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

by
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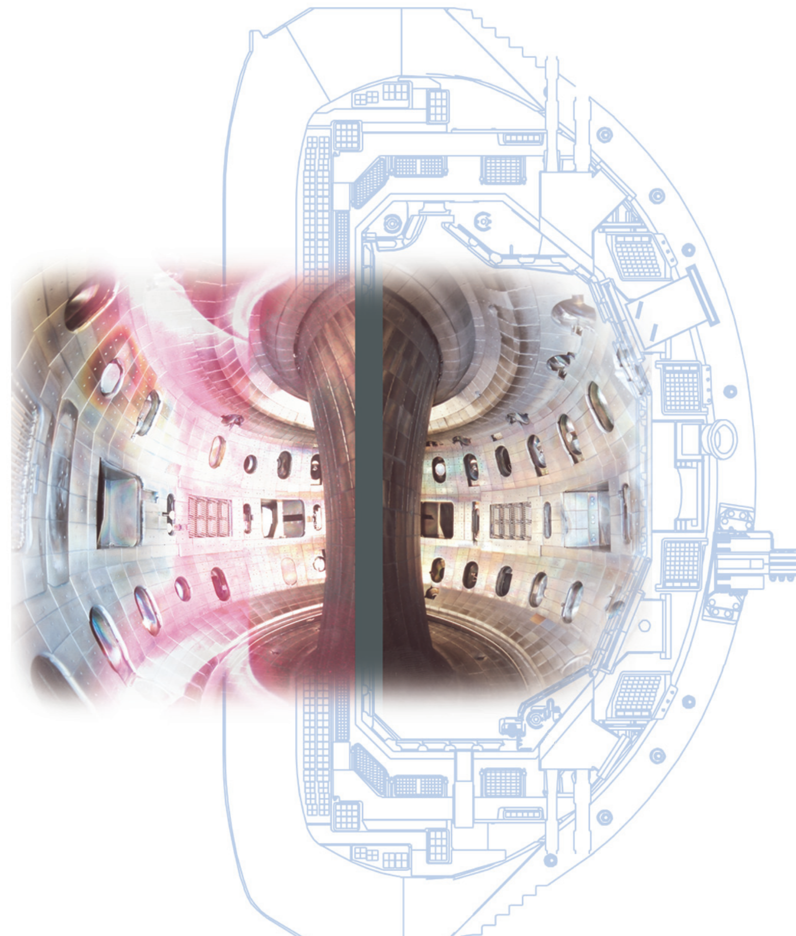
for the DIII–D and
NSTX Research Teams



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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 $J(\rho)$: $\beta_N = 3.5$, $G \equiv (\beta_N {*} H_{89})/q_{95}^2 = 0.3$, $f_{NI} = 100\%$, with $f_{BS} = 60\%$
- **Summary**

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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 $q_{95}>4$**
  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**

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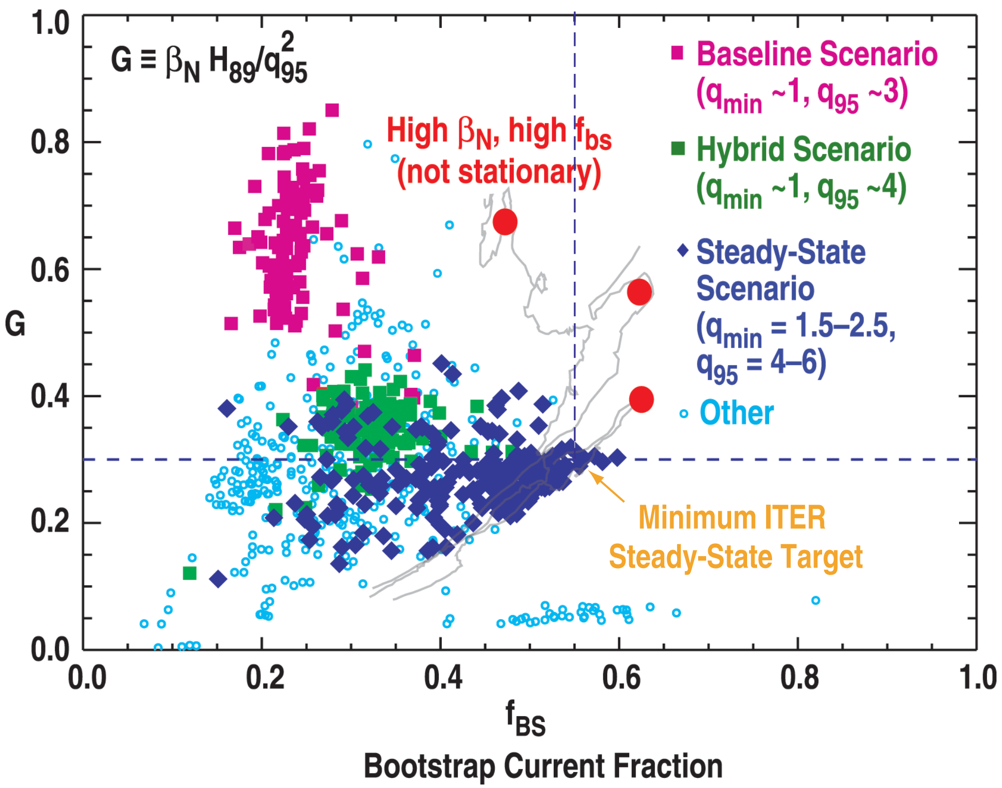
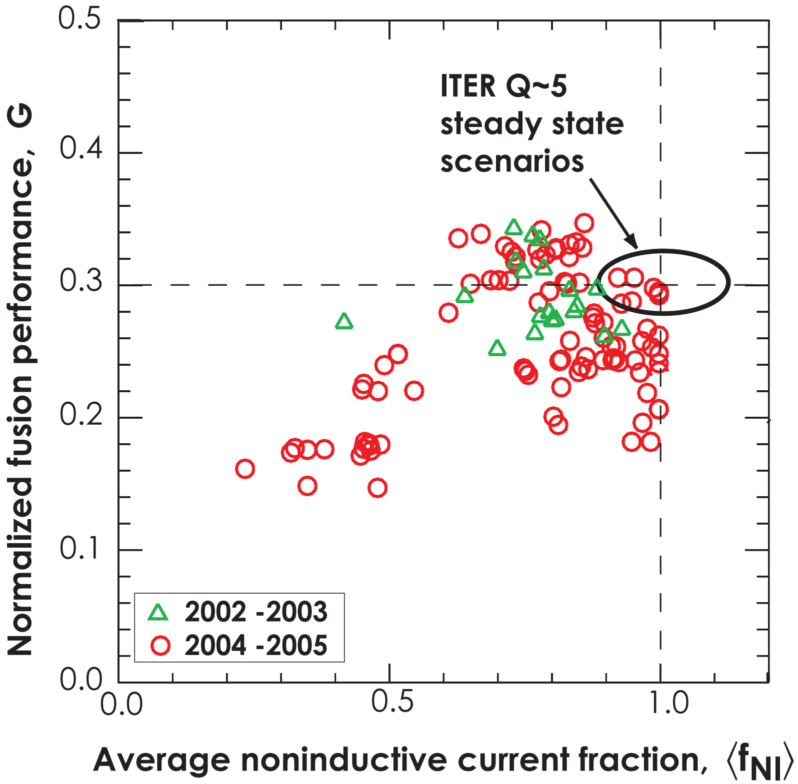
DIII-D has achieved noralized ITER steady-state performance targets

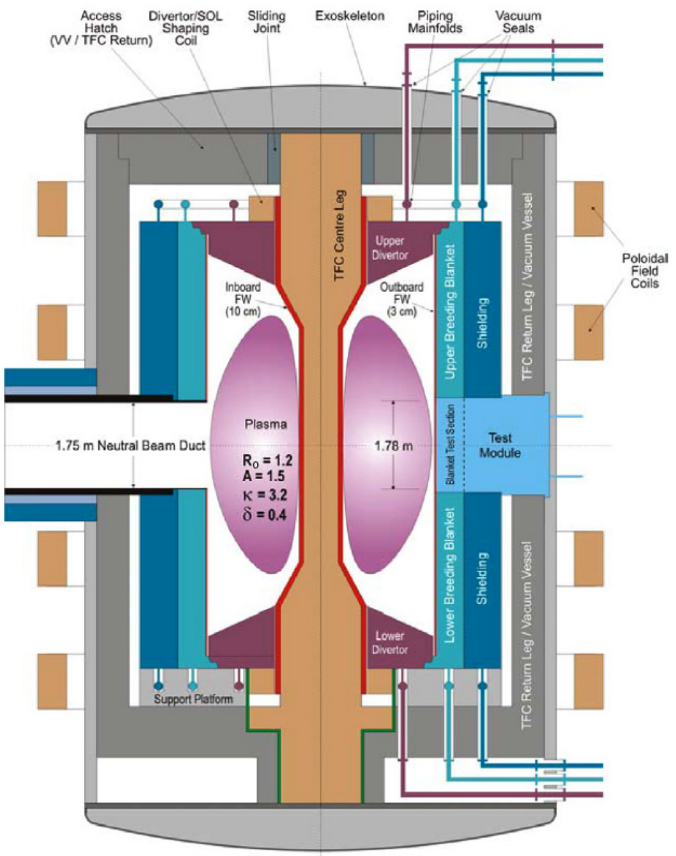
- **DIII-D seeks to match ITER steady-state performance targets, e.g.**
  - $f_{BS} \geq 60\%$, with $q_{min} > 1.5$
  - $G \geq 0.3$, with q_{95} of 5, $H_{89} > 2$, $\beta_N > 3$

