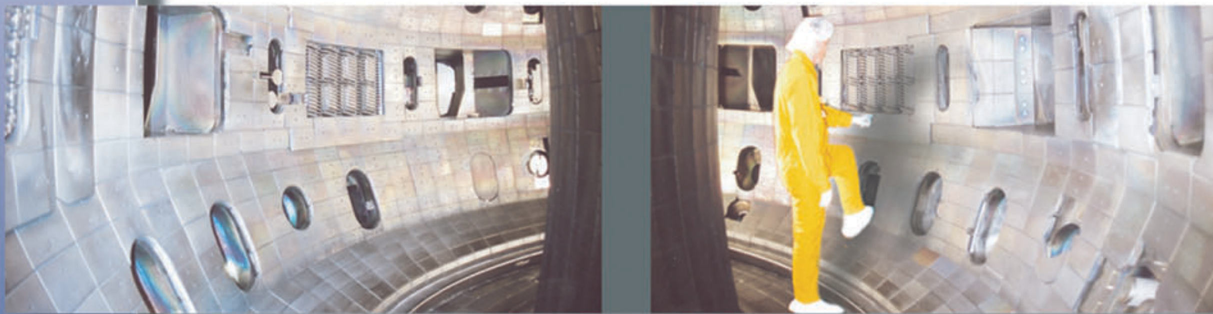

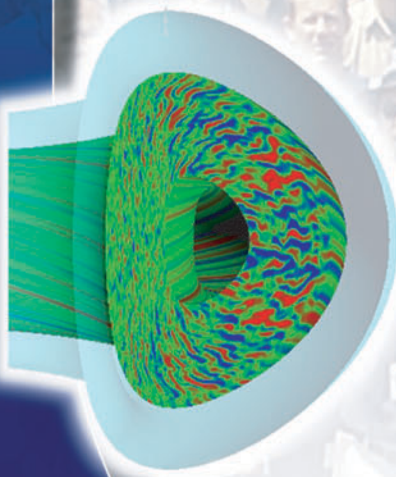

Development, Physics Basis, and Projections of Hybrid Scenario Operation in ITER on DIII–D

by
M.R. Wade
for the DIII–D Team

M.R. Wade,[1] T.C. Luce,[2] R.J. Jayakumar,[3] P.A. Politzer,[2] A.W. Hyatt,[2] J.R. Ferron,[2] C.M. Greenfield,[2] E.H. Joffrin,4 M. Murakami,[1] C.C. Petty,[2] R. Prater,[2] J.C. DeBoo,[2] J. La Haye,[2] P. Gohil,[2] T.L. Rhodes,[5] and A.C.C. Sips[6]

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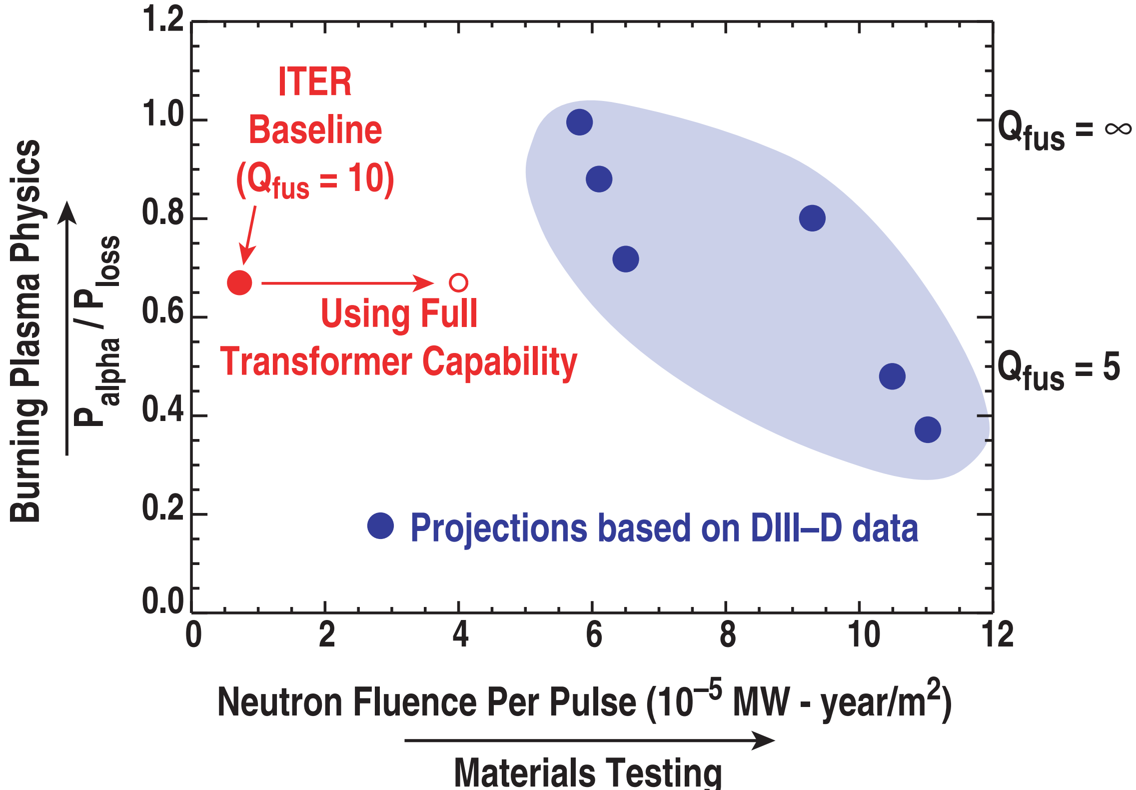
248-04/MRW/jy

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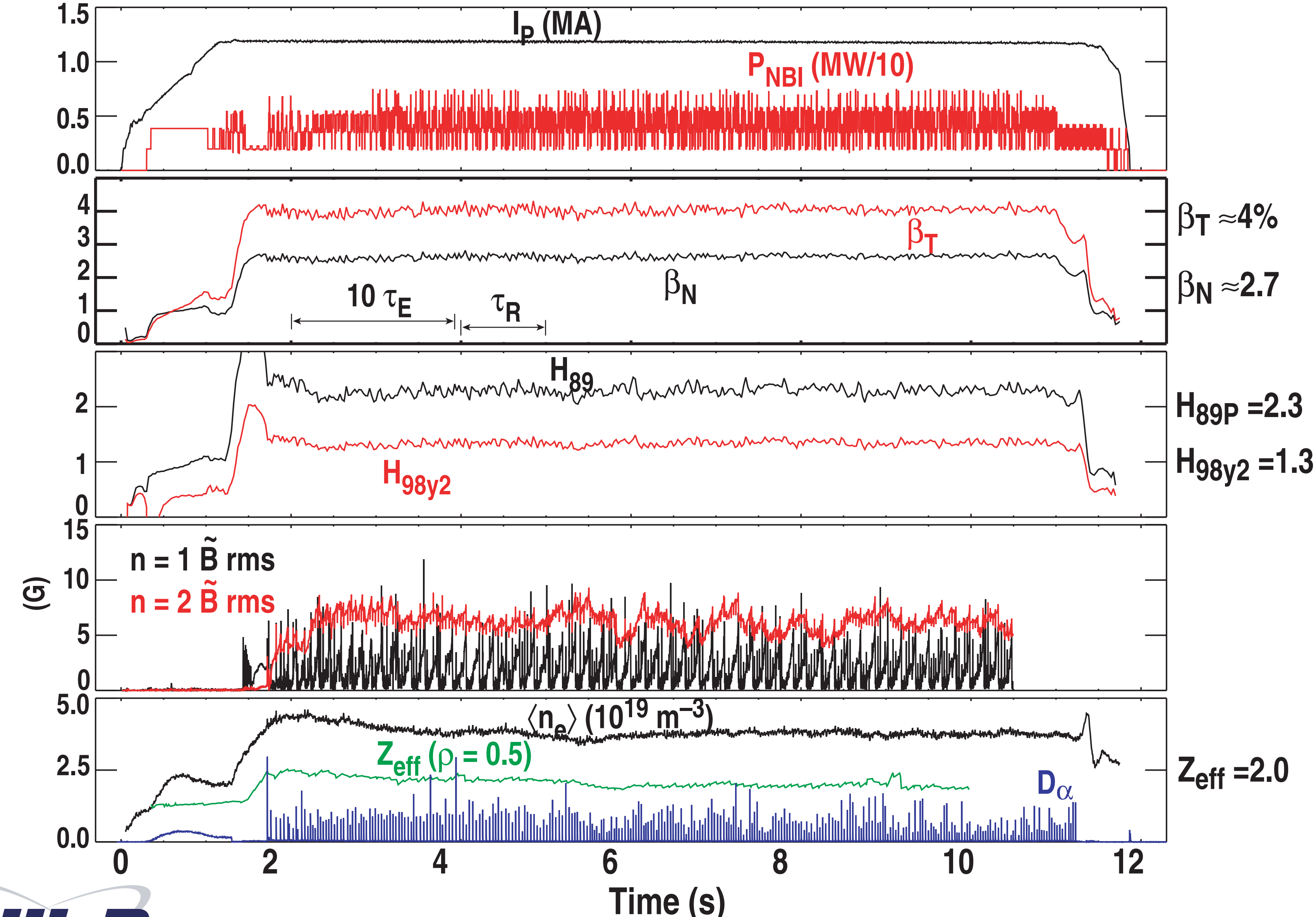
RECENT EXPERIMENTS HAVE DEMONSTRATED TRULY STATIONARY (> 9 τ_R), HIGH PERFORMANCE OPERATION



