Report on ITER-relevant Scenario Experiments on DIII-D

Presented by
T.C. Luce

Presented at
ITPA Integrated Operation Scenarios
Topical Group Meeting
Kyoto, Japan

Oct. 18–21, 2011

DIII-D
NATIONAL FUSION FACILITY

GENERAL ATOMICS

What’s Here, What’s Not

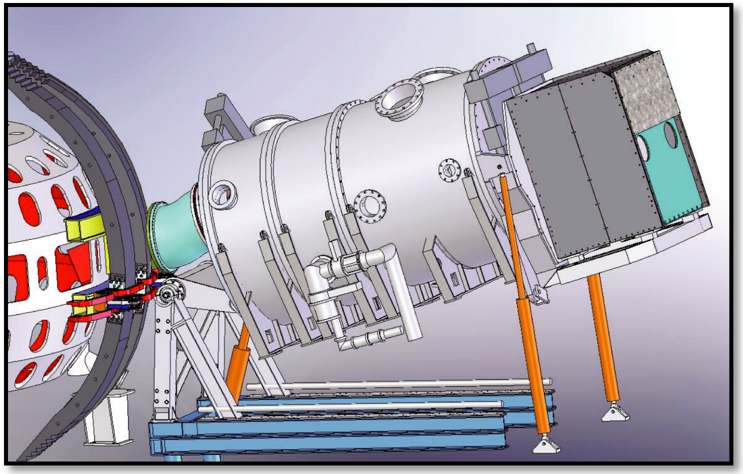
- **Talk tries to cover DIII-D experiments of interest to ITER and potential future joint experiments from the last run (May-Sept.)**
  - Steady-state scenario with off-axis NBI
  - Advanced inductive with low or no external torque input
  - QH mode with no external torque source
  - Divertor characterization
  - Closed-loop demonstration of current profile control with a physics-based model
- **Plans for Oct. run will be shown**
  - Plans for 2012 very uncertain at this point
- **Most, if not all, of the results directly in support of joint experiments will be reported through the joint experiment spokespersons**

Steady State Scenario Work Focused on min(q)>2 with Off-axis NBI

- **Previous attempts to probe the β limit with min(q)>2 found central co-NBI overdrove the central current at the powers needed**
  - Insufficient power at higher B

- **Theoretical and experimental studies indicated higher β limits when the pressure and current profiles were broader**

- **Both considerations motivated modifying 1 beamline in DIII-D to tilt vertically to give off-axis NBI**



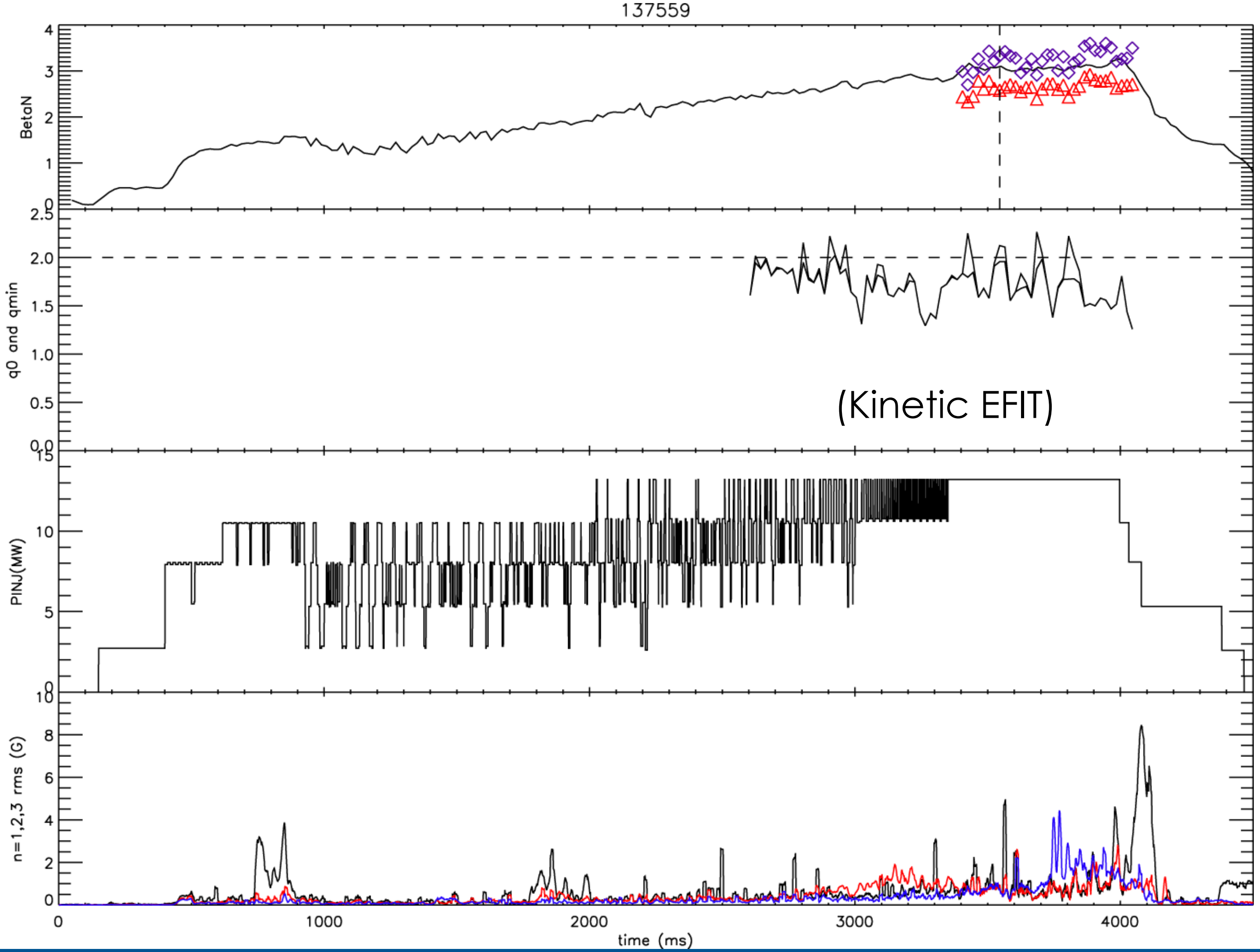
With On-Axis NBI, it is Difficult to Maintain min(q)>2 and Achieve High β_N

