Advances in Steady-State Hybrid Regime in DIII-D – A Fully-Noninductive, ELM-Suppressed Scenario for ITER

by

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In collaboration with

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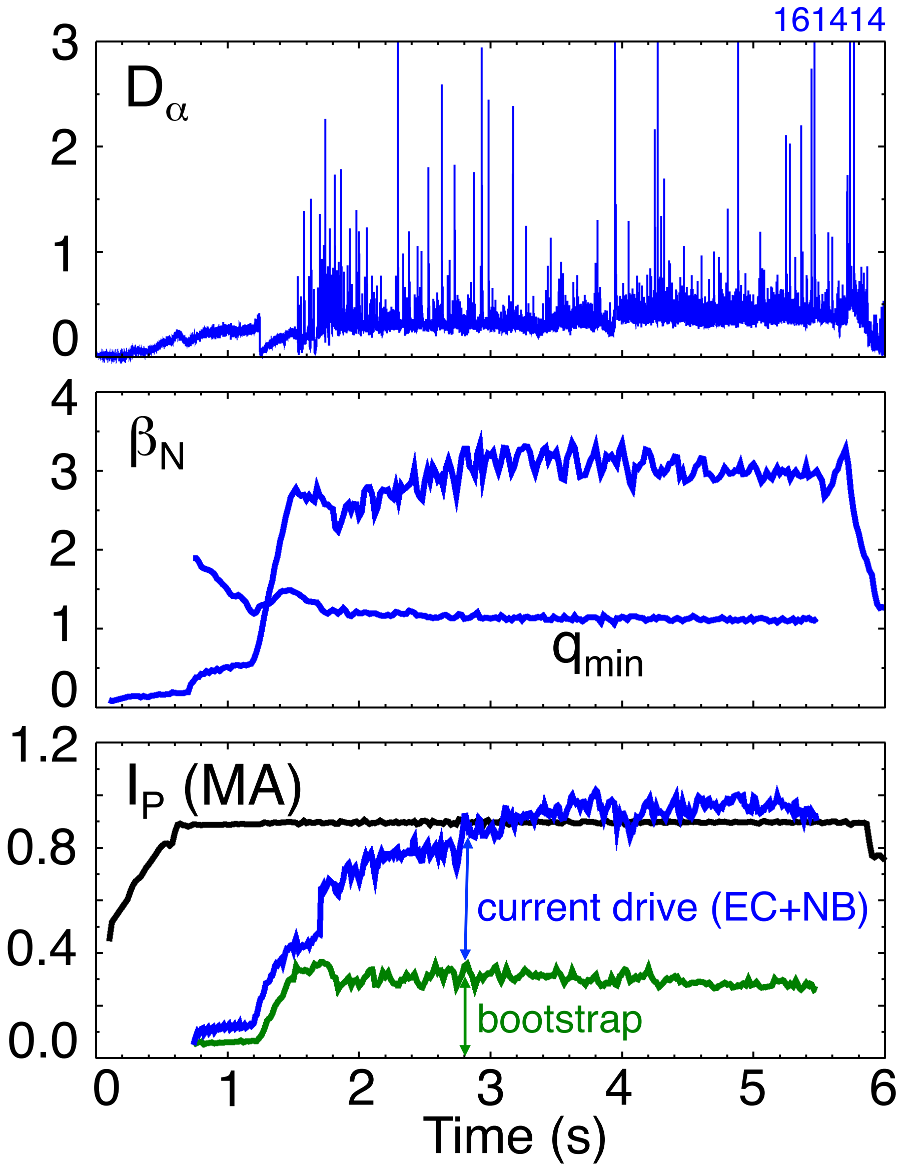
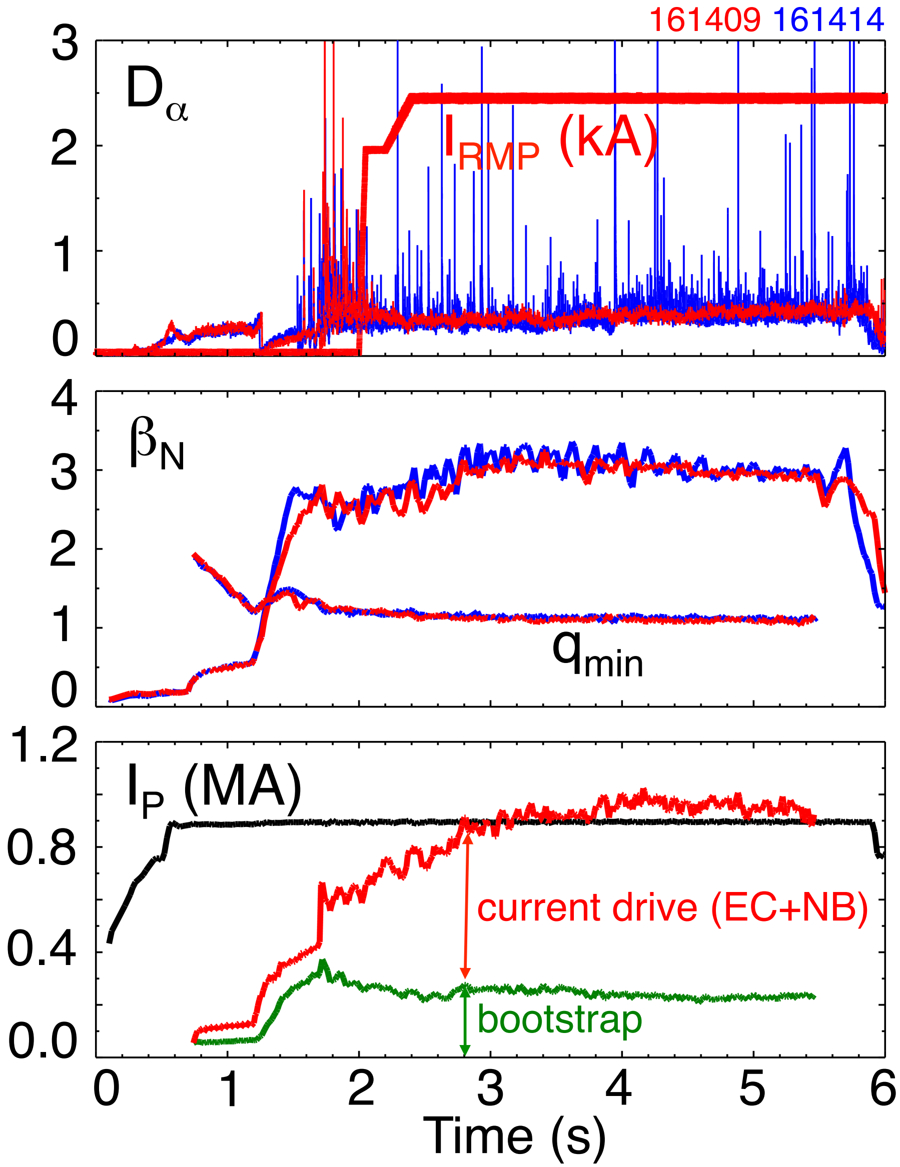
Experiments in DIII-D Have Coupled ELM Suppression With High-β, Fully Noninductive Scenario for First Time

- **Goal is to develop a regime that extrapolates to steady-state mission (Q_{fus} = 5) for ITER**



Experiments in DIII-D Have Coupled ELM Suppression With High-β, Fully Noninductive Scenario for First Time

- **Goal is to develop a regime that extrapolates to steady-state mission (Q_{fus} = 5) for ITER**
  - ELM suppression using resonant magnetic perturbations (RMP)
  - Integration of high-β hybrid scenario with Argon radiating divertor



Outline

I. Characteristics of Steady-State Hybrids

II. Integration With RMP ELM Suppression

III. Impurities and Radiating Divertor

IV. Extrapolation to ITER Steady-State

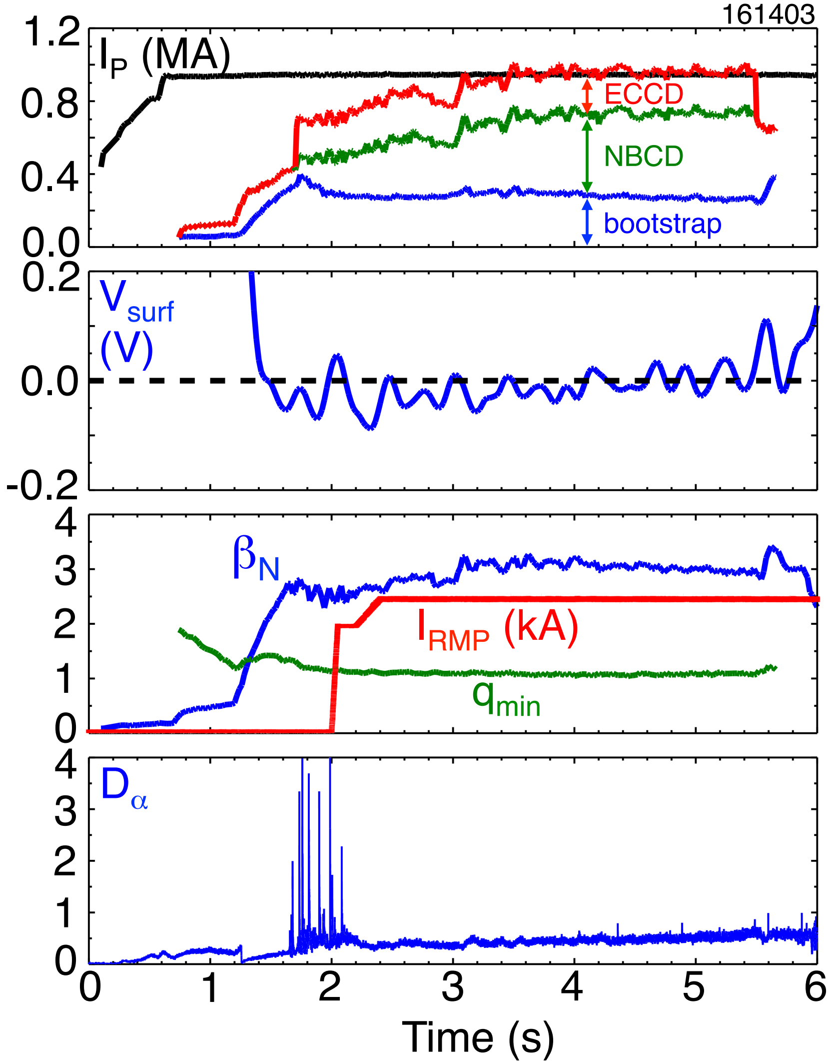
V. Summary

What is a “Hybrid”? – Low q_{min} Scenario With High Stability, Excellent Confinement and Good Stationarity

- **Self-organized current profile with $q_{min} \gtrsim 1$**
- **An n = 2 or n = 3 tearing mode is present**
- **Beta can exceed ideal (n = 1) no-wall limit**
- **Pulse length in DIII-D limited only by NBI duration**

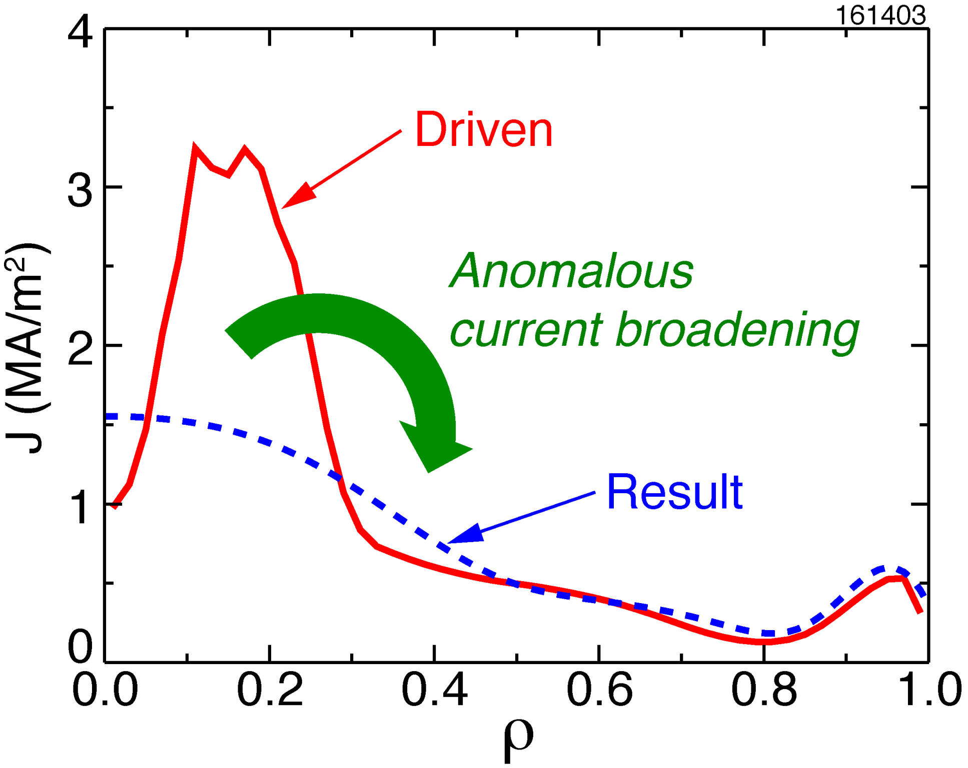
H_{98y2}	1.2
q_{95}	6.6
β_P	1.9
β_T	2.5 %

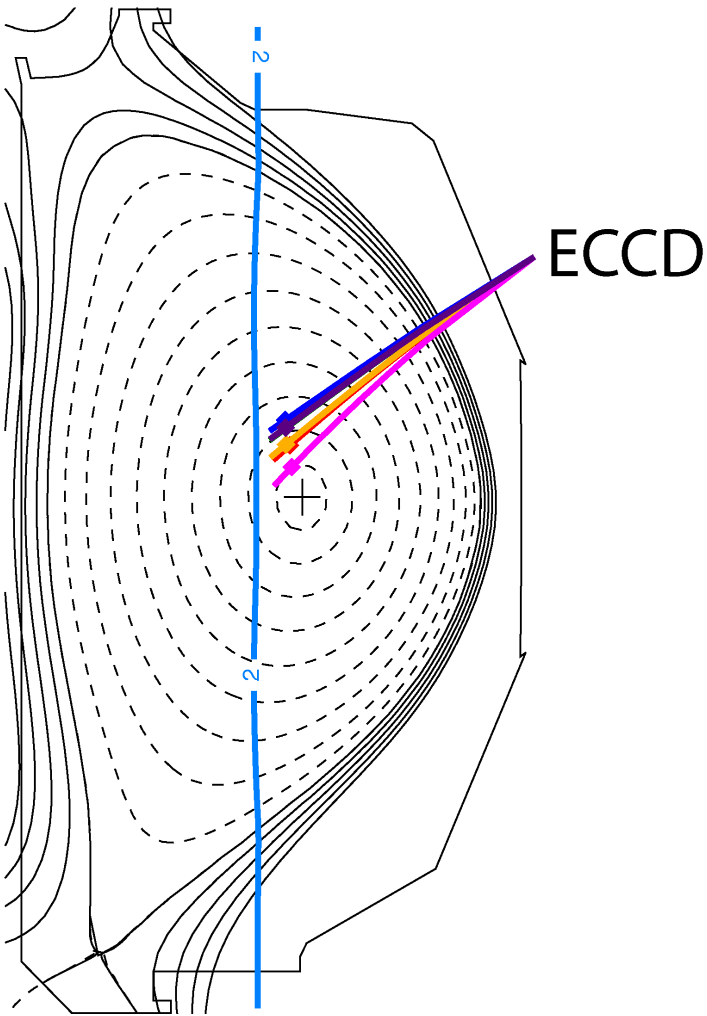
P_{NB}=9.9 MW, P_{EC}=3.5 MW



Current Profile Alignment is Not Needed in Hybrids Owing to Flux Pumping from Tearing Modes

