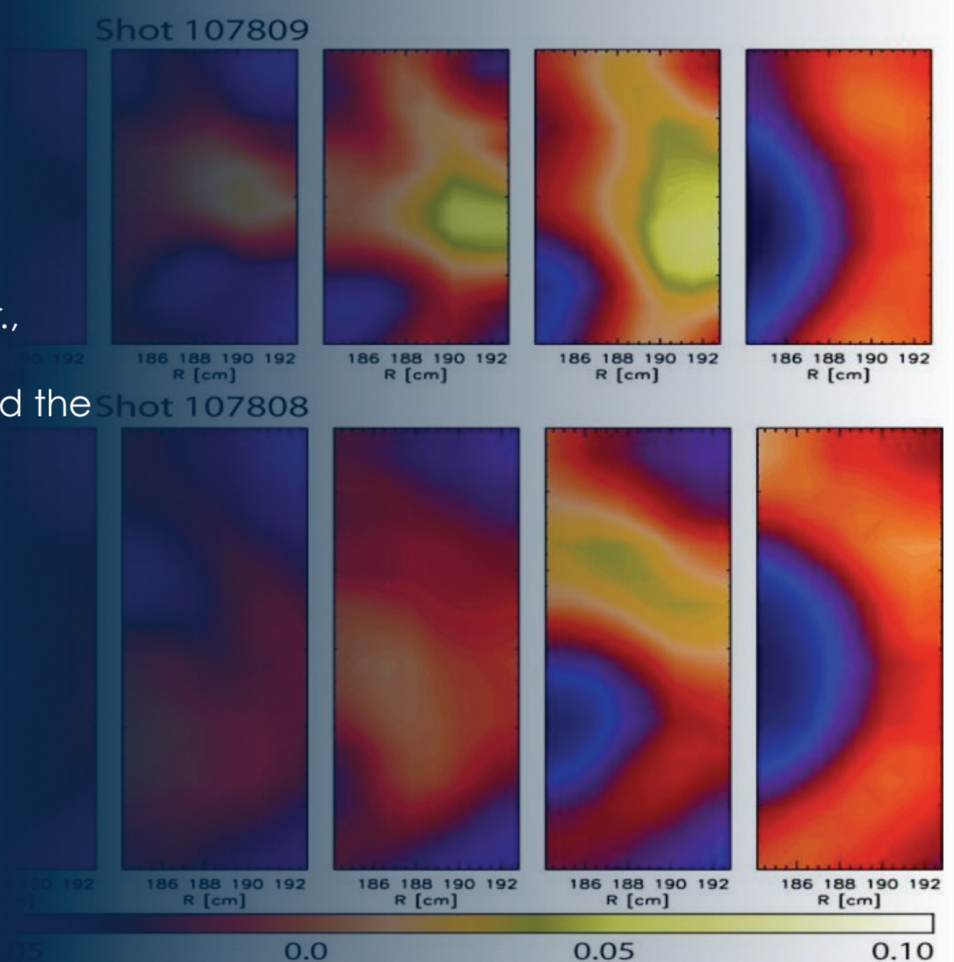
# Electron Cyclotron Emission Imaging of MHD Activity on the DIII-D, TEXTOR, ASDEX-U, and KSTAR Tokamaks


by

**B. Tobias**

*University of California at Davis*

R.L. Boivin, J.E. Boom, I.G.J. Classen, C.W. Domier,
A.J.H. Donné, W.W. Heidbrink, W. Lee, N.C. Luhmann, Jr.,
T. Munsat, C. Muscatello, R. Nazikian, H.K. Park,
D.A. Spong, A. Turnbull, M.A. Van Zeeland, G.S. Yun, and the
ASDEX-Upgrade, DIII-D, KSTAR, and TEXTOR teams


**Presented at the**
**52nd Annual Meeting of**
**the APS Division of Plasma Physics**
**Chicago, Illinois**

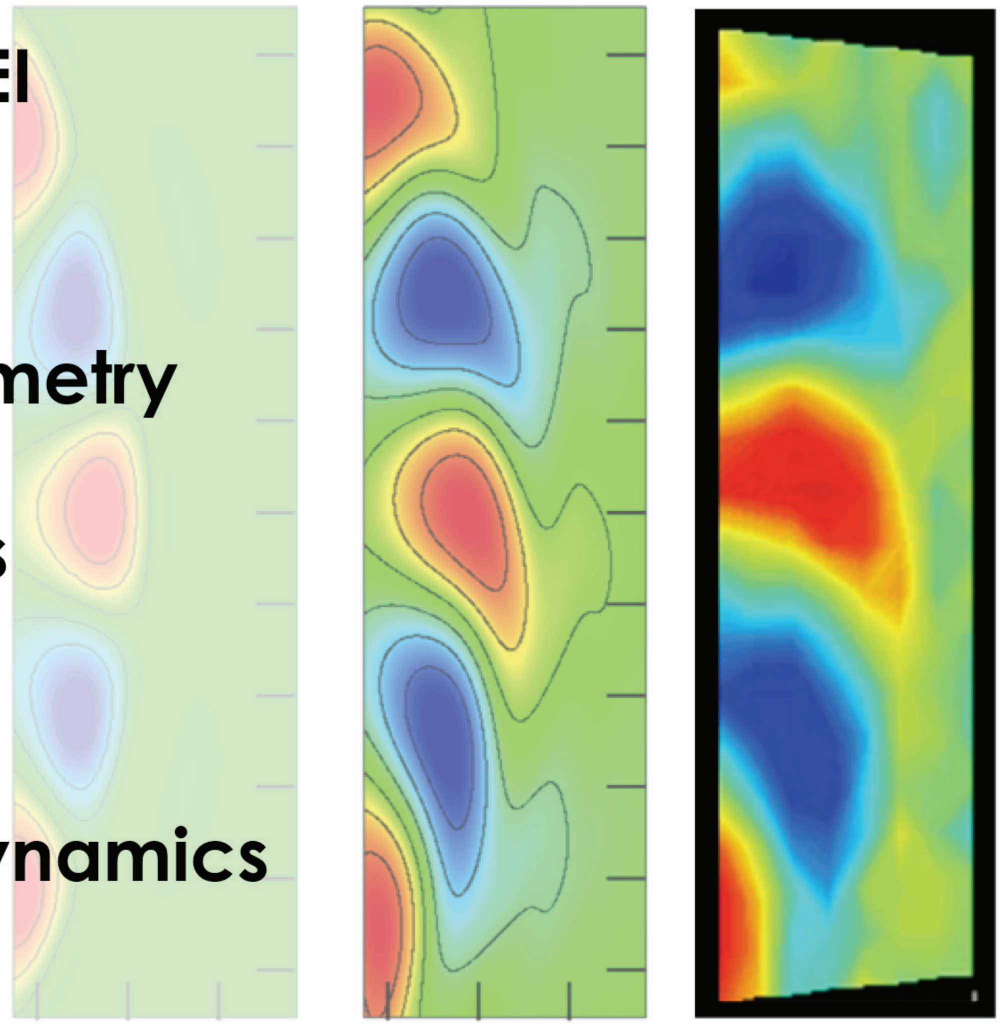
**November 8-12, 2010**



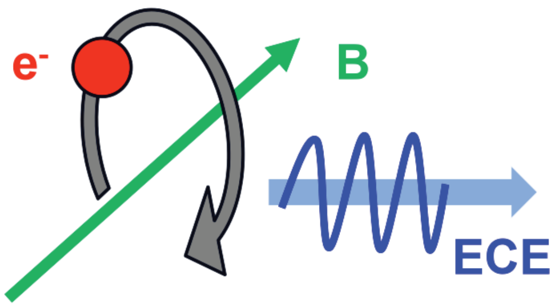
UC DAVIS
PLASMA
DIAGNOSTICS
GROUP

# Outline

- An introduction to ECEI diagnostic systems
- Fast ion induced symmetry breaking in Alfvén eigenmode structures
- *m*/*n* = 1/1 sawtooth precursors and the dynamics of the sawtooth crash

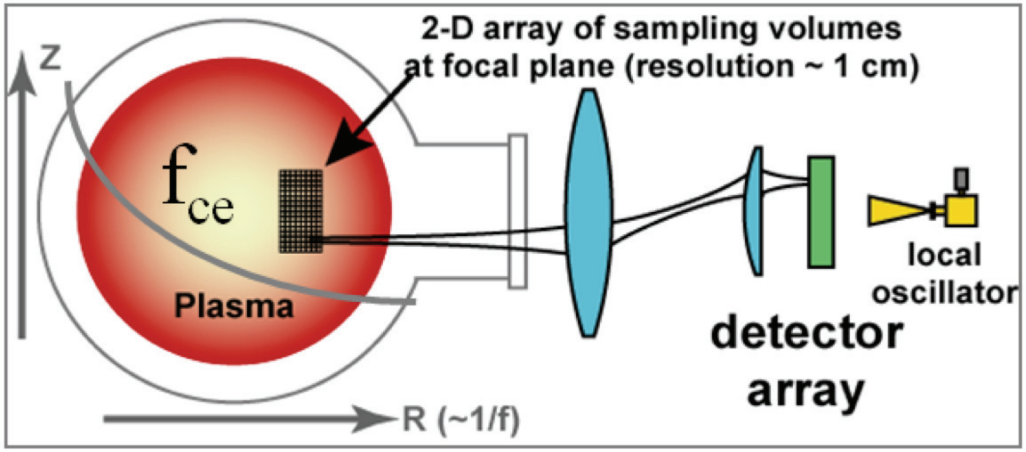


# 2-D ECE Imaging (ECEI)
# Imaging of Localized Electron Temperature



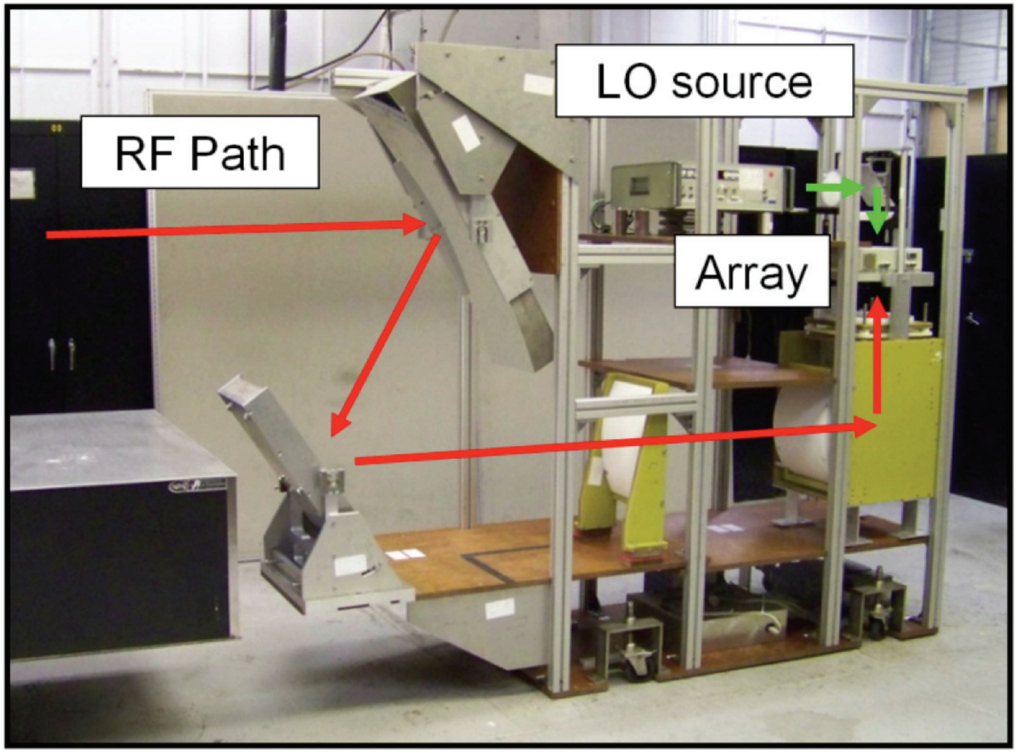

***Radial localization is determined by cyclotron resonance***
***Vertical and horizontal localization are determined by view***

- **Poloidal cross-section**
- **Up to 1 cm² spatial resolution**
- **Real-time $T_e$ down to <1% with μ-sec time resolution**



# The TEXTOR ECEI Prototype Provided Immediate Contributions to Physics

- **Proof-of-principle demonstration of imaging in heterodyne radiometry**
- **TEXTOR ECEI data continues to provide new physics**
- **The TEXTOR ECEI system remains a platform for benchmarking new techniques**

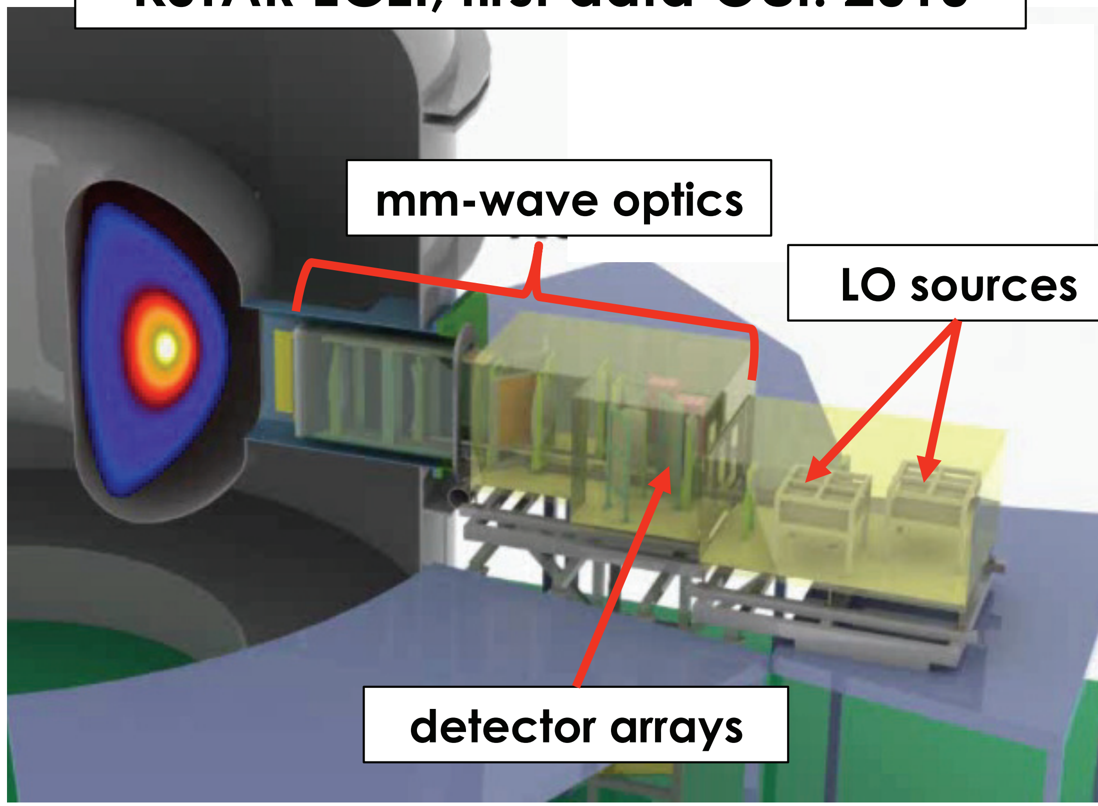



*H.K. Park, et. al., Rev. Sci. Instrum.* ***74****, 1426 (2004)*
*H.K. Park, et. al., Phys. Rev. Lett.* ***96****, 195003 (2006)*
*H.K. Park, et. al., Phys. Rev. Lett.* ***96****, 195004 (2006)*
*H.K. Park, et. al., Phys. of Plasmas* ***13****, 055907 (2006)*
*T. Munsat, H.K. Park, et. al., Nucl. Fusion* ***47****, L31-L35 (2007)*
*I.G.J. Classen, et. al., Phys. Rev. Lett.* ***98****, 035001 (2007)*

# ECEI Has Since Matured as a Diagnostic Technique

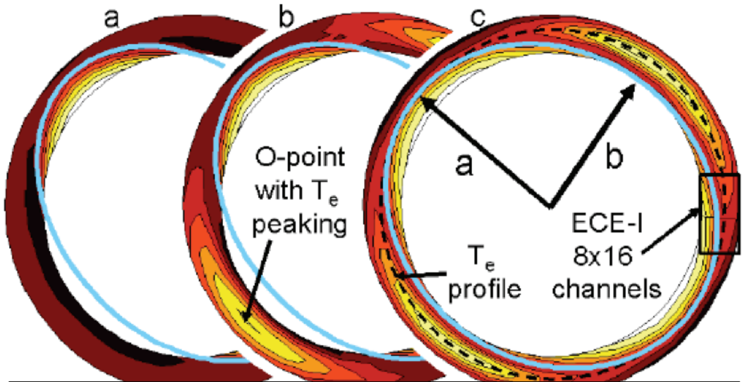
- Modern ECEI systems are distinguished by versatile, flexible optical coupling
- ECEI is in operation on ASDEX-Upgrade, DIII-D, and KSTAR
- ECEI to be installed on the EAST tokamak, March 2011

KSTAR ECEI, first data Oct. 2010

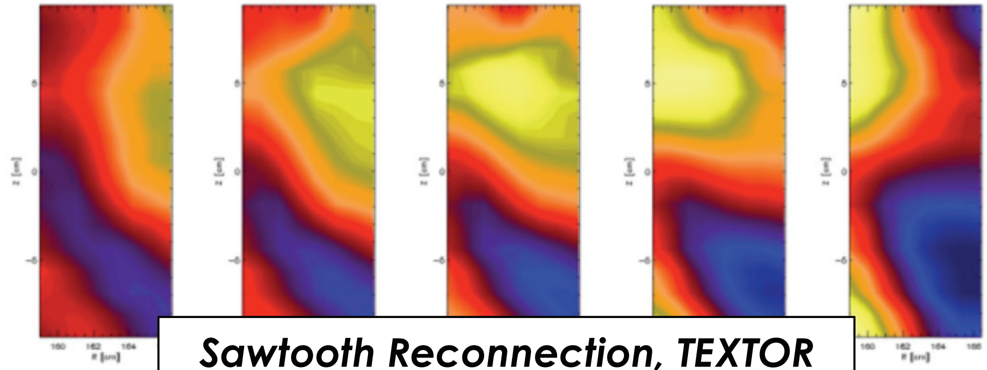



*See G.S. Yun (PO4.00015) and J. Lai (GP9.00071)*

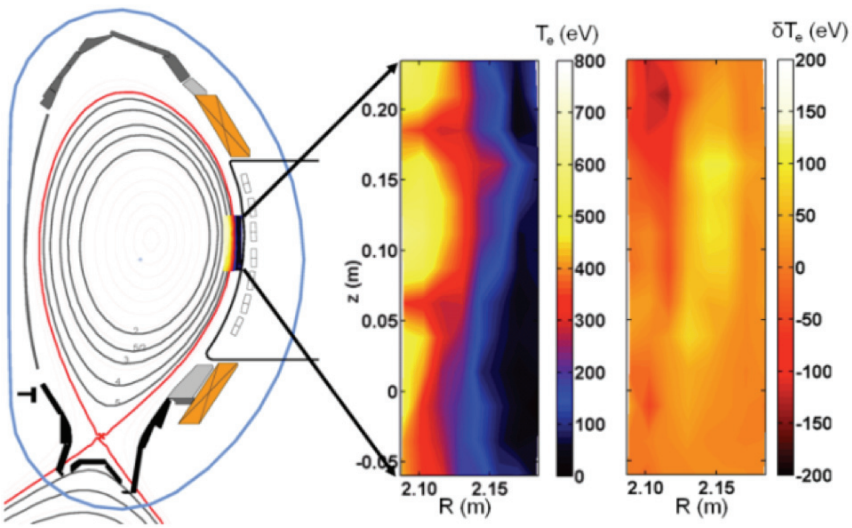
# ECEI Finds Application in a Broad Range of Physical Investigations




