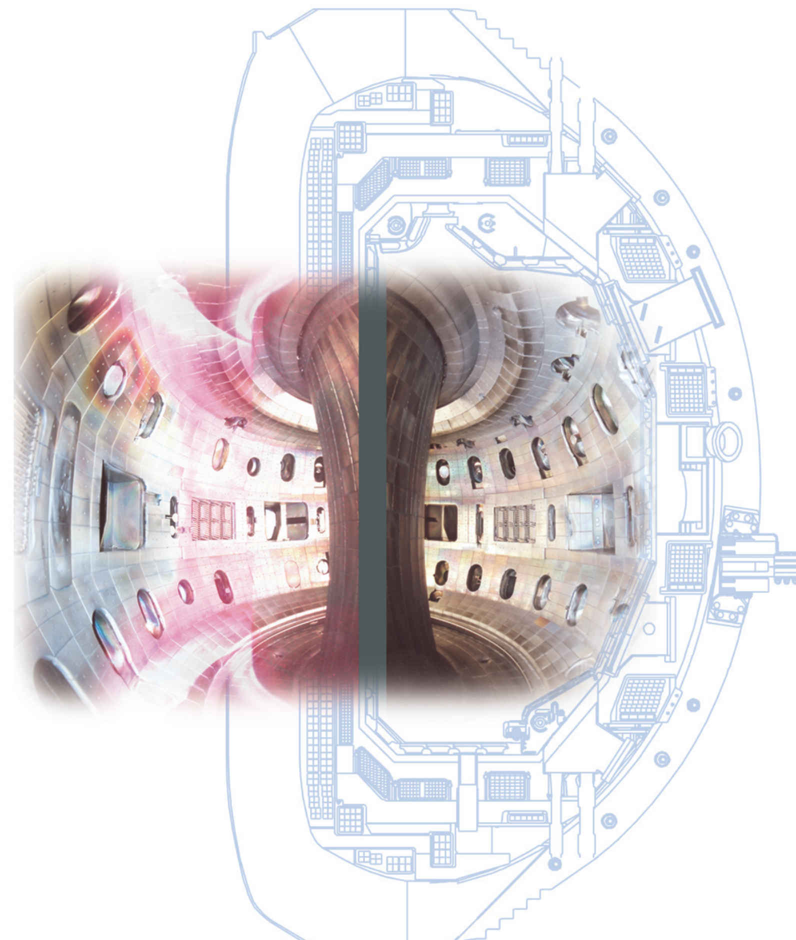
Progress on Advanced Tokamak and Steady-state Scenario Development on DIII–D and NSTX

by
E.J. Doyle
University of California,
Los Angeles

for the DIII–D and
NSTX Research Teams



Presented at the
33rd European Physical Society
Conference on Plasma Physics
Rome, Italy

June 19-23, 2006

DIII–D NATIONAL FUSION FACILITY NSTX UCLA

Overview

- **Introduction — steady-state performance requirements**
  - Global DIII-D and NSTX progress
- **Plasma control capabilities are key to realizing steady-state scenarios:**
  - On DIII-D: Improved active RWM control for high β operation, new co-/counter-NBI capability for q-profile control, new lower divertor for improved density control
  - On NSTX: New active RWM control system, improved shaping
- **Improved understanding provides ability to predict and optimize plasma:**
  - Emerging understanding of ITB triggering at rational q values
  - Improved access to high β_N with q_{min}>2 and broad current profiles
- **Improved control and understanding improves performance:**
  - On DIII-D and NSTX sustained, but non-stationary discharges with $\beta_N \geq 4$
  - On DIII-D, stationary ITER demonstration discharges with relaxed $J(\rho)$: $\beta_N = 3.5$, $G \equiv (\beta_N{*}H_{89})/q_{95}^2 = 0.3$, $f_{NI} \sim 100\%$, with $f_{BS} \sim 60\%$
- **Summary**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Advanced Tokamak (AT) performance requirements for steady-state operation

- **Steady-state operation with Q≥5 is one of two key ITER performance objectives**
  - AT research seeks to develop steady-state, high performance operating scenarios for ITER and beyond, from a demonstrated scientific basis. Major program element on both DIII-D and NSTX

- **Steady-state operation requires simultaneously achieving both:**

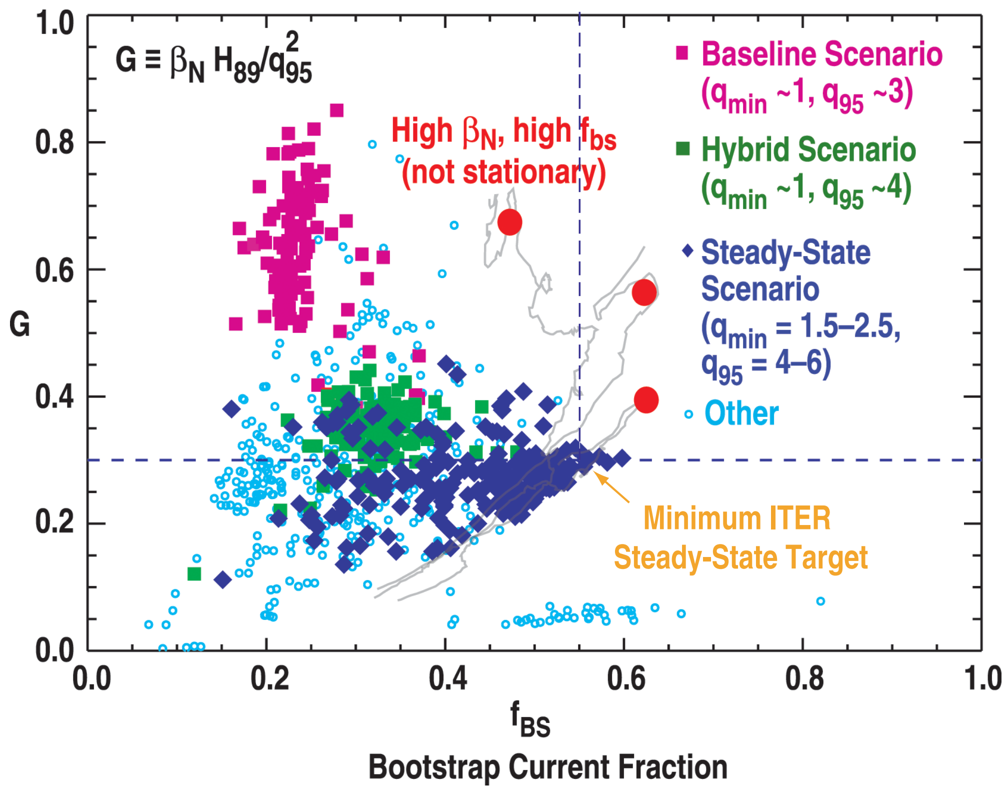
  1) 100% non-inductively (NI) driven current, from combination of bootstrap current and external current drive
  - **To be economic, bootstrap current f_{BS}>60%, implying q_{min}>1.5**
  - **Operate at reduced plasma current, e.g. 9-12 MA rather than 15 MA on ITER**

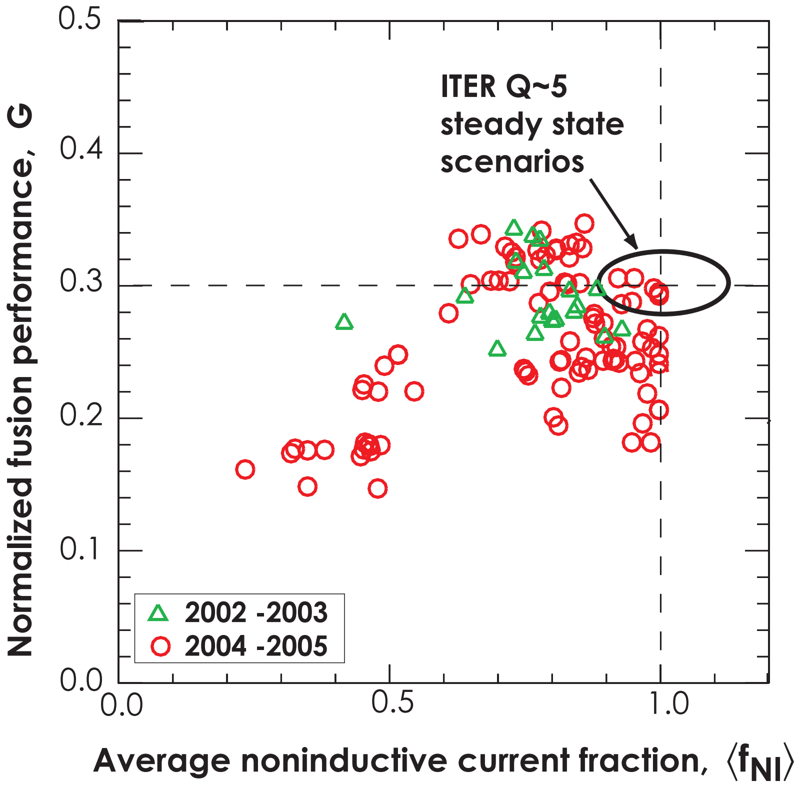
  2) High fusion gain, to maximize fusion power with reduced I_P
  - **Figure of merit for fusion performance is $G \equiv (\beta_N * H_{89})/q_{95}^2$, implying high beta, high confinement and high current-carrying capacity**
  - **G=0.3 corresponds to Q=5 operation on ITER**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

DIII-D has achieved ITER steady-state performance targets

- **DIII-D seeks to match ITER steady-state performance targets, e.g.**
  - f_{BS}>60%, with q_{min}>1.5
  - G ≥0.3, with q_{95} of 5, H_{89}>2, β_N >3





DIII-D NATIONAL FUSION FACILITY SAN DIEGO

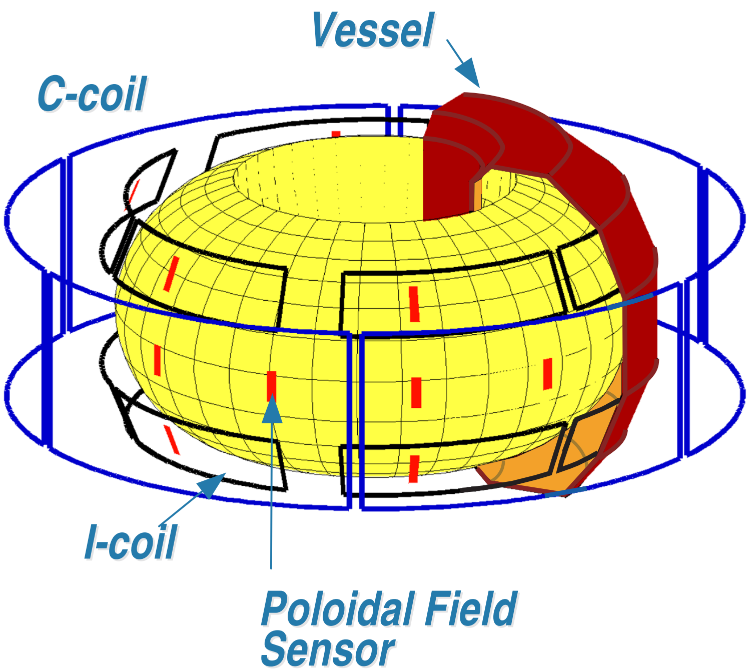
NSTX Performance now….