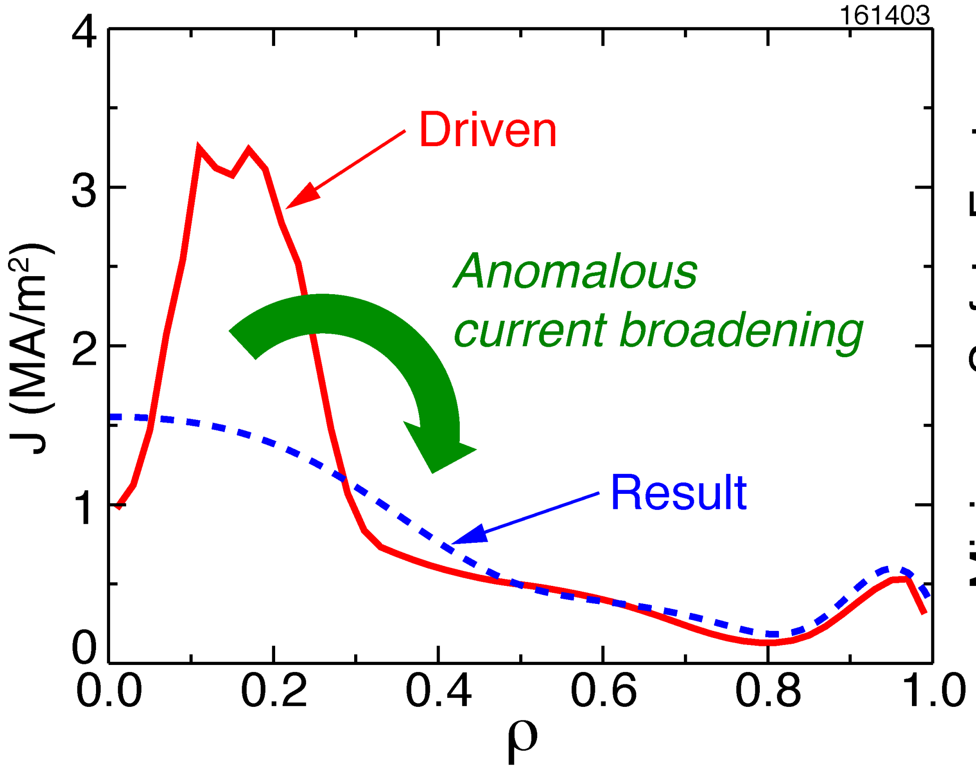
- **Self-organized current profile “ignores” peaked current drive ➔ high CD efficiency maintained**

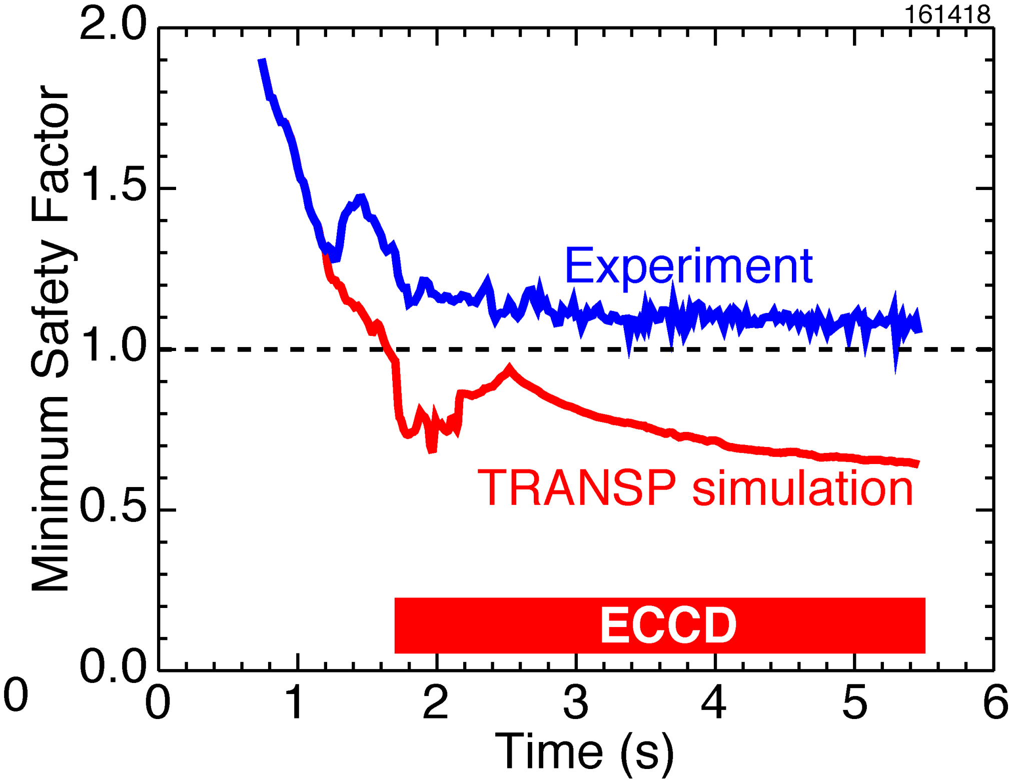




Current Profile Alignment is Not Needed in Hybrids Owing to Flux Pumping from Tearing Modes

- **Self-organized current profile “ignores” peaked current drive ➔ high CD efficiency maintained**
- **TRANSP modeling confirms current profile is anomalously broad ➔ q_{min} should drop well below 1**





“Flux pumping” physics discussed in EX/1-1 by P. Piovesan

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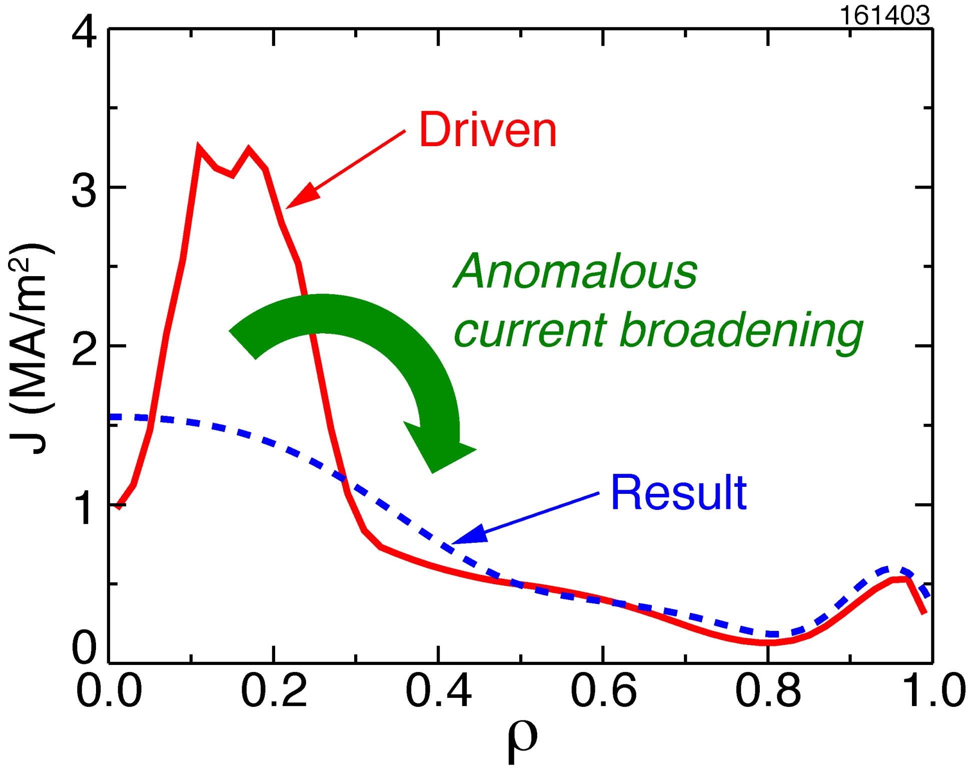
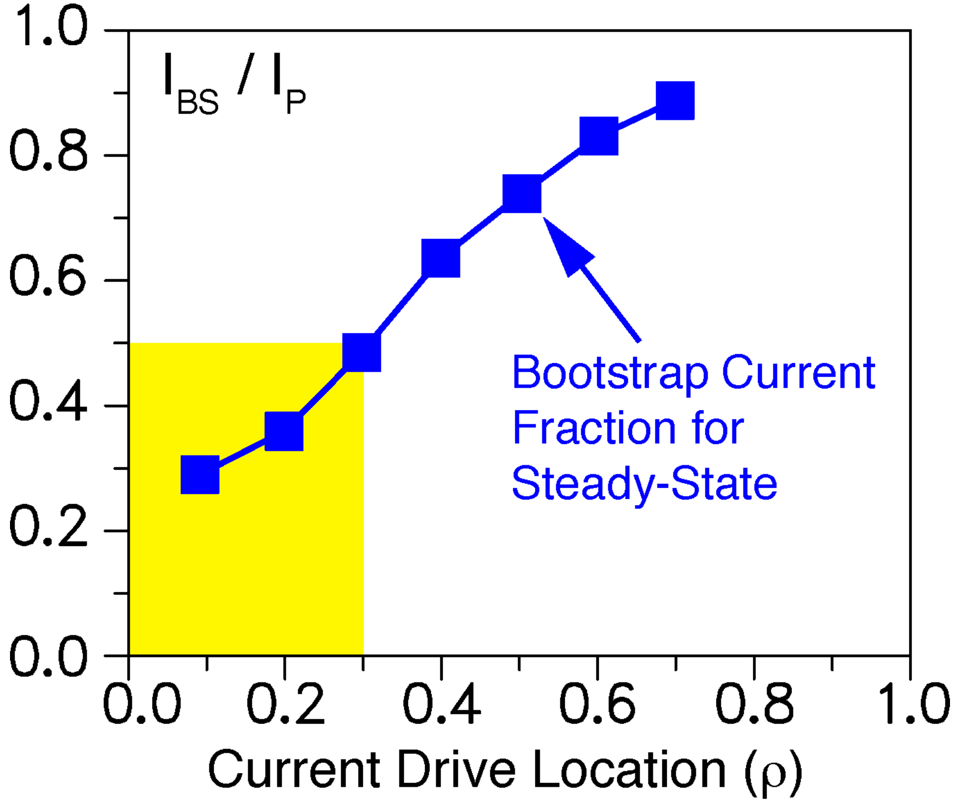


- **High CD efficiency allows 100% noninductive operation at modest bootstrap current fraction**



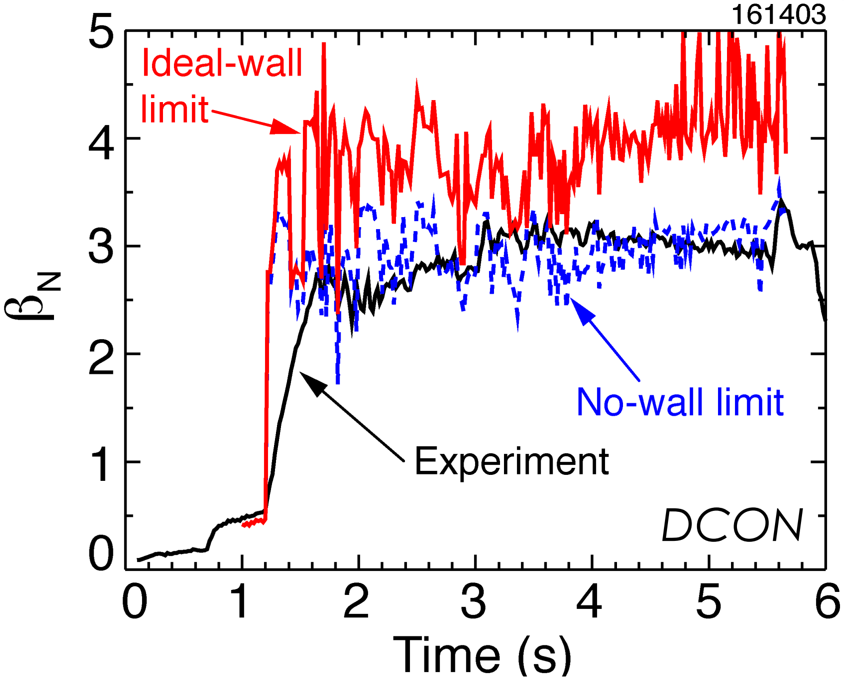
Experimental β_N can Reach 80–90% of Calculated Ideal-Wall n=1 Limit

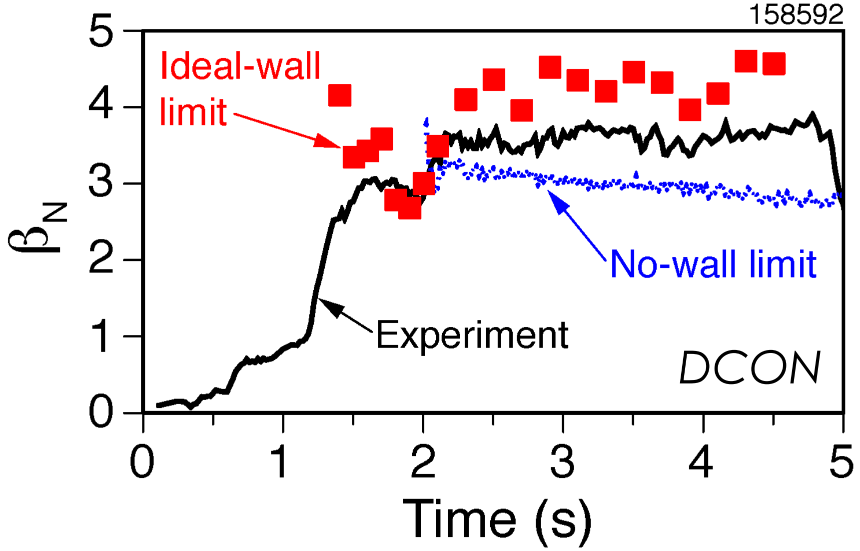
- **Hybrids with RMP ELM-suppression and *ITER similar shape* reach ideal no-wall limit**

> ***Aim for β_N ~ 4 in the future***

- **With higher confinement (H_{98y2} = 1.6) in *DND plasma shape*, steady-state hybrids achieve β_N/ℓ_i=4.9**

