Progress Toward High Beta, Steady-State Conditions in DIII-D

by
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for the DIII–D
Advanced Scenario Thrust Group

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DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

GENERAL ATOMICS

308-04/CMG/cmg

DIII-D ADVANCED TOKAMAK PROGRAM GOAL: SCIENTIFIC BASIS FOR STEADY STATE HIGH PERFORMANCE OPERATION IN FUTURE TOKAMAKS

- **Steady-state operation**
  - 100% noninductive fraction: $f_{NI} = I_{NI}/I_p$
  - High Bootstrap current fraction: $f_{BS} = I_{BS}/I_P \propto \beta_p$

- **Maintaining sufficient fusion gain with reduced engineering parameters**
  - High β_T
  - High τ_E

  ⇒ High normalized fusion performance:
  $G = \beta_N H_{89}/q_{95}^2$

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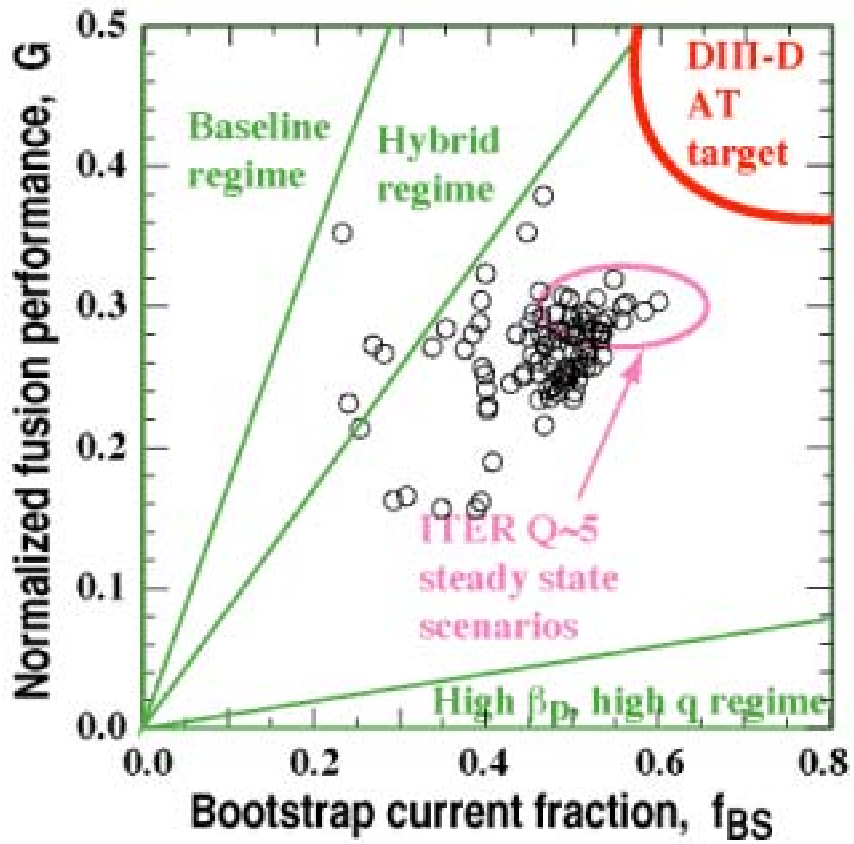
  - ⇒ High normalized fusion performance: $G = \beta_N H_{89}/q_{95}^2$
- **DIII-D *AT* experiments have demonstrated performance required for *ITER* steady state scenario**



THE DIII–D ADVANCED TOKAMAK RESEARCH PROGRAM

- ***Integrated*** **efforts to produce and study Advanced Tokamak (AT) regimes**
  - High β: Maximize and operate near the ideal-wall limit
  - Noninductive current drive
    - Most current driven by bootstrap
    - Remainder from external sources: Neutral Beam (NBCD) and Electron Cyclotron Current Drive (ECCD), Fast Wave (FWCD; coming soon)
  - Scenarios are developed using theory-based modeling

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- **Recent results:**
  - **100% noninductive conditions achieved both globally and locally across the plasma**
    - **Pressure profile still not stationary $\Rightarrow$ can lead to pressure driven instabilities**
  - **Nearly (~90%) noninductive conditions can be sustained for the duration of the hardware systems**

