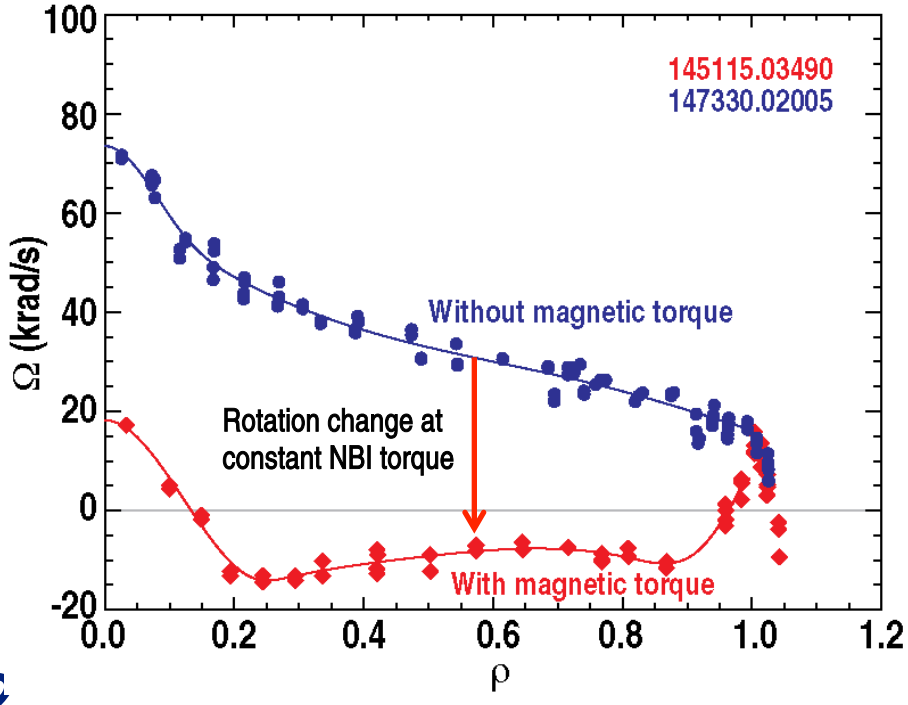
ELM-free, Quiescent H-mode Operation in DIII-D under Reactor-relevant Conditions using Non-axisymmetric Magnetic Fields from Coils Outside the Toroidal Field Coil

by

K.H. Burrell[1], A.M. Garofalo[1], W.M. Solomon[2], M.E. Fenstermacher[3], D.M. Orlov[4], T.H. Osborne[1], J.-K. Park[2], and P.B. Snyder[1]

1. General Atomics
2. Princeton Plasma Physics Laboratory
3. Lawrence Livermore National Laboratory
4. University of California, San Diego



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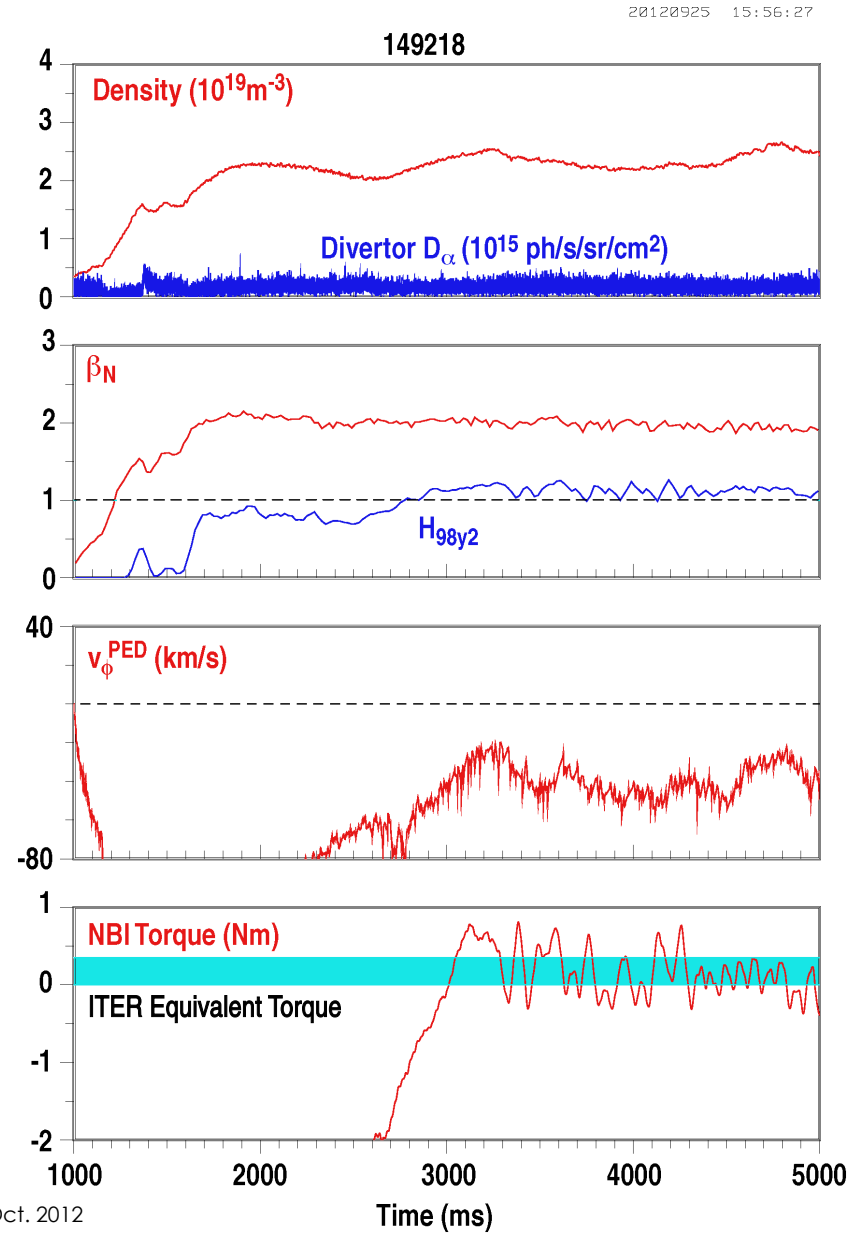
Quiescent H-mode Sustained by Neoclassical Torque From 3D Fields is a Promising Operating Mode For Future Burning Plasmas

- **Future machines require H-mode operation without ELMs in plasmas with low or no co-I_p NBI torque**
- **QH-mode operation without ELMs achieved using torque from DIII-D's external 3D coil set (outside toroidal coil) at reactor-relevant co-I_p torque levels**
  – Torque range used brackets ITER's



