Advances in the Physics Basis of the Hybrid Scenario on DIII-D

by
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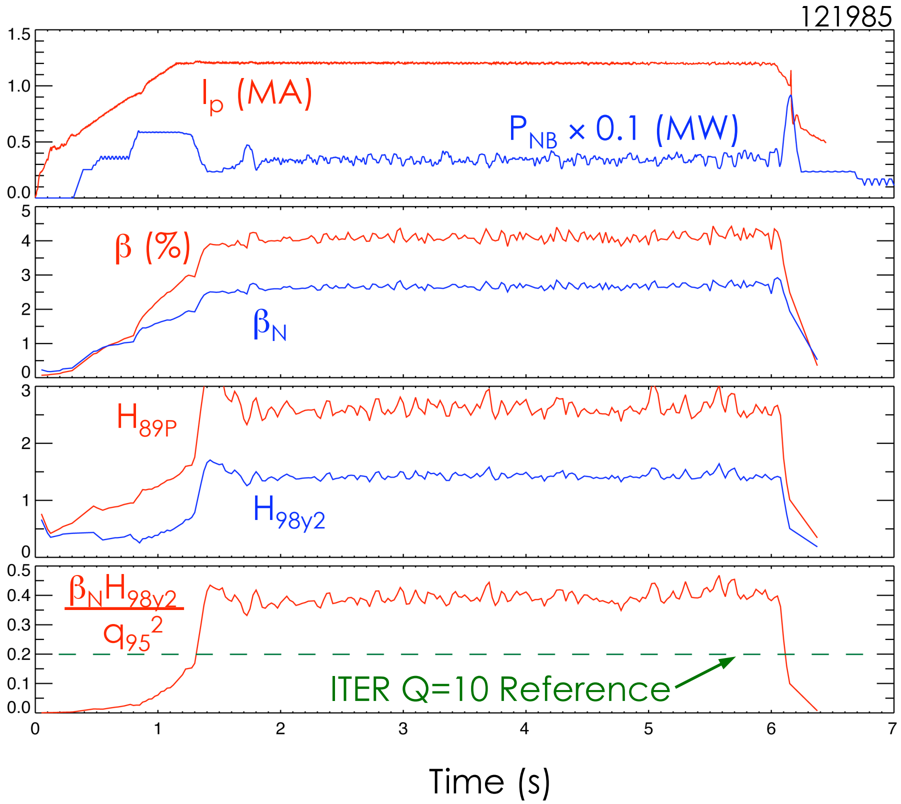
Advancing Hybrid Plasmas as a Baseline Operating Scenario for ITER

- **Recent experiments on DIII-D have extended the hybrid scenario towards the burning plasma regime by incorporating:**
  - Low torque injection (*i.e.*, low toroidal Mach number)
  - Strong electron heating to achieve $T_e \approx T_i$
  - Complete ELM suppression using resonant magnetic perturbation
  - Central current drive to obtain ≈100% noninductive operation
- **In addition, high-performance hybrid and steady-state scenario operation has been obtained with reduced frequency of wall conditioning with a >95% graphite plasma-facing wall**

Hybrid Scenario Refers to Long Duration, High Performance Discharges That Have Favorable Fusion and Neutron Fluence Characteristics for ITER