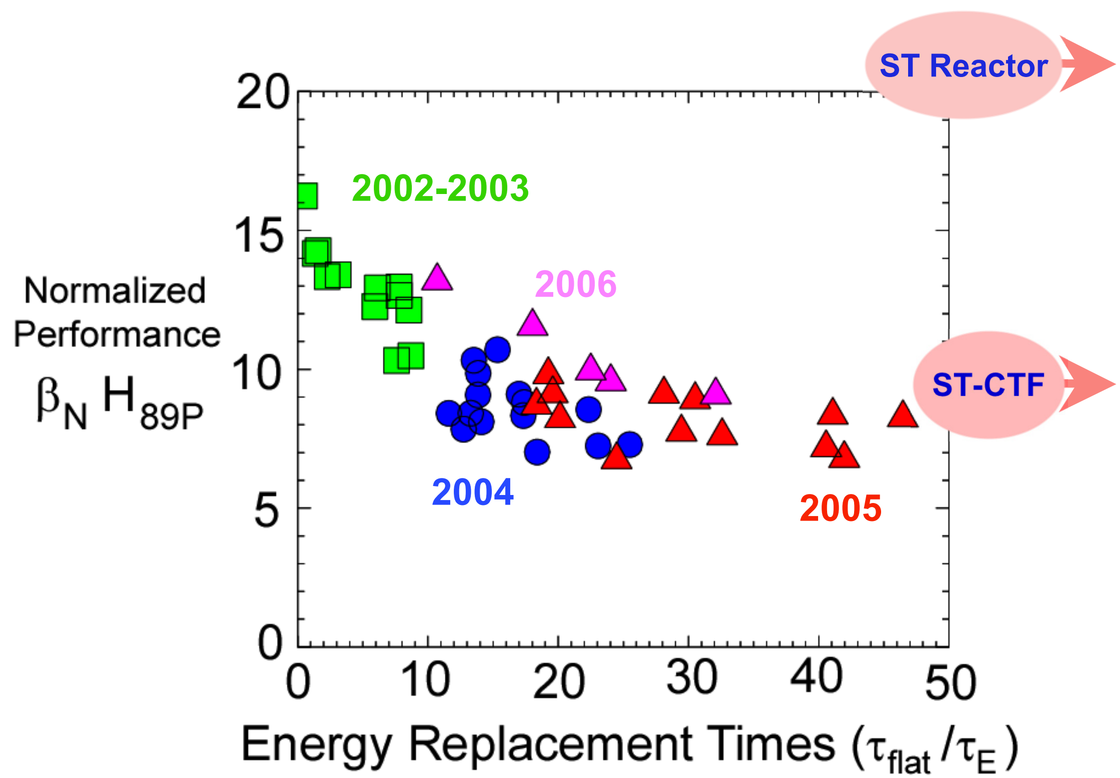




NSTX, a spherical torus, has achieved normalized targets for steady-state operation of a Component Test Facility (CTF)

- **NSTX seeks to match CTF performance targets, with ITER relevance**
- **ST-CTF goals are neutron flux of 2MW/m², β_N=4, β_T=21% H_{98}=1.3, f_{BS}=50%, with I_p=11 MA, R=1.2 m, A=1.5**





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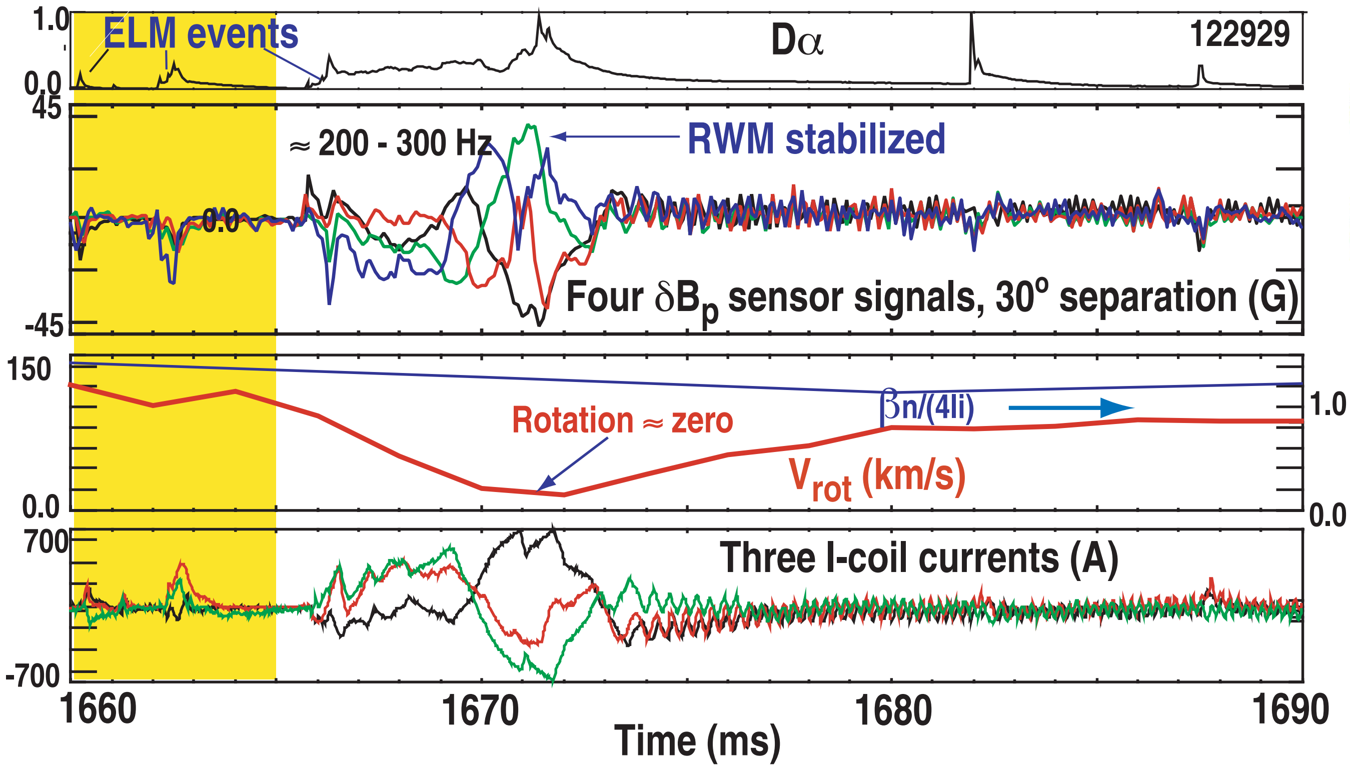
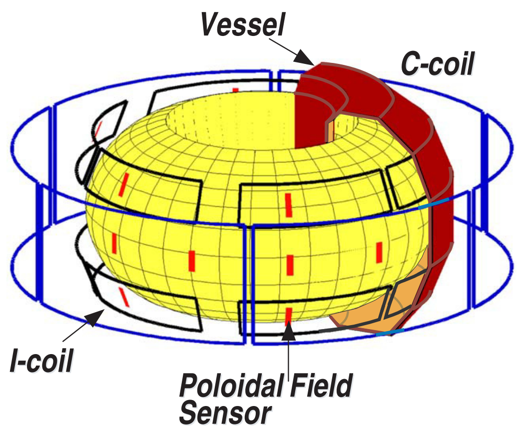
Robust RWM control is key to sustained high β_N operation at up to 50% above no-wall limit on DIII-D

- Combination of slow feedback control of external C-coils maintains high plasma rotation by dynamic error field correction, while fast feedback control of internal I-coils allows stabilization of RWM





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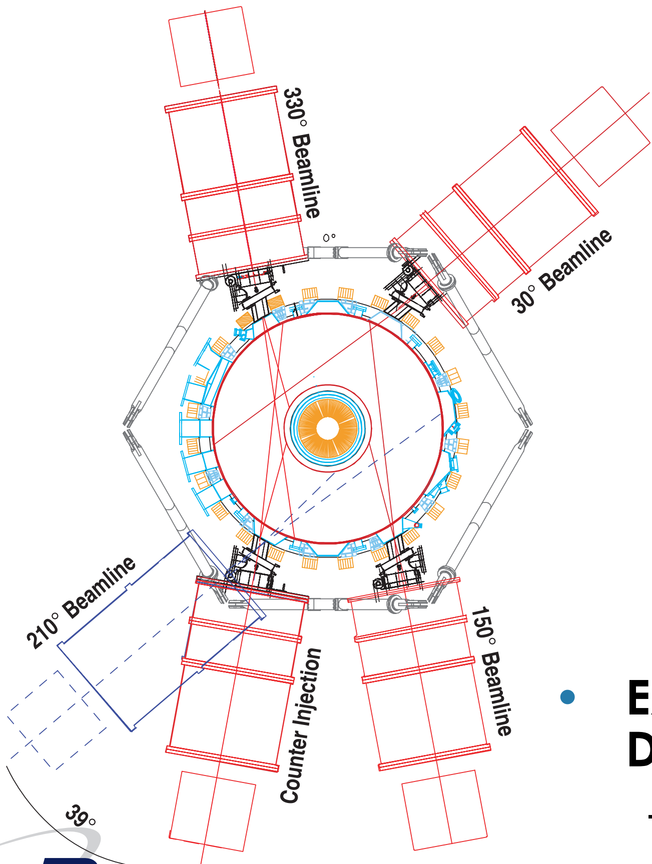
Counter-beamline implemented on DIII-D for improved transport and current profile control

- **Reoriented, counter-beamline provides:**
  - Reduced NBCD overdrive on axis, which tends to drive q_0 down
  - Extensive possibilities for transport control via changes in rotation. E_r shear, q-profile



- **Need plot here of new rotation data!**

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

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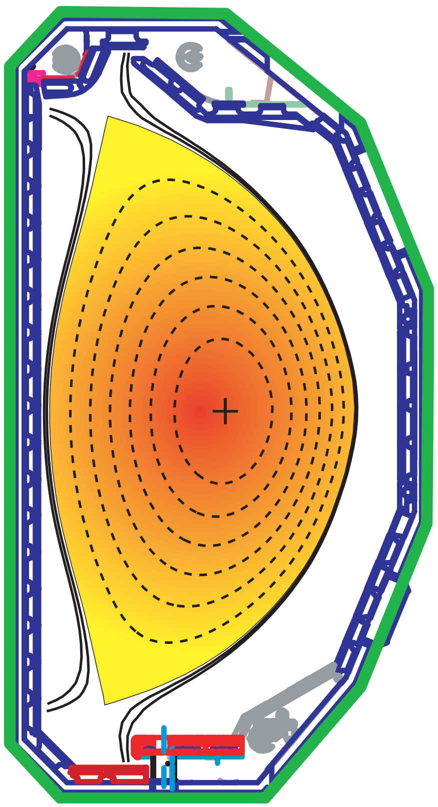
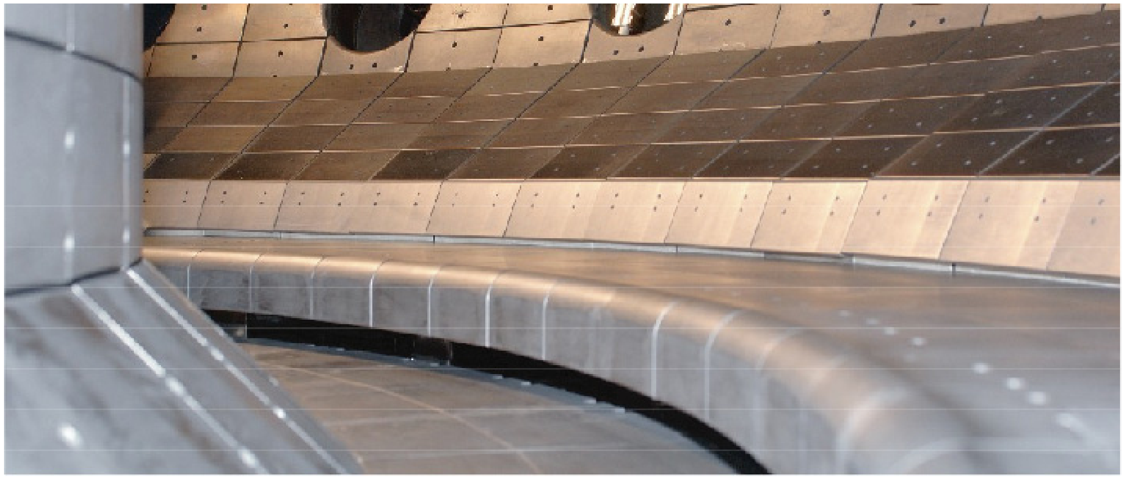
New high δ pumped lower divertor for density control over larger range of shapes