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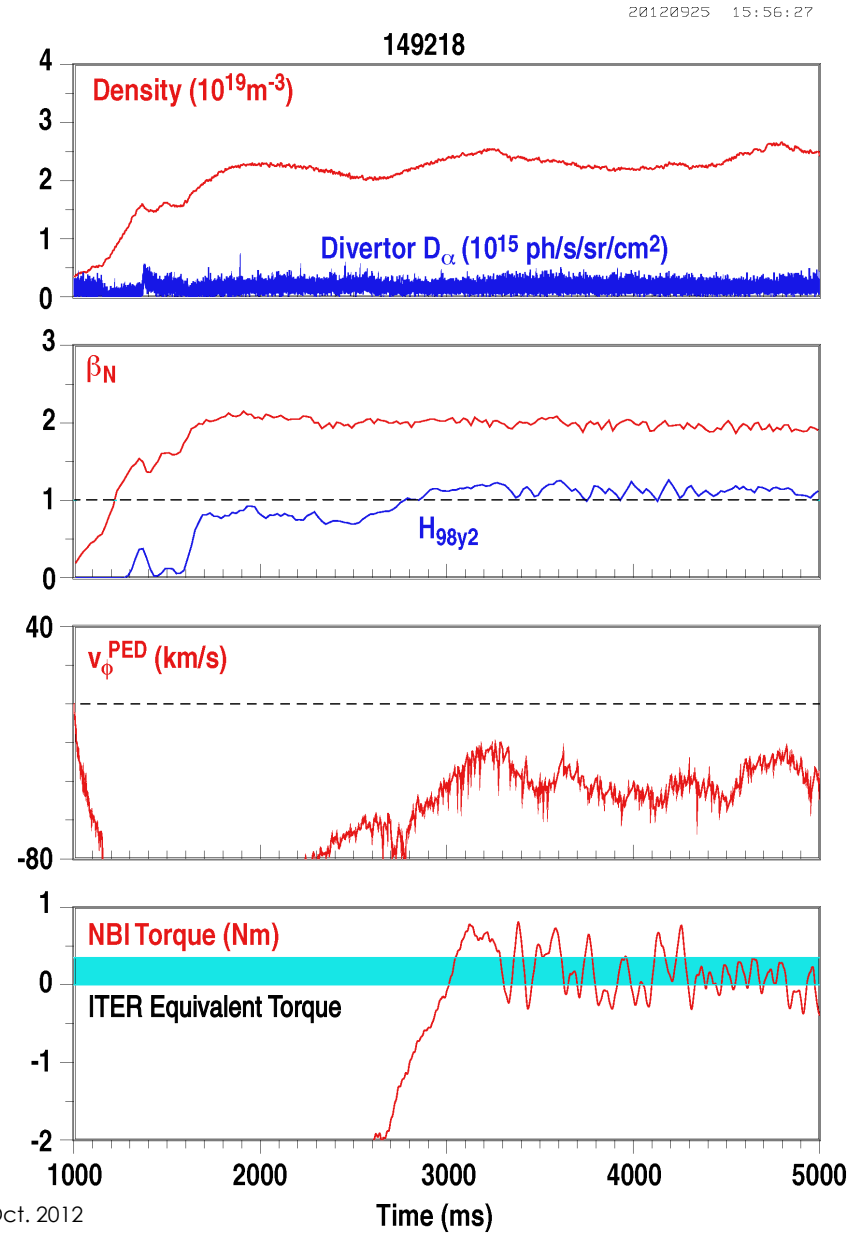
- **QH-mode with 3D fields maintains excellent energy confinement time even at low torque (H_{98y2} ≳1.3)**



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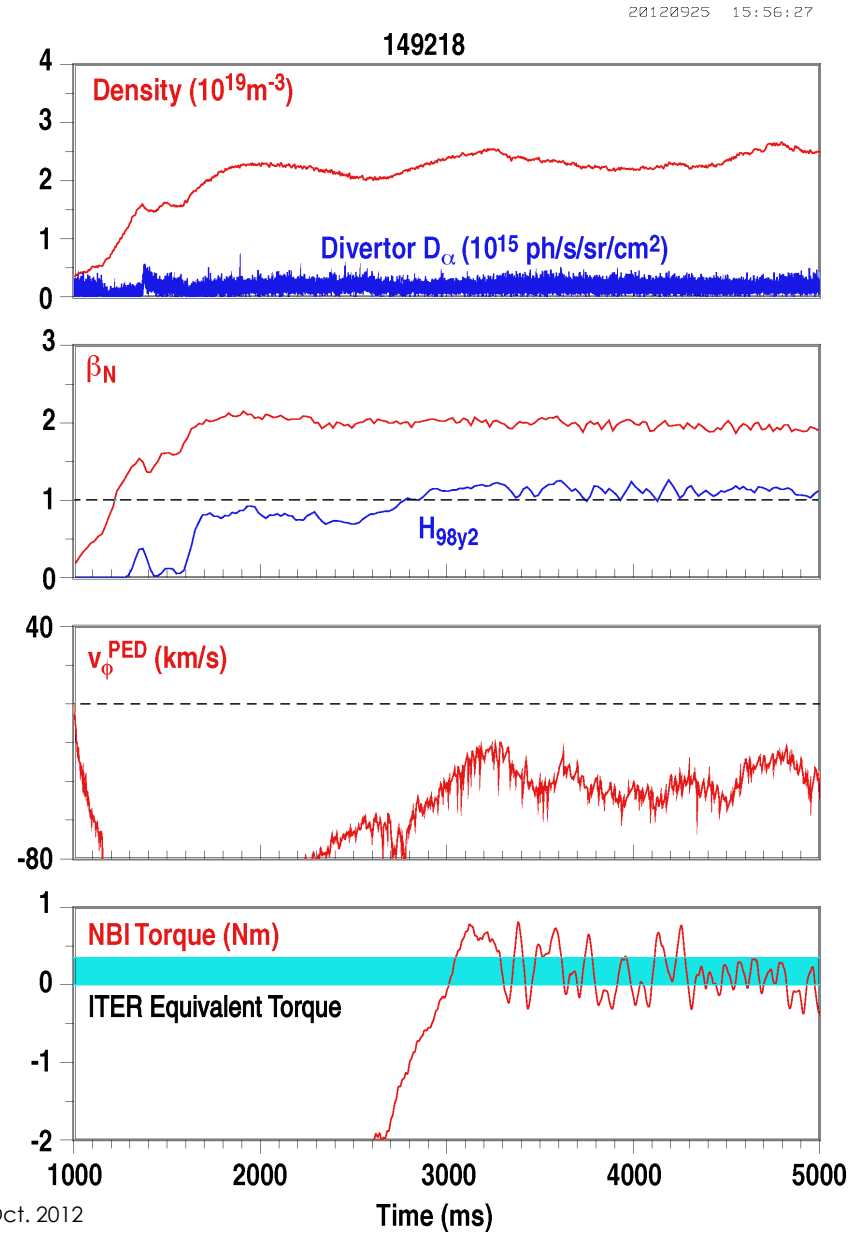
  - Torque range used brackets ITER's
- **QH-mode with 3D fields maintains excellent energy confinement time even at low torque ($H_{98y2} \gtrsim 1.3$)**
- **Research has made significant contact with theory**
  - Peeling-ballooning mode theory explains operating regime and need for edge rotational shear
  - Theory of neoclassical toroidal viscosity consistent with observed magnetic torque