Tearing Mode Suppression, TEXTOR

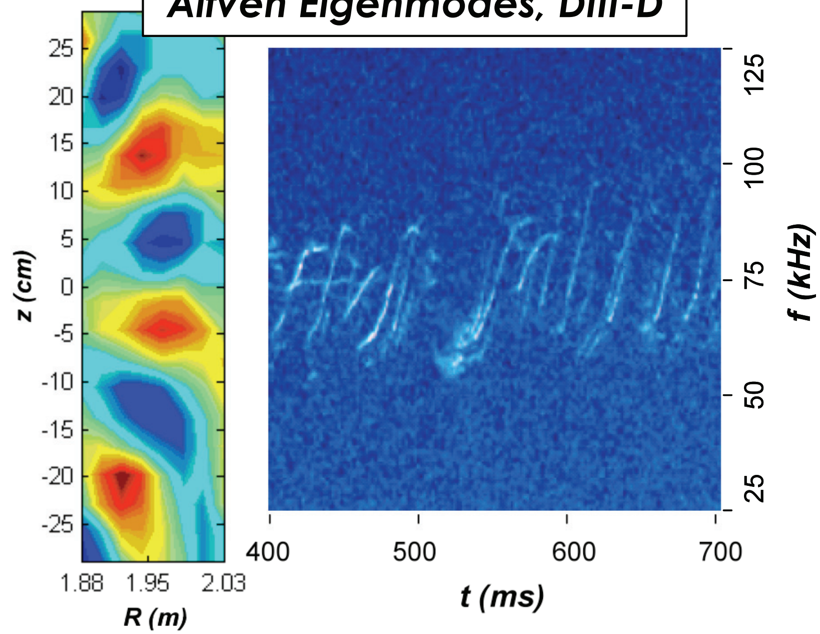


Sawtooth Reconnection, TEXTOR



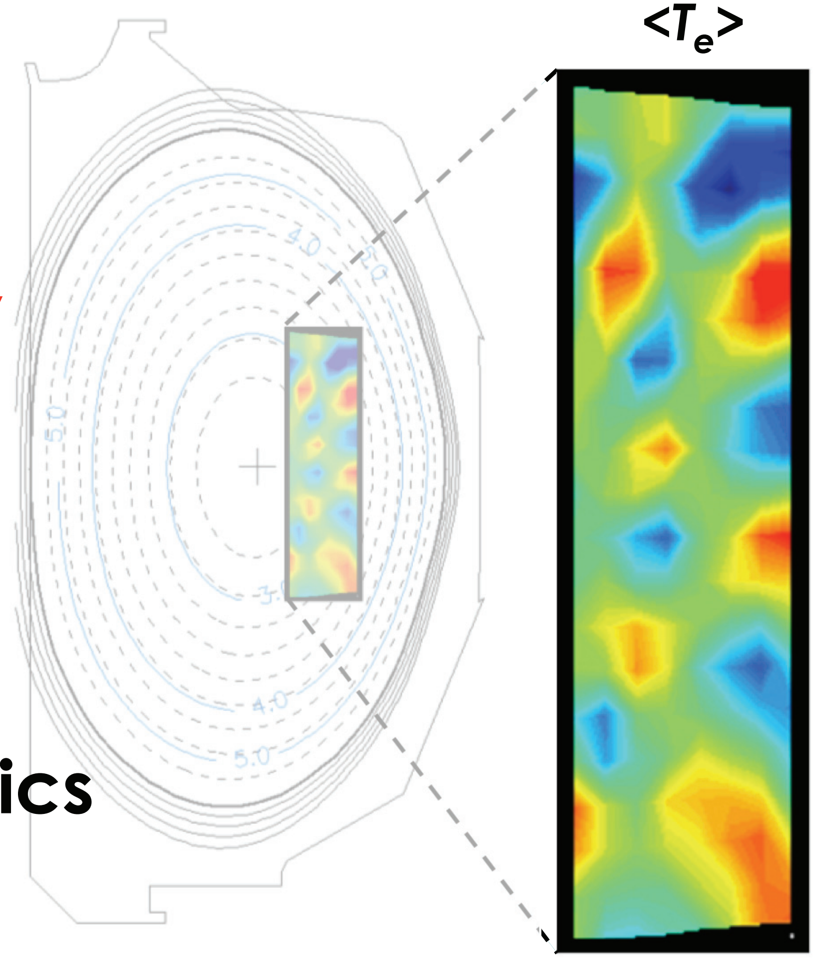

Edge Localized Modes, ASDEX-Upgrade

Alfvén Eigenmodes, DIII-D



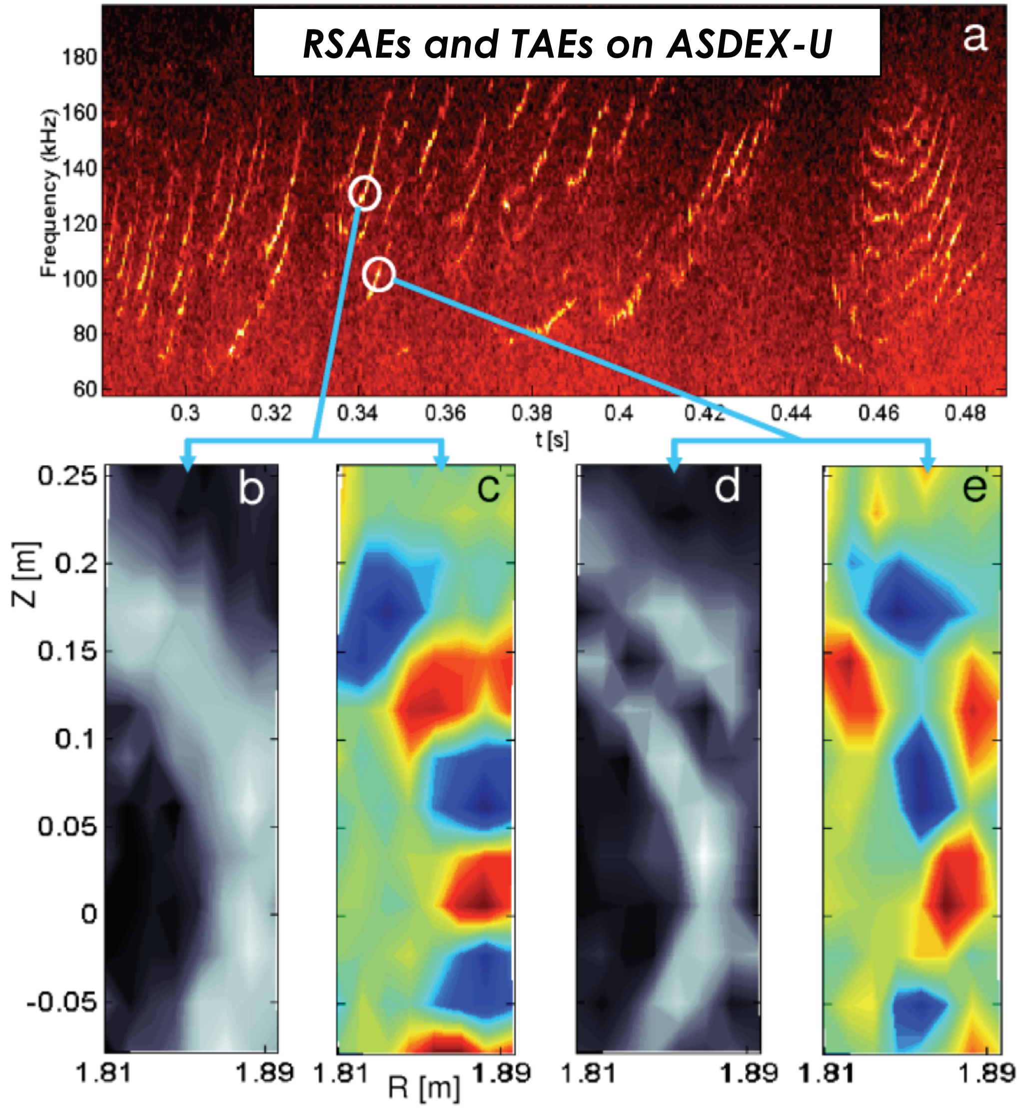
# Outline

- An introduction to ECEI diagnostic systems
- Fast ion induced symmetry breaking in Alfvén eigenmode structures
- *m*/*n* = 1/1 sawtooth precursors and the dynamics of the sawtooth crash



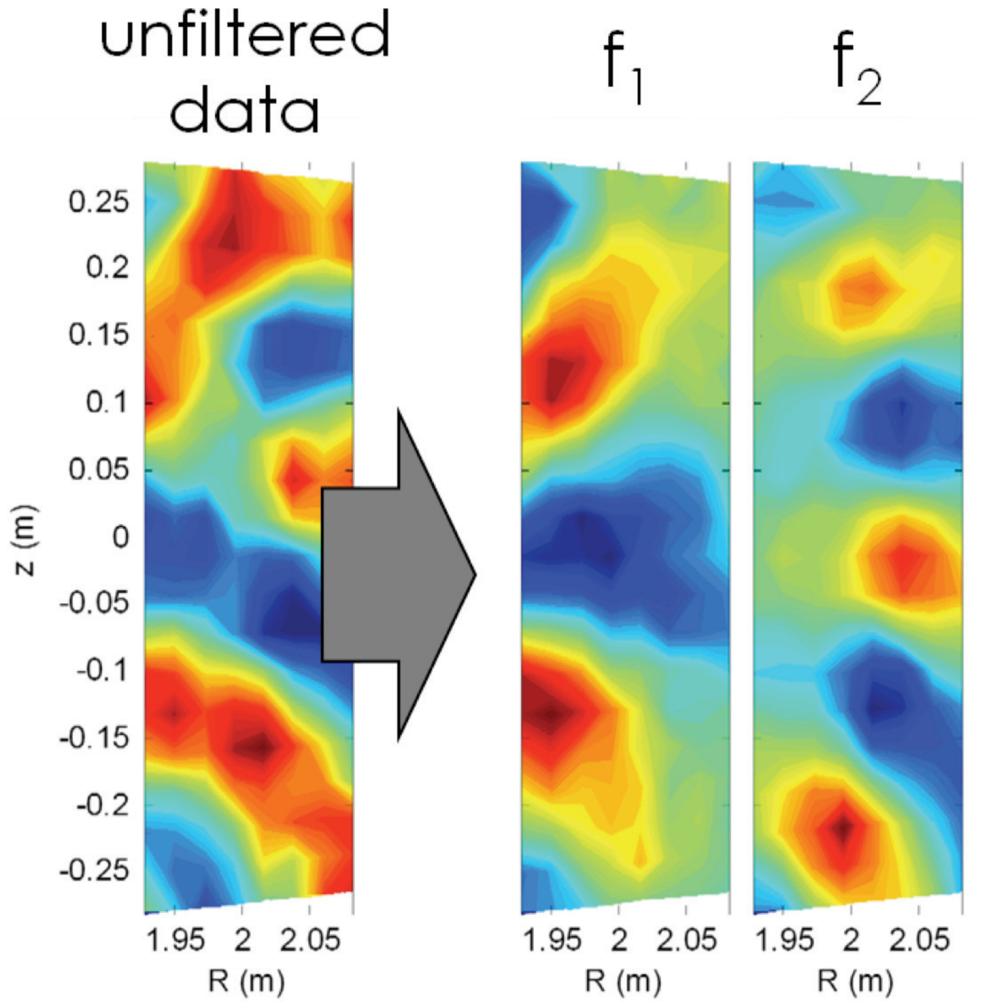
# ECEI is Well Suited to Imaging Alfvén Eigenmodes

- **Localized measurement: unambiguous eigenmode structure**
- **Readily images core plasma fluctuations**
- **Frequency filtering and singular value decomposition (SVD) allow detection of fluctuations below 1%**




*I.G.J. Classen, et al., Rev. Sci. Instrum.* ***81****, (2010)*

# Modes at Distinct Frequencies May Be Imaged and Modeled Individually




- **No evidence of nonlinear mode interaction**
  - Zero bicoherence
- **Composite modes are the result of linear superposition**

*B. Tobias, et al., Rev. Sci. Instrum.* ***81****, (2010)*

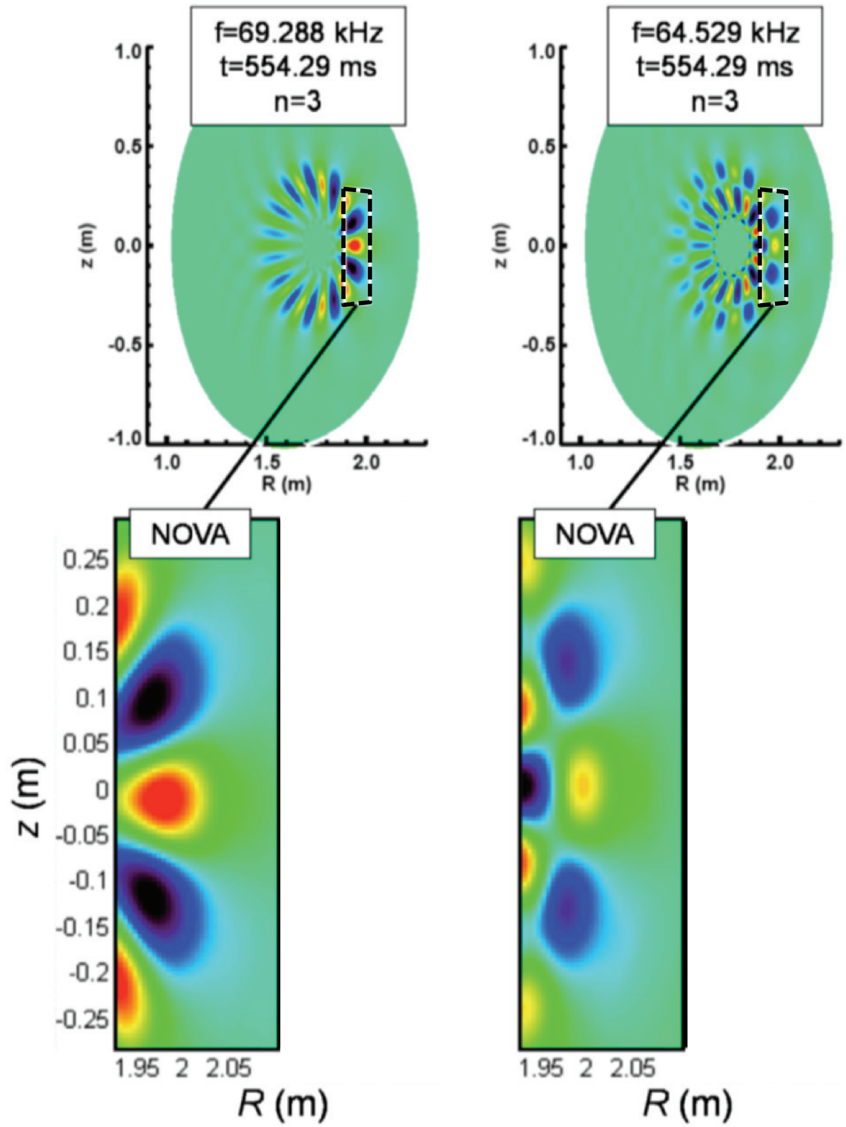
# NOVA* Correctly Predicts Important Features

- **Frequency and mode number agree with experimental observations**
- **Radial harmonic modes diagnose plasma shape**
  - node confined to a flux surface
- **Constraints of symmetry are implicit:**

$$\psi = \sum_{m,n} \psi_{mn} \cos(m\theta - n\zeta)$$

**C.Z. Cheng, Phys. Rep. **211**, 1 (1992)*

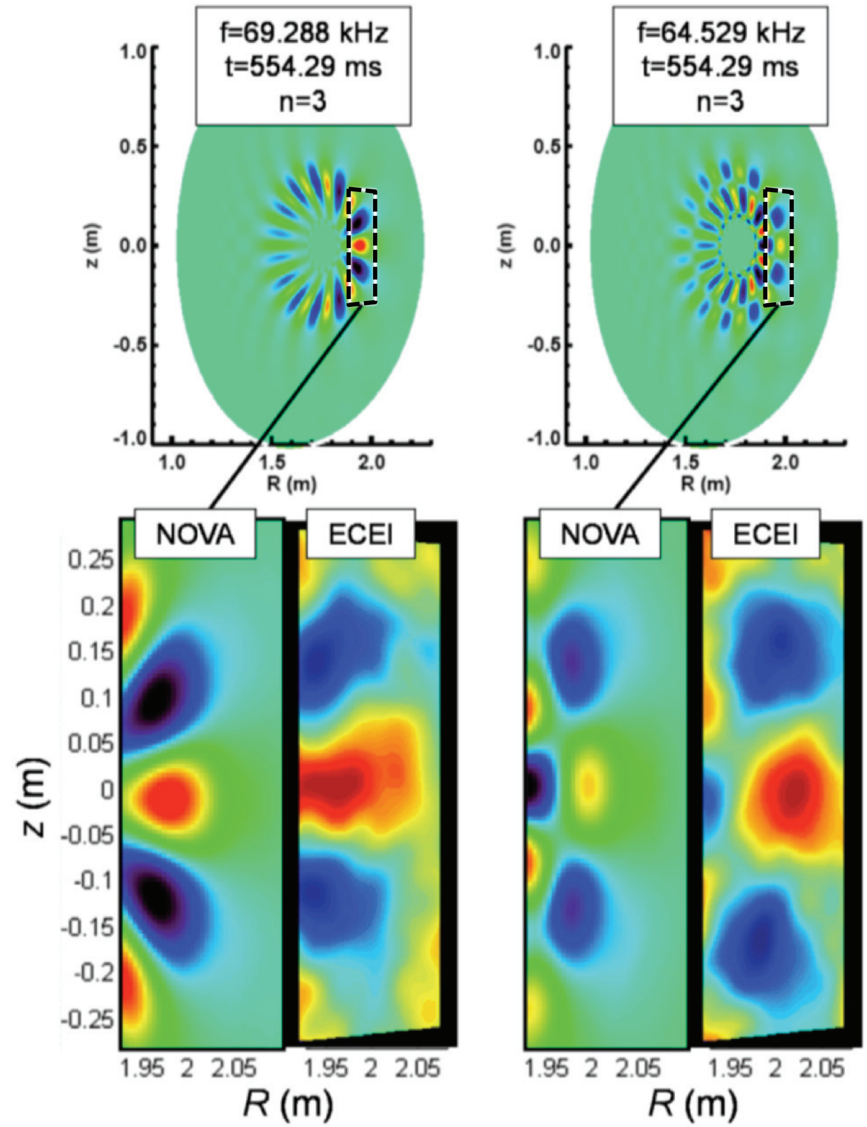
*B. Tobias, et al., Phys. Rev. Lett. (submitted Aug., 2010)*



# NOVA* Correctly Predicts Important Features

- **Frequency and mode number agree with experimental observations**
- **Radial harmonic modes diagnose plasma shape**
  - node confined to a flux surface
- **Constraints of symmetry are implicit:**

$$\psi = \sum_{m,n} \psi_{mn} \cos(m\theta - n\zeta)$$




**C.Z. Cheng, Phys. Rep. **211**, 1 (1992)*

*B. Tobias, et al., Phys. Rev. Lett. (submitted Aug., 2010)*

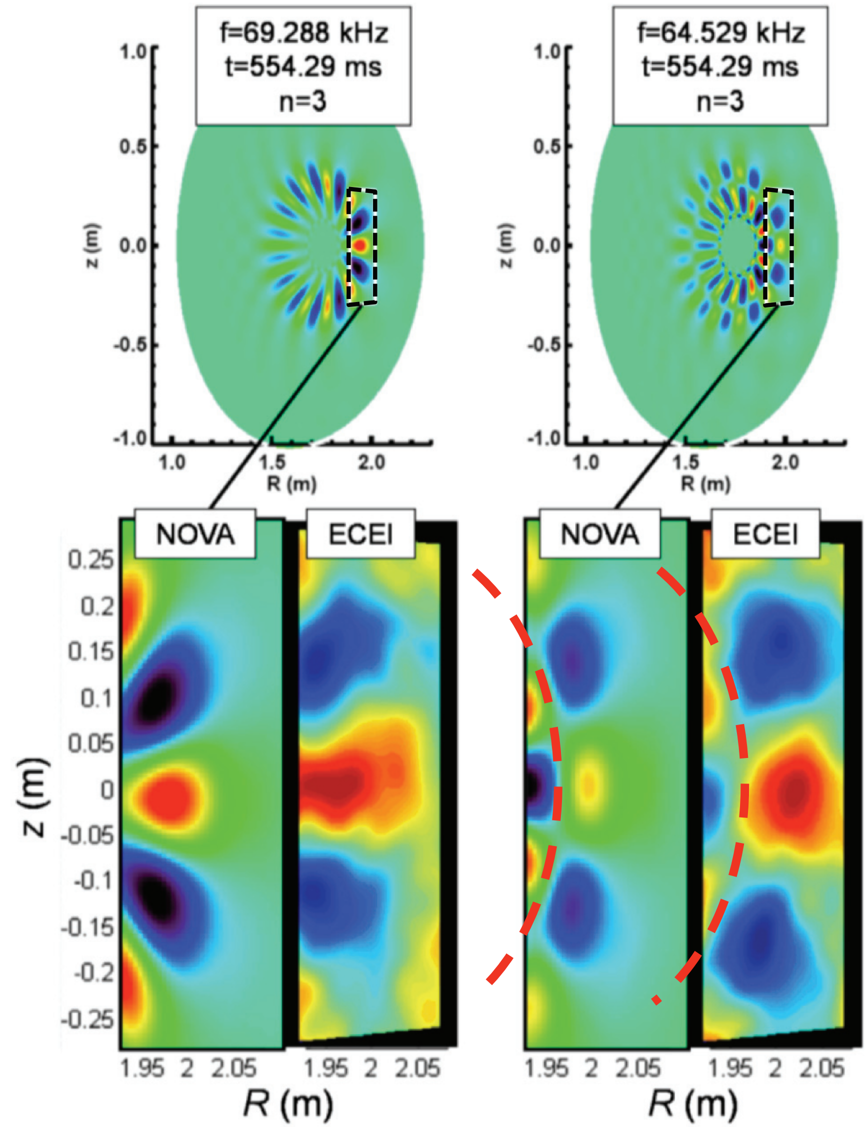
# NOVA* Correctly Predicts Important Features

