Excitation of Alfven Eigenmodes and Formation of ITB during Off-Axis Sawteeth in EAST Tokamak

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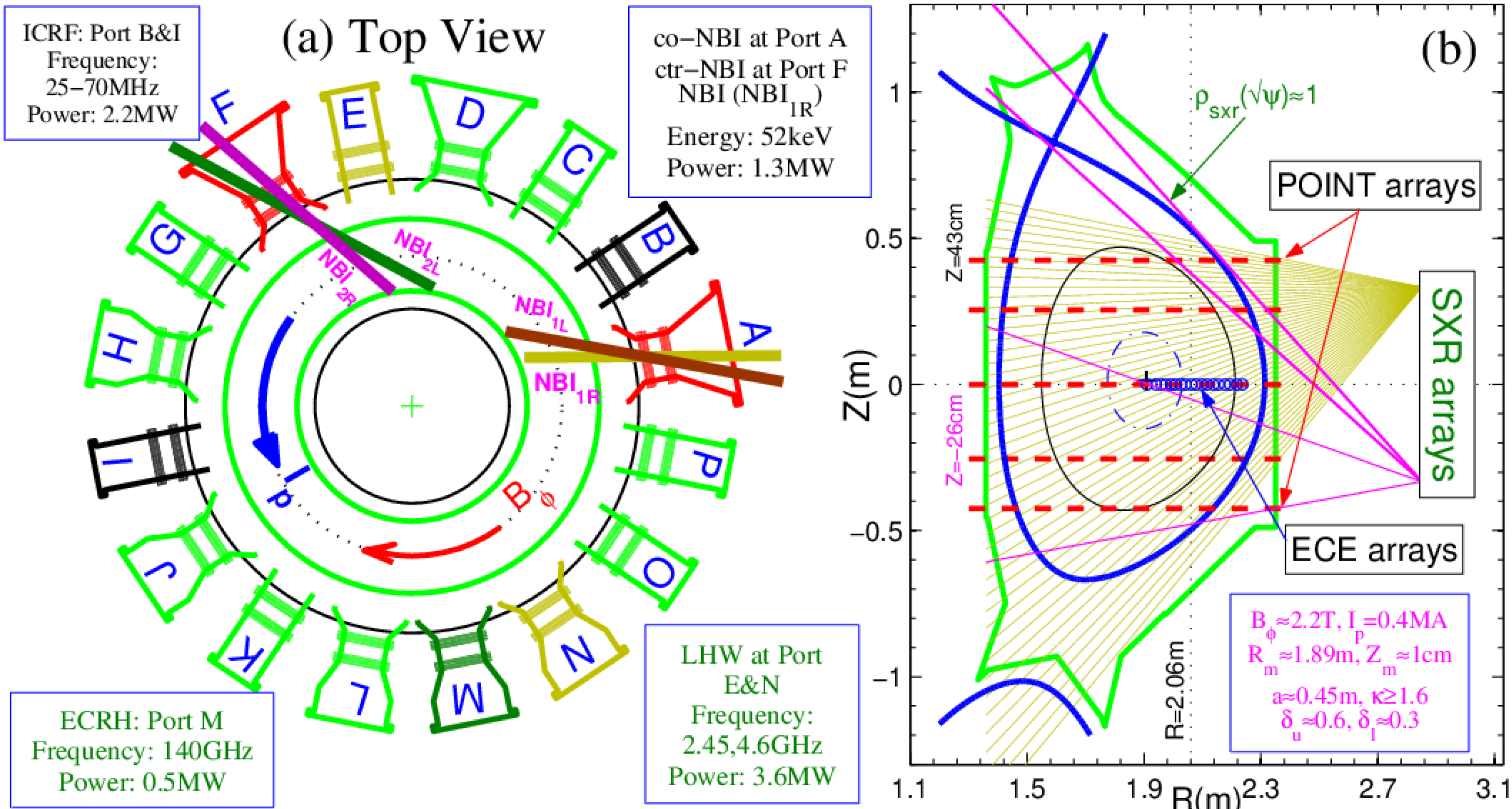
OUTLINE

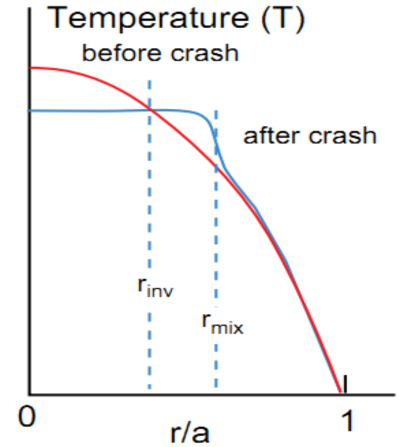
- Background
  - EAST layout
  - On/Off axis Sawteeth
  - $q_{min} \leq 1$ for the upward sweeping of RSAEs
- Experimental Observation in EAST
  - BAEs-RSAEs pairs
  - Transport of Energetic ions and thermal particles
  - Formation of ITB for electron temperature
  - Coexistence of BAAE and BAEs-RSAEs
- Conclusion and Discussion

EAST layout



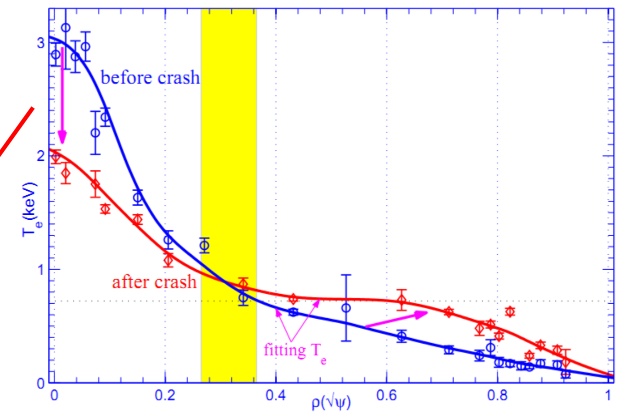
The layout of heating systems on EAST are listed in (a), and partial diagnostics are given schematically in (b), where only the co-NBI with beam NBI_{1R} is used in the following.

