Advancing Tokamak Physics with the ITER Hybrid Scenario on DIII–D

by

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with

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DIII–D NATIONAL FUSION FACILITY

GENERAL ATOMICS

The Hybrid Scenario is an High Performance Inductive Operating Regime for ITER

- The major tokamak programs have been developing the hybrid scenario for a number of years.
- It provides high gain and high neutron fluence options for ITER operation.
- This talk will cover two areas where we've made significant advances, leading to better capability to forecast performance:
  - MHD & the current profile,
  - rotation & confinement,
  - and will give a brief sampling of other areas of tokamak physics being addressed in hybrids.

increasing complexity & benefit ↓

Conventional H-mode:
$\beta_N \approx 1.8$,
$q_{95} \sim 3$, $f_{BS} \ll 1$
baseline

Advanced inductive:
$\beta_N \leq \beta_{no\text{-}wall}$,
$q_{95} \sim 3$, $f_{BS} \sim 0.3$
high gain

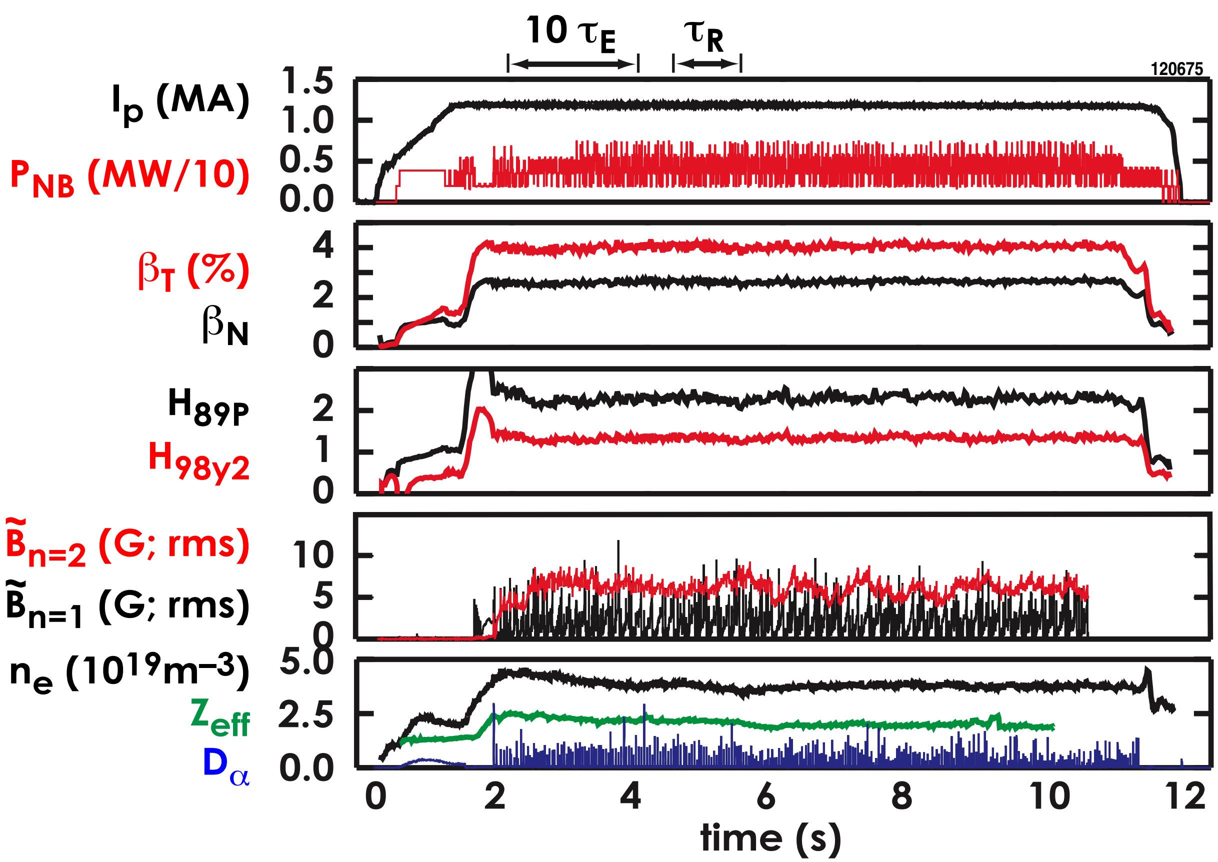
Hybrid:
$\beta_N \approx \beta_{no\text{-}wall}$,
$q_{95} \geq 4$, $f_{BS} \sim 0.5$
high fluence

"hybrids" (Advanced inductive and Hybrid)

Advanced tokamak:
$\beta_N \leq \beta_{ideal\text{-}wall}$,
$q_{95} \geq 5$, $f_{BS} \sim 0.8$
steady-state

Stationary, High Performance Hybrids are Studied in DIII-D

- Stationary conditions are maintained for many τ_E and τ_R.
  ➜ limited only by hardware.

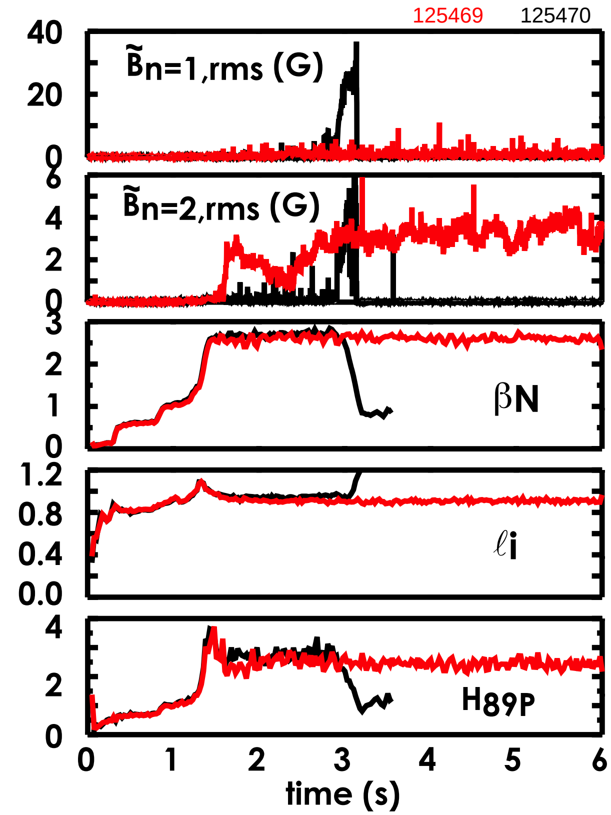


	ITER scenarios #2(base)	#3(hybrid)
$\beta_T \approx 4\%$	2.5%	2.8%
$\beta_N \approx 2.7$	1.8	1.9
$H_{89P} \approx 2.3$	2.4	2.1
$H_{98y2} \approx 1.3$	1.0	1.0
$\frac{\beta_N H_{89}}{q_{95}^2} \approx 0.58$	0.43	0.32
$Z_{eff} \approx 2$		

MHD and the current profile

MHD Activity is an Integral Part of Hybrid Operation – Usually a m/n = 3/2 NTM in DIII-D

