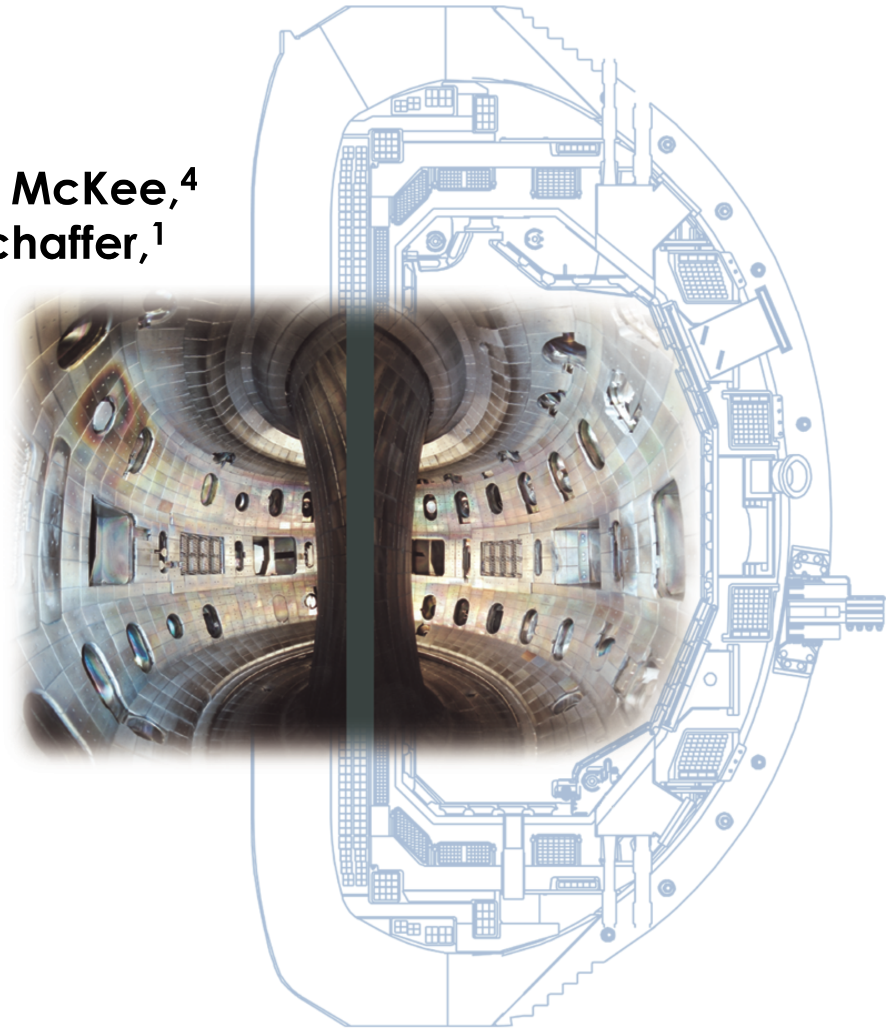
Advances Toward QH-mode Viability for ELM-free Operation in ITER

Andrea M. Garofalo[1]

In collaboration with:

W.M. Solomon,[2] K.H. Burrell,[1] M.J. Lanctot,[3] G.R. McKee,[4] T.H. Osborne,[1] J.K. Park,[2] H. Reimerdes,[2] M.J. Schaffer,[1] L. Schmitz,[5] and P.B. Snyder[1]

[1]General Atomics
[2]Princeton Plasma Physics Laboratory
[3]Columbia U.
[4]U. Wisconsin-Madison
[5]University of California-Los Angeles



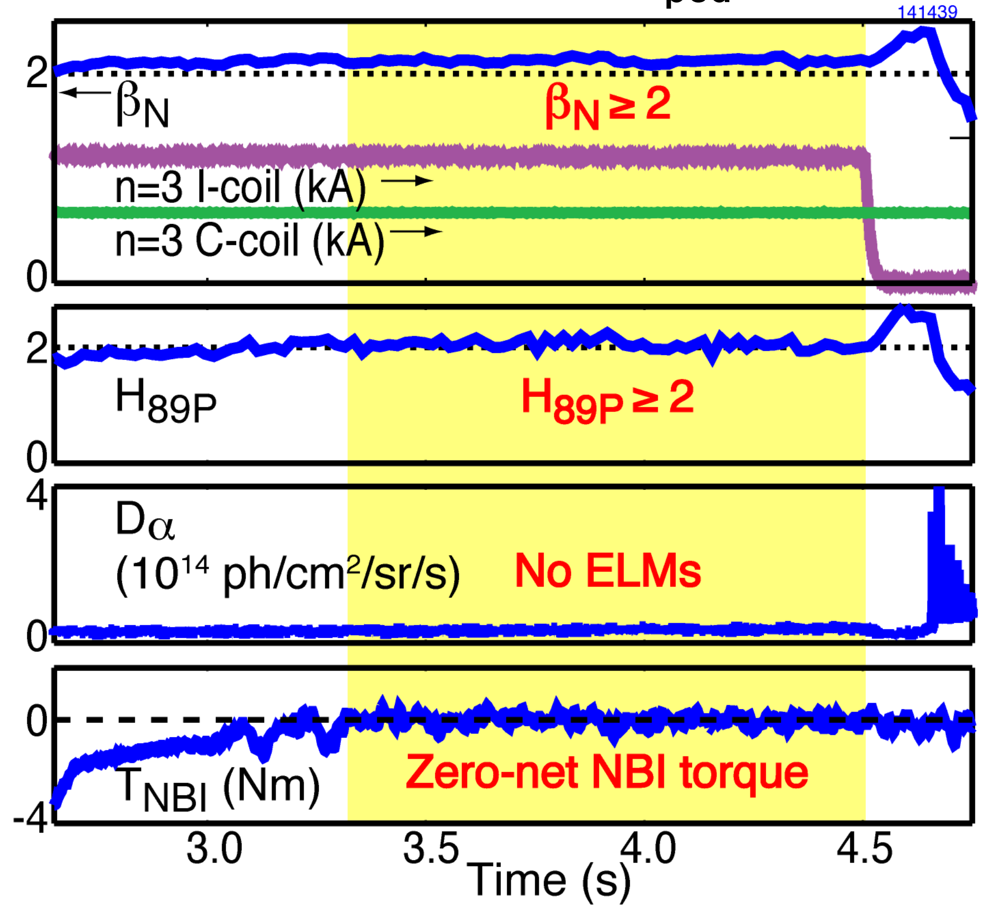
Presented at the
23rd IAEA Fusion Energy Conference
Daejeon, Republic of Korea

October 11-16, 2010

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

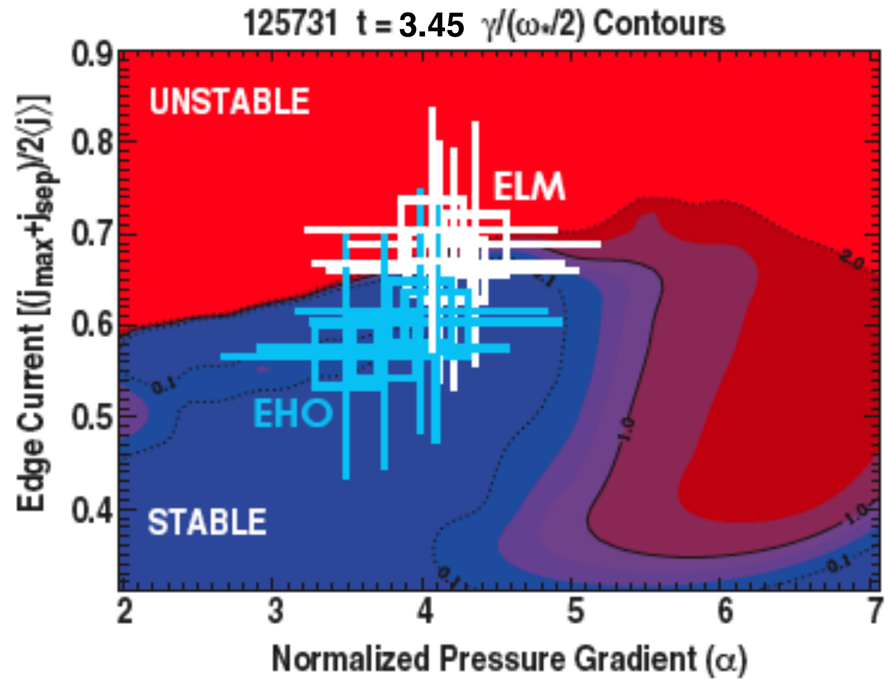
- **ELMs a serious challenge for acceptable edge conditions in ITER**
- **ELM-stable regime of quiescent H-mode (QH-mode) seen in many low-collisionality tokamaks**
  - Previously required significant NBI torque
- **Application of nonresonant magnetic fields enables QH-mode operation in plasmas with zero-net NBI torque**
  - Path toward QH-mode in self-heated burning plasma regime
- **We propose this as a new regime to be investigated for ITER**

Pedestal collisionality ν^*_{ped}~0.07



Background – QH-mode

- **QH-mode is an ideal H-mode**
  - H-mode confinement without ELMs
  - Role of ELMs for edge particle transport replaced by "edge harmonic oscillation"(EHO)

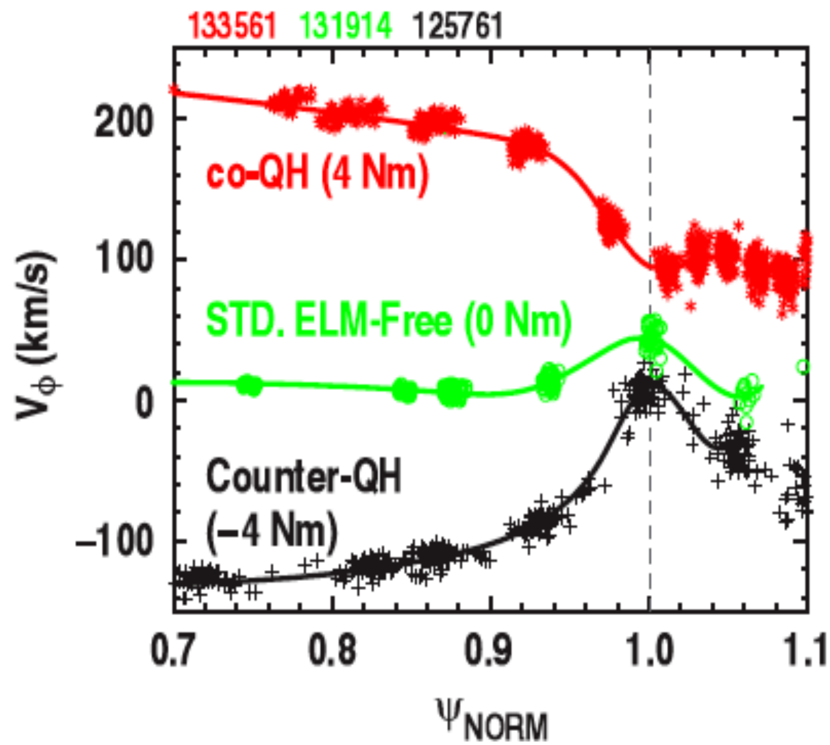


- **Theory identifies EHO as nonlinearly saturated kink-peeling ELM, destabilized by rotational shear before edge reaches zero-rotation stability boundary**

Snyder et al., Nucl. Fusion (2007)

Background – QH-mode

- **QH-mode is an ideal H-mode**
  - H-mode confinement without ELMs
  - Role of ELMs for edge particle transport replaced by "edge harmonic oscillation"(EHO)
- **QH-mode can be accessed both with co-I_p and counter-I_p rotation**
- **Minimum pedestal velocity shear necessary for QH-mode, consistent with theory predictions**
  - Previously required significant NBI torque



