Neoclassical Toroidal Viscosity from Non-axisymmetric Magnetic Fields Allows ELM-free, Quiescent H-mode Operation in DIII-D Under Reactor-relevant Conditions

by

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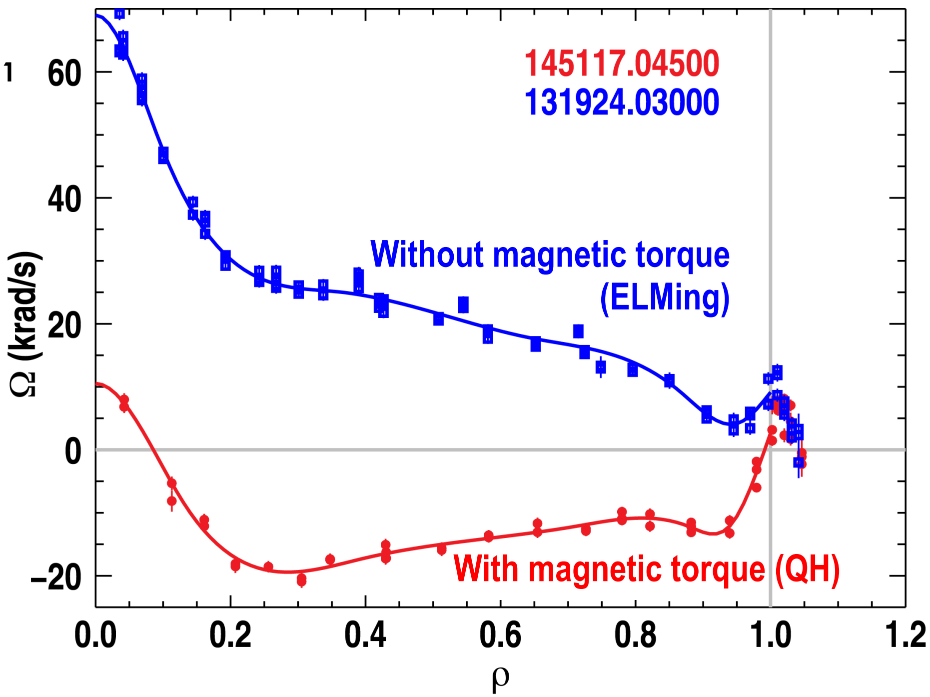

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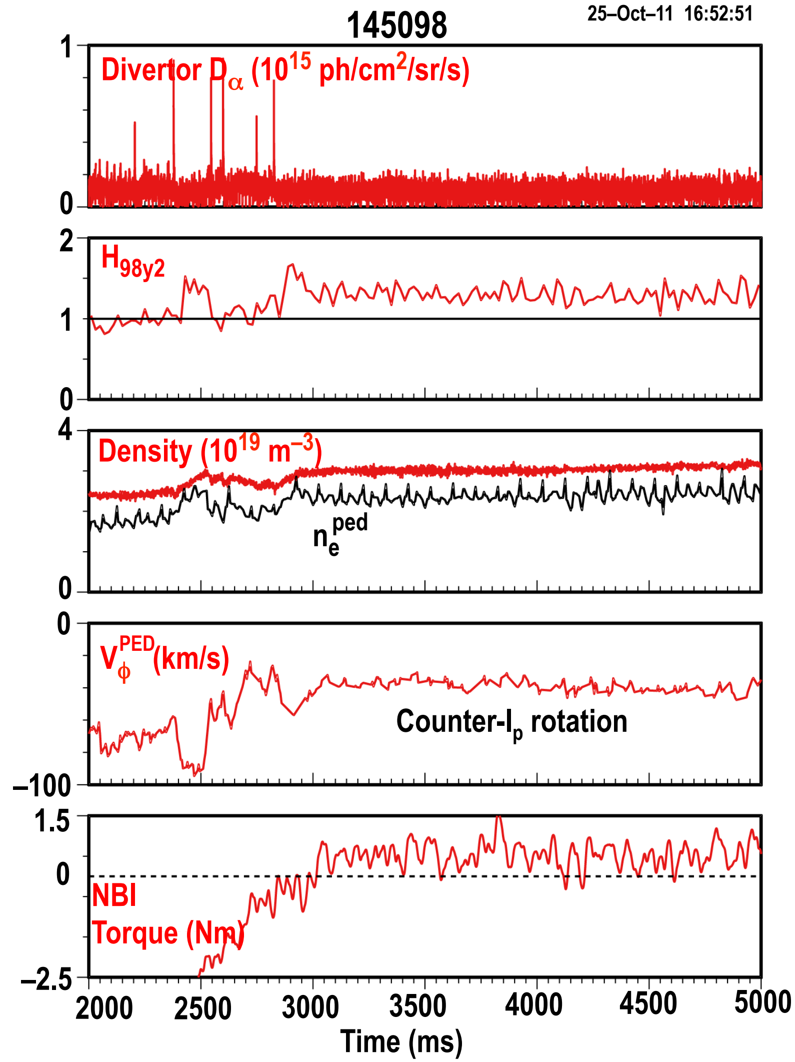
Quiescent H-mode Provides H-mode Confinement without ELMs at Low Injected Co-I_p Torque

- **H-mode confinement is required to meet fusion goals in future devices such as ITER**
  - Pulsed divertor heat loads from edge localized modes (ELMs) will rapidly ablate the divertor tiles
- **QH-mode operates without ELMs and has H-mode confinement levels (ITER $H_{98y2} > 1$)**
- **QH-mode requires significant shear in edge rotation**
  - Easiest to produce with neutral beam injection (NBI) in direction opposite to plasma current (counter-I_p)
  - Future devices want to use co-I_p NBI or no NBI
- **Sustained QH-mode with reactor relevant level of co-I_p NBI by using counter-I_p torque driven by non-resonant magnetic fields (NRMF)**
  - Counter-I_p torque sustains edge rotation shear
  - Physics is consistent with theory of neoclassical toroidal viscosity (NTV)



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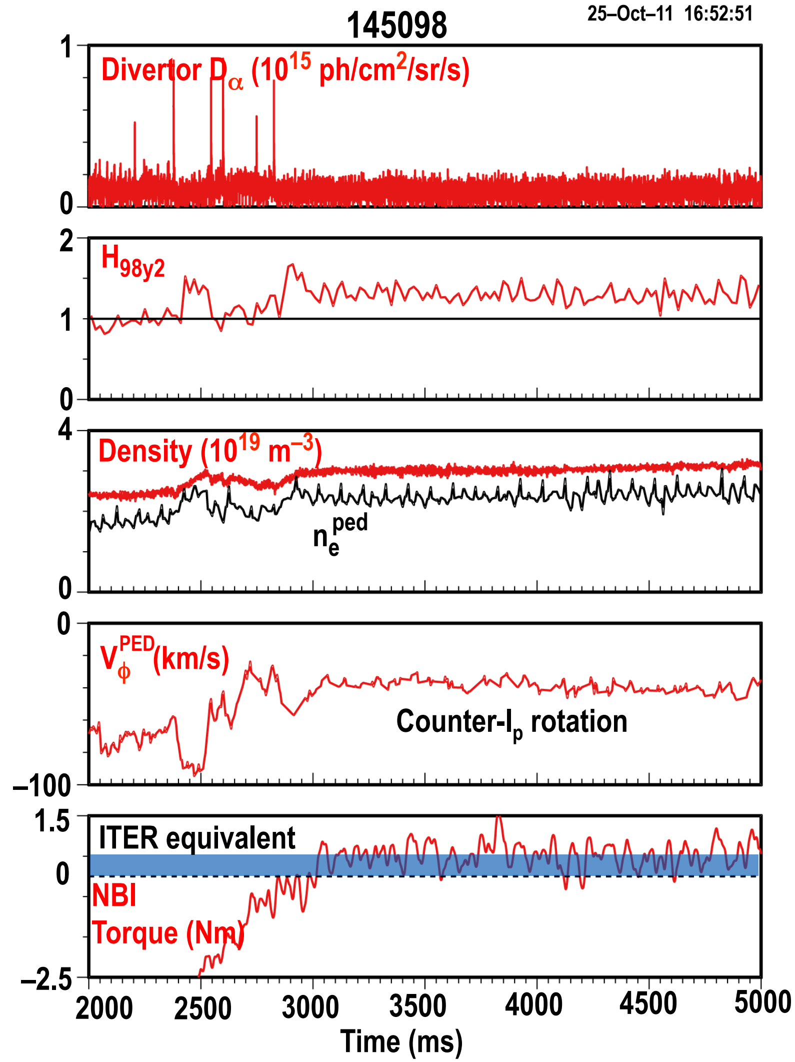
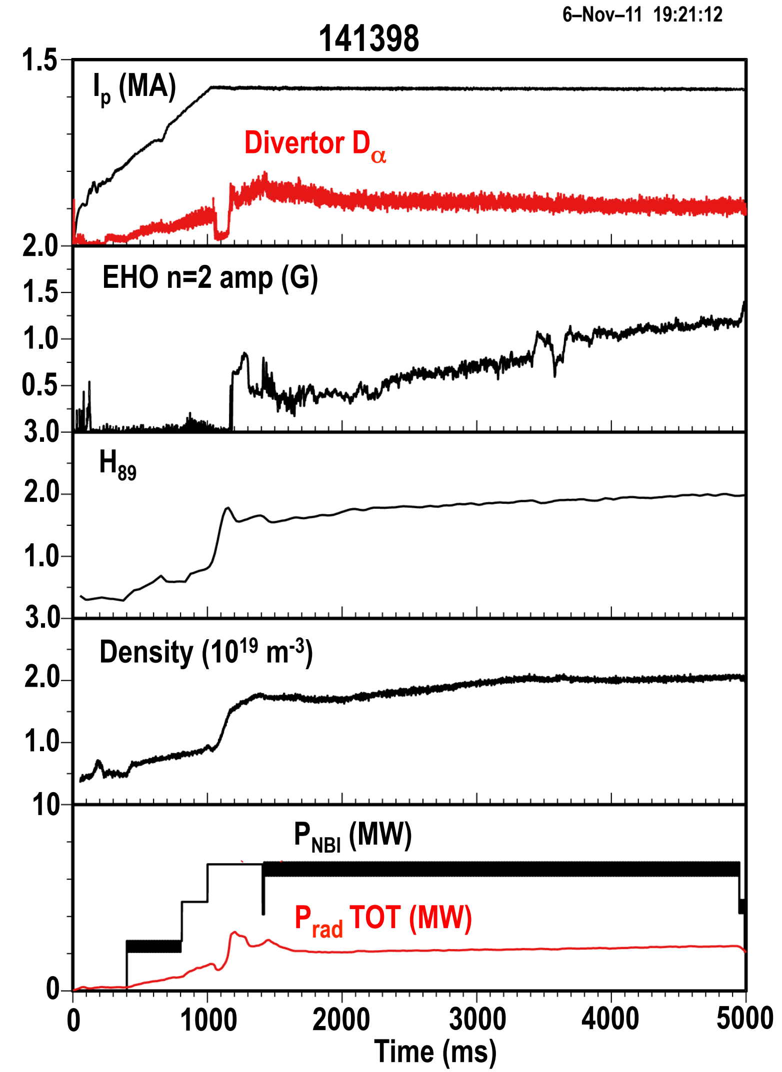


Outline

- Introduction to QH-mode
- NTV from nonaxisymmetric fields
- Co-I_p torque experiments
- Comparison with NTV theory
- Confinement improvement at low torque
- Extrapolation to ITER

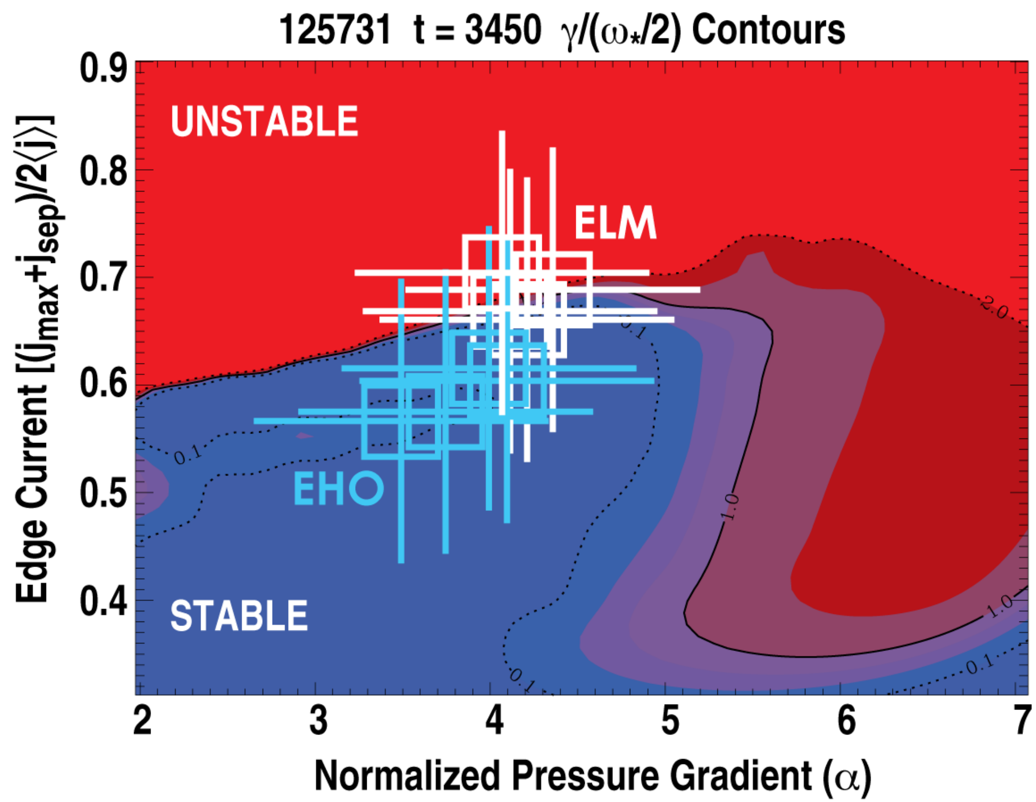
Quiescent H-modes are the Ideal H-mode Plasmas