F. Turco, Phys. Plasmas 2015





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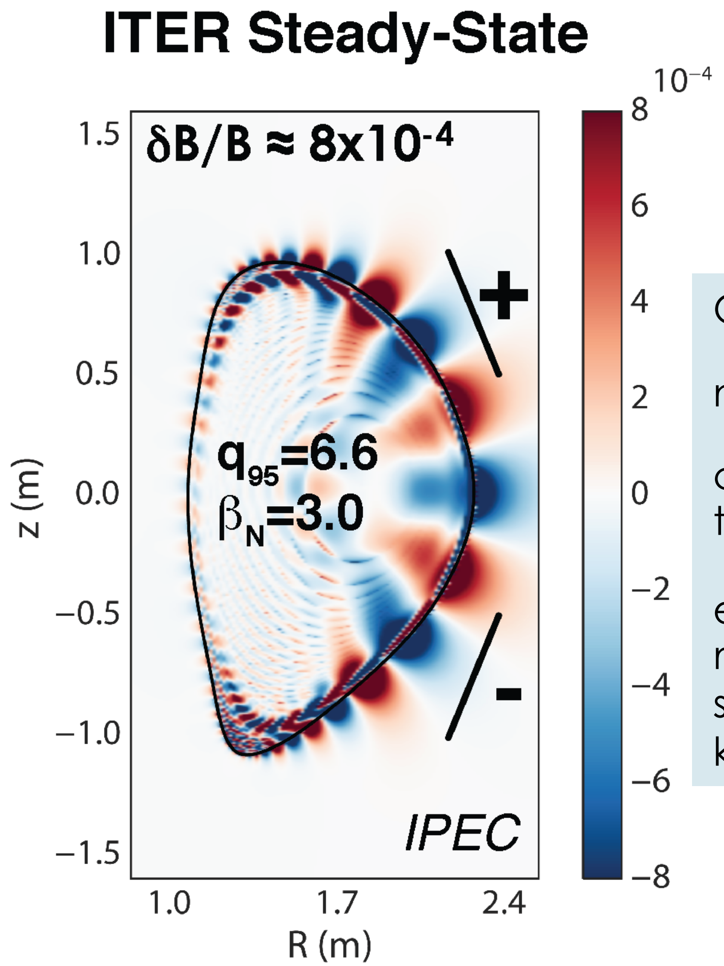
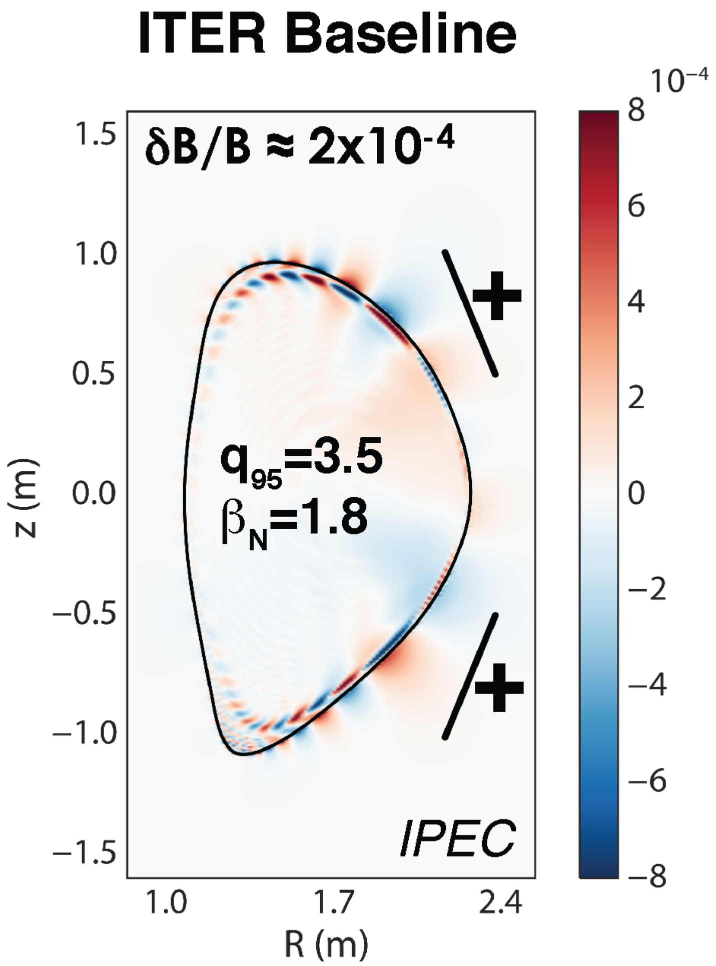
RMP ELM Suppression in Steady-State Hybrids Uses Novel High-β Amplification of Modest-Level 3D Fields

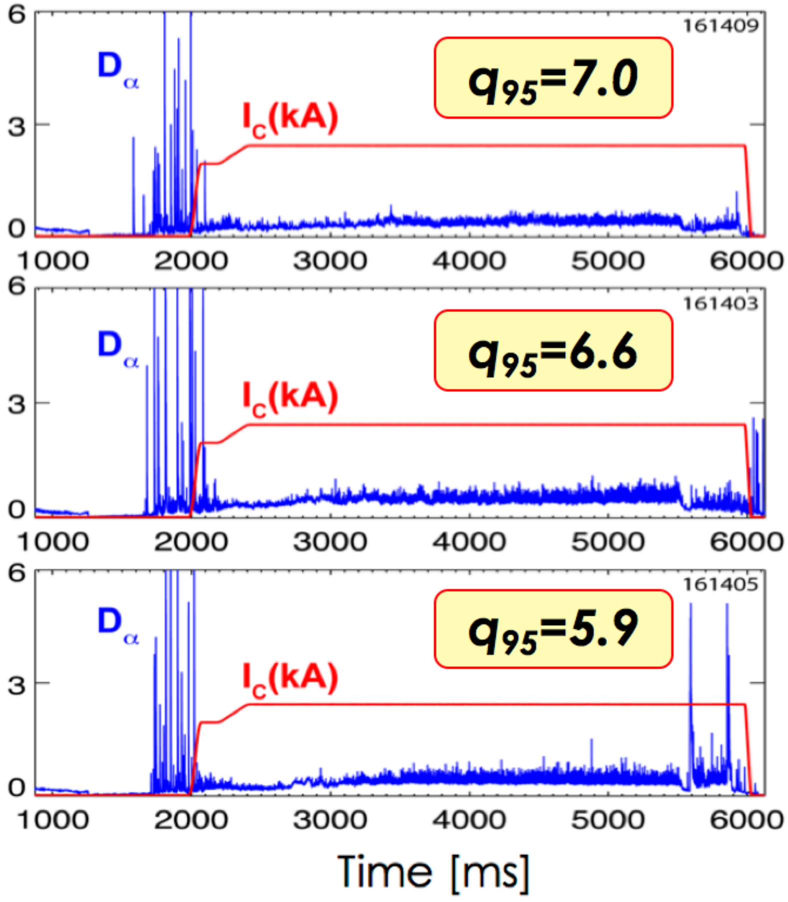
DIII-D has two rows of six coils for spectral control



Odd parity	Even Parity
n=3	n=3
couples well to high-q_{95}	couples well to low-q_{95}
excites marginally stable edge kink mode	excites more stable edge kink mode



High Density of Rational Surfaces at Top of Pedestal May Explain Wide q_{95} Window for ELM Suppression



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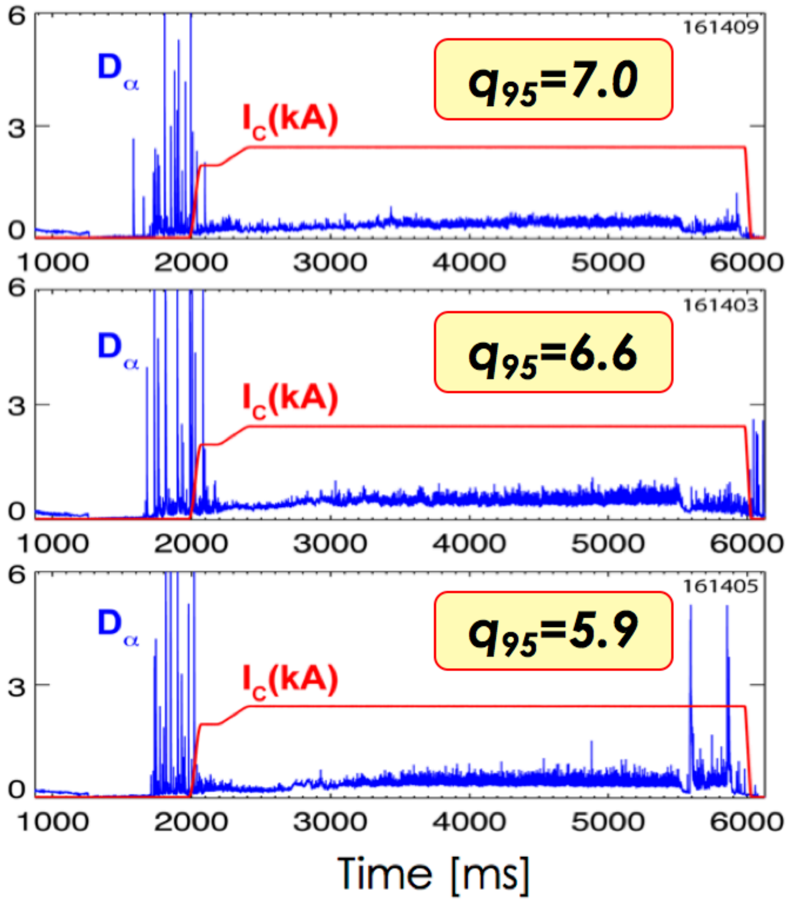
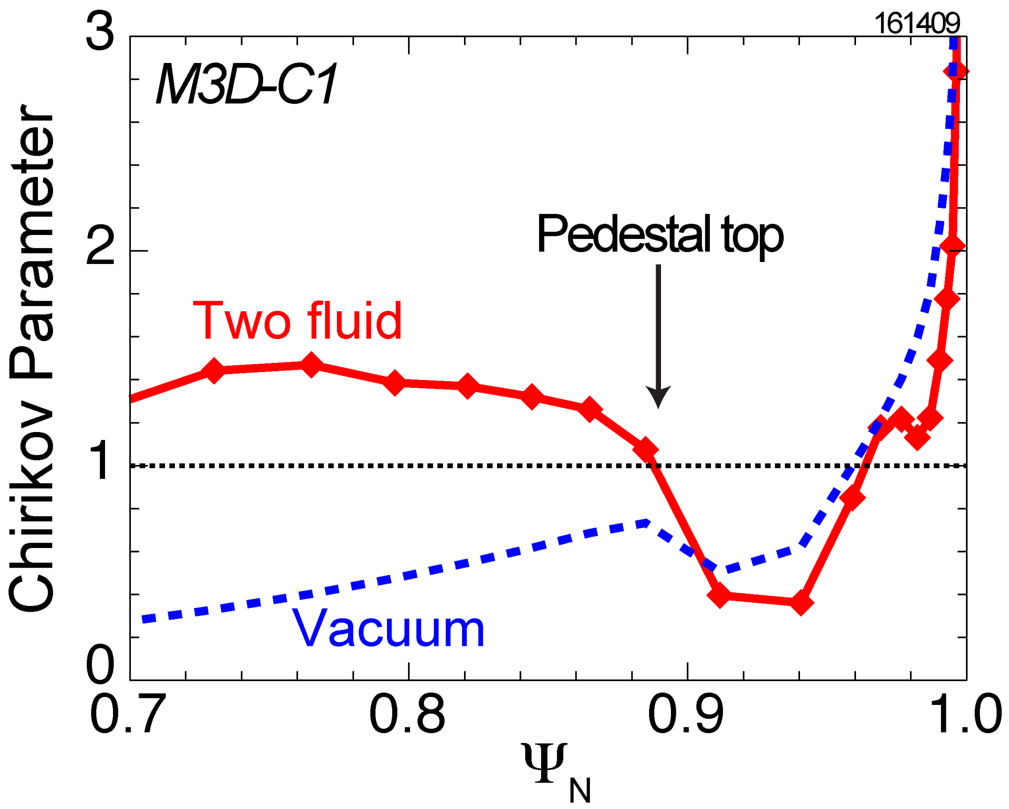


- **Linearly-calculated Chirikov parameter for island overlap suggests magnetic island chain forms at top of pedestal**



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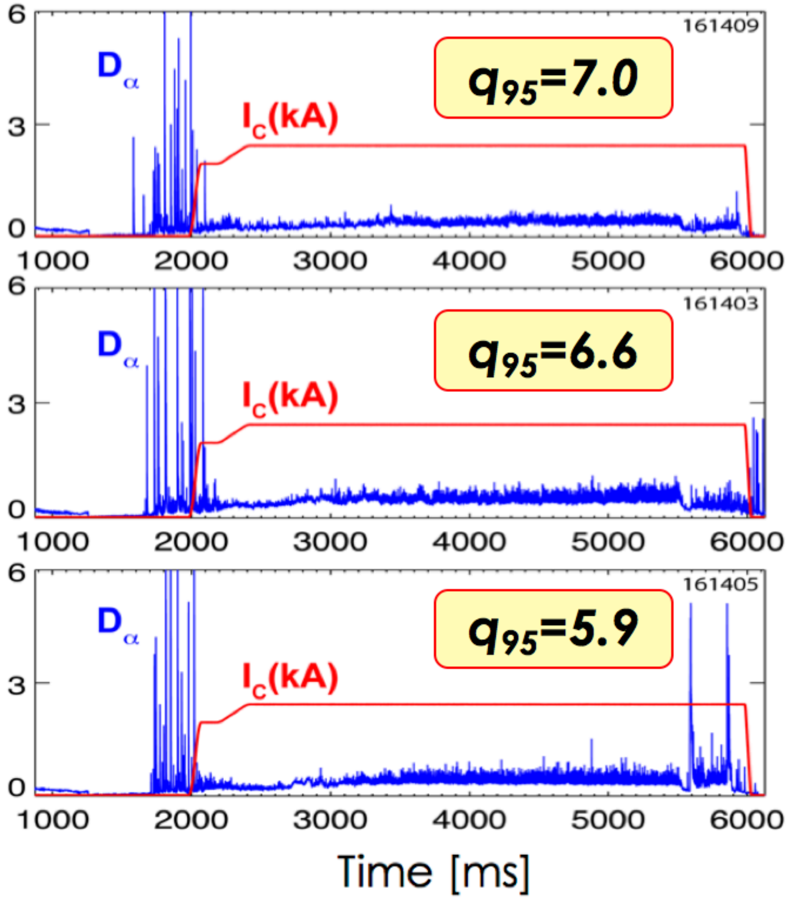

