Expanding the Physics Basis of the Baseline Q=10 Scenario Toward ITER Conditions

by

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with

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GENERAL ATOMICS

Introduction

Physics basis for the ITER baseline scenario is dominated by plasmas with co-NB injection, which implies:

- **Dominant ion heating**
- **Significant torque**
- **Significant core fueling**

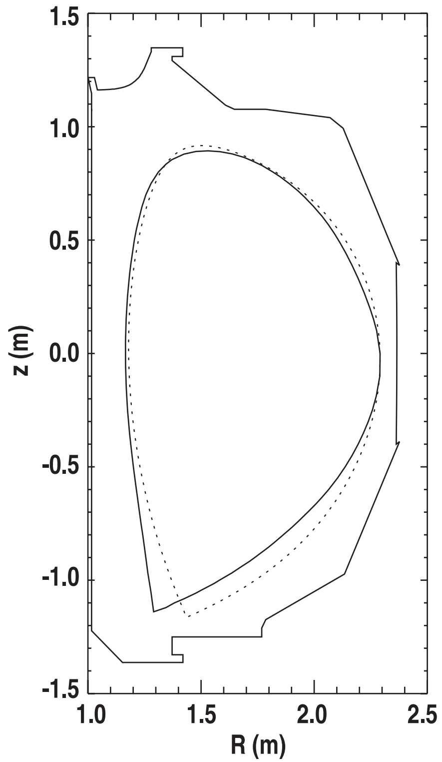
Stationary plasmas have been obtained in DIII-D with normalized performance sufficient for Q=10 in ITER ($\beta_N \geq 1.8$, $H_{98y2} \geq 1$, $q_{95} \approx 3$) for longer than 2 τ_R with normalized source conditions similar to ITER:

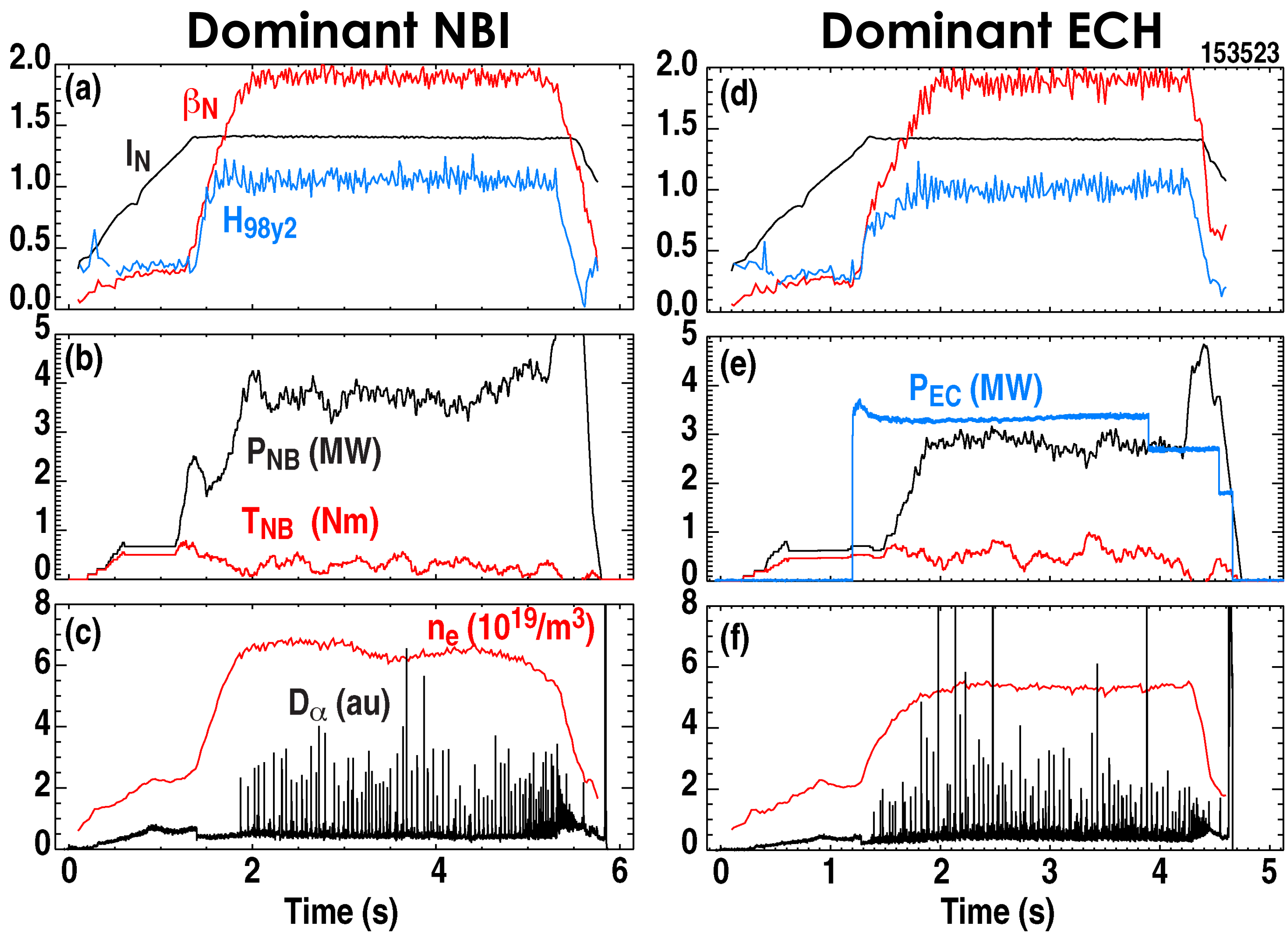
- **Electron dominant heating (ECH+NB):** $P_{electron}/P_{ion} = 3$ **(ITER: 3)**
- **Low applied torque (0.5 Nm):** $(T_{NB} / M)\ \tau_E\ \omega_* = 5\times10^4$ **(ITER: 9×10^4)**
- **Reduced core fueling (2.2 10^{20} el/s):** $S_{NB}\tau_E / nV = 6\times10^{-2}$ **(ITER: 6×10^{-3})**

