Improving Stability and Confinement of Slowly Rotating Tokamak Plasmas Using Static 3D Magnetic Fields

by

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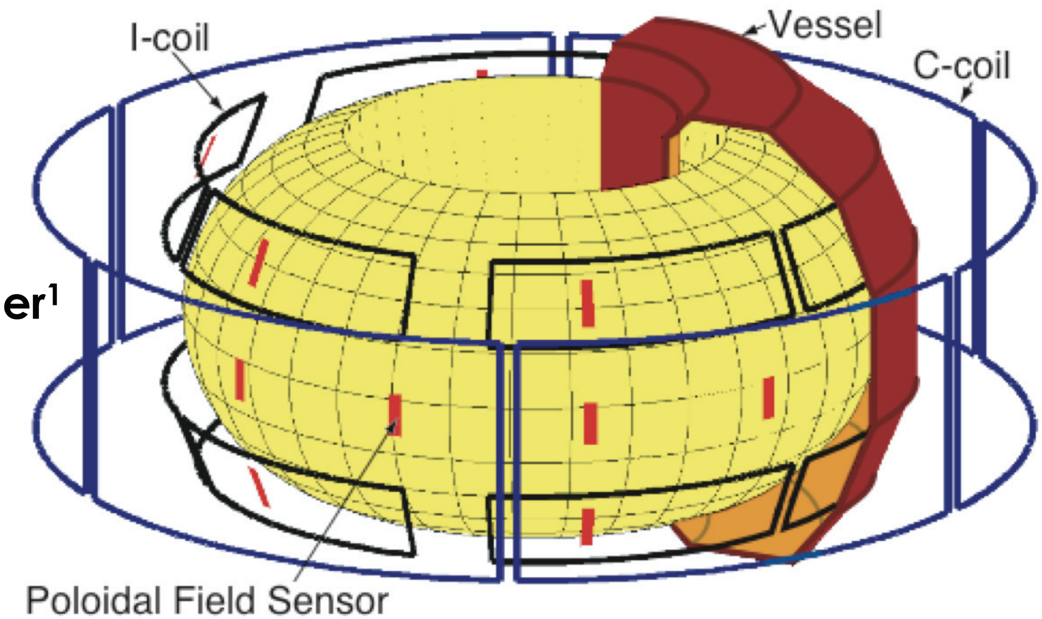

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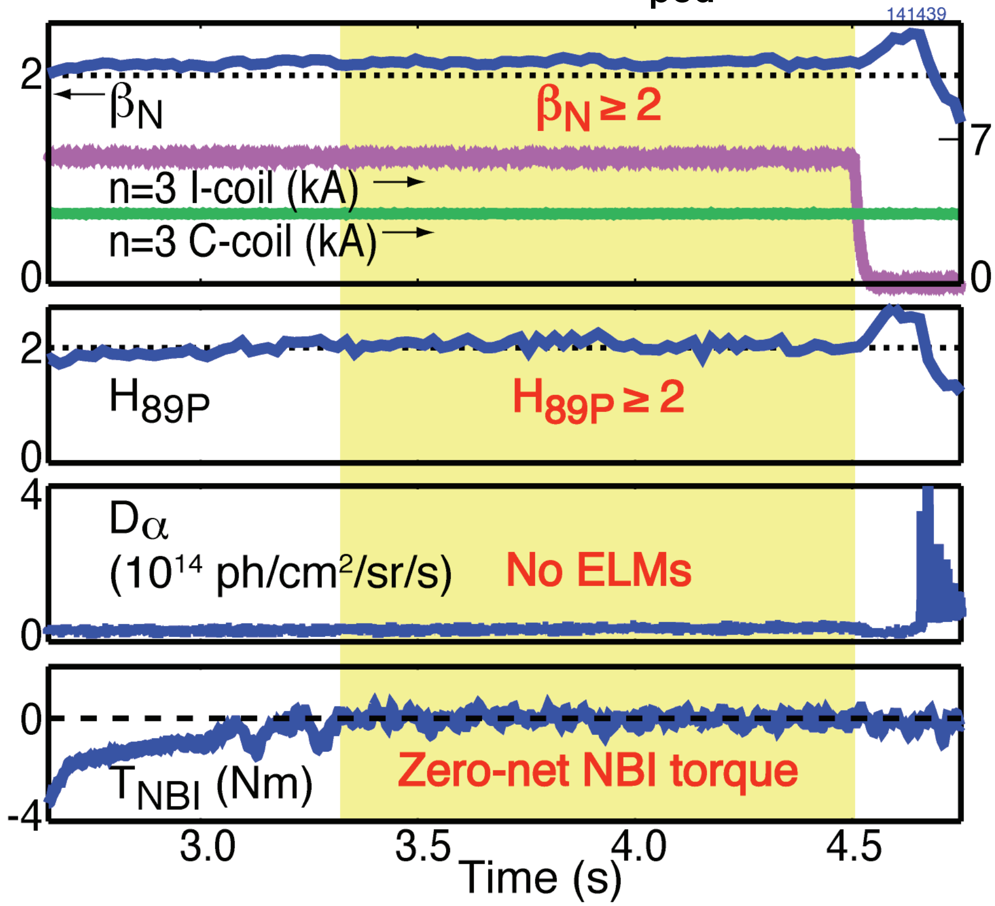
External 3D Fields Sustain Low Collisionality H-mode Plasma With No ELMs and Zero-Net NBI Torque