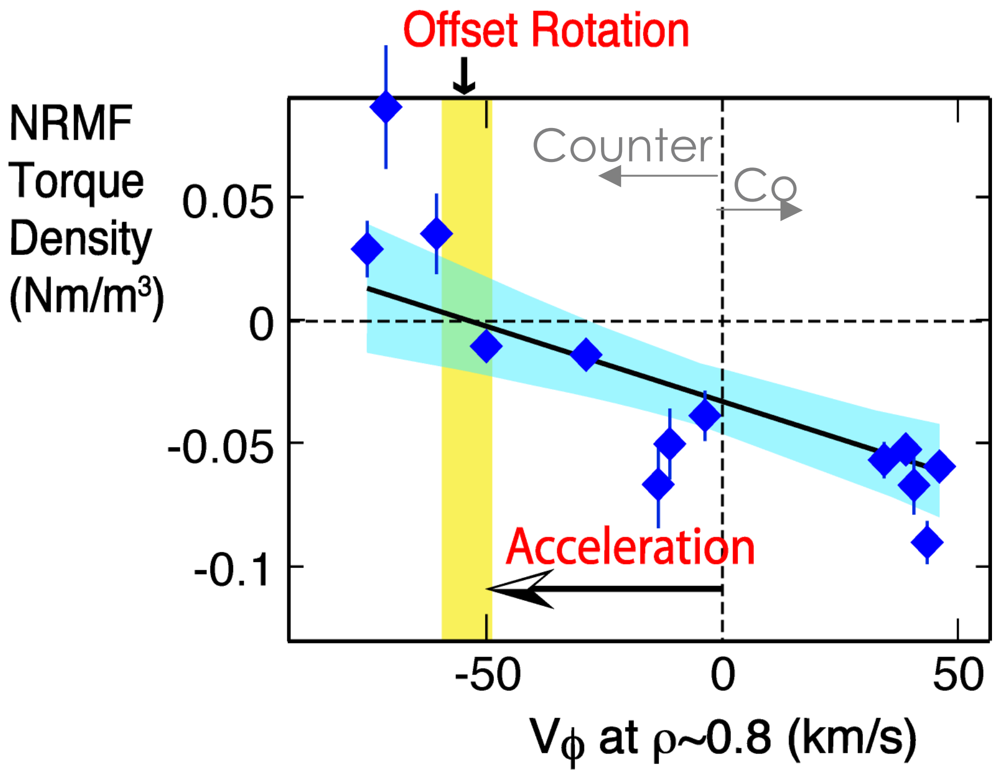
Burrell et al., PRL (2009)

Background – Nonresonant Magnetic Field Torque

- **Neoclassical "offset" rotation**

⇒ **Nonresonant magnetic fields (NRMFs) can accelerate plasma in counter-I_p direction**

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



Garofalo et al., PRL (2008)

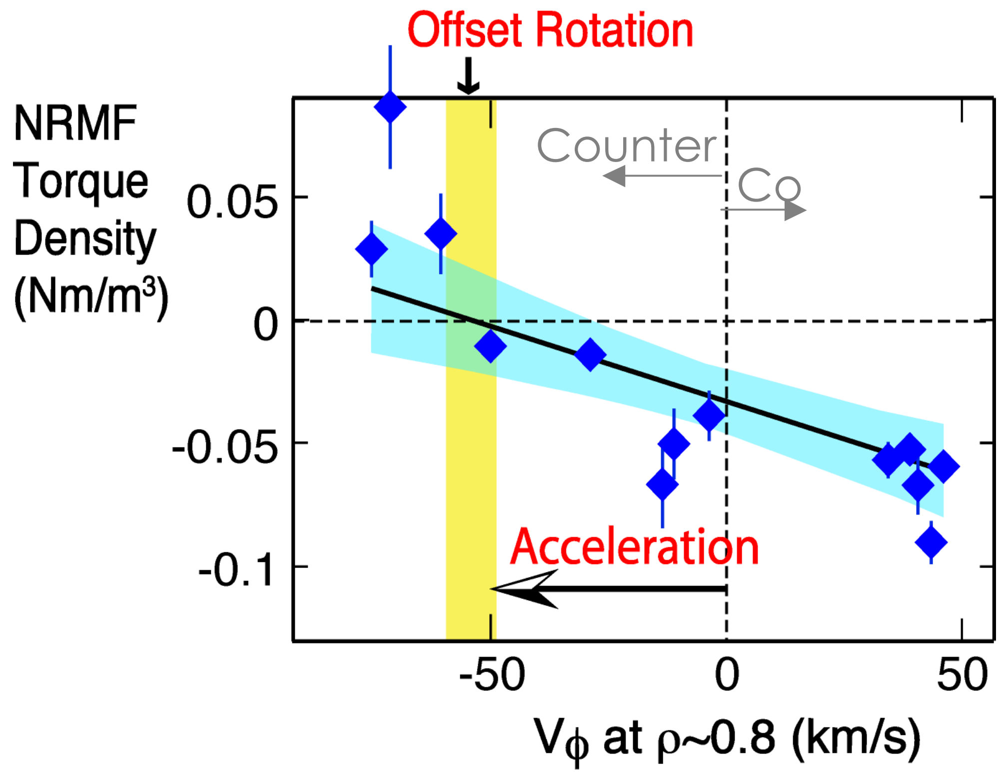
Background – Nonresonant Magnetic Field Torque

- **Neoclassical "offset" rotation**

⇒ **Nonresonant magnetic fields (NRMFs) can accelerate plasma in counter-I_p direction**

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

- **Can the NRMF torque provide a counter-rotation profile suitable for QH-mode with:**
  - NBI torque =0 (**DEMO**)
  - slightly co-I_p NBI torque (**ITER**)

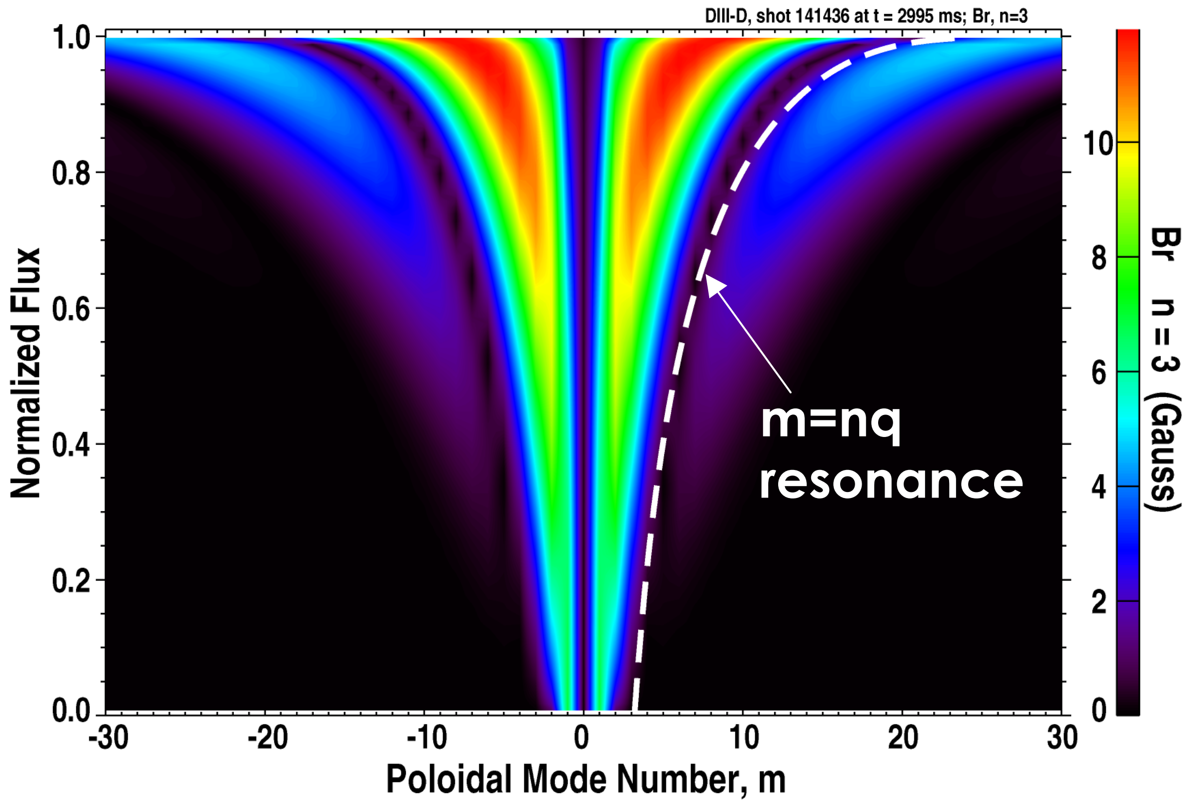


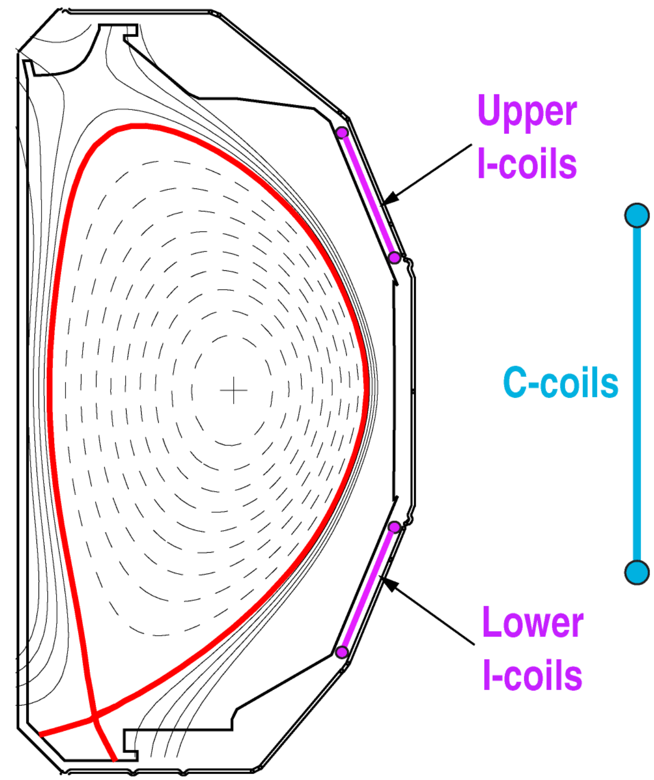
Garofalo et al., PRL (2008)

Mostly Nonresonant Magnetic Fields (NRMFs) Applied Using the I-coil

- Toroidal mode number n=3
- Odd-parity (up-down anti-symmetric) configuration

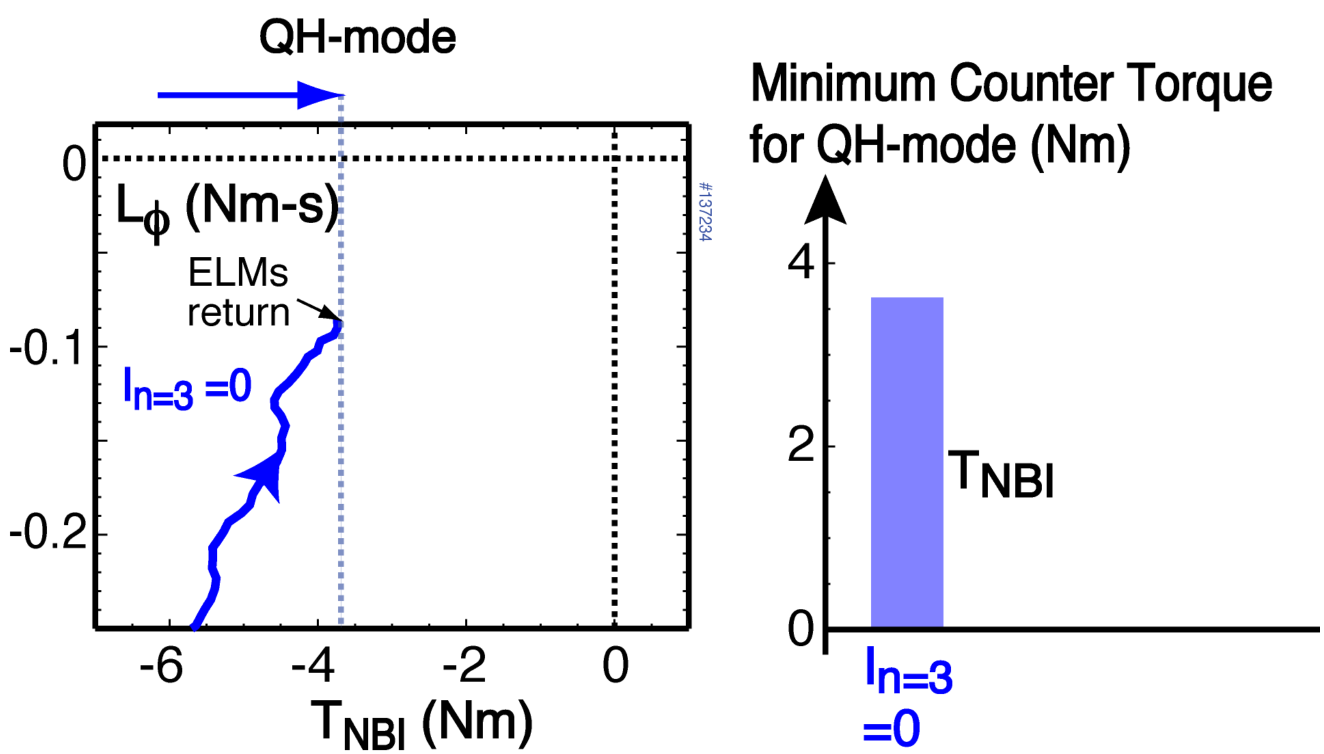
- C-coil can augment n=3 field, but adds more resonant components





