106008 (2021);
[5] Ming Xu et al **CPL** 38 085201 (2021);
[6] Ming Xu et al **NF** 60 112005 (2020); [7] Ming Xu et al **NF** 59 084005 (2019).

Series of discharge conditions with different T_i-profiles are featured by excitation of RSAEs ($q_{min} \approx 2$)



- Low confinement: $P_{NB+IC} < 4MW, \beta_N < 1.1$
- High confinement: $P_{NB+IC} \geq 4MW, \beta_N > 1.1$

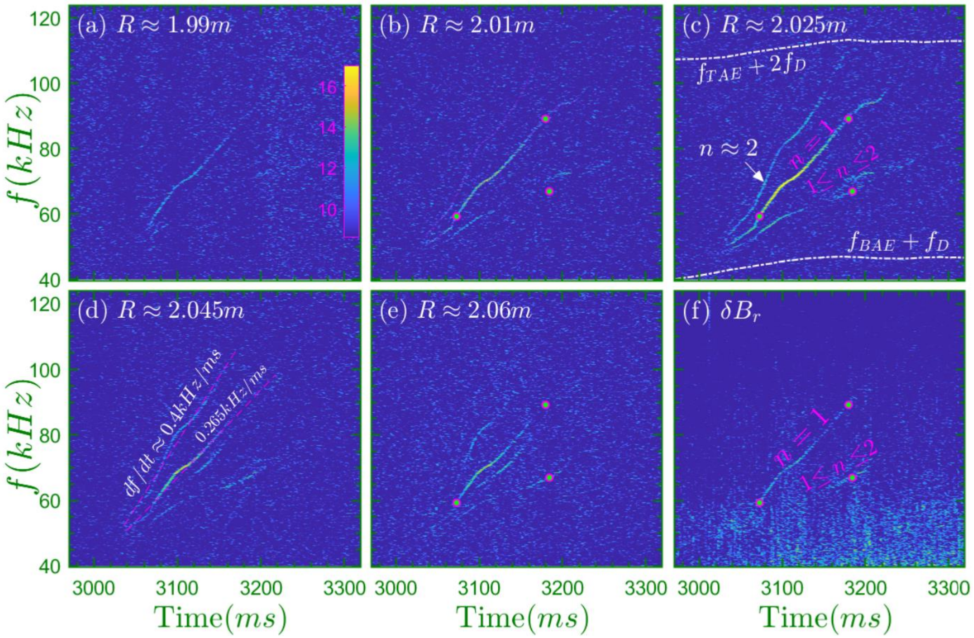
Radial coverage and toroidal mode numbers of the RSAEs instability

- Radial position of RSAEs: $1.98 \le R \le 2.07m$ $(0.2 \le \rho \le 0.4)$.
- Upward sweeping of RSAEs:
  - The frequency is located between BAE and TAE;
  - The primary mode: m/n=2/1;
  - The higher m/n=4/2 is speculated: $df/dt \approx 0.4kHz/ms$.

$$\omega_{RSAE}^2 = \frac{v_A^2}{R^2}\left(n - \frac{m}{q_{min}}\right)^2 + \omega_{BAE}^2 + \Delta\omega^2 \qquad (1)$$

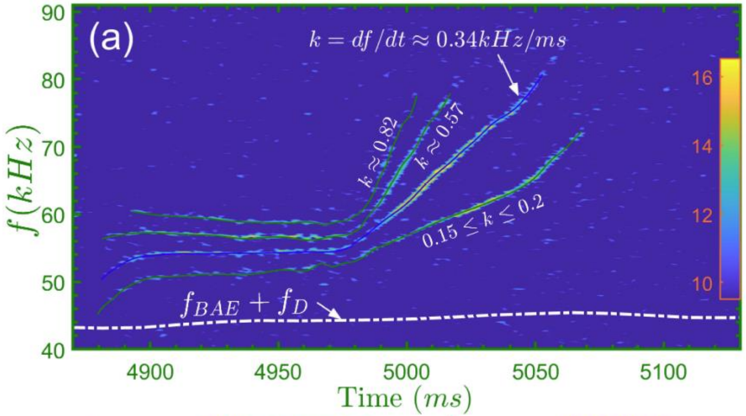
$$\frac{d}{dt}\omega_{RSAE}(t) \approx m\frac{v_A}{R}\frac{d}{dt}q_{min}^{-1}(t) \qquad (2)$$

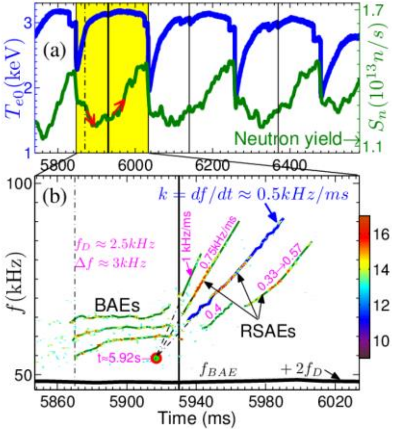
$$\omega_{BAE} \approx (2T_i/m_i)^{1/2} \cdot (7/4 + T_e/T_i)^{1/2}/R \qquad (3)$$

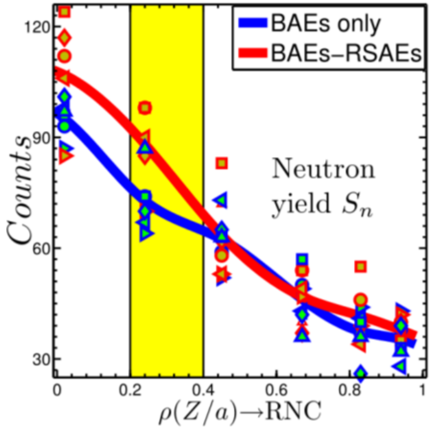


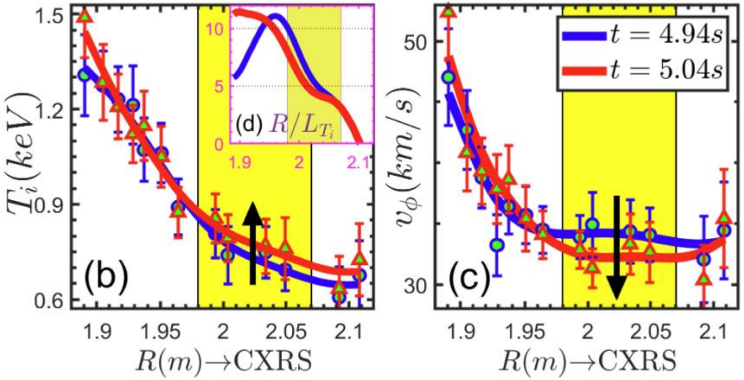
Relationship between RSAEs and fast/thermal ions

- **Relationship with fast ions:**
  - Increases fast ions (S_n) after RSAEs;
  - Increases of S_n focused in the core;
- **Relationship with thermal ions:**
  - The T_i in the off-axis region increases;
  - The v_ϕ at the same region decreases.









