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2D Te patterns of various disruptive events and retardation of turbulence-associated disruption with the non-resonant magnetic field

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Introduction

- Most disruptions are caused by nonlinear growth of MHD instabilities
  - They are inherently complex process
- High dimensional diagnostics are essential to study the nonlinear evolution of the disruptive instabilities
  - The better understanding would allow the better mitigation/avoidance or the earlier warning
- In KSTAR experiments, various disruptive events have been observed by a local 2D electron temperature (T_e) diagnostics (Electron Cyclotron Emission Imaging, ECEI)

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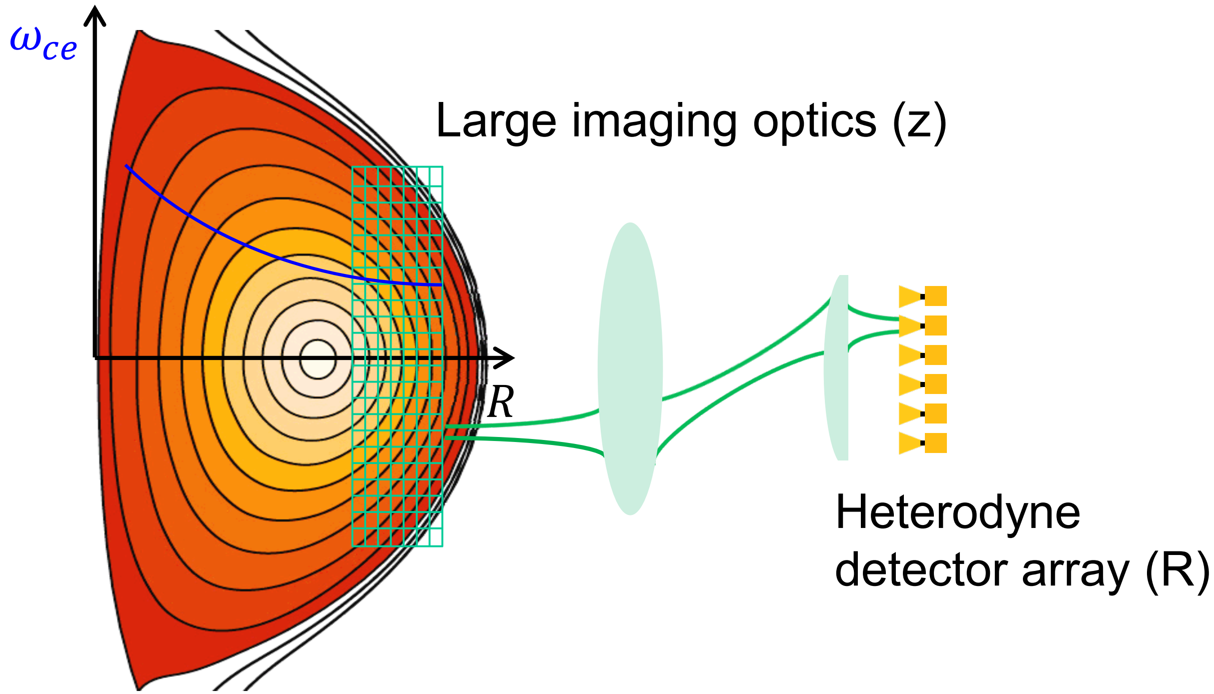
KSTAR ECEI diagnostics

- In tokamaks, $\omega_{ce}(R,z) \propto B(R,z) \approx B_t(R) \propto 1/R$
- If the plasma is *optical thick* for radiation at some frequency ω, radiation intensity = black body level, $I(\omega) = I_{\text{BB}}(\omega) = \frac{\omega^2}{8\pi^3 c^2} T_{\text{e}}$

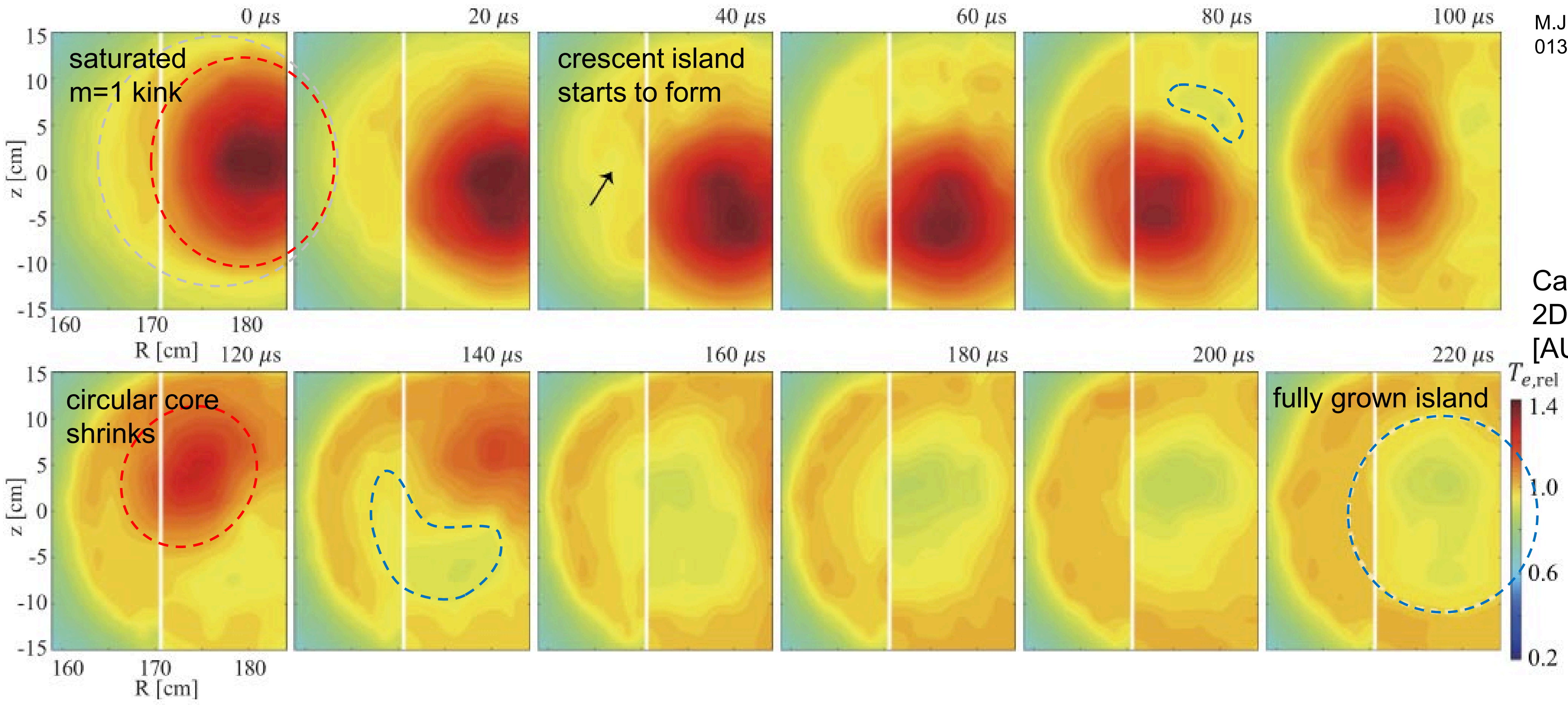


- KSTAR ECEI
  - 3 ECEI systems at two toroidal ports
  - Diagnostics characteristics
    - Spatial resolution ~ 2 cm
    - Temporal resolution ~ 1 us

Outline

- 2D observations of various disruptive events
  - Sawtooth crash (m=1 internal kink driven magnetic reconnection)
    - Off-normal sawtooth crash (m=3)
  - Tearing mode disruption
  - Interchange mode disruption
  - Multi mode disruption (kink + tearing + interchange)
  - Anomalous cases
    - Ballooning fingers in density limit disruption
    - T_e turbulence in locked mode disruption
- Retardation of the turbulence-associated locked mode disruption with the additional non-resonant magnetic perturbation (NRMP) field

Sawtooth crash: m=1 internal kink driven disruption



M.J. Choi, RSI, 87, 013506, 2016

Calibrated 2D T_e profile [AU]

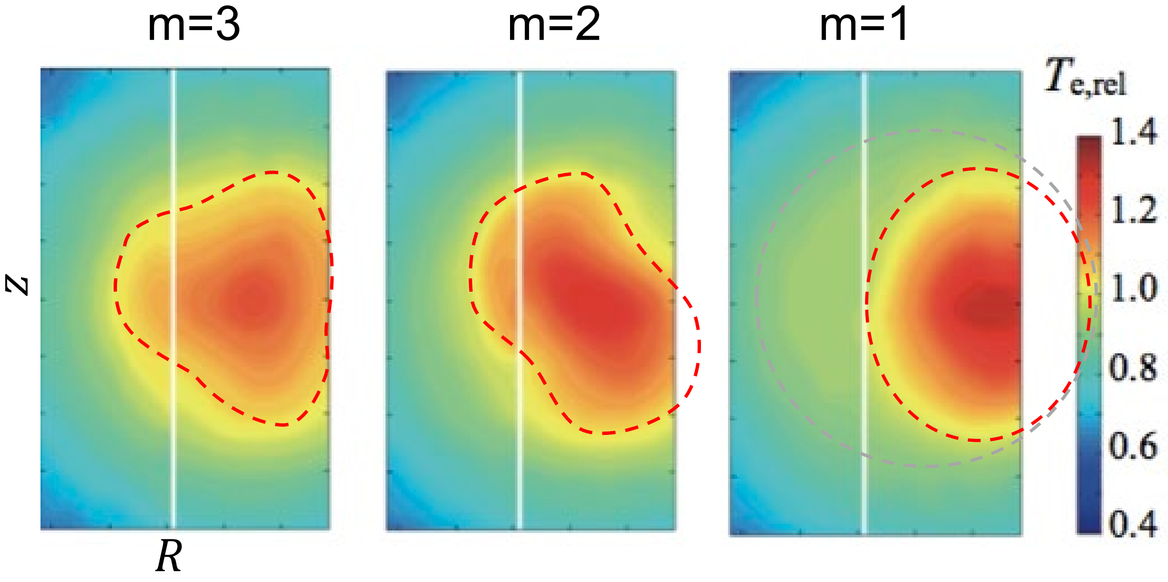
- m=1 kink → Crescent island growth + shrinkage of circular hot core → Full reconnection until the island is fully grown