Sawteeth on/off-axis Oscillation



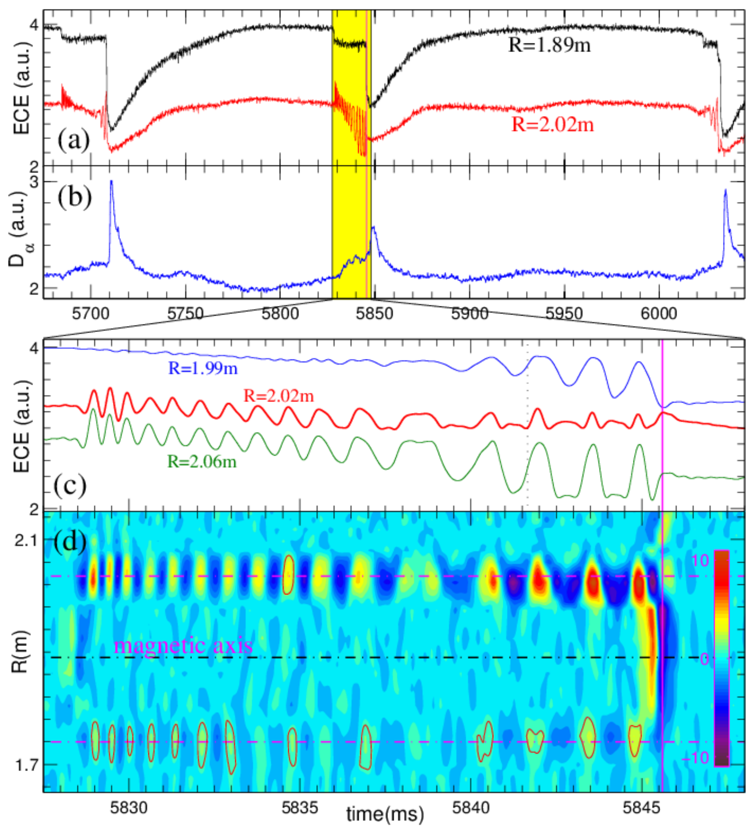
The conventional sawteeth (on-axis) is excited easily for $q_0 \leq 1$, and the precursor mode is characterized by 1/1 kink-tearing mode that rotated along the magnetic axis, and inversion radius and mixing radius are shown in the right.

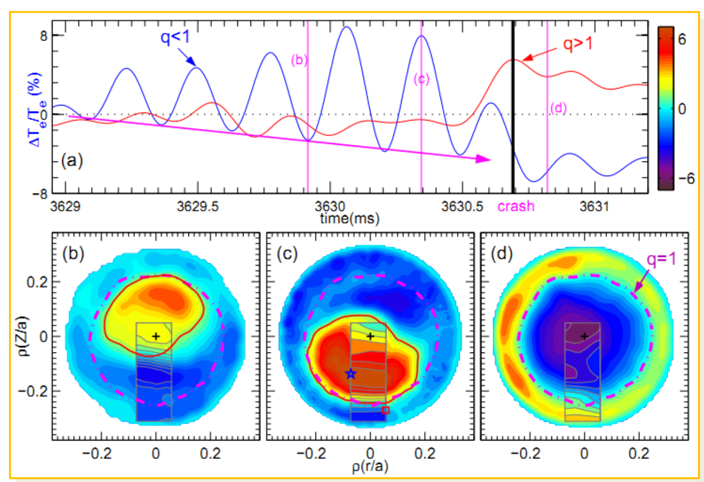
The **off-axis sawteeth** is excited occasionally in EAST for the condition of $q_{min} \leq 1$, and the sawteeth crash is triggered by the magnetic reconnection of double tearing modes, where the mixing radius is disappeared as shown in the right middle figure.



The collapse of off-axis sawteeth oscillation causes strong heat pulse in (a) and (b).

The precursor oscillation is more complicated, and one example is given in (c)-(d): e.g. the transition from kink to tearing instabilities is observed, and the structure of islands can be observed, where the mode number is m=2/n=1.

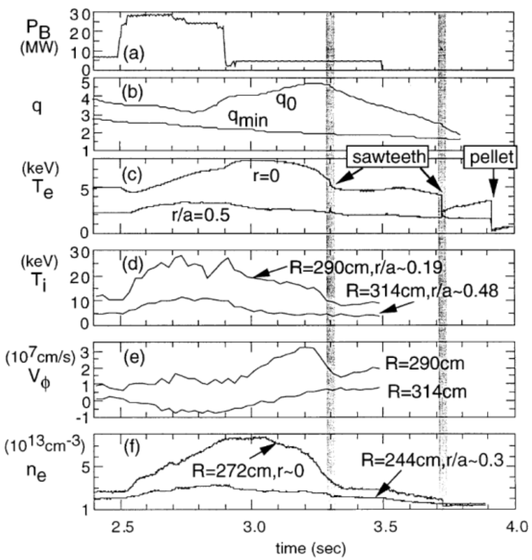


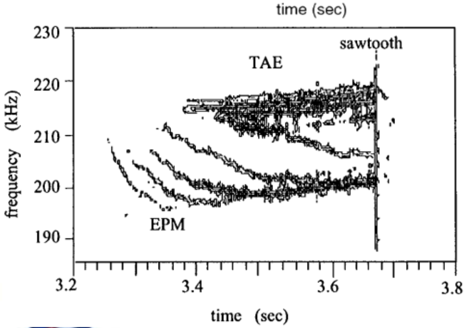


Background: AEs & Sawteeth

The off-axis sawteeth was firstly observed in TFTR that is triggered by the reconnection of m=2/n=1 DTM. Subsequently, abundant of AEs instabilities are observed during the monster sawteeth oscillation, e.g. TAEs and EPM are observed in TFTR(2000), RSAEs and EAEs in JT-60U (1998,2000), TAEs and EAEs in JET(2002), et al. Notes: the energetic ions are produced by the combination of ICRF and NBI, and the monster sawteeth should be one kinds of off-axis sawteeth.