Radiative divertor operation will likely be needed to mitigate heat loads to the divertor (stationary and transient)

Stationary Conditions Similar to ITER Q=10 Requirements Obtained at Low Torque

- **ITER shape closely reproduced (including aspect ratio)**





Results and Conclusions

Primary results:

- **ITER Q=10 conditions reached in stationary plasmas with low torque and dominant electron heating at $q_{95} \approx 3$**
- **Radiative divertor with neon has ~80% input power radiated**
- **Plasmas more likely to be unstable to m=2/n=1 tearing mode at low torque**
- **Confinement is reduced relative to co-NBI cases, but $H_{98y2} \approx 1$**
  - Reduction in τ_E with electron heating (up to 50%), low torque (up to 50%), or radiative divertor (more than 10%)

Primary conclusions:

- **Tearing stability may set the limit on ITER performance at low q_{95} with low absolute and differential rotation**
- **Rotation and T_e/T_i have significant impact on confinement**

Open Questions

- **Is stable stationary operation in the ITER baseline scenario possible with zero torque input?**
  - Need to understand the variation in stability with torque—how much is DIII-D tool/machine specific?
  - Variety of paths to instability suggests there is no 'magic bullet' to ensure stability unless underlying common mechanism found
  - Experiments probing stability at zero torque as a function of q_{95} at fixed B and β (not β_N) may be needed to optimize fusion performance
- **Is the confinement reduction seen with reduced torque and dominant electron heating included in ITER projections?**
  - Need to compare with theory-based modeling to see if effects are explained by the models

Motivates DIII-D ECH power upgrade to demonstrate ITER baseline scenario with no torque and no core fueling

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Stability

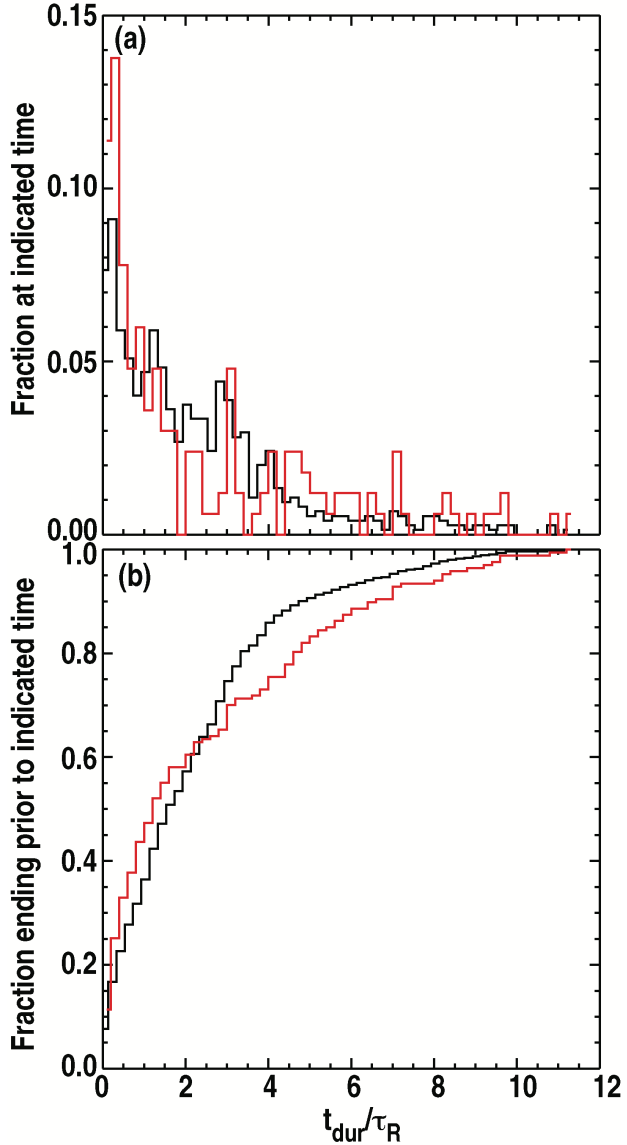
Low Torque Plasmas More Frequently Unstable to Tearing Modes

Two phases to stability question:

- **Stability of resistive equilibrium ($t_{dur} > 2\tau_R$)**
  - 10-20% unstable in this phase
- **Access to resistive equilibrium ($t_{dur} < 2\tau_R$)**
  - Low torque (<1 Nm) cases 50% more likely to be unstable
- **Caution: Frequency ≠ Probability!**