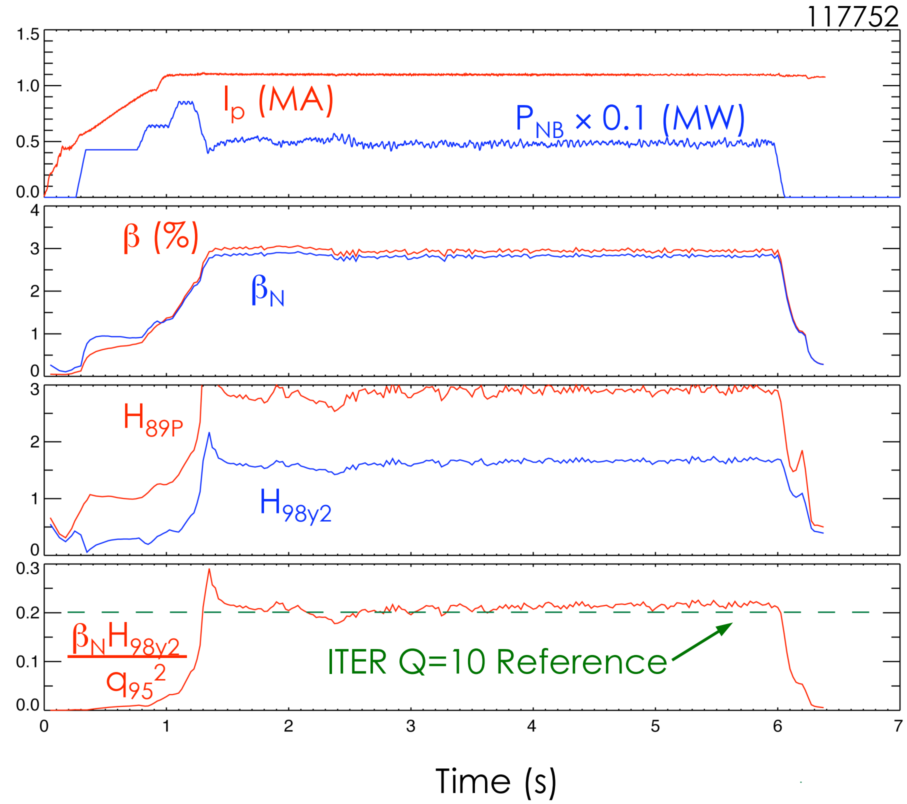
- **"Advanced Inductive" Regime**

High fusion gain, q_{95} = 3.1



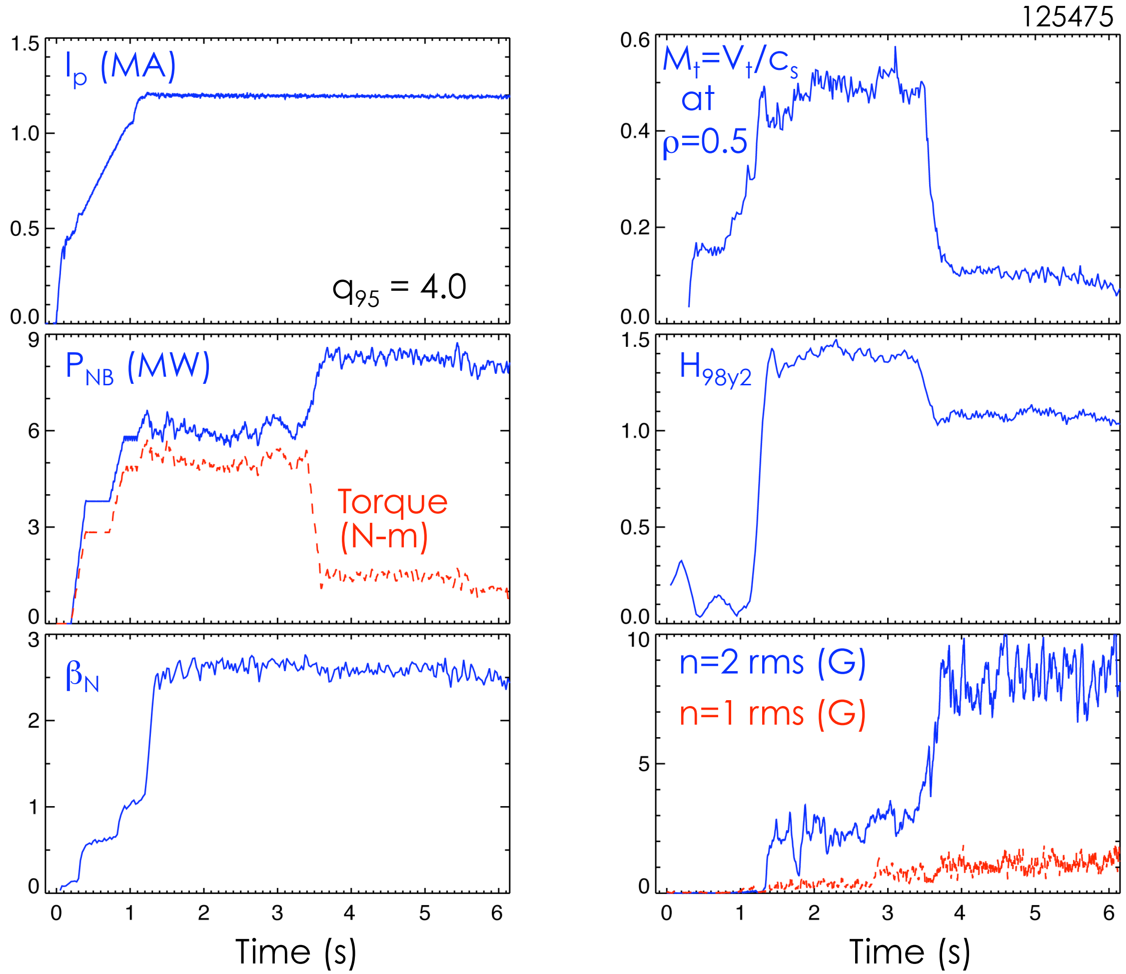
- **Standard "Hybrid" Regime**

High neutron fluence, q_{95} = 4.7



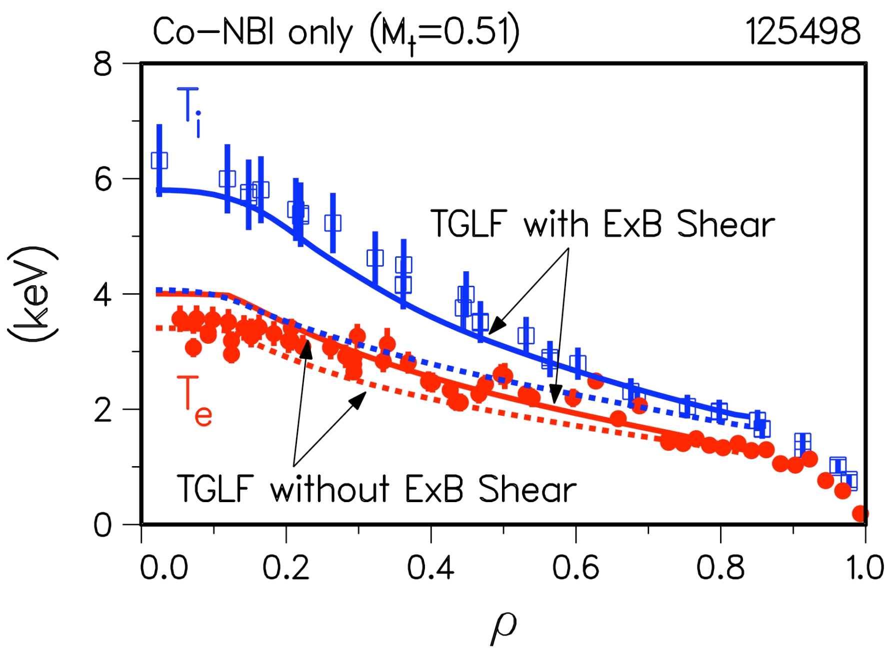
Beneficial Characteristics of Hybrid Scenario are Maintained in Slowly Rotating Plasmas

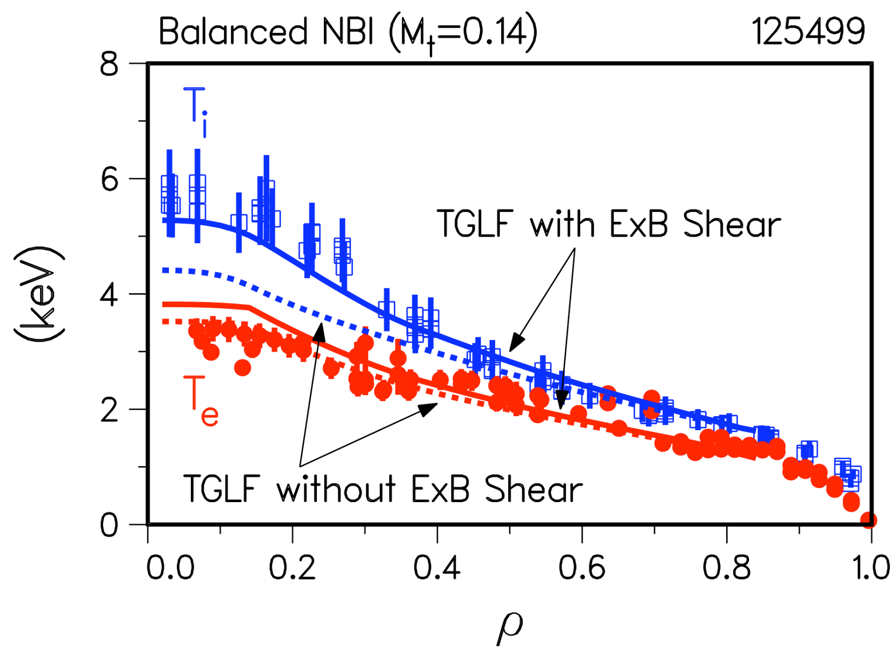
- **Switch from co-NBI to nearly balanced-NBI at 3.5 s reduces toroidal Mach no. by ≈ 80%**
- **While confinement decreases with lower rotation, value is still good (H_{98y2} = 1.1)**
- **High stability limits are maintained in low rotation hybrids**
  - Achieved β_N up to 3
- **Benign 3/2 NTM continues to suppress sawteeth**
  - Reduced flow-shear increases 3/2 island



Changes in E×B Shear Can Explain the Effect of Torque on Heat Transport

- **With high toroidal rotation, E×B shear must be included in model to reproduce measure profiles**
- **At low toroidal rotation, E×B shear is much less important**