H.K. Park, Advances in Physics X, 4, 1633956, 2019

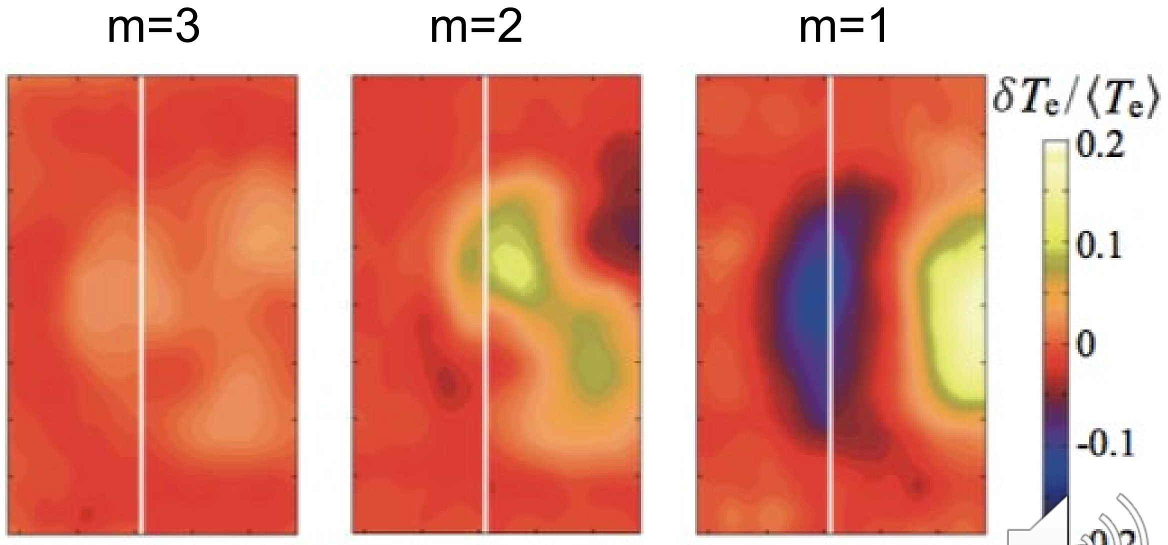
$m \geq 1$ kink modes in the ECE image

- ECRH is often used to control the sawtooth crash
- ECRH around q=1 leads to onset of m>1 modes G.S. Yun, PRL, 109, 145003, 2012 G.H. Choe, NF, 55, 013015, 2015
- $(T_e - \langle T_e \rangle)/\langle T_e \rangle$ images are useful to identify the mode structure

Flux displacements by kink modes in calibrated 2D T_e profiles



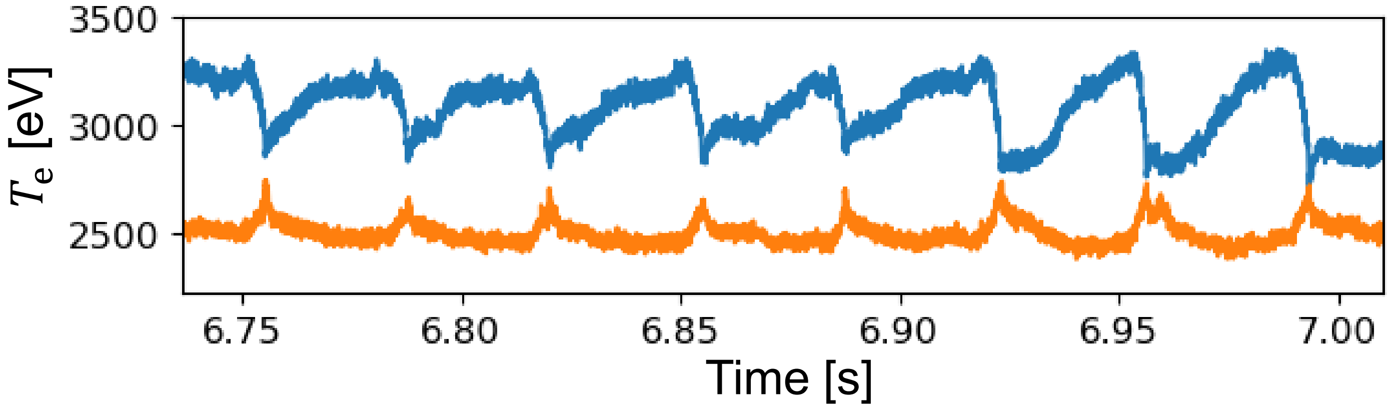
Normalized T_e perturbation of kink modes in $(T_e - \langle T_e \rangle)/\langle T_e \rangle$ images



M.J. Choi, RSI, 87, 013506, 2016

Off-normal sawtooth crash with m=3

- Discharge condition
  - $B_T = 3.0$ T, $I_p = 0.5$ MA, $q_{95} = 7.0$, NBI ~ 4.0 MW, ECRH ~ 0.8 MW, L-mode limiter plasma



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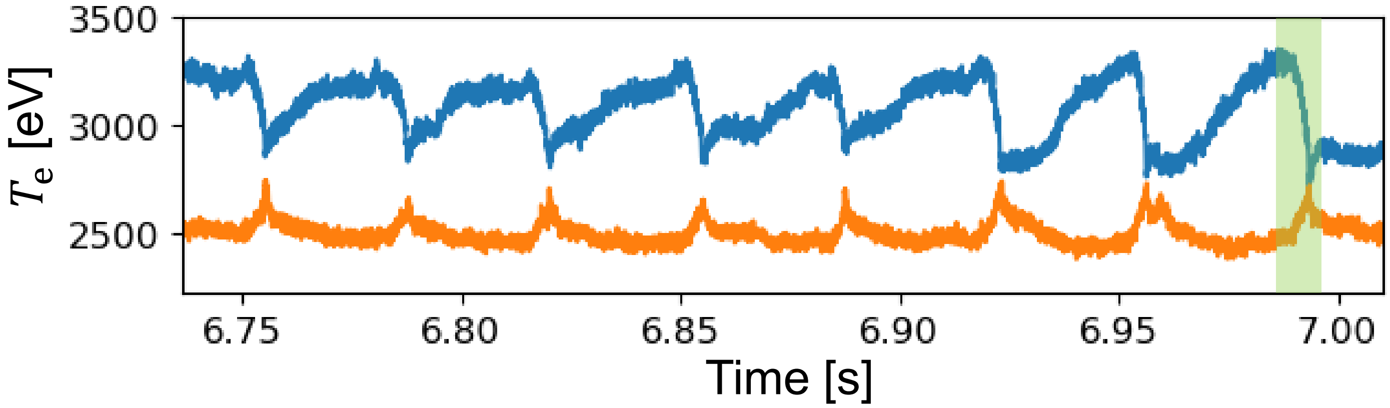
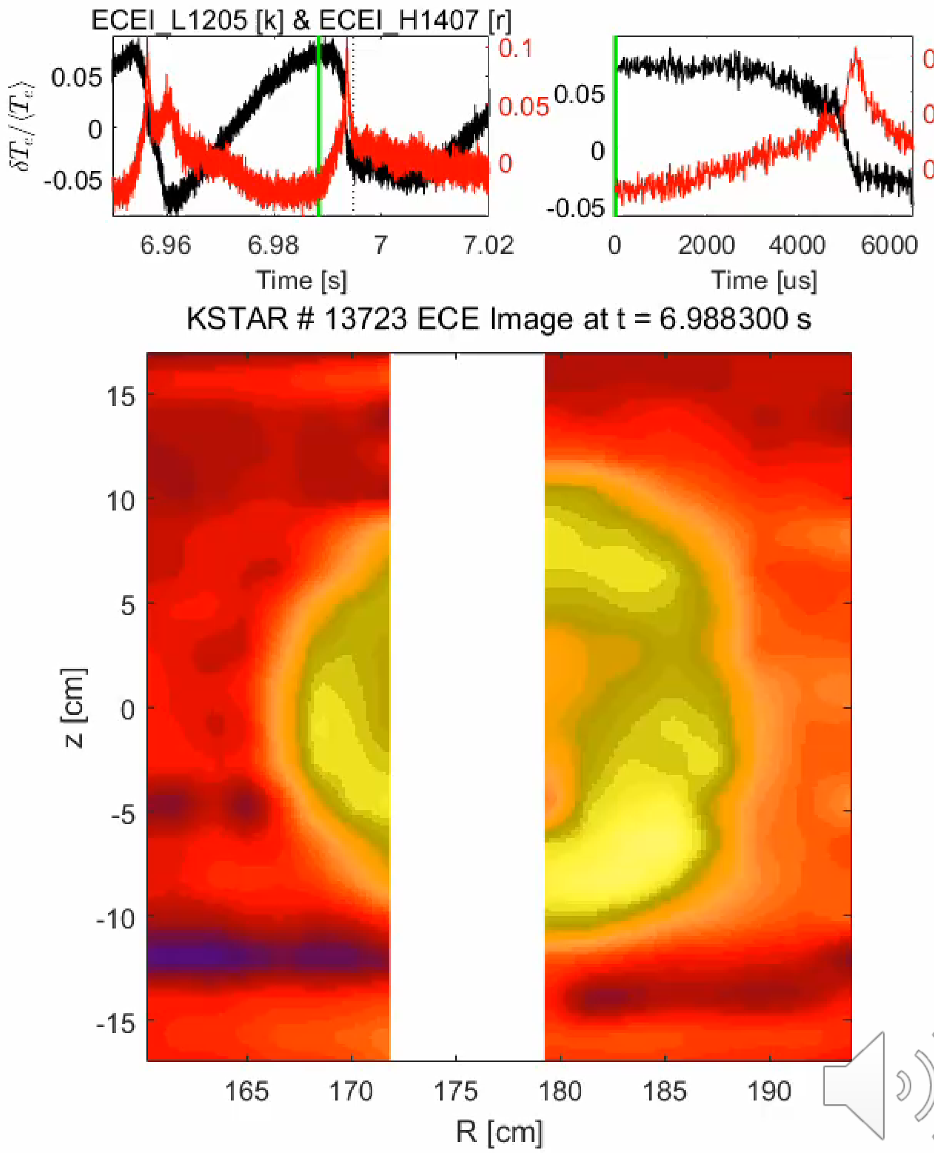


