Advanced Inductive Plasmas With Low Torque Startup

by

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In collaboration with

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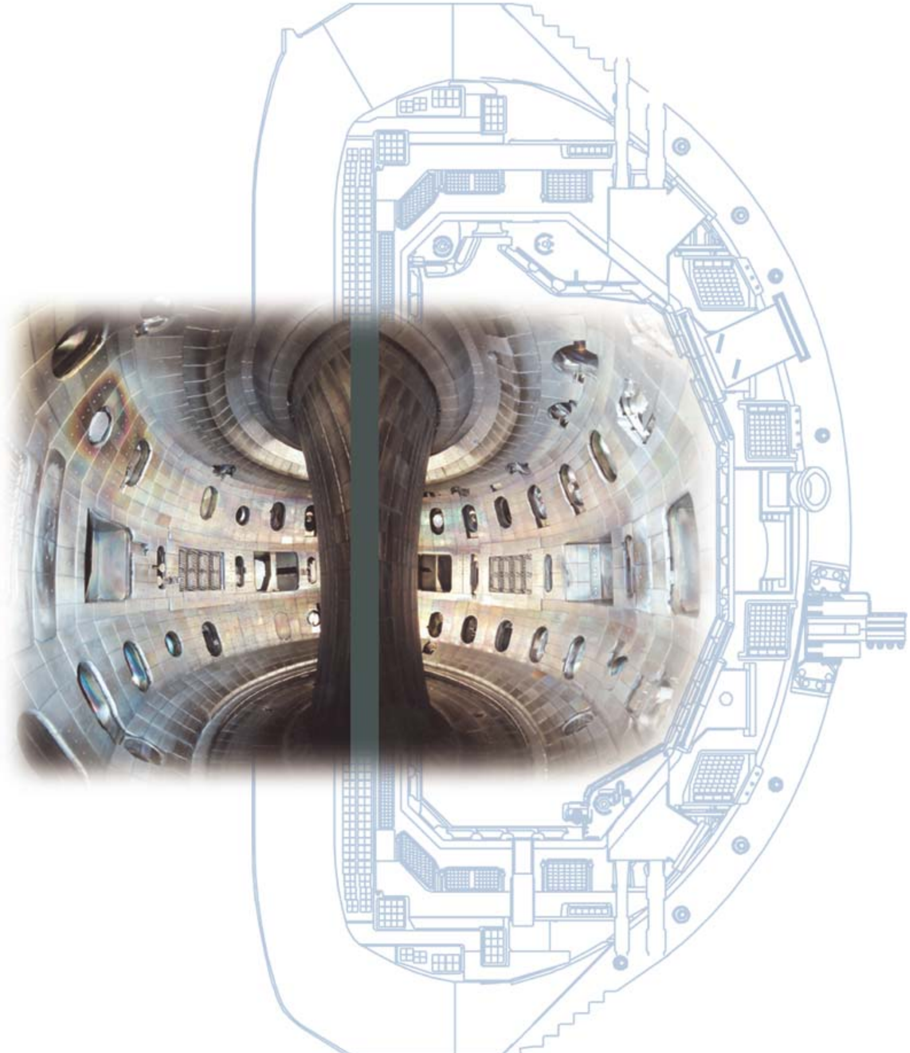

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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PPPL PRINCETON PLASMA PHYSICS LABORATORY