TFTR: Z. Chang PRL 77 3553 (1996)

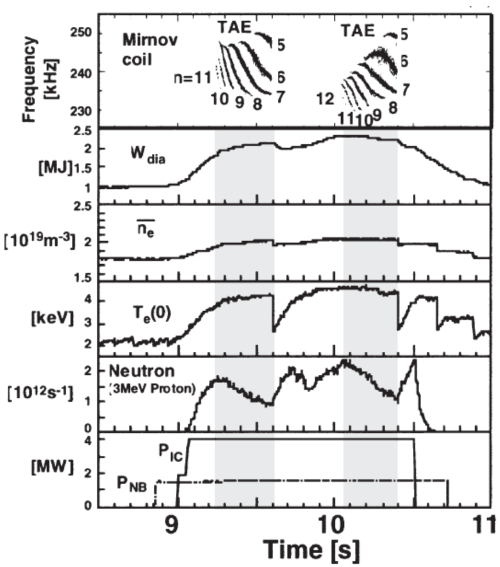




JT-60U: RSAEs

H. Kinura NF 38 1303 (1998)

Y. Kusama NF 38 1215 (1998)

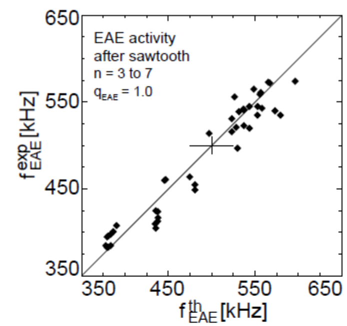


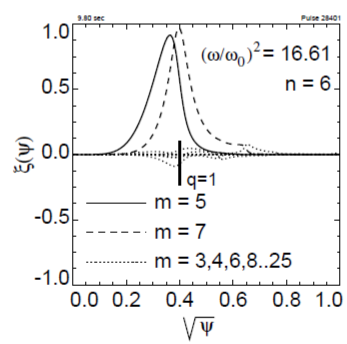
TFTR: TAEs and EPM

S. Bernabei PRL 84 1212 (2000)

JT-60U: EAEs

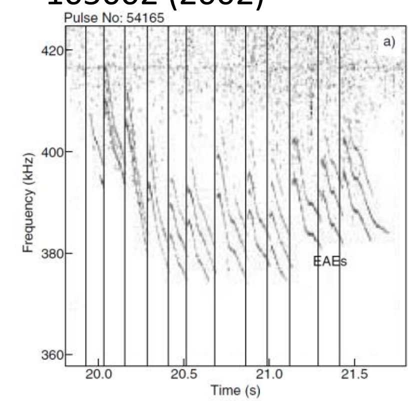
G.J. Kramer NF 40 1383 (2000)

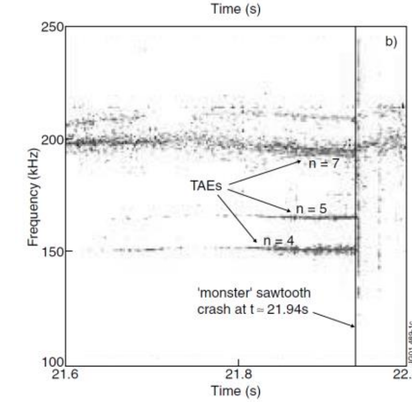




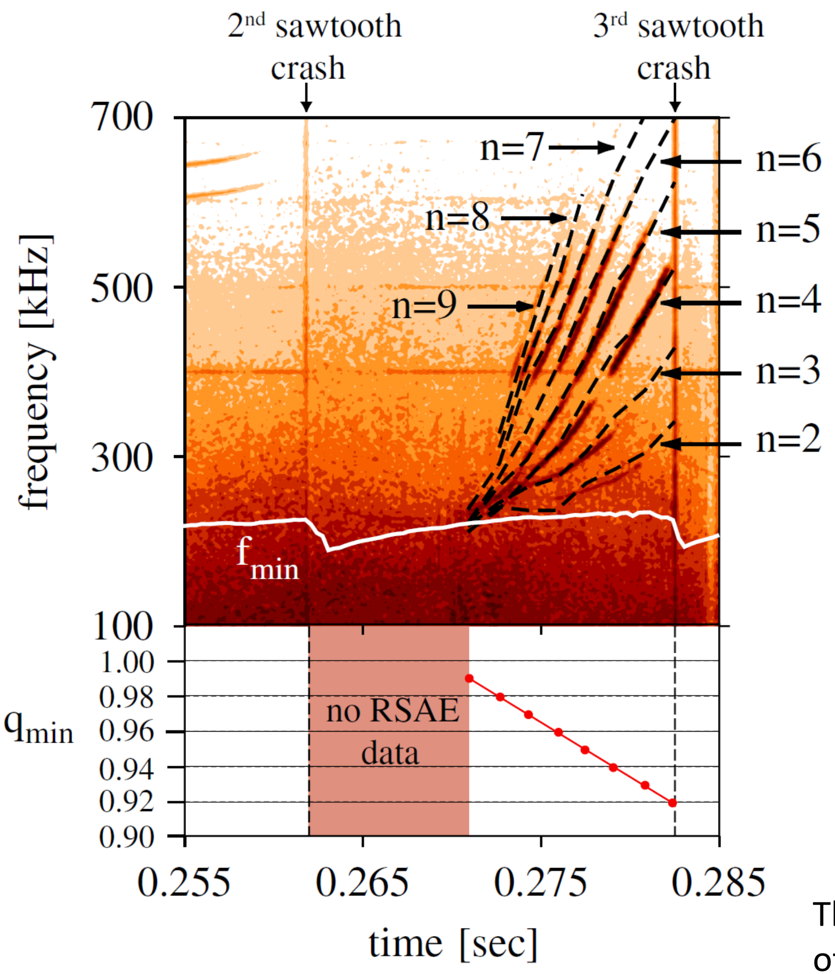
JET: TAEs and EAEs

M.J. Mantsinen PRL 88 105002 (2002)

