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


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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

- Poloidal cross-section
- Up to 1 cm² spatial resolution
- Real-time \( T_e \) down to <1% with µ-sec time resolution

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

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

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
- Alfvén Eigenmodes, DIII-D
- Edge Localized Modes, ASDEX-Upgrade
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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%

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

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:
  \[ \psi = \sum_{m,n} \psi_{mn} \cos(m\theta - n\xi) \]

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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
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Curved lines of constant phase
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)*
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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

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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
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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
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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
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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
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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
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Convective Core Destabilization is Transitory

- **Brief, explosive instability**
  - Linear growth rates ~1500 s\(^{-1}\) \((\gamma^{-1} \sim 600 \ \mu s)\)
  - 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
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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

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

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

Formation of an apparent “pressure finger”
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**
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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
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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.