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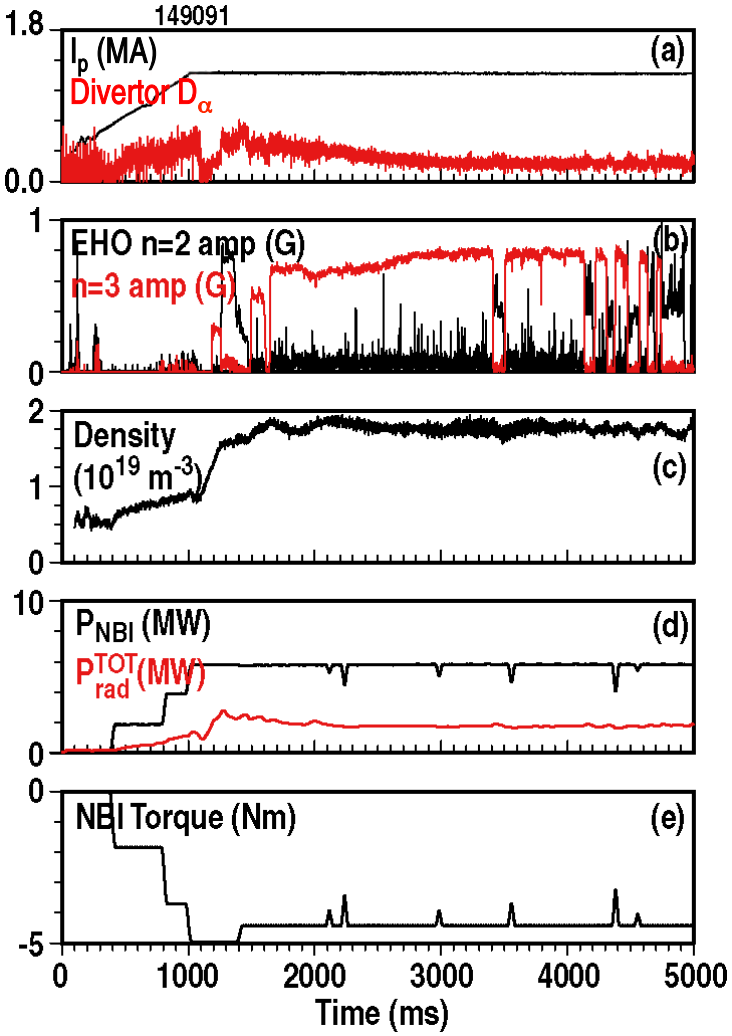
Quiescent H-modes are the Ideal H-mode Plasmas

- **QH-modes exhibit the H-mode confinement improvement and operate ELM-free with**
  - Constant density and 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



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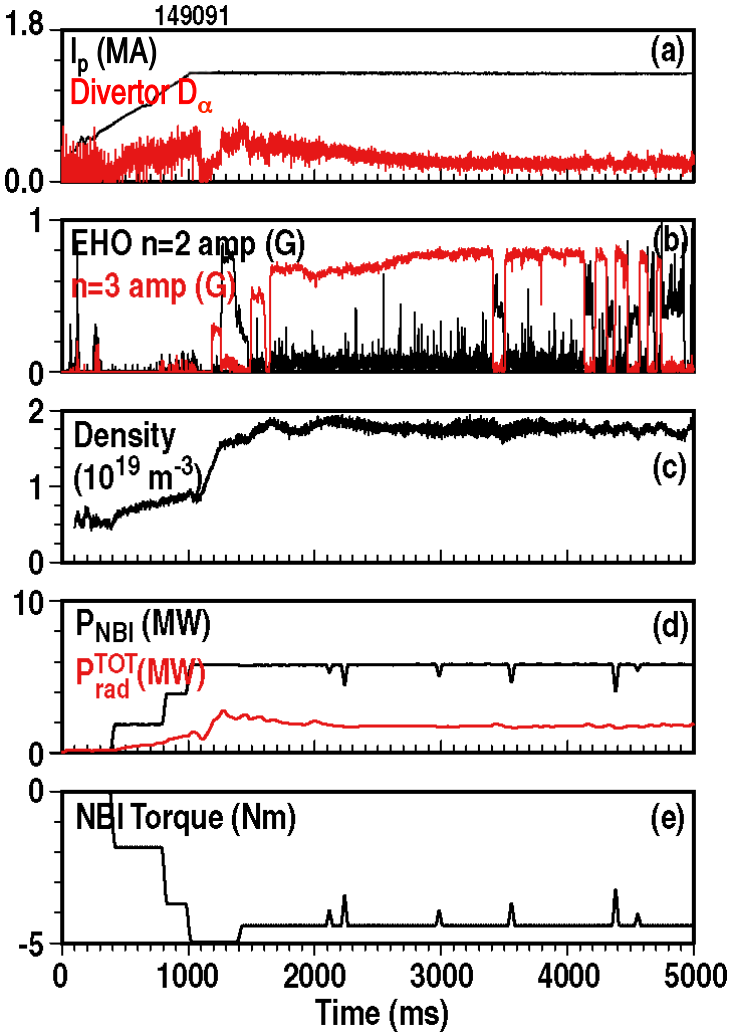
- **QH-mode seen with injected power from 3 MW over 15 MW**
  - Maximum power limited by core beta limit
- **QH-mode discovered first in counter-injected discharges in DIII-D**
  - Subsequently seen in JT-60U, JET and ASDEX-U



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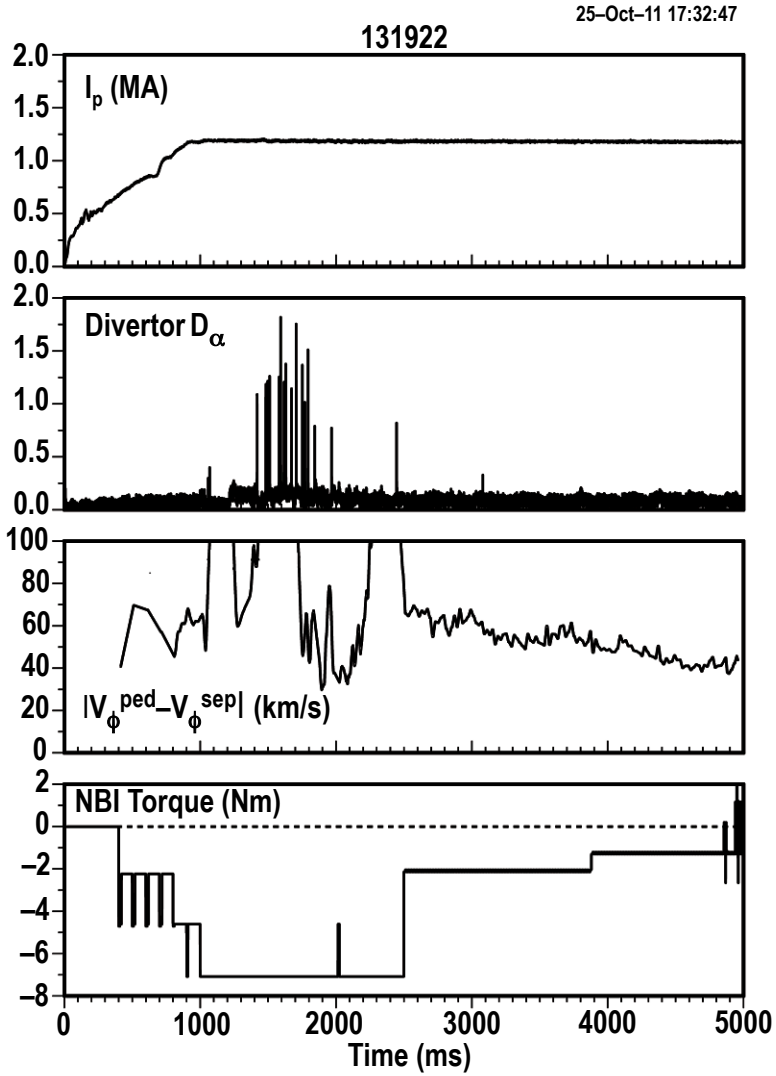
QH-mode Operation in Future Devices Requires Technique to Maintain Shear in Edge Rotation at Small NBI Torque

- 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 3D magnetic fields, as NBI torque goes from counter to co-I_p, magnitude of edge rotational shear decreases and ELMs return