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





- **New capabilities expand and complement existing key DIII-D AT control tools:**
  - Strong shaping
  - ECCD, NBCD, FWCD
  - Density control via divertor pumping

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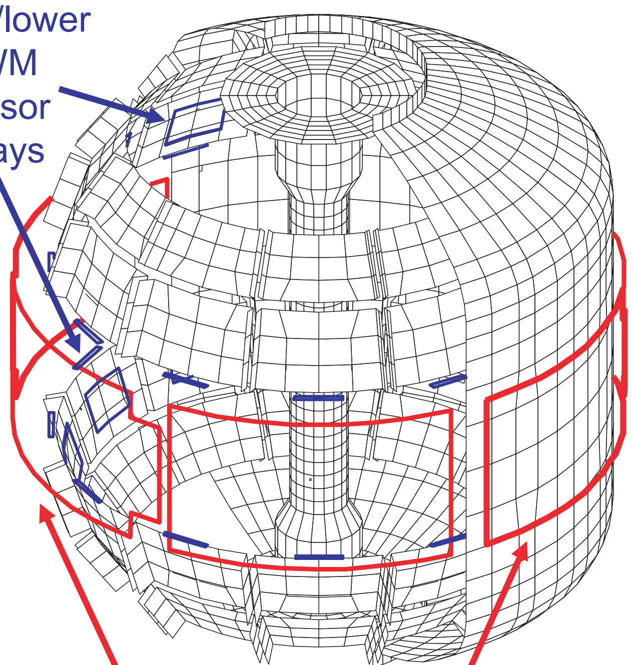
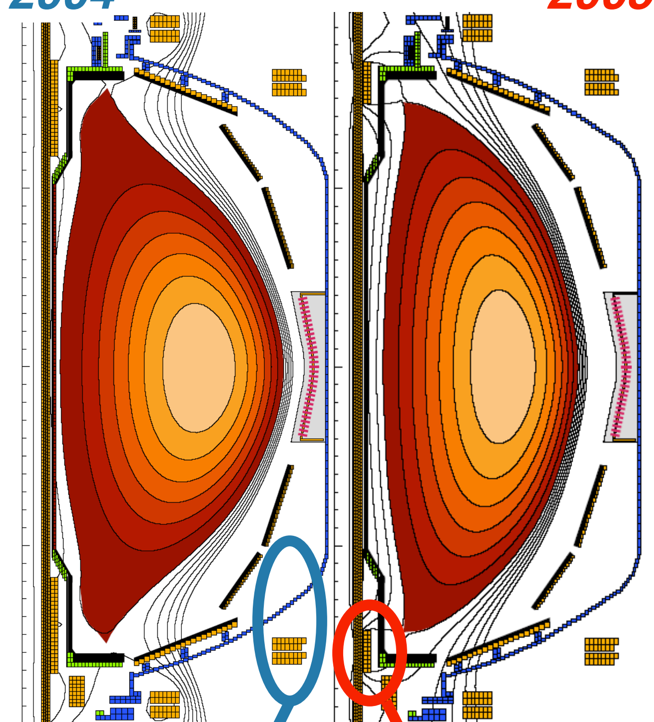
NSTX RWM and shaping control capabilities improved for long pulse higher performance

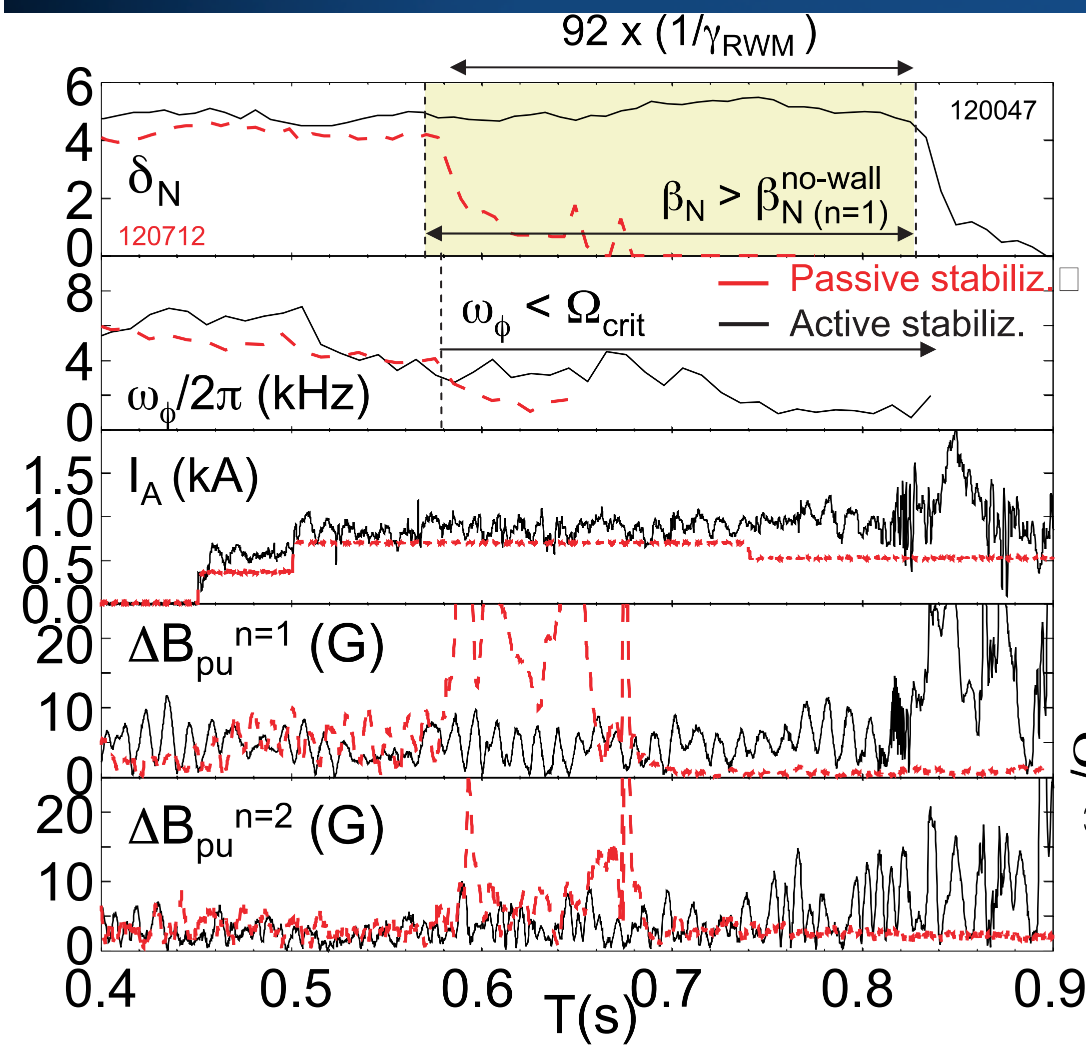
- **Active RWM control system with 6 external midplane coils, closely coupled to vacuum vessel, similar to ITER port plug designs**



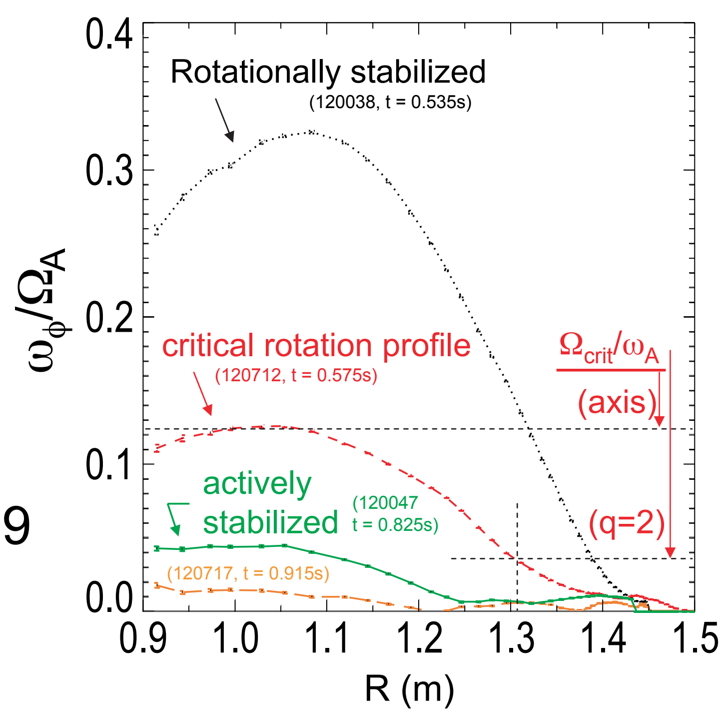
- **Coil modifications allow stronger shaping for higher performance**
  - $\delta \rightarrow 0.8$, $\kappa \rightarrow 2.7$



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



- **Rotation is far below (1/3-1/5) critical value needed for rotational RWM stabilization (Sabbagh, et al., sub. to PRL)**
- **Plasma rotation reduced by non-resonant n=3 magnetic braking (Zhu, et al., PRL 2006)**