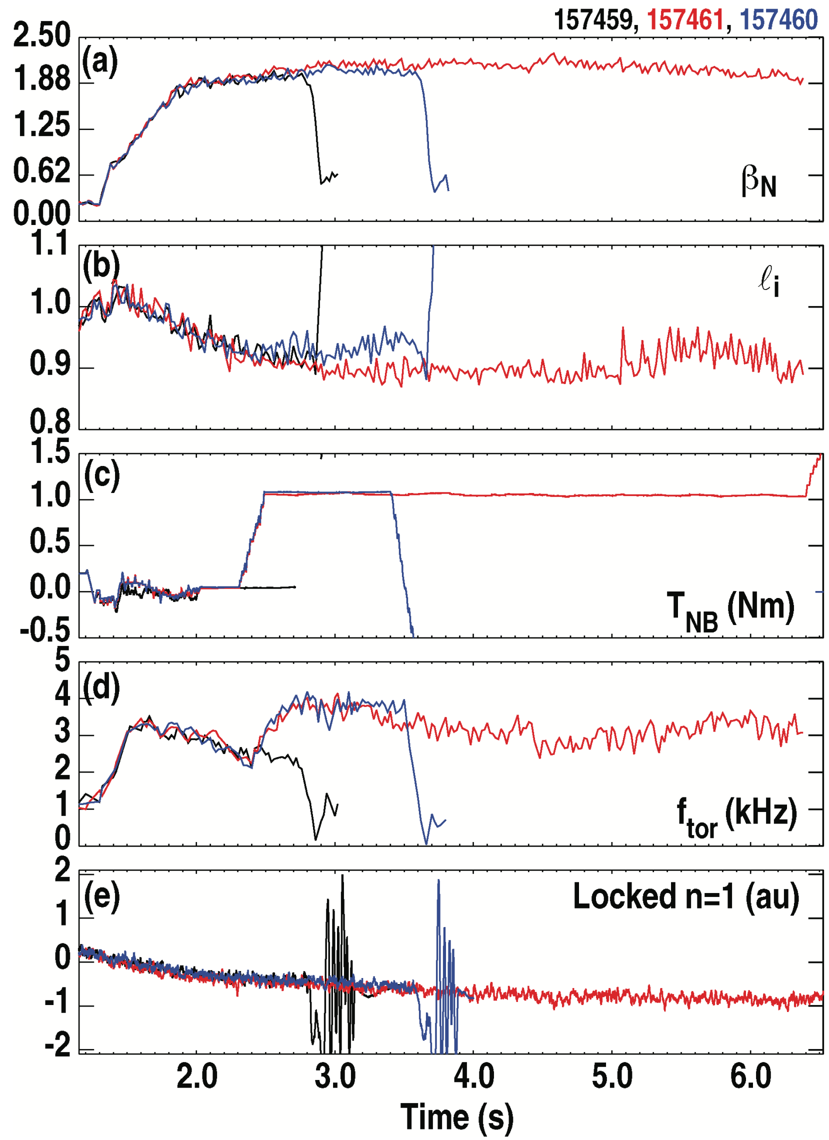
Hypotheses to explain why operation at low torque is more difficult:

- **Uncorrected non-axisymmetric fields**
- **Loss of differential rotation between rational *q* surfaces**
- **Change of current profile**



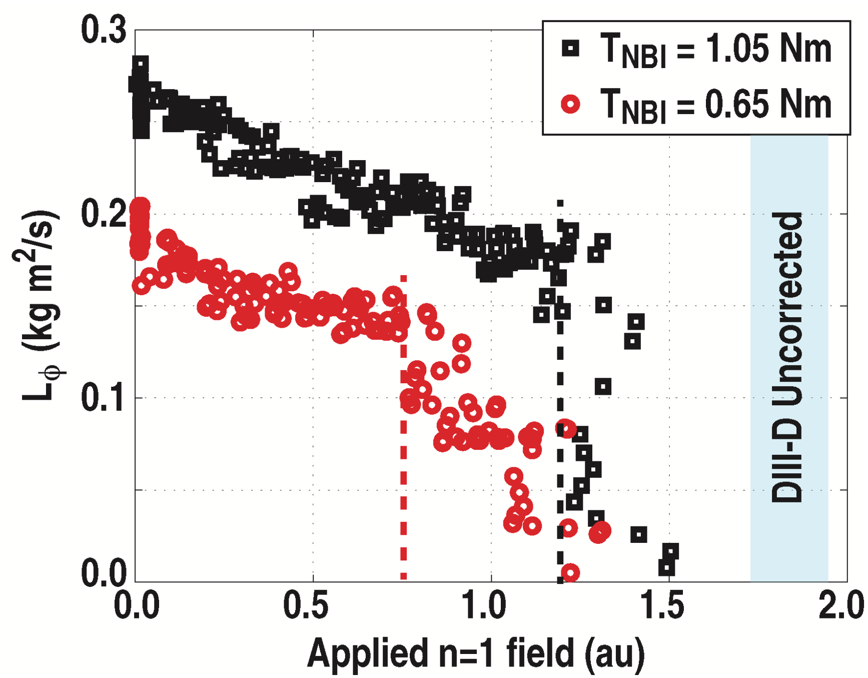
Stable Operation Can Be Extended By Adding Torque

- **Near-zero torque startup gives reproducible access**
- **Rotation decay at fixed torque was typical**
- **Addition of 1 Nm torque step extends stable operation phase—why?**
  - Increased lab frame rotation?
  - Maintains differential rotation?
  - Pedestal current density change?
  - Parallel conductivity/current drive change?
- **Torque step-down leads to rapid instability**



Sensitivity to Non-Axisymmetric Fields and Optimal Correction Determined Empirically

- **DIII-D has a significant non-axisymmetric magnetic field due to construction imperfections**
  - Of concern here is *n*=1 component
- **Optimal correction determined from feedback to null the plasma response at *n*=1**
- **Sensitivity to uncorrected *n*=1 determined by intentional detuning around optimum**
  - Optimum verified by phase independence
  - Required optimization measured by rotation response vs amplitude of detuning
- **Is stable operation with zero torque possible even with optimized compensation?**