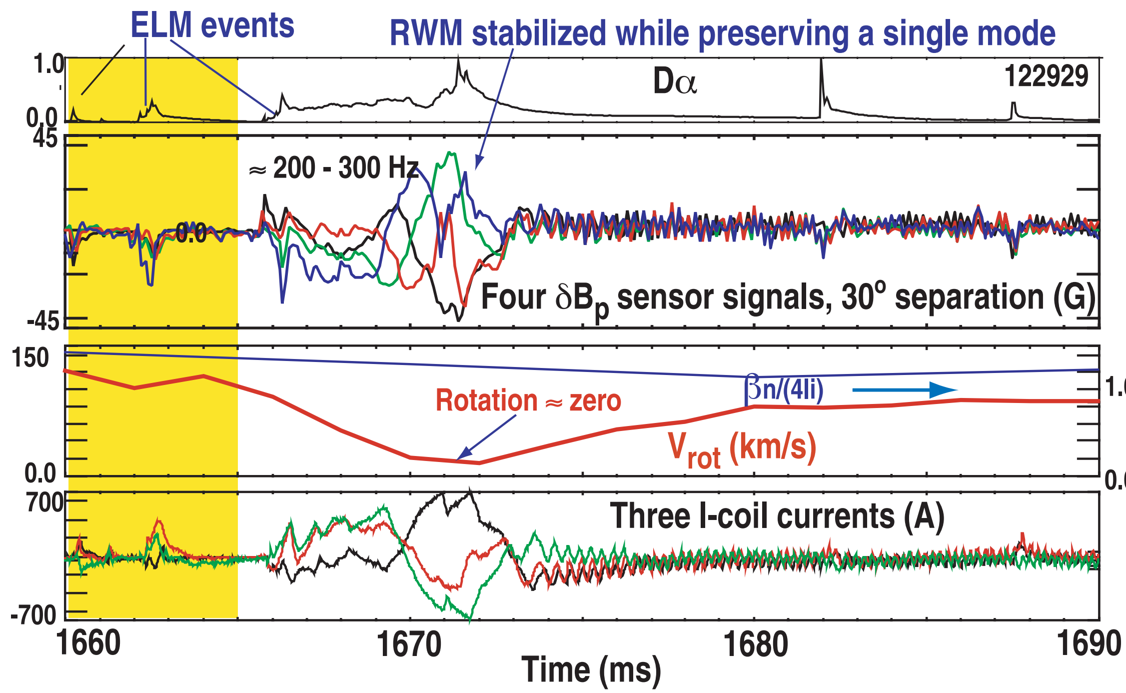
- NSTX, a spherical torus, seeks to match CTF performance targets, with ITER relevance

NEED PLOT HERE!

On DIII-D, new simultaneous control of error fields and resistive wall mode is key to sustained high β_N

- **Slow feedback control of external C-coils maintains high plasma rotation by dynamic error field correction**
- **Fast feedback control of internal I-coils allows stabilization of RWM**

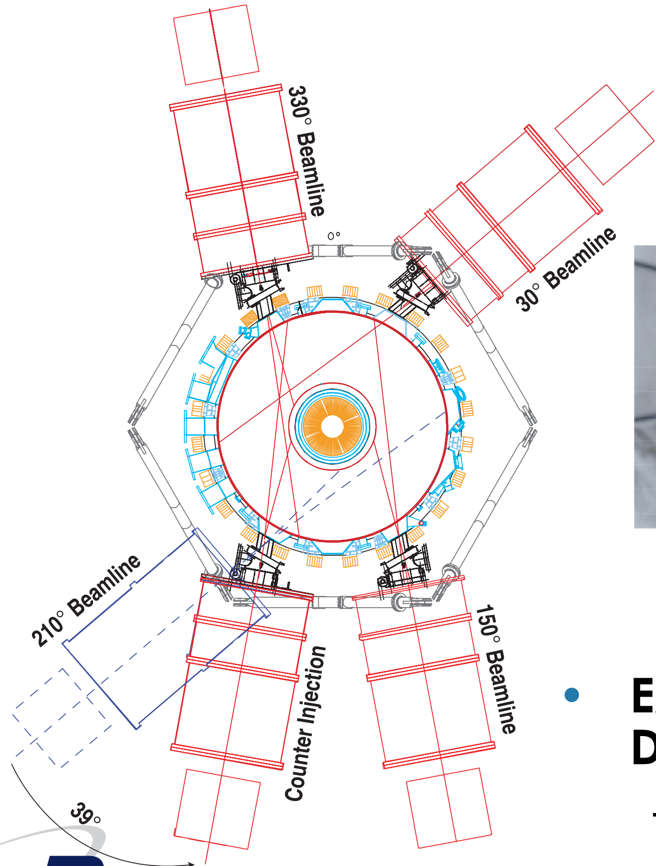


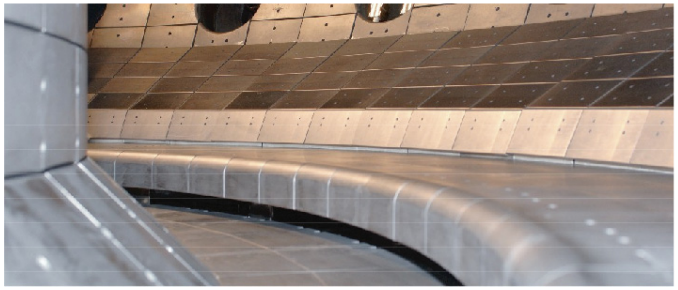


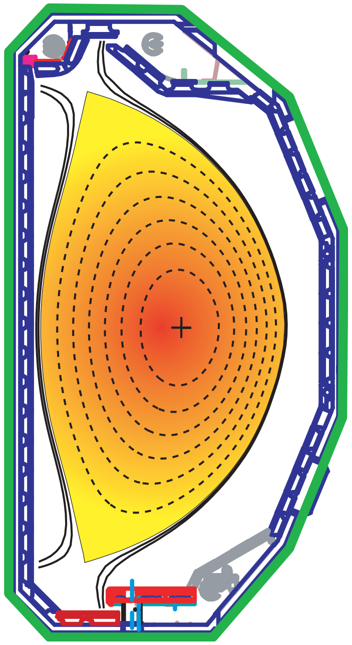
Major new AT control capabilities now operational on DIII-D, after machine upgrade

- **Reoriented counter beamline provides:**
  - Current drive/profile control
  - Rotation control

- **New high δ pumped lower divertor:**
  - ITER SN divertor configuration
  - Also ability to pump high δ, double null AT plasmas





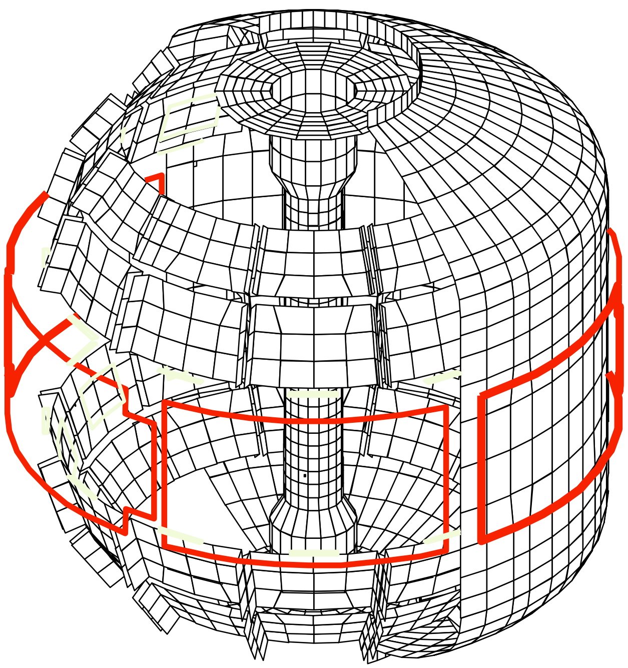


- **Expands and complements existing key DIII-D AT control tools:**
  - Strong shaping, ECCD, NBCD, density control via divertor pumping

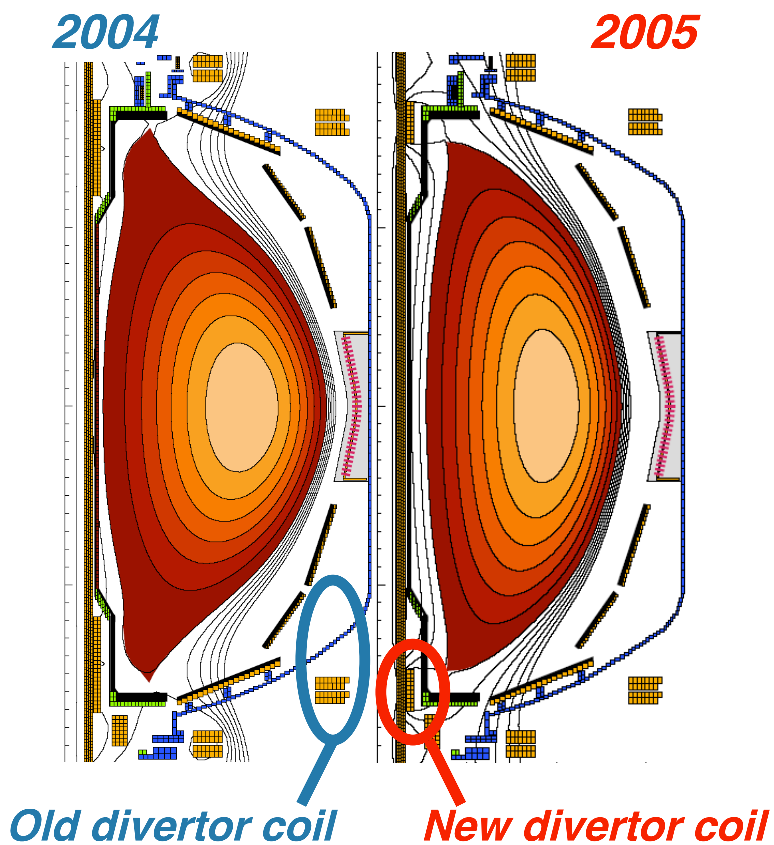
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