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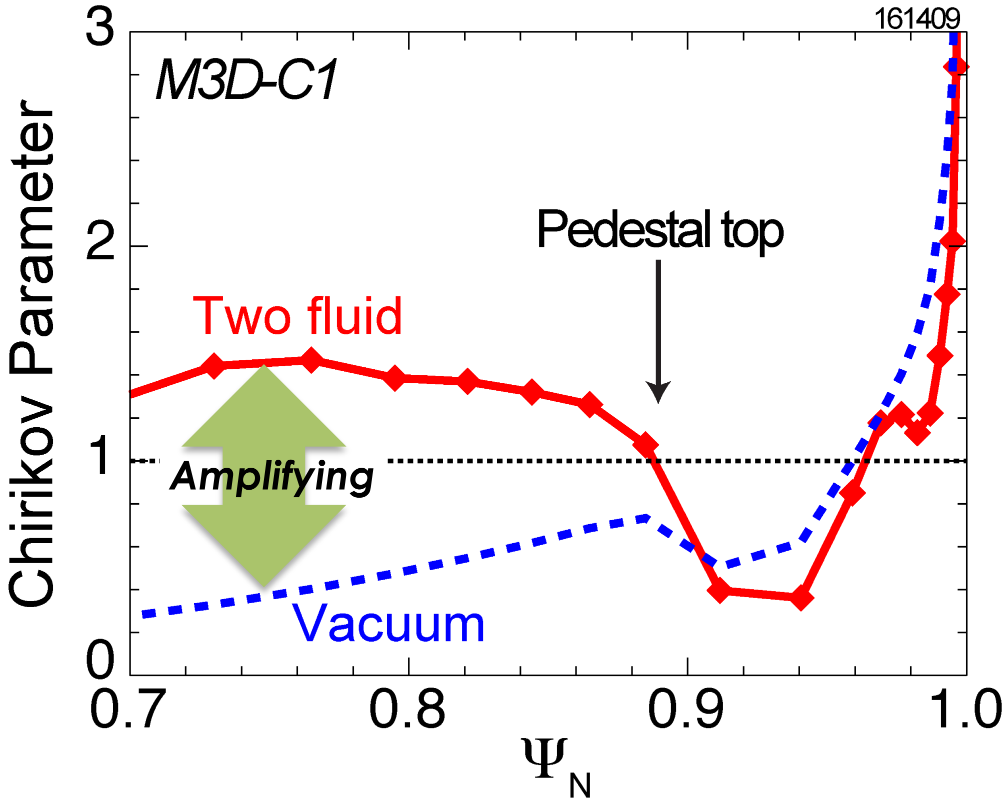
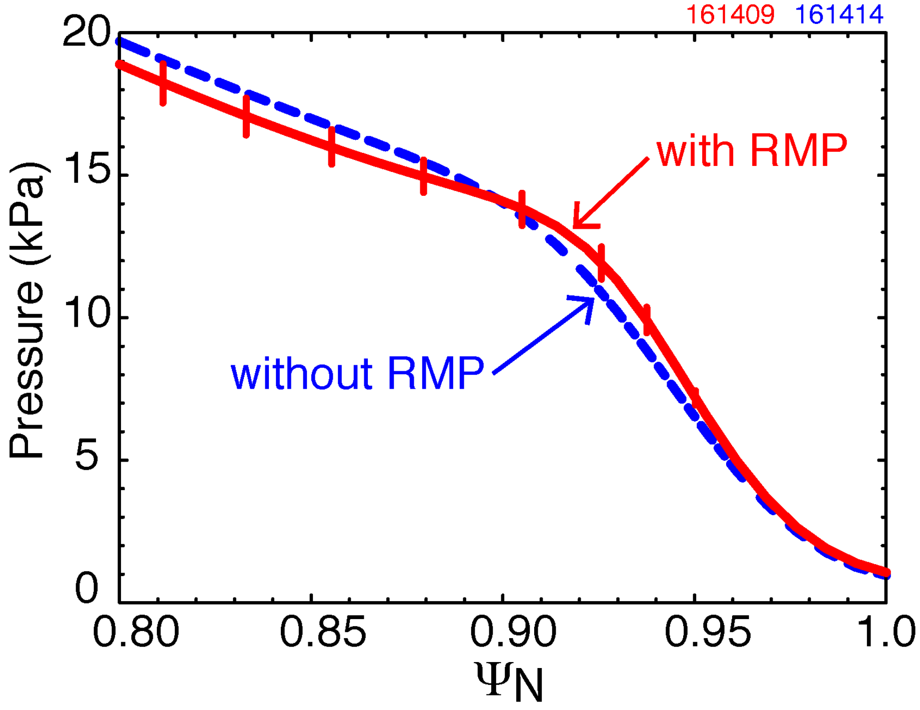
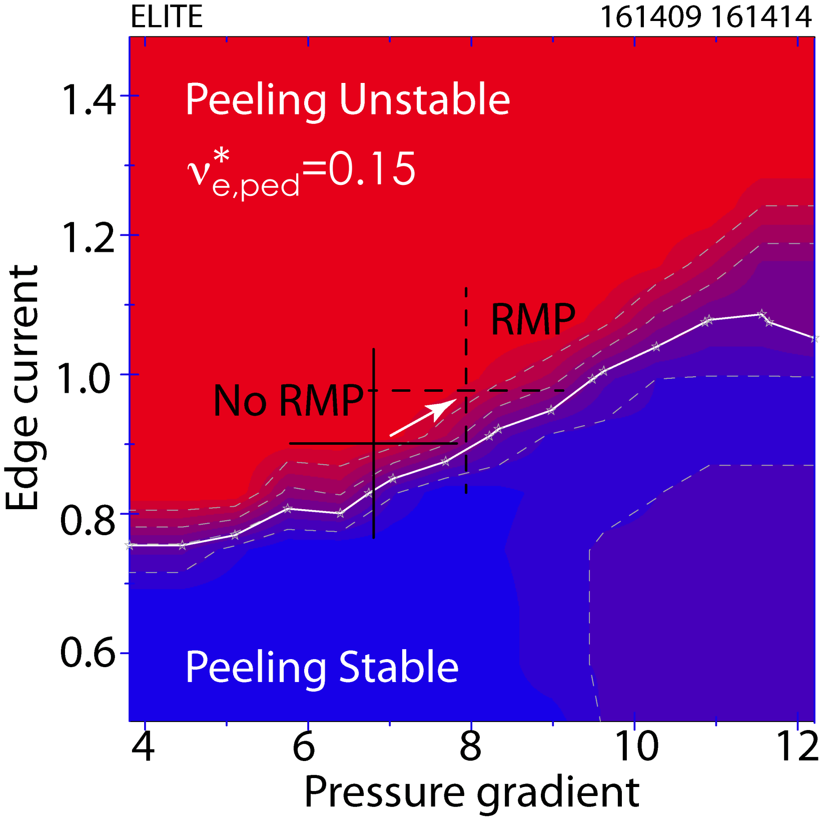


Magnetic Perturbations Have Only a Minor Effect on Pedestal Pressure and Confinement

- **Pedestal slightly narrows with RMP, small reduction in pedestal height correlates with small drop (≈10%) in H_{98y2}**

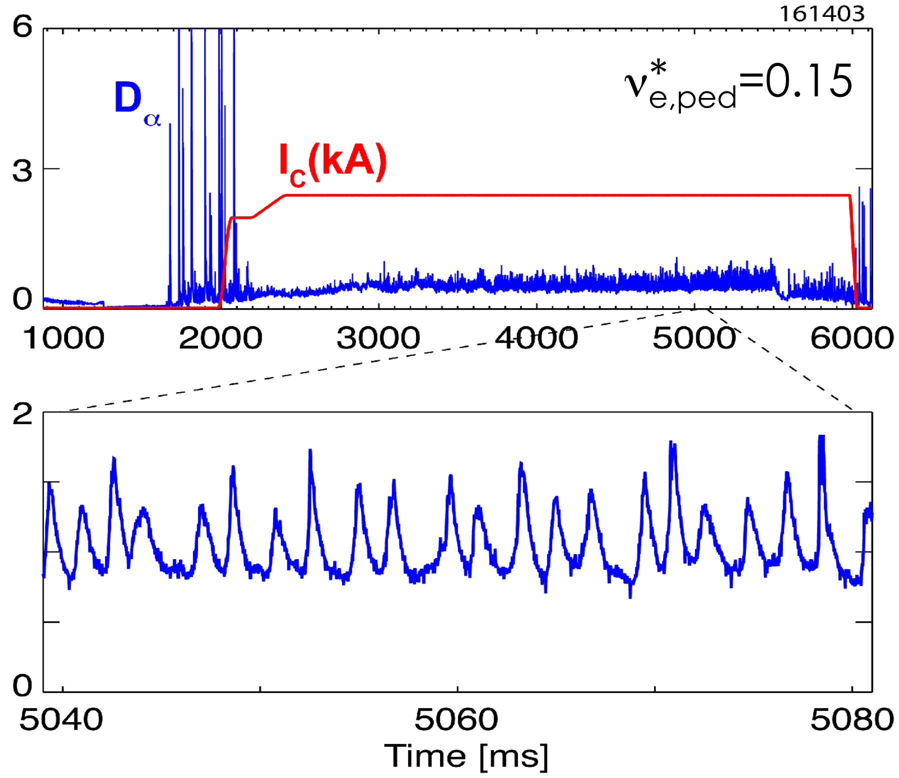


- **Pedestal remains close to low-collisionality kink-peeling stability boundary with RMP**

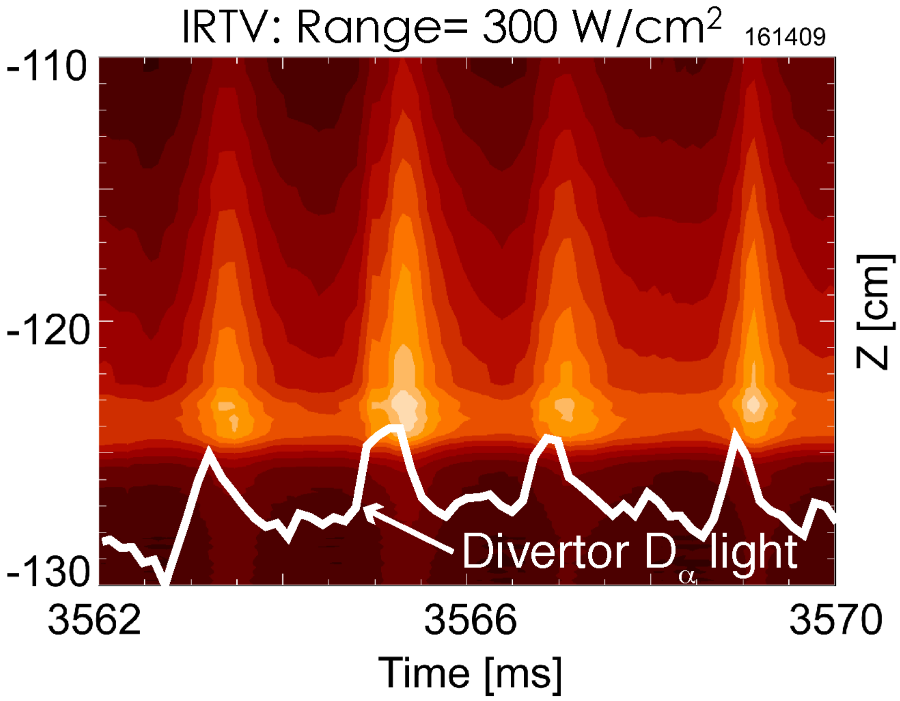


Small, High Frequency Bursts of Particle and Energy Loss to Divertor Persist Throughout ELM Suppression

- **Frequency ≈ 500 Hz**



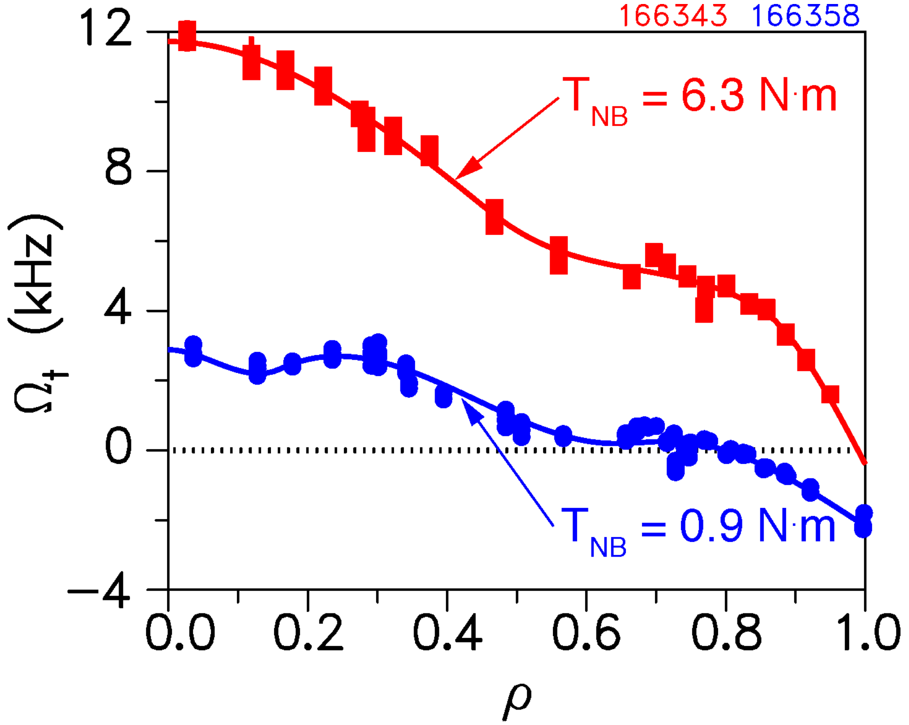
- **Peak heat flux exceeds average heat flux by only 20–30%**



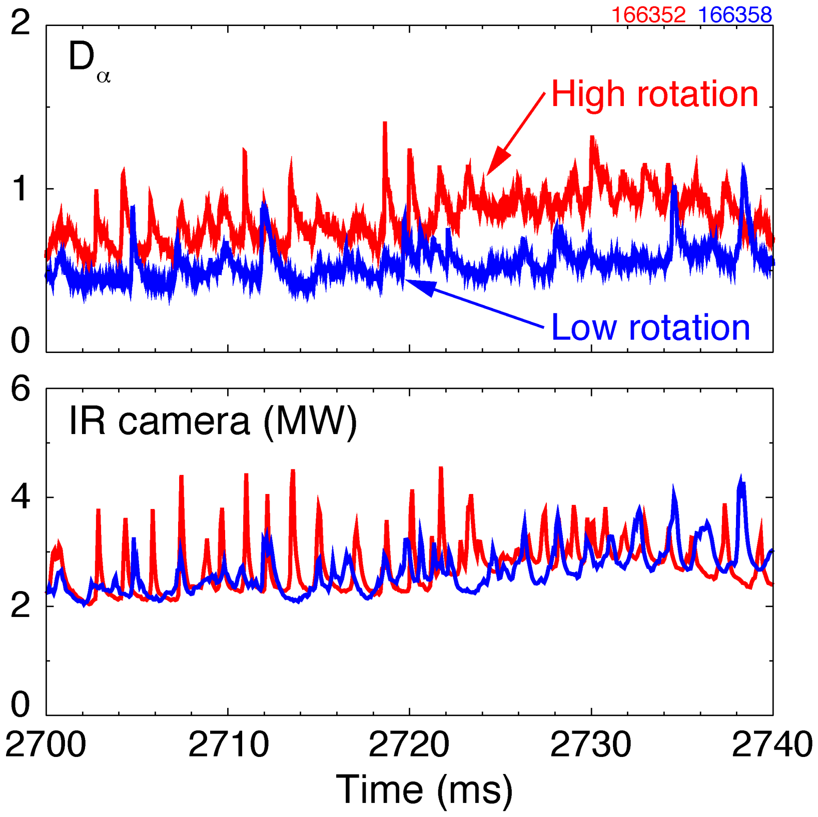
IR camera measurement of inner strike point

Coupling of RMP to Weakly-Stable Edge Kink Mode Allows ELM Suppression to Survive at Low Rotation

- **Neutral beam torque is stepped down to ITER-relevant value**
  - ELM suppression usually lost at low torque in ITER baseline