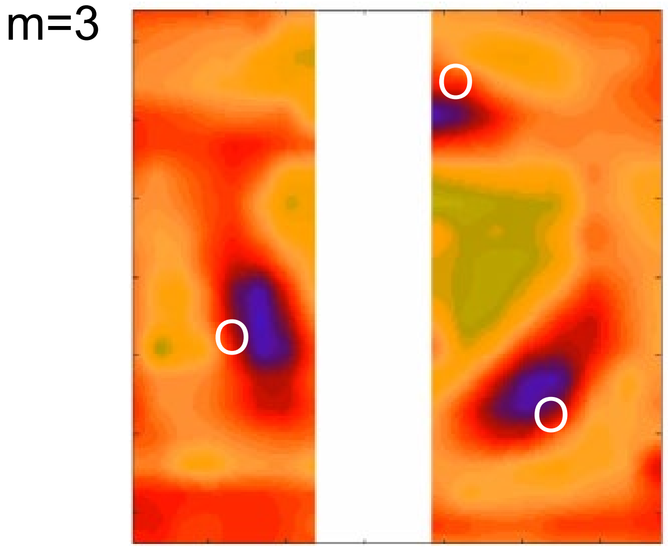
- m=3 kink → Slow leakage of heat with island growth → Fast heat release with poloidally overlapping islands

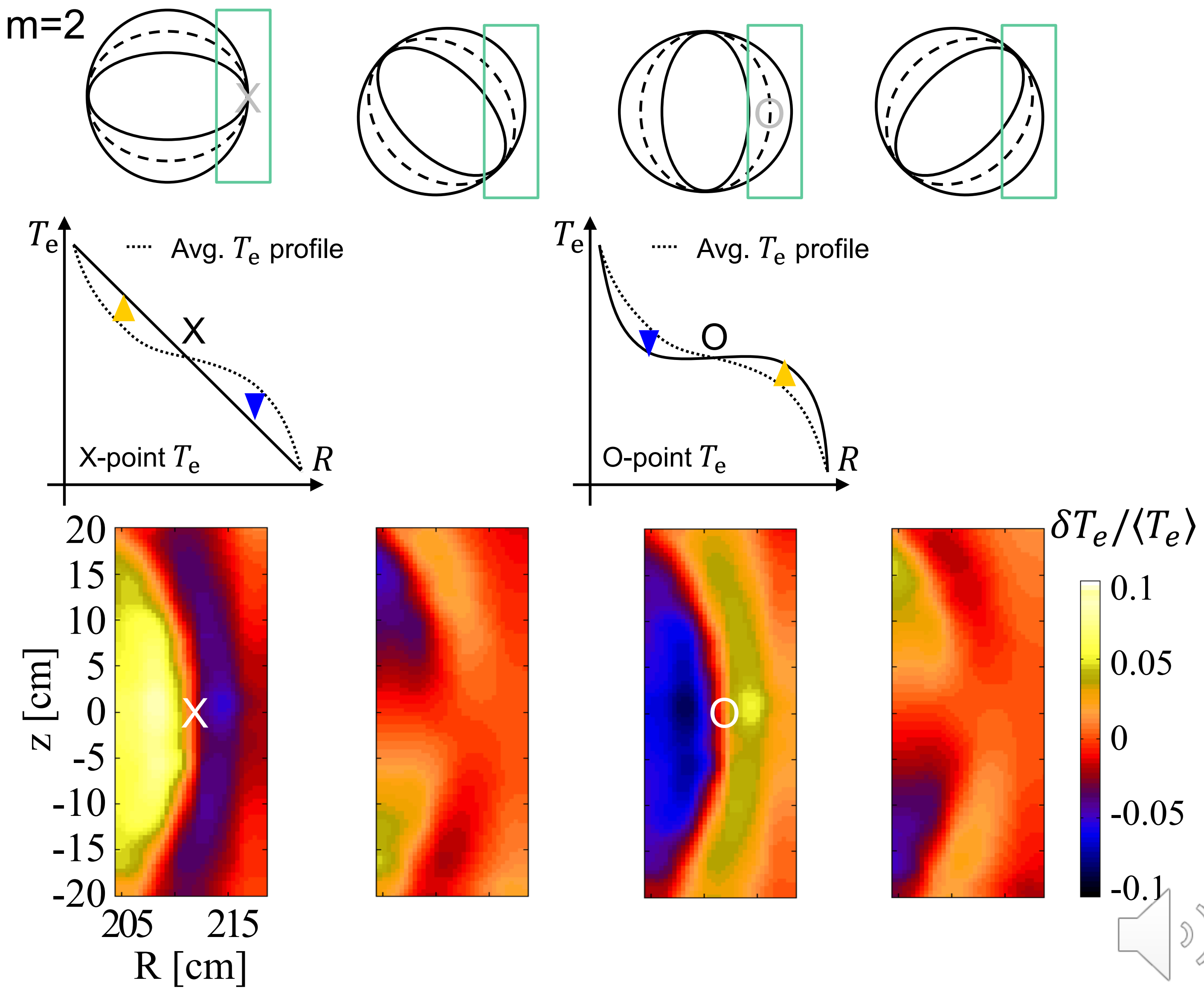


Rotating magnetic island in the ECE image

- $\delta T_e/\langle T_e \rangle$ images of magnetic island show a radial phase inversion across X/O-point

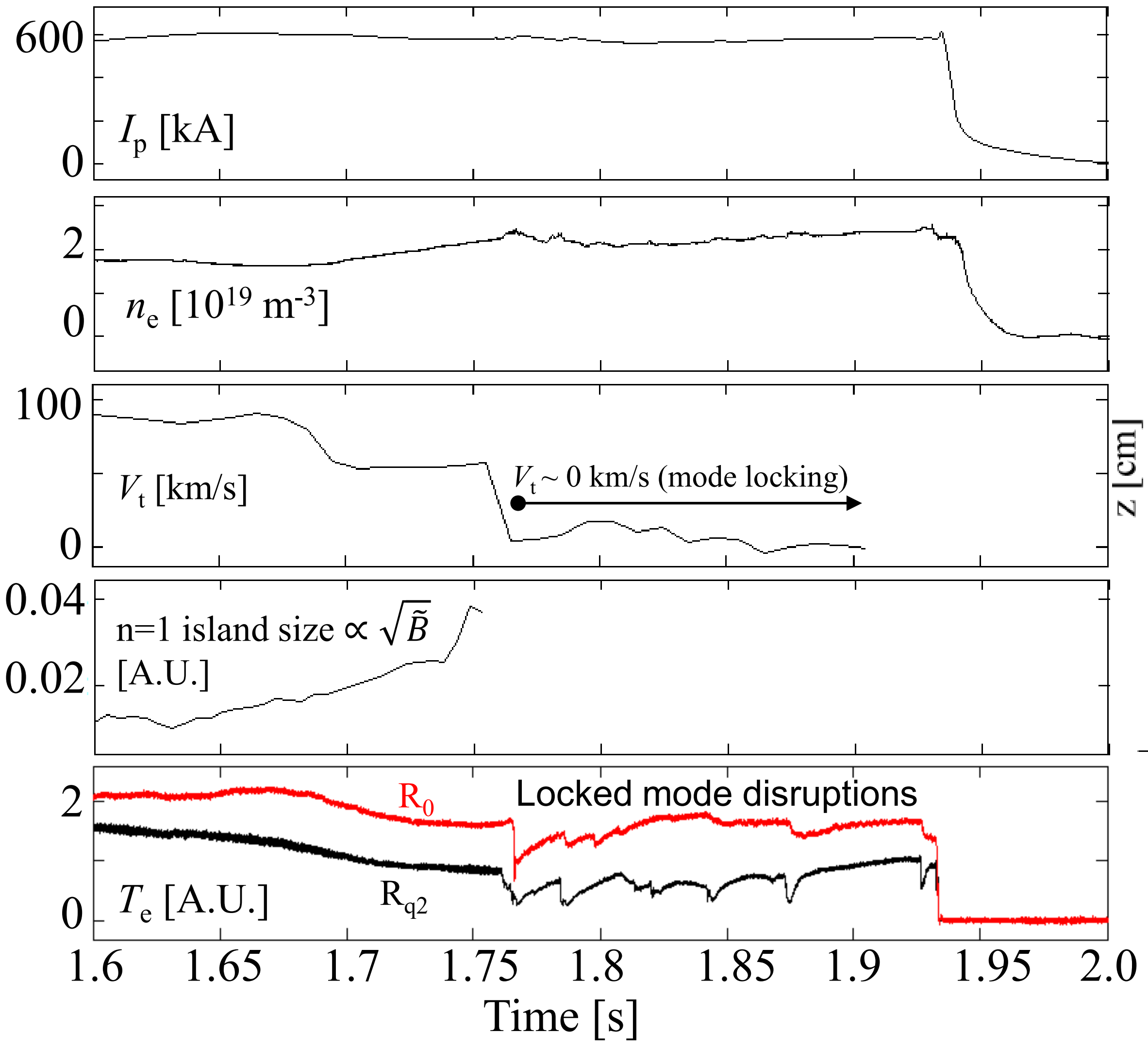
▲ X-point ▼ ▼ O-point ▲

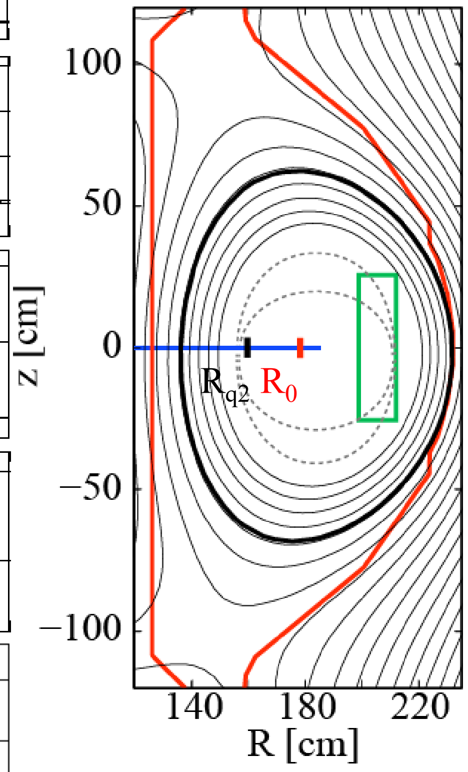




Locked mode disruption

- Discharge condition
  - $B_T = 2.0$ T, $I_p = 0.6$ MA, $q_{95} = 4.0$, NBI ~ 2.6 MW, L-mode limiter plasma