- **QH-modes exhibit the H-mode confinement improvement and operate ELM-free with**
  - Controlled density and constant radiated power
  - Long duration (>4 s or 30 τ_E) limited only by hardware constraints
- **Additional edge particle transport provided by edge harmonic oscillation (EHO)**
  - Allows edge plasma to reach transport equilibrium with gradients below ELM stability limit
  - Time-averaged edge particle transport is faster than in ELMing H-mode
- **ELM stabilization does not require externally imposed non-axisymmetric fields**
- **QH-mode seen with injected power from 3 MW over 15 MW**
  - Maximum power limited by core beta limit
- **QH-mode discovered first in counter-injected discharges in DIII-D**
  - Subsequently seen in JT-60U, JET and ASDEX-U



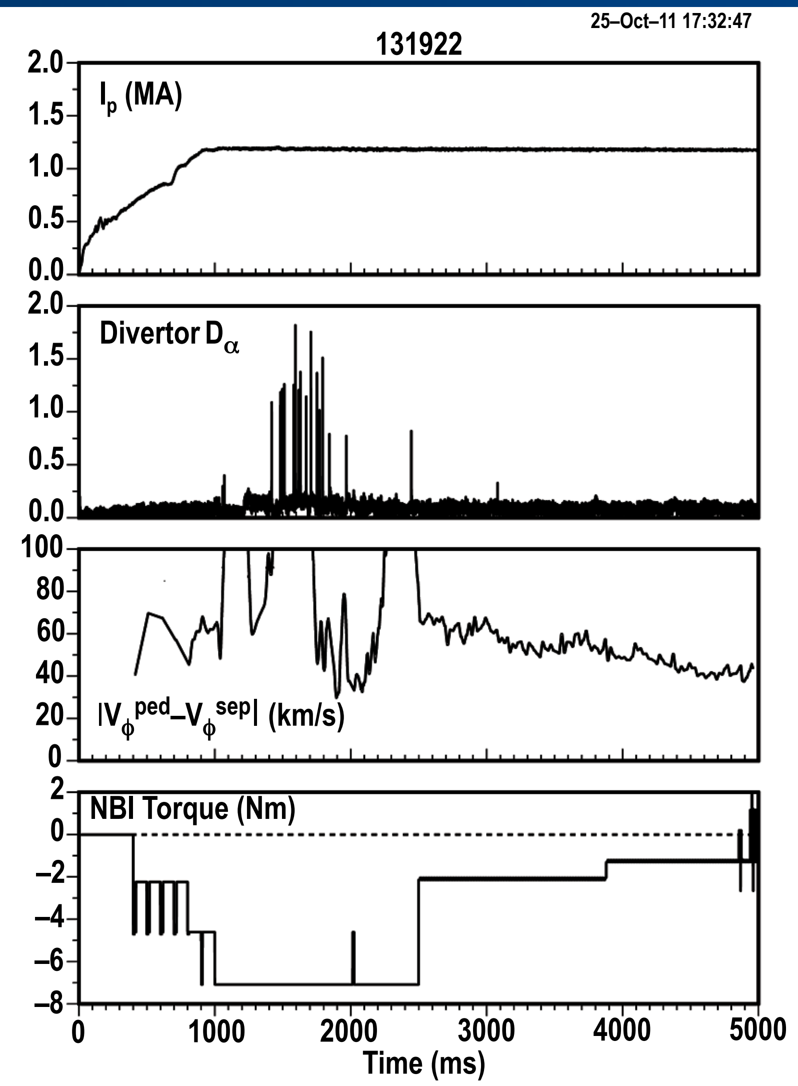
Edge Operating Points of QH-mode Discharges are Near but Below Peeling-ballooning Mode Stability Boundary

- Stability is calculated with ELITE code [P.B. Snyder et al., Phys Plasmas (2002)]
- Modes are driven unstable by edge pressure gradient and edge current
- QH-mode plasma with EHO operates near but below peeling stability boundary
- ELMing cases are closer to peeling boundary



QH-mode Operation in Future Devices Requires Technique to Maintain Shear in Edge Rotation at Small NBI Torque

- **Previous experimental work demonstrated importance of edge rotational shear [K.H Burrell et al., Phys. Rev. Lett. (2009)]**
- **Observations consistent with theory of EHO as low-n kink-peeling mode destabilized by rotational shear [P.B. Snyder et at., Nucl. Fusion (2007)]**
- **Without NRMF, as NBI torque goes from counter to co-I_p, magnitude of edge rotational shear decreases and ELMs return**



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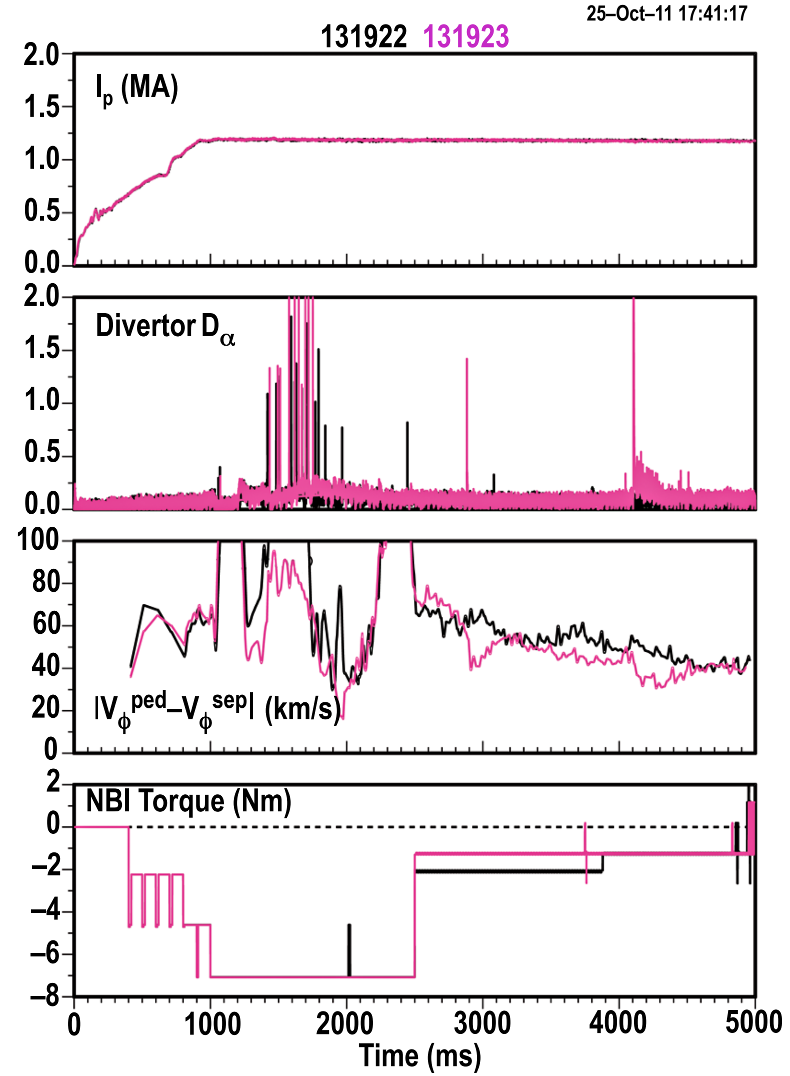

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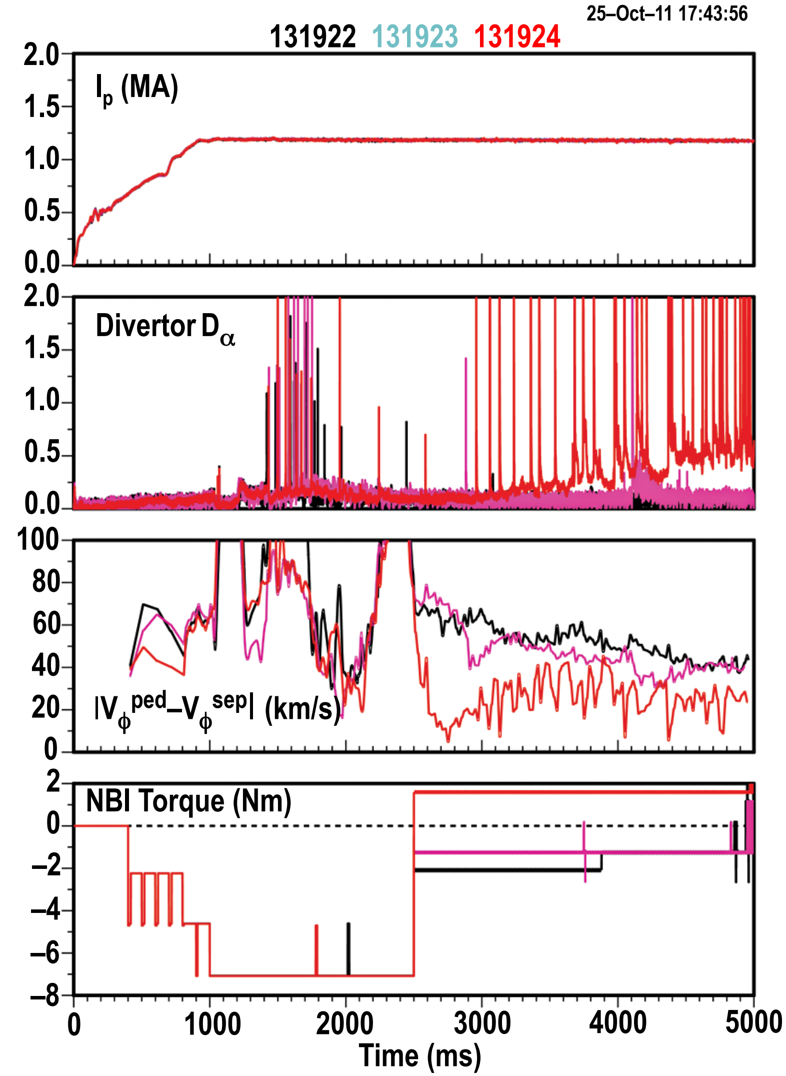
- Without NRMF, as NBI torque goes from counter to co-I_p, magnitude of edge rotational shear decreases and ELMs return
- Alternate means needed to maintain edge rotational shear at low co-I_p NBI torque



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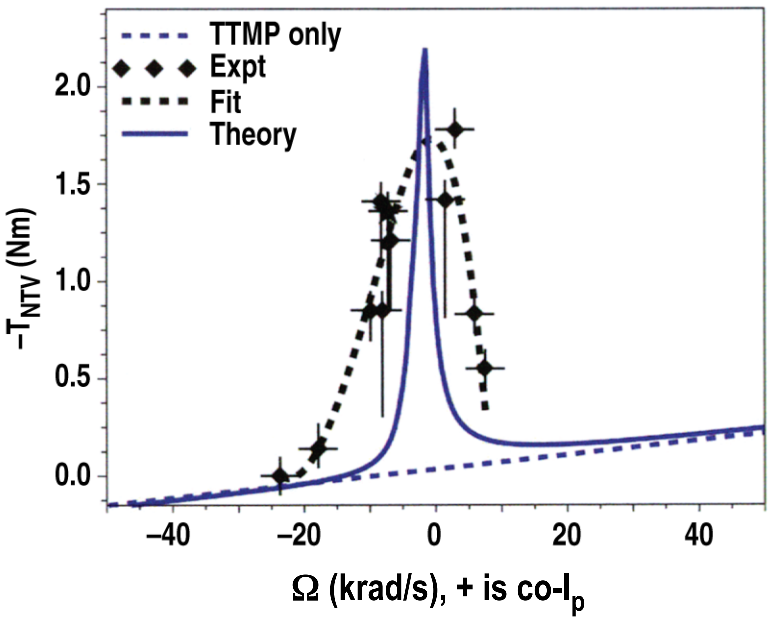
Non-axisymmetric Fields can Generate Significant Torques through Neoclassical Toroidal Viscosity

