ECE-based Tearing Mode Suppression and Equilibrium Reconstruction

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PRINCETON UNIVERSITY

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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  - **Why do we need ECE-centered methods?**

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Diagnostic constraints exist for a pilot plant

- Diagnostic challenges on ITER arise from: [A.J.H. Donné et al., Nucl. Fusion 2007]
  - **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" [A.E. Costley et al., Fusion Eng. Des. 2005]
  - Less sensitive to first-mirror degradation than TS
  - Requires only waveguides an antennas near plasma
- Systems that require only a single diagnostic are easier to implement

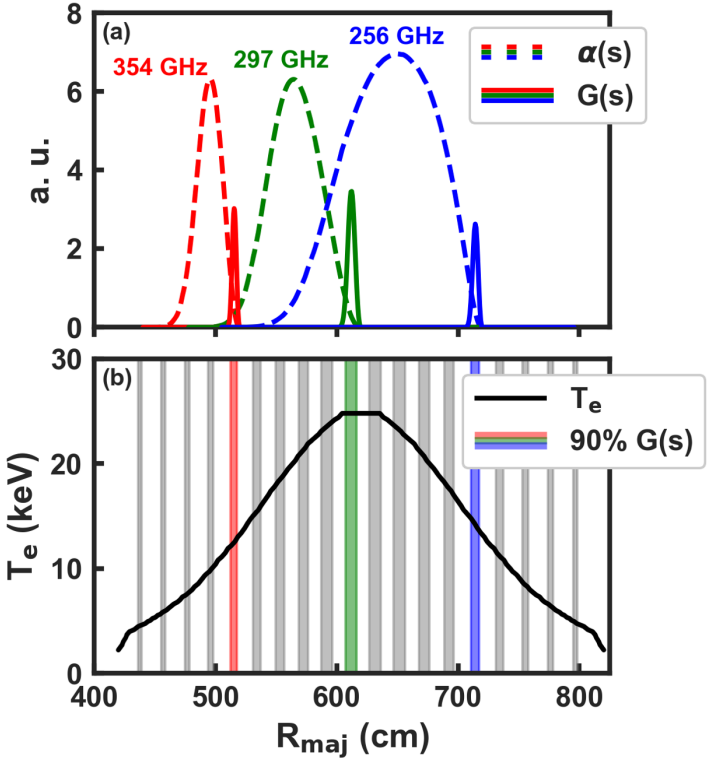
ECE slated as an essential diagnostic for ITER

[G. Taylor et al., EPJ 2015]

- 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

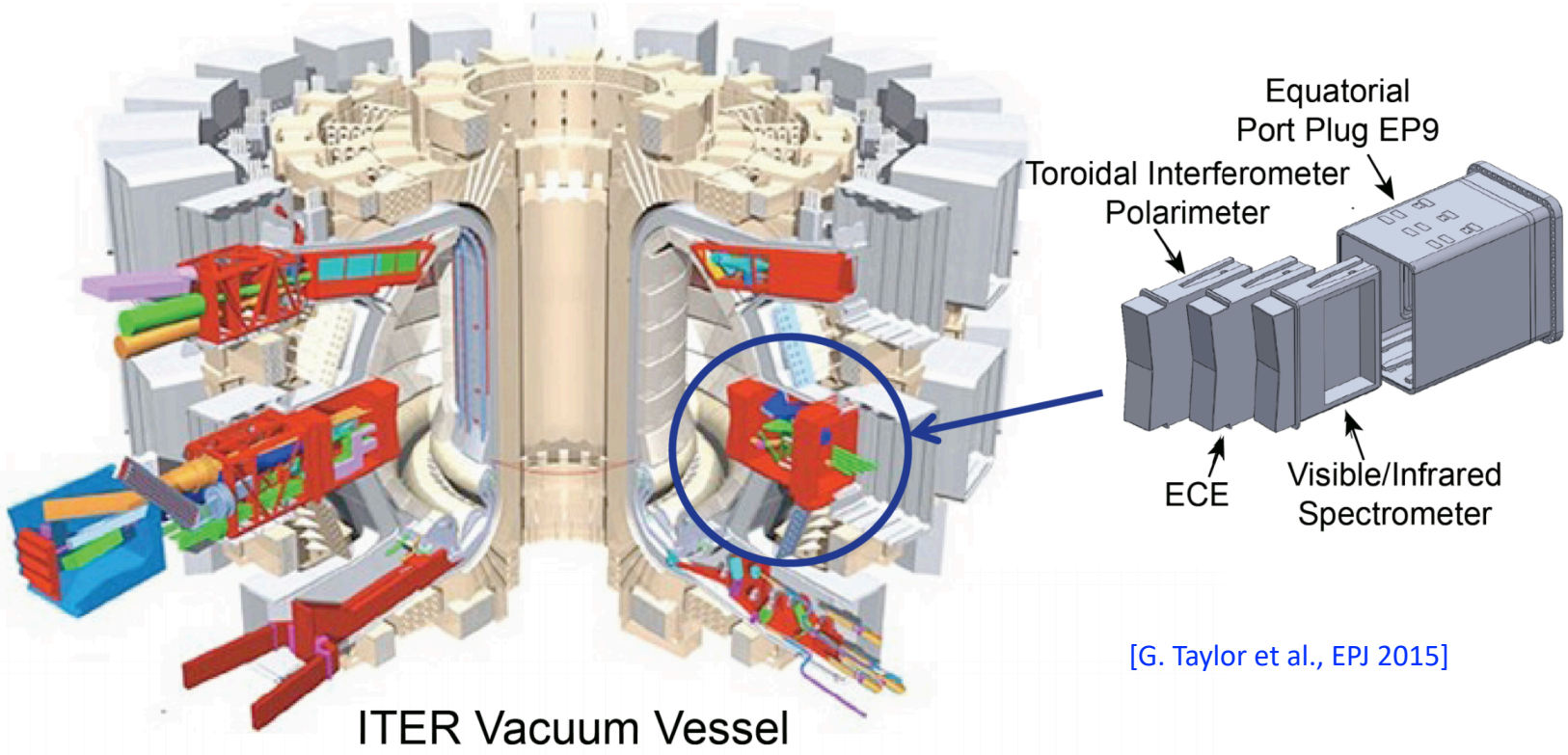
High ITER temps lead to ECE broadening

- 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



[G. Taylor et al., EPJ 2015]