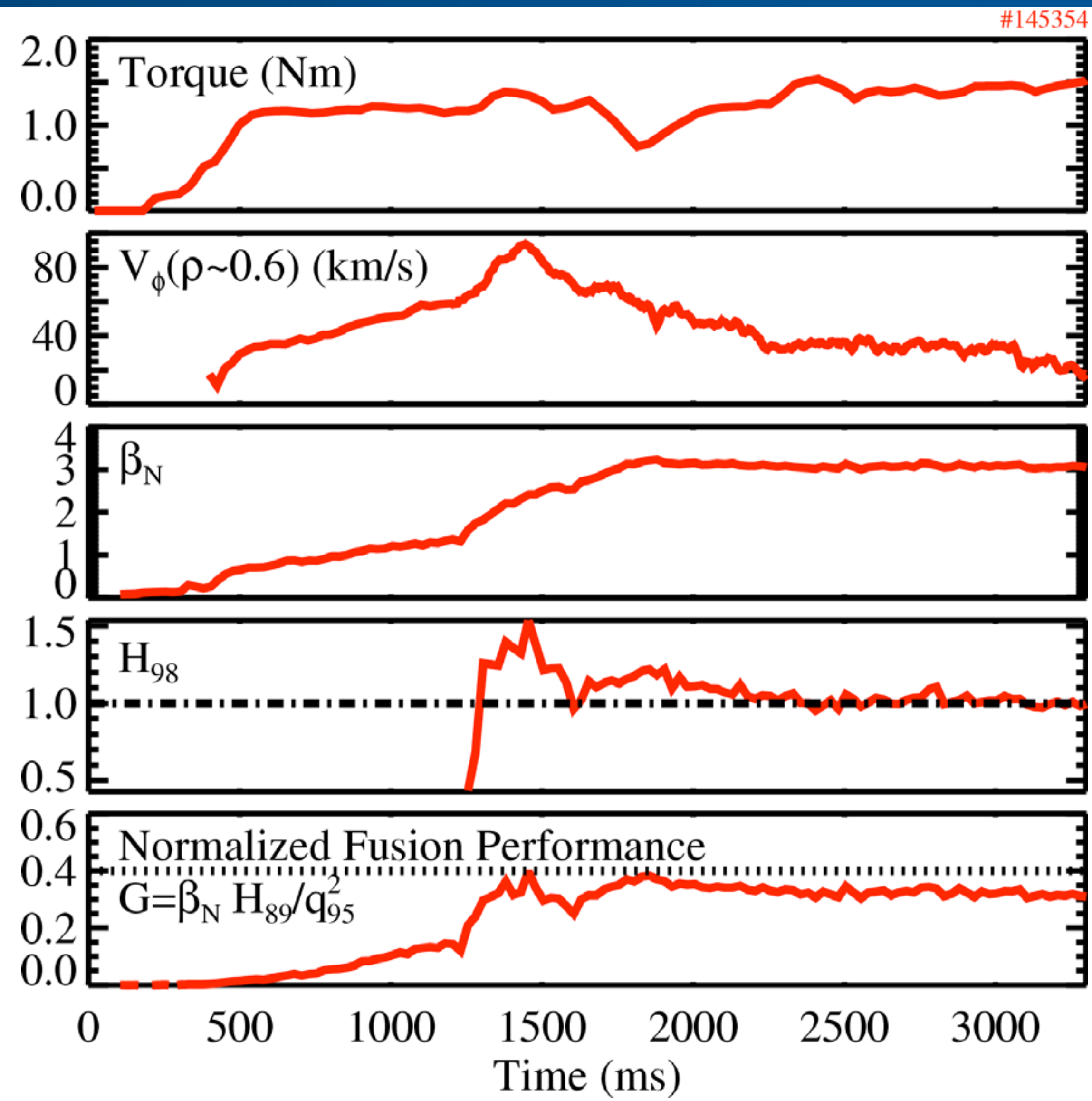
Motivation

- **Advanced inductive discharges offer an attractive alternative to the baseline scenario for ITER operation**
  - Higher confinement coupled with high β_N allows operation at lower plasma current while still reaching Q=10 mission

- **Goal is to develop plasmas with high fusion performance using rotation and relative momentum input comparable to that of ITER**
  - Improved confinement and stability often achieved by exploiting high levels of rotation
  - Due to the rapidly increasing moment of inertia with machine size compared with confinement time, it becomes more difficult to drive significant rotation in ITER and beyond
  - Key issue is determining access and performance characteristics at low rotation

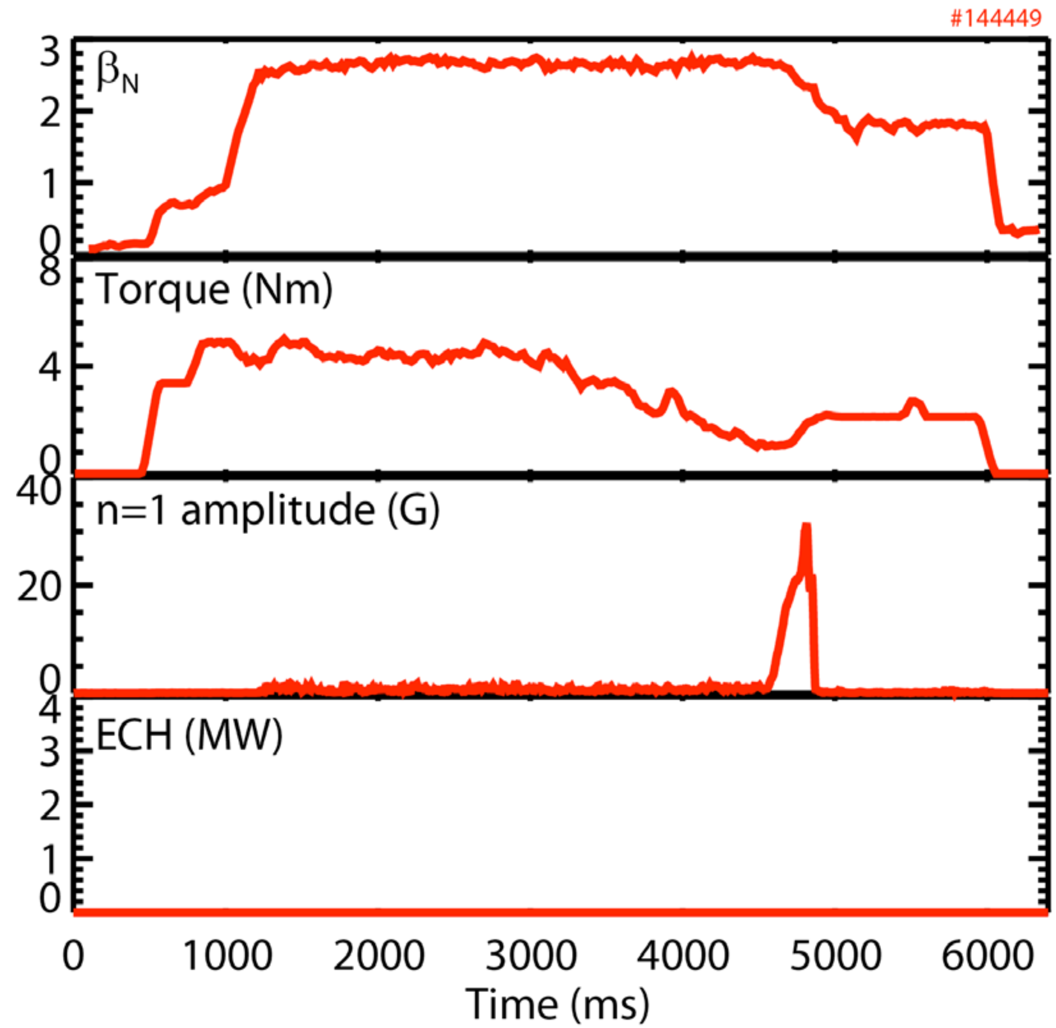
Advanced Inductive Discharge Approaching ITER Q=10 Equivalent Achieved with Low Torque Startup