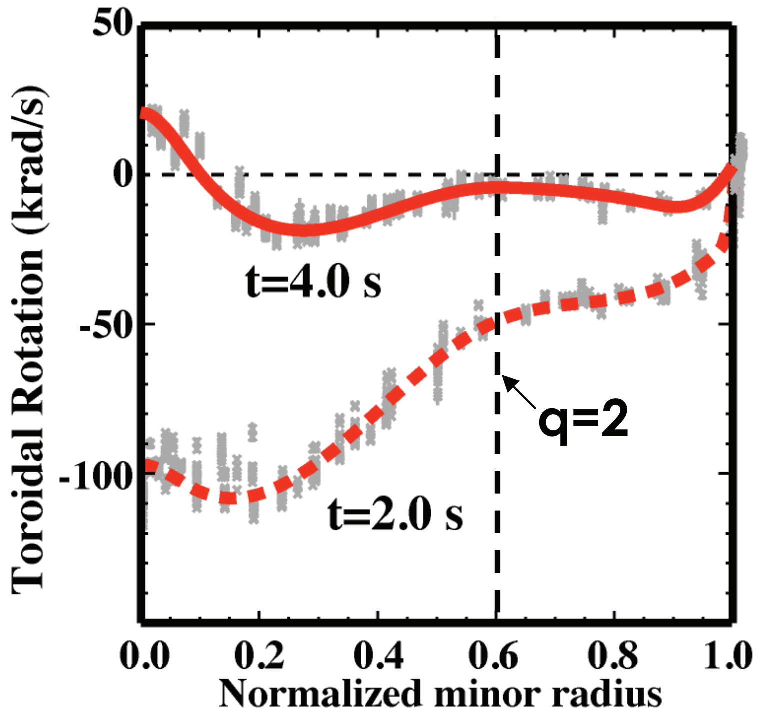
- **ELMs a serious challenge for acceptable edge conditions in ITER**
- **ELM-stable regime of quiescent H-mode (QH-mode) seen in many low-collisionality tokamaks**
  - ITER's pedestal predicted to be in the QH-mode parameter range of collisionality and beta
  - Previously QH-mode required significant NBI torque
- **Application of nonresonant magnetic fields enables QH-mode operation in plasmas with zero-net NBI torque**
  - Path toward QH-mode in ITER

Pedestal collisionality ν^*_{ped}~0.07



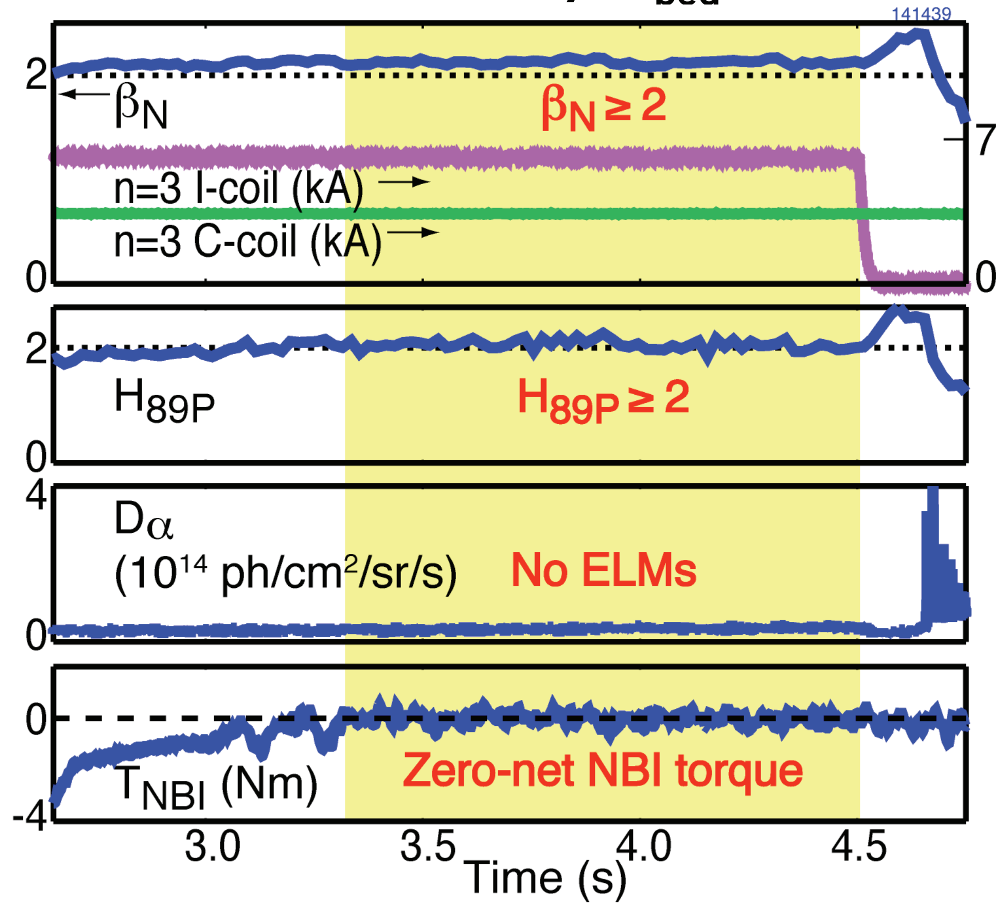
n=3 NRMFs Expand Tokamak Operating Space

- Sustained QH-mode without net NBI torque
- High beta and low rotation without tearing modes
- Low rotation and low density without locked modes