- **Little change in ELM suppression observed as rotation is reduced**



Note: locked modes are still an issue for low torque plasmas

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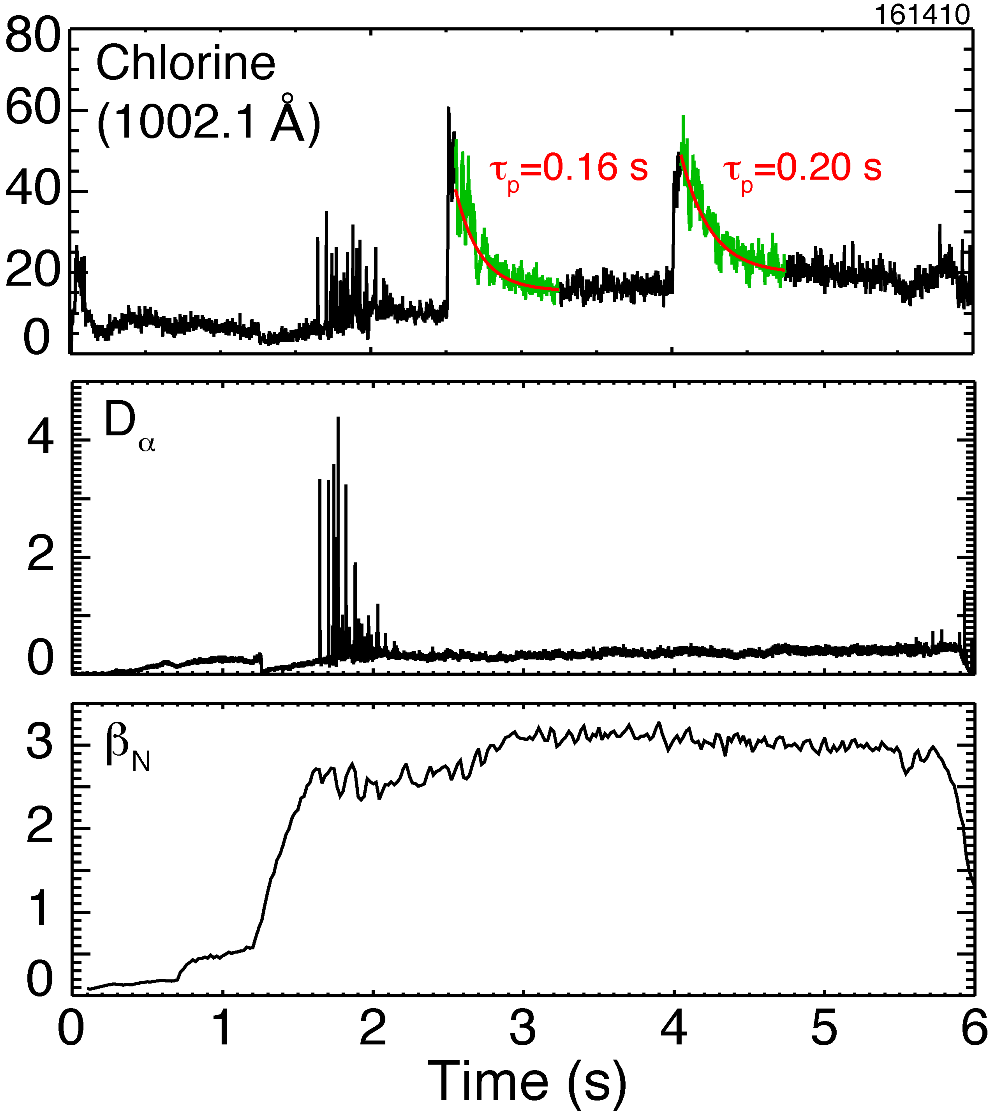
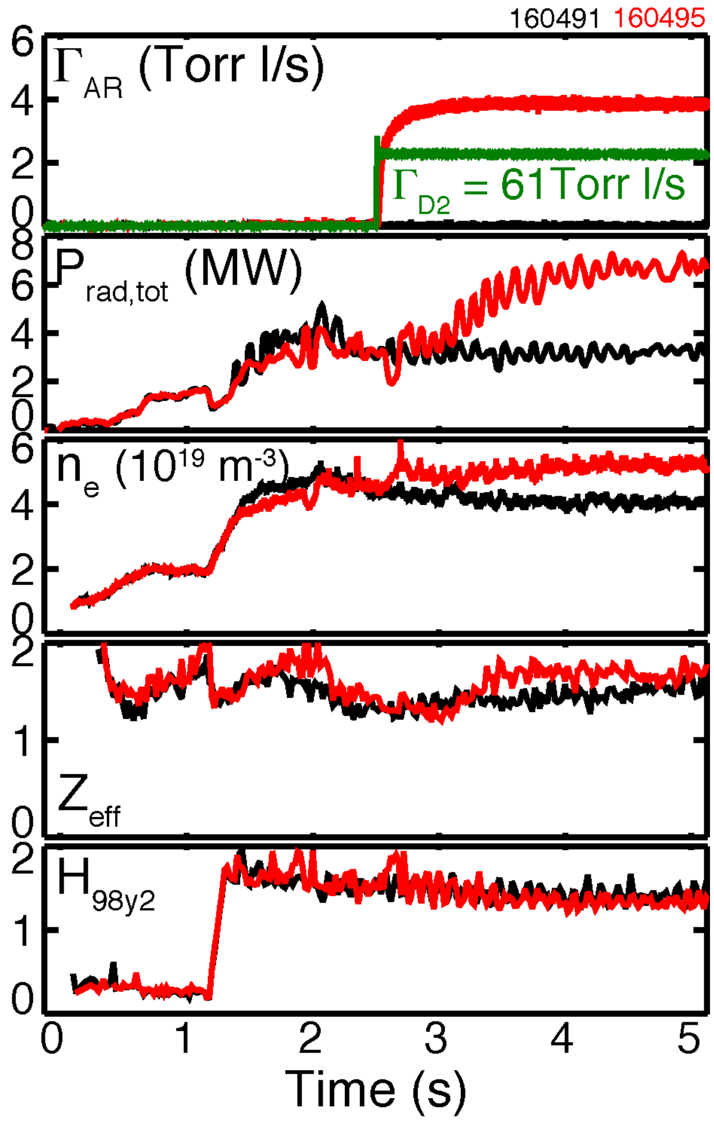
Impurity Accumulation is Not Problematic in ELM-Suppressed, Steady-State Hybrids

- **Particle confinement time of non-recycling Cl atoms measured with short (~10 ms) gas puffs**
- **Particle confinement (^{17}Cl) ~ $2\tau_E$ to $3\tau_E$, similar to ELMy H-mode**



High Power, High-β Hybrid Scenario is Integrated With Argon Radiating Divertor for Heat Flux Mitigation

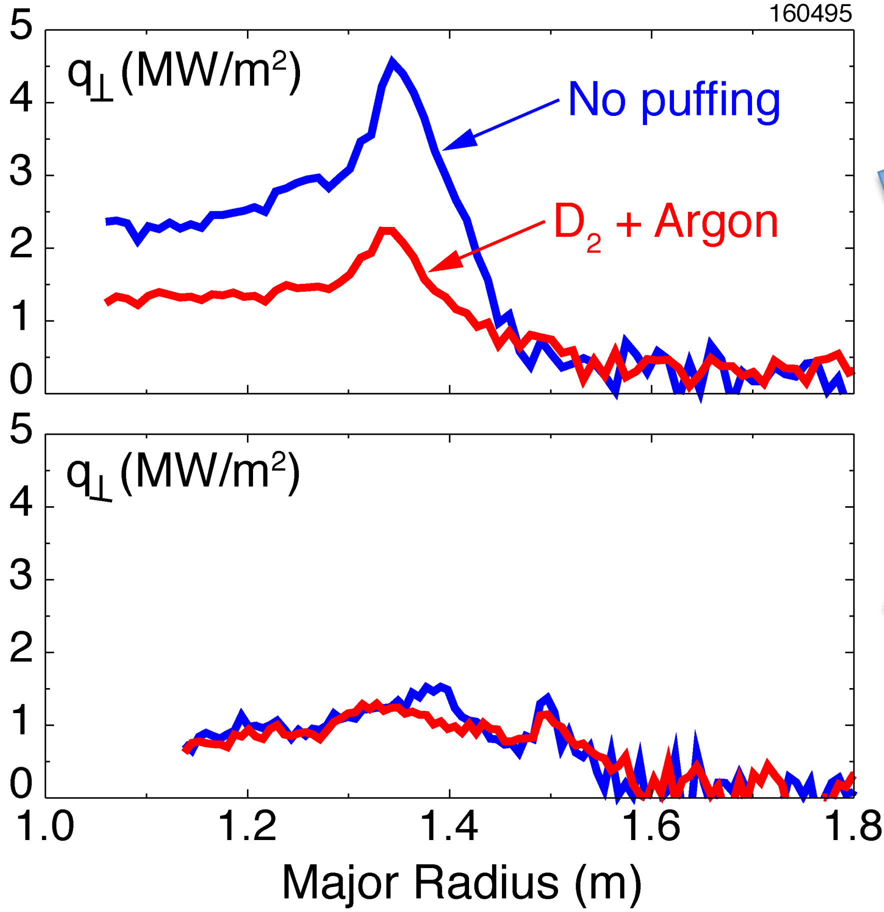


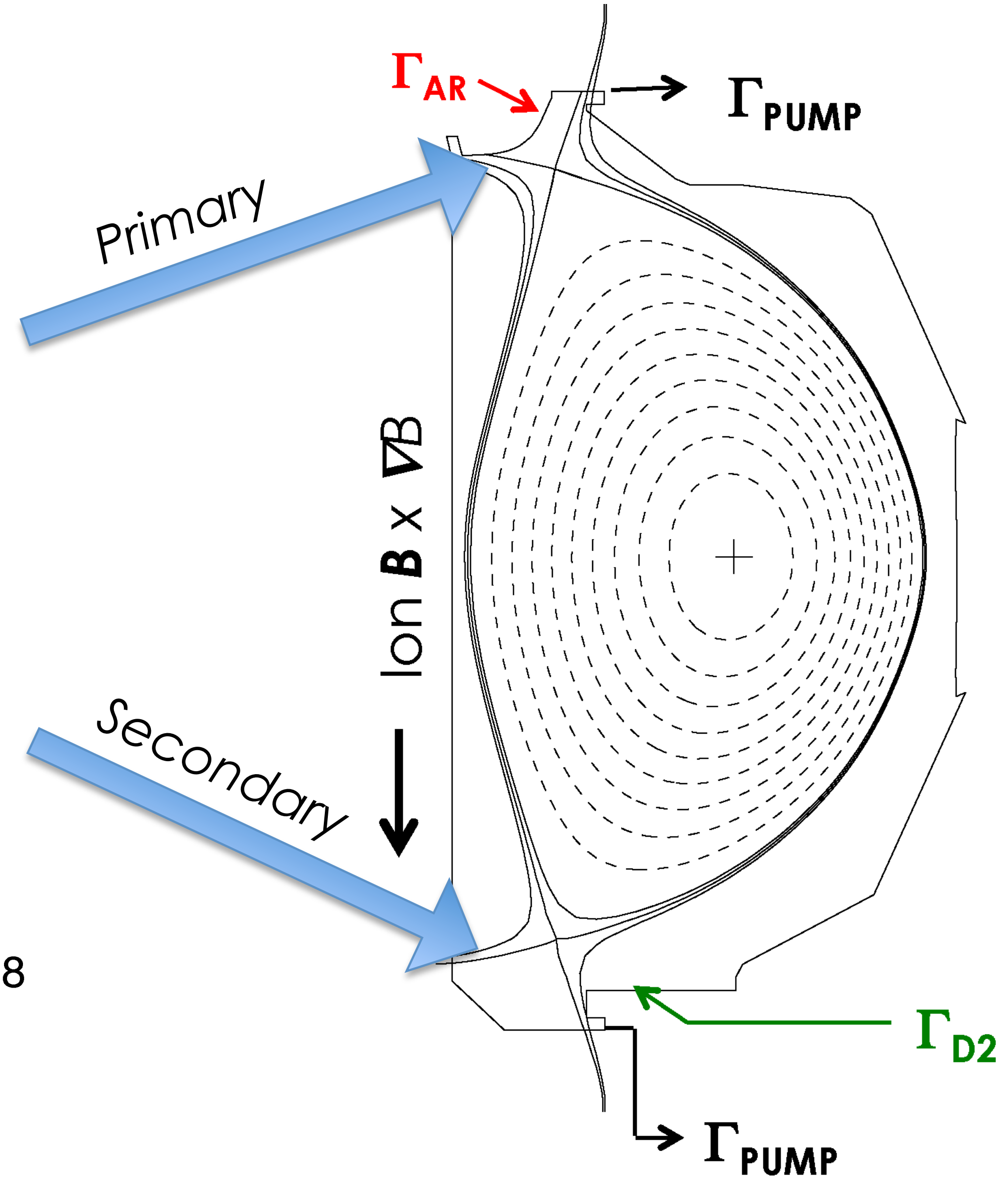
- **Combined Argon seeding and strong D_2 puffing doubles radiative power to 55% of input power**
  - Characteristic radiative fraction for ITER is 70% – 80%
- **High performance is maintained during radiating divertor operation**
  - $\beta_N = 3.0$, $H_{98y2} = 1.35$
  - Density increase with puffing ➔ not fully noninductive
- **Zeff increases by less than 10%**

See EX/P3-27 by T. Petrie

Peak Heat Flux in Upper Outer Divertor Falls by a Factor of Two for Argon-Based Radiating Divertor