- **Small ($\delta B/B_0 \sim 10^{-3}$) non-resonant magnetic fields (NRMF) generate neoclassical toroidal viscous torque on bulk plasma of the form**

$$\left.\frac{\partial\langle\rho_m R^2\Omega\rangle}{\partial t}\right|_{NTV} = -\rho_m \mu_{||}(\Omega, \nu_i)\left(\frac{\delta B_{3D}}{B_0}\right)^2\left(\langle R^2\Omega\rangle - \langle R^2\Omega_{NTV}\rangle\right)$$

which is absent in perfect axisymmetry

- **Neoclassical offset velocity $V_\phi^{NTV} = R\Omega_{NTV}$ is in the counter I_p direction**
  - Nonzero offset has been seen experimentally [A.M. Garofalo et al., Phys. Rev. Lett. (2008)]
- **NTV torque is in the counter-I_p direction for $V_\phi > V_\phi^{NTV}$**
- **$\mu_{||}$ (Ω ν_i) has a strong local peak near $\Omega = 0$**
  - Peak has been seen experimentally [A.J. Cole et al., Phys. Rev. Lett. (2011)]



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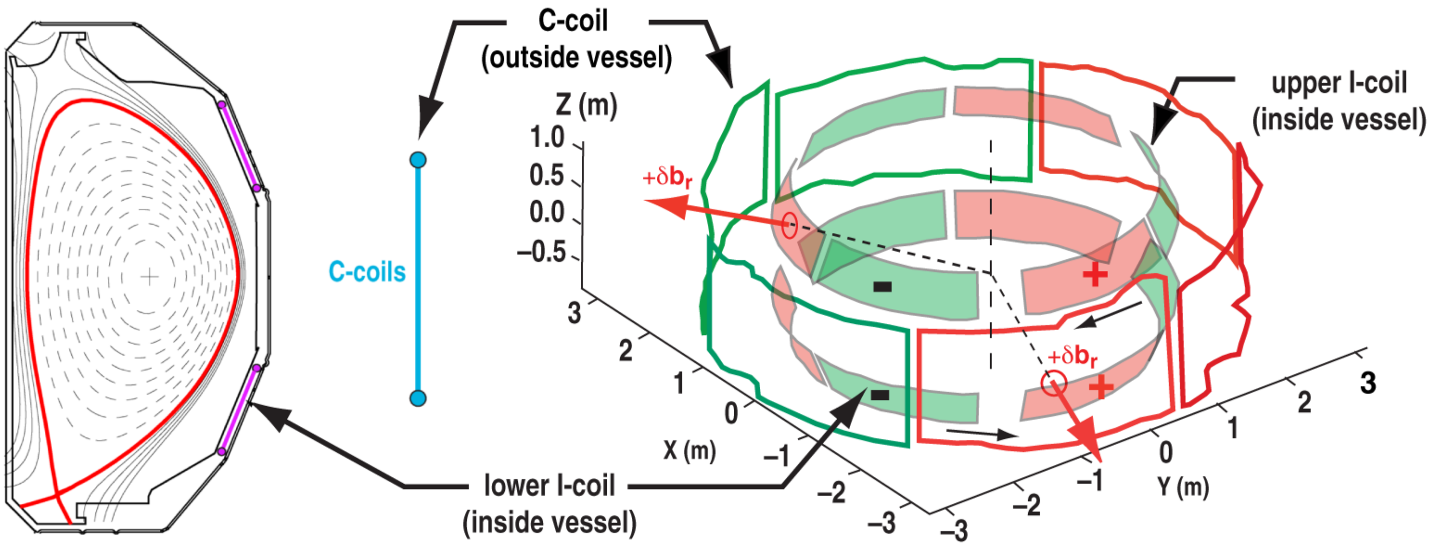
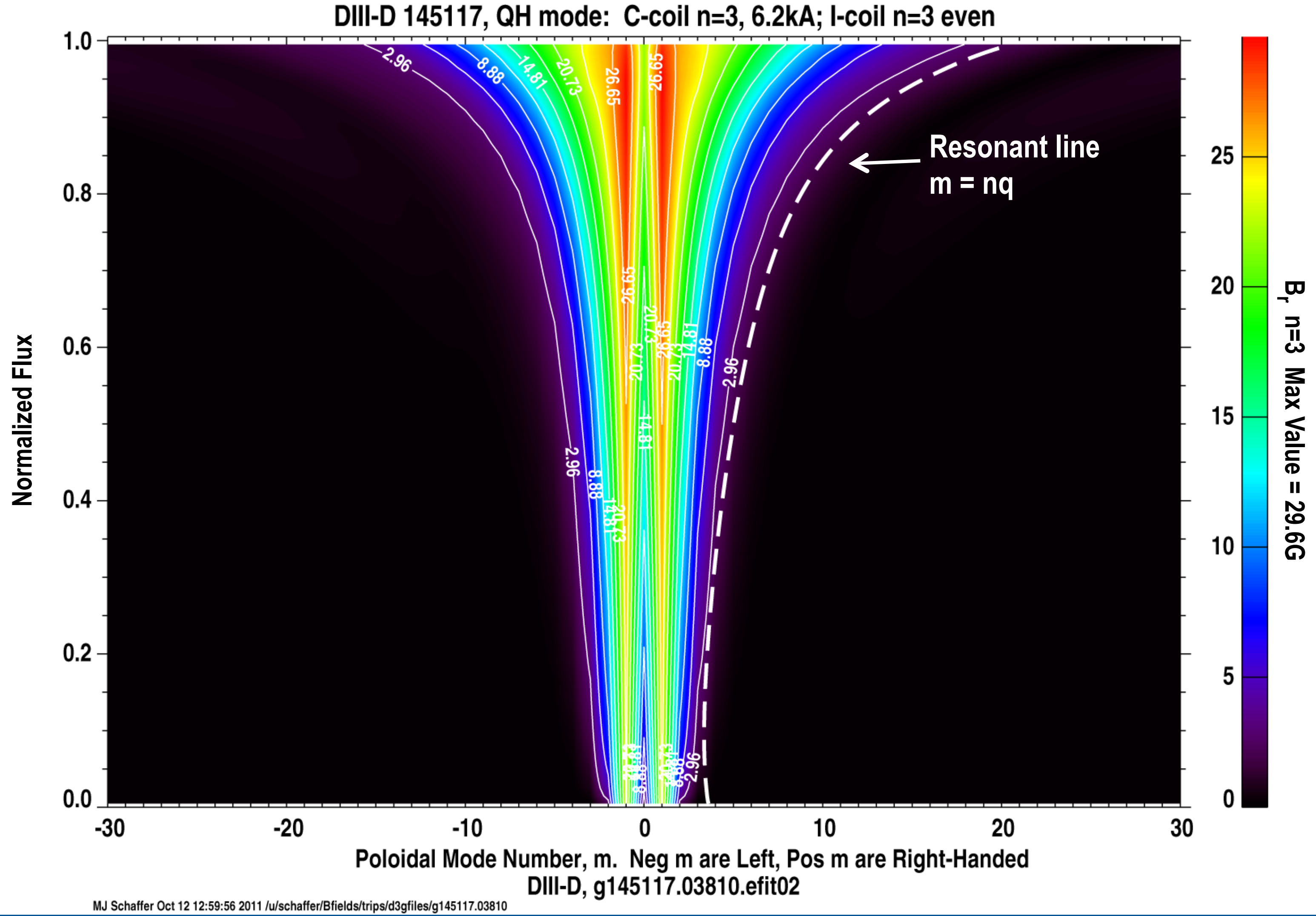
Non-axisymmetric Coils on DIII-D Allow Creation of Magnetic Perturbations



n=3 I-coil and n=1 C-coil configuration
(with up-down symmetric, even parity, I-coil)

- **Two sets of non-axisymmetric coils can be used to correct intrinsic error fields and apply magnetic perturbations**
- **For experiments in 2011, C-coil was used to create even parity n=3 field**
- **I-coil was configured for intrinsic error field correction and to apply small even parity n=3 field in some cases**

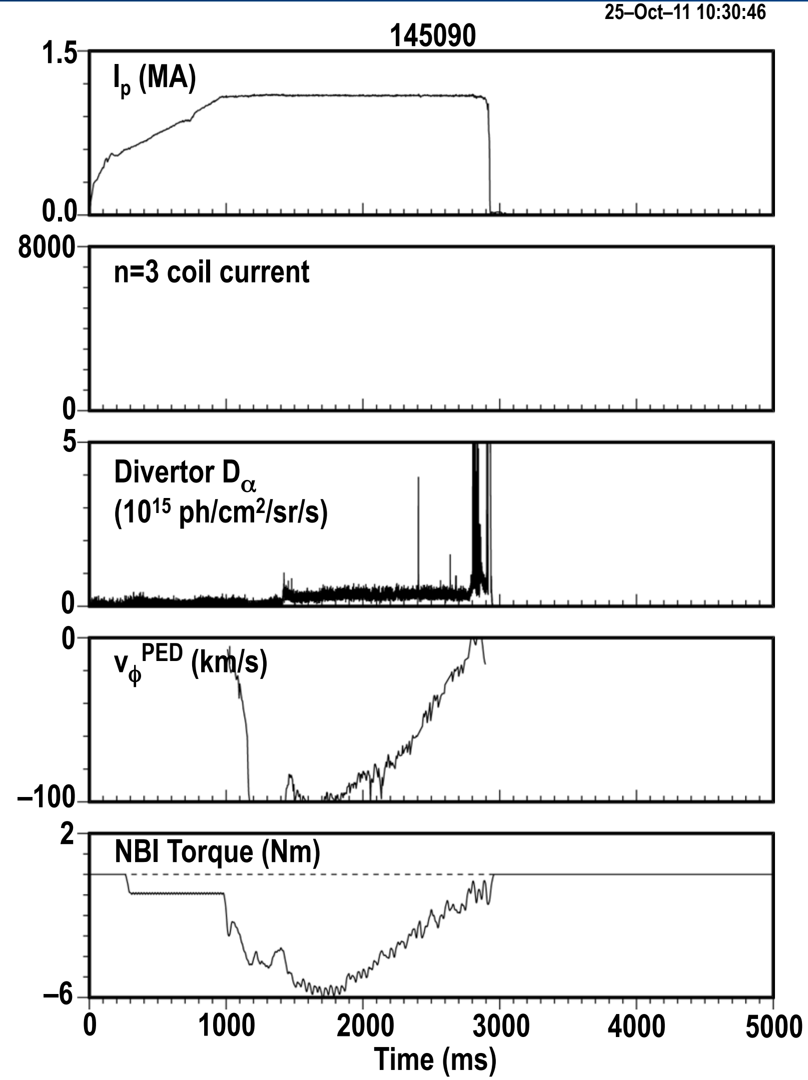
Non-axisymmetric Fields used in Present Experiment are Primarily Nonresonant



Addition of NTV Torque Allows QH-mode Operation with Greater co-I_p NBI Torque

- **Gradually changing NBI torque to greater co-I_p value allows testing of torque limits**

- **Shot without n=3 NRMF has lower rotation speed and, ultimately, disrupts due to locked mode**