NSTX

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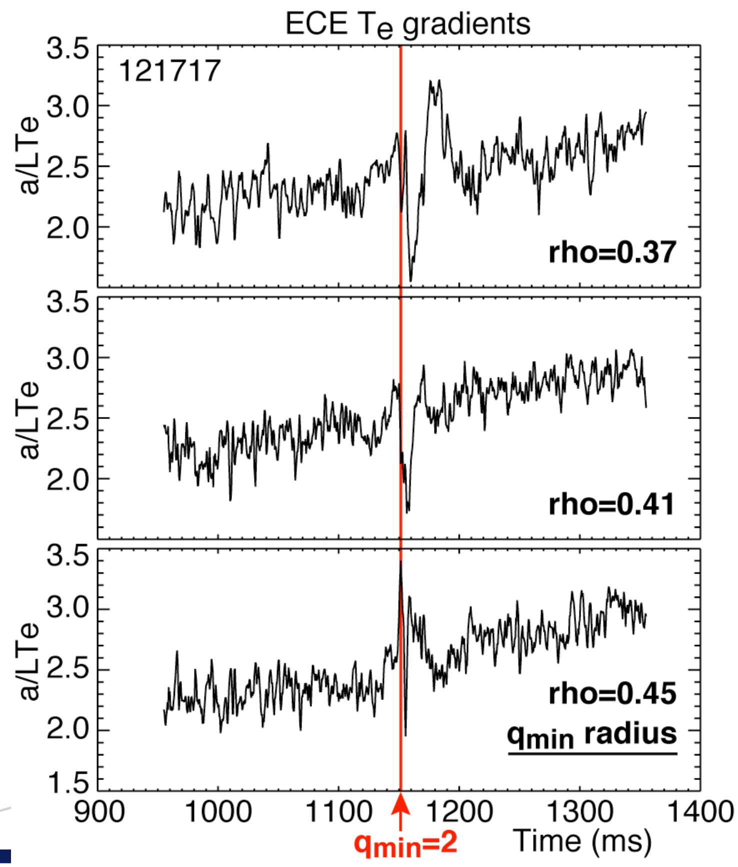
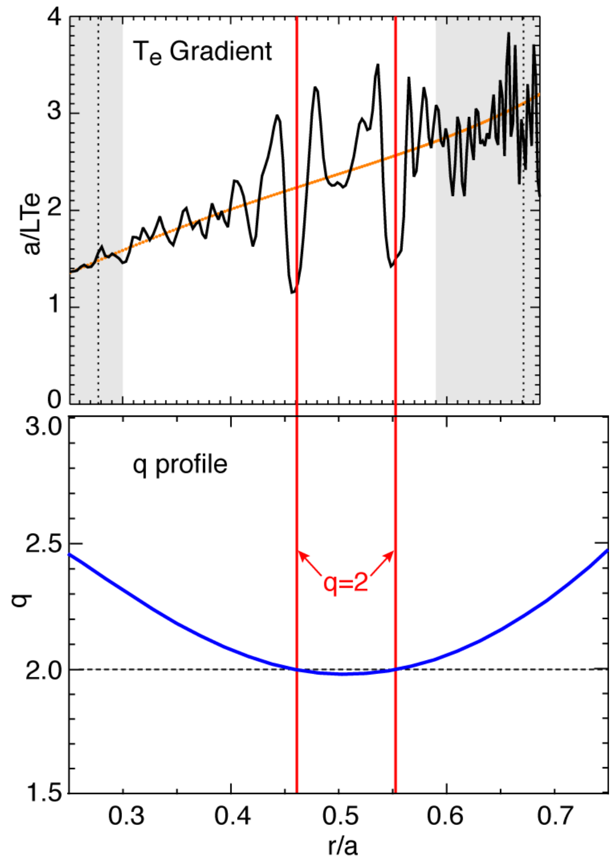
H-factor can be improved with ITBs - understanding of ITB triggering at rational q values is now emerging

- **ITBs are typically triggered at rational q values on JET, also expected to be the case on ITER, due to low input power density**
- **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")**



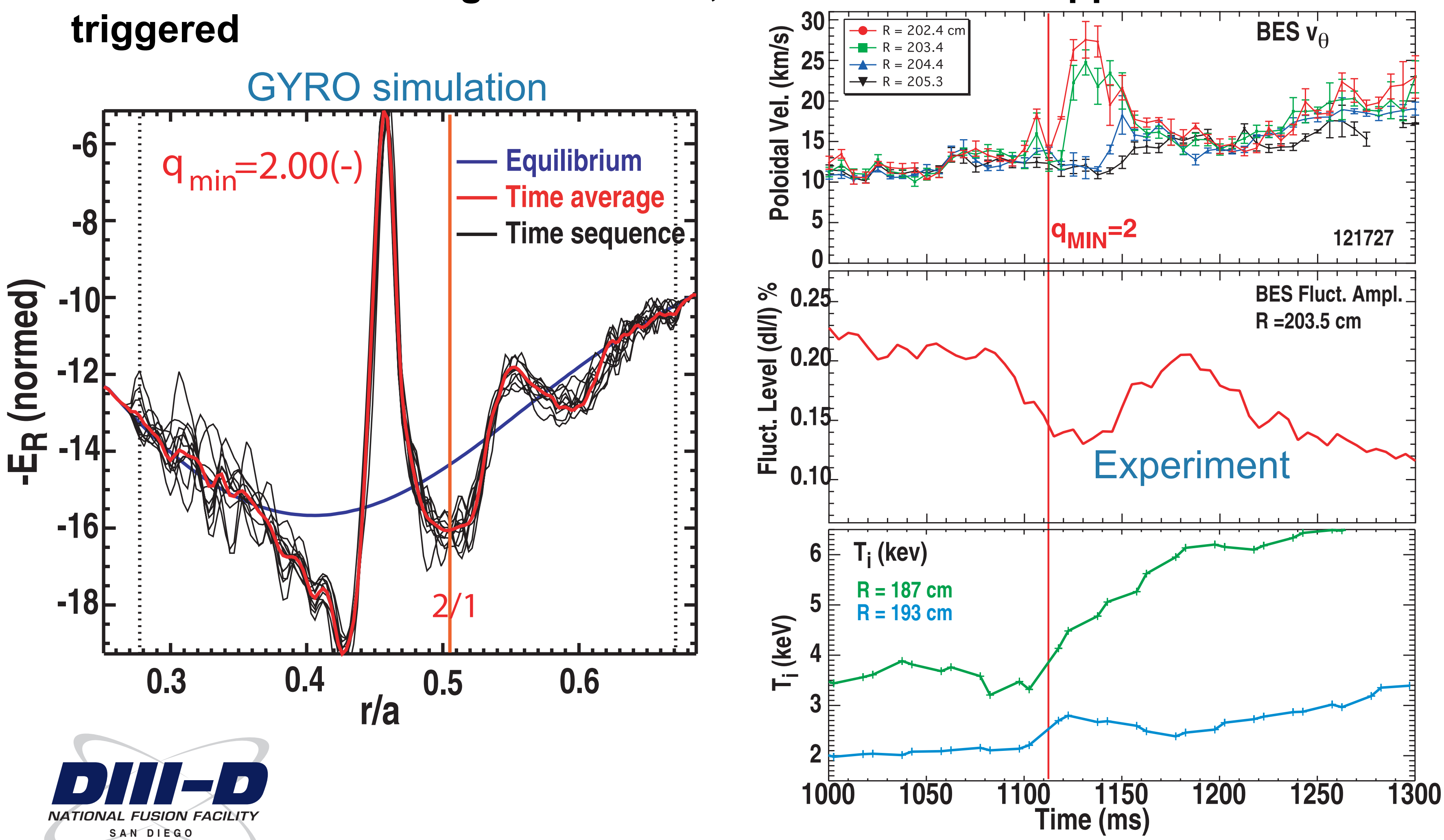
Experiment



GYRO simulation

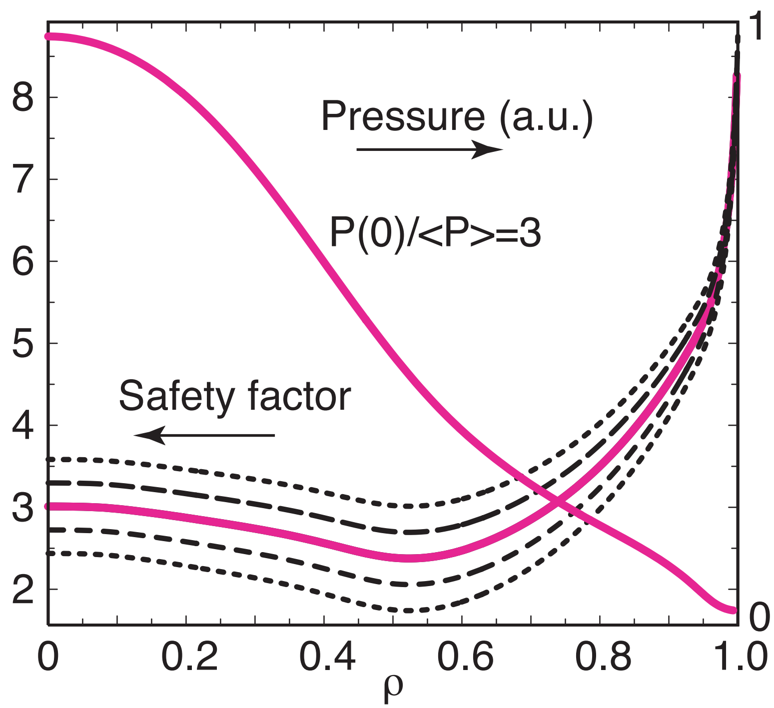
Simulations and experimental data indicate ExB shear is the ITB trigger at rational q values

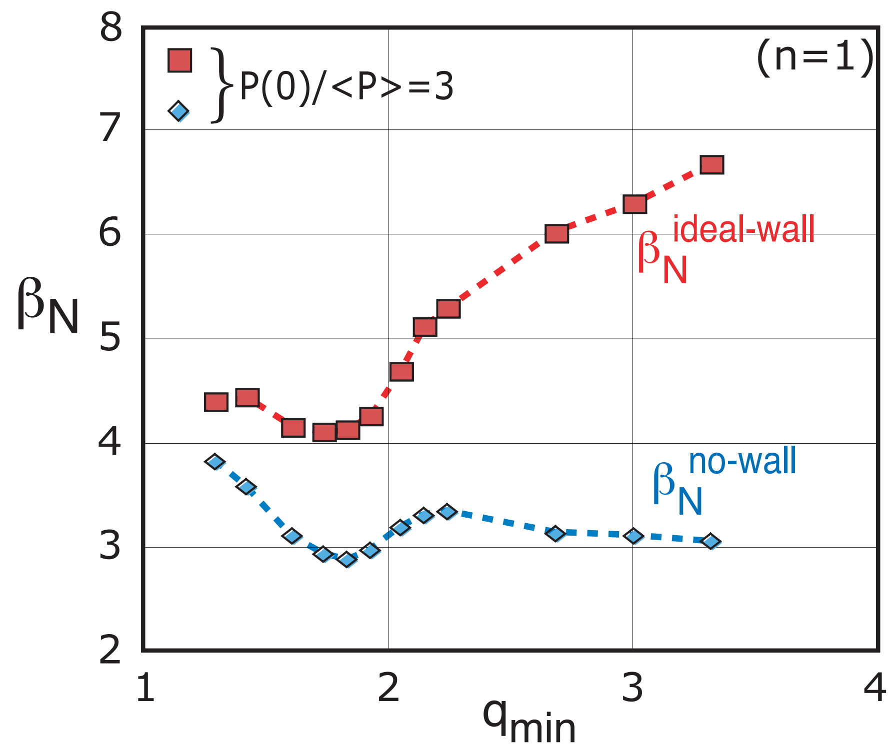
- **GYRO simulations show large time averaged E_r profile corrugation inside rational surface, generating large local ExB shear**
- **BES data indicate large flow shear, and turbulence suppression as ITB is triggered**



