New Regime for High-Beta Hybrid Using Off-Axis Electron Cyclotron Current Drive on DIII-D

by

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In collaboration with

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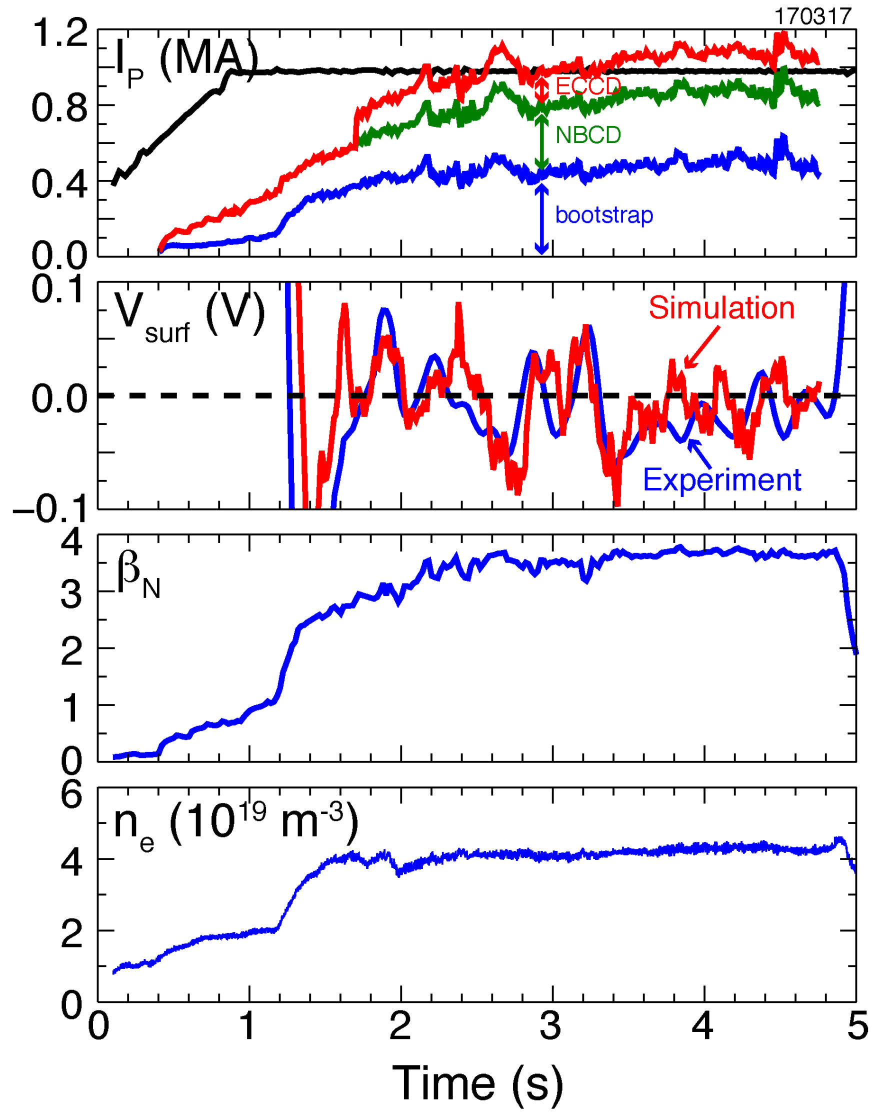
What is a "Steady-State Hybrid"? – Low q_{min} Scenario With High Beta Limit, High Confinement Factor, V_{loop} = 0

- **Steady-state hybrid scenario achieves complete current drive with a combination of ECCD, NBCD and bootstrap**

  $I_P = 1.0$ MA
  $\beta_N = 3.7$
  $H_{98} = 1.5$
  $P_{tot} = 14.6$ MW

- **Anomalous poloidal flux pumping maintains $q_{min} > 1$**
- **This poster examines new hybrid regime where the broad current profile is achieved via off-axis ECCD instead**



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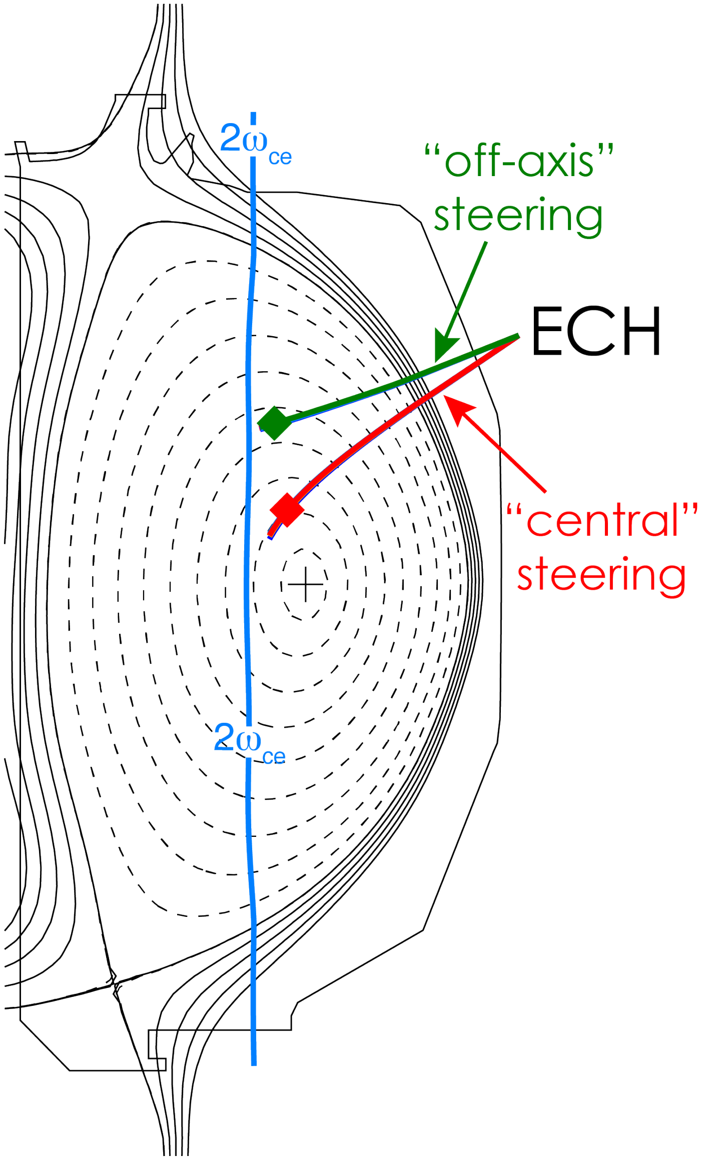
Outline

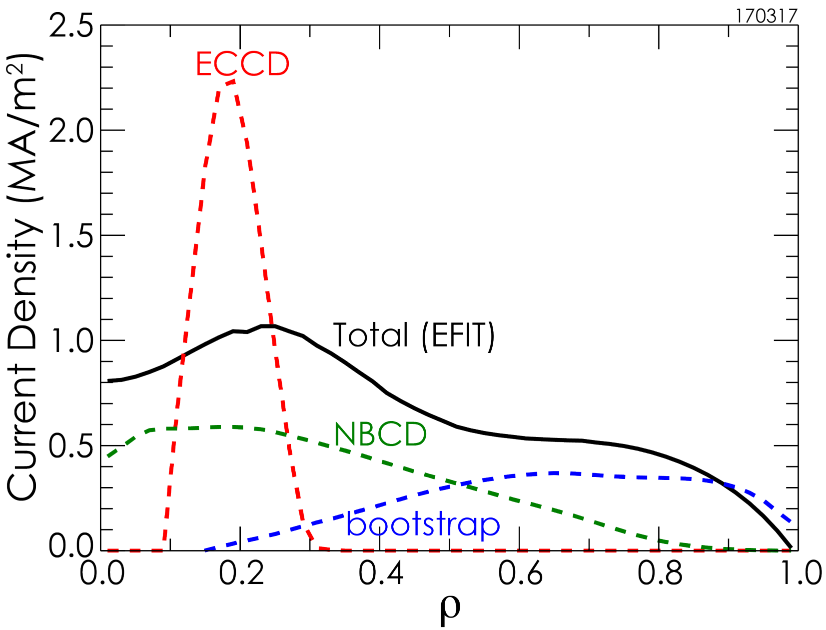
I. **High-beta hybrid plasmas with off-axis vs. on-axis ECCD**
   a. Change in current profile
   b. Change in fast ion and thermal transport

II. **Off-axis ECCD hybrid plasmas with high vs. low density**
   a. Effect on non-inductive current
   b. Effect on fast ion and thermal transport
   c. Power threshold for pedestal collapse

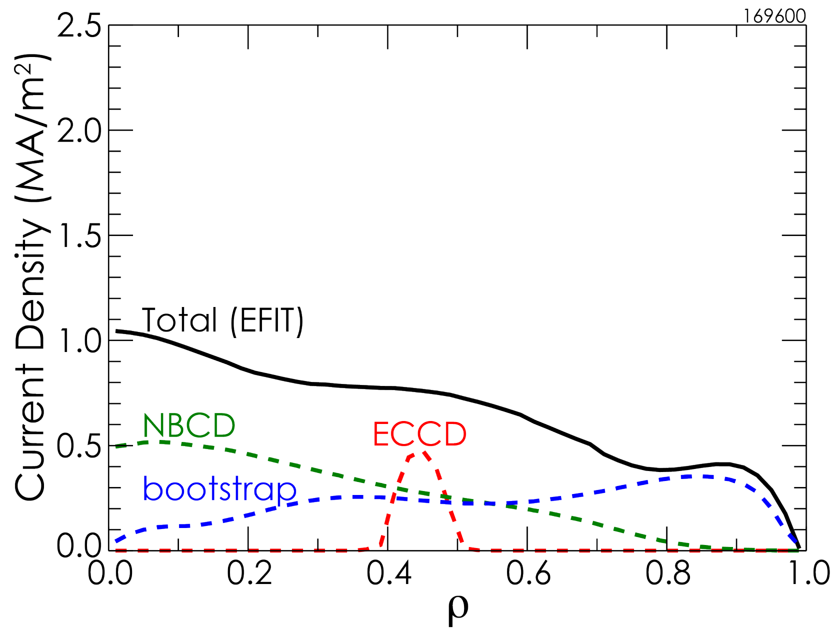


New High-Beta Hybrid Regime With Off-Axis ECCD – is Poloidal Flux Pumping Still Required?

- **For ρ_{ec} = 0.20, current profile is overdriven near plasma center but anomalous poloidal flux pumping keeps q_{min} > 1**



- **For ρ_{ec} = 0.45, current profile is expected to broaden but ECCD drops from 0.21 MA to 0.08 MA due to lower efficiency**



Non-Inductive Current is Measured from Evolution of Poloidal Magnetic Flux from Equilibrium Reconstruction