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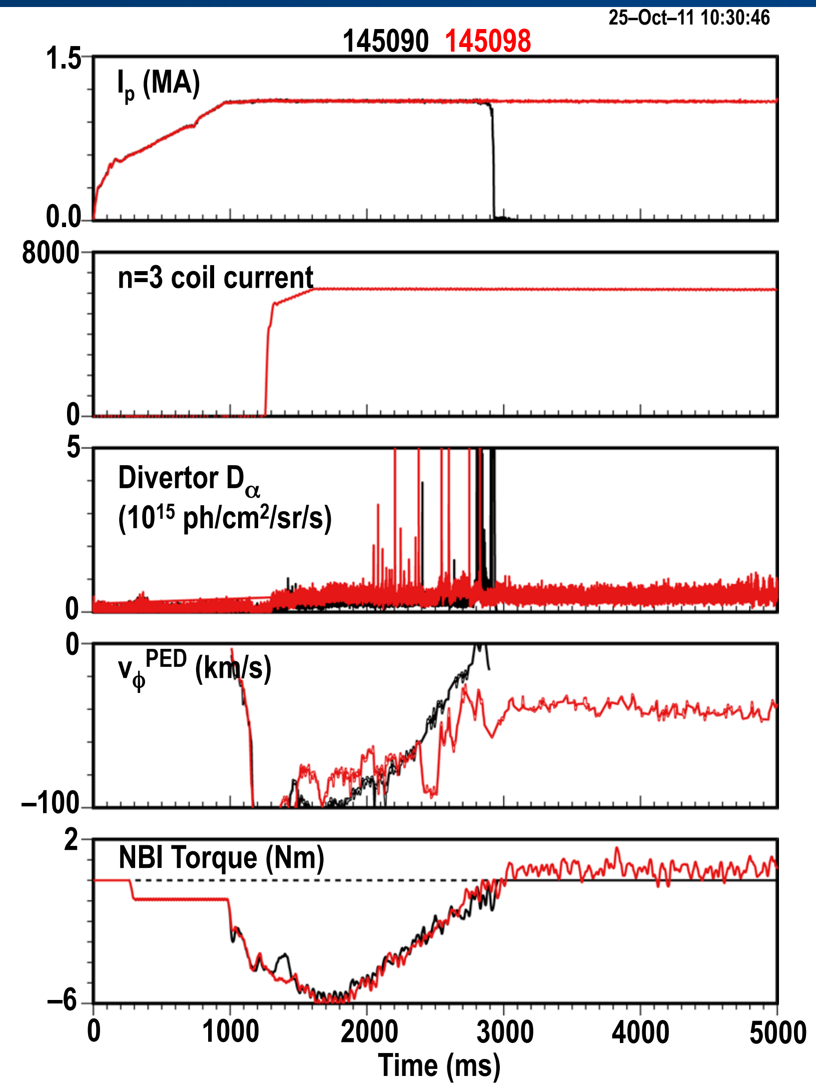
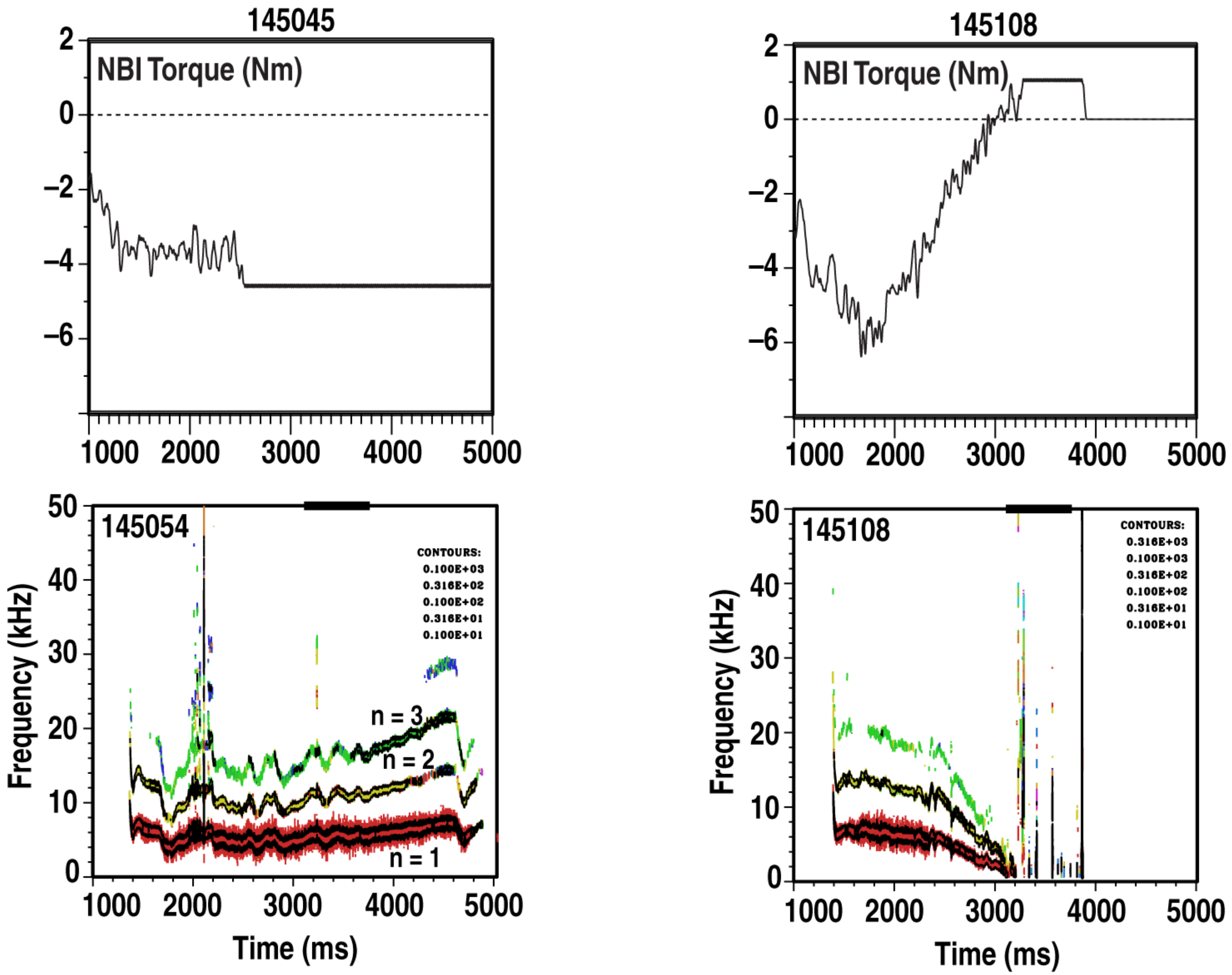
- **With n=3 NRMF, discharge maintains QH-mode with counter-I_p rotation even though NBI torque is co-I_p**

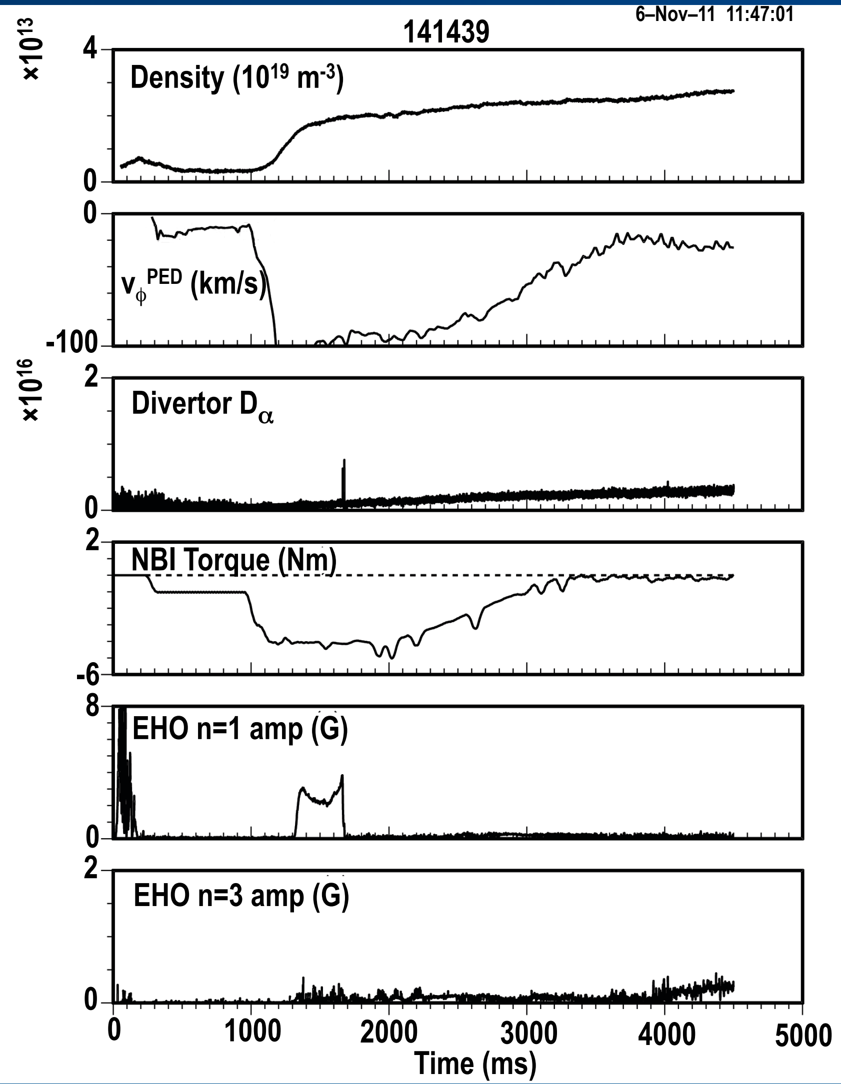


Even with NRMF, Torque from n=1 EHO causes Locking During Torque Rampdown



Achieving QH-mode with Counter-I_p Rotation and co-I_p NBI Torque Requires Suppression of n=1 Component of the EHO

- **In experiments in 2008-2010, EHO had toroidal mode number n=3**
  - EHO flipped from n=1 to n=3 when NRMF was turned on
  - These experiments used C-coil for error field correction and I-coil to produce odd parity n=3 NRMF



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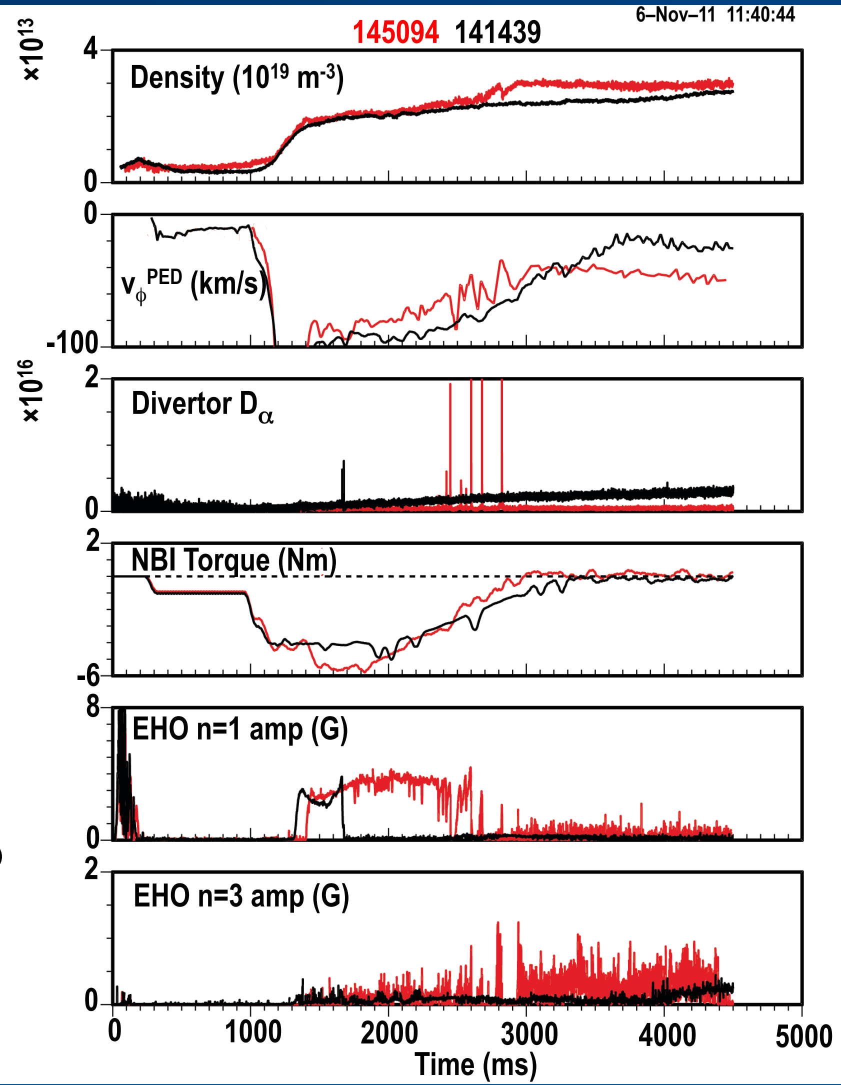
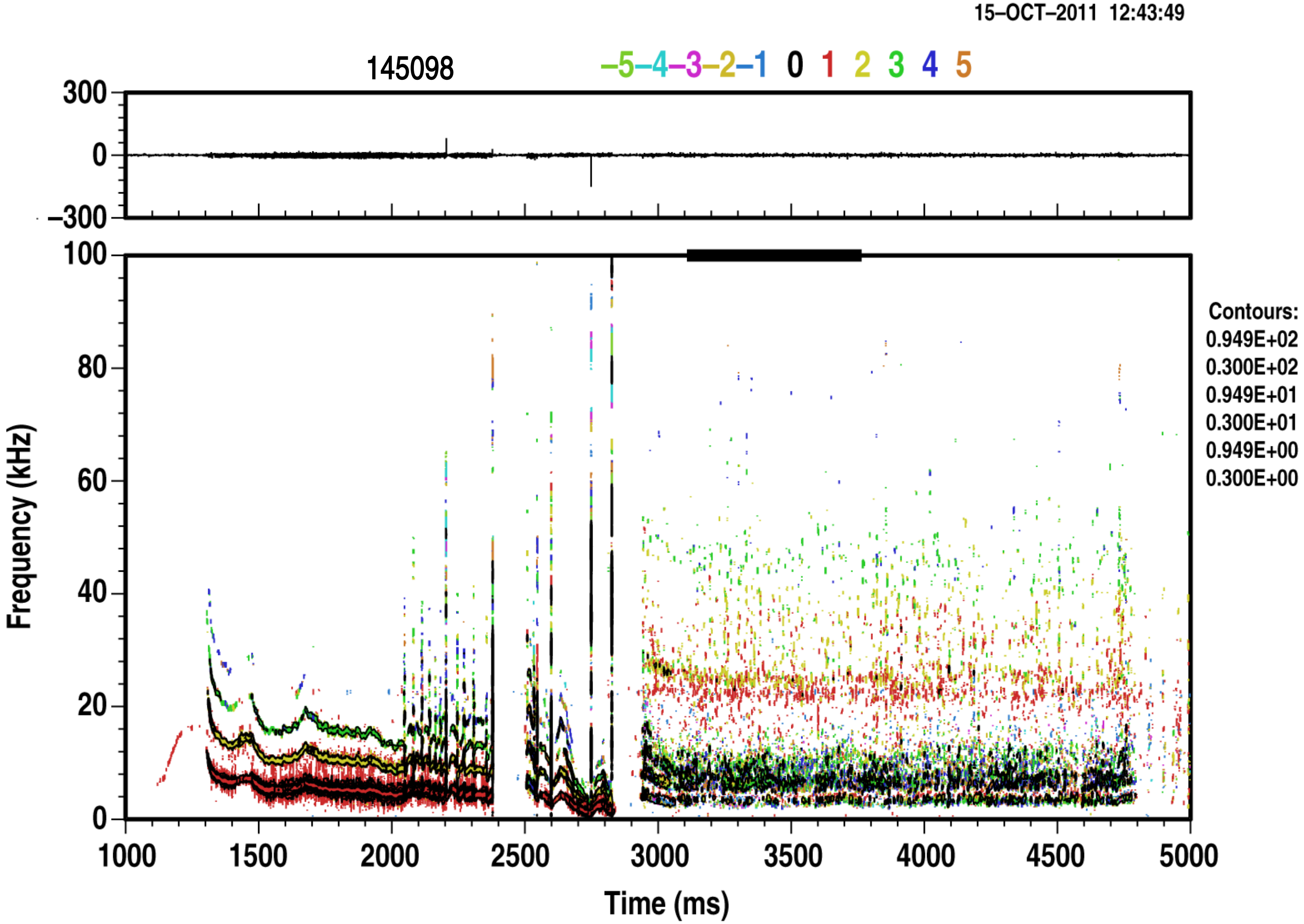
  - EHO flipped from n=1 to n=3 when NRMF was turned on
  - These experiments used C-coil for error field correction and I-coil to produce odd parity n=3 NRMF
- **In 2011 experiments, NRMF did not change EHO toroidal mode number**
  - n=3 from I-coil and C-coil has even parity (up-down symmetric)
- **In 2011 experiments, eliminated n=1 EHO later in shot by exploiting previous observation that EHO changes from coherent mode to broadband MHD as density increases**