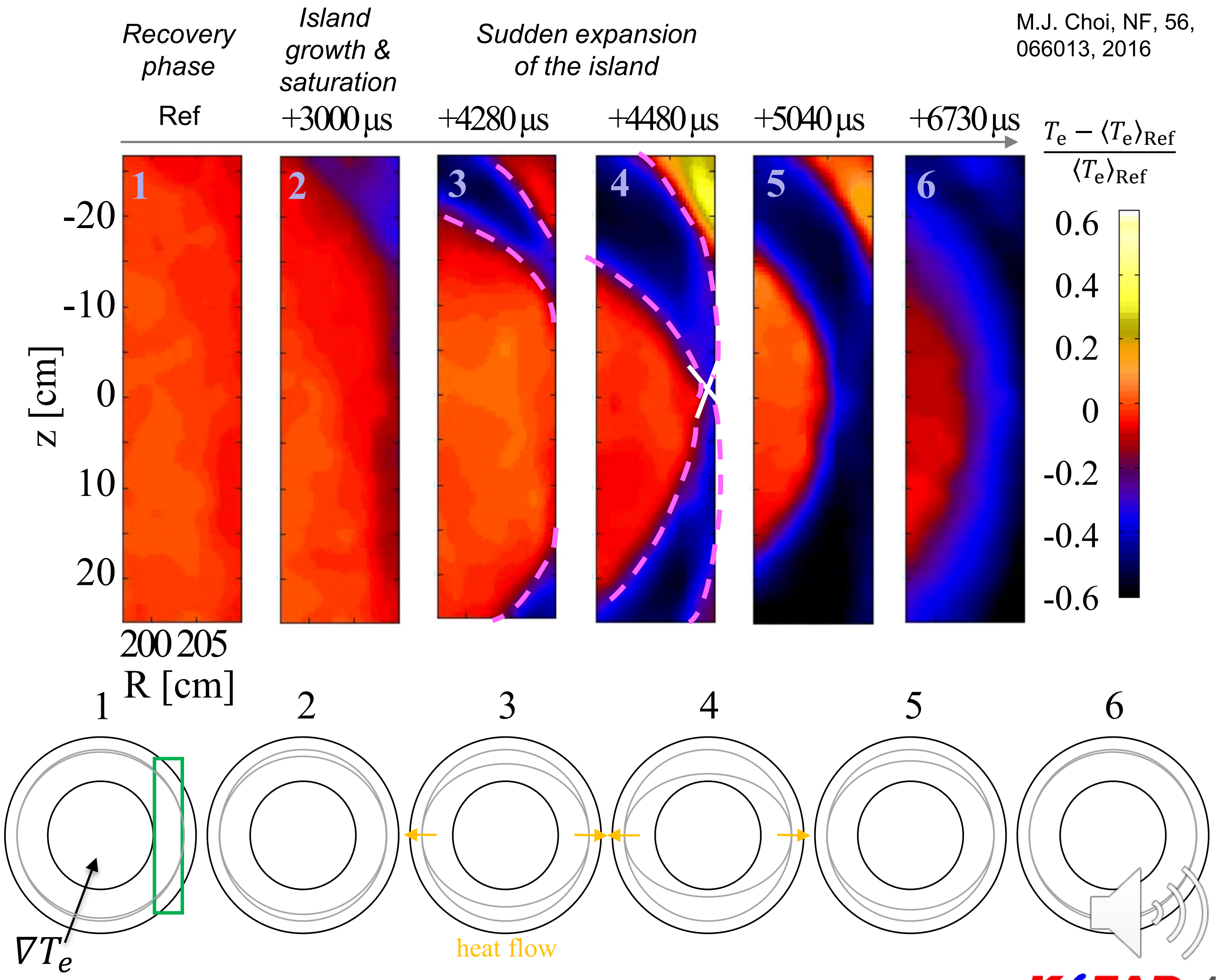


- Tearing mode growth → Mode locking → Locked mode disruption

Sudden expansion of the locked island

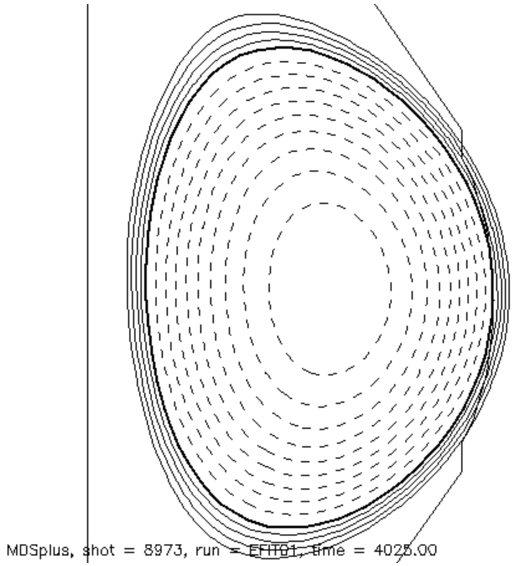
- $(T_e - \langle T_e \rangle_{Ref})/\langle T_e \rangle_{Ref}$ images provide a relative T_e change against the Ref period

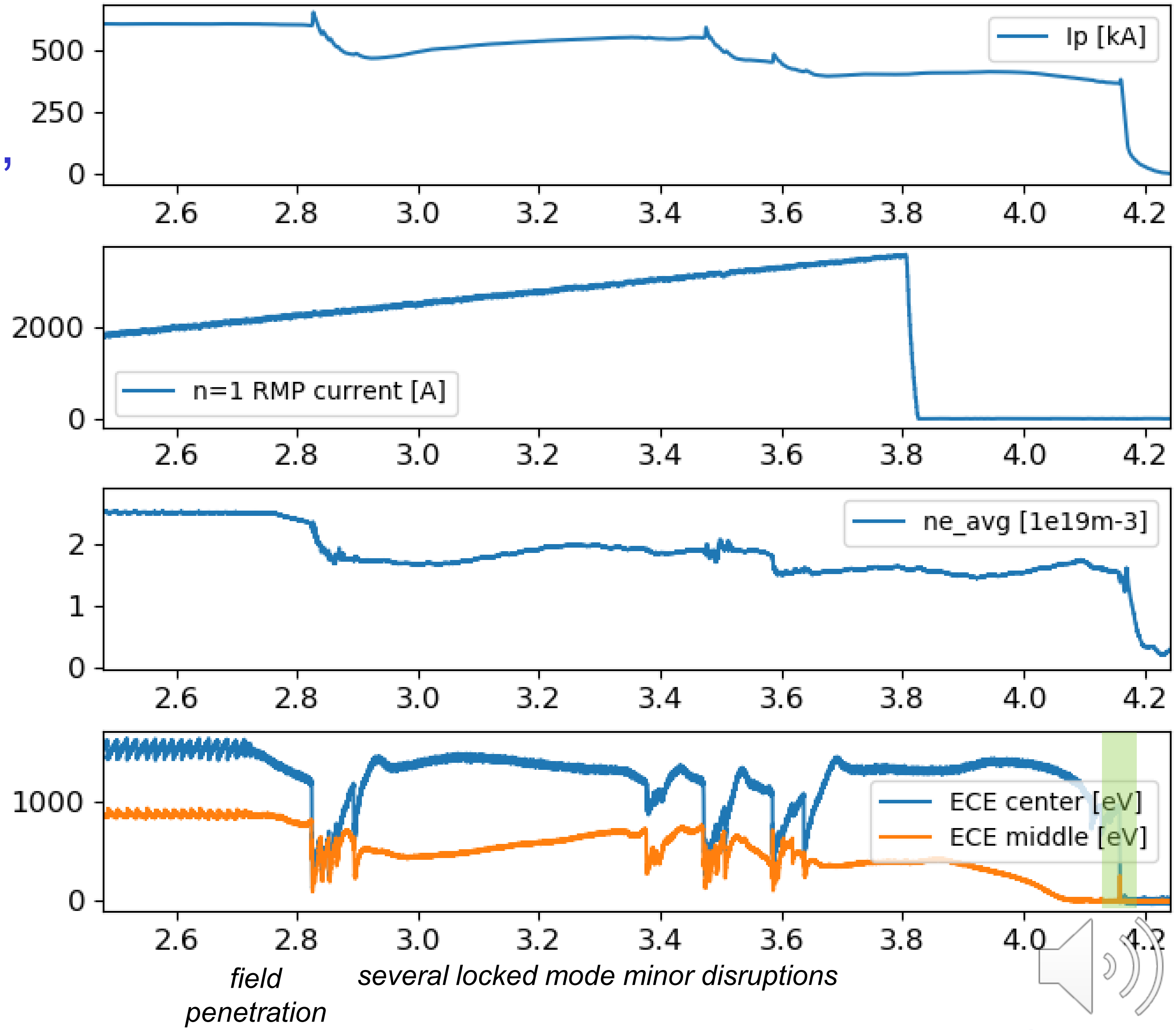
- Tearing mode growth → Mode locking → Locked mode disruption by a sudden expansion of the locked island



Interchange mode disruption

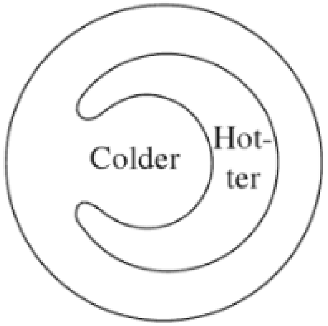
- Discharge condition
  - $B_T = 2.0$ T, $I_p = 0.6$ MA, $q_{95} = 4.4$, Ohmic plasma with n=1 RMP
  - Plasma was pushed to the outboard wall by control loss after several locked mode disruptions