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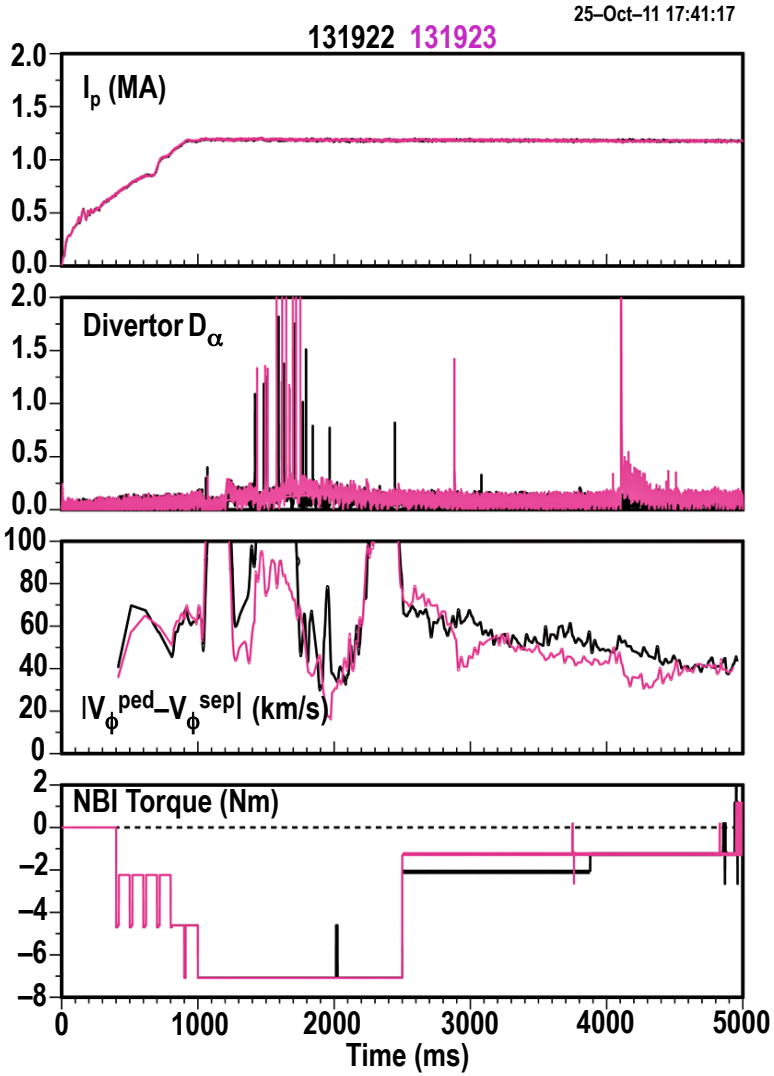

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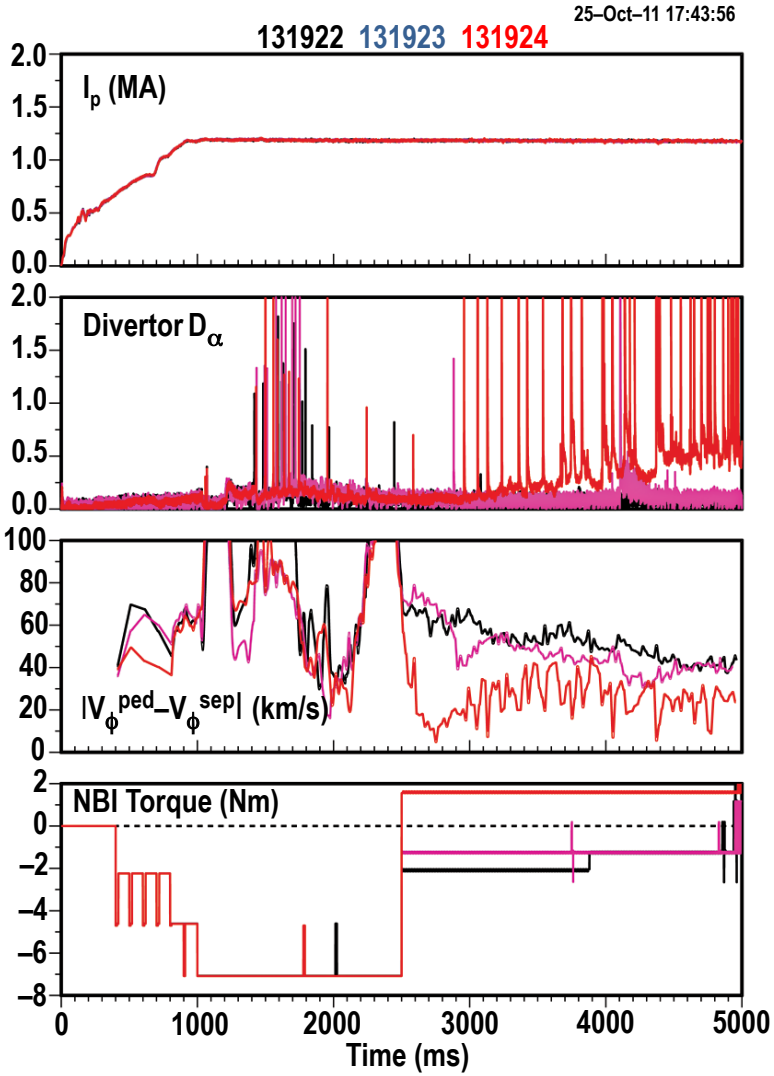
- Without 3D magnetic fields, as NBI torque goes from counter to co-I_p, magnitude of edge rotational shear decreases and ELMs return
- 3D magnetic fields can maintain edge rotational shear at low co-I_p NBI torque



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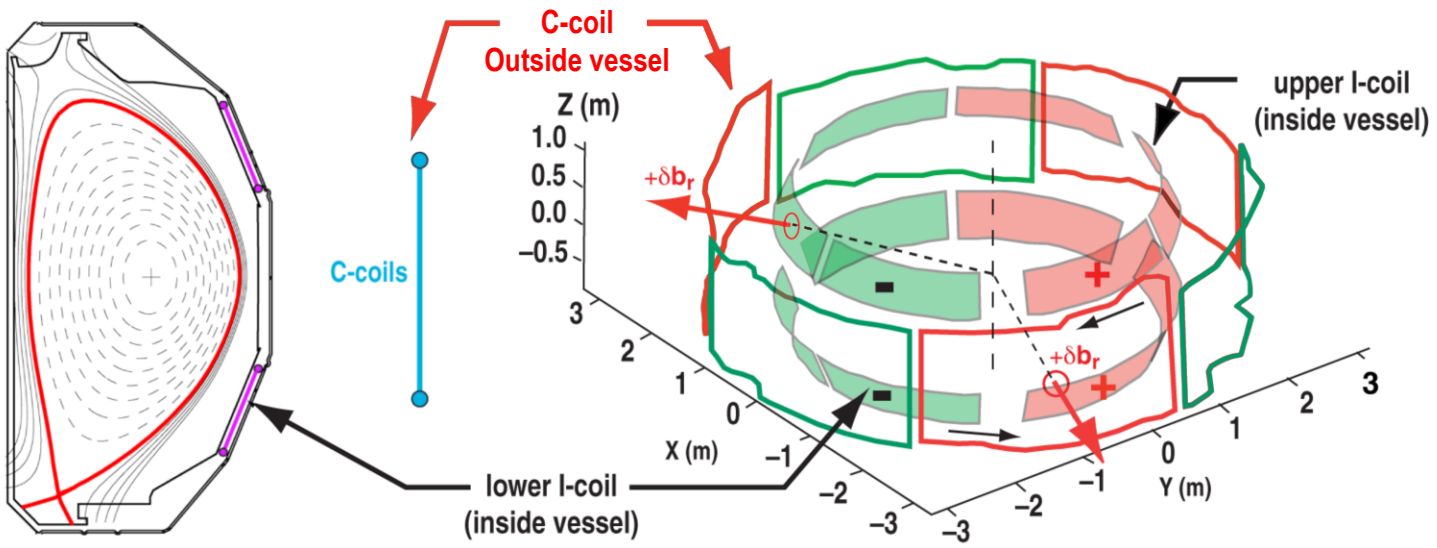
Non-axisymmetric Coils on DIII-D Allow Creation of Magnetic Perturbations