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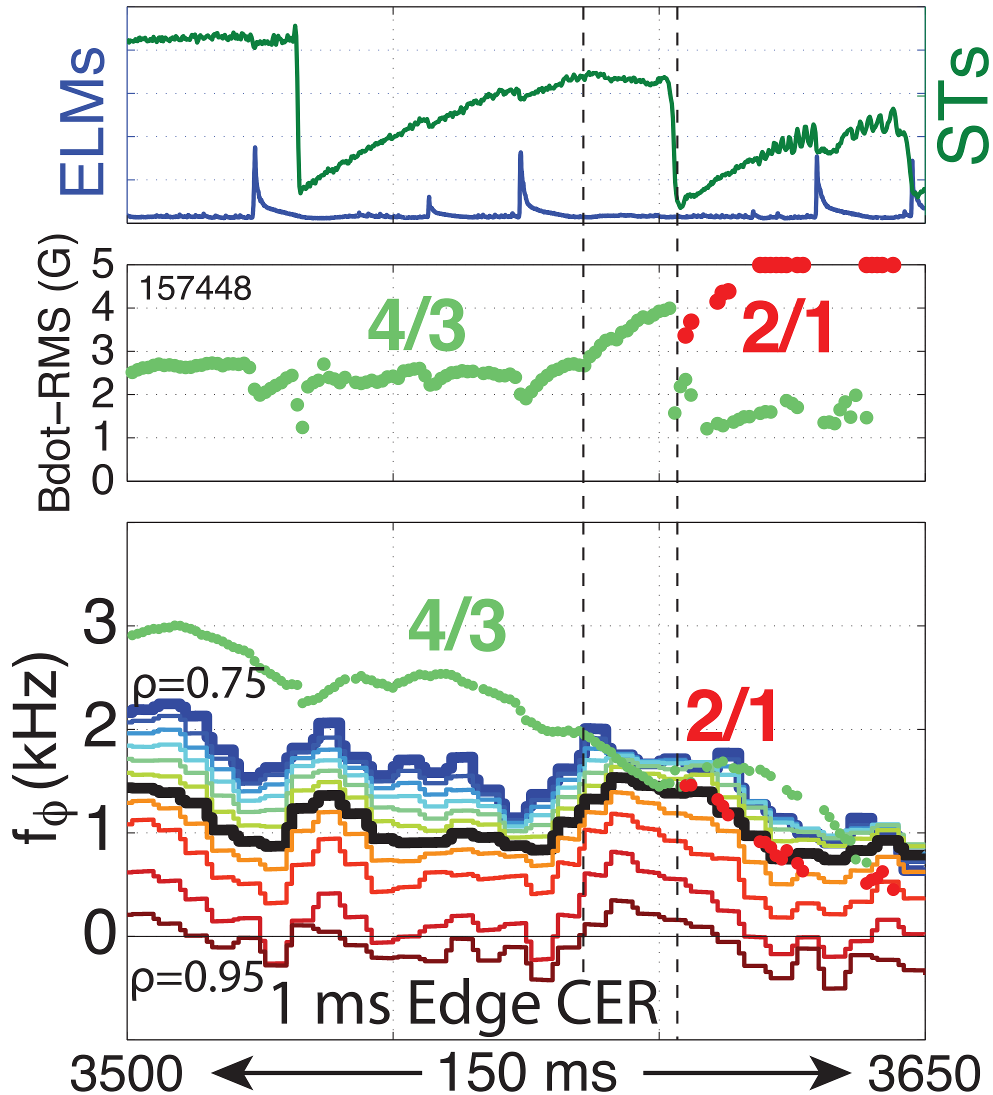
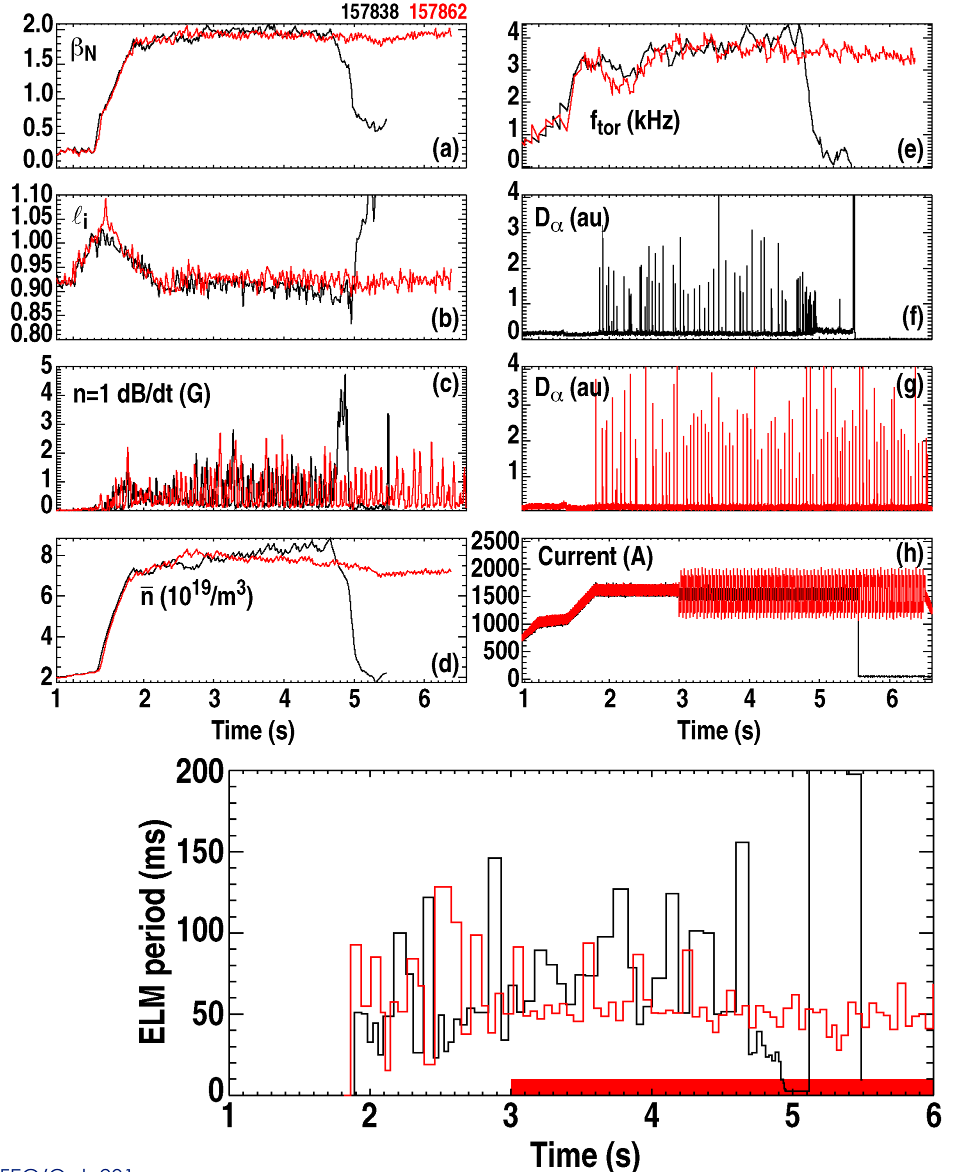
Loss of Differential Rotation Between Rational *q* Surfaces May Reduce Stability Margin