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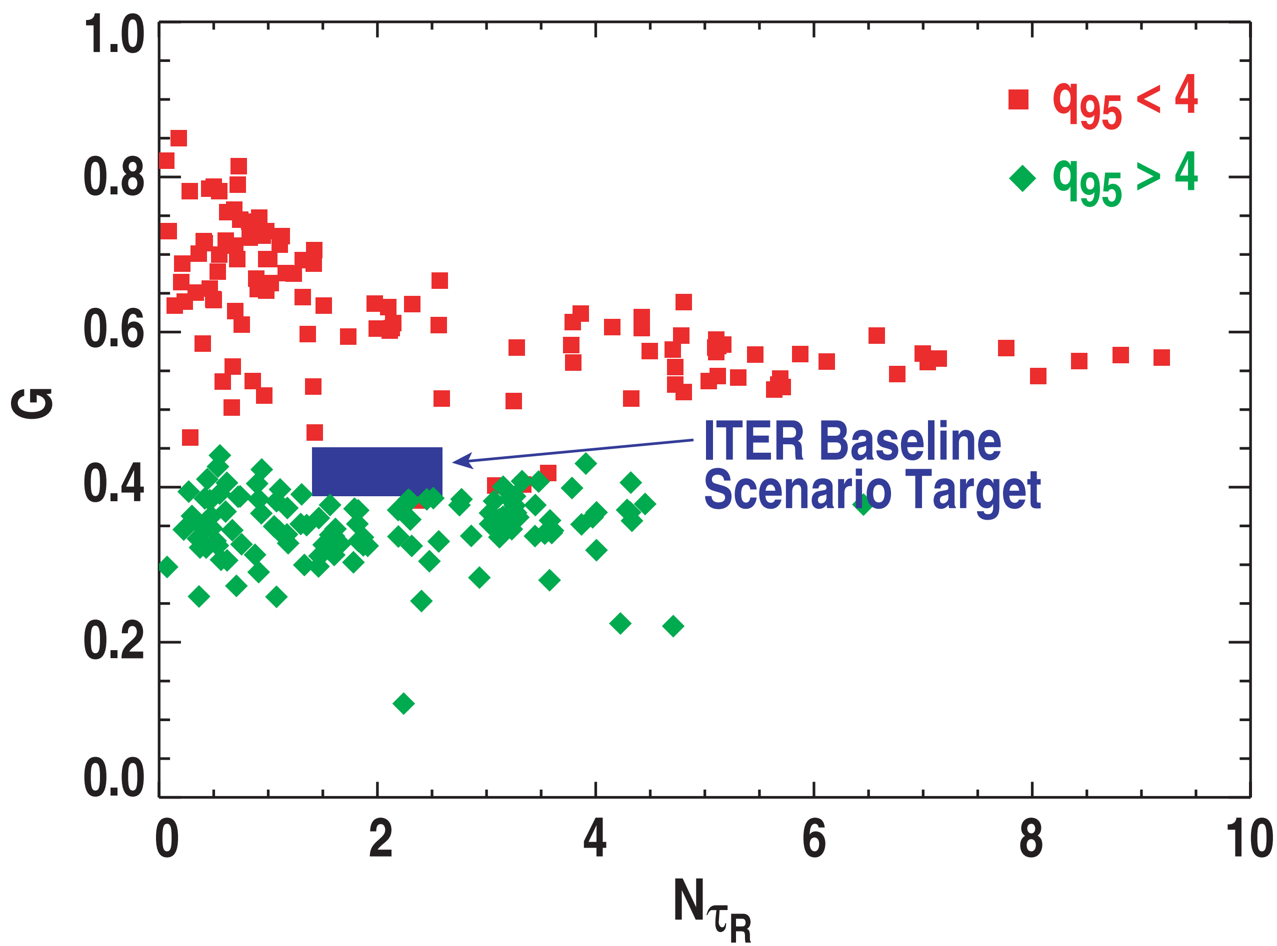
NORMALIZED FUSION PERFORMANCE AND DURATION COMFORTABLY EXCEED THAT OF ITER BASELINE SCENARIO

- **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



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

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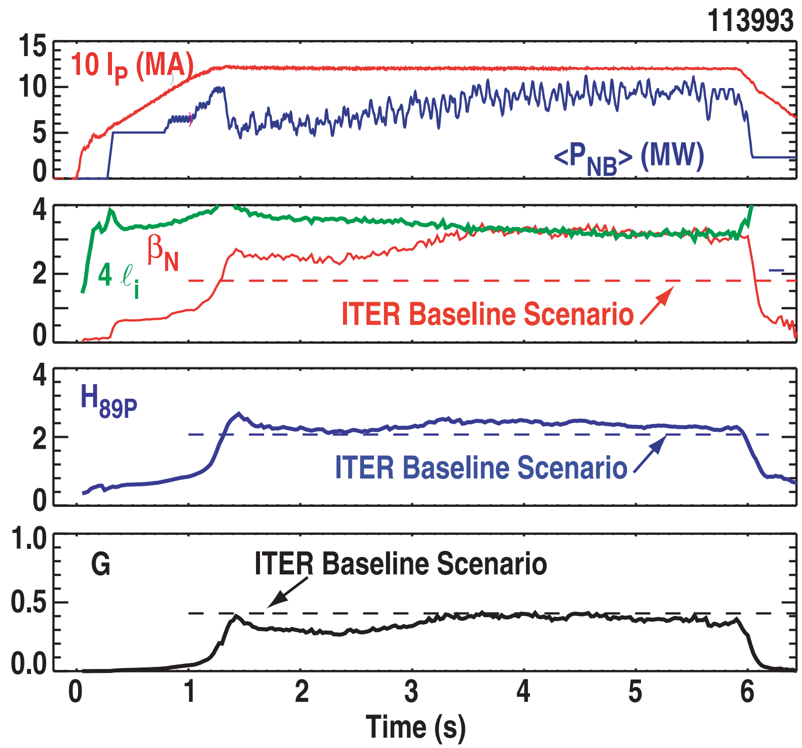
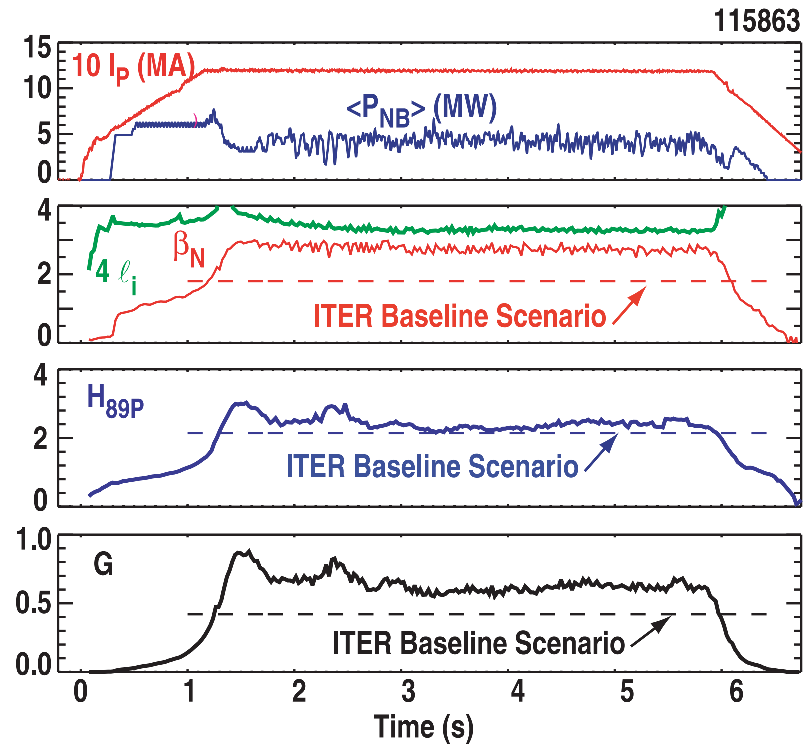
PERFORMANCE AT OR ABOVE ITER BASELINE DESIGN HAS BEEN ACHIEVED OVER A WIDE RANGE IN q_{95}





