Contributions of Electron Cyclotron Waves to Performance in Advanced Regimes on DIII-D

by

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in collaboration with

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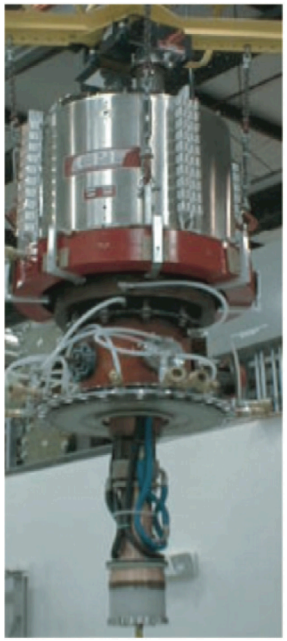
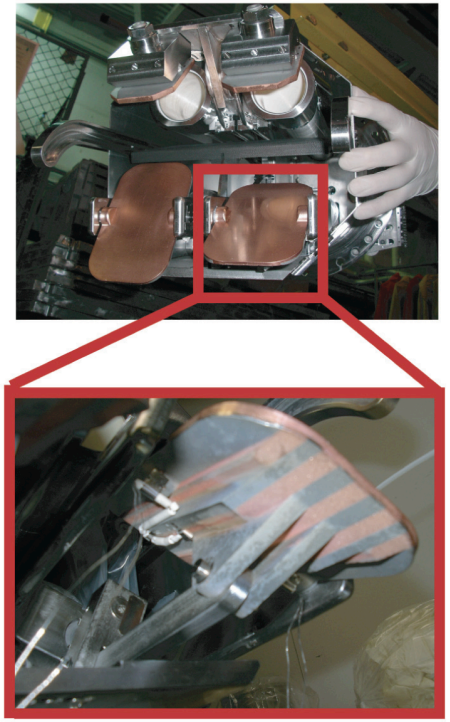
ECH/ECCD is an Important Tool for Tailoring the Current and Pressure Profiles on DIII-D

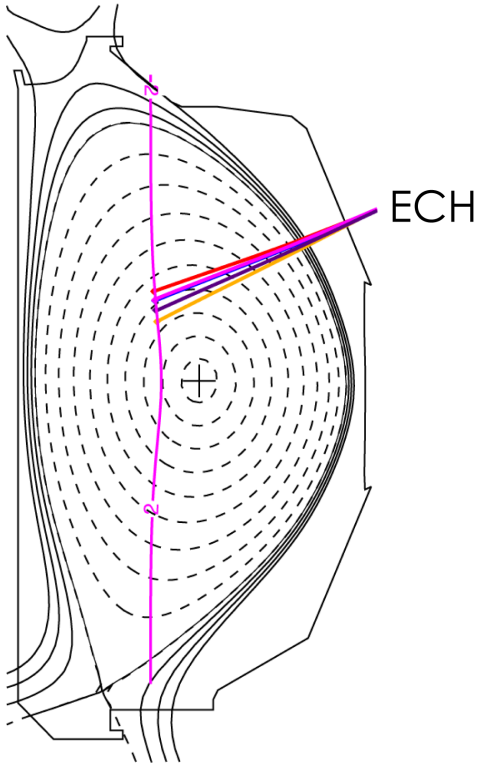
- **Electron cyclotron heating (ECH) and current drive (ECCD) play a crucial role in Advanced Tokamak (AT) regimes, which need simultaneously:**
  - High noninductive current
  - High beta
  - High confinement
- **EC waves have been used to increase performance in three different AT scenarios on DIII-D**
  I. Quiescent High-confinement mode (QH-mode)
  II. High bootstrap fraction, "high q_{min}" AT regime
  III. Hybrid scenario with $q_{min} \approx 1$

Flexible Six Gyrotron System Supports a Variety of Research on DIII-D

- Peak injected power of 3.5 MW, pulse length up to 5 s
- Six steerable launchers
- 2nd harmonic X-mode at 110 GHz

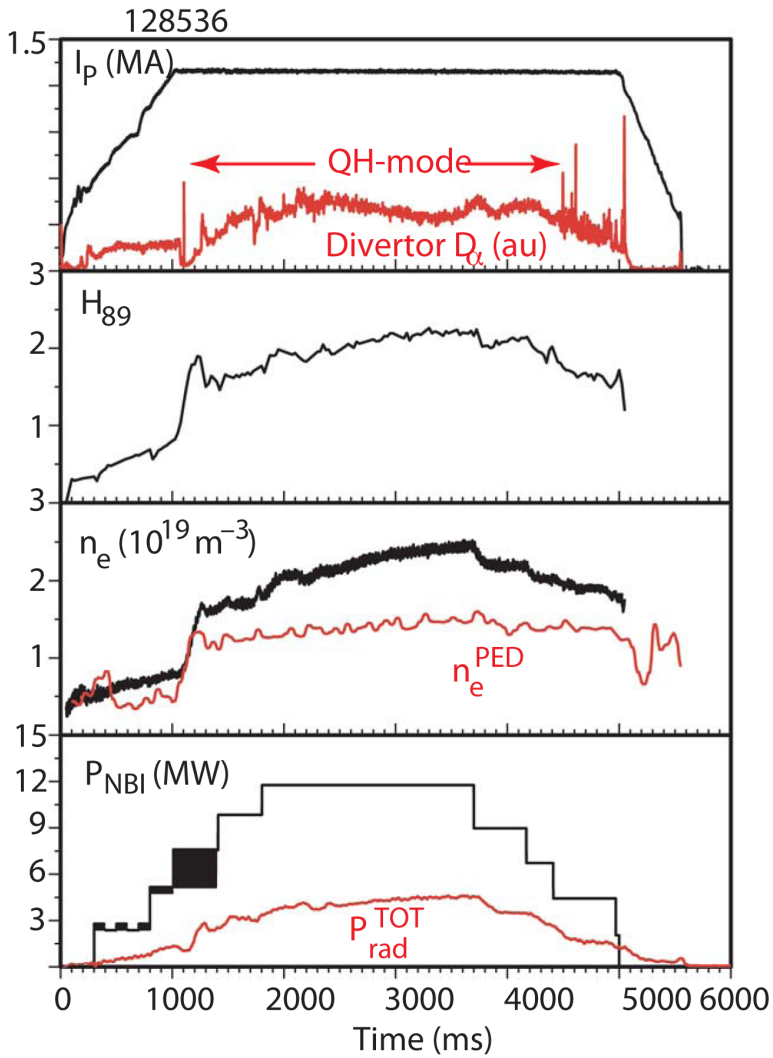






I. ECCD and Electron Transport in QH-Mode

- **Quiescent H-modes (QH-mode) combine H-mode confinement with ELM-free operation**
  - Edge Harmonic Oscillation (EHO) enhances particle transport, placing edge parameters in stable region for peeling-ballooning modes



Noninductive Current Profile Measured Using Periodic Response of MSE Signals to ECCD Modulation

- **Evolution of poloidal flux is governed by diffusion equation arrived at by combining Ampere's, Faraday's and Ohm's laws:**

$$\frac{\partial^2\tilde{\psi}}{\partial\rho^2}+\left[\frac{1}{\rho}+\frac{\partial}{\partial\rho}\ln\left(\hat{F}\hat{G}\hat{H}\right)\right]\frac{\partial\tilde{\psi}}{\partial\rho}-\frac{i}{\hat{D}}\tilde{\psi}=-\mu_0R_0\rho_b^2\frac{\hat{F}}{\hat{G}}\left[\left\langle\tilde{J}_{EC}\right\rangle+\frac{\tilde{\eta}}{\eta}\left\langle J_{oh}\right\rangle\right],$$

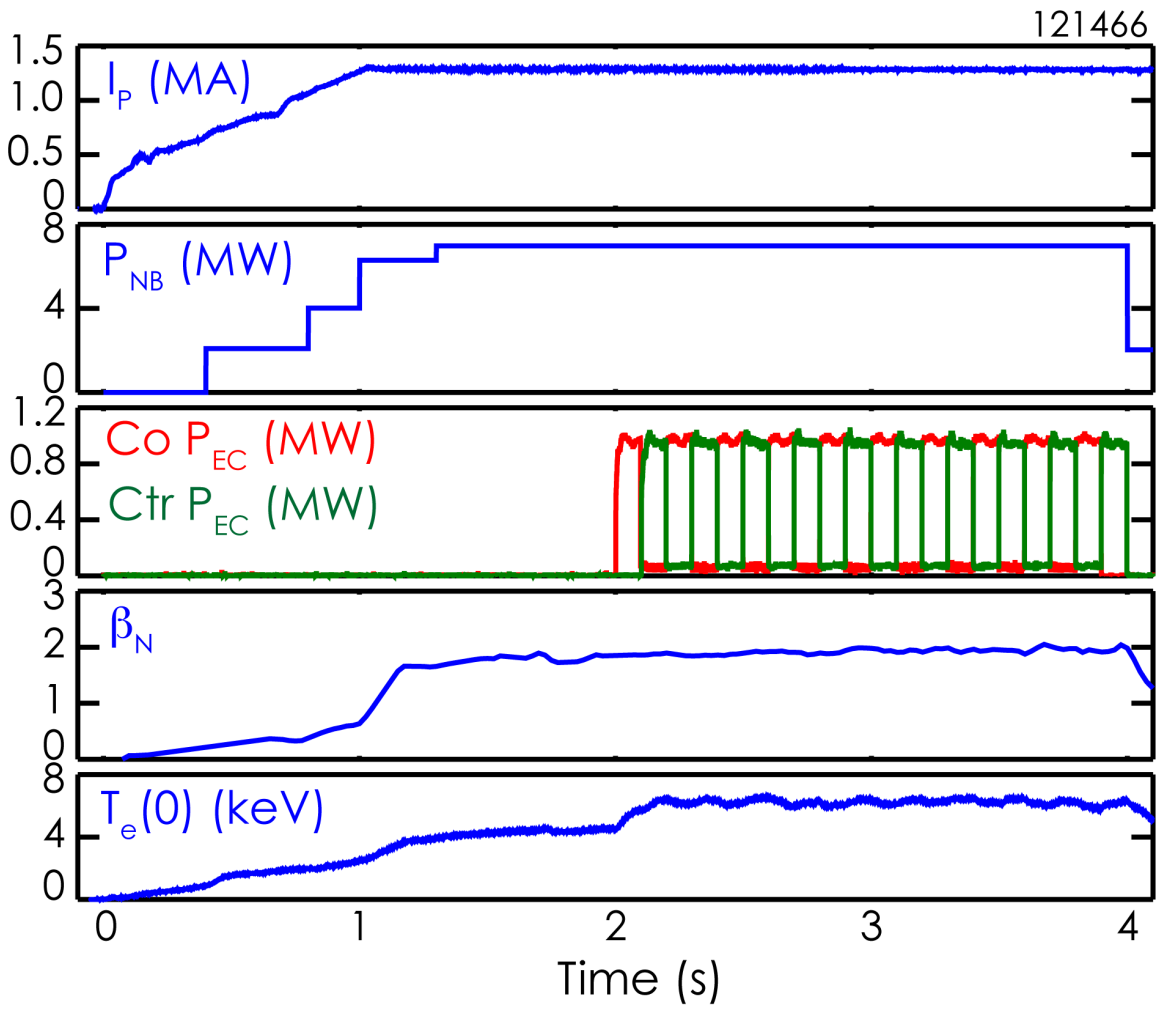
$$\hat{D}=\frac{\eta}{\mu_0\rho_b^2\omega}\frac{\hat{G}\hat{H}}{\hat{F}},$$