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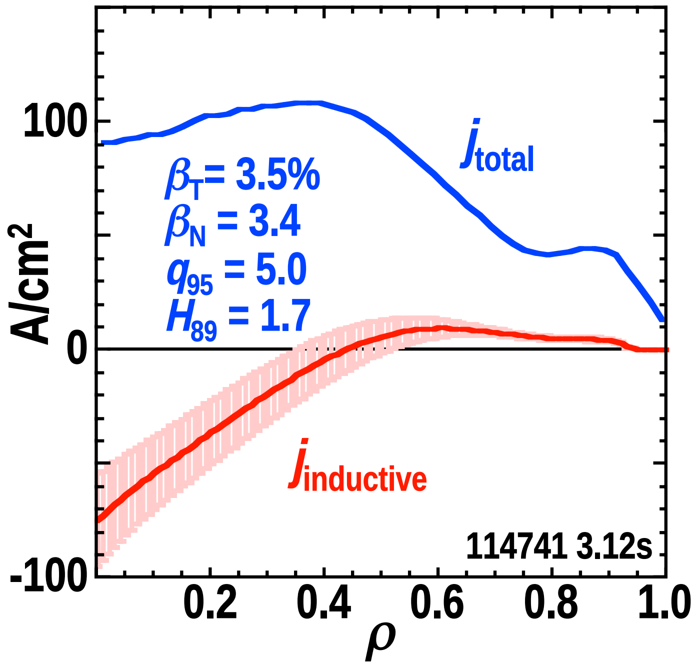
100% NONINDUCTIVELY DRIVEN PLASMAS OBTAINED WITH GOOD CURRENT DRIVE ALIGNMENT

Previously reported:



- Globally fully noninductive, but locally not relaxed

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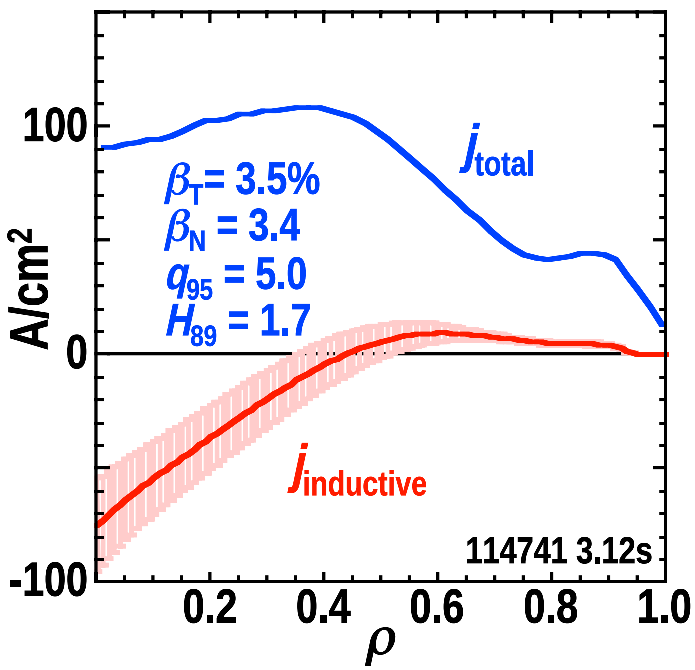
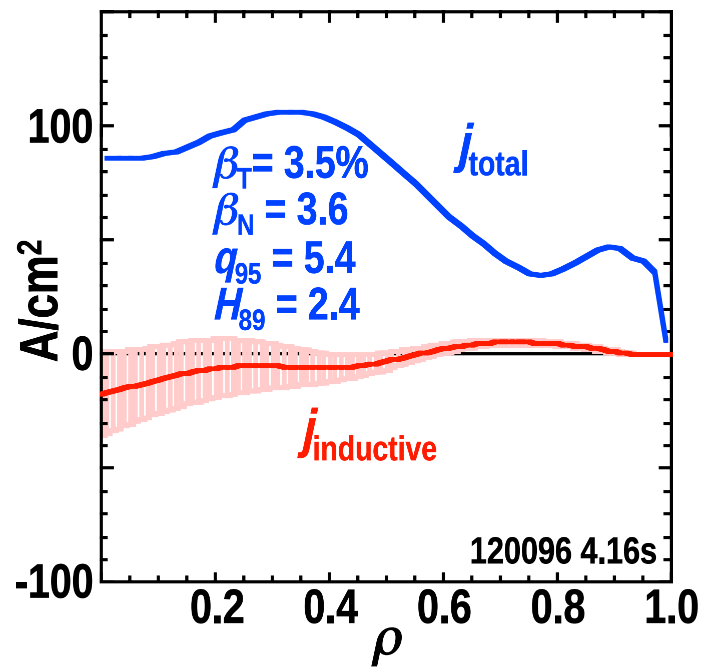