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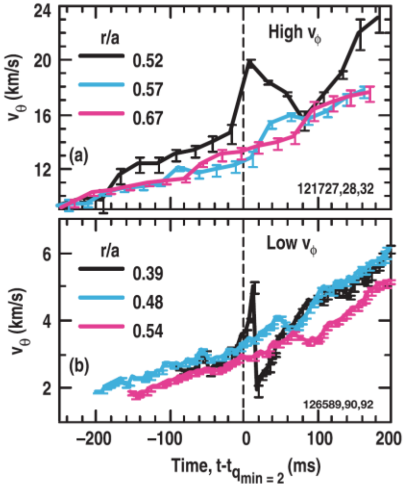
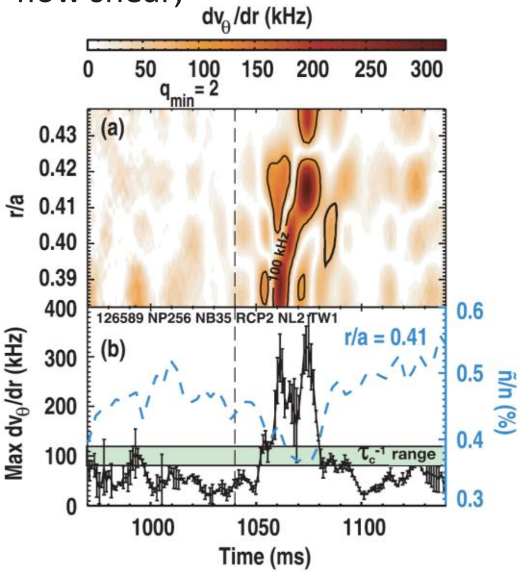
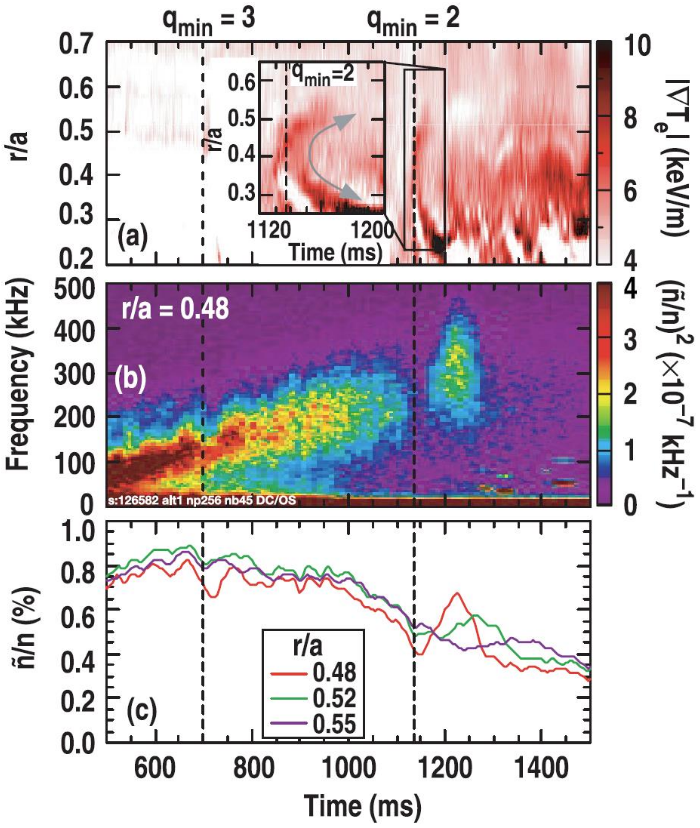
Background: micro-instability of thermal particle transport is observed at $q_{min} \approx 2$ in DIII-D

- Near the $q_{min} = 2$ surface:
  - Increases in ∇T_e near the $q_{min} = 2$ surface, Propagates wavelike inward and outward radially;
  - Reduction in turbulence amplitude of density fluctuation;
  - Increased of poloidal flow and flow shear;

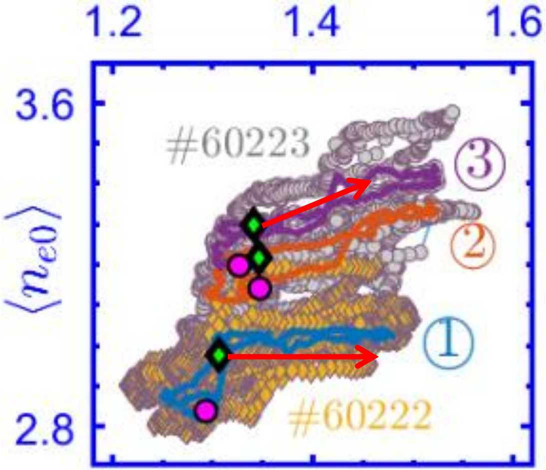


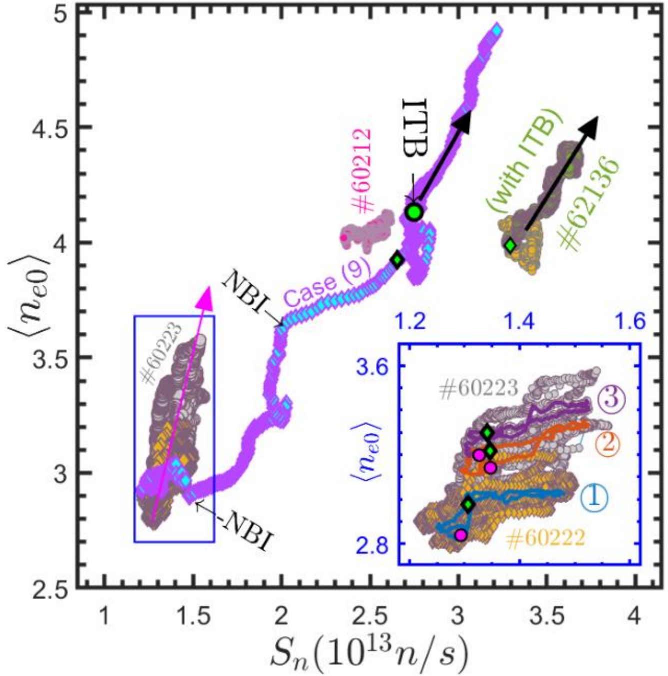




Shafer et al PRL 103 075004 (2009)

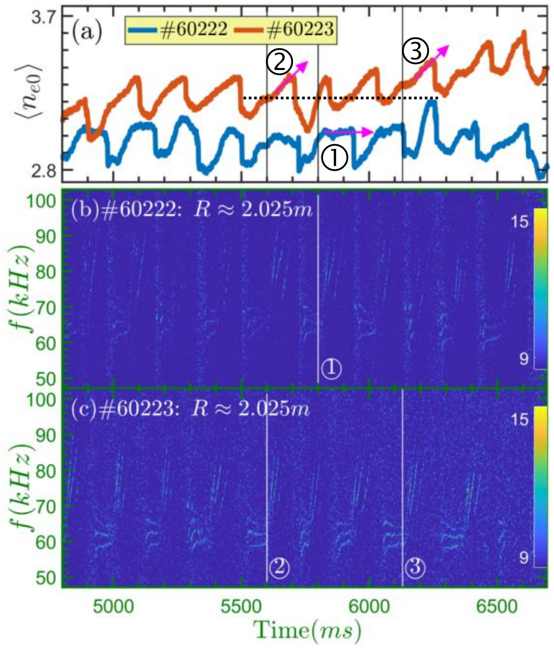
Relationship between thermal particles ($\langle n_{e0} \rangle$) and fast ions (S_n)