2009 Shot

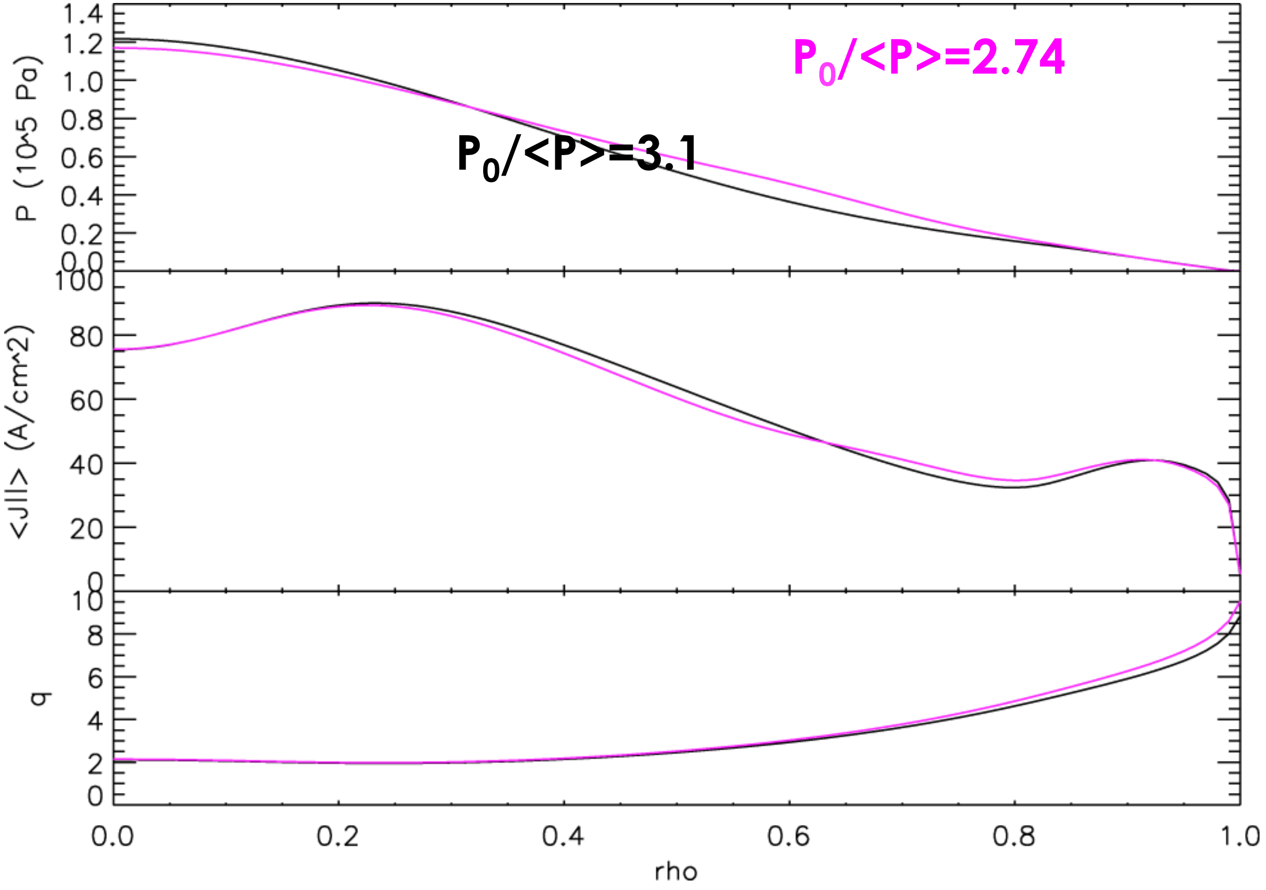
β_N at ideal wall n=1 limit

Target q_{min}=2 not maintained

B_T=2 T, H_{89}=2 require all available co-NBI power



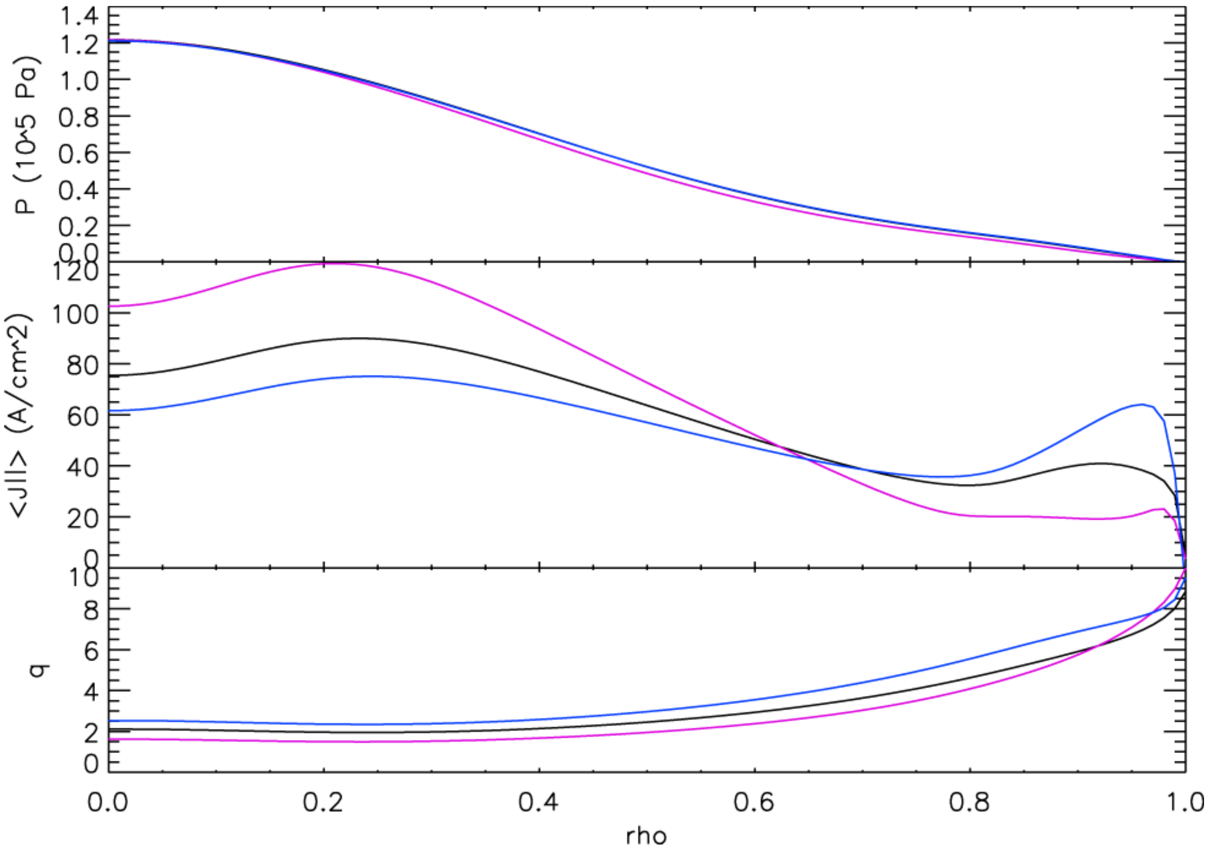
Modeling Indicates Only Modest Gain In β Limit by Broadening Only the Pressure Profile



- Changed P at fixed Ip
- DCON results

P0/<P>	3.1	2.74
βN n=1 nw	2.59	2.84
βN n=2 nw	3.32	3.41
βN n=3 nw	3.66	3.61
βN n=1 iw	3.34	4.25
βN n=2 iw	3.66	3.93
βN n=3 iw	3.8	3.86