NSTX RWM and shaping control capabilities significantly expanded since 2004

- **Active RWM control system now operational. 6 external midplane coils, closely coupled to vacuum vessel, similar to ITER port plug designs**

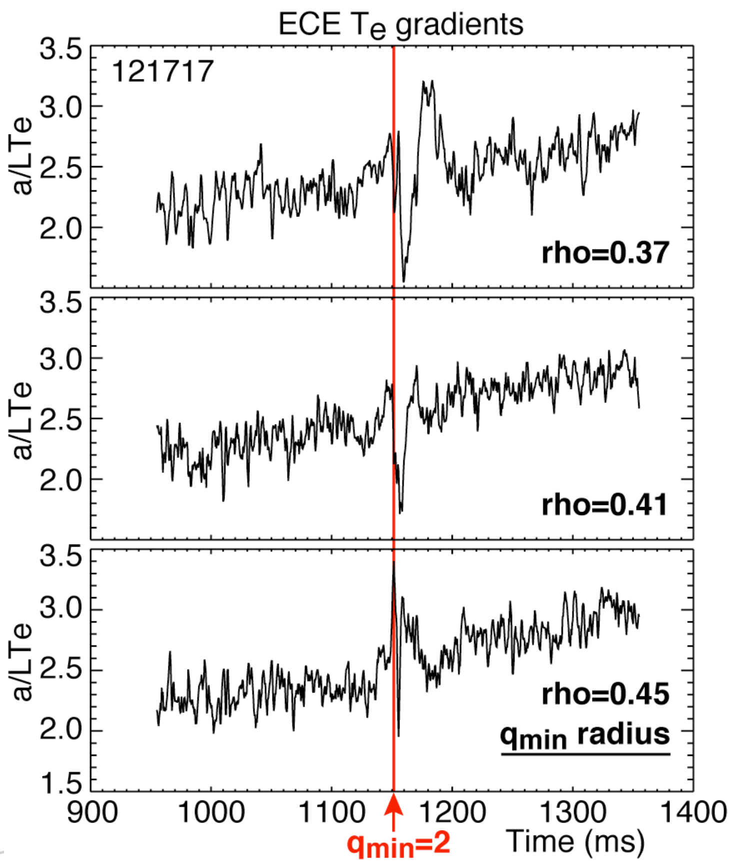


- **Coil modifications allow stronger shaping for higher performance**
  - $\delta \rightarrow 0.8$, $\kappa \rightarrow 2.7$

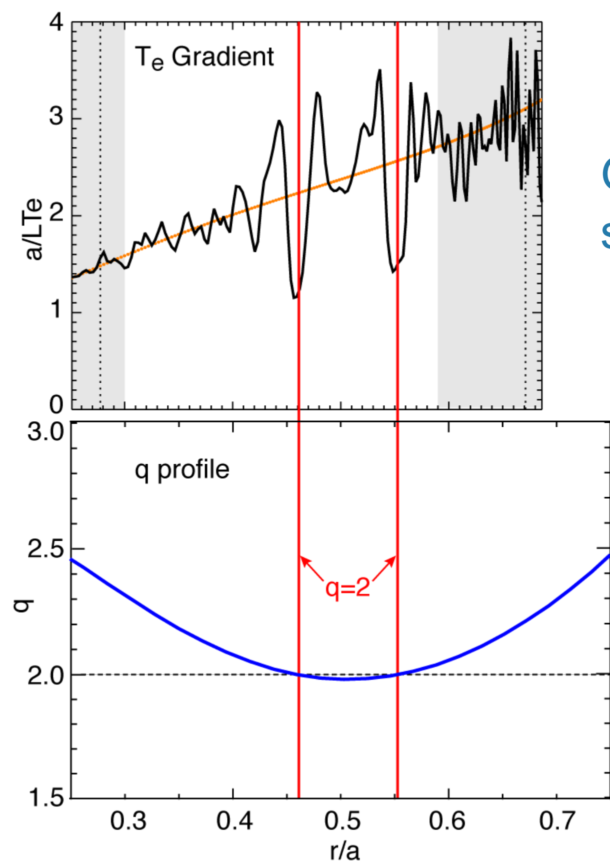


Emerging understanding of ITB triggering at rational q values as effect of zonal flow structures

- **ITBs typically triggered at rational q values on JET, also expected to be the case on ITER**
- **Comparisons of DIII-D data and nonlinear simulations using the GYRO code suggest that transport improvement is due to modifications in zonal flow structures associated with the low density of rational surfaces in the vicinity of low-order rational-q values ("gaps")**



Experiment

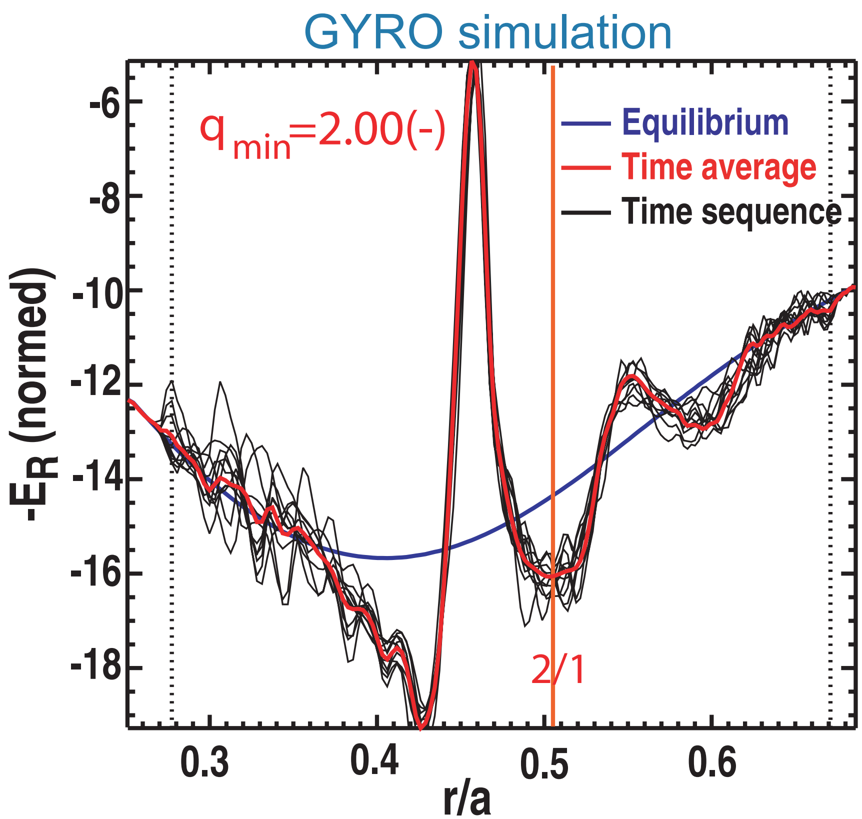


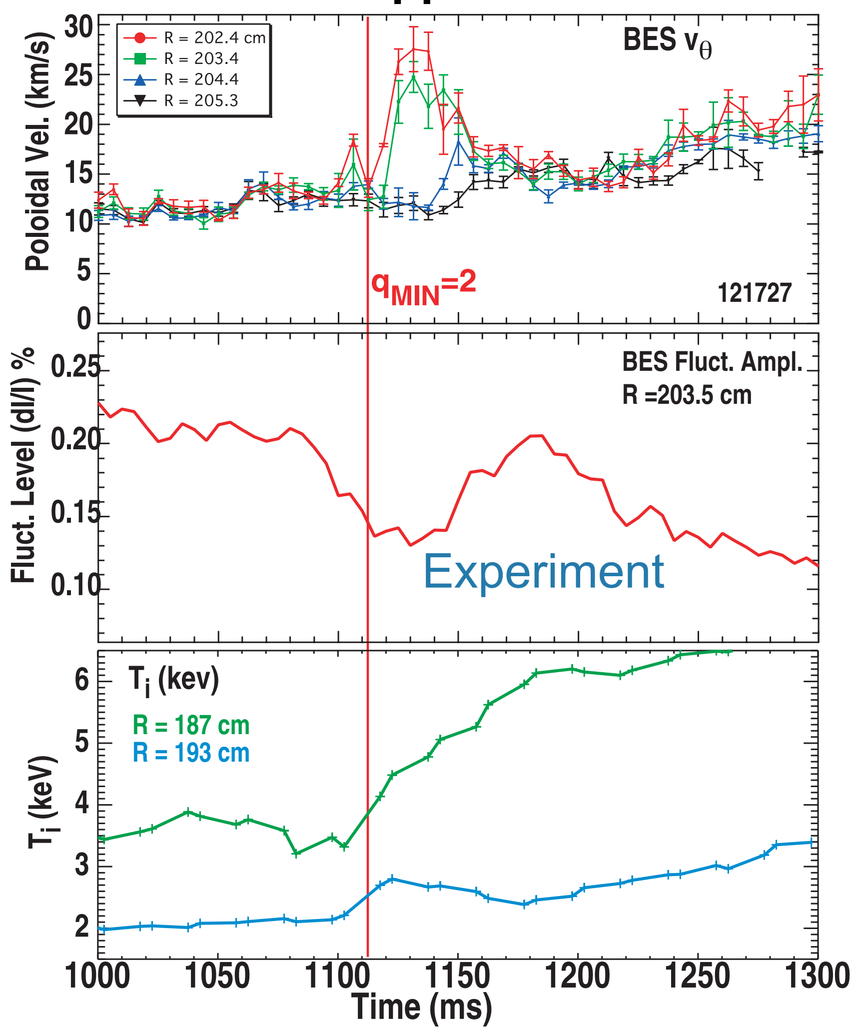
GYRO simulation

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Simulations and experimental data indicate ExB shear is the ITB trigger at rational q values