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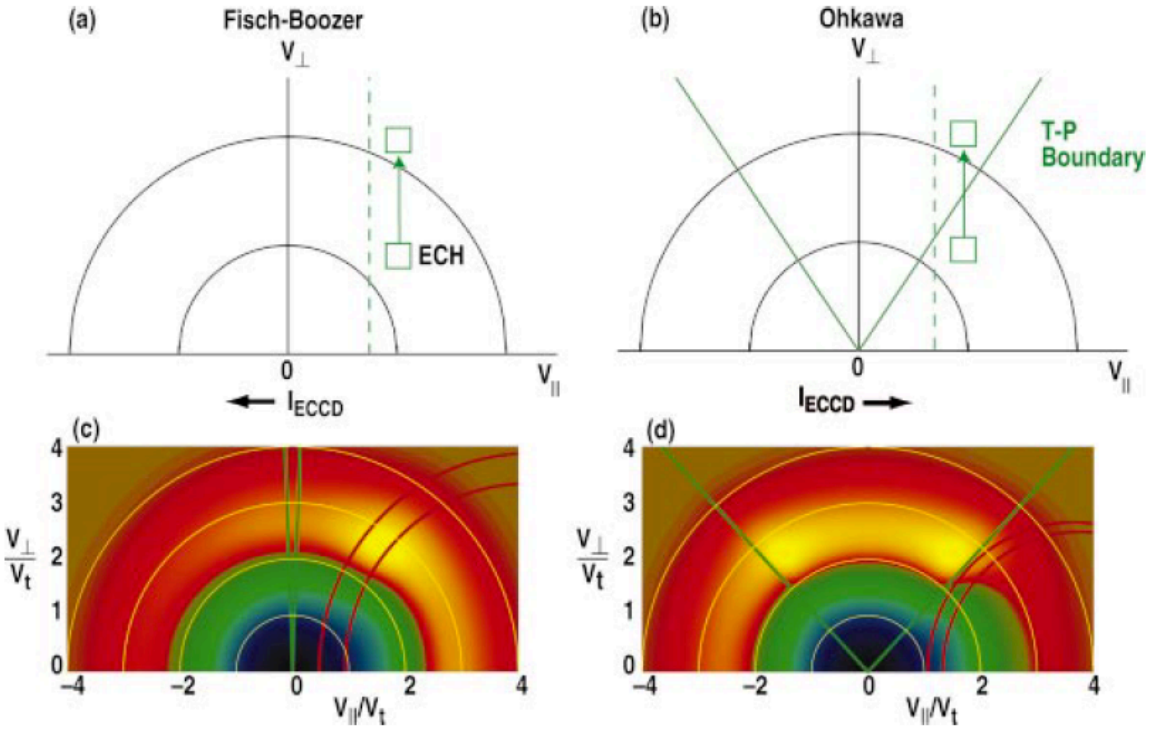
ECCD allows localized current drive

- 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 [R.J. La Haye et al., Phys. Plasmas 2002]

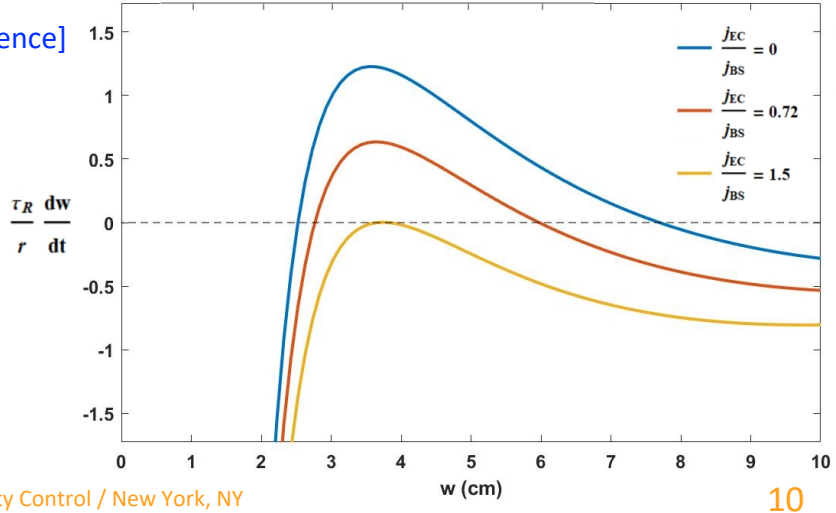
$$\frac{\tau_R}{r}\frac{\mathrm{dw}}{\mathrm{dt}} = \Delta' r + \epsilon^{1/2}\left(\frac{L_q}{L_p}\right)\beta_\theta\left[\frac{\mathrm{rw}}{w^2 + w_d^2} - \frac{\mathrm{rw}_{\mathrm{pol}}^2}{w^3} - \frac{8\mathrm{qr}\delta_{\mathrm{EC}}}{\pi^2 w^2}\left(\eta\frac{j_{\mathrm{EC}}}{j_{\mathrm{BS}}}\right)\right]$$

  - Current condensation could lead to improvements in suppression [A. Reiman, this conference]

[A.O. Nelson et al., Fusion Eng. Des. 2019]

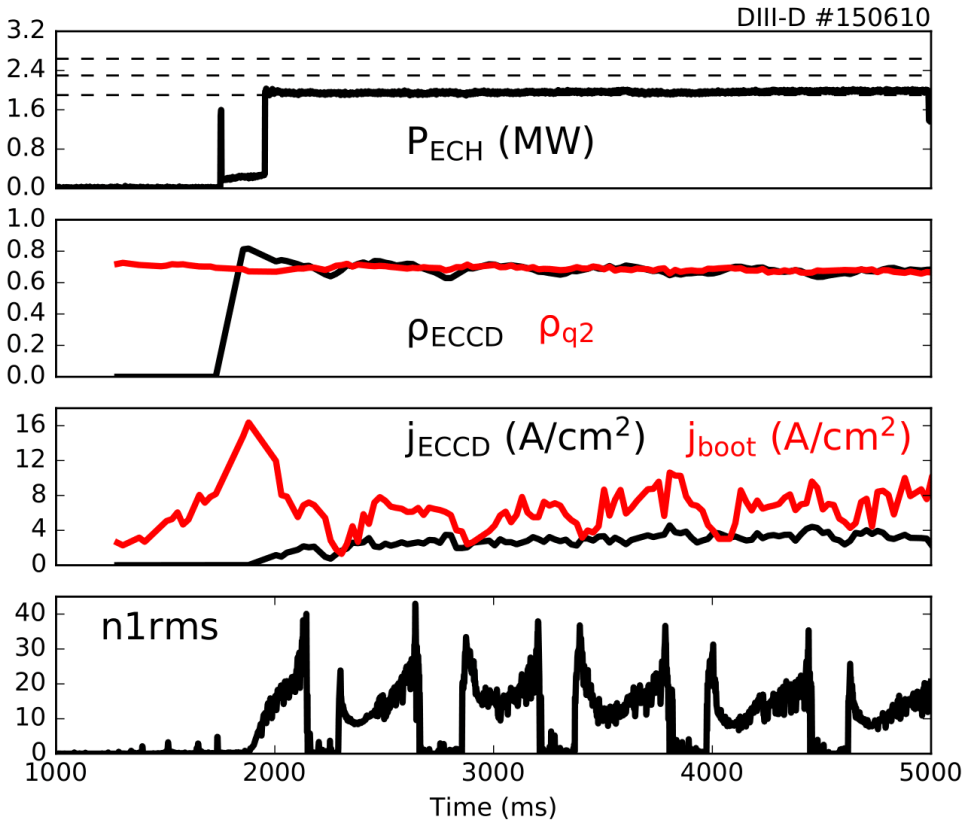
- Suppression **extremely sensitive** to alignment of ECCD with island:

$$\eta = \frac{\eta_0}{1 + 2\delta_{\mathrm{EC}}^2/w^2}\exp\left[-\left(\frac{5\Delta R}{3\delta_{\mathrm{EC}}}\right)^2\right]$$