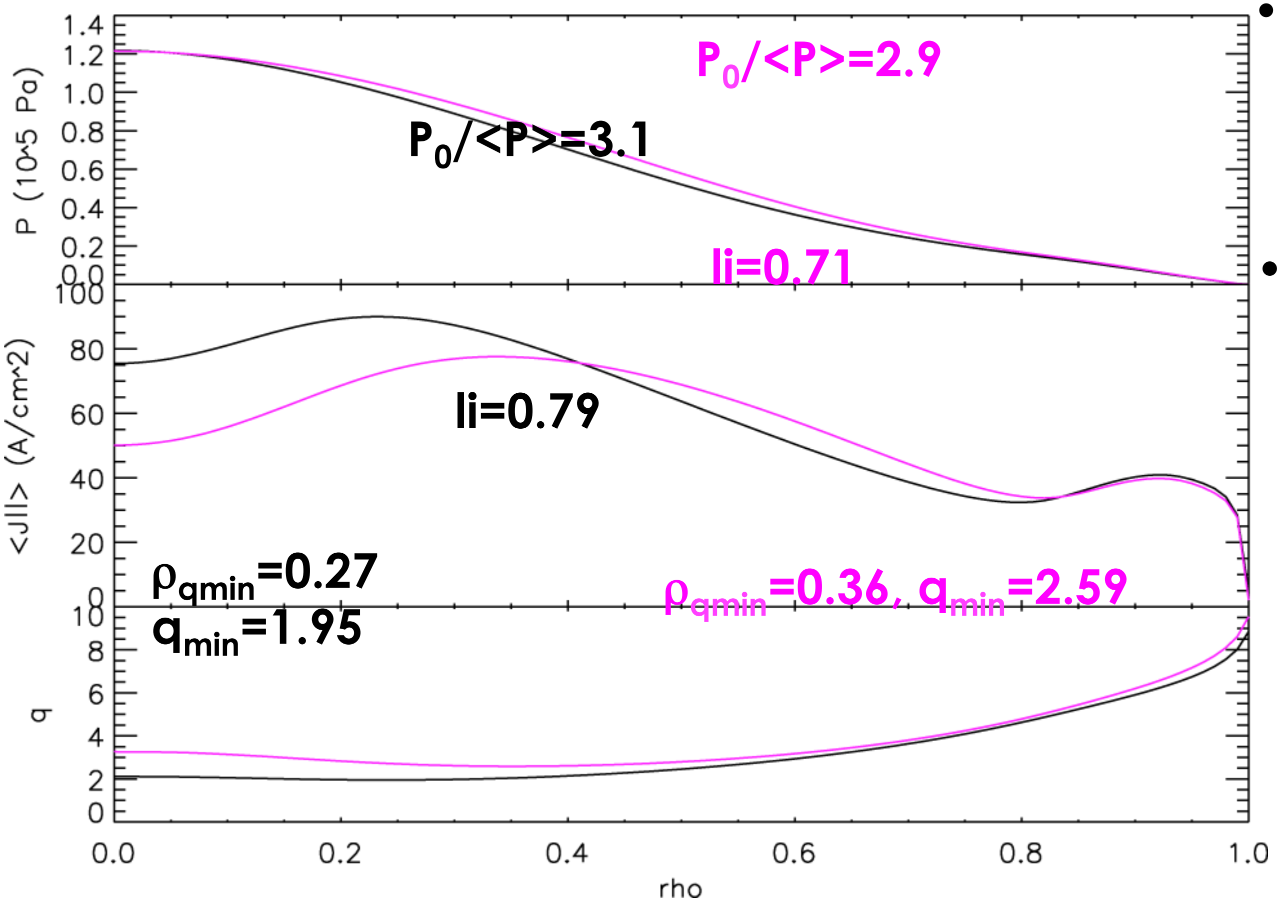
Modest Improvement in the Calculated β Limit by Increasing min(q) While Holding ρ_{qmin} Fixed



- Scaled q_{min} at fixed Ip
- DCON results

q_{min}	1.495	1.95	2.35
li	1	0.79	0.6
β_N n=1 no-w	3.56	2.59	2.48
β_N n=2 no-w	3.59	3.32	3.15
β_N n=3 no-w		3.66	3.64
β_N n=1 ideal	4.35	3.34	3.87
β_N n=2 ideal	3.62	3.66	3.97
β_N n=3 ideal	3.90	3.80	4.12