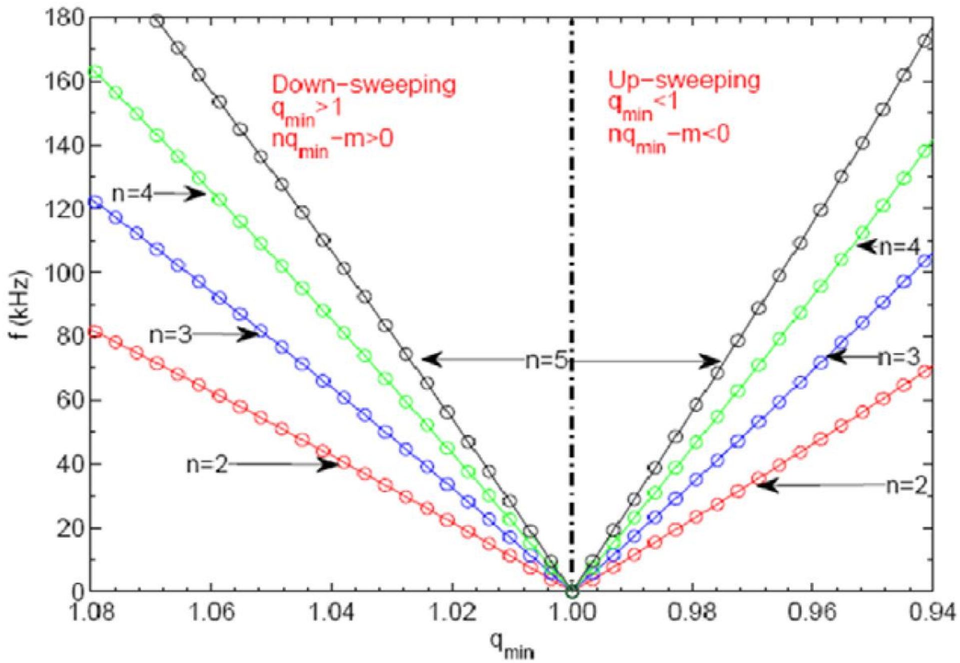




Background: RSAEs versus q_{min}



C-Mod: E.M. Edlund PRL 102 165003 (2009)



HL-2A: W. Chen NF 54 104002 (2014)

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

The simulation by NOVA in C-Mod has shown the upward sweeping of RSAEs with the decreasing of q_{min} .
Similar phenomena in HL-2A clearly show that the $q_{min} = 1$ is the boundary condition of RSAEs, and the upward sweeping of RSAEs can be observed for $q_{min} \leq 1$.

Alfven Eigenmodes and the transport of thermal particles and energetic ions during off-axis Sawteeth oscillation in EAST tokamak

Excitation conditions: off-axis Sawteeth

(a). Total injected powers: 7.6MW, and the **NBI** and **ICRF** are 1.3MW and 2.2MW respectively.

(b). Off-axis sawteeth with period $100 \leq \tau_{saw} \leq 230ms$ are observed, and τ_{saw} are sensitive to the output power of ICRF.

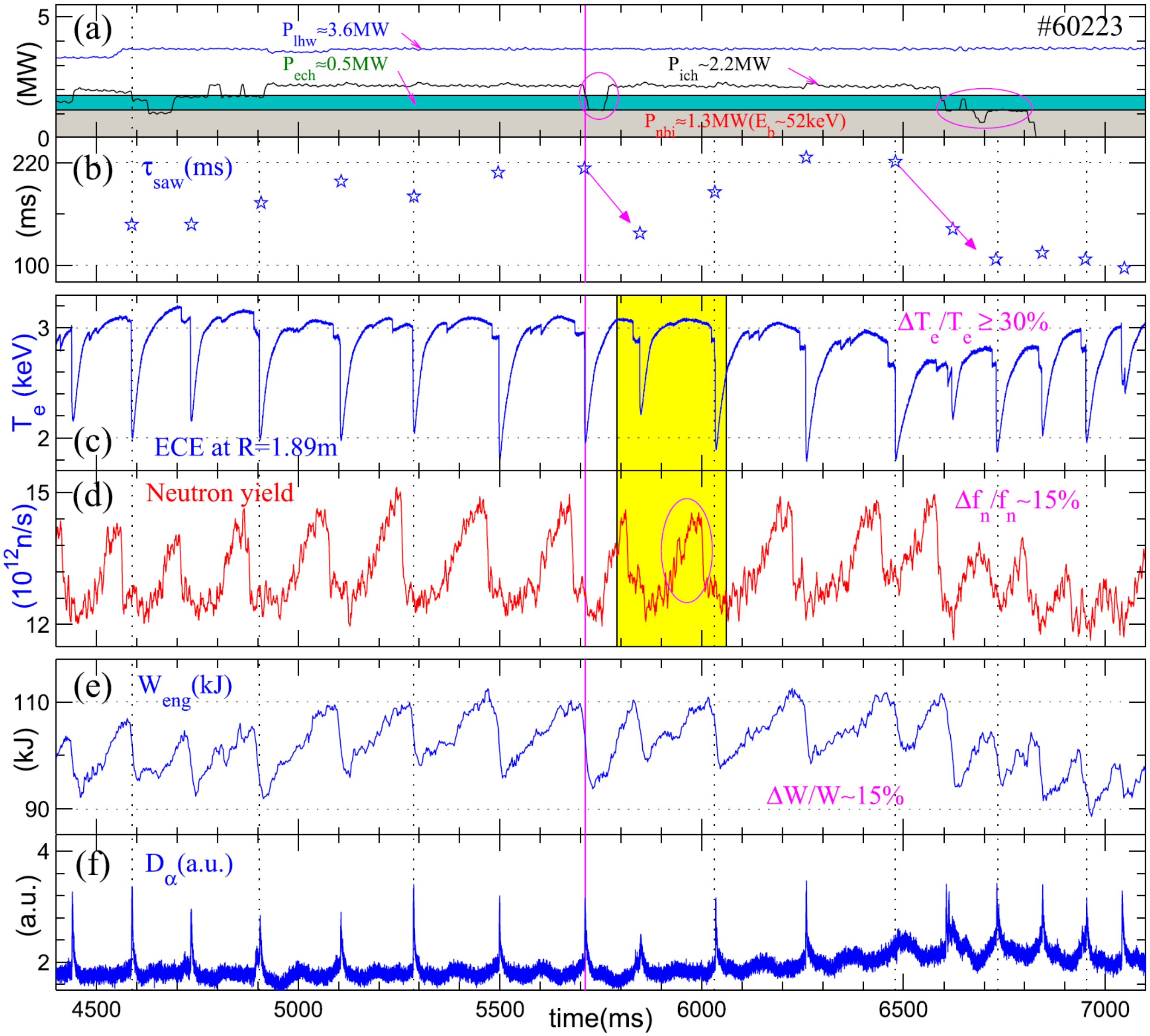
(c). Central electron temperature fluctuation: $\Delta T_e/T_e \geq 30\%$.

