Physics Advances in the ITER Hybrid Scenario on DIII–D

by

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for

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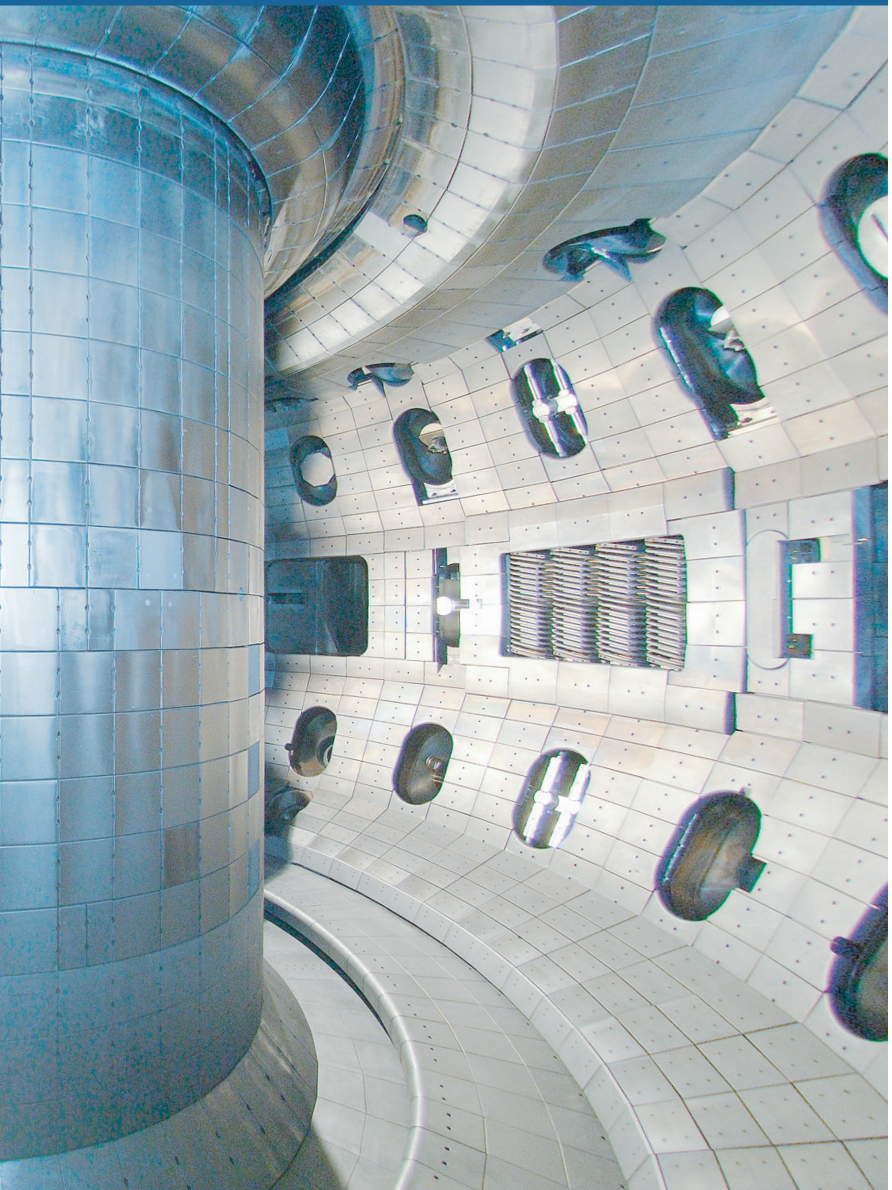

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Outline and Summary

This paper[a] discusses advances in understanding of the hybrid scenario in three areas:

– Rotation Effects

- The new counter-NBI capability on DIII-D has enabled initial experiments on the dependence of hybrid scenario performance on toroidal rotation.
- The toroidal velocity has been reduced by up to a factor of 6 while maintaining stationary conditions, to a central Mach number $M = v_\phi/c_s = 0.075$. $[v/v_A = M \bullet (\beta_e/Z)^{1/2} \approx 0.1\ M]$
- At the lowest rotation, the fusion performance parameter $G = \beta_N H_{89}/q_{95}^2$ is reduced by 10-30%, but remains above ITER requirements.
- Energy confinement improves with increasing rotation (and torque).
- We show here details of the changes that occur in a single discharge when the torque is reduced, and some preliminary results for a range of conditions.

– Improved Confinement in Hybrid Plasmas Dominated by an *m/n* = 4/3 NTM

- Occasionally we observe a hybrid plasma with an 4/3 NTM instead of a 3/2 NTM.
- With either NTM, both the electron and ion thermal diffusivities are small, but the electron channel consistently dominates the conduction loss. χ_i is within a factor of two of the neoclassical value, and χ_e is typically ~$4\chi_i$.
- With a dominant *m/n* = 4/3 NTM both χ_e and χ_i are further reduced by a factor of 2, with χ_i approaching χ_{ineo}. The 4/3 NTM dominated plasmas also have a higher core rotation velocity.
- The effect of the *m/n* = 3/2 NTM on the bootstrap current profile has been seen explicitly for the first time, using direct analysis of MSE data.

