ECE-based Tearing Mode Suppression and Equilibrium Reconstruction

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Outline

• Motivation
  • Why do we need ECE-centered methods?

• Tearing mode suppression
  • Simultaneous ECCD and NTM localization

• Equilibrium reconstruction
  • Determining the $q$-profile with ECE
  • $q$-constrained equilibria reconstruction

• Conclusions
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Diagnostic constraints exist for a pilot plant

- Diagnostic challenges on ITER arise from:
  - **Relatively harsh environment** – new diagnostic phenomena
  - **Real time control** – high accuracy and reliability
  - **Long pulse length** and **high duty cycle drive** – high stability and longevity
  - **Nuclear environment** – stringent demands on diagnostic engineering

- ECE is “relatively well suited to the ITER environment”
  - Less sensitive to first-mirror degradation than TS
  - Requires only waveguides and antennas near plasma

- Systems that require only a single diagnostic are easier to implement

[A.J.H. Donné et al., Nucl. Fusion 2007]
[A.E. Costley et al., Fusion Eng. Des. 2005]
ECE slated as an essential diagnostic for ITER

- ITER plasmas dominated by electron heating
  - Alpha particle heating of electrons during the DT phase

- At the hottest conditions:
  - Electron cyclotron radiation transport could exceed plasma energy transport
  - **Power loss due to ECE** is expected to exceed bremsstrahlung
  - **Fast electrons tail** can modify and enhance the ECE power loss

- The ITER ECE diagnostic system will:
  - Provide $T_e$ measurements for time evolution of alpha particle heating
  - Provide real-time **MHD mode measurements**
  - Detect the presence of **non-thermal electrons**
  - Measure **power loss** from the plasma via ECE radiation

[G. Taylor et al., EPJ 2015]
High ITER temps lead to ECE broadening

- In ITER, spatial averaging of the ECE signals from:
  - relativistic broadening (at $T_e > 10$ keV)
  - thermal broadening
  - relativistic shift towards the high-field side

- Broadening for an ITER H-mode scenario calculated using ECESIM [M. Austin et al., Fusion Sci. Tech. 2011]

- Minimum ECE-detectable island width: $w \sim 2$ cm

- Small islands can still be localized by interpolation

[A.O. Nelson et al., PPCF 2019]
ITER will have radial and oblique ECE

[Image of ITER Vacuum Vessel with various diagnostic tools indicated]

Equatorial Port Plug EP9
Toroidal Interferometer Polarimeter
ECE
Visible/Infrared Spectrometer

[G. Taylor et al., EPJ 2015]
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ECCD allows localized current drive

- **Fisch-Boozer:**
  - Collisional relaxation process
  - Conserves toroidal momentum
  - Current in the *negative* toroidal direction

- **Ohkawa:**
  - Asymmetric detrapping process
  - Current in the *positive* toroidal direction

[R. Prater, Phys. Plasmas 204]
Tearing mode suppression via ECCD

- ECCD suppression of NTMs well demonstrated on various machines
  - Replacement of missing bootstrap current
    \[
    \frac{\tau_R}{r} \frac{dw}{dt} = \Delta' r + \epsilon^{1/2} \left( \frac{L_q}{L_p} \right) \beta_g \left[ \frac{rw}{w^2 + w_d^2} - \frac{rw^2}{w^3} \right] - \frac{8qr \delta_{EC}}{\pi^2 w^2} \left( \frac{j_{EC}}{j_{BS}} \right)
    \]
  - Current condensation could lead to improvements in suppression [A. Reiman, this conference]
  - Suppression **extremely sensitive** to alignment of ECCD with island:
    \[
    \eta = \frac{\eta_0}{1 + 2 \delta_{EC}^2 / w^2} \exp \left[ -\left( \frac{5\Delta R}{3\delta_{EC}} \right)^2 \right]
    \]

NTM suppression example: low power

• $P_{ECH} = 1.9$ MW slowed the 2/1 mode but was not able to suppress

• ECCD driven current lower than bootstrap current
NTM suppression example: marginal power

- $P_{ECH} = 2.3$ MW has marginal $\dot{J}_{ECCD} \sim \dot{J}_{boot}$

- Need to either increase power or reduce density
NTM suppression example: enough power

- $P_{ECH} = 2.65$ MW has marginal suppression
- Better alignment/early catch needed for negative growth rate
ECCD is aimed at island via steerable mirrors

- Real-time NTM control system uses:
  - Mirnov diagnostics – detecting MHD modes
  - Motional Stark effect (MSE) diagnostics – current profile reconstruction
  - Magnetic sensors – equilibrium reconstruction
  - Interferometer – density measurement

- DIII-D PCS control logic:
  - \(q\)-surface location from MSE-EFIT
  - intersection of \(q\) - and \(2f_{ce}\)-surfaces
  - feedback and search algorithms


[14] [E. Kolemen et al., Nucl. Fusion 2014]
Phase of $T_e$ oscillations inverts at island center

- $T_e$ constant along flux surface $\Rightarrow$ $T_e$ constant within islands
- As island rotates around plasma, $\delta T_e$ fluctuations observed on ECE channels

$T_e$ on flux surface near island

$T_e$ measured in ECE channels as island rotates
ECE localization of NTM location