  - Dimensionless factors $\hat{F},\hat{G},\hat{H}$ handle arbitrary geometry

- **Modulated ECCD current density $(\tilde{J}_{EC})$ can be directly determined from the measured modulation in poloidal flux $(\tilde{\psi})$ and the calculated neoclassical resistivity (η)**

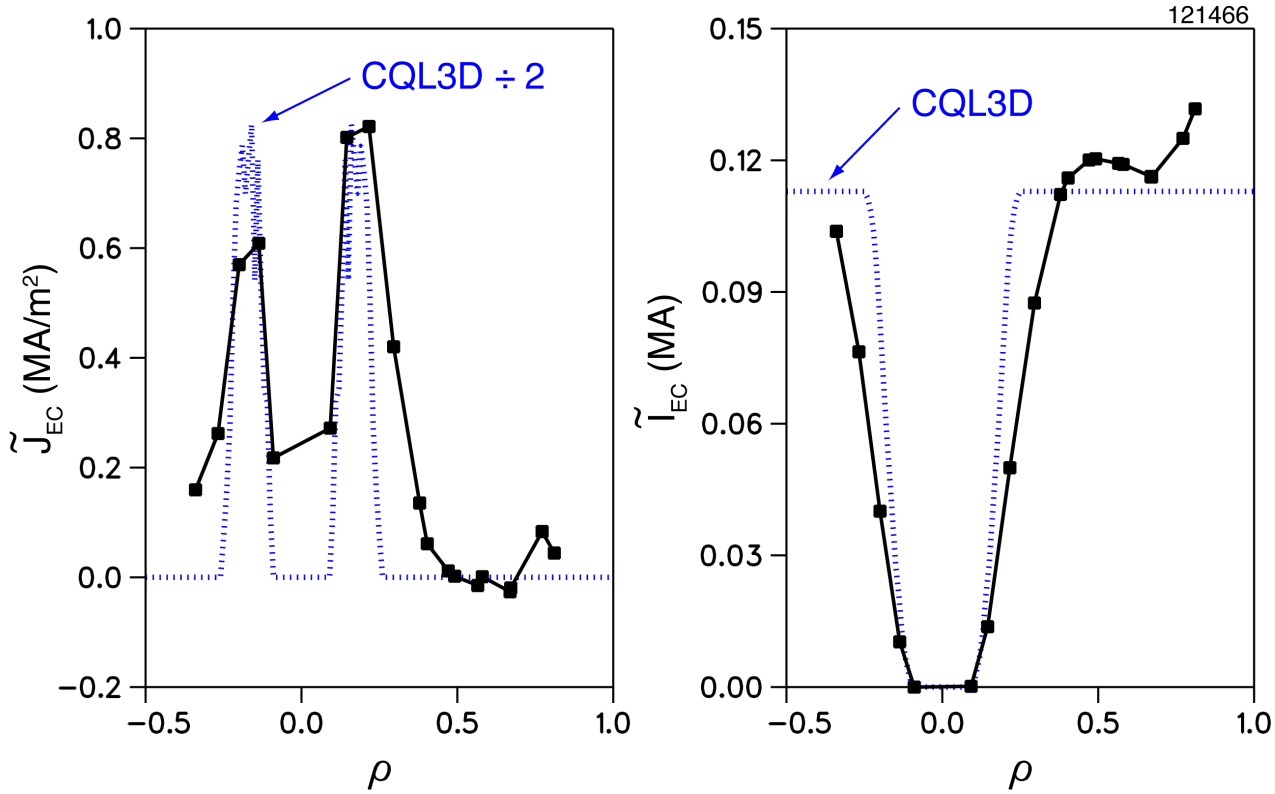
- **MSE pitch angle (γ) gives:** $B_Z=B_{\phi,0}\left(\frac{R_0}{R}\right)\tan\gamma,\qquad \psi=R_0B_{\phi,0}\int_0^R(\tan\gamma)dR$

ECCD is Modulated at 5 Hz With "Push/Pull" Configuration to Keep η Approximately Constant



- **ECCD is alternated between co/counter injection at ρ ≈ 0.2**
- **This push/pull operation diminishes T_e modulation to obtain $\tilde{\eta}/\eta << 1$**

ECCD Measured by Modulation Technique is Broader Than Theory, But Integrates to Predicted Value



- **Broadening may be due to radial transport of the current carrying electrons**

Quasi-linear ECCD enhancement = 15%

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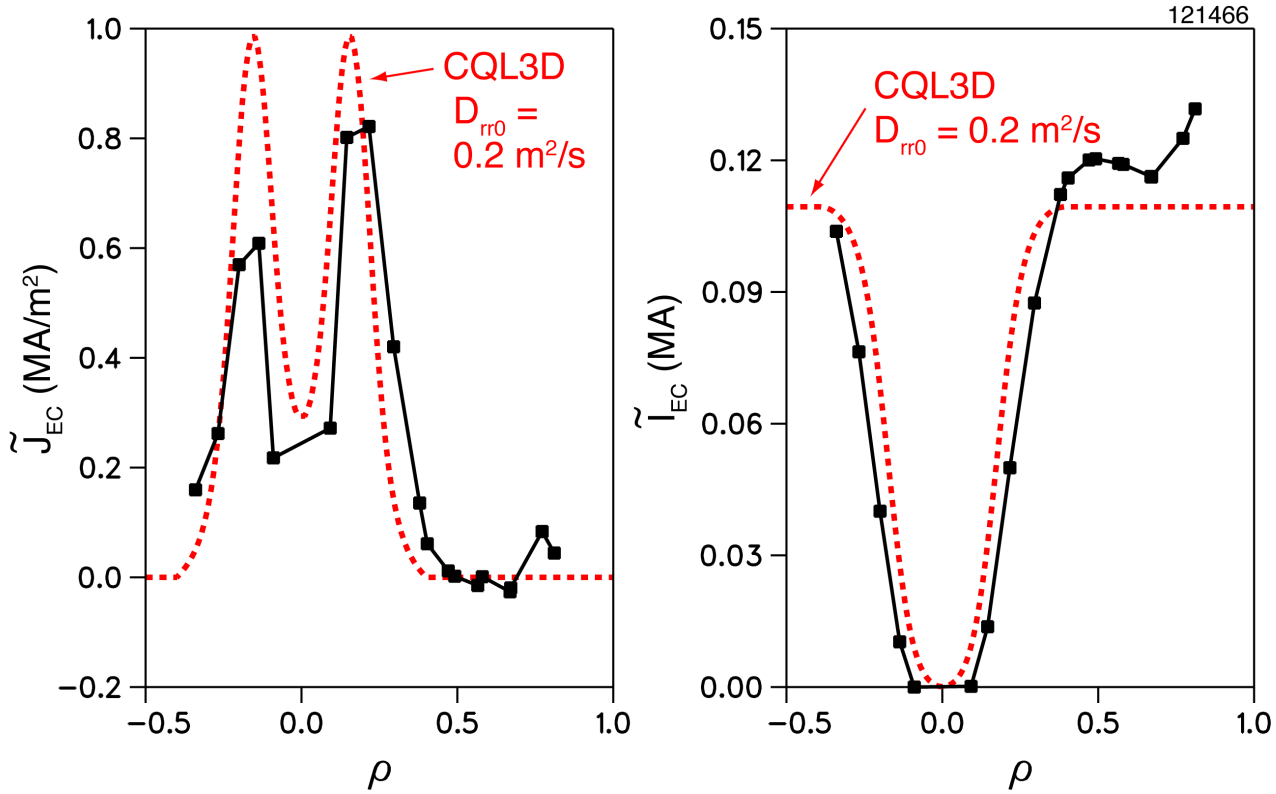
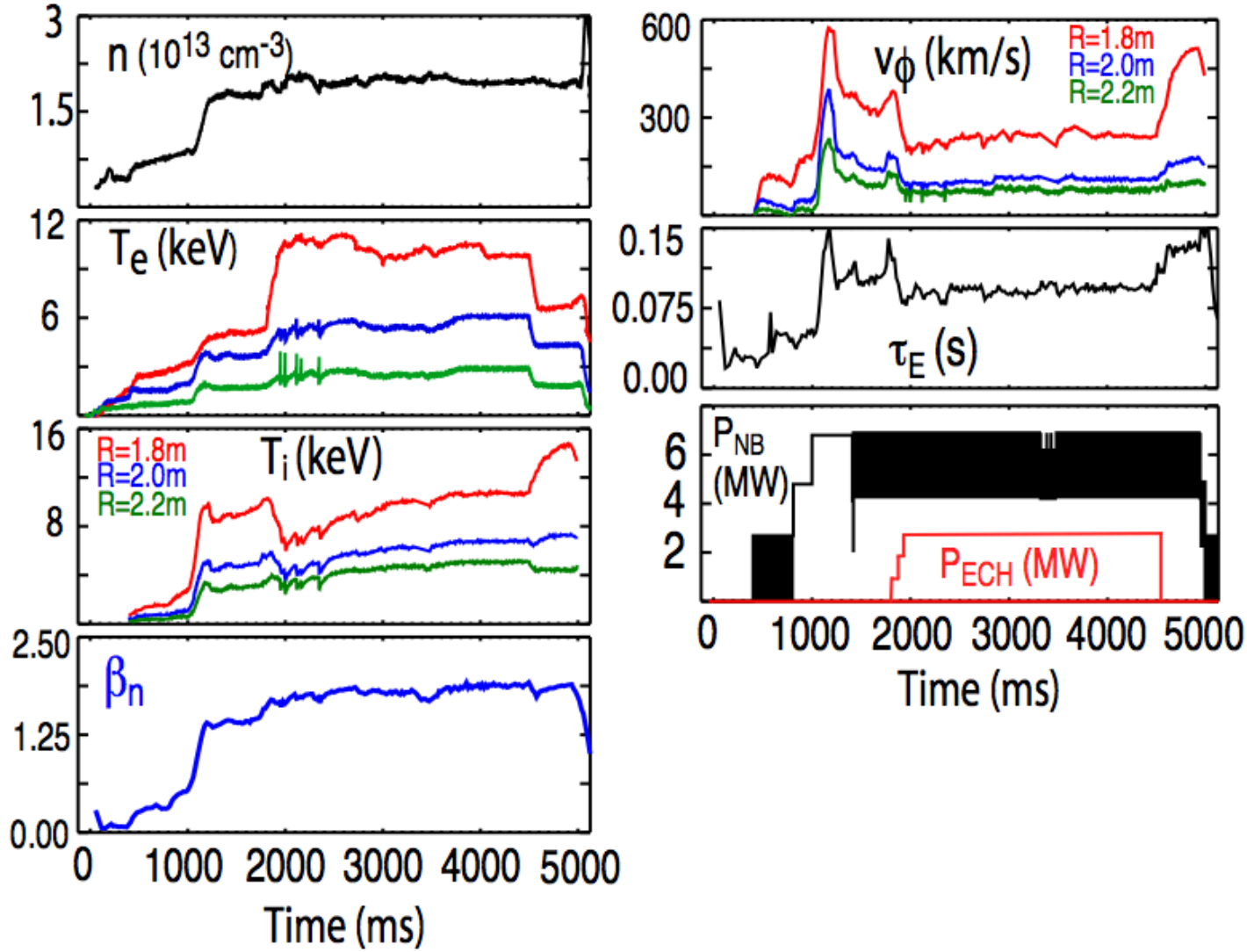


