Reducing the L-H Power Threshold in ITER-Similar-Shape DIII-D Hydrogen Plasmas

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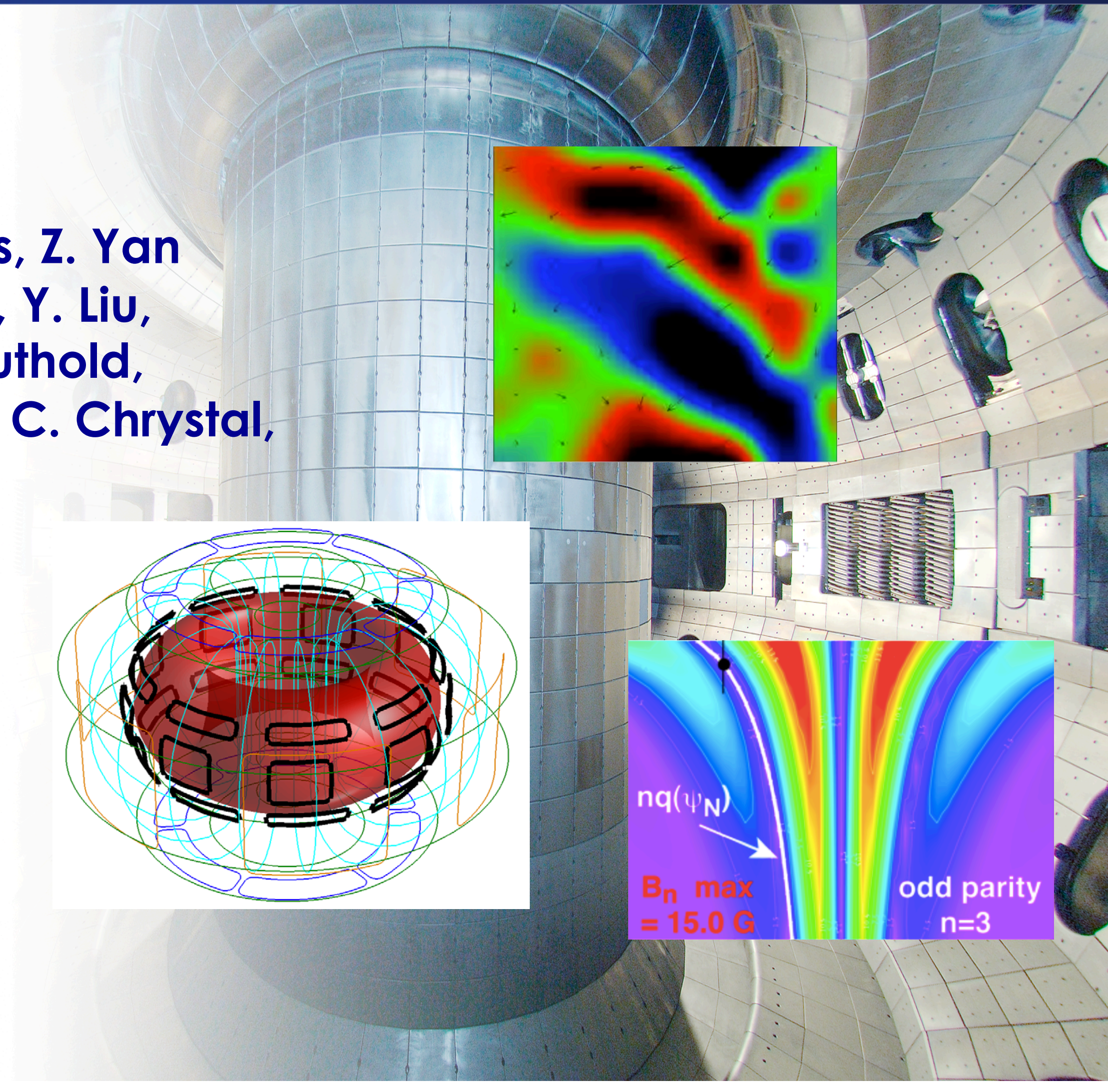

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Successful Reduction of P_{LH} in DIII-D ITER Similar Shape Hydrogen Plasmas

- **Without mitigation, the L-H power threshold in very high in Hydrogen with dominant electron heating:**

  P_{LH} (H) ~ 3× P_{LH} (D) in this regime at ITER-relevant q_{95} ~ 3.6
  P_{LH} (H) ~ 2× P_{LH} (D) at higher q_{95} ~5.1

- **Achieved ≤ 30% Reduction of P_{LH} in ITER-Similar Shape (ISS) Plasmas with Dominant Electron Heating**

- **Identified several promising methods to reduce P_{LH} in ITER-relevant hydrogen plasmas:**

Approach	Helium Injection	n=3 NRMF/ NTV	Increased Lower Triangularity
Observed P_{LH} Reduction	20-30%	15-25%	5-10%

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Motivation: Reduce L-H Power Threshold in ITER PFPO-1 Hydrogen Plasmas (Heating Power May be Marginal)

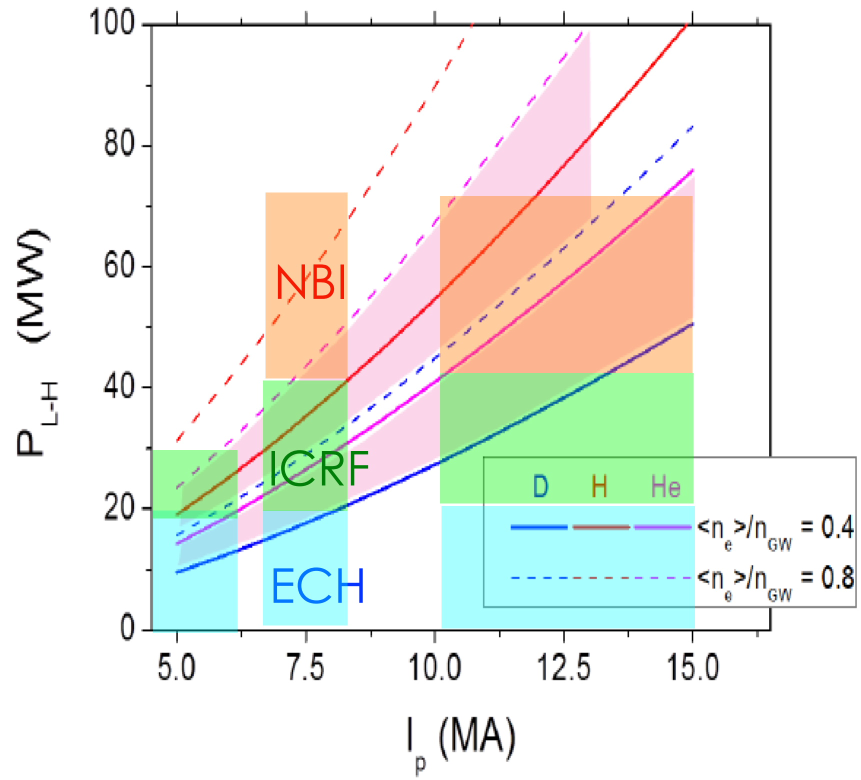
- **ITER Pre-Fusion Power Operation 1: Hydrogen Plasmas at 1/3 B_T**
  - **2008 ITPA Scaling (Martin Scaling):** $P_{LH-08}[MW] = 0.049 n[10^{20} m^{-3}]^{0.72} B[T]^{0.8} S[m^2]^{0.96} A_i$

    shown here for Deuterium (A_i=1), Hydrogen (A_i=2) and Helium (A_i=1.4) for two line-averaged densities:

    $\langle n_e \rangle / n_{Gr}$ =0.4 and $\langle n_e \rangle / n_{Gr}$ =0.8

- **Available heating power during PFPO-1 is only 20-30 MW ECH (or 20 MW ECH and 10 MW ICRF)**

- **H-mode access in Hydrogen may be challenging in particular at high Greenwald fraction (dashed red line)**



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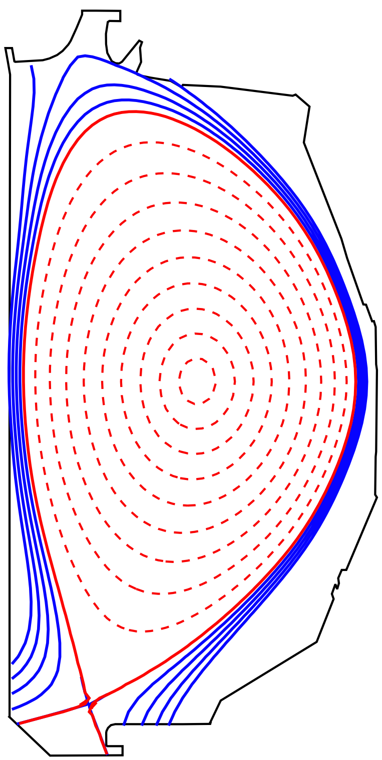
Electron-Heat Dominated Hydrogen Plasmas in ITER-Similar-Shape (ISS): L-Mode Profiles