- **Differential rotation is expected to enhance MHD stability**
  - Isolation by conductivity screening
  - Sideband reduction by viscous damping
- **Loss of differential rotation often observed prior to *n*=1 instability**
- **Sawtooth precursor is even *m***
  - Need radially resolved measurements of the tearing mode perturbation
  - Frequency mapping is clearly not applicable



Irregular ELMs Often Precede Instability

- **Otherwise stationary plasmas can exhibit significant variability in ELM period**
  - Rise in density and drop in ℓ_i suggests pedestal bootstrap current is changing
- **Application of oscillating *n*=1 perturbations locks the ELM period to the applied frequency**
  - Perturbation at 0.5 and 1 Nm is within the measured tolerable *n*=1 without rotation collapse
  - No working solution found at near-zero torque
- **ELMs during ECH exhibit different behavior**



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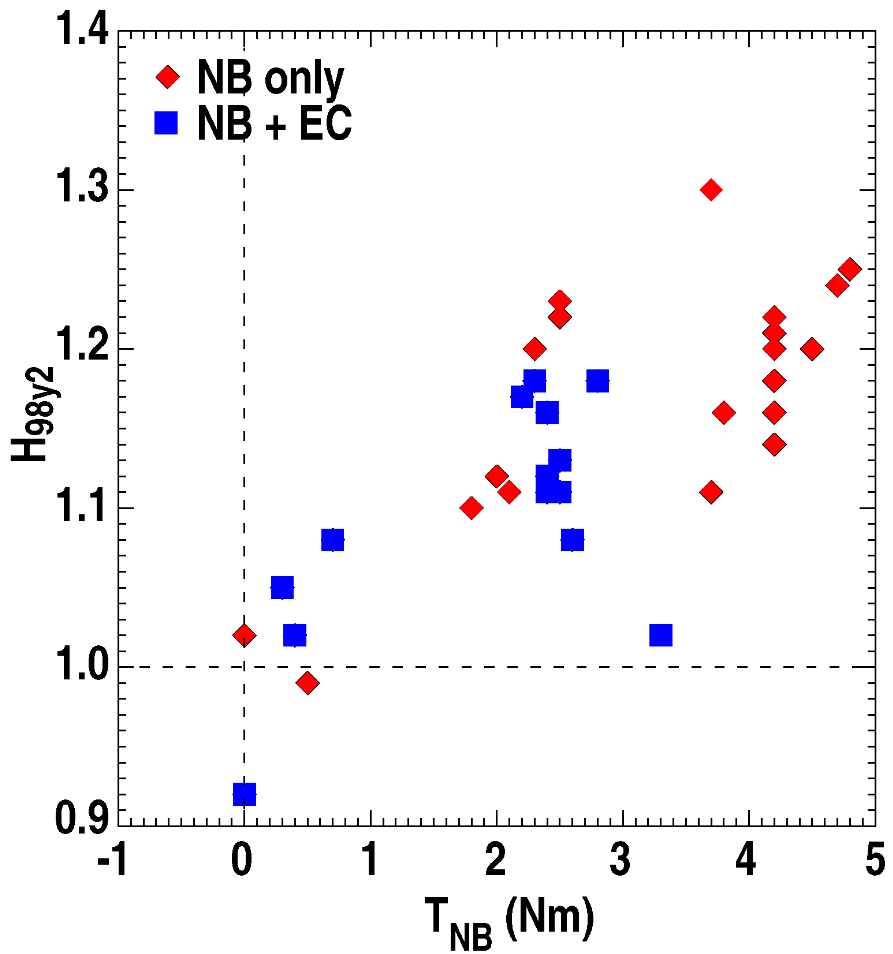
Confinement

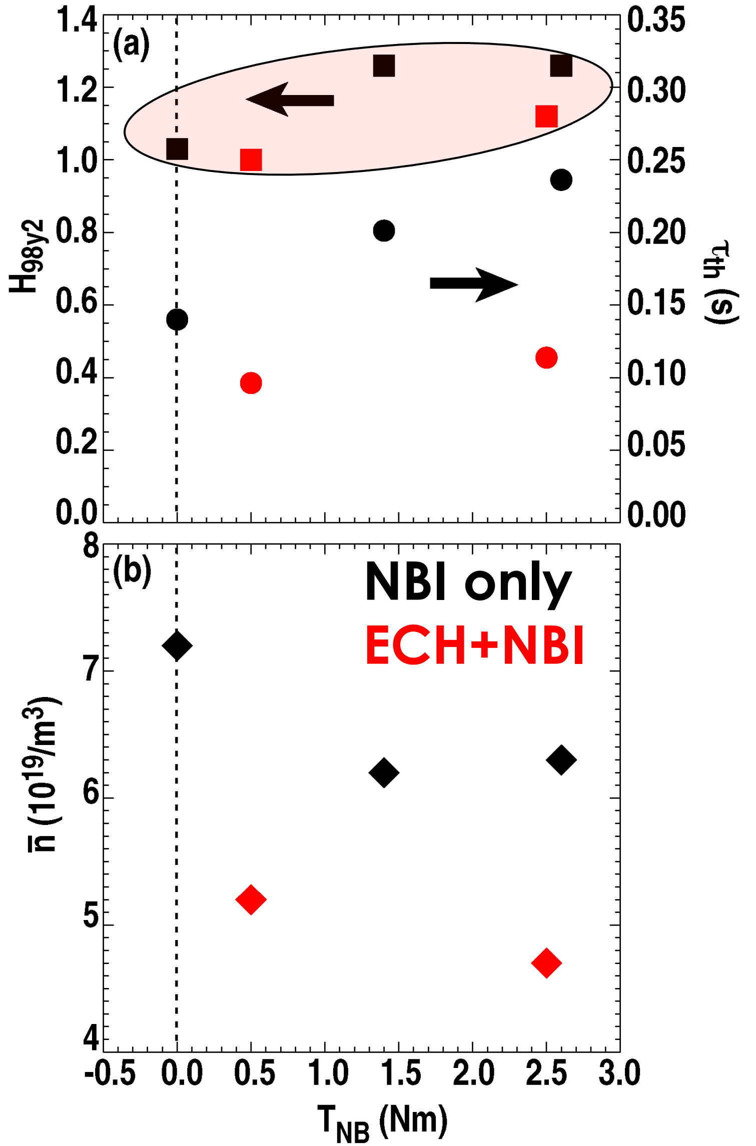
Normalized Confinement Strongly Increases with Applied Torque