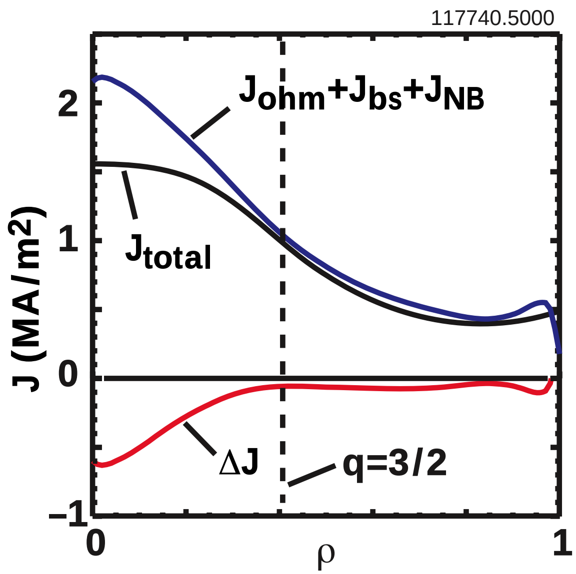
- The effect of the ~stationary NTM
  - is to broaden the current profile
    ➜ raises q(0)
    sawteeth are reduced (for q95 ≤ 4)
    or eliminated (for q95 > 4)
    › better confinement
    › removes one trigger for the 2/1 NTM
  - increases stability of 2/1 mode
  - with only a modest confinement reduction
    est $\Delta\tau_E/\tau_E \approx -$ 6-15%
    depending on q95, rotation
  - leading to high β operation;
    $\beta_N \sim 4\ell_i$ (~ no-wall limit)



➤ Without a 3/2 mode, the discharge evolves to an unstable 2/1 tearing mode
➜ controlled shut-down

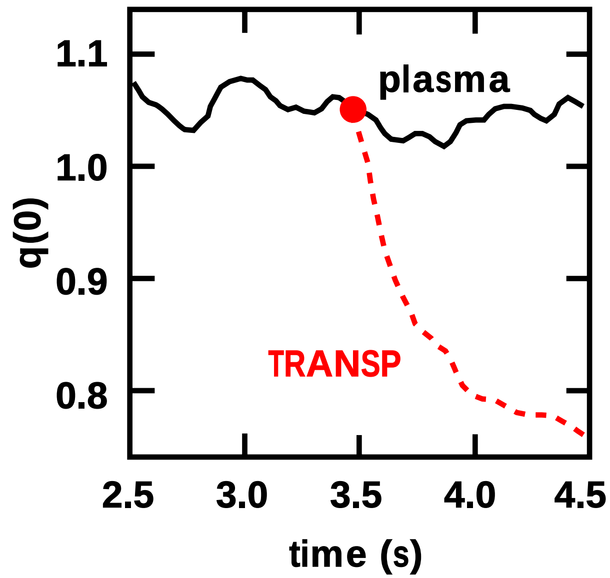
The Current Near the Axis is Reduced, Increasing q(0)

DIII-D current profile



- **Measured current profile shows deficit at center compared to sum of calculated currents.**
- **Only ~5% of total current, but strongly affects q(0).**

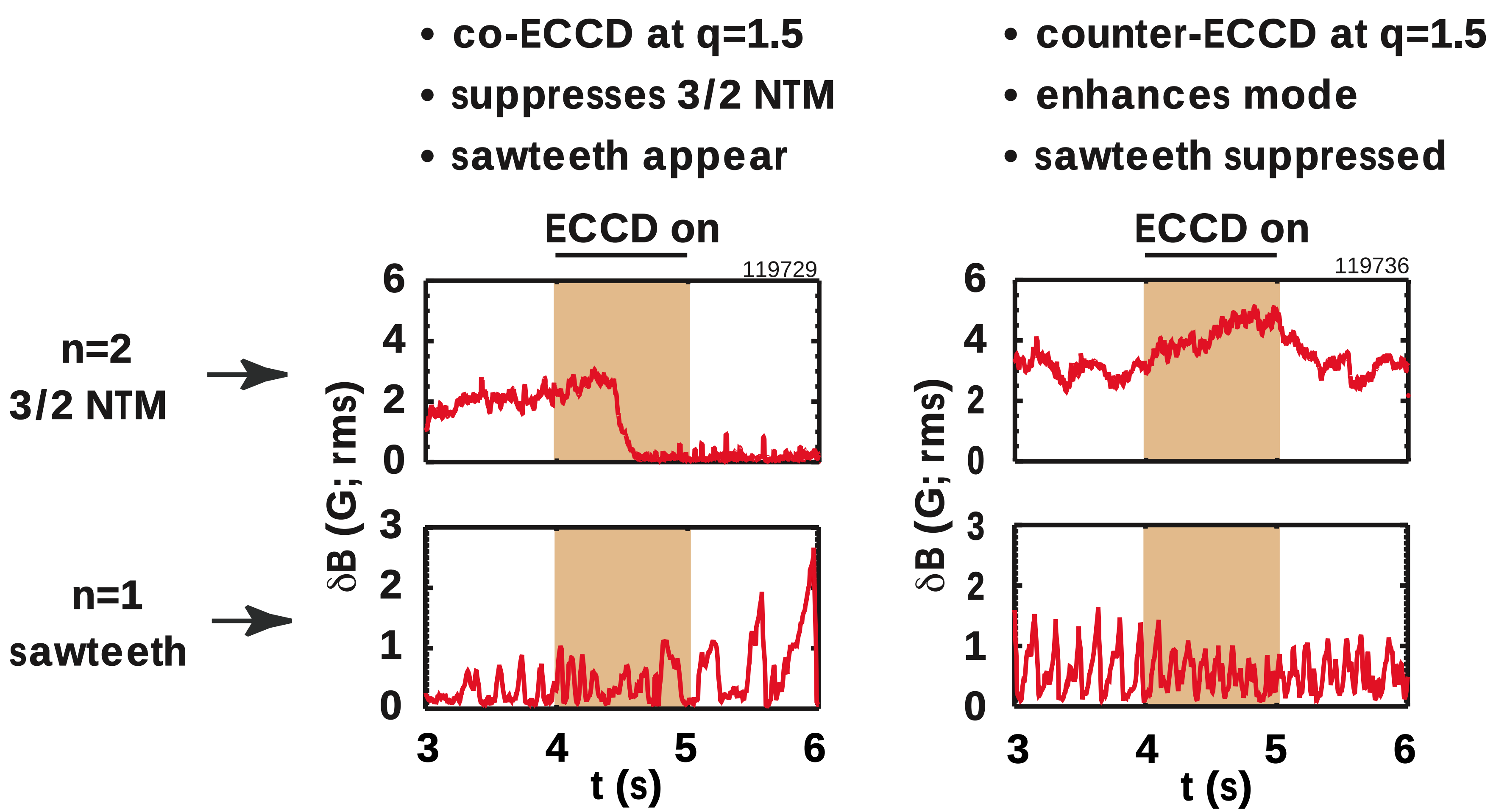
simulation



- **TRANSP simulation switches to neoclassical resistivity and current transport at 3.5 s.**
  - **current profile peaks and q(0) drops.**

The NTM is Responsible for Modifying the q Profile: Changing the NTM Amplitude with ECCD Affects Sawteeth

- **Decreasing NTM amplitude increases sawtooth size, indicating peaking of the central current and reduction of q(0), and vice versa.**



- **Raises the question: how does the NTM act on the current profile?**

Several Mechanisms Suggested to Explain the Effect of the 3/2 Mode on q & J

- **Making progress, but no definitive conclusion yet.**

– Direct current drive by the 3/2 mode
  – as seen from the magnetic axis,
    the NTM island looks like an Alfvén wave antenna
  - interesting physics; calculated magnitude too small