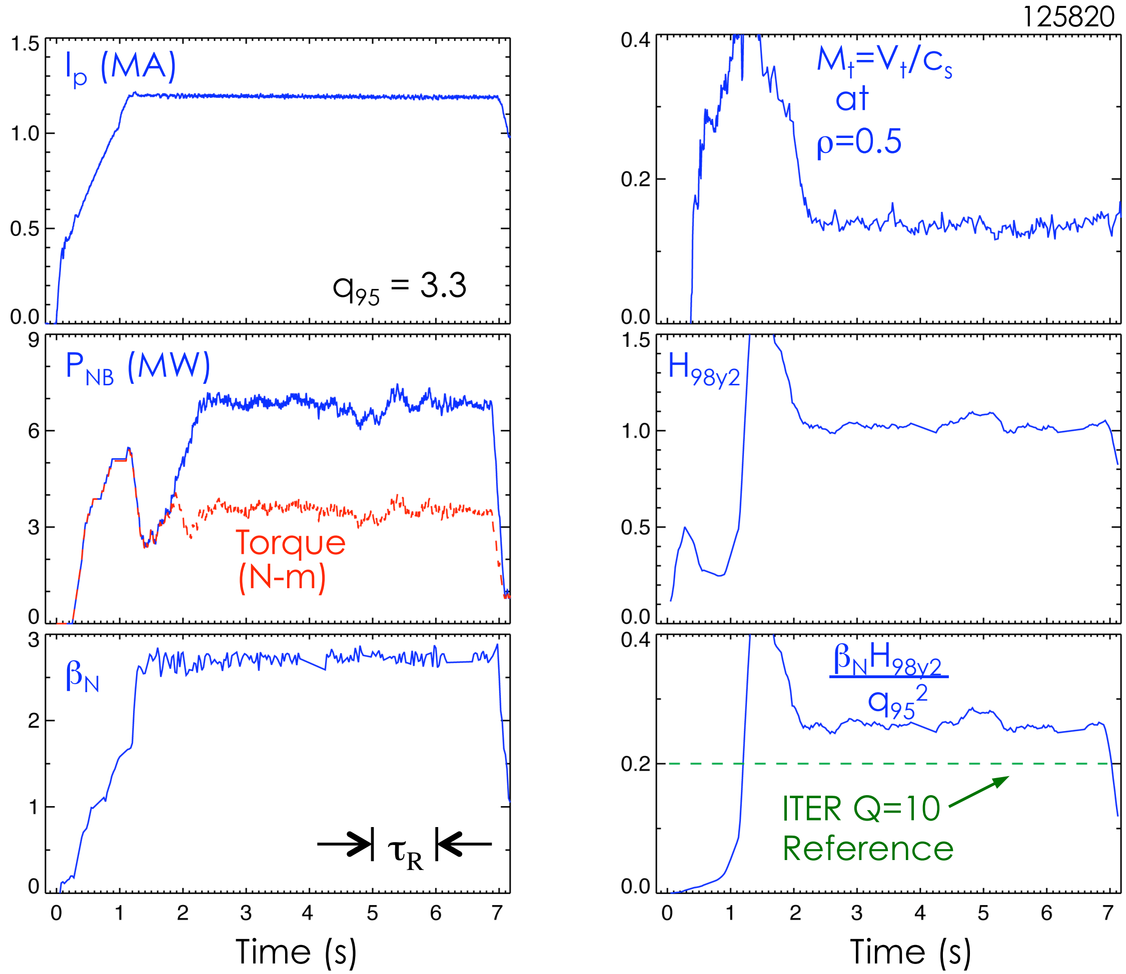


- **H_{98y2} = 1.4 - excellent confinement!**
- **H_{98y2} = 1.1 - good overall confinement still maintained**

Advanced Inductive Discharges Achieve Conditions Consistent With Q > 10 in ITER With Low Rotation

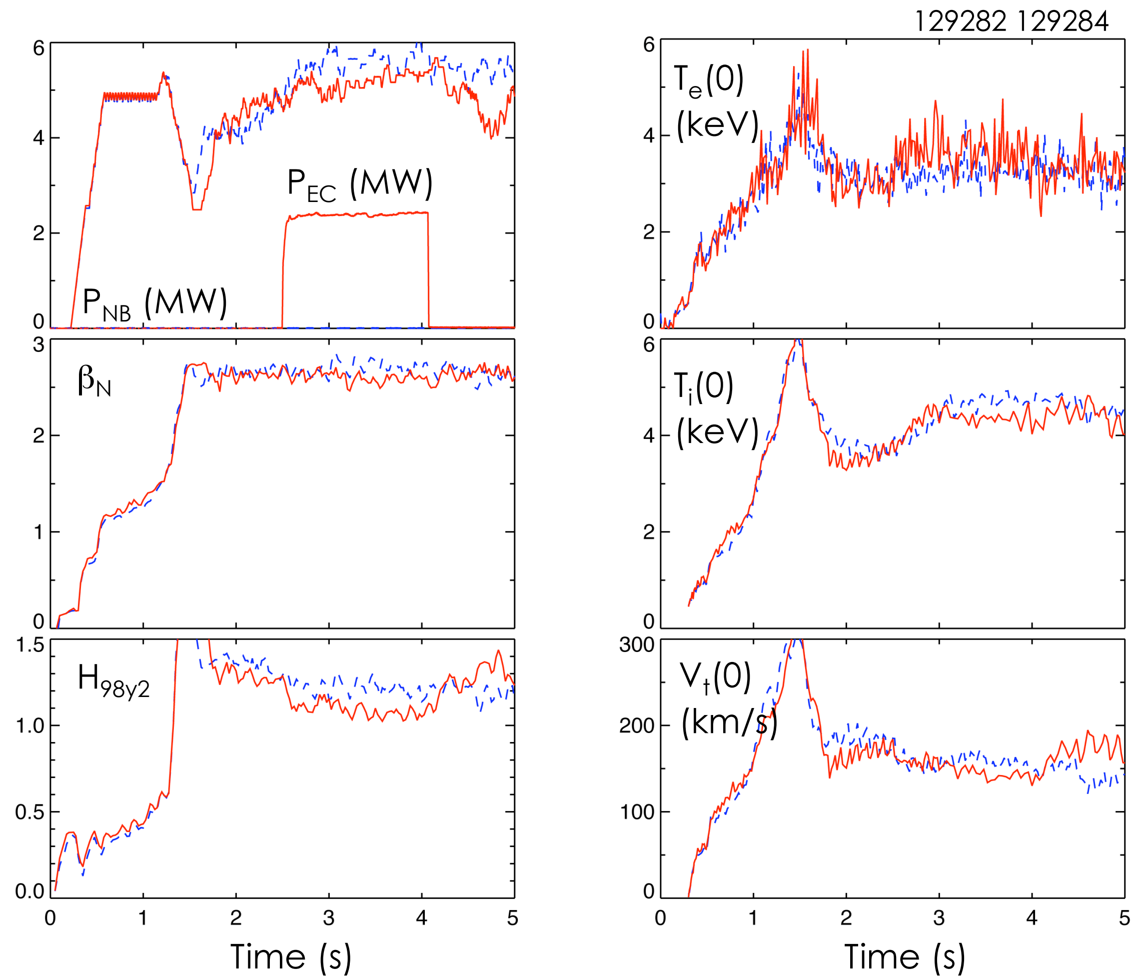
- **Transition to low rotation occurs at the initiation of the high β_N phase**
- **High performance at low rotation is maintained for $t > 4\tau_R$**
- **Extrapolates to Q > 10 in ITER at 15 MA for several common scalings:**

ITER89-P:	Q = 10.3
IPB98y2:	Q = 10.2
DS03:	Q = ∞



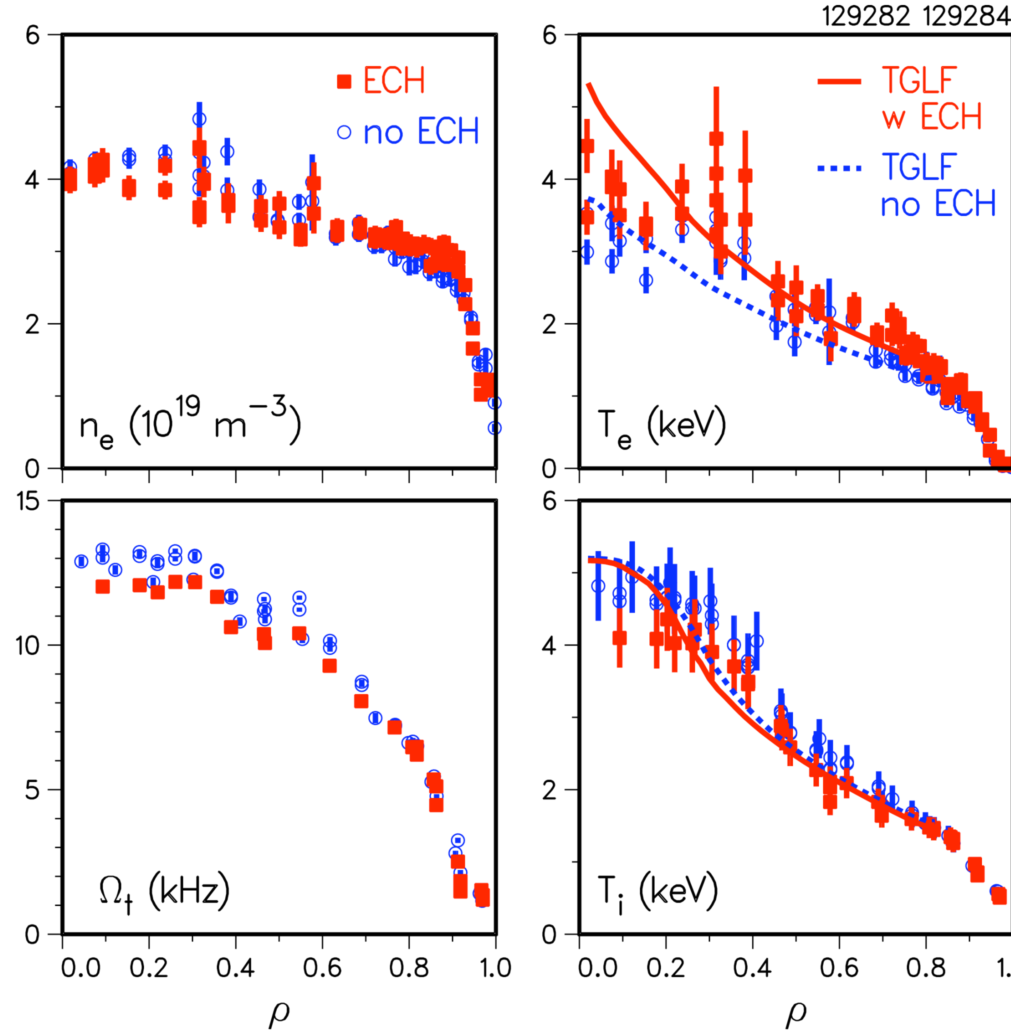
Role of $T_i > T_e$ in Achieving High Confinement in Hybrids Studied By Replacing Some NBI With ECH