- **IR camera measurement of divertor heat flux**





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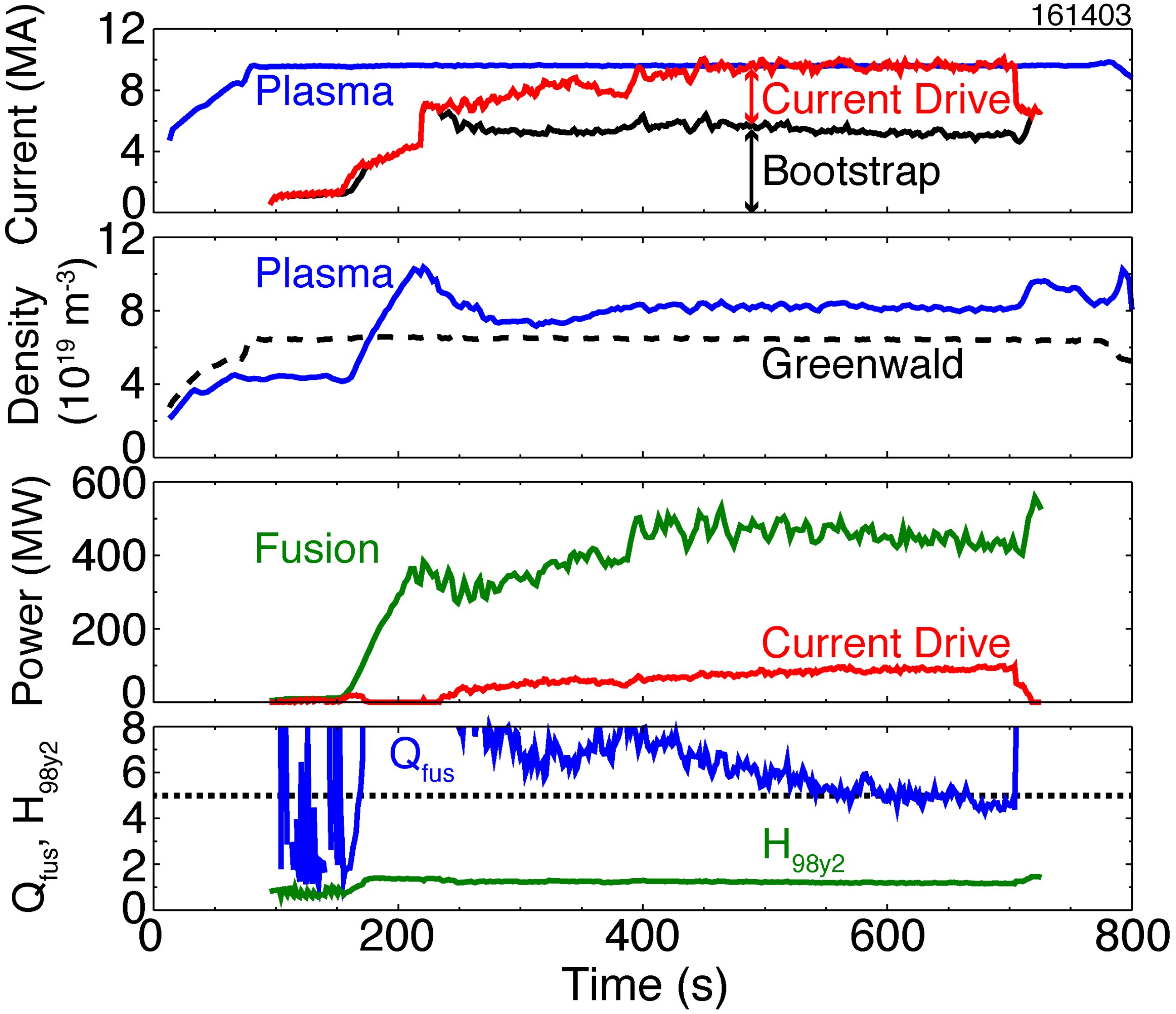
ELM-Suppressed Hybrids Scale Favorably to ITER Steady-State Scenario With I_P = 9.6 MA and $Q_{fus} \geq 5$



- **Extrapolation done at fixed β, ν*, *q* and plasma shape**
- **Current drive power (≈85 MW) calculated using CD efficiency from ITER Physics Basis**
- **Required confinement scaling is**

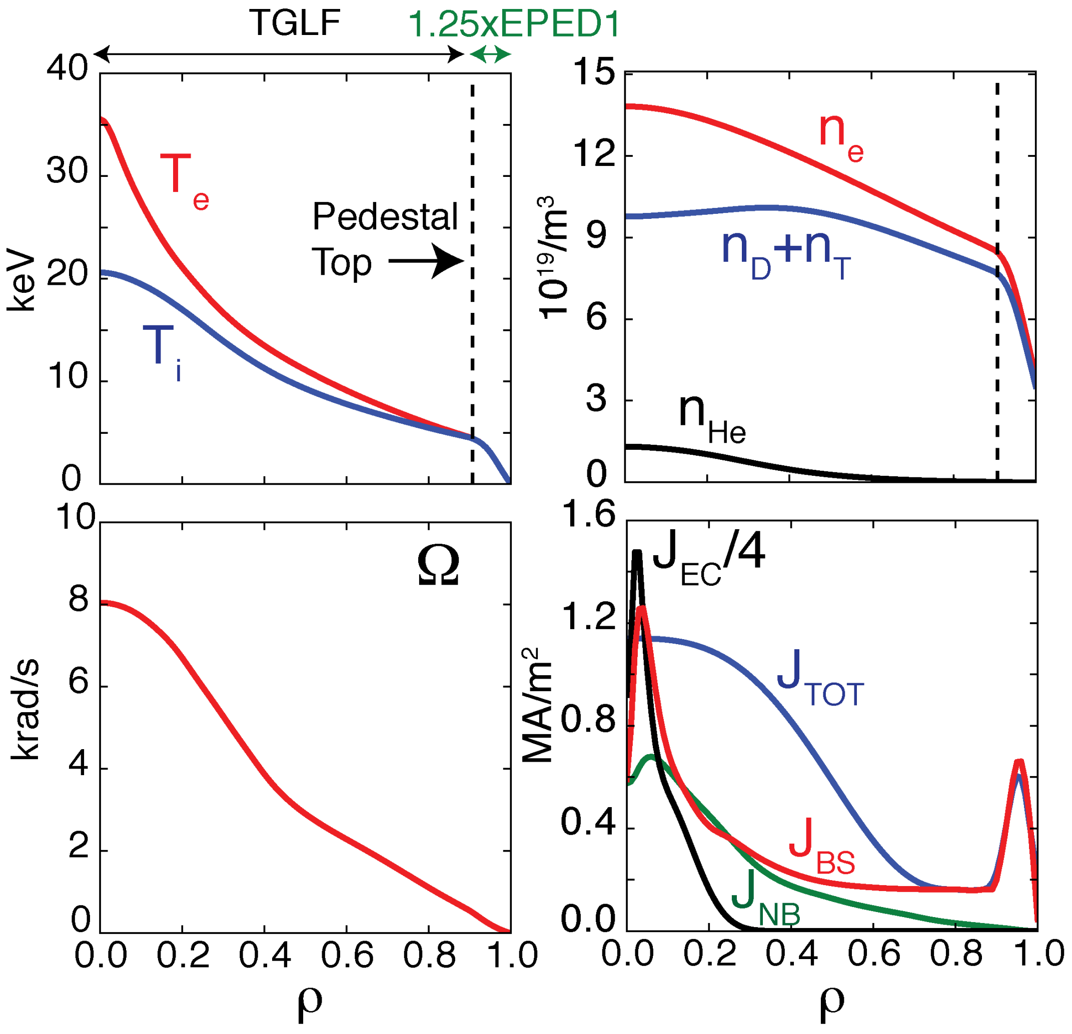
$$H_{98y2} = 1.2$$

$$\chi \propto \chi_B \left(\rho^*\right)^{0.5}$$

Simulation of Hybrid Plasmas With Central Current Drive in ITER Shows Steady-State Mission is Attainable

- **Self-consistent steady-state prediction of core transport (TGLF), edge pedestal (EPED1), current drive (NUBEAM, TORAY) and equilibrium (ESC)**
  - Pedestal height raised 1.25× to better match experiment
  - J_{TOT} profile broadened to give q_{min}=1.05 to be “hybrid-like”

I_P	**9.5 MA**	**I_{NI}/I_P**	**1.01**
n_e/n_{GW}	**1.14**	**P_{fus}**	**487 MW**
β_N	**3.0**	**P_{CD}**	**106 MW**
H_{98y2}	**1.2**	**Q_{fus}**	**4.6**



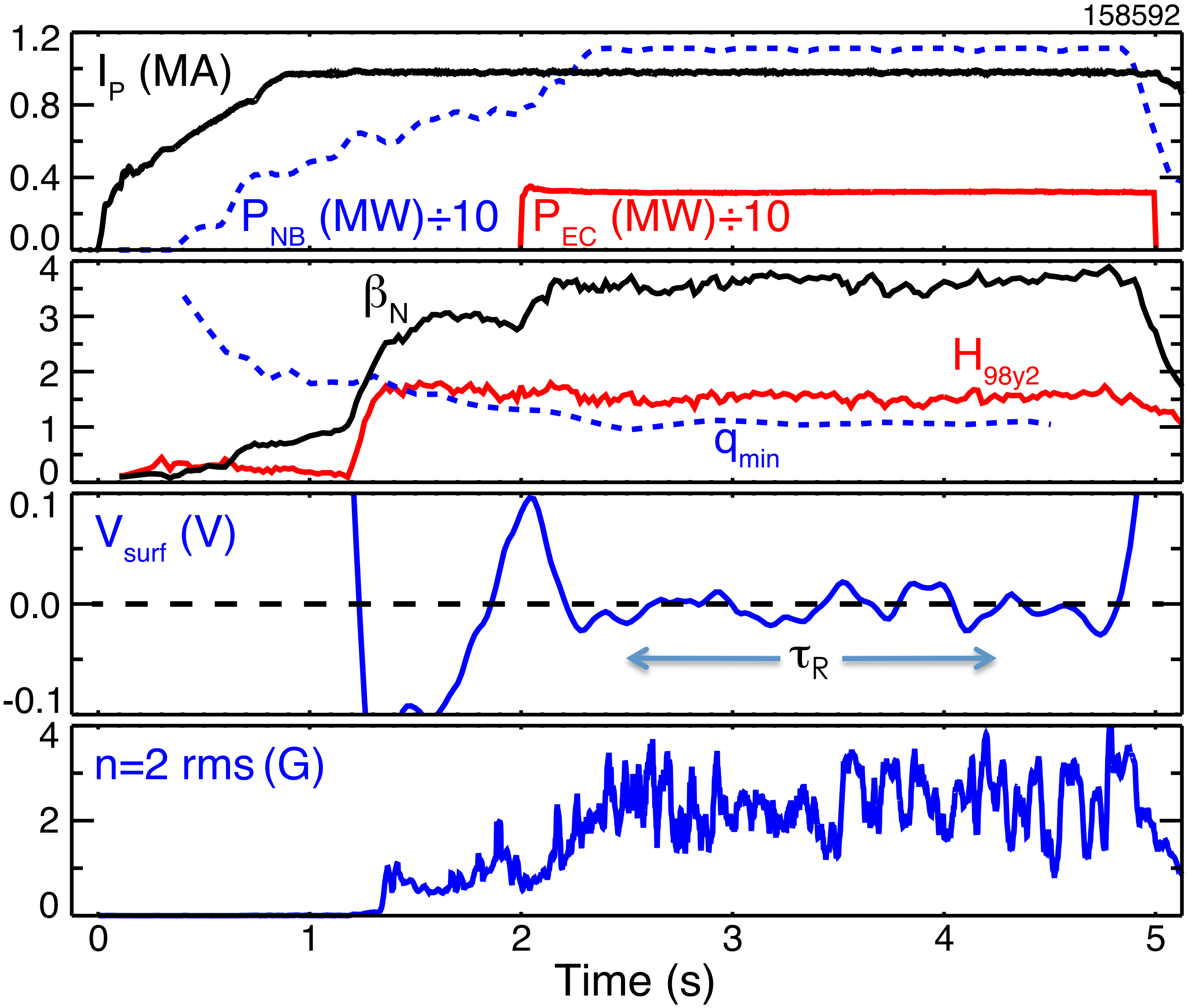
FASTRAN/IPS simulation

Summary – ELM Suppression has been Integrated With High-β, Steady-State Hybrid Scenario Relevant to ITER

- **Uses n = 3, odd parity RMP to excite edge kink modes that are marginally stable and amplifying**
  - *Benefits: modest RMP amplitude, wide q_{95} window, small effect on pedestal, ELM suppression at low rotation*
- **High power, high-β hybrid scenario is also integrated with an Argon-based radiating divertor, reducing heat flux by 50%**
- **Scenario scales to steady-state in ITER with $P_{fus} \approx 460$ MW @ $Q_{fus} \approx 5$ and $H_{98y2} = 1.2$ (further optimization possible)**

Additional Slides

Hybrid With Central Current Drive Sustains 1.0 MA Fully Noninductively With $\beta_N \approx 3.7$ and $H_{98y2} \approx 1.6$



- **Pulse length limited by NBI duration**
- **Reproducible zero loop voltage**
- **Small 3/2 tearing mode prevents sawteeth**

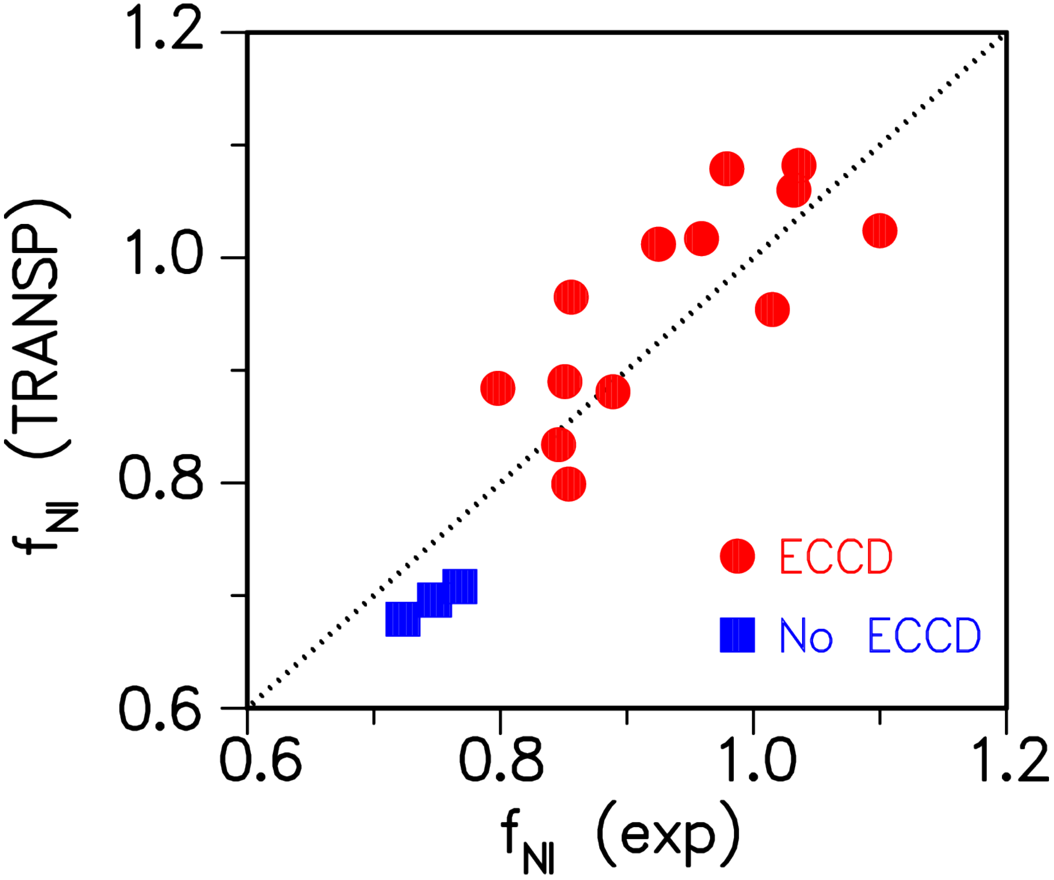
Experimental Noninductive Current Fraction Matches TRANSP Modeling