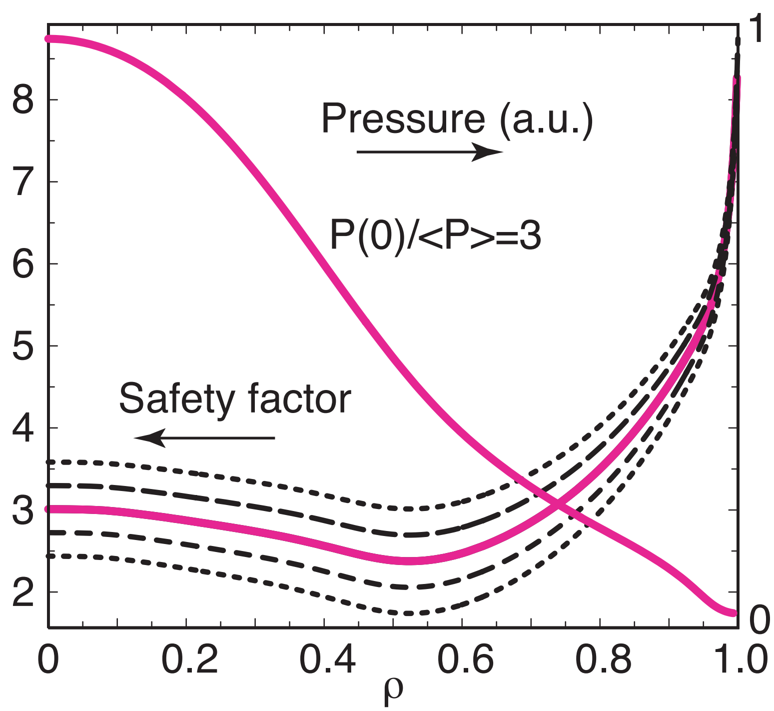
- **GYRO simulations show large time averaged E_r profile corrugation inside rational surface, generating large local ExB shear**
- **BES data indicate large flow shear, and turbulence suppression as ITB is triggered**

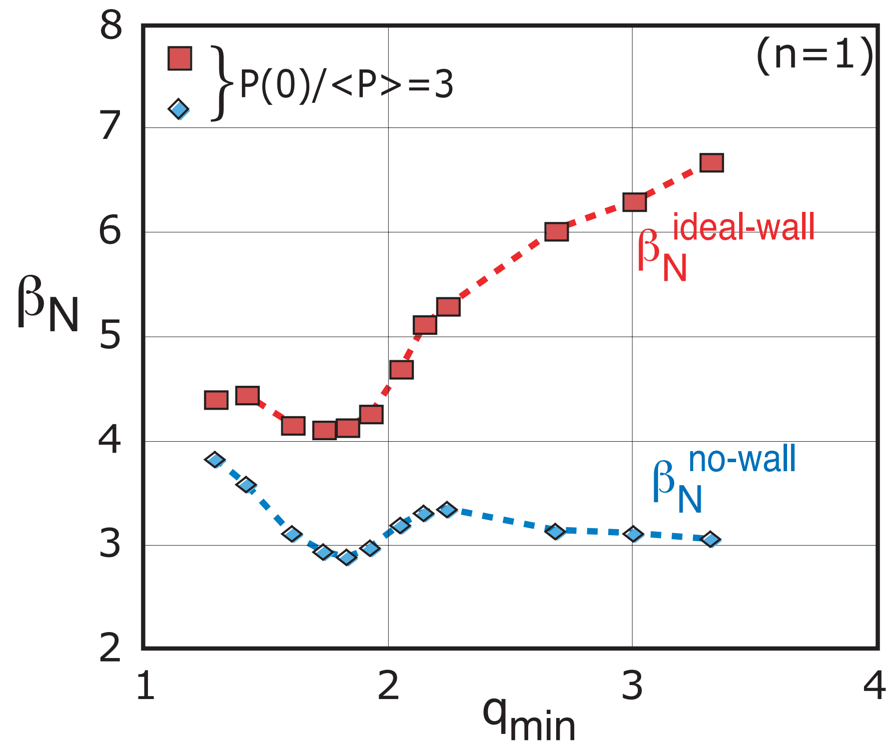




Stability modeling indicates path to high beta ($\beta_N \geq 4$) on DIII-D with $q_{MIN} \geq 2$ and broad current profiles

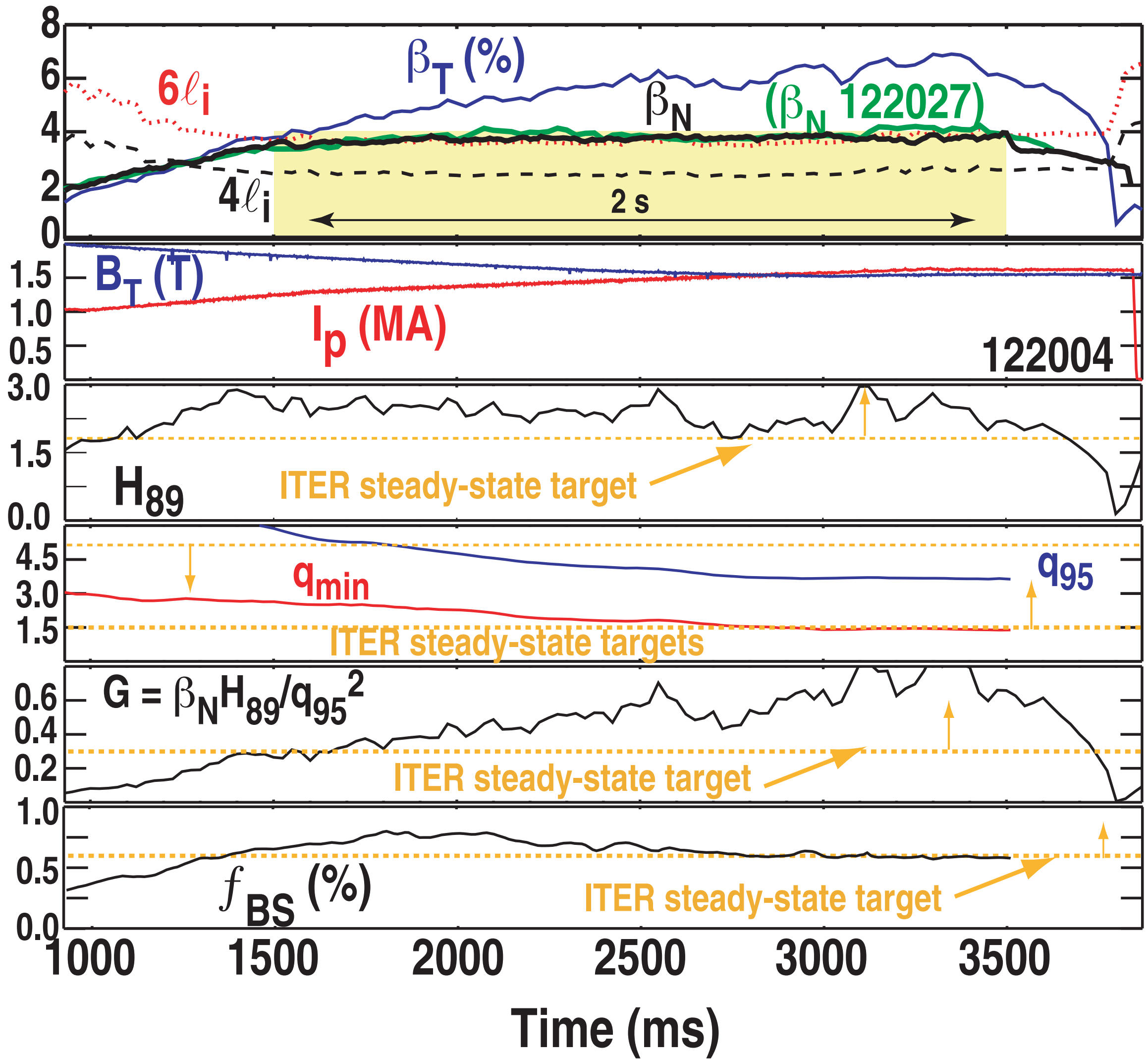
- **High n=1 ideal wall limit calculated with broad, hollow current profile, P(0)/<P>~3 and $q_{min} \geq 2$, due to improved coupling to wall**
  - **Broad q profile with weak NCS also favors ITB at large radius**





Credibility of AT scenarios strengthened by DIII-D operation with β_N=4 for 2 s, with broad current profile