(d). Total neutron yield fluctuation: $\Delta f_n/f_n \approx 15\%$.

(e). Plasmas stored energy fluctuation: $\Delta W/W \approx 15\%$.

(f). Plasma facing components are ablated by the collapse of off-axis sawteeth oscillation.

Note: the neutron yield is also modulated by the sawteeth oscillation, and the loss of energetic ions is ahead of the final crash.



BAEs-RSAEs pairs during Sawteeth Oscillation

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

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

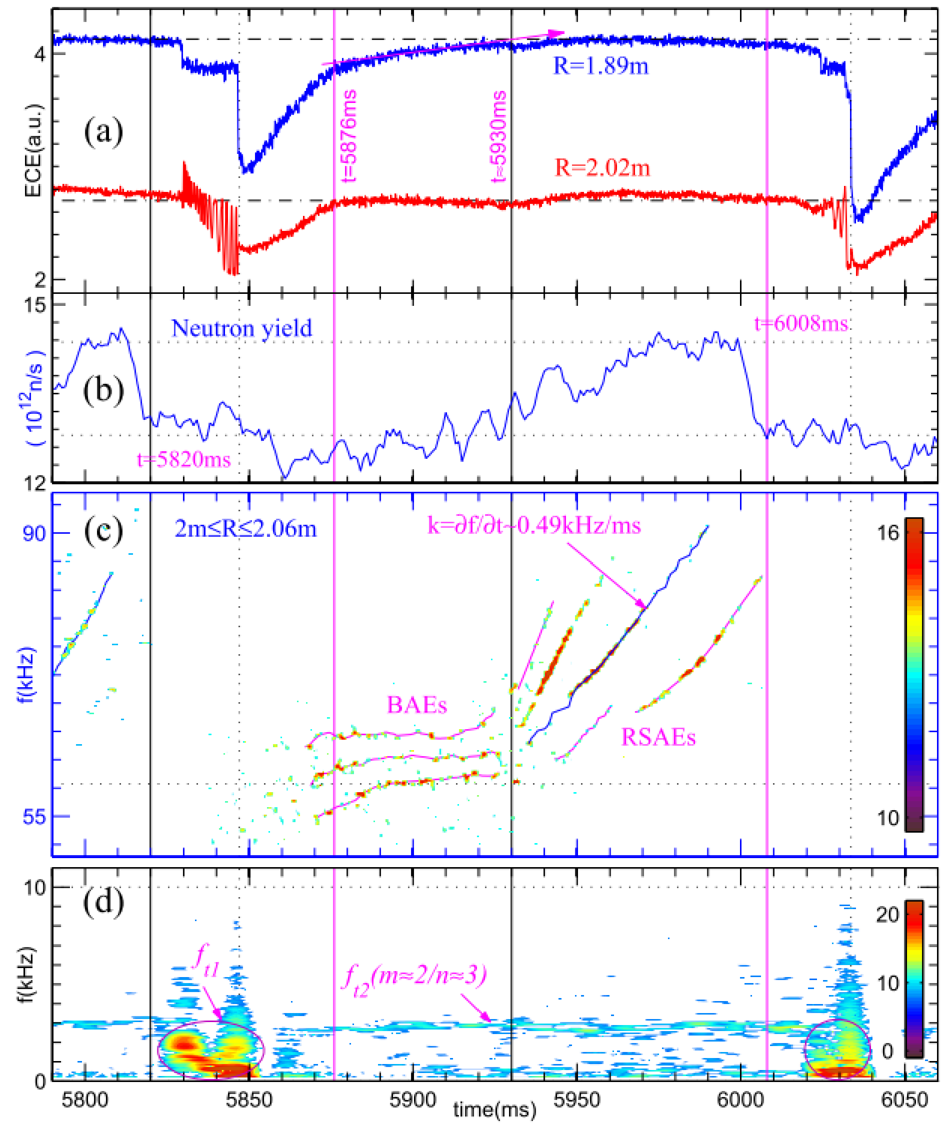
MHD spectroscopy can be explained the transition from BAEs to RSAEs successfully, and one example is shown in the right.