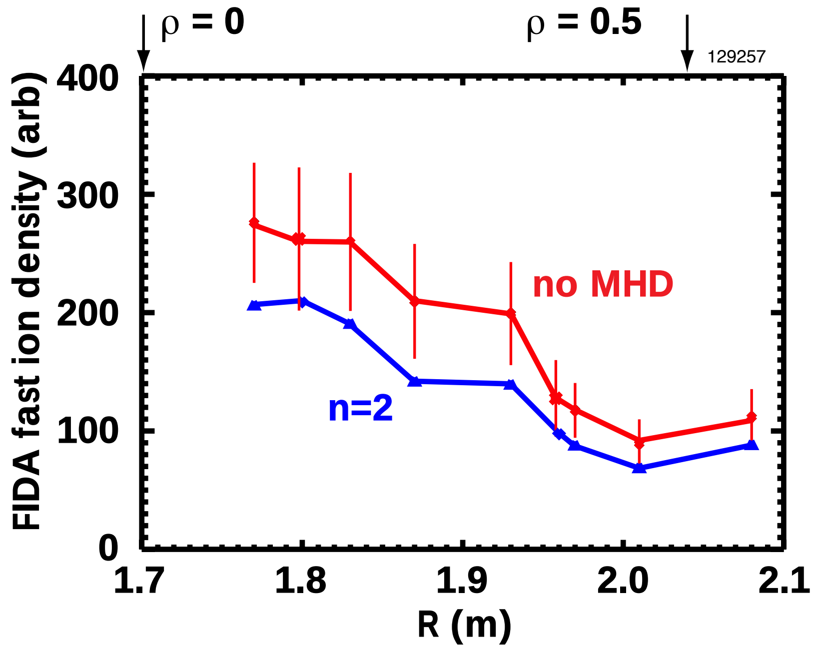
– Broadening of the fast ion spatial profile by the 3/2 mode
  ➜ • change in fast ion profile is observed;
    modeling indicates small effect on current profile

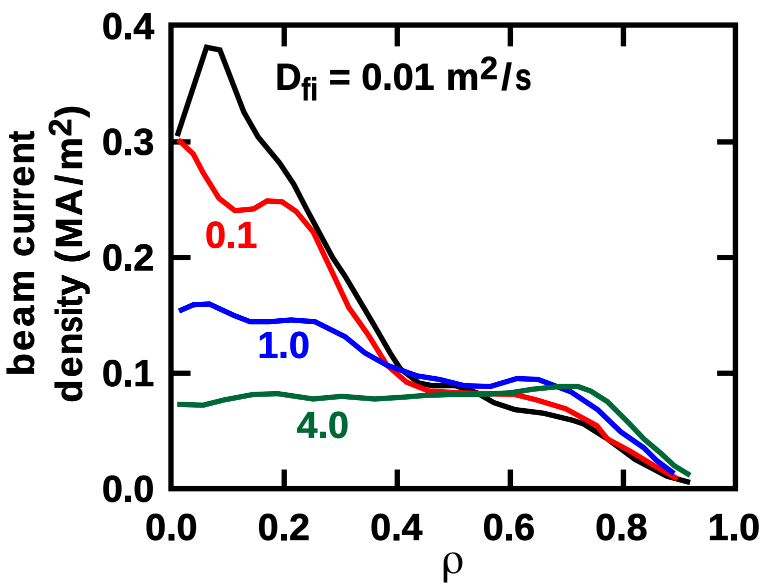
– Modulation of the NTM amplitude by ELMs
  ➜ – asymmetry in time ⇒ flux pumping
      (analogous to the effect of sawteeth on q & J)
  - evidence for effect is seen

– Dynamo
  – conversion of kinetic to magnetic energy via $\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle$
  - no data; need nonlinear resistive MHD modeling

The Central Fast Ion Density is Reduced by the 3/2 NTM

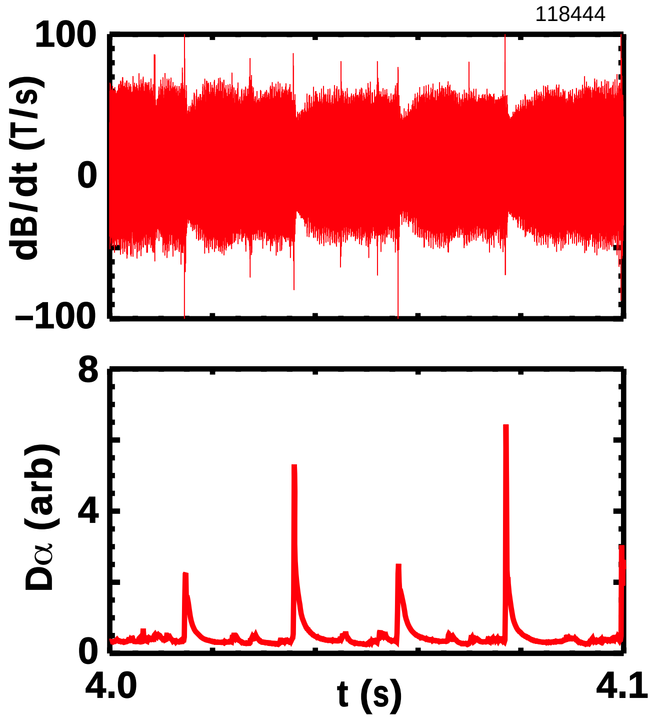
- The FIDA (fast ion D_α) diagnostic indicates that the density of fast ions drops in the inner region of the plasma when the 3/2 NTM appears.





- Preliminary TRANSP analysis using uniform fast ion diffusion shows a large drop in central NBCD.
- TRANSP indicates that most of this is replaced by increased ohmic current, yielding a very small change in q(0).

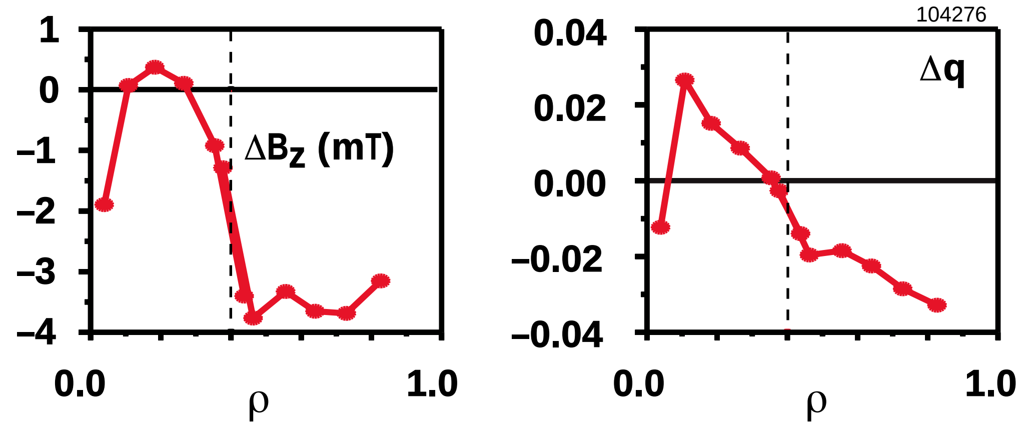
Modulation of the 3/2 NTM by ELMs Leads to Current Profile Broadening



- This modulation can lead to a poloidal magnetic flux pumping effect
(similar to the process whereby sawteeth maintain q0 ~ 1).

- Averaging over many ELMs, analysis of MSE data shows that, at an ELM, q increases inside the q=3/2 surface.

Profile change at an ELM (from direct MSE analysis)



[Petty, JP8.00084]

Rotation and confinement

Hybrid Performance Depends on Toroidal Rotation

- **Most of the tokamak experience base has been limited to plasmas with strong toroidal rotation (thanks to NB heating).**
- **There is concern that ITER (& DEMO & reactors) will have low rotation.**

➜ **To study this issue, we've used the recently modified NB configuration in DIII-D to study the effect of rotation on the performance of hybrid plasmas.** (5 sources co-NBI; 2 sources counter-NBI.)