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**
  - **High q_{min} favors high f_{BS}**
  - **Broad q profile with weak NCS and P(0)/<P>~3 also consistent with large radius ITB for confinement improvement**





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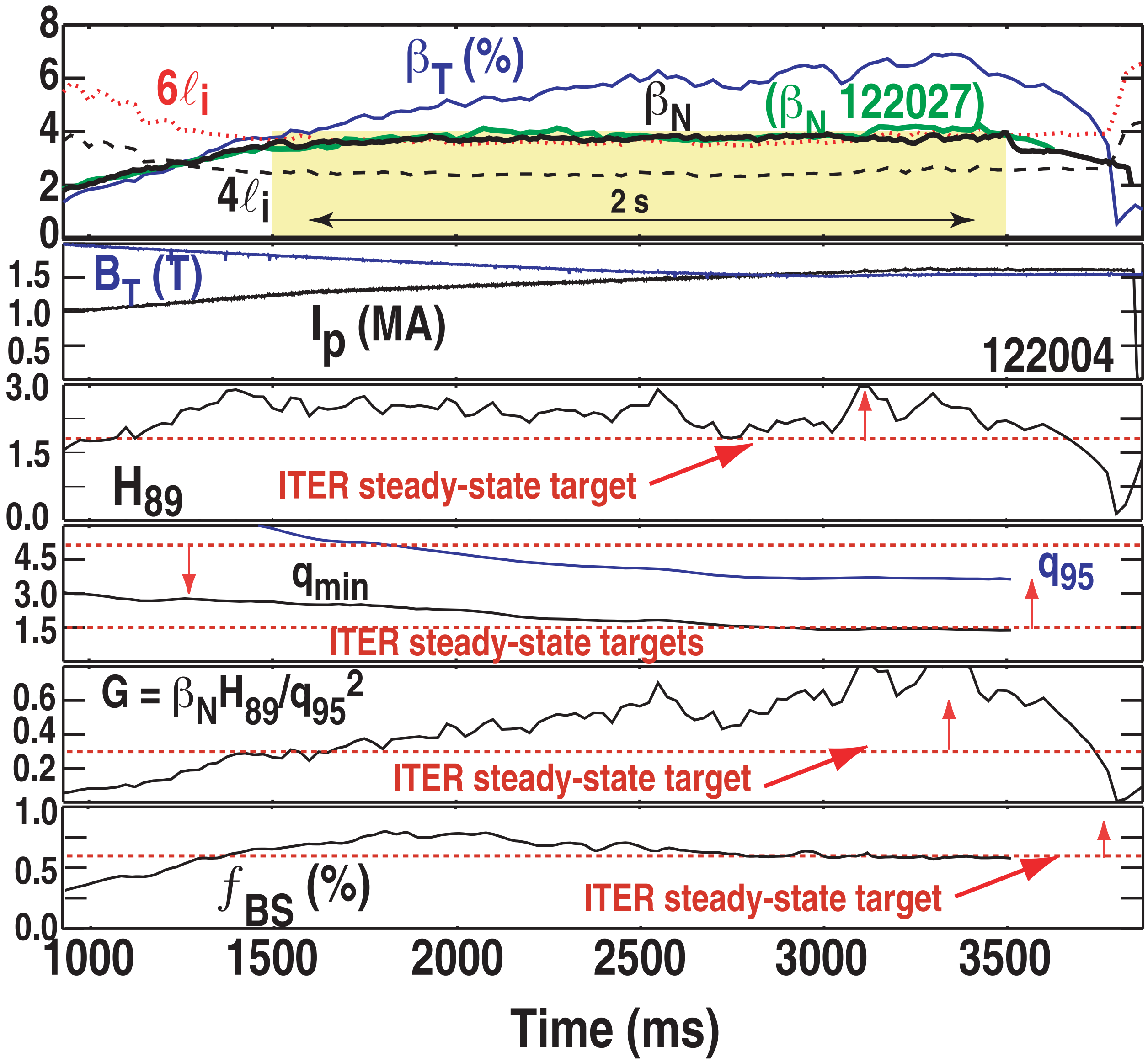
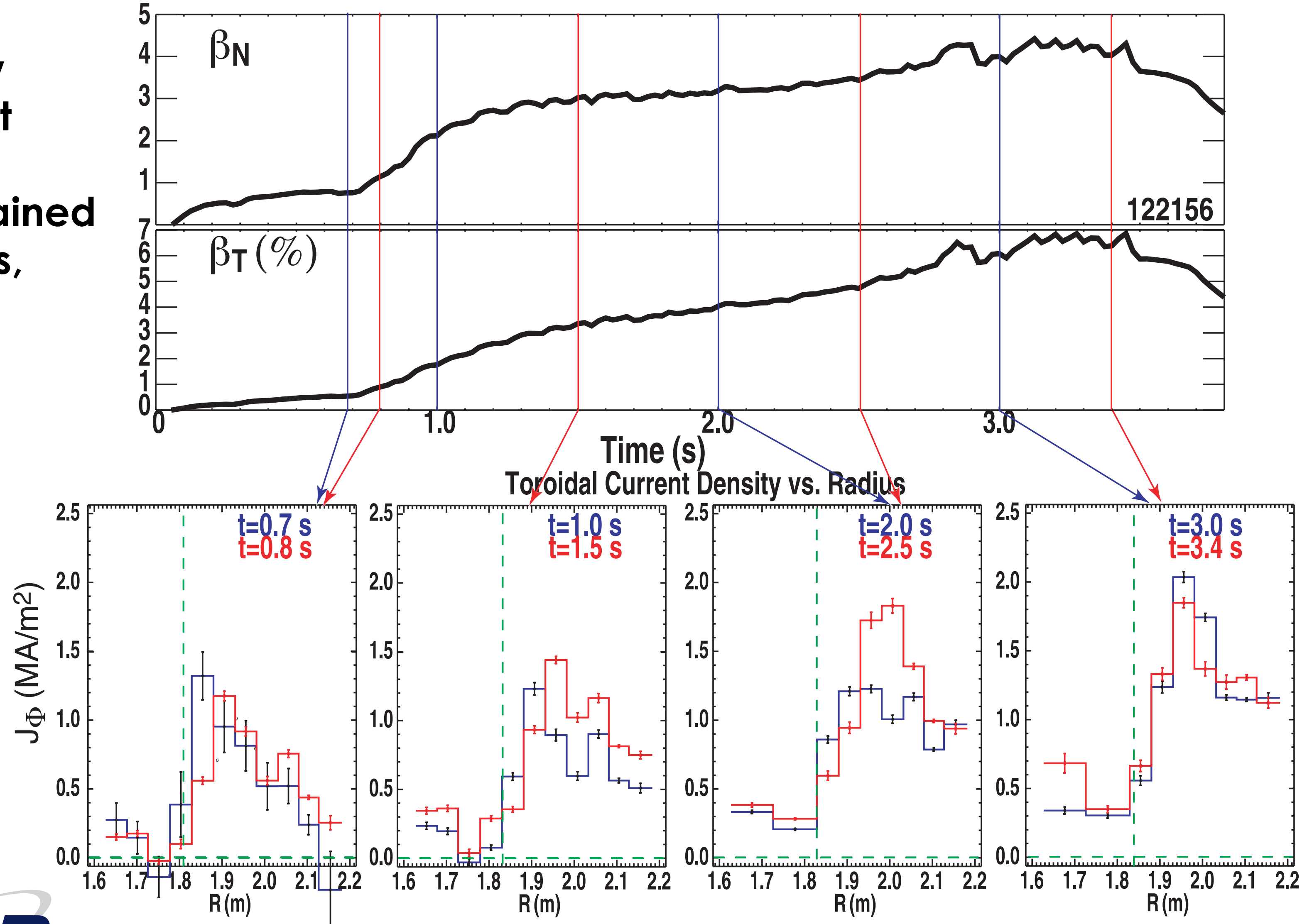
Sustained DIII-D operation with β_N=4 and broad current profile for 2 s, consistent with stability modeling