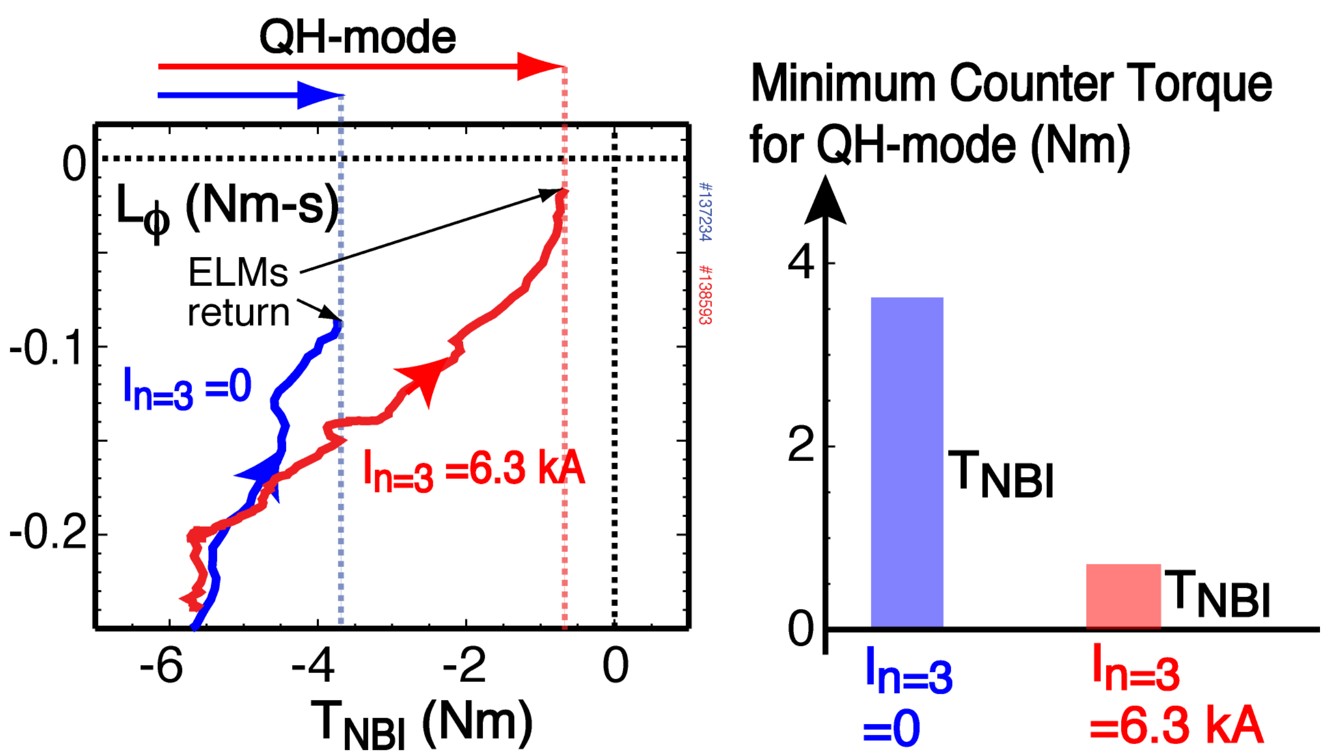
NRMF Maintains QH-mode at Lower NBI Torque by Helping Provide Sufficient Counter Torque on Plasma

- **n=3 NRMF allows sustained QH-mode with lower NBI torque magnitude than required without NRMFs**



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

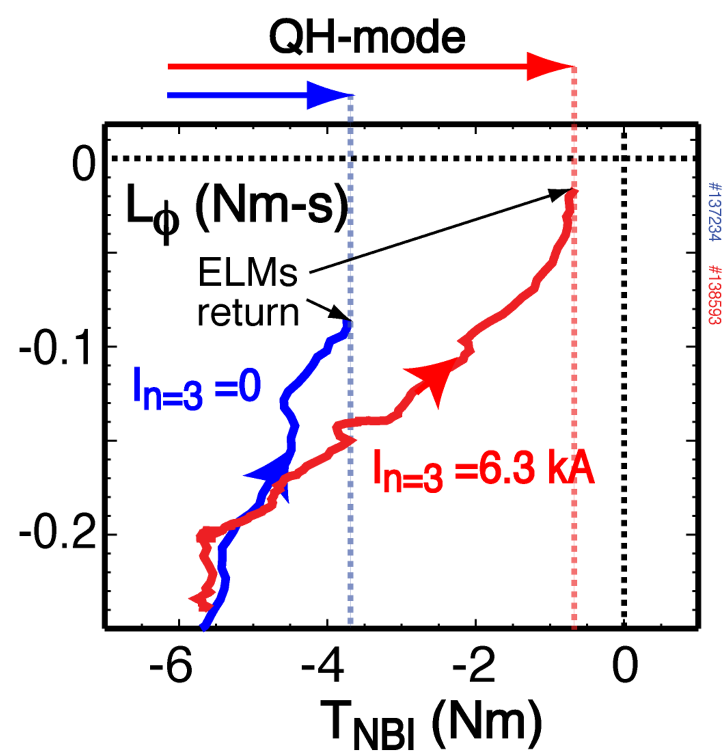
- n=3 NRMF allows sustained QH-mode with lower NBI torque magnitude than required without NRMFs

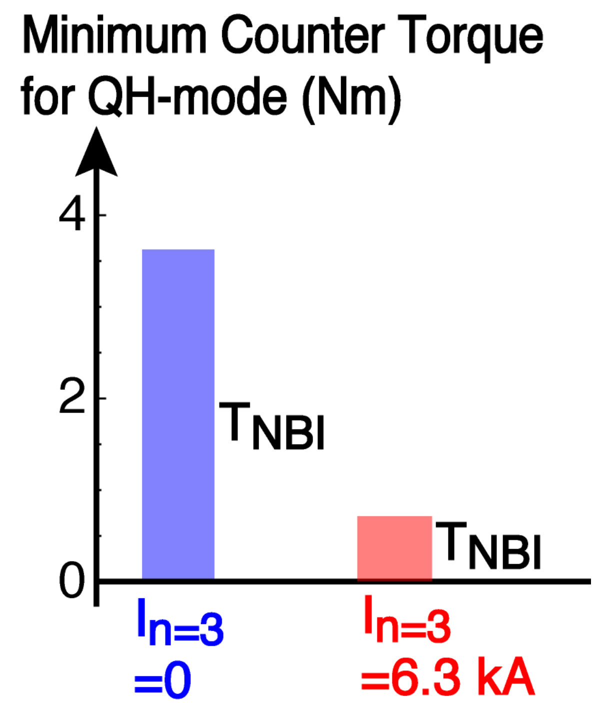


NRMF Maintains QH-mode at Lower NBI Torque by Helping Provide Sufficient Counter Torque on Plasma

- **n=3 NRMF allows sustained QH-mode with lower NBI torque magnitude than required without NRMFs**
- **Plasma rotation shear at plasma edge is dependent on total torque integrated up to edge**

$$mnR\frac{\partial V_\phi}{\partial t} = \eta + \frac{\partial}{\partial r}\left[mnR\left(\chi_\phi \frac{\partial V_\phi}{\partial r}\right)\right] \qquad T(edge) = -\left|mnR\left(\chi_\phi \frac{\partial V_\phi}{\partial r}\right)\right|_{edge}$$

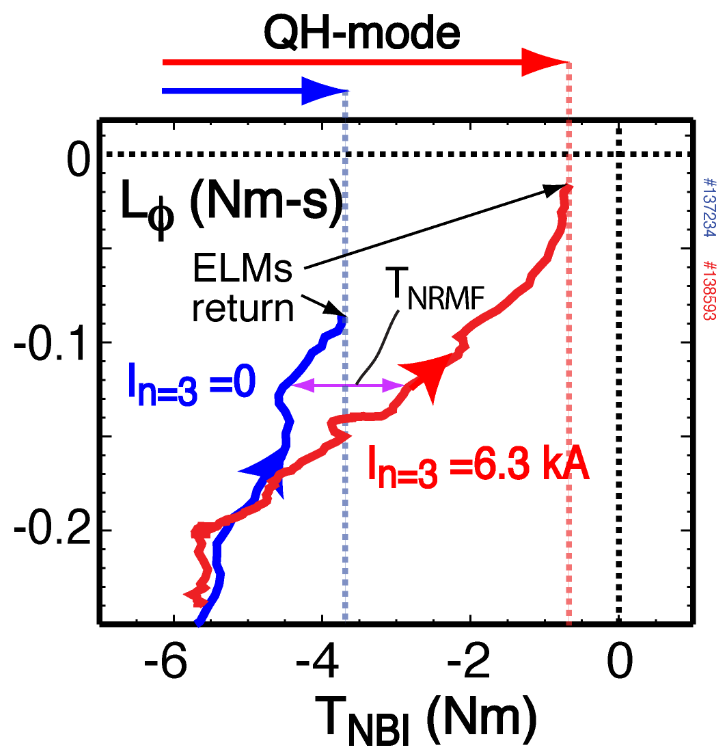


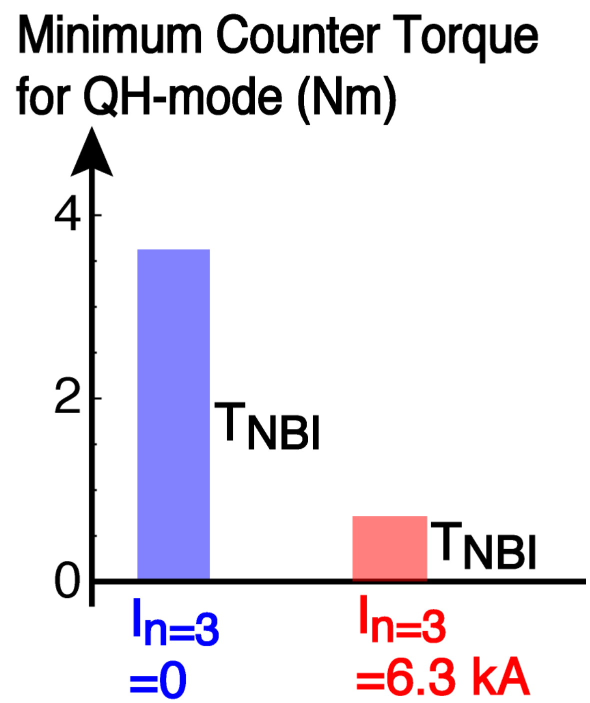


NRMF Maintains QH-mode at Lower NBI Torque by Helping Provide Sufficient Counter Torque on Plasma