Broadening J Increases the Calculated β_N Limit Significantly

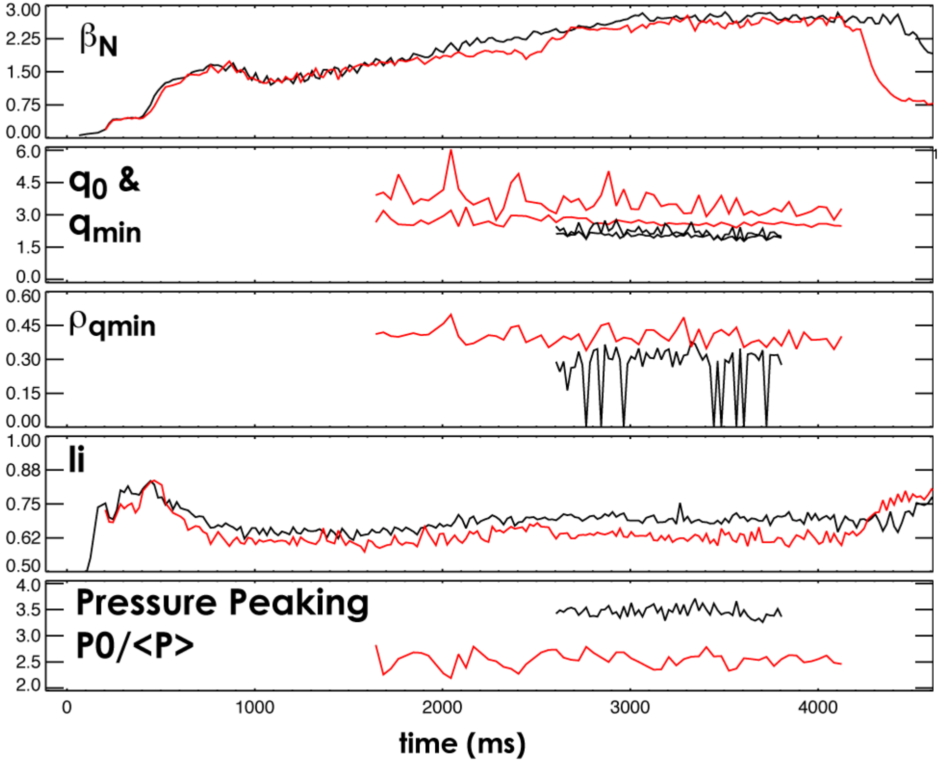


- $\Delta J_{||}$ derived from difference between simulations of NB on-axis and NB off-axis
- Fixed Ip

β_N n=1 no-wall	2.59	2.69
β_N n=2 no-wall	3.32	3.53
β_N n=3 no-wall	3.66	3.93
β_N n=1 ideal-w	3.34	4.26
β_N n=2 ideal-w	3.66	4.27
β_N n=3 ideal-w	3.80	4.31

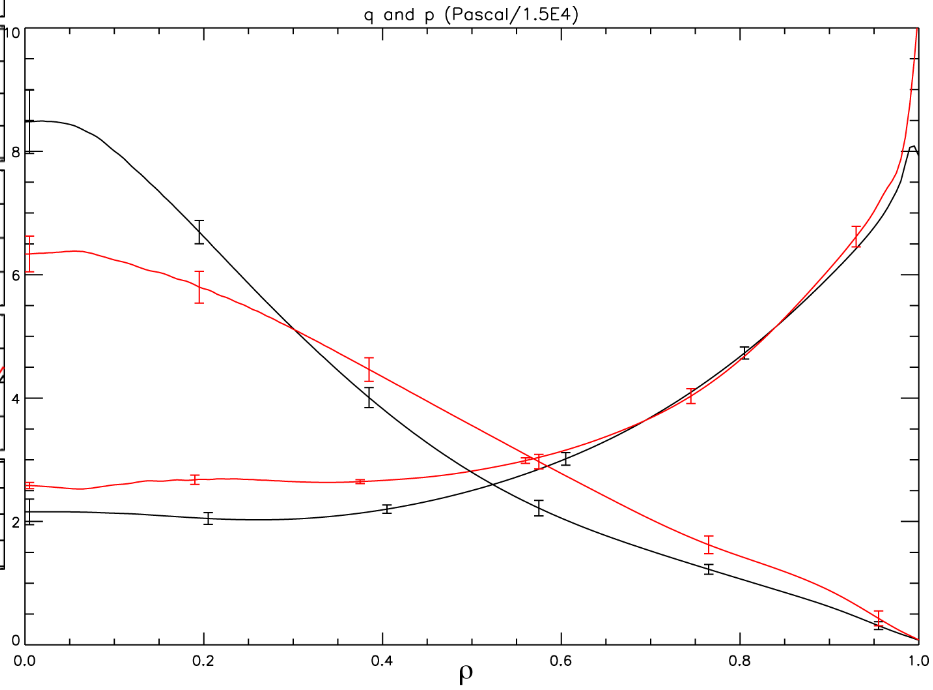
Experimental Pressure and Current Profiles Are Broader With Off-Axis NBI and More ECCD Power

B_T=2 T, q_{95}=6.8, Matched β_N≈2.8 of 2009 Reference Shot



(Kinetic EFITs)