- **Broadening may be due to radial transport of the current carrying electrons**
- **$D_{rr0} \approx 0.2$ m²/s in CQL3D is reasonable match to experiment**

Quasi-linear ECCD enhancement = 15%

ECH-Assisted QH-Mode Tests Effect of Core Electron Heating (Simulates α-Heating) on Electron Transport

- T_e/T_i (0) > 1 and T_e (0) > 10 keV achieved during ECH
- Reduced T_i(0) and rotation with ECH
- Collisionality ν*~0.02-0.04 comparable to ITER



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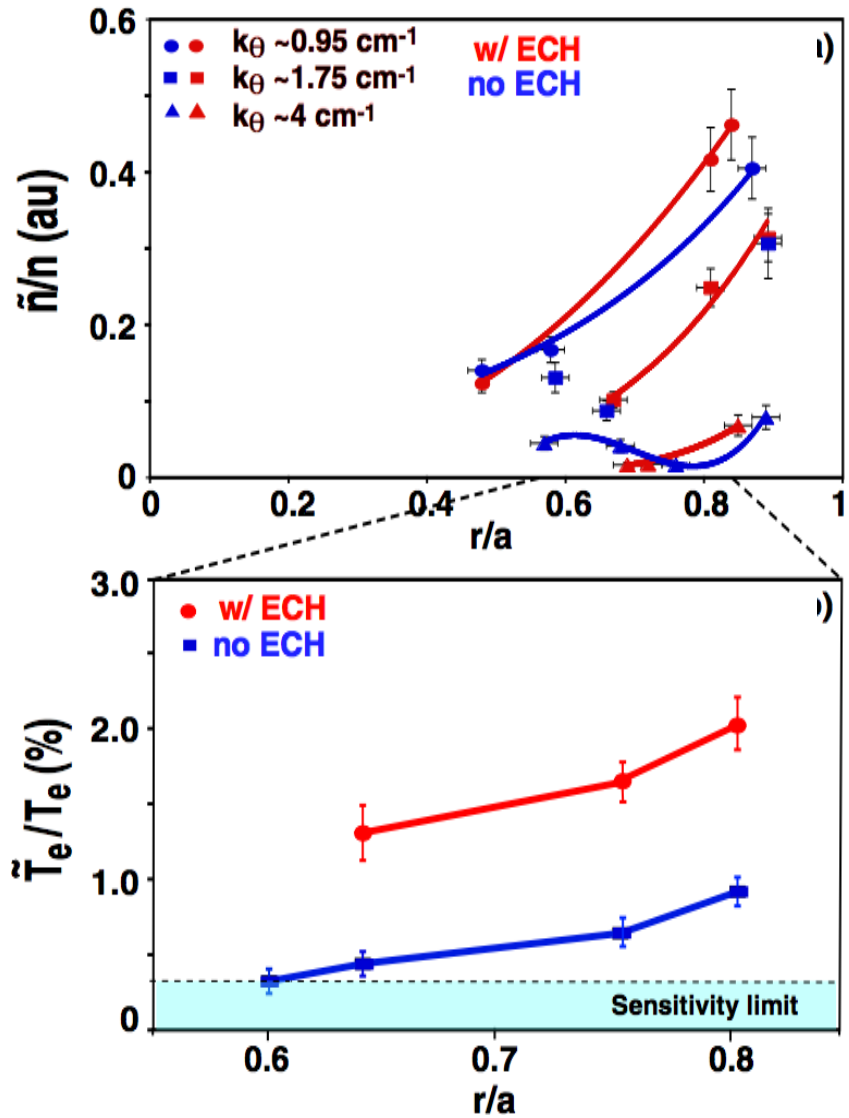
Electron Temperature Fluctuations Strongly Increase With ECH, Indicating Transition from ITG to TEM

- **Density fluctuations at constant k_θ are virtually unchanged with ECH**

ITG = Ion Temperature Gradient mode
TEM = Trapped Electron Mode

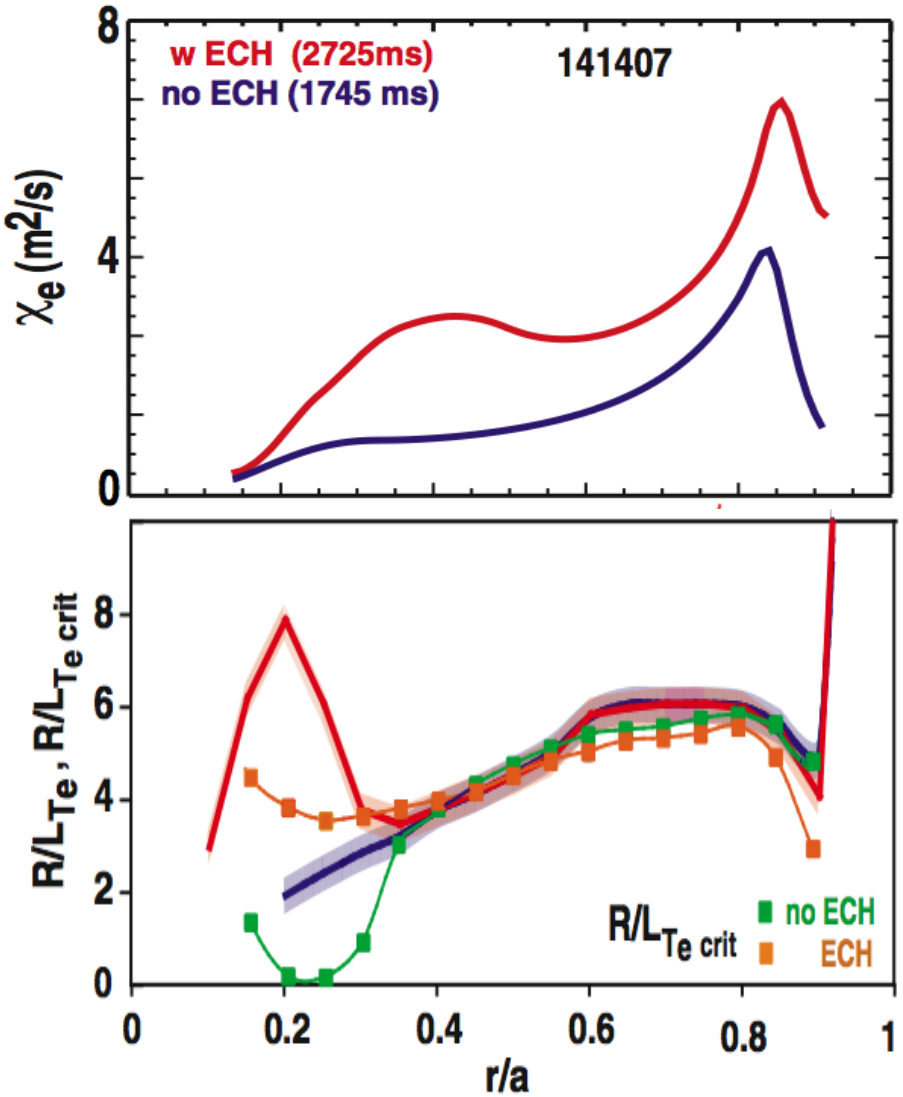


Electron Transport Increases During ECH, Consistent With TEM Becoming Dominant Mode