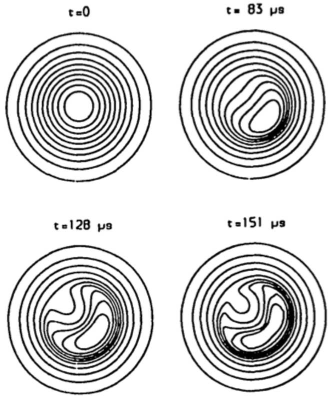


Infiltration of cold bubble

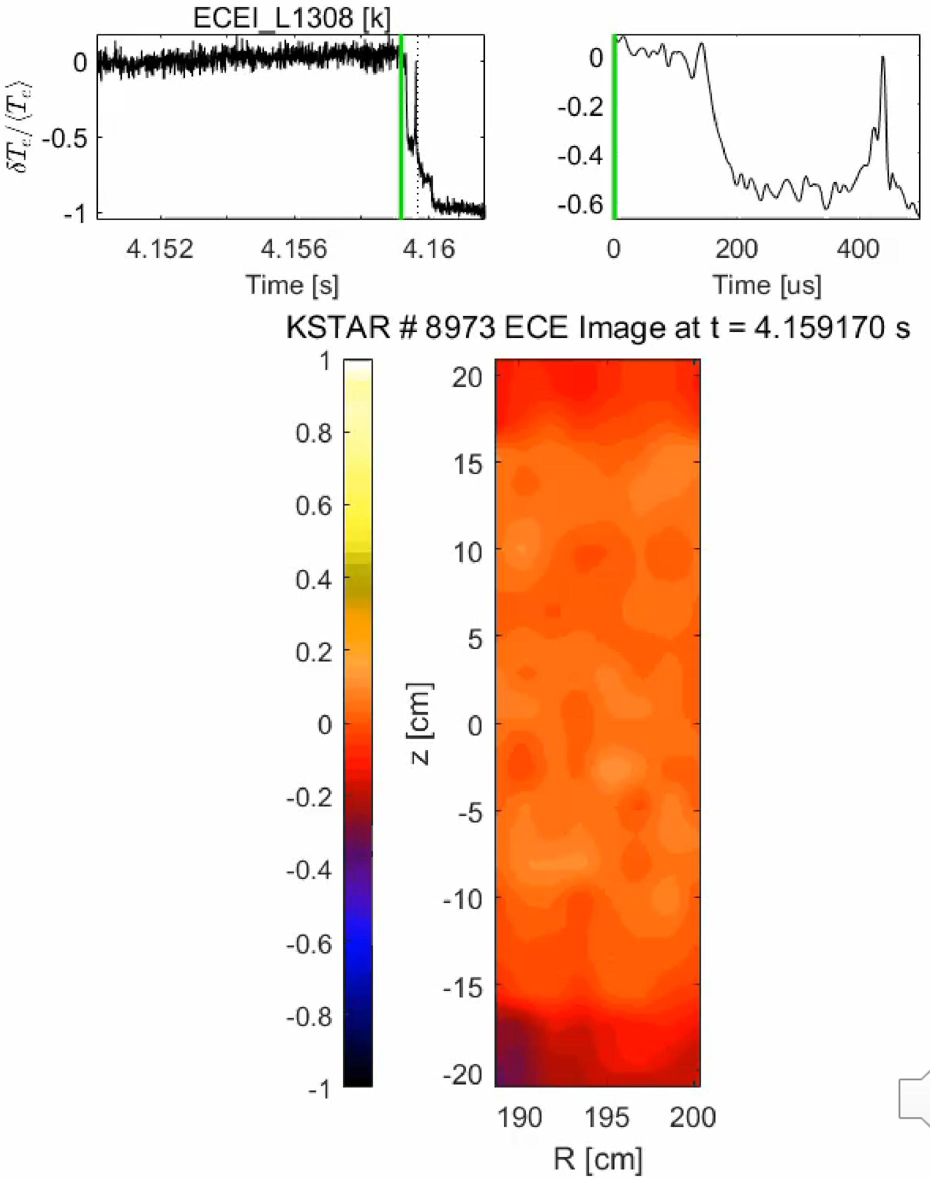
- Discharge condition
  - $B_{\mathrm{T}} = 2.0$ T, $I_{\mathrm{p}} = 0.6$ MA, $q_{95} = 4.4$, Ohmic plasma with n=1 RMP
  - Plasma was pushed to the outboard wall by control loss after several locked mode disruptions
- Quasi-interchange like mode grows, leading to major disruption



Wesson, PPCF, 28, 243, 1986
Wesson, Tokamaks

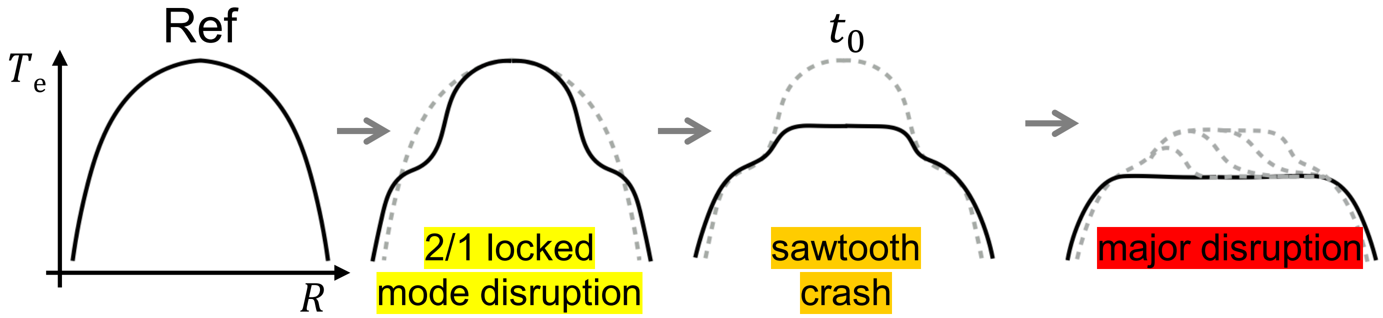


Kirby, NF, 28, 231, 1988

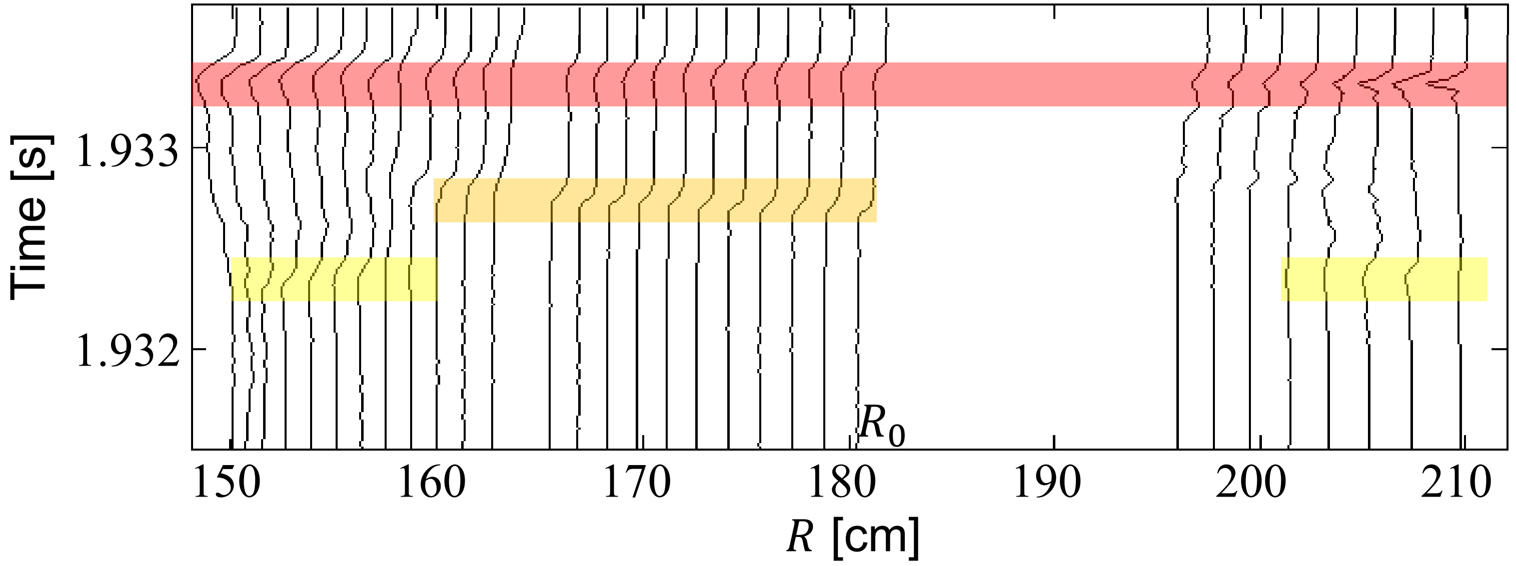


Disruption by multi mode interactions

- Discharge condition
  - $B_T = 2.0$ T, $I_p = 0.6$ MA, $q_{95} = 4.0$, NBI ~ 2.6 MW, L-mode limiter plasma



- Tearing mode growth → Mode locking → Locked mode disruption → Sawtooth crash → Major disruption