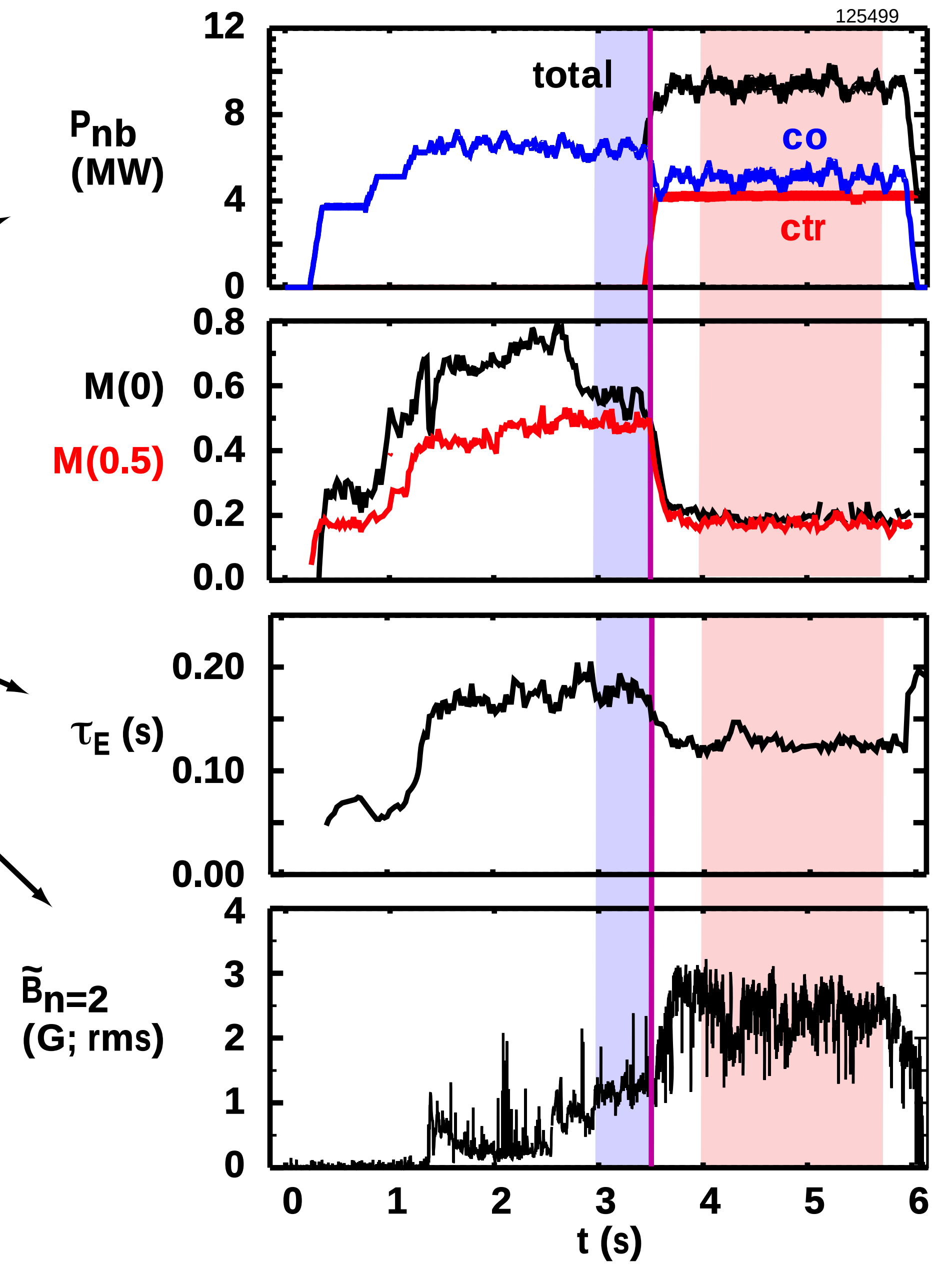
– **We did systematic scans of rotation for both hybrid (q_{95} ~ 4.2 & 4.6) and advanced inductive (q_{95} ~ 3.2) plasmas.**

– **The central Mach number has been reduced by up to a factor of 5, to M(0) ≈ 0.1, maintaining stationary conditions.**

➜ **Both the confinement and the MHD properties are affected.**

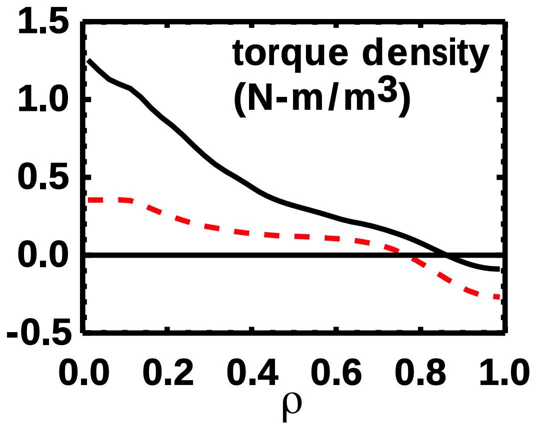
Reducing Rotation Strongly Affects Plasma Characteristics

- Density and β_N held constant, under feedback control
- High vs. low rotation:
  - add counter-NBI
  - reduce torque; rotation decreases
  - confinement decreases; total power increases
  - 3/2 NTM amplitude increases
- Experiments and modeling are sorting out what's happening.

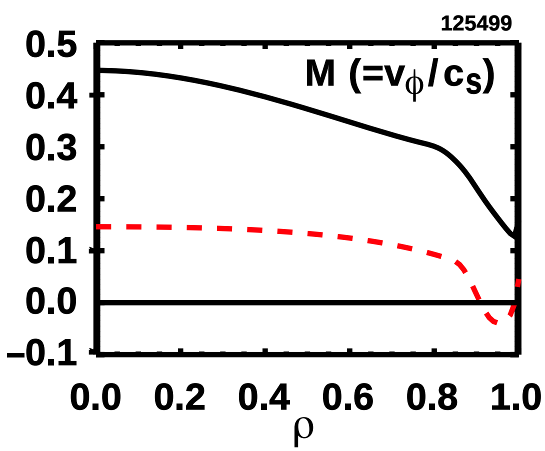


Density, Temperature, and Current Profiles are Unaffected by Changing Torque

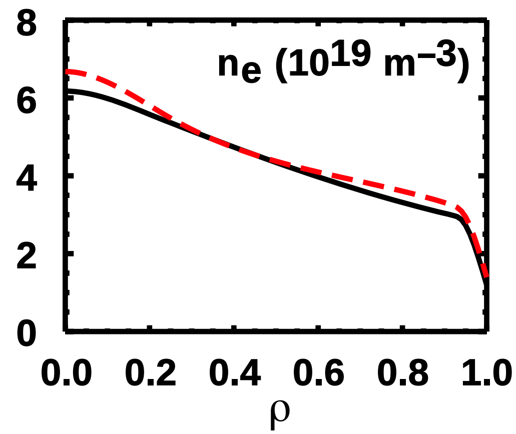
Changing torque and power:

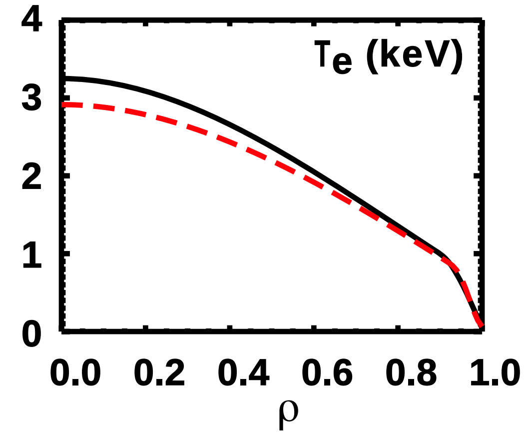


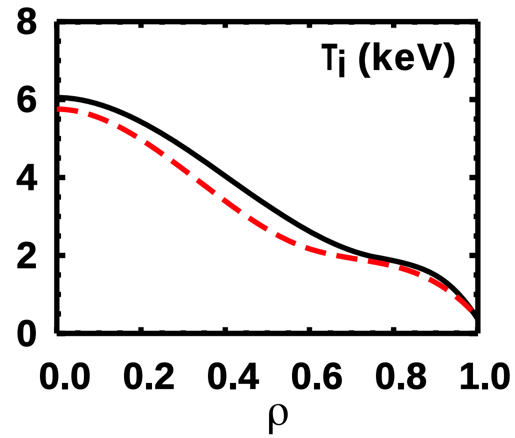
Results in a large change in the rotation profile:



But the density and temperature profiles vary little
(β_N and density are controlled):



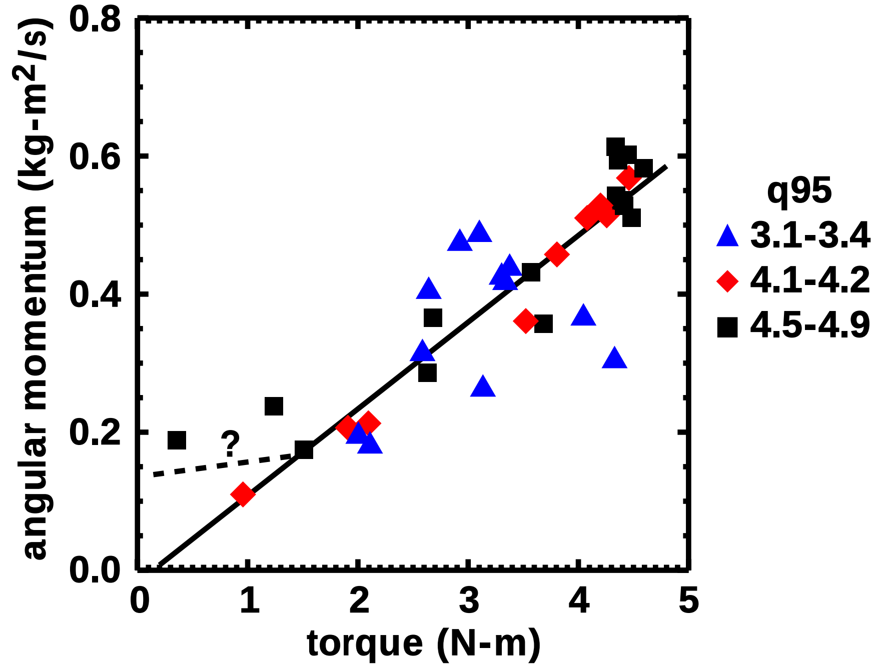




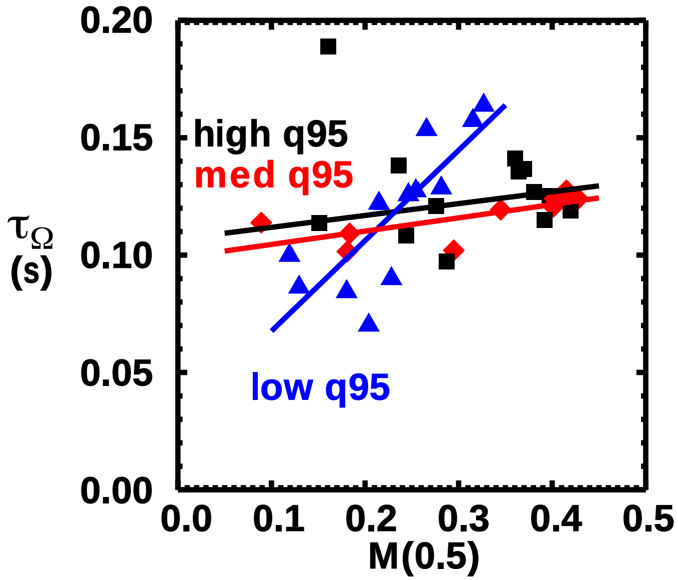
Also, J_{NBCD} is halved (0.12→0.06 MA), but the effect on q and J_{total} profiles is negligible.

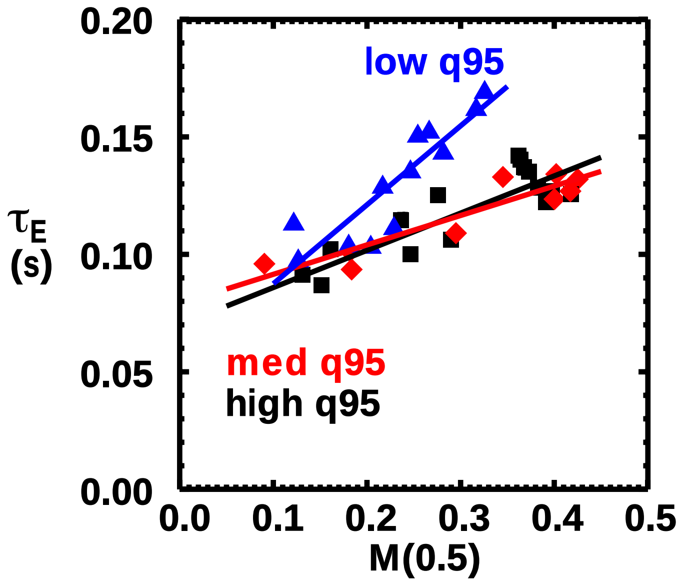
Angular Momentum is Roughly Proportional To Torque

- **Vary the applied torque (T) over the range 0.4-4.6 N-m.**
- **Characterize rotation by either**
  L = total angular momentum
  M(0.5) = Mach number at ρ = 0.5
  › these are strongly correlated
- **L ∝ T**
  ⇒ τ_Ω = L/T ~ independent of L, except for a possible indication of 'inherent' rotation at low torque.
- **Very low (and zero) rotation was inaccessible because of error field penetration and locking of the 3/2 NTM.**