- **Ohmic current found from measured loop voltage profile using MSE-constrained EFITs and neoclassical resistivity**

$$V_{\text{loop}} = -2\pi \frac{\partial \psi}{\partial t}$$

$$I_{\text{ohm}} = \int \sigma \frac{V_{\text{loop}}}{R_0} \rho \, d\rho$$

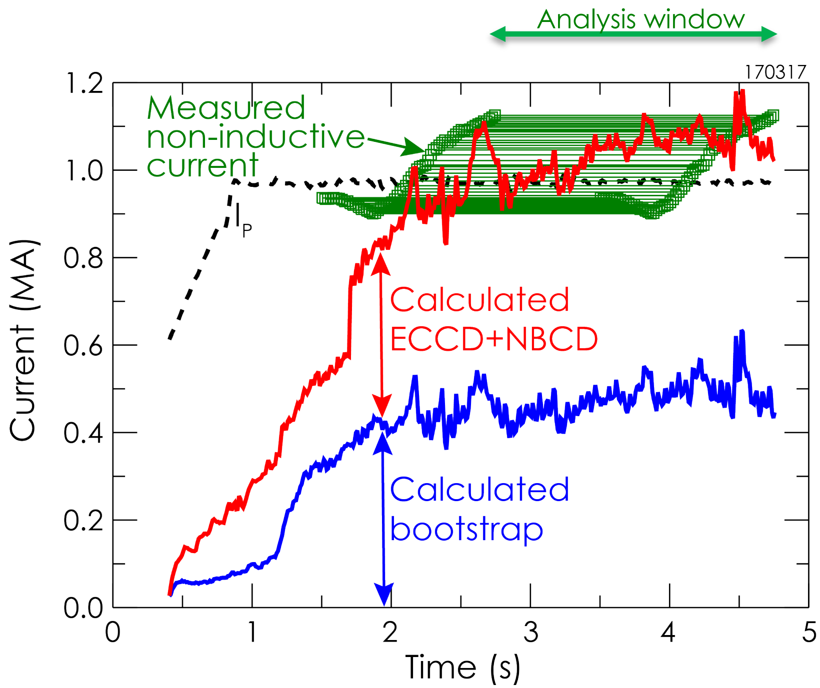
- **Non-inductive current is the difference between the total plasma current and the Ohmic current**

$$I_{NI} = I_P - I_{\text{ohm}}$$

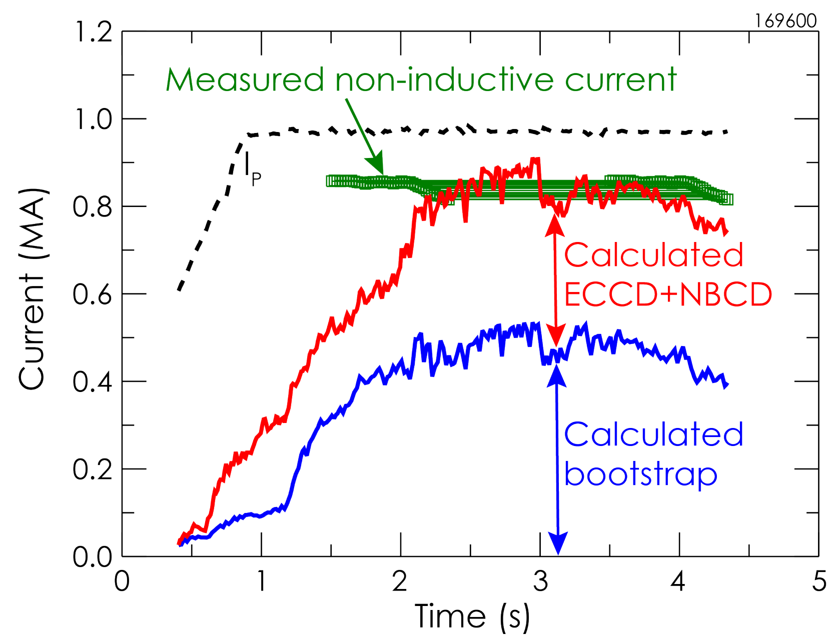
Care should be taken in interpreting the V_{loop} profile in the presence of anomalous poloidal flux diffusion

Measured and Calculated Non-Inductive Currents are in Good Agreement for Both On-Axis and Off-Axis ECCD

- **For ρ_{ec} = 0.20, analysis of poloidal flux evolution confirms prediction of 100% non-inductive current**

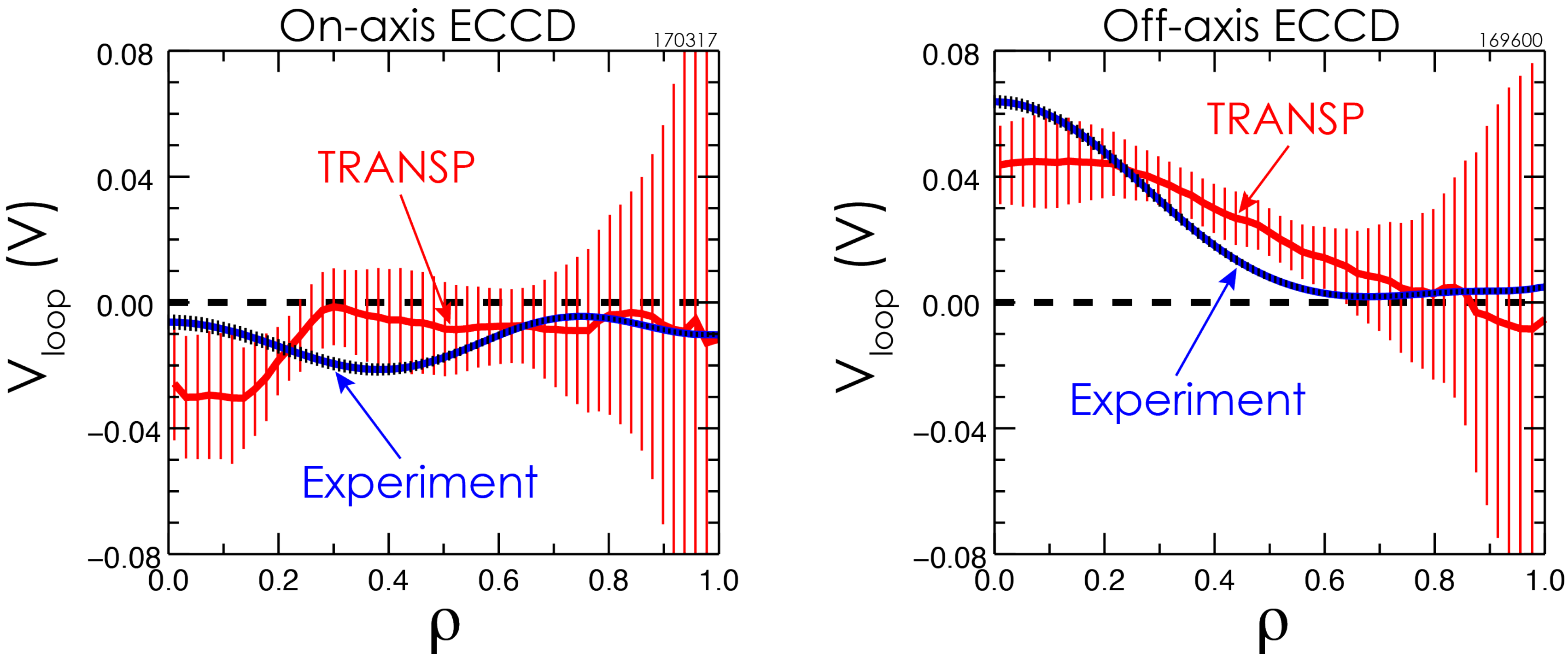


- **For ρ_{ec} = 0.45, experiment verifies non-inductive fraction drops to ≈87% due to decreased ECCD**



While Surface Loop Voltage is ≈ 0 for Off-Axis ECCD, This is not Indicative of 100% Non-Inductive Current

- **For ρ_{ec} = 0.20, measured V_{loop} profile is < 0 and flat, showing current profile is relaxed**
- **For ρ_{ec} = 0.45, measured V_{loop} profile is > 0 and peaked, showing current profile is still broadening**



Measured and modeled V_{loop} profiles are in good agreement for both cases

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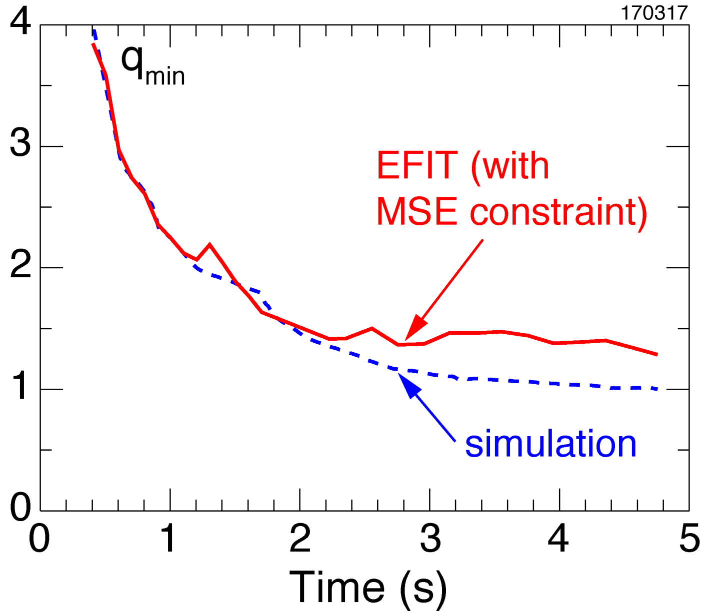
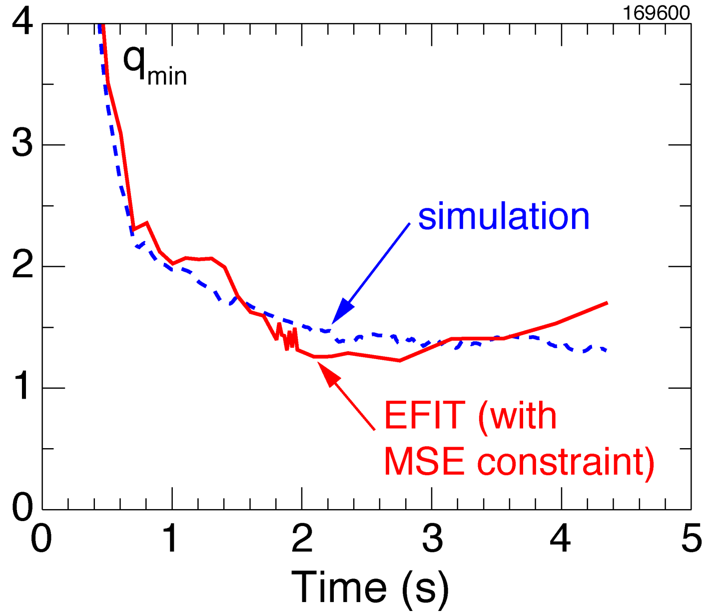
While Hybrids With Strong Off-Axis Current Drive Have a Broad Current Profile, It is not Anomalously So

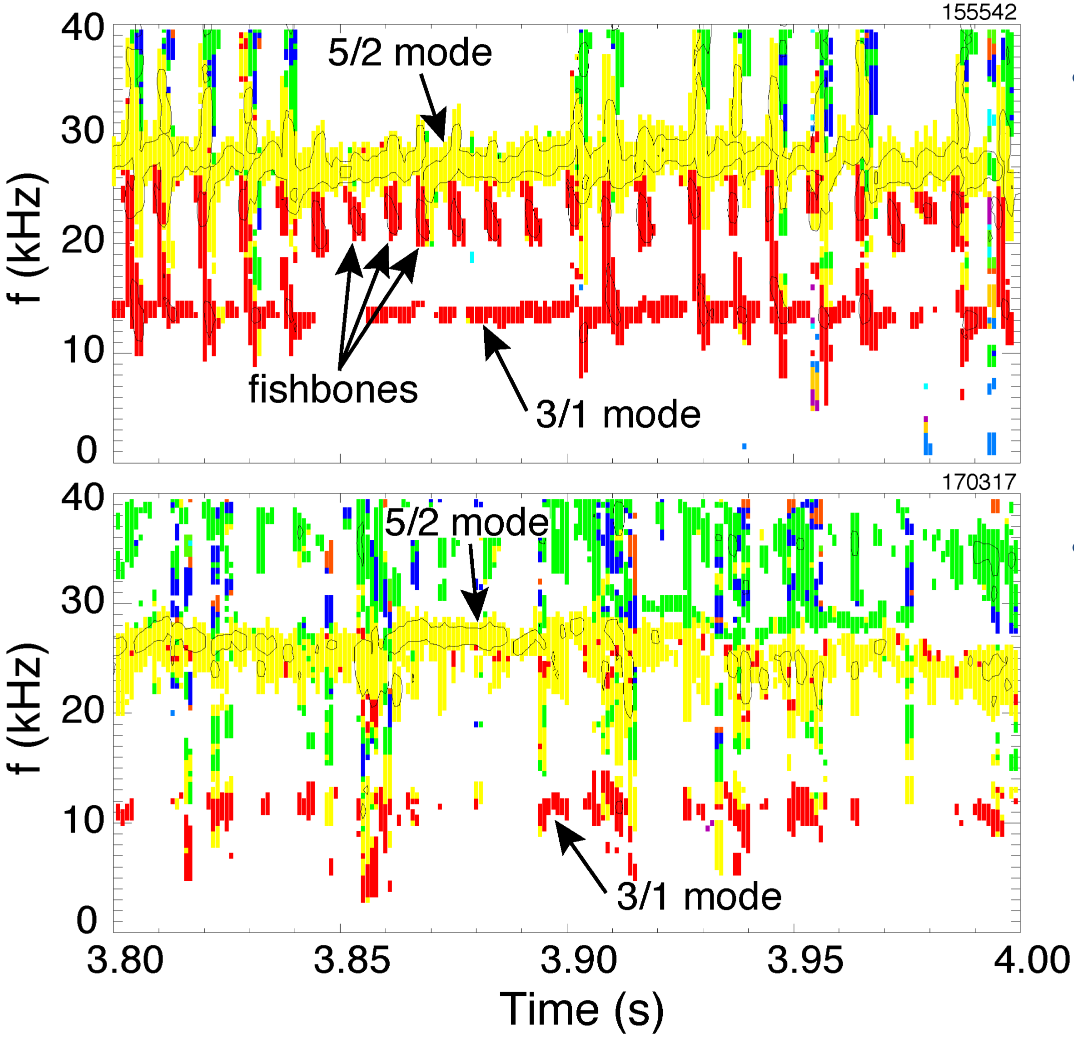
- **For ρ_{ec} = 0.20, current profile is anomalously broad compared to simulation (normal for hybrids)**
- **For ρ_{ec} = 0.45, measured and TRANSP simulated safety factor evolution are in agreement**