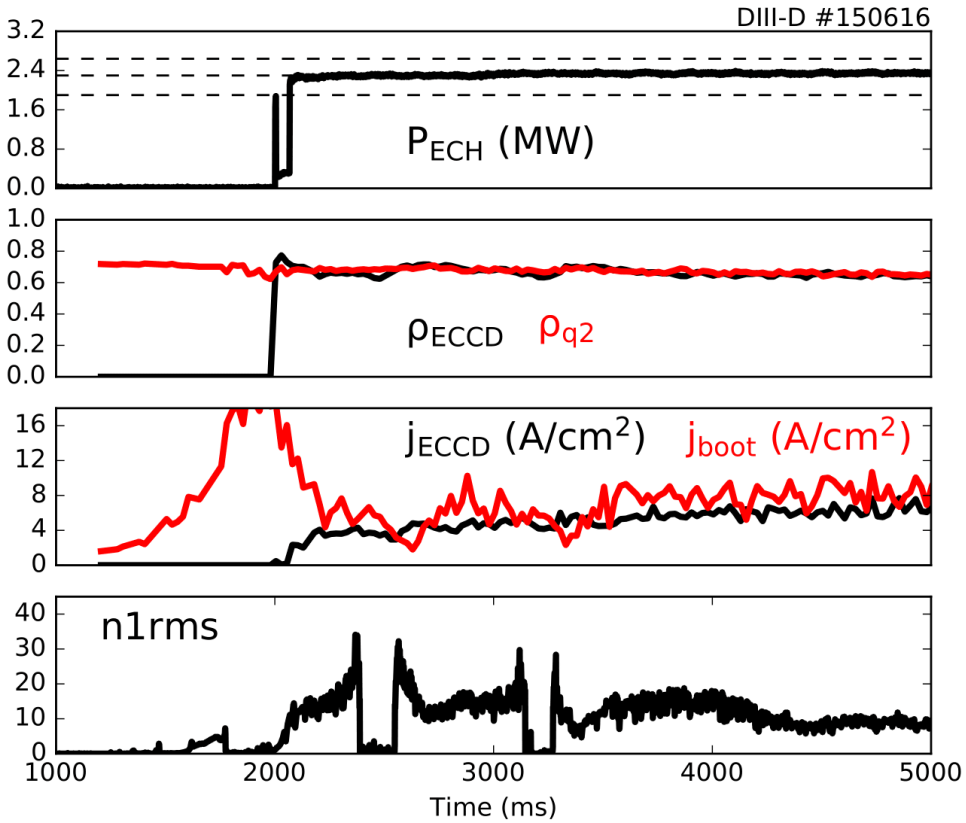
NTM suppression example: low power

- $P_{ECH} = 1.9$ MW slowed the 2/1 mode but was to able to suppress
- ECCD driven current lower than bootstrap current



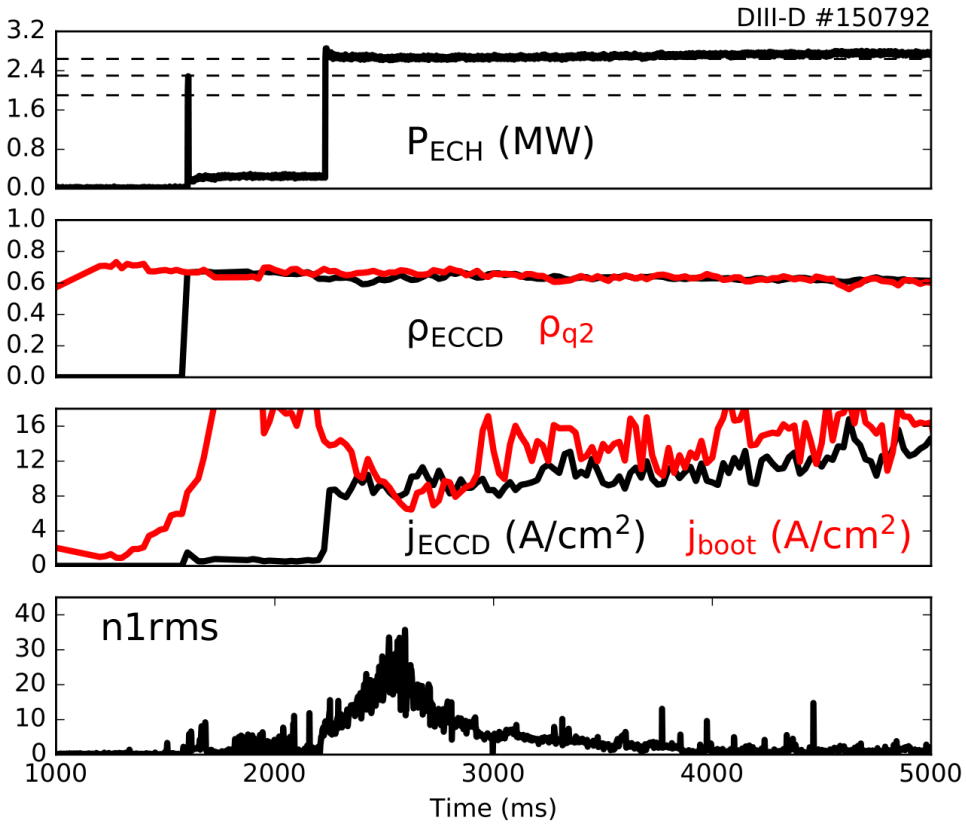
NTM suppression example: marginal power

- $P_{ECH} = 2.3$ MW has marginal $j_{ECCD} \sim j_{boot}$
- Need to either increase power or reduce density



NTM suppression example: enough power

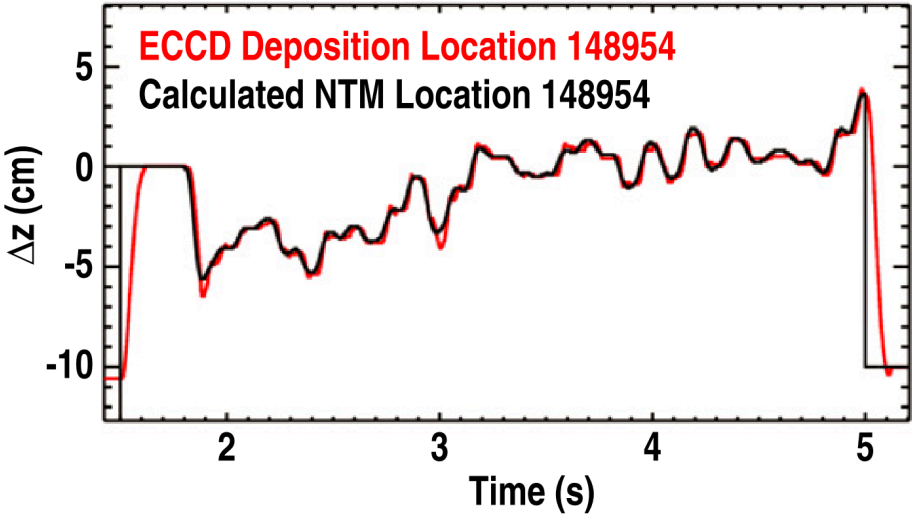
- $P_{ECH} = 2.65$ MW has marginal suppression
- Better alignment/early catch needed for negative growth rate



ECCD is aimed at island via steerable mirrors

[E. Kolemen et al., Nucl. Fusion 2014]