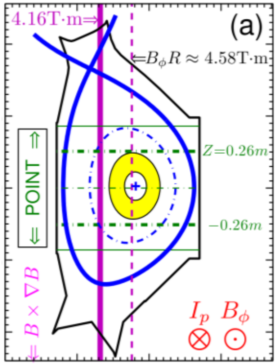




- ➢ Usually, the confinement of thermal particles is proportional to fast ions density;
- ➢ The steady $\langle n_{e0} \rangle$ persists throughout EAST shot #60222, concurrently with a notable rise in the neutron yield S_n.

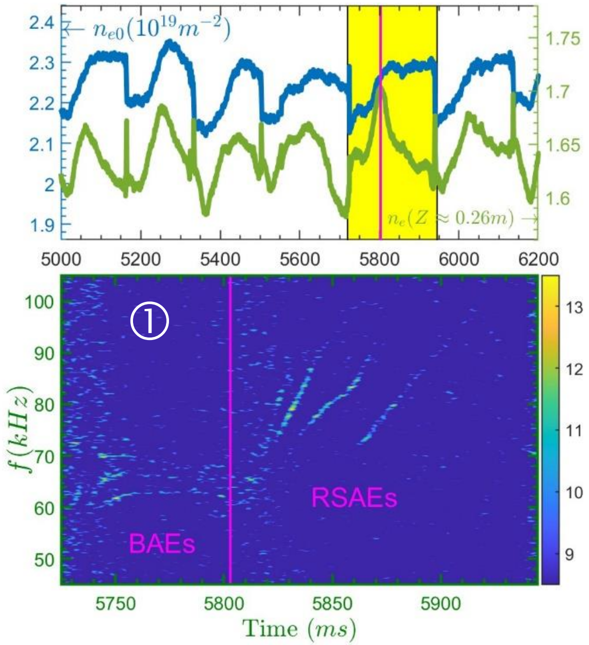
Different amplitude of thermal particle transport are observed in two similar conditions





#60222 and #60223 with similar discharge parameters;

Three cases: ①→#60222, ②,③→#60223 are shown in left, while the response of n_{e0} are different.



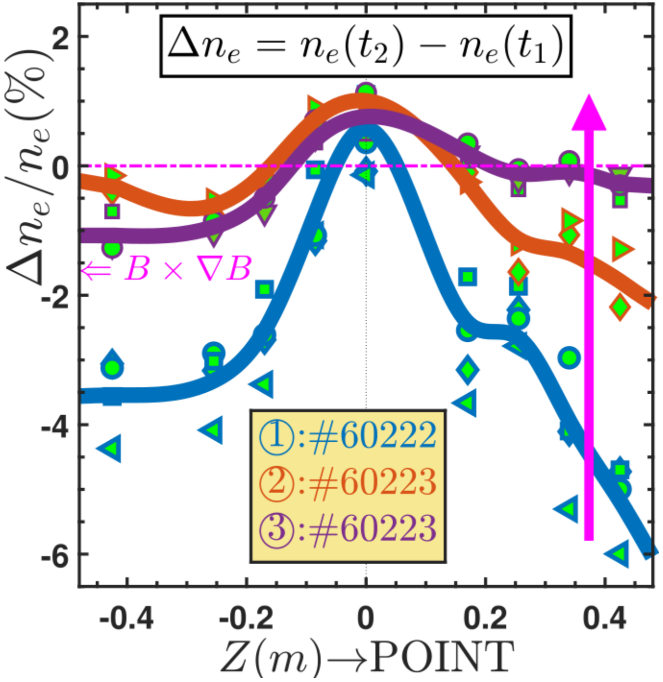
- The inflection points of $\langle n_e \rangle$ are observed for the transition of BAEs and RSAEs;
- Transport of thermal particles is captured by POINT diagnostic, with decreases of $\langle n_e \rangle$ at $|Z| \neq 0$.

Micro-instability featured by transport of thermal particles is demonstrated by the POINT diagnostic

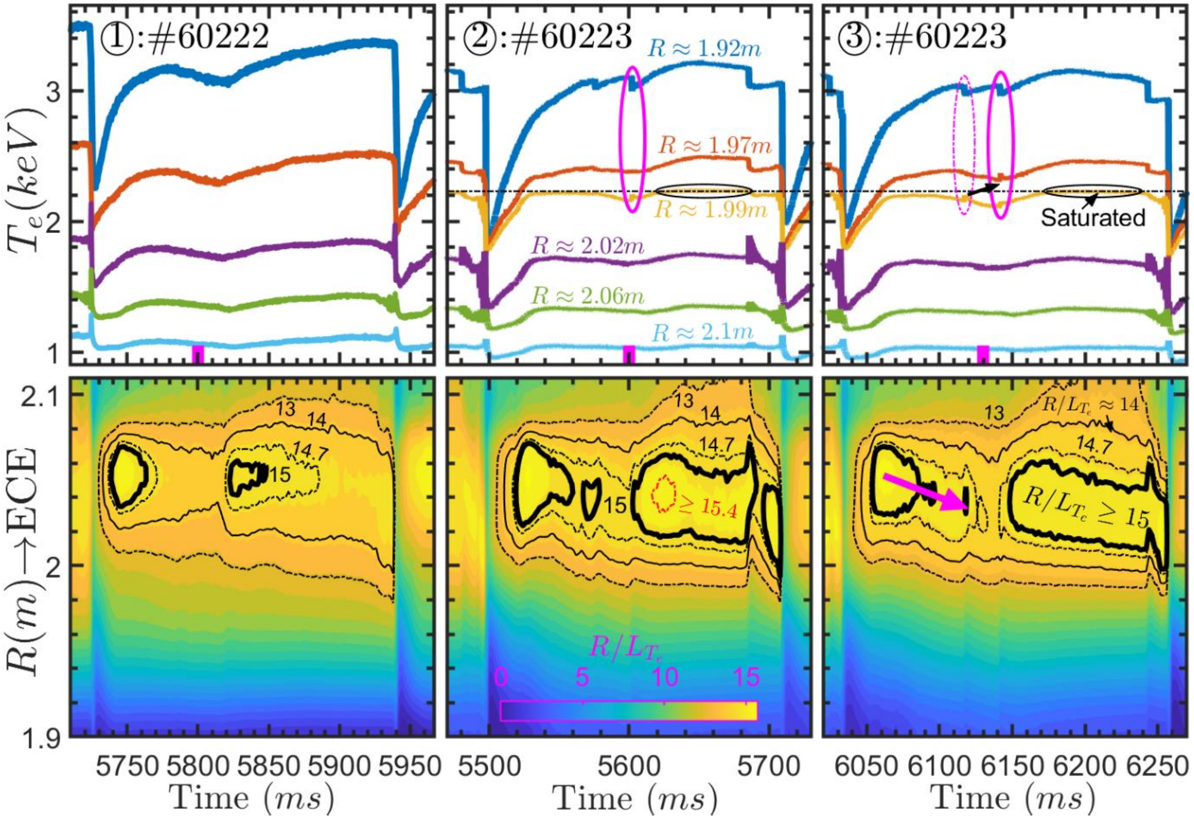
- Transport of thermal particles can be featured by POINT array:
  - t_1 and t_2 are two different moments before and after the modes transition of BAEs and RSAEs.
  - Bottom $(Z < 0)$ related to $\boldsymbol{B} \times \boldsymbol{\nabla B}$ drift instability.
- Fluctuation amplitude:
  - #60222: $|\Delta n_e/n_e| \approx 6\%$;
  - #60223: decreases by magenta arrow.