Strong off-axis current drive results in higher q_{min} than usual for hybrid scenario

Absence of Fishbone Instability Confirms High q_{min} Values (≈1.5) in Off-Axis ECCD Hybrids



- **Steady-state hybrids with on-axis ECCD and $q_{min} \approx 1$ generate strong fishbones**
- **New hybrid regime with off-axis current drive and $q_{min} \approx 1.5$ has no discernable fishbone activity**

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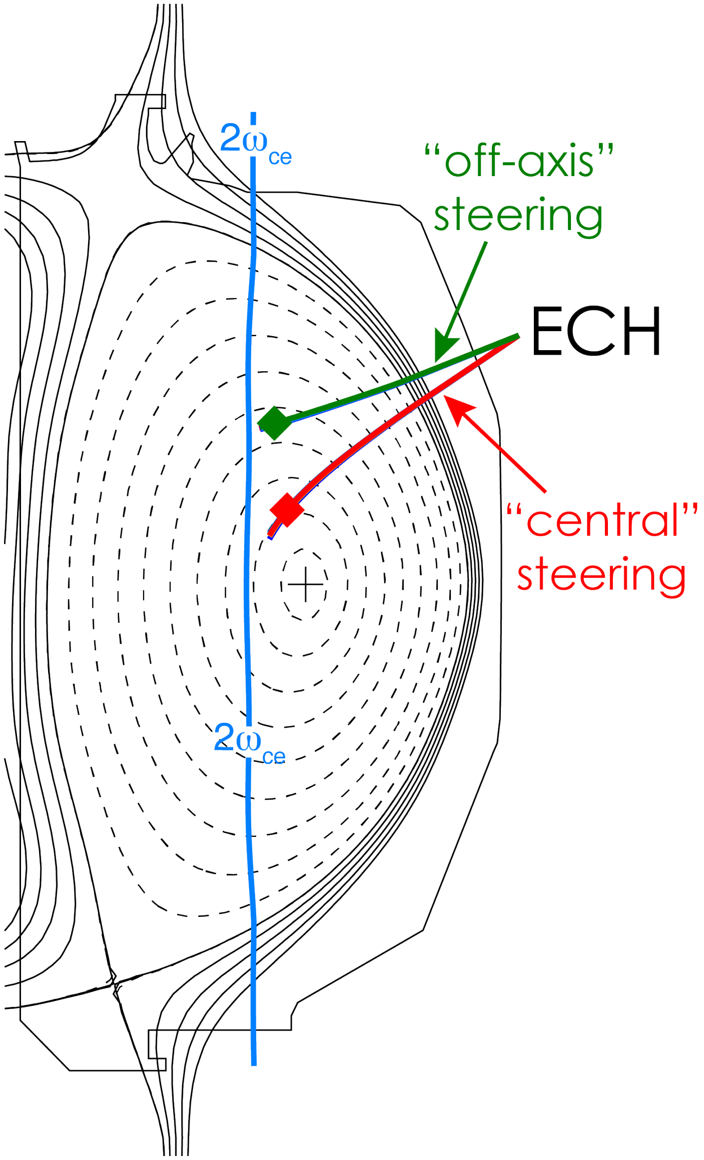
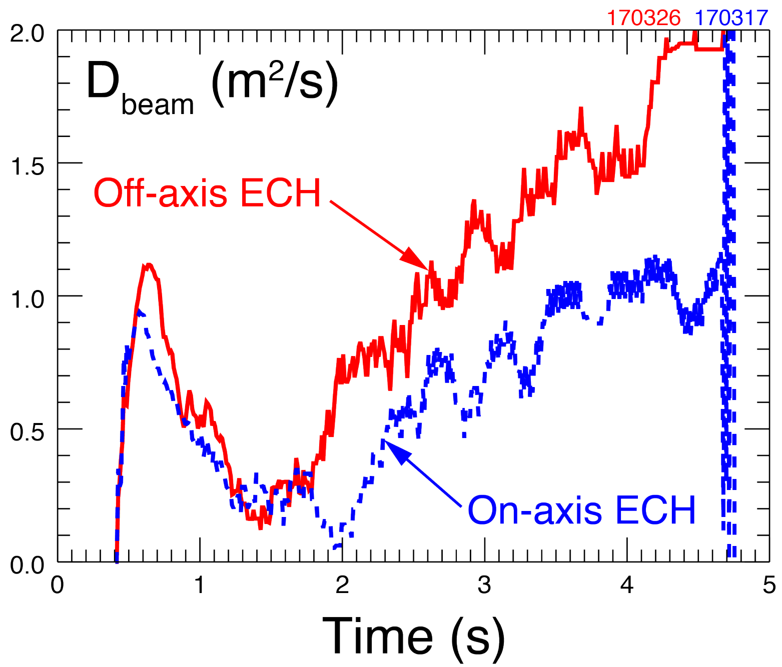
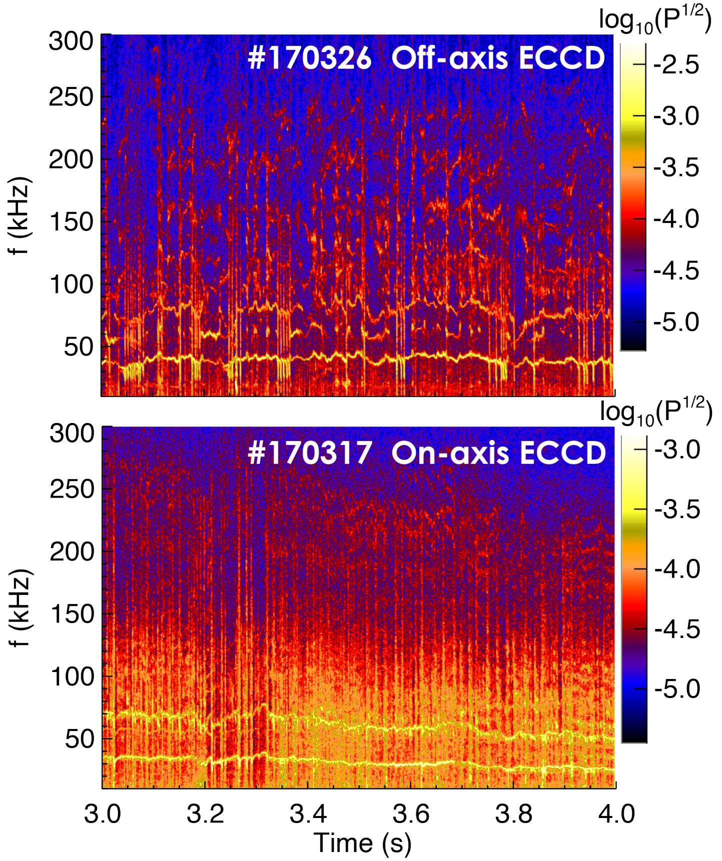


Alfvén Eigenmode (AE) Activity is Stronger in Hybrids With Off-Axis ECCD Compared to On-Axis ECCD

- **Anomalous beam ion diffusion, determined by matching experimental neutron rate, is larger for off-axis ECCD case**

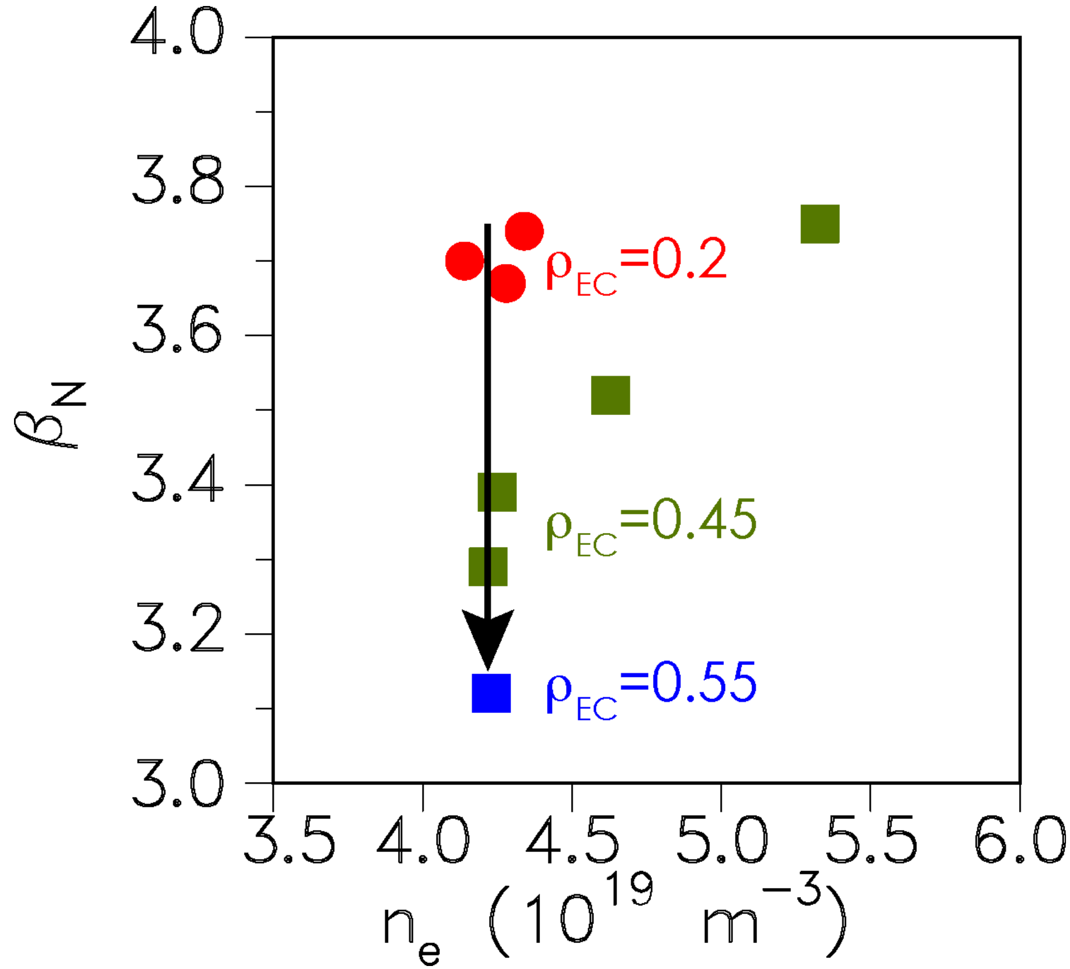


- **Larger D_{beam} for off-axis ECCD is consistent with stronger toroidal AE activity above 100 kHz**



For Fixed Heating Power and Density, Confinement and Beta Decrease as ECCD is Moved Off-Axis

- **Question is whether reduced β_N is due to change in local transport or decrease in heating effectiveness**