- **Applied torque varied by two means:**
  - Mixture of co- and ctr-NBI
  - Addition of ECH
- **H_{98y2} varies by about 20% as torque varies from near zero to pure co-NBI**
- **H_{98y2} roughly the same with pure NBI or ECH+NBI at equal torque**



Confinement Time Drops Significantly with Electron Heating or Low Torque

- **Strong power degradation in IPB98y,2 ($\tau_{th} \propto P^{-0.69}$) hides large variations in τ_{th} with torque and ECH**
  - Density dependence also mitigates some of the change with ECH
- **Since $H_{98y2} \geq 1$, projections to ITER with low torque and ECH still yield Q ≥ 10**
  - Remember that fusion gain for a specified fusion power depends on τ_{th}, not H
  - Need to see if 1-D models reproduce these results and the IPB98y,2 scaling



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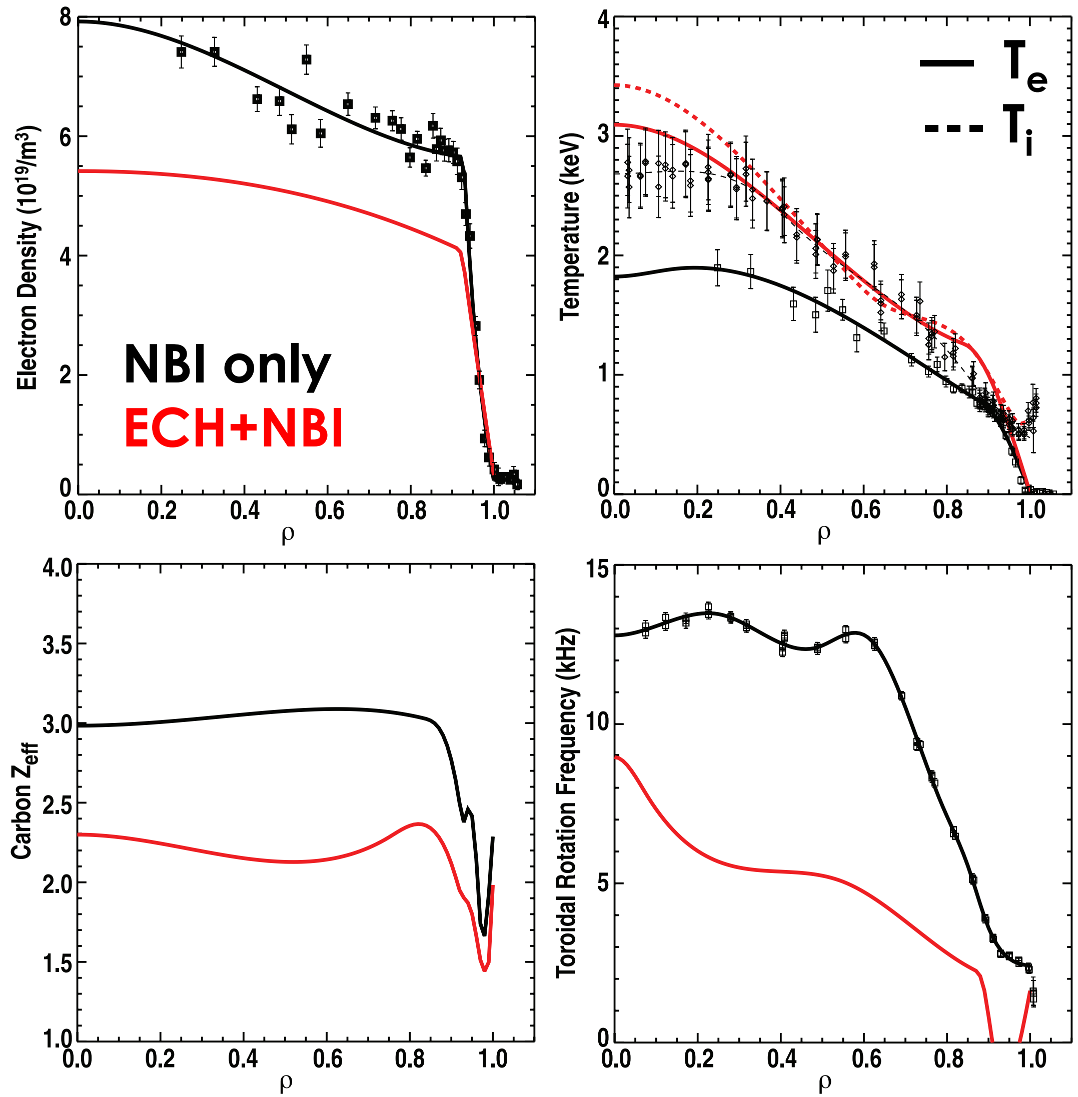
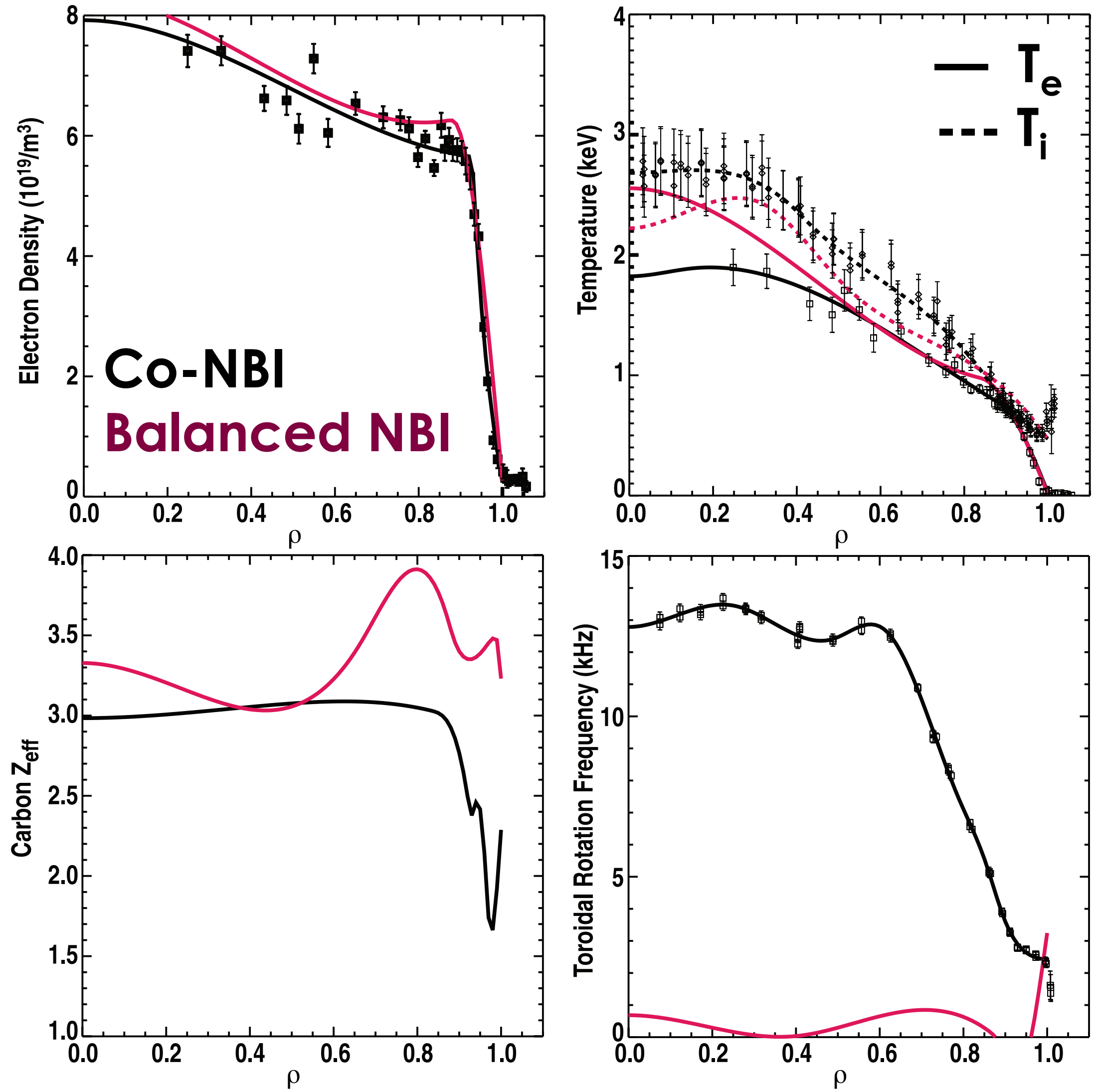
Transport of Particles, Momentum, and Energy Change Dramatically with Addition of ECH