ITER-Similar-Shape (ISS) Equilibrium



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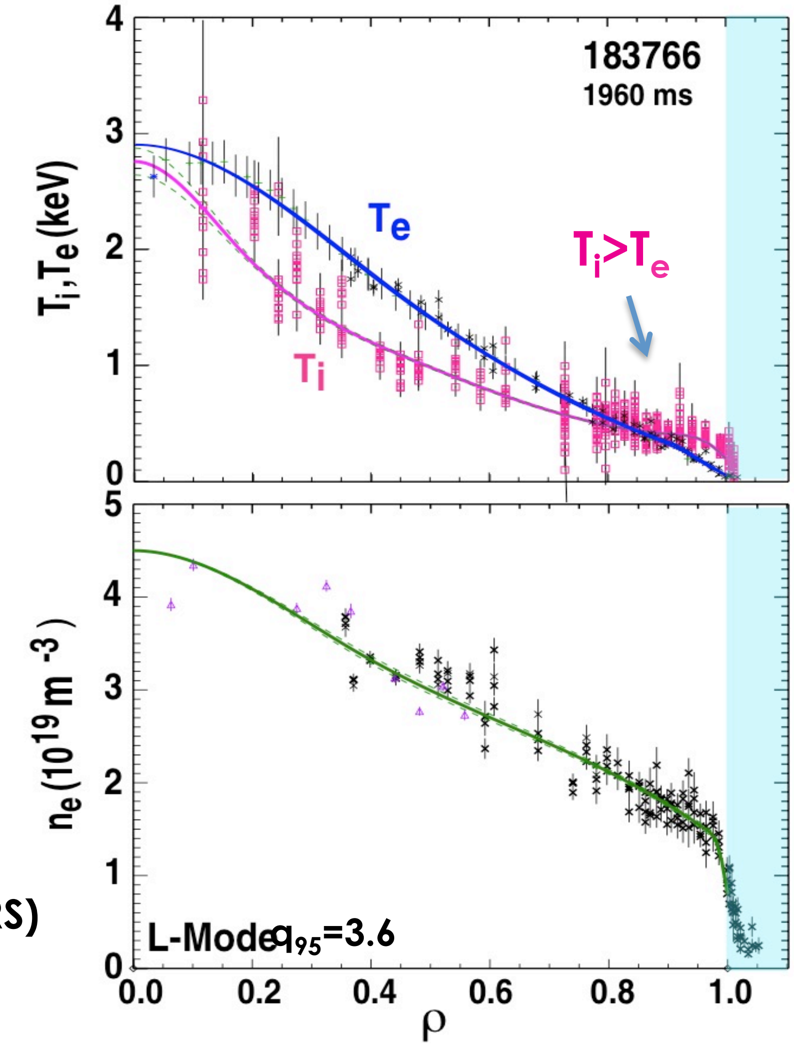
- $T_e/T_i > 1$ (core plasma)
- $T_e/T_i < 1$ (edge)
- $\langle n_e \rangle = 1.5\text{-}3.7 \times 10^{19}\ m^{-3}$
- B_t =1.95-2.05 T
- q_{95} =3.6-5.1
- Balanced NBI ≤ 8 MW + ECH ≤1.5 MW
- Hydrogen purity (CHERS) n_H/n_D ~90-95%

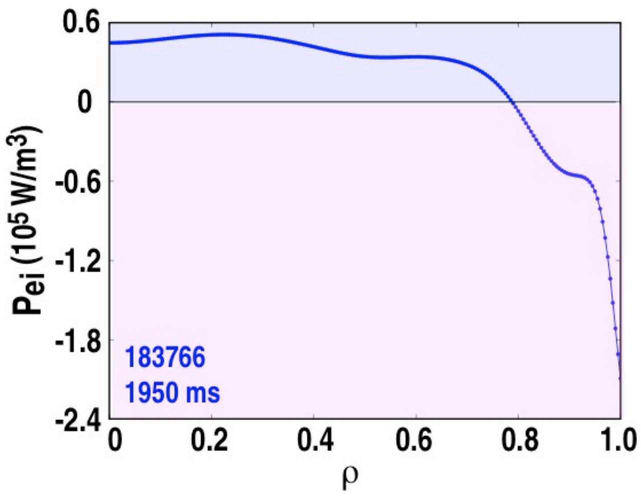


ITER–Relevant Regime: Electron-Heat-Dominated ISS Plasmas (ECH, Large Ion-electron Thermal Exchange)

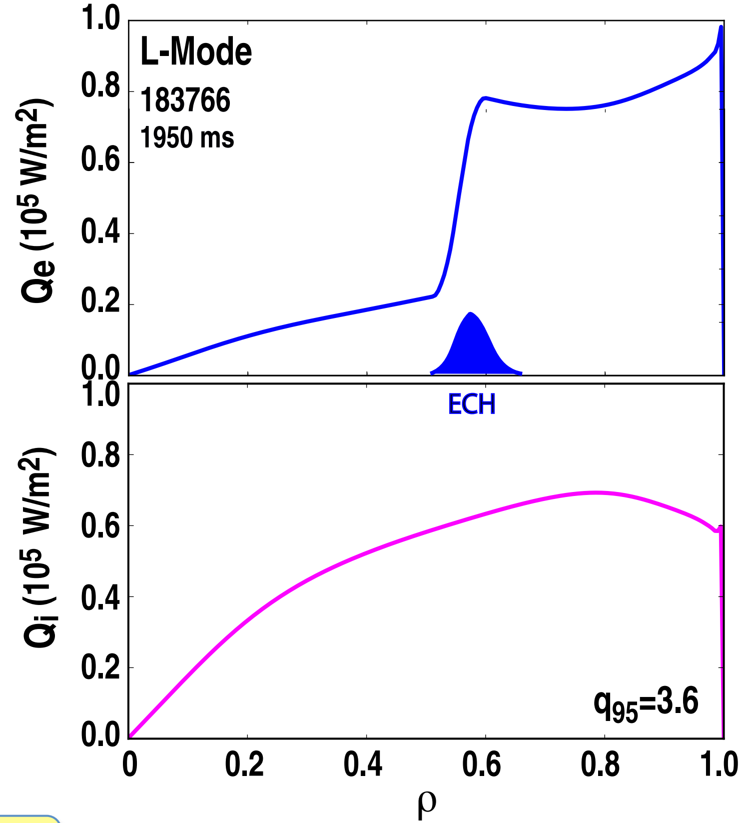
- **Plasma core: $T_e \geq T_i$, Edge: $T_i > T_e$:**
- **Ion–electron thermal exchange P_{ie} is important in the edge:**

$$P_{ie} \sim n_i n_e (Z_i^2 / m_i)(T_i - T_e) T_e^{-3/2}$$

- **Collisional exchange P_{ie} is larger in H than in D**



With ECH: Electron heat flux is dominant in the edge



P_{LH} is increased by the electron power loss!

With ECH: $\dfrac{Q_e(\rho = 0.95)}{Q_i(\rho = 0.95)} \geq 1.4$

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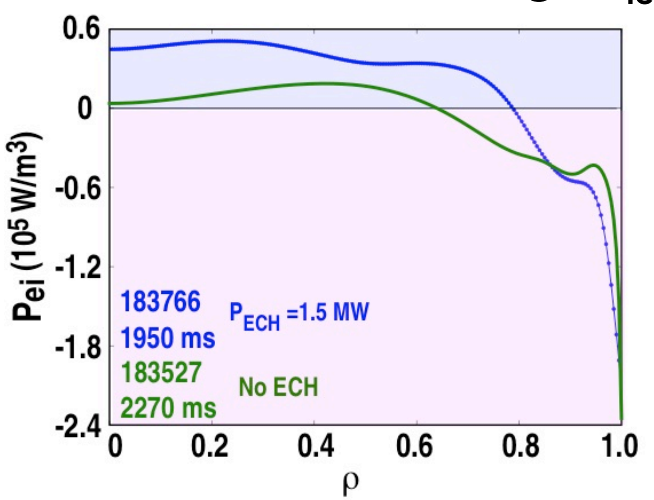
ITER–Relevant Regime: Electron-Heat-Dominated ISS Plasmas (No ECH, Large Ion-electron Thermal Exchange)

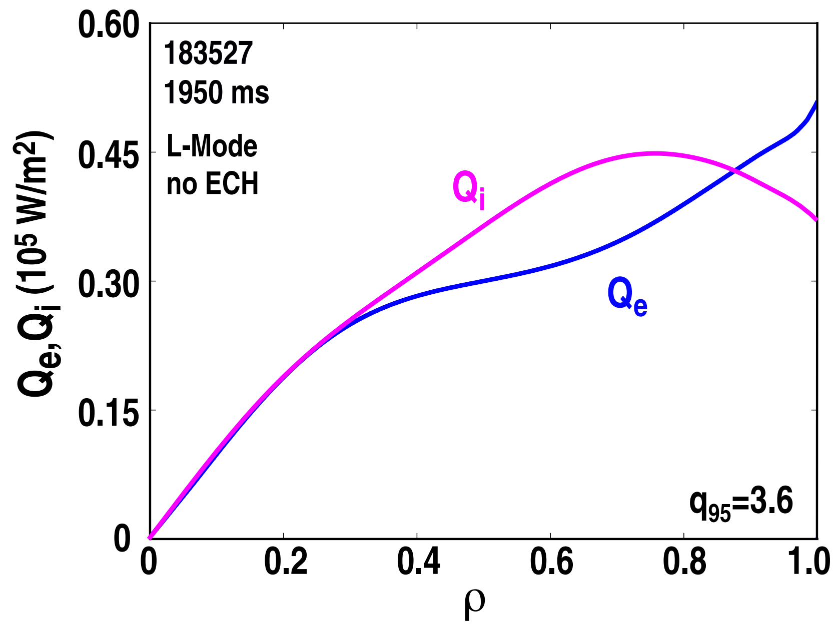
- **Plasma core: $T_e \sim T_{i,}$ Edge: $T_i > T_e$:**
- **Ion–electron thermal transfer P_{ie} is important in the edge:**

$$P_{ie} \sim n_i n_e (Z_i^2 / m_i)(T_i - T_e) T_e^{-3/2}$$

Collisional exchange P_{ie}



No ECH: Electron heat flux Is closer to Q_i in the edge



P_{LH} is increased by the electron power loss!