- **n=3 NRMF allows sustained QH-mode with lower NBI torque magnitude than required without NRMFs**
- **Plasma rotation shear at plasma edge is dependent on total torque integrated up to edge**
  - NRMF torque contribution?

$$mnR\frac{\partial V_\phi}{\partial t} = \eta + \frac{\partial}{\partial r}\left[mnR\left(\chi_\phi \frac{\partial V_\phi}{\partial r}\right)\right] \qquad T(edge) = -\left|mnR\left(\chi_\phi \frac{\partial V_\phi}{\partial r}\right)\right|_{edge}$$

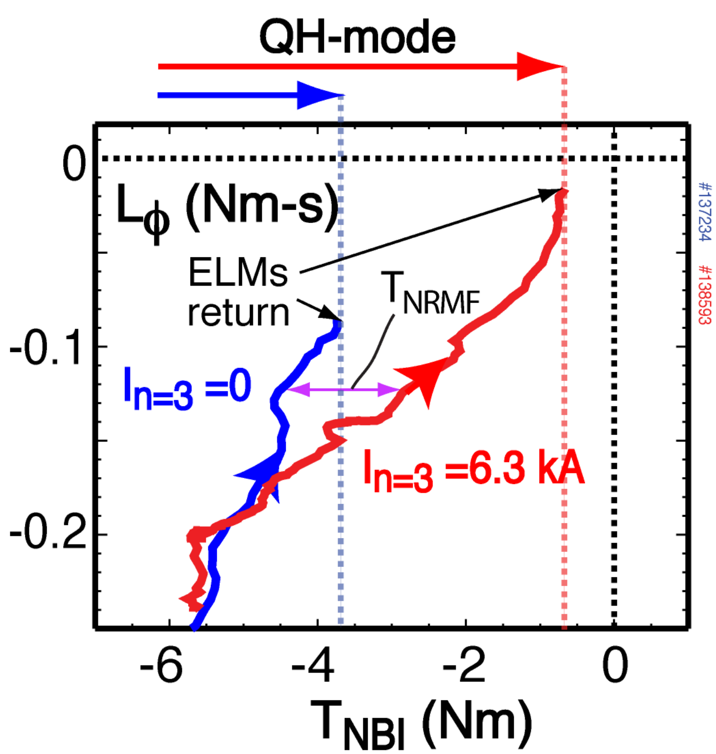


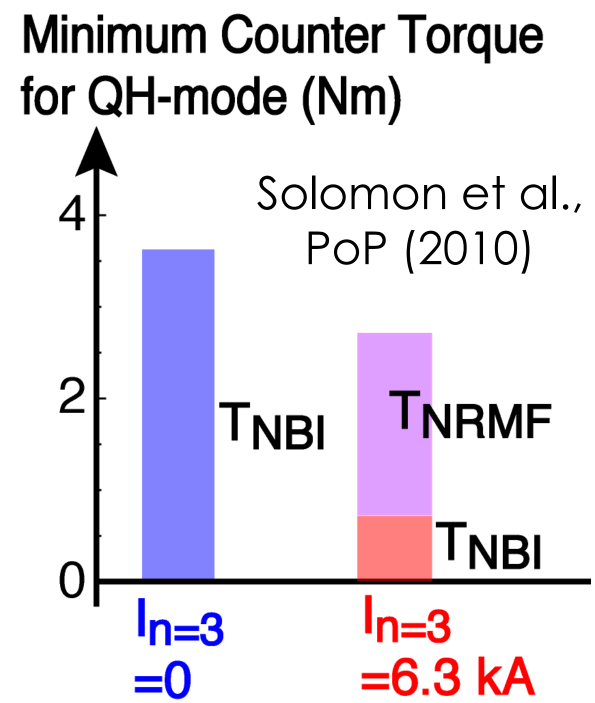


NRMF Maintains QH-mode at Lower NBI Torque by Helping Provide Sufficient Counter Torque on Plasma

- **n=3 NRMF allows sustained QH-mode with lower NBI torque magnitude than required without NRMFs**
- **Plasma rotation shear at plasma edge is dependent on total torque integrated up to edge**
  - NRMF torque contribution?
- **NRMF torque partially compensates for lower NBI torque**
  - Other effects must be at play

$$mnR\frac{\partial V_\phi}{\partial t} = \eta + \frac{\partial}{\partial r}\left[mnR\left(\chi_\phi \frac{\partial V_\phi}{\partial r}\right)\right] \qquad T(edge) = -\left|mnR\left(\chi_\phi \frac{\partial V_\phi}{\partial r}\right)\right|_{edge}$$



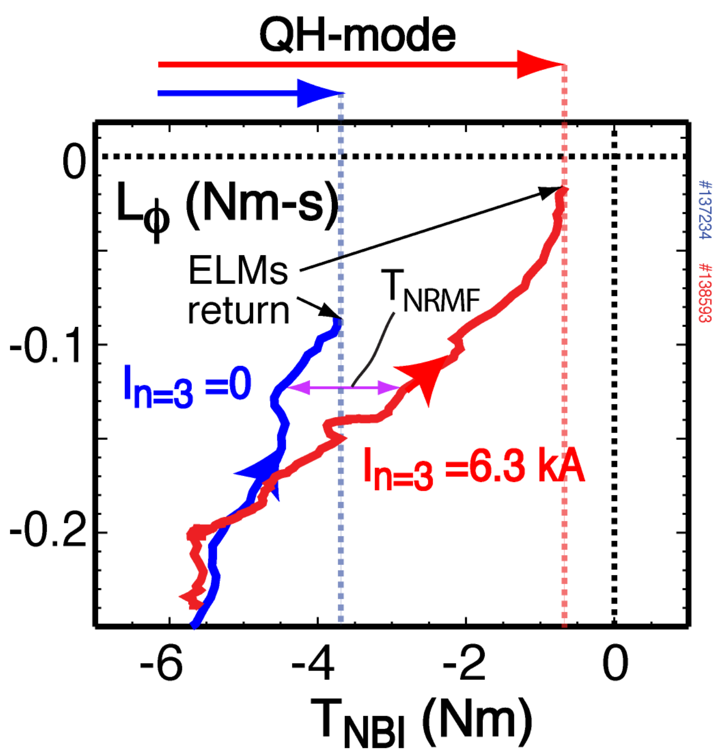


NRMF Maintains QH-mode at Lower NBI Torque by Helping Provide Sufficient Counter Torque on Plasma

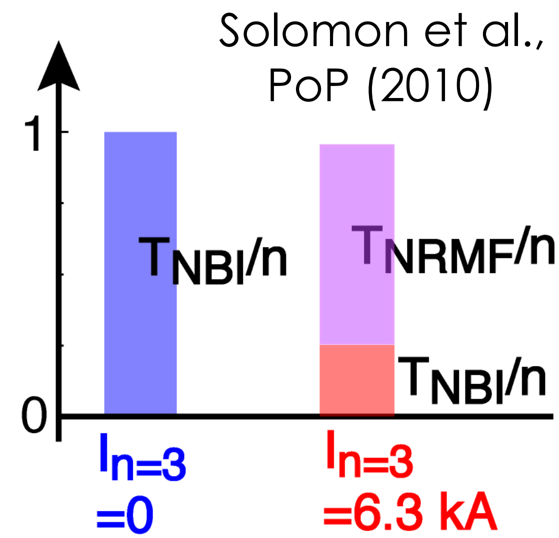
- **n=3 NRMF allows sustained QH-mode with lower NBI torque magnitude than required without NRMFs**
- **Plasma rotation shear at plasma edge is dependent on total torque integrated up to edge**
  - NRMF torque contribution?
- **NRMF torque partially compensates for lower NBI torque**
  - Other effects must be at play:

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

$$mnR\frac{\partial V_\phi}{\partial t} = \eta + \frac{\partial}{\partial r}\left[mnR\left(\chi_\phi \frac{\partial V_\phi}{\partial r} \right) \right] \qquad T(edge) = -\left| mnR\left(\chi_\phi \frac{\partial V_\phi}{\partial r} \right) \right|_{edge}$$

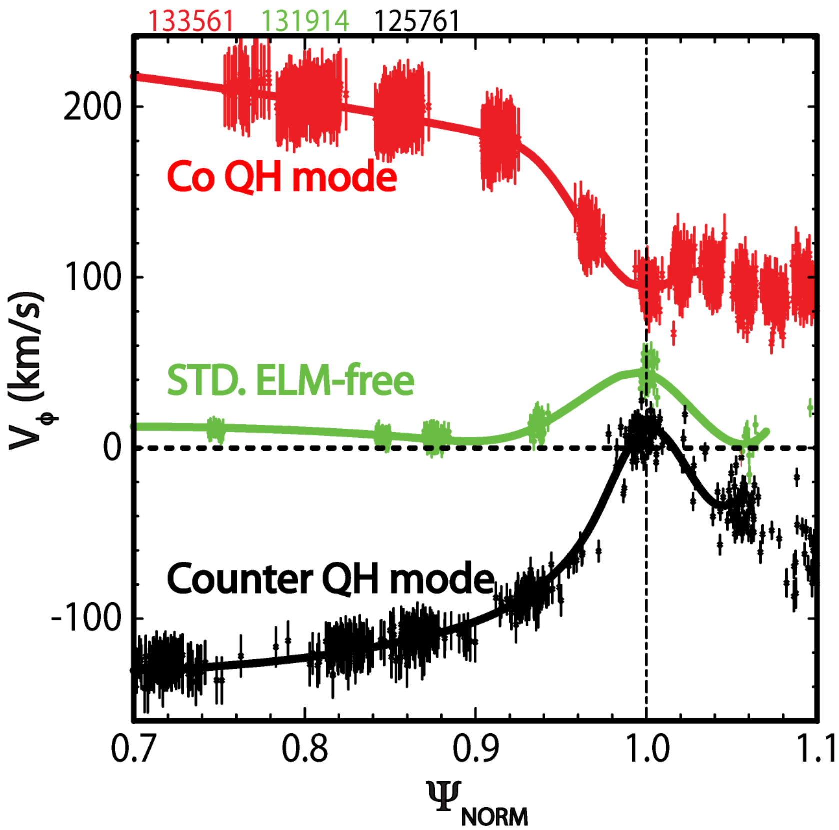


Minimum Counter Torque for QH-mode normalized to density (au)



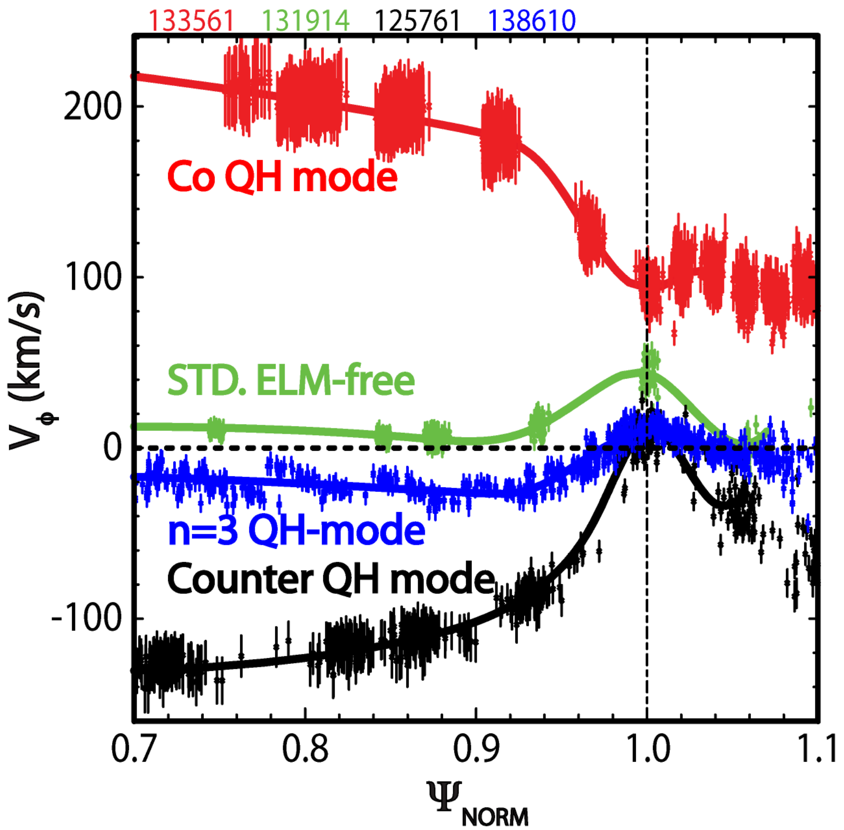
Shear in Edge Rotation Driven by Radial Electric Field Is Important Quantity in Maintaining QH-mode Edge