The minimum frequencies of RSAEs can be achieved as given in formula (1), i.e. the third item is omitted when q_{min}=m/n=integer, and $\omega_{RSAE,min} \approx \omega_{BAE}$.

The transition from BAEs and RSAEs are taken place when $q_{min} \neq m/n$, and the frequencies of RSAEs increase with decreases of q_{min}, where the $q_{min} \leq 1$ [1,2] for the upward sweeping.

The bigger poloidal mode number m has higher slope according to the formula (2), and the ratio of the slopes for the above three branches is 2:3:4.

The neutron yield increases dramatically with decreasing of q_{min}.



[1]. E.M. Edlund, et al PRL 102 165003 (2009)
[2]. W. Chen, et al NF 54 104002 (2014)

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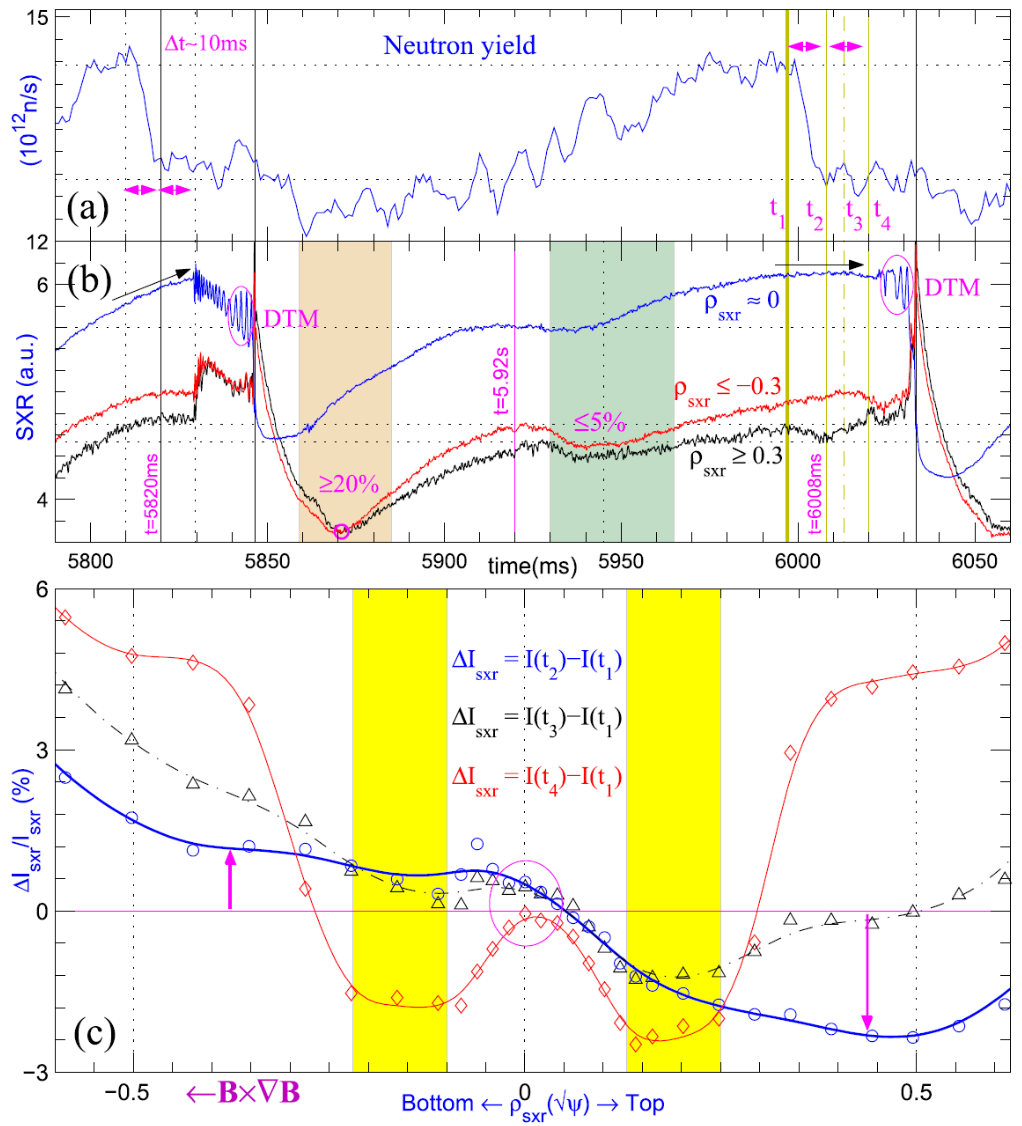
Transport of energetic ions

The collapse of Neutron yield is ahead of sawteeth final crash with $\Delta t \geq 20ms$.

Interestingly, the SXR arrays are sensitive to the activities of energetic ions, e.g. four moments are selected, and the neutron yield is fully collapsed at t=6008ms.

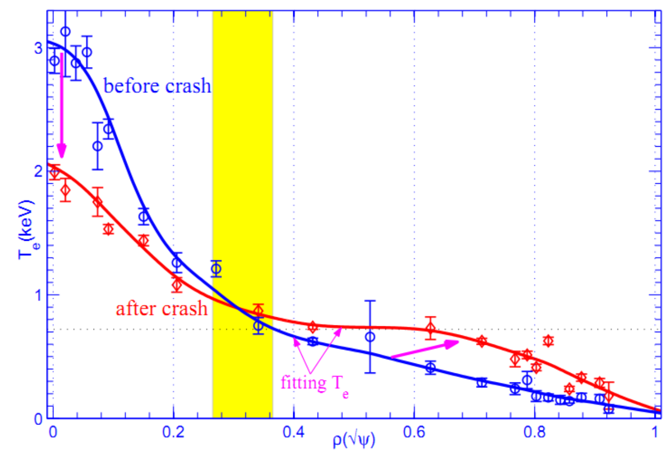
- The outward transport of energetic ions are taken place for $t \geq t_1$, and the intensities of SXR arrays in top section with $\rho_{sxr} > 0$ decrease accordingly.
- The decreasing of SXR signals are terminated at t=6008ms when the loss of energetic ions are over, where the SXR signals with $\rho_{sxr} \approx 0$ sustain stably, while the intensities at $\rho_{sxr} < 0$ are not influenced.
- The energetic ions in the top section are lost swiftly and can be captured by SXR arrays, where the ion $B \times \nabla B$ drift direction is downward.
- Subsequently, the heat particles at the position of q_{min} are decreasing gradually, and one possible condition of q_{min} is increasing, where the SXR signals with $\rho_{sxr} > 0.3$ are restored swiftly.