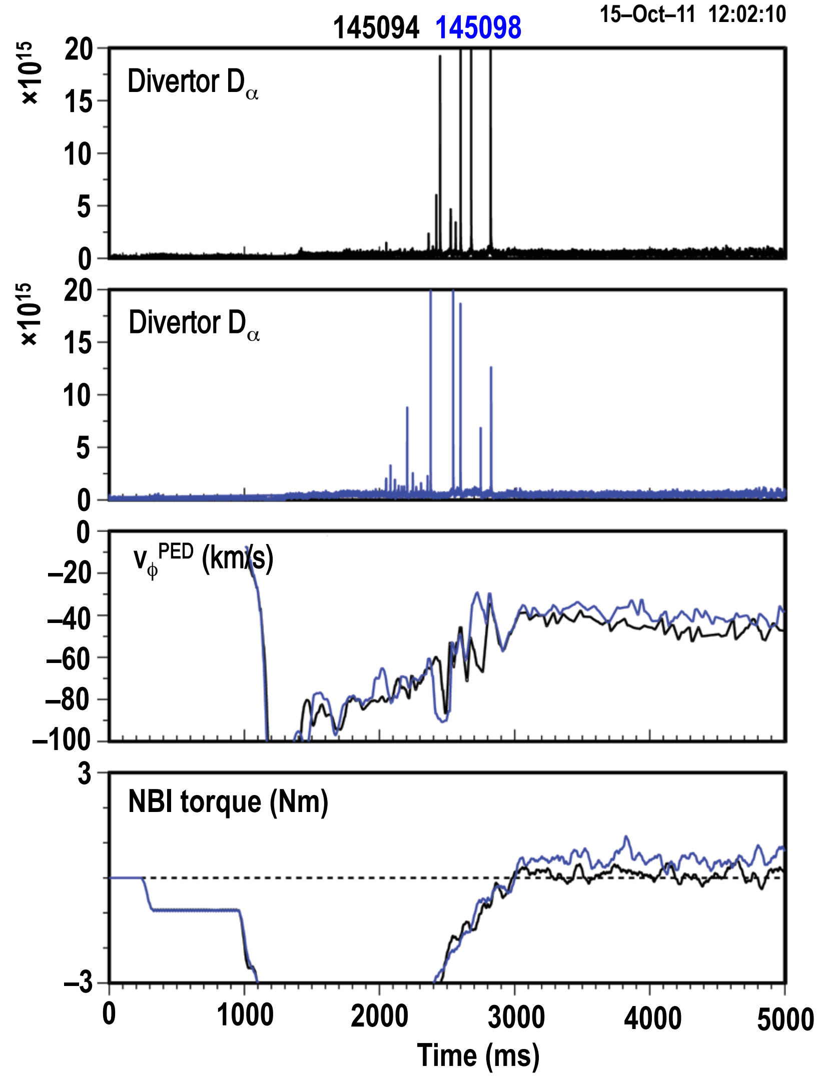


EHO Changes from Coherent Mode to Broadband MHD as Rotation Decreases and Density Increases



QH-mode with Counter-I_p Rotation Maintained with co-I_p NBI Torque up to about 1-1.2 Nm

- Raise NBI torque level from shot to shot to determine co-I_p limit
- Digital plasma control system adjusts neutral beams to maintain constant β_N = 2.1 while torque is ramped from counter-I_p to co-I_p
- Pedestal rotation remains counter-I_p even with co-I_p NBI torque



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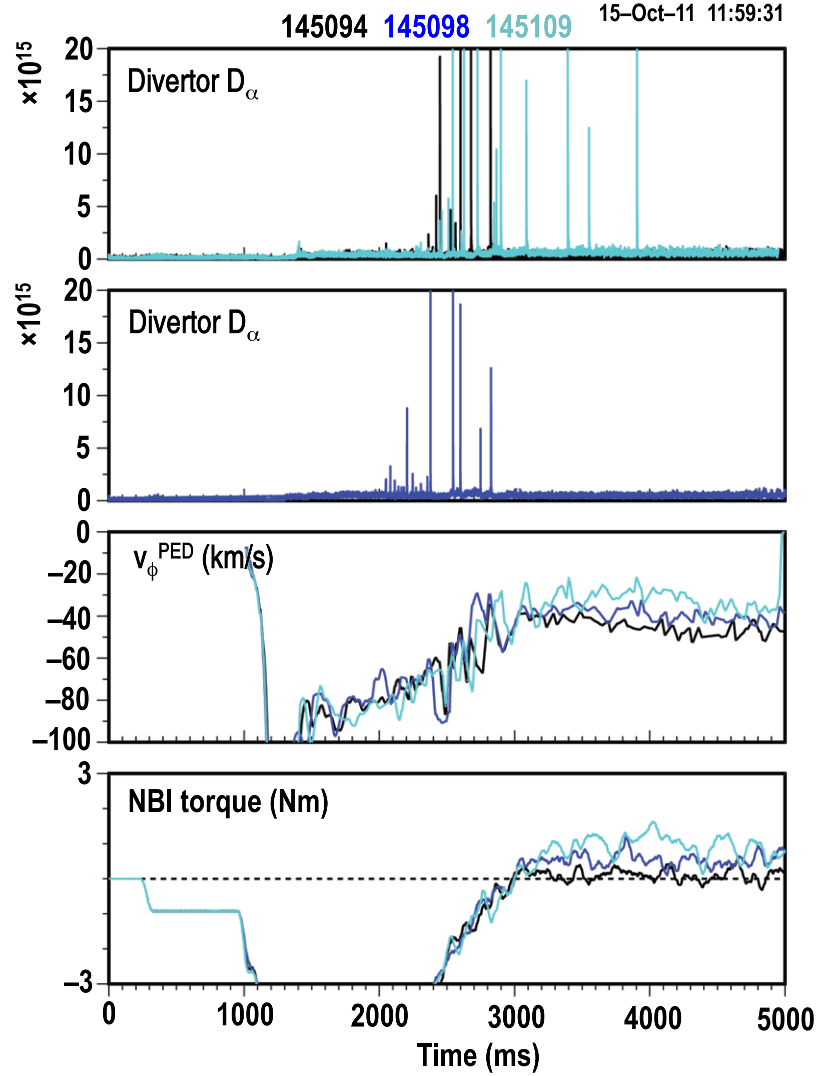

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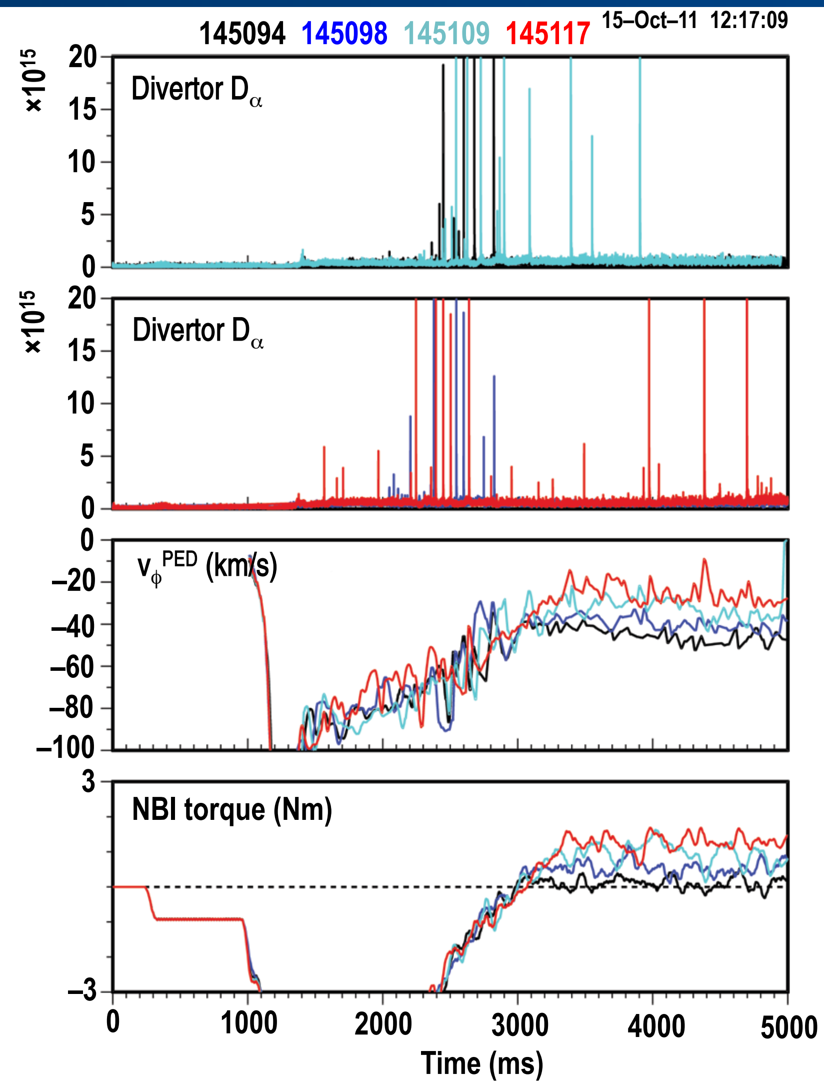
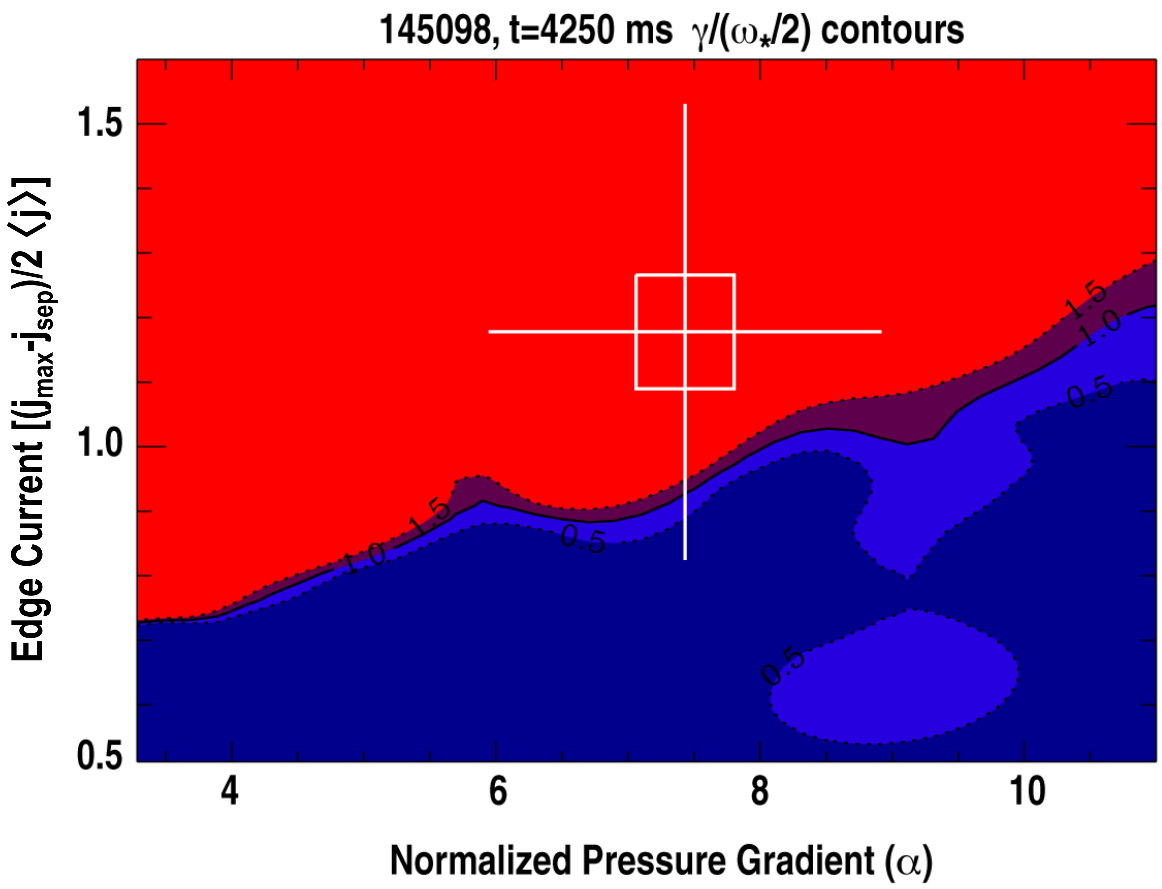


