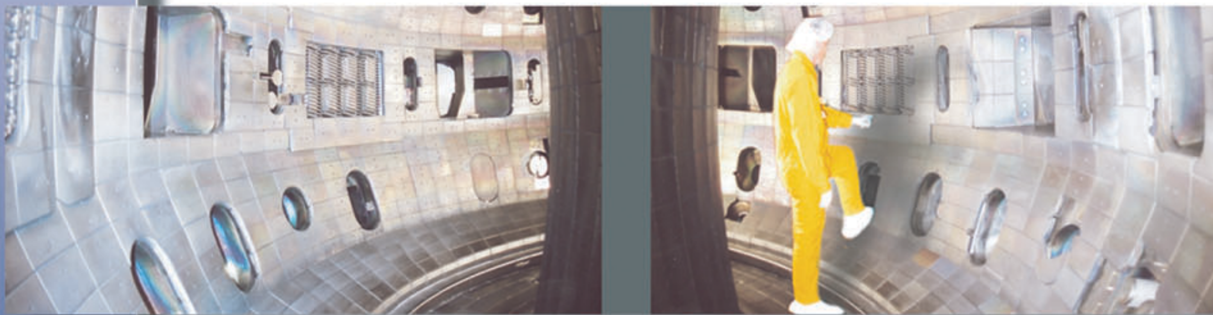

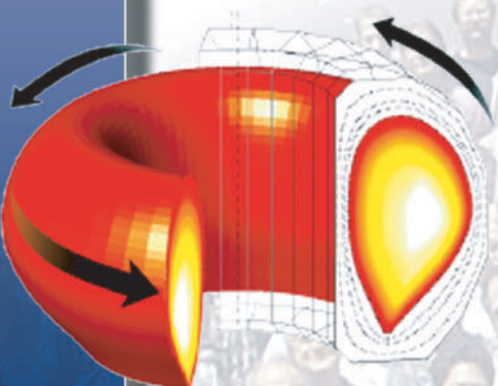

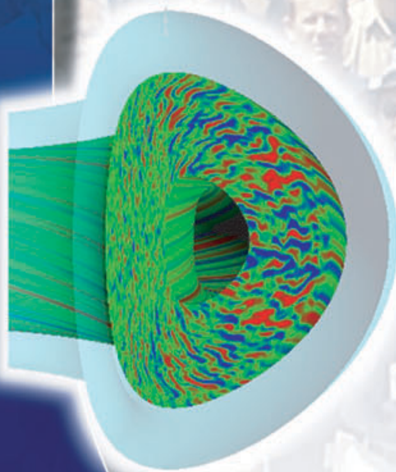

Development, Physics Basis, and Projections of Hybrid Scenario Operation in ITER on DIII–D

by
M.R. Wade
for the DIII–D Team

Presented at
20th IAEA Fusion Energy Conference
Vilamoura, Portugal

November 3, 2004

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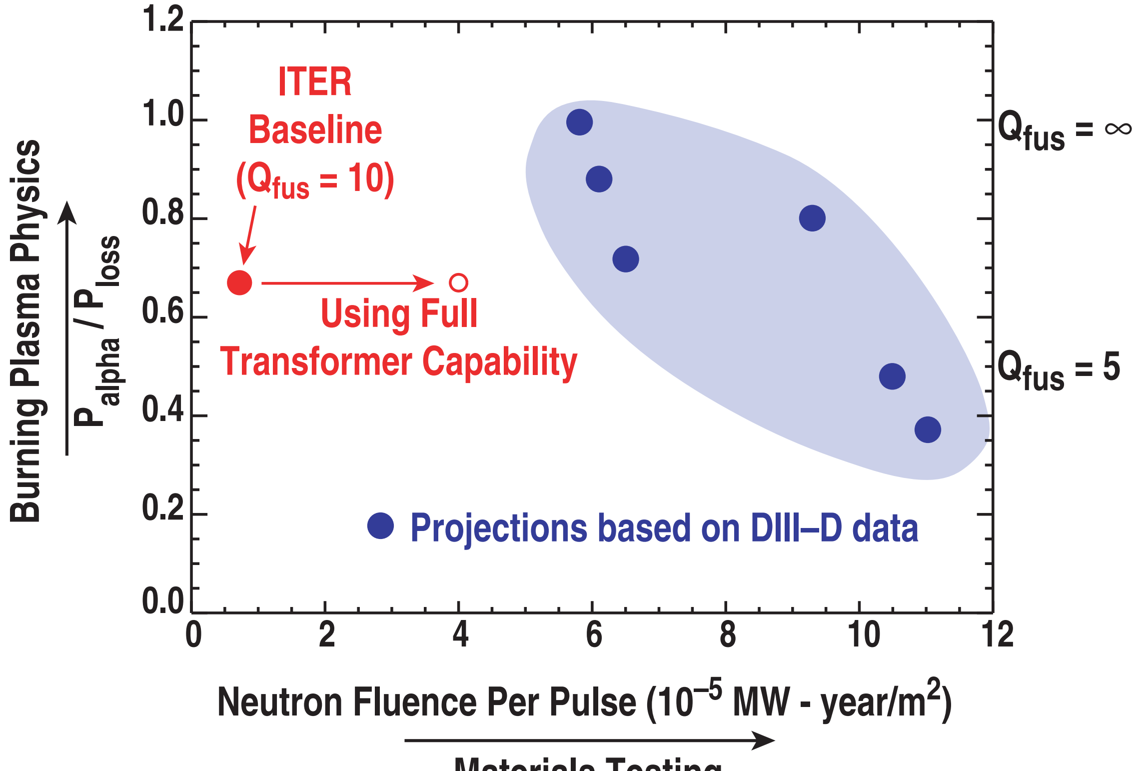
'HYBRID' REGIME: A NEW STANDARD IN STATIONARY TOKAMAK PERFORMANCE THAT OFFERS ENHANCED RESEARCH OPPORTUNITIES IN ITER

- 'Hybrid' Regime was originally conceived to take advantage of improved performance and current drive capabilities to achieve long-pulse operation in ITER (at $Q_{fus} < 10$)

- Over the past few years, DIII–D has demonstrated stationary operation with $\beta \geq 80\% \beta^{no\text{-}wall}$ and $H_{89} > 2$ over a wide range in q_{95} ($2.8 < q_{95} < 5$) and density ($0.3 < n_{eo}/n_{GW} < 0.75$)

- Projections based on this data are uniformly positive and offer a wide range of operating options in ITER
  - $Q_{fus} = \infty$ ($q_{95} = 3$)
  - $Q_{fus} = 10$ for 3900 s ($q_{95} = 4.4$)



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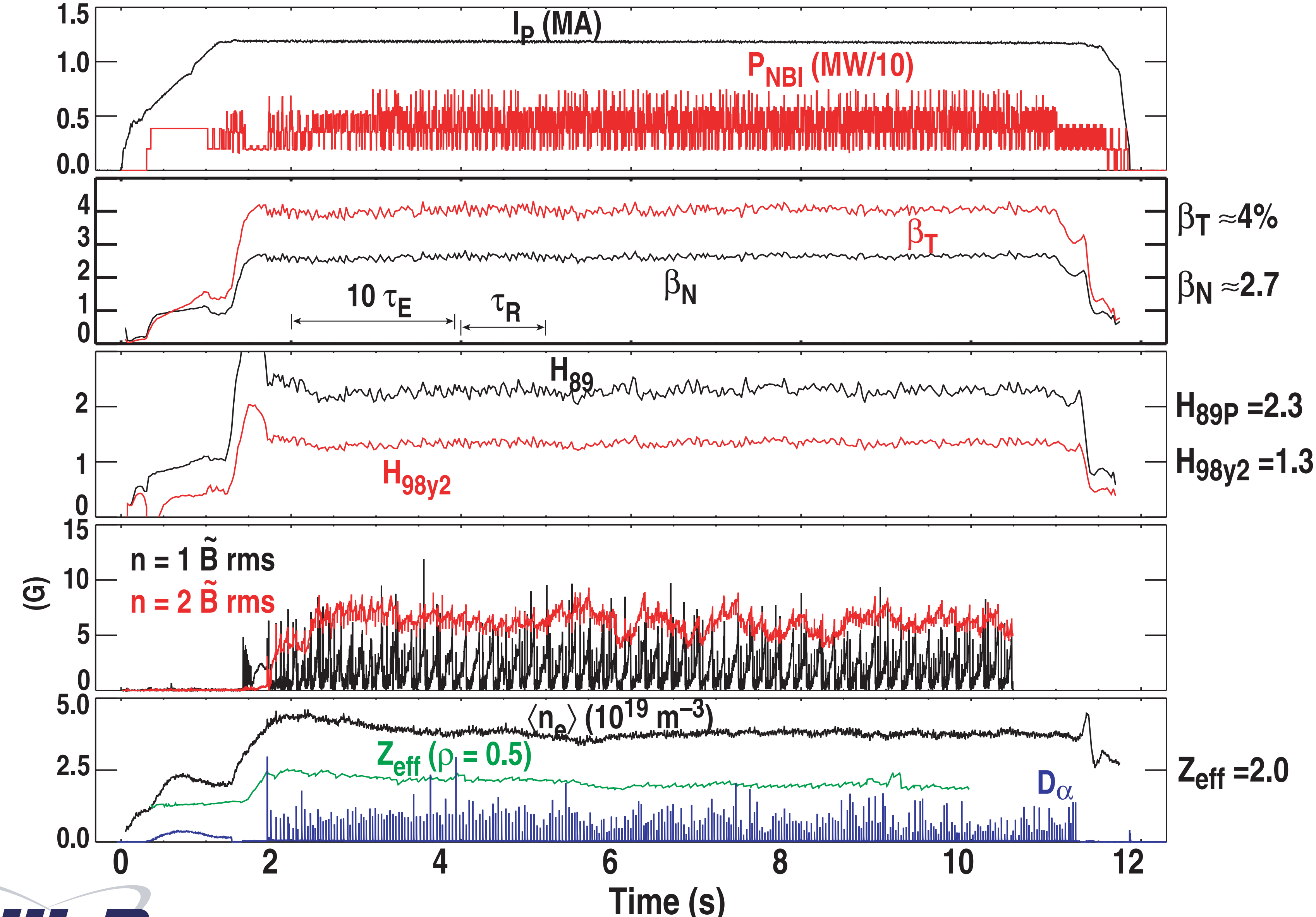
RECENT EXPERIMENTS HAVE DEMONSTRATED TRULY STATIONARY (> 9 τ_R), HIGH PERFORMANCE OPERATION