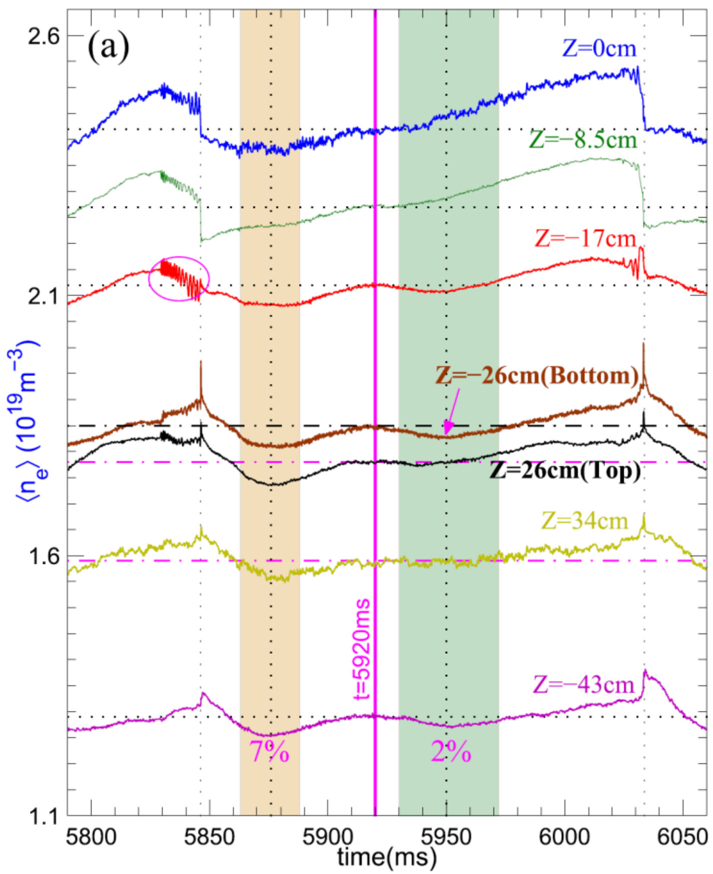
Formation: e-ITB

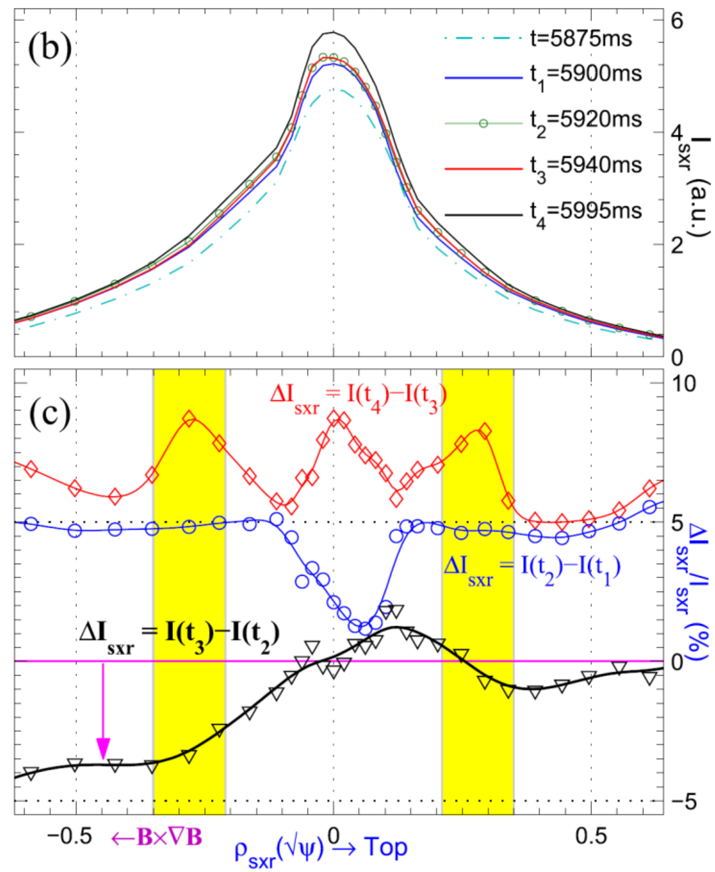
The steep electron temperature is formed in the central region after the excitation of RSAEs, namely the e-ITB is formed accordingly.

Interestingly, several inflection points (t=5875ms, t=5920ms, t=5950ms) can be observed during the formation of e-ITB, and the process can be divided into three stages with different gradients of electron temperature: k_1, k_2, k_3, and $k_1 < k_2 \leq k_3$.



- t=5875ms, the outward transport of thermal particles are suppressed for k_1.
- t=5920ms, the electron densities at bottom section with Z<0 decrease for further increasing of k_2 (in the direction of the ion $B \times \nabla B$ drift direction), namely one kinds of turbulence is formed.
- t=5930ms, the transition from BAEs to RSAEs are taken place.
- Note: the confinement is excellent after the formation of e-ITB, and the SXR signals at q_{min} increase dramatically.