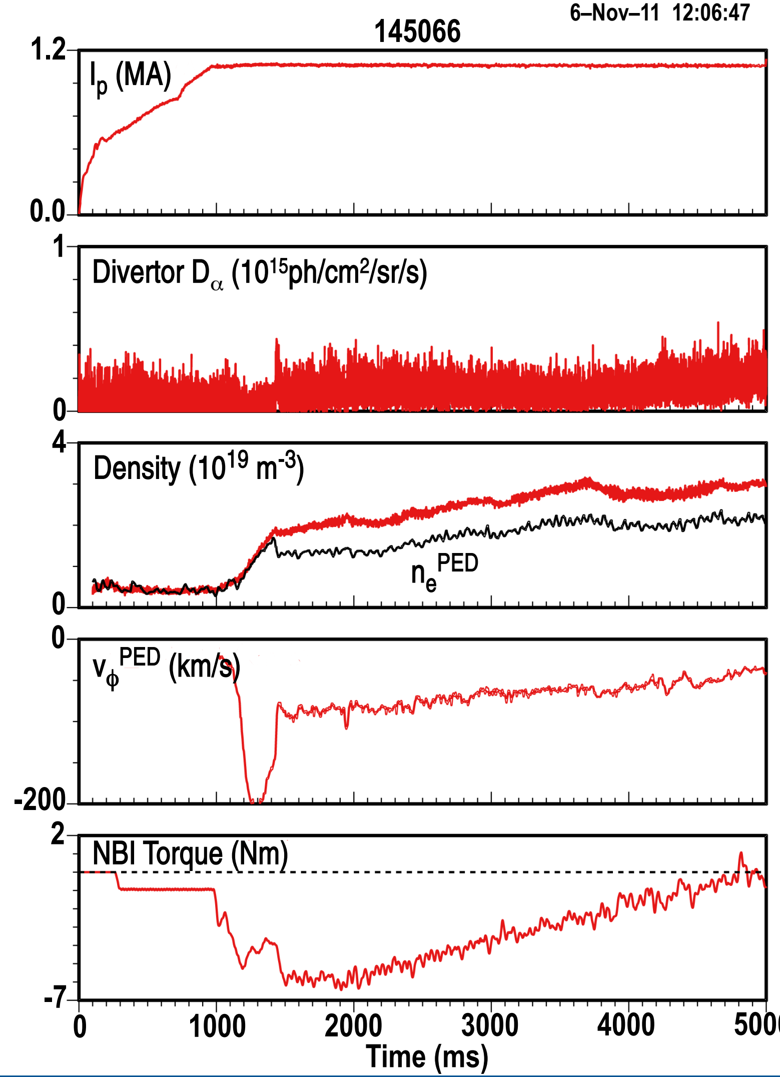
QH-modes with Non-Resonant Magnetic Fields Operate Near Peeling Stability Boundary

- **Operating point near peeling boundary is similar with and without NRMF**

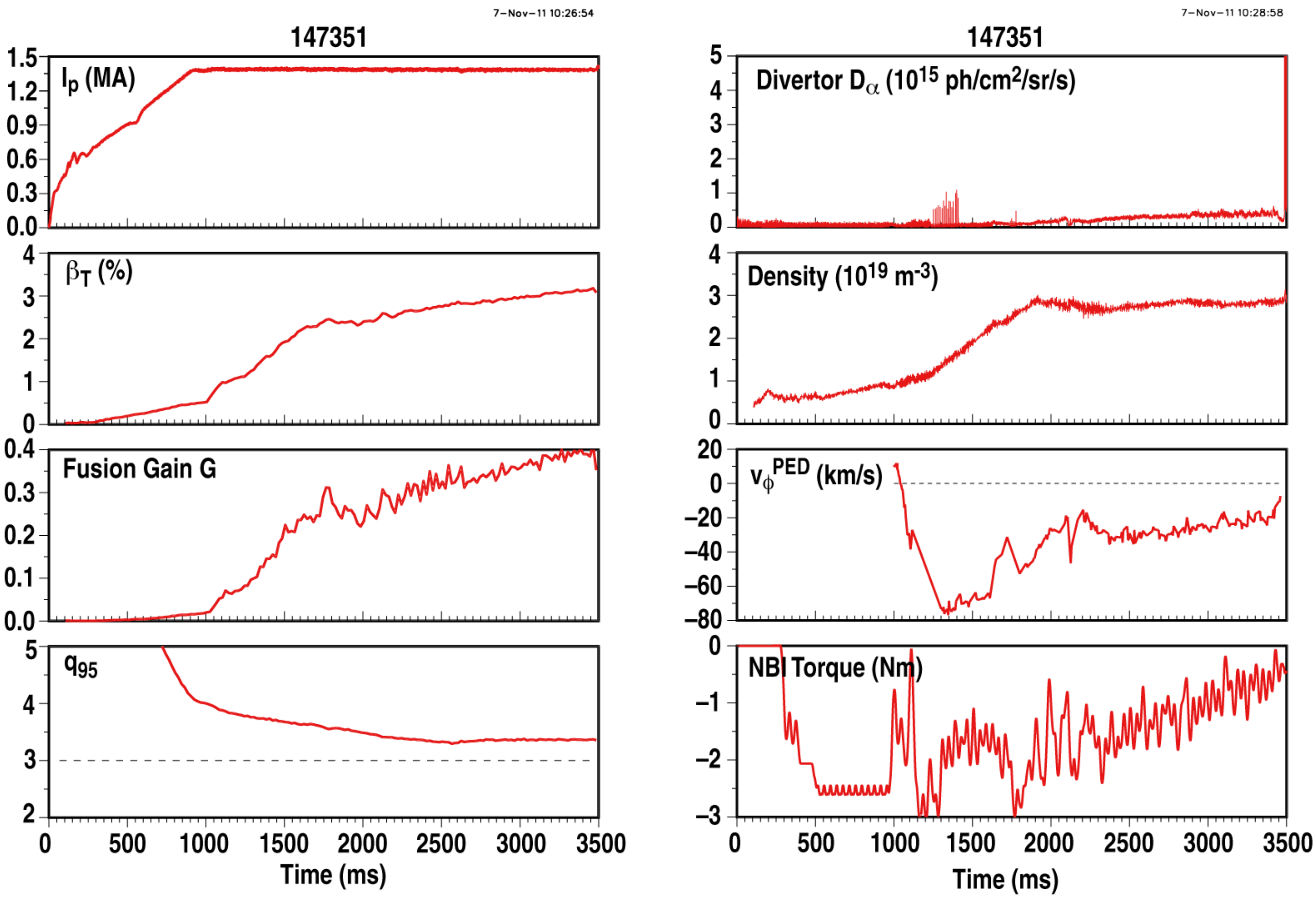


Preliminary Experiment Investigated QH-mode using NTV Torque Produced only by Coil Outside Toroidal Field Coil

- **Shot runs with n=3 field from C-coil only**
  - C-coil located outside toroidal coil
- **Counter-I_p rotation obtained with zero net NBI torque**
- **Co-I_p NBI torque limit not yet established for this coil configuration**



Initial Investigation of Low q, Low NBI Torque QH-mode has Fusion Gain Reaching ITER Design Value G = 0.4



- $G = \beta_N H_{89}/q_{95}^2$
- NRMF from coil outside toroidal coil (C-coil)
- $q_{95} = 3.4$

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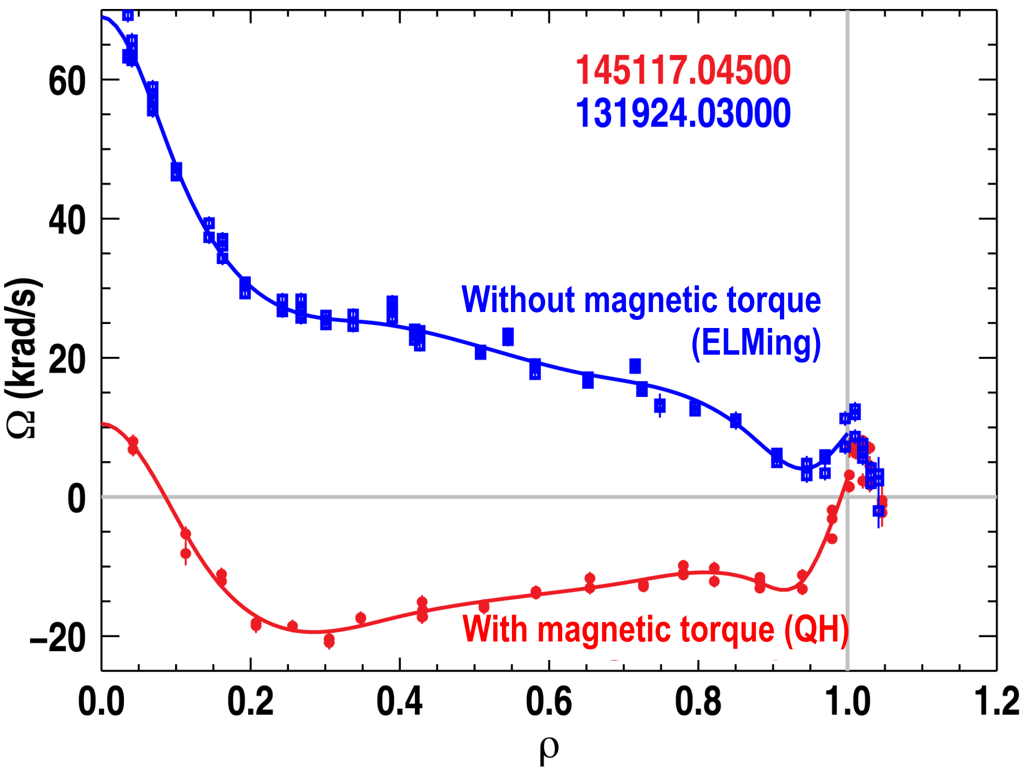
Radial Profiles of Rotation with and Without Torque from NRMF Show Clear Effect of n=3 Field

- **With NRMF, counter-I_p rotation and strong edge rotational shear maintained even for co-I_p NBI torque**
  - QH-mode needs edge rotational shear
- **Without NRMF, co-I_p NBI torque yields co-I_p rotation**
- **Comparison made at similar NBI torque (~1.4 Nm) and density (~3.6 x $10^{19}m^{-3}$)**