- **Torque ~1 Nm on DIII-D expected to drive similar rotation as ITER beams (~30 Nm)**
- **Does not utilize high torque in the startup**
- **β_N~3.1, H_{98}~1, q_{95}~4 sustained for maximum duration of counter NBI**
- **Normalized fusion performance, $G=\beta_N H_{89}/q_{95}^2$ ~ 0.35**
  - G~0.42 → ITER Q=10



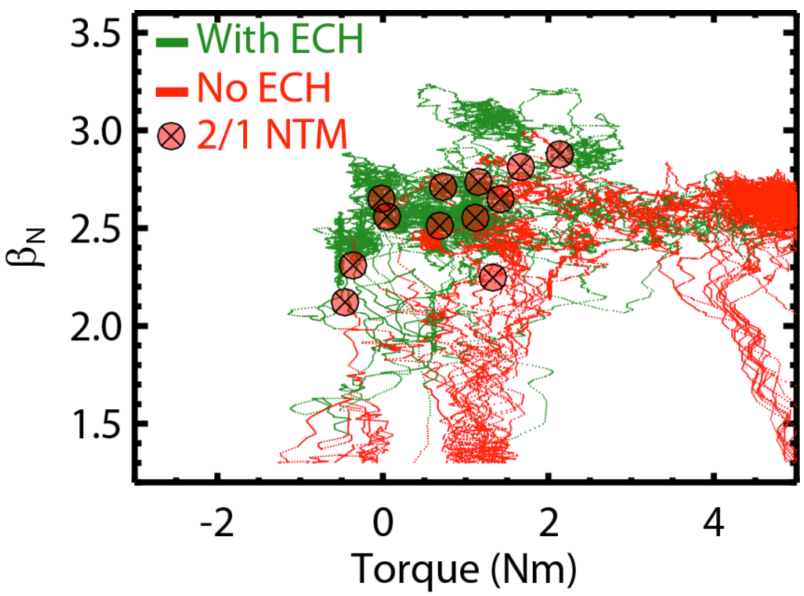
At Reduced Torque, Plasma Becomes Increasingly Susceptible to 2/1 Neoclassical Tearing Modes

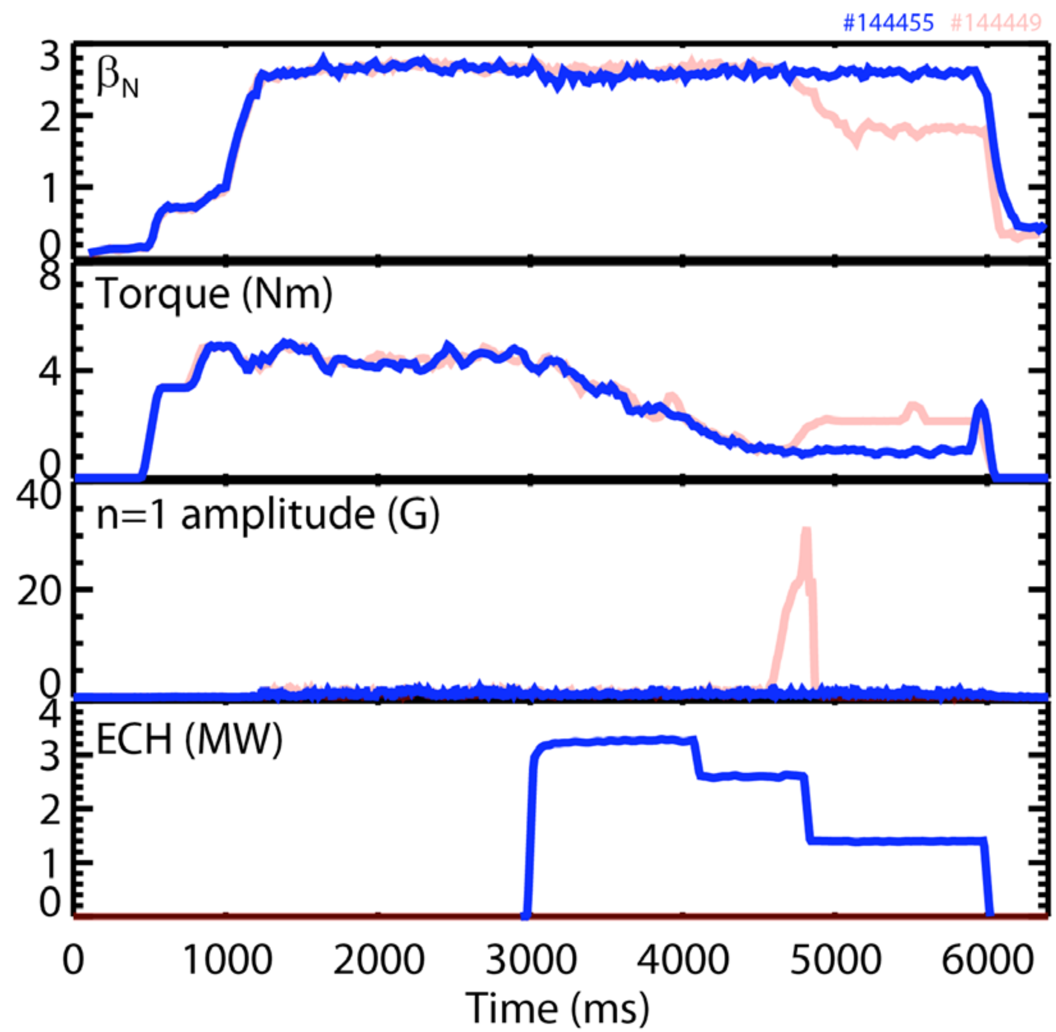
- **Generally slow and lock, terminating high performance phase**
- **Does not appear a result of uncorrected error fields**
  - 2/1 NTM occurred at the same torque level even with Improved error field correction