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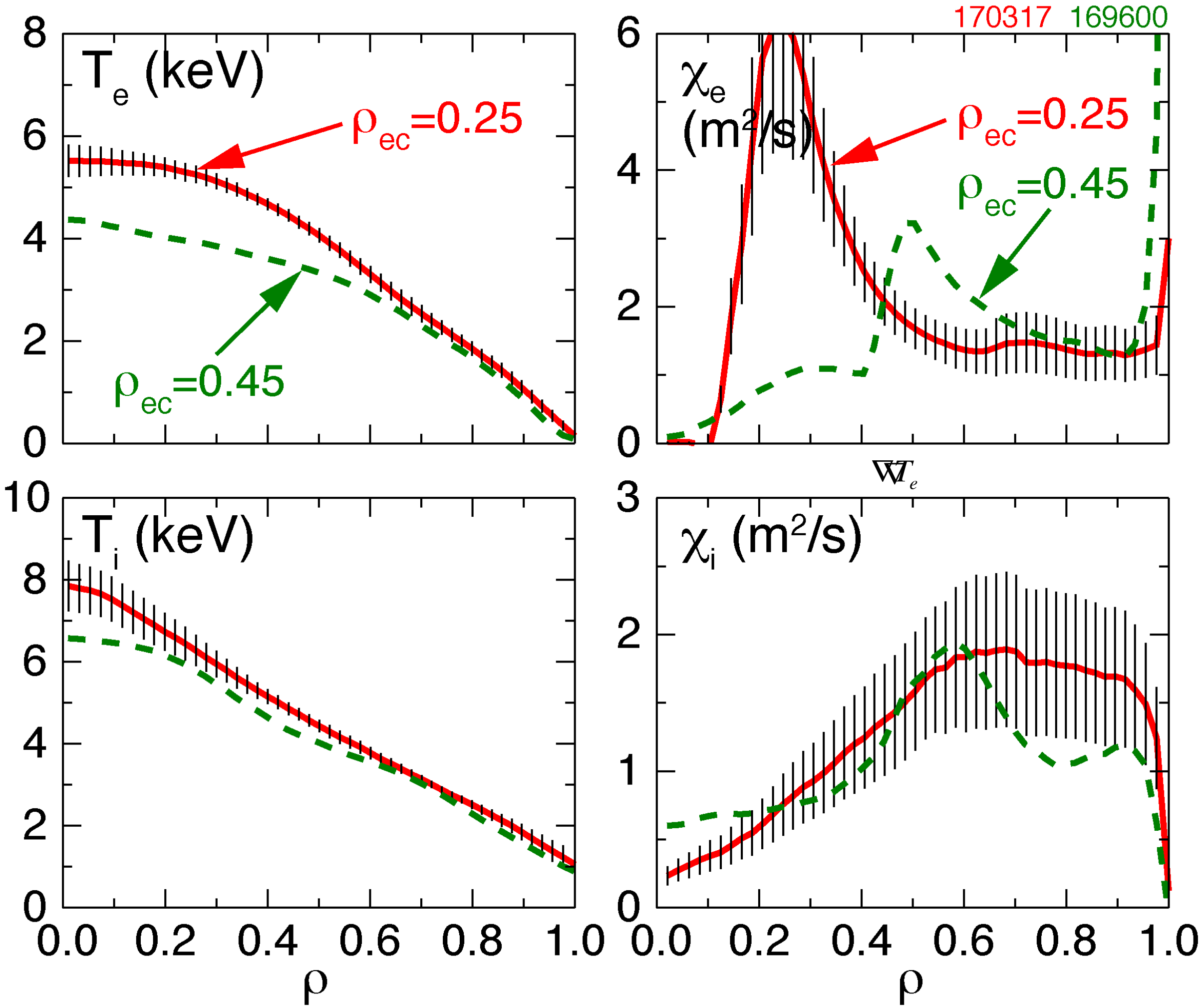
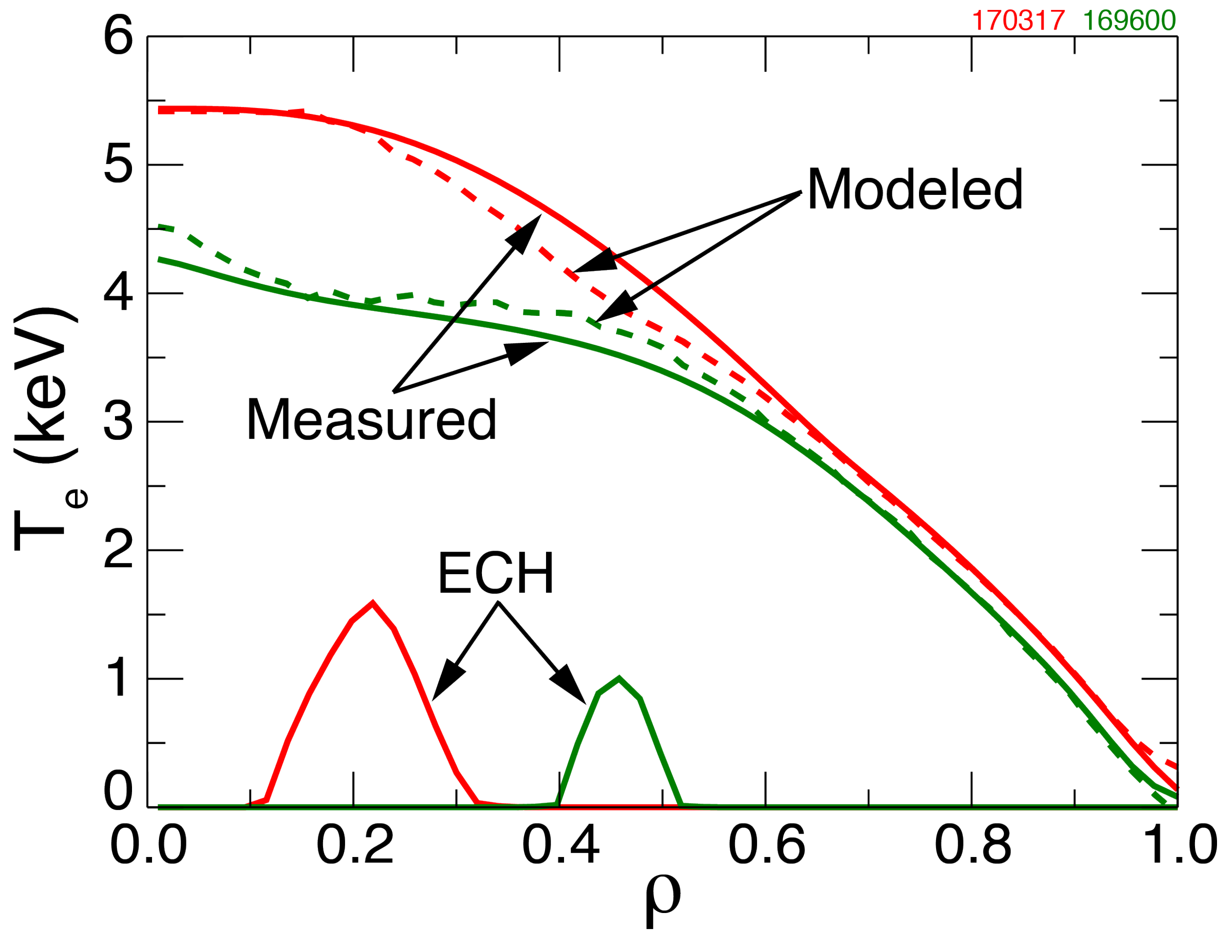
Electron Thermal Diffusivity Increases Near EC Deposition Location, But on Average χ_e Barely Changes



- **Ion thermal diffusivity slightly improves for off-axis ECCD case**
- **Main difference is lower ∇T_e inside EC deposition region**

Heat Flux Modeling Shows Lower T_e for Off-Axis ECH is Mainly Due to Reduced Heating Effectiveness



- **T_e profiles are determined by integrating TRANSP electron heat flux profiles using a fixed χ_e profile (average of both shots)**
- **Change in T_e profiles is well reproduced by simulations ➔ lower heating effectiveness, not transport, is dominant factor**

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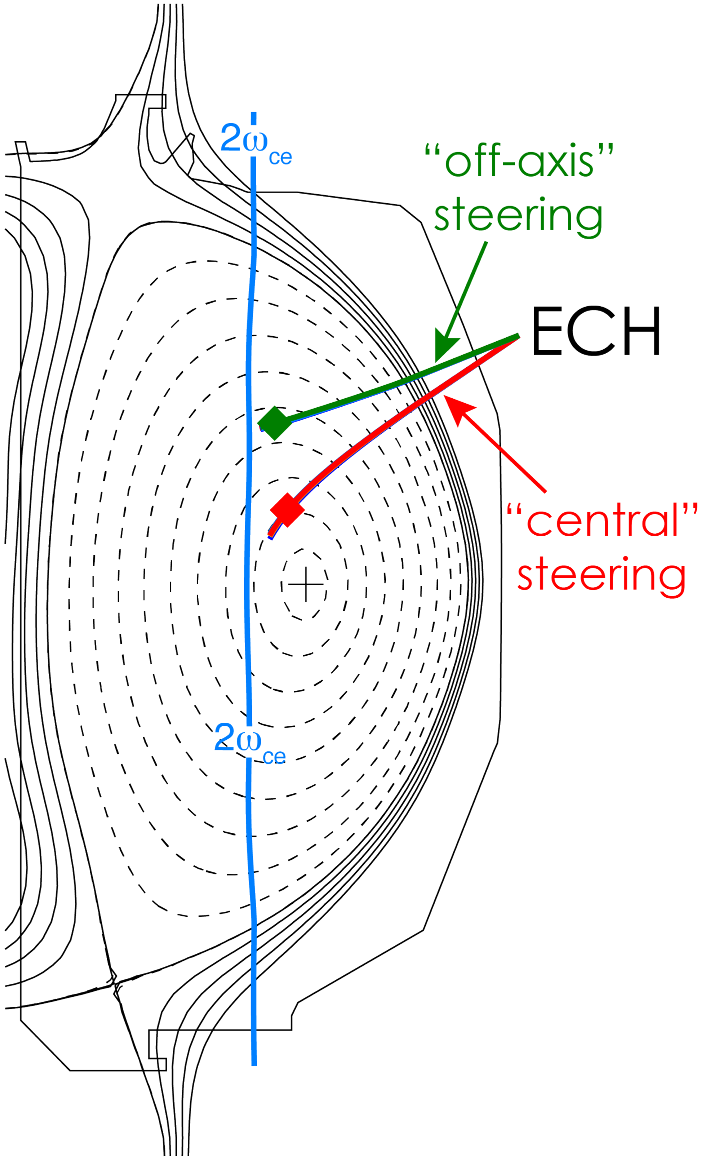
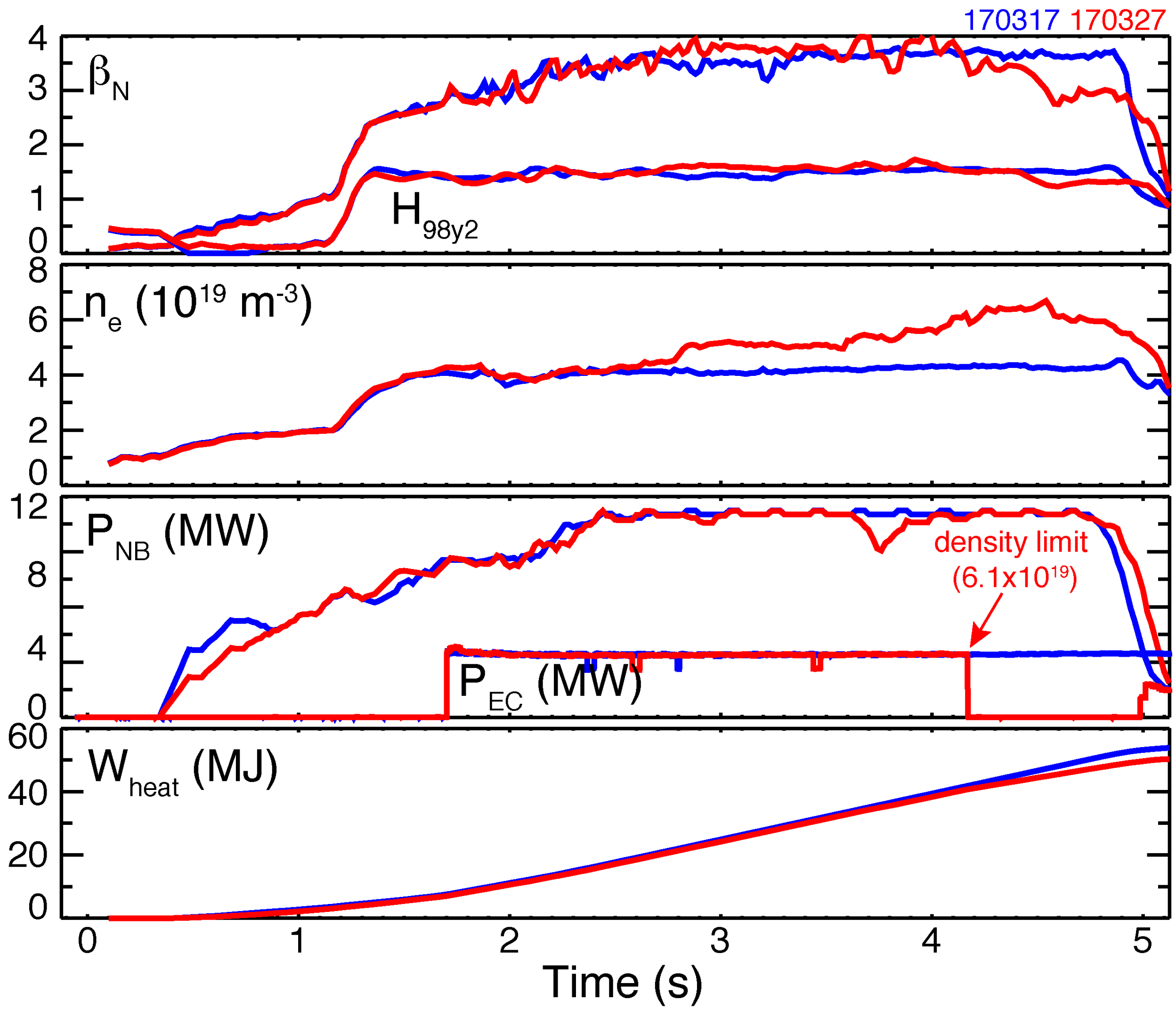