Kink + tearing + interchange mode

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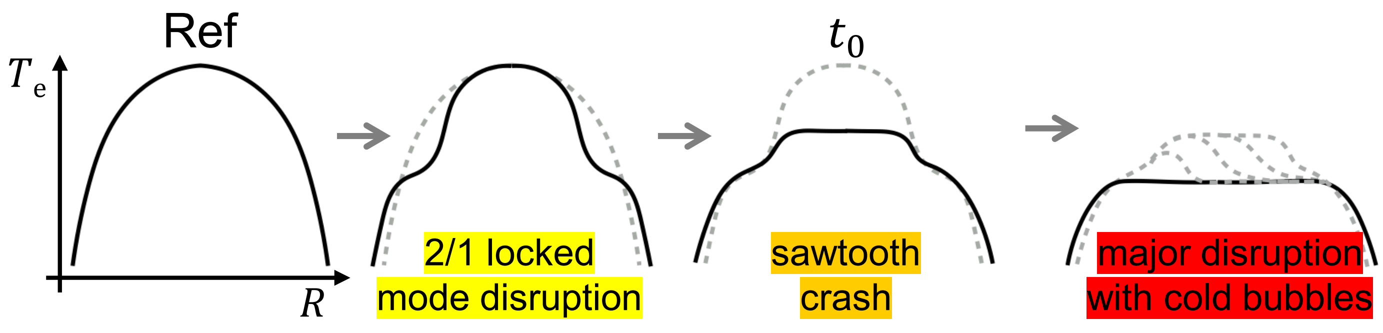
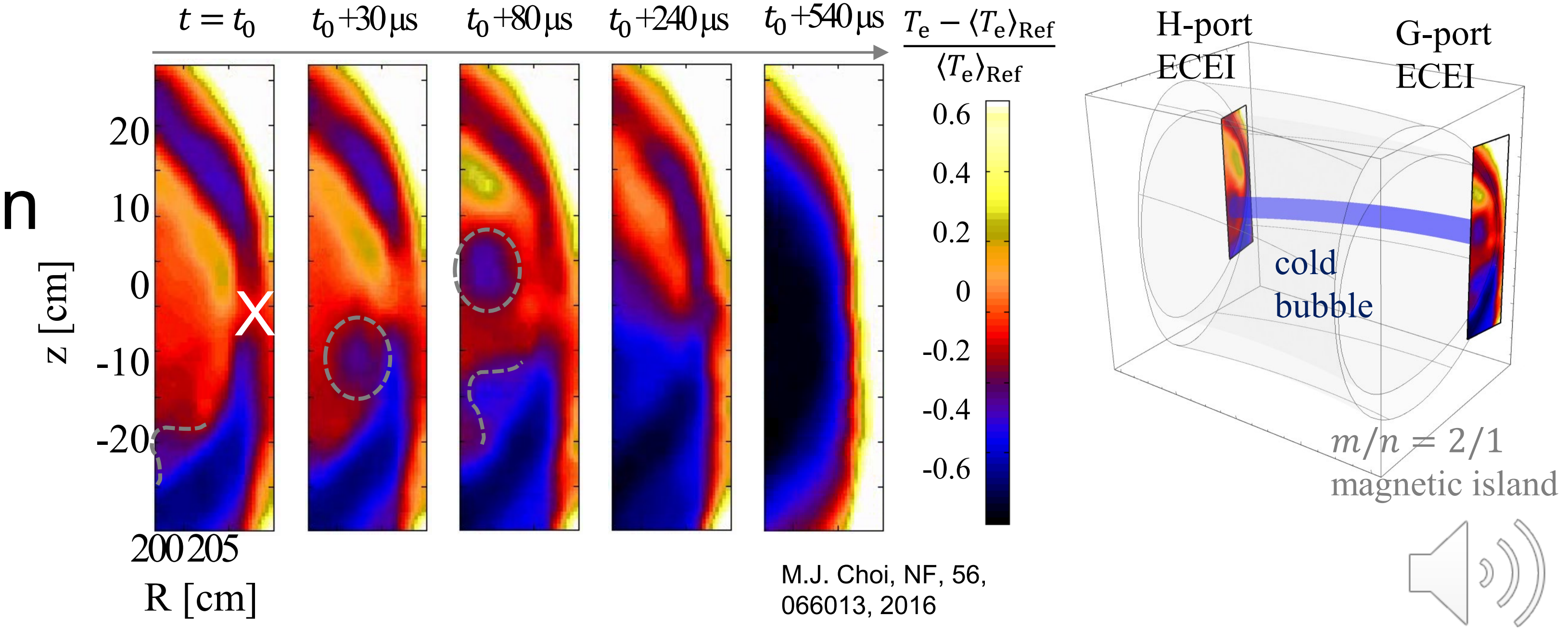


- Tearing mode growth → Mode locking → Locked mode disruption → Sawtooth crash → Major disruption by a coalescence btw cold bubbles and the island

inward expansion of 2/1 island with cold bubbles

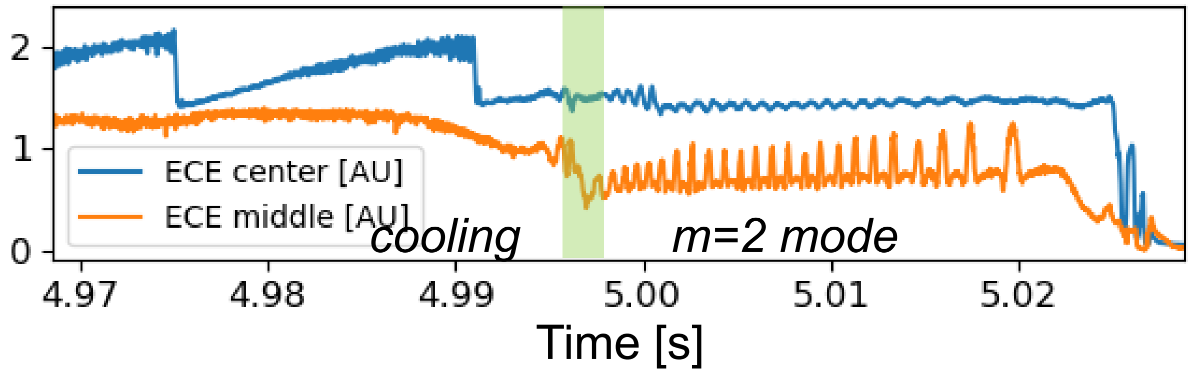


M.J. Choi, NF, 56, 066013, 2016

Density limit disruption

- Discharge condition
  - $B_T = 2.0$ T, $I_p = 0.6$ MA, $q_{95} = 4.0$, NBI ~ 1.5 MW, ECH ~ 0.6 MW, H-mode plasma with SMBI pulses

- Profile contraction by edge cooling → Growth of 2/1 tearing mode → Disruption



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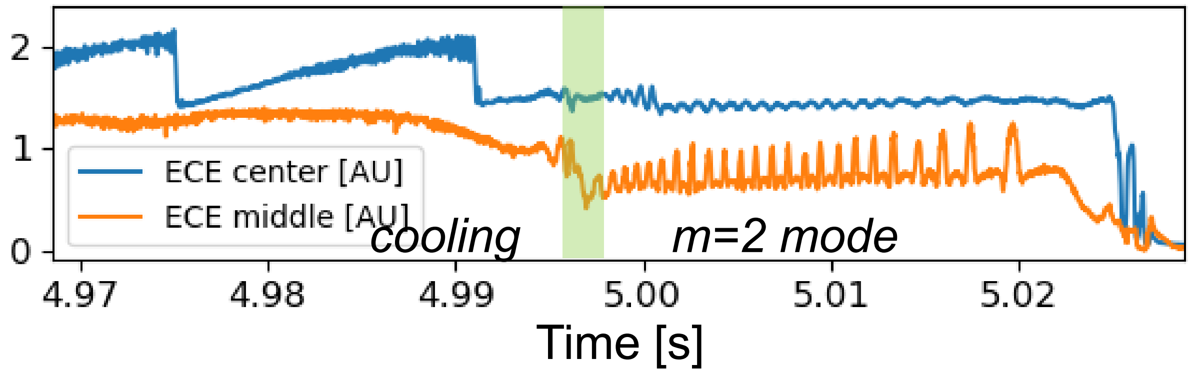
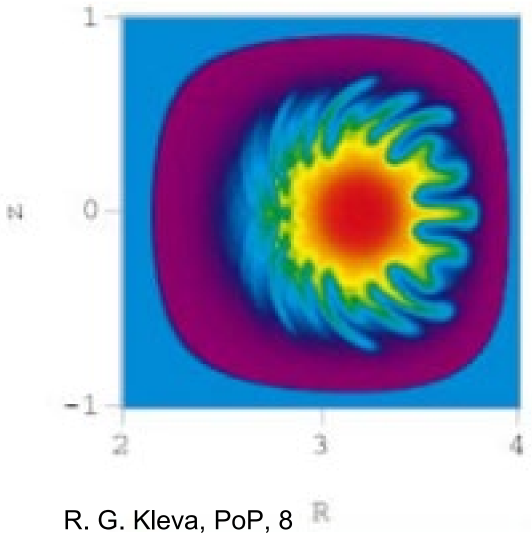
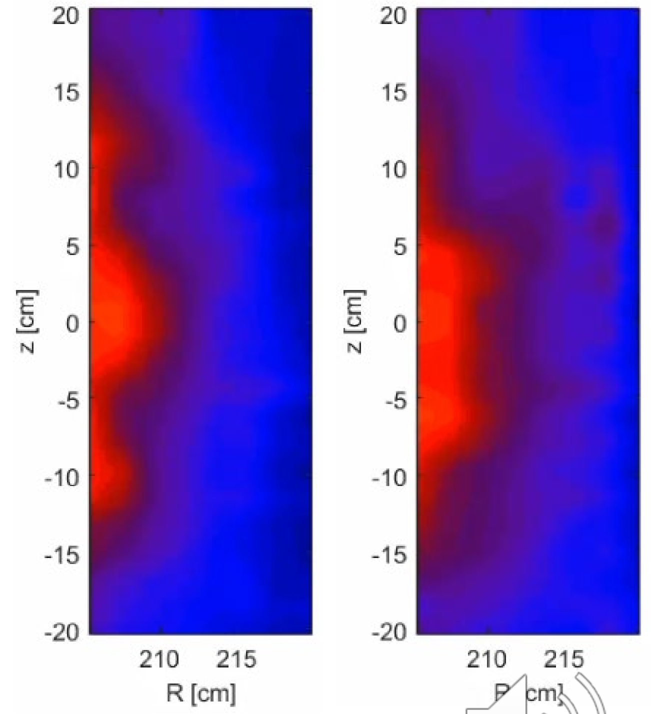


- Heat release with ballooning fingers is observed



R. G. Kleva, PoP, 8 103, 2001

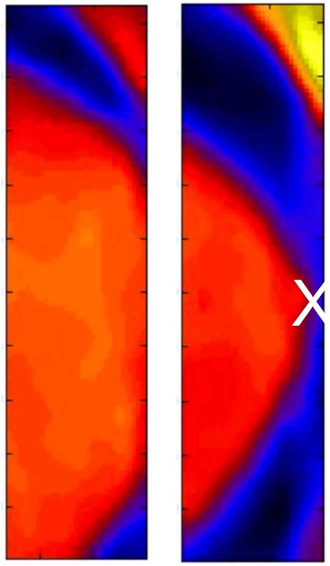
t = 4.996159 sec   +40 us



Anomalous locked mode disruption

- Discharge condition
  - $B_{\mathrm{T}} = 2.2$ T, $I_{\mathrm{p}} = 0.6$ MA, $q_{95} = 4.8$, NBI ~ 1.0 MW, L-mode plasma with n=1 RMP
- Typical locked mode disruption
  - Largest heat release occurs when the island expands

m=2 island expansion



The largest heat release by axisymmetric T_e collapse near the locked mode region