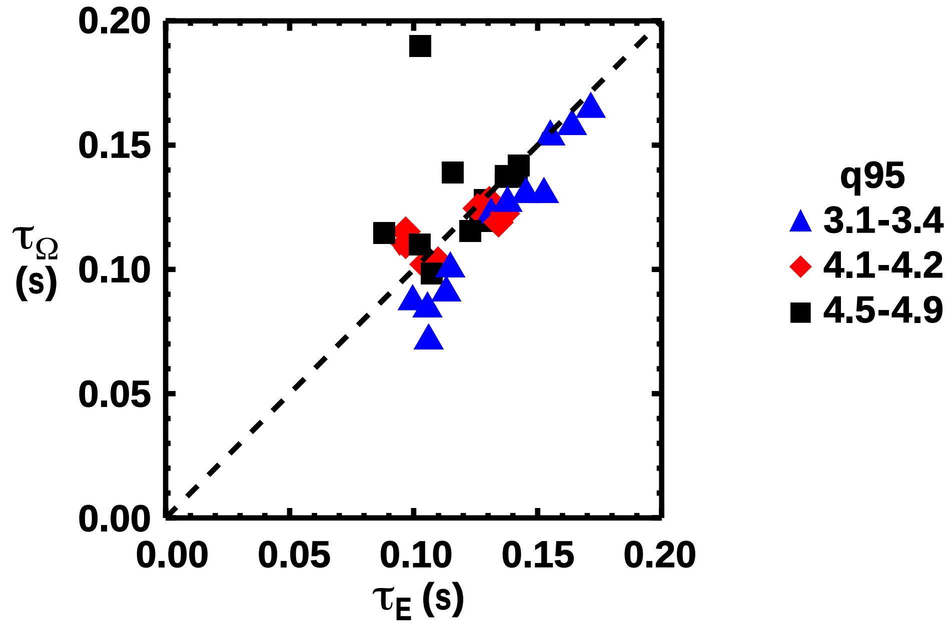


Global Confinement Improves As Toroidal Rotation Increases

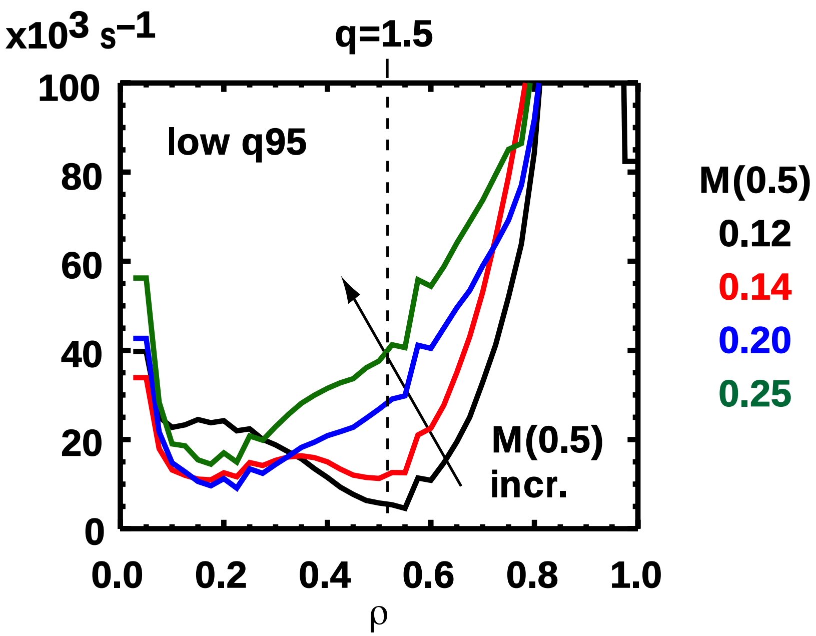


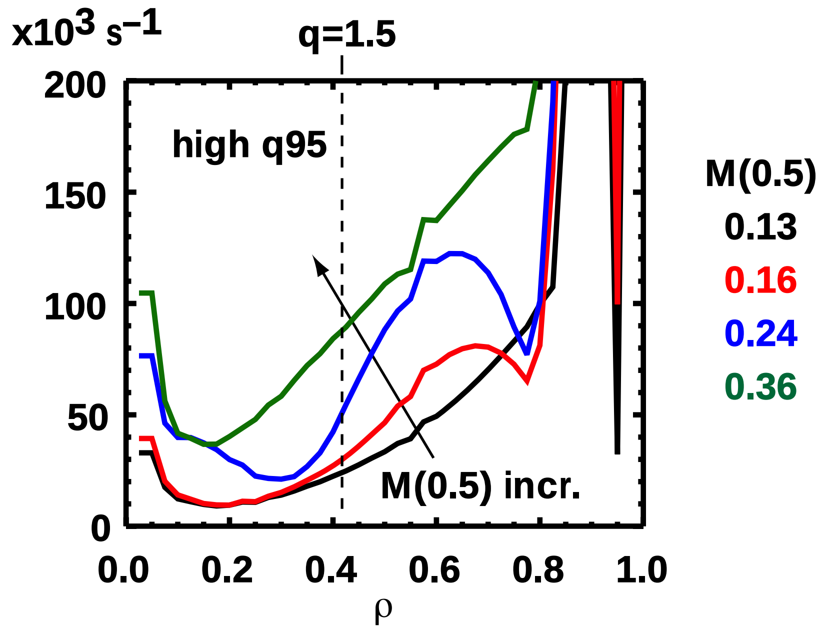


- Weak dependence of τ_E and τ_Ω on M(0.5) at q95 > 4; stronger for low q95.
- Medium & high q95 indistinguishable.
- τ_E and τ_Ω close to numerically equal, except at low NB torque.



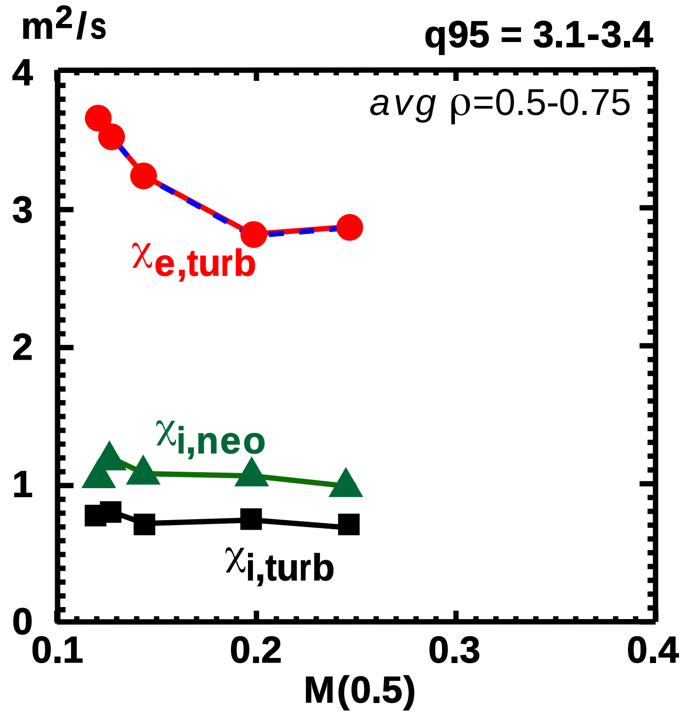
ExB Flow Shearing Rate Increases With Rotation

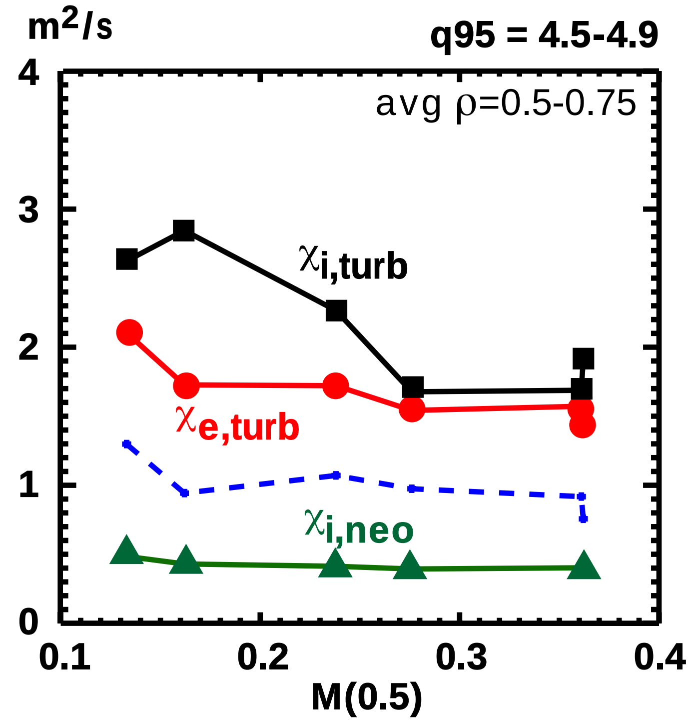




- ExB flow shear at high q95 is is ~2x value at low q95.