Higher Density is Explored to Raise Performance of High-Beta Hybrids With Off-Axis ECCD

- **ECH moved off-axis to ρ = 0.45 to raise density limit to ≈ 6.1×10^{19} m^{-3}**
- **High performance with β_N = 3.8 and H_{98y2} = 1.6 maintained until ECH turns off**
  - Note hybrids are far from steady-state for off-axis ECCD and high n_e
- **Total injected energy of up to 56 MJ achieved**



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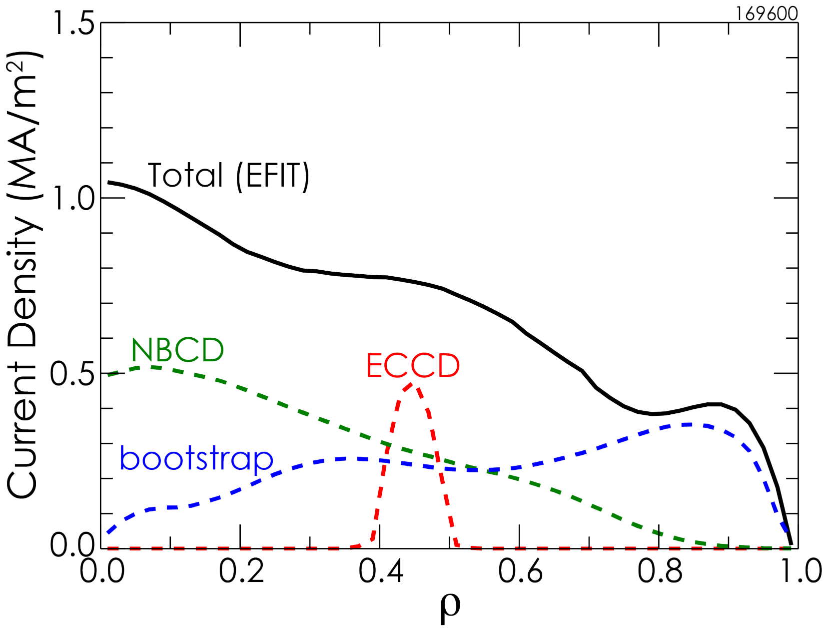
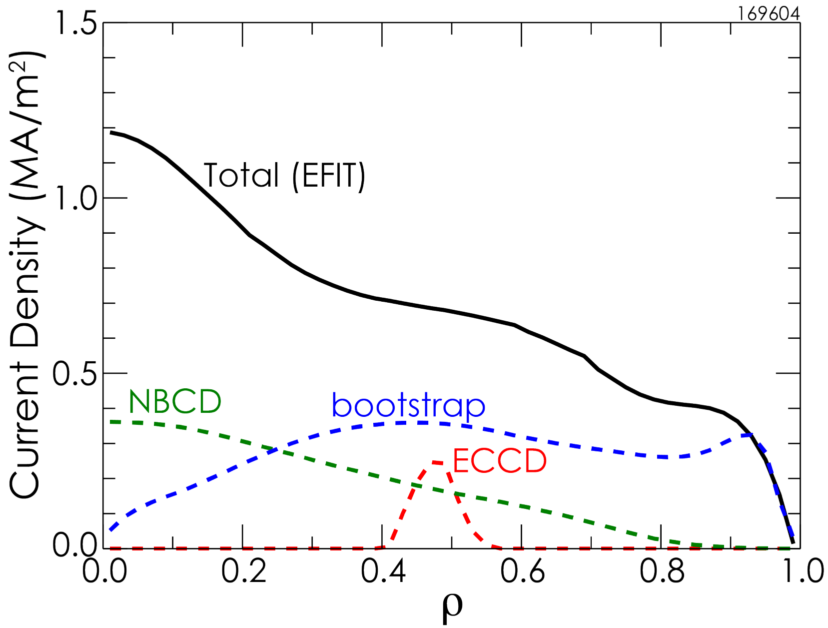
Hybrid Current Profile Becomes More Peaked at High Density Owing to Reduced External Current Drive

- **For $n_e = 4.4 \times 10^{19} m^{-3}$, calculated non-inductive current fraction is 87%**



- **For $n_e = 5.6 \times 10^{19} m^{-3}$, calculated non-inductive current fraction decreases to 75%**



Bootstrap current fraction is unchanged between low and high density hybrids

CC Petty/IAEA FEC/May 2021

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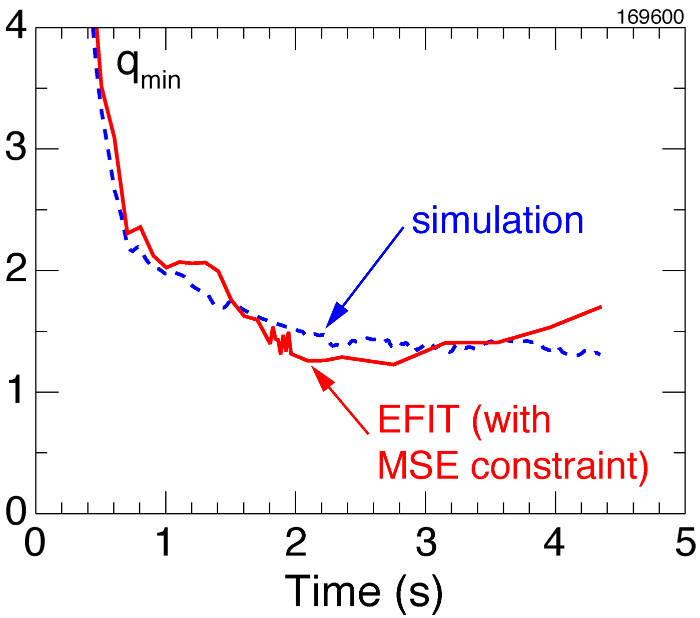
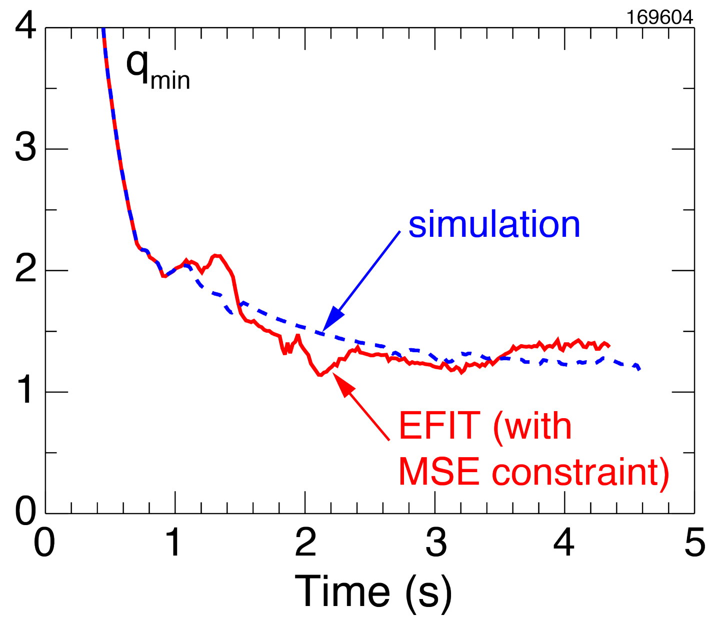
No Indication of Anomalous Current Profile Evolution of Off-Axis ECCD Hybrids at Either Low or High Densities

- **For $n_e = 4.4 \times 10^{19} m^{-3}$, measured and TRANSP simulated safety factor evolution are in agreement**



- **For $n_e = 5.6 \times 10^{19} m^{-3}$, both measurement and simulation show q_{min} decreases by ≈ 0.15**