- **Electron temperature gradient is close to TEM critical gradient**
- **Empirical TEM critical gradient from GS2:**

$$\frac{R}{L_{T_e crit}} = \frac{0.357\sqrt{\varepsilon} + 0.271}{\sqrt{\varepsilon}}\left[4.9 - 1.31\frac{R}{L_n} + 2.68\hat{s}\right]$$

Peeters *et al.*, , PoP 2005



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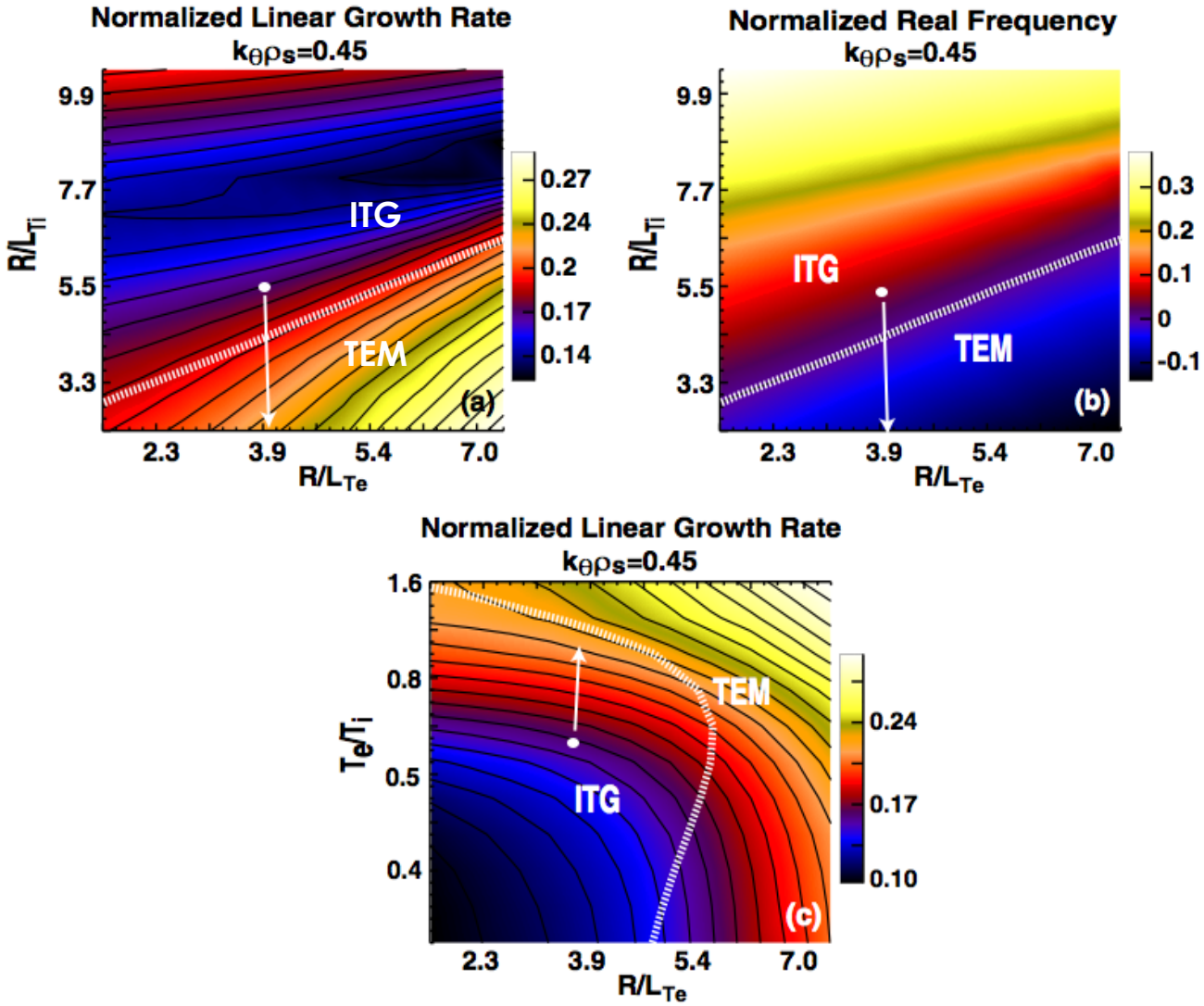
Linear Growth Rate Indicates Transition From ITG- to TEM-Dominant Regime With ECH

- Linear growth rate calculated at ρ = 0.4 using TGLF code
- Arrows show change in growth rate with ECH
- Growth rate increases due to higher T_e/T_i and reduced R/L_{Ti}



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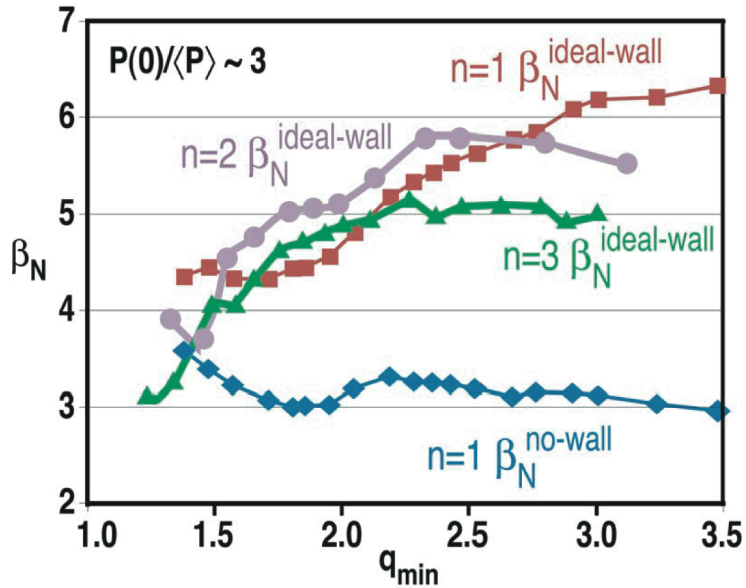
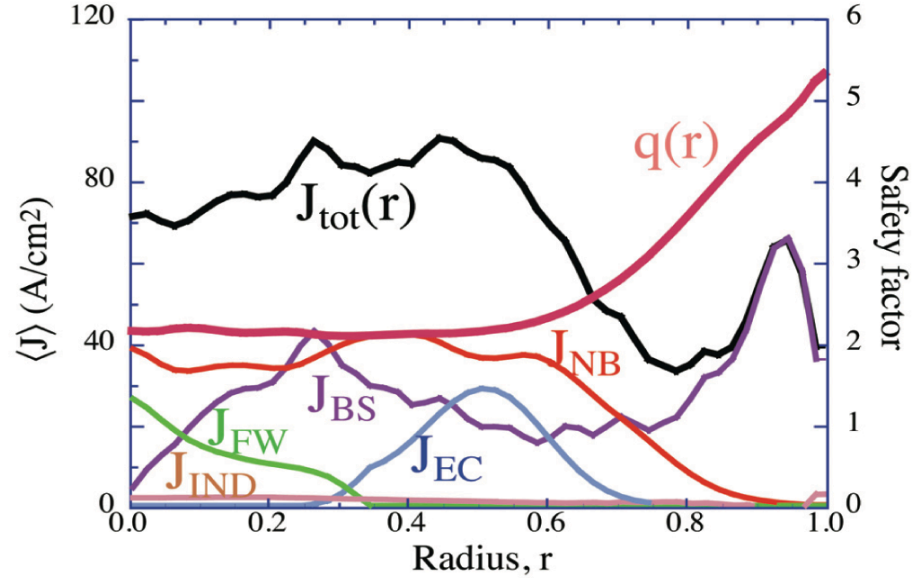
II. ECCD in "High q_{min}" AT Regime

- **Both the "ideal-wall" stability limit and bootstrap current fraction increase with higher q_{min}** ➔ Goal is 70-80% bootstrap current
  - Computed β_N limits for kink modes
  - Fully noninductive simulation with β_N =4.5 and 70% bootstrap