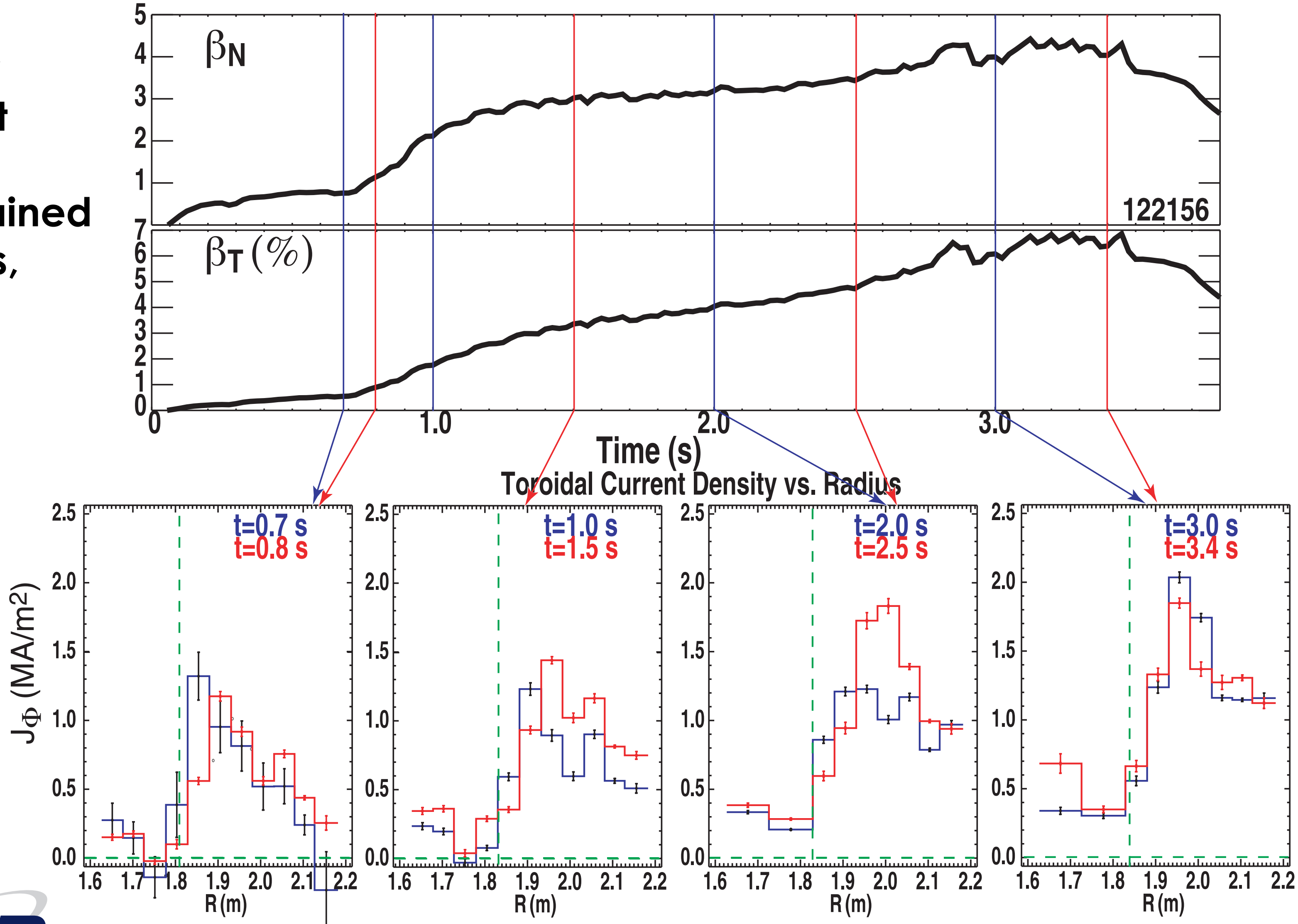
- $\beta_N > 6\ell_i$ for ~2 s
  - Relies on wall stabilization of the n=1 external kink mode (no-wall stability limit ~$4\ell_i$)
- **Non-stationary, due to I_p, B_T ramps**
- **ITB gives H_{89} ~2.5 for ~2 s**
- **High q_{min} leads to high bootstrap current fraction, f_{BS} >60%**



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

MSE measurements show hollow, broad current profile is created and maintained for > 1 τ_R

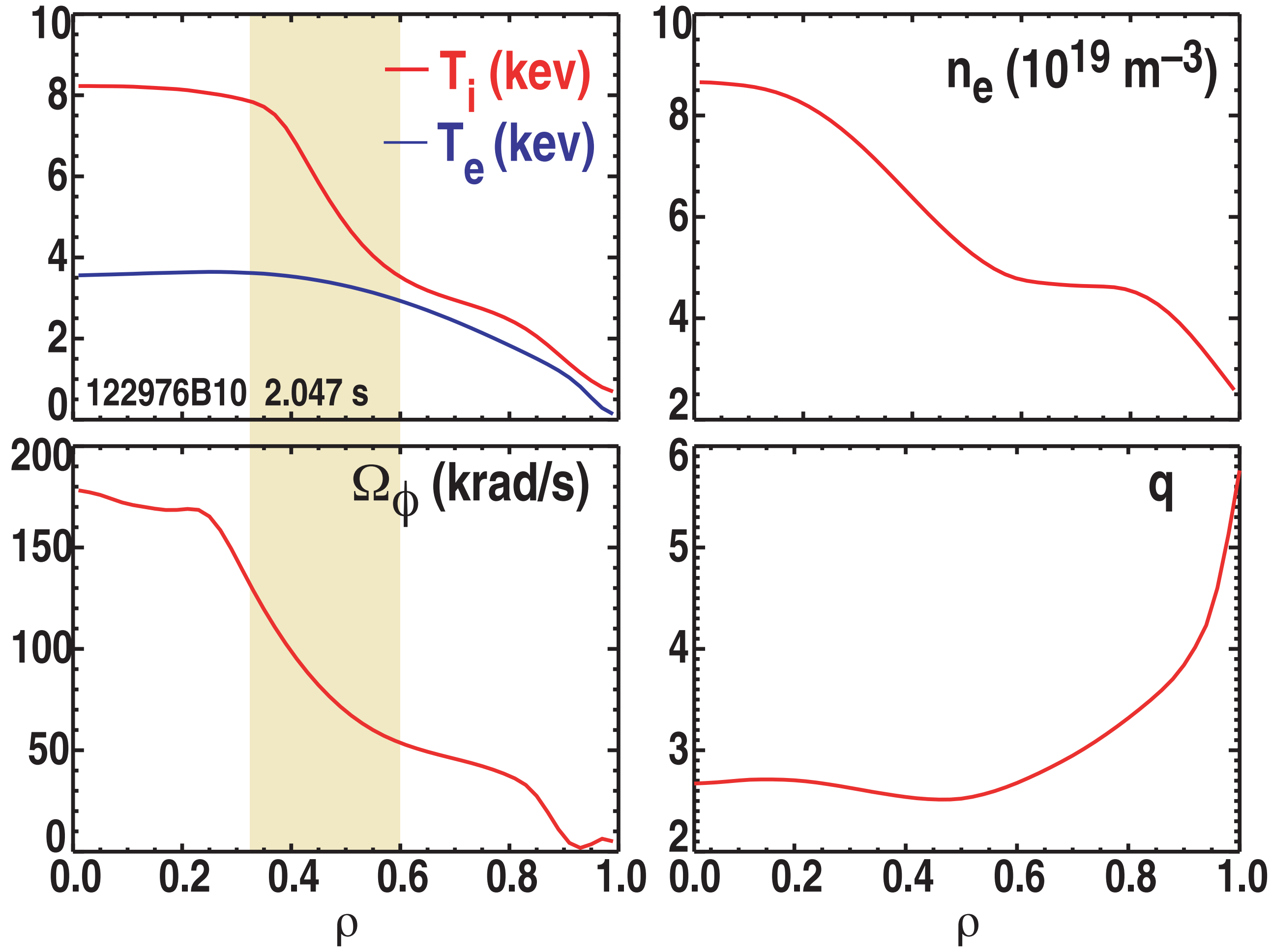
- **Hollow current profile maintained for >3 s, τ_R~2 s**



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

These discharges also demonstrate that ITBs are compatible with high β (β_N=4) operation

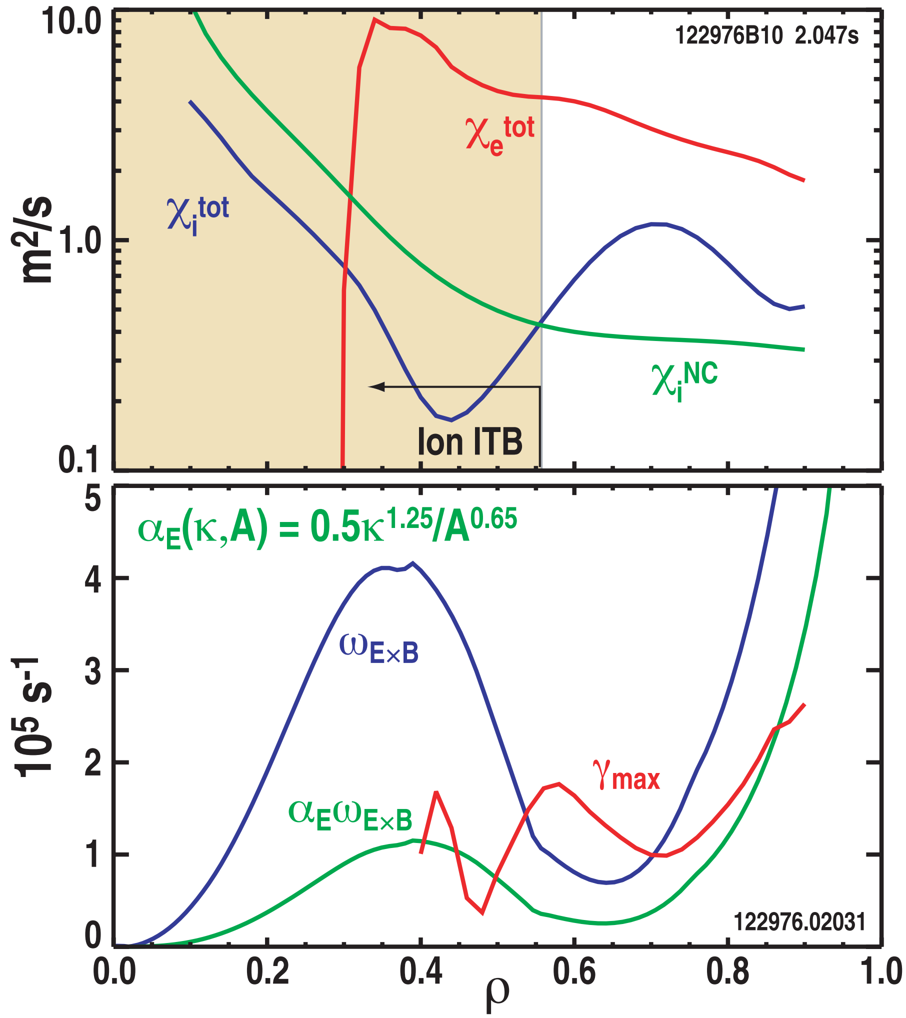
- ITBs are observed in T_i, n_e and rotation profiles, but not in T_e
- Previously, ITB discharges limited to moderate β_N<3
- Pressure peaking factor is ~3



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Transport analysis confirms presence of ITBs