- Instead of from MSE-EFIT reconstruction, NTM location can be found with ECE
- Magnetic island flattens temperature profile
- Matched amplitude switches sign at island center

\[ A(t) = \sum_{t=T_{\text{smo}}}^{t} (T_e - \bar{T}_e) \cos \Omega \div \sum_{t=T_{\text{smo}}}^{t} \cos^2 \Omega \]


[10/28/19]

Other ECE-based NTM localization methods

• Numerous methods exist to determine the radial location of magnetic islands:
  • Phase contrast method based on the cross correlation of contiguous channels (FTU)
    [J. Berrino et al., Nucl. Fusion 2005]
  • Direct detection from the electron temperature perturbation profile (JT-60U)
    [A. Isayama et al., Nucl. Fusion 2003]
  • Temperature oscillations on ECE radiometer correlated with Mirnov coils (ASDEX-U)
    [A. Keller et al., 30th EPS Conference 2003]
  • X-ray imaging crystal spectroscopy (KSTAR)
  • Matched amplitudes of island temperature fluctuations (DIII-D)
  • Oblique ECE measurements (TEXTOR, TCV and DIII-D)
ECE localization of ECCD location

- Power (amplitude) of the ECCD launcher is modulated
  - Modulation reflected in ECE channels at mode location
  - Linear interpolation to find ECCD location between channels
Simultaneous ECCD and NTM localization

- Combined capability of ECE and NTM localization with ECE allows for a single-diagnostic ECCD control scheme


- Real-time applicable
- Better time resolution than MSE/TORBEAM reconstruction
- Potential augmentation for existing schemes
Early mode detection is crucial

• Early mode detection is a key ingredient for fast mode suppression

• In the cases where the mode has been caught at smaller size, prompt suppression follows.

• When the island size at detection increases, the mode cannot be suppressed before saturation

[E. Kolemen et al., Nucl. Fusion 2014]
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Islands provide an opportunity to measure $q$

- Multiple islands can exist in a discharge
- Real-time magnetics can be used to extract the mode number
  \[ q = \frac{m}{n} \]
- ECE can be used to localize $q$!
- Example use: precise localization of $q=1$ in sawtooth studies

[A.O. Nelson et al., PPCF 2019]
$q$-profile from ECE agrees with MSE constraints

- Other opportunities for $q$-localization:
  - Alfvén eigenmodes
    \[ q_{\text{min}} \text{ and } q < 1 \]
  - Geometric expressions
    \[ q_{95} = q_{\text{cyl}} \left( \frac{1.17 - 0.65a/R}{[1 - (a/R)]^2} \right) \]
  - Plasma perturbations
    (ECCD or 3D)

![Graph showing safety factor vs. R with points from ECE and EFIT reconstruction](image)

[DIII-D 163117, t = 4361 ms]

[A.O. Nelson et al., PPCF 2019]
Grad–Shafranov equation needs 3 inputs

- Grad–Shafranov equation is fully specified by three profiles:
  - $\psi_0(\vec{r})$ – last closed flux-surface boundary conditions
  - $P(\psi)$ – pressure profile
  - $FF'(\psi)$ – related to current through $B_\phi$

\[
\Delta^* \psi = -\mu_0 r^2 \frac{dp}{d\psi} - \frac{1}{2} \frac{dF'^2}{d\psi}
\]

- We can replace these profiles!
  - $\psi_0(\vec{r})$ – last closed flux-surface boundary conditions
  - $q(\psi)$ – $q$-profile $\rightarrow$ FROM ECE
  - $T_e, sym(\psi)$ – symmetry constraint on the $T_e$ profile $\rightarrow$ FROM ECE
\( T_{e, \text{sym}}(\psi) \) used as an equilibrium constraint

- Flux surfaces should have equal \( T_e \) on inboard and outboard side
- \( T_e \) measured from ECE gives unique symmetry mapping
- Reconstruction can be constrained to symmetry mapping
Plasma boundary measured from emission

- Optical boundary reconstruction developed on MAST
- Camera data do not suffer from drift
- Robust against startup transients
- Independent measurement of the optical plasma boundary
- Comparison of optically reconstructed shapes with EFIT show strong spatial and temporal agreement

$q$-profile as basis for equilibrium reconstruction

- Iterations performed over the Isolver Grad–Shafranov solver
- Error on $T_e$ symmetry and $q$-profile minimized

[A.O. Nelson et al., PPCF 2019]

[R. Andre, APS 2012]
NSTX equilibrium constructed from $q$ constraints

Equilibrium comparison

Safety factor comparison

Symmetry Mapping

[A.O. Nelson et al., PPCF 2019]
NSTX equilibrium constructed from $q$ constraints

Equilibrium comparison

Error

[A.O. Nelson et al., PPCF 2019]
ECE is a flexible, ITER-capable control diagnostic

• ECE is “relatively well suited to the ITER environment”
  • Less sensitive to first-mirror neutron degradation than TS
  • Can be robustly built to withstand heat and neutron fluxes
  • Small islands can be located even with relativistic broadening

• Two new ECE-based control techniques:
  • Simultaneous ECCD and NTM localization
  • Equilibrium reconstruction from $q$-profile
    [A.O. Nelson et al., PPCF 2019]