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

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

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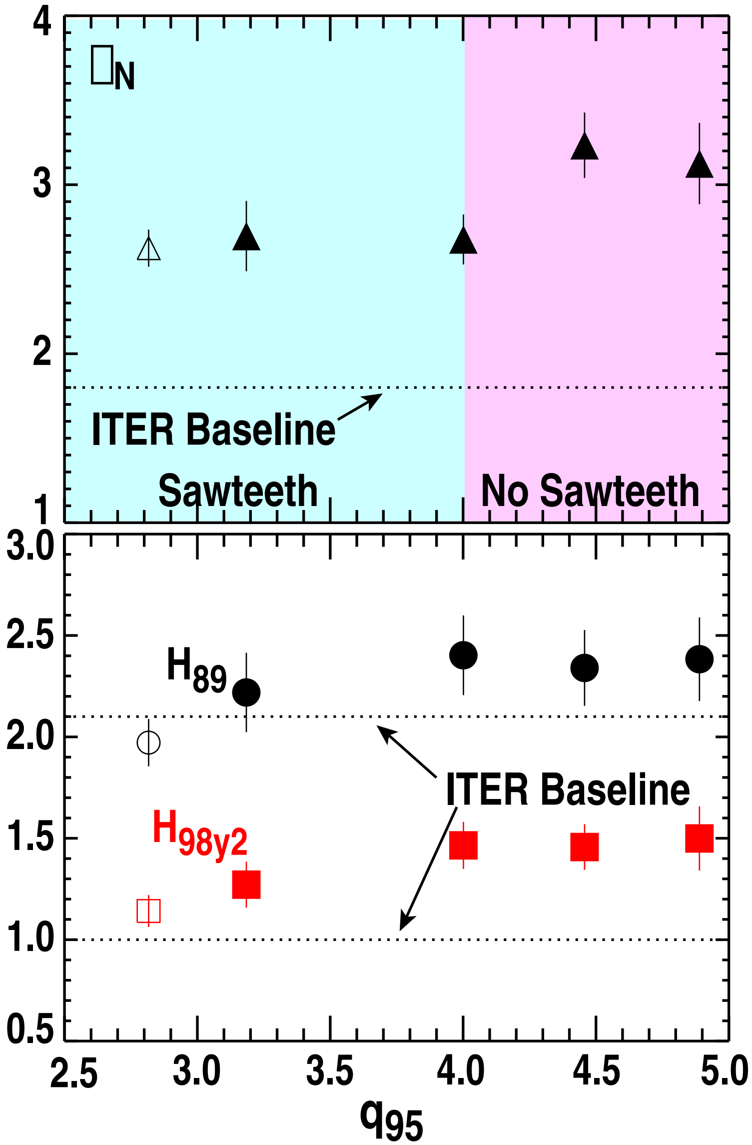
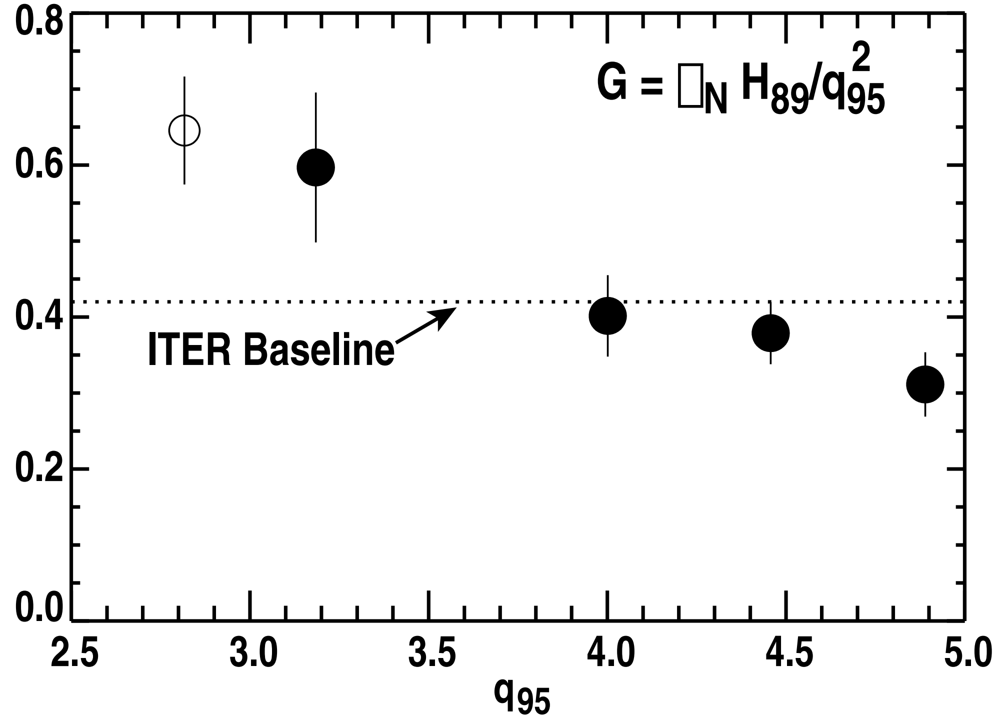
FUSION PERFORMANCE MAXIMIZES AT LOW q95; G □ G_{ITER} AT q_{95} = 4.5



- All sustained for at least □R



ITPA Joint Experiment

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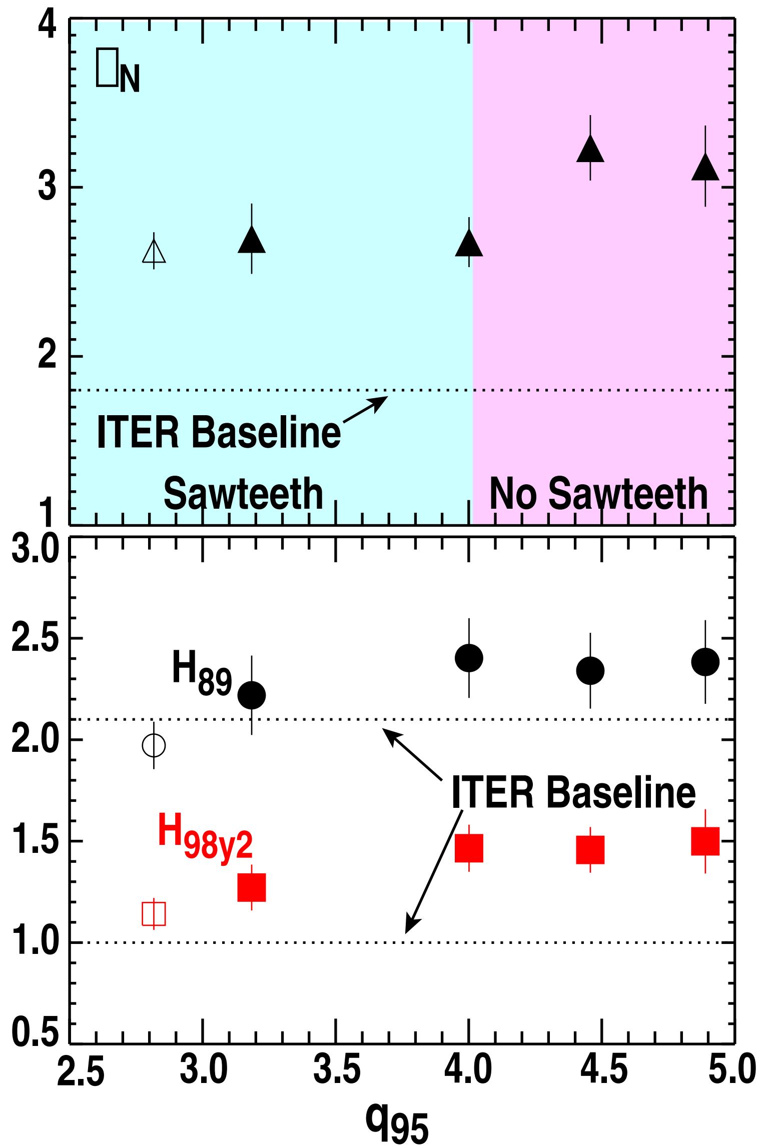