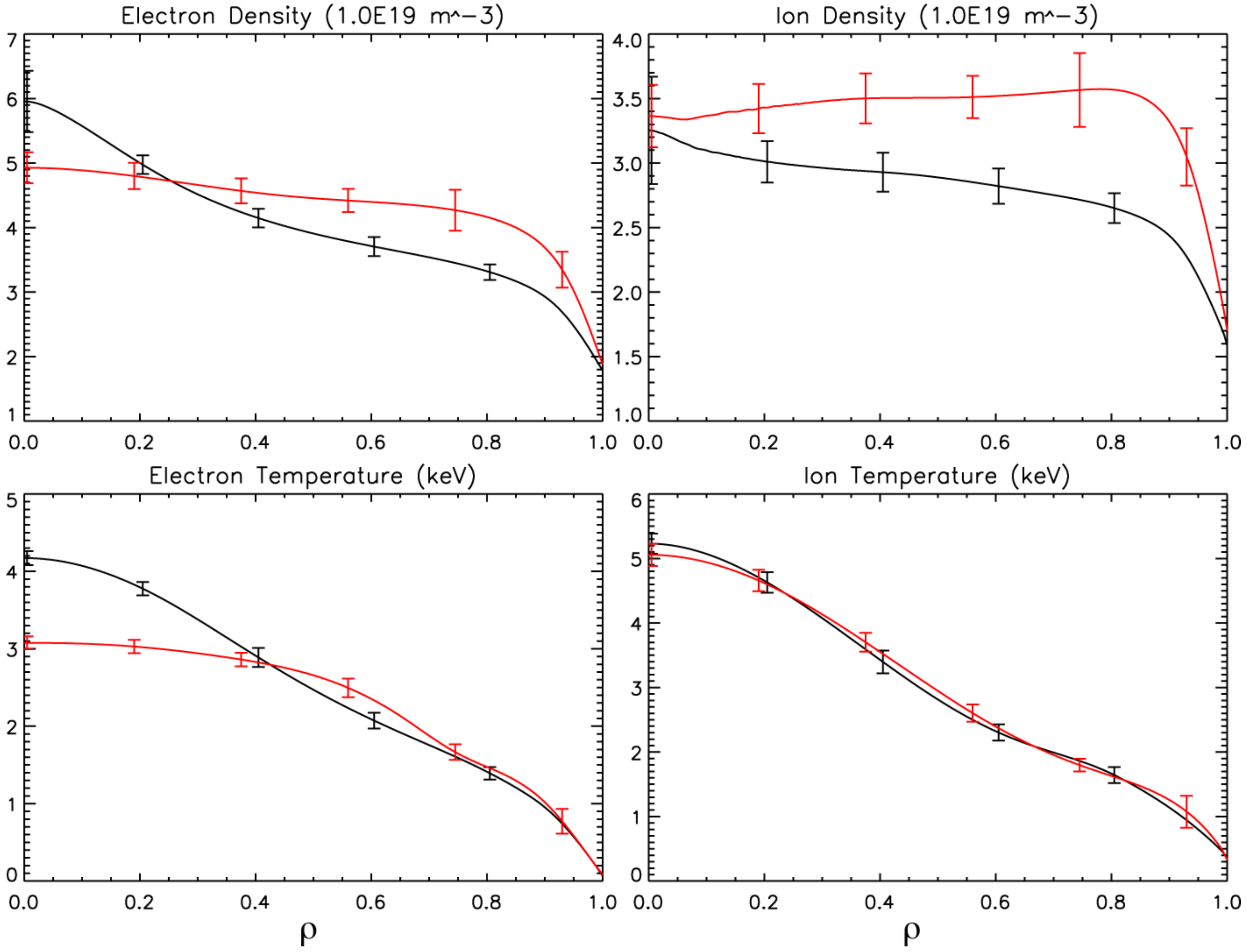
Time Averaged Profiles in β_N flattop:
With central NBI, with off-axis NBI