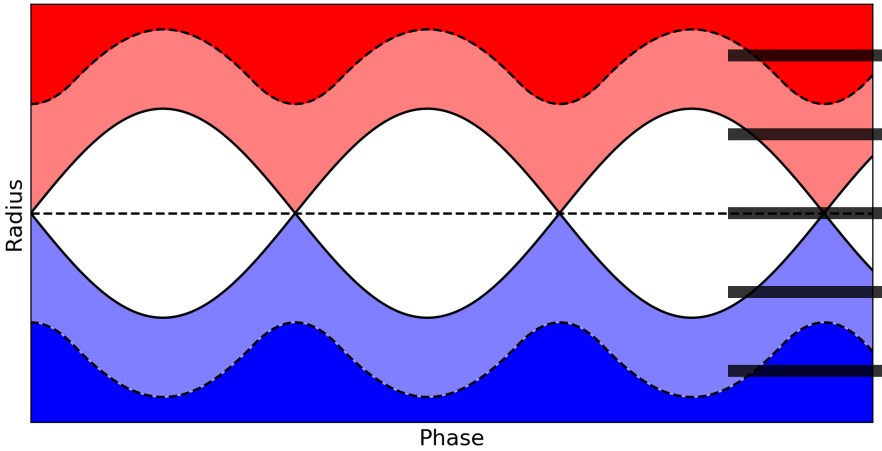
- Real-time NTM control system uses:
  - **Mirnov diagnostics** – detecting MHD modes
  - **Motional Stark effect (MSE) diagnostics** – current profile reconstruction
  - **Magnetic sensors** – equilibrium reconstruction
  - **Interferometer** – density measurement
- DIII-D PCS control logic:
  - q-surface location from MSE-EFIT
  - intersection of q- and $2f_{ce}$-surfaces
  - feedback and search algorithms



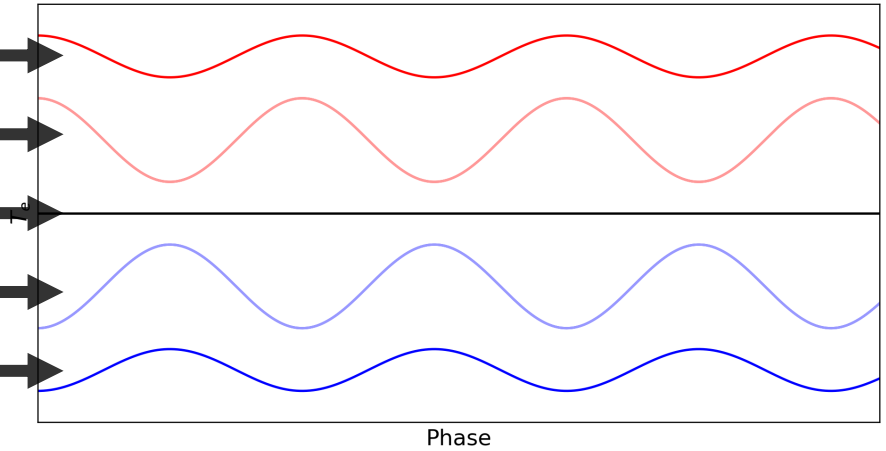
Phase of T_e oscillations inverts at island center

- T_e constant along flux surface → T_e constant within islands
- As island rotates around plasma, δT_e fluctuations observed on ECE channels

T_e on flux surface near island



T_e measured in ECE channels as island rotates

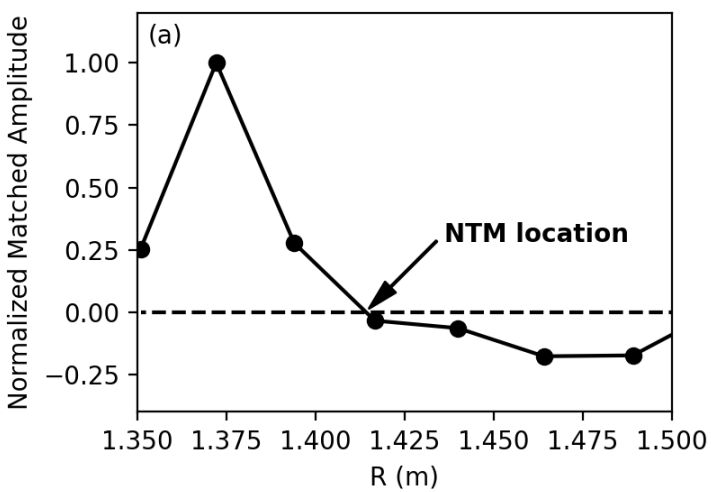


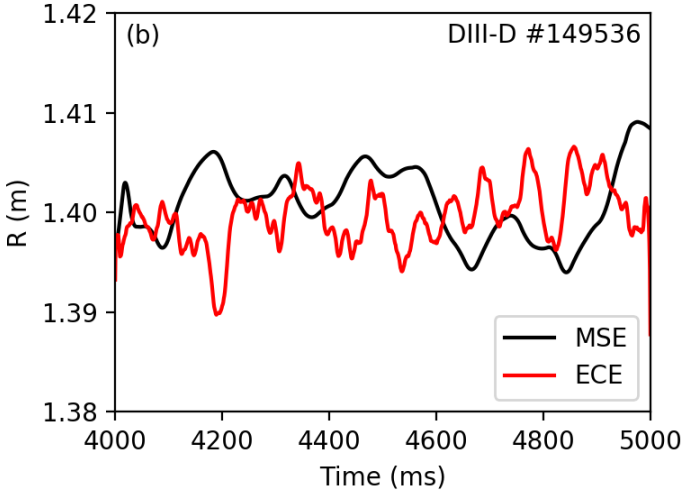
ECE localization of NTM location

- 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

$$A(t) = \sum_{t-T_{\mathrm{smo}}}^{t} (T_{\mathrm{e}} - \bar{T}_{\mathrm{e}}) \cos \Omega \Big/ \sum_{t-T_{\mathrm{smo}}}^{t} \cos^2 \Omega$$

[Y.S. Park et al., Plasma Phys. Control. Fusion 2006]





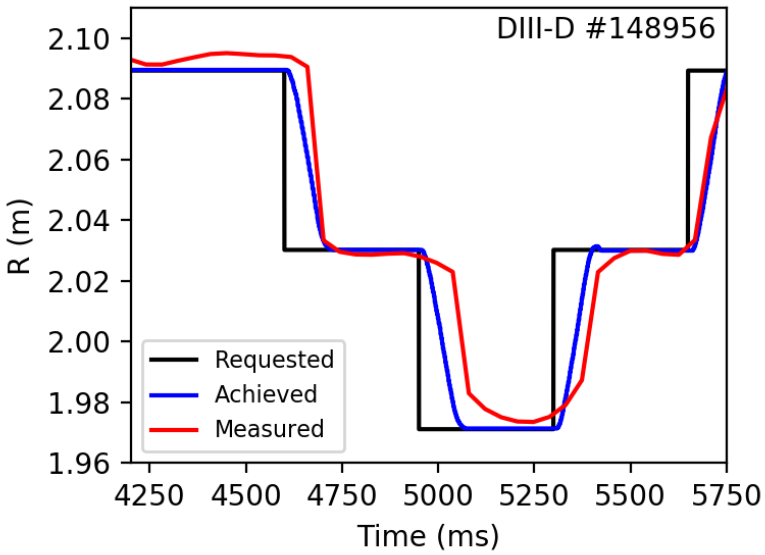
[A.O. Nelson et al., Fusion Eng. Des. 2019]