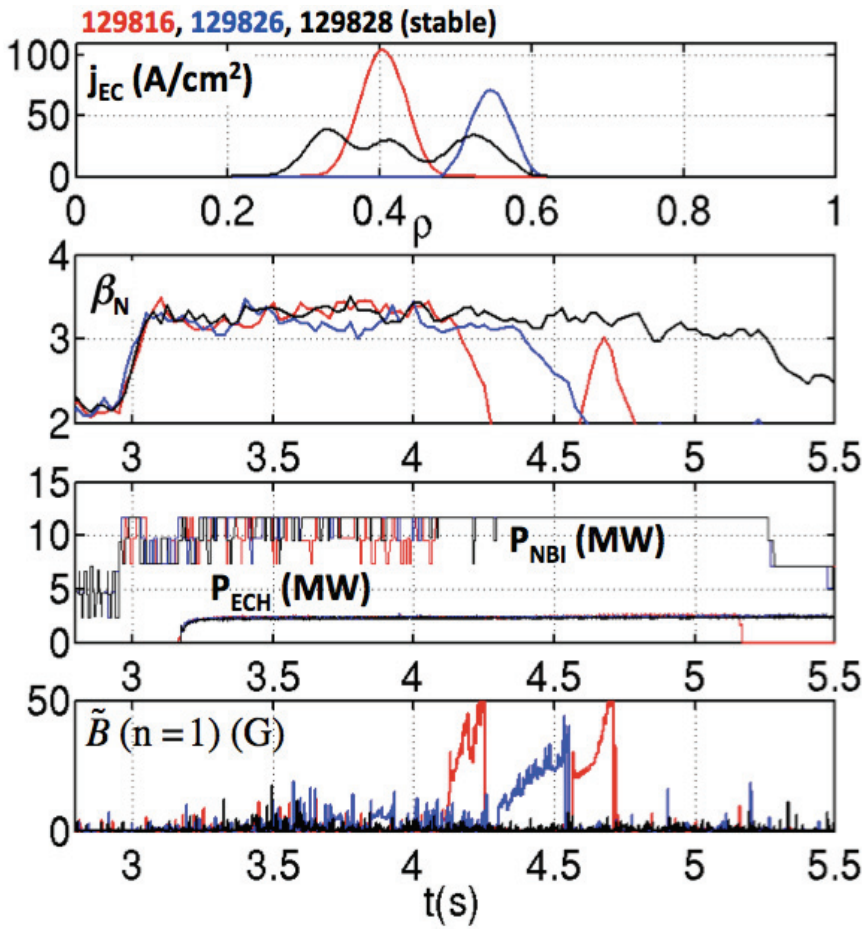


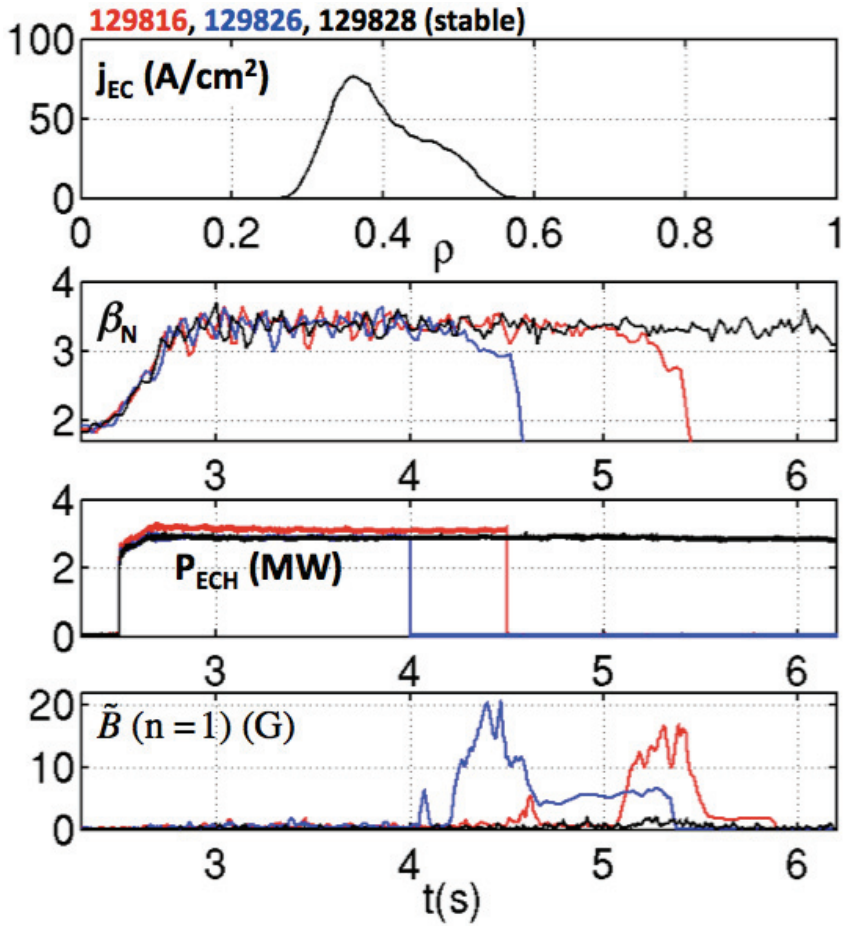


- **ECCD is used to drive noninductive current off-axis and help produce a tearing stable equilibrium**

Broad EC Deposition Helps to Avoid Tearing Modes That Limit the Discharge Duration

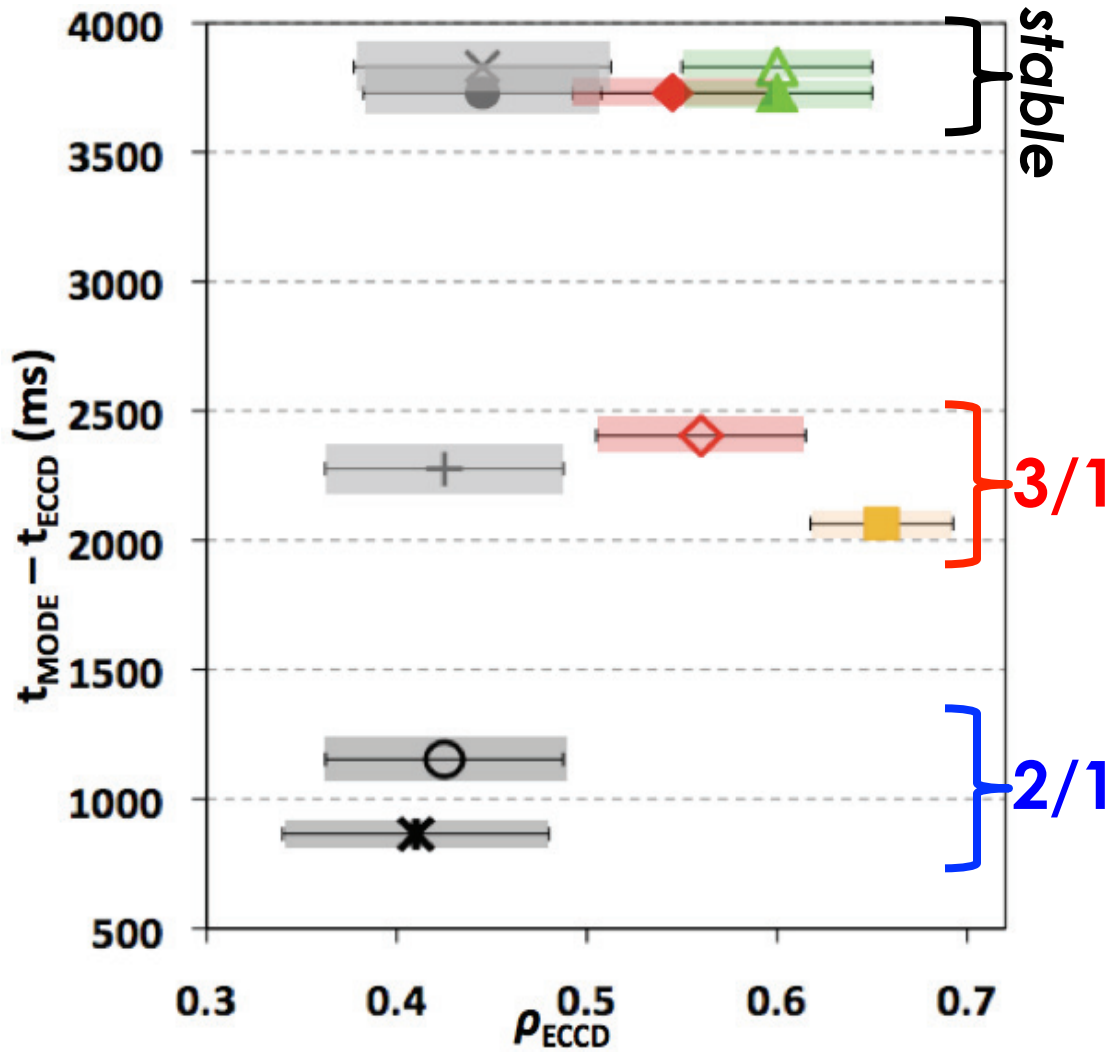
- **Broad vs narrow deposition**
- **With vs without broad ECCD**





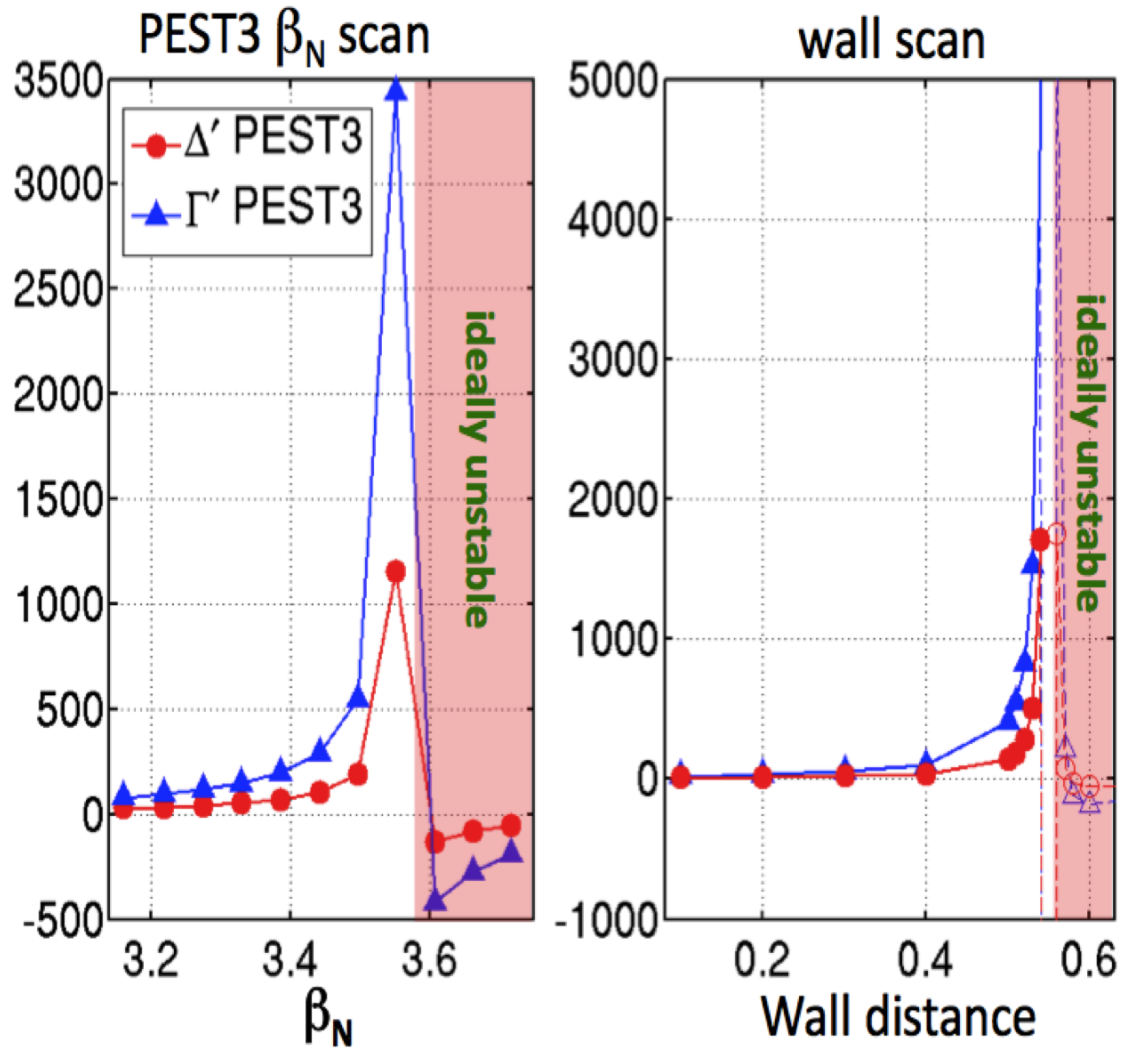
Scan of the Broad EC Deposition Location Produces Both Stable and Unstable Discharges