– The Effect of the *m/n* = 3/2 NTM on the Current Profile

- The beneficial broadening of the current profile in hybrid plasmas has been shown to be associated with the presence of the 3/2 NTM. We are exploring the physical mechanism(s) involved.
- One possibility is that the modulation of the 3/2 mode by ELMs leads to a poloidal flux pumping process (akin to the sawtooth mechanism) which raises q_0.
- Another possibility is that the effect is associated wih the growth in the *m/n* = 2/2 component of the 3/2 mode as q_0 approaches 1.
- We are also exploring the role of fast ion profile modification in the broadening of the overall current profile.

A Brief Introduction to Hybrid Scenario Plasmas

Definitions

– A high performance scenario for ITER operation.

– Stationary, inductive operation with bootstrap fraction ≈ 0.3-0.5 enables long pulse (≥3000 s) ITER operation.

– High beta ($\beta_N \geq 2.5$) gives high neutron fluence in ITER.

– High fusion performance parameter ($G = \beta_N H_{89}/q_{95}^2 > 0.25$) projects to $Q_{fus} \geq 10$ in ITER.

• For $q_{95} < 4$, "Hybrid" ⇒ "Advanced Inductive"

General Characteristics

– The hybrid mode is a variant of ELMy H-mode. It has an H-mode edge/pedestal structure and behavior.

– Hybrid plasmas are stationary, lasting several current redistribution times.

– Compared to standard H-mode, a hybrid plasma has a broader current profile ($0.75 < \ell_i < 0.95$). The current profile broadening is associated with the presence of MHD activity – in DIII-D usually an *m/n* = 3/2 neoclassical tearing mode (NTM).

– As a consequence of the broader current profile,
  - the hybrid is more stable to the deleterious *m/n* = 2/1 NTM, allowing higher β operation;,
  - sawteeth are weaker (for $q_{95} < 4$) or absent (for $q_{95} \geq 4$), improving confinement and removing a trigger for the 2/1 NTM, and
  - growth rates for drift wave turbulence are reduced, allowing higher confinement.

Some Other Papers related to Hybrid Plasmas in DIII-D at this Conference

– EX/P1-16: Petrie, T.W., *et al.*, “Compatibility of the Radiating Divertor With High Performance Plasmas in DIII-D”

– EX/4-2: Prater, R., *et al.*, “Prevention of the 2/1 Neoclassical Tearing Mode in DIII-D”

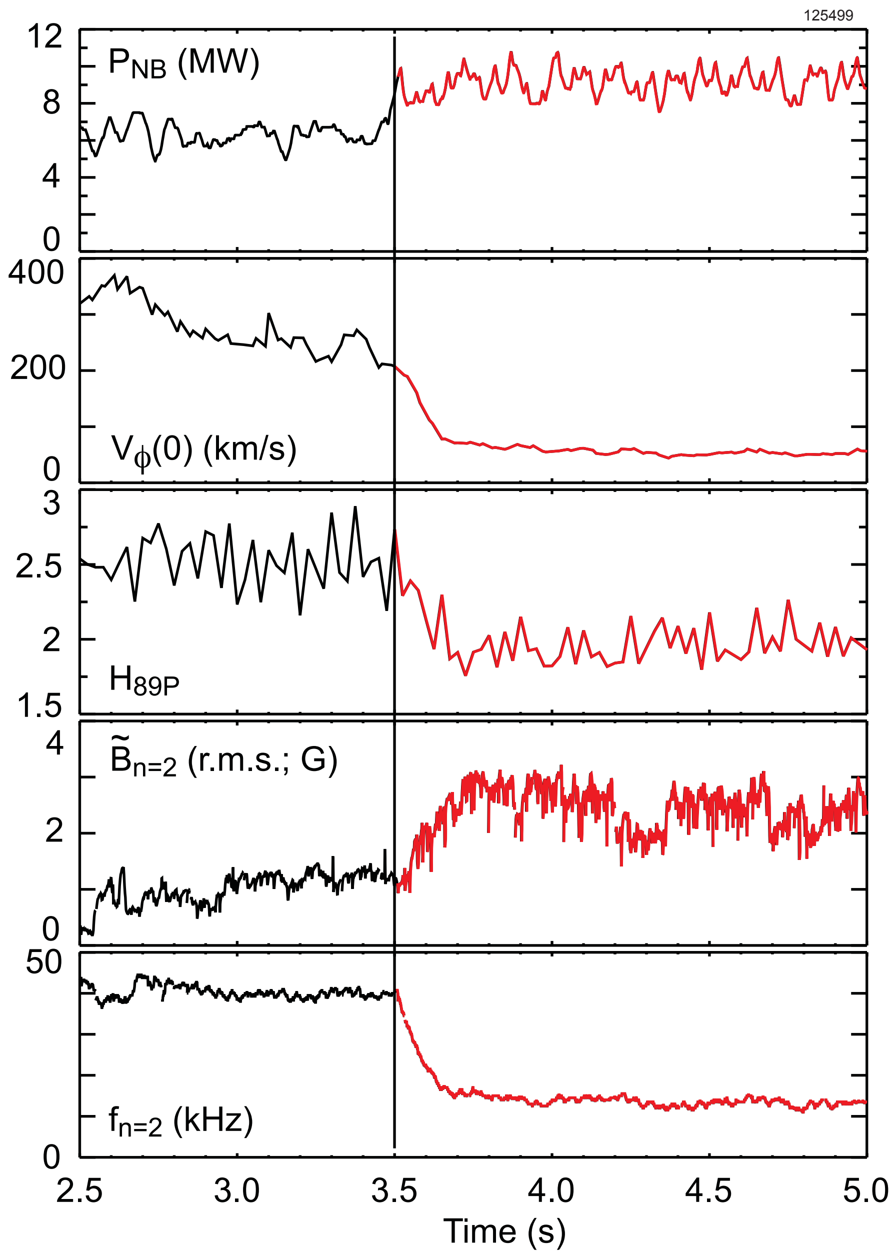
– EX/1-5: Chu, M.S., *et al.*, “Maintaining the Quasi-Steady State Central Current Density Profile in Hybrid Discharges”