Recent progress:



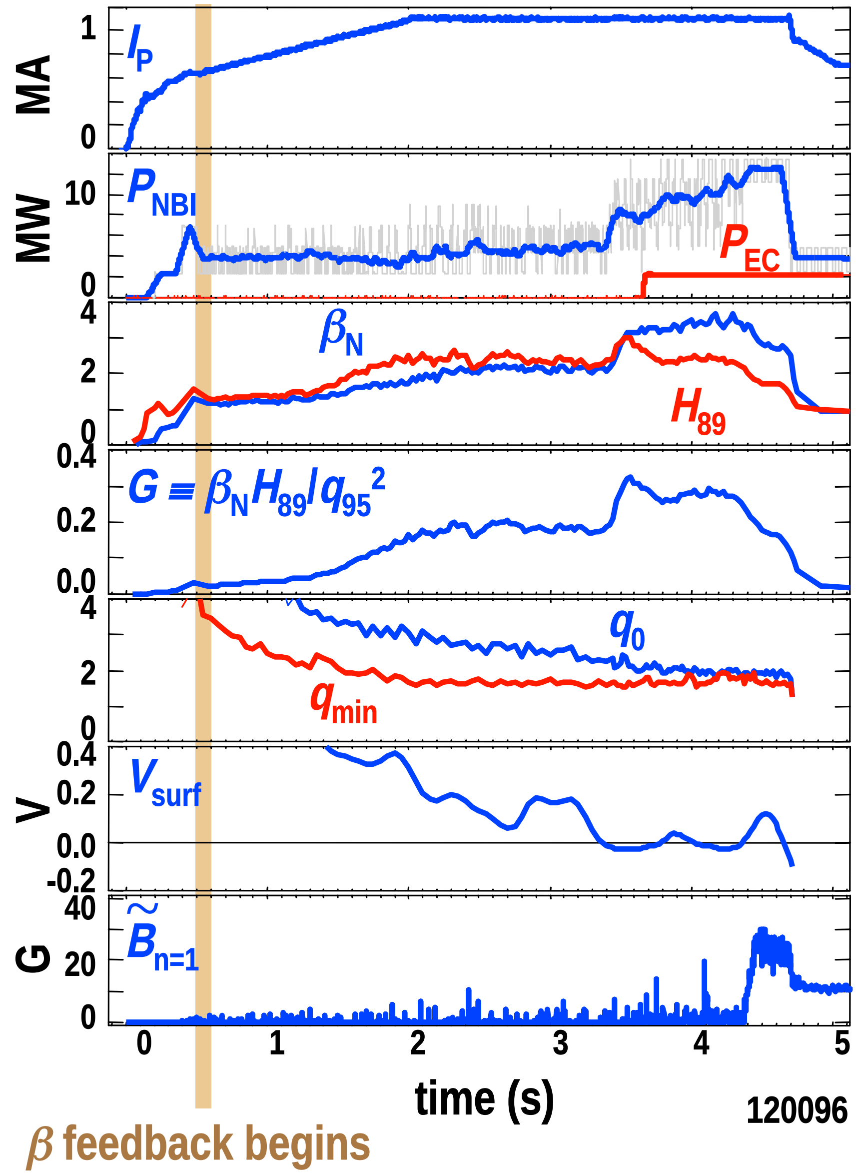
- Globally fully noninductive, but locally not relaxed

- Inductive current profile nearly relaxed across profile
  - Improved target *q* profile preparation
  - Improved confinement during high performance phase

EARLY BETA FEEDBACK FACILITATES RELIABLE FORMATION OF *AT* TARGET CONDITIONS

- β feedback initiated shortly after L–H transition
  - Conditions during current ramp become very reproducible
  - Allows adjustment of q_{min}, q_0-q_{min},… prior to high performance phase

β_T= 3.5%
β_N = 3.6
q_{95} = 5.4
H_{89} = 2.4



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- Target q profile is suitable for sustainment using off-axis ECCD
  - Not much evolution needed to reach final state