No ECH: $\dfrac{Q_e(\rho = 0.95)}{Q_i(\rho = 0.95)} \sim 1.15$

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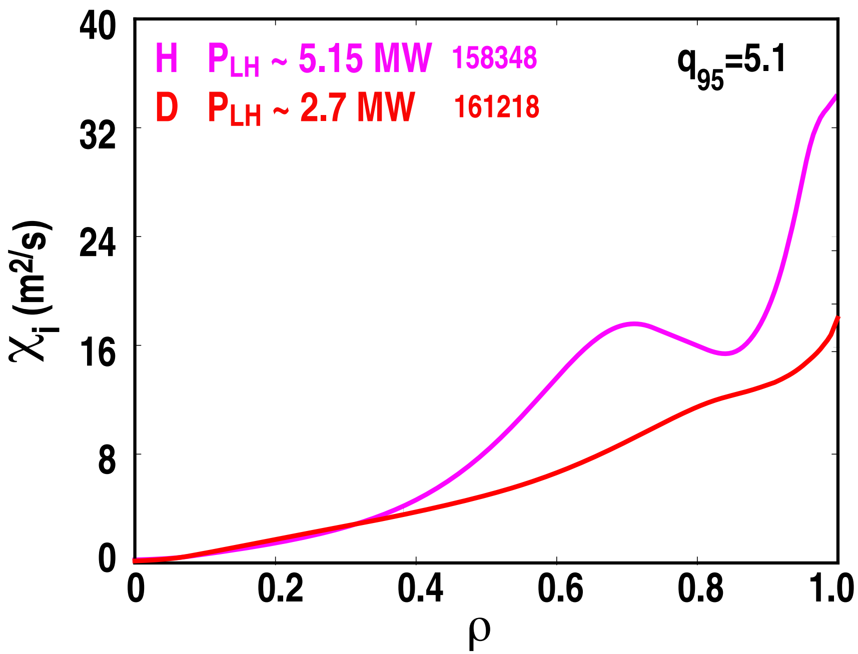
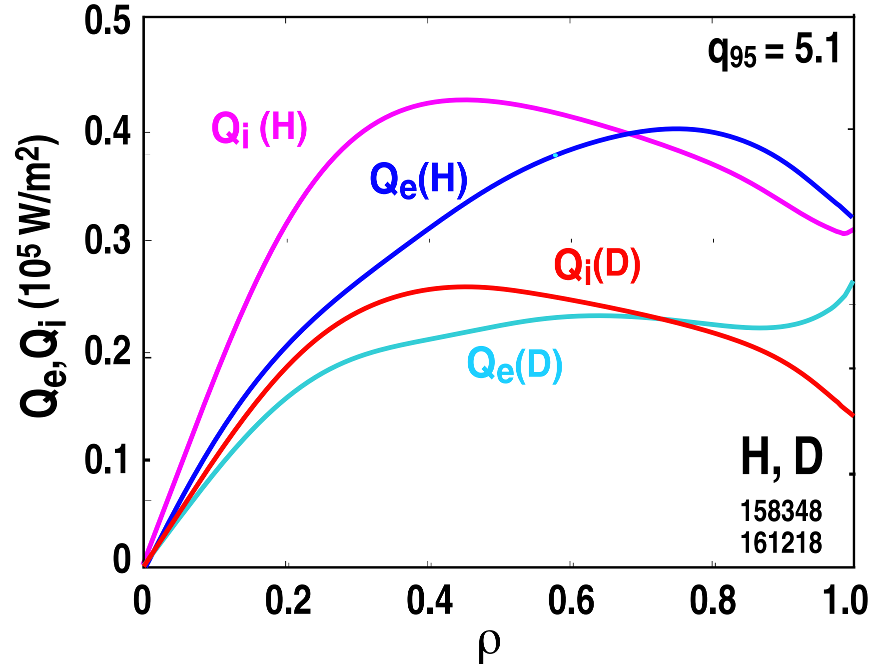
Hydrogen plasmas have ~2× Higher Ion Thermal Diffusivity and Ion Heat Flux than Deuterium Plasmas





- $Q_i^H(\rho=0.95) \sim 2\times Q_i^D(\rho=0.95)$ in agreement with earlier work*
- Ion Thermal Diffusivity also Increased: $\chi_i^H(\rho=0.95) \sim 2\times\chi_i^D(\rho=0.95)$
- Both H and D ISS plasmas have $Q_e/Q_i(\rho=0.95) \geq 1$
  - Thermal fluxes are reduced at high q_{95} but Q_e remains an additional loss channel that increases P_{LH}

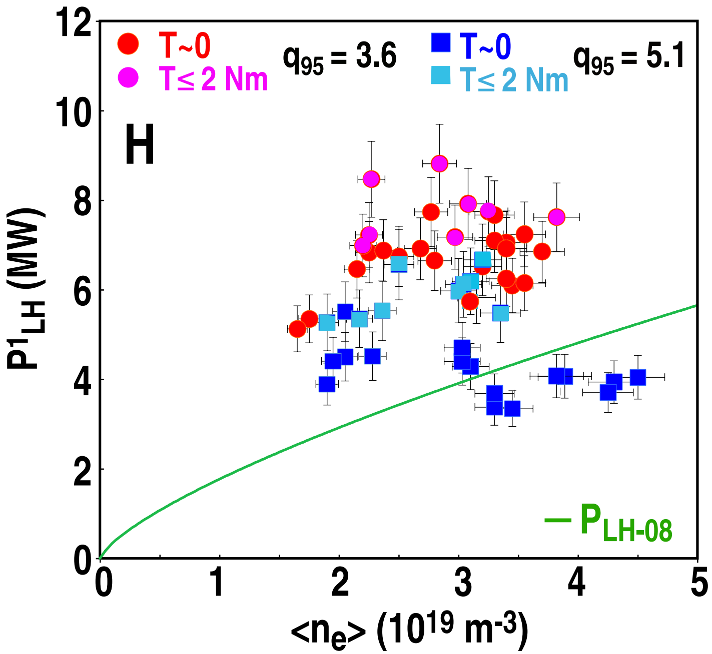
* F. Ryter et al., Plasma Phys. Control. Fusion 58, 014007 (2015).

Outline

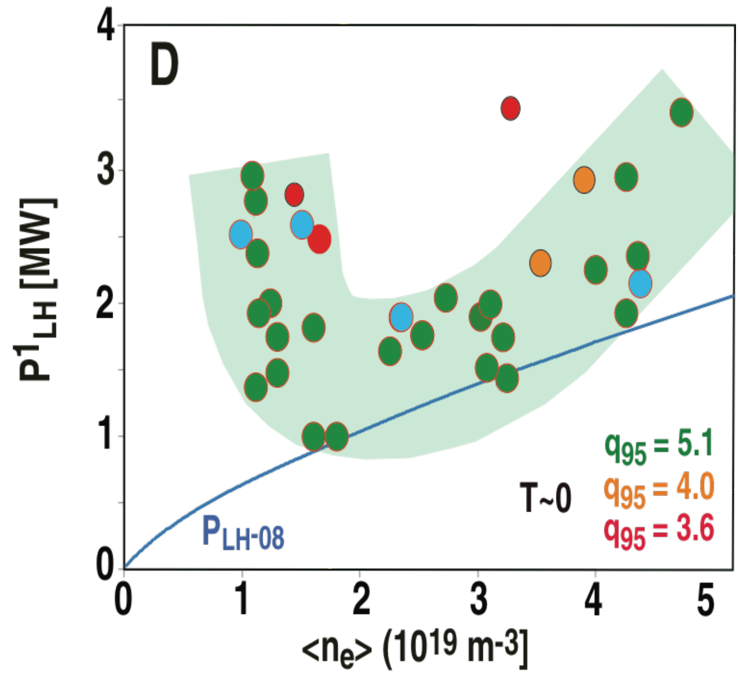
Safety Factor Dependence of P_{LH}

P_{LH} in Hydrogen Depends Strongly on Edge Safety Factor: $P_{LH}(H) \sim 3\times P_{LH}(D)$ at low q_{95}

ISS Hydrogen Plasmas



ISS Deuterium Plasmas



At low q_{95}=3.6, $P_{LH}^H \sim 3xP_{LH}^D$ (low torque)

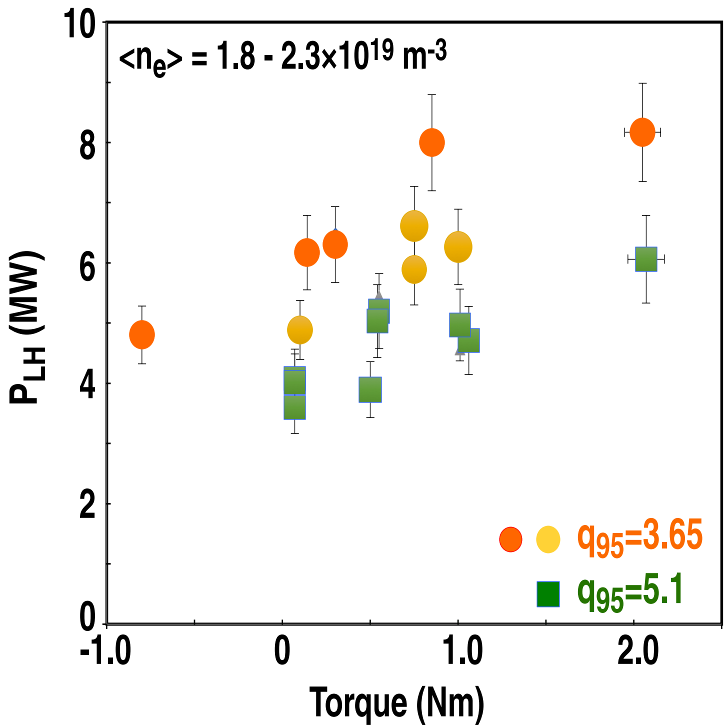
At high q_{95}=5.1, $P_{LH}^H \sim 2xP_{LH}^D$ (low torque)