- **Frequency and mode number agree with experimental observations**
- **Radial harmonic modes diagnose plasma shape**
  - node confined to a flux surface
- **Constraints of symmetry are implicit:**

$$\psi = \sum_{m,n} \psi_{mn} \cos(m\theta - n\zeta)$$

**C.Z. Cheng, Phys. Rep. **211**, 1 (1992)*

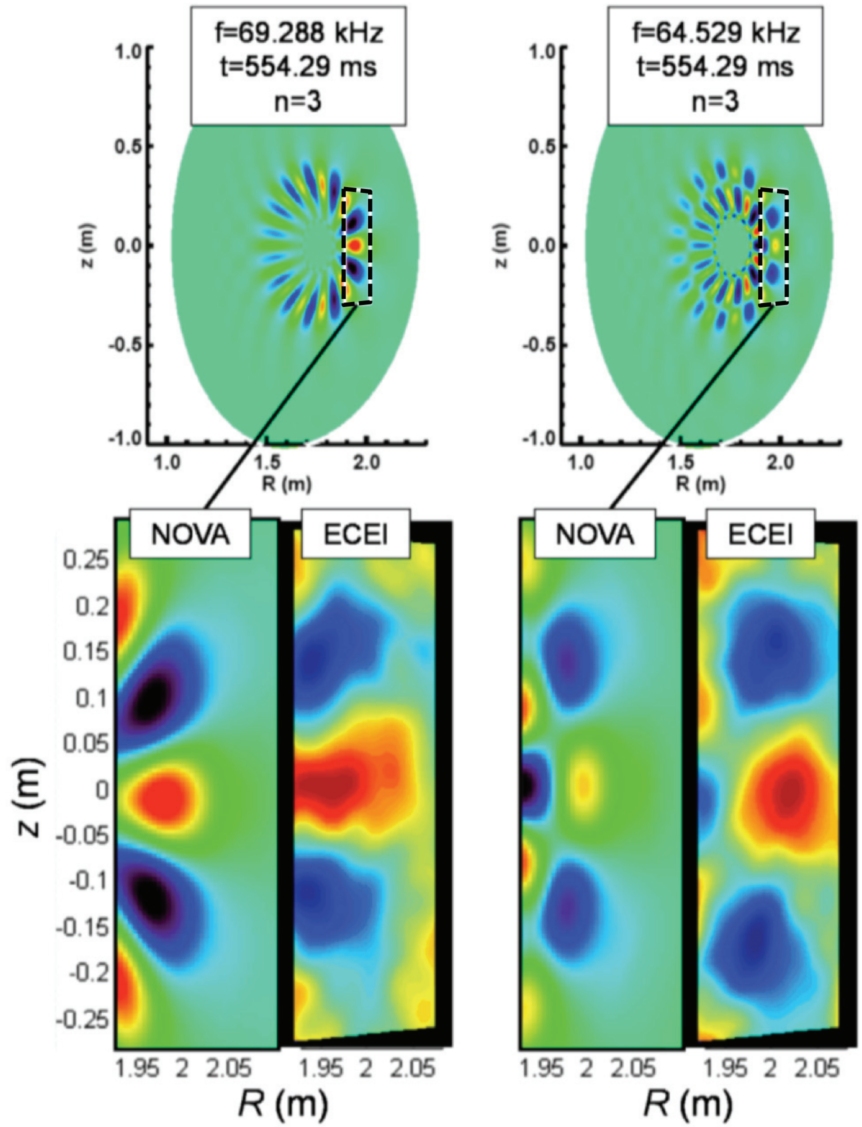
*B. Tobias, et al., Phys. Rev. Lett. (submitted Aug., 2010)*



# NOVA* Correctly Predicts Important Features

- **Frequency and mode number agree with experimental observations**
- **Radial harmonic modes diagnose plasma shape**
  - node confined to a flux surface
- **Constraints of symmetry are implicit:**

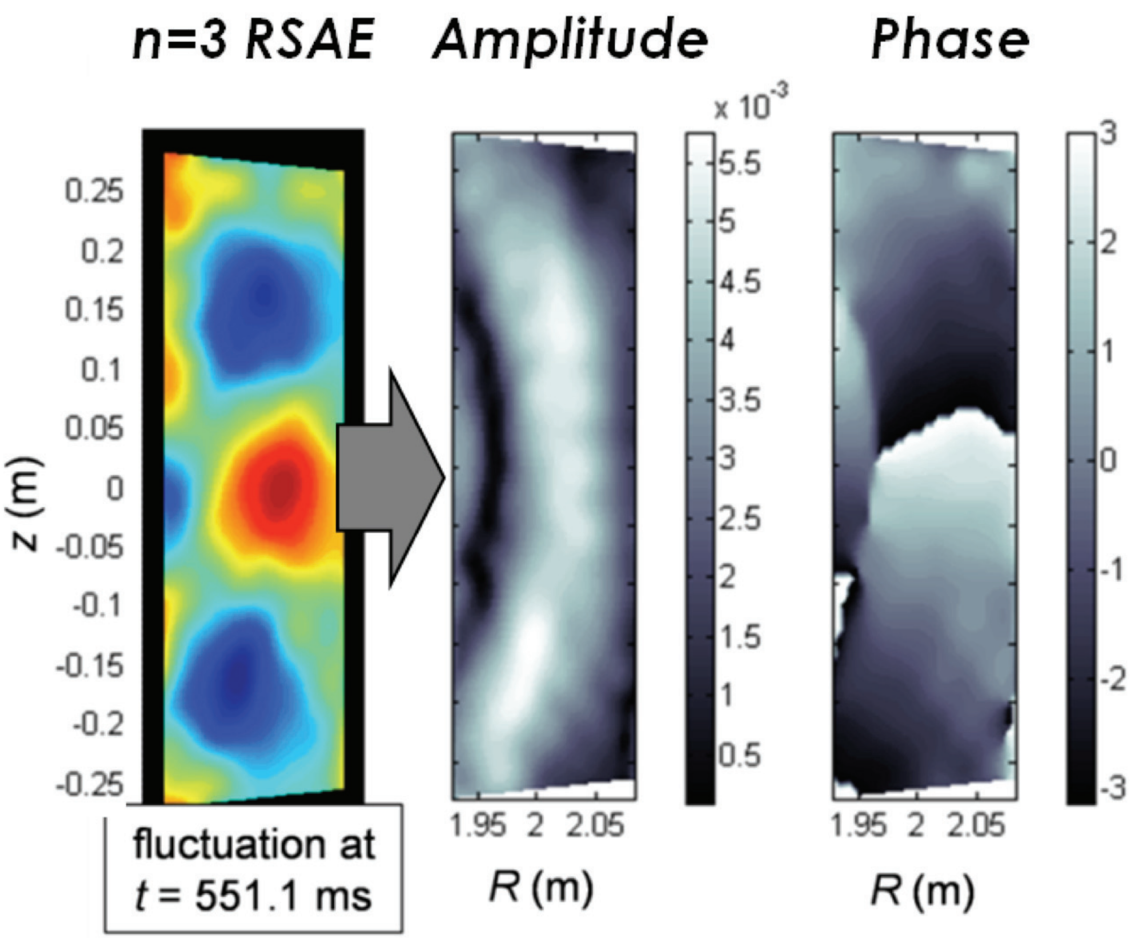
$$\psi = \sum_{m,n} \psi_{mn} \cos(m\theta - n\zeta)$$




*C.Z. Cheng, Phys. Rep. **211**, 1 (1992)

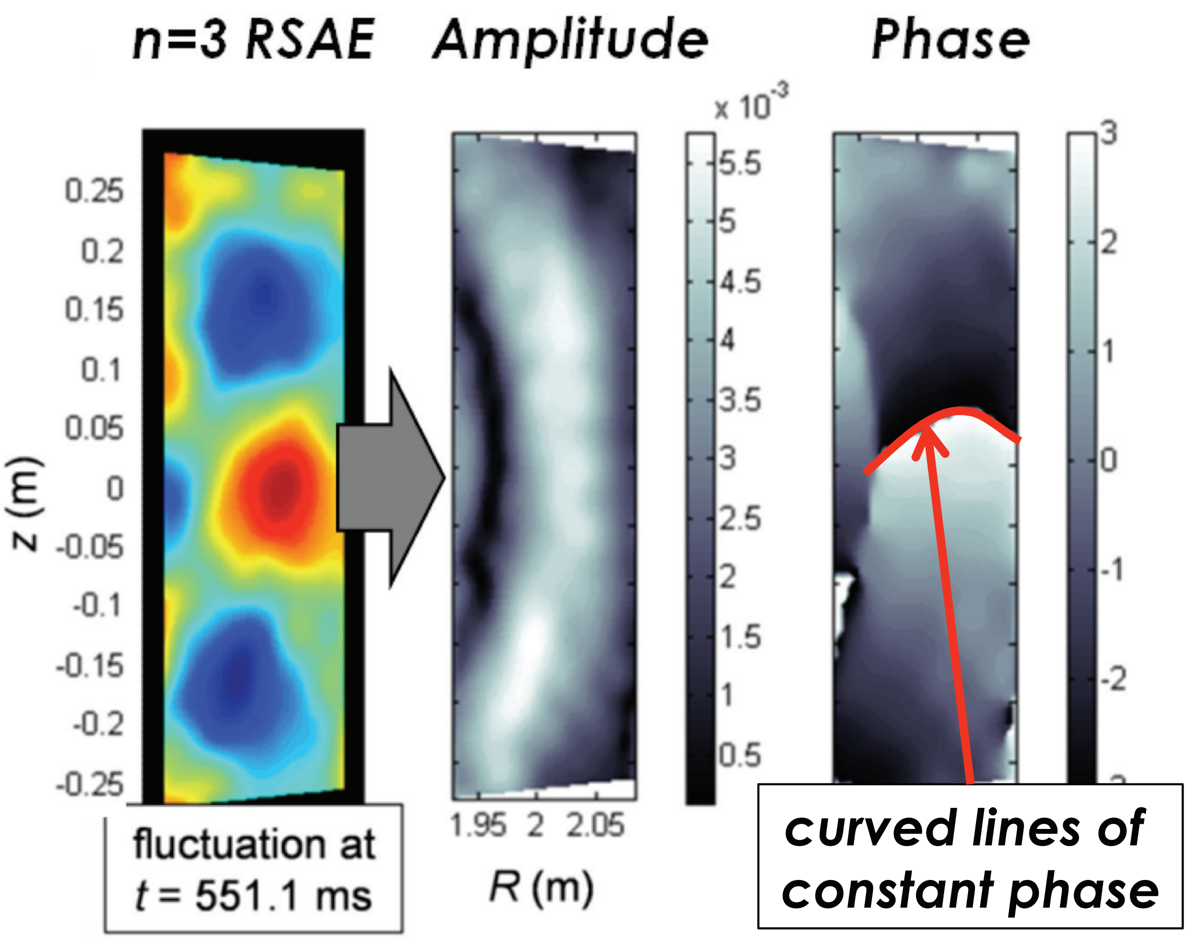
*B. Tobias, et al., Phys. Rev. Lett. (submitted Aug., 2010)*

# Decomposition of 2-D Images Reveals Poloidal Symmetry Breaking




- Poloidal distortion of eigenmode structure
- Clearly illustrated in phase plots
- Present in all modes to varying degree

# Decomposition of 2-D Images Reveals Poloidal Symmetry Breaking




- **Poloidal distortion of eigenmode structure**
- **Clearly illustrated in phase plots**
- **Present in all modes to varying degree**

# TAEFL*: Hybrid Gyrofluid-MHD Modeling Includes Fast Ion Contributions to Eigenmode Structure

- **Thermal plasma: reduced MHD vorticity equations and Ohm's Law**
- **Fast ions: closed gyrofluid moment equations**
- **Non-perturbative, initial value eigenmode solver**
- **Coupling to both even and odd terms**

$$\psi = \sum_{m,n} \left[ \psi_{mn,c} \cos(m\theta - n\zeta) + \psi_{mn,s} \sin(m\theta - n\zeta) \right]$$

  – No constraint on eigenmode symmetry

**D.A. Spong, et. al., Phys. Fluids B **4**, 3316 (1992)*

# TAEFL*: Hybrid Gyrofluid-MHD Modeling Includes Fast Ion Contributions to Eigenmode Structure

- **Thermal plasma: reduced MHD vorticity equation and Ohm's Law**
- **Fast ions: closed gyrofluid moment equations**
- **Non-perturbative, initial value eigenmode solver**
- **Coupling to both even and odd terms**

$$\psi = \sum_{m,n} \left[ \psi_{mn,c} \cos(m\theta - n\zeta) + \psi_{mn,s} \sin(m\theta - n\zeta) \right]$$

  – No constraint on eigenmode symmetry

**D.A. Spong, et. al., Phys. Fluids B **4**, 3316 (1992)*

# TAEFL*: Hybrid Gyrofluid-MHD Modeling Includes Fast Ion Contributions to Eigenmode Structure

- **Thermal plasma: reduced MHD vorticity equation and Ohm's Law**
- **Fast ions: closed gyrofluid moment equations**
- **Non-perturbative, initial value eigenmode solver**
- **Coupling to both even and odd terms**

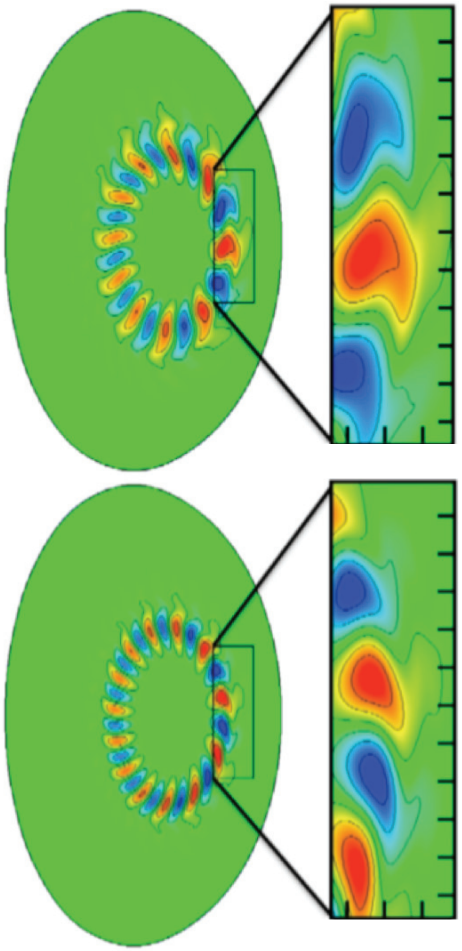
$$\psi = \sum_{m,n} \left[ \psi_{mn,c} \cos(m\theta - n\zeta) + \psi_{mn,s} \sin(m\theta - n\zeta) \right]$$

  – No constraint on eigenmode symmetry

**D.A. Spong, et. al., Phys. Fluids B **4**, 3316 (1992)*

# ECEI Provides Validation of Predicted Subtleties

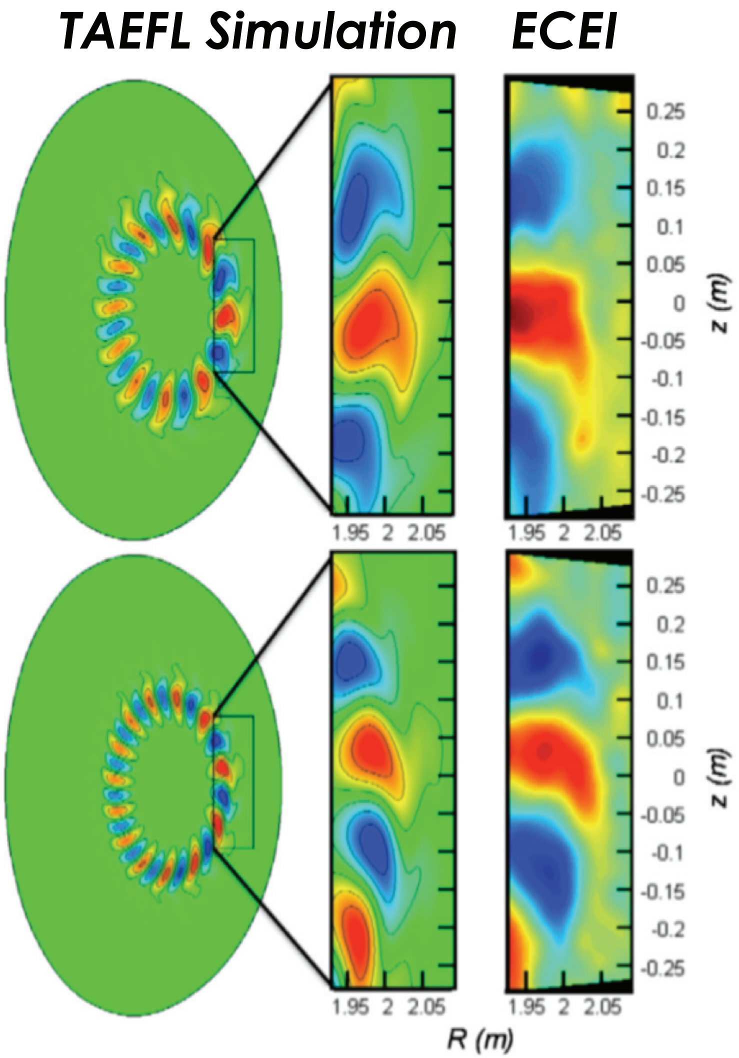
***TAEFL Simulation***



- **Fast ion diamagnetic flows break mode symmetry**
  - Strong dependence on fast ion energy and kinetic pressure
  - Only modest dependence on radial electric fields
- **Inclusion of acoustic coupling provides excellent agreement in mode frequency without modification of the eigenmode structure**

*B. Tobias, et al., Phys. Rev. Lett. (submitted Aug., 2010)*

# ECEI Provides Validation of Predicted Subtleties

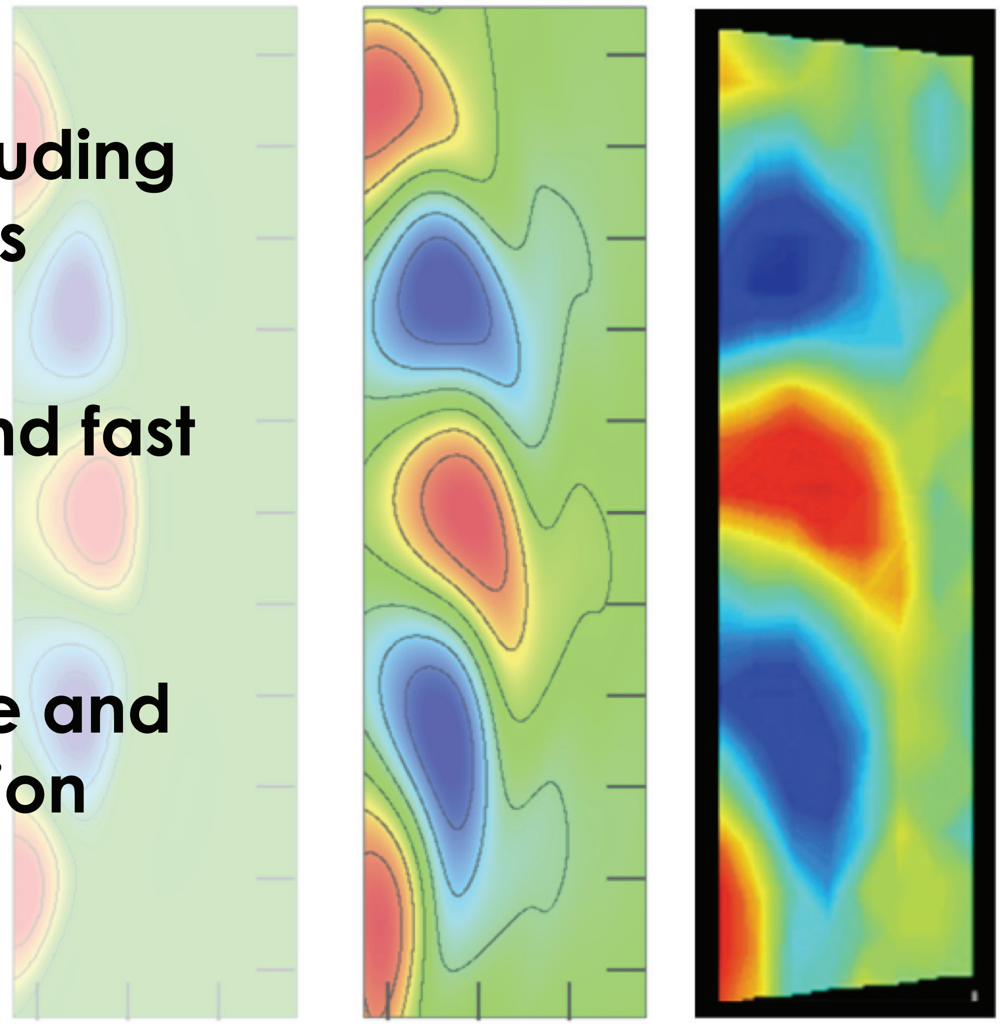



- **Fast ion diamagnetic flows break mode symmetry**
  - Strong dependence on fast ion energy and kinetic pressure
  - Only modest dependence on radial electric fields
- **Inclusion of acoustic coupling provides excellent agreement in mode frequency without modification of the eigenmode structure**