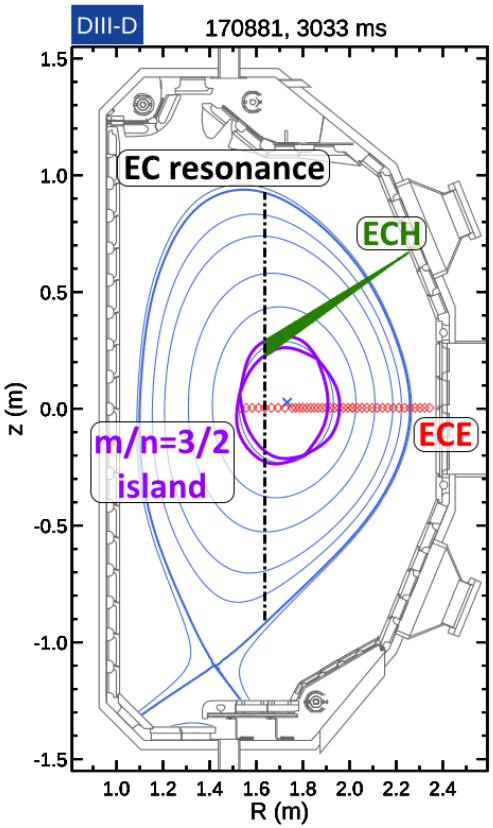
Other ECE-based NTM localization methods

- 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)
    [K. Kim et al., Curr. Appl. Phys. 2015]
  - Matched amplitudes of island temperature fluctuations (DIII-D)
    [Y.S. Park et al., Plasma Phys. Control. Fusion 2006]
  - Oblique ECE measurements (TEXTOR, TCV and DIII-D)
    [W.A. Bongers et al., Fusion Sci. Technol. 2008; U.A. Sheikh et al., Nucl. Fusion 2018; F.A.G. Volpe, et al., Phys. Plasmas 16 2009]

ECE localization of ECCD location

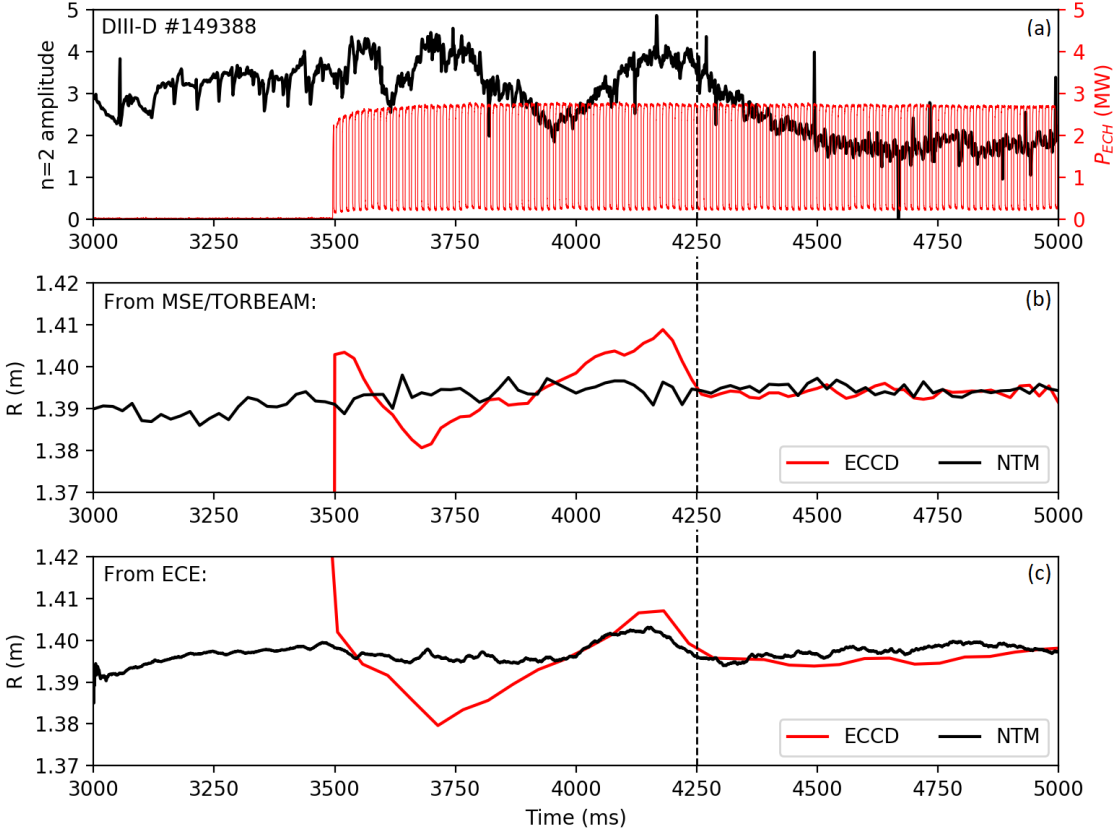
- Power (amplitude) of the ECCD launcher is modulated
  - Modulation reflected in ECE channels at mode location
  - Linear interpolation to find ECCD location between channels