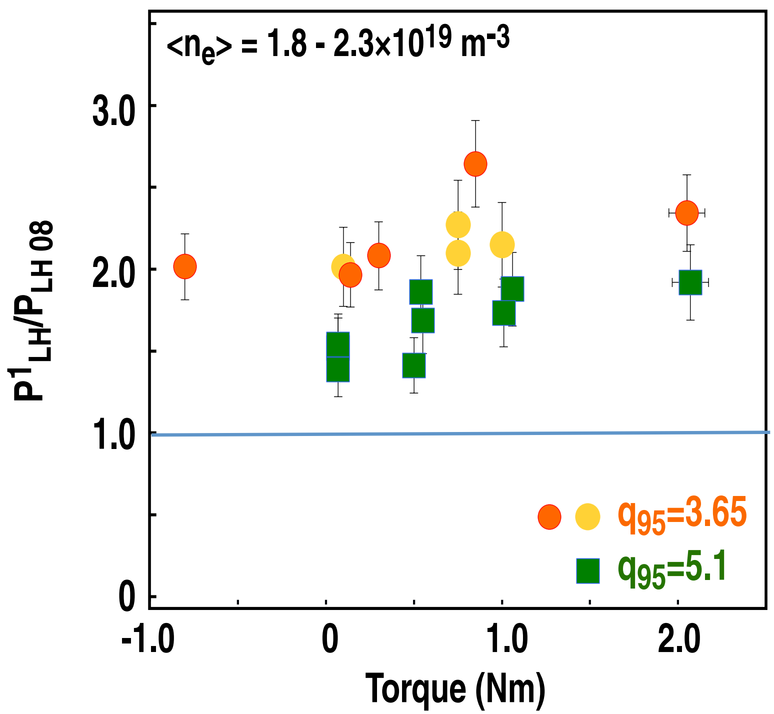
$$P_{LH}^1 = P_{NBI} + P_{ECH} + P_{OH} - dW_{dia} / dt$$

Martin scaling (Hydrogen: A_i= 2):

$$P_{LH-08}[MW] = 0.049 n[10^{20} m^{-3}]^{0.72} B[T]^{0.8} S[m^2]^{0.96} A_i$$

At Low Density, P_{LH} is Increased ~1.5× at Low q_{95} in Comparison to High q_{95}





- Strong Torque dependence for low and high q_{95}
- Threshold is above Martin scaling high and low and q_{95}

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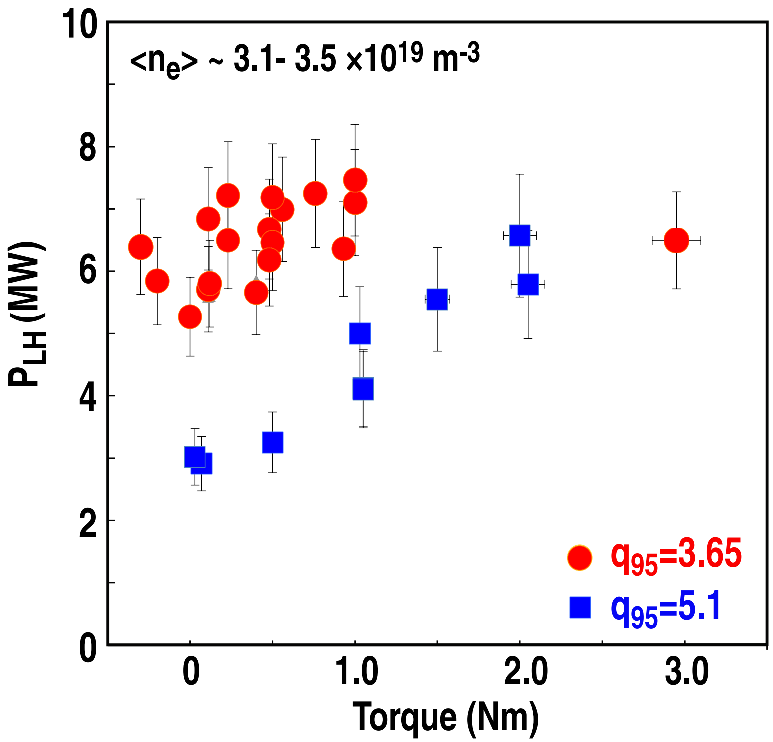
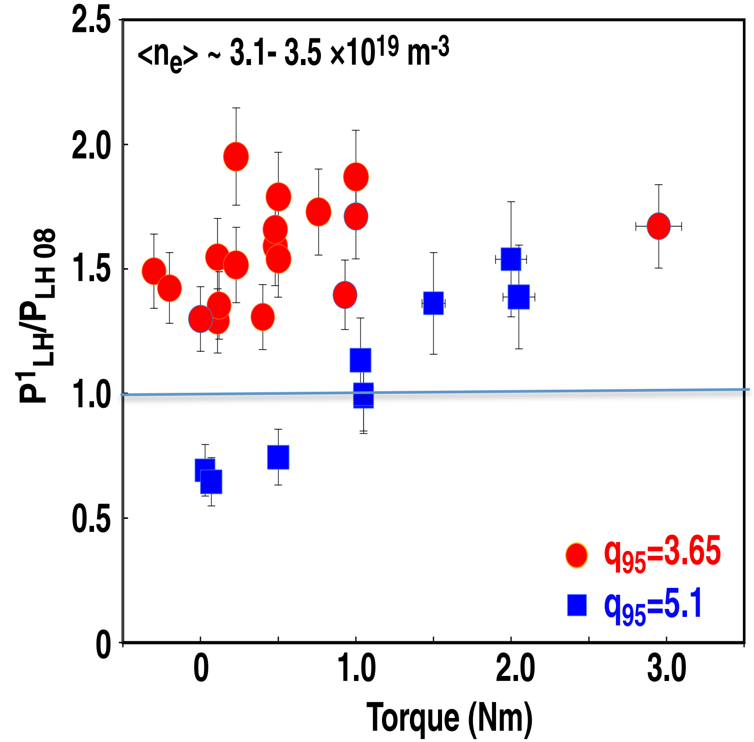
More Pronounced Safety Factor Dependence of P_{LH} at Higher Density

- At high q_{95} and low torque, threshold is below the Martin scaling





- Favorable P_{LH} scaling if L-H transition is initiated during ITER current ramp
- Safety factor dependence of P_{LH} is more pronounced in hydrogen than in deuterium

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Outline

Helium Admixtures

He-Admixtures: 10-20 ms Moderate Helium Puff Reduces P_{LH}

No He puff:

No Transition
up to P_{loss} ~ 7.2 MW

He puff 10 ms:

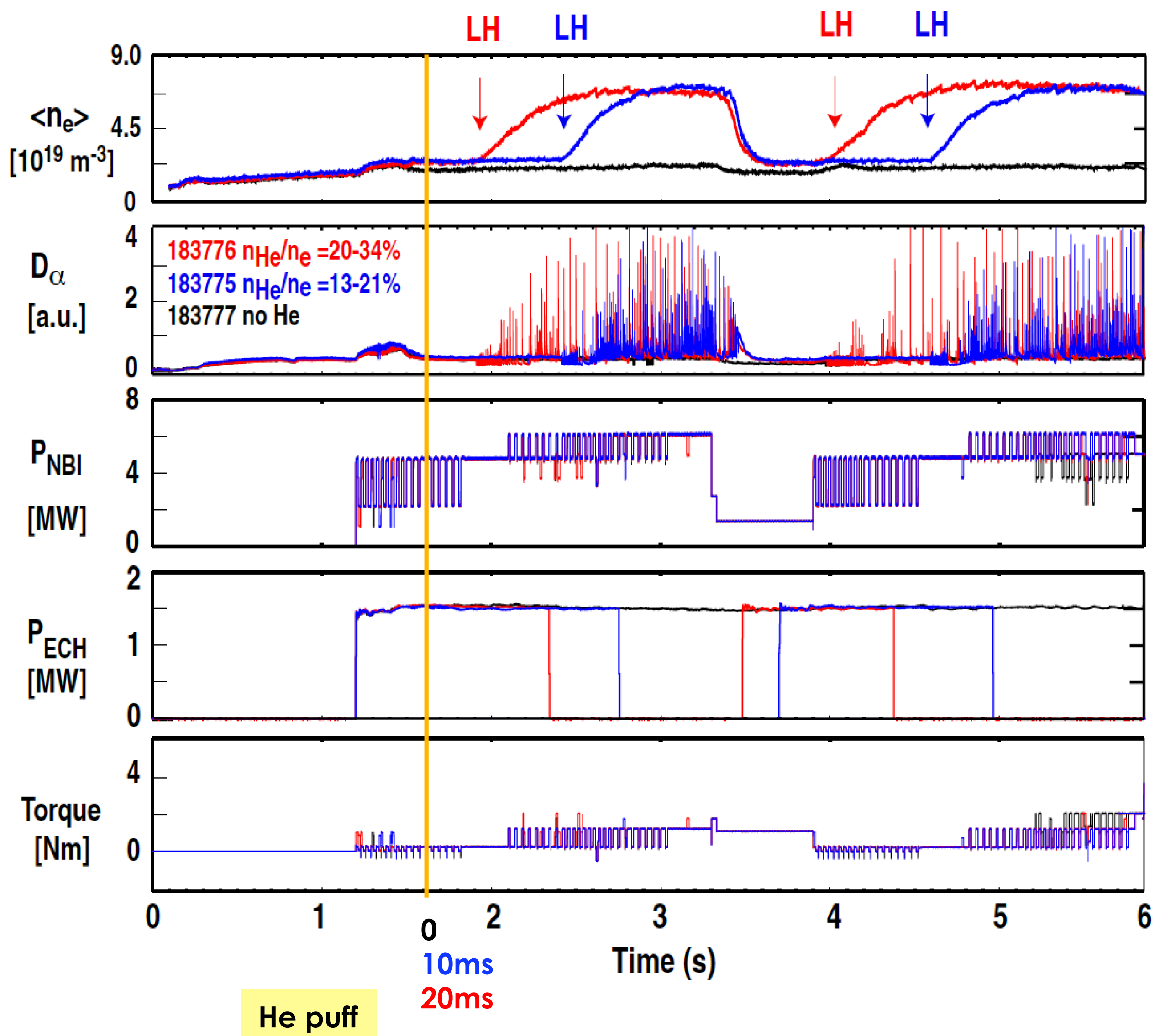
n_{He}/n_e=13%: P_{LH}= 6.7 MW
n_{He}/n_e=20%: P_{LH}= 5.7 MW