*B. Tobias, et al., Phys. Rev. Lett. (submitted Aug., 2010)*

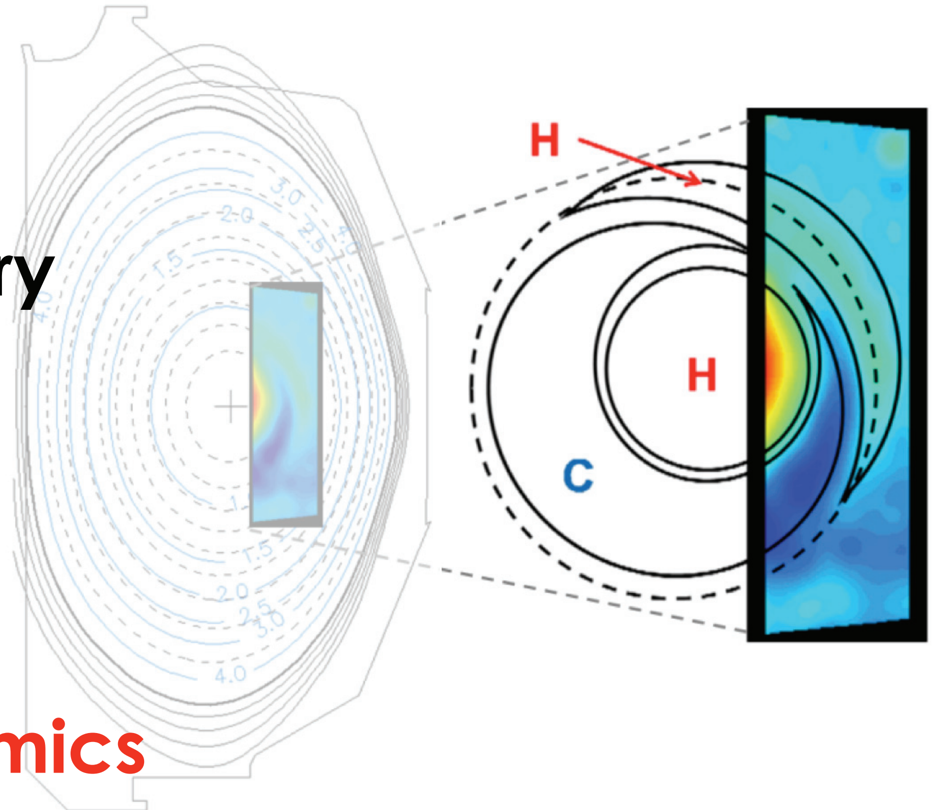
# ECEI Serves as a Powerful Validation Tool for Non-perturbative Alfvén Eigenmode Modeling

- Determination of the eigenmode structure, including fine detail, is unambiguous
- Implications for thermal and fast ion transport
- Inference of plasma shape and characteristics of the fast ion pressure profile



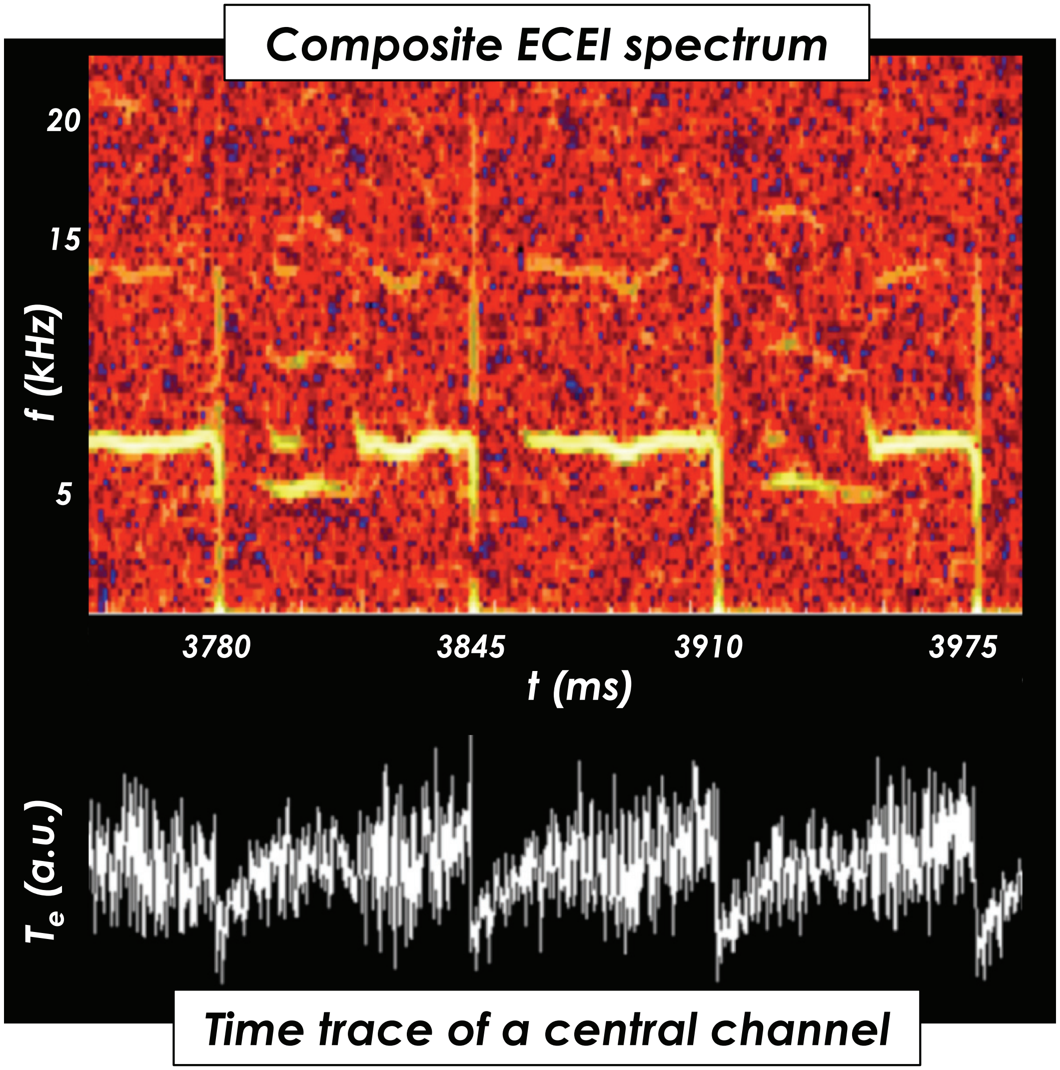
# Outline

- An introduction to ECEI diagnostic systems
- Fast ion induced symmetry breaking in Alfvén eigenmode structures
- *m*/*n* = 1/1 sawtooth precursors and the dynamics of the sawtooth crash



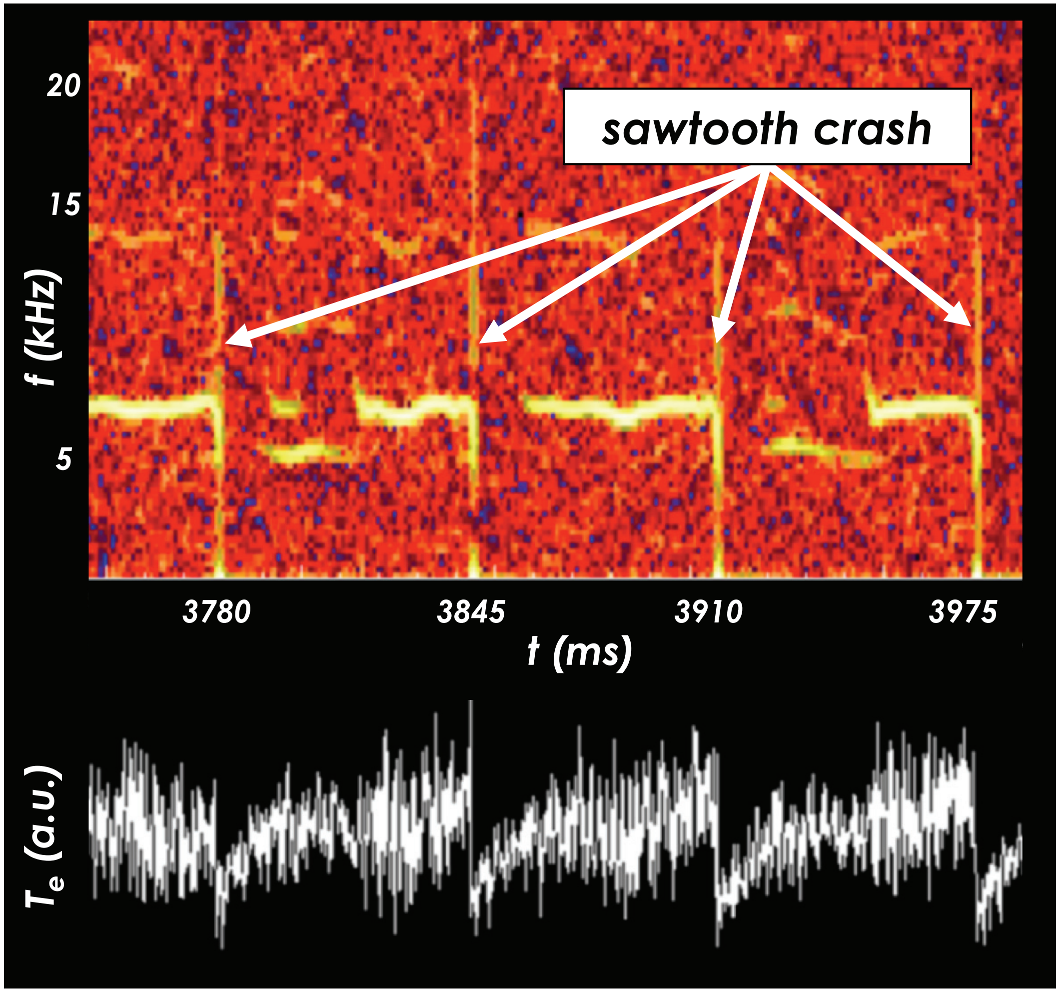

*See also C.M. Muscatello (UP9.00056) and M.J. Choi (GP9.00081)*

# Elongated, Neutral Beam Heated Plasmas Exhibit Long-lived Precursor Modes



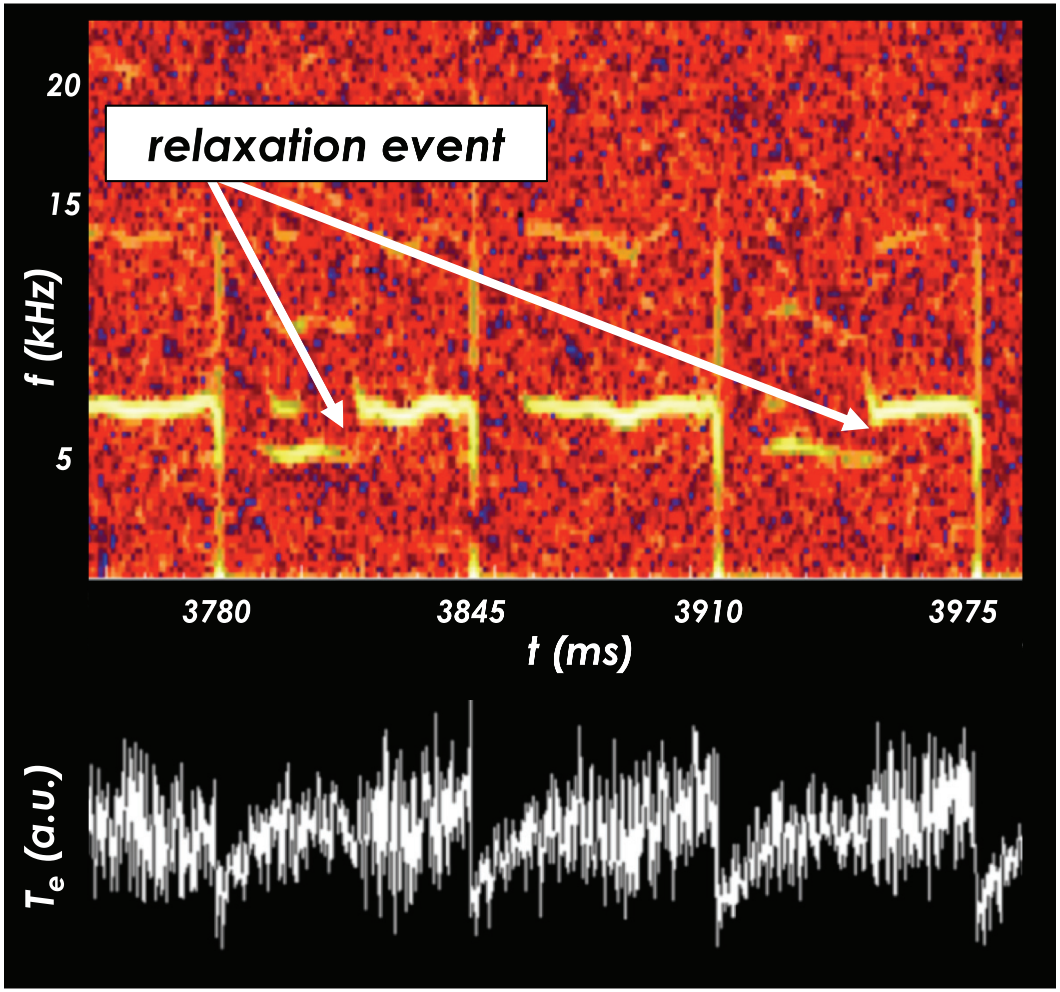

- **Sawtooth crashes at regular intervals**
- **Relaxation events observed in plasma profiles and MHD**
- **Down-shifted mode at ~5 kHz**
  - Downshift comparable to diamagnetic frequency
- **1/1 mode at ~7 kHz**

# Elongated, Neutral Beam Heated Plasmas Exhibit Long-lived Precursor Modes



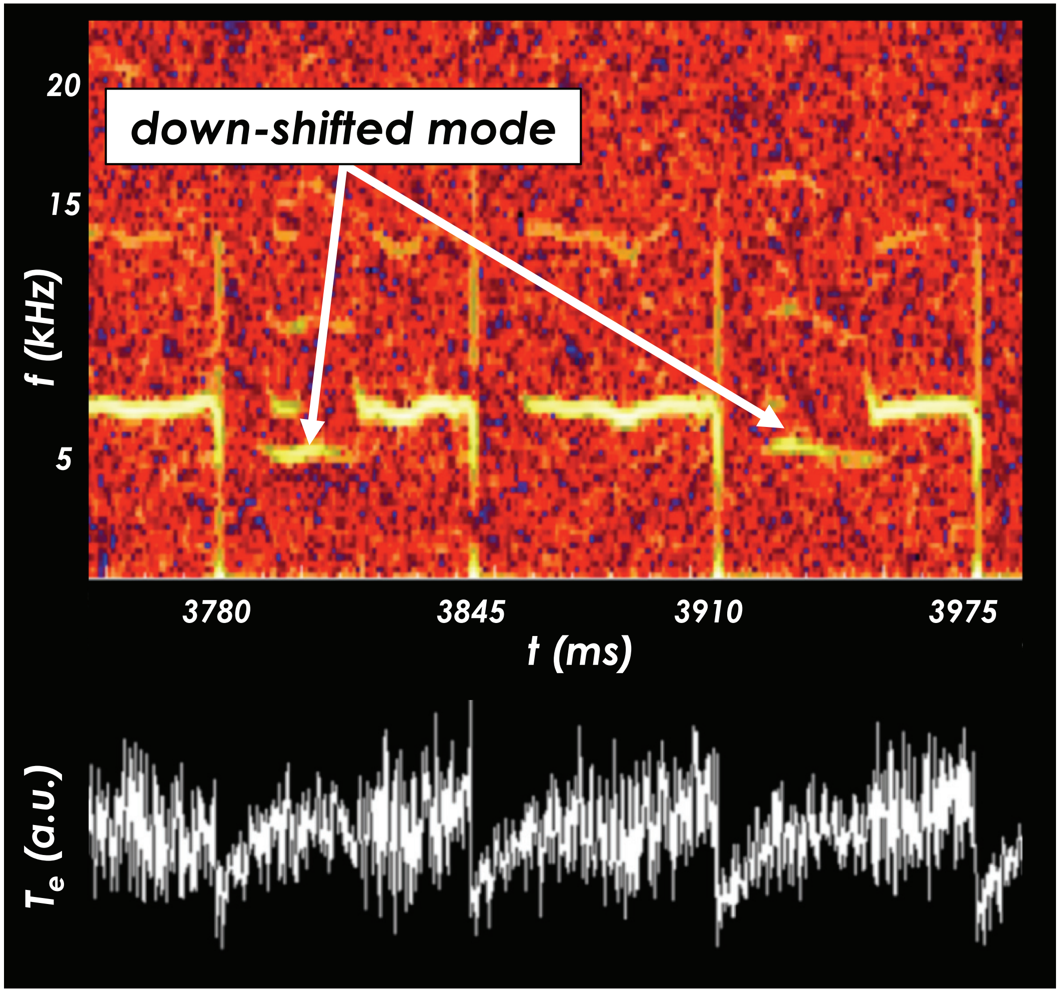

- **Sawtooth crashes at regular intervals**
- **Relaxation events observed in plasma profiles and MHD**
- **Down-shifted mode at ~5 kHz**
  - Downshift comparable to diamagnetic frequency
- **1/1 mode at ~7 kHz**

# Elongated, Neutral Beam Heated Plasmas Exhibit Long-lived Precursor Modes



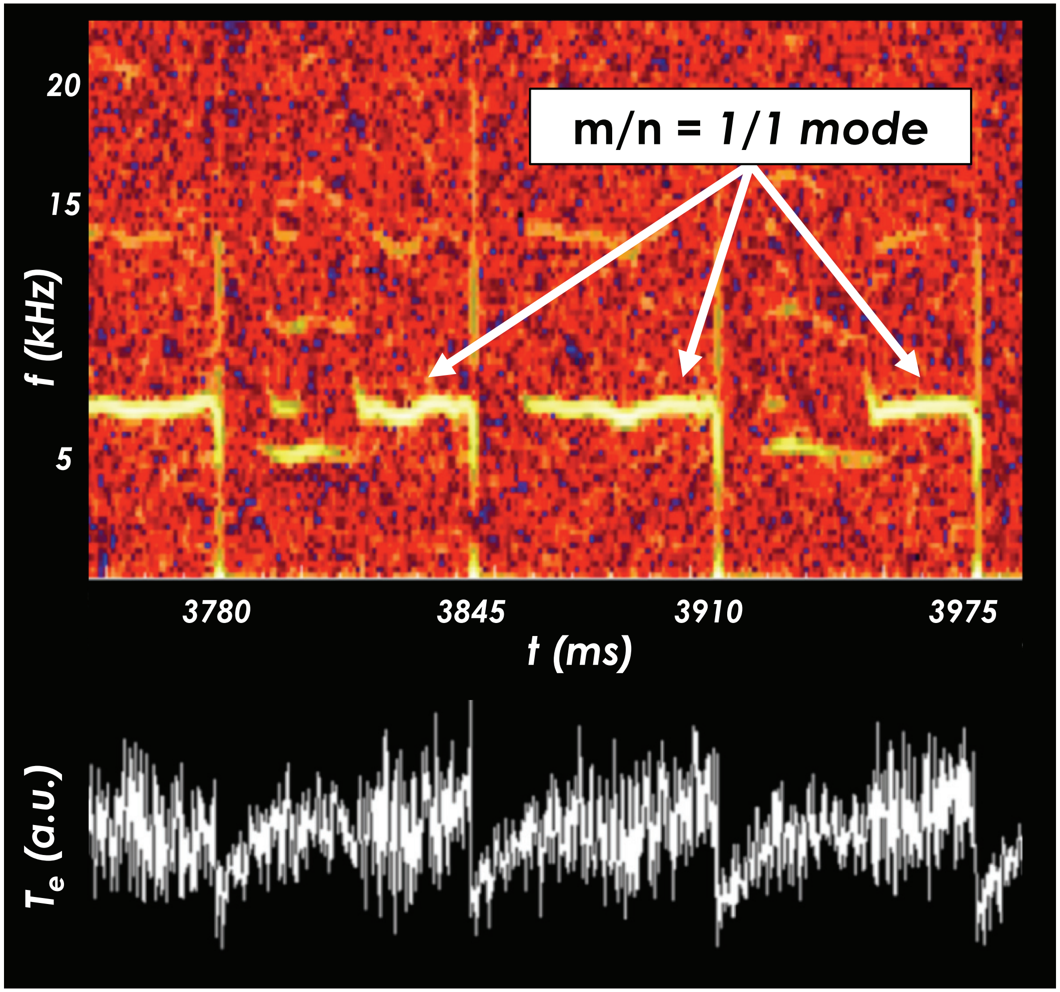

- **Sawtooth crashes at regular intervals**
- **Relaxation events observed in plasma profiles and MHD**
- **Down-shifted mode at ~5 kHz**
  - Downshift comparable to diamagnetic frequency
- **1/1 mode at ~7 kHz**

# Elongated, Neutral Beam Heated Plasmas Exhibit Long-lived Precursor Modes




- Sawtooth crashes at regular intervals
- Relaxation events observed in plasma profiles and MHD
- Down-shifted mode at ~5 kHz
  - Downshift comparable to diamagnetic frequency
- 1/1 mode at ~7 kHz