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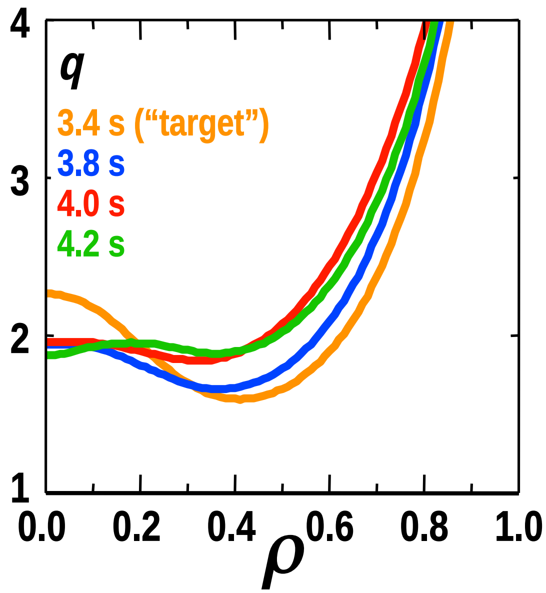

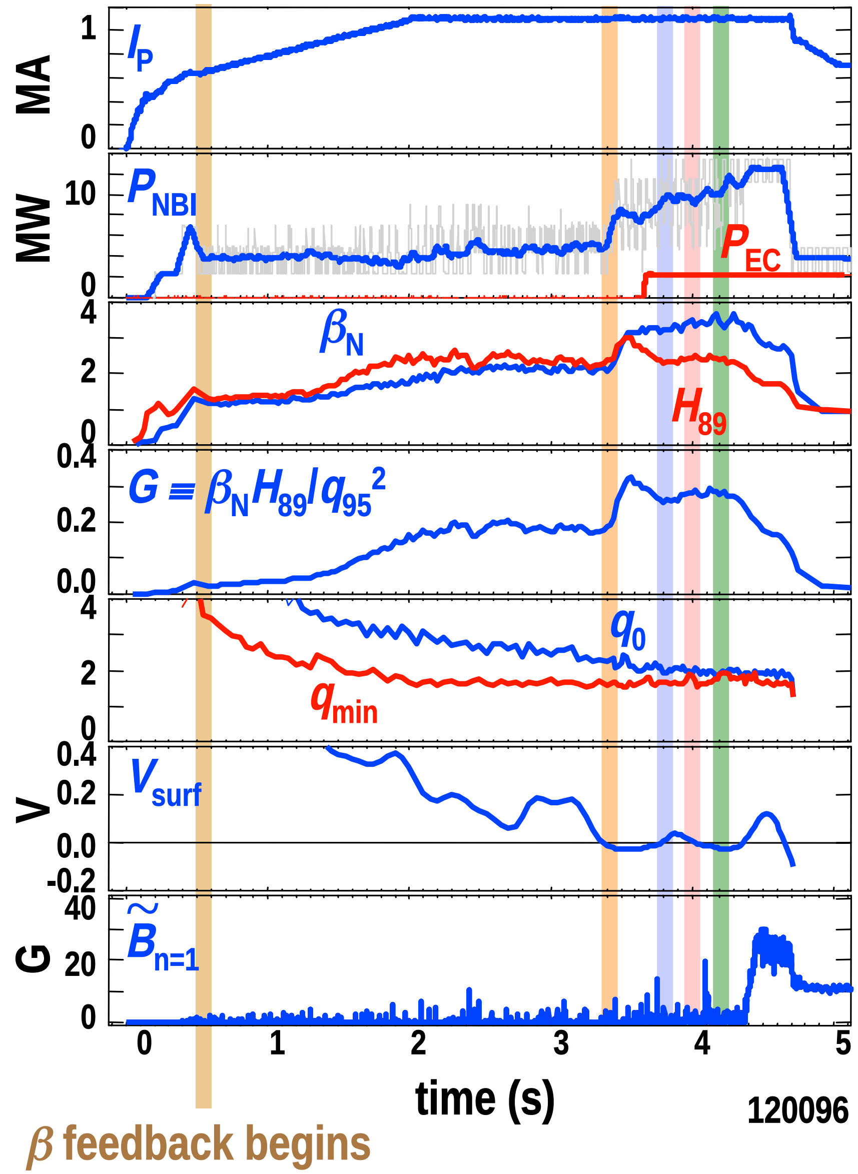

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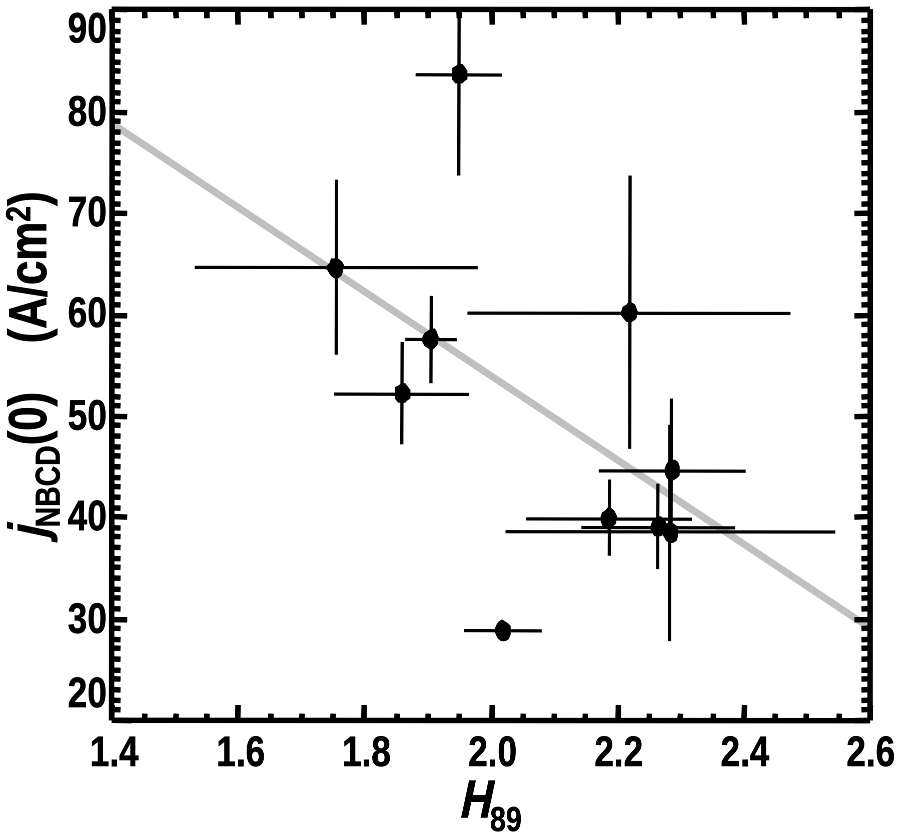
IMPROVED CONFINEMENT RESULTS IN REDUCED NEUTRAL BEAM CURRENT DRIVE NEAR THE AXIS



- **Neutral beam power is feedback controlled to maintain fixed β_N**
  - Lower confinement ⇒ higher NBI demand ⇒ more NBCD
  - Overdriven NBCD ⇒ Ohmic current cannot relax to zero
- **Confinement improvement in recent experiments is attributed to:**
  - Optimized non-axisymmetric field feedback
  - Slightly negative central shear