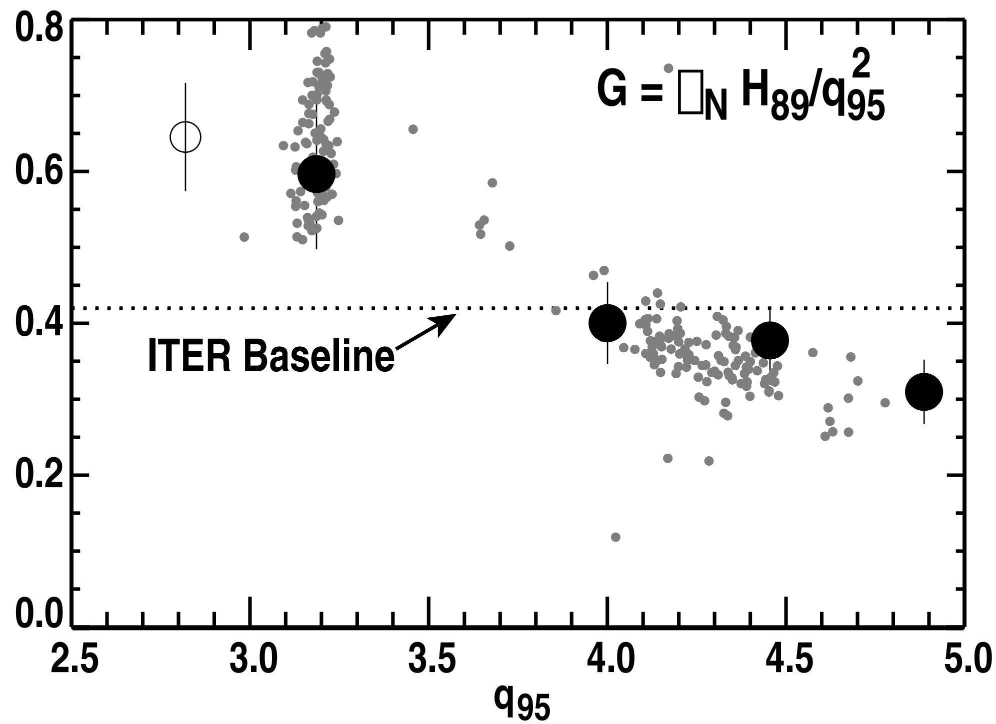

ITPA Joint Experiment

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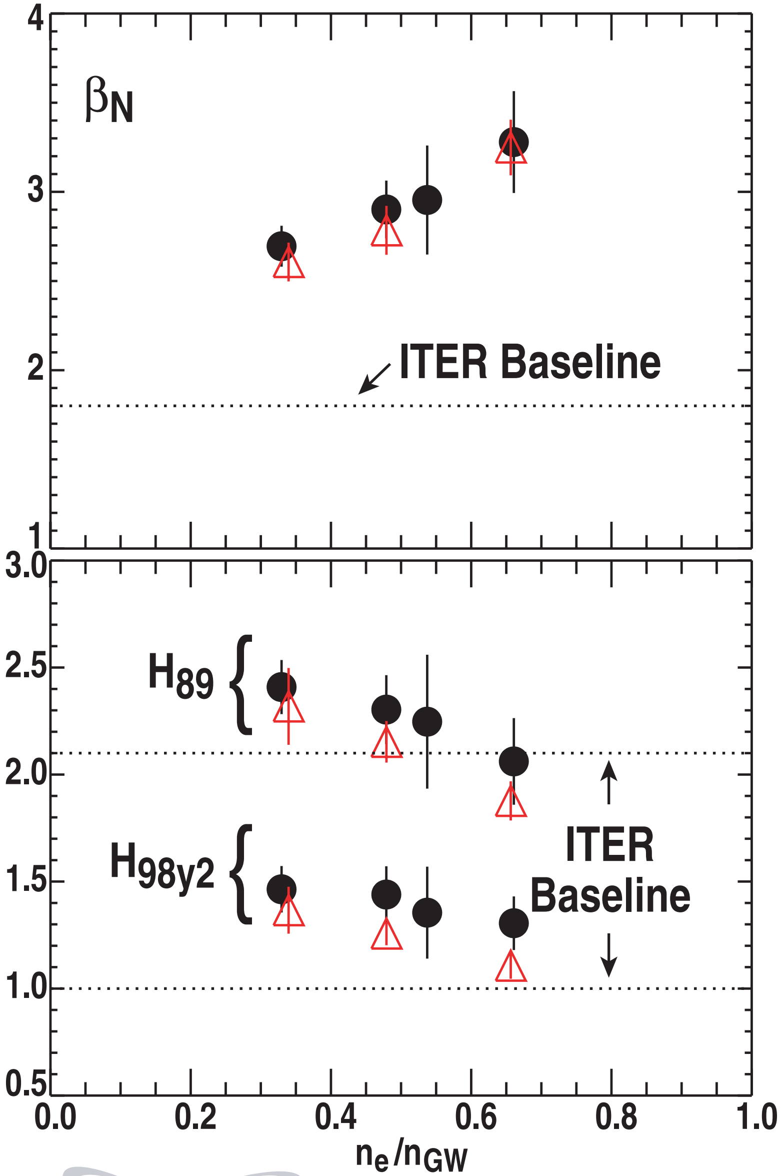
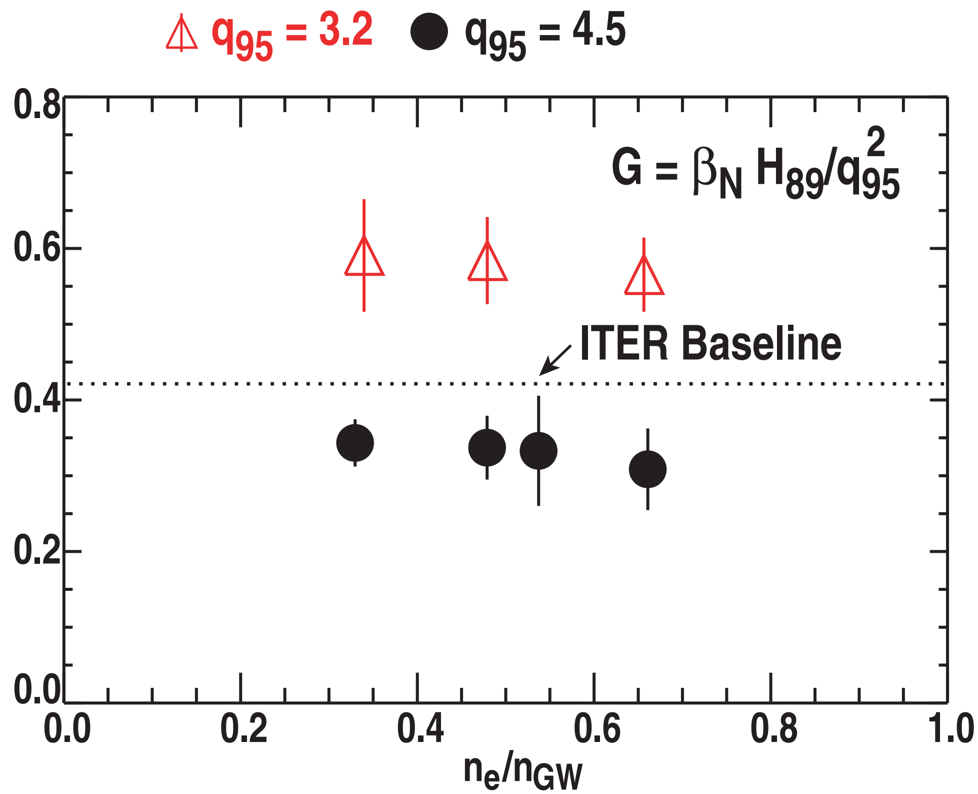
FUSION PERFORMANCE WEAKLY DEPENDENT ON PLASMA DENSITY