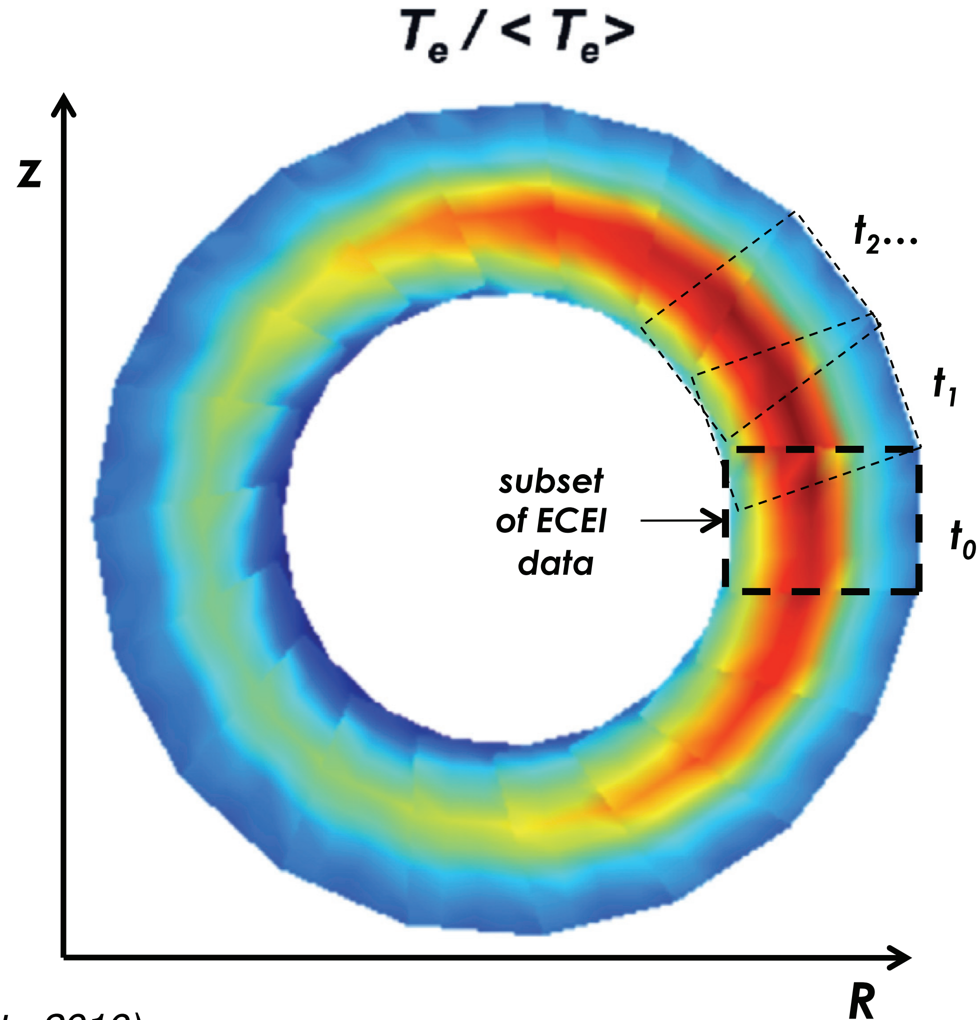
# Elongated, Neutral Beam Heated Plasmas Exhibit Long-lived Precursor Modes




- **Sawtooth crashes at regular intervals**
- **Relaxation events observed in plasma profiles and MHD**
- **Down-shifted mode at ~5 kHz**
  - Downshift comparable to diamagnetic frequency
- **1/1 mode at ~7 kHz**

# ECEI Allows for a Comparison of these Two Modes

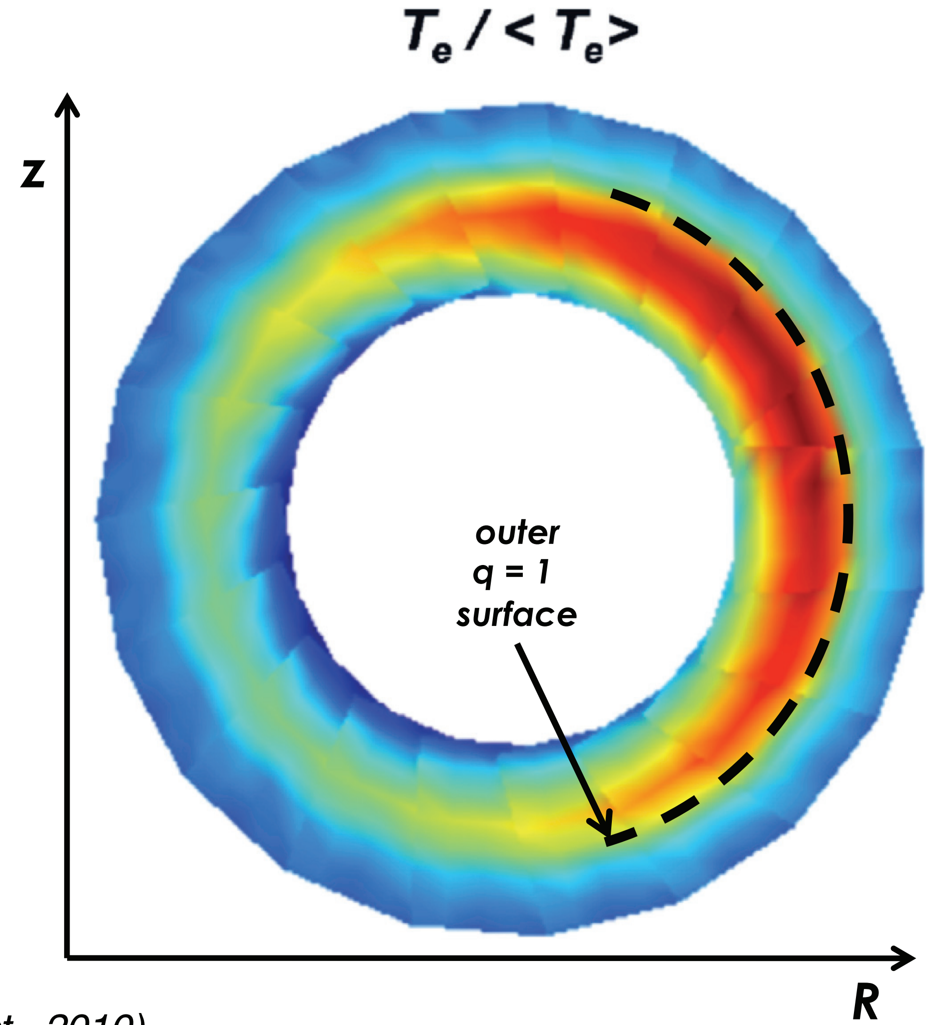
- **Rigid-body rotation is assumed for reconstruction**
- **Down-shifted mode:**
  - Flattened core temperature profile
  - Elongated hot crescent mode
- ***m/n* = 1/1 mode**
  - Peaked core temperature profile
  - Dislocated hot core and cold crescent




*B. Tobias, et al., IEEE Trans. Plasma Sci. (submitted Oct., 2010)*

# ECEI Allows for a Comparison of these Two Modes

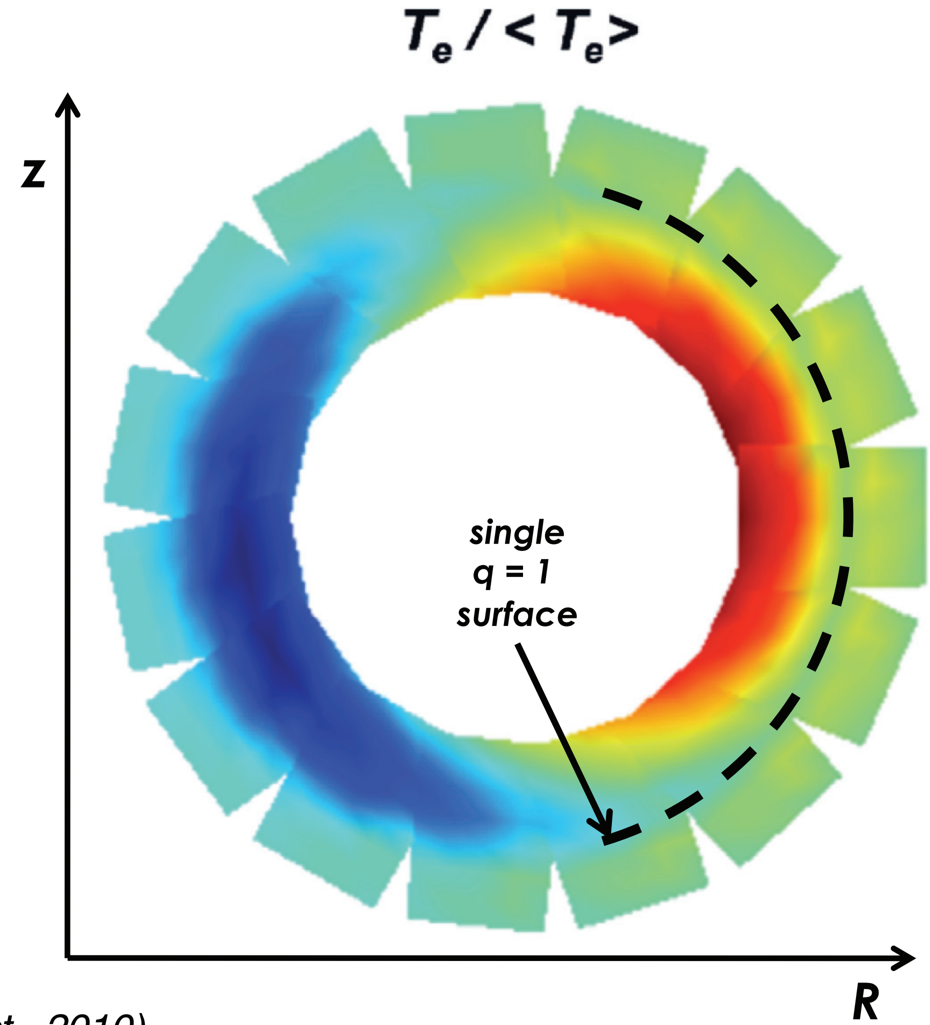
- **Rigid-body rotation is assumed for reconstruction**
- **Down-shifted mode:**
  - Flattened core temperature profile
  - Elongated hot crescent mode
- ***m*/*n* = 1/1 mode**
  - Peaked core temperature profile
  - Dislocated hot core and cold crescent




*B. Tobias, et al., IEEE Trans. Plasma Sci. (submitted Oct., 2010)*

# ECEI Allows for a Comparison of these Two Modes

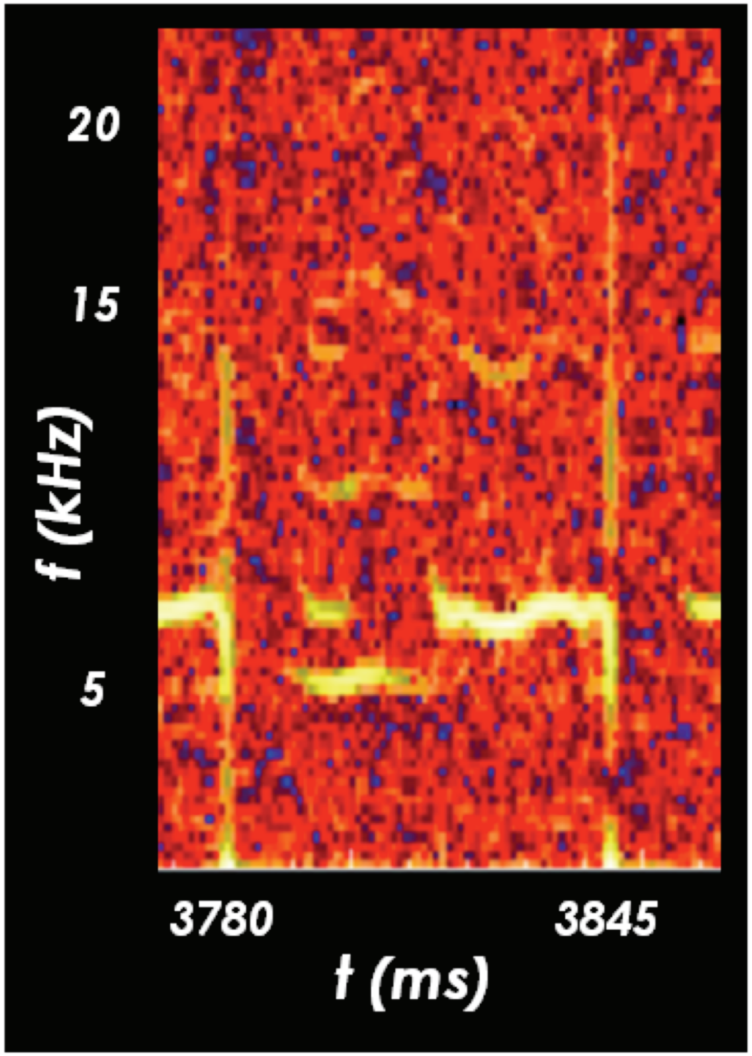
- **Rigid-body rotation is assumed for reconstruction**
- **Down-shifted mode:**
  - Flattened core temperature profile
  - Elongated hot crescent mode
- ***m/n* = 1/1 mode**
  - Peaked core temperature profile
  - Dislocated hot core and cold crescent




*B. Tobias, et al., IEEE Trans. Plasma Sci. (submitted Oct., 2010)*

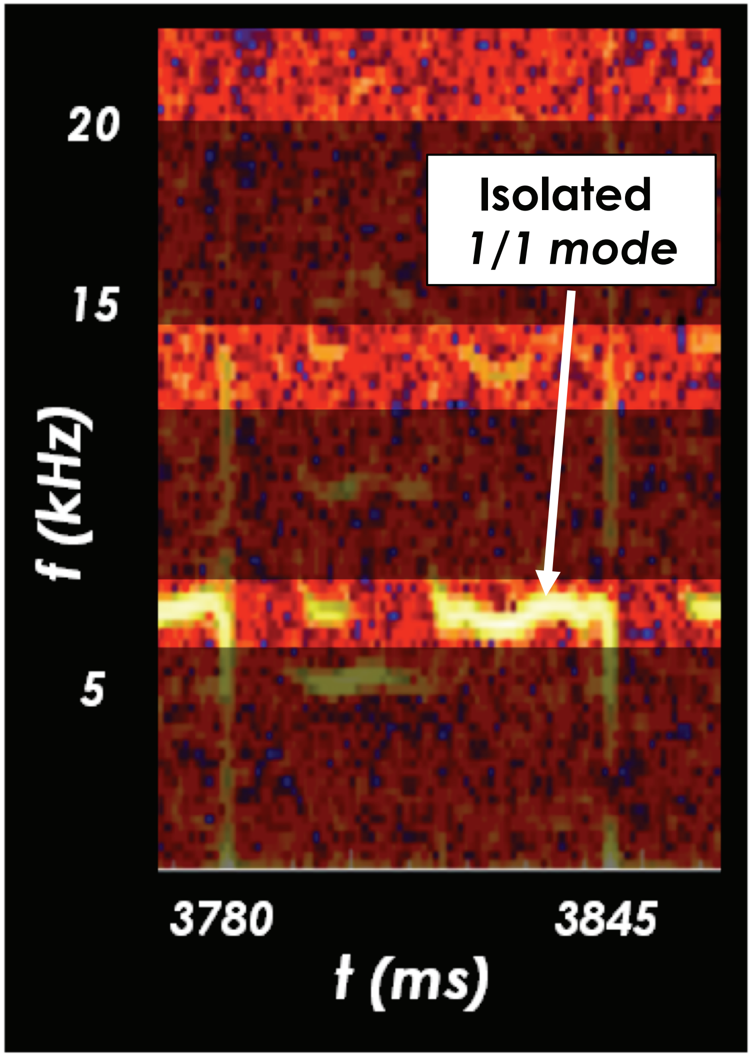
# Determining the Plasma Displacement Begins with Filtering ECEI Data

- **The sawtooth ramp includes activity on multiple timescales**
  - Slow evolution of the temperature profile
  - MHD oscillations
- **SVD enhances coherent mode activity**
- **Digital frequency filtering isolates MHD while retaining harmonic structure**



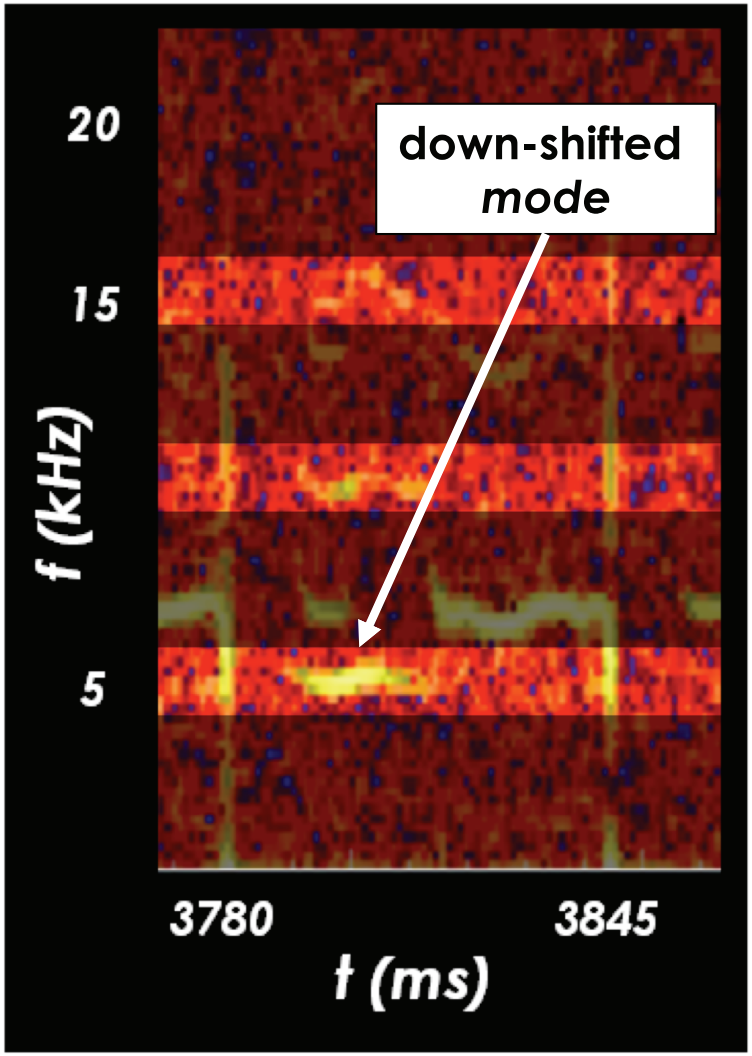
# Determining the Plasma Displacement Begins with Filtering ECEI Data

- **The sawtooth ramp includes activity on multiple timescales**
  - Slow evolution of the temperature profile
  - MHD oscillations
- **SVD enhances coherent mode activity**
- **Digital frequency filtering isolates MHD while retaining harmonic structure**



# Determining the Plasma Displacement Begins with Filtering ECEI Data

- **The sawtooth ramp includes activity on multiple timescales**
  - Slow evolution of the temperature profile
  - MHD oscillations
- **SVD enhances coherent mode activity**
- **Digital frequency filtering isolates MHD while retaining harmonic structure**