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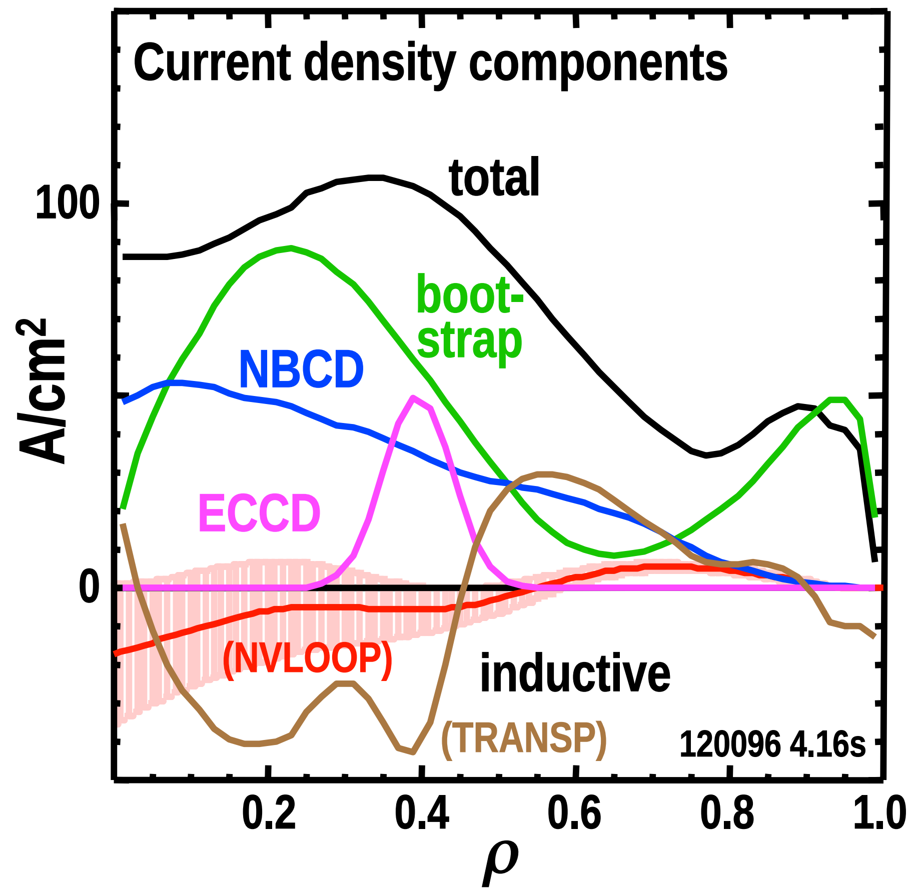
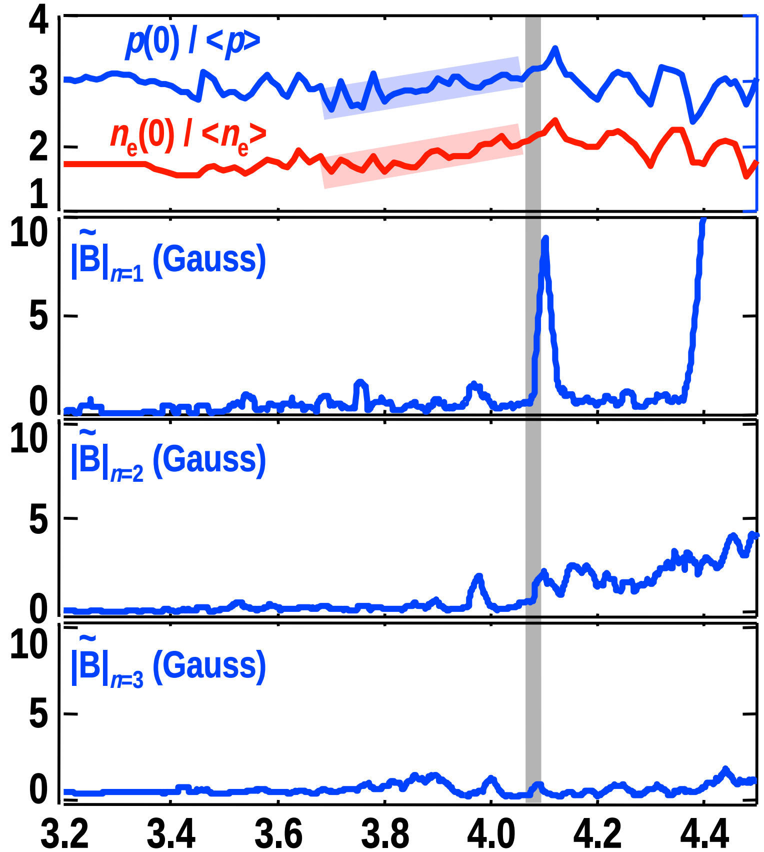