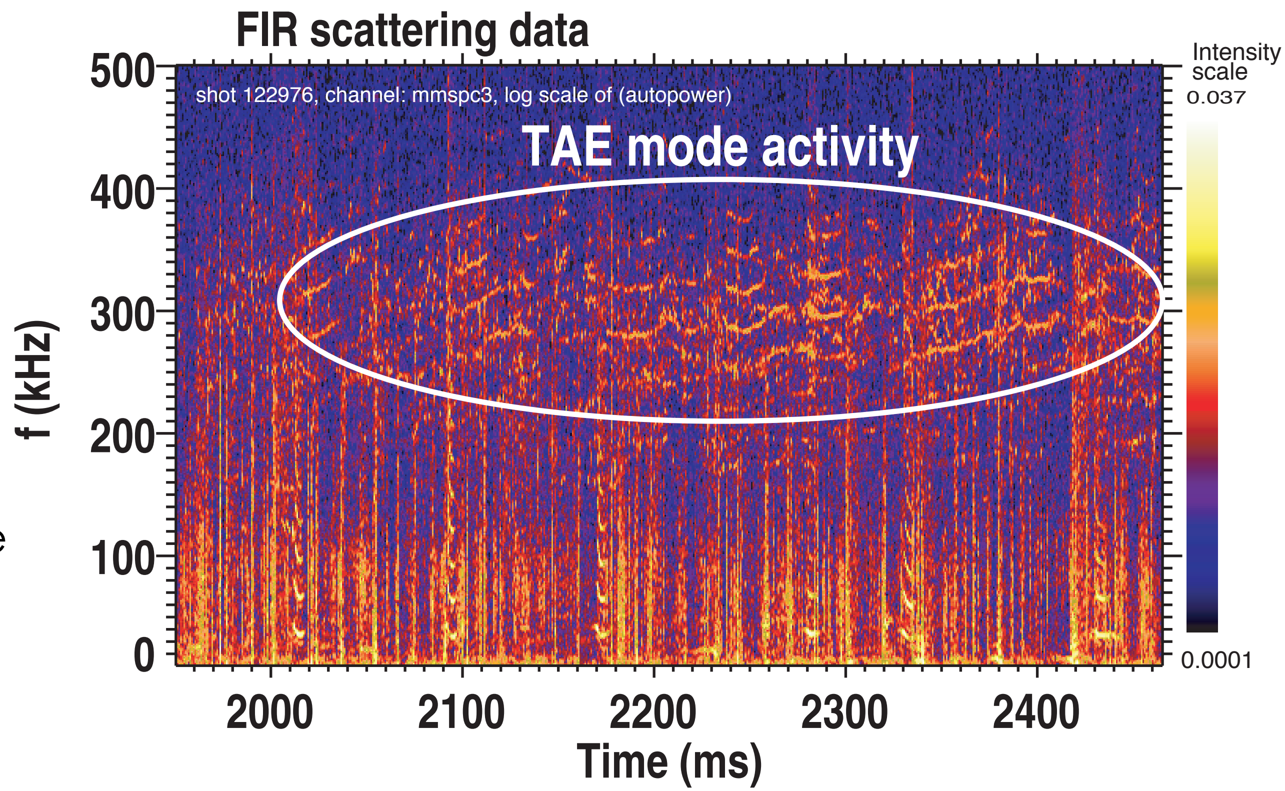
- **Ion transport reduced to neoclassical level - strict definition of ITB**
- **Gyrokinetic calculations with GKS code indicate ExB shearing rate is sufficient to quench or affect turbulence over much of plasma radius**
  - Recent GYRO calculations indicate α_E multiplier for ω_{ExB} may be appropriate
- **To match experiment, analysis needs to invoke anomalous fast ion diffusion**



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Aflven mode activity is ubiquitous in AT plasmas, and may be responsible for transport anomalies

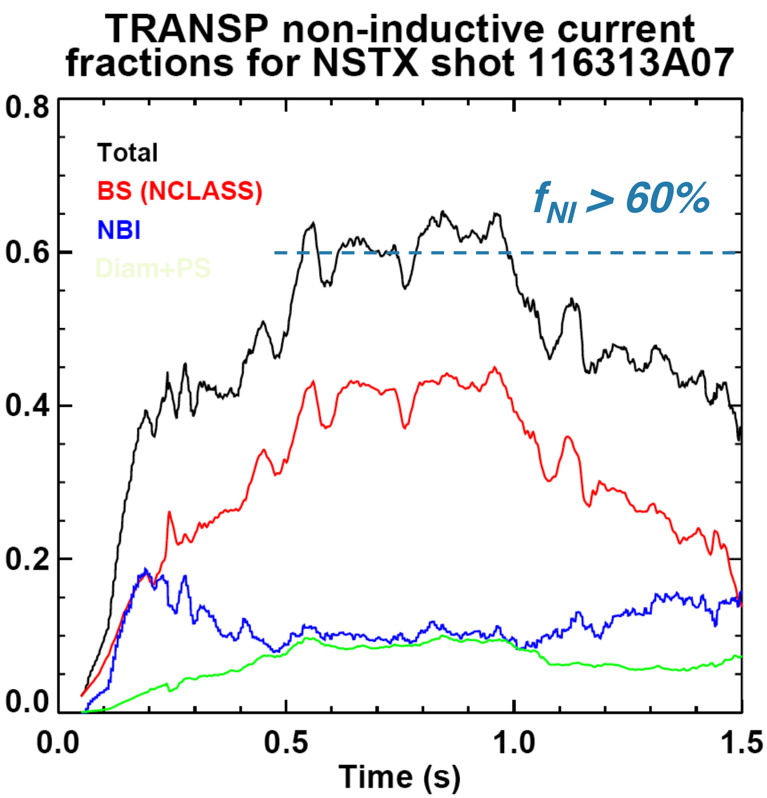
- **Transport caused by Alfven modes, NTMs, etc, is not accounted for in transport modeling**
- **Density fluctuations monitored by FIR scattering system at k~0.5-2.5 cm^{-1} show significant high frequency TAE modes**
  - Alternative/complementary explanation to "turbulence spreading" for transport analysis issues in AT discharges

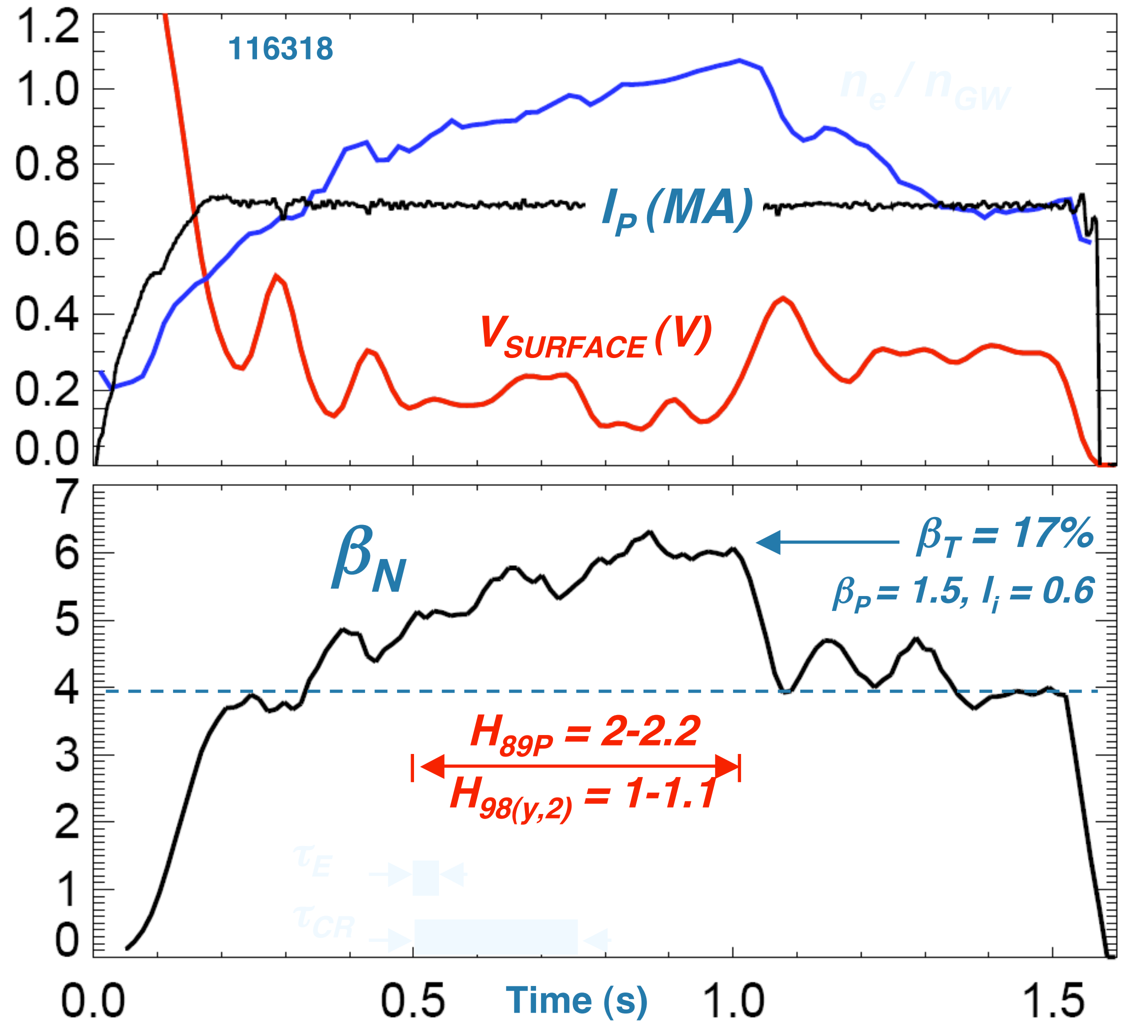


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

New sustained, high performance discharges open path to AT research on NSTX spherical torus