- Two sets of non-axisymmetric coils can be used to correct intrinsic error fields and apply magnetic perturbations
- For experiments in 2012, coil outside vessel (C-coil) was used to create n=3 field
- I-coil was configured for intrinsic n=1 error field correction

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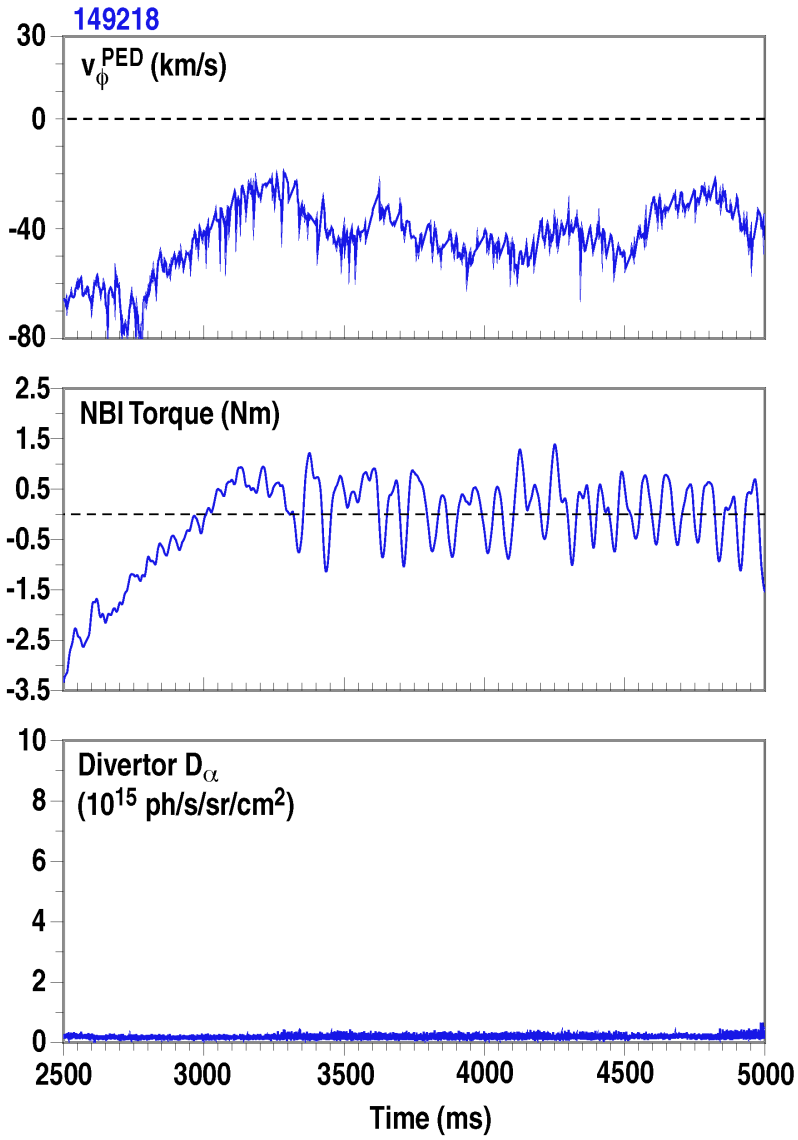
QH-mode with Counter-I_p Rotation Maintained with co-I_p NBI Torque up to 1 Nm Using 3D Field from Coil Outside Toroidal Coil

- Raise NBI torque level from shot to shot to determine co-I_p limit
- Pedestal rotation remains counter-I_p until torque limit is reached
- Beyond limit, rotation jumps up and locked mode occurs
- n=3 3D field from C-coil only (7.1 kA)



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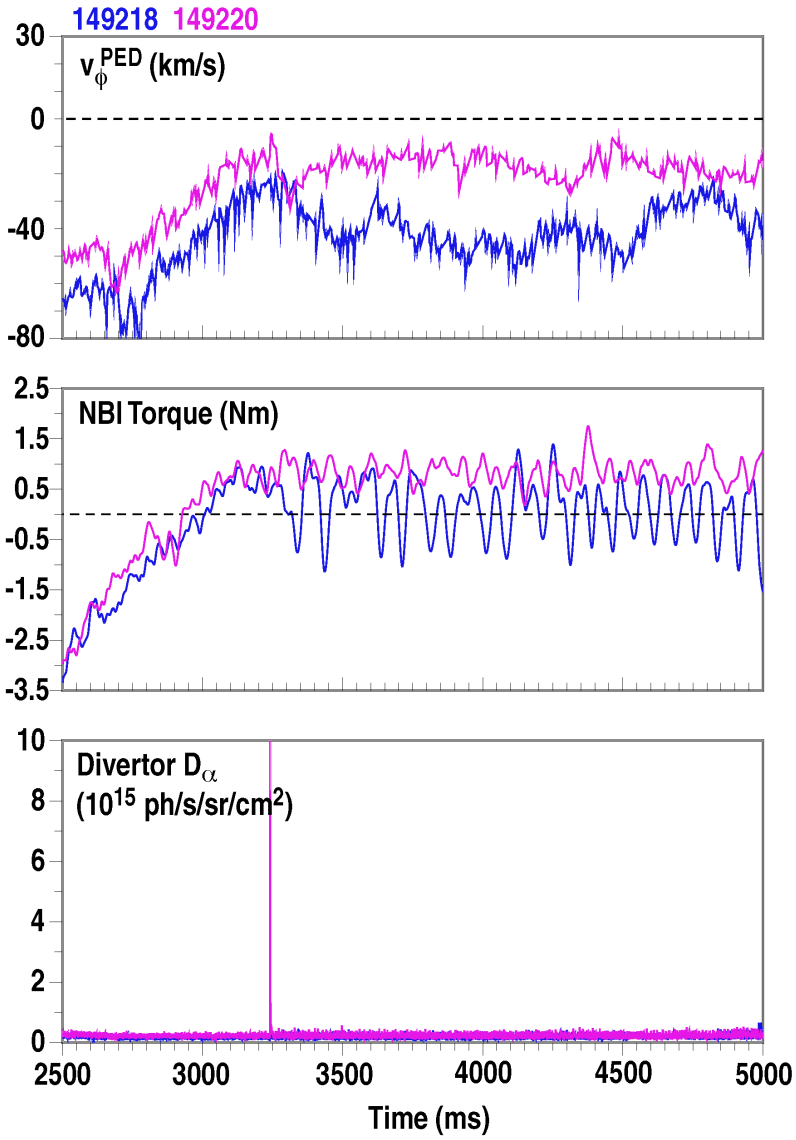