- **Minimum edge rotation shear necessary for QH-mode**
  - Measured rotation of impurity C ions proxy for plasma fluid rotation



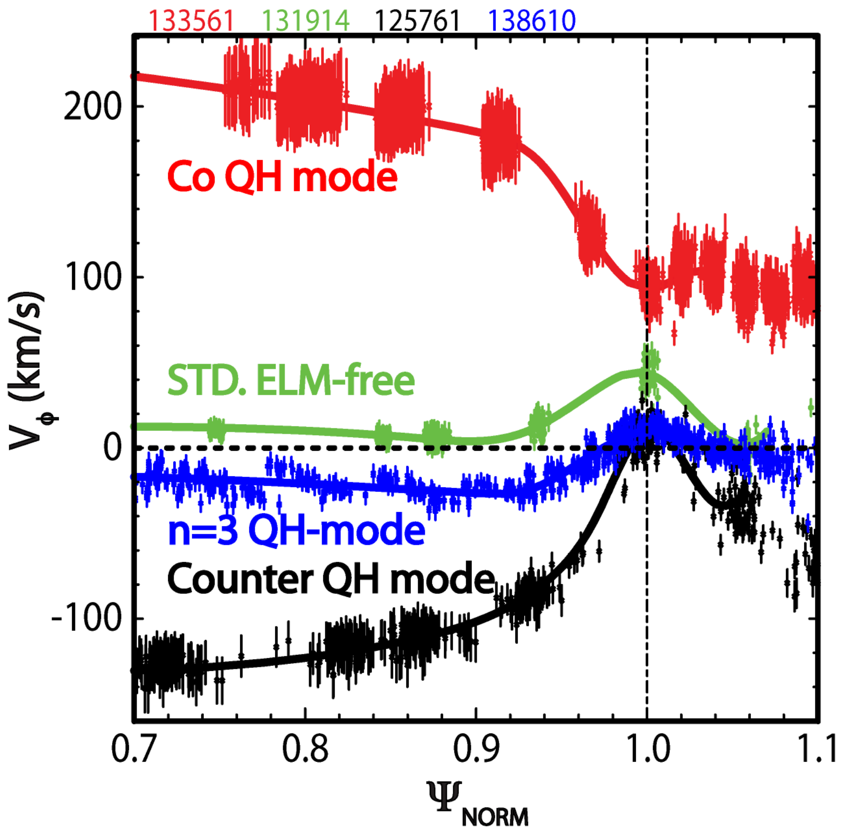
Shear in Edge Rotation Driven by Radial Electric Field Is Important Quantity in Maintaining QH-mode Edge

- **With NRMF: large shear in edge velocity of impurity C ions not required to sustain QH-mode**

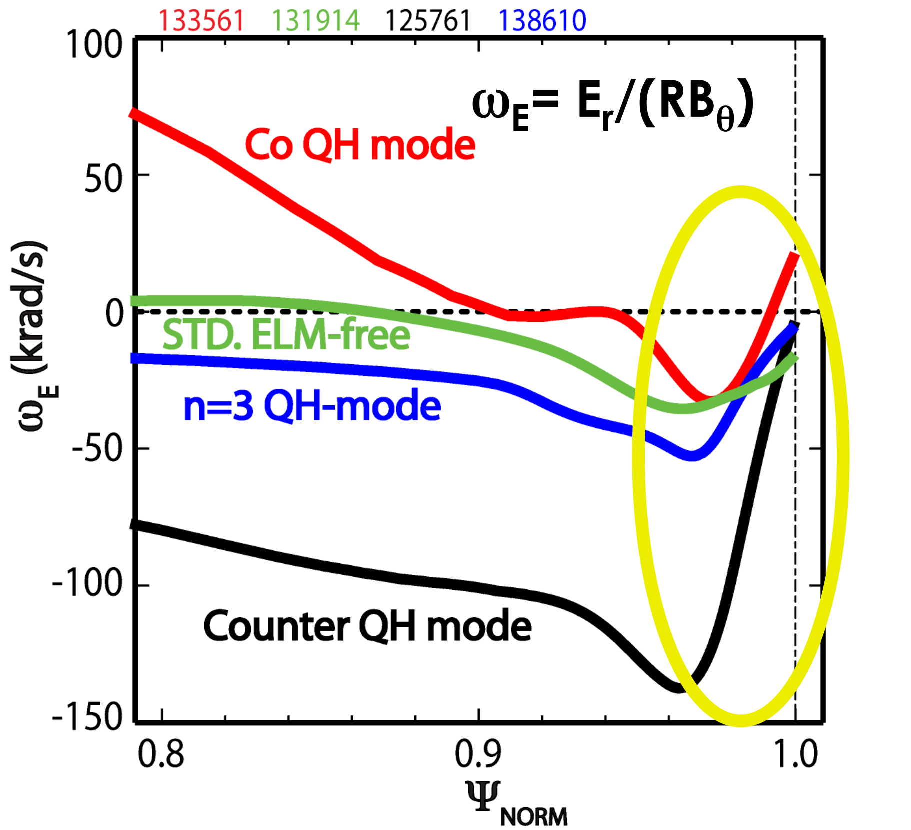


Shear in Edge Rotation Driven by Radial Electric Field Is Important Quantity in Maintaining QH-mode Edge

- **With NRMF: large shear in edge velocity of impurity C ions not required to sustain QH-mode**

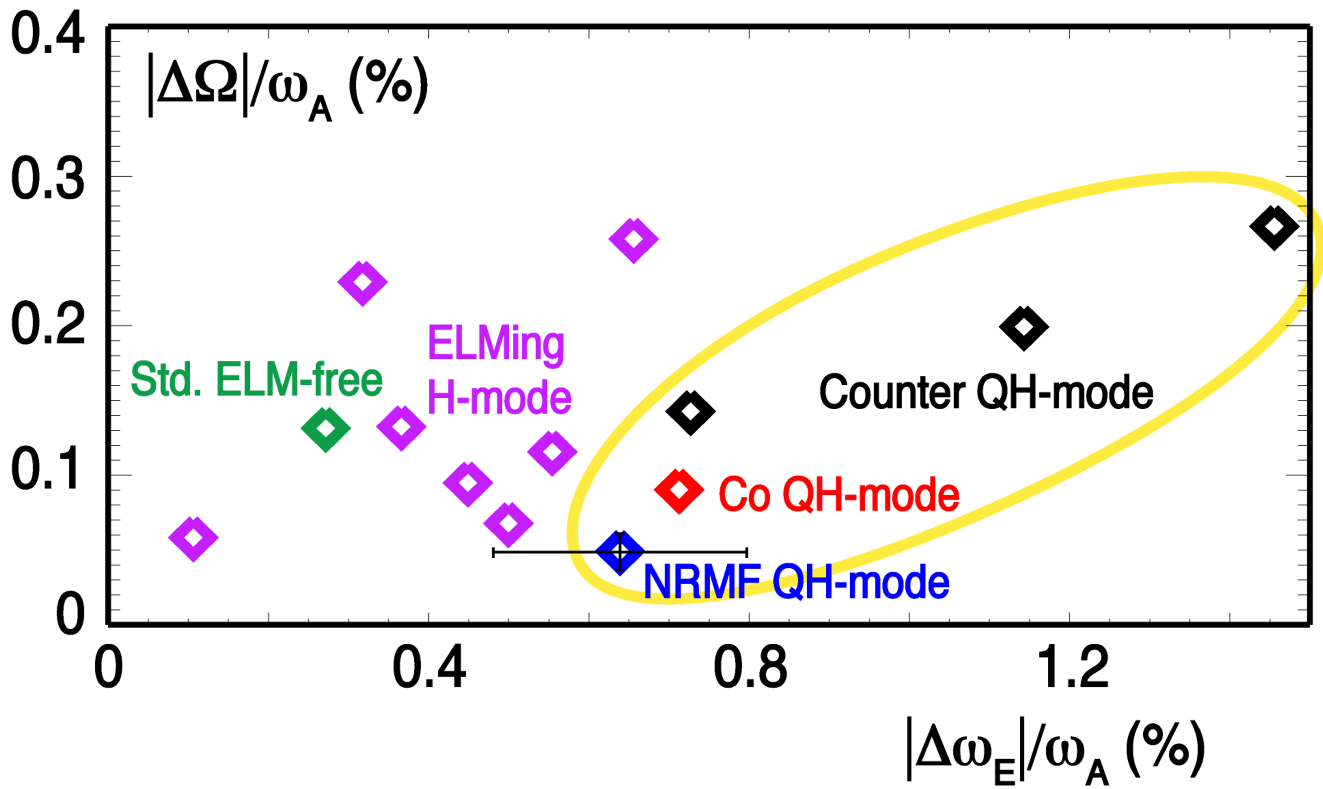


- **Large shear in edge ω_E rotation (toroidal rotation driven by ExB drift) better correlates with QH-mode**



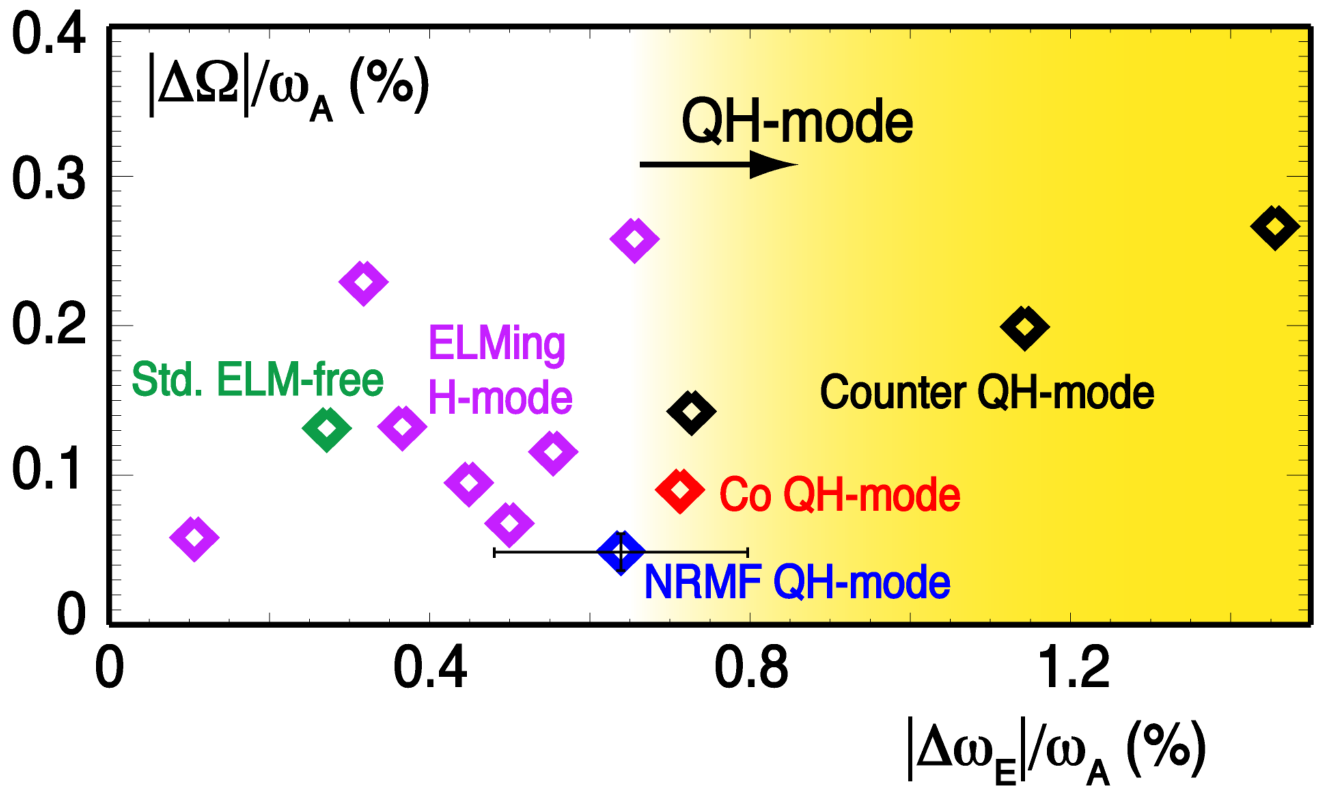
Shear in Edge Rotation Driven by Radial Electric Field Is Important Quantity in Maintaining QH-mode Edge