Turbulent Transport Coefficients Decrease As Rotation and Rotation Shear Increase (Tglf Modeling)



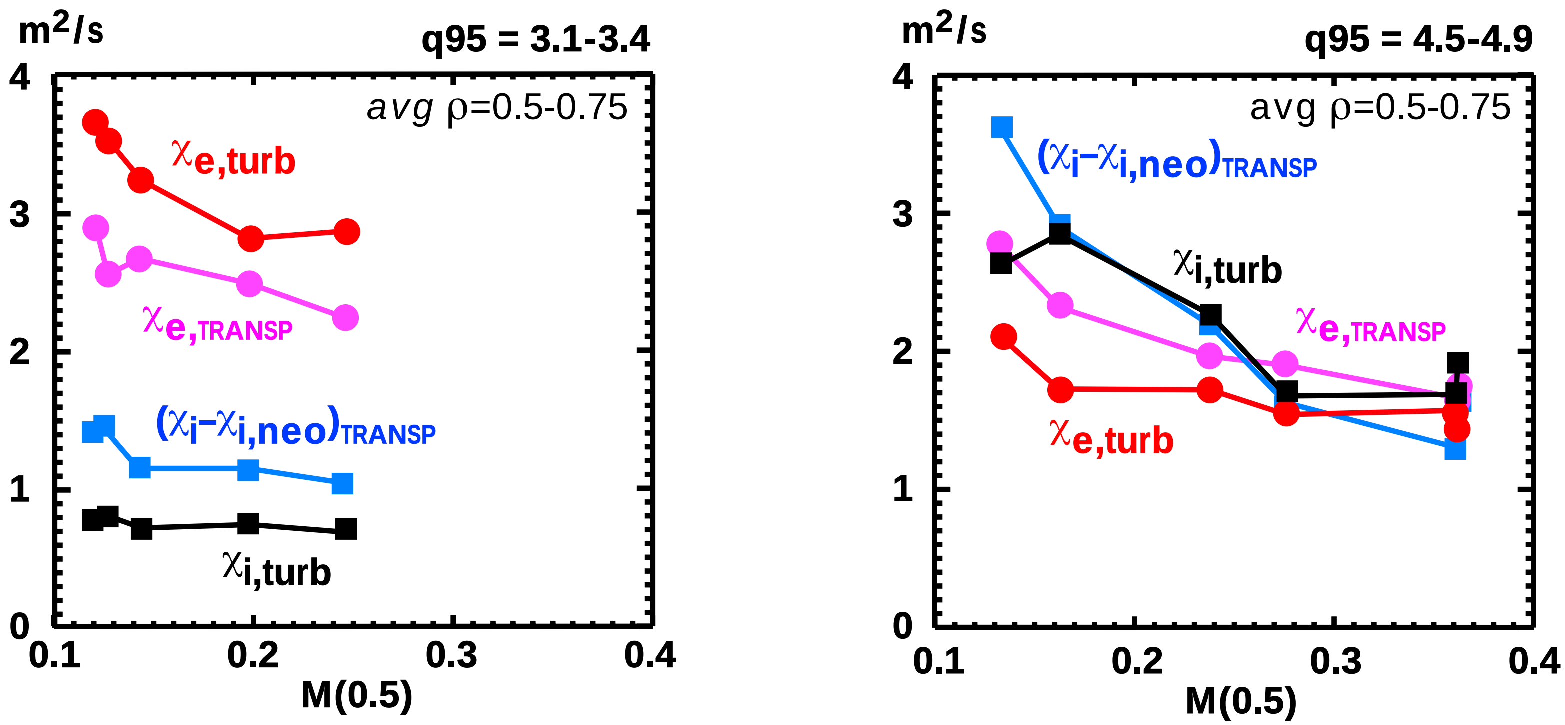


dashed blue lines give χ_e due to $k_\theta \rho_i > 1$ modes

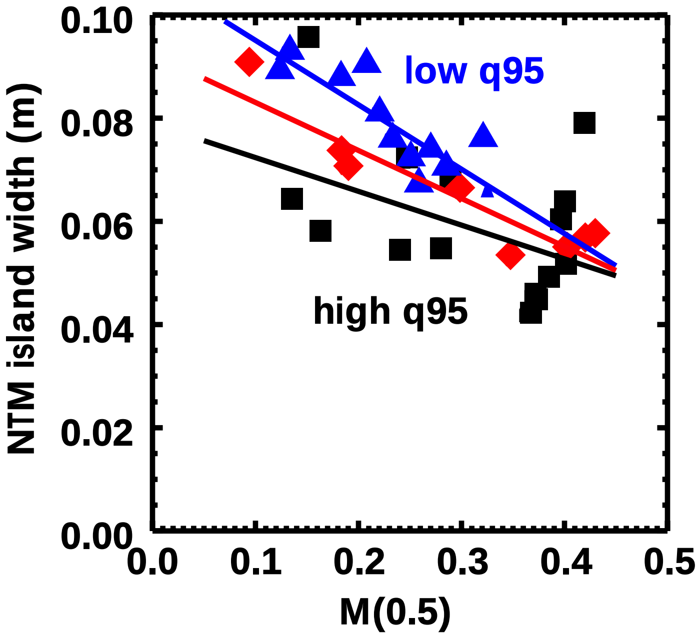
- **At high q95: χ_e & χ_i are comparable, and well above $\chi_{i,neo}$.**
- **At low q95: χ_i is comparable to $\chi_{i,neo}$, but χ_e is much larger.**

➜ **Using $\chi_i+\chi_e$ as a measure of overall turbulent transport, going from high to low rotation the turbulent transport increases by ~25% at low q95 and by ~40% at high q95.**

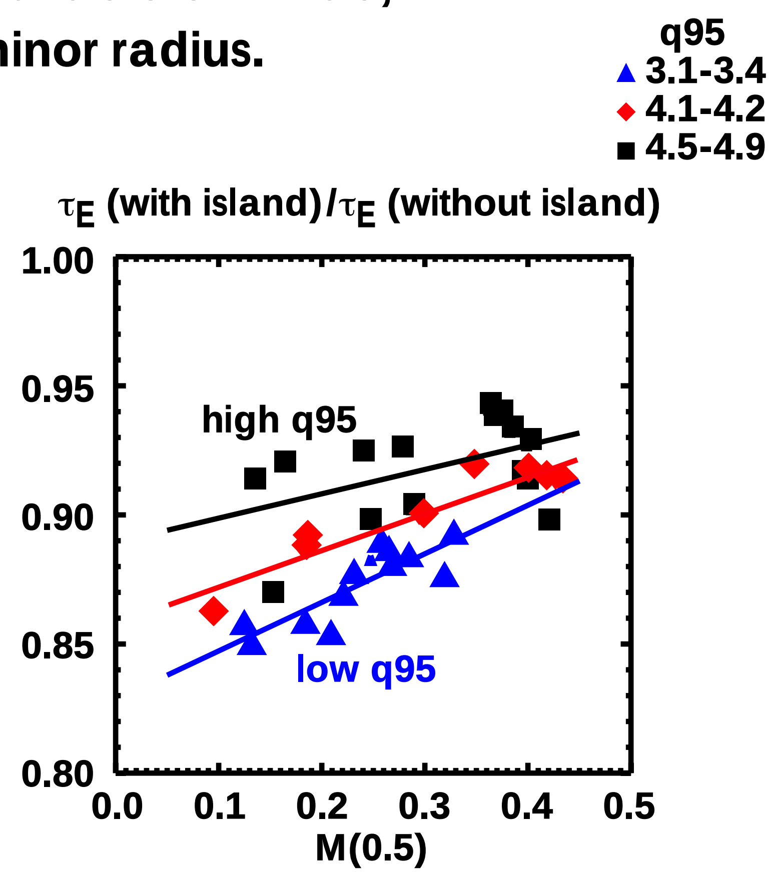
Turbulent Transport Coefficients From TGLF Reproduce Trends Seen In Transp Analysis of Profiles



Change In 3/2 Island Width Is Calculated To Have A Moderate Effect On Confinement



- Island width is larger at low q95 at all rotations.
- Change in width with rotation is larger at low q95.
- Largest island is 9.5 cm wide, ~16% of minor radius.



- Assess effect on τ_E using Chang-Callen 'belt model':
  - At high rotation, island reduces τ_E to 90-96% of est'd unperturbed value.
  - For higher q95, increasing width has a small effect.
  - For low q95, τ_E is reduced to ~85% of unperturbed value.