- **Several stable discharges are obtained, even with**
  - Outermost depositions
  - Low driven currents
- **Unstable discharges have both 2/1 and 3/1 modes**
- **An explanation for the variability of the results is the sensitivity of the tearing stability when close to the ideal limit**



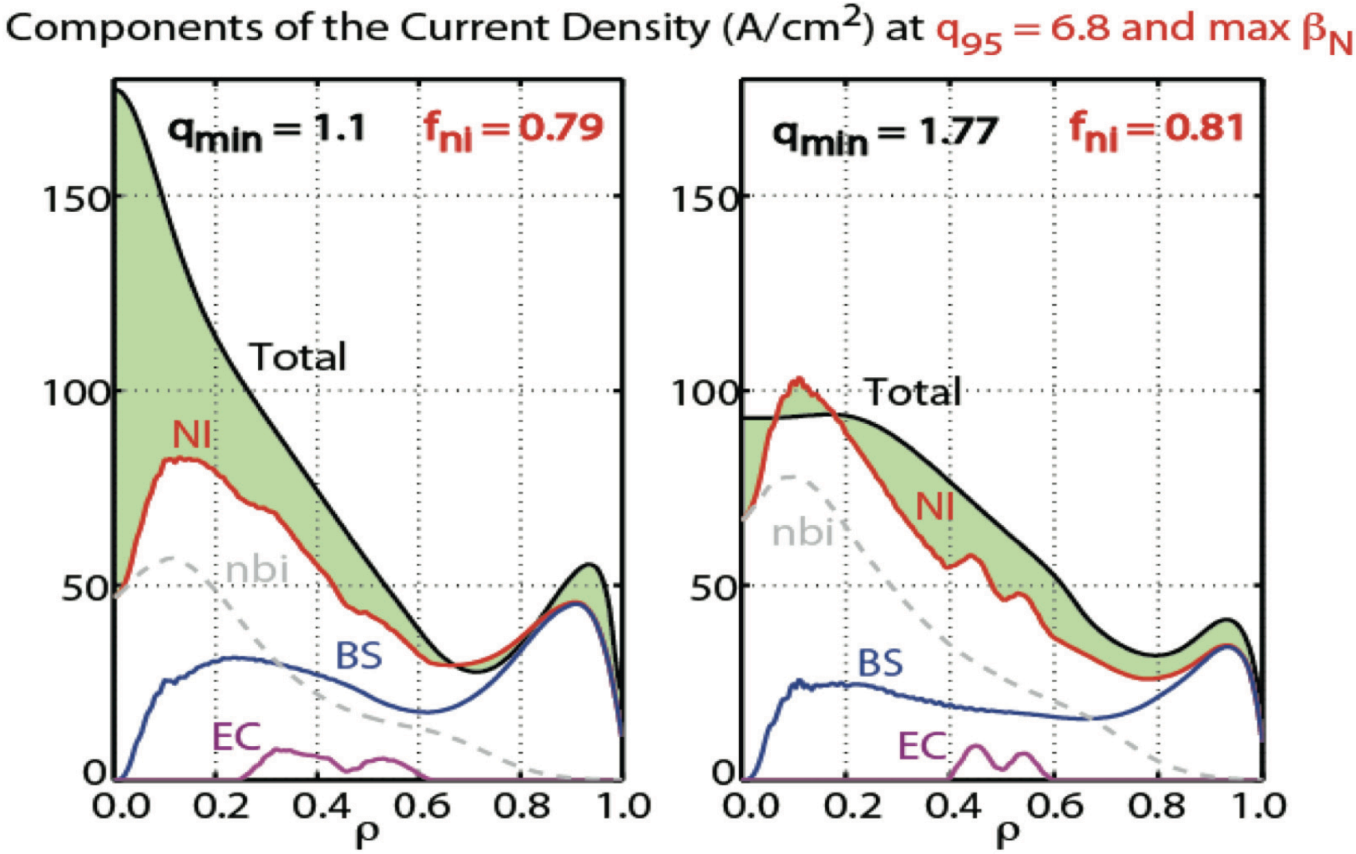
Resistive Stability Calculations Confirm Sensitivity of Tearing Stability When Close to Ideal Limit

- **In PEST3 code, ideal limit approached by**
  - Increasing pressure (β_N)
  - Increasing plasma-wall distance
- **Classical tearing index Δ' increases sharply at the ideal stability boundary**



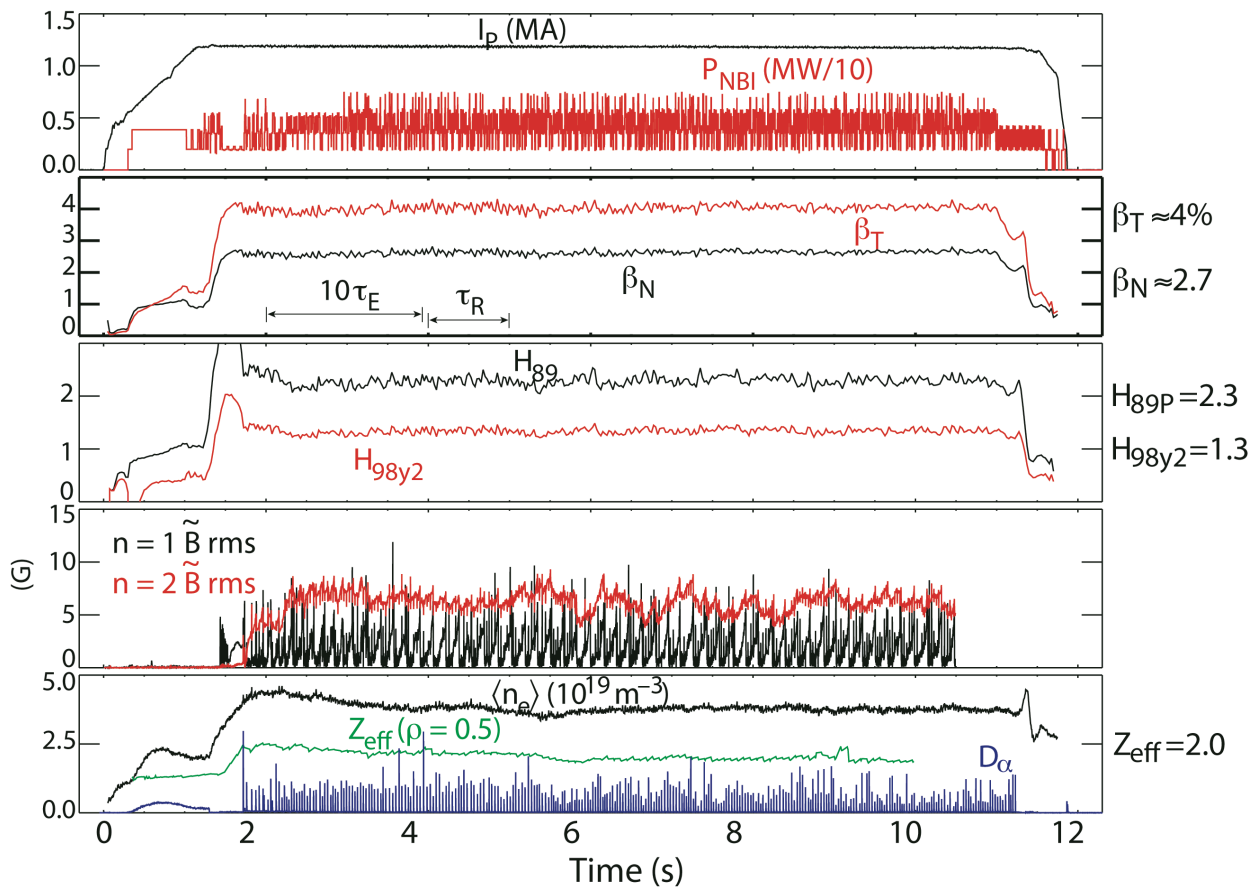
Broad, Off-Axis ECCD for Stability is Well Aligned With Desired Current Profile for "High q_{min}" AT Scenario