– EX/P6-4, Casper, T.A., *et al.*, "Evidence for Anomalous Effects on the Current Evolution in Tokamak Operating Scenarios"

Changing Toroidal Rotation by Adding Counter-NBI Affects Most Aspects of Hybrid Plasma Behavior

A detailed example: β_N = 2.58 (2.45), n_e = 4.3 (4.4) x 10^{19} m^{-3}, q_{95} = 4.6, B_T = 1.92 T, I_P = 1.20 MA.
[() indicates values at low rotation.]

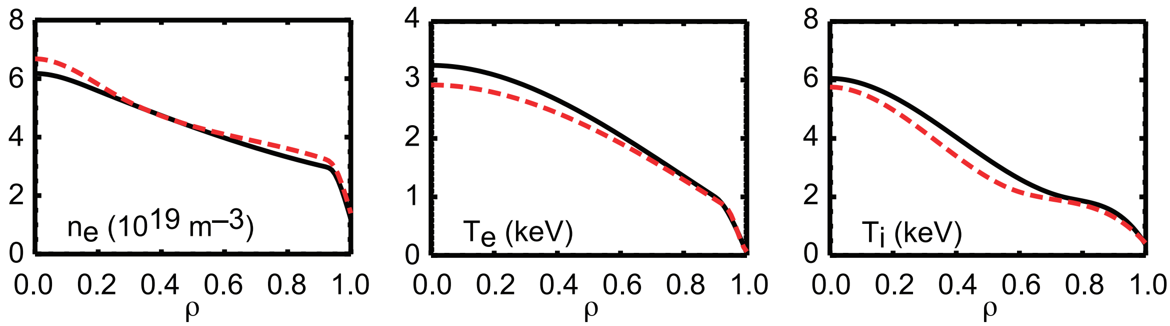
t ≤ 3.5 s:	t ≥ 3.5 s:	
P_{co} = 6.4 MW	P_{co} = 5.2 MW	T_{co} = 4.2 N-m
T_{co} = 4.9 N-m	P_{ctr} = 4.2 MW	Tctr = –3.2 N-m
	P_{net} = 9.4 MW	T_{net} = 1.0 N-m