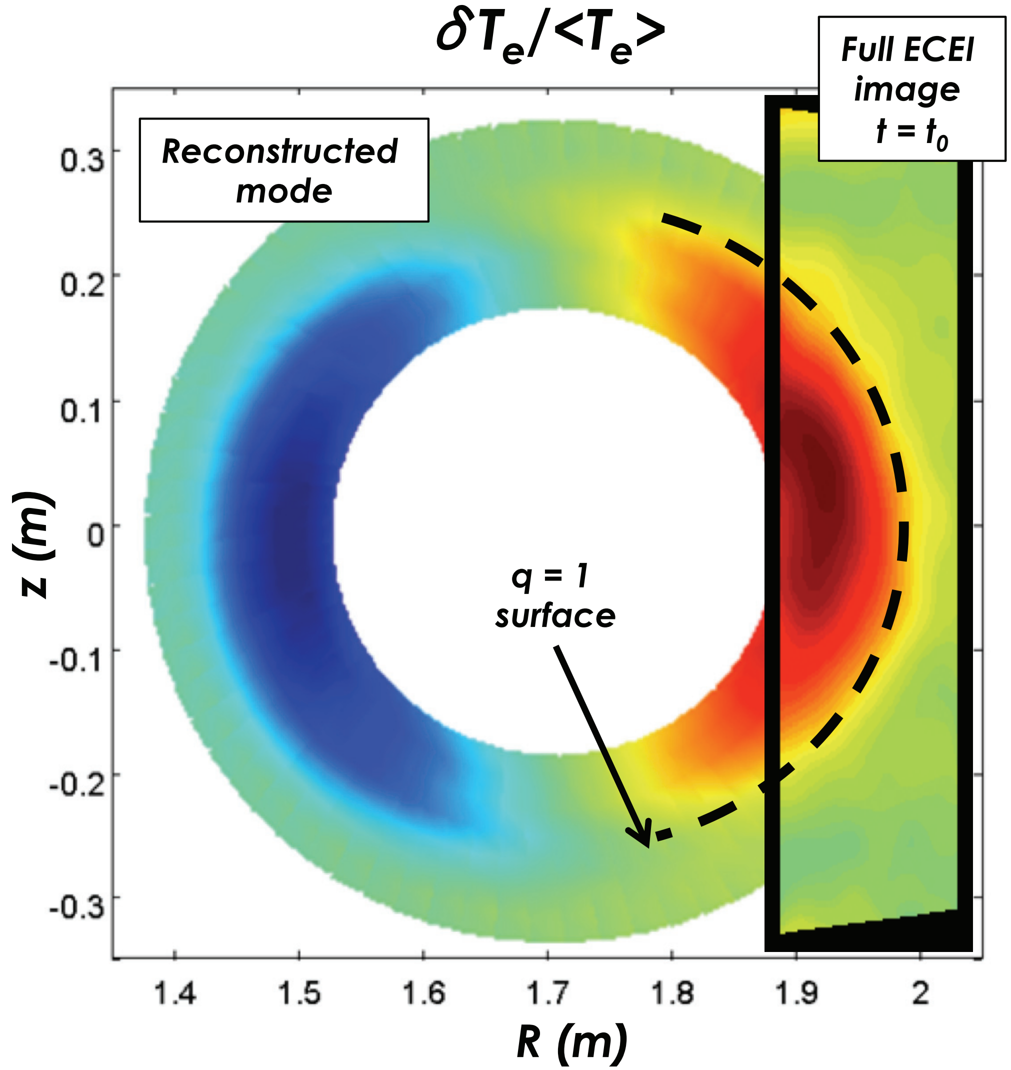


# Both Modes Correspond to the Same Temperature Perturbation

- **ECEI does not reveal the mechanisms which distinguish these modes**
- **Only limited features of the underlying plasma displacement may be inferred**
  - Smoothly varying radial displacement
  - Lines of convection in the core are parallel

$$\xi_\psi = \xi_{\psi 0} \cos\theta$$

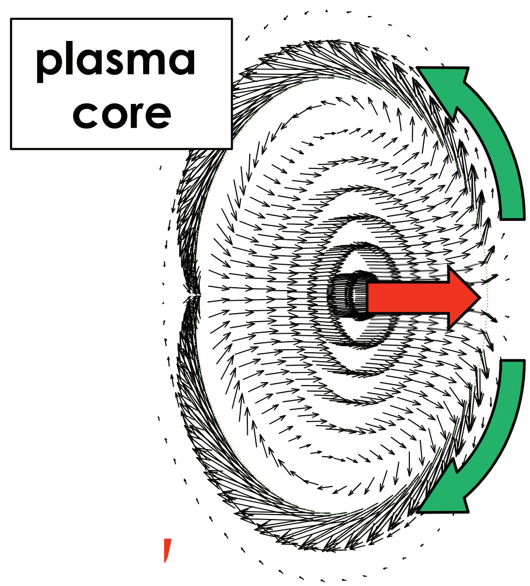
$$\xi_\psi \equiv \xi \cdot \nabla\psi / |\nabla\psi|$$

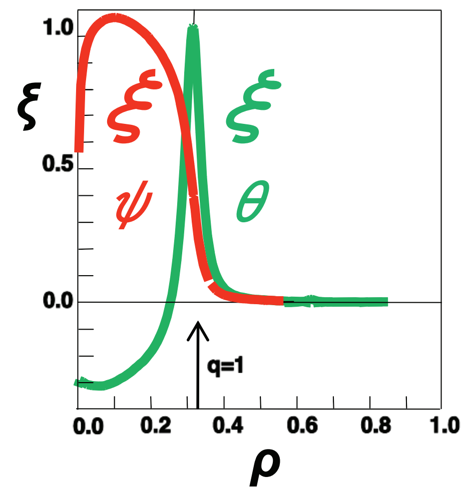


# These are Necessary, but not Sufficient Conditions for Quasi-interchange Behavior

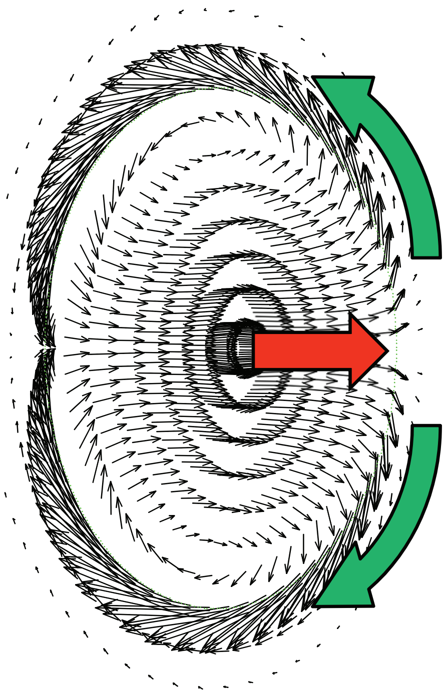
- **The quasi-interchange model is distinguished by plasma flows**
  - Rayleigh-Taylor like convection cell
  - Smoothly varying radial displacement
- **Only the radial flow produces a temperature perturbation**
  - Poloidal flow is directed along isothermals and not detected by ECEI

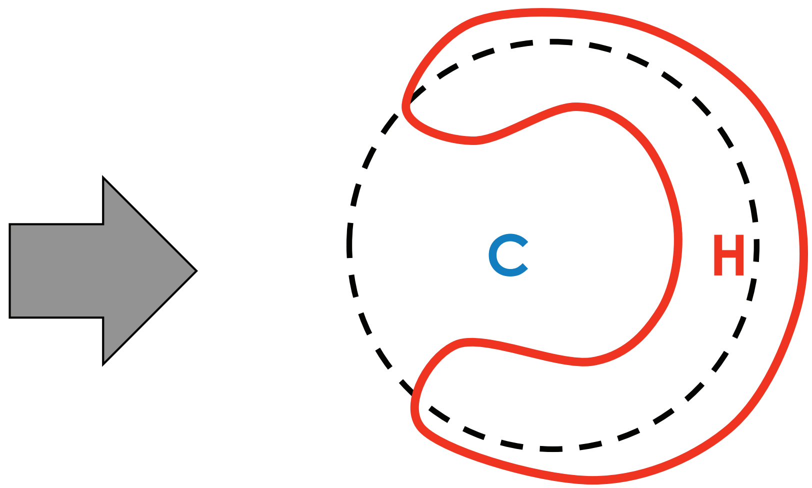
$$\nabla \cdot \xi = 0 \Rightarrow \frac{\delta T_e}{\langle T_e \rangle} = -\xi \cdot \frac{\nabla \langle T_e \rangle}{\langle T_e \rangle}$$



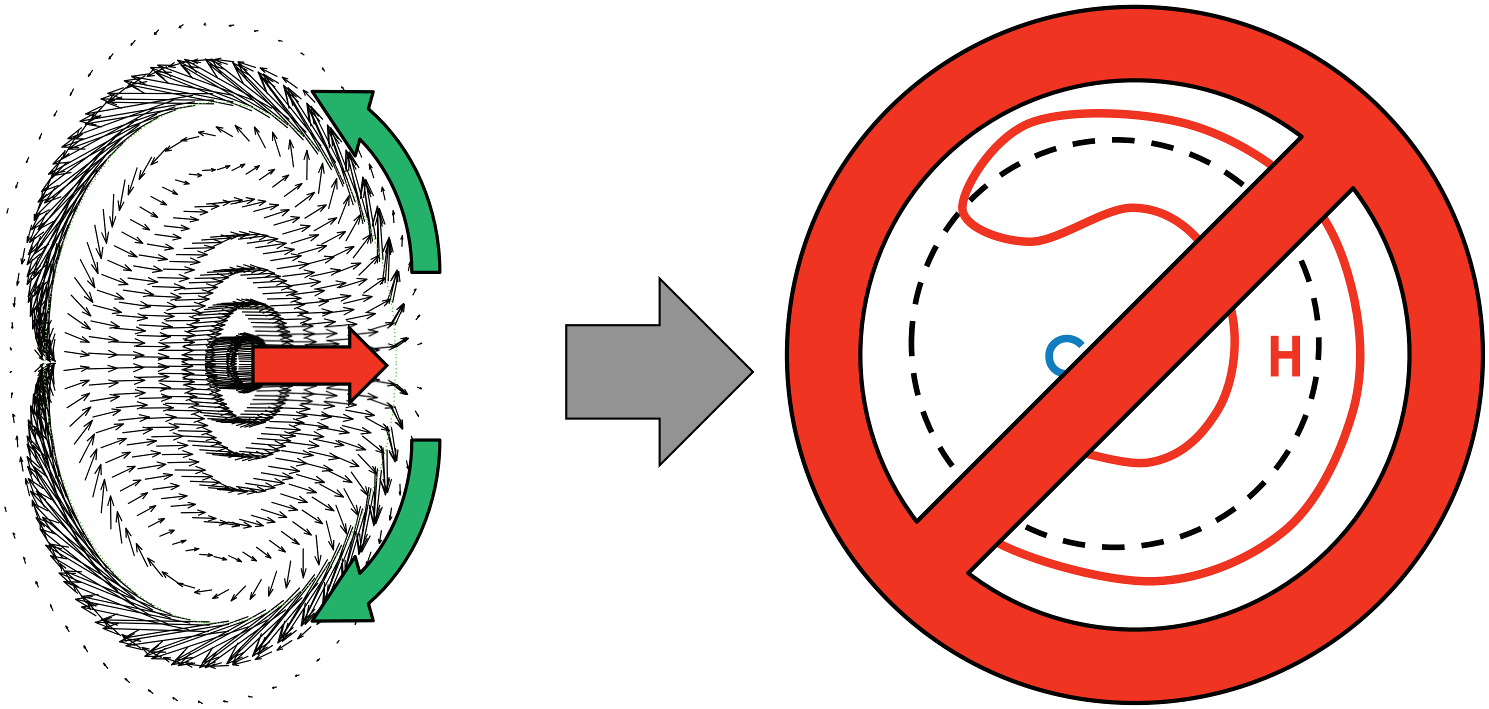
# The Expectation Eigenmodes for Quasi-interchange Convection Must be Re-evaluated






- **Poloidal flow is not represented in ECE Imaging**
- **Quasi-interchange convection does not lead to an easily distinguishable temperature eigenmode**

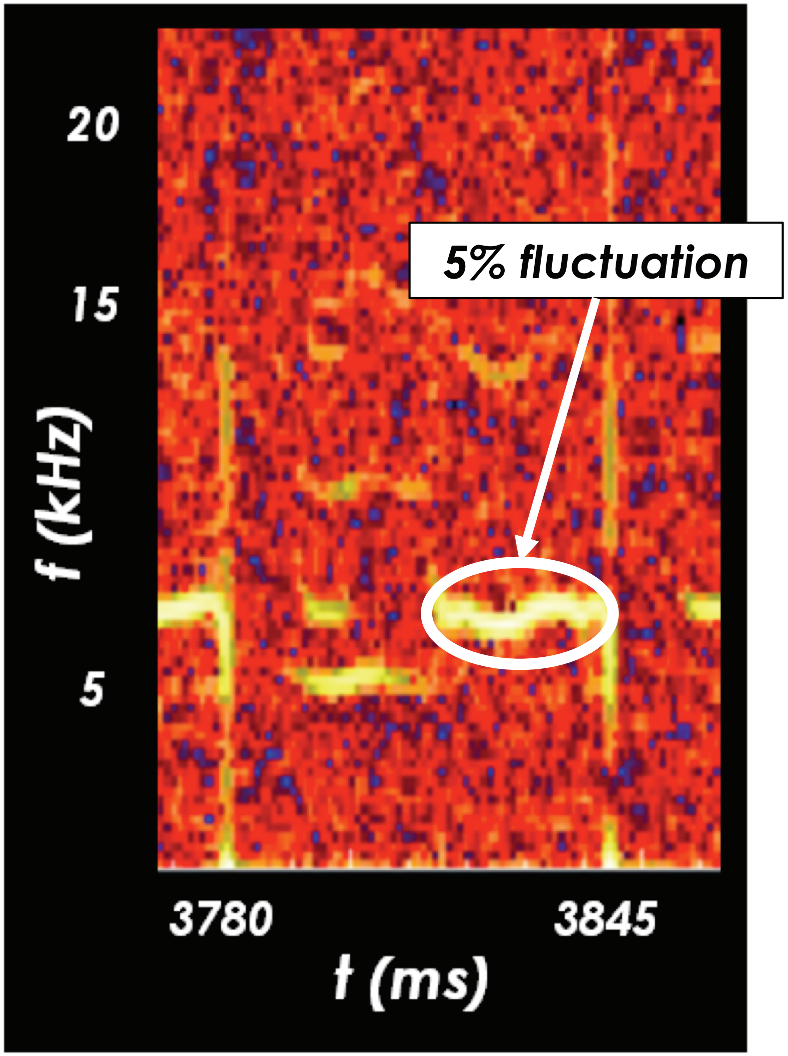
# The Expectation Eigenmodes for Quasi-interchange Convection Must be Re-evaluated




- **Poloidal flow is not represented in ECE Imaging**
- **Quasi-interchange convection does not lead to an easily distinguishable temperature eigenmode**

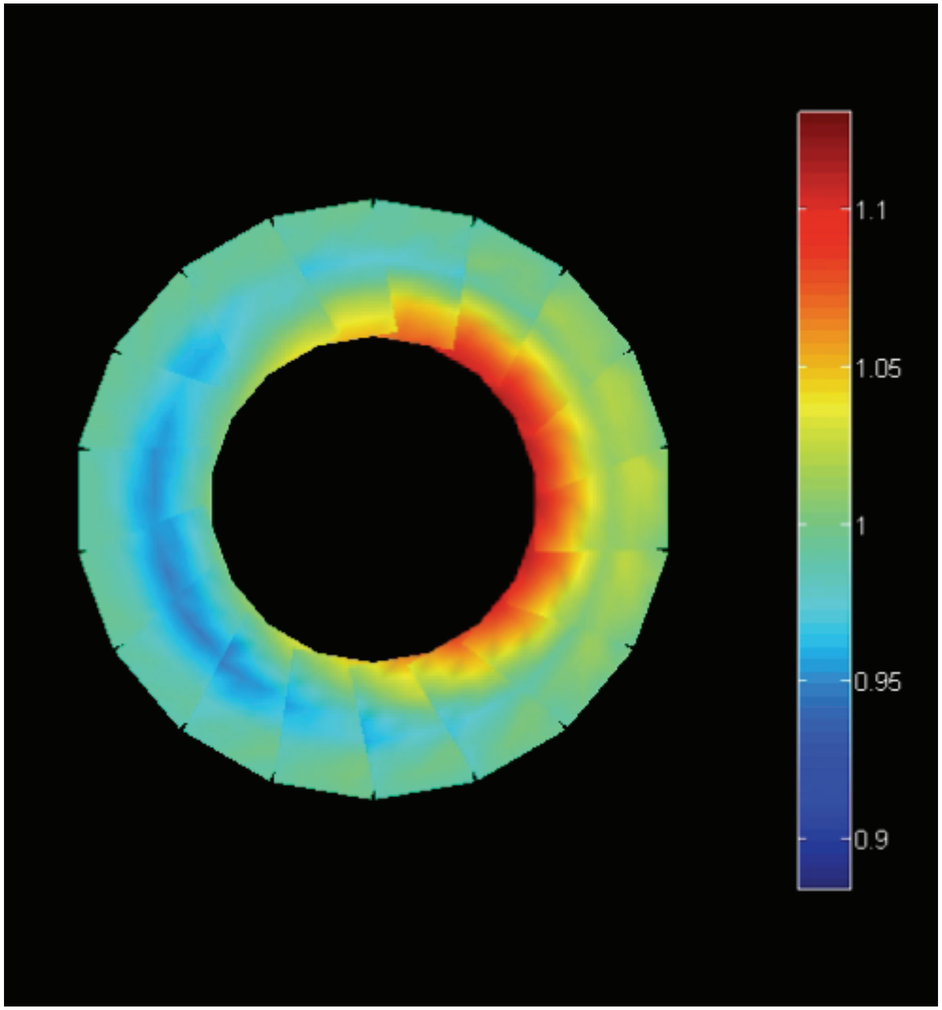
# Convective Core Destabilization is Transitory

- **Brief, explosive instability**
  - Linear growth rates ~1500 $s^{-1}$ ($\gamma^{-1}$ ~600 $\mu$ s)
  - Similar to instability growth rate preceding sawtooth crash
- **Prolonged saturated behavior**
  - Temperature fluctuation from 3 to 8%



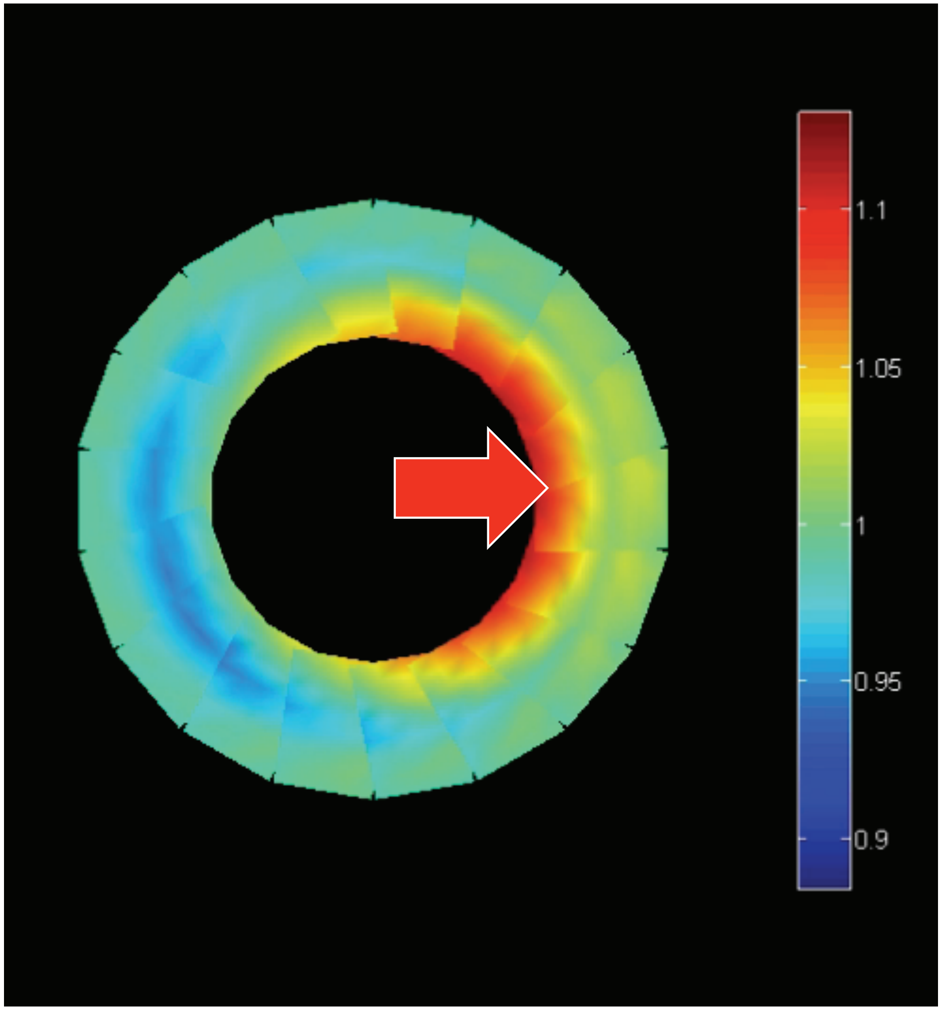
# Mode Structure Evolves Rapidly in the Moments Preceding a Sawtooth Crash

- **The sawtooth crash follows a secondary phase of instability**
  - Mode migrates outward
  - Mode contracts in poloidal and toroidal angle
  - Temperature perturbation intensifies
- **During penetration of the *q* = 1 surface, pronounced phase slipping occurs**