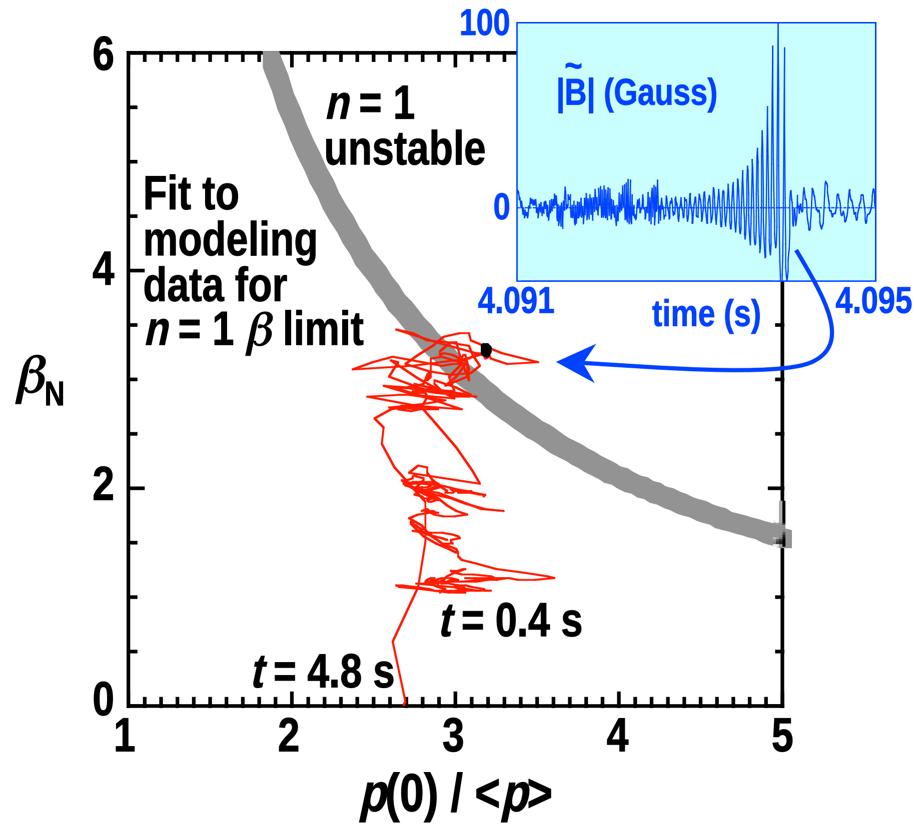
WITH IMPROVED CONFINEMENT, f_{NI}=100% ACHIEVED WITH GOOD CD ALIGNMENT