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

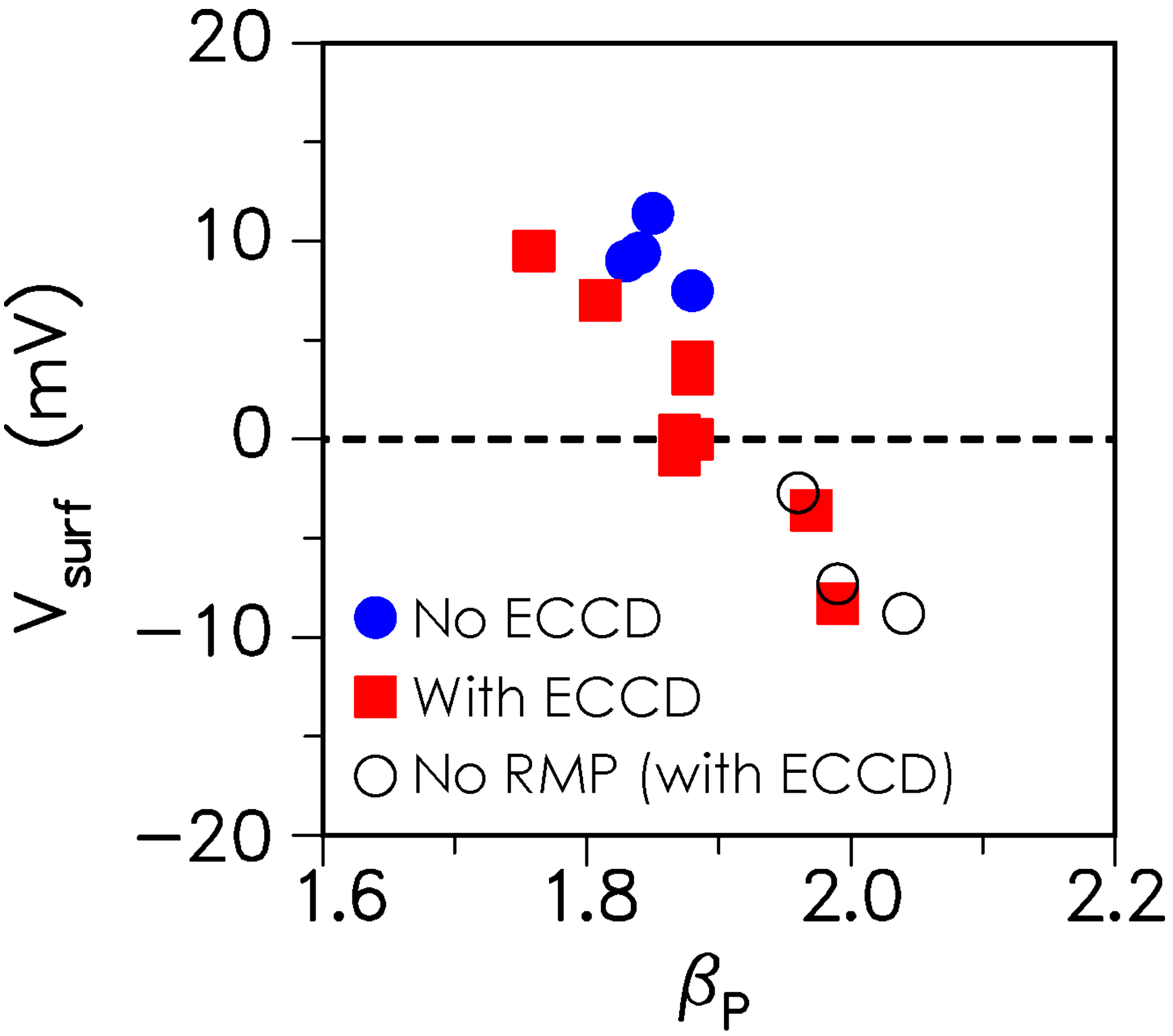
- **Ohmic current found from measured loop voltage profile using MSE-constrained EFITs**

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

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



Combination of Central ECCD and High β_P (i.e., Bootstrap Current) Drives Surface Loop Voltage to Zero

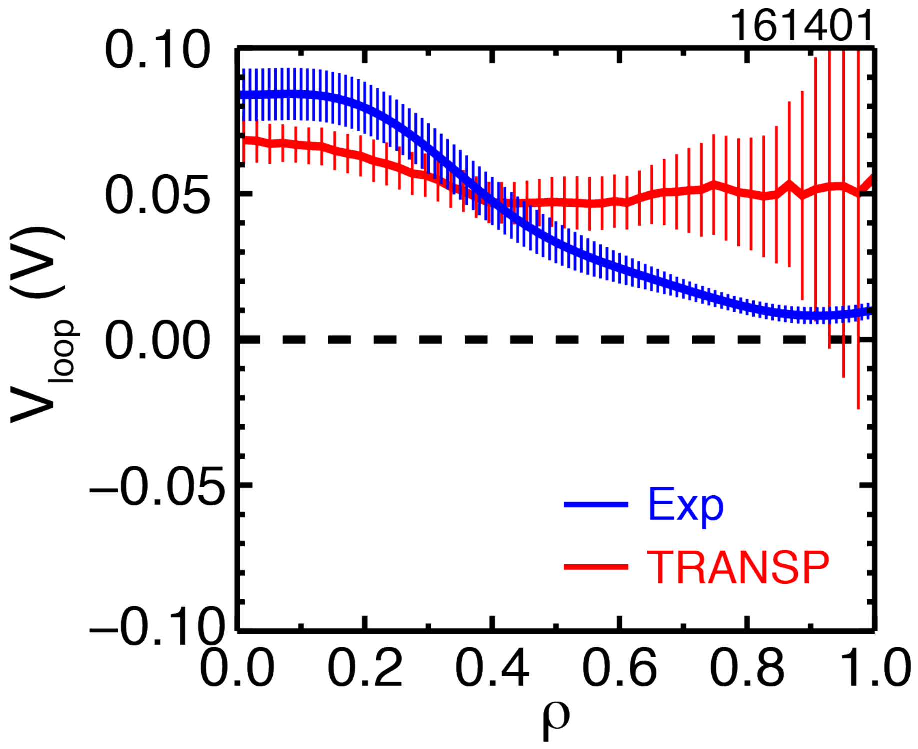


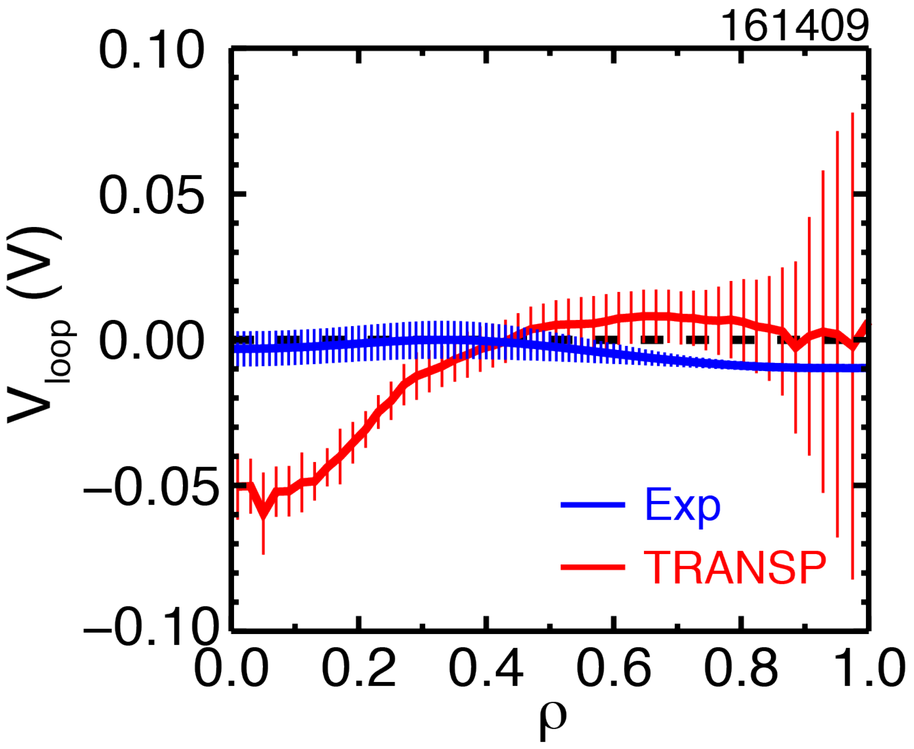
- V_{surf} lower with ECCD for same β_P
- Overdrive of plasma current (i.e., $V_{surf} < 0$) is observed when $\beta_P > 1.9$

Measured Loop Voltage Profile Supports Contention That Current Profile is Broader Than Predicted by TRANSP

- **For NBI-only hybrid, TRANSP predicts a flat V_{loop} profile, but actual peaked V_{loop} indicates current profile is still broadening**

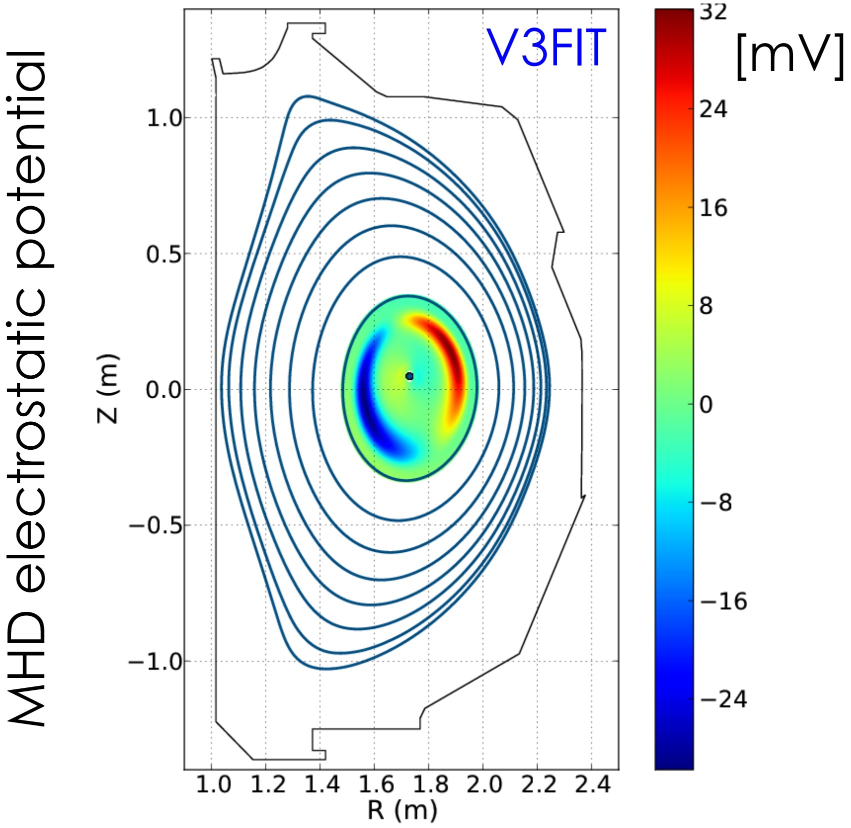
- **For ECCD hybrid, TRANSP predicts center is overdriven, but actual flat V_{loop} (≈0) profile indicates current profile is stationary**

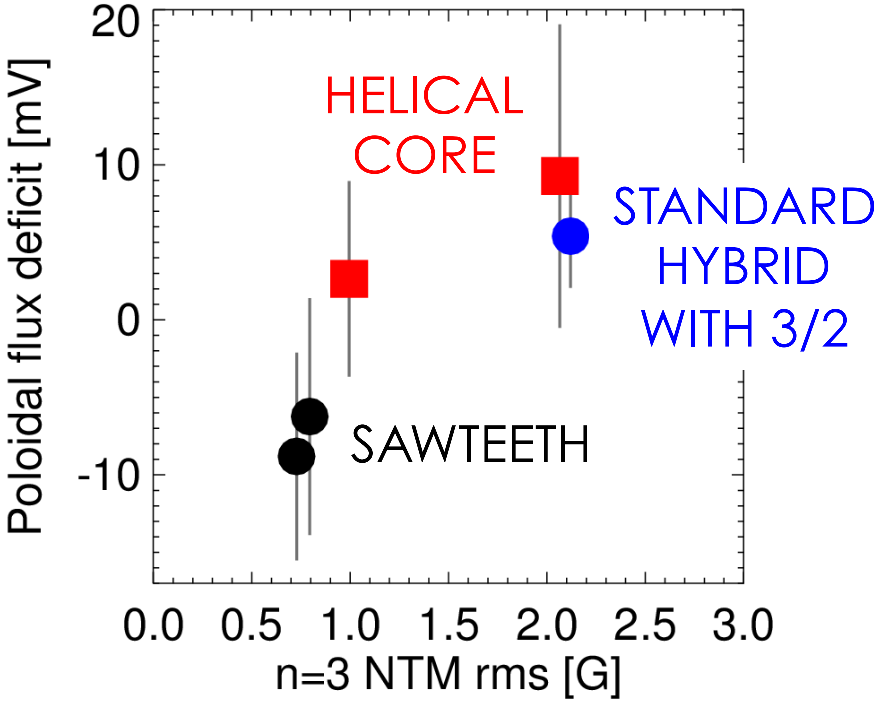




Experiments Support Theory That Helical Core Displacements can Broaden Current Profile

- **An electrostatic dynamo EMF arises to balance helical modulation of parallel current density**
- **Imposing helical core using n = 1 field in plasma without 3/2 mode drives measurable flux pumping**

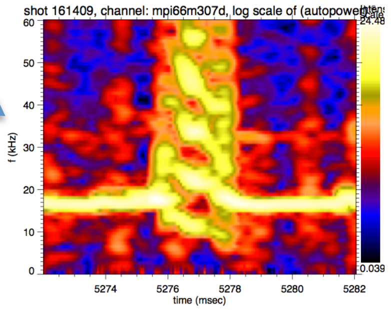


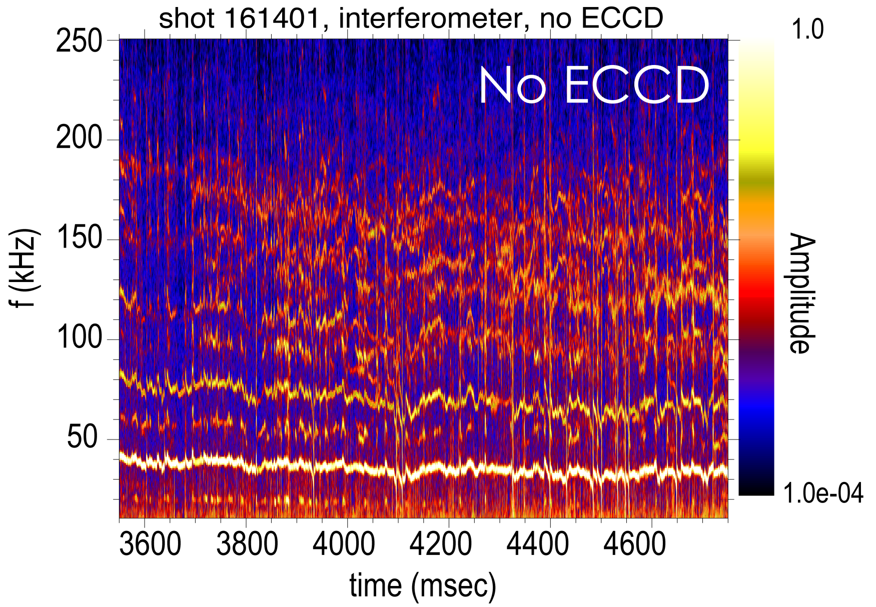


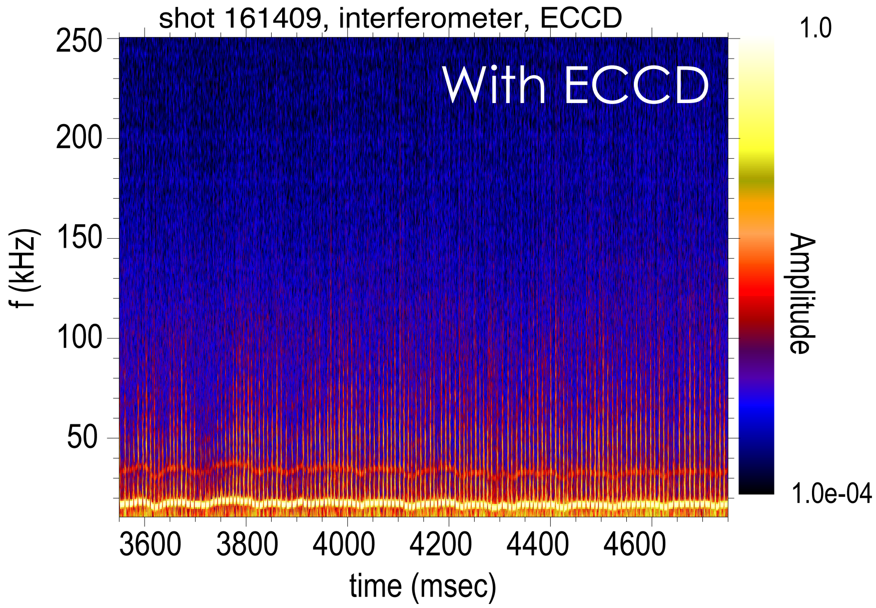
See EX/1-1 by P. Piovesan

Plasmas With ECCD Exhibit Much Weaker Core MHD Than Similar Plasmas Without ECCD

- **Cross-amplitude spectrum from CO_2 interferometer**
- **Large number of modes (8-10) excited in case without ECCD**
  - Combination of low frequency NTM and (likely) TAE/EAE
- **High frequency AEs disappear in case with ECCD, replaced by fishbones**