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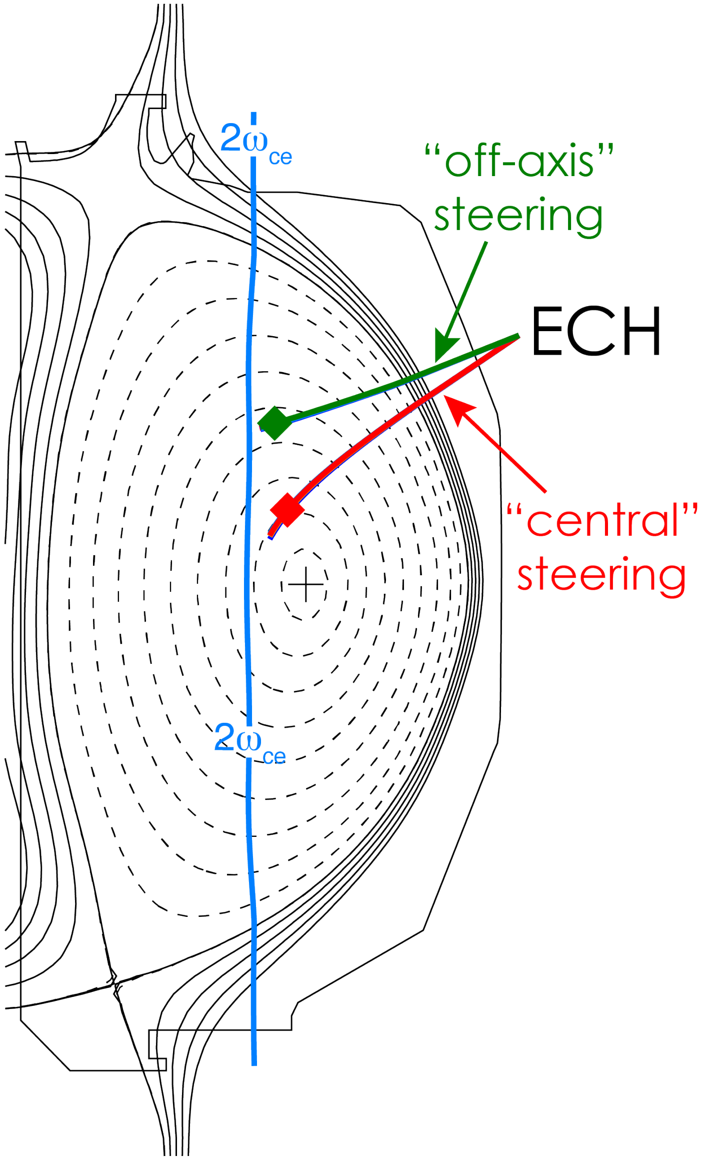
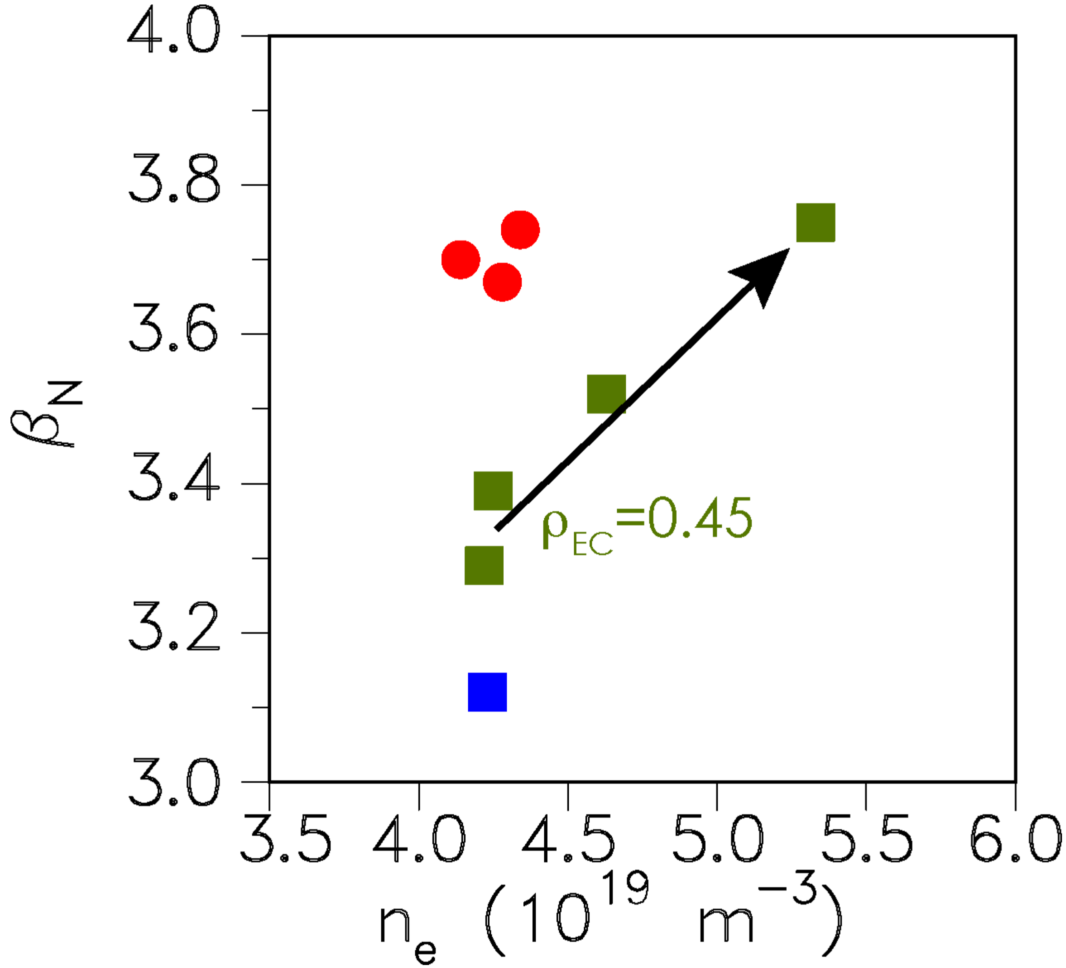


For Fixed Heating Power, Higher Confinement and Beta Achieved by Increasing Density With Gas Puffing

- **Question is whether higher β_N is due to change in beam ion diffusion, core heat transport or pedestal height**



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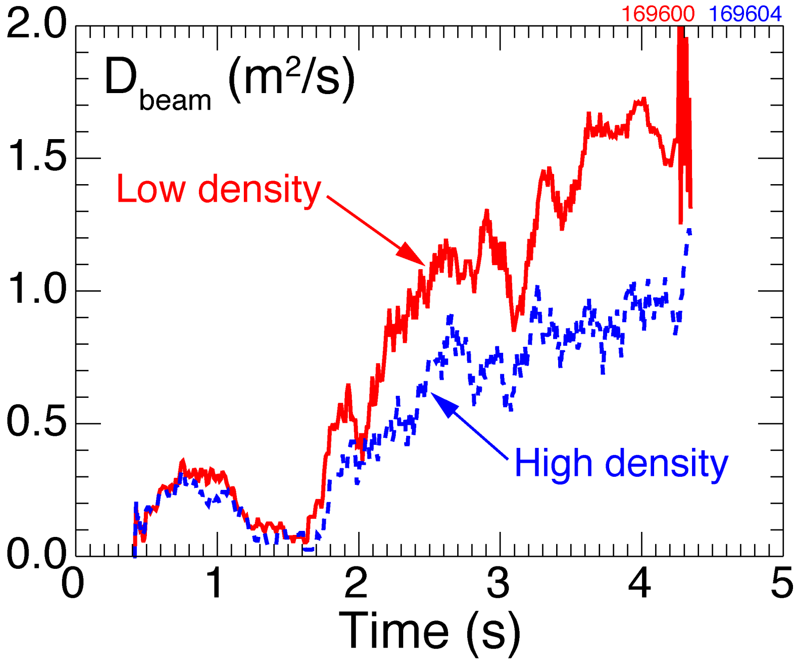
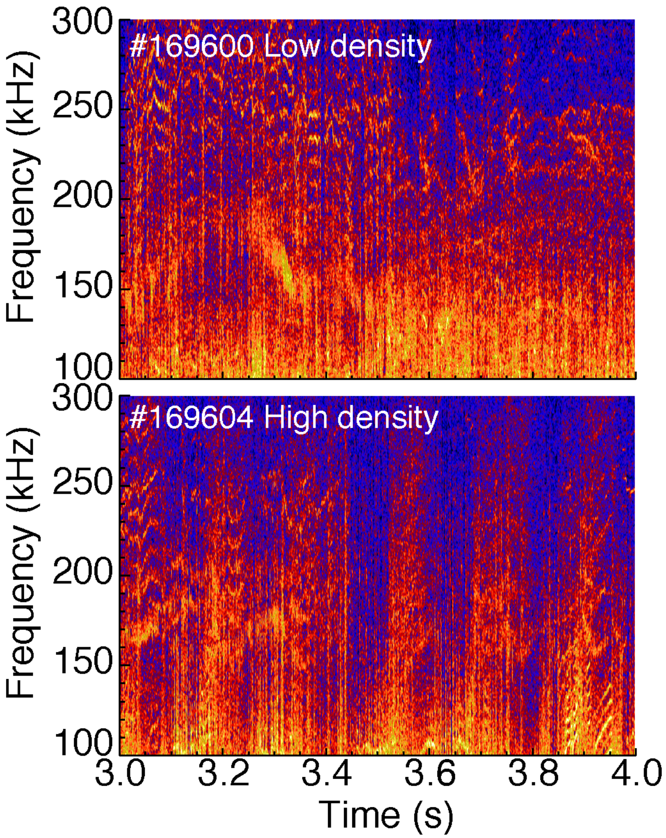
About Half of Confinement Improvement at Higher Density is Due to Reduced Beam Ion Transport

- **Anomalous beam ion diffusion is deduced by matching experimental neutron rate**

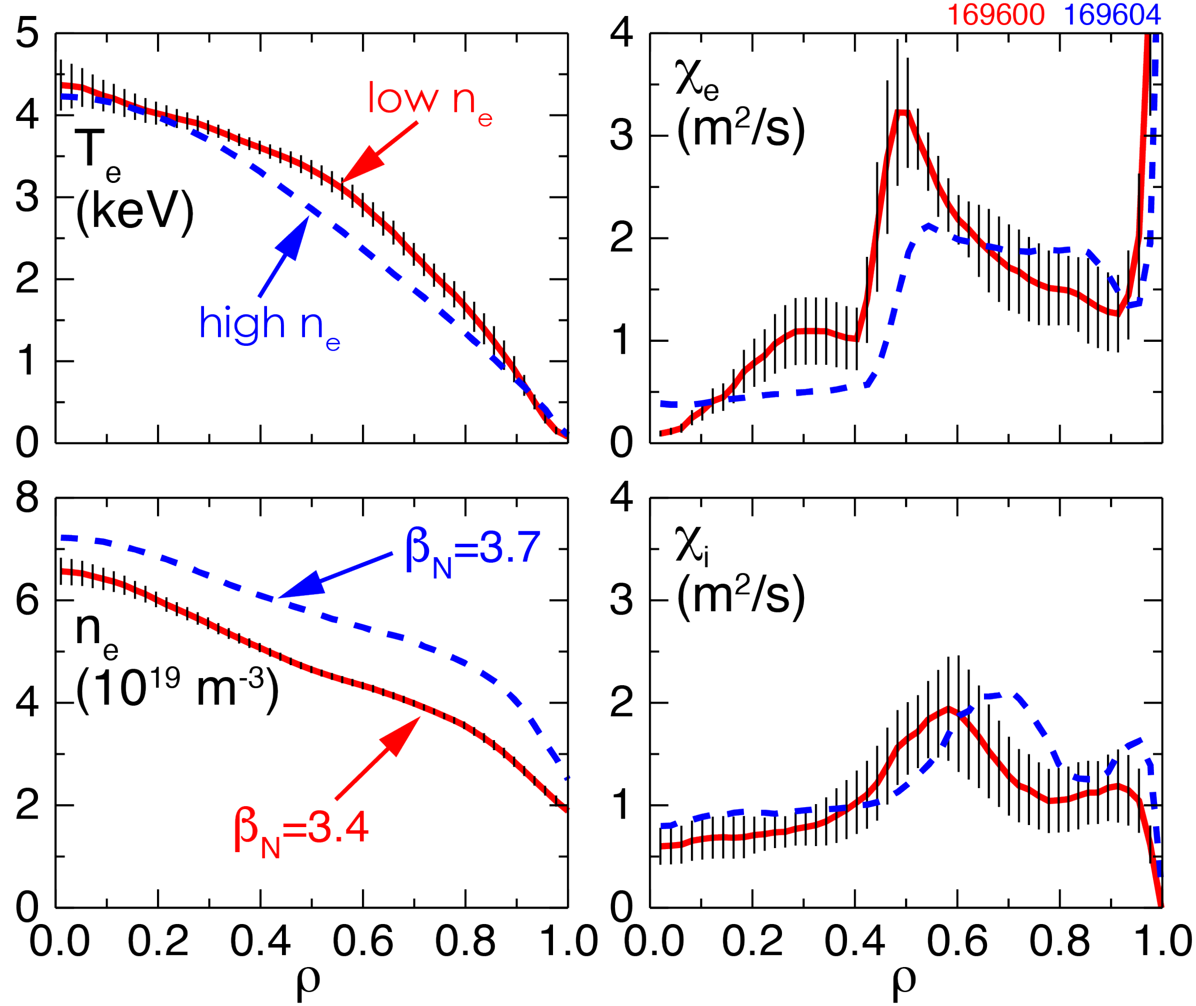


- **Lower D_{beam} at higher n_e is consistent with weaker toroidal Alfvén eigenmode activity**



Remaining Confinement Improvement at Higher Density is Due to Lower Electron Thermal Transport

- **Electron thermal diffusivity is ≈ 30% smaller for higher n_e case**
- **Ion thermal diffusivity has opposite behavior, i.e., slightly larger (< 10%) for higher n_e case**