He puff 10 ms:

n_{He}/n_e=34%: P_{LH}= 4.4 MW
n_{He}/n_e=21%: P_{LH}= 5.5 MW

Γ_{He}=0.6-1.2 torr-l
Γ_D~35-70 torr-l

L-mode density:
n_e ~ $2.2 \times 10^{19} m^{-3}$



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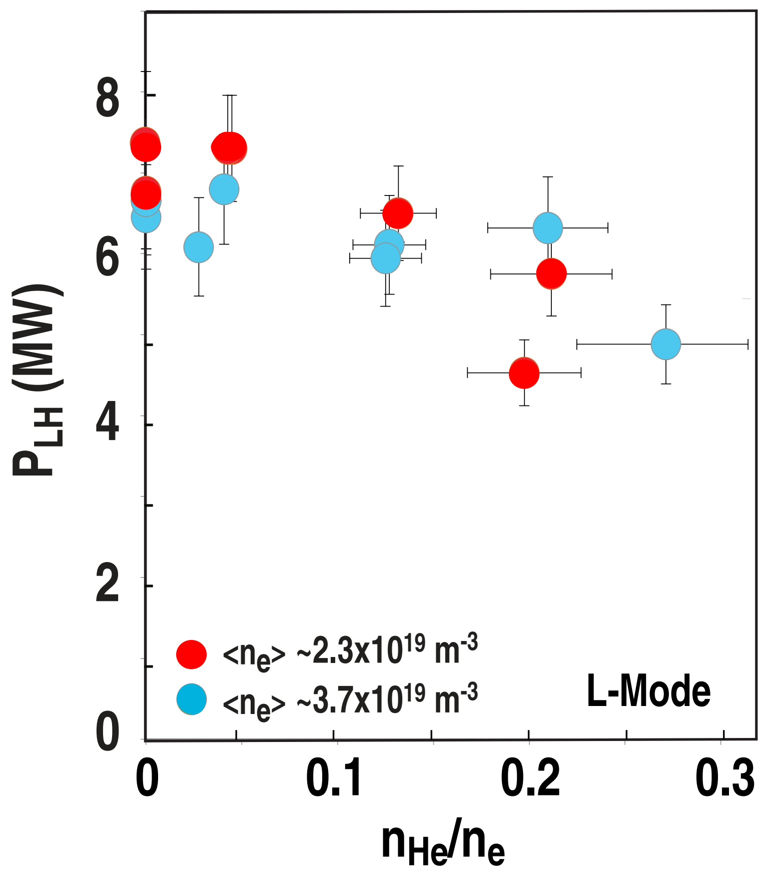
Helium Admixtures n_{He}/n_e~25% Reduce the L-H Power Threshold in Hydrogen Plasmas by ~ 30%

- **P_{LH} reduction observed at low and high L-mode density**
  - below/above the predicted power threshold minimum:*

$$n_{\min} = 0.7 I_p^{0.34} B_T^{0.62} a^{-0.95} (R/a)^{0.4}$$
$$\sim 3.1 - 3.5 \times 10^{19} m^{-3}$$

- **n_{He}/n_e ratio in the plasma edge determined via CHERS**
  - n_{He}/n_e integrated over ρ=0.75-1
  - n_H/n_D ~ 90-95% also inferred from CHERS and divertor spectroscopy

P_{LH} vs. relative Helium Density



Low Torque
T ≤ 0.4 Nm

*F. Ryter el al.
Nucl. Fusion 2014

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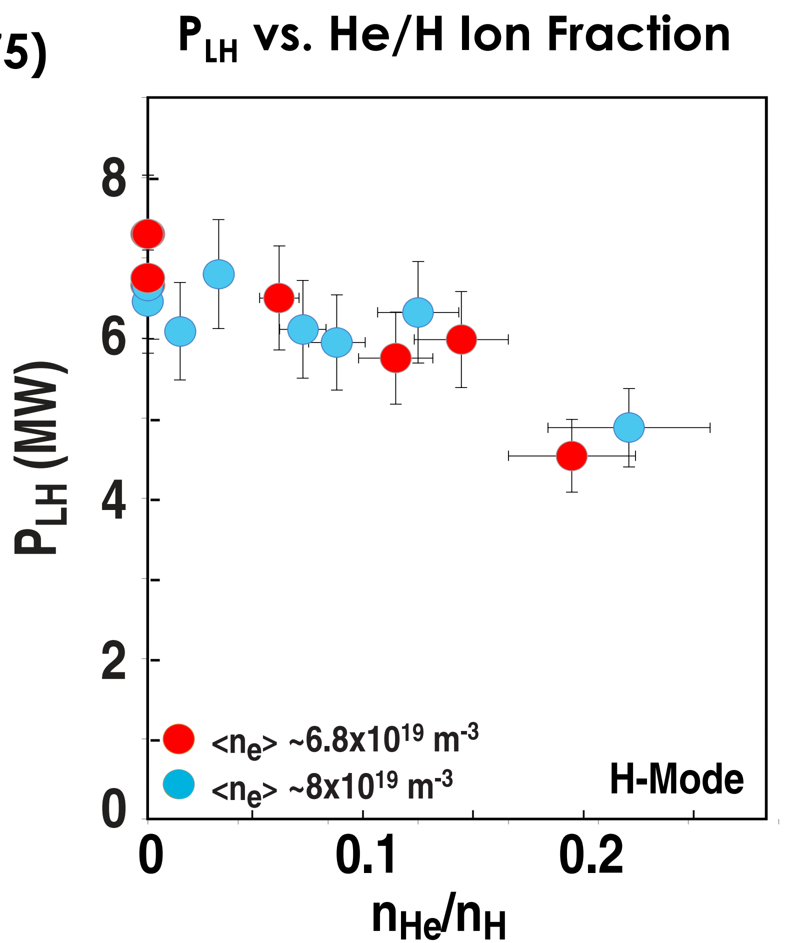
Moderate He Fractions Reduce P_{LH} by up to 30% in Hydrogen ISS Plasmas

- He/H ratio in the plasma edge ($\rho \geq 0.75$) determined via CHERS
- Shown is P_{LH} vs. the Helium ion fraction in the ensuing H-mode
- P_{LH} reduction measurable at n_{He}/n_H ~ 10%
- Z_{eff} (including He and C) remains reasonable:

Z_{eff} (H-mode) $\leq$ 2.2



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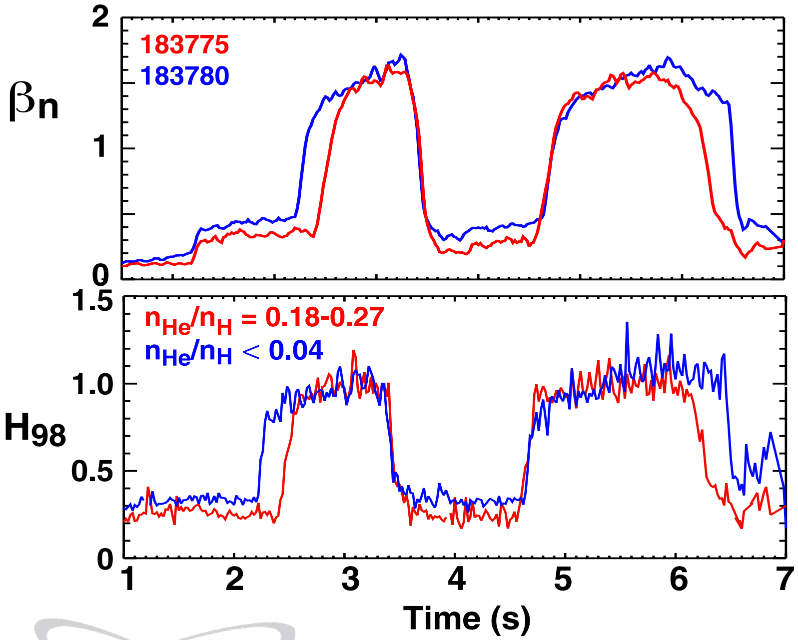
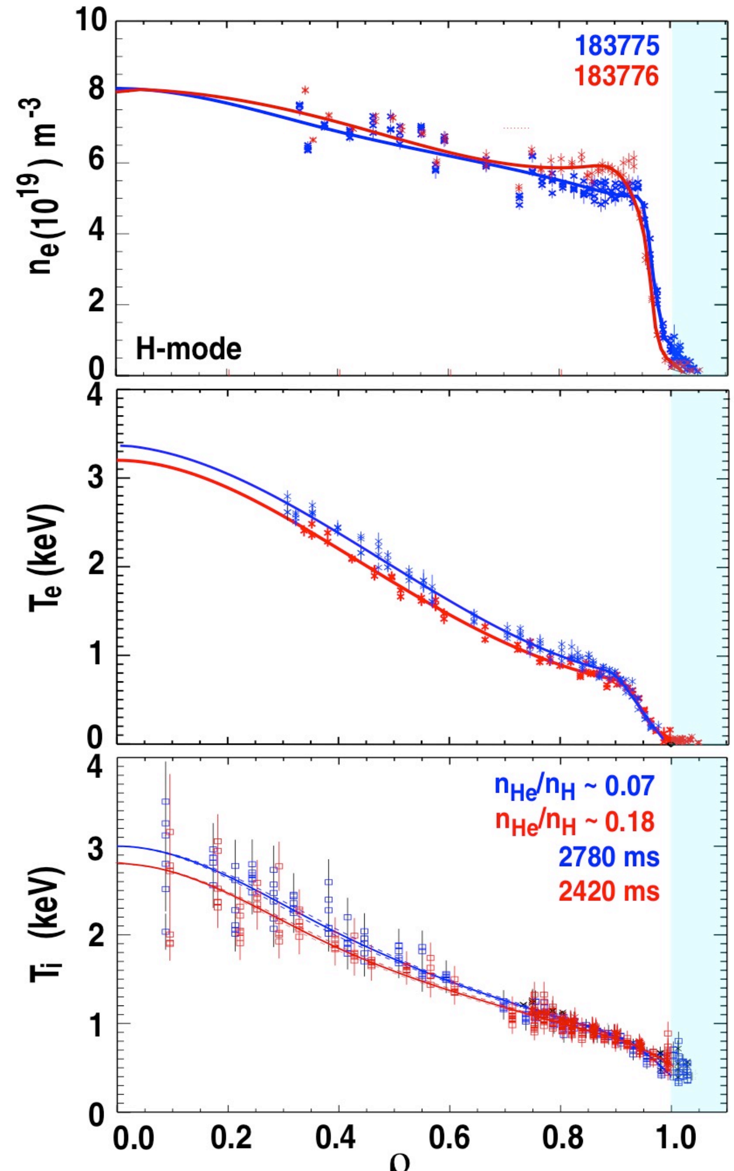
H-mode Confinement Degradation is Minimal even at Relatively High Helium Ion Faction