- **Maximize ECH/NBI power ratio by studying low B_t (1.3 T), low q_{95} (3.3) advanced inductive discharges**
  - Use 3rd harmonic ECH with calculated first pass absorption of 94%
- **H_{98y2} decreases by ≈ 13% during ECH**
- **High fusion performance factor, $\beta_N H_{98y2}/q_{95}^2$=0.26, achieved during ECH**
  - For Q=10 on ITER, need $\beta_N H_{98y2}/q_{95}^2 = 0.20$



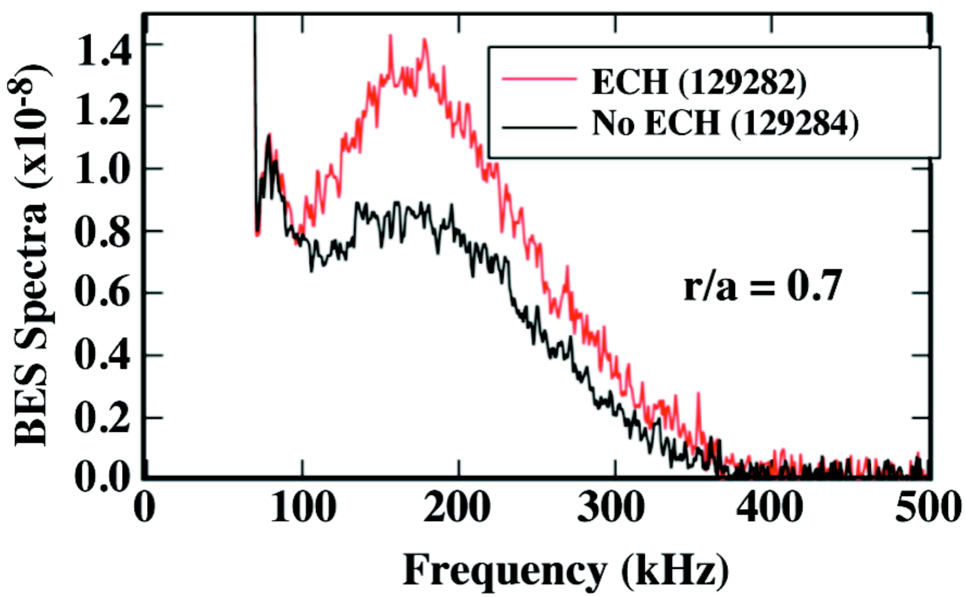
ECH Decreases T_i/T_e by ≈ 20%, Making Ion and Electron Temperatures Nearly Equal and Increasing Transport

- **Increased D_2 gas injection keeps density fixed during ECH**
- **Toroidal rotation rate during ECH is matched in NBI-only case by adding counter-injection**
  - τ_{mom} ≈10% lower with ECH
- **Near $\rho \approx 0.6$, χ_e increases from 1.5 → 3.9 m^2/s during ECH, while χ_i goes from 1.7 → 2.9 m^2/s**
- **TGLF code reproduces rise in T_e during ECH, predicts that ≈ 75% of electron transport due to high-k modes**

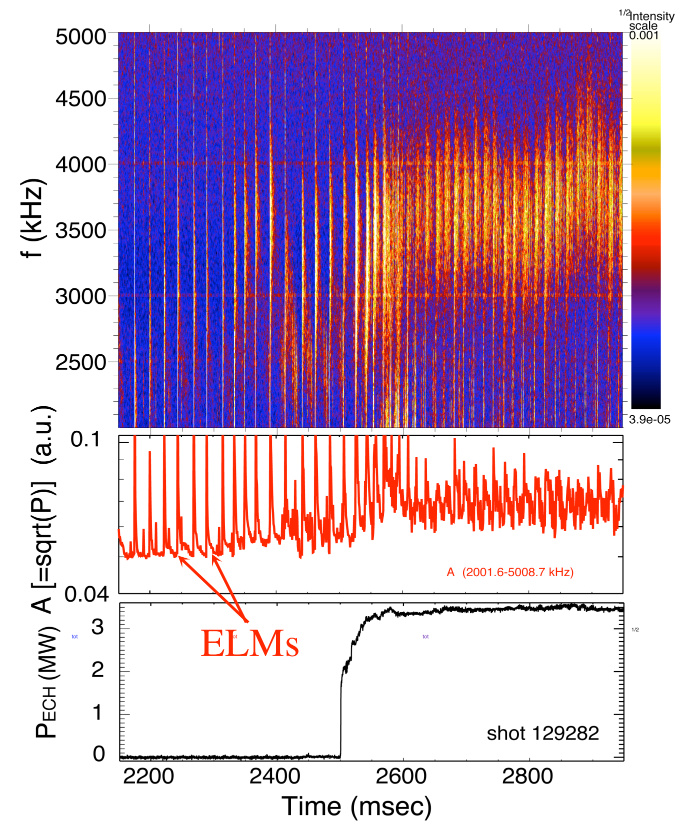


Increase in Transport With Lower T_i/T_e Correlates With Higher Turbulence at Low and Intermediate Wavenumbers

- **Beam Emission Spectroscopy measures long-wavelength ($k<3$ cm^{-1}) density fluctuations**