- For q_{min}=1.77 case, current drive between ρ = 0.2 and ρ = 0.8 is needed for steady-state
- For q_{min}=1.1 case, current drive needs to be more on-axis for steady-state



III. ECCD in High-Beta, Steady-State Hybrids

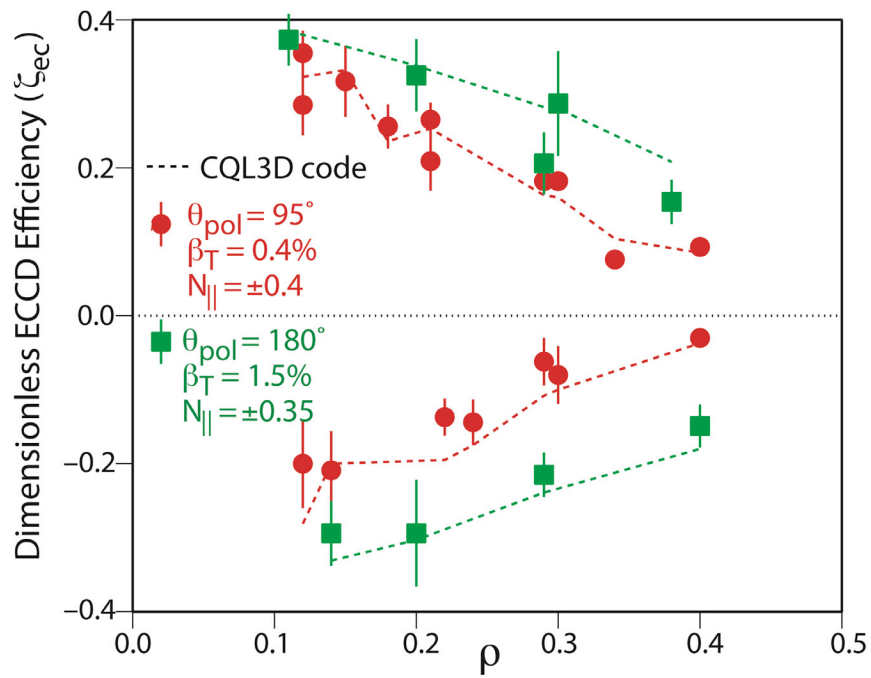
- **"Hybrid scenario" refers to stationary (>9τ_R), high beta, high confinement discharges with $q_{min} \approx 1$**



Hybrid is an Attractive Steady-State AT Regime if External Current Drive is Concentrated On-Axis

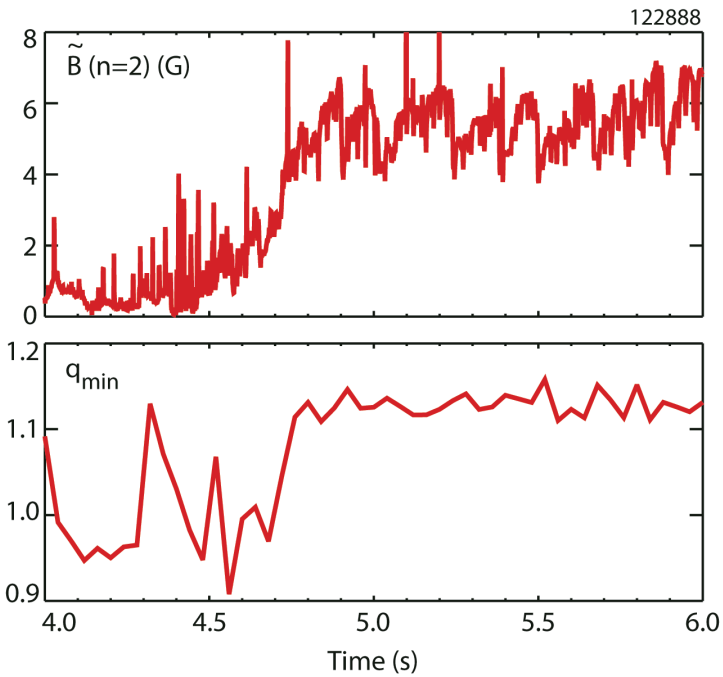
- **Stability limit of $\beta_N < 4$ and $q_{min} \approx 1$ limits bootstrap current fraction in hybrids to ≈ 50%**
- **To be competitive, hybrid scenario needs twice the current drive efficiency (in Amps/Watt) as "high q_{min}" AT scenario**
  - This can be accomplished for on-axis current drive (compared to far off-axis for "high q_{min}" AT scenario)

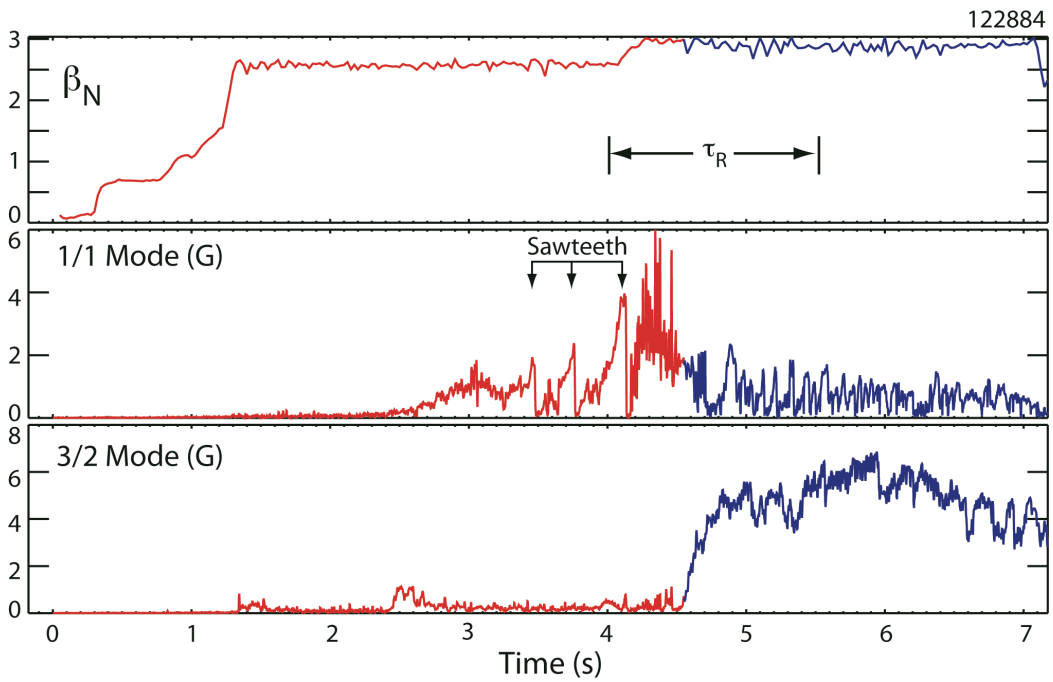
Measured and predicted ECCD efficiency on DIII-D



In Hybrid Scenario, 3/2 Tearing Mode Anomalously Broadens the Current Profile

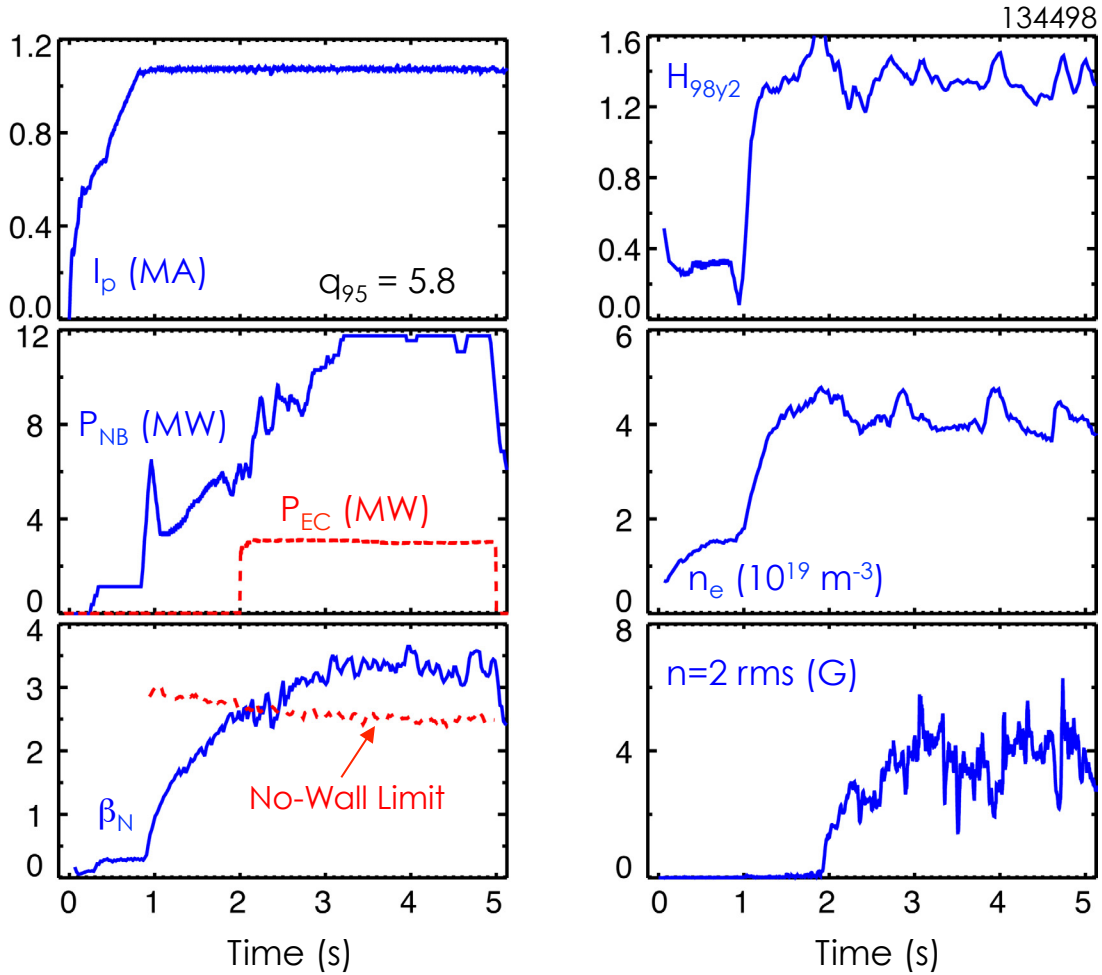
- **MSE measurement of q_{min} jumps above 1 after 3/2 mode onset**
- **Sawteeth activity suppressed after 3/2 mode destabilized by high beta**