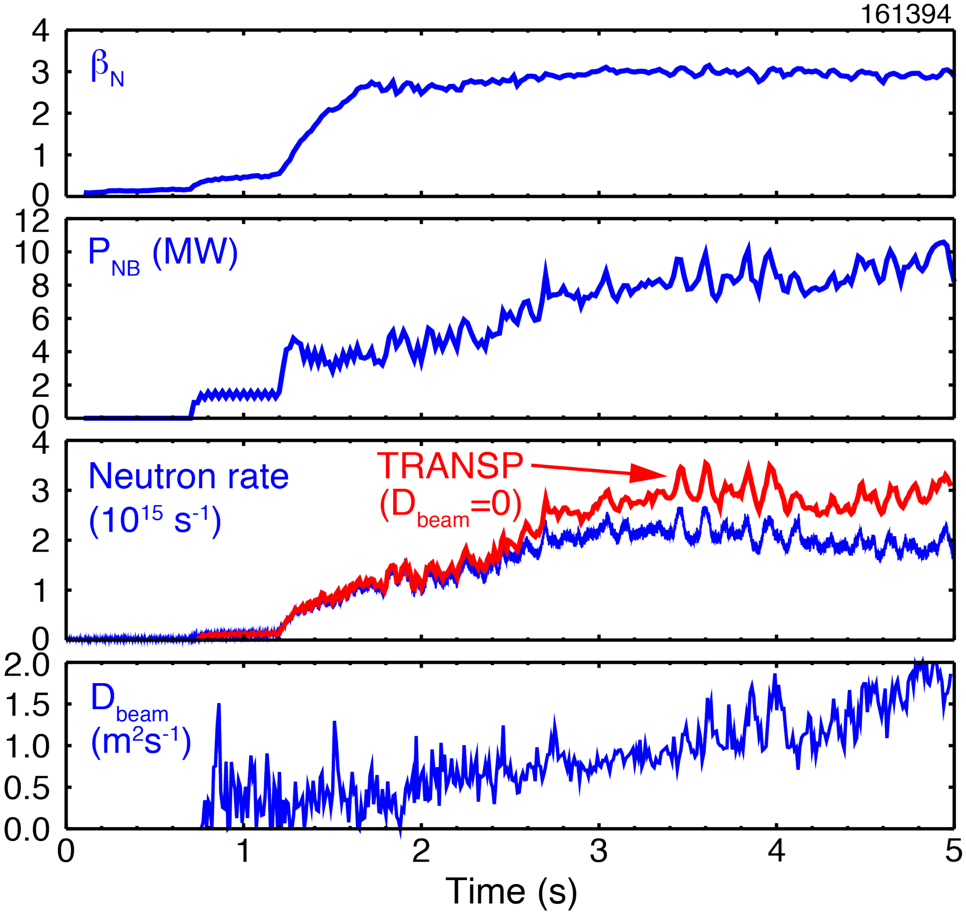



shot 161401, interferometer, no ECCD

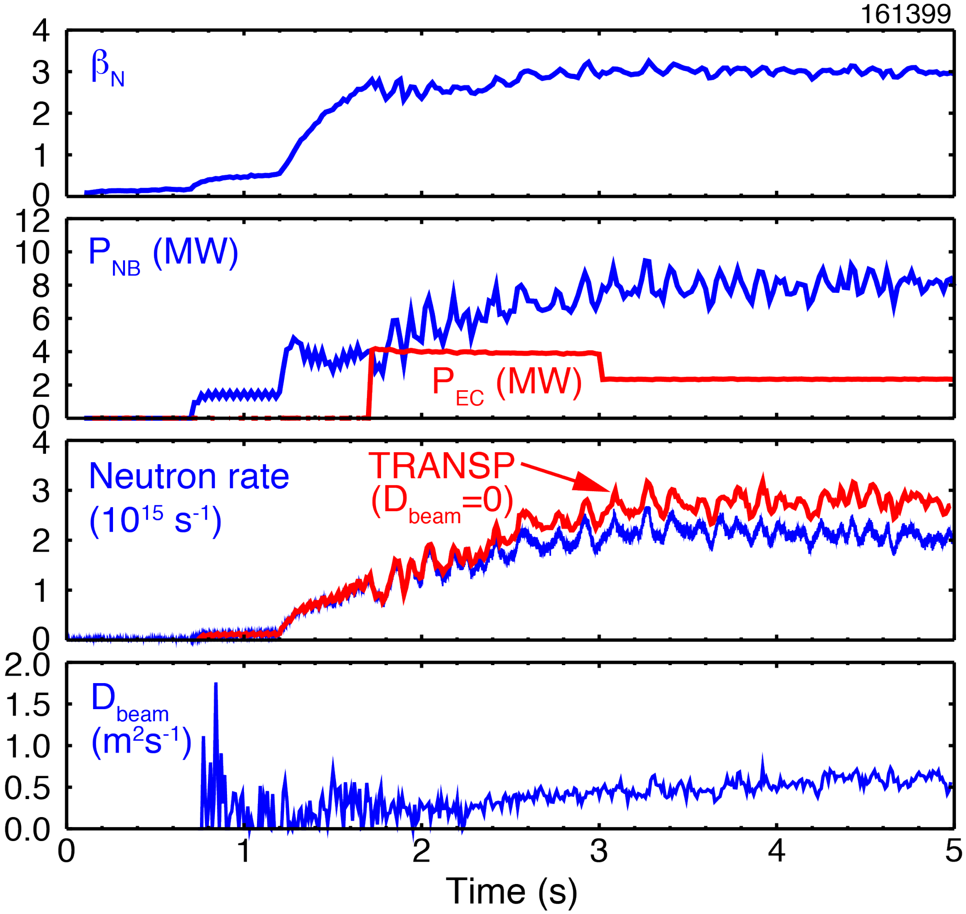

shot 161409, interferometer, ECCD

Without ECCD, Large Beam Ion Diffusion is Needed in TRANSP to Match Experimental Neutron Rate

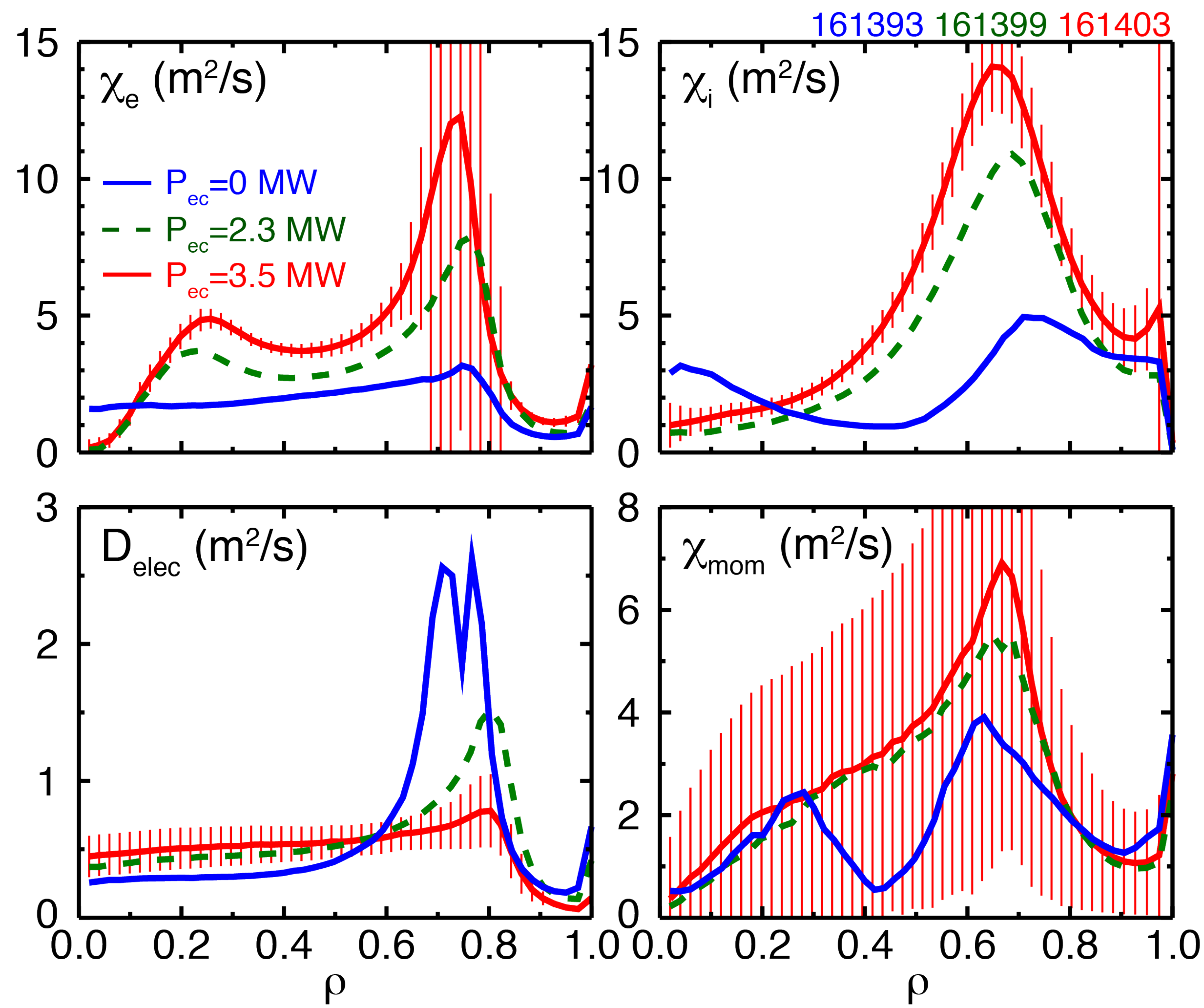
- **Without ECCD**



- **With ECCD**



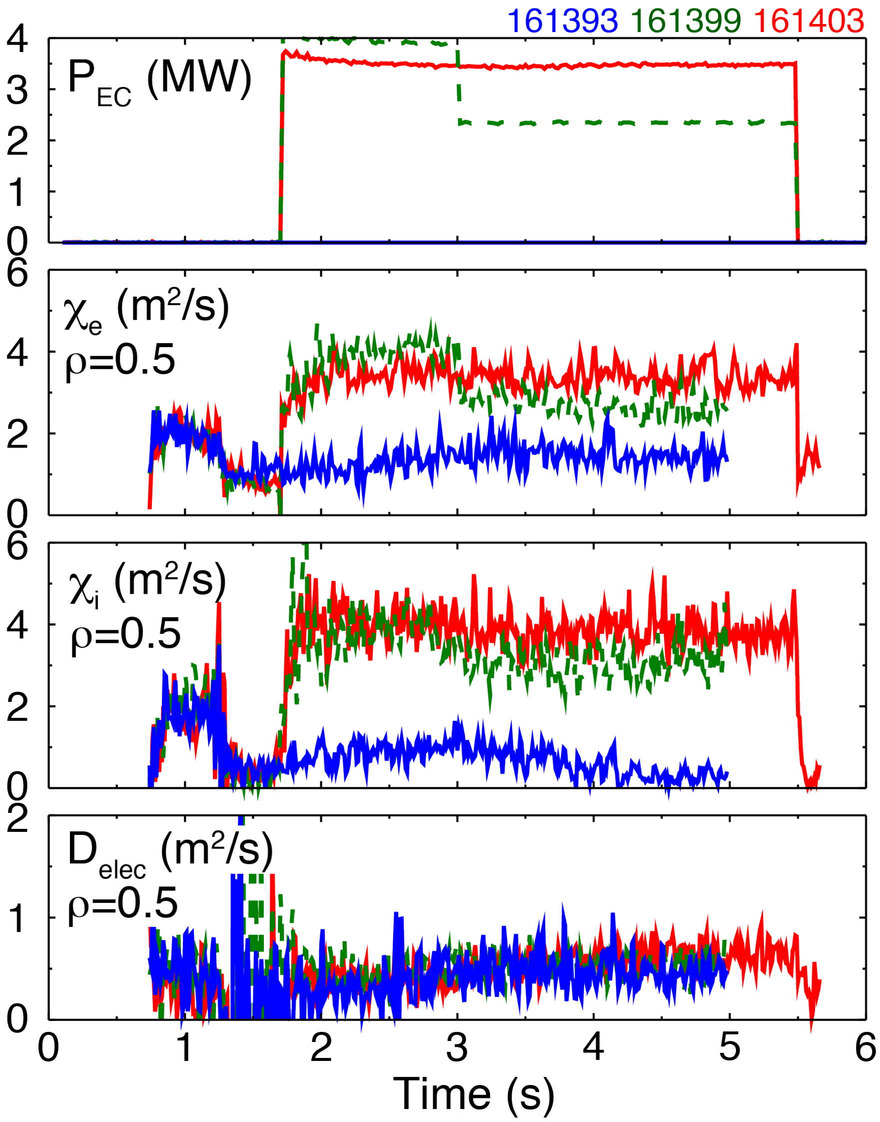
Thermal Diffusivities Increase Systematically With ECH Power, With Ions Having the Largest Increase



- **Since $\chi_e \approx \chi_i$, using equal amounts of electron and ion heating will naturally give $T_e \approx T_i$**
- **Flattening of D_{elec} profile during ECH causes density profile to broaden**

Central Electron Heating Rapidly Increases Electron and Ion Thermal Diffusivities

- **Transport coefficients take into account the time varying beam ion transport**
- **Diffusivities are nearly constant with time (except when ECH power changes)**
- **Compared to thermal diffusivities, particle diffusivity has weak dependence on ECH**



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