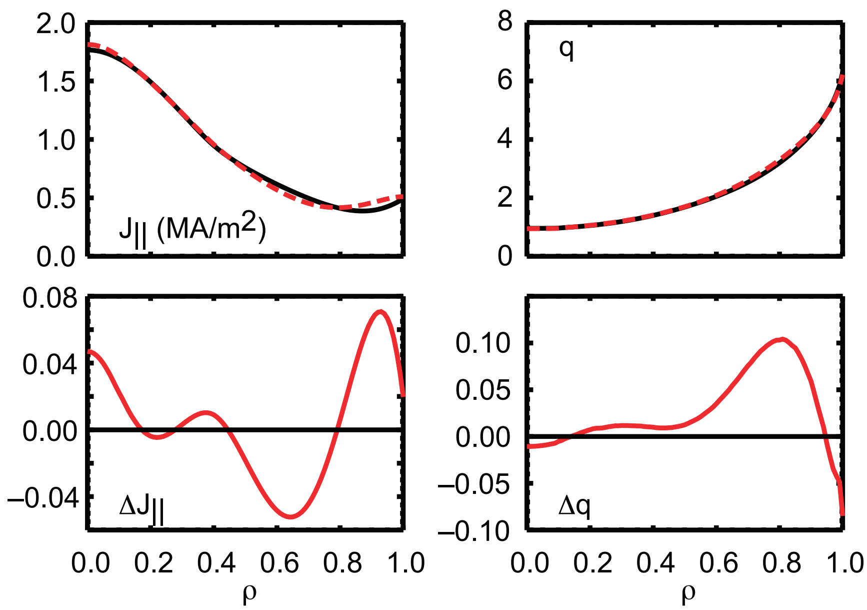
- **β is held constant, power needed increases.**
- **toroidal rotation velocity decreases**
- **β is held constant, confinement decreases.**
- **3/2 NTM island width increases (q = 3/2 surface does not move)**
- **NTM frequency decreases**

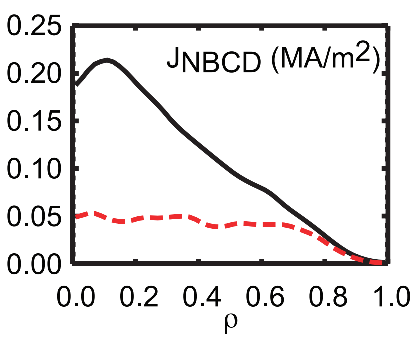
Even with a significant reduction in rotation, there are only small changes in the kinetic profiles. (In part this is because β_N and n_e are under feedback control.)

(profiles averaged 2.99-3.48 s and 4.05-5.72 s)



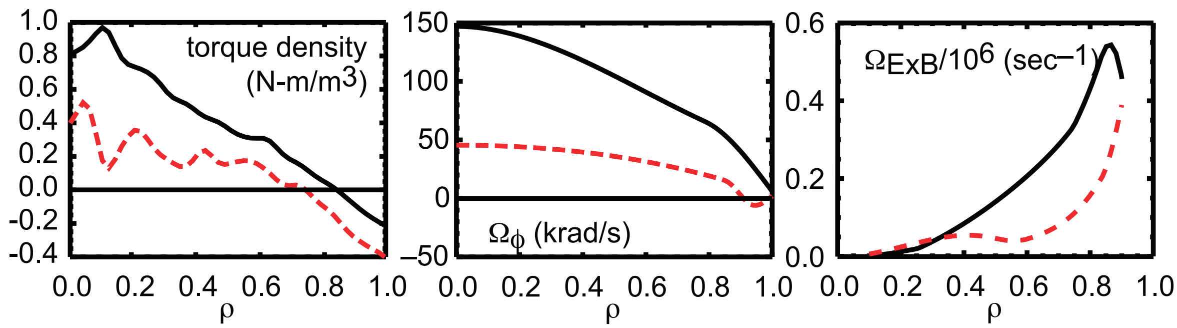
The changes in the *J* and *q* profiles are also small, consistent with the broader deposition profile of the counter-NBI.



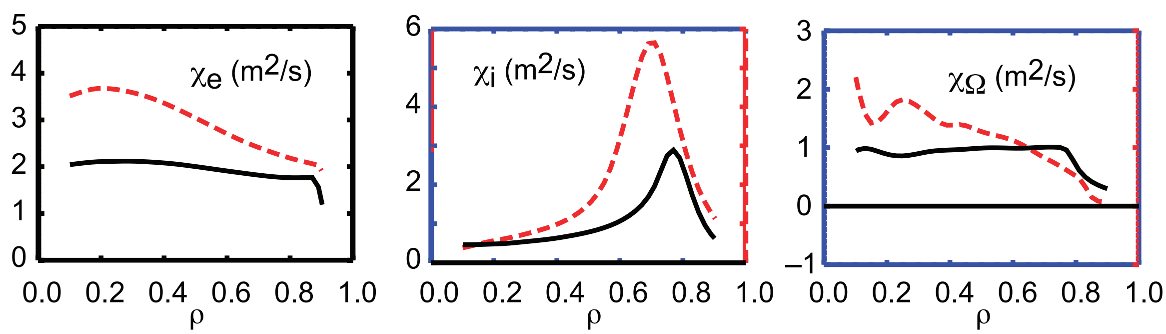


The relative change in the NBCD profile is large. The profile is much flatter (broader) and the total NBCD is reduced. However this affects only a small fraction of the total current.