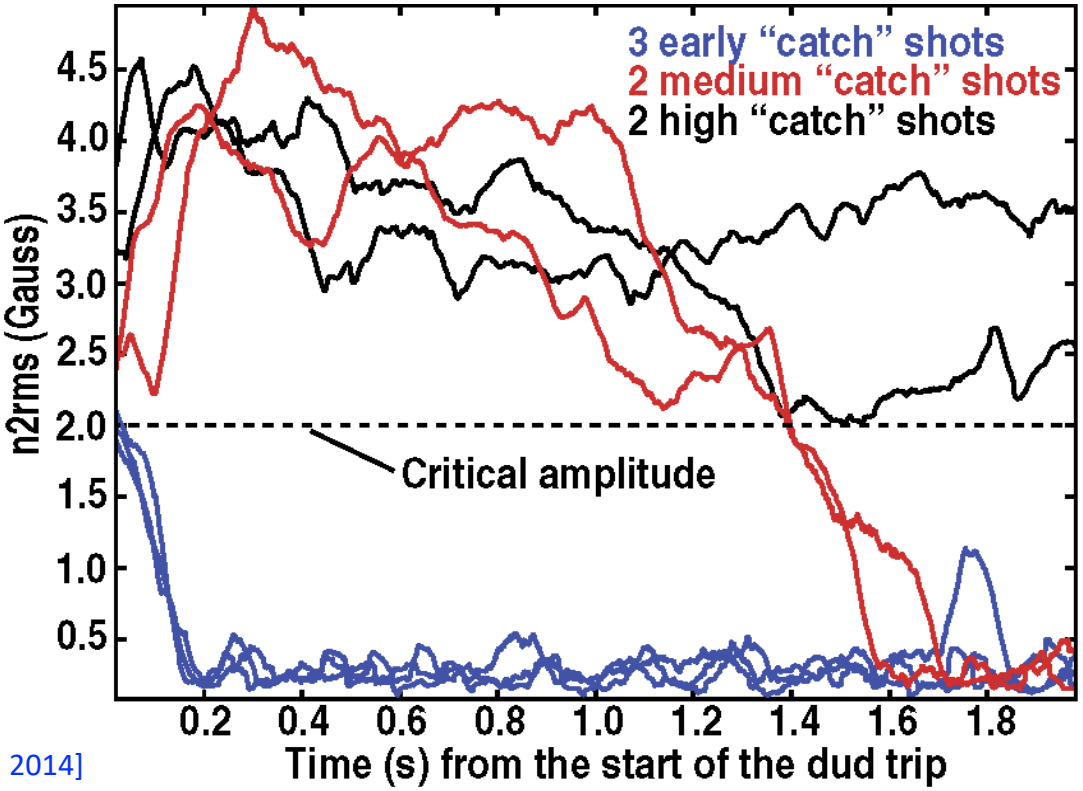
Simultaneous ECCD and NTM localization

- Combined capability of ECE and NTM localization with ECE allows for a **single-diagnostic** ECCD control scheme
  [A.O. Nelson et al., Fusion Eng. Des. 2019]
- 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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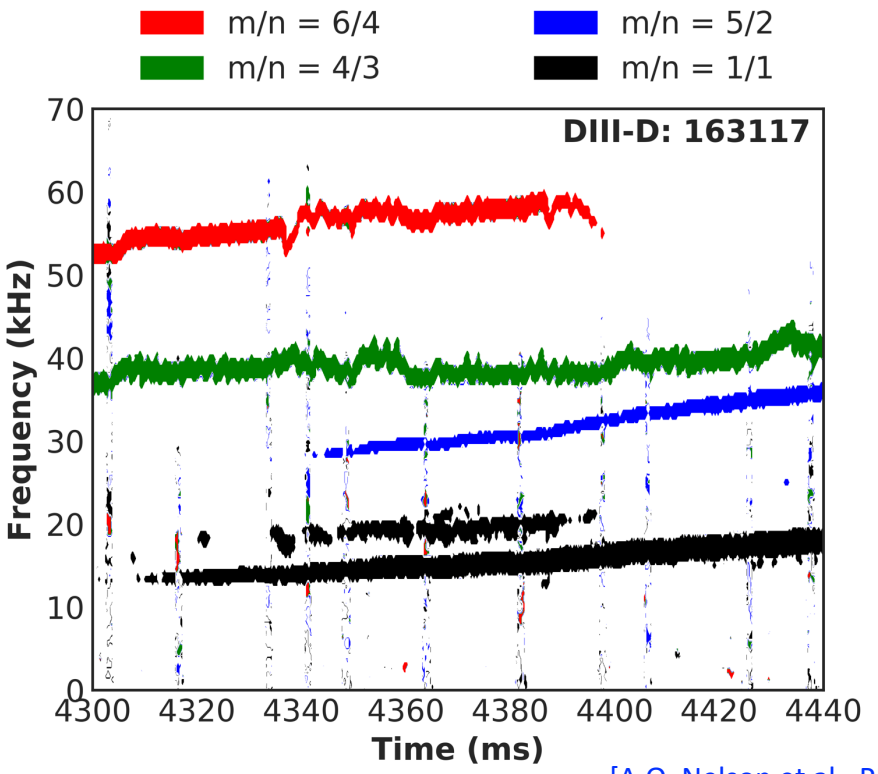
Islands provide an opportunity to measure q

- 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

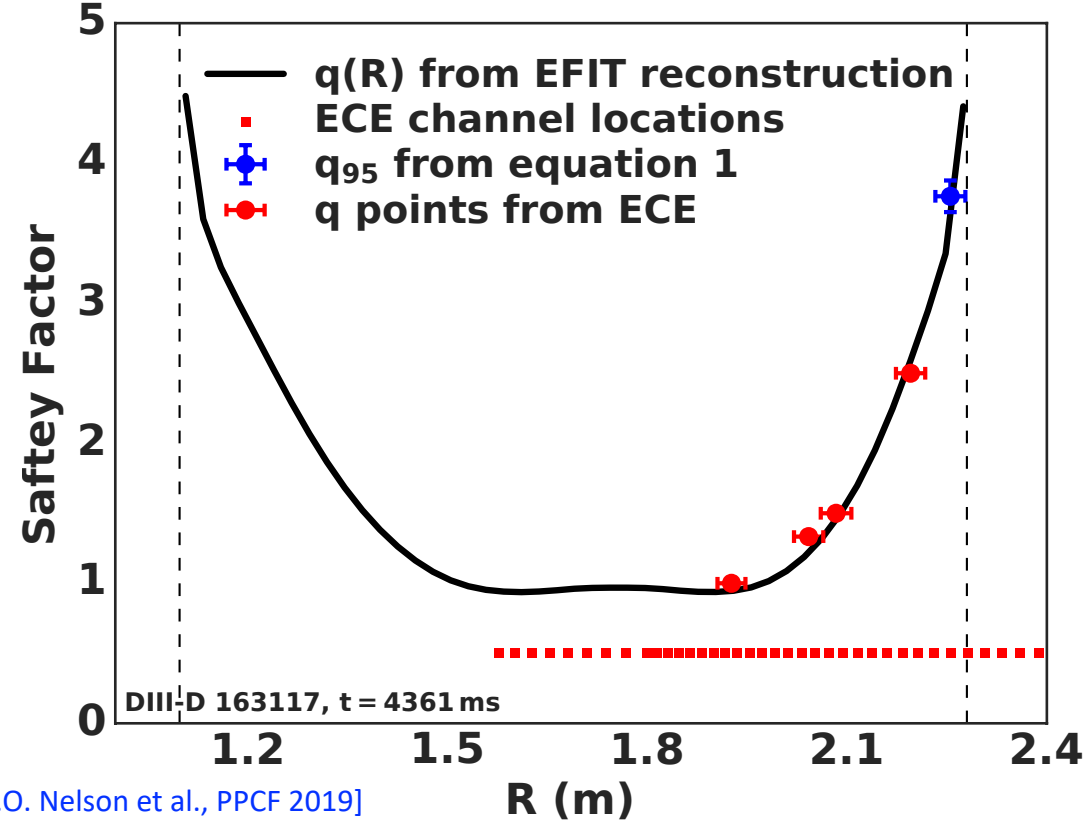
- Other opportunities for q-localization:
  - Alfvén eigenmodes

    (q_{min} and $q < 1$)
  - Geometric expressions

$$q_{95} = q_{cyl}\left(\frac{1.17 - 0.65a/R}{[1-(a/R)]^2}\right)$$

  - Plasma perturbations

    (ECCD or 3D)



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

Grad–Shafranov equation needs 3 inputs

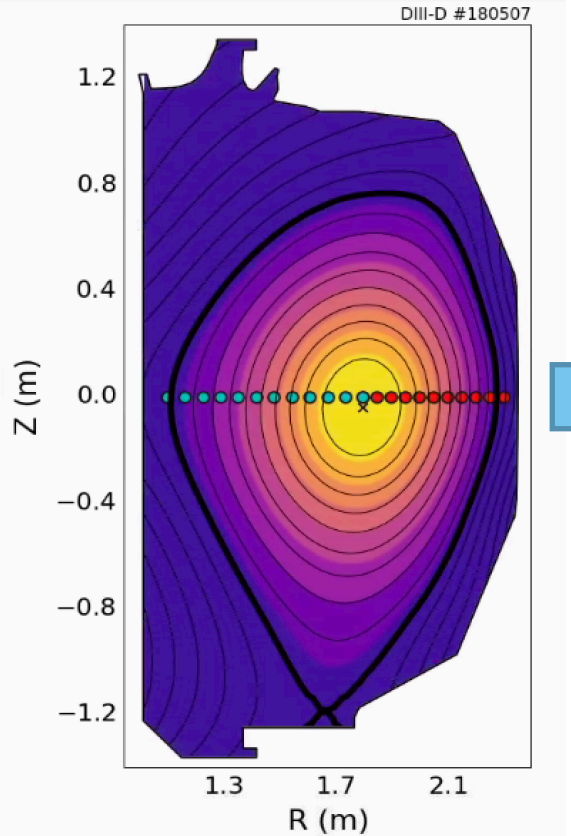
- Grad–Shafranov equation is fully specified by three profiles:
  - $\psi_0(\vec{r})$ – last closed flux-surface boundary conditions
  - $P(\psi)$ – pressure profile
  - $FF'(\psi)$ – related to current through B_ϕ