Use of Electron Cyclotron Heating Beneficial for Tearing Mode Control at Low Torque Regimes

- **Application of ECH generally results in suppression of such modes**
- **Typically configured to drive current near q=2 surface**
  - But actual current drive may not be essential here



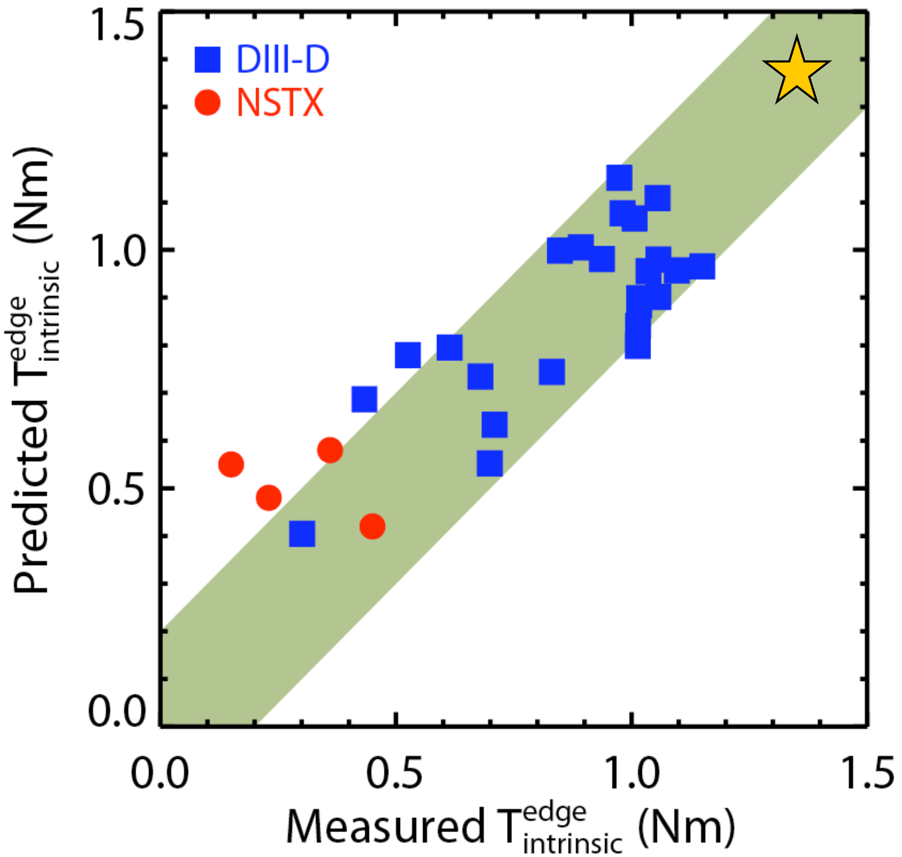


Intrinsic Drive in Low Torque AI Plasmas Closely Matches Previously Determined Scaling

- **An excellent predictor of edge intrinsic torque has been established for DIII-D H-modes**
  - Empirically includes physics associated with turbulent Reynolds stress and thermal ion orbit loss
    [Solomon et al., *Nucl. Fusion* (2011)]