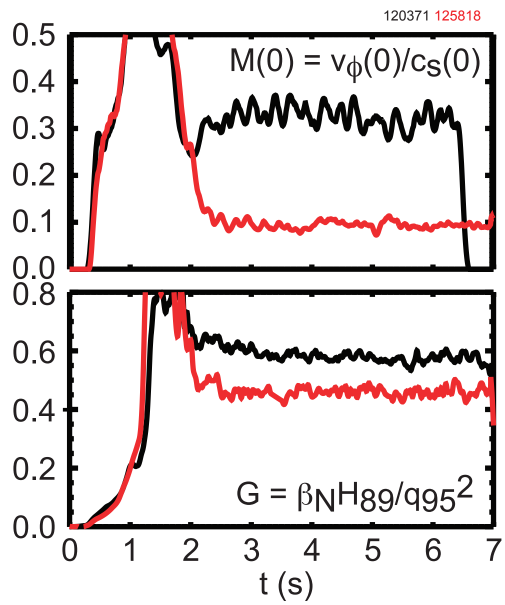
The large change in torque leads to a reduction in rotation (which becomes negative near the edge), and in the shearing rate of the ExB velocity.



Electron and ion thermal diffusities increase (by about a factor of 2), as does the momentum diffusivity.

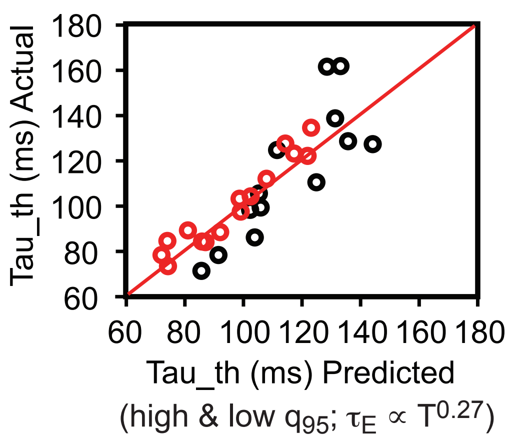


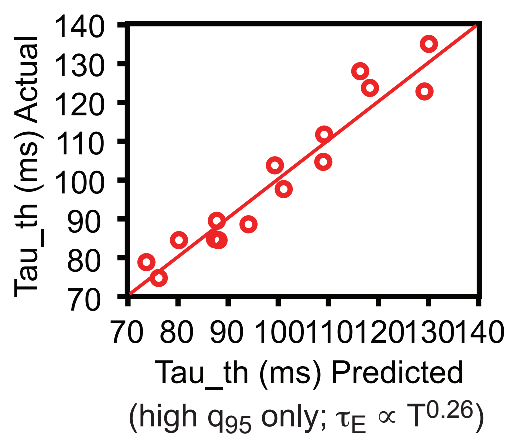
The low rotation hybrids still meet ITER requirements, even with somewhat reduced performance..



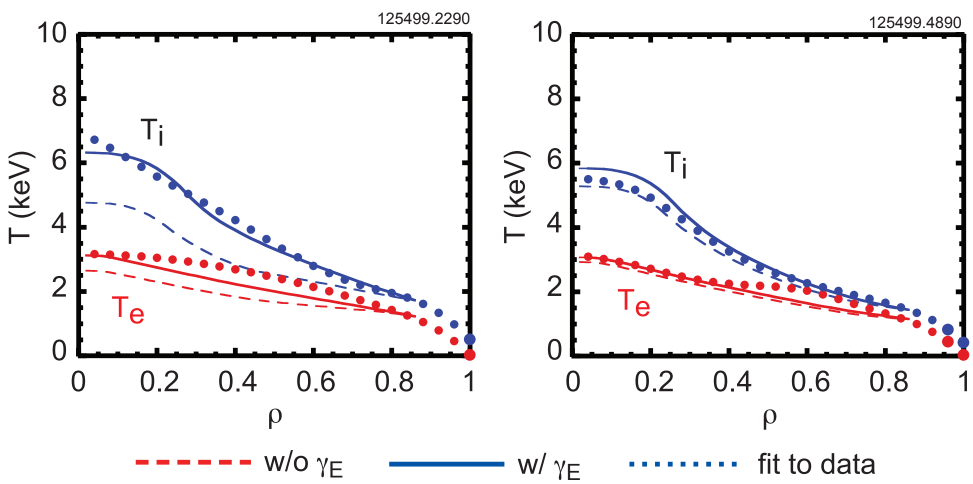
- Compare similar discharges with β_N = 2.7, q_{95} = 3.2.
- A factor of 3 reduction in central Mach number results in a 20% reduction in G.
- G = 0.46, exceeding the ITER requirement of 0.42.

Preliminary scaling analysis indicates that $\tau_E \propto$ torque^(~1/4) best fits both high and low q_{95} data.