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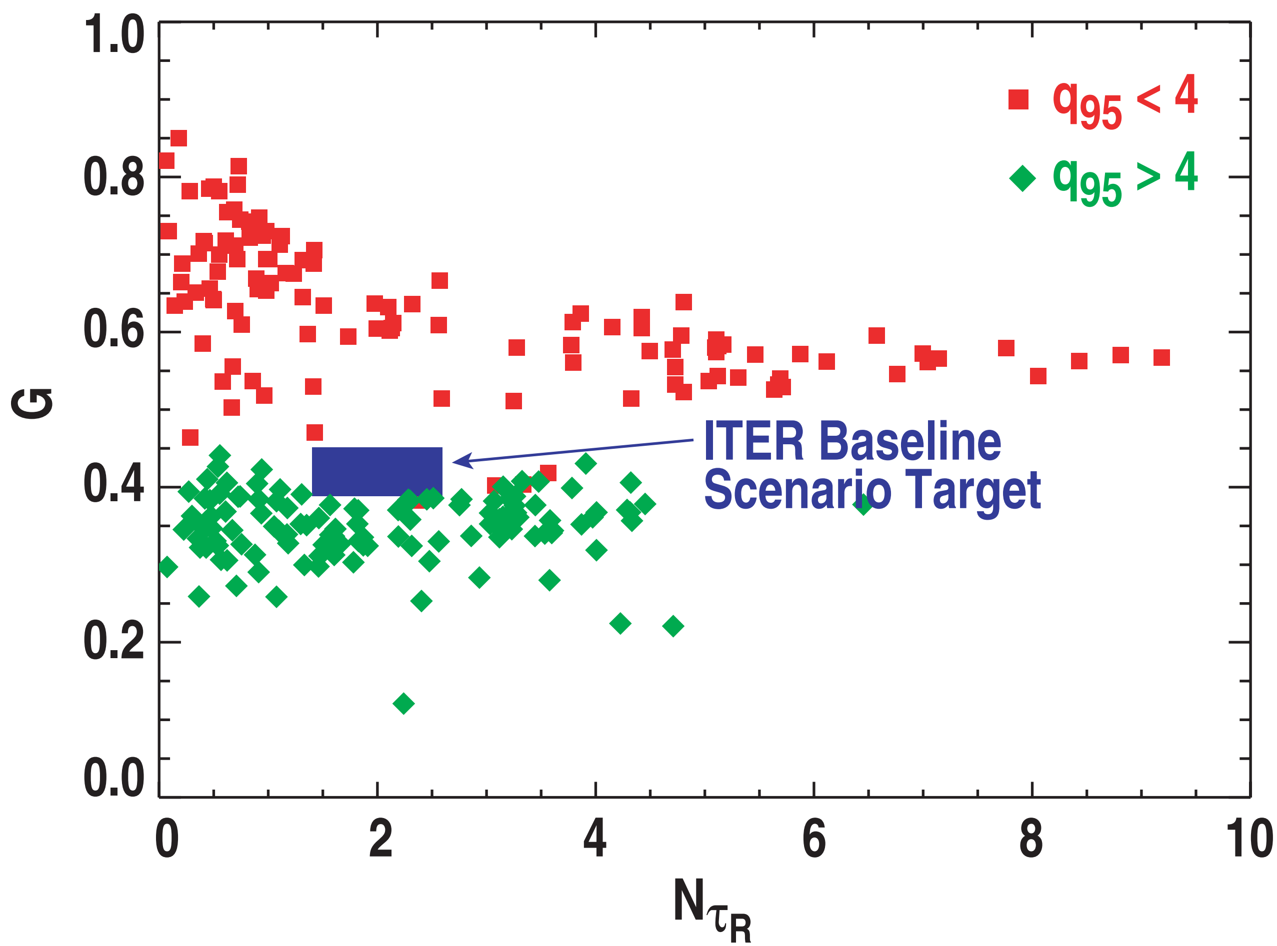
NORMALIZED FUSION PERFORMANCE AND DURATION COMFORTABLY EXCEED THAT OF ITER BASELINE SCENARIO

- **Fusion Performance:**
  $G = \beta_N H_{89}/q_{95}^2$ as measure of P_α/P_{LOSS}

- **Duration:**
  $N_{\tau_R} = t_{dur}/\tau_R$ as measure of stationarity



[Mikkelsen, Phys. Fluids B 1 333 (1989)]

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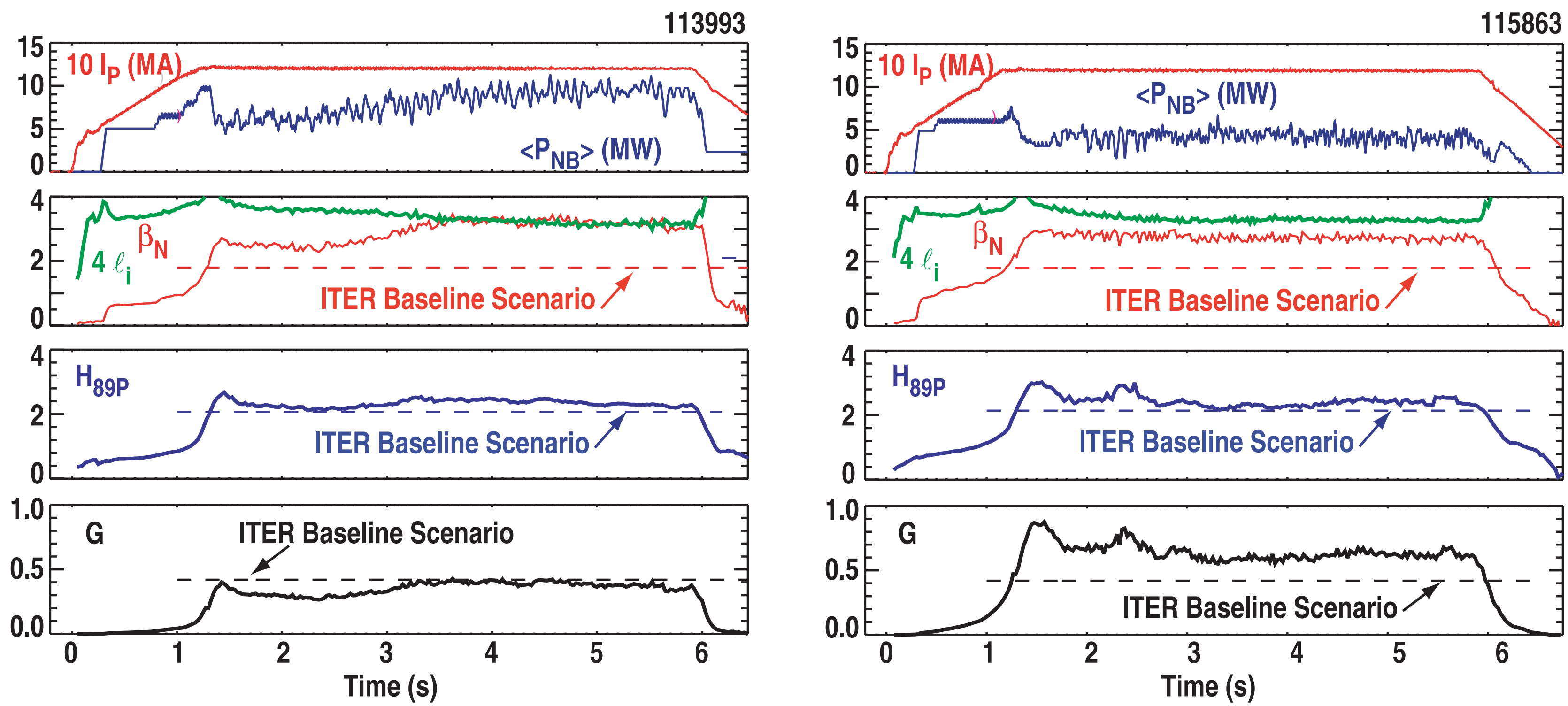
PERFORMANCE AT OR ABOVE ITER BASELINE DESIGN HAS BEEN ACHIEVED OVER A WIDE RANGE IN q_{95}