Discussion: (1) Excitation of BAAE, (2) Interaction among energetic ions, BAAE and BAEs-RSAEs

- New branch is observed under the BAEs, and the characteristics of upward sweeping frequency is also observed when the q_{min} decreases, namely as BAAE.
- The position of BAAE locates outward than the BAEs, which has been predicted in Ref [1].
- The excitation condition of BAAE strongly relied on the proportional of energetic ions.

Some nonlinear interaction should exist among energetic ions, BAAE and BAEs-RSAEs, e.g. new branch of RSAE with low mode number is excited after the terminated of BAAE.

The BAAE should be excited when $\tau_{saw} > 85$ms, and can be detected when $\tau_{saw} \geq 110$ms in EAST.

It seems that the energetic ions produced by ICRF is more important for the excitation of BAAE, and the relationship between BAAE and e-ITB?

[1] J. Cheng POP 24 092516 (2017)

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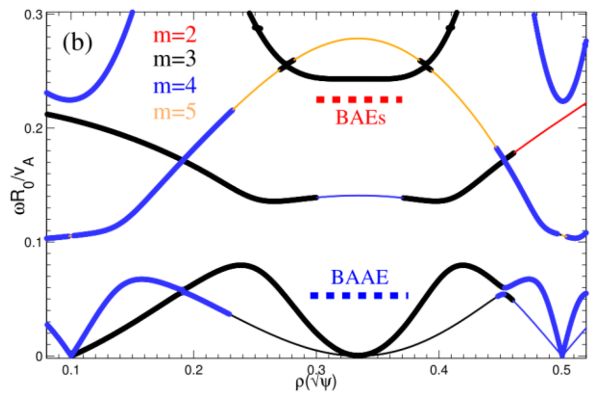

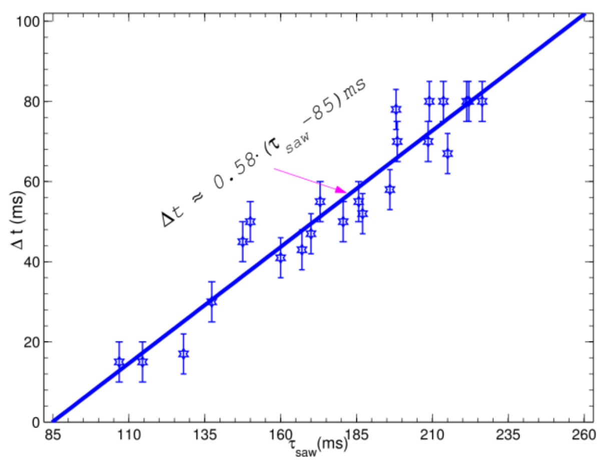

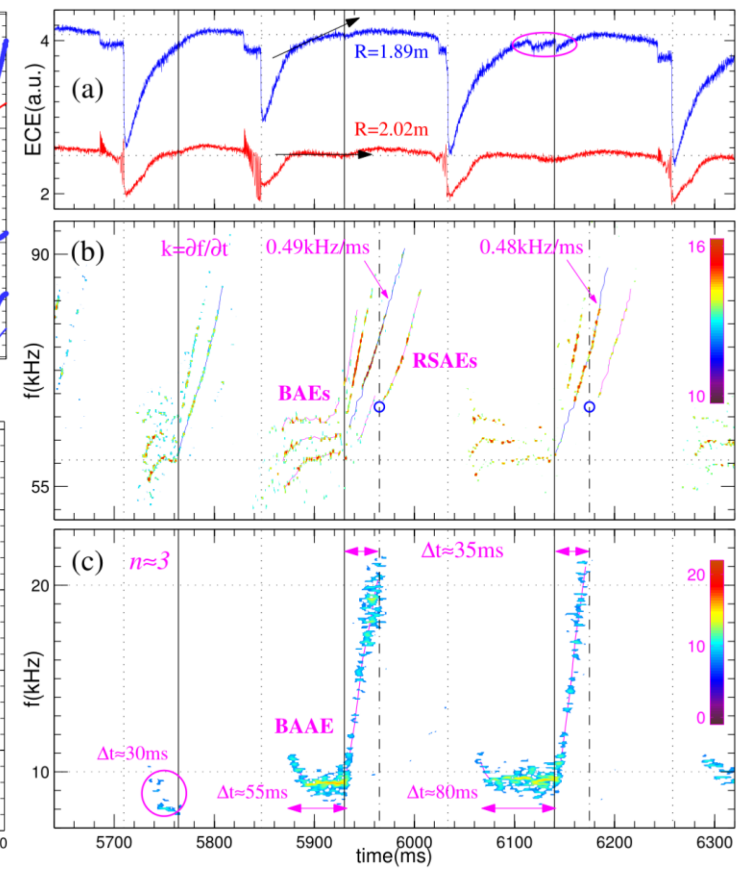

Conclusion and Discussion

- The off-axis sawteeth is excited in EAST, and the condition of $q_{min} \leq 1$ can be confirmed by the transition from BAEs to RSAEs.
- The e-ITB (electron temperature internal transport barrier) is formed during off-axis sawteeth oscillation, and three typical characteristics are observed for the formation.
  - Big transport process has been terminated firstly;
  - Small scale turbulence is produced secondly during the forming of e-ITB;
  - E-ITB is formed eventually during the transition of BAEs-RSAEs.
- Two kinds of transport processes are given and compared for the thermal particles and energetic ions, and the transport of energetic ions have been detected indirectly by the horizontal SXR arrays for the first time.
  - Transport of thermal particles is observed in the bottom section;
  - Transport of energetic ions can be detected in the top section.
- The coexistence of BAAE and BAEs-RSAEs are also observed during the off-axis sawteeth oscillation, and the possible interplay among energetic ions, BAAE and BAEs-RSAEs will be discussed in future.

Thank you very much!