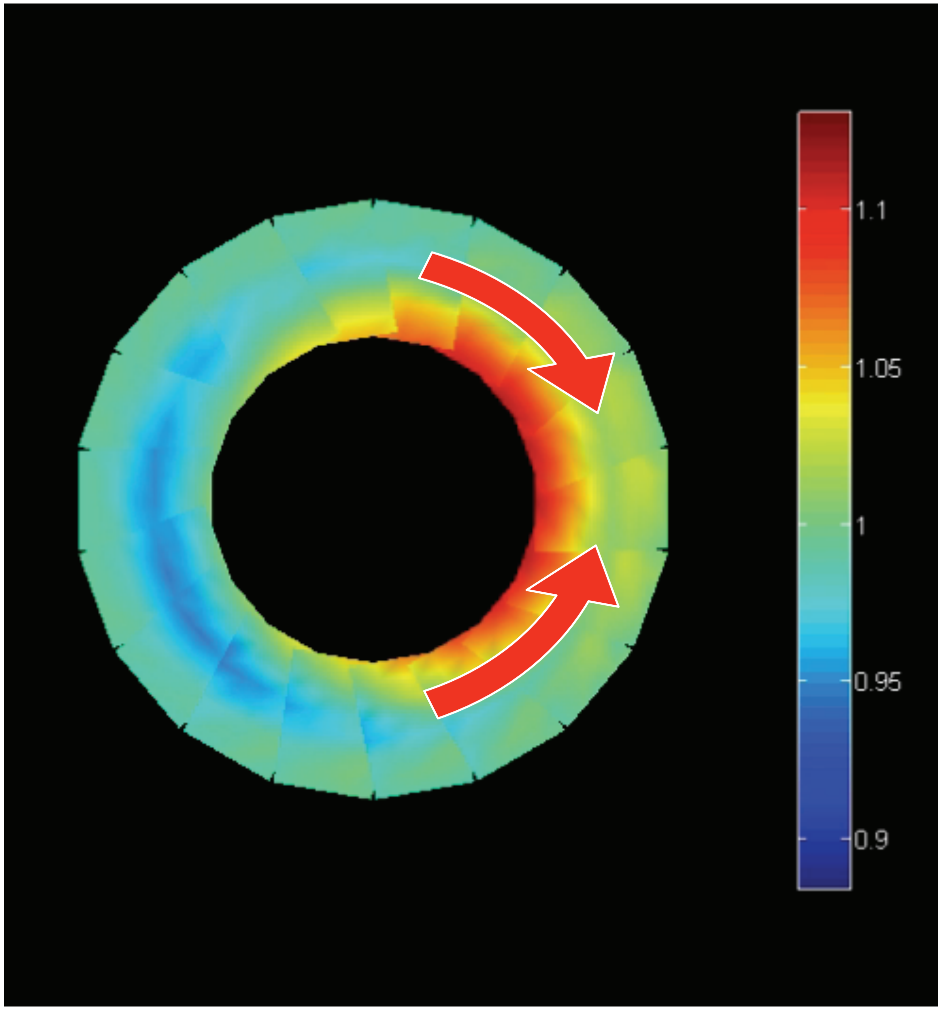
# Mode Structure Evolves Rapidly in the Moments Preceding a Sawtooth Crash

- **The sawtooth crash follows a secondary phase of instability**
  - Mode migrates outward
  - Mode contracts in poloidal and toroidal angle
  - Temperature perturbation intensifies
- **During penetration of the *q* = 1 surface, pronounced phase slipping occurs**



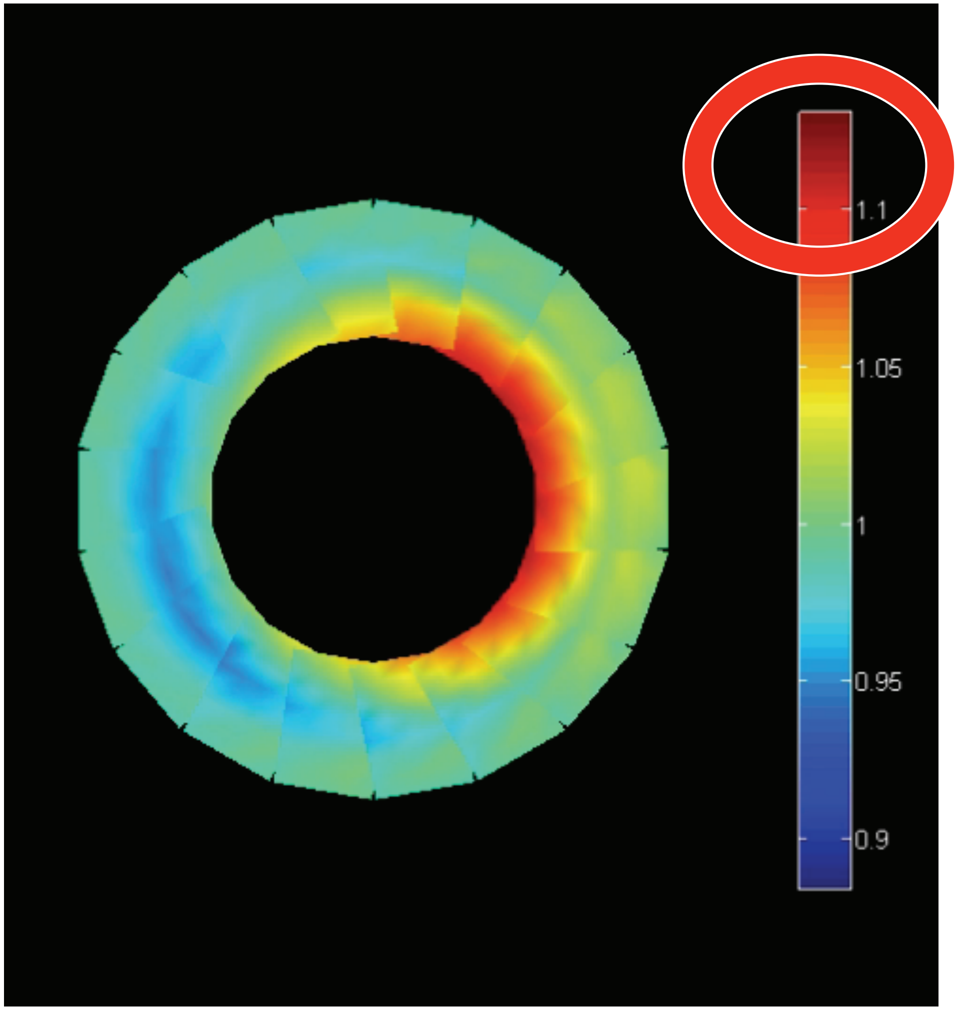
# Mode Structure Evolves Rapidly in the Moments Preceding a Sawtooth Crash

- **The sawtooth crash follows a secondary phase of instability**
  - Mode migrates outward
  - Mode contracts in poloidal and toroidal angle
  - Temperature perturbation intensifies
- **During penetration of the $q$ = 1 surface, pronounced phase slipping occurs**



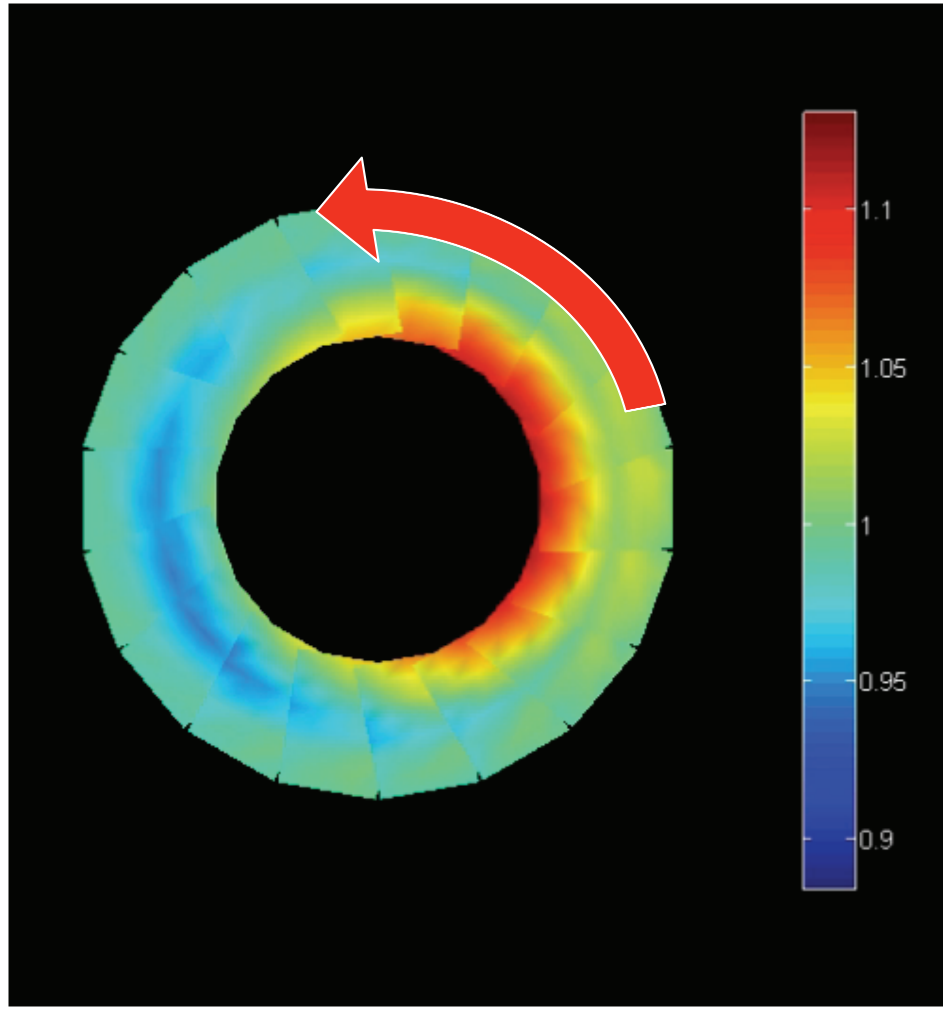
# Mode Structure Evolves Rapidly in the Moments Preceding a Sawtooth Crash

- **The sawtooth crash follows a secondary phase of instability**
  - Mode migrates outward
  - Mode contracts in poloidal and toroidal angle
  - Temperature perturbation intensifies
- **During penetration of the $q$ = 1 surface, pronounced phase slipping occurs**



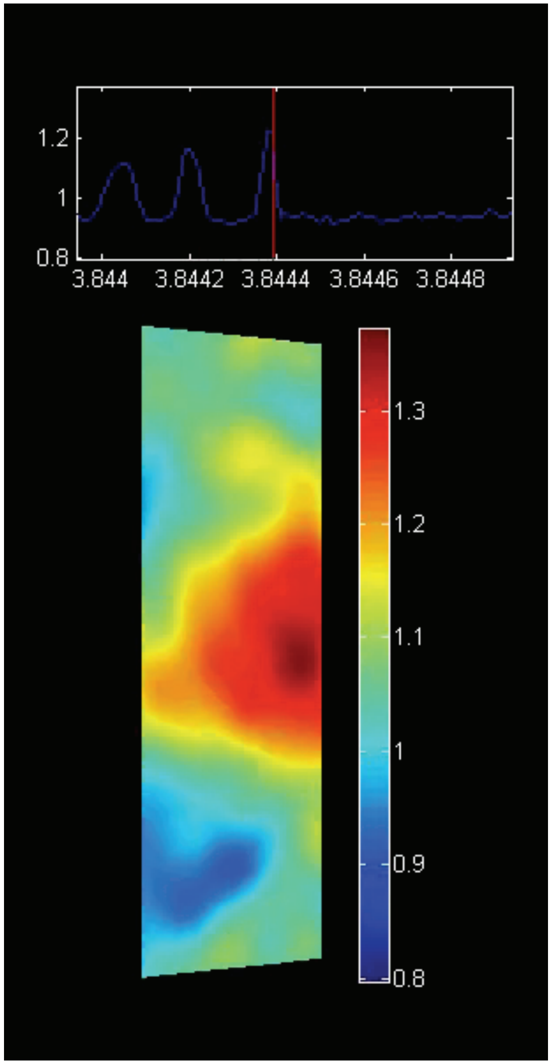
# Mode Structure Evolves Rapidly in the Moments Preceding a Sawtooth Crash

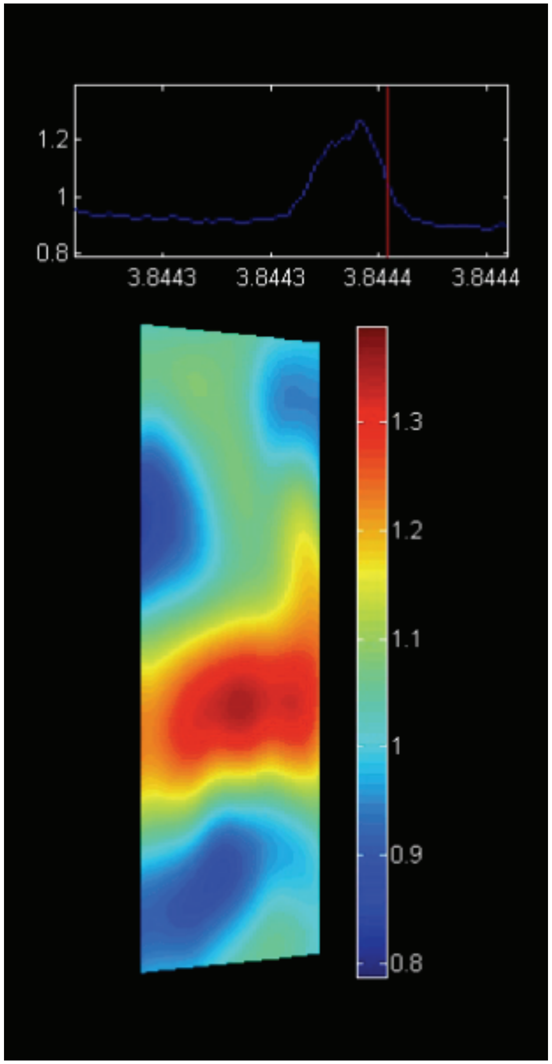
- **The sawtooth crash follows a secondary phase of instability**
  - Mode migrates outward
  - Mode contracts in poloidal and toroidal angle
  - Temperature perturbation intensifies
- **During penetration of the *q* = 1 surface, pronounced phase slipping occurs**



# Heat Flow During the Crash is Highly Collective

- **Rotating with the plasma, the precursor mode migrates toward the inversion radius**
  - Heat "leaks" across the inversion radius
- **Localized heat flow indicates the formation of an X-point**
  - On TEXTOR and KSTAR, multiple X-points are sometimes observed
- **Complete ejection of the hot core follows**



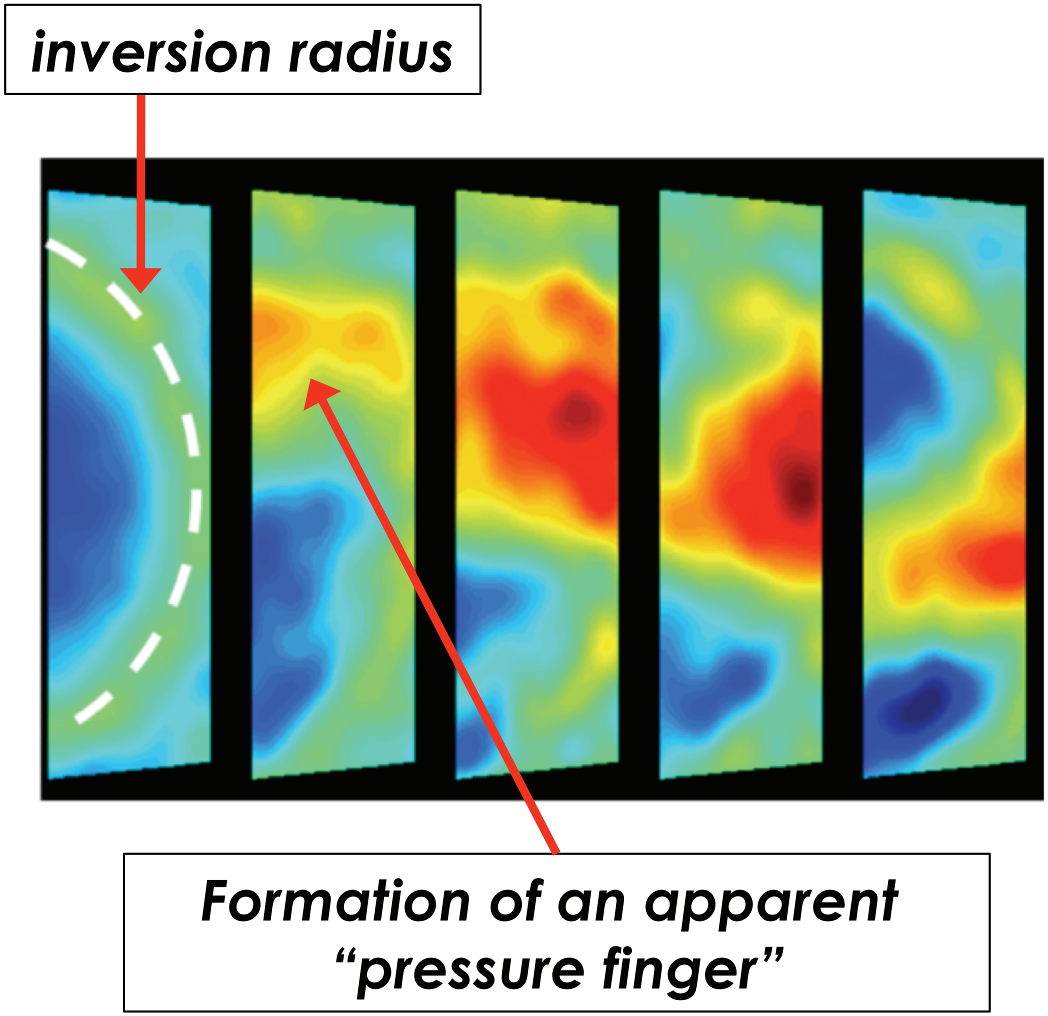



# Determination of Dynamic Plasma Displacement is Complicated by Possible Localized Pressure Effects

- **ECEI alone cannot distinguish between convective flow and adiabatic compression**

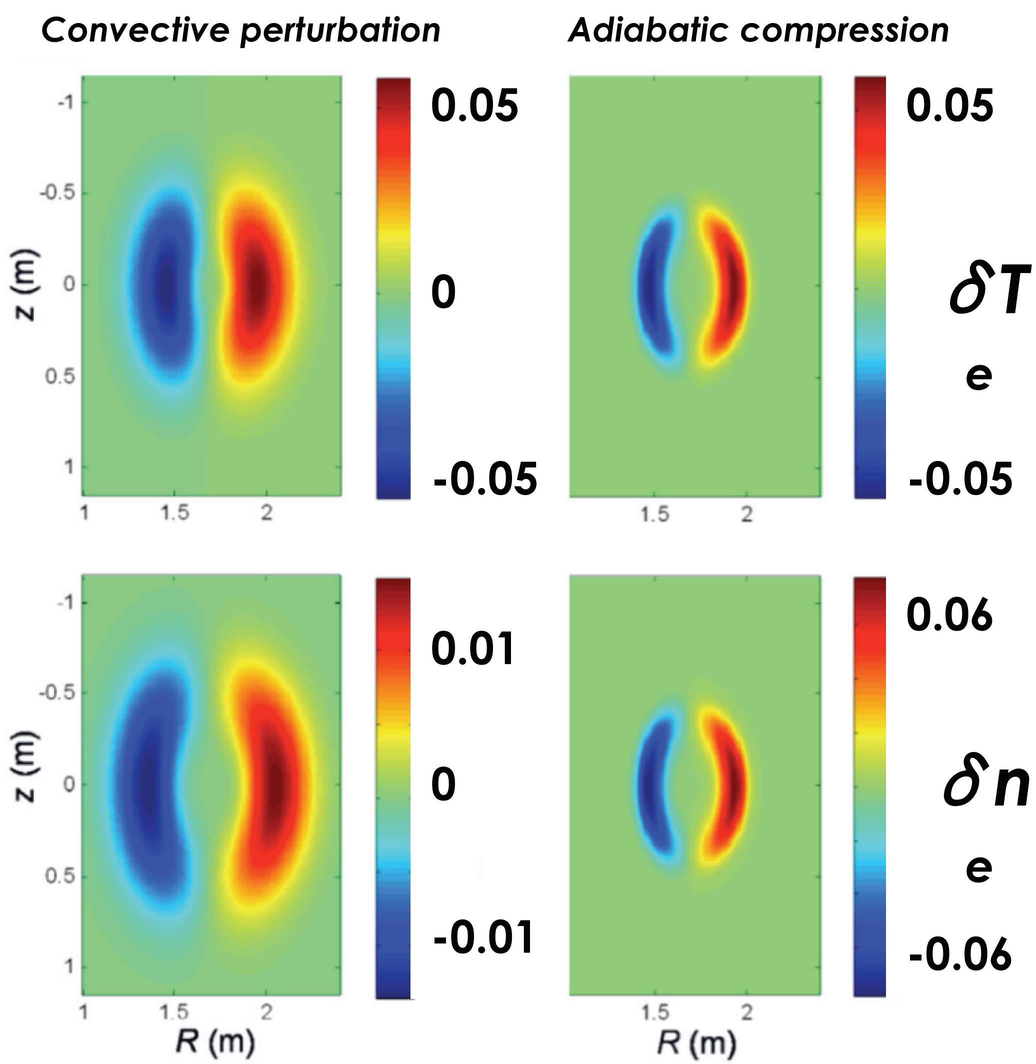
$$\frac{\delta T_e}{\langle T_e \rangle} = -\xi \cdot \frac{\nabla \langle T_e \rangle}{\langle T_e \rangle} - (\gamma - 1)\nabla \cdot \xi$$

- **Modeling the sawtooth crash requires distinction between resistive and pressure driven instability**