- $q_{95} = 4.4$
- $\beta_N \approx \beta_N^{no\text{-}wall}$
- $G \approx G_{ITER}$
- No Sawteeth

- $q_{95} = 3.2$
- $\beta_N \gtrsim 0.8\, \beta_N^{no\text{-}wall}$
- $G \approx 1.5\, G_{ITER}$
- Small Sawteeth

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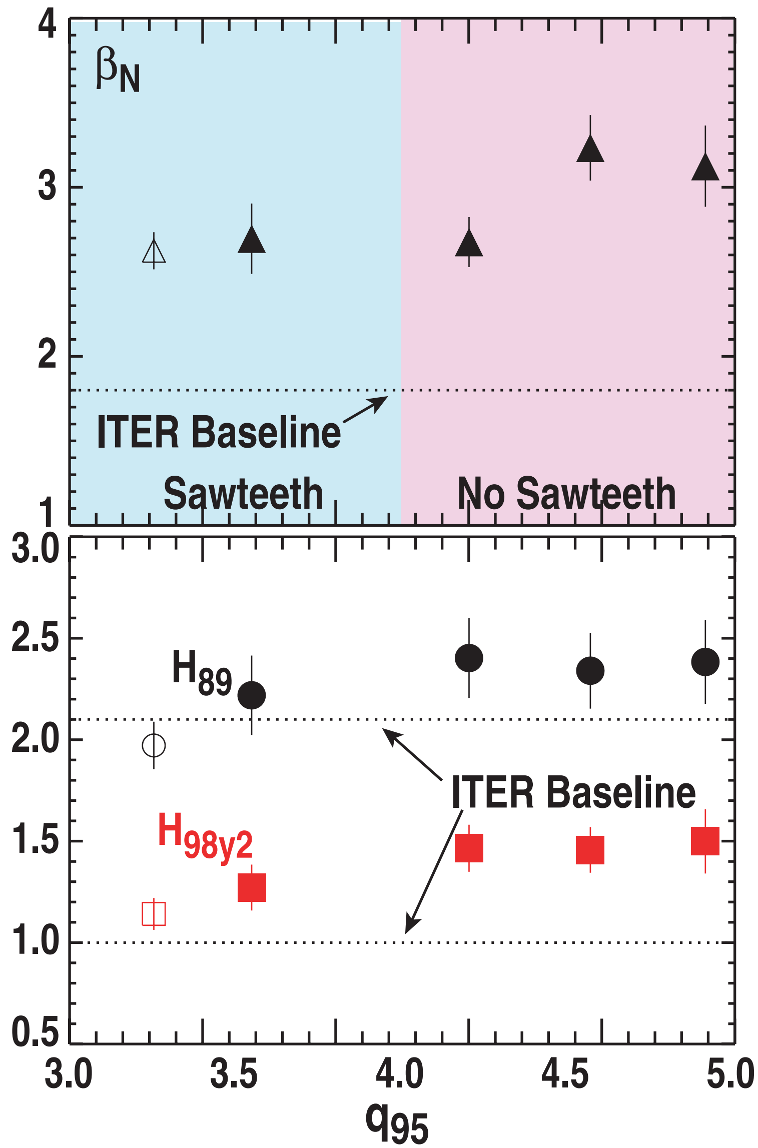
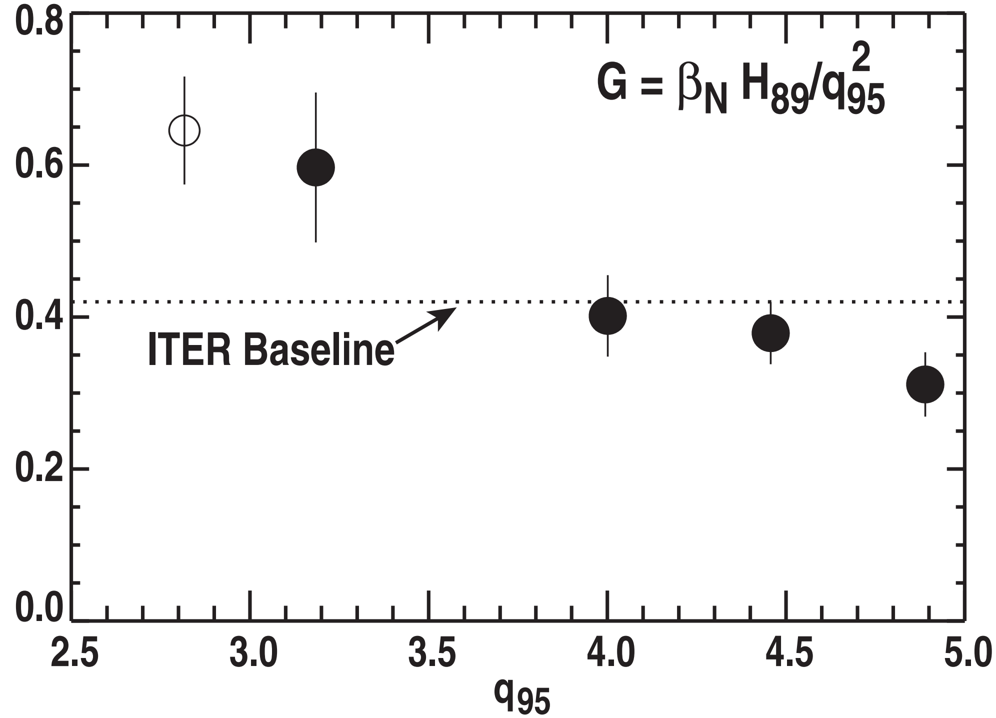
FUSION PERFORMANCE MAXIMIZES AT LOW q95; $G \approx G_{ITER}$ AT $q_{95} = 4.5$



- All sustained for at least τ_R



ITPA Joint Experiment

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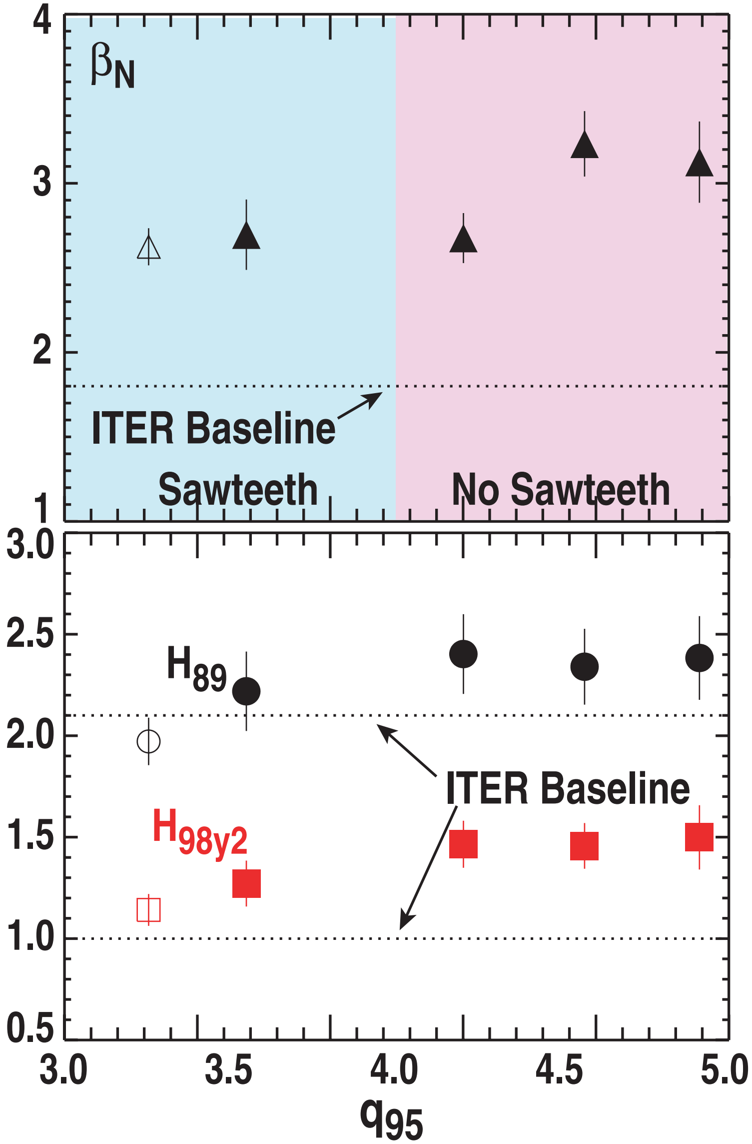