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

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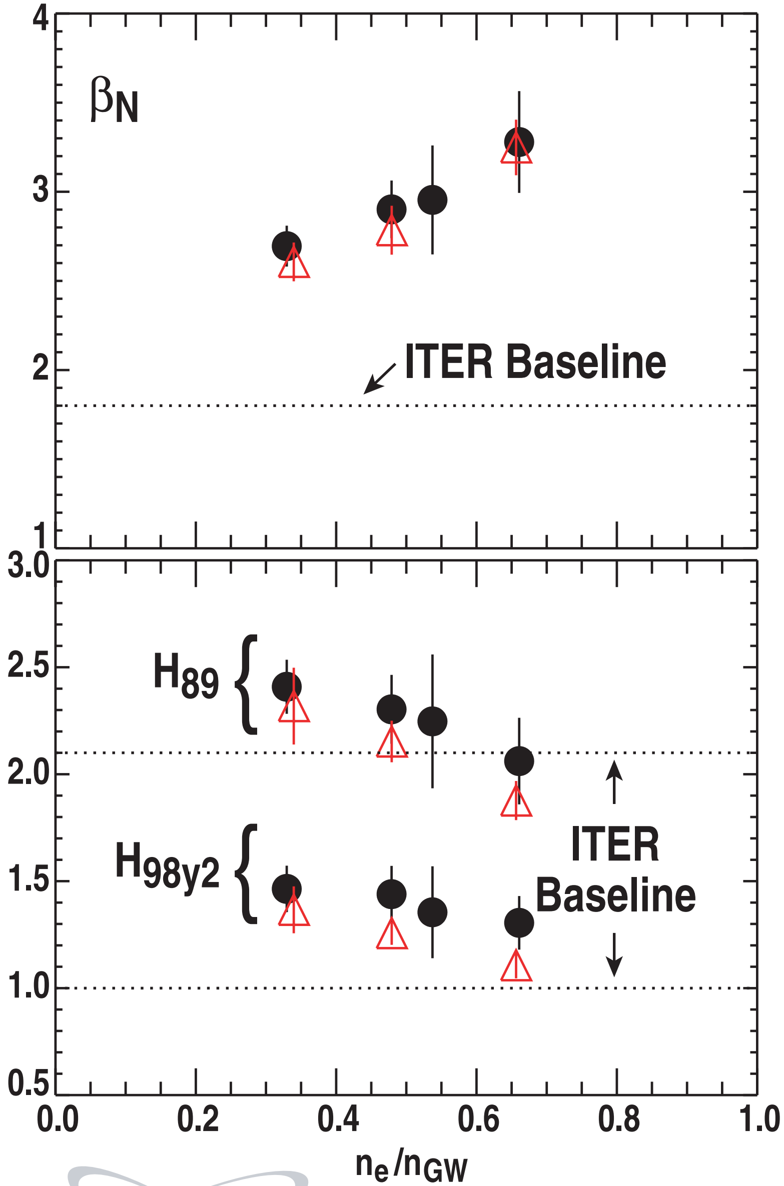

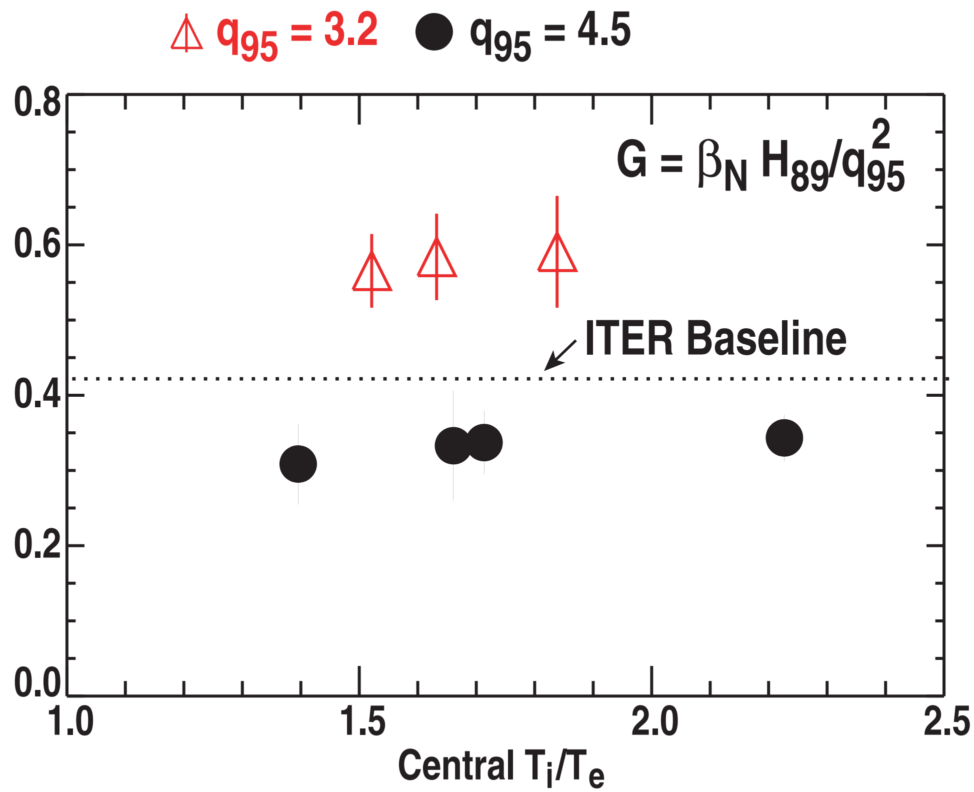

- All discharges are at stationary (> τ_R) β limit

ITPA Joint Experiment

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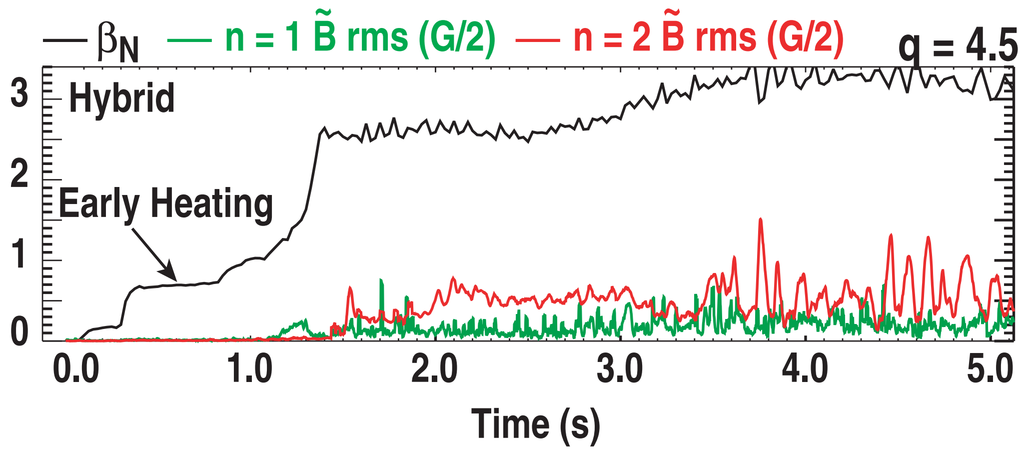
SAWTEETH BEHAVIOR DISTINGUISHES HYBRID REGIME FROM CONVENTIONAL REGIME