Density and Electron Temperature Profiles Are Broader With Off-axis NBI

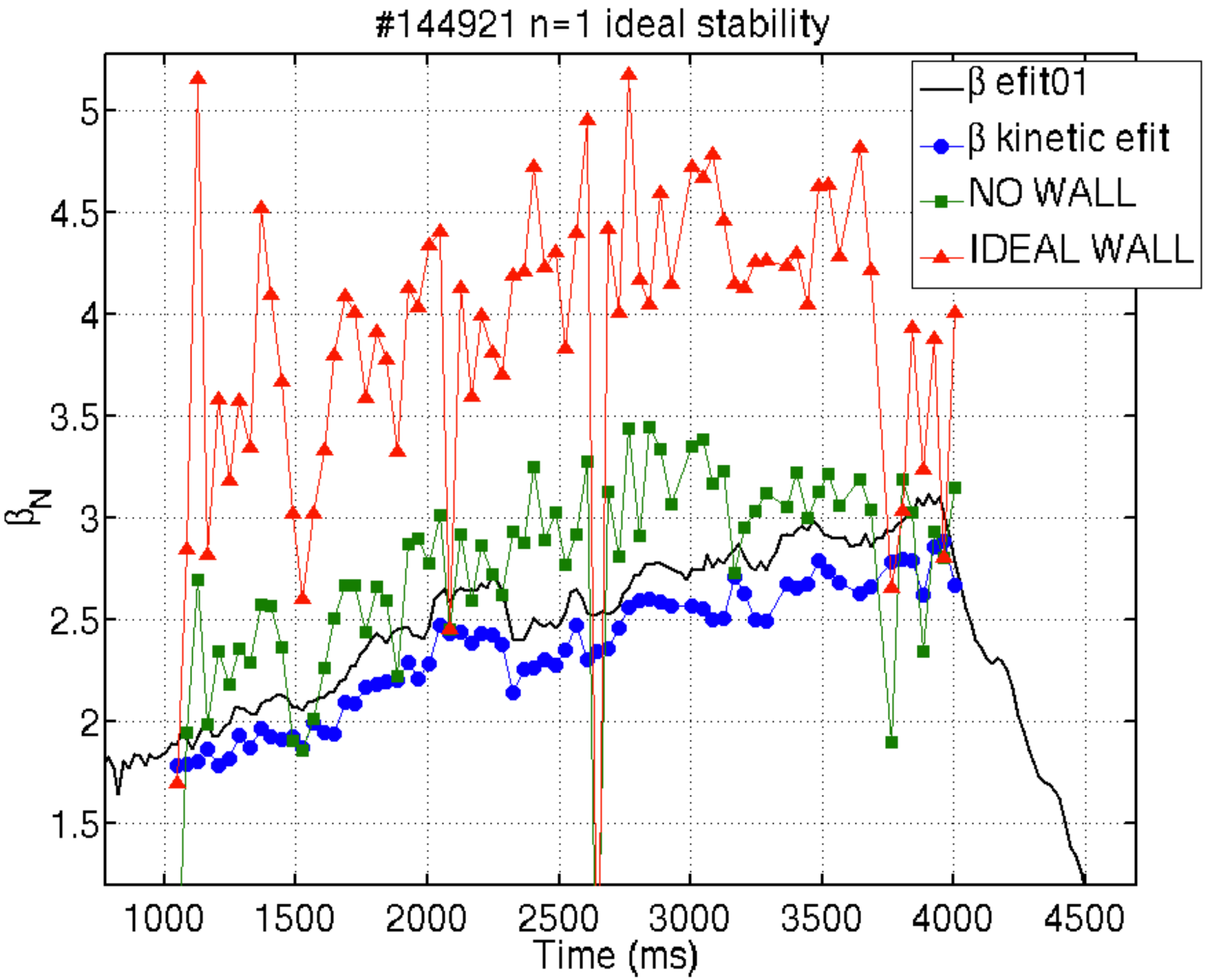
Time Averaged Profiles in β_N flattop

Not clear why the density profile is different



Stability Analysis Indicates the Ideal-Wall n=1 β_N Limit is Typically Over 4 With Off-axis NBI

- **Min(q)>2 easily sustained**
- **Confinement limits β with the available power for this B**



Recent Experiments Are Pushing Advanced Inductive Regime toward Zero External Torque Input