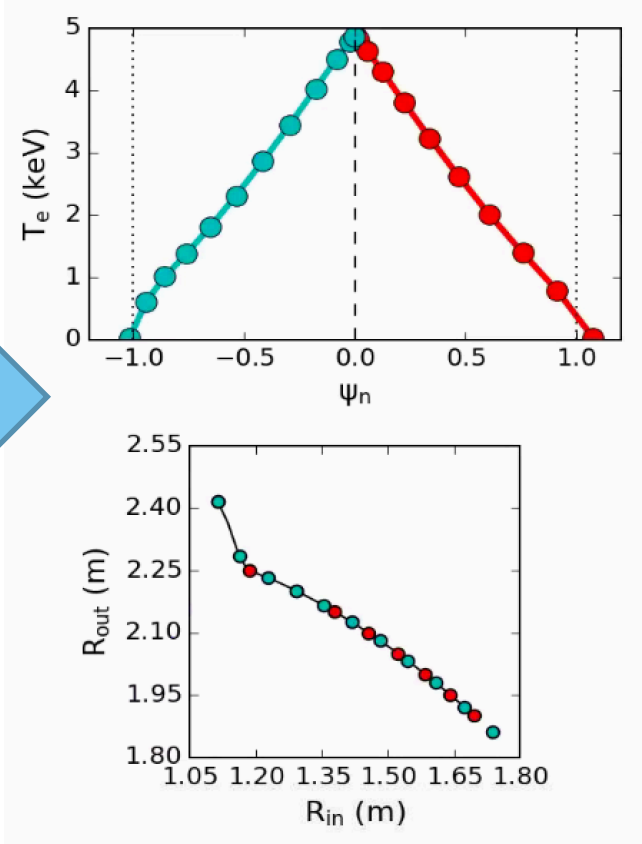
$$\Delta^* \psi = -\mu_0 r^2 \frac{dp}{d\psi} - \frac{1}{2}\frac{dF^2}{d\psi}$$

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

$T_{e,sym}(\psi)$ 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

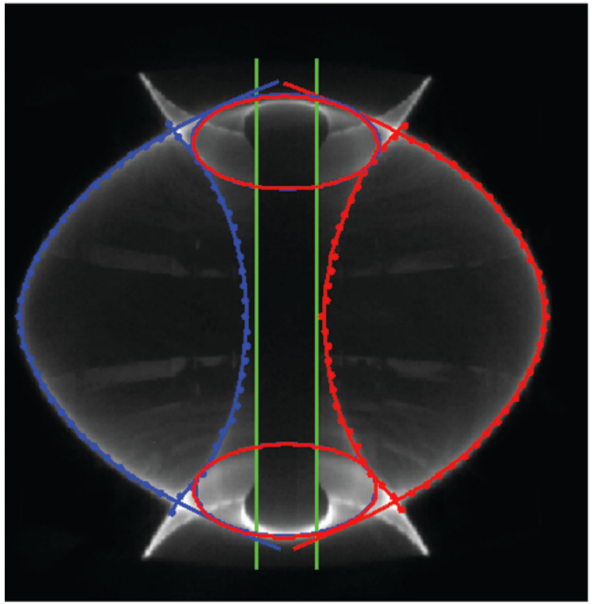


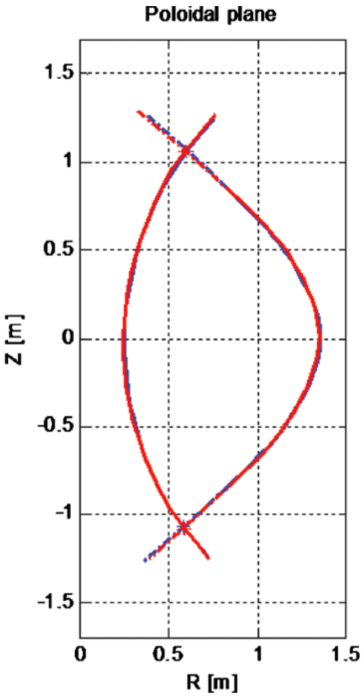


Plasma boundary measured from emission

- 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

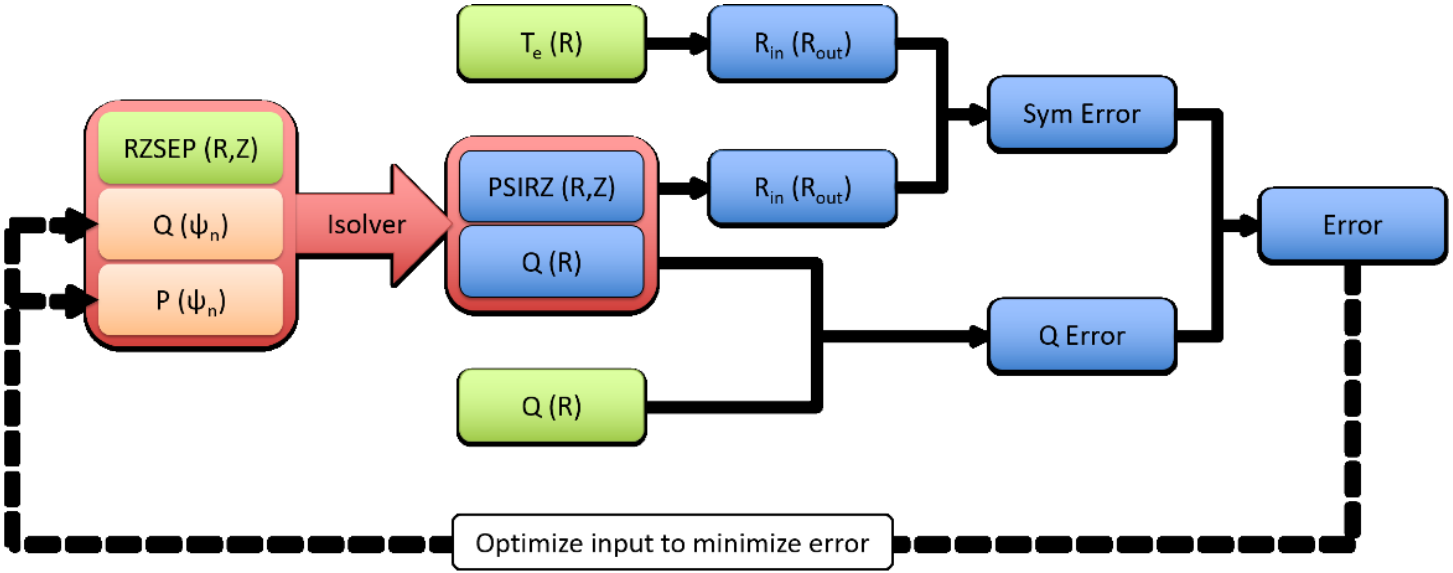
[G. Hommen et al., Rev. Sci. Instrums. 2010]