- **NVLOOP analysis:**
  - f_{OH} = 0.5%, f_{NI} = 99.5%
  - j_{ind} calculated directly from parallel electric field
  - Challenge: Difficult to parameterize current profile details with EFIT
- **TRANSP analysis:**
  - f_{BS}=59%, f_{NB}=31%, f_{EC}= 8%, f_{NI}= 98%
  - $j_{ind} = j_{total} - j_{bs} - j_{NBCD} - j_{ECCD}$
  - Challenge: In addition to above, depends on accuracy of bootstrap and source models



SUSTAINMENT OF $f_{NI} \approx 100\%$ LIMITED BY PRESSURE PROFILE EVOLUTION RATHER THAN CURRENT PROFILE EVOLUTION





- *n* = 1 ideal instability caused by pressure peaking primarily due to density peaking
  - Triggers *n* = 1 NTM, which in turn terminates high performance phase

[Ferron, RI1.005]

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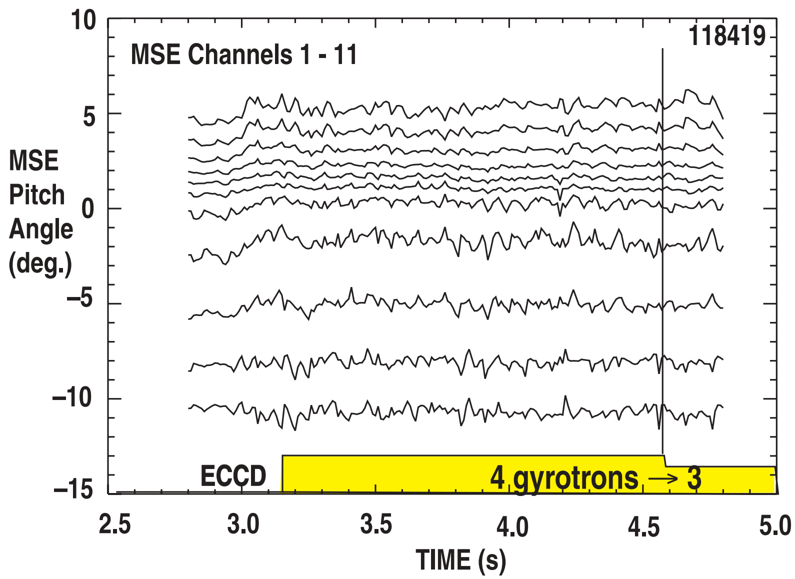
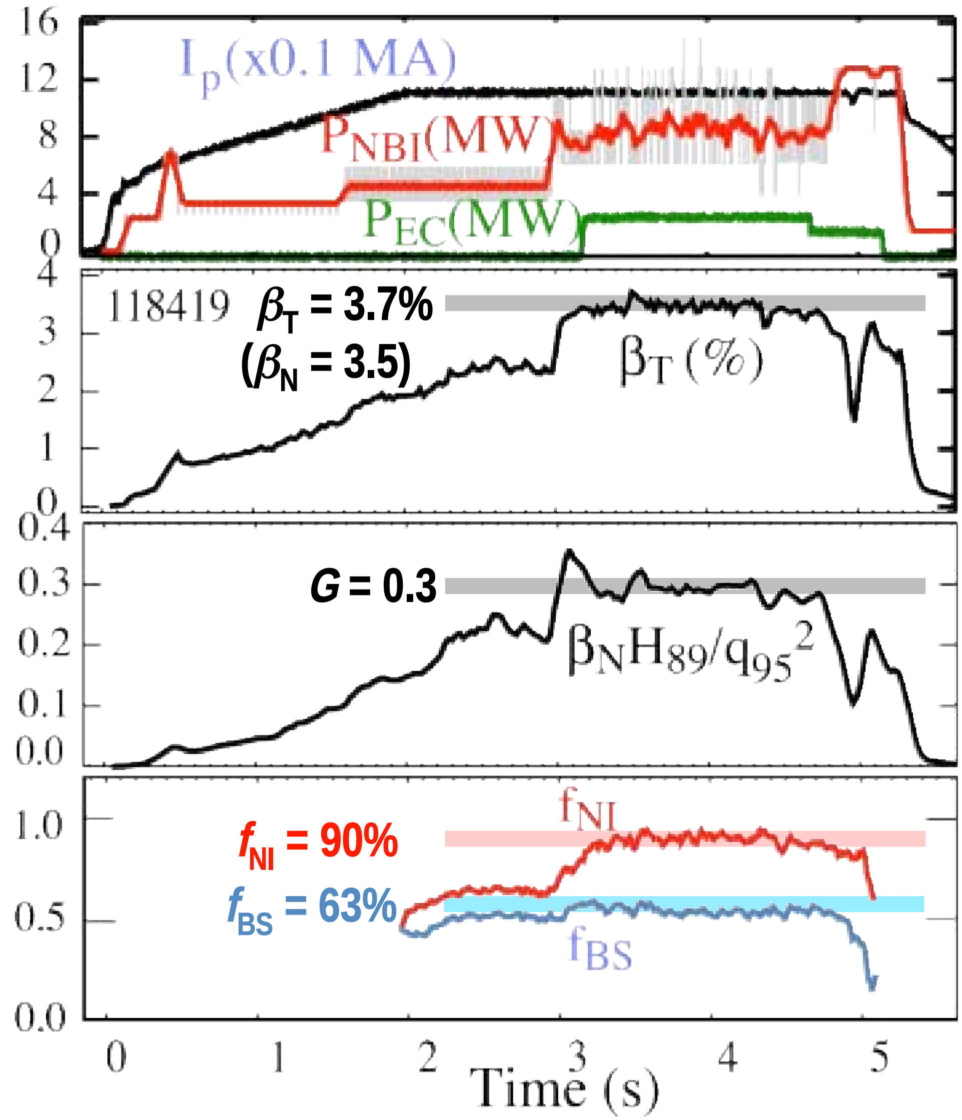
NEARLY FULL NONINDUCTIVE, STATIONARY DISCHARGE OBTAINED, LIMITED ONLY BY GYROTRON PULSE LENGTH





Slightly lower β request:

- $J_\phi(\rho)$ stopped evolving
- Maintained for $1 \times \tau_R$ (≈1.8s)

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PERFORMANCE REQUIRED FOR ITER STEADY STATE SCENARIO HAS BEEN DEMONSTRATED IN DIII–D *AT* EXPERIMENTS

- **100% noninductive conditions achieved both globally and locally across the plasma**