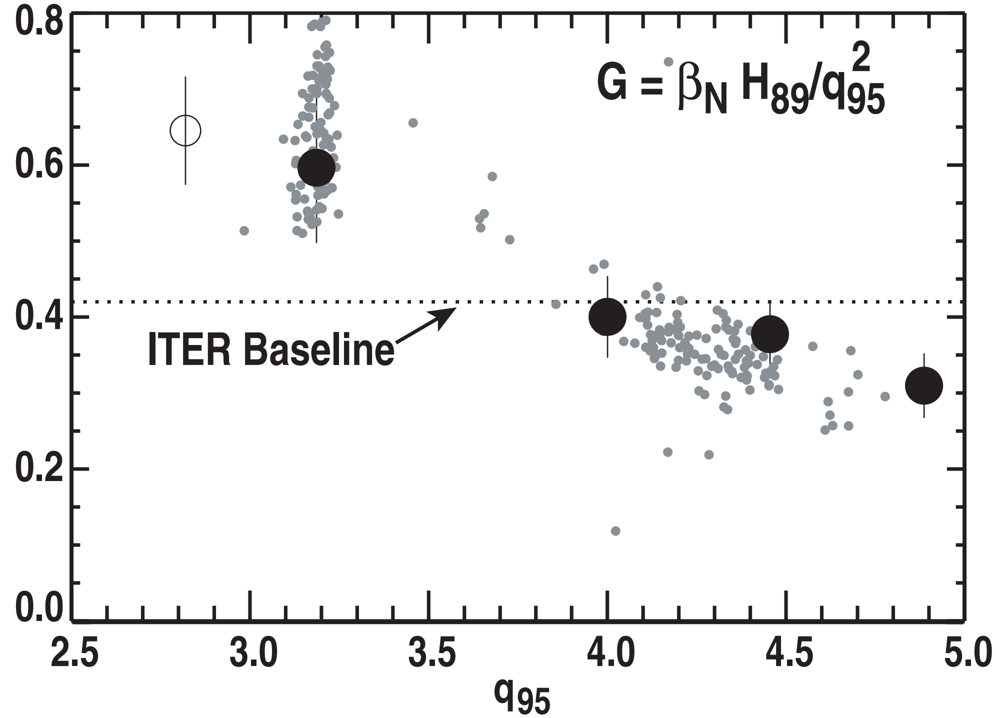

ITPA Joint Experiment

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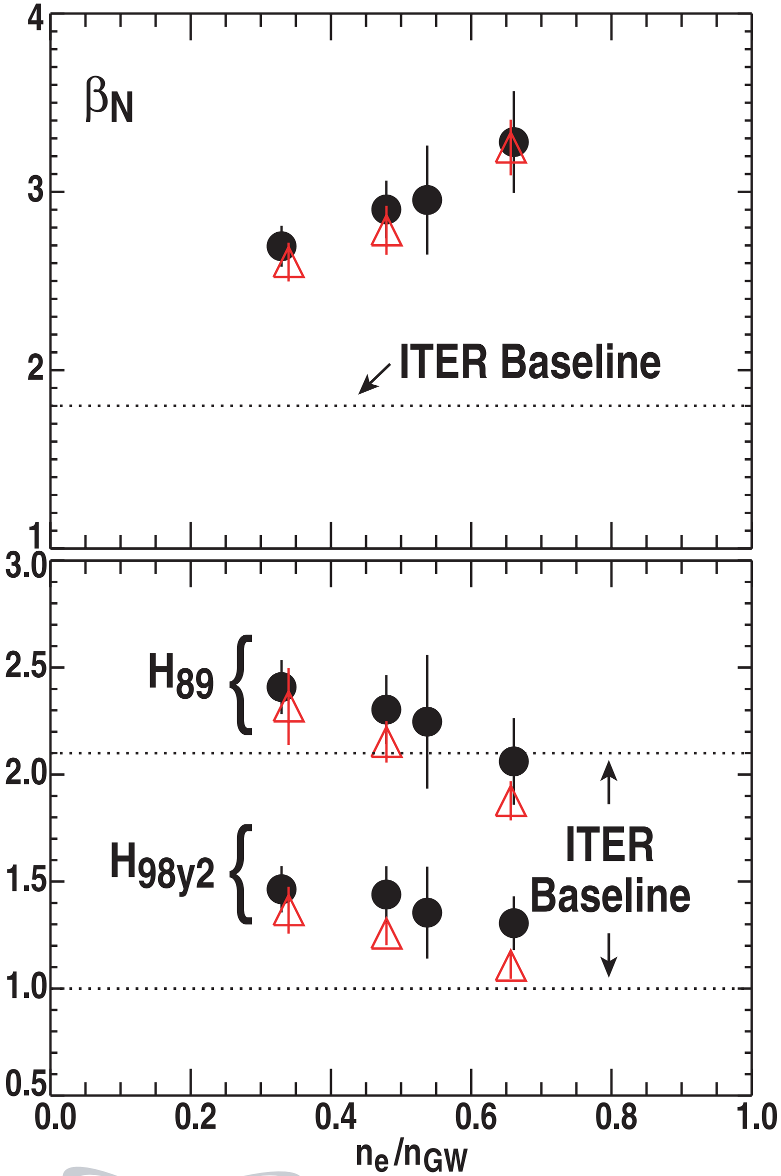
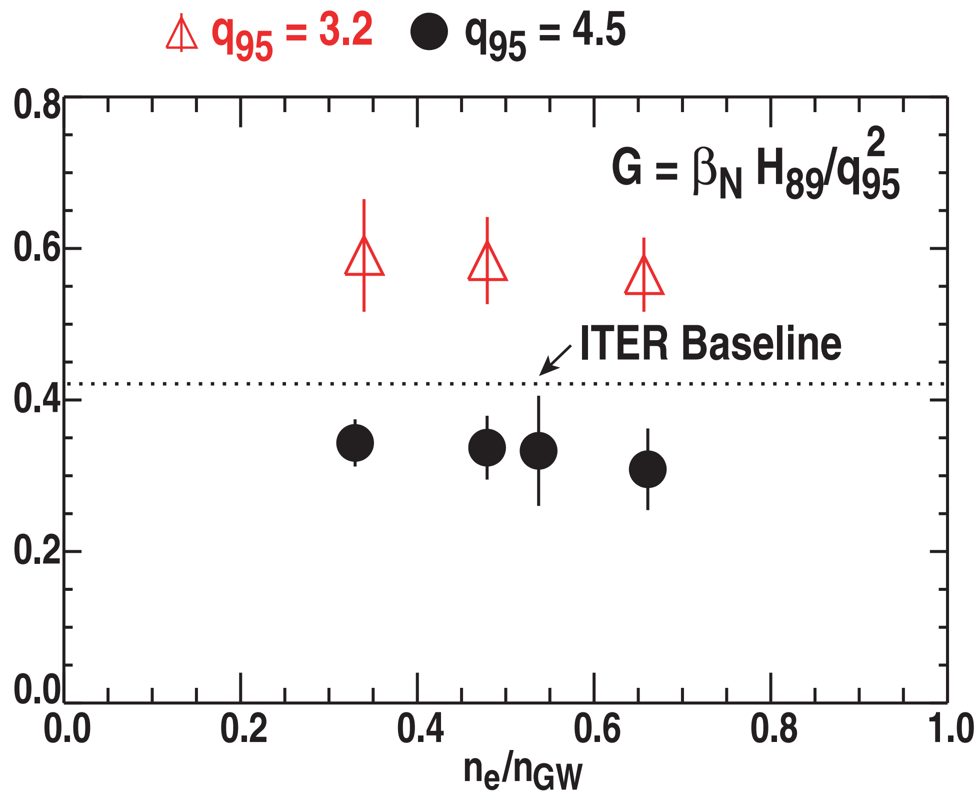
FUSION PERFORMANCE WEAKLY DEPENDENT ON PLASMA DENSITY





- All discharges are at stationary ($> \tau_R$) β limit

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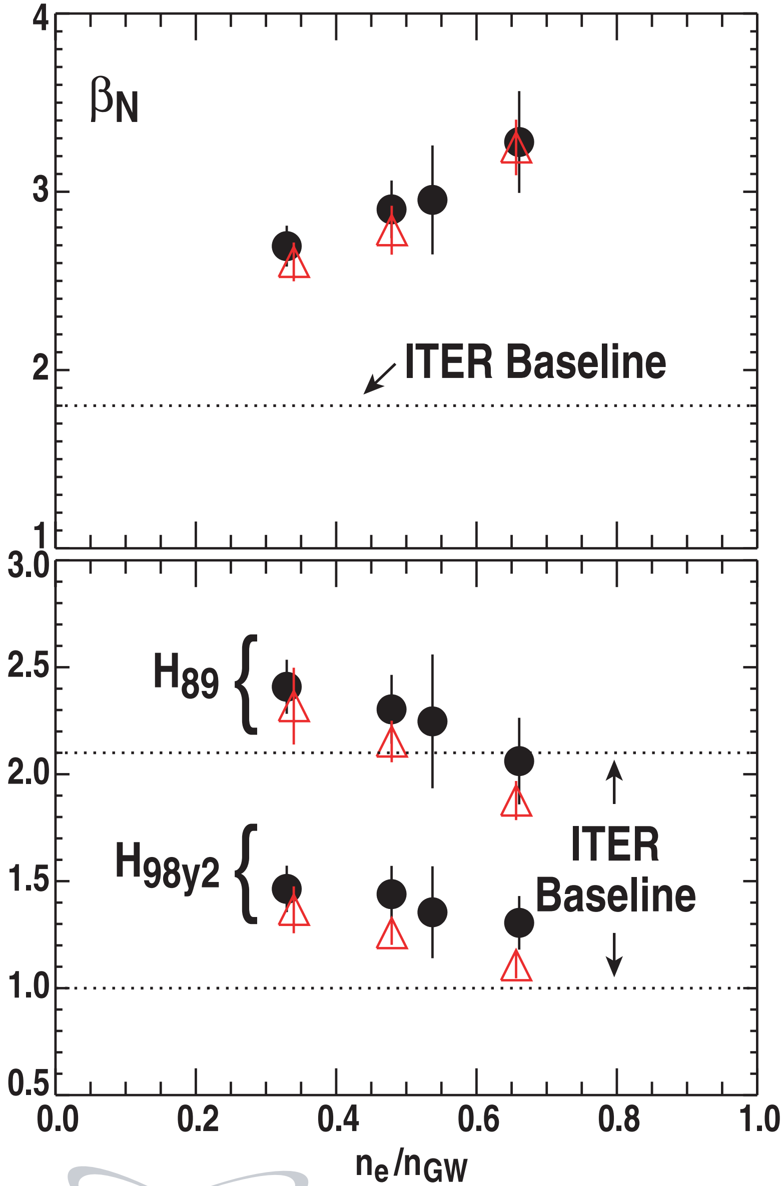