Other tokamak physics with hybrids

Many Other Physics Studies And Results Using Hybrids

- **The role of Te/Ti; changes in turbulence levels & confinement of energy and momentum.** [Doyle, GO3.00006]
- **The effect of shaping on confinement (triangularity, squareness, upper/lower null, double null).** [Groebner, GO3.00012, Leonard BI1.00003]
- **The effect of triangularity and squareness on the pedestal.** [Leonard, BI1.00003, Groebner GO3.00012]
- **The effect of rotation on the pedestal pressure.** [Leonard, BI1.00003]
- **Demonstration of radiative divertor operation and divertor heat flux reduction.** [Petrie, UP8.00035]**.**
- **ELM suppression with RMP.** [Fenstermacher, BI1.00002]
- **The effect of wall conditioning on hybrid performance.** [West, GO3.00005]

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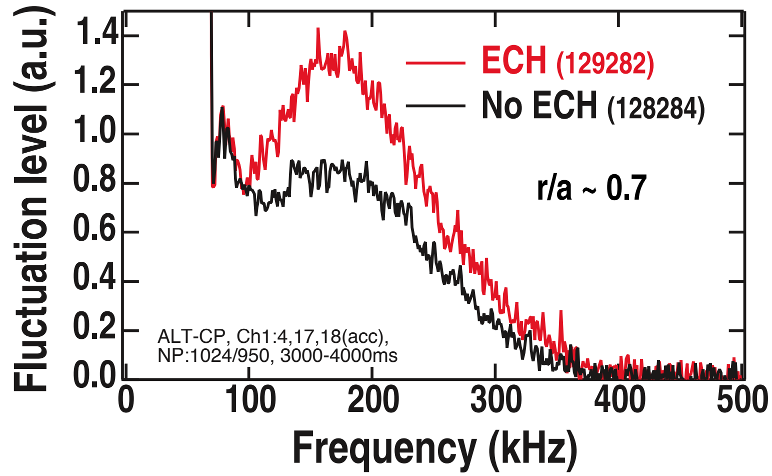
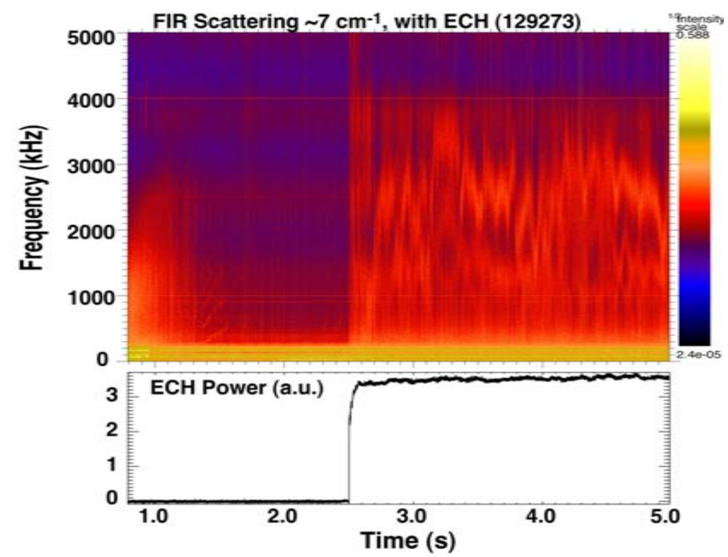
Increasing T_e/T_i Leads to Increased Fluctuations and Reduced Confinement

- Increase Te/Ti by adding 2.3 MW of ECH.
- Te/Ti at center increases by 22% (0.67-0.82).
- Rotation is reduced.
- Low-k & medium-k density fluctuations increase.
- To separate T_e/T_i and rotation effects, compare with NBI-only plasma, matched for the same rotation and β;
  – by adding ~0.6 MW of counter-NBI instead of ECH.
- H_{89} is ~15% lower with ECH.

BES (0-3.5 cm–1)

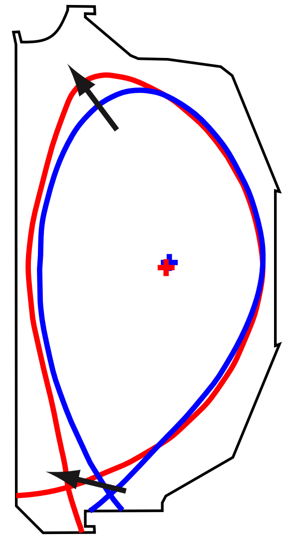


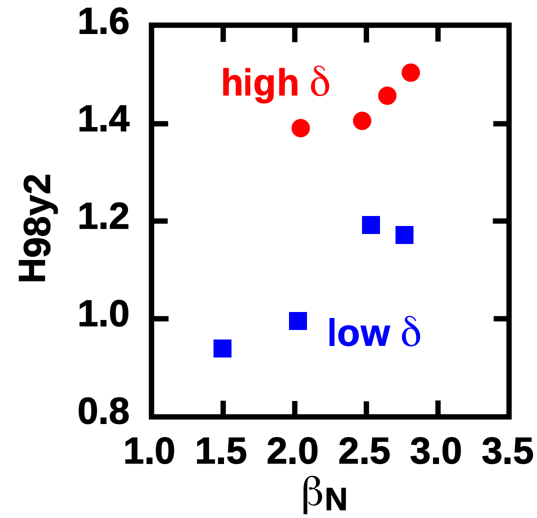
FIR scattering (7 cm–1)



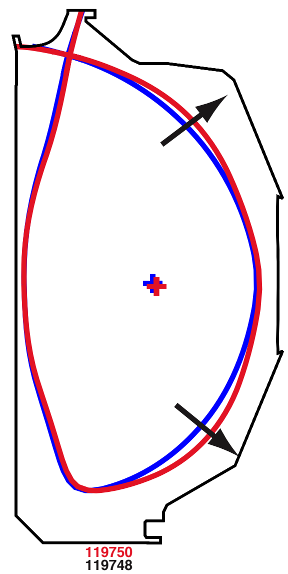
Confinement, Pedestal, And ELMs All Depend On Shape

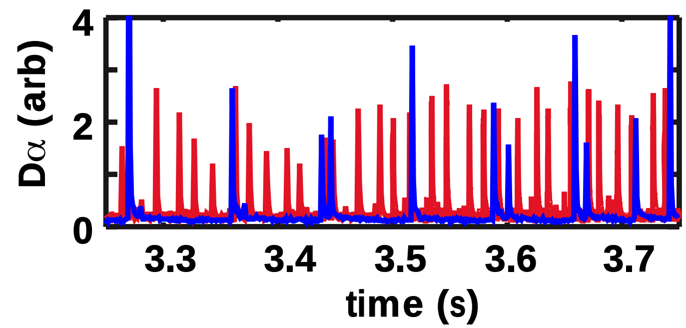
- **With increased triangularity:**
  - **confinement improves at fixed β_N**
  - **pedestal β increases**





- **With increased squareness:**
  - **pedestal β decreases**
  - **smaller, faster ELMs (consistent with theory)**
  - **reduce triggering of 2/1 NTM**





Conclusions

- The presence of a stationary NTM is an inherent feature of ITER hybrid scenario plasmas in DIII-D
  - the NTM contributes to the beneficial modification of the current profile
  - the confinement penalty due to the NTM is modest (5-15% lower than no-NTM estimate)
- Rotation and rotation shear have strong effects on confinement:
  - Scanned the central Mach number 0.1-0.5
  - At low rotation, the fusion performance parameter G (= $\beta_N H_{89}/q_{95}^2$) is reduced by 10-30%, but remains above the ITER level for Q_{fus} = 10 operation at low q_{95}.
  - 3/2 NTM island width increases as rotation is reduced, with a moderate effect on confinement.
  - Primary confinement effect of changing rotation is via changes in ExB flow shear and turbulent transport.
- In addition to being a demonstrated scenario for improved ITER operation, the hybrid scenario is a good place for studying tokamak physics.