Density ~2.5 10^{-19} m^{-3}

Pedestal collisionality $\nu^*_{ped}<0.1$

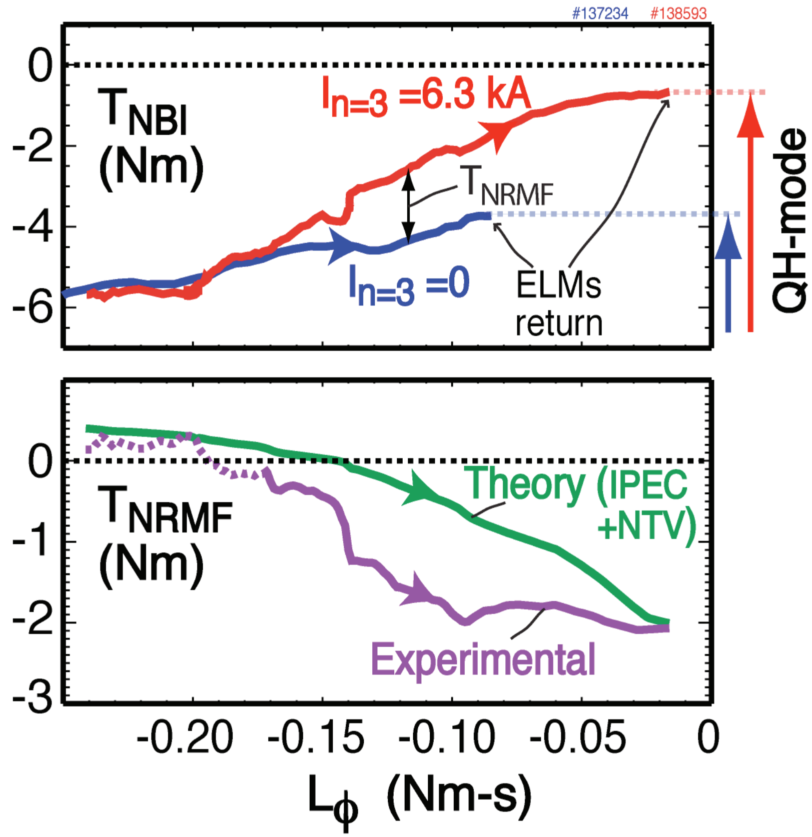


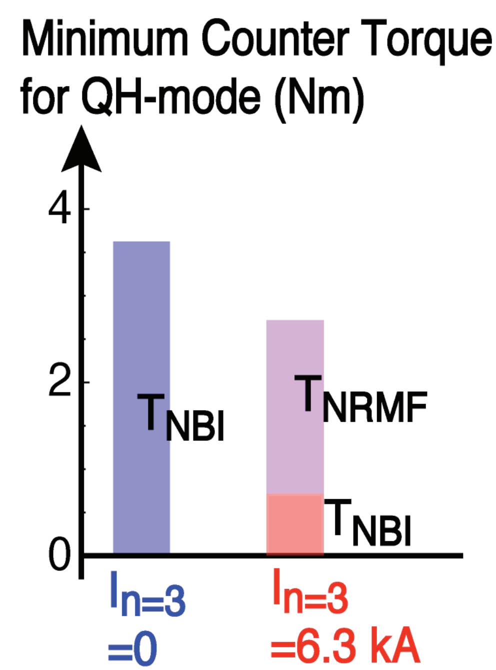
NRMF Maintains QH-mode at Lower NBI Torque by Helping Provide Sufficient Counter Torque on Plasma

- n=3 NRMF allows sustained QH-mode with lower NBI torque magnitude than required without NRMFs
- QH-mode requires exceeding minimum edge rotation shear, which depends on total torque integrated up to edge

$$T(edge) = -\left| mnR\left(\chi_\phi \frac{\partial V_\phi}{\partial r} \right) \right|_{edge}$$

- NRMF torque partially compensates for lower NBI torque
  - Other effects must be at play





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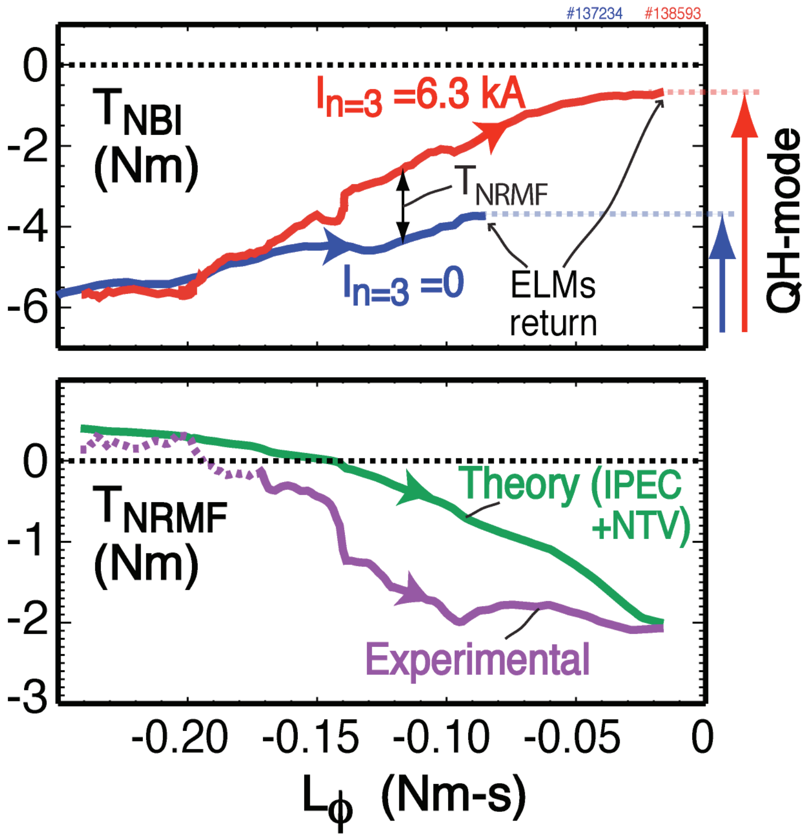
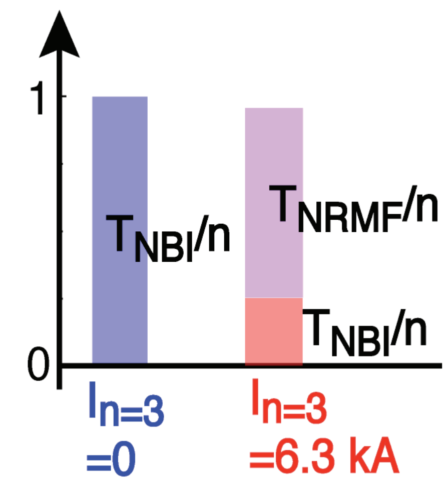
$$T(edge) = -\left| mnR\left(\chi_\phi \frac{\partial V_\phi}{\partial r} \right) \right|_{edge}$$

- NRMF torque normalized to density compensates for lower NBI torque

$$\frac{T}{n}(edge) = -\left| mR\left(\chi_\phi \frac{\partial V_\phi}{\partial r} \right) \right|_{edge}$$



Minimum Counter Torque for QH-mode normalized to density (au)