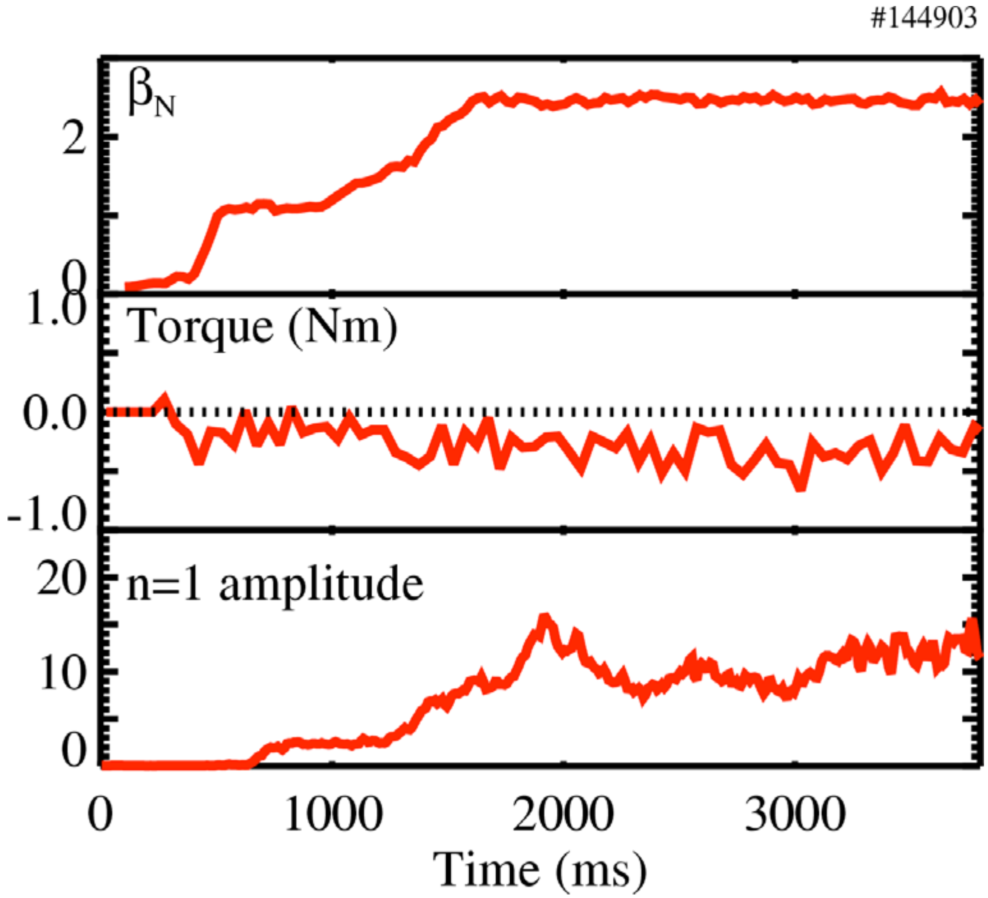
- **New advanced inductive discharges show notable levels of intrinsic torque**
  - Significantly exceed range of data set used to construct scaling

- **If holds for ITER scenario 2, compute intrinsic torque of only 2 Nm**
  - Much smaller than even NBI torque



Advanced Inductive Discharges Have Been Run With Zero Net Input Torque For Full Discharge

- **Using only modest EC power (~1 MW), 2/1 NTM is reduced in amplitude sufficiently to allow operation at β_N~2.5**
  - Maximum achievable with available heating power in these conditions