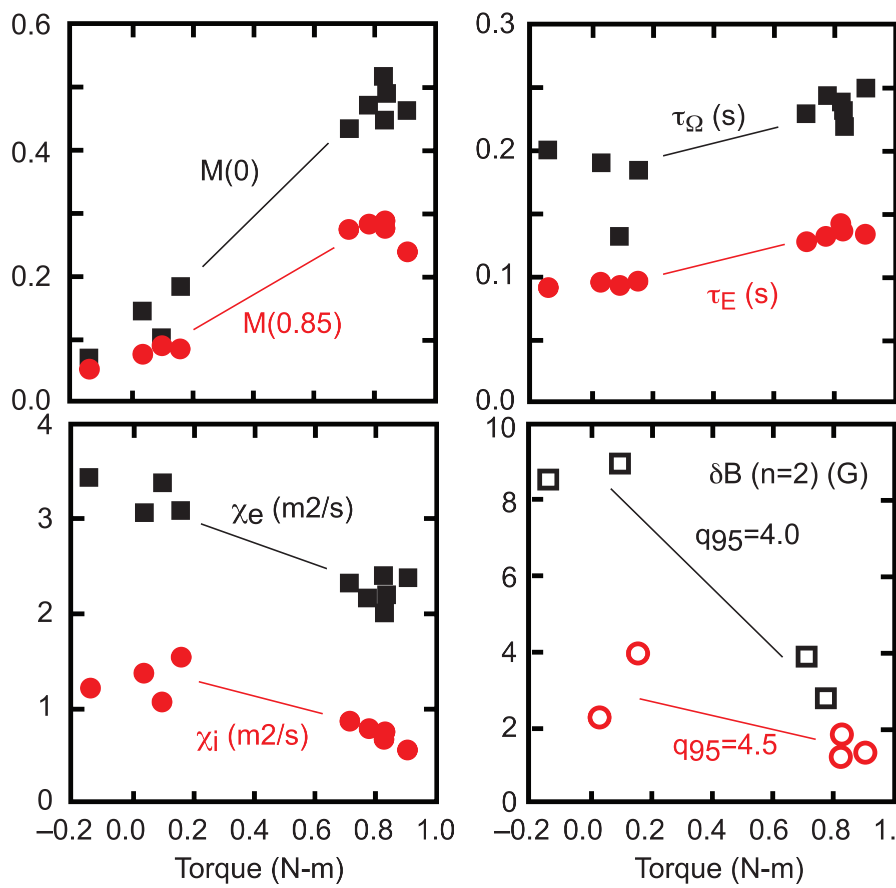


GLF23 accurately predicts the ion and electron temperature profiles at both high and low rotation. At high rotation, GLF23 requires inclusion of ExB flow shear at high rotation. At low rotation, the ExB flow shear makes little difference.



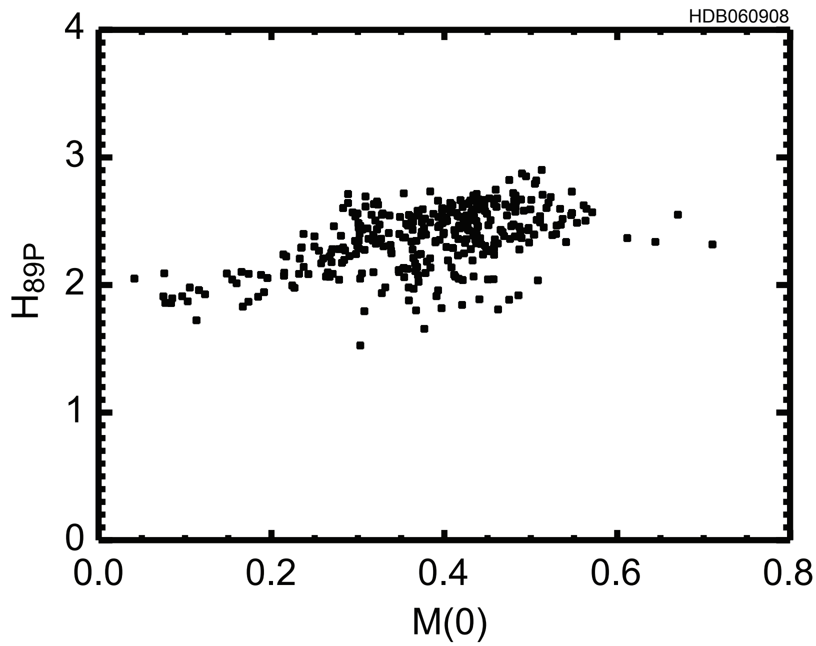
The dependence of confinement parameters on NB torque is consistent over the range 4.0 ≤ q_{95} ≤ 4.6.

As the torque is reduced, the amplitude of the 3/2 NTM increases, more rapidly at lower q_{95}.



Our database of DIII-D hybrid plasmas (2000-06) illustrates the systematic dependence of confinement on toroidal rotation.

(The database has 417 discharges with stationary conditions for >1 s; with parameters averages over the stationary period.)