- **Density gradient does not change much, but pedestal is reduced**
  - Pedestal width unchanged
- **Temperature increases, pedestal is higher and wider**
  - $T_e \approx T_i$
- **Rotation is reduced despite the removal of the *m*=3/*n*=2 tearing mode**
- **Z_{eff} is reduced**



Only Rotation is Strongly Affected With Low Torque NBI

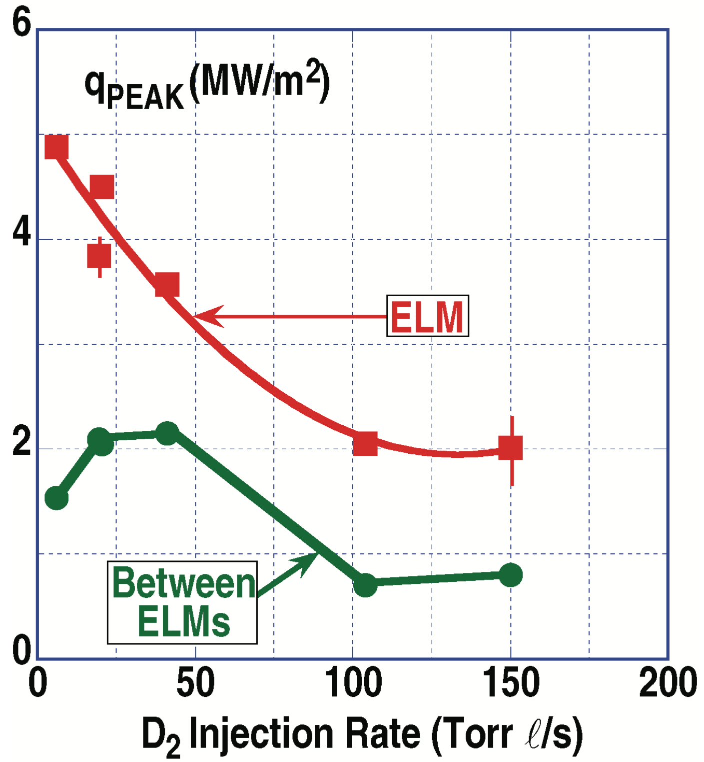
- **Density does not change**
- **Electron and ion temperature closer**
- **Rotation is strongly reduced as expected**
- **Z_{eff} may be higher**