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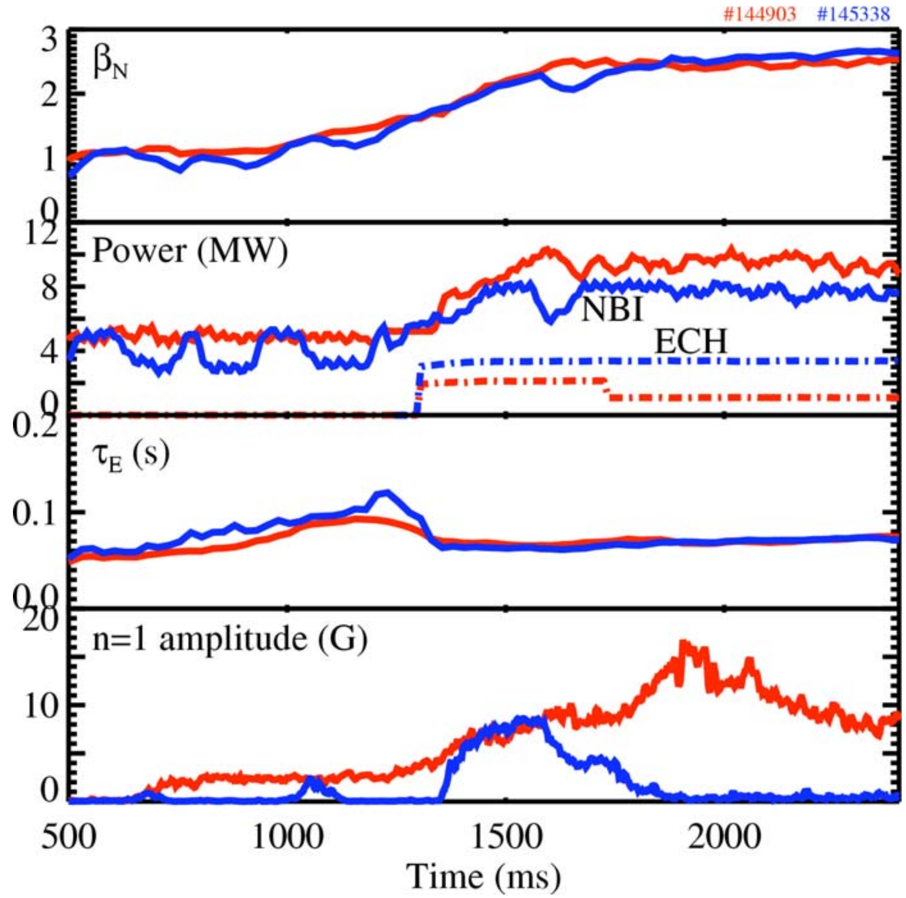
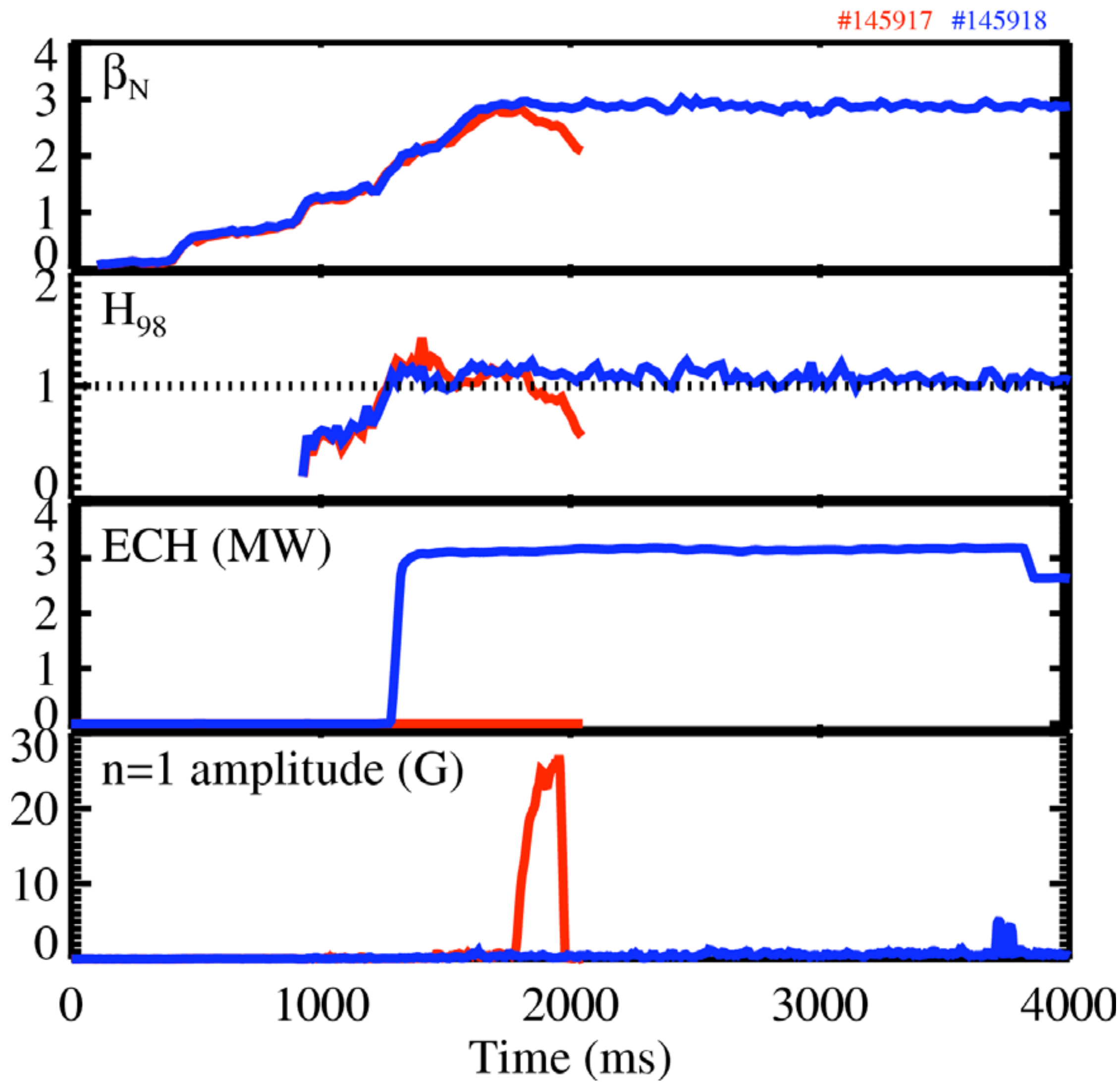
- **Additional EC power allows complete stabilization of 2/1 mode**
  - Energy confinement time the same
  - Similar β_N for similar combined NBI+ECH

- **Significant cost to confinement for using ECCD aimed at q=2**
  - Avoids disruptive locked mode
  - But gain is not notably improved



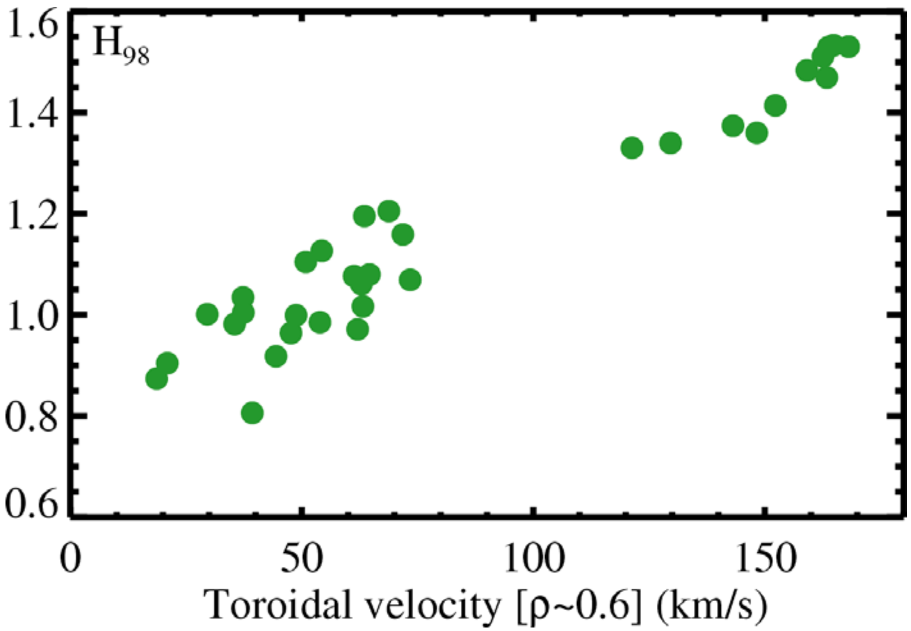
Advanced Inductive Plasmas with High β_N~3 Achieved Using More Central ECH (no q=2 ECCD)