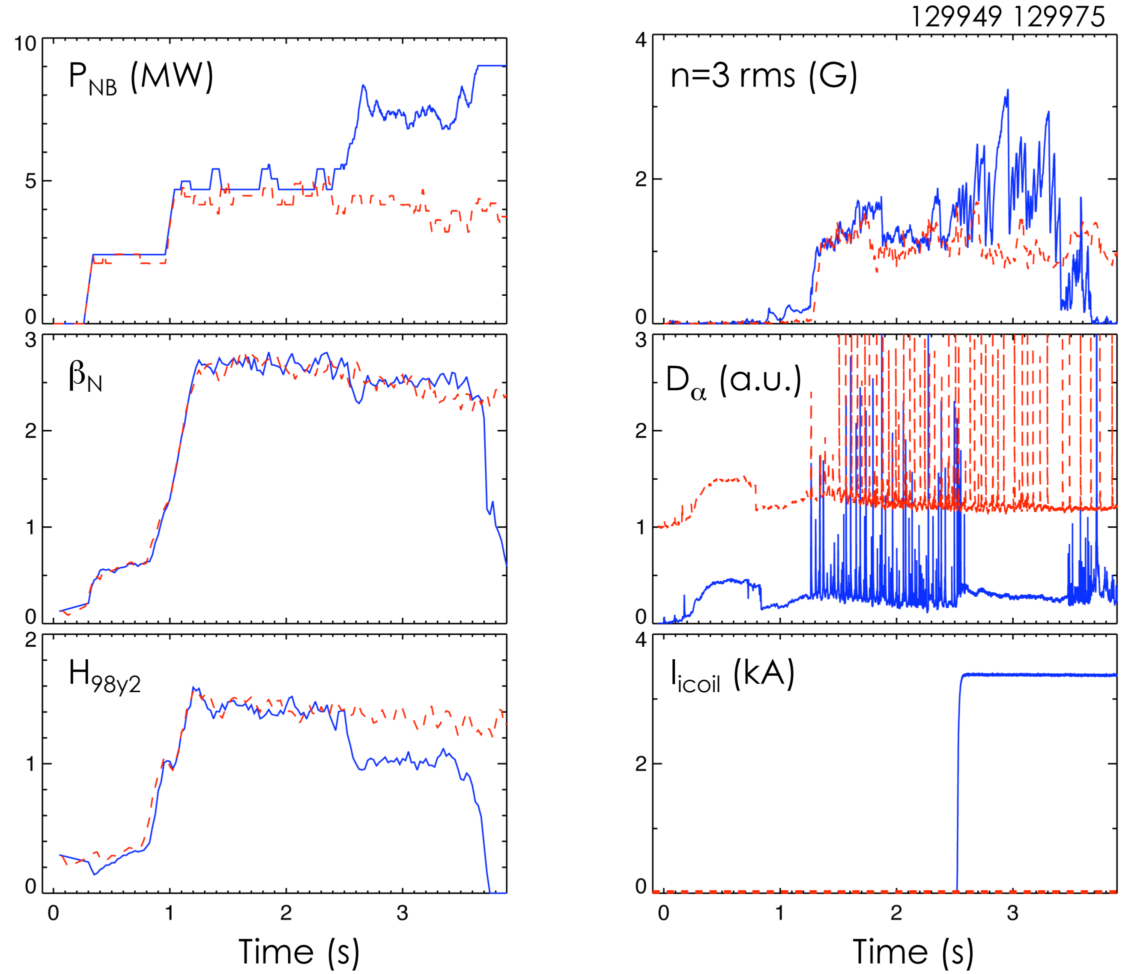


- **Doppler Backscattering measures intermediate-wavelength ($k \approx 7$-8 cm^{-1}) density fluctuations**



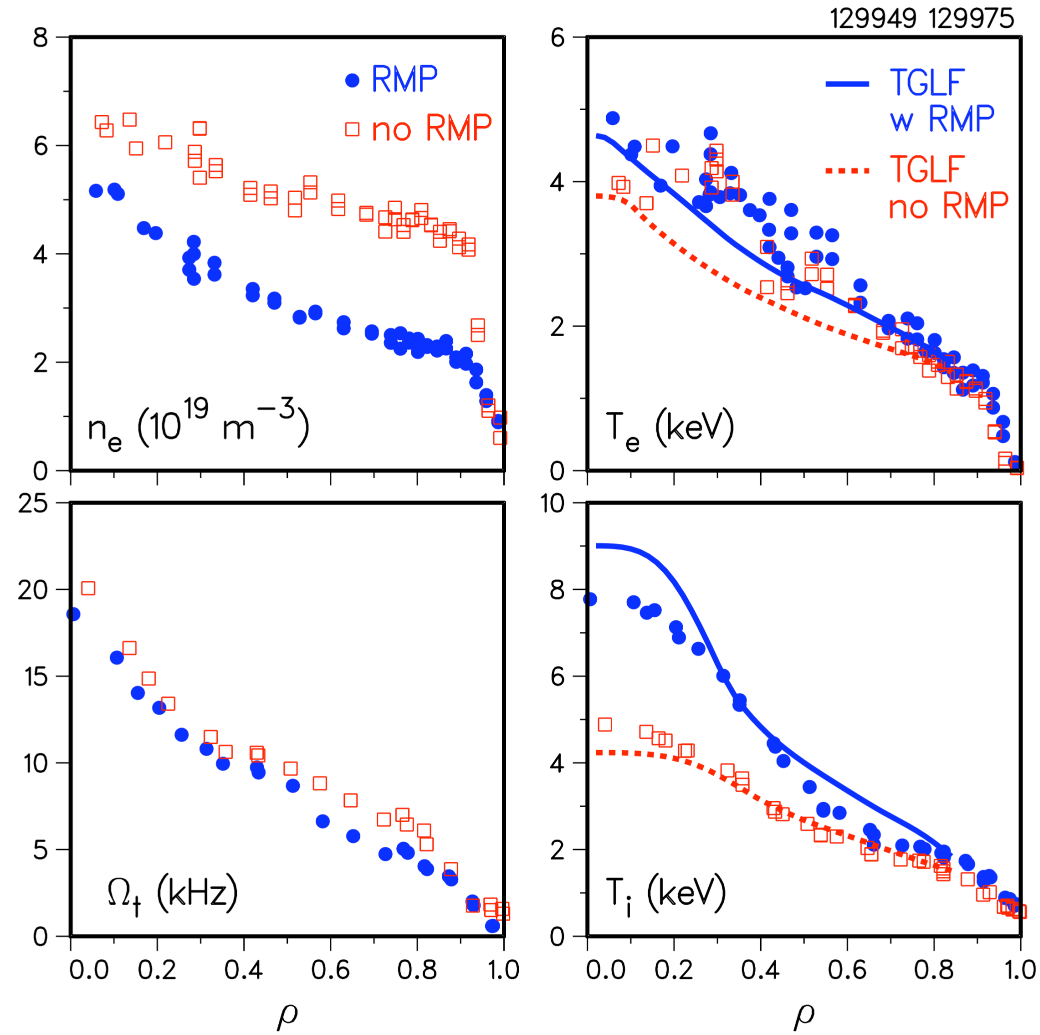
Resonant Magnetic Perturbation (RMP) Has Suppressed ELMs in Hybrid Plasma With β_N=2.5

- **Important advance in developing hybrid as baseline-operating scenario for ITER**
- **RMP applied by I-coil with toroidal mode number n=3**
- **ELM suppression by RMP is a resonant effect around q_{95}=3.6±0.2**
- **ELMs reappear when 3/2 NTM onsets around 3.4 s, slows down, and locks to the vessel wall**