- With early heating, sawteeth do not appear

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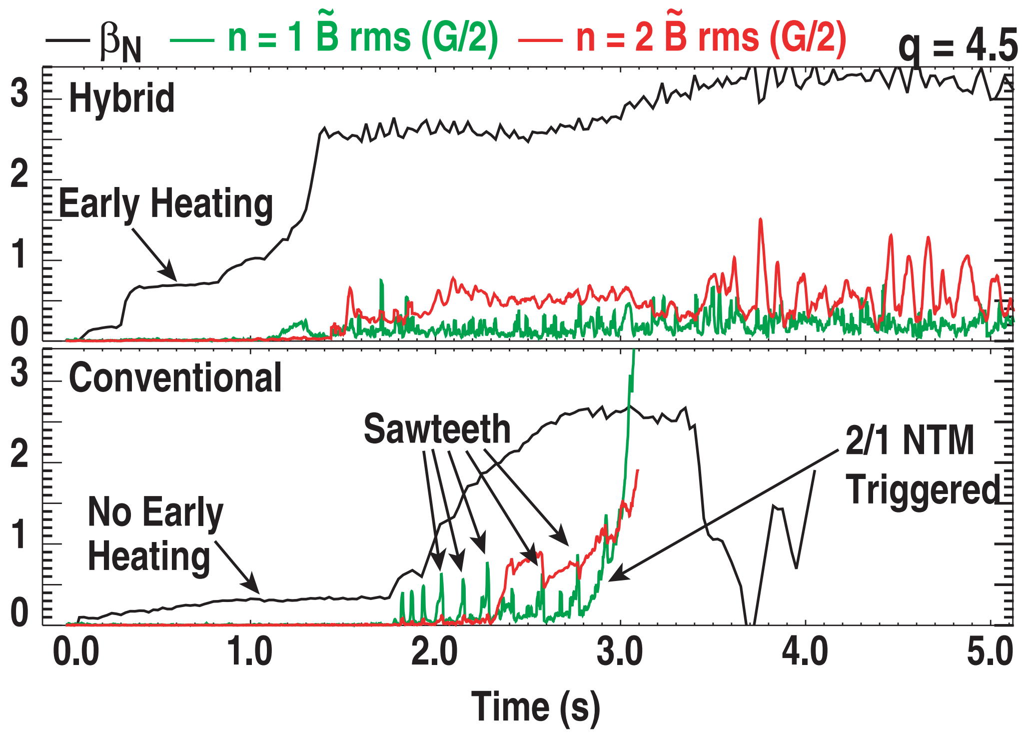

- With early heating, sawteeth do not appear
- Without early heating, m =2, n =1 NTM triggered by sawteeth at 20% lower β_N

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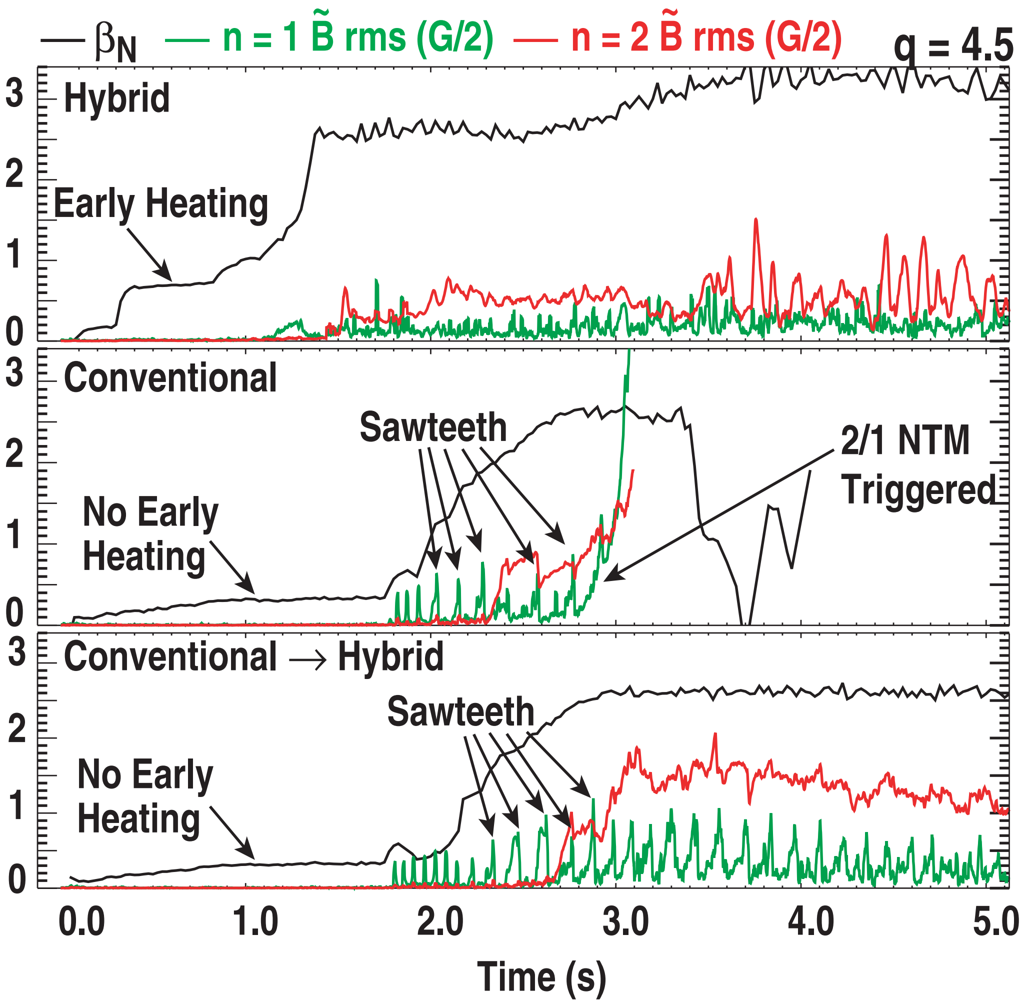

- With early heating, sawteeth do not appear
- Without early heating, m =2, n =1 NTM triggered by sawteeth at 20% lower β_N
- At slightly lower β_N, 2/1 mode not destabilized
- After 3/2 mode grows, sawteeth diminish

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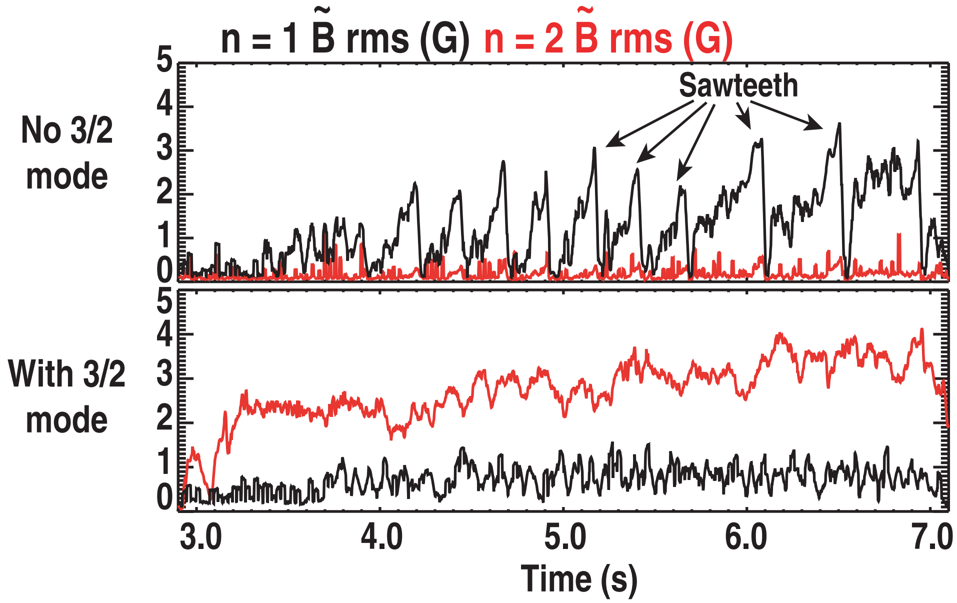
STUDIES HAVE SHOWN 3/2 NTM AMPLITUDE IS KEY TO AVOIDANCE OF SAWTEETH