Thus far we have not maintained stationary hybrid performance at zero rotation. Instead, braking due to the residual error field and to the interaction between the 3/2 NTM and the wall leads to locking and the appearance of a static n = 1 perturbation.

Hybrid Discharges Can Have a Dominant m/n = 4/3 NTM Rather Than a 3/2 NTM

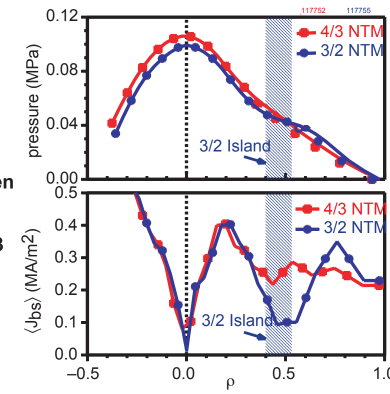
- All hybrid plasmas have some MHD activity. In DIII-D this is usually an *m/n* = 3/2 NTM. Occasionally we see a hybrid plasma dominated by an *m/n* = 4/3 mode.
- The 4/3 dominated hybrid plasmas have better confinement than the 3/2 dominated plasmas, and meet or exceed the ITER requirement for $G = \beta_N H_{89}/q_{95}^2$.
- Compared to the 3/2 NTM dominated cases, the 4/3 NTM has a weaker effect on plasma profiles.
- This would be the preferred operating mode except for the observation that, as β_N is increased the 4/3

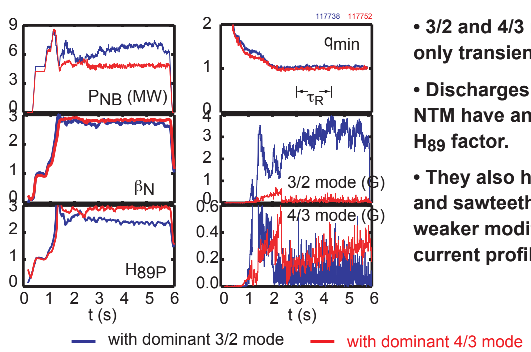
• Direct analysis of MSE data yields the pressure and pressure-driven current profiles.
[C.C. Petty, *et al.*, PPCF **47** (2005) 1077.]

• Flattening of p(ρ) by the 3/2 mode reduces confinement. The Chang-Callen belt model gives an ~8% reduction.

• Little or no flattening is seen in the 4/3 mode dominated case.

• This analysis shows the “missing” bootstrap current associated with the pressure profile flattening.



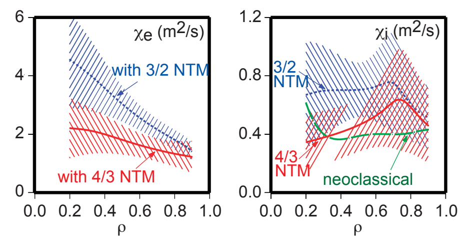


• 3/2 and 4/3 modes coexist only transiently.

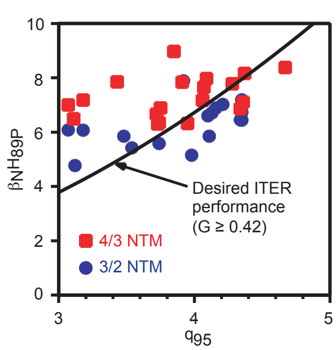
• Discharges with a 4/3 NTM have an ~25% higher H_{89} factor.

• They also have $q_{min} < 1$ and sawteeth, indicating a weaker modification of the current profile.

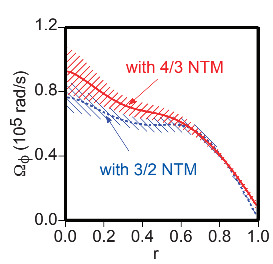
With the 4/3 NTM, thermal diffusivities are ~1/2 the diffusivities obtained with 3/2 NTM, and χ_i is close to $\chi_{neoclassical}$.



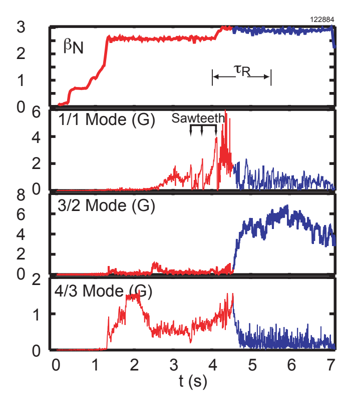
Hybrids with dominant 4/3 NTM exceed ITER baseline performance over a wide range of q_{95}.



The 4/3 NTM has a weaker effect on the central rotation profile than the 3/2 NTM.