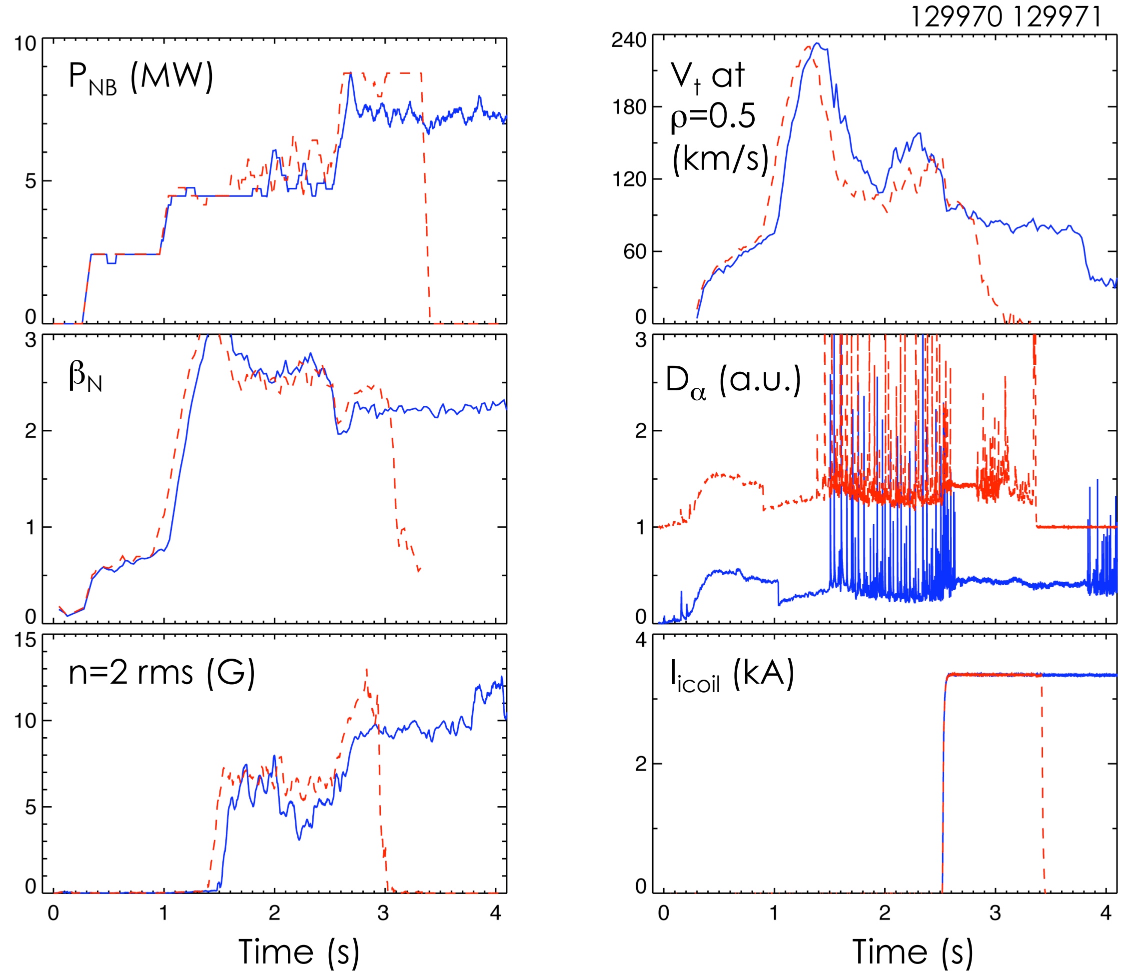
RMP Increases Particle Transport and Reduces Rotation During ELM Suppression, But Performance Remains High

- **Reduction in H-mode pedestal responsible for ELM stabilization**
- **RMP non-resonant and resonant braking effects lower toroidal rotation, which reduces confinement**
- **Fusion performance factor $\beta_N H_{98y2}/q_{95}^2$=0.20 during ELM suppression equals value needed to obtain Q = 10 on ITER**
- **Changes in temperature profiles well simulated by TGLF transport model**
  - High-k modes ~50% of χ_e



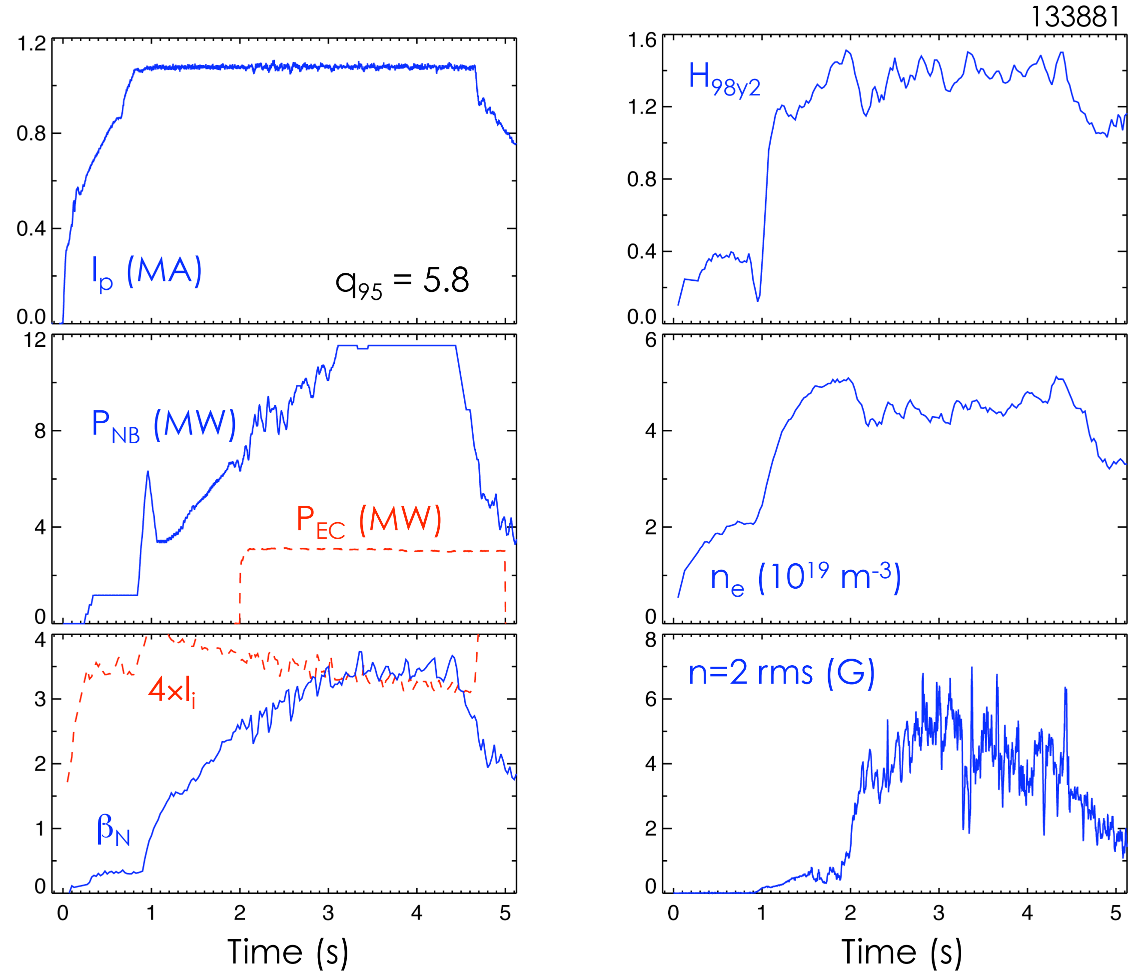
RMP ELM Suppression in Hybrid Regime With 3/2 NTM Has Been Achieved for β_N Up to 2.2

- **ELM suppressed for 1.2 s, approaching current re-distribution time of 1.5 s**
- **Coupling at 3.8 s between 3/2 NTM and sideband of 1/1 mode increases 3/2 island size and lowers toroidal rotation rate**
- **Increasing β_N to 2.4 causes rotation rate of 3/2 island to quickly drop below critical level for locking (≈ 6 kHz), perhaps due to RFA**
  - In future, I-coil for RMP will be redesigned to reduce drag effects



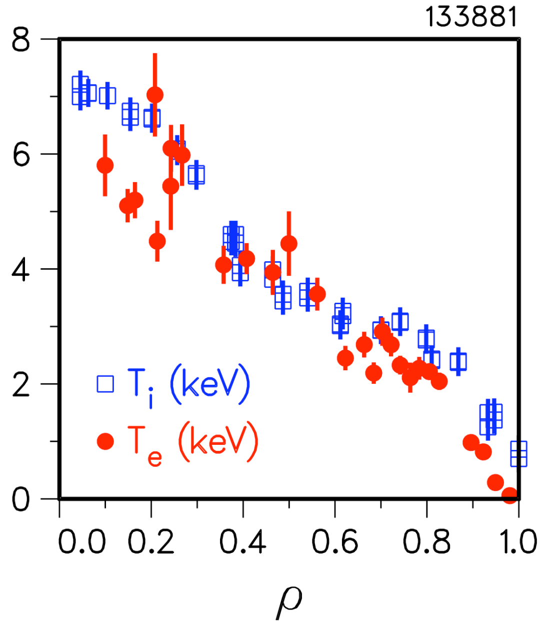
Steady-State Potential of High-Performance Hybrid Demonstrated Using Central ECCD + NBCD