- Ω = Carbon impurity ion rotation
- $\omega_E = E_r/(RB_\theta)$ = Toroidal rotation driven by ExB drift
- Δ evaluated across the outer half of the edge pedestal

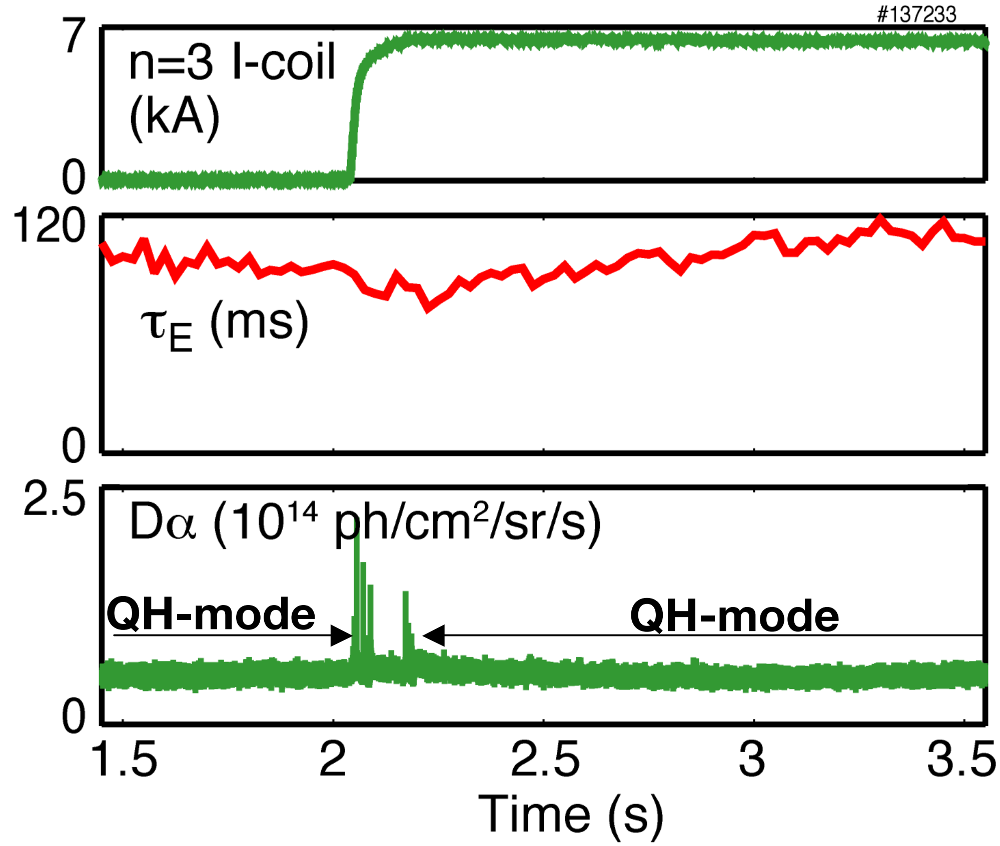


Shear in Edge Rotation Driven by Radial Electric Field Is Important Quantity in Maintaining QH-mode Edge

- Threshold near $\Delta\omega_E/\omega_A$ ~ 0.7% emerges for QH-mode operation

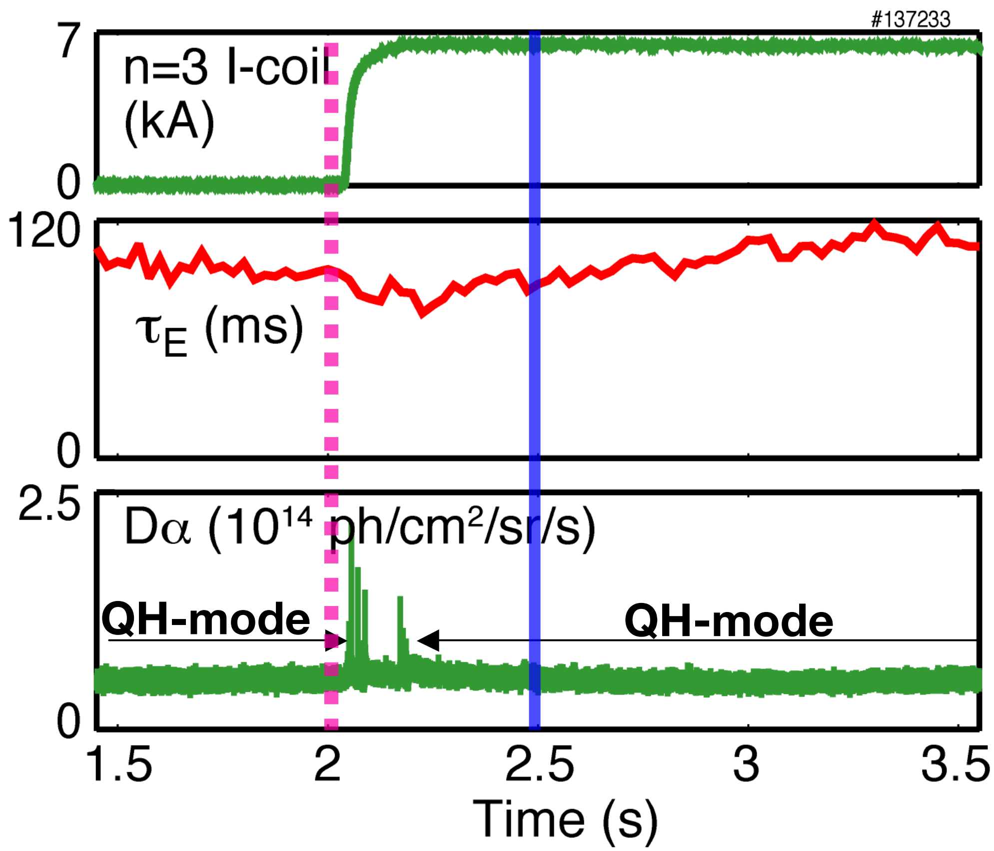


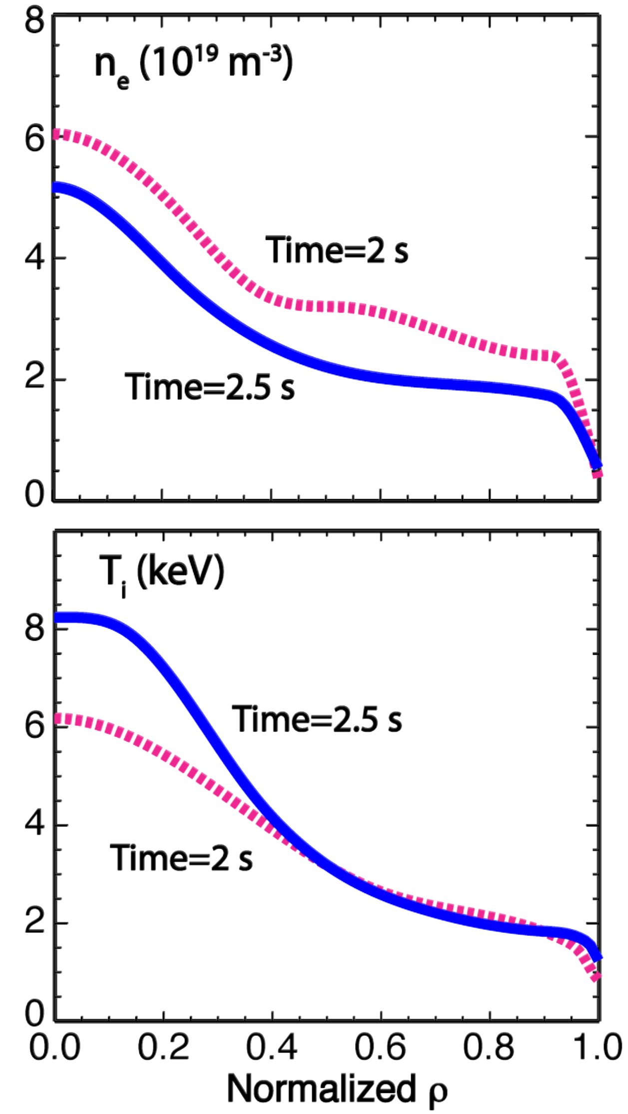
No Adverse Impact of NRMF on Global Energy Confinement Is Observed



No Adverse Impact of NRMF on Global Energy Confinement Is Observed

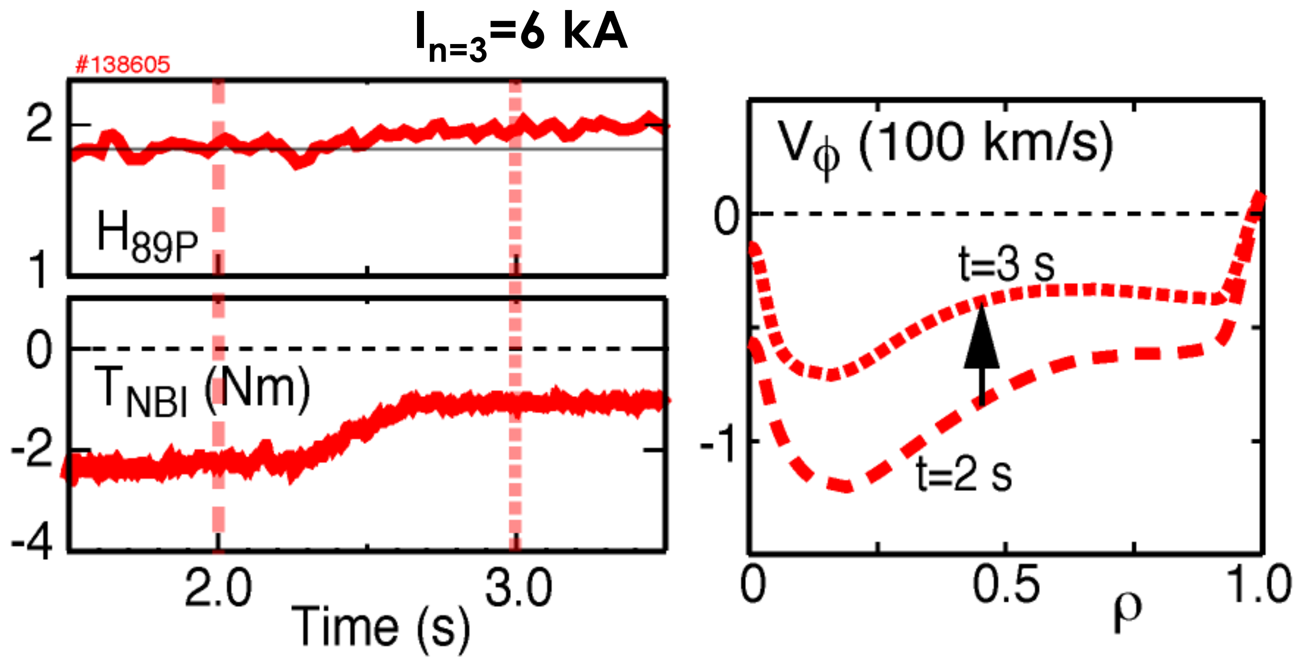
- **Density is reduced, core ion temperature is increased, electron temperature ~unchanged**