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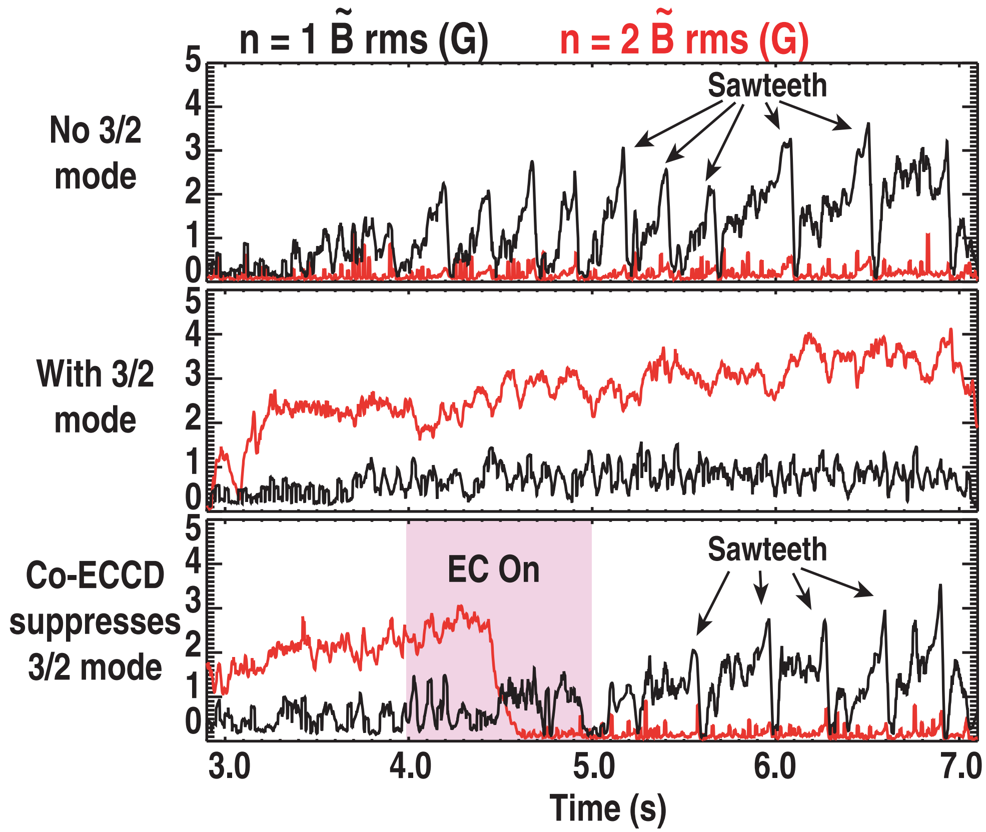

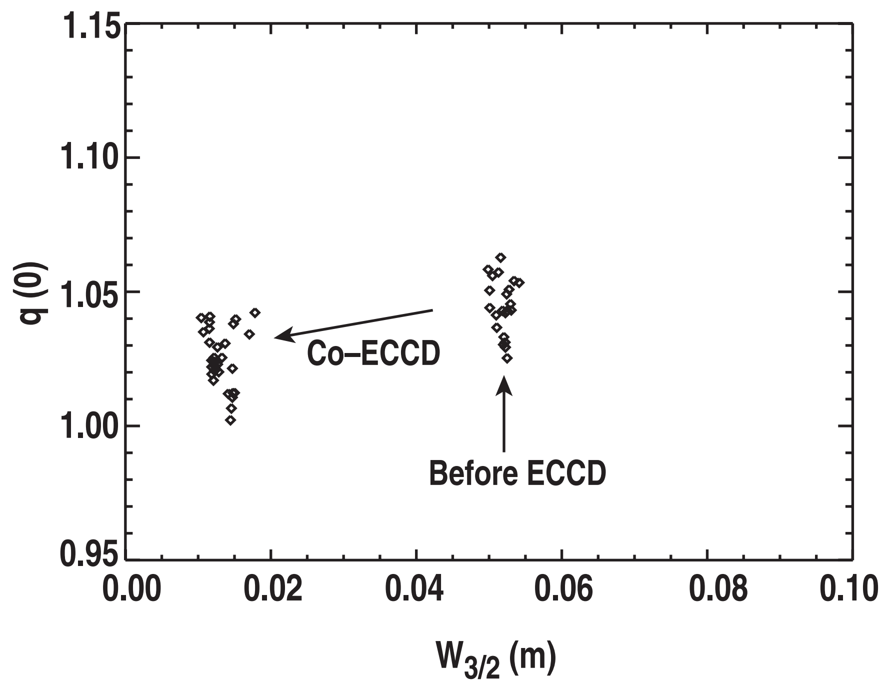

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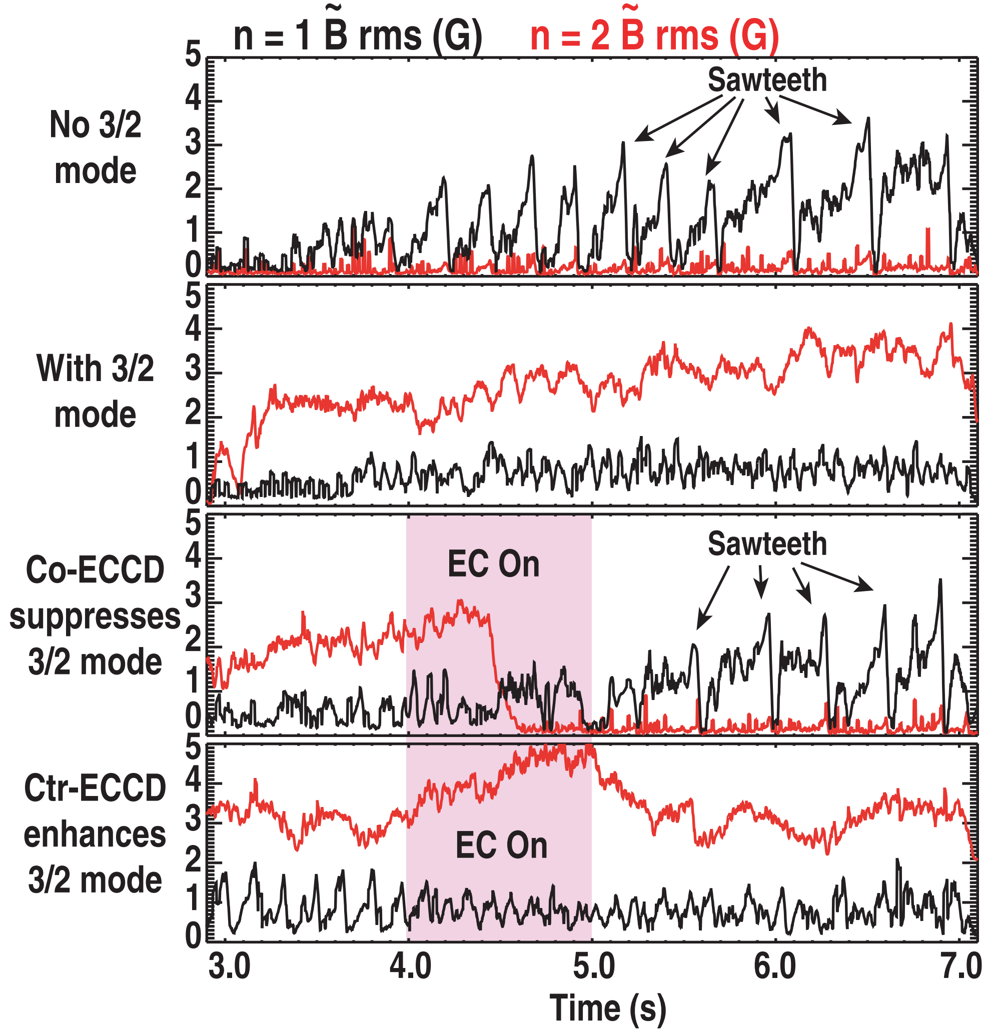