$$v_{\nabla B} \propto \cos\theta + (\hat{s}\theta - \alpha \sin\theta)\sin\theta$$

Transport: $\boldsymbol{\Delta n_e/n_e < 0}$



The reason is related to different q-profiles: different pressure profile with higher $R/L_{T_e} \geq 15$



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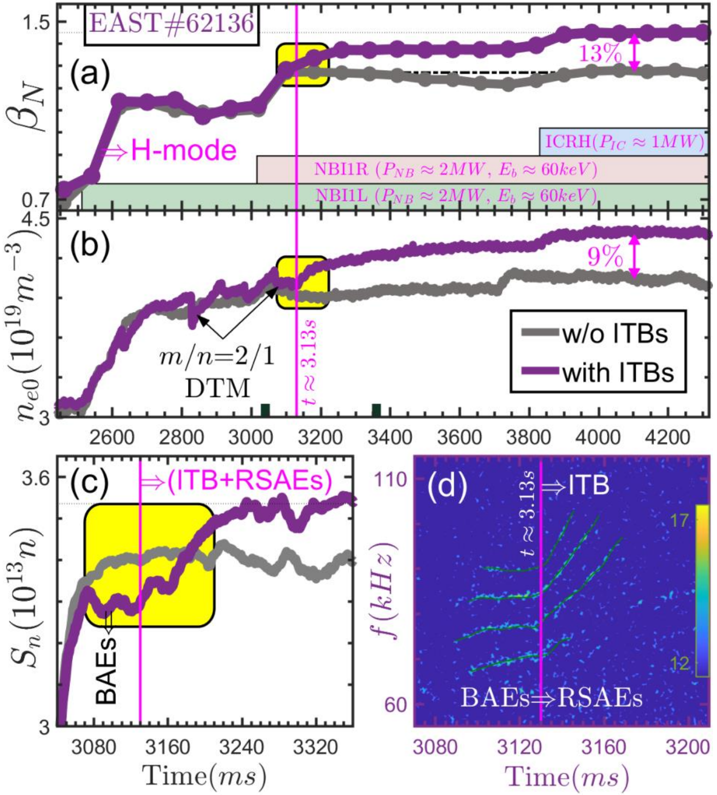
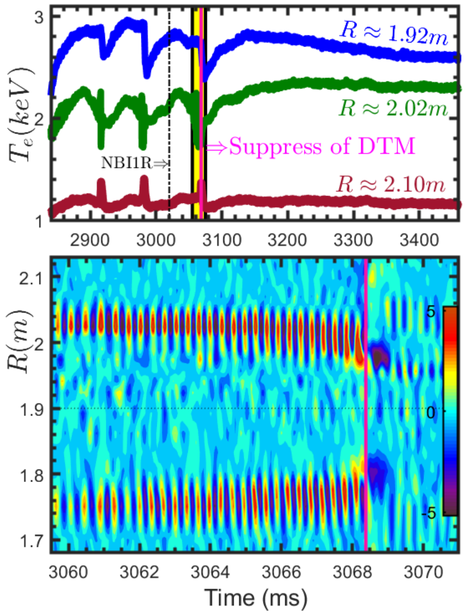
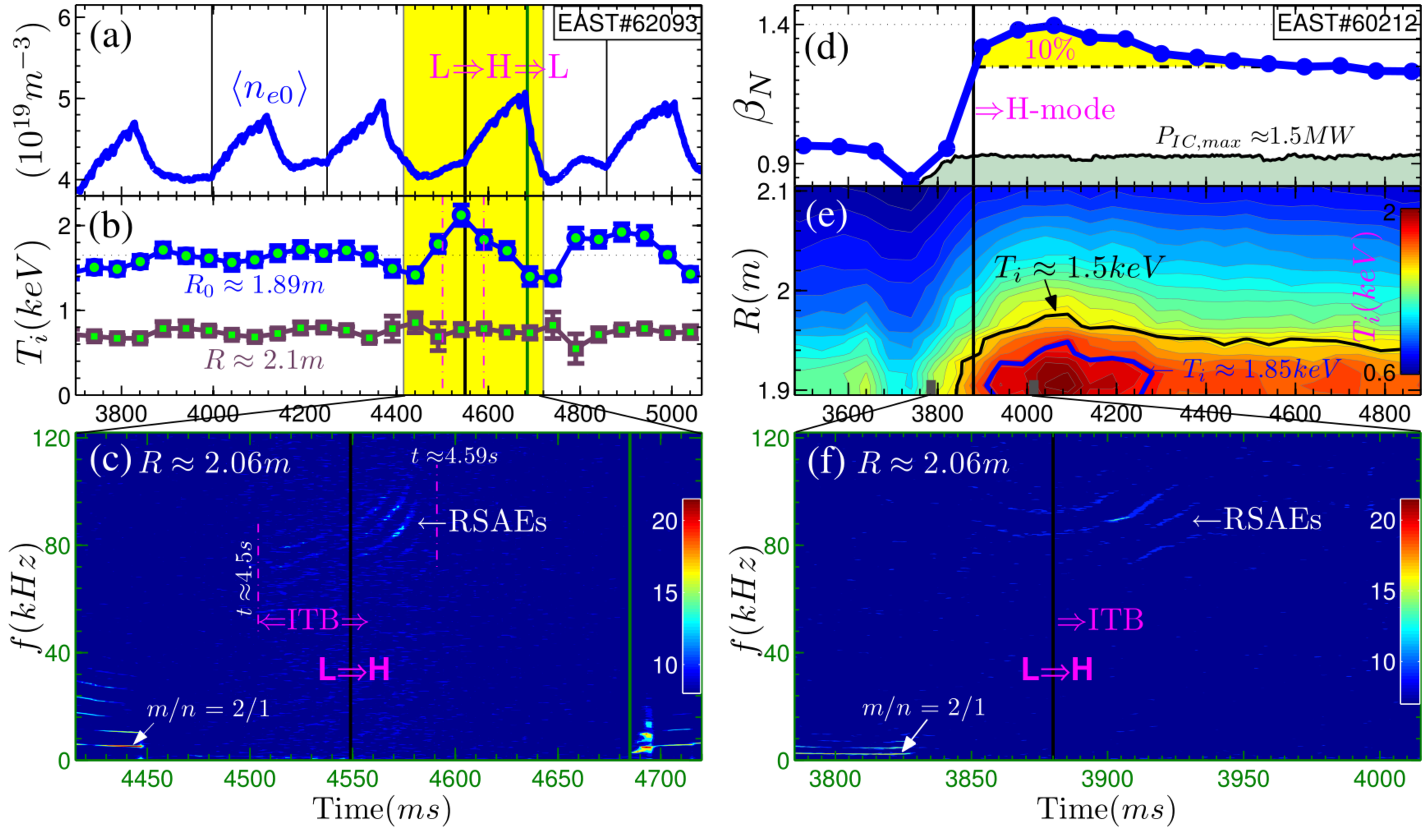
The ITB is established by the suppression of DTM and excitation of RSAEs instabilities