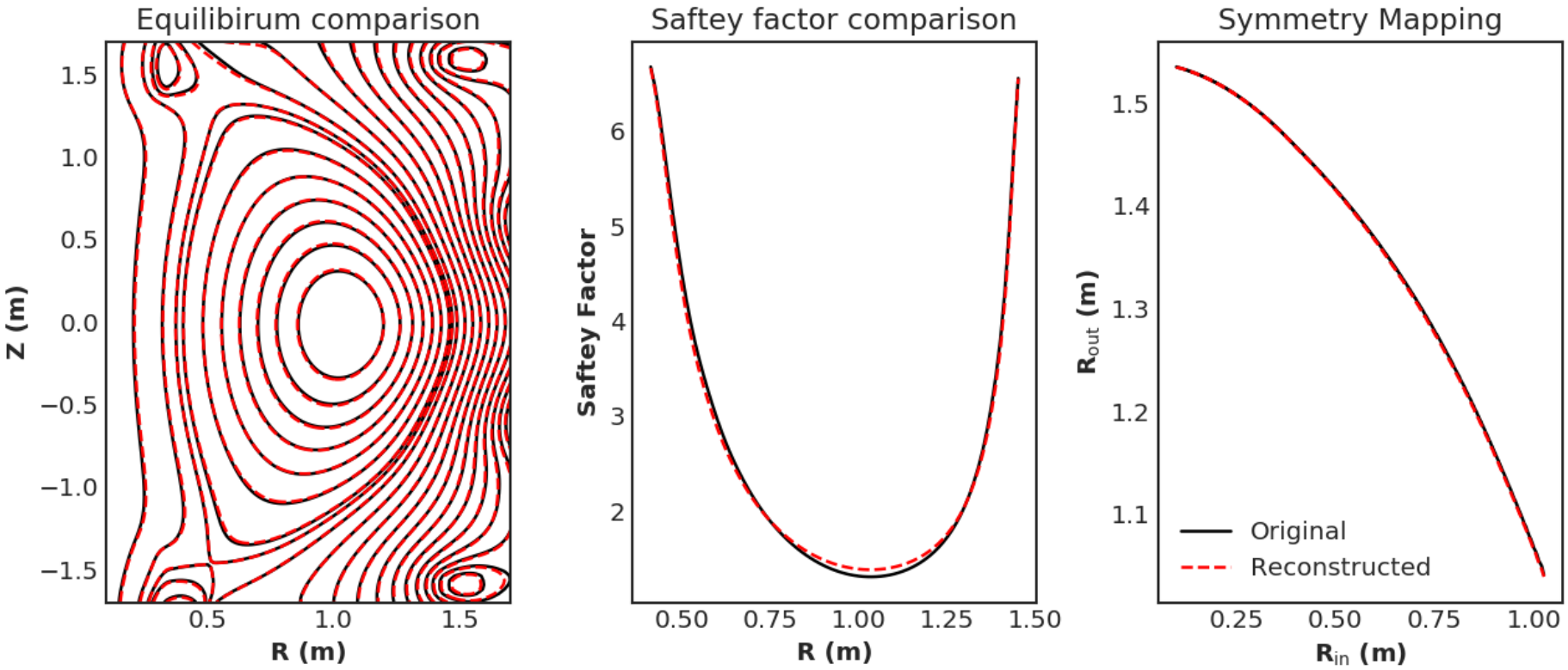
q-profile as basis for equilibrium reconstruction

- Iterations preformed over the Isolver Grad–Shafranov solver [R. Andre, APS 2012]
  - Error on T_e symmetry and q-profile minimized



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

NSTX equilibrium constructed from q constraints



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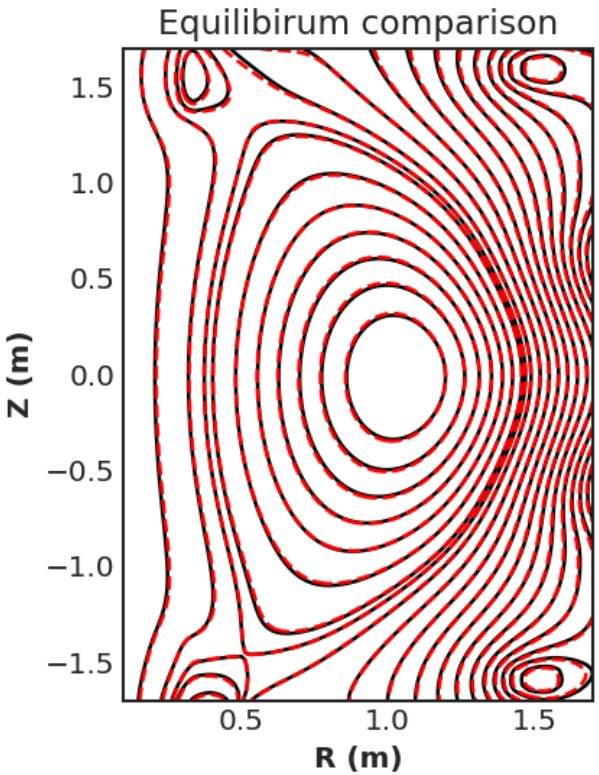

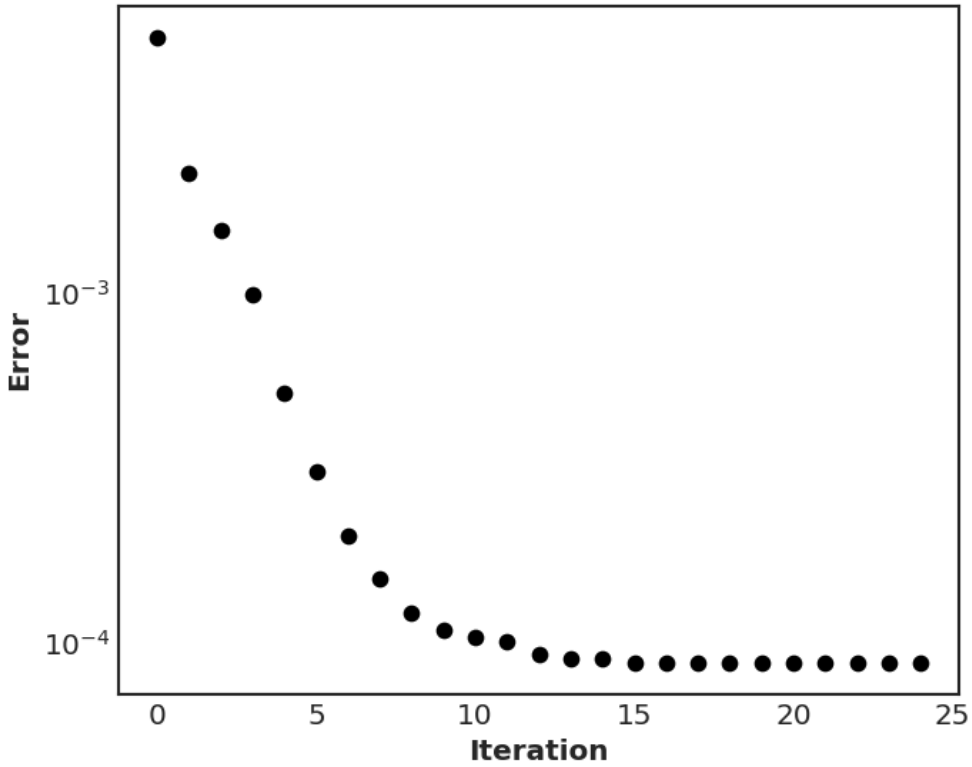

[A.O. Nelson et al., PPCF 2019]

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
    [A.O. Nelson et al., Fusion Eng. Des. 2019]
  - Equilibrium reconstruction from q-profile
    [A.O. Nelson et al., PPCF 2019]