- $\beta_N > 6\ell_i$ 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%**



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



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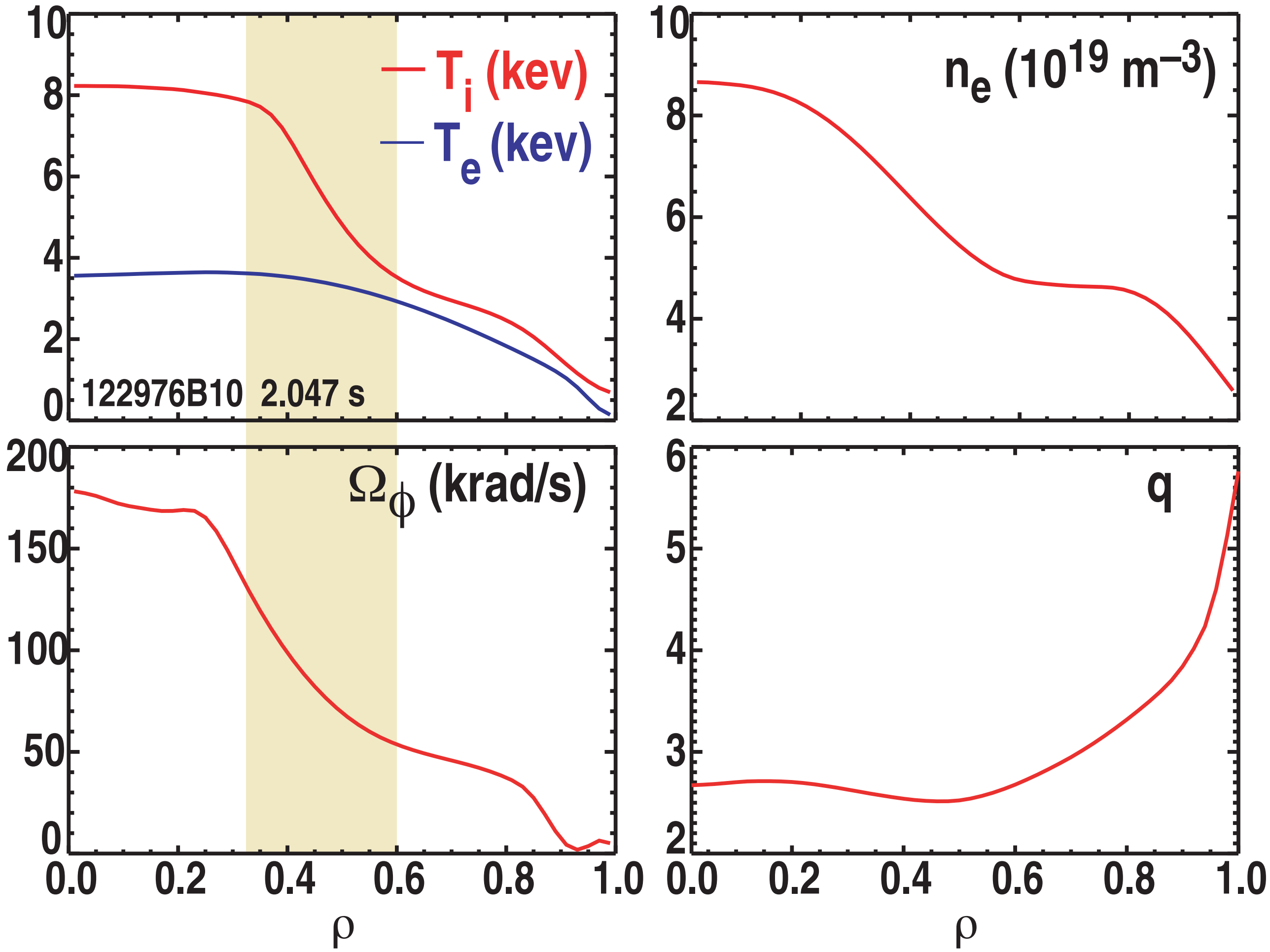
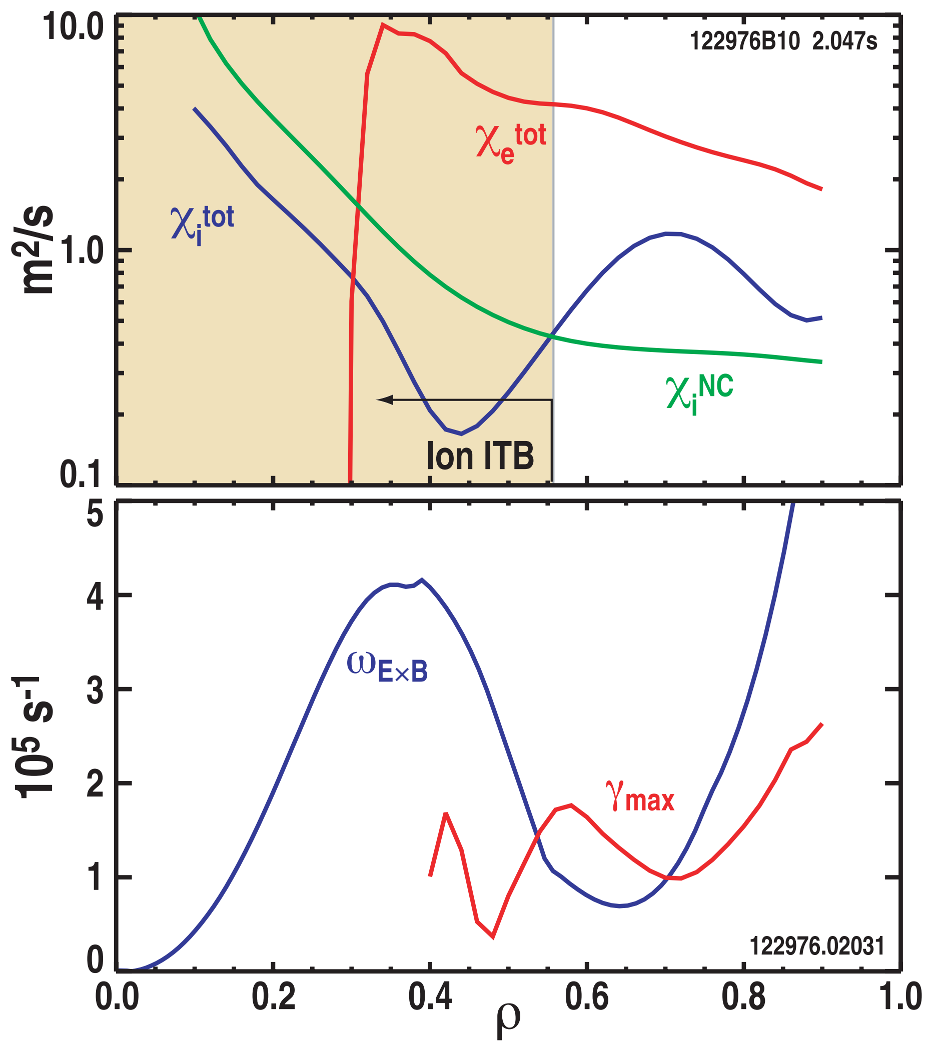
These discharges demonstrate that ITBs are compatible with high β (β_N=4) operation

- **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**



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**
  - ITG dominated turbulence
- **To match experiment, analysis commonly needs to invoke anomalous fast ion diffusion**
  - Small in this case, ~0.3 m^2/s



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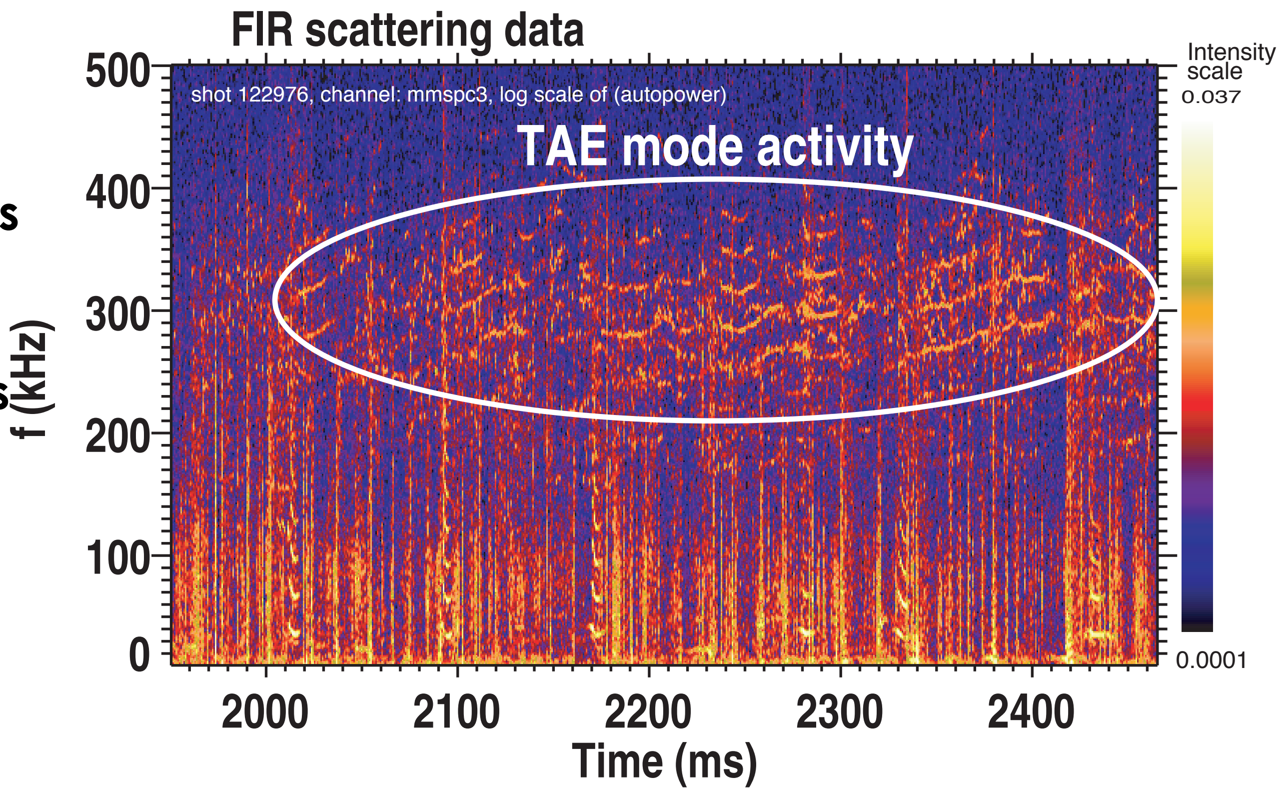
Alfven mode activity is ubiquitous in AT plasmas, and may be responsible for transport anomalies

- **Density fluctuations monitored by FIR scattering system at k~0.5-2.5 cm^{-1} show significant high frequency TAE modes**

- **Transport caused by Alfven modes, etc., is not accounted for in transport modeling**
  - Alternative or complementary explanation to "turbulence spreading" for transport analysis issues in AT discharges