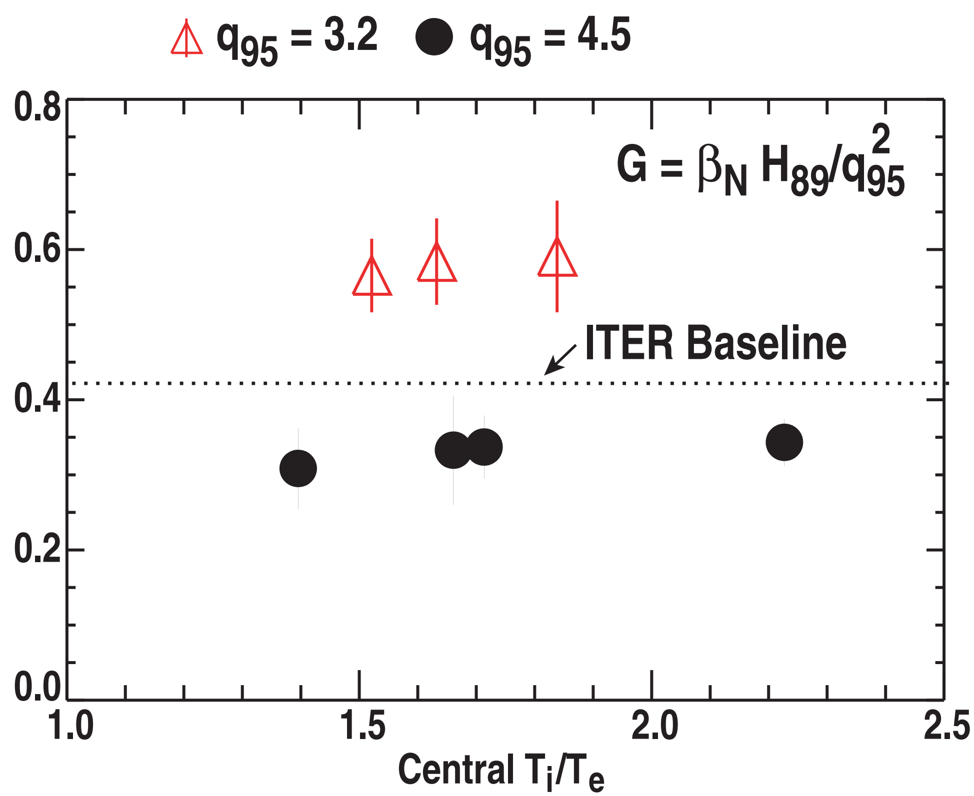

- All discharges are at stationary (> τ_R) β limit

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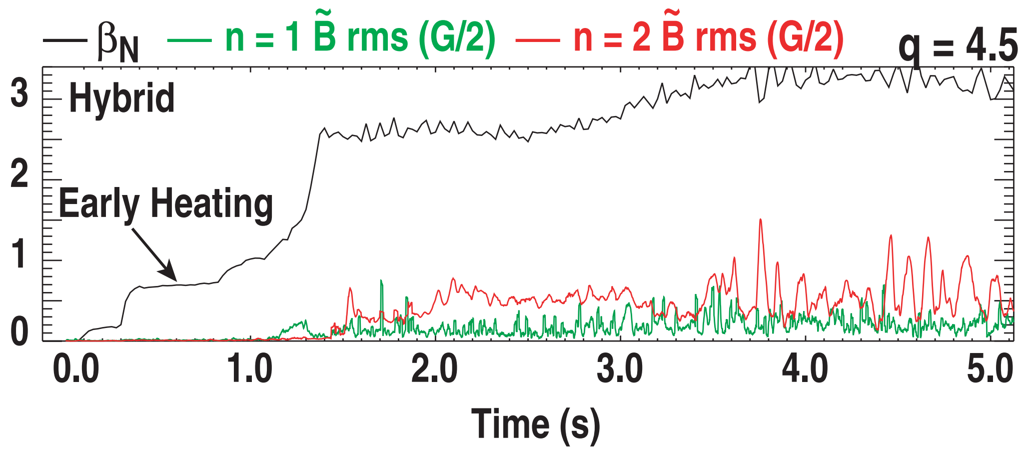
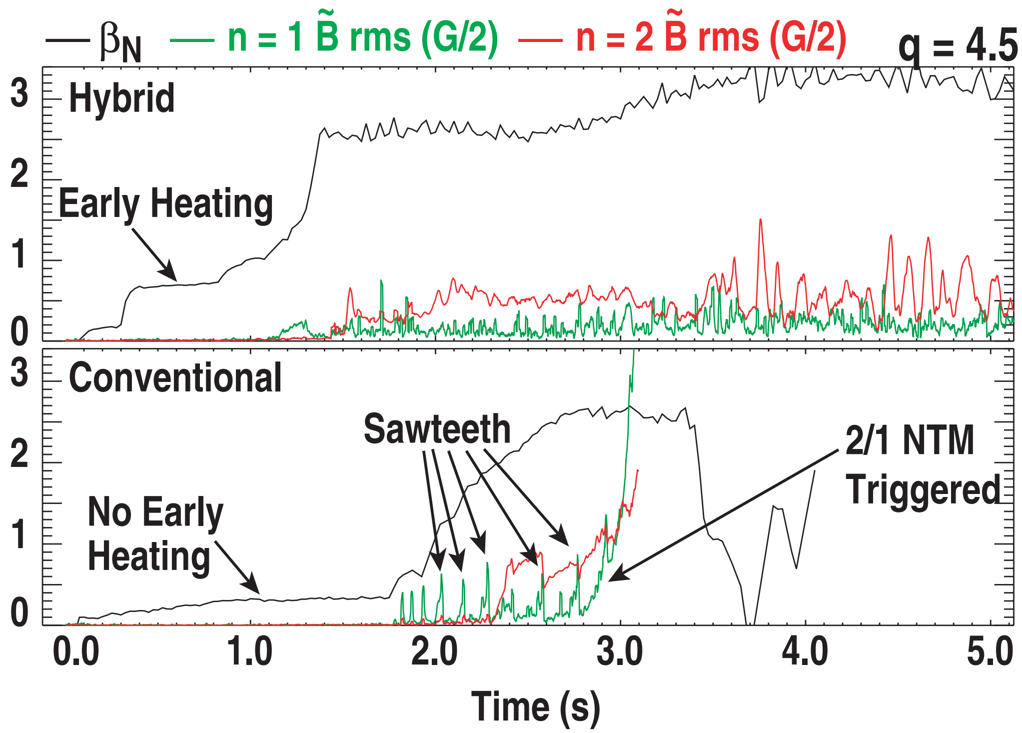
SAWTEETH BEHAVIOR DISTINGUISHES HYBRID REGIME FROM CONVENTIONAL REGIME



- With early heating, sawteeth do not appear

SAWTEETH BEHAVIOR DISTINGUISHES HYBRID REGIME FROM CONVENTIONAL REGIME



- With early heating, sawteeth do not appear
- Without early heating, m =2, n =1 NTM triggered by sawteeth at 20% lower β_N