- Two cases with different q-profiles:
  - $q_{min} \approx 2$ → DTM + "grand cascade" of RSAEs;
  - S_n → BAEs + RSAEs;
  - ITBs → accompanied by RSAEs.
  - NBI power: ~4MW

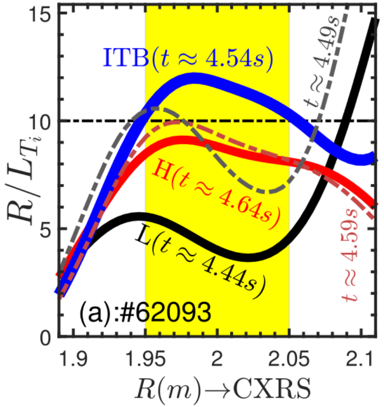


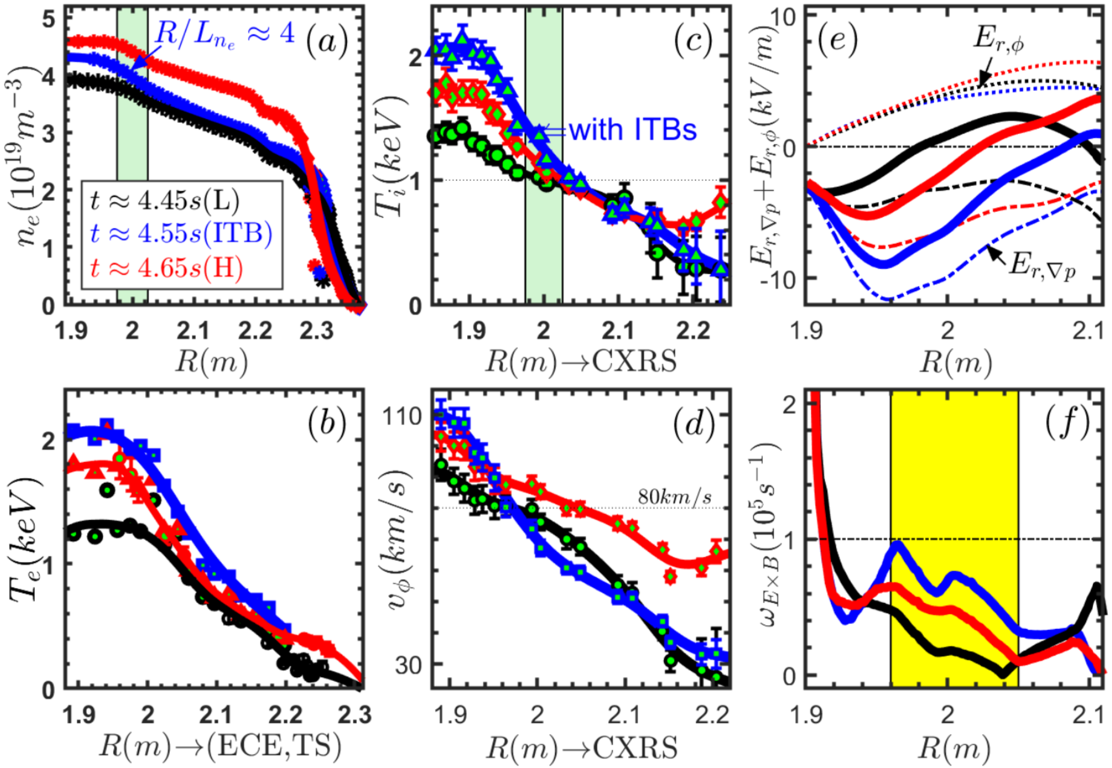


ITB is formed temporally before and after the H-mode plasma with $q_{min} \approx 2$



The higher $R/L_{T_i} \geq 10$ with negative E_r is observed after the formation of ITB





- Three cases: L-mode (black), ITB (blue), H-mode (red);
- Higher $T_{i0} \geq 2keV$ with $R/L_{T_i} \geq 10$ are observed;
- Bigger pressure gradient contributes negative E_r;