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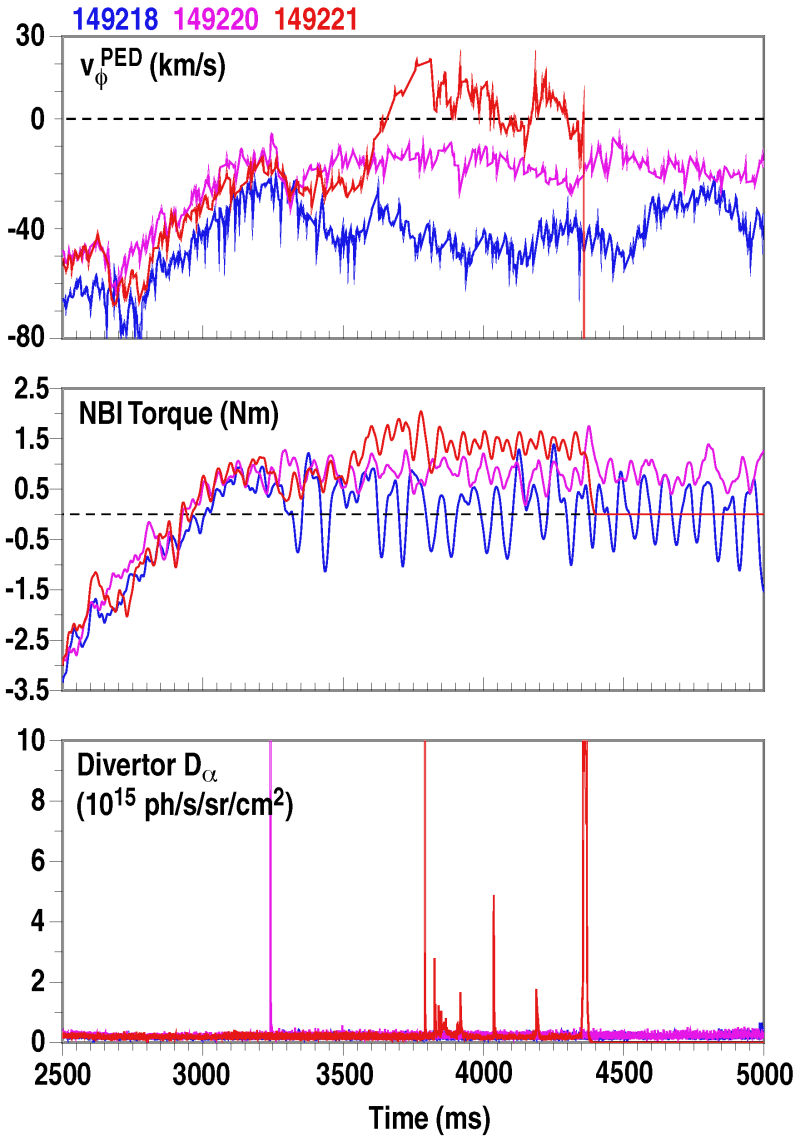

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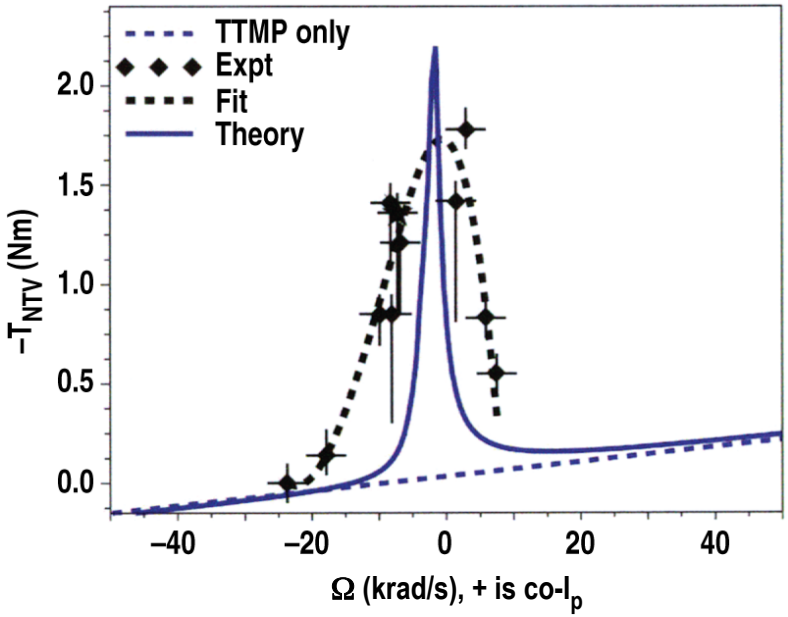
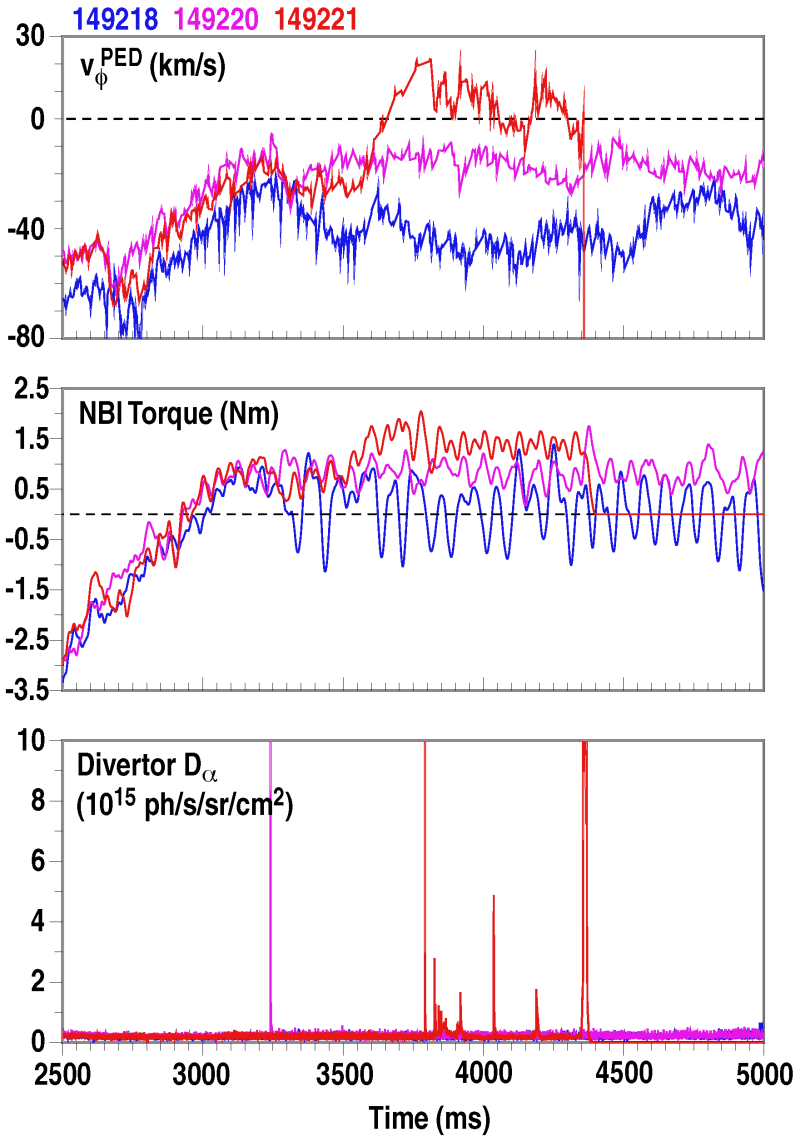
Rotation Bifurcation as NBI Torque Increases is Qualitatively Consistent with Theory of NTV Torque