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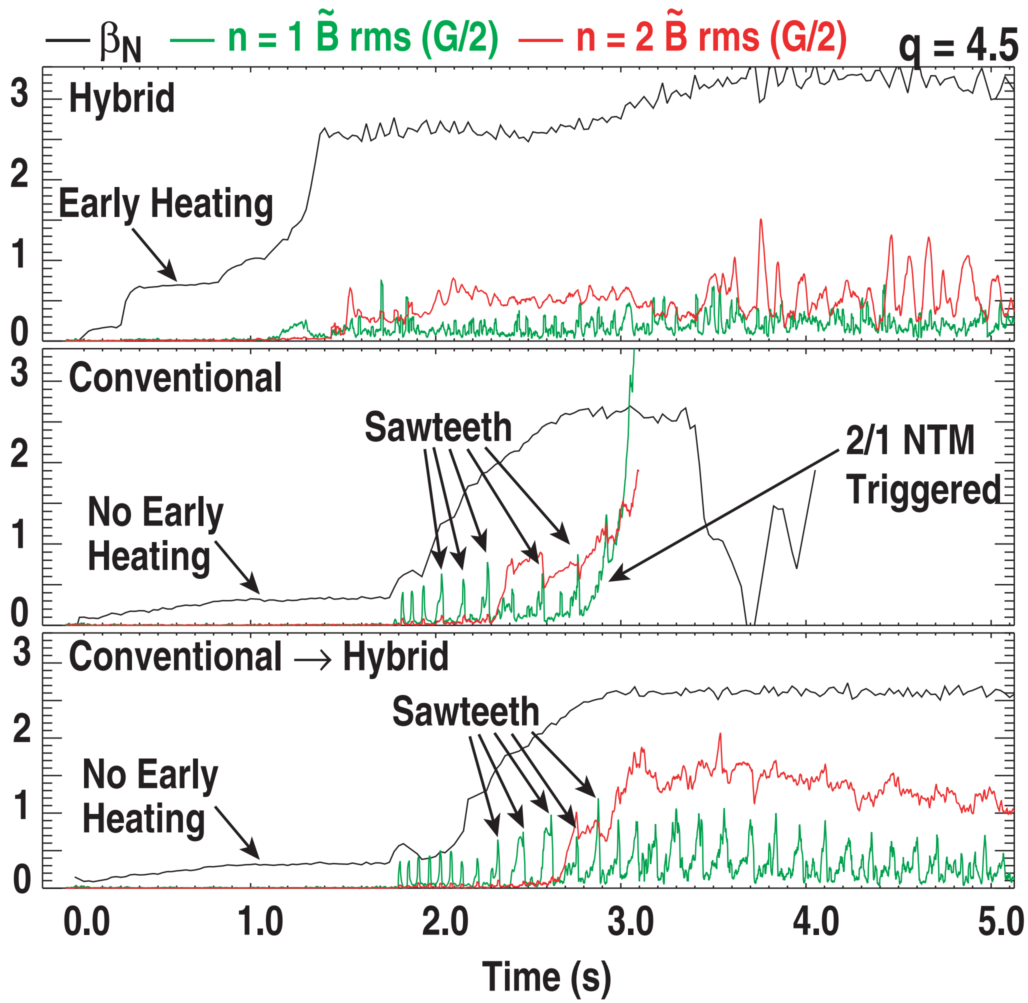

- With early heating, sawteeth do not appear
- Without early heating, m =2, n =1 NTM triggered by sawteeth at 20% lower β_N
- At slightly lower β_N, 2/1 mode not destabilized
- After 3/2 mode grows, sawteeth diminish

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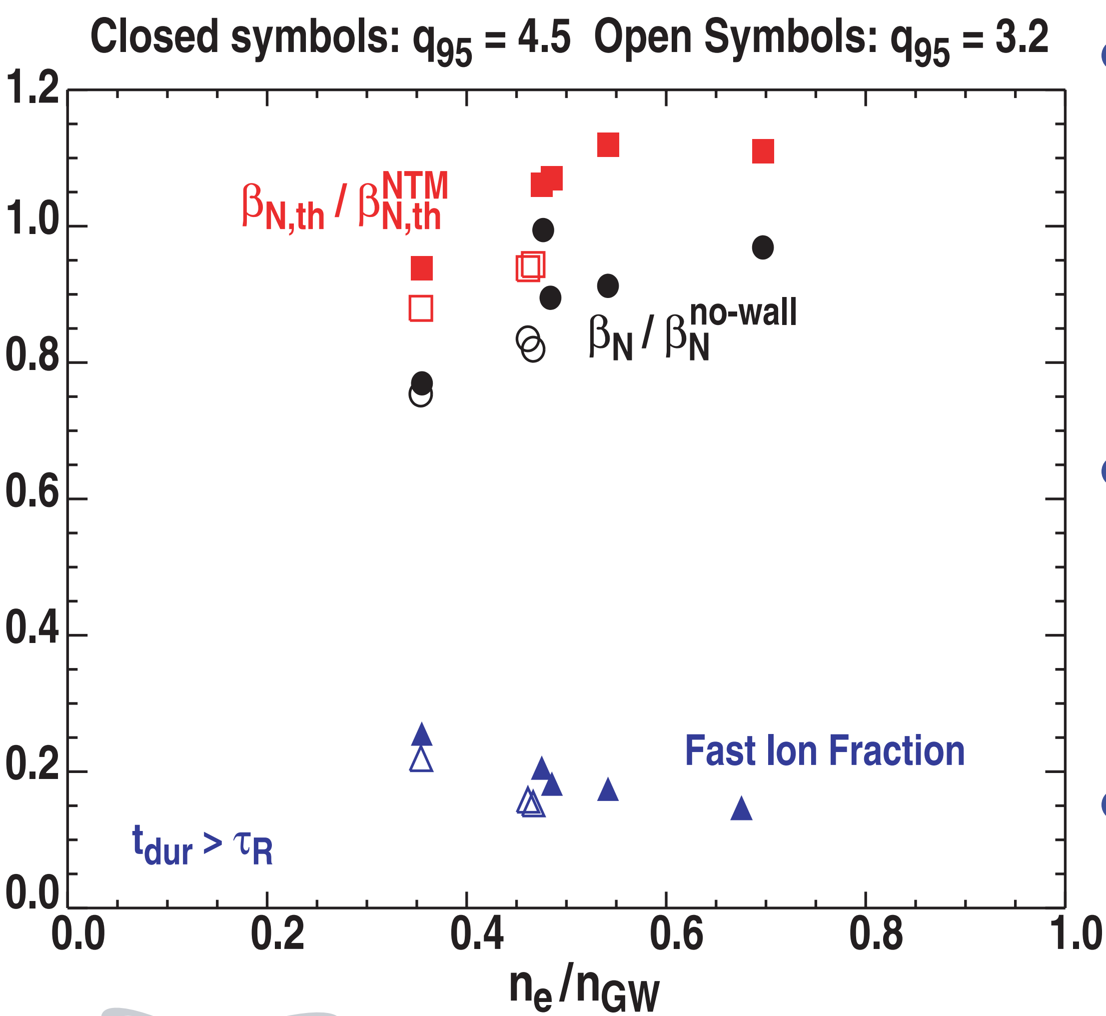
STATIONARY (> τ_R) CONDITIONS ARE MAINTAINED WITH $\beta_N \approx \beta_N^{no\text{-}wall}$ AND $\beta_{N,th}^{NTM} \gtrsim \beta_{N,th}$



- $\beta_N^{no\text{-}wall} \approx 4\ \ell_i$
  - confirmed by stability calculations
  - RWMs seen at slightly higher β
- $\beta_{N,th}^{NTM} = 550\ \rho_*^{1.02}\ \nu_*^{0.19}$
  [Hender NF 2004]
  - Scaling based on 2/1 onset in less than τ_R at given β
- Fast ion fraction is small
  - Low AE activity

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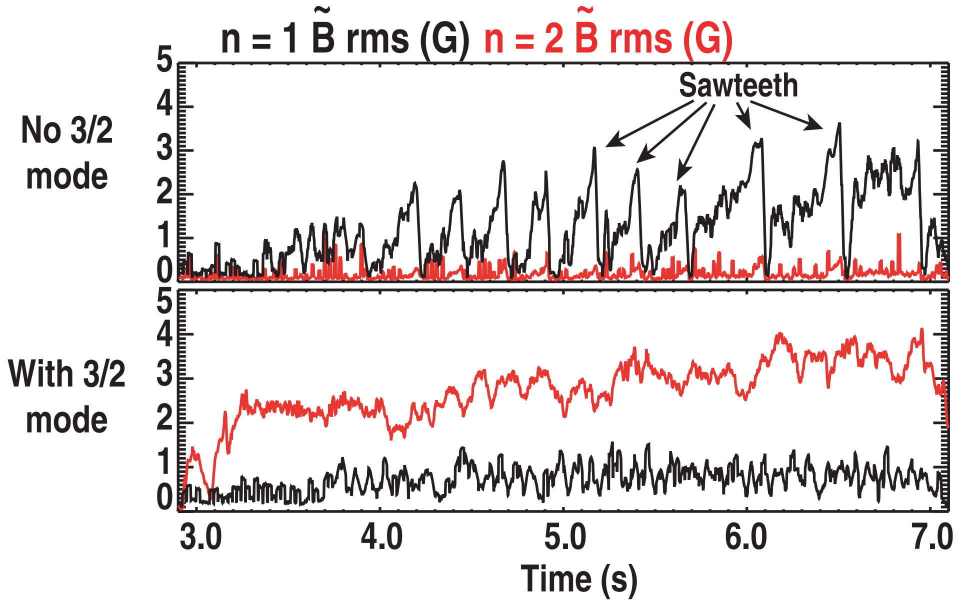
STUDIES HAVE SHOWN 3/2 NTM AMPLITUDE IS KEY TO AVOIDANCE OF SAWTEETH