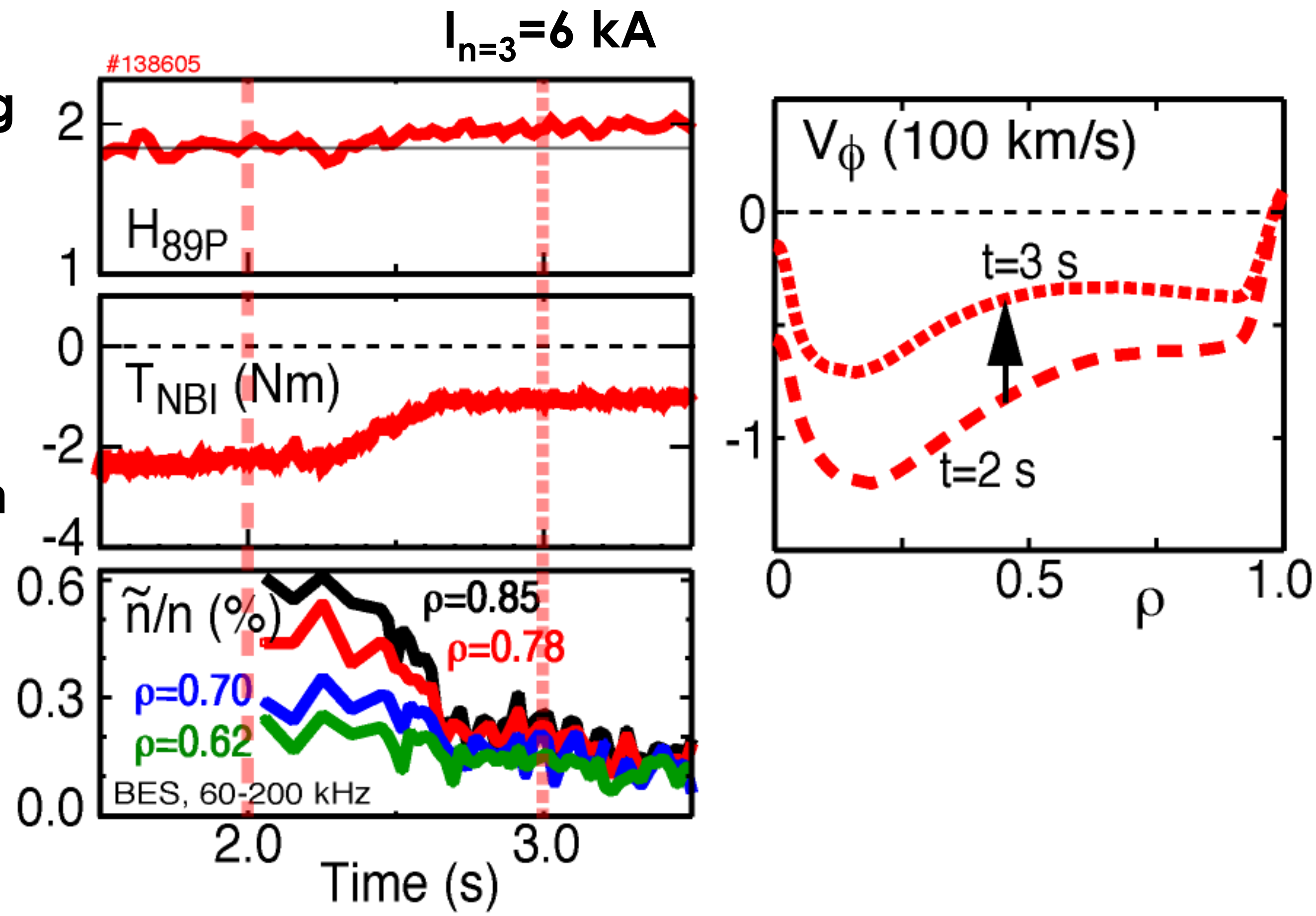
At Higher β_N, Energy Confinement Increases with Lower NBI Torque (and Lower Rotation)

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



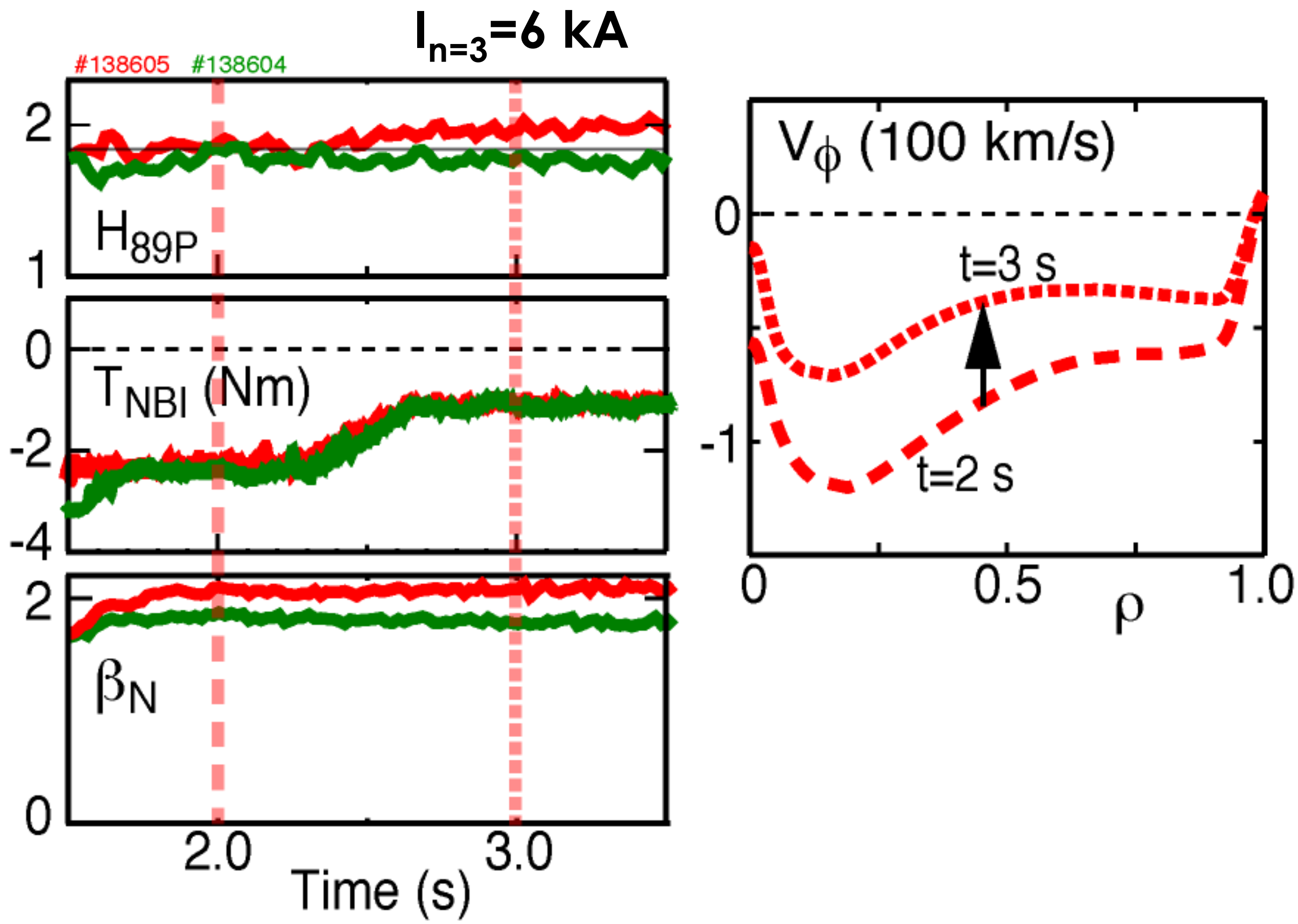
At Higher β_N, Energy Confinement Increases with Lower NBI Torque (and Lower Rotation)

- Energy confinement increases with reducing NBI torque and rotation
- Measured turbulence (density fluctuations from BES, DBS) is reduced at lower rotation, consistent with improved confinement



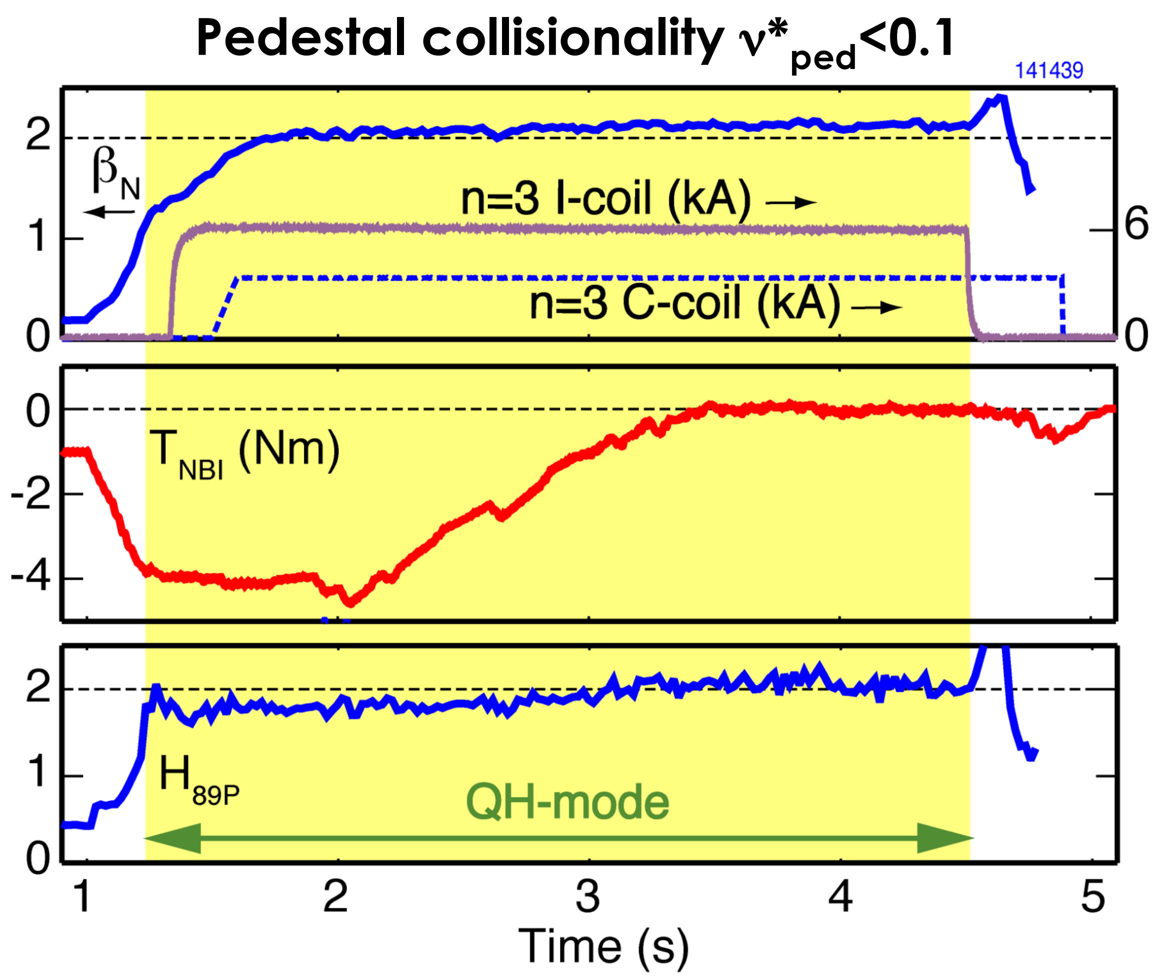
At Higher β_N, Energy Confinement Increases with Lower NBI Torque (and Lower Rotation)

- **Energy confinement increases with reducing NBI torque and rotation**
- **Measured turbulence (density fluctuations from BES, DBS) is reduced at lower rotation, consistent with improved confinement**
- **Confinement improvement sensitive to beta**