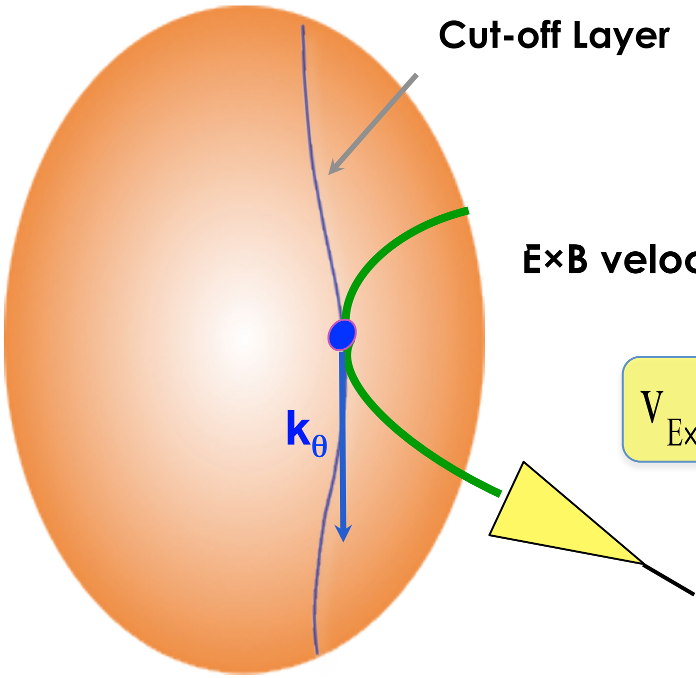
- **Pedestal Density Increases by ≤10%.**
- **Electron and ion temperatures decrease by less than 5% across the minor radius**
- **β_n, H_{98} decrease by ≤ 5%**





Doppler Backscattering and Beam Emission Spectroscopy for Turbulence and Flow Measurements

DBS measures E×B flow and density fluctuation levels ñ ($k_\perp$)



E×B velocity from Doppler shift:

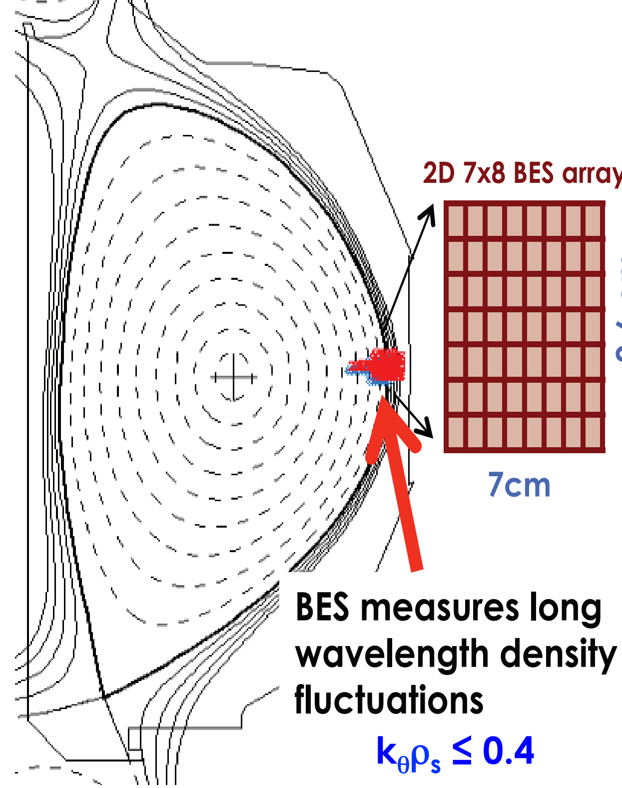
$$V_{E\times B} = 2\pi f_D / k_\theta - V_{ph}$$

Backscattering off density fluctuations.

Here, $k_\theta \rho_s \sim 0.6$

BES provides Reynolds stress from velocimetry analysis

- ITER similar Shape
Balance beam injection



BES measures long wavelength density fluctuations

$k_\theta \rho_s \leq 0.4$

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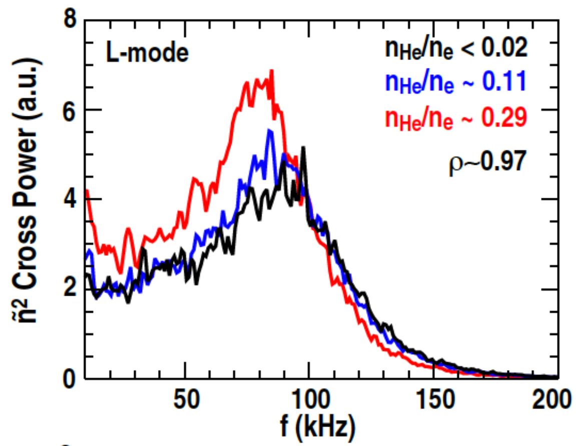
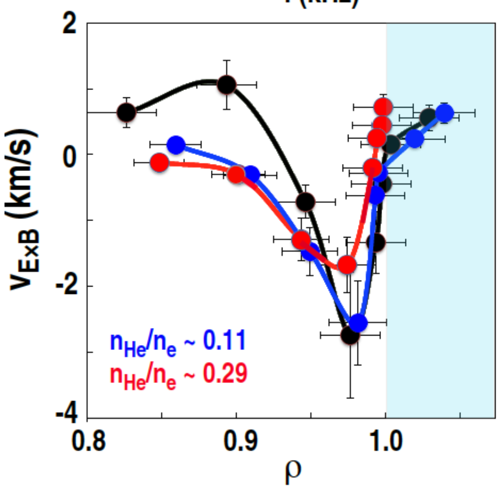
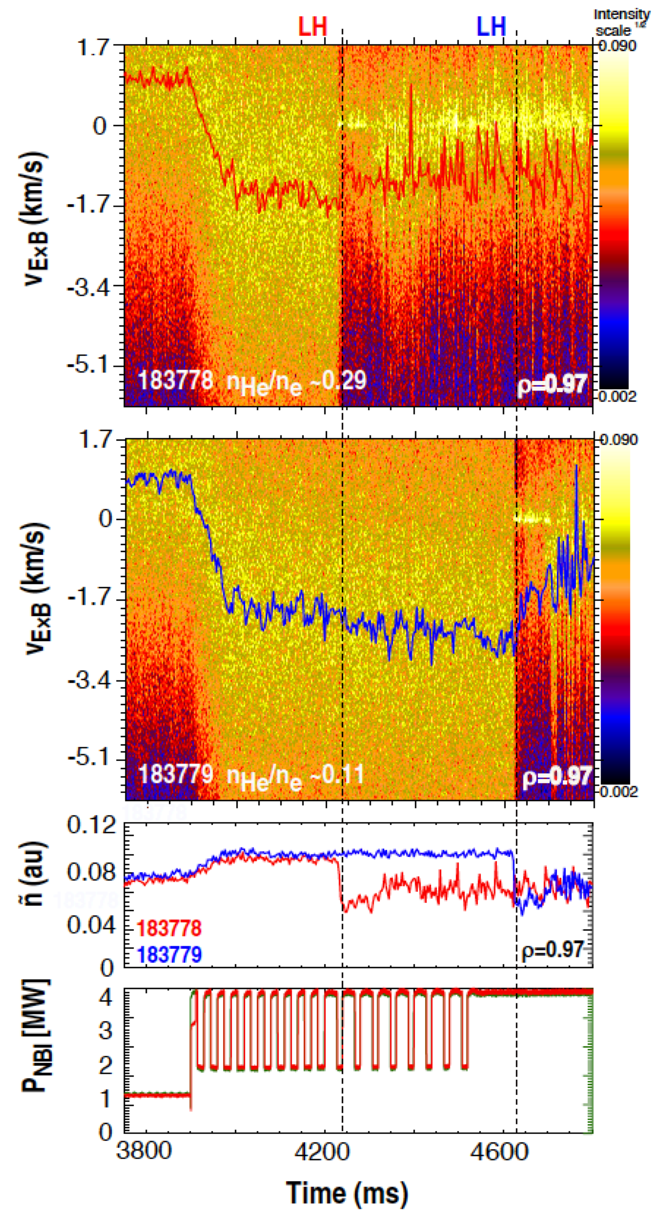
With Significant Helium Fraction, the Transition Occurs at Lower Edge Ion Pressure Gradient and E×B Shear





- **Hydrogen: High core χ_i :** Increased core efflux (heating power) required to build a critical (normalized) edge pressure gradient
- **Reduced core χ_i with Helium:** Transition at lower edge pressure gradient and E×B shear with higher He fraction
- Reduced ***E***×***B*** shear: Edge density fluctuation level Is increased!