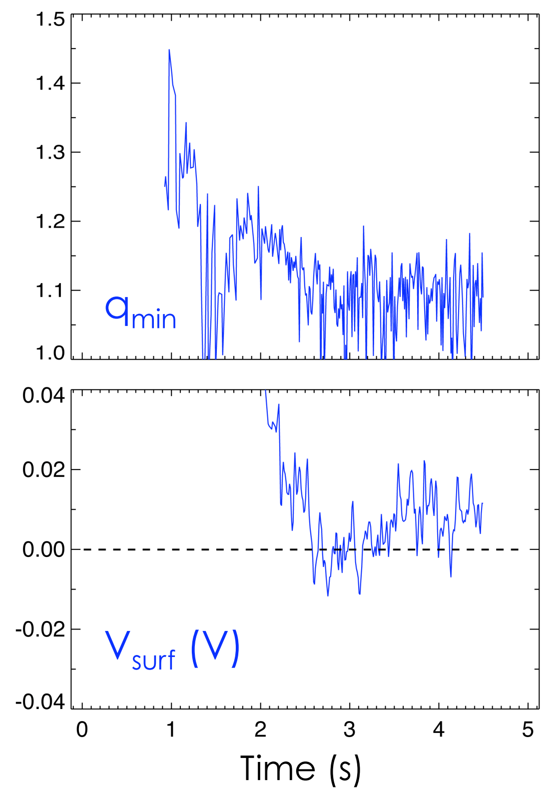
- **Utilizes all available co-beams and gyrotrons**
  - Pulse length limited by joule limit of co-beams
- **Surface loop voltage ~10 mV during peak performance phase**
- **β_N exceeds ideal no-wall stability limit**
- **High H_{98y2} achieved with strong electron heating**
- **Fusion performance factor $\beta_N H_{98y2}/q_{95}^2$=0.14 sufficient for Q=5 on ITER**



Calculated Current Drive is Consistent With Achieving ≈100% Fully Noninductive Hybrid

- **Strong electron heating results in nearly equal ion and electron temperatures**



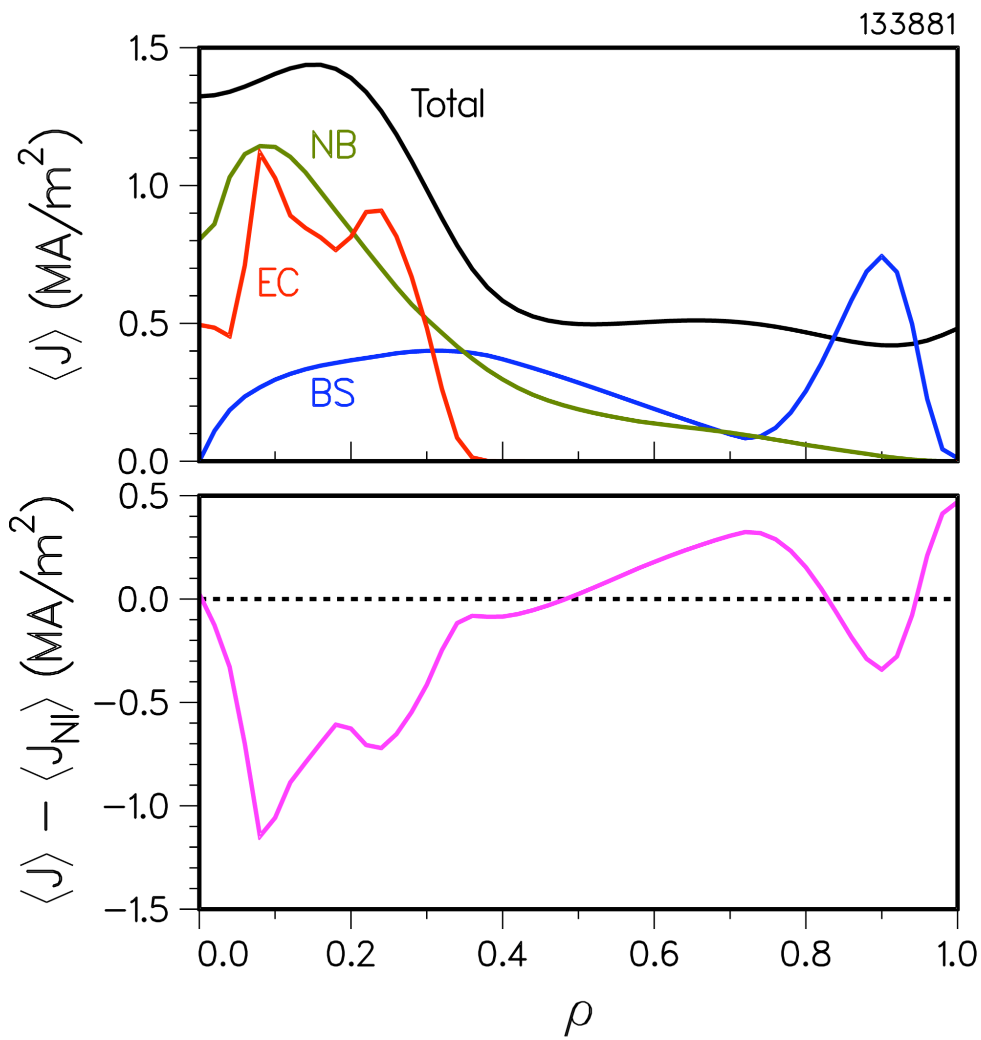


- **Despite strong central current drive, q_{min} > 1 and sawteeth are suppressed**
- **Surface loop voltage ~ 10 mV during high-performance period (β_N = 3.4)**

Calculated Current Drive:	NBCD	0.36 MA	Total	1.07 MA
	ECCD	0.17 MA	Ip	1.08 MA
	Bootstrap	0.54 MA		