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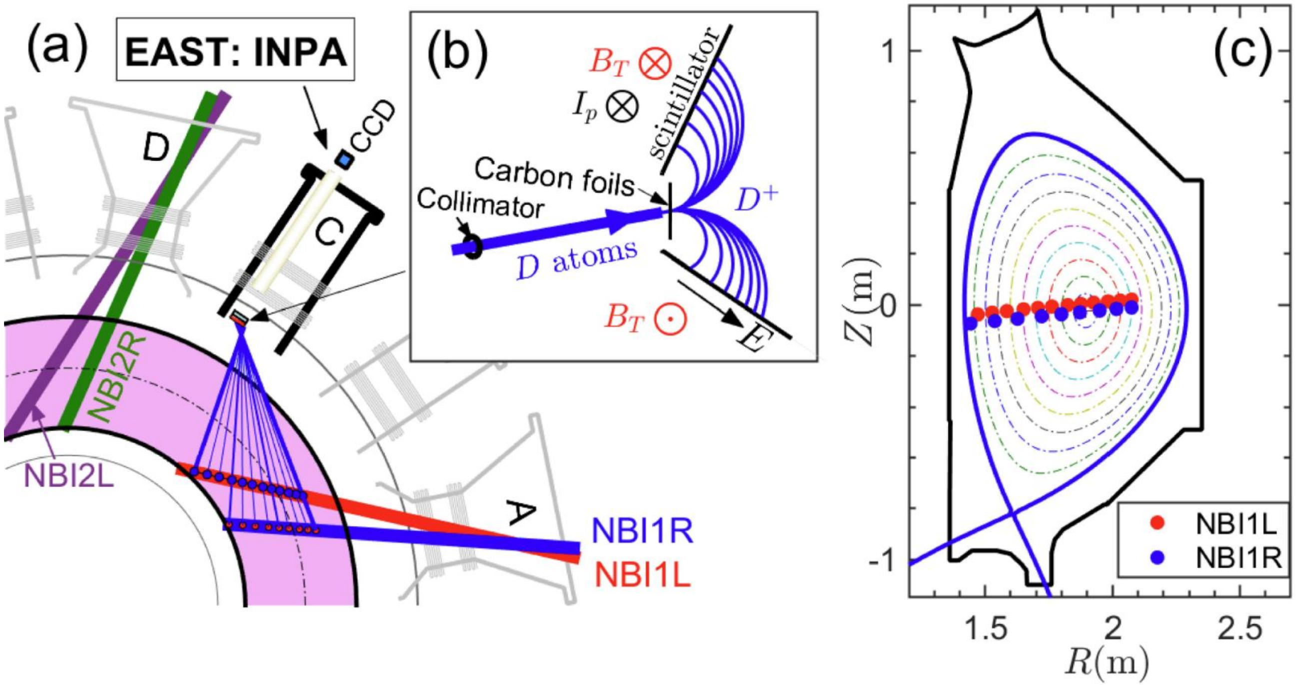
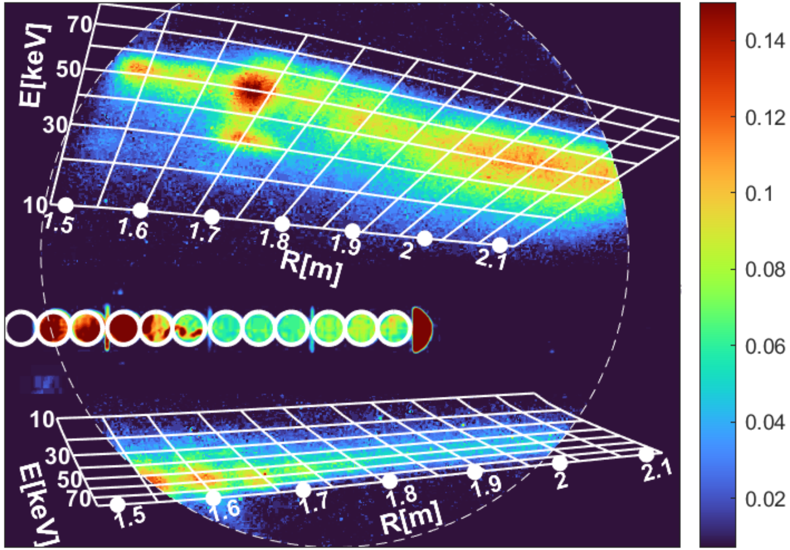
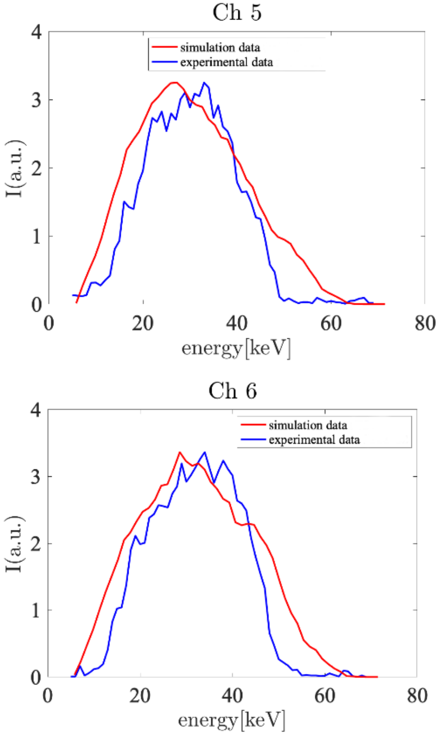
Layout of INPA diagnostic on EAST

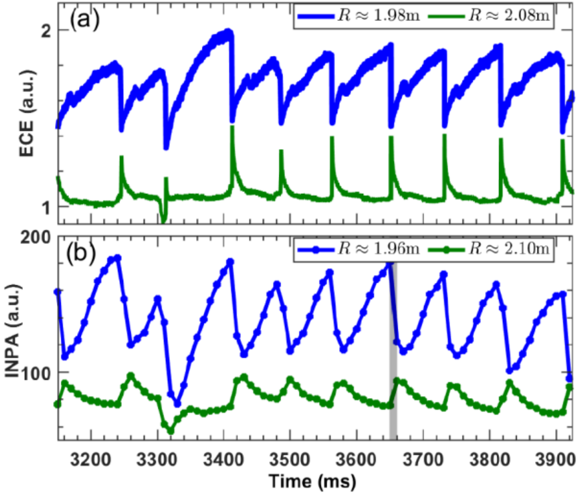


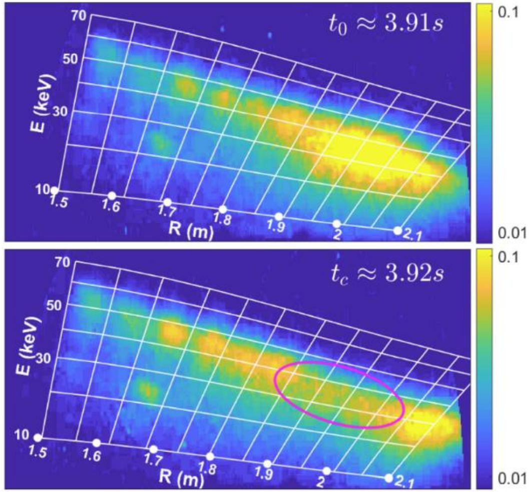
INPA experimental result versus simulation