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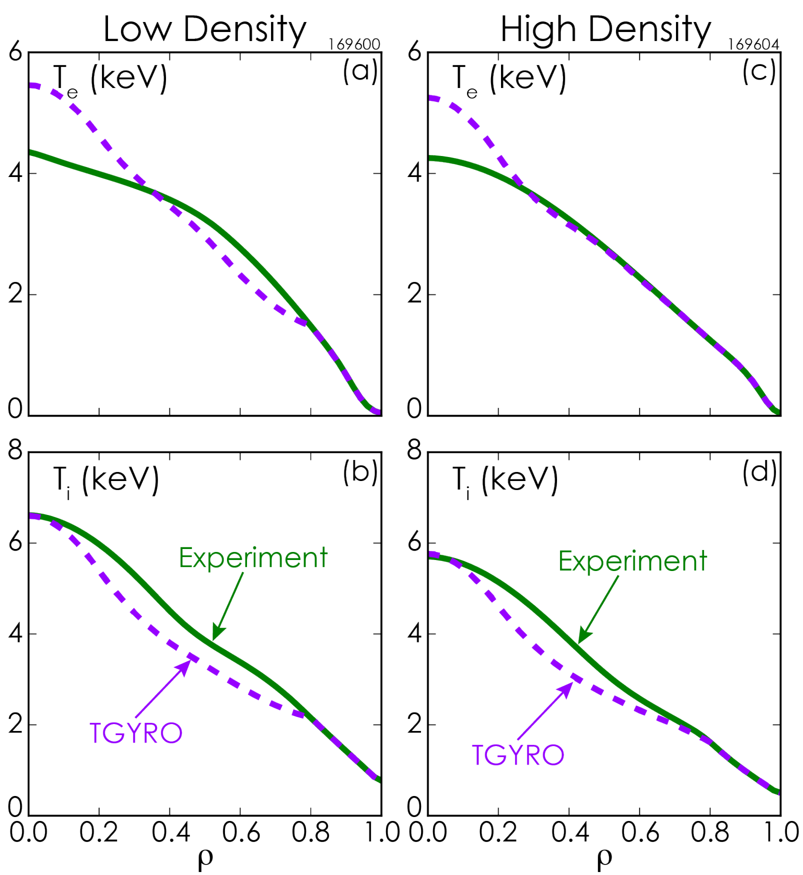
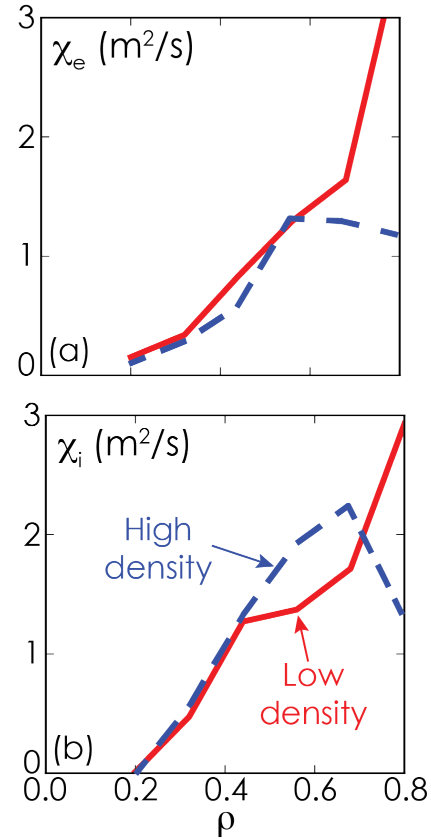
Flux-Matched TGYRO Simulations of Thermal Transport Exhibit Same Trends as Experiment Over Density Scan

- **TGLF + NEO transport modeling with fixed density and rotation profiles**

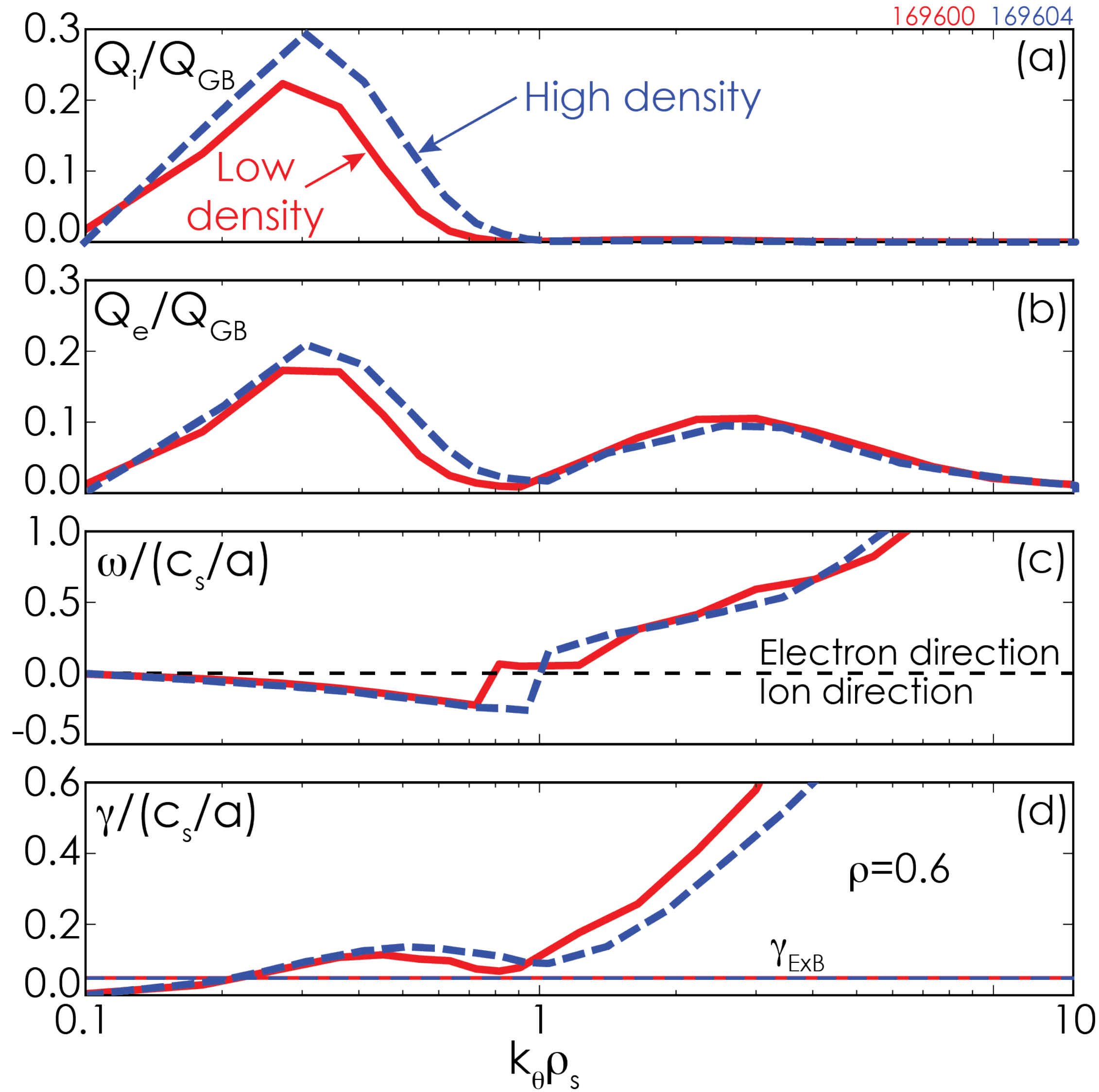


- **Modeled decrease in χ_e and increase in χ_i with density is in same direction as experiment**



Linear Stability Modeling Shows ITG Mode Strengthens With Higher Density, Offset by Weakening of TEM and ETG Mode

- **Ion turbulent energy flux resides at low wavenumber for all simulations**
- **Low and high wave-numbers both contri-bute to electron tur-bulent energy flux**
- **High-*k* electron energy flux is 46% at low density, decreas-ing to 39% at high density**



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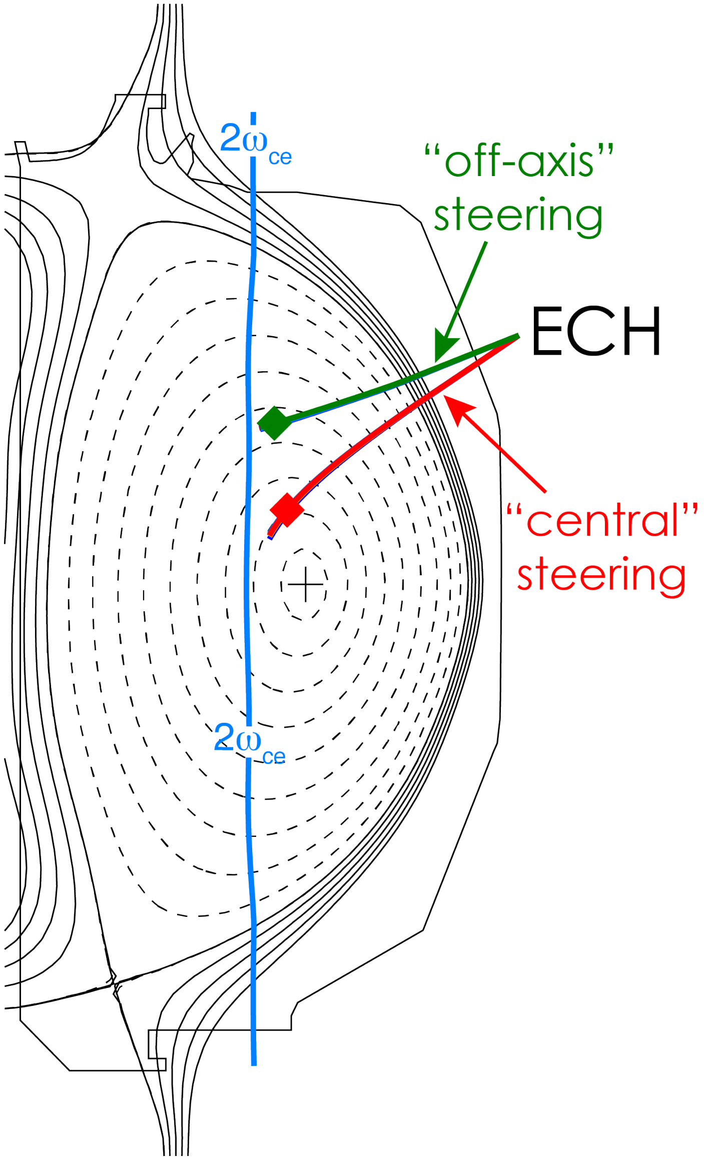
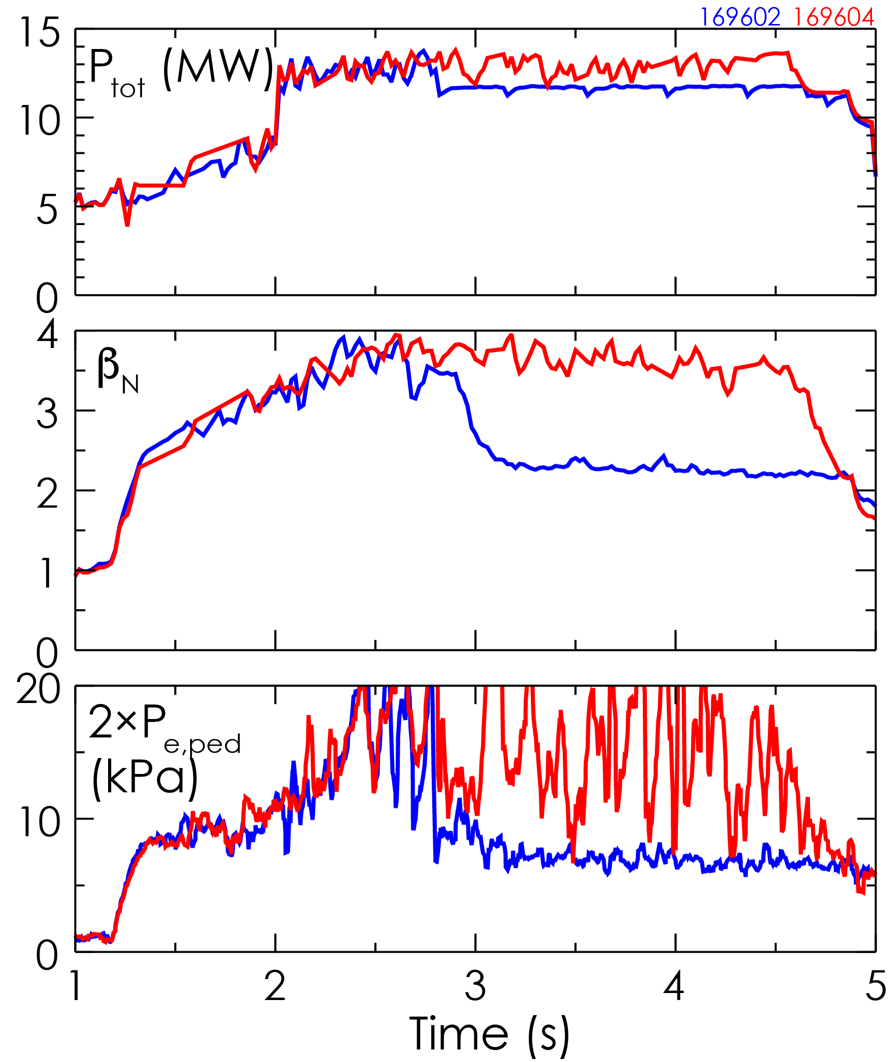