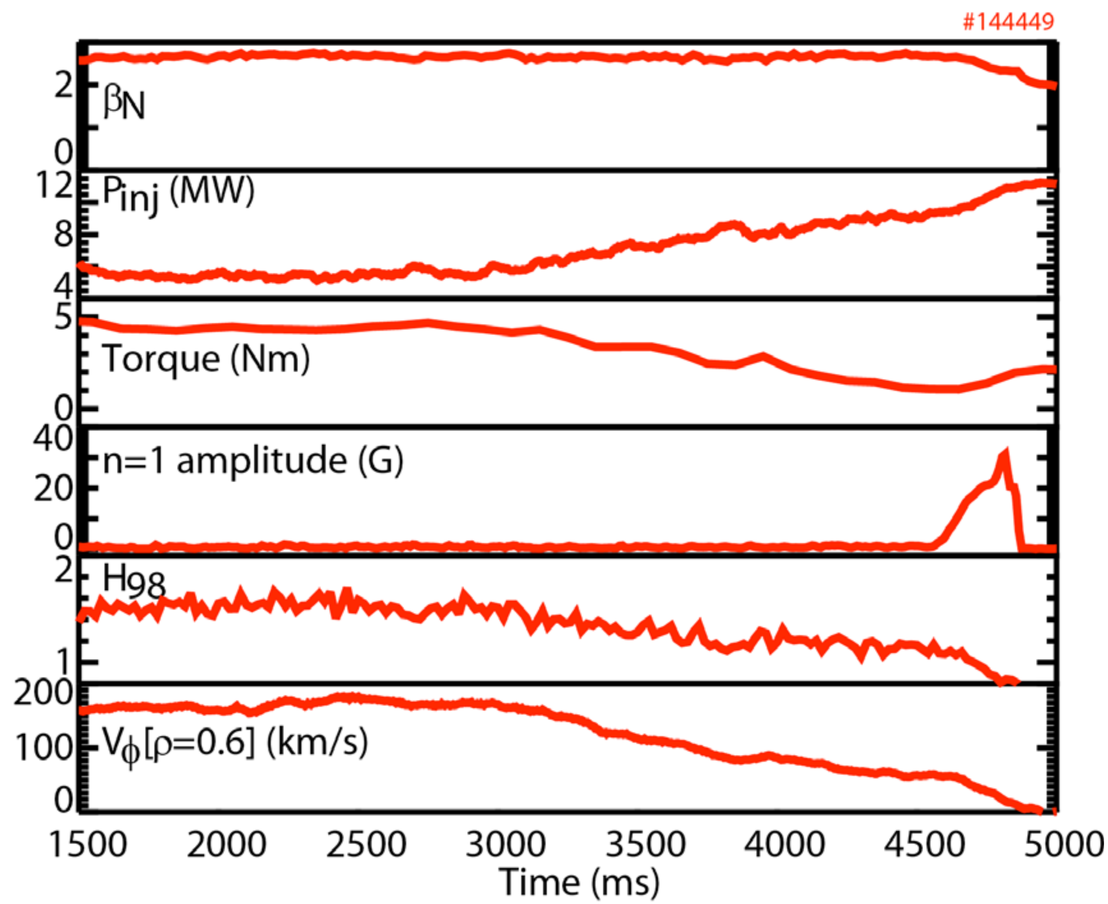
- **Torque ~1 Nm, H_{98}~1**
- **In this case, ρ_{ECH}~ 0.3 (cf $\rho_{q=2}$~ 0.6) and configured for heating without current drive**
- **Insensitivity to deposition location or heating vs current drive suggests different mechanism than standard NTM stabilization**