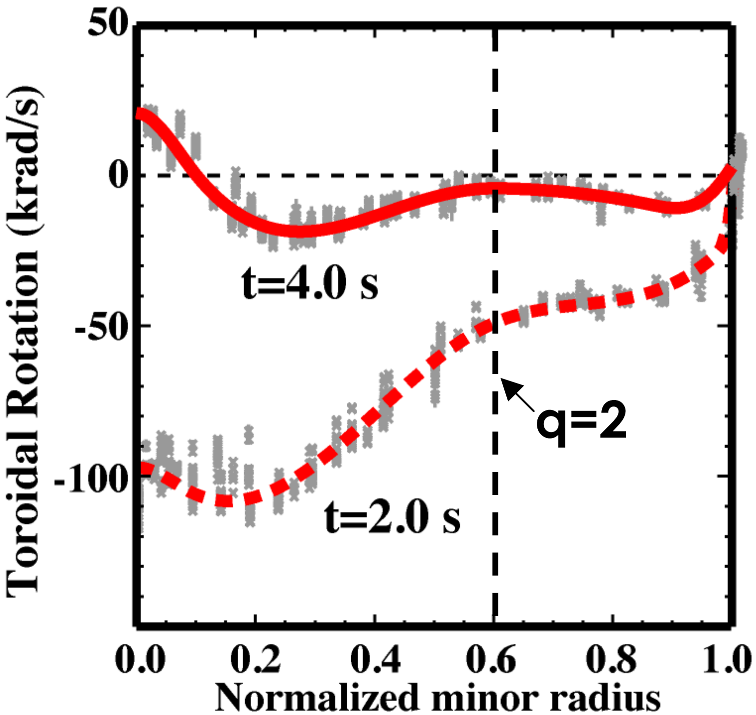
Counter NBI torque Required for QH-mode Reduced to Zero With Addition of C-coil n=3 Field

- C-coil n=3 field increases total NRMF by ~50% at plasma boundary (vacuum)

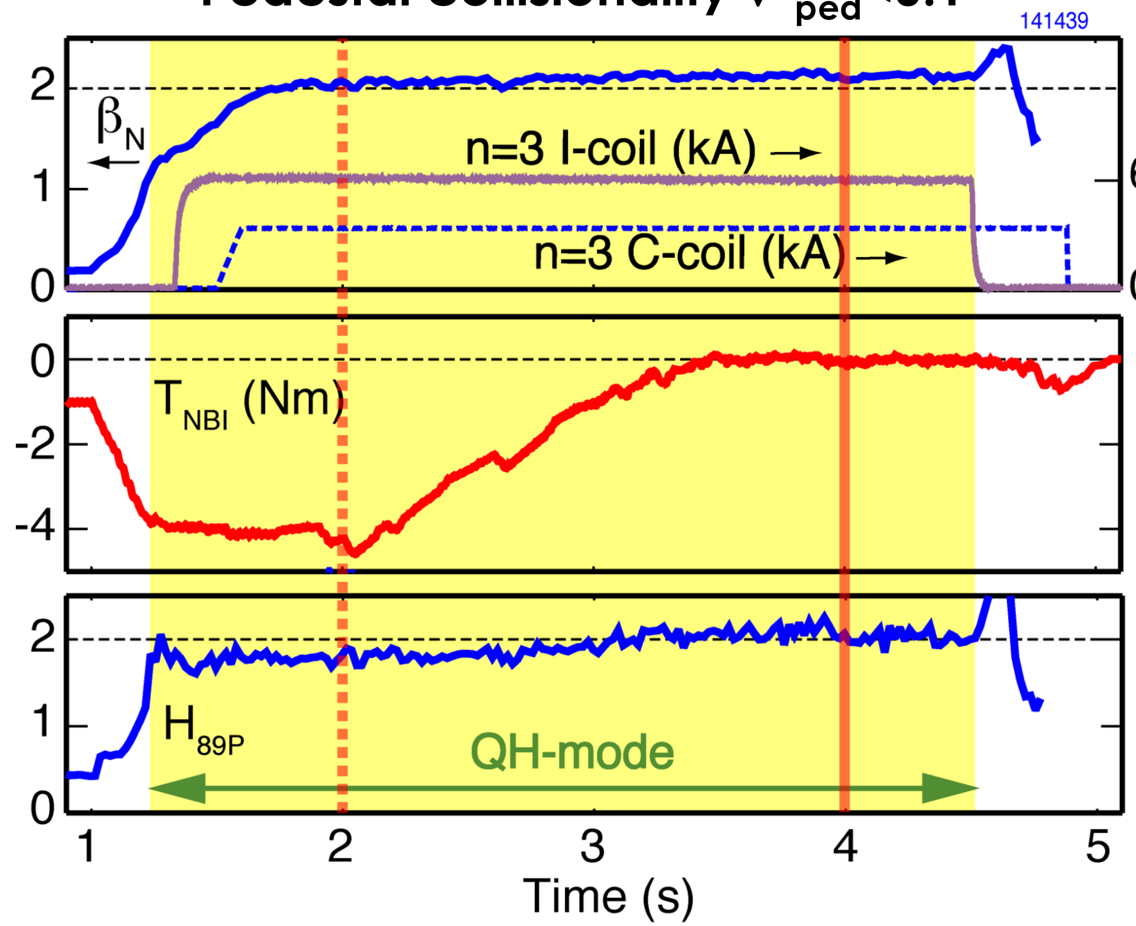


n=3 NRMFs Expand Tokamak Operating Space

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

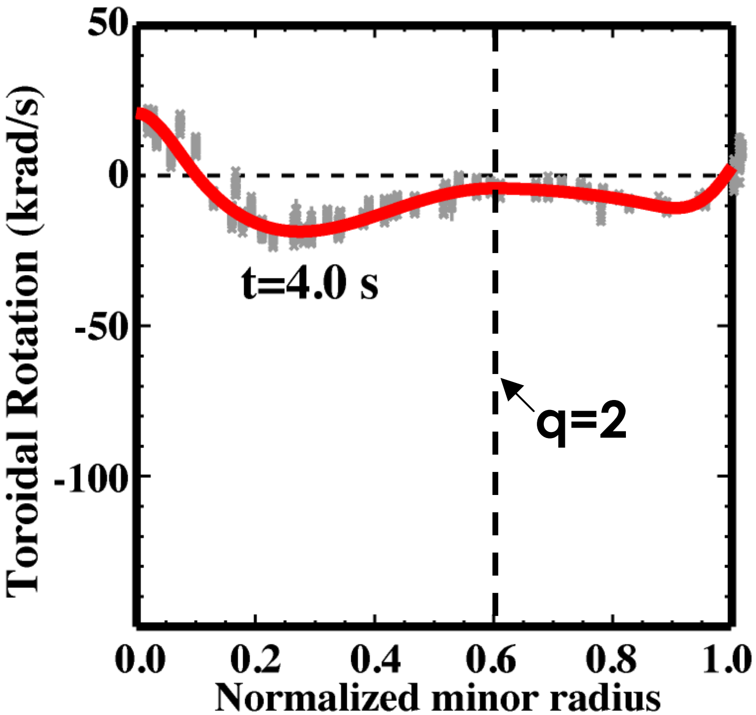


Pedestal collisionality ν^*_{ped}<0.1



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

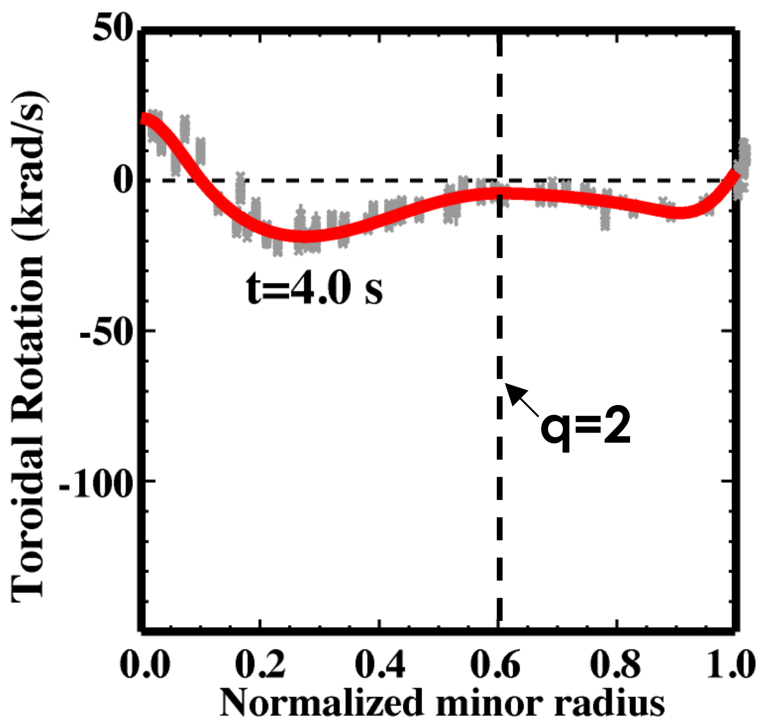


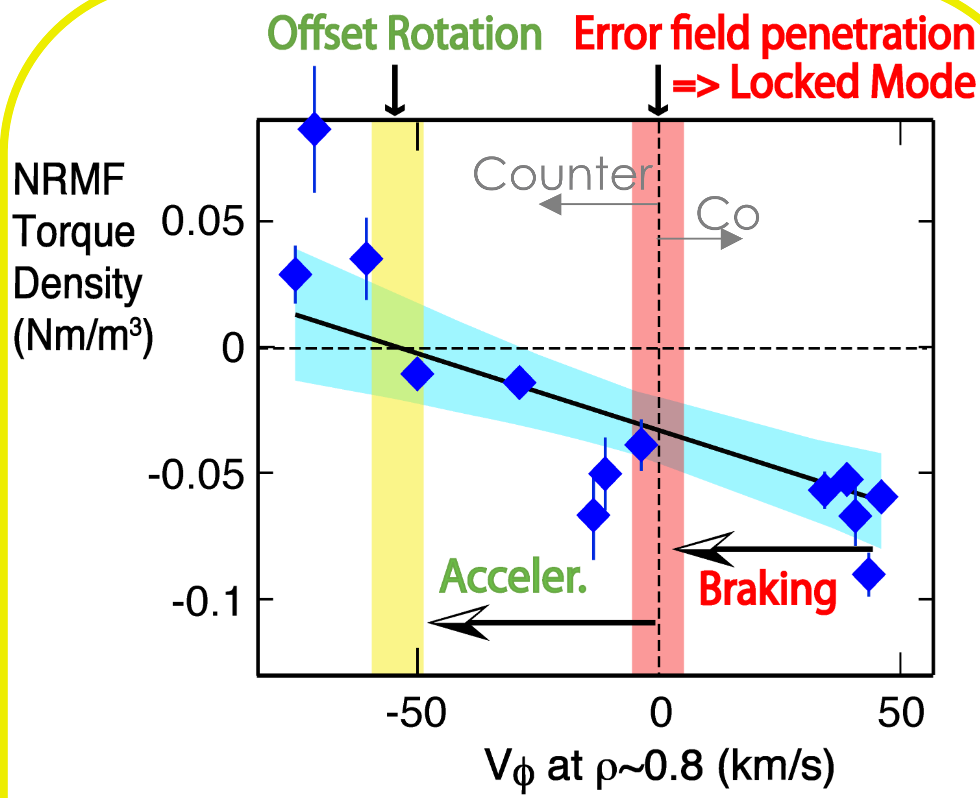
- May be case of "NTM suppression by large externally applied helical modes"

  Q. Yu, S. Gunter, and K. Lackner, PRL (2000)

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





- In counter-rotation, NRMF maintains rotation shielding

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

Static NRMFs Sustain Low Collisionality H-mode Plasma With No ELMs and Zero-Net NBI Torque

- NRMF torque replaces counter NBI torque in driving edge rotation shear
- No adverse impact of the NRMF on the energy confinement
- Improved resilience to locked modes, as expected from theory for counter-rotation

⇒ Possible path to QH-mode in burning plasmas, with little or no NBI torque

NEAR TERM RESEARCH

- Investigate how much co-I_p NBI can be used and still maintain QH-mode
- Investigate and improve models of NRMF torque