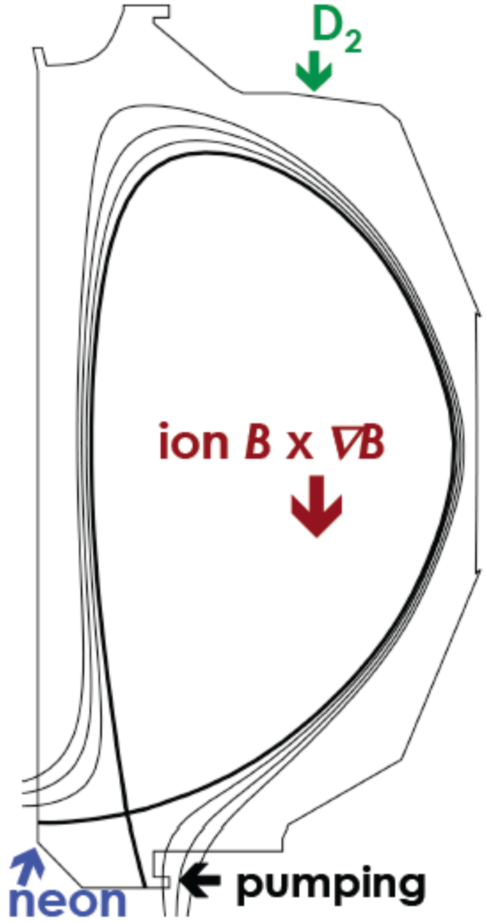


Radiative Divertor

Radiative Divertor Mitigates Steady and Transient Heat Flux to the Divertor

- Radiation from inside and outside the plasma boundary is likely necessary to protect the ITER divertor
- 'Puff and pump' technique has demonstrated ~60% reduction in the between-ELM and ELM heat flux to the outer divertor

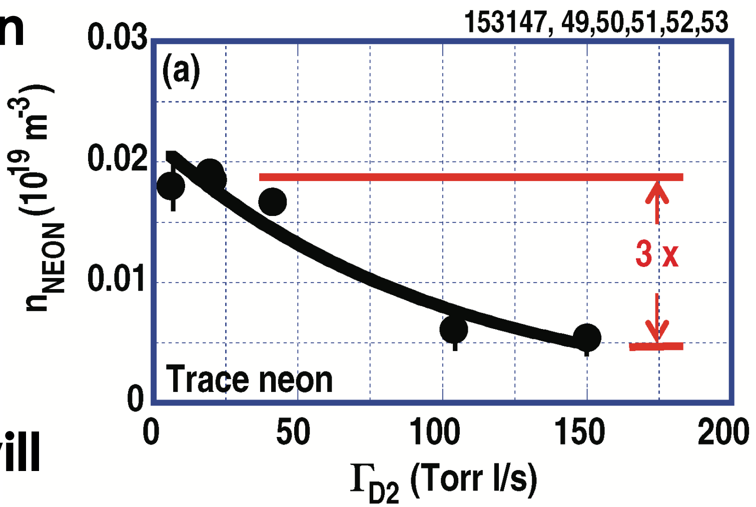


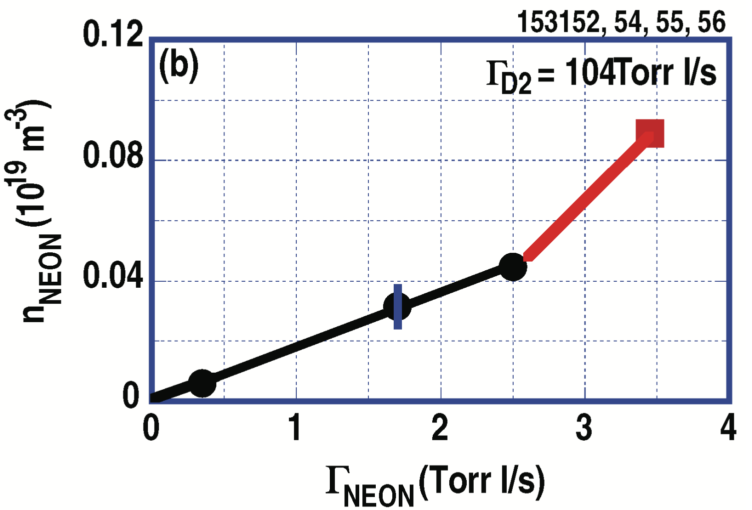


Combination of Deuterium and Neon Gives Radiative Fraction of ~80%

- **Deuterium gives mostly divertor radiation**
- **Addition of neon increases radiative fraction and core radiation**
- **Deuterium flow necessary to minimize fuel dilution**
  - Neon contribution is $\Delta Z_{eff} = 0.55$
- **Choice of impurity for other tokamaks will depend on pedestal temperature**

Γ_{NEON} (t l/s)	0.35	2.50
$P_{R,SOL+DIV}/P_{IN}$	0.58	0.64
$P_{R,CORE}/P_{IN}$	0.10	0.15
$P_{R,TOT}/P_{IN}$	0.68	0.79





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Confinement Reduction During Radiative Divertor Operation Is Modest

- **Energy confinement reduced by ~25% with strong deuterium flow**
  - Part of the reduction is due to an *m*=3/*n*=2 tearing mode
  - Correlates stability with pedestal behavior
- **ELM heat flux is mitigated in part by more rapid ELMs**
  - Implies a reduced pedestal height and reduced confinement
- **Radiative divertor operation should be applied only as necessary**
  - Costs in performance from dilution and confinement reduction