- **Theory predicts rotation speed should jump when sum of other torques exceeds peak counter-I_p NTV torque**





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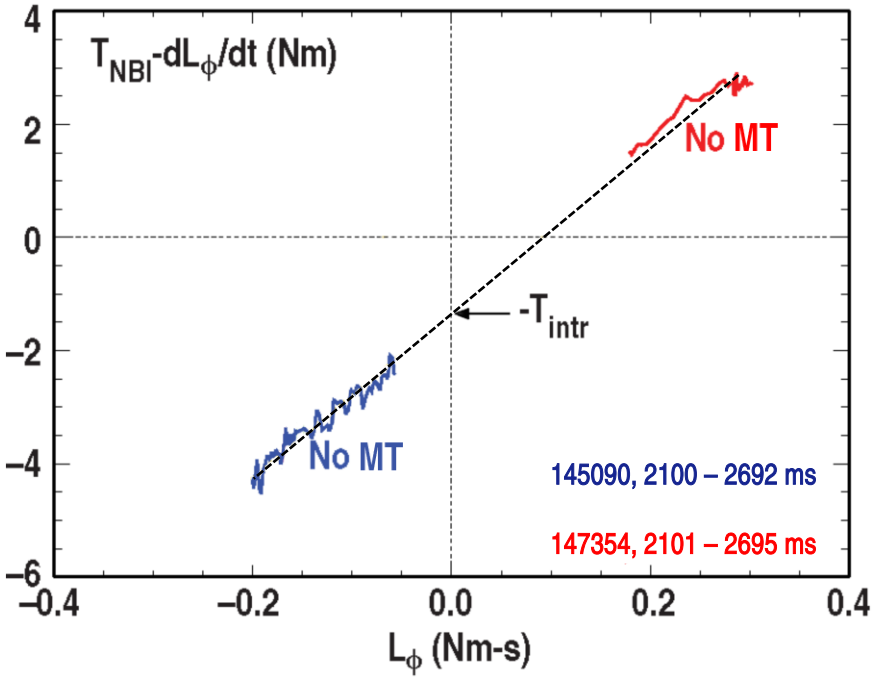
Magnetic Torque Determined from Global Torque Balance of QH-mode Discharges Agrees with IPEC + NTV Prediction

- $dL_\phi/dt = -L_\phi/\tau_\phi + T_{NBI} + T_{MT} + T_{intr}$
- In shots without magnetic torque (MT), plot of $T_{NBI} - dL_\phi/dt$ versus L_ϕ gives straight line whose intercept is T_{intr}



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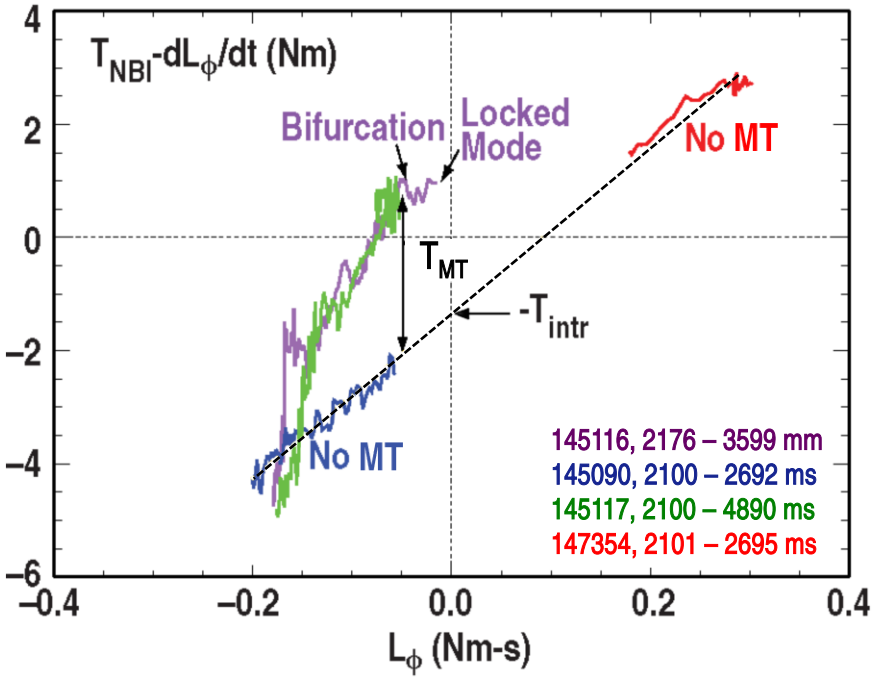

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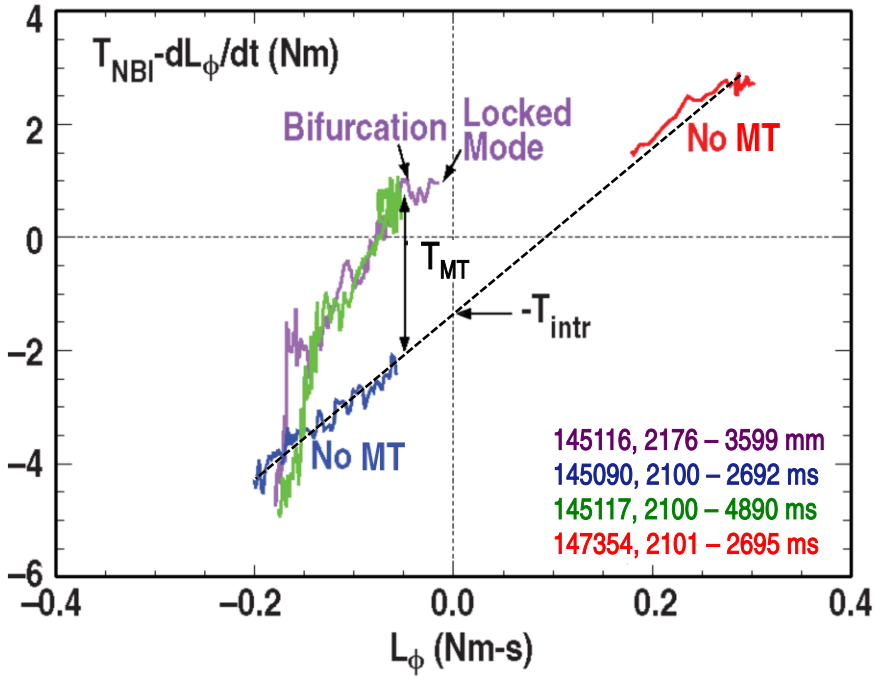
- In shots without magnetic torque (MT), plot of $T_{NBI} - dL_\phi/dt$ versus L_ϕ gives straight line whose intercept is T_{intr}
- In shots with MT, slope is different because T_{MT} depends on L_ϕ
- Comparing shots with and without MT gives T_{MT} = 3 Nm
- IPEC + NTV codes also give 3 Nm
  - IPEC (Park, PoP 2007)
  - NTV (Park, PRL 2009)