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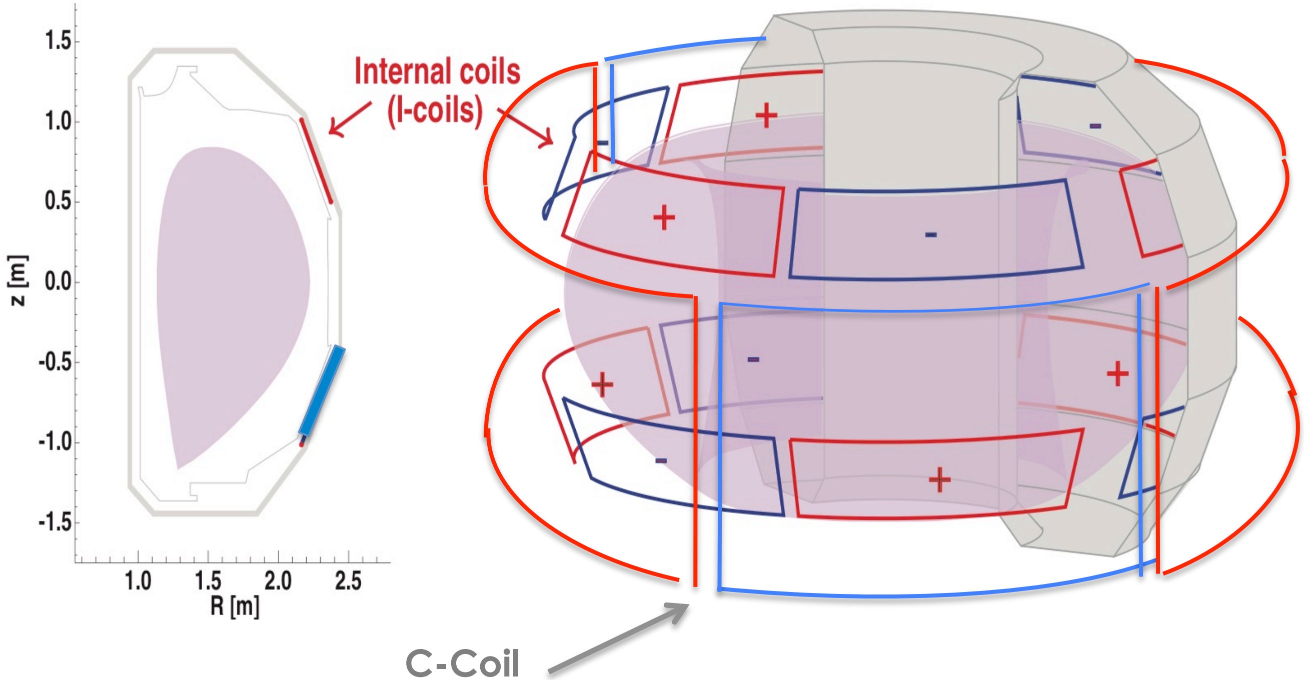
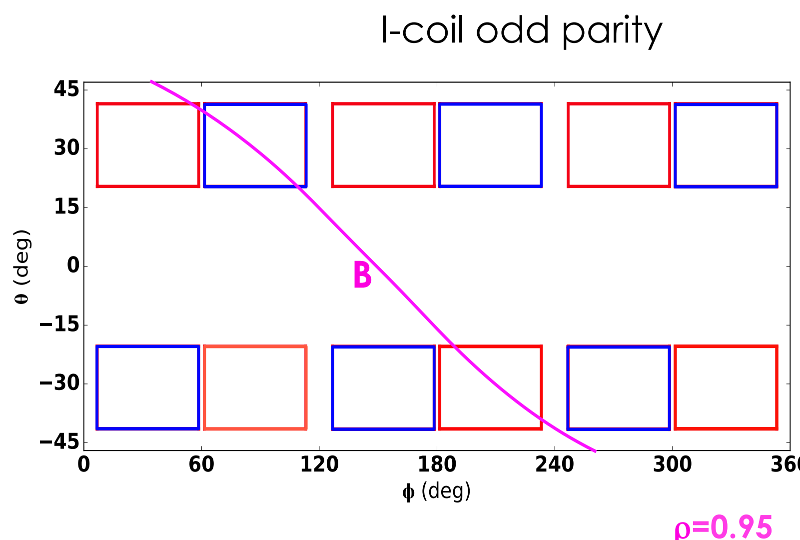
Outline

Applied NRMF/NTV

n=3 Non-Resonant Magnetic Perturbations (C-Coil/I-Coil) Potentially Impact Edge ExB Shear and P_{LH} via NTV





ITER-similar (ISS) shape (LSN)
LSN, B_t=1.95T, q_{95}~3.6
Balanced Torque (low rotation)

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n=3 Non-Resonant Magnetic Perturbations (C-Coil/I-Coil) Potentially Impact Edge ExB Shear and P_{LH} via NTV*

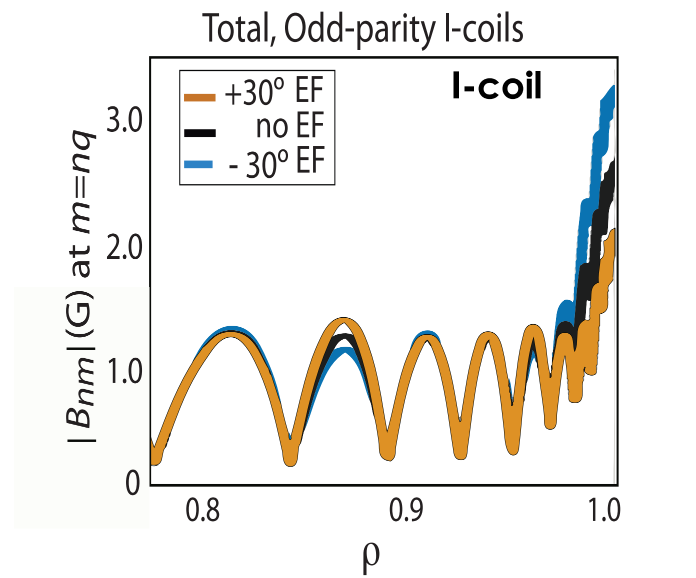
- **n=3 C-coil or odd parity I-coil**
- **Non-resonant perturbations can generate edge counter-torque via Neoclassical Toroidal Viscosity (NTV)**
- **Expect NTV torque up to ~1.5 Nm at low ion collisionality**
- **Can we tailor n=3 field profile and NTV via combination of I-coil and C-coil?**

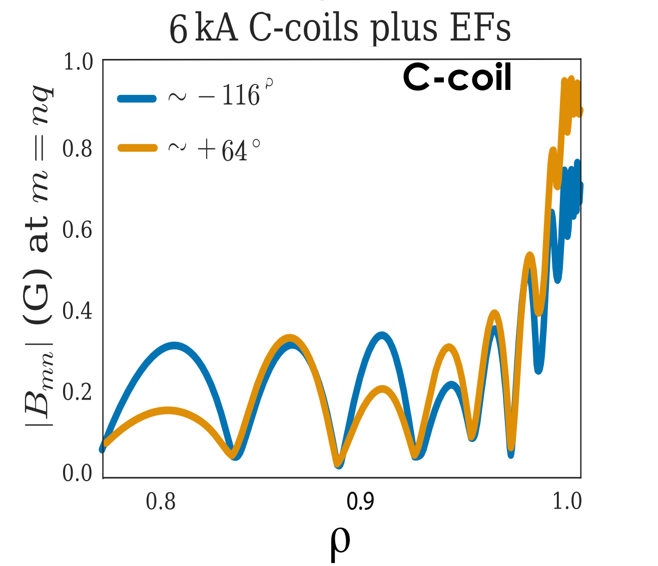
$$\frac{nm_i \partial \left\langle R^2 \Omega_\phi \right\rangle}{\partial t} = -nm_i \mu_{II}(\nu_{ii}) \left[\frac{\delta B_{NRMF}}{B} \right] \left(\left\langle R^2 \Omega_\varphi \right\rangle - \left\langle R^2 \Omega_{NTV} \right\rangle \right)$$

Ω_{NTV}: Offset rotation

*A.J. Cole et al. Phys. Plasmas 3527 055011 (2011)

Non-res. Field w/ Plasma Response





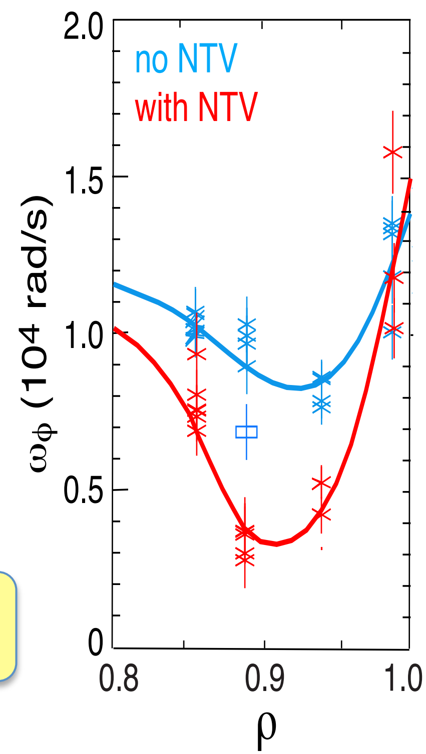
Initial Evidence: NTV from Applied Non-resonant Magnetic Fields Reduces Edge Toroidal Rotation and P_{LH}

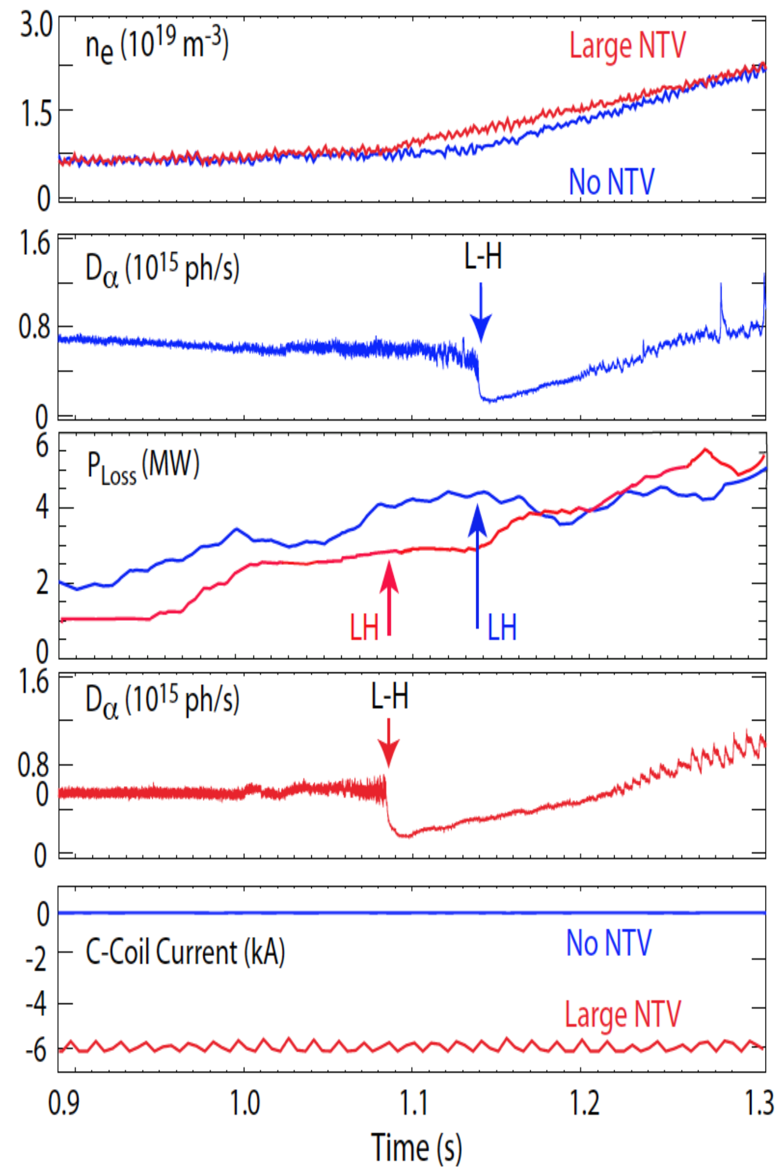
- **Largest NTV expected at low collisionality**