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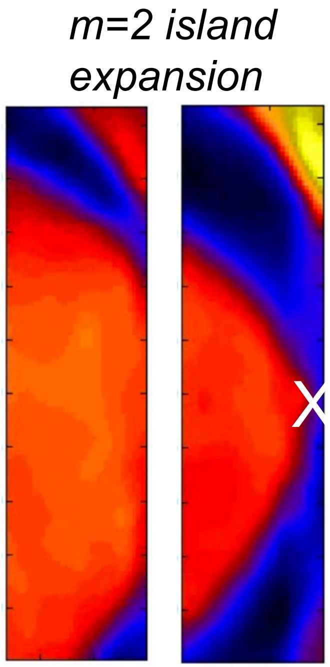
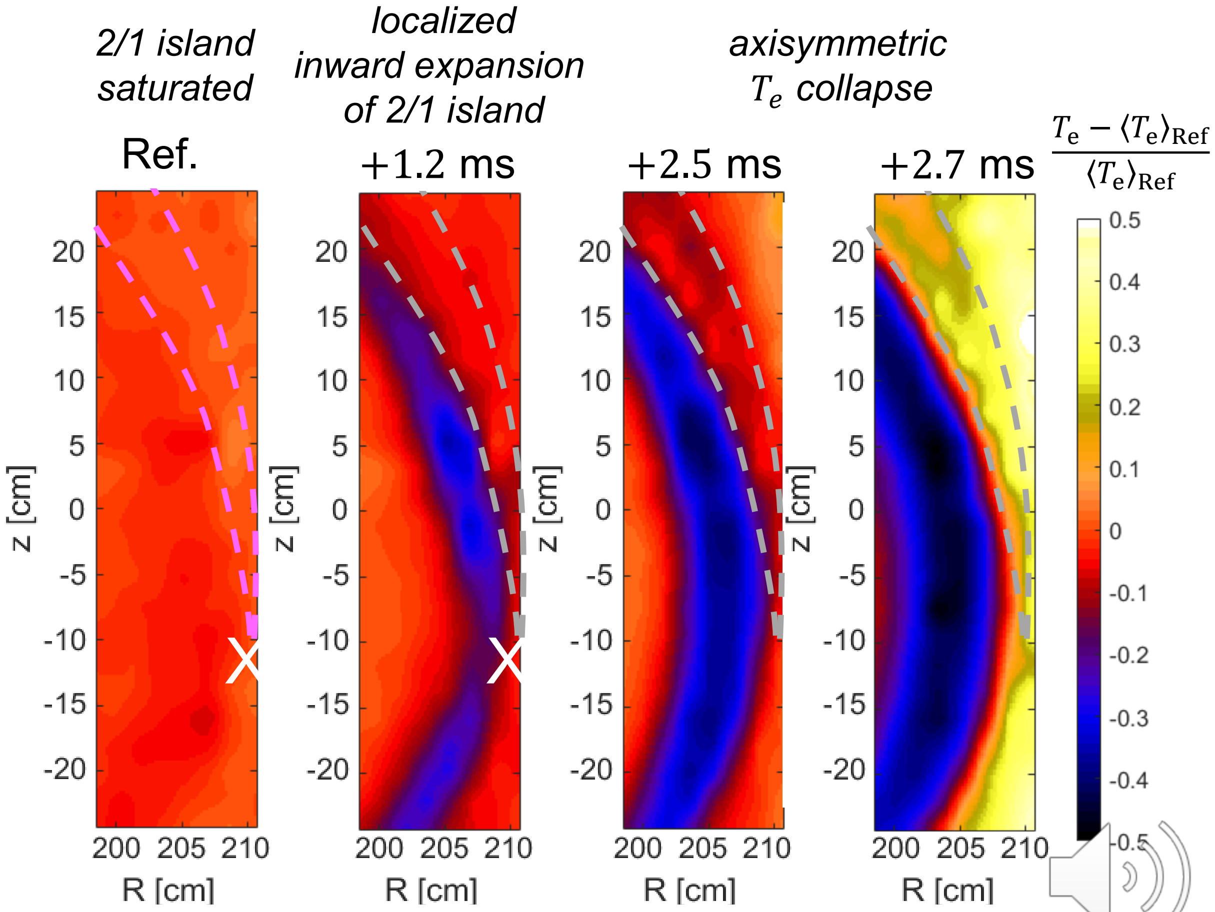


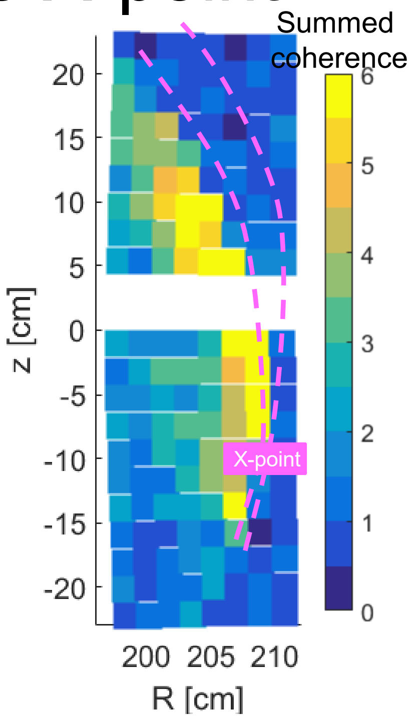
- Locked mode disruption with axisymmetric T_e collapse



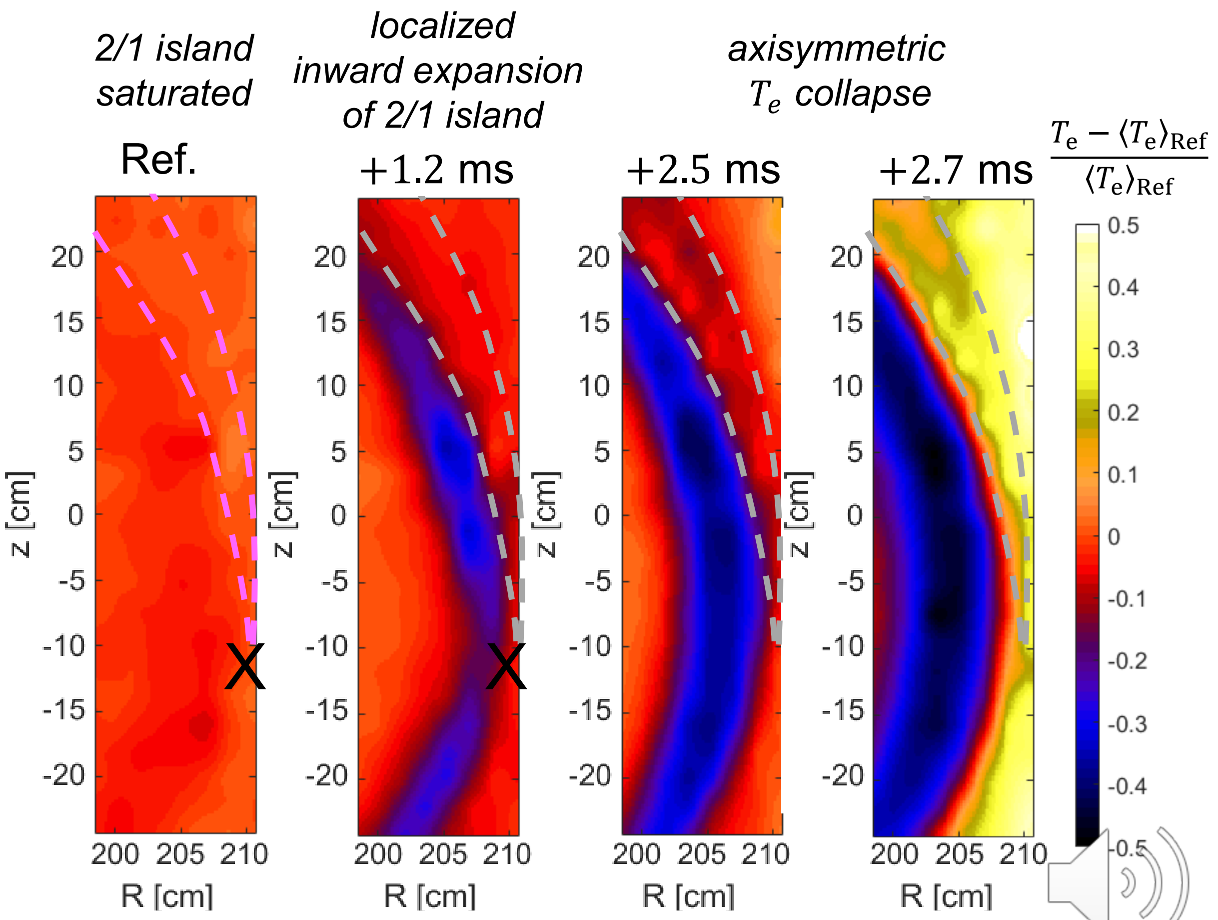
M.J. Choi, IAEA FEC, 2018

T_e turbulence near the X-point of the locked mode can play a role in the anomalous locked mode disruption

- Discharge condition
  - $B_T = 2.2$ T, $I_p = 0.6$ MA, $q_{95} = 4.8$, NBI ~ 1.0 MW, L-mode plasma with n=1 RMP
- T_e turbulence near the X-point
  - Broadband $\tilde{T}_e$ power was increased before the disruption
  - Turbulence can cause further reconnection and stochastic transport



- Locked mode disruption with axisymmetric T_e collapse



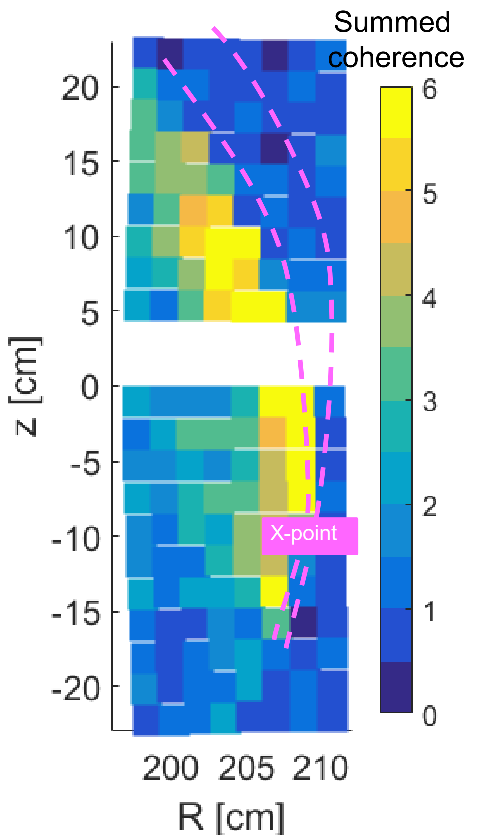
M.J. Choi, IAEA FEC, 2018

Interim summary of 2D observations

- Sawtooth crash
  - Off-normal sawtooth crash (m=3): kink → magnetic reconnection → poloidal overlapping of islands
- Tearing mode disruption: sudden expansion of the locked island
- Interchange mode disruption: infiltration and expansion of cold bubble
- Multi mode disruption: kink + tearing + interchange
- Anomalous cases
  - Ballooning fingers in density limit disruption
  - T_e turbulence in locked mode disruption