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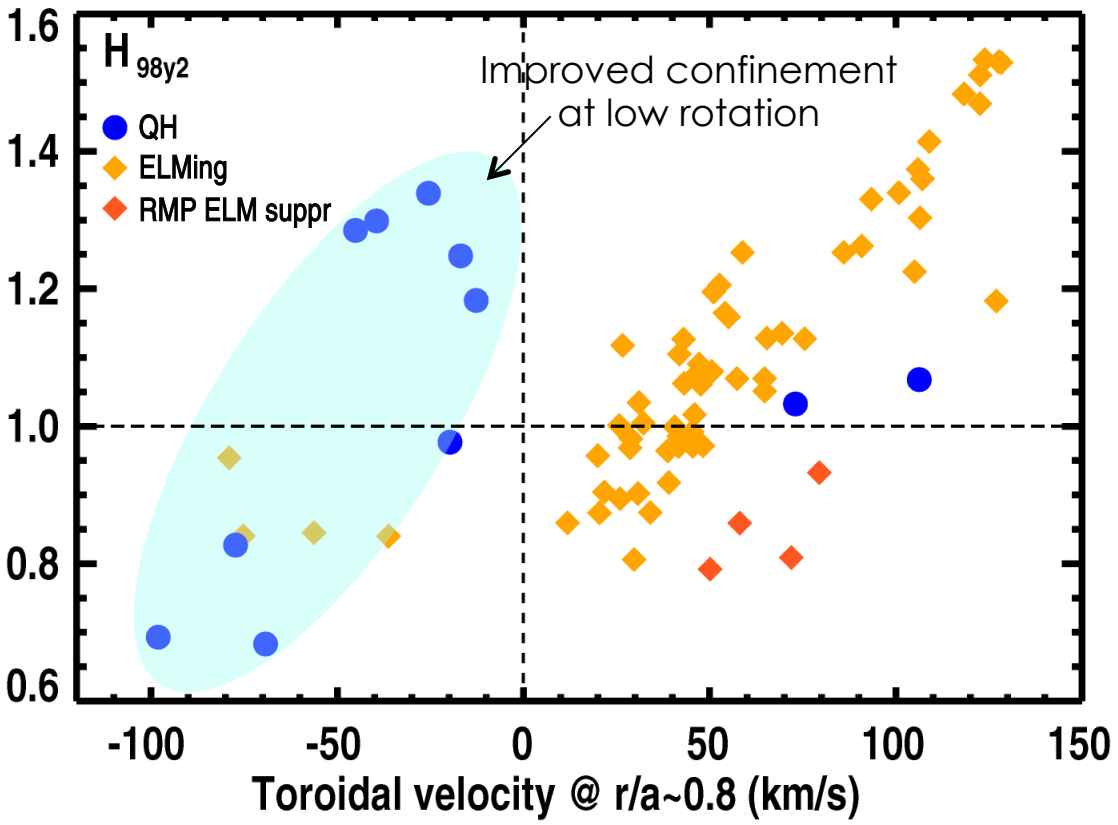
QH-mode Shows Surprising Improvement in Confinement at Low NBI Torque and Rotation

- **Confinement quality of other H-mode plasmas in DIII-D is generally reduced with lower NBI torque and rotation rate**

  [Solomon et al., TTF (2012)]

  - Standard type I ELMing
  - RMP ELM suppressed
  - Advanced inductive
  - ITER baseline (q_{95}~3.1, shape, beta…)



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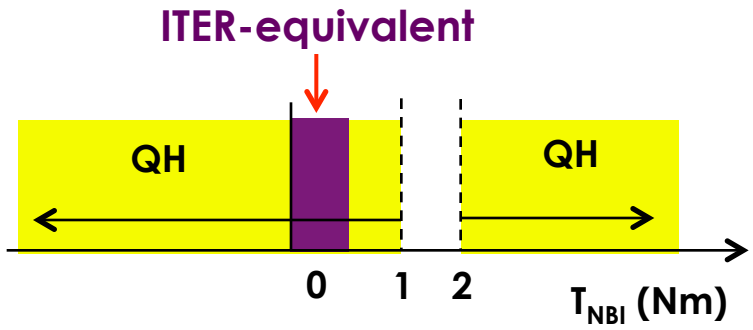
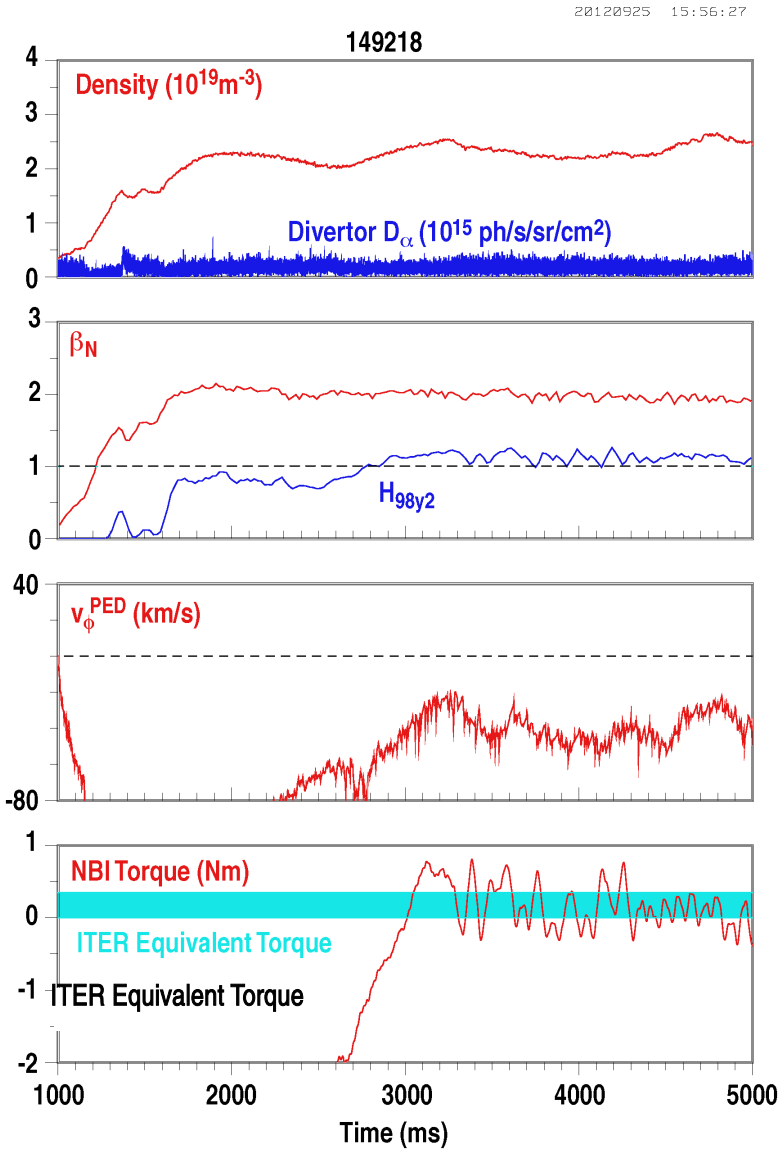
QH-mode Sustained by Neoclassical Torque from 3D Fields is a Promising Operating Mode for Future Burning Plasmas

- Counter-rotating QH-mode edge sustained with ITER relevant co-Ip NBI torque, using 3D coil outside toroidal coil
- Stationary, constant density H-mode operation without ELMs at ITER pedestal beta and collisionality
- Excellent energy confinement quality at low rotation: $H_{98y2} \approx 1.3$
- QH-mode NBI torque brackets ITER's





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