  – **Pressure profile still not stationary ⇒ can lead to pressure driven instabilities**

- **Nearly (~90%) noninductive conditions can be sustained for the duration of the hardware systems**

- **Future:**
  – **Improved control of both current and pressure profiles with additional long-pulse EC and fast wave power**
  – **Continued improvements to plasma control system**
  – **High triangularity cryopump at vessel floor will allow density control in double-null divertor configurations**

FOR MORE INFORMATION

- **Advanced Tokamak high β stability:**
  - **Friday morning invited talk [RI1.005] J.R. Ferron, "*Optimization of DIII-D Advanced Tokamak Discharges With Respect to the Beta Limit*"**
  - **Next! [EO3.003] J.E. Menard: "*Ideal and Resistive Plasma Stability Modeling for DIII-D AT Scenarios*"**
  - **[EO3.004] A.M. Garofalo: "*RWM Feedback Stabilization in DIII-D: Experiment-Theory Comparisons*"**

- **Profile control tools:**
  - **[EO3.015] C.C. Petty: "*Electron Cyclotron Current Drive at High Electron Temperature on DIII-D*"**
  - **[FP1.093] F. W. Baity: "*Restart of the Fast Wave RF Systems on DIII-D*"**

- **Poster sessions**
  - **FP1, Tuesday afternoon**
  - **NP1, Thursday morning**

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