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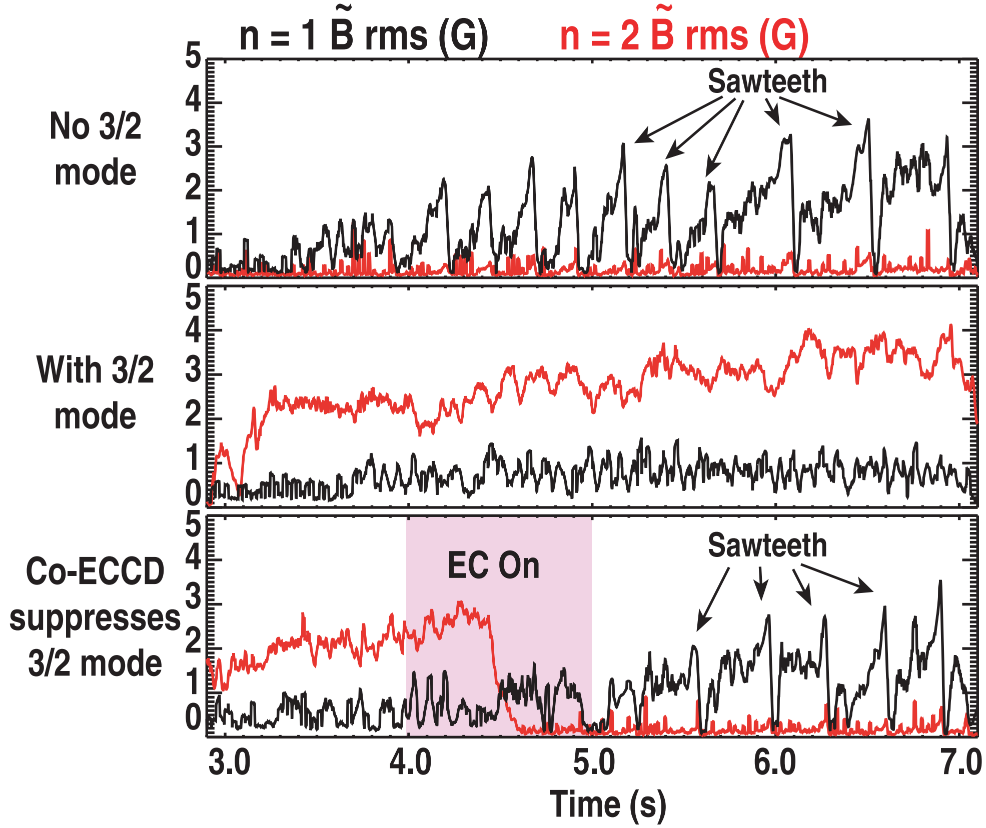

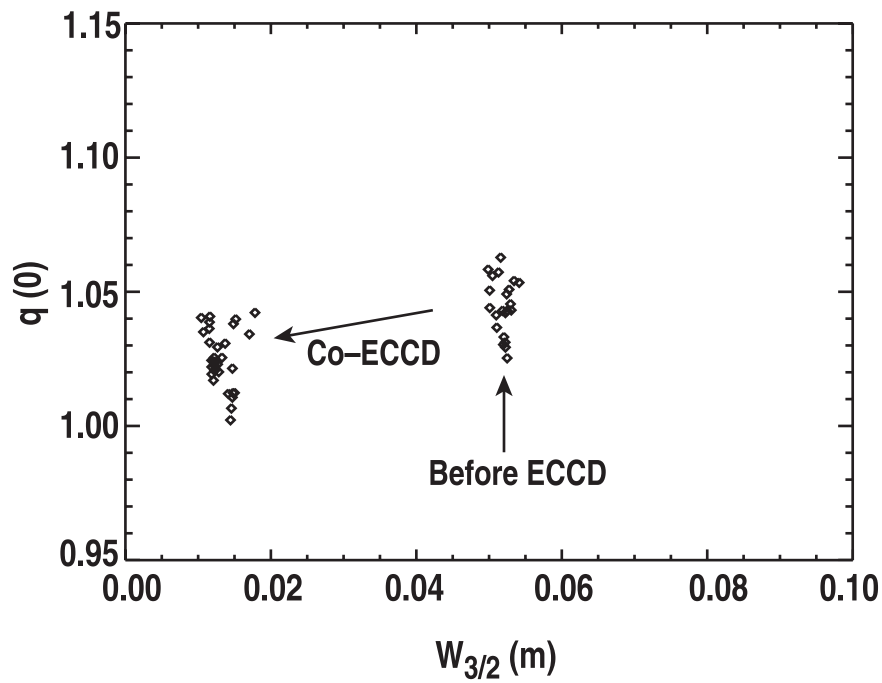

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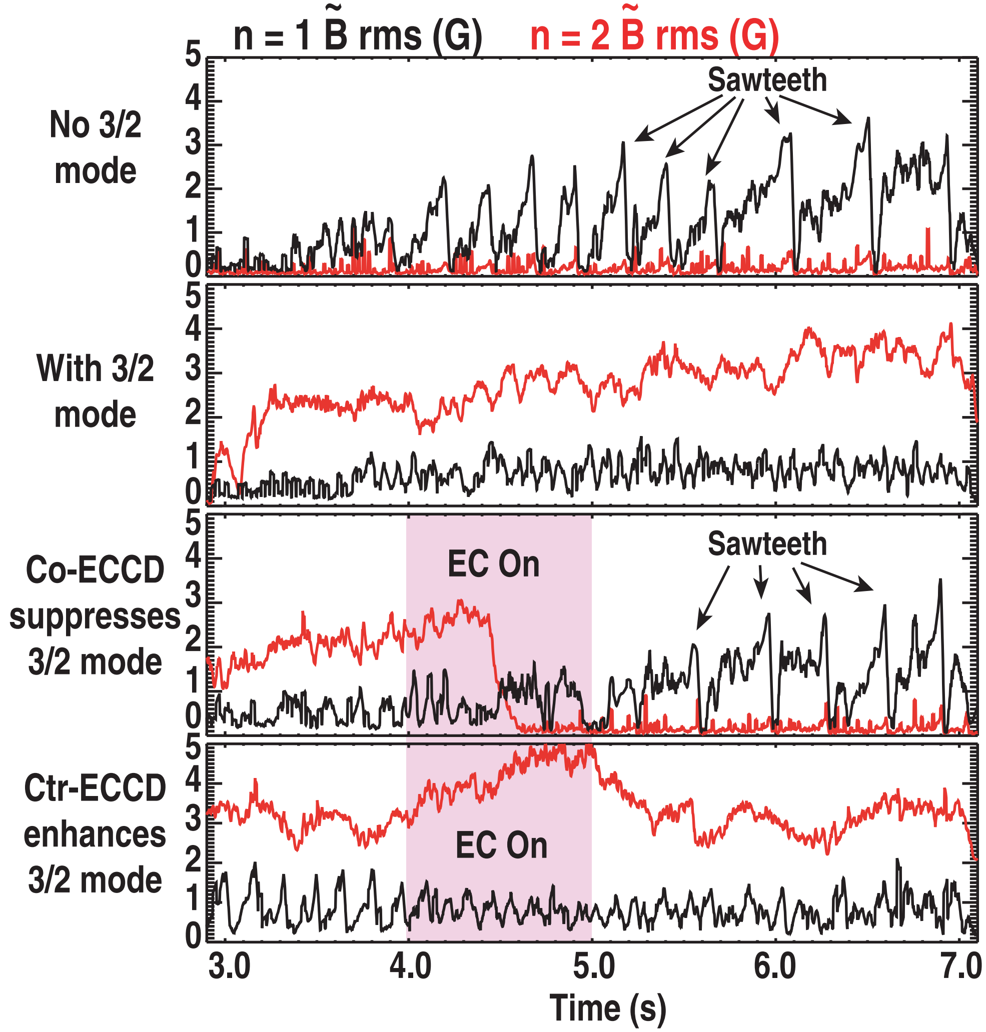
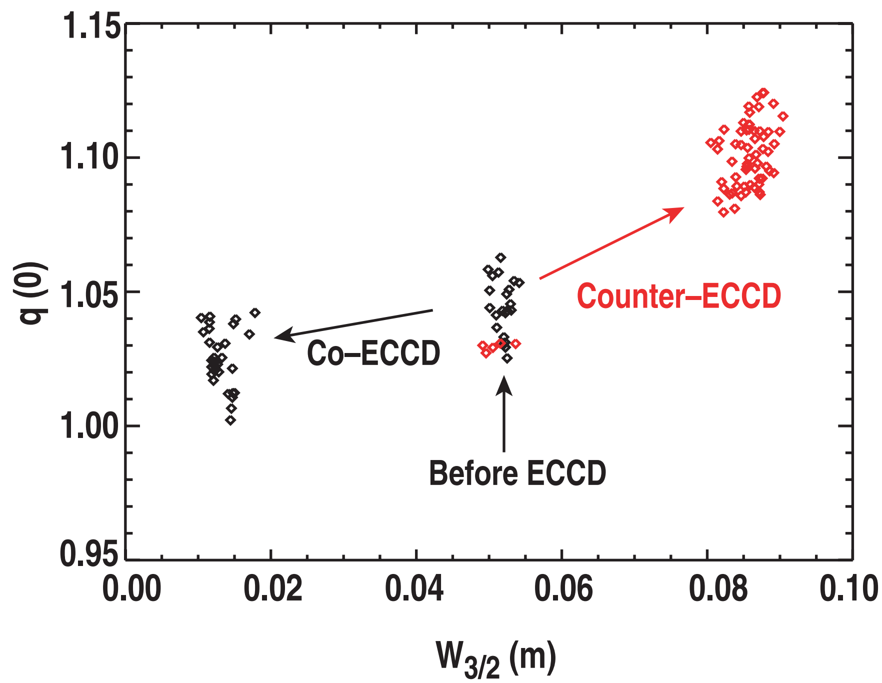
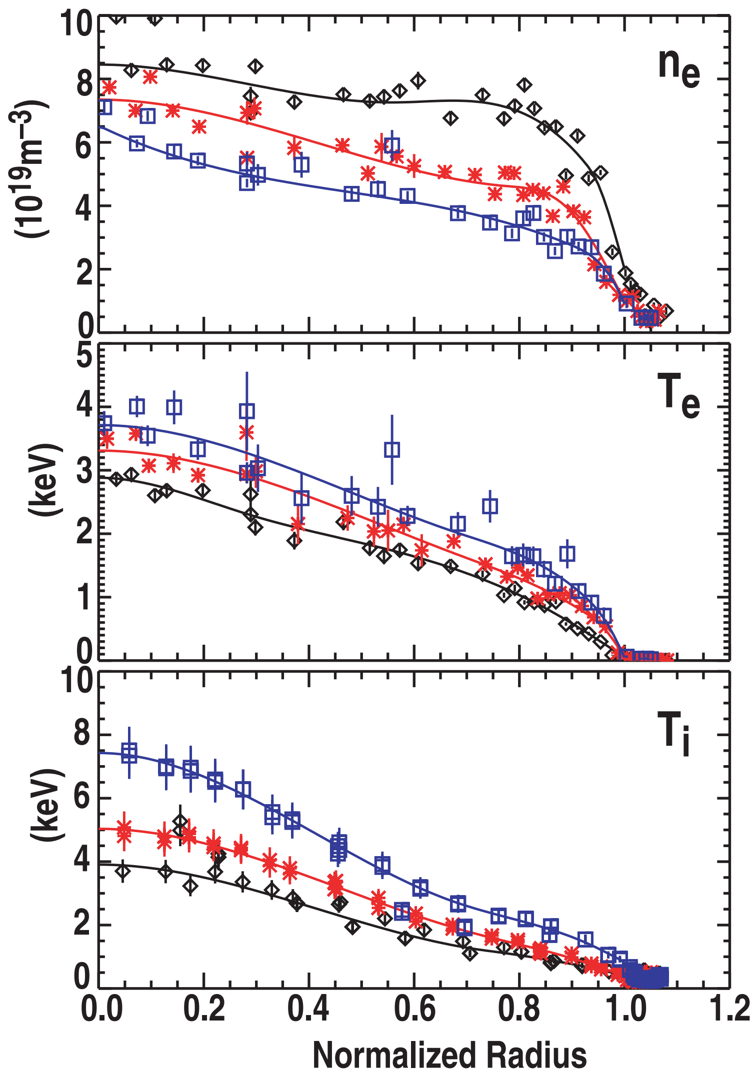
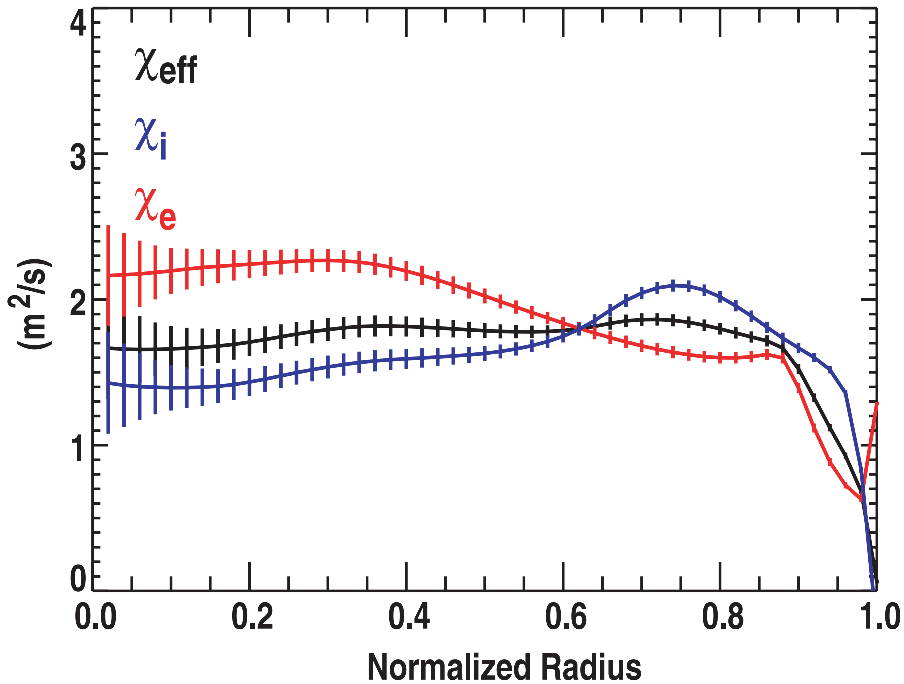