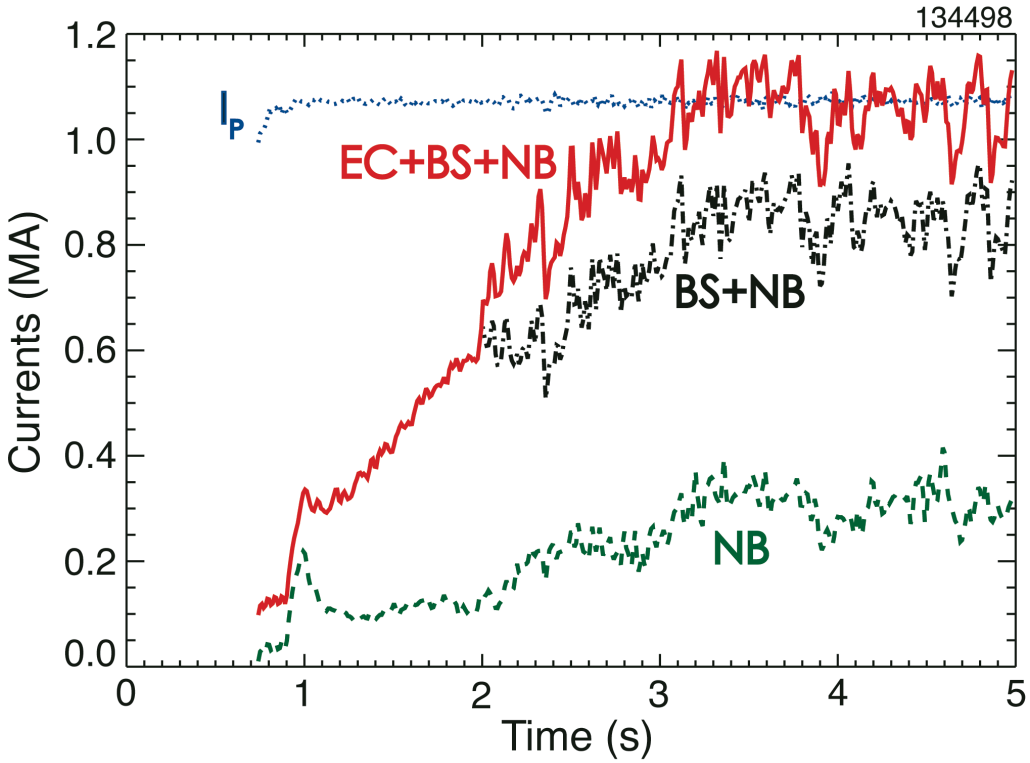
Steady-State Potential of High-Performance Hybrid Demonstrated Using Central ECCD + NBCD

- **β_N exceeds ideal n=1 "no-wall" limit calculated by DCON**
- **High H_{98y2} achieved with strong electron heating**
  - $T_e \approx T_i$ for outer 80% of radius



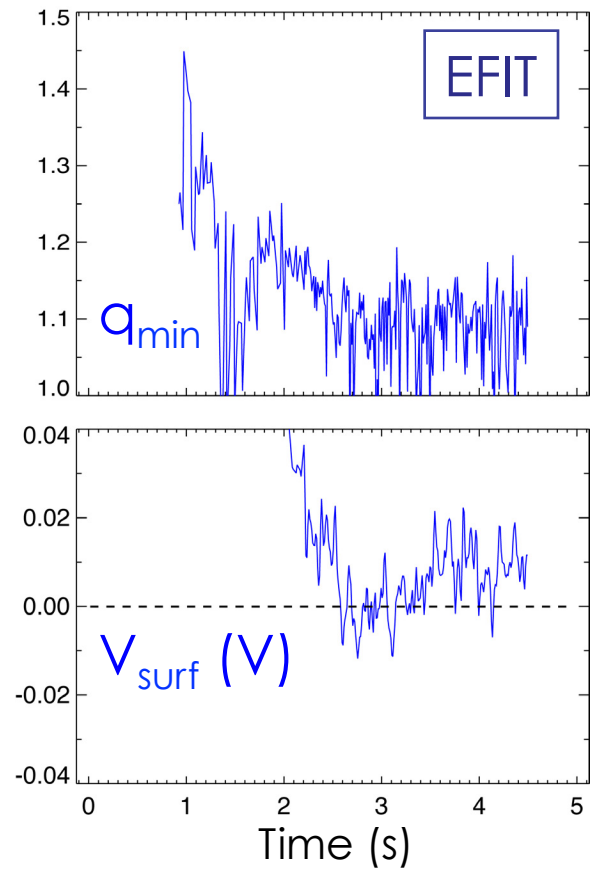
Calculated Current Drive is Consistent With Achieving ≈100% Noninductive Hybrid

- **TRANSP modeling of high-beta hybrid (ECCD from CQL3D) ➔ 50% bootstrap**



Efficiencies: ECCD=0.07 A/W
NBCD=0.03 A/W

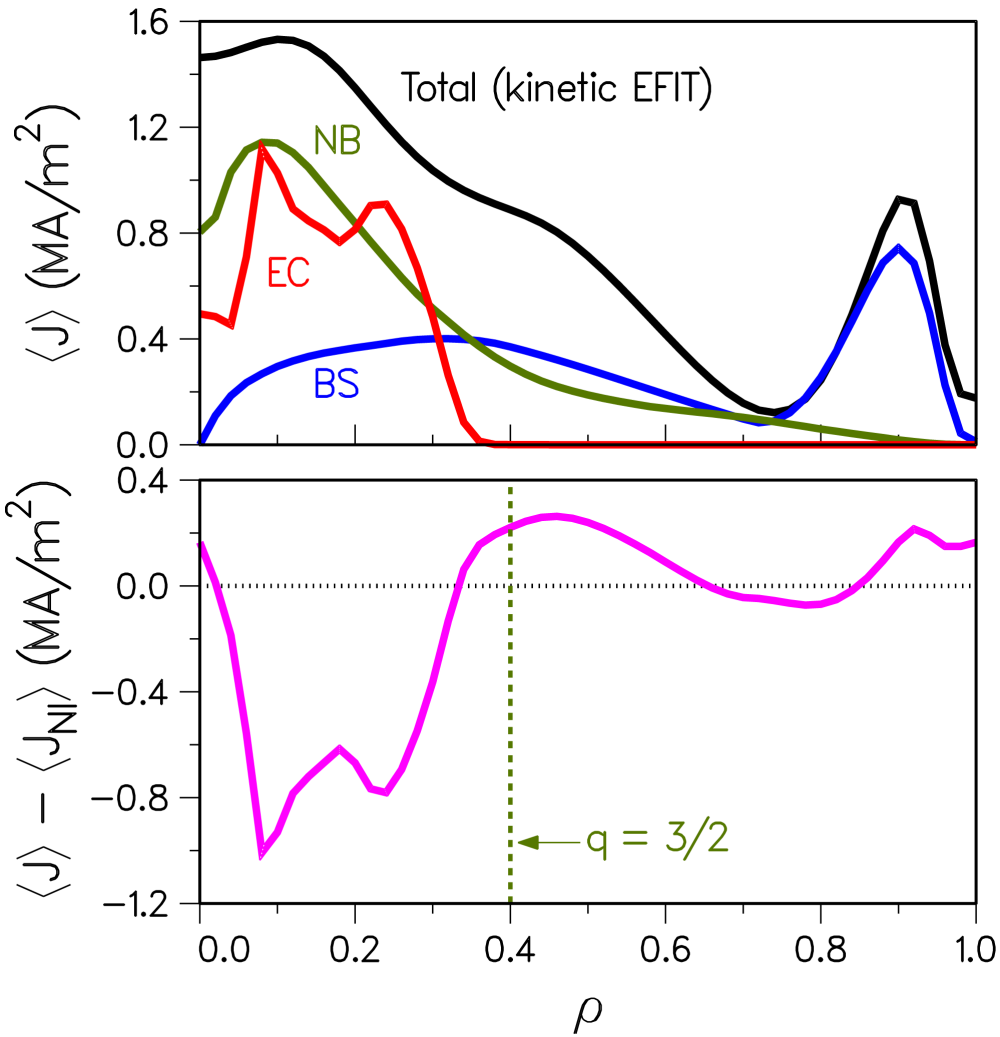
- **Despite strong central current drive, q_{min}>1 and sawteeth are suppressed**



Hybrid Scenario Doesn't Require Good Current Alignment Because of Flux Pumping Action by 3/2 Mode

- **Noninductive current profile is more peaked than total current profile**
- **Negative inductive current density is inconsistent with positive loop voltage profile**
  - Poloidal flux pumping yields broad current profile independent of current drive profile

Petty *et al.*, PRL 2009



Conclusions

- **Electron cyclotron heating and current drive greatly contributes to Advanced Tokamak regimes on DIII-D**
  - In QH-mode, core ECH causes transition to TEM dominant regime (simulates α-heating)
  - In "high q_{min}" AT regime, off-axis ECCD with a broad profile helps to avoid tearing modes and sustain the high q_{min} profile
  - In hybrid regime, fully noninductive discharges have been demonstrated using efficient, on-axis ECCD without the need for good current alignment