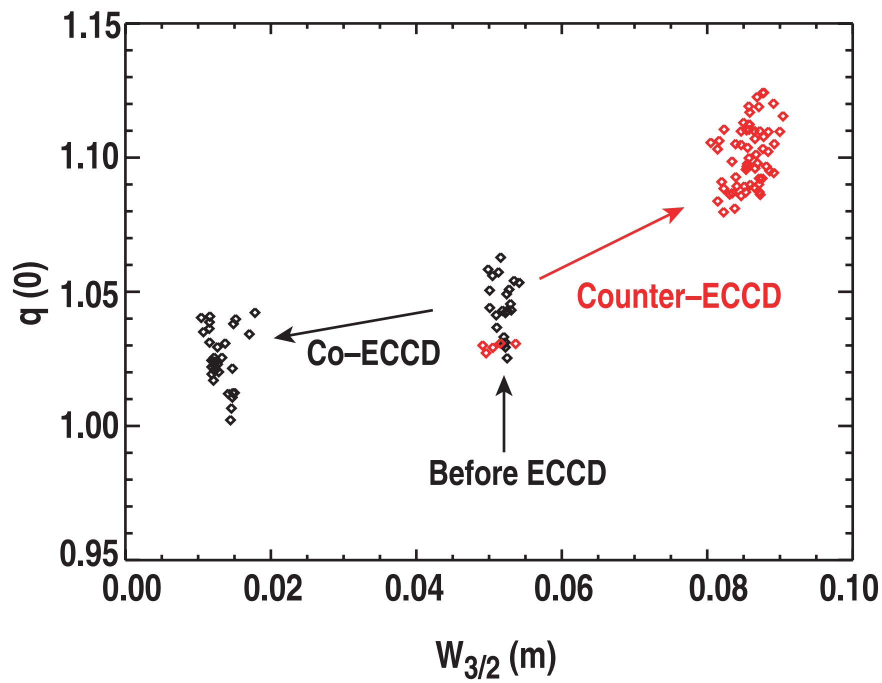

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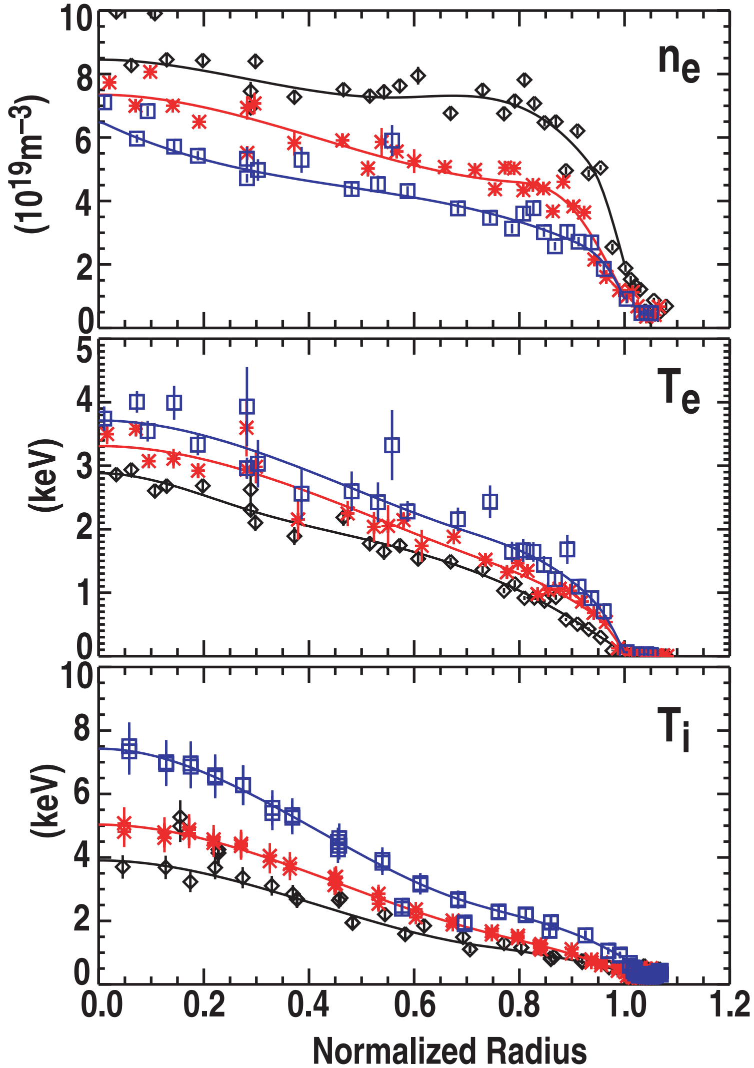
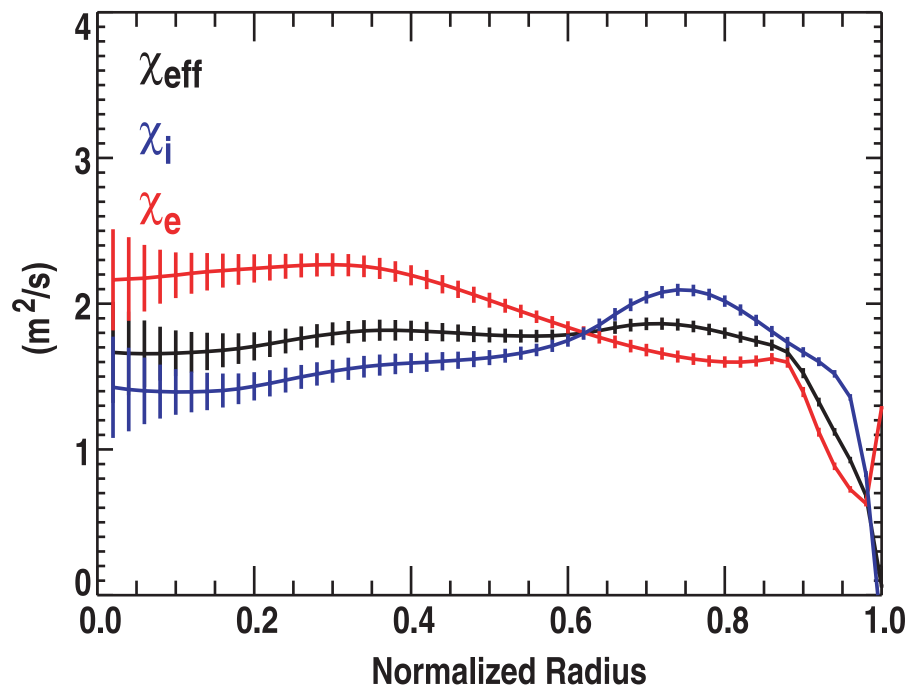
IMPROVED CONFINEMENT IS DUE TO GOOD TRANSPORT ACROSS ENTIRE PROFILE





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

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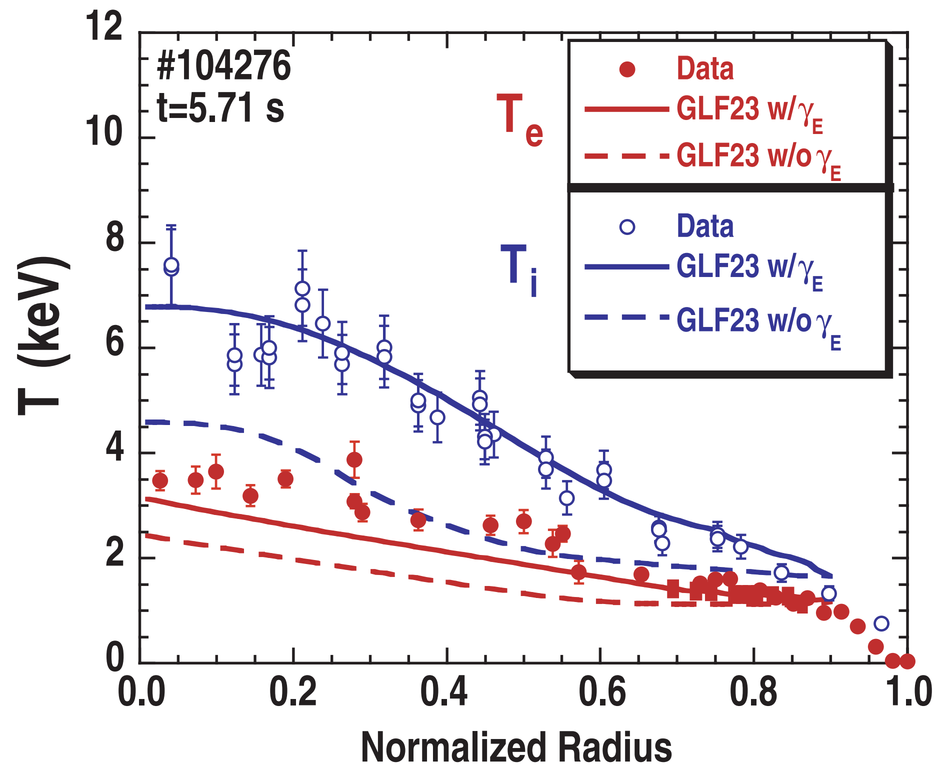
IMPROVED TRANSPORT APPEARS TO BE DUE TO THE INTERACTION OF SEVERAL EFFECTS

- 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



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 s			1900 s		
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