Hybrid Current Profile Remains Broad Despite Strong Central Current Drive

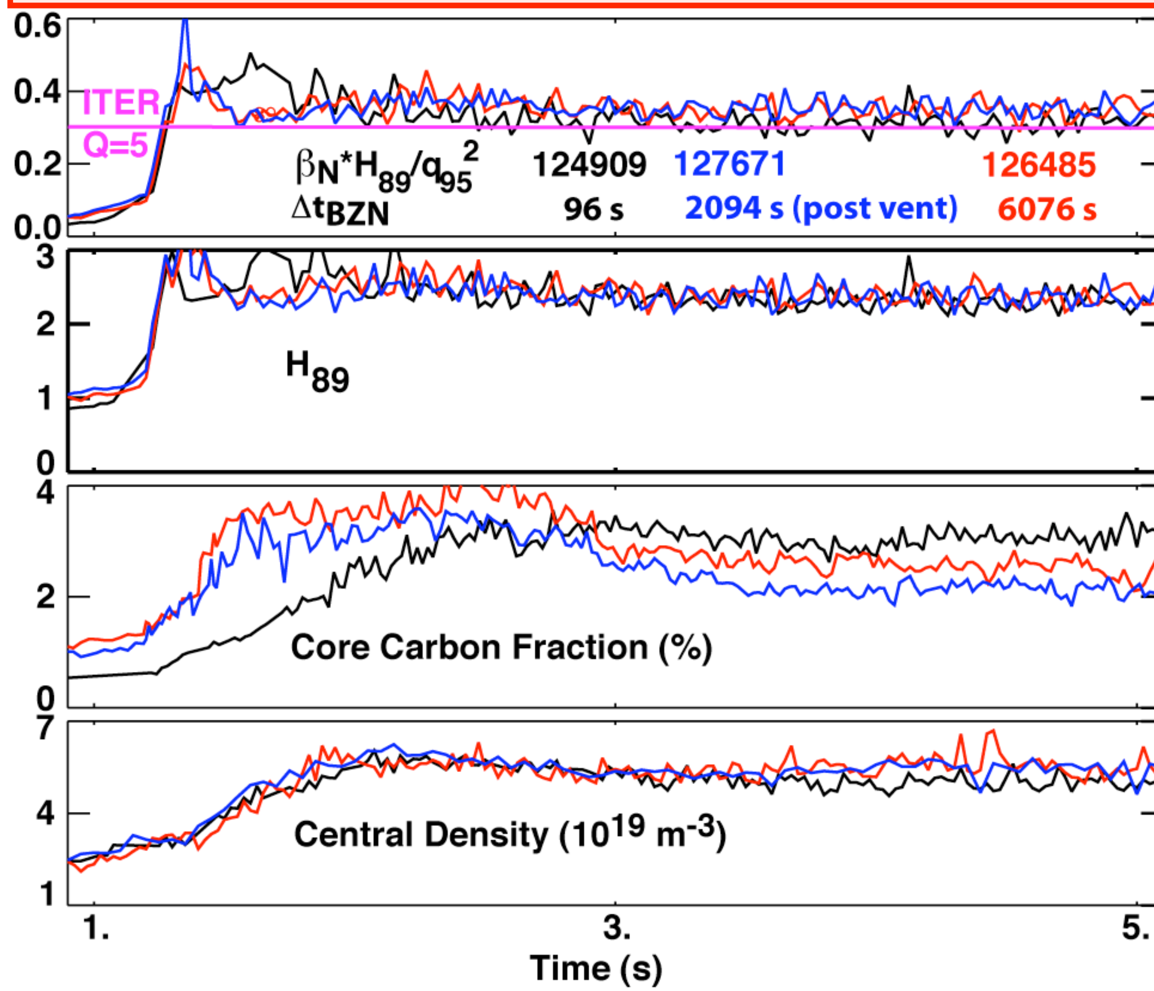
- **Characteristic feature of hybrids with 3/2 NTM is anomalous broadening of current profile**
  - Raises q_{min} > 1 and suppresses sawteeth
- **Calculated noninductive current profile is more peaked than total current profile**
- **Negative core value of effective ohmic current is inconsistent with time-average (positive) loop voltage profile**
  - Some form of magnetic flux pumping may be broadening current profile



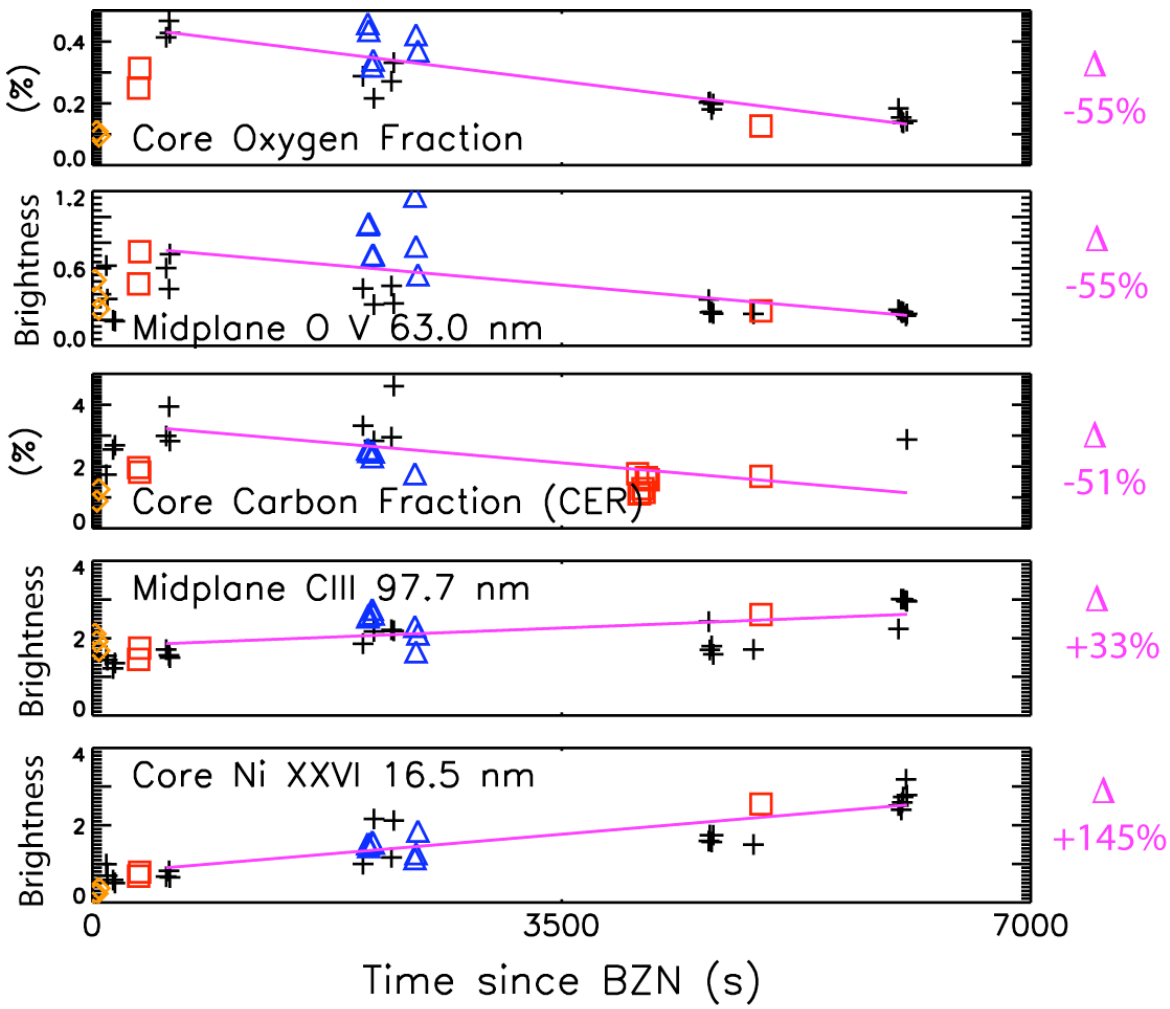
Good Hybrid Performance Maintained Over 3 Month Campaign with No Intervening Boronization

Over 6000 s of plasma operation since last BZN
With no degradation in Hybrid performance

- **Hybrids provide good high-performance benchmark operation**
- **Normalized performance above the ITER Q=5 Scenario**
- **Core Carbon Fraction not increasing**
- **Density well controlled**
- **Hybrid shot 127671 was after long entry vent and before first BZN of 2007.**
- **For these shots q_{95}~4.4, β_N ~2.7, $\beta_N H_{89}$ ~6.4**



Hybrid database shows mostly favorable trends in impurities across 2006–2007 campaigns



- **Core Oxygen and Carbon content remain low**
- **Ni, a very minor contributor to Z_{eff} and P_{RAD}, is increasing with time since BZN**
- **Hybrid performance is resilient with a low Z graphite wall.**

+ 2006 between early and late BZN
◇ 2006 after late BZN
△ 2007 after vent, before BZN
□ 2007 after BZN

Conclusions

- **Experiments on DIII-D show that the hybrid scenario is robust and relevant to burning plasma regime**
  - Confinement remains good (H_{98y2} > 1) even for low torque injection (M_t ~ 0.1) or strong electron heating ($T_i/T_e \approx 1$)
    - Strong E×B flow shear makes confinement excellent (H_{98y2} ~ 1.5)
    - Low-k and intermediate-k turbulence increase with electron heating, high-k modes predicted to be important
  - Type-I ELMs completely suppressed using RMP for β_N = 2.5
  - Hybrid scenario shown to be compatible with high-performance, steady-state operation
- **Hybrid performance is resilient with a low-Z graphite wall**
  - Maintained good impurity and particle control even after more than 6000 s of operation since last boronization