- **Previous results with a co-NBI startup followed by a transition toward more balanced injection showed:**
    - Significant degradation of confinement as external torque was reduced
    - Lower limit on external torque set by locked mode
- **New approach taken this year to start with zero-torque or low-torque from the beginning**

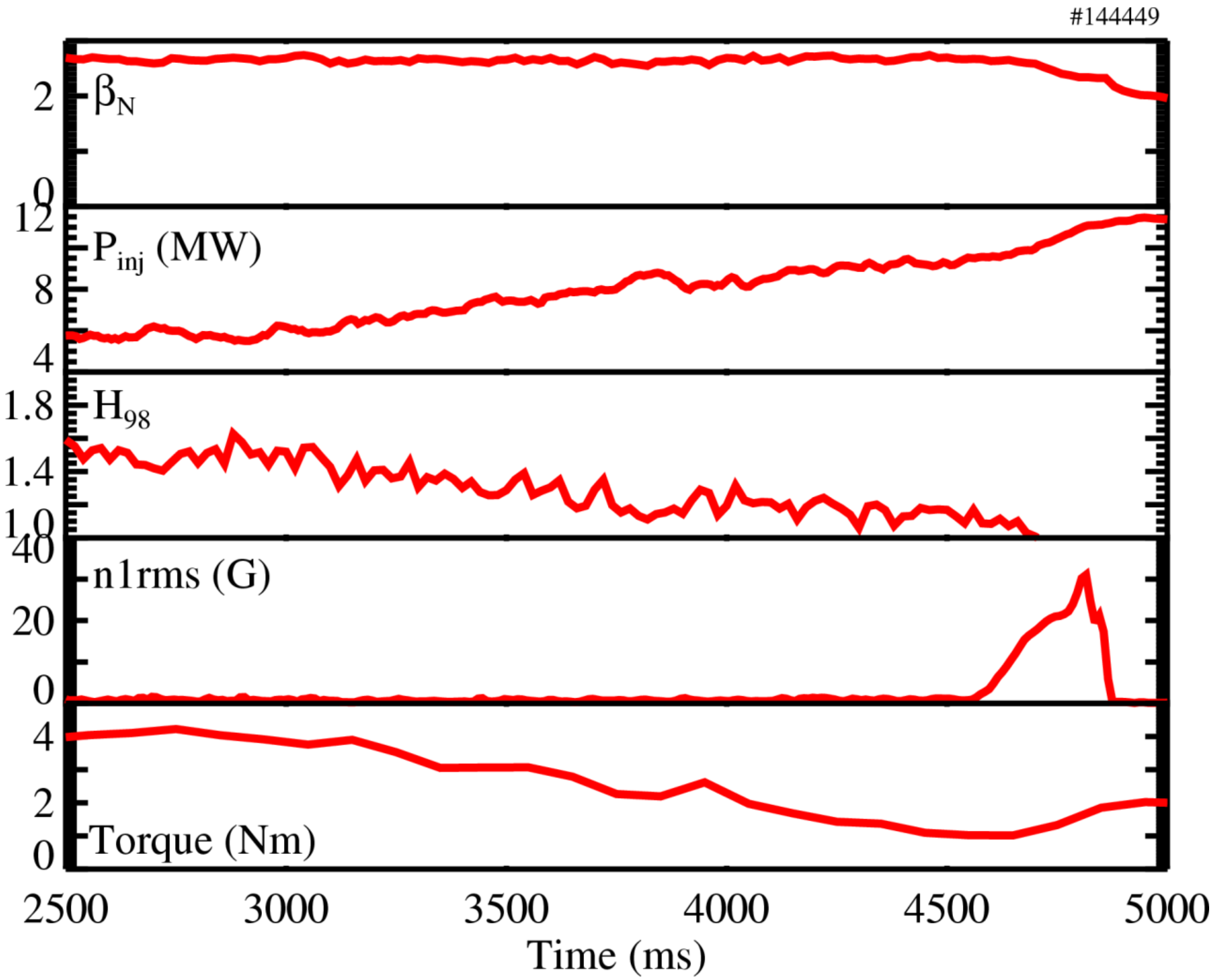
Significant Reduction in Confinement Observed as Torque Is Reduced