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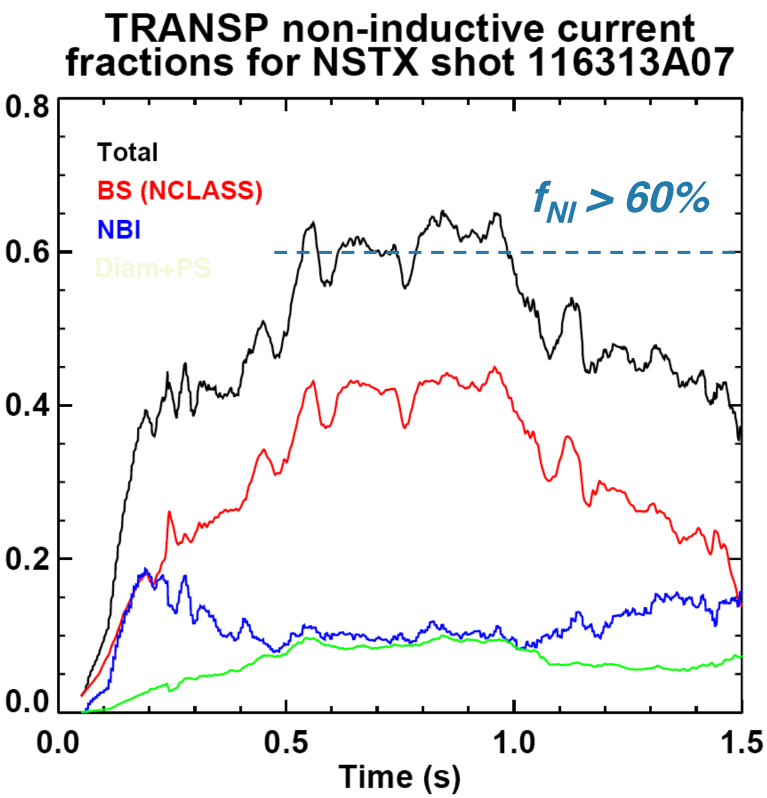
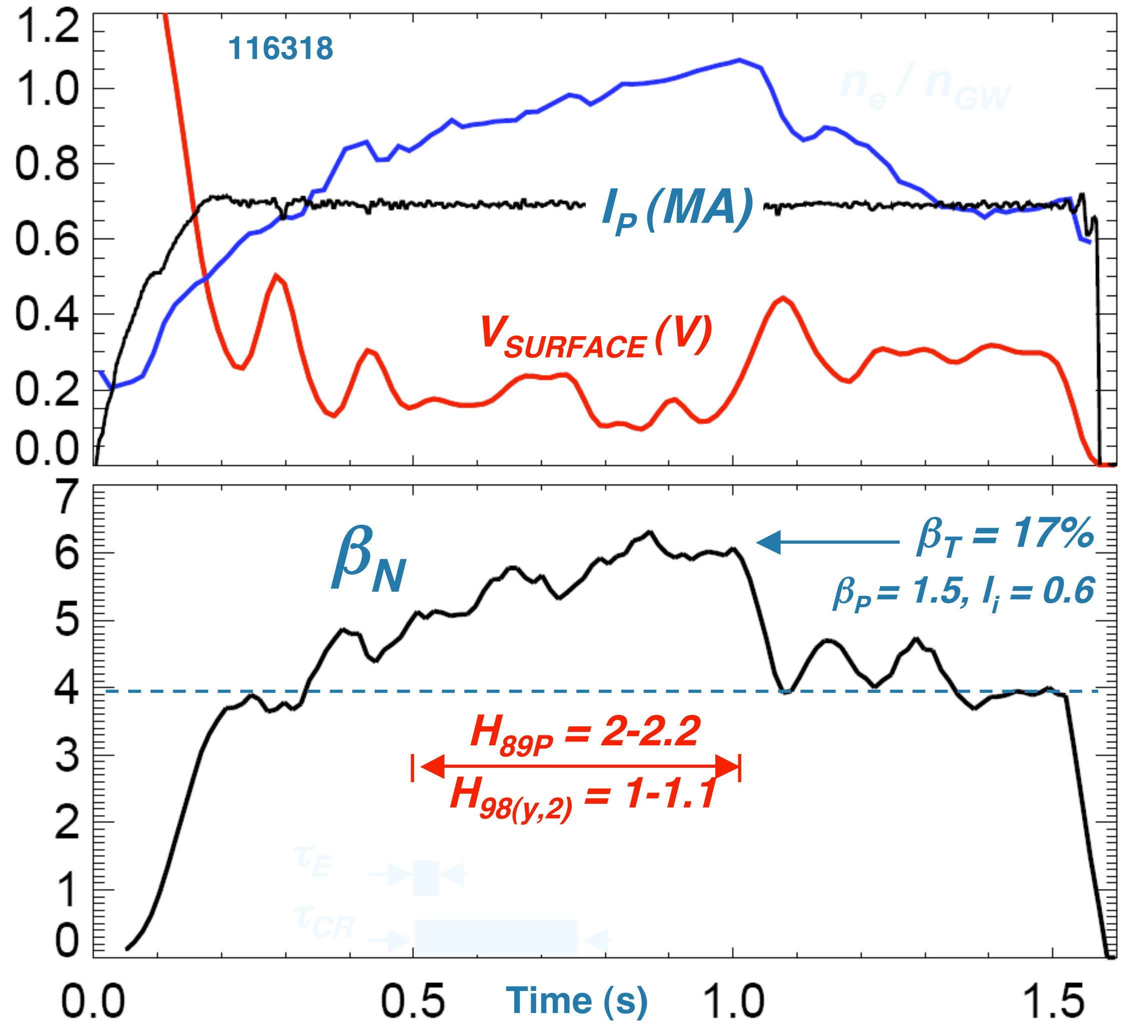
New sustained, high performance discharges open path to AT research on NSTX