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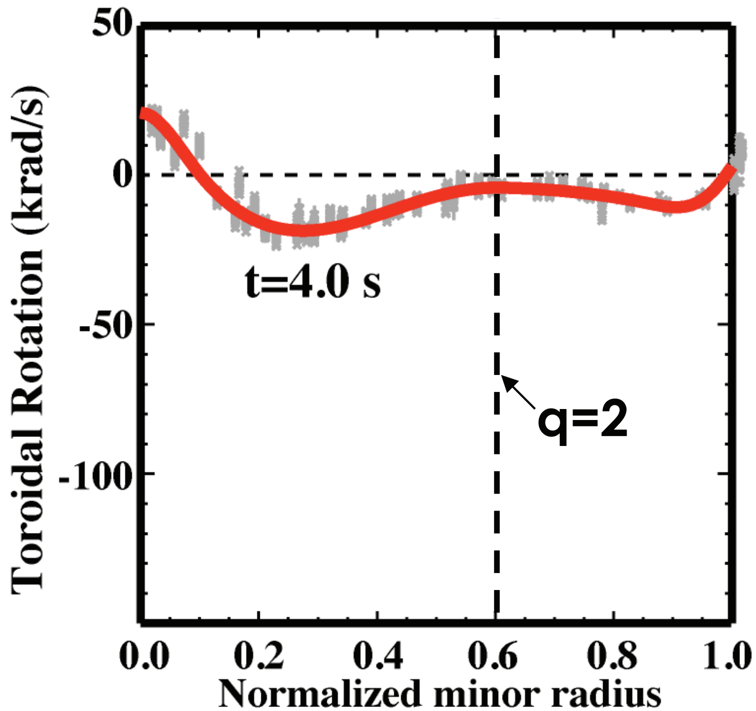
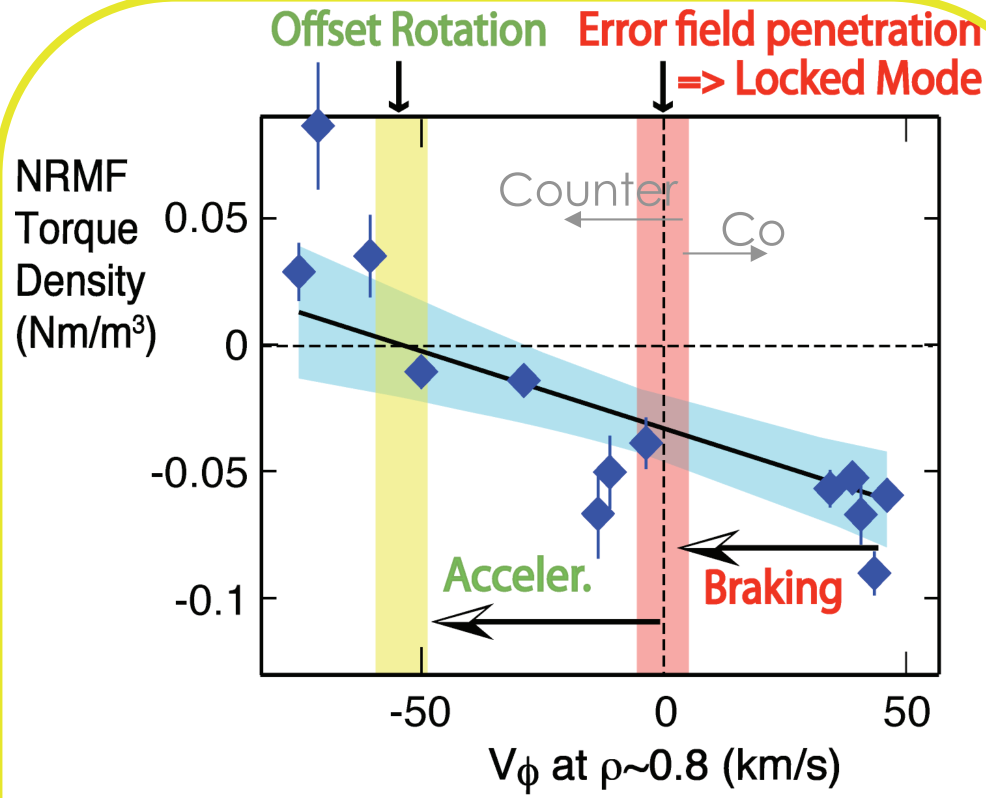
- **Sustained QH-mode without net NBI torque**
- **Low rotation and low density without locked modes**
- **High beta and low rotation without tearing modes**





$$T_{NRMF} \propto -(V_\phi - V_\phi^{0,NC})$$

- **At slow counter-rotation, NRMF torque opposes penetration of resonant error field**