Increase in Confinement and Beta With Higher Density Only Occurs Above a Threshold Heating Power

- **In high density hybrids with off-axis ECCD, drop of ≈ 10% in total heating power results in ≈ 35% drop in stored energy**
- **Decrease in stored energy & confinement time is slightly proceded (≈ 0.1 s) by collapse in H-mode pedestal**
- **This sensitivity to heating power is typically not seen in low density hybrids**



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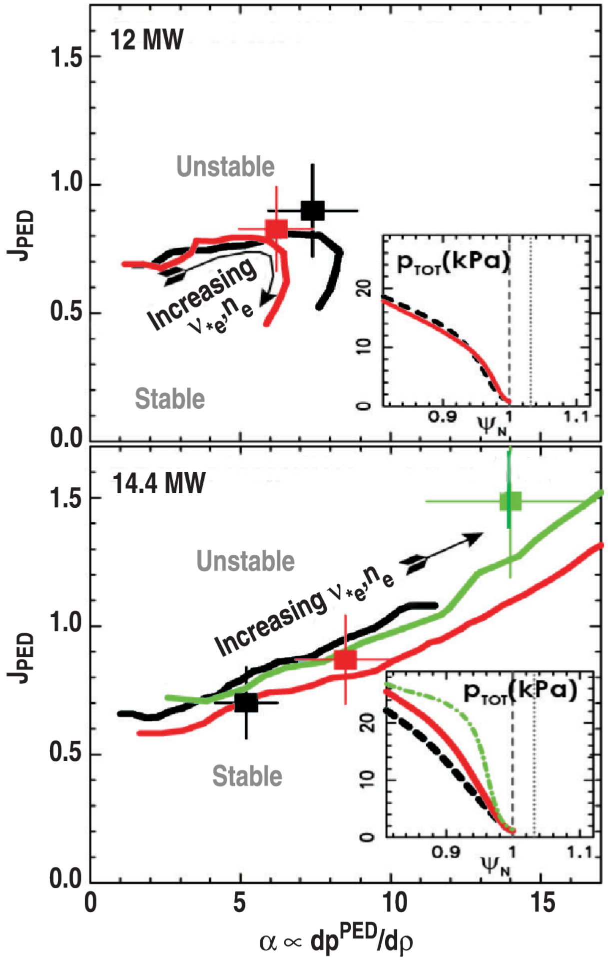
Collapse in Pedestal Height With Lower Heating Power may be Due to Decreased Peeling-Ballooning Stability

T.W. Petrie et al. (2017) Nucl. Fusion 086004

Lower Power

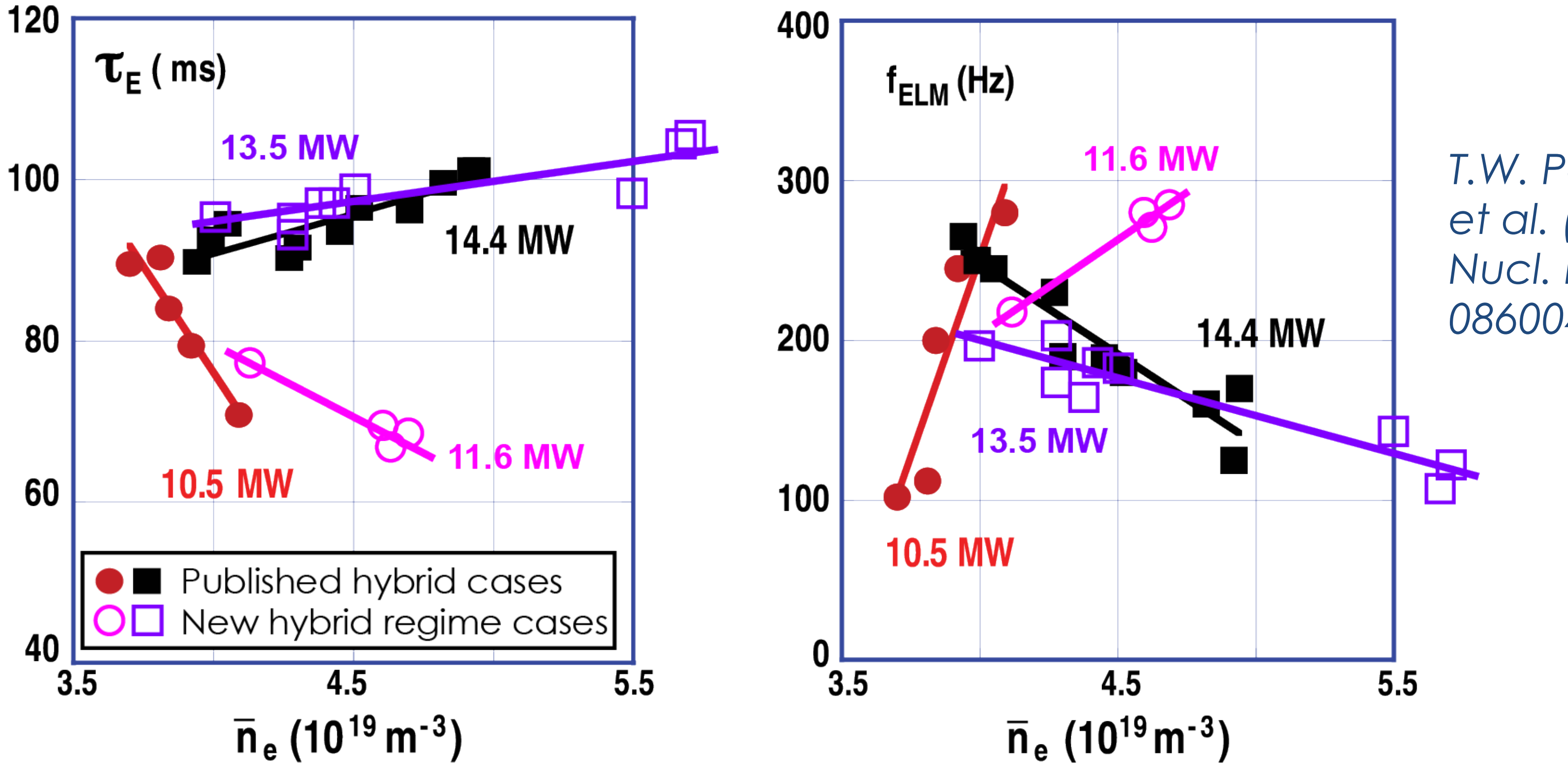
Higher Power



- **Previously published ELITE simulations for hybrids with central ECCD predict heating power threshold for opening a path between the peeling and ballooning stability limits**
- **Improved pedestal stability along peeling branch allows higher pedestal pressure (and higher confinement) with higher density**

Phenomenology of Off-Axis ECCD Hybrid Regime Shows Similar Power Threshold in Pedestal Stability

- **Trends in confinement time and ELM frequency with density and heating power are same in new and old hybrid regimes**

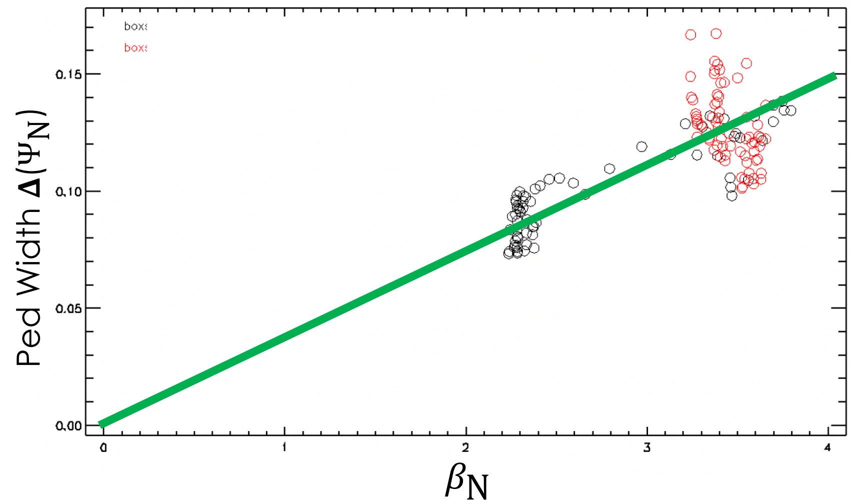


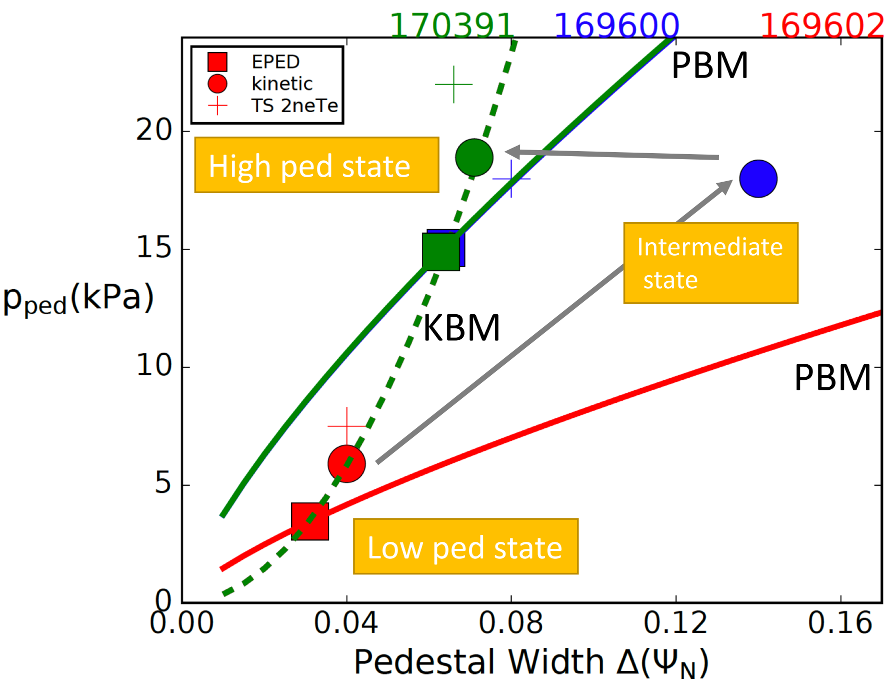
T.W. Petrie et al. (2017) Nucl. Fusion 086004

Pedestal bifurcation occurs over a narrow power window

Hypothesis is Bifurcation Between P-B Stability Limits at High Power and Gas Puffing Stabilizes Low-n Modes & Allows Pedestal Pressure to Increase With Density Along Peeling Branch

- **Measured pedestal width increases linearly with beta (~Shafranov shift)**





- **For low power case (169602), pedestal height and width agree with EPED1 prediction**
- **With more power (169600) the higher pedestal height and width don't agree with EPED1 prediction – this is termed an intermediate state**
- **At highest power (170391), pedestal height and width again agree with EPED1 with $\beta_N = 3.9$ and $H_{98y2} = 1.6$**

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Summary of New Hybrid Regime Using Off-Axis ECCD

- **Using steady-state hybrid scenario as a target, high-density, high-β plasmas were successfully created using off-axis ECCD**
  - Achieved $\beta_N = 3.9$ and $H_{98y2} = 1.6$
- **Strong off-axis current drive results in naturally broad current profiles ($q_{min} \approx 1.5$) without poloidal flux pumping – a new type of hybrid scenario**
- **Moving ECCD from $\rho \lesssim 0.2$ to $\rho = 0.45$ reduces its heating effectiveness, but higher density operation recovers loss of confinement**
  - Reduced fast ion & electron thermal transport
  - Higher pedestal height with higher density when kink-peeling stability branch is accessed at high power