Significant Reduction in Confinement Observed as Torque Is Reduced

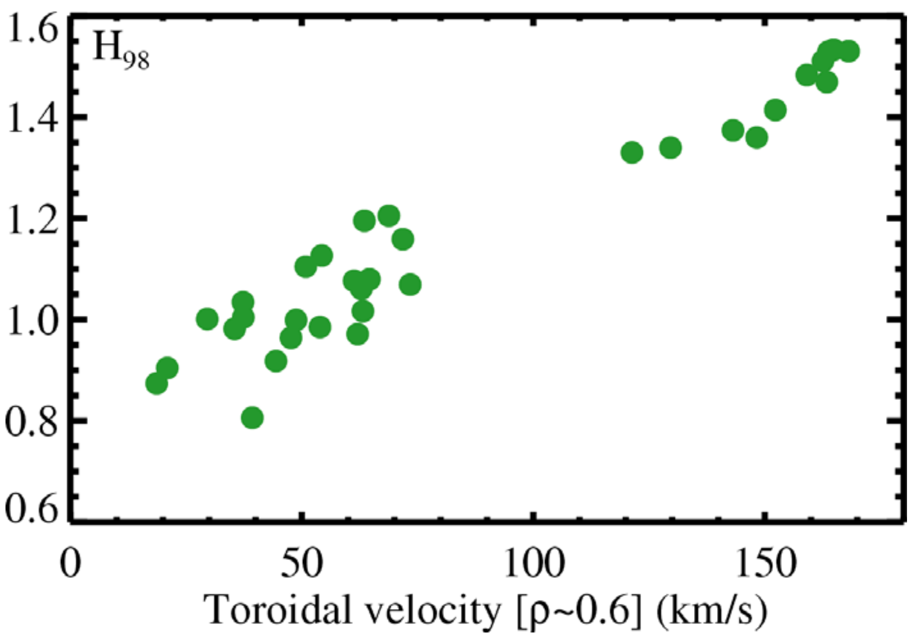
- For fixed β_N, power demand increase ~70% at low torque
- H_{98} reduced from >1.5 to approx 1.0
- No obvious evolution in q-profile
- Similar to previously reported results [Politzer, Nucl. Fusion **48**, 075001 (2008)]

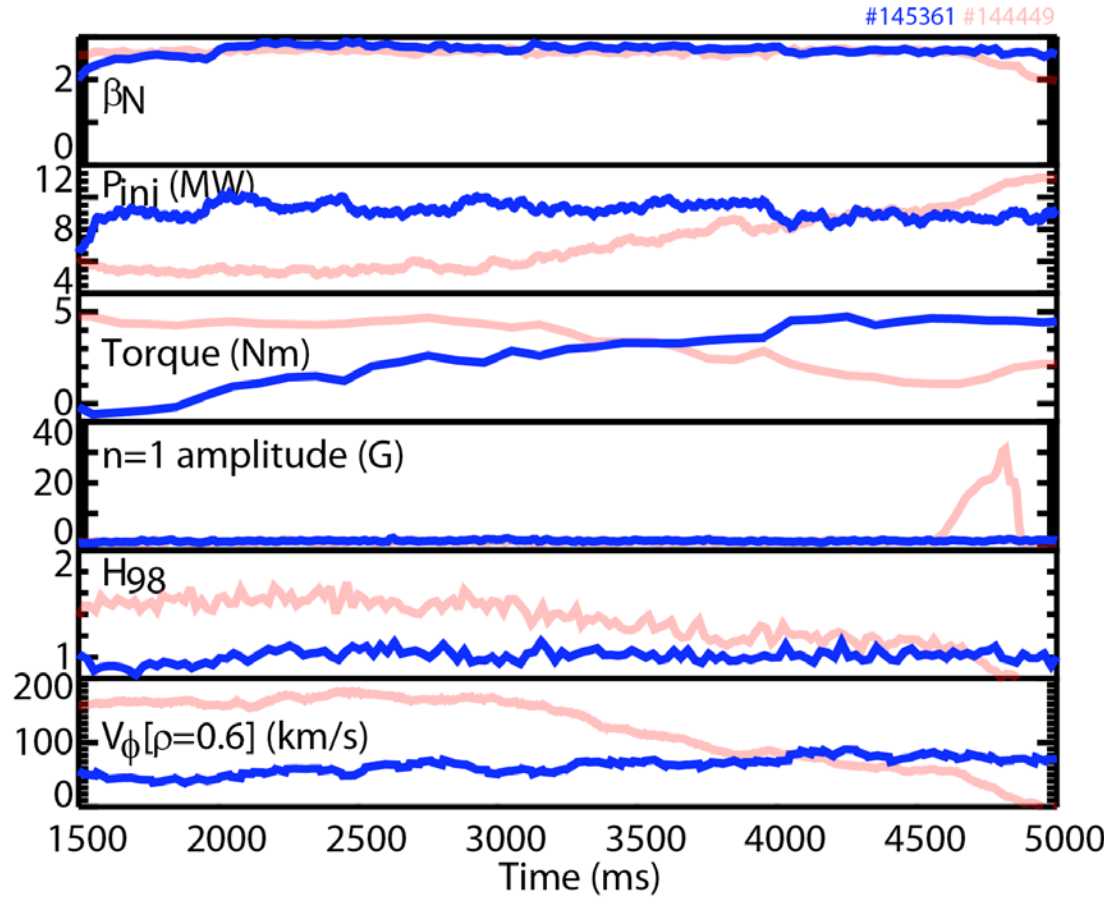




Higher Confinement Conditions Are Not Simply Recoverable by Ramping Up Torque

- **Relatively difficult to spin the plasma up from low rotation state**
  - Torque increased a factor of 4, rotation barely increased a factor of 2
- **Path-dependence in achieving high H factor**
- **Interesting case to study with transport models**





Summary

- **Advanced inductive discharges with normalized fusion performance G~0.35 approaching ITER Q=10 equivalent have been demonstrated with torque ~1 Nm and q_{95}~4**

- **Mechanism by which ECH assists low torque operation not yet clear**
  - Apparently different than replacement of helical deficit in bootstrap current associated with island
  - ECH leading to direct modification of classical Δ' stability parameter?

- **High β_N AI discharges exhibit significant levels of intrinsic torque**
  - As expected from previously determined scaling of DIII-D intrinsic drive

- **Significant reduction in confinement observed at reduced rotation**
  - Want to find ways to recover performance to further enhance attractiveness of scenario for low rotation operation