IMPROVED CONFINEMENT IS DUE TO GOOD TRANSPORT ACROSS ENTIRE PROFILE





- Leads to broad pressure profile which is favorable for high β limit

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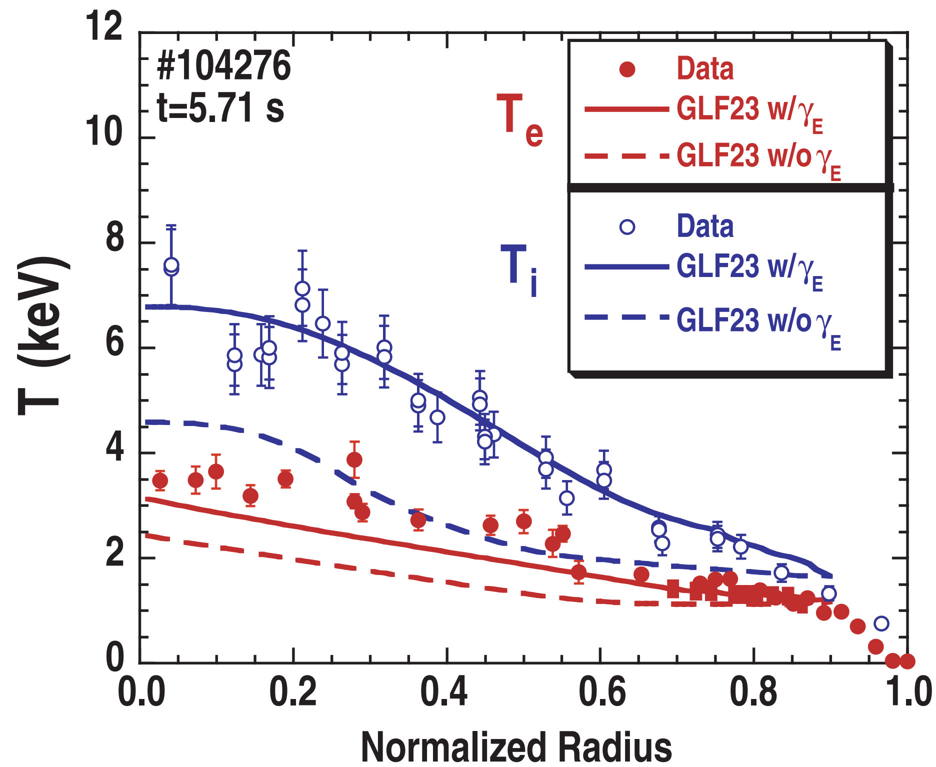
IMPROVED TRANSPORT APPEARS TO BE DUE TO THE INTERACTION OF SEVERAL EFFECTS

- Improved transport is likely due to a combination of reduced turbulence drive (γ_{max}) associated with $T_i/T_e > 1$ and a favorable current profile and increased stabilization via ExB shear

- GLF23 indicates sensitivity to ExB shear
  - Is this due to small γ_{max} or large ExB shear?

- Experiments in 2006 should help resolve this issue
  - Balanced NBI
  - Increased electron heating capability



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PROJECTIONS TO ITER ARE UNIFORMLY FAVORABLE AND SUGGESTS IGNITION IS POSSIBLE

Projections

	$q_{95} = 4.5$			$q_{95} = 3.2$		
Plasma current	10.3 MA			13.9 MA		
Duration	3900			1900		
Scaling	H_{89}	H_{98y2}	H^{*}_{DS03}	H_{89}	H_{98y2}	H^{*}_{DS03}
P_{fusion}	440	440	370	780	740	700
Q_{fus}	9.0	8.9	∞	12.9	39	∞

* Petty, Fusion Sci. Tech. 43 1 (2003)

Primary difference is β scaling:

H_{89}: $\beta^{-0.5}$ H_{98y2}: $\beta^{-0.9}$ H_{DS03}: β^{0}

Projection Methodology:

— Use plasma shape, q95, and β_N, and H_{xx} from experiment

— 50/50 D-T mix, Z_{eff} prescription from ITER, He ash treated self consistently

— Use DIII–D n_e, T_e profiles, fix $T_e = T_i$

— Choose $n/n_{GW} = 0.85$; $\tau^{*}_{He} / \tau_E = 5$; $C_{EJIMA} = 0.6$

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SUMMARY

- Stationary, high normalized performance operation has been demonstrated on DIII–D over a wide range in operating space.

  $q_{95} = 3.2$: $G = \beta_N H_{89}/q_{95}^2 > 1.4\ G_{ITER}$ for $> 9\ \tau_R$

  $q_{95} = 4.5$: $G \approx G_{ITER}$ for $> 4\ \tau_R$

- Projections are uniformly favorable for ITER and suggest the possibility of very high fusion gain (possibly $Q_{fus} = \infty$) operation as well as long pulse, $Q_{fus} > 5$ operation in ITER

- Stability and confinement characteristics are similar to that of the conventional, ELMing H-mode case (ITER physics basis is still valid)

  — Measurements indicate the importance of a small m=3/n=2 NTM in controlling the current profile to prevent or minimize sawteeth, thereby allowing high β, good confinement operation