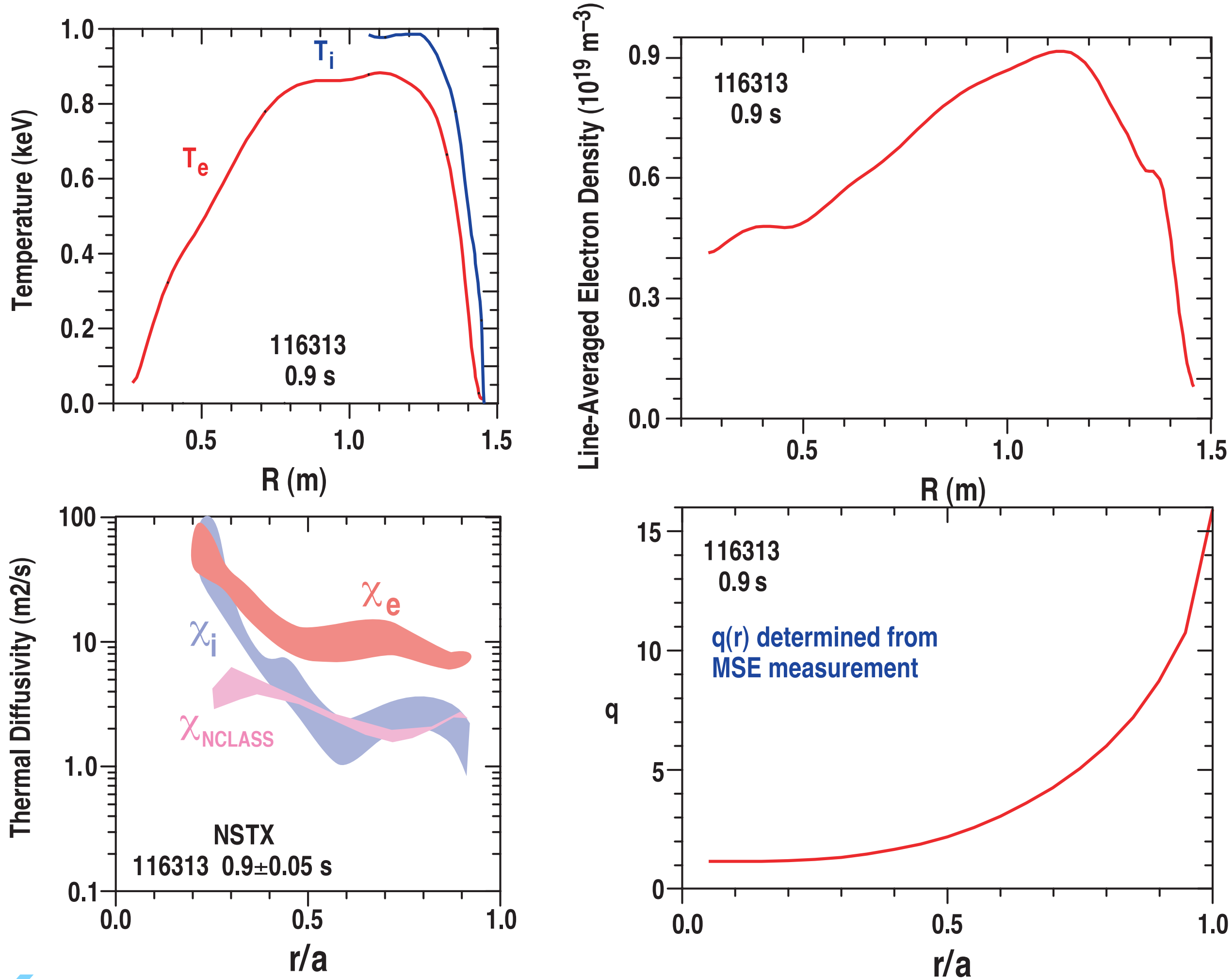
- β_N>4 maintained for >1 s, with f_{NI}>60%



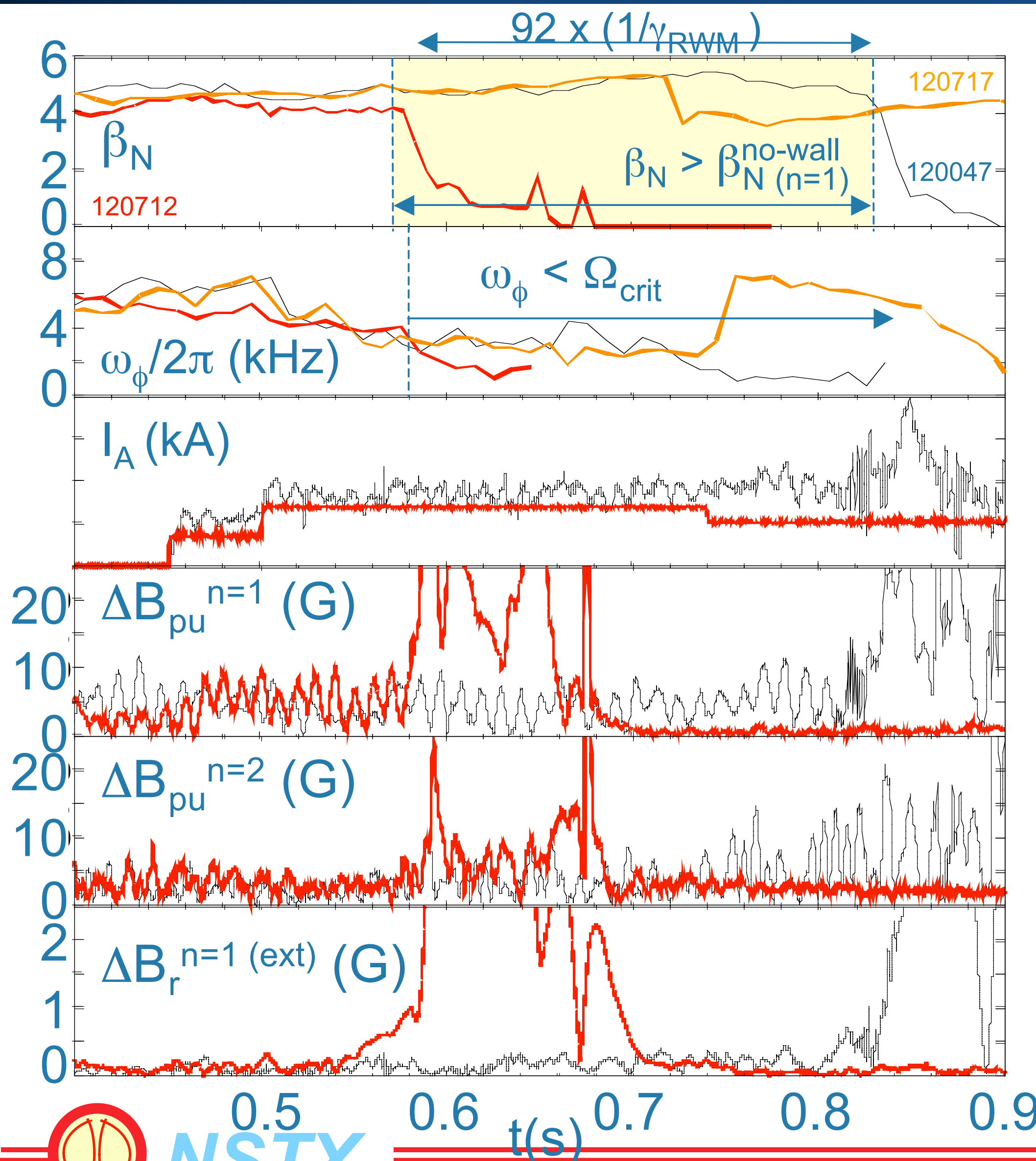


Transport analysis shows ion transport is routinely at neoclassical level on NSTX

- **Transport at neoclassical level is strict definition of ITB**
- **High frequency *AE activity also common on NSTX**



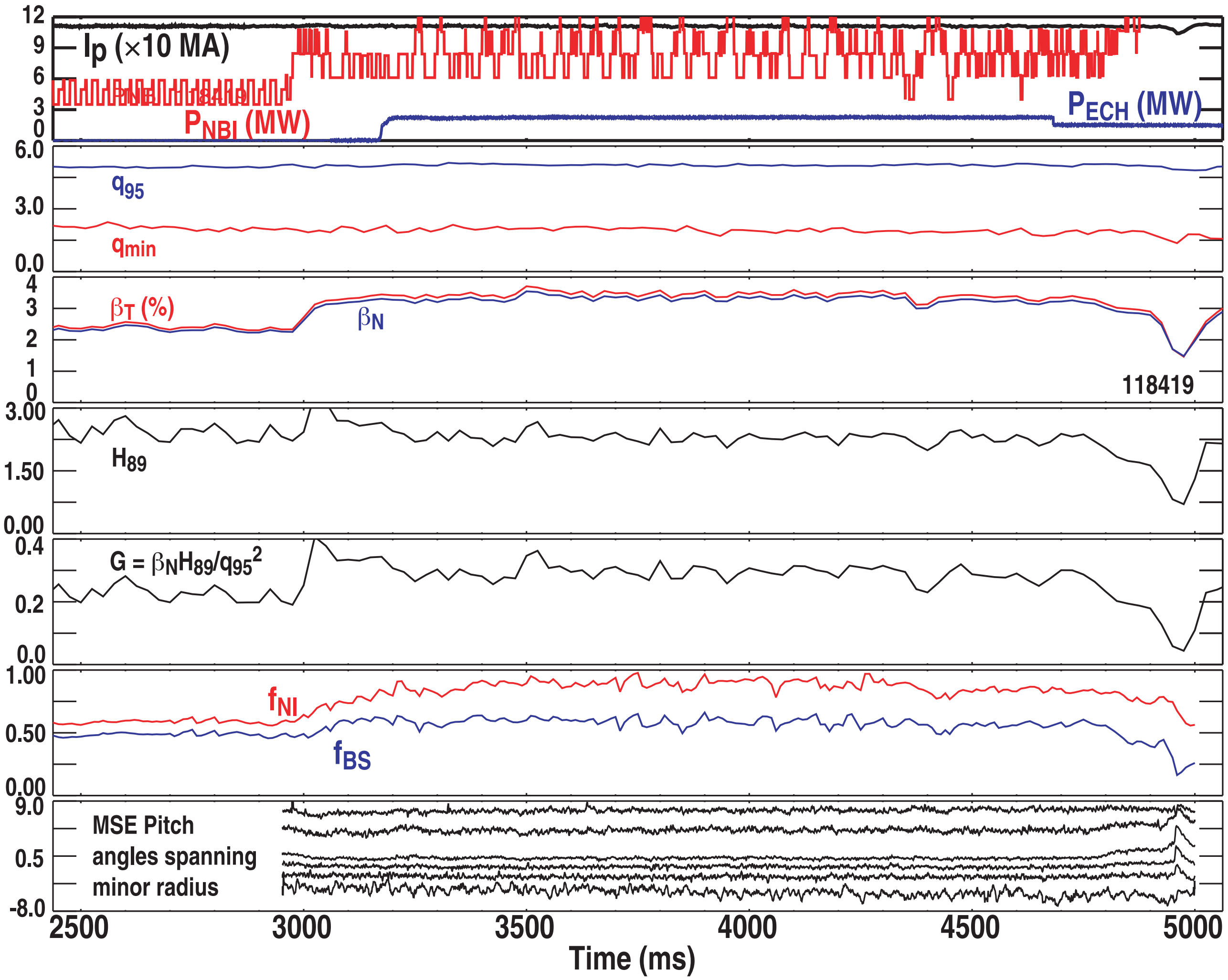
New NSTX RWM control system has demonstrated stabilization for ~90/γ_{RWM} at low ITER-relevant rotation