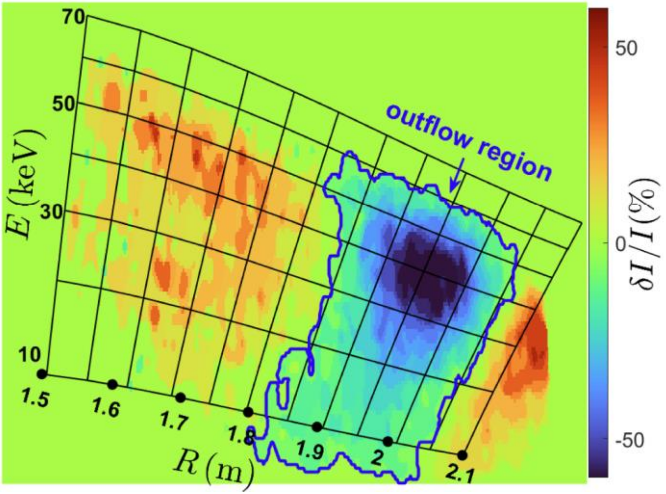


Verified INPA signal through sawteeth instability

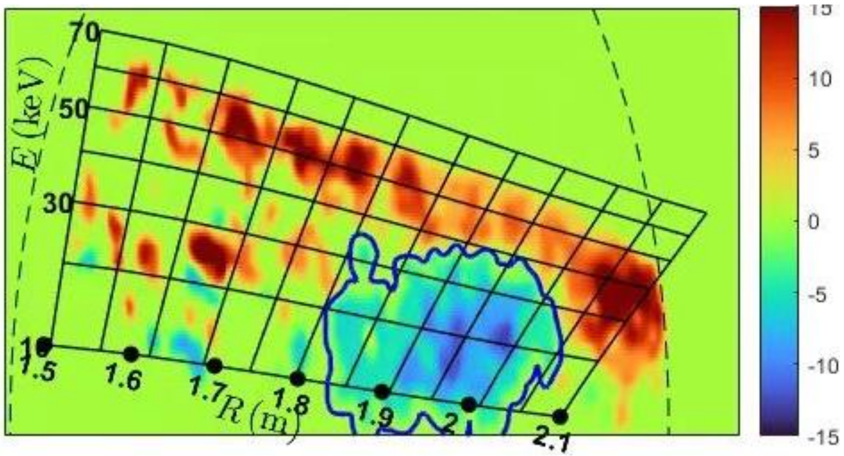




Redistribution of fast ions caused by two different MHD instabilities

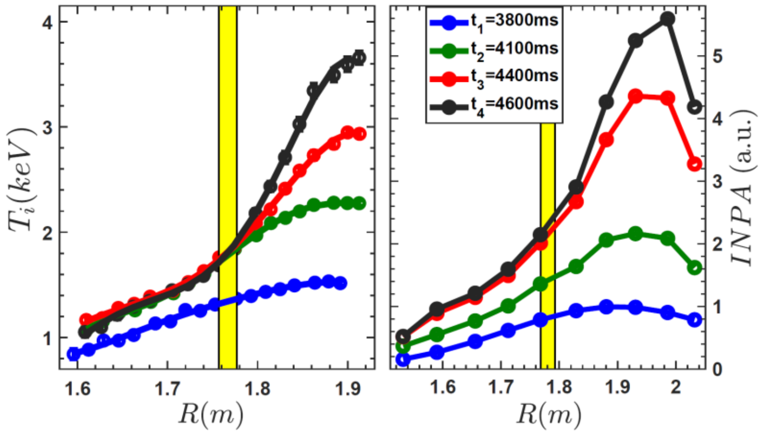


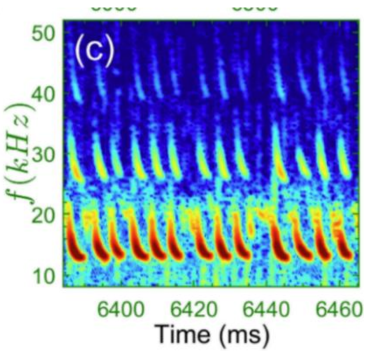
Sawteeth instability

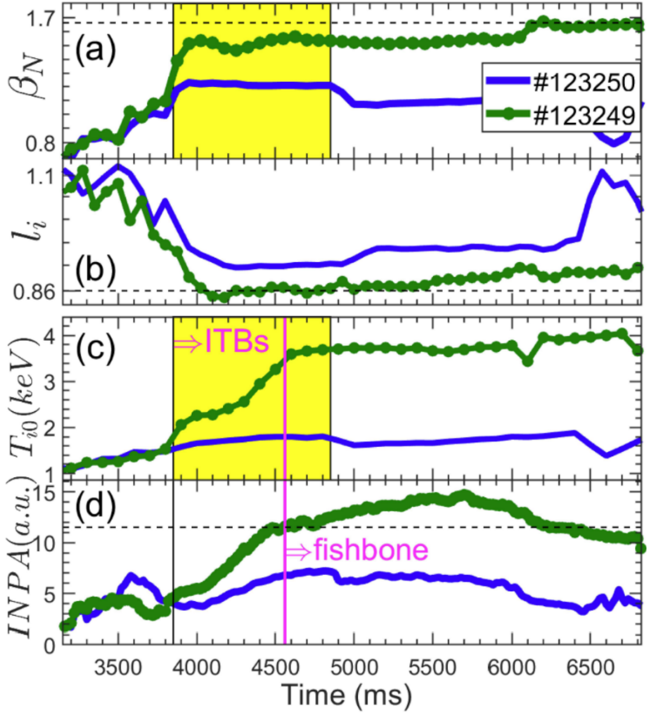


fishbone instability

Establishment of ITB is accompanied by the excitation of fishbone instability and redistribution of fast ions



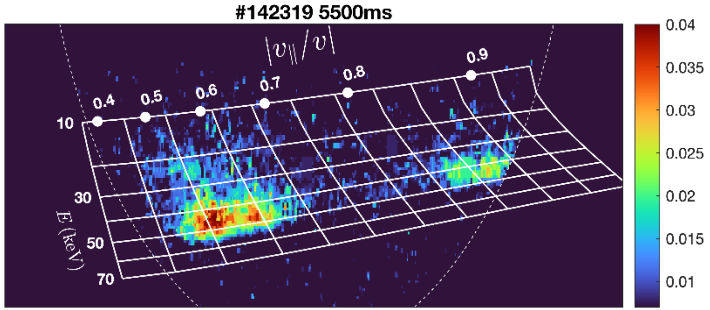


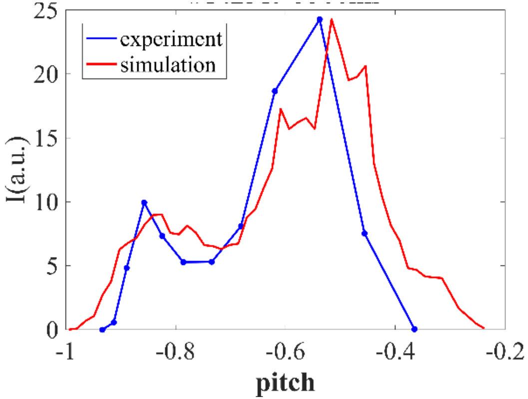


- ITB plasma is formed for #123249 with lower internal inductance;
- The excitation of fishbone instability and redistribution of fast ions are observed subsequently.

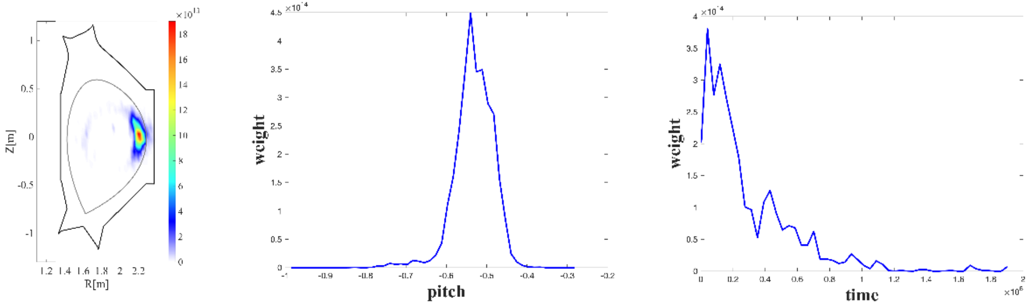
Simulation result about passive NPA signal caused by NBI2L on EAST