L-mode edge co-rotation is reduced via NTV counter-torque:

Edge E×B Shear is substantially increased

P_{LH} is reduced by 20-25% with $\delta B/B$ ~2.5×10^{-4}





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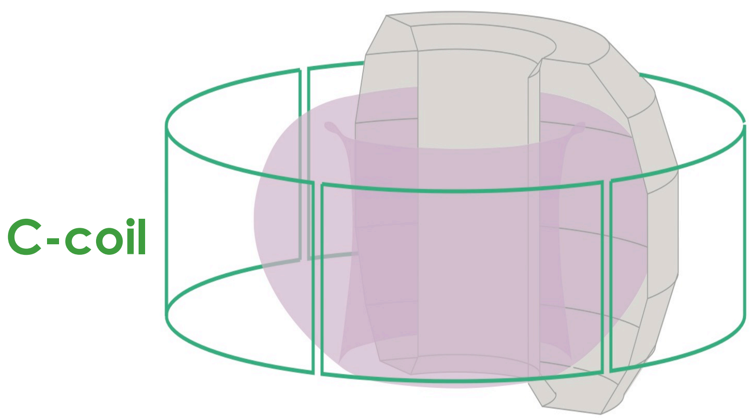
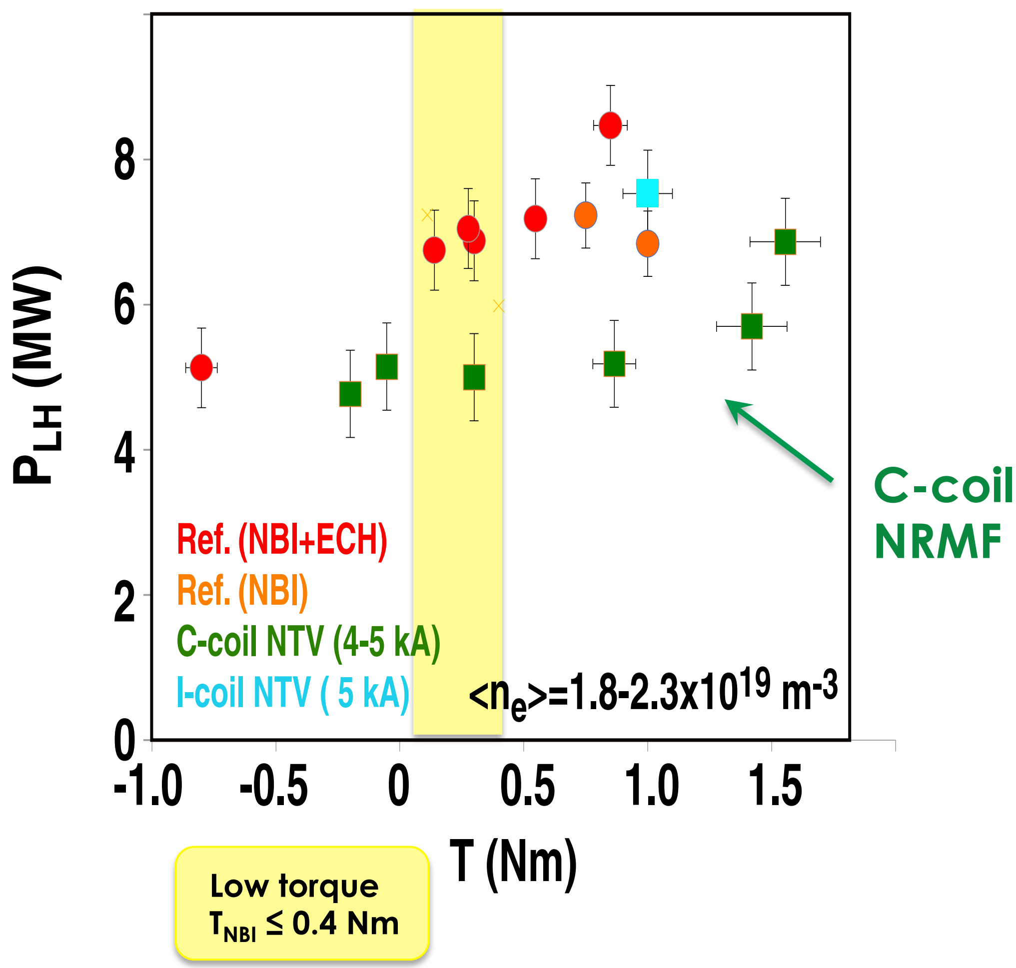
Applied n=3 NRMF Reduces P_{LH} by 15-25% in ISS Hydrogen Plasmas (q_{95}=3.6)

- Largest effect from C-coil NRMF (I-coil not tested sufficiently)
- Initial evidence that Counter-I_p torque from Neoclassical Toroidal Viscosity increases edge E×B shear
- Experiments conducted at low ion edge collisionality to enhance NTV



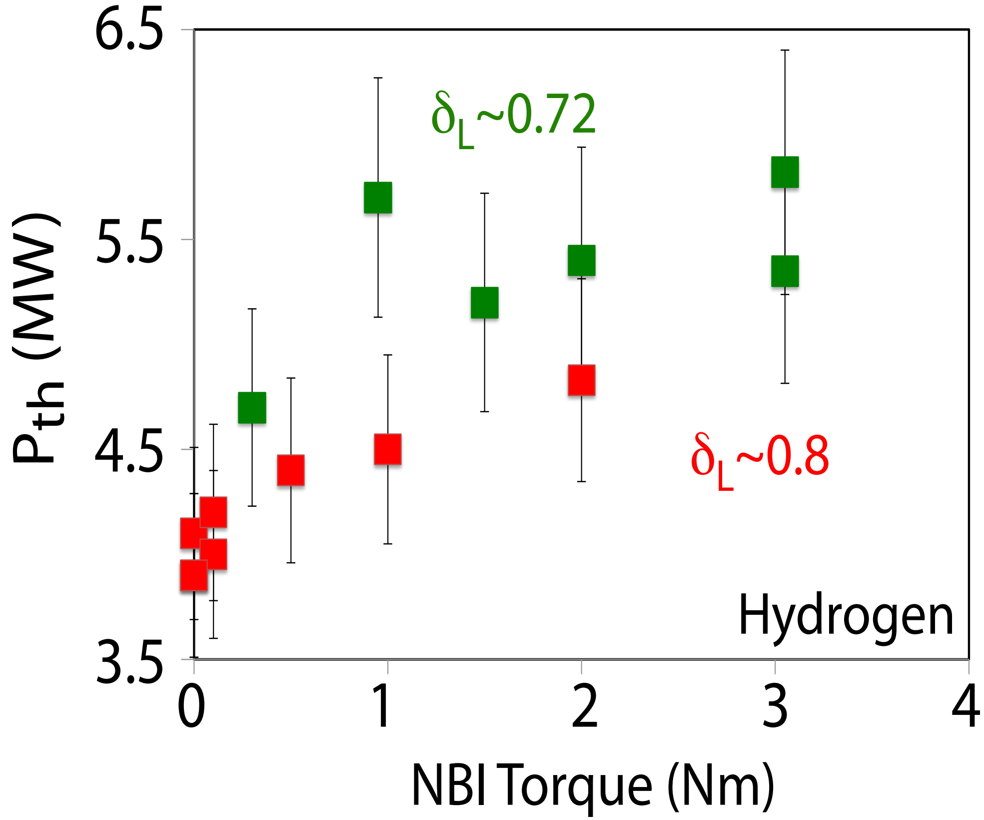
- P_{LH} reduced due to edge NTV counter-torque?

P_{LH} w/wo NTV vs. Torque



A Small Reduction in Lower Triangularity Reduces P_{LH} in Hydrogen Plasmas by 5-10%

- P_{LH} is reduced when the Lower triangularity changed from δ_L ~0.8 to 0.72 (10%)
- Potential concomitant increase in divertor neutral pressure
- Reduction observed across range of NBI torque
- (Very) small database of deuterium shots showing a similar reduction effect



Summary

- **Helium injection reduces P_{LH} substantially in electron-heat-dominated ISS hydrogen plasmas (≤ 30% for n_{He}/n_H ~ 25%)**
- **Applied n=3 NRMF (C-coil) reduces P_{LH} by ~ 15-25%**
  - most effective at finite co-torque
  - ITER can likely produce sufficient edge NTV with partial set of 3D-coil power supplies during PFPO-1
- **A pronounced q_{95} dependence of power threshold was observed in Hydrogen: P_{LH}^H is $3 \times P_{LH}^D$ at ITER-relevant (low) q_{95}**
  - Accessing H-mode at higher q_{95} during the current ramp may be beneficial in ITER
- **Without mitigation measures, the power threshold is expected to be significantly higher than $2 \times P_{LH\text{-}08}$ in electron-heat-dominated ITER hydrogen plasmas**

*Part of the data analysis was performed using the OMFIT integrated modeling framework; O. Meneghini et al., Nucl. Fusion 55 083008 (2015).