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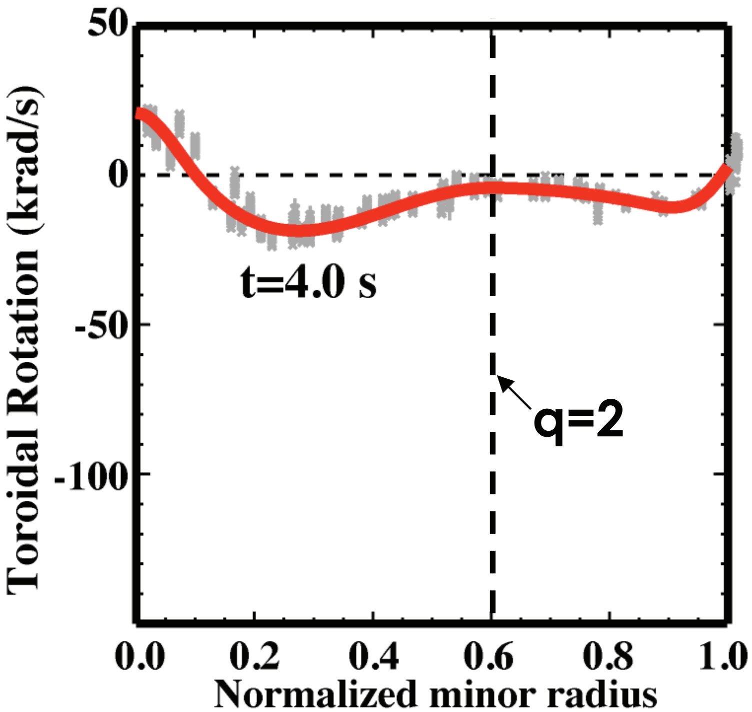
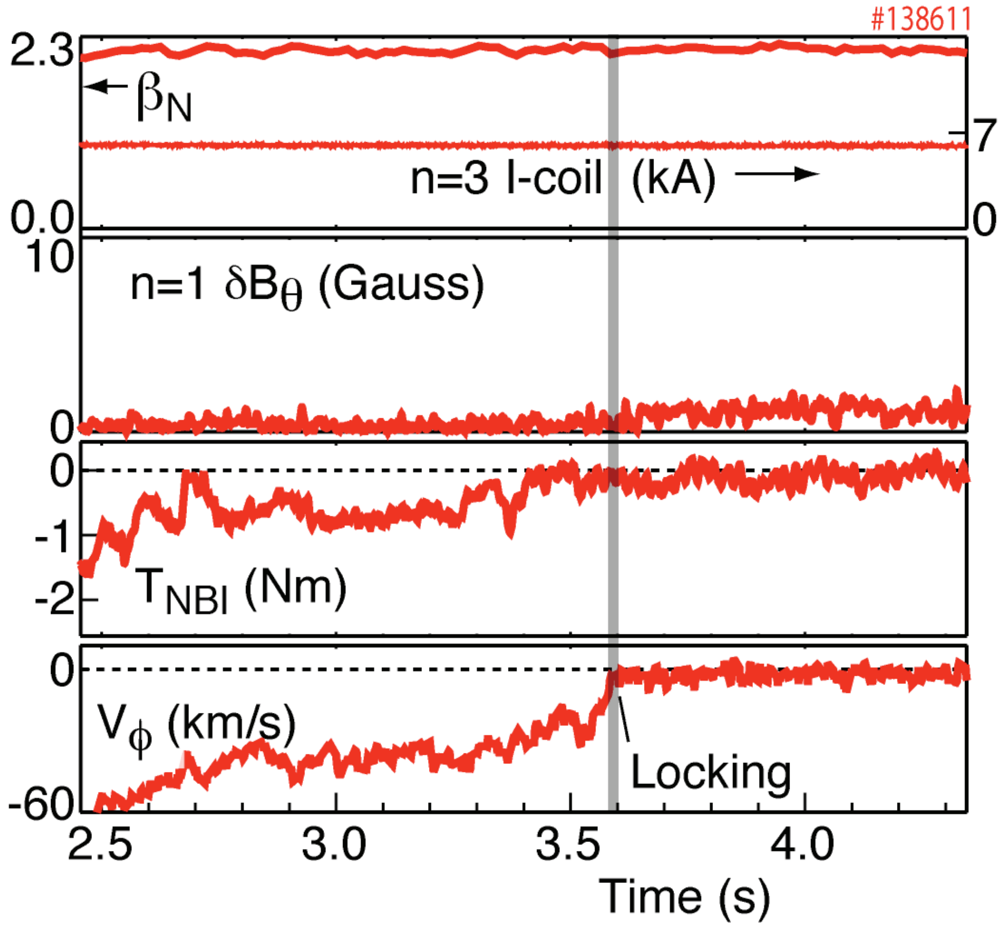


- **May be case of "NTM suppression by large externally applied helical modes"**
  - Enhanced $\chi_\perp$ weakens helically perturbed bootstrap destabilization

Q. Yu, S. Gunter, K. Lackner, PRL (2000)
La Haye, et al., PoP (2002)

Locked Plasma with n=3 NRMF Sustains Good Performance

- At zero rotation, n=1 error field can easily penetrate
- Magnetic island must open, but remains stable as long as n=3 field is on



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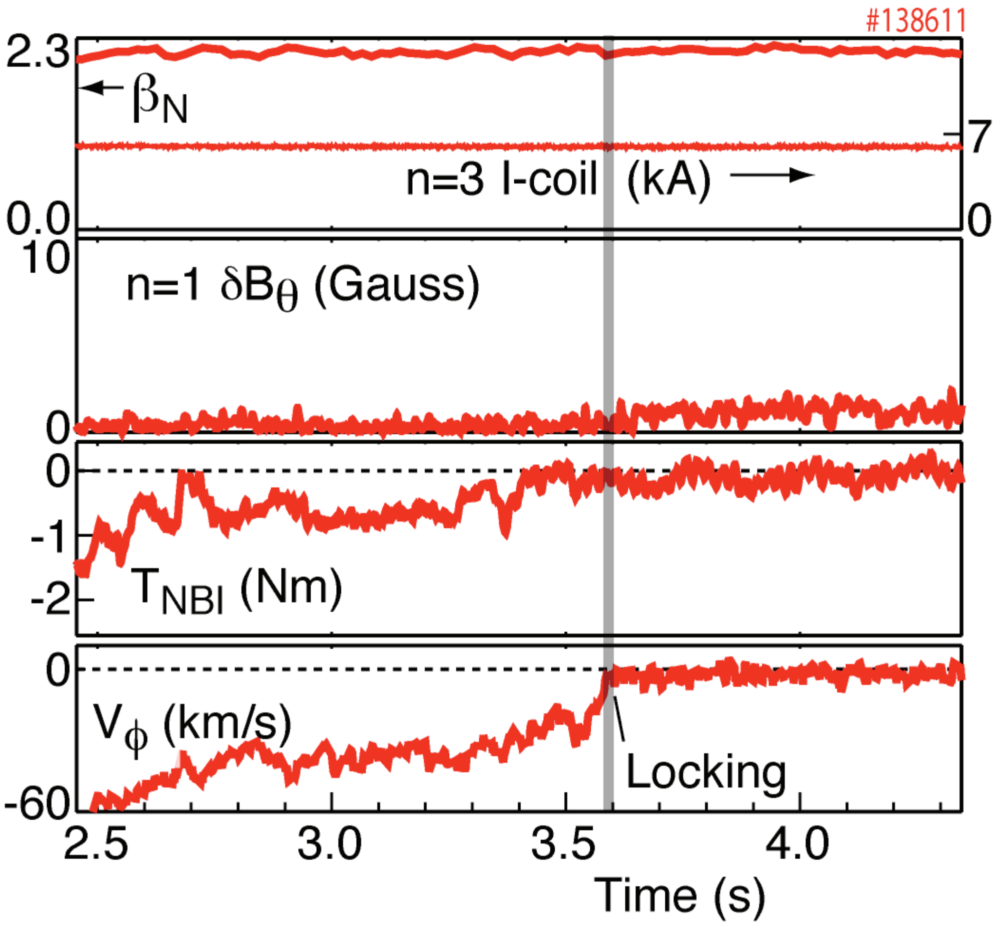