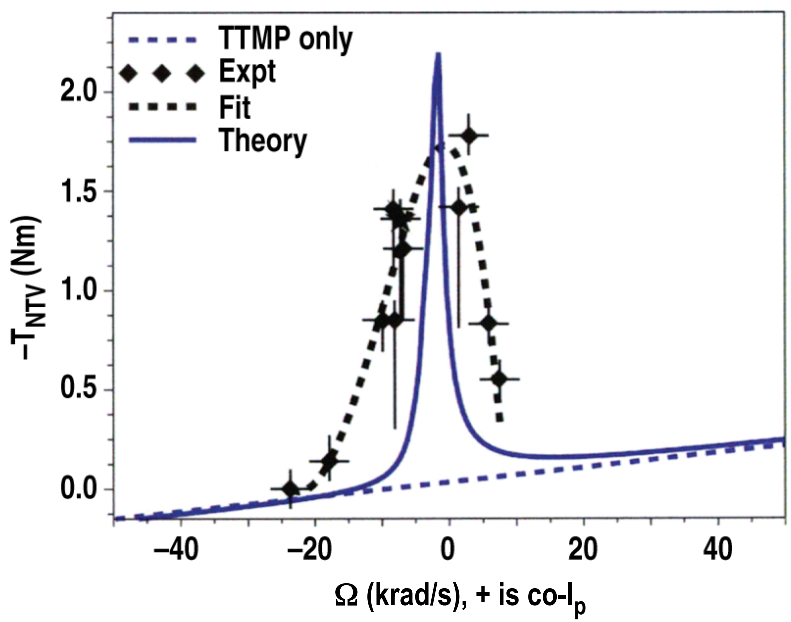


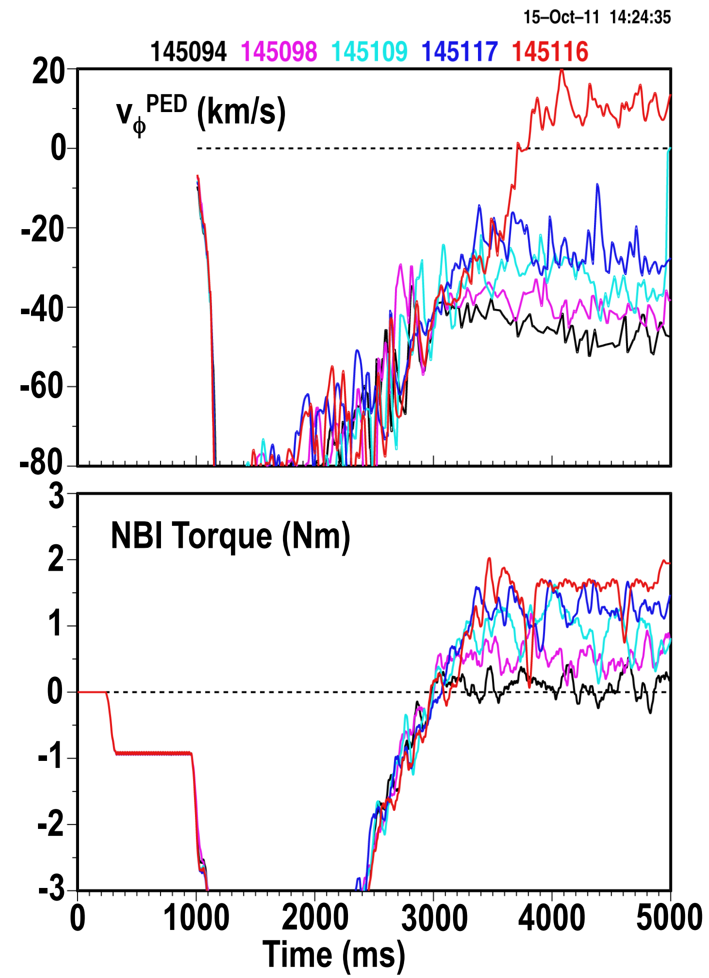
Quantitative NTV Torque Calculations use IPEC+NTV Code

- **Most difficult part of evaluating NTV torque is calculation of perturbed field in the plasma**
- **IPEC code evaluates $\delta B/B_0$**
  – [J.-K. Park et al., Phys. Plasmas (2007)]
- **Generalized neoclassical model used to evaluate NTV torque**
  – [J.-K. Park et al., Phys. Rev. Lett. (2009)]

Rotation Bifurcation as NBI Torque Increases is Qualitatively Consistent with Theory of NTV Torque

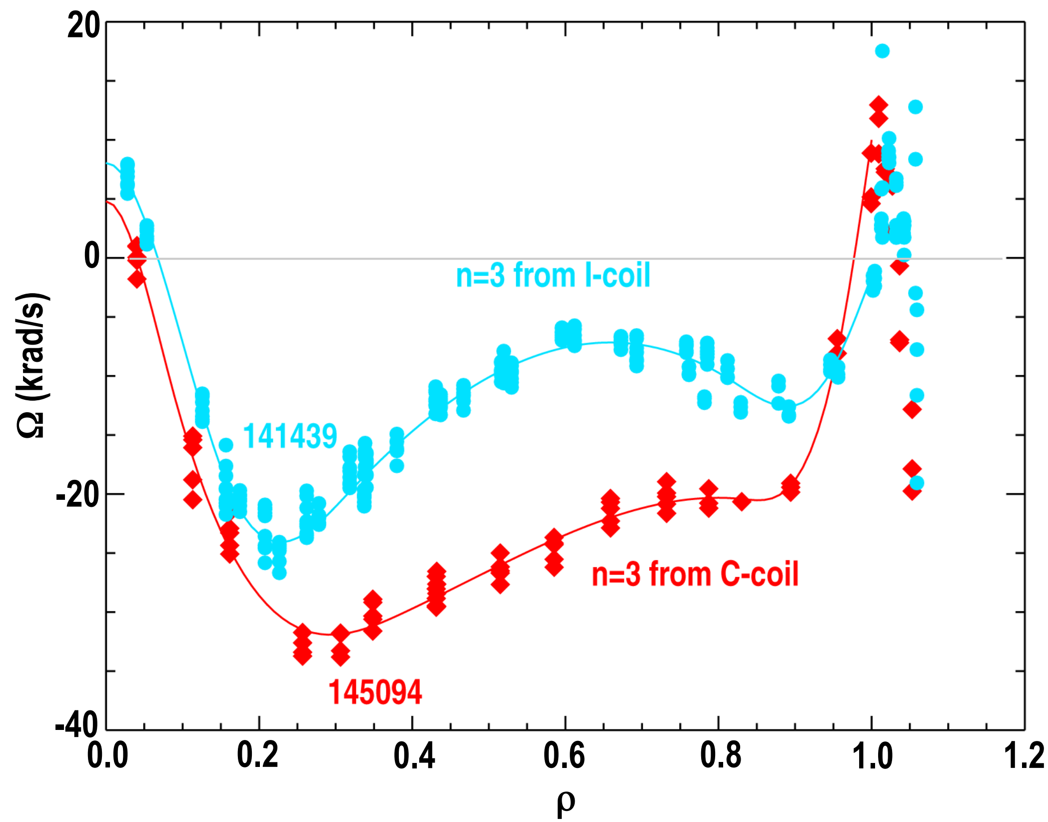
- **Theory predicts rotation speed should jump when sum of other torques exceeds peak counter-I_p NTV torque**
- **IPEC+NTV calculates peak NTV torque ~3 Nm**





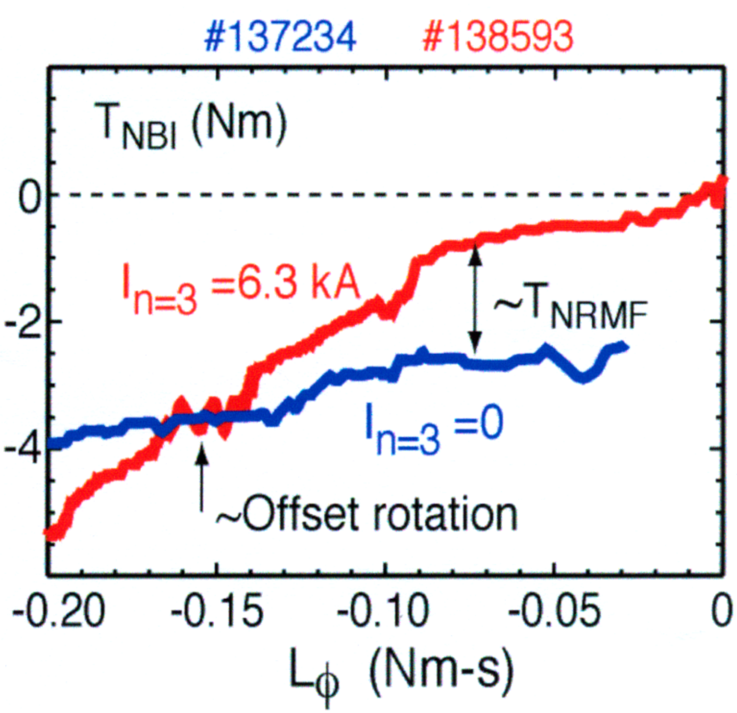
Larger Counter-I_p Rotation with n=3 NRMF from C-coil Qualitatively Consistent with Prediction from NTV Theory

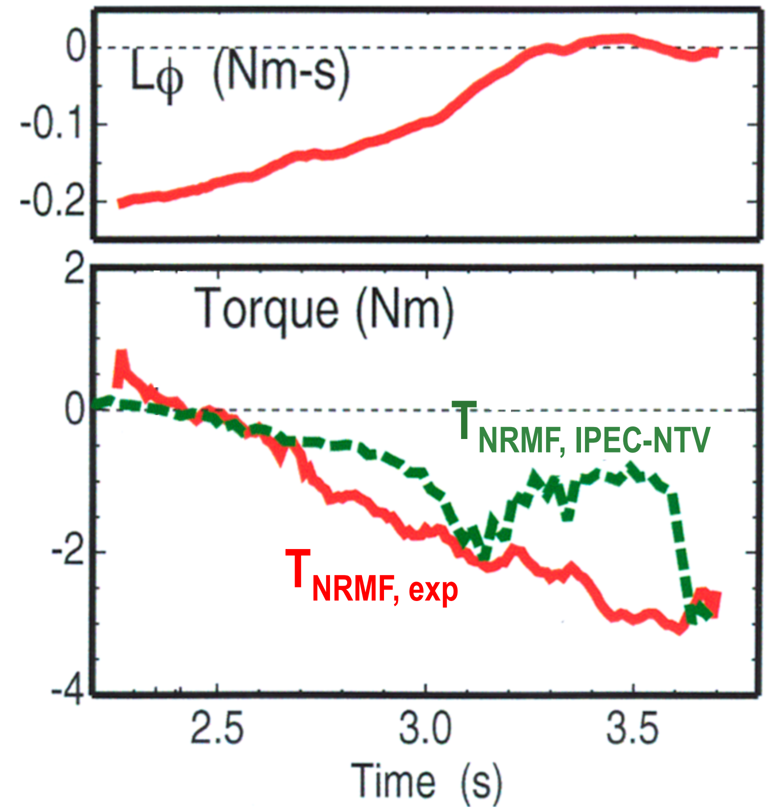
- Shots both have zero net NBI torque and similar density
- Shot with greater counter-I_p rotation has dominant n=3 NRMF from C-coil while other shot has dominant n=3 NRMF from I-coil
- Greater counter-I_p rotation for same NBI torque implies greater counter-I_p torque from NTV
- IPEC+NTV code predicts that n=3 from C-coil produces more NTV torque



Theory Calculations of NRMF Torque (IPEC+NTV) Consistent with Experimental Observations

- **Prediction of NRMF torque evolution as toroidal rotation is slowed down is compared with transport analysis of experimental data**





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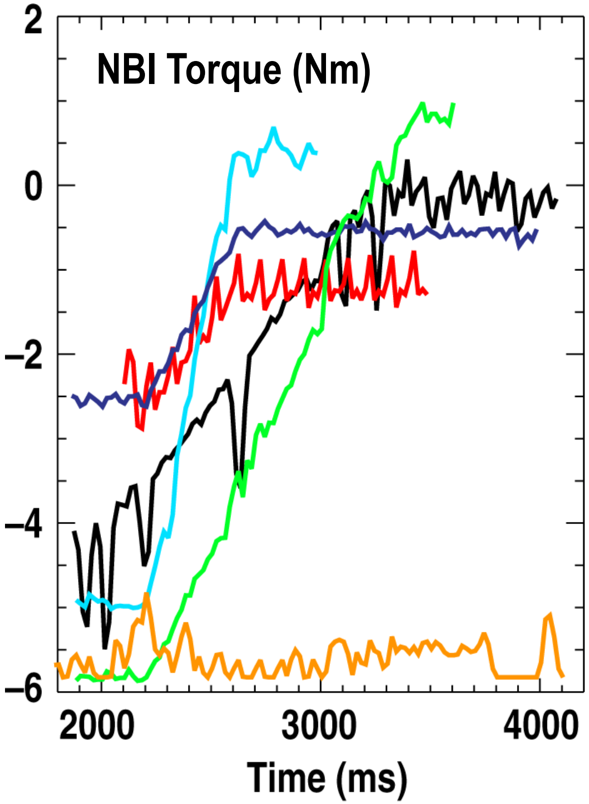
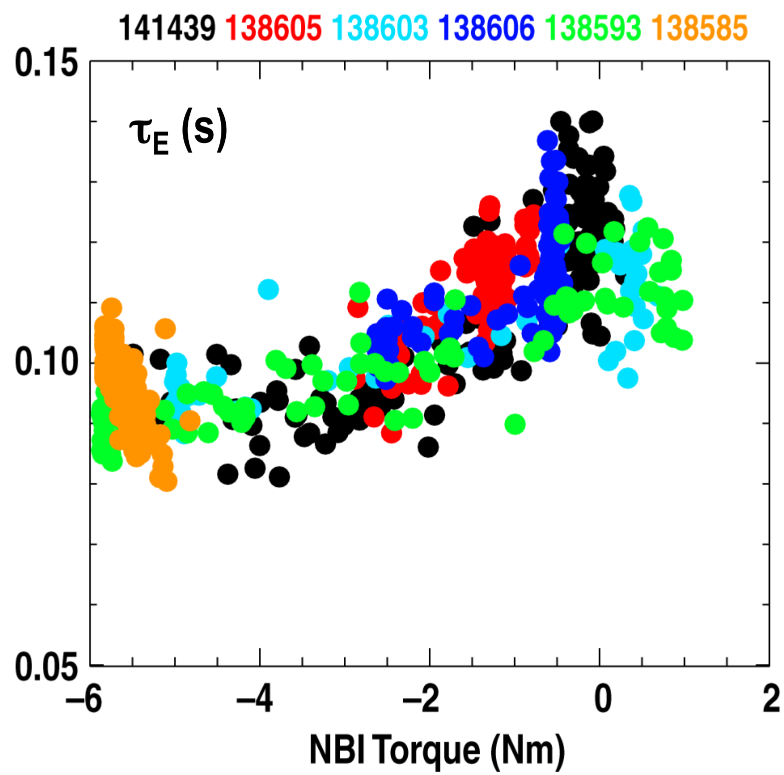
Confinement Improves with NBI Torque Reduction