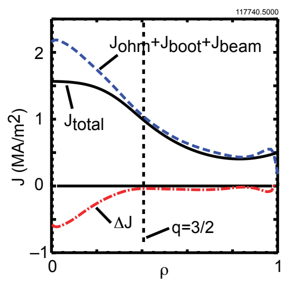
Raising β_N above 2.8 leads to a 4/3 ⇒ 3/2 NTM transition.



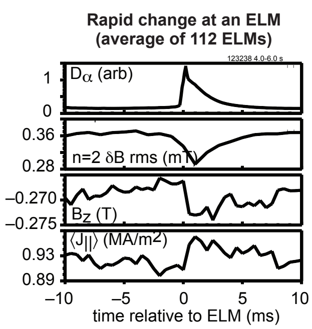
The m/n = 3/2 NTM Has Been Shown to Modify the Current Profile in Hybrid Plasmas – What Is The Mechanism?

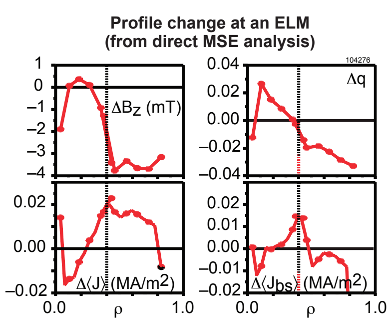
- Experiments using ECCD to stabilize the 3/2 NTM have shown that the NTM is responsible for broadening the current profile in hybrid plasmas. This is also clear from the differences between 3/2 and 4/3 NTM dominated plasmas.
- This effect leads to much of the inproved performance of the hybrid. The cost to confinement of the presence of an island structure is more than compensated by the inproved stability to n=1 modes and by improved confinement in the rest of the plasma.
- While there is as yet no clear answer as to the details of the physical mechanism causing the change in the current profile, we are continuing to examine several possibilities.

- **The sum of the calculated current components matches the measured $J_{||}$, except in the core (inside the q=3/2 surface).**
- **The difference (integrated to the q=3/2 surface) is small, ~50 kA.**
- **The 25-30% decrease in J(0) increases q0 by an equal**

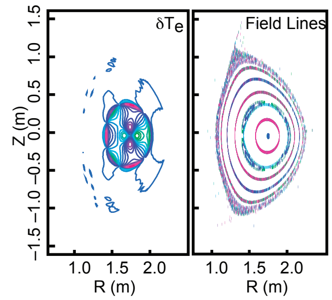


- **The 3/2 NTM amplitude is modulated by ELMs.**
- **This can lead to a poloidal magnetic flux pumping effect (similar to the process whereby sawteeth maintain q0 ~ 1).**
- **At an ELM, q increases inside the q=3/2 surface.**



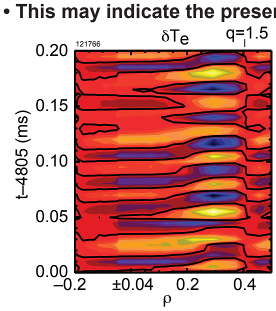


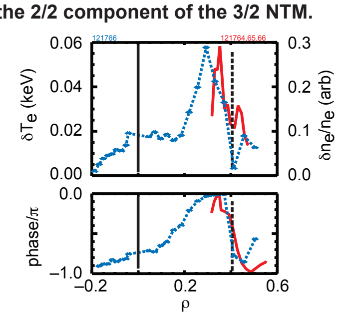
The redistribution of current by the NTM occurs when q0 approaches 1. One explanation for this is related to the global structure of the mode.



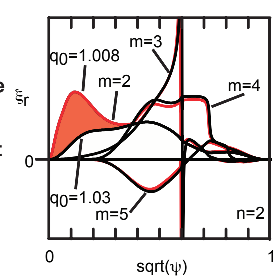
- **The NIMROD code models the 3/2 NTM.**
- **In addition to the m=3 island, there are strong kink-like perturbations with m=2, 4, 5, ... structure.**

- **The BES (δn_e) and ECE (δT_e) diagnostics shows the signature of an island structure as expected.**
- **$\delta T_e \neq 0$ near the axis, but is ~30% of the maximum near the island. Also there is a phase shift of ~2π/3 between the axis and the island.**
- **This may indicate the presence of the 2/2 component of the 3/2 NTM.**





- **Construct a sequence of equilibria with varying q0 (near 1).**
- **Use PEST3 to analyze the linear n=2 mode structure.**
- **Little change occurs as q0⇒1, except that the 2/2 component increases rapidly.**
- **Some possible consequences of this are discussed in paper EX/1-5, M.S.Chu, et**



✧ **Finally, spatial redistribution of the fast ion population may also play a role in the modification of the current profile in hybrids, through changes in the NBCD profile.**

✧ **Very recent experiments have been done to address this directly, and we are presently analyzing data from the new FIDA (fast ion D_α) diagnostic to determine whether such changes occur.**