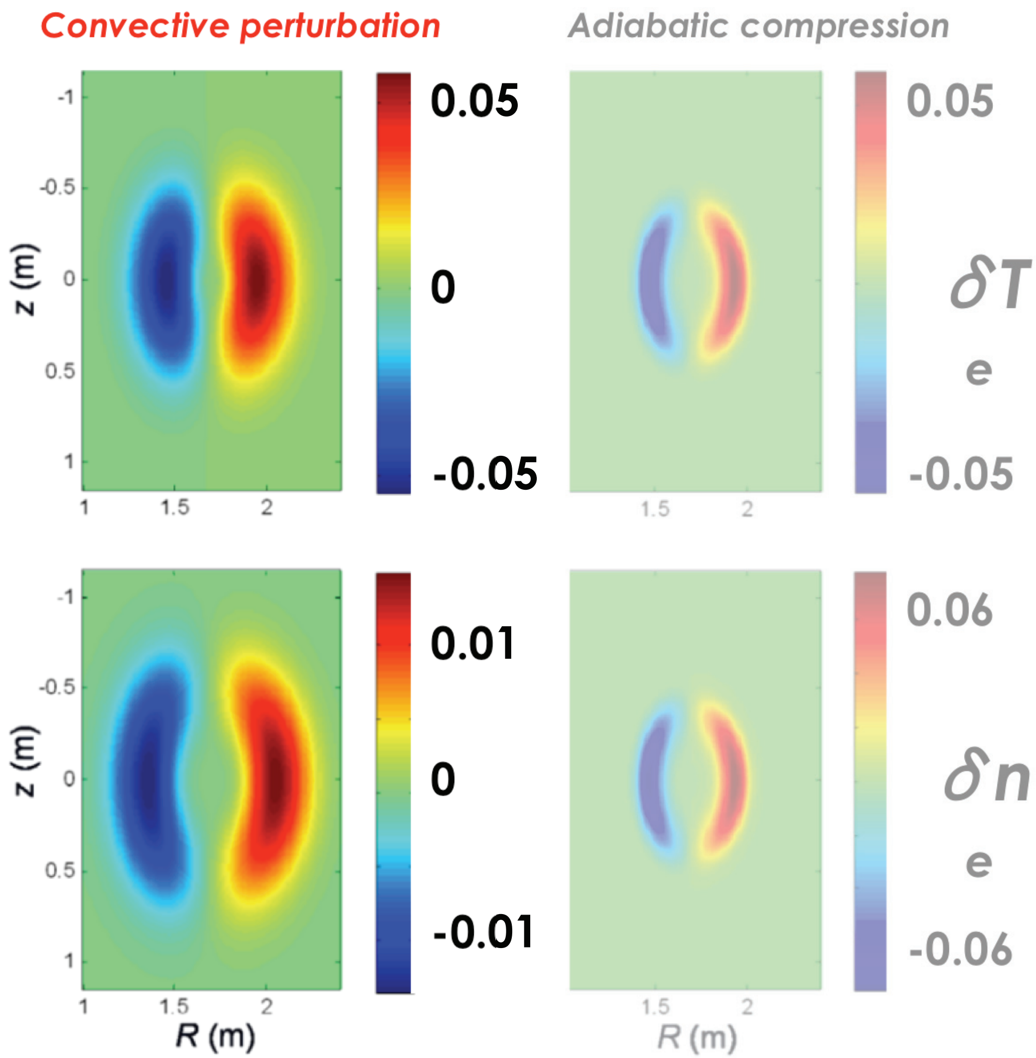
# Localized Density Measurements are Required to Determine Crash Dynamics

- **Convective:**
  - $\delta T_e$ and $\delta n_e$ are proportional to local gradients
- **Compressive:**
  - $\delta T_e / \delta n_e$ is determined by the adiabatic constant
- **Chord-averaged density fluctuation does not differ in these cases**



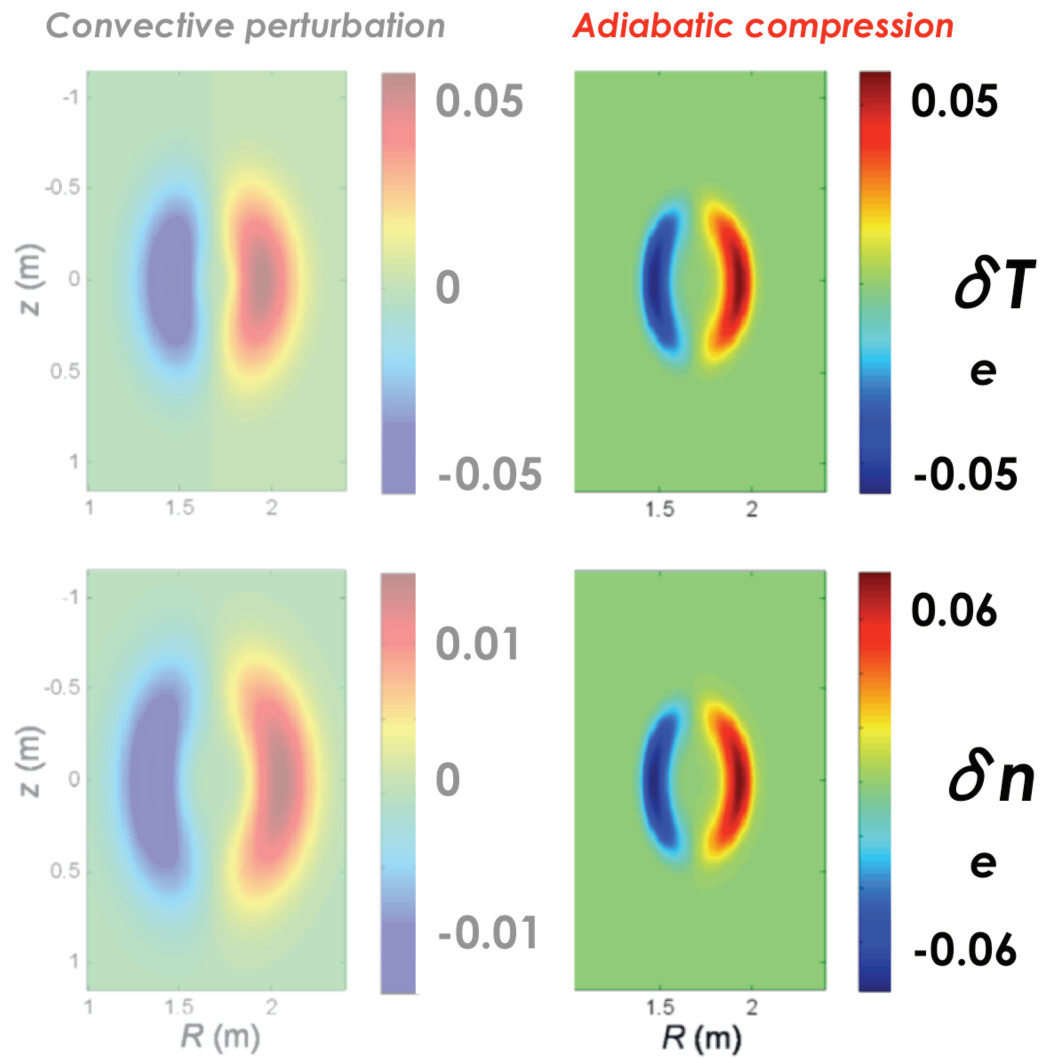
# Localized Density Measurements are Required to Determine Crash Dynamics

- **Convective:**
  - $\delta T_e$ and $\delta n_e$ are proportional to local gradients
- **Compressive:**
  - $\delta T_e / \delta n_e$ is determined by the adiabatic constant
- **Chord-averaged density fluctuation does not differ in these cases**



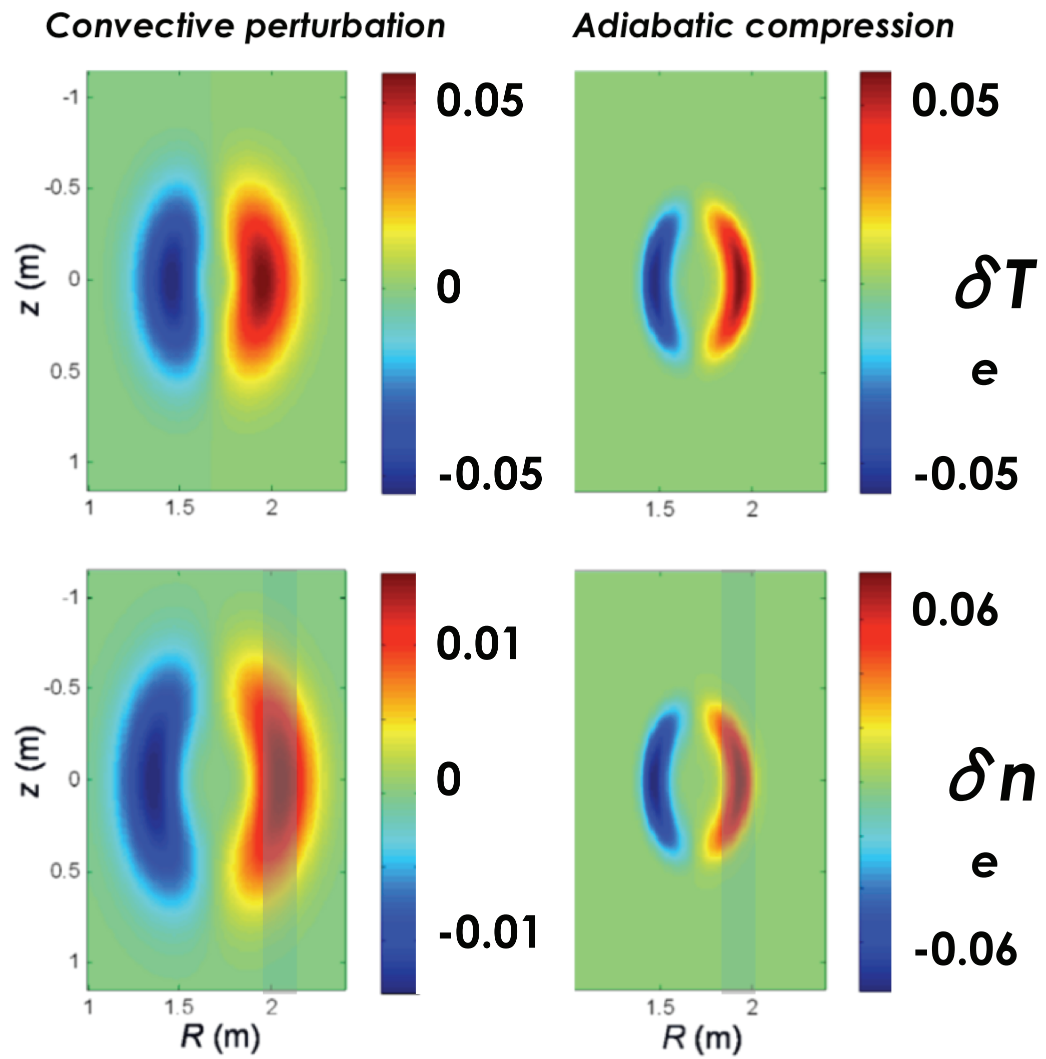
# Localized Density Measurements are Required to Determine Crash Dynamics

- **Convective:**
  - $\delta T_e$ and $\delta n_e$ are proportional to local gradients
- **Compressive:**
  - $\delta T_e / \delta n_e$ is determined by the adiabatic constant
- **Chord-averaged density fluctuation does not differ in these cases**



# Localized Density Measurements are Required to Determine Crash Dynamics

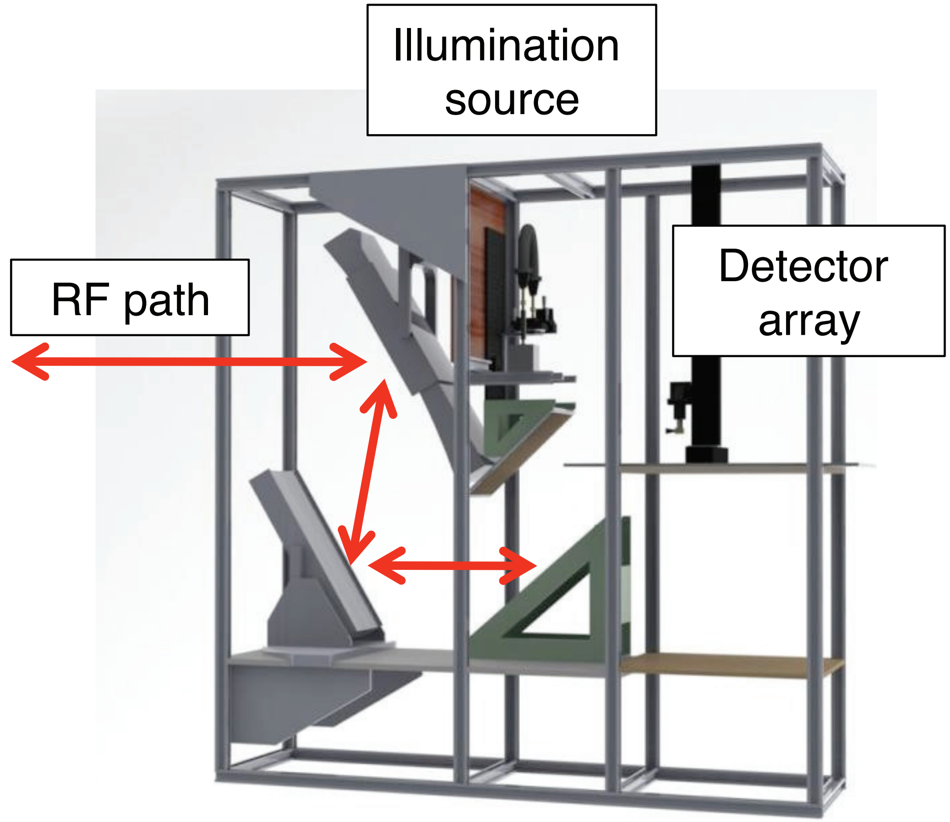
- **Convective:**
  - $\delta T_e$ and $\delta n_e$ are proportional to local gradients
- **Compressive:**
  - $\delta T_e / \delta n_e$ is determined by the adiabatic constant
- **Chord-averaged density fluctuation does not differ in these cases**



# Microwave Imaging Reflectometry (MIR): Localized Measurement of Perturbed Density

- **MIR has the potential for capabilities comparable to ECEI**
  - Multiple probing frequencies
  - Multiple imaging receivers
  - Localized density fluctuation measurement
- **Success depends on synthetic diagnostics**

*See H.K. Park (PO4.00014)*




***Simultaneous ECEI/MIR planned for DIII-D and KSTAR***

# ECEI is a Powerful Tool for the Validation of Theoretical Models

- Imaging provides immediate contributions to physics

# ECEI is a Powerful Tool for the Validation of Theoretical Models

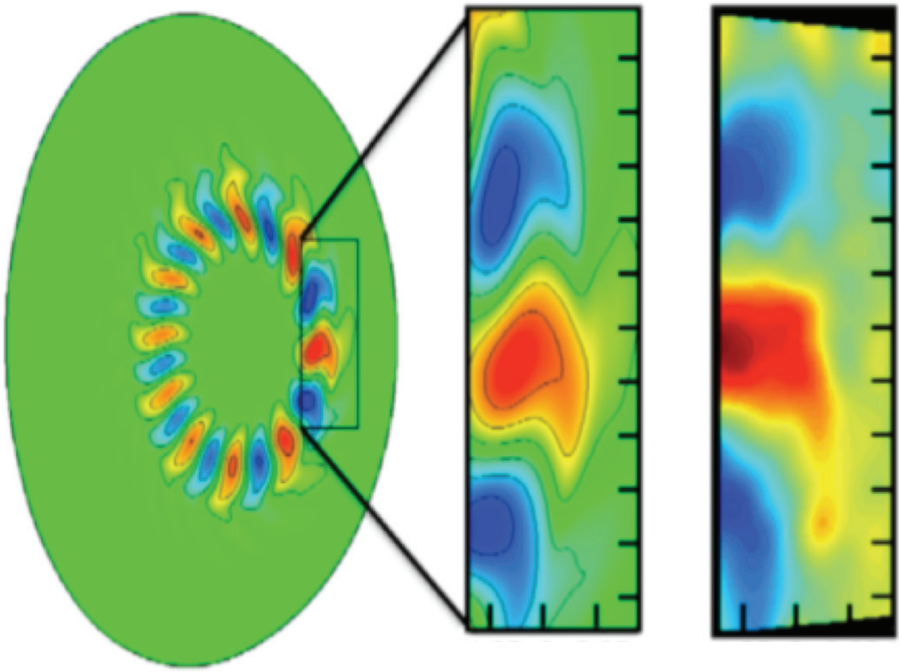
- Imaging provides immediate contributions to physics

*However…*

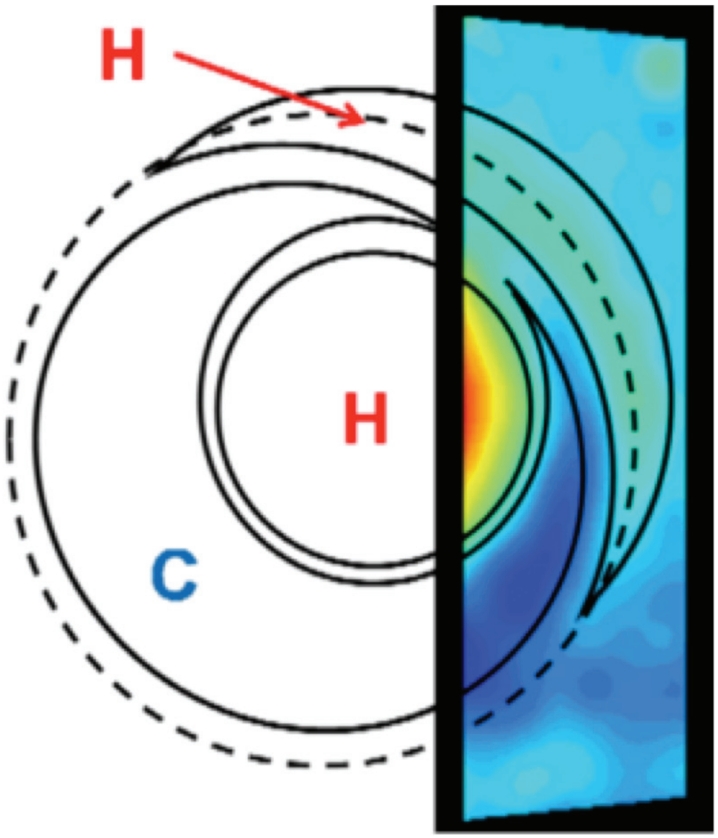
- ECEI data alone is not always sufficient to distinguish between MHD behaviors

# ECEI is a Powerful Tool for the Validation of Theoretical Models

- For transverse Alfvén wave instabilities, ECEI provides a unique solution for the relevant plasma displacement
- This allows unambiguous identification of predicted deviations from symmetry
- Non-perturbative fast ion contributions are integral to Alfvén eigenmode structure

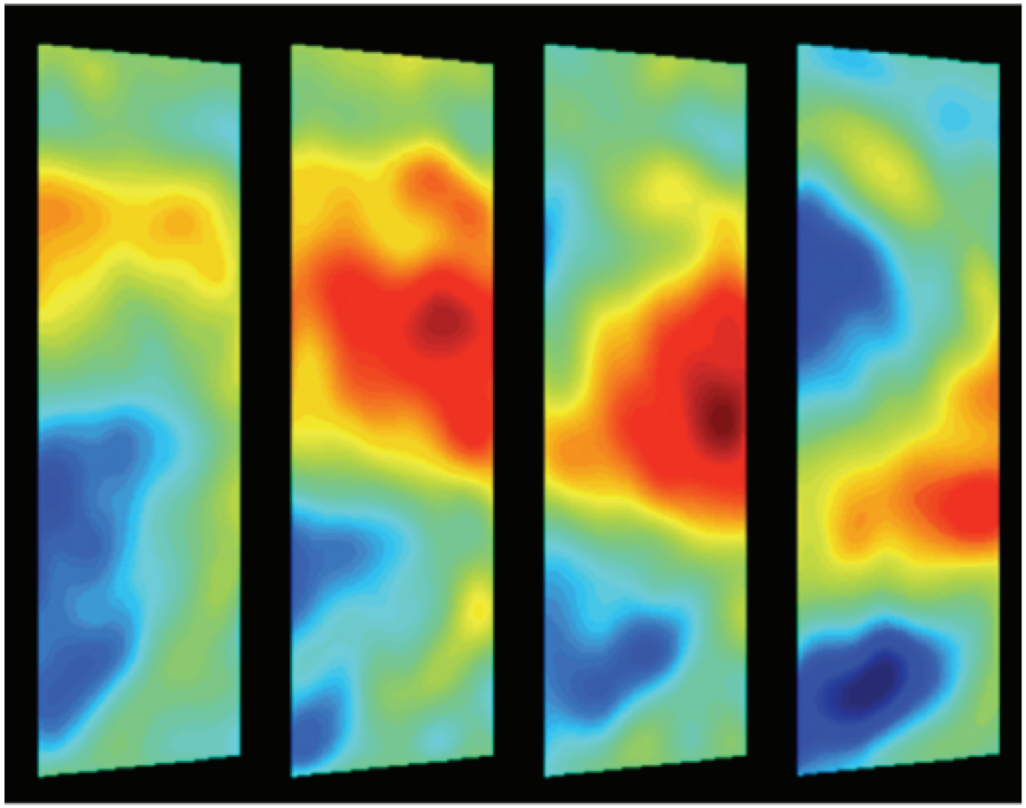


# ECEI is a Powerful Tool for the Validation of Theoretical Models




- ECEI identifies a smoothly varying radial displacement in sawtooth precursors
- This is a necessary, but not sufficient, condition for quasi-interchange behavior
- Poloidal flow is not detected by ECEI

# ECEI is a Powerful Tool for the Validation of Theoretical Models



- Collective heat flow indicates localized reconnection during the sawtooth crash
- However, localized density measurements are needed to obtain a unique solution for plasma flows