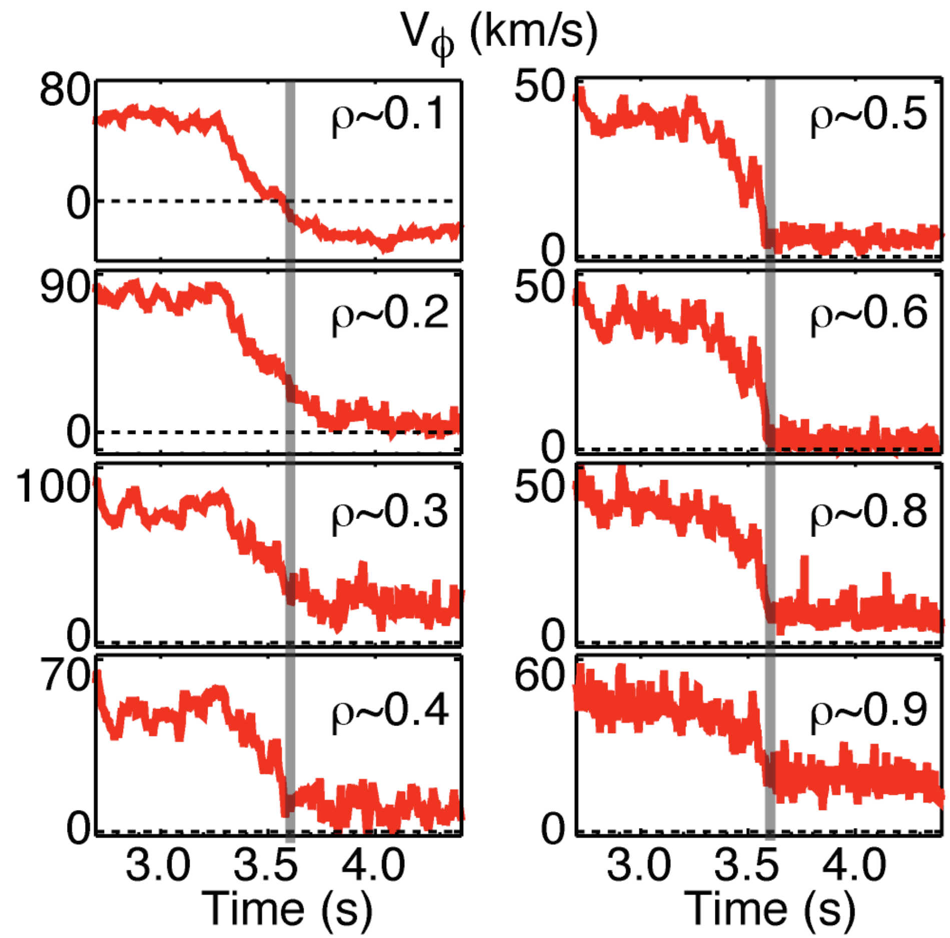

Removing n=3 NRMF in Locked Plasma Leads to n=1 Locked Mode

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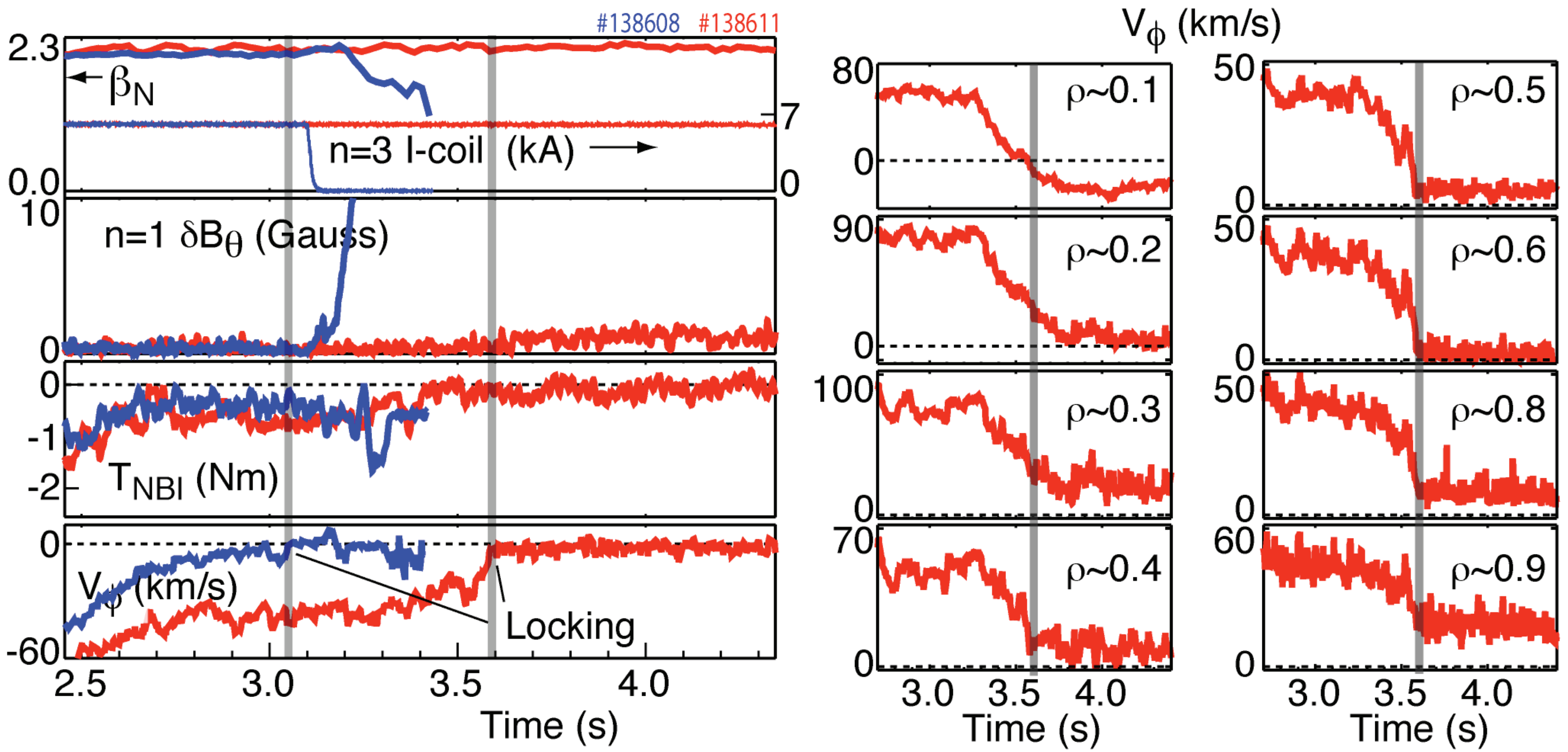
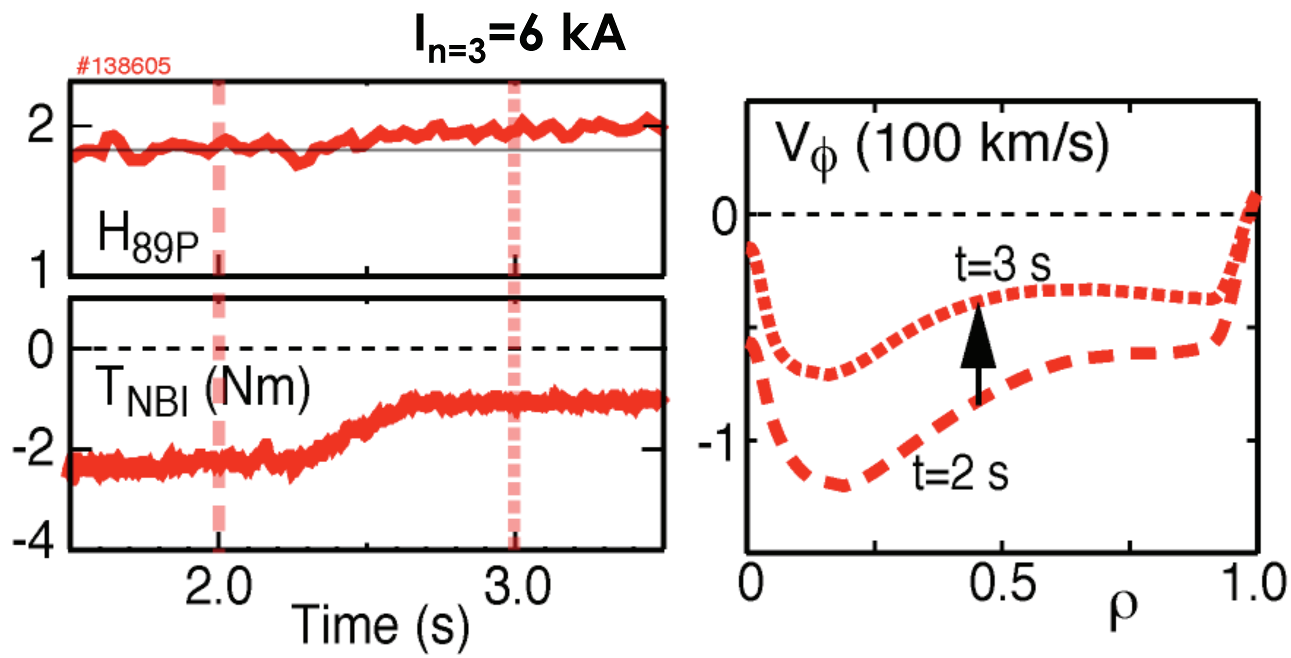