--Poster: Synthetic diagnostic of INPA passive signal in EAST

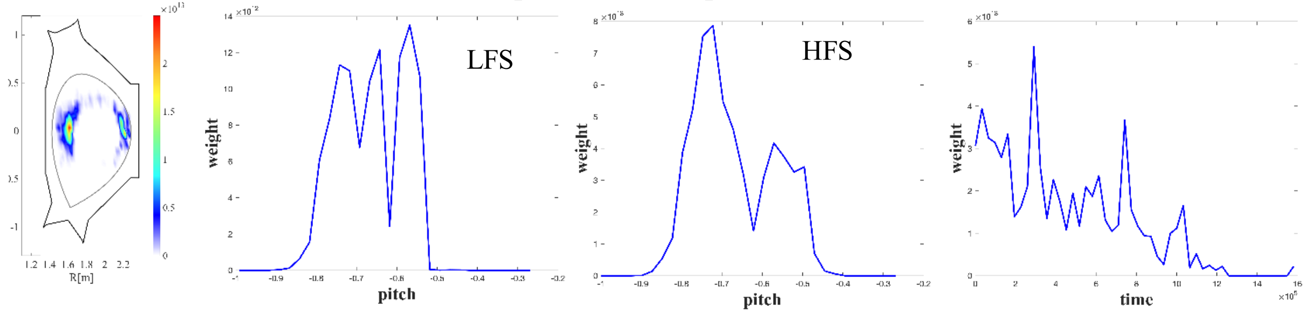




Deposition (-0.4>pitch>-0.6)

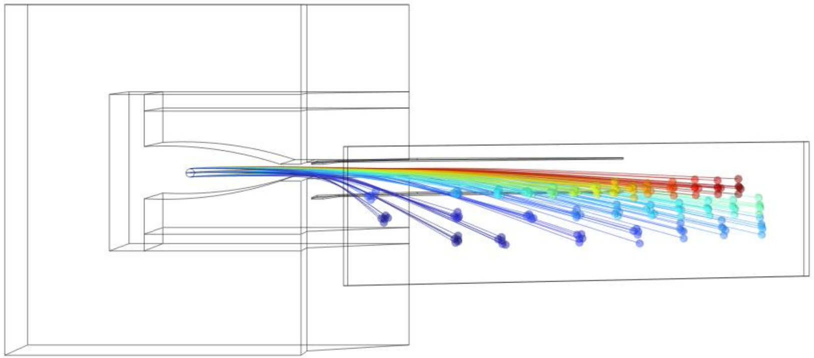


Deposition (-0.8>pitch>-0.9)



- -0.4 > pitch > -0.6: is contributed by the fast ions on LFS, experience a shorter collision time.
- -0.8 > pitch > -0.9: is contributed by the fast ions on HFS, experience a longer collision time.

Future plan for developing of E//B NPA diagnostic on EAST



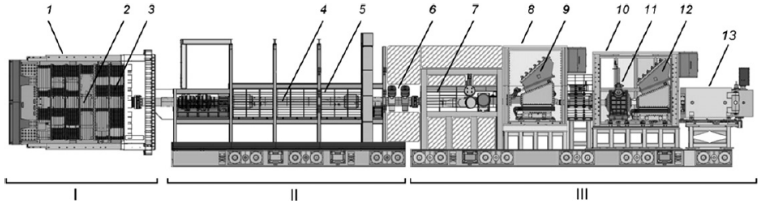
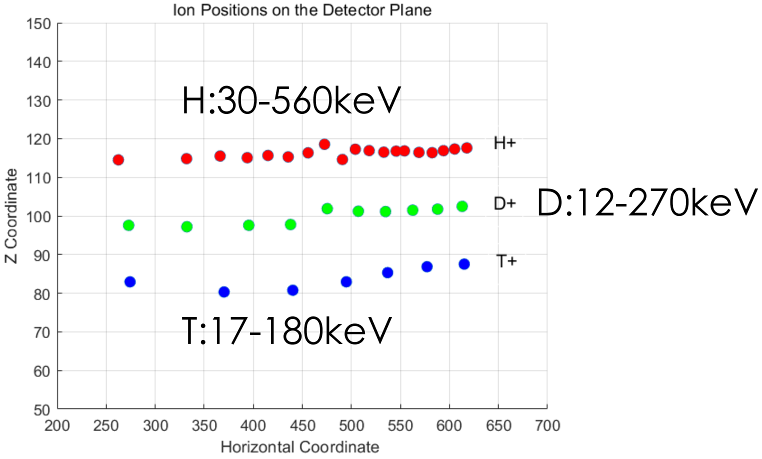
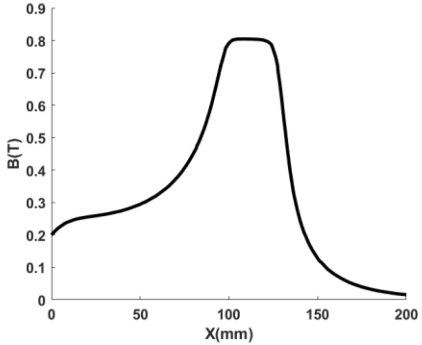


Figure 1. NPA based diagnostic complex in equatorial port #11 of the ITER tokamak: 1 — diagnostic shield module (DSM), 2 — neutron collimator, 3 — neutron shield in the DSM, 4 — NPA vacuum channel, 5 — NPA neutron shield in the interspace area, 6 — double vacuum gate valve, 7 — NPA neutron shield in the port cell, 8 — HENPA magnetic shield, 9 — HENPA, 10 — LENPA magnetic shield, 11 — LENPA accelerator, 12 — LENPA, 13 — neutron dump, I — port plug area, II — interspace area, III — port cell area. The hatched rectangles indicate the space occupied by other diagnostic systems and additional neutron shielding.





OUTLINE

- Operational Region on EAST
  - $q \approx 1$ (fishbone) and $q_{min} \approx 2$ (AEs)
  - DTMs instability at $q_{min} \approx 2$
- RSAEs instability on EAST
  - RSAEs with micro-instability
  - ITB with RSAEs instability
- Development of NPA on EAST
  - Diagnostic of INPA on EAST
  - ITB with fishbone instability
  - Future plan of E//B NPA
- **Conclusion and Discussion**

Conclusion and Discussion

- Two operation regions of EAST are discussed, and the DTM instability is investigated for its important role in determining the reversed q-profile with $q_{min} \approx 2$.
- RSAEs instability has been investigated:
  - Radial coverage: $\mathbf{1.98 \leq R \leq 2.07m}$ (normalized minor radius of $0.2 \leq \rho \leq 0.4$).
  - Toroidal mode number: $\boldsymbol{n \geq 1}$.
  - Thermal ion temperature $\boldsymbol{T_i}$ is increased at the off-axis region.
  - **Micro-instability** featured by outward transport of thermal particles is observed after the excitation of RSAEs instability, which is mitigated for the alteration of magnetic shear.
  - **ITB plasma** is also observed during the upward sweeping frequency of RSAEs, accompanied by higher $R/L_{T_i} \geq 10$ with negative radial Electric field E_r.
- Fast ions diagnostic has been developed on EAST:
  - **INPA** diagnostic is applied, and some important results (sawteeth, fishbone) are analyzed;
  - A plan is in place to develop the **E//B NPA** diagnostic on EAST in the future.

Thank you!