Retardation of the turbulence-associated locked mode disruption with the additional non-resonant field

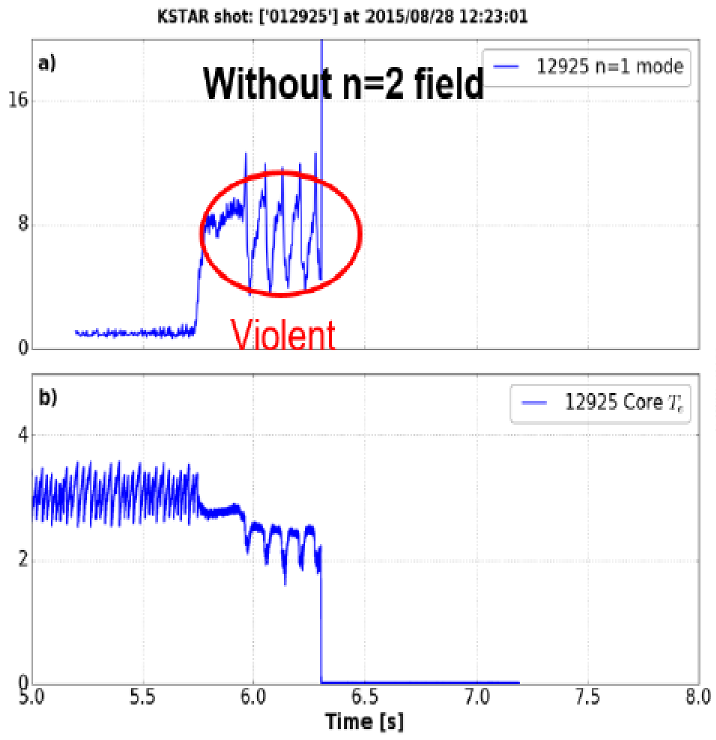
- Turbulence near the X-point seems to play a role in a locked mode disruption
- What happens if we suppress the turbulence by varying the local flow shear?
  - The non-resonant magnetic perturbation (NRMP) field can perturb the flow profile



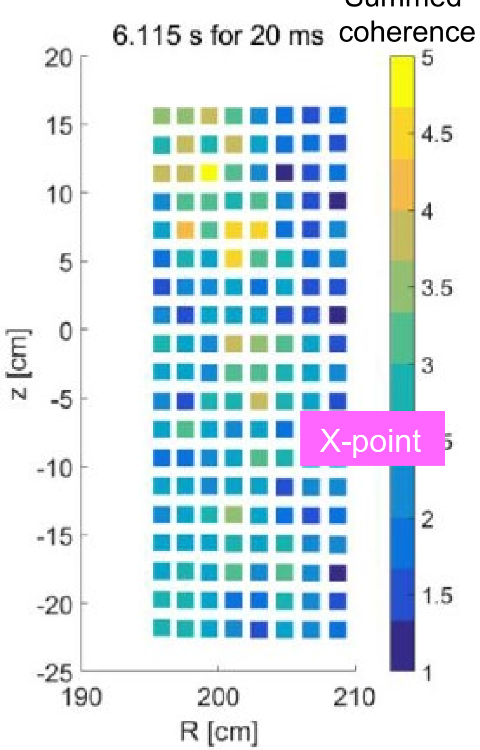
Retardation of the turbulence-associated locked mode disruption with the additional non-resonant field

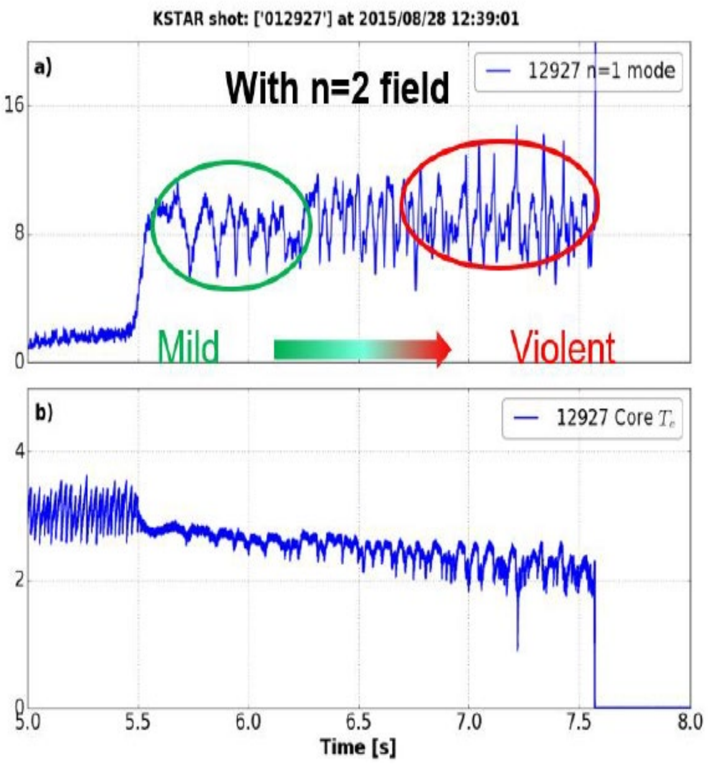
J. Kim et al, *ITPA-MHD* (2019)

- Discharge condition
  - The n=1 RMP leads to the violent locked mode disruption
- The additional n=2 NRMP resulted in mild locked mode disruptions

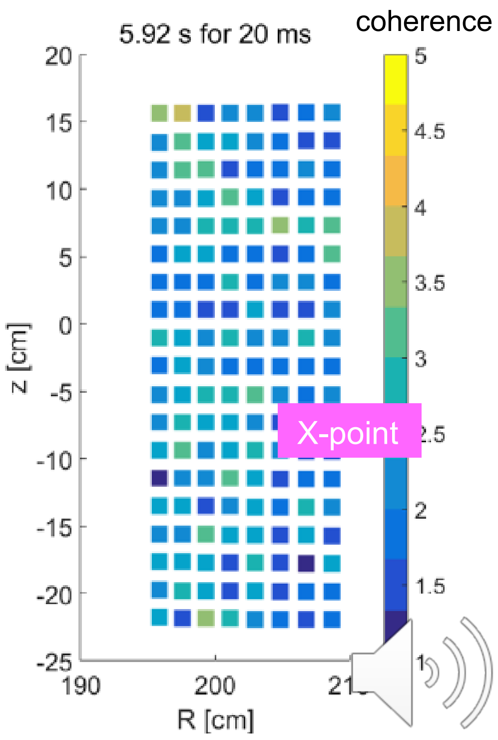


violent case





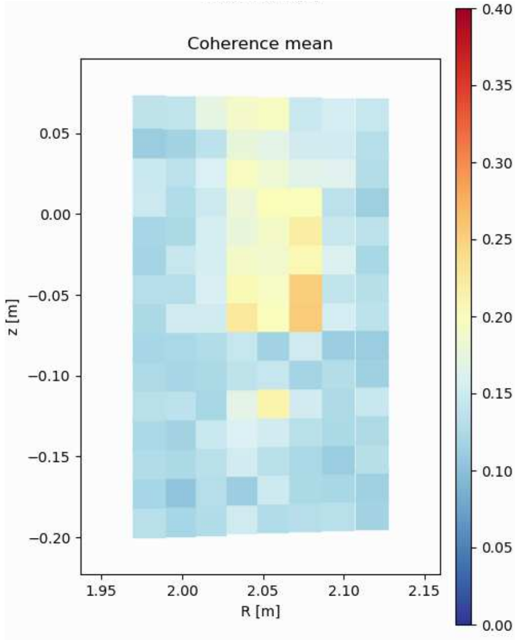
mild case



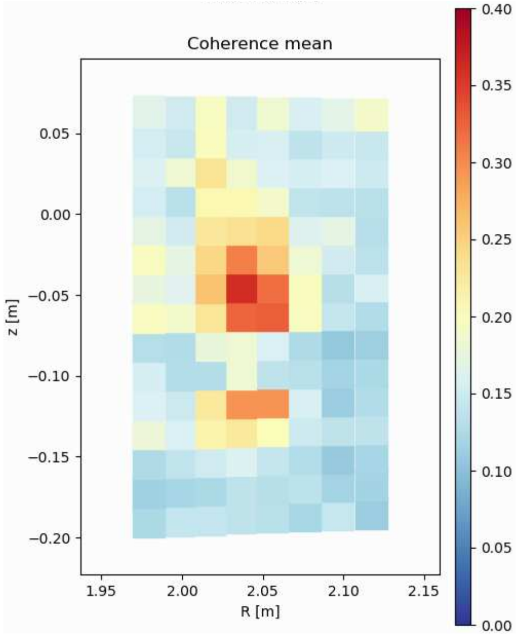
Dependence of turbulence strength and flow on the NRMP field amplitude

- The stronger n=2 NRMP field resulted in the weaker turbulence near the X-point of the n=1 island
  - The local flow (and probably shear across the region) is larger with the stronger n=2 perturbation field, which might be responsible for the weaker turbulence

n=2 current ~ 1.3 kA



n=2 current ~ 0.6 kA



Summary

- 2D measurements revealed detail process of various disruptive events
  - Disruption warning system should consider stability of various MHD instabilities including $m \geq 1$ kink, tearing mode, and interchange-ballooning mode
  - Coupling between multi mode can be more dangerous
- Retardation of the turbulence-associated disruption
  - The better understanding of the disruption process enables the better mitigation or avoidance of the disruption