At Higher β_N, Energy Confinement Increases with Lower NBI Torque (and Lower Rotation)

- **Energy confinement increases with reducing NBI torque and rotation**



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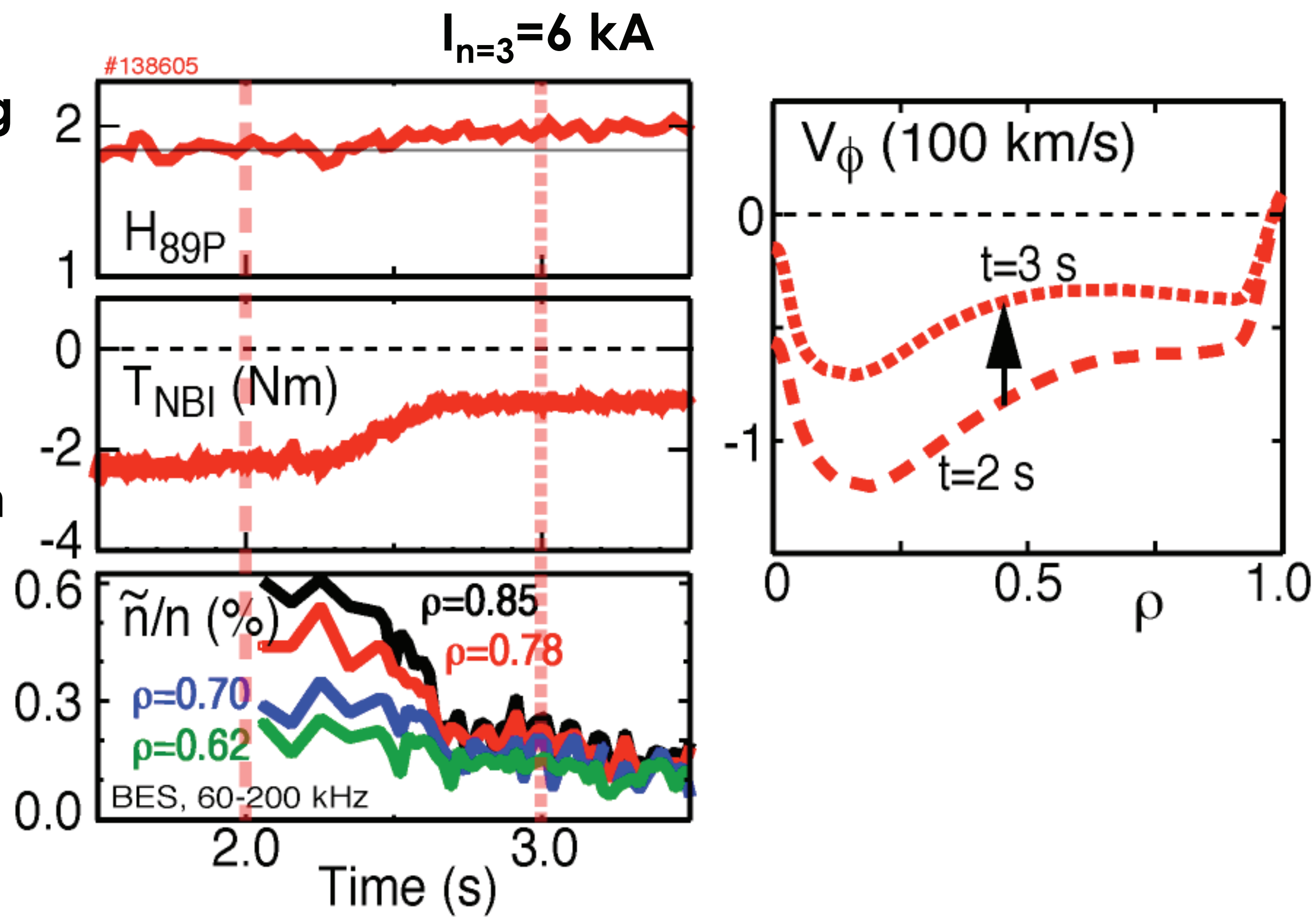