- **Plasma rotation reduced by non-resonant n=3 magnetic braking to less than half predicted ITER critical rotation rate**
  - Zhu, et al., PRL June 2006

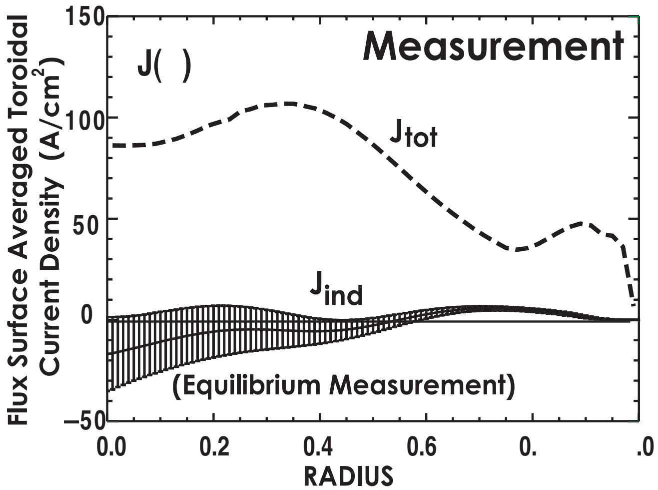
Stationary DIII-D discharge with near-ITER steady-state performance

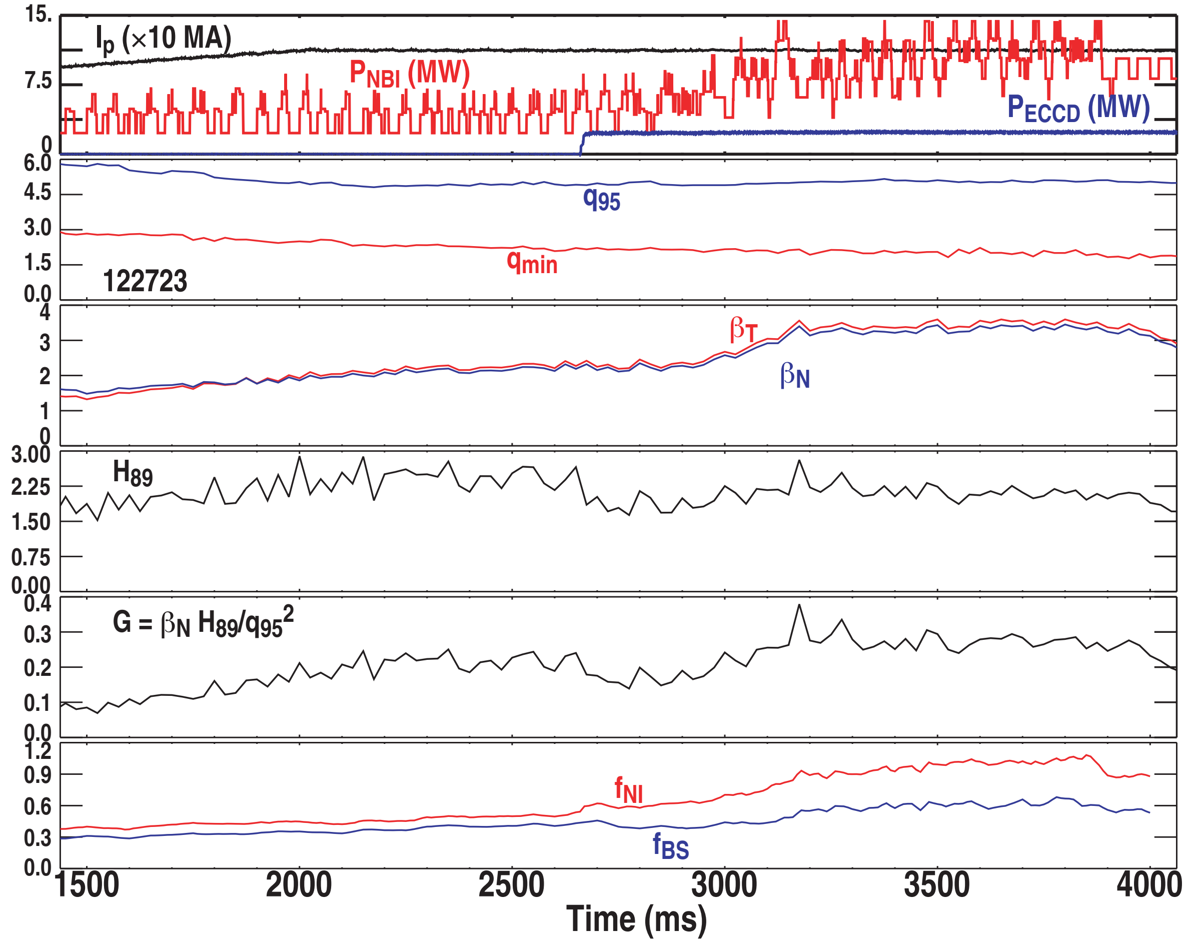
- **Meets all ITER steady-state requirements, except f_{NI} of 90-95%, rather than 100%. MSE signals are stationary for ~1 τ_R**



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

ITER steady-state demonstration discharge, meeting all target requirements, with good current profile alignment

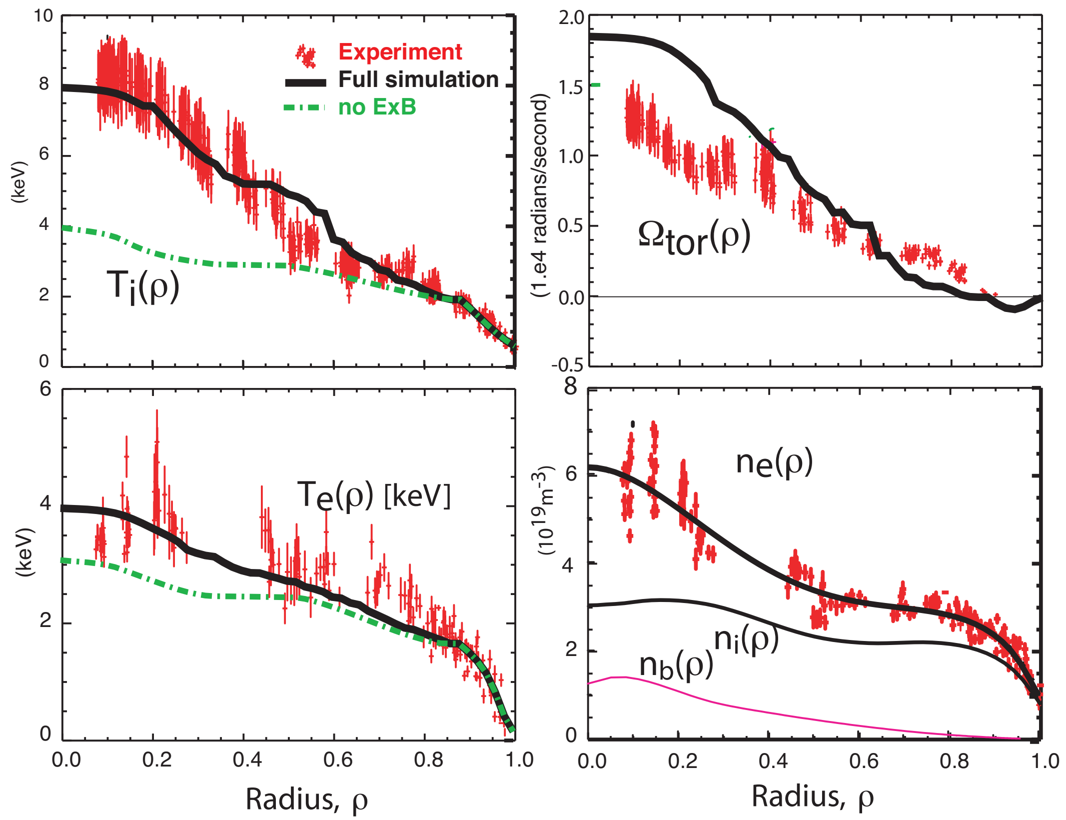




DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GLF23/ONETWO model agrees reasonably with experiment, providing benchmarked ITER modeling capability

- **GLF23 transport model reproduces experimental profiles if ExB shear effects included**



- **Model predicts ITER is capable of steady-state performance with Q>5 [Murakami, et al., PoP (2005)]**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Summary

- **Demonstration discharges on DIII-D greatly enhance confidence in achieving ITER steady-state performance targets**
  - β_N =3.5, $H_{89} \geq 2.25$, G~0.3, f_{BS} =60%, with f_{NI} = 100%

- **NSTX and DIII-D have sustained high performance operation at $\beta_N \geq 4$**
  - Offers prospect of higher steady-state performance on ITER, and meeting ST CTF goals

- **Improved control and understanding is key to progress**
  - E.g. active RWM control for sustained high beta operation
  - Modeling indicates operation at $\beta_N \geq 4$ possible with broad current profiles and q_{MIN}>2
  - Emerging understanding of ITB triggering at rational q values as effect of zonal flow structures

DIII-D NATIONAL FUSION FACILITY SAN DIEGO