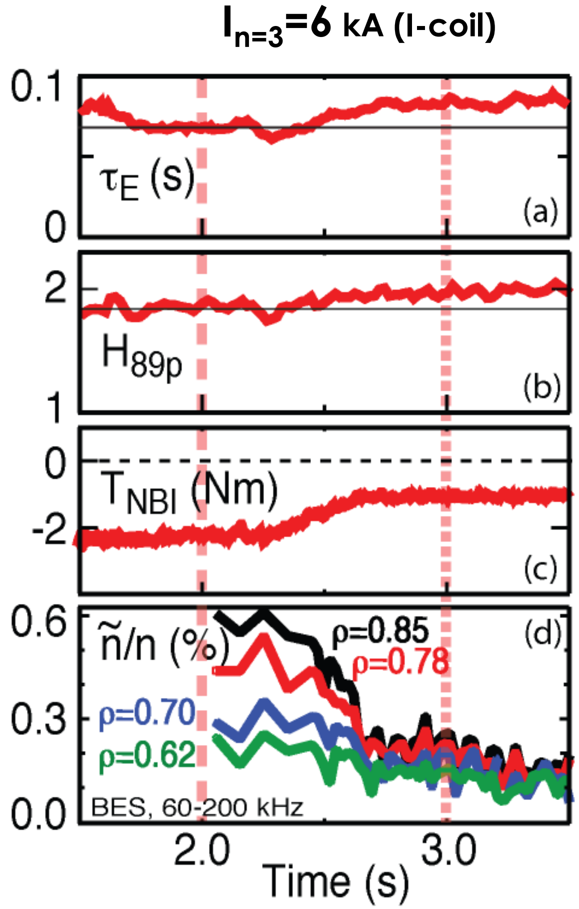
- All discharges MHD quiet, all with NRMF applied
- Confinement does not change with time at constant NBI torque
- Confinement improvement does not depend on NBI torque ramp rate



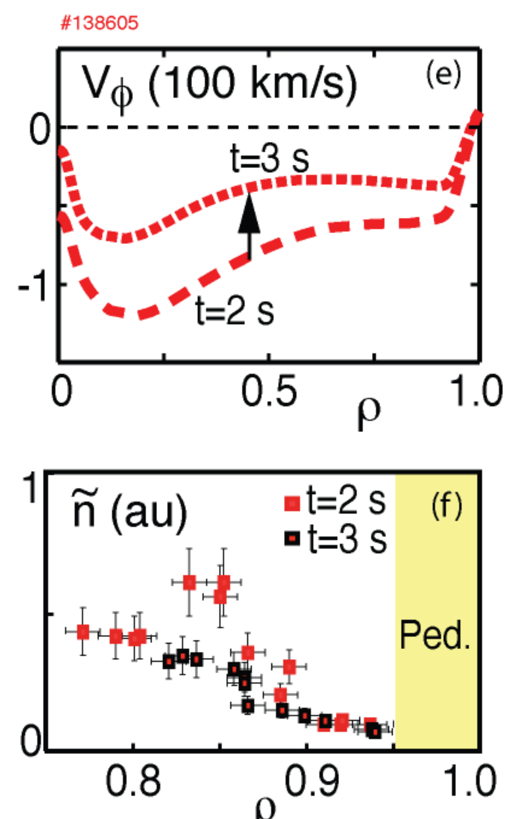


Reduced Density Fluctuations at ρ≥0.8 Accompany Confinement Improvement

- **Energy confinement increases with decreasing NBI torque and rotation**
  - Increase not due to differences in beam absorption with varying mix of co- and ctr-NBI
- **Measured turbulence (density fluctuations from BES, DBS) is reduced at lower rotation, consistent with improved confinement**

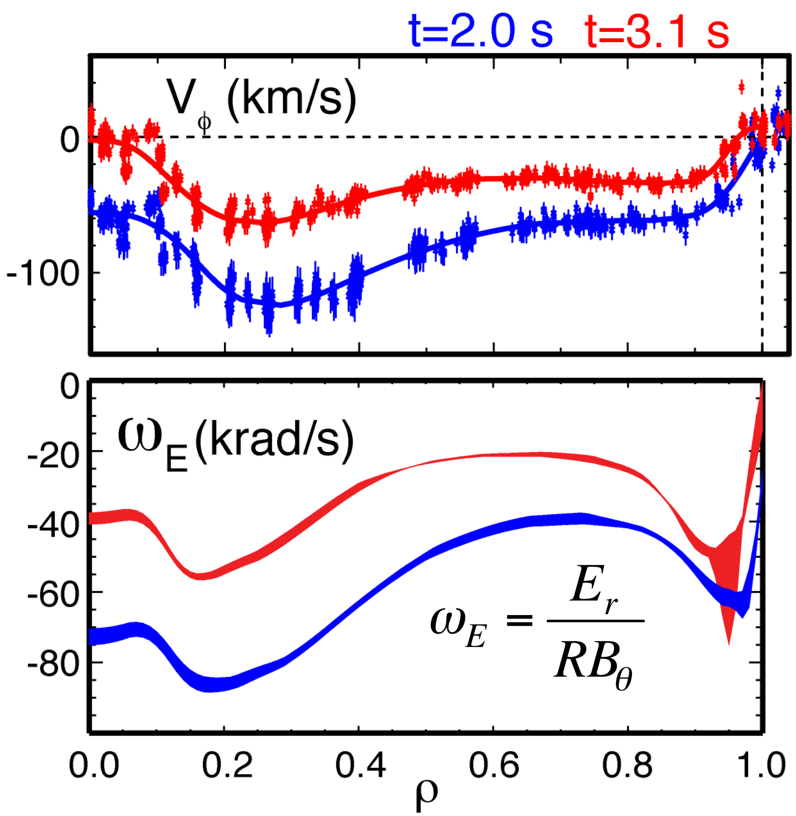


BES, $0.04 \leq k_\theta\rho_s \leq 0.4$



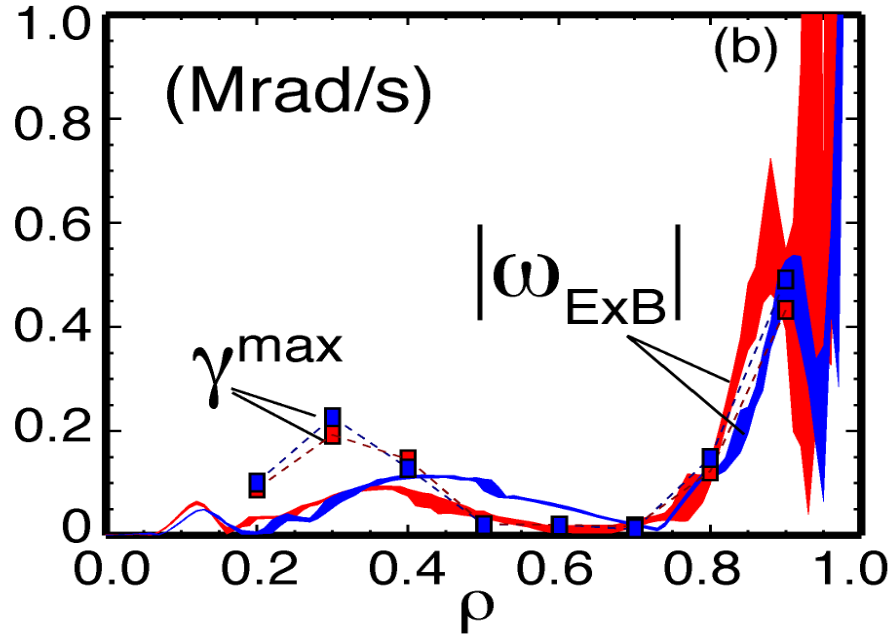
DBS, $k_\theta\rho_s \sim 1$

Edge Shearing Rate at ρ>0.8 Increases at Lower Rotation



$$\omega_{ExB} = \frac{(RB_\theta)^2}{B}\left(\frac{\partial}{\partial\psi}\right)\frac{E_r}{RB_\theta}$$

- **Measured shearing rate comparable to calculated linear growth rates**
  - Maximum growth rate taken over wavelength range of density fluctuations measured by BES



Garofalo et al., Nucl. Fusion (2011)

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Scaling the DIII-D NBI Torque to ITER

- **Define torque T_{DIII-D} as equivalent to T_{ITER} when NBI-driven angular rotation speeds match $\omega_{DIII-D} = \omega_{ITER}$**

- **Considering global torque balance (0-D), angular momentum L, torque T and moment of inertia I are related by**

$$L = I\omega = T\,\tau_L$$

- **If we assume τ_L and τ_E scale the same way, the DIII-D torque equivalent to ITER is**

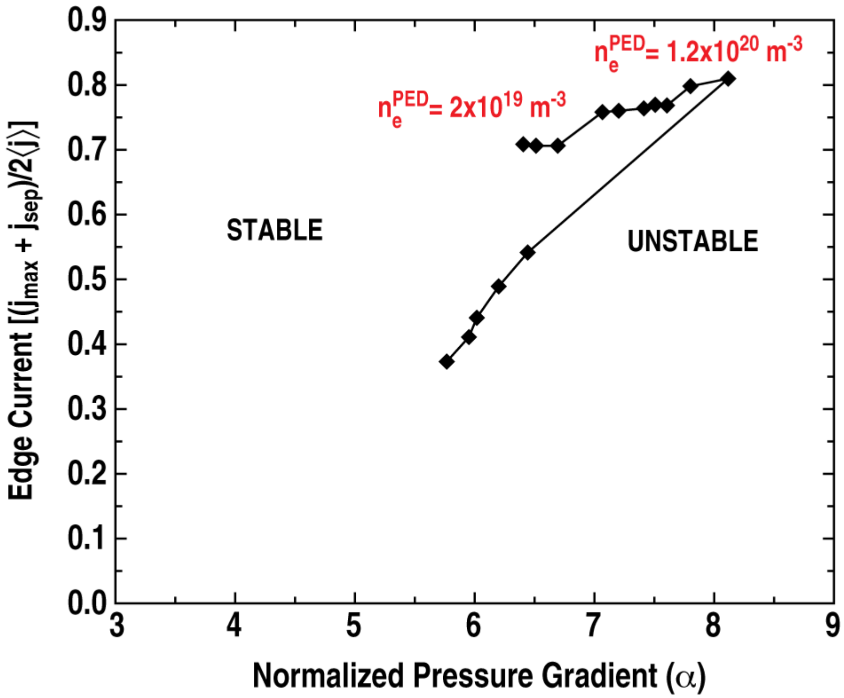
$$T_{DIII-D} = T_{ITER}\,\frac{I_{DIII-D}}{I_{ITER}}\,\frac{\tau_E^{ITER}}{\tau_E^{DIII-D}}$$

- **Using values from ITER scenario 2, $T_{DIII-D} \approx 0.01 T_{ITER}$**

- **This means that the ITER NBI torque of 35 Nm is equivalent to 0.35 Nm NBI torque on DIII-D**

Peeling Ballooning Stability Calculations Predict that ITER Pedestal Will Operate on Peeling Boundary Where QH-mode can Exist

- **Theory model (P.B. Snyder) applies EPED 1 pedestal model to ITER**
- **Model allows calculation of edge pedestal stability for various assumed pedestal densities**
- **Results show that ITER edge will be on the peeling stability boundary for pedestal densities below 1.2 x 10^{20} m^{-3}**
  - Pedestal density of 1.2 x 10^{20} m^{-3} is well above ITER design value



- **All QH-mode plasmas analyzed to date operate at or near the peeling boundary**
- **Accordingly, ITER's pedestal will be in the QH-mode parameter range of collisionality and beta**

QH-mode Sustained by NTV Torque from Non-axisymmetric Fields is a Promising Operating Mode for Future Burning Plasmas

- **Using NTV torque to replace counter-I_p NBI torque, achieved long duration QH-mode with co-I_p NBI torque up to 1.0-1.2 Nm**
  - Co-I_p NBI torque is 3-4 times scaled torque from ITER beams
  - Used ITER-relevant shape, ν^*_{ped}, β_N^{ped} and H_{98y2}
  - Preliminary low q_{95} = 3.4 QH-mode reaches fusion gain G=0.4
- **Demonstrated net zero NBI torque operation using n=3 field from C-coil only**
  - Co-I_p NBI torque limit not determined yet in this configuration
  - If limit is high enough, co-NBI torque QH-mode would be possible with n=3 field from coils outside the toroidal coil
- **In this regime, global energy confinement improves with decreasing rotation (H_{98y2} =1.3)**
  - Improvement correlates with increase in E x B shear and decrease in density fluctuations around ρ = 0.8-0.9
- **QH-mode work has made significant contact with theory**
  - Importance of edge rotational shear is consistent with edge peeling-ballooning theory
  - Qualitative and semi-quantitative agreement with predicted NTV torque