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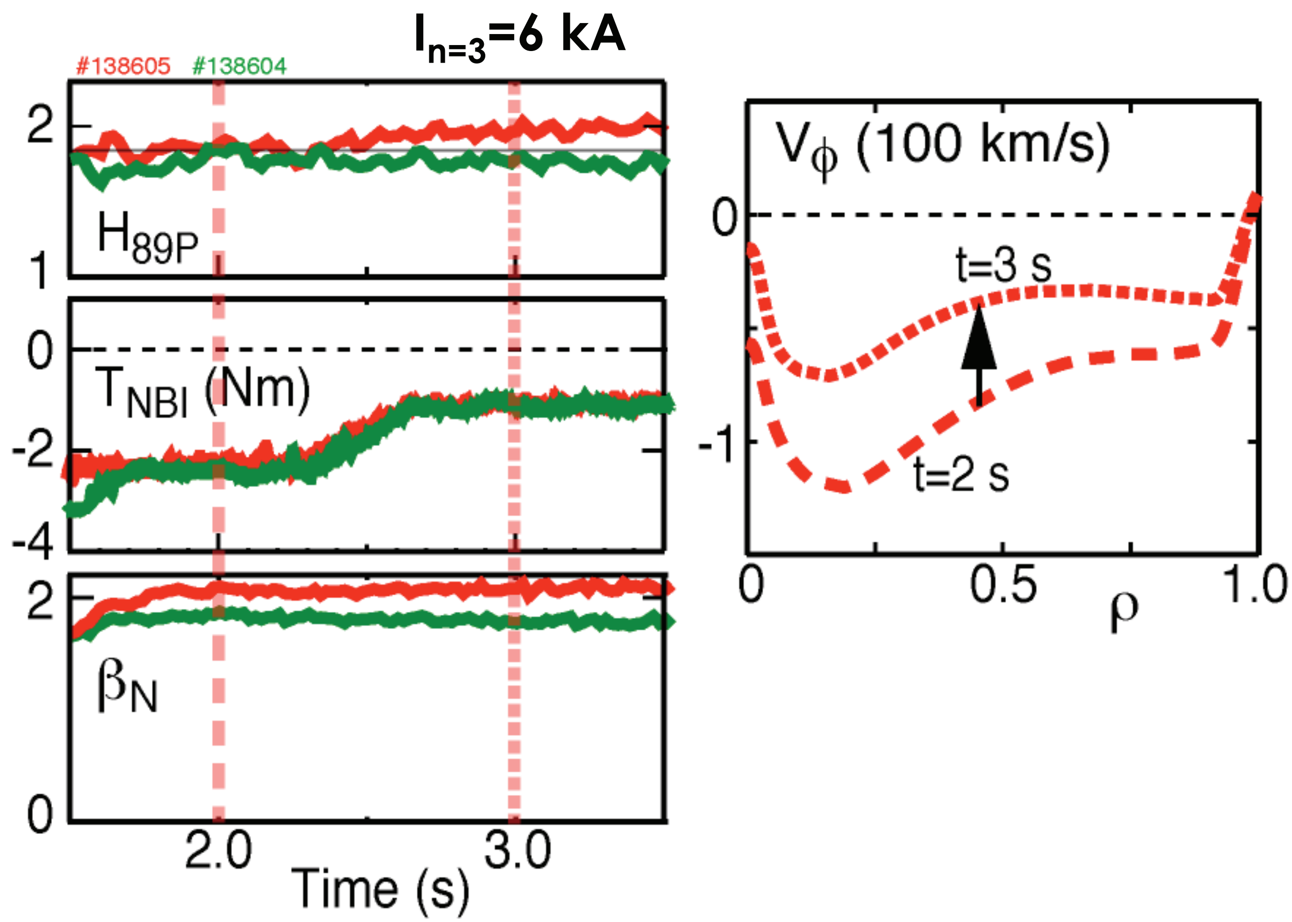
- Confinement improvement sensitive to beta



Static 3D Magnetic Fields Can Improve the Tokamak Configuration

- **Nonresonant magnetic fields sustain low collisionality H-mode plasma with no ELMs, zero-net NBI torque, and near-zero rotation**
  - NRMF torque replaces counter NBI torque in driving edge rotation shear
- **In this regime, the energy confinement improves with higher plasma pressure**
  - The reduction in energy transport is correlated with a reduction in turbulent fluctuations
- **Improved resilience to tearing modes and locked modes is observed**

$\Rightarrow$ **Path to QH-mode in burning plasmas, with little or no NBI torque**