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

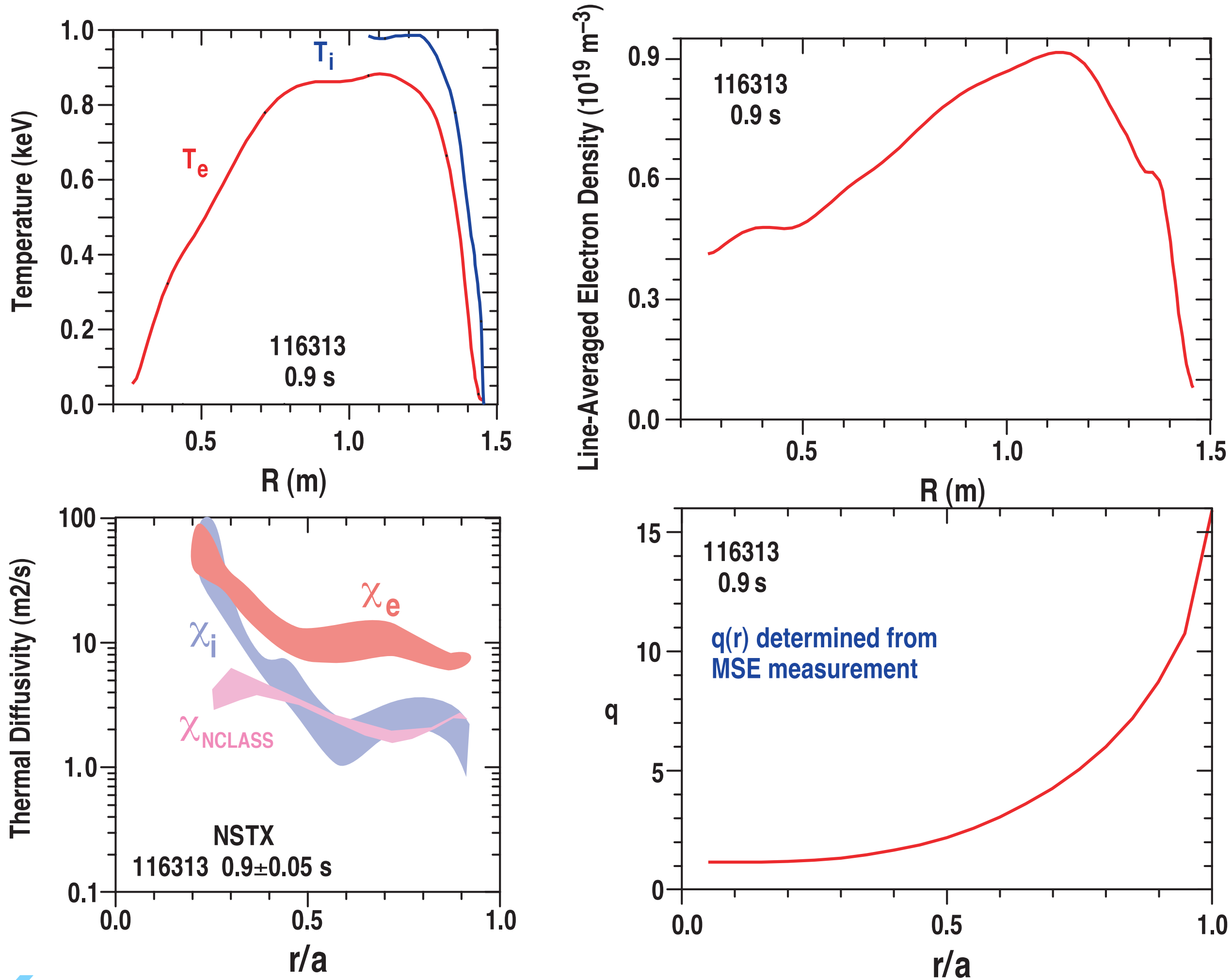




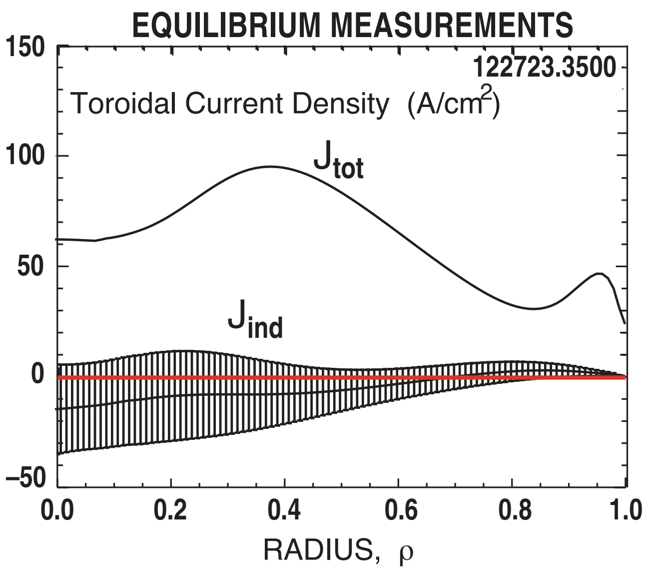
NSTX

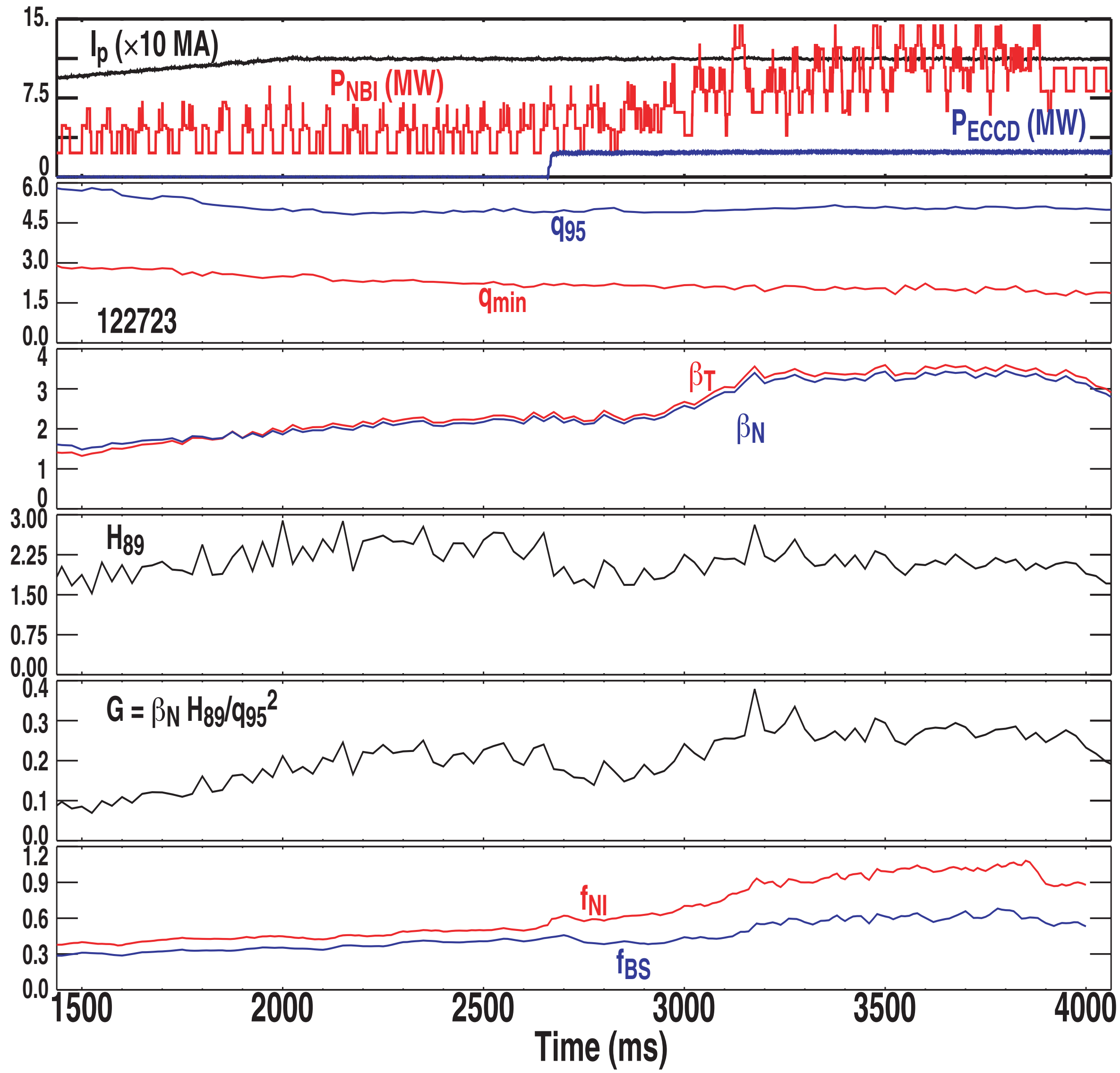
Transport analysis shows ion transport is routinely at neoclassical level on NSTX

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



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





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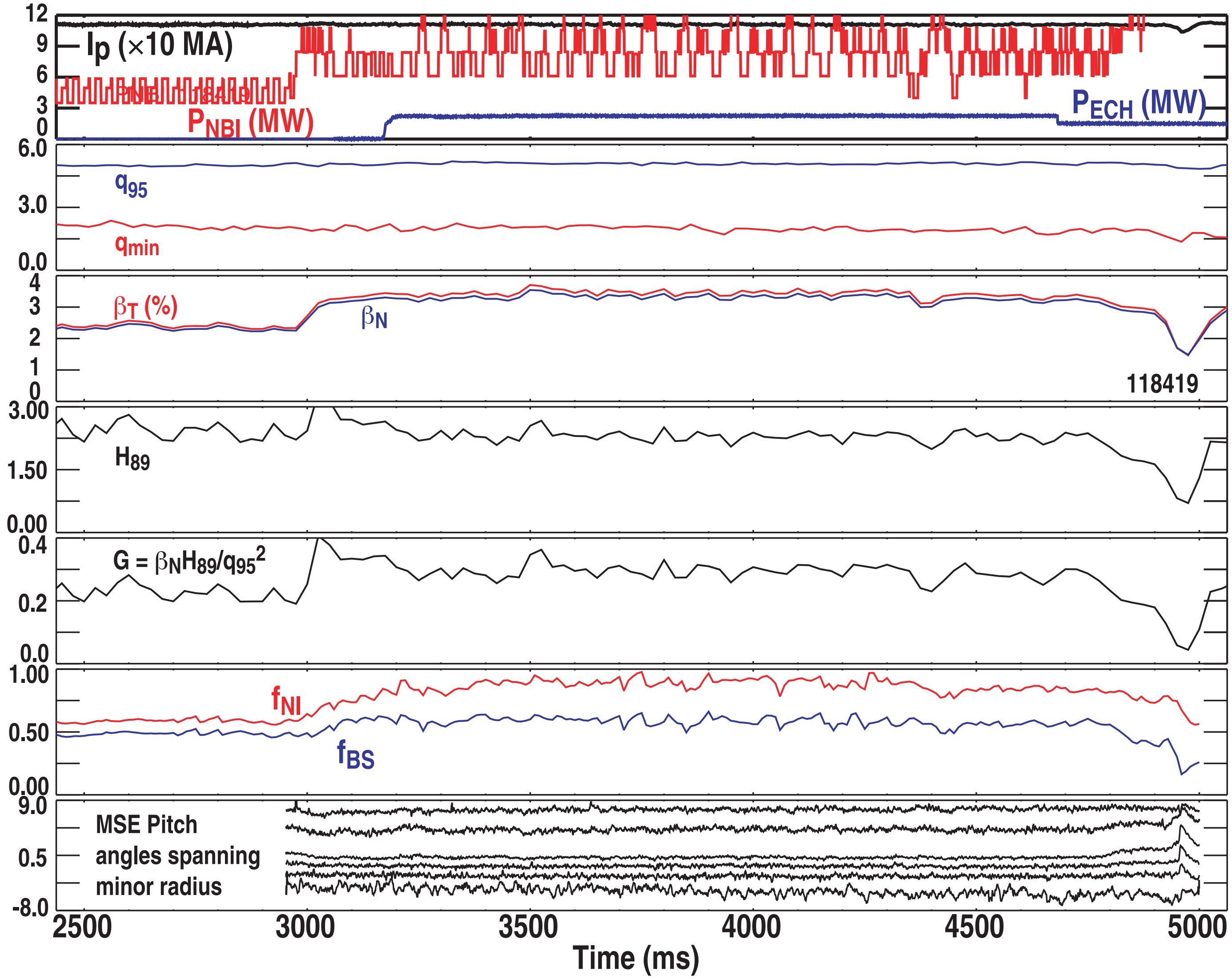
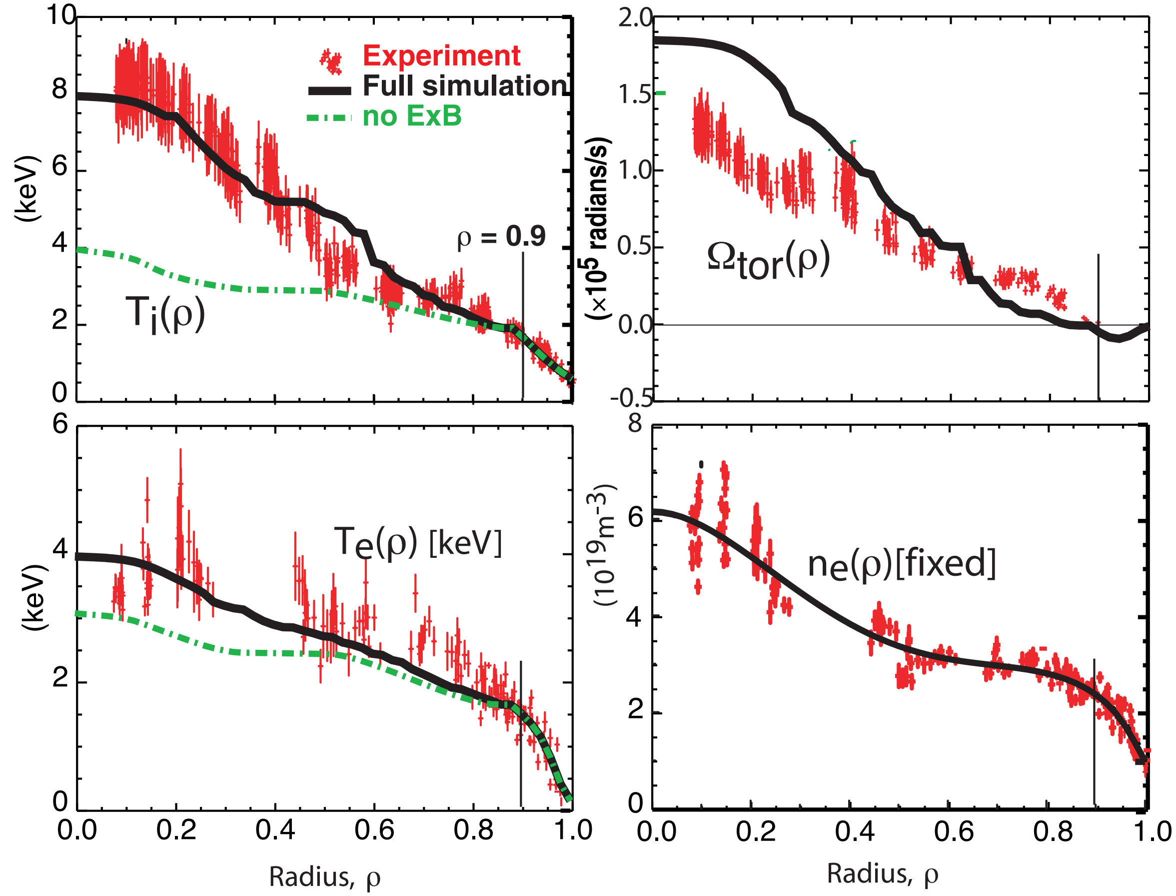
Longer, stationary discharges also demonstrated, with small inductive fraction (5-10%)

- **MSE signals are stationary for ~1 τ_R**



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)]**

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Summary

- **DIII-D demonstration discharges have achieved normalized ITER performance targets, greatly enhancing confidence in steady-state operation on ITER with Q ≥ 5**
  - β_N =3.5, $H_{89} \geq 2.25$, G=0.3, f_{BS} =60%, and 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 are key to progress and optimization**
  - 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
  - ITBs are consistent with high beta operation, and an understanding of ITB triggering at rational q values as effect of zonal flow structures is emerging

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