- **2/1 NTM invariably encountered at low torque**

- **Power demand increase ~70% for fixed β_N (before 2/1 onset)**

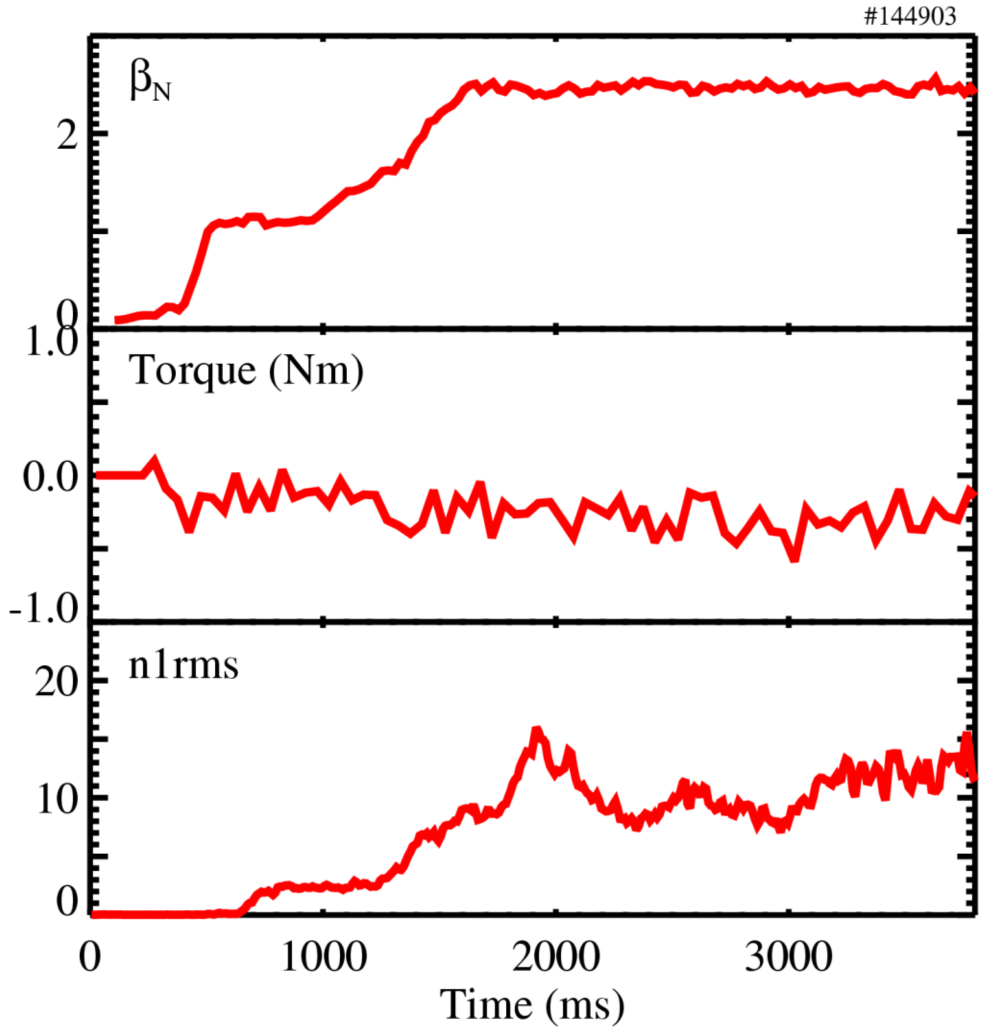
- **H98 reduced from >1.5 to approx 1.0**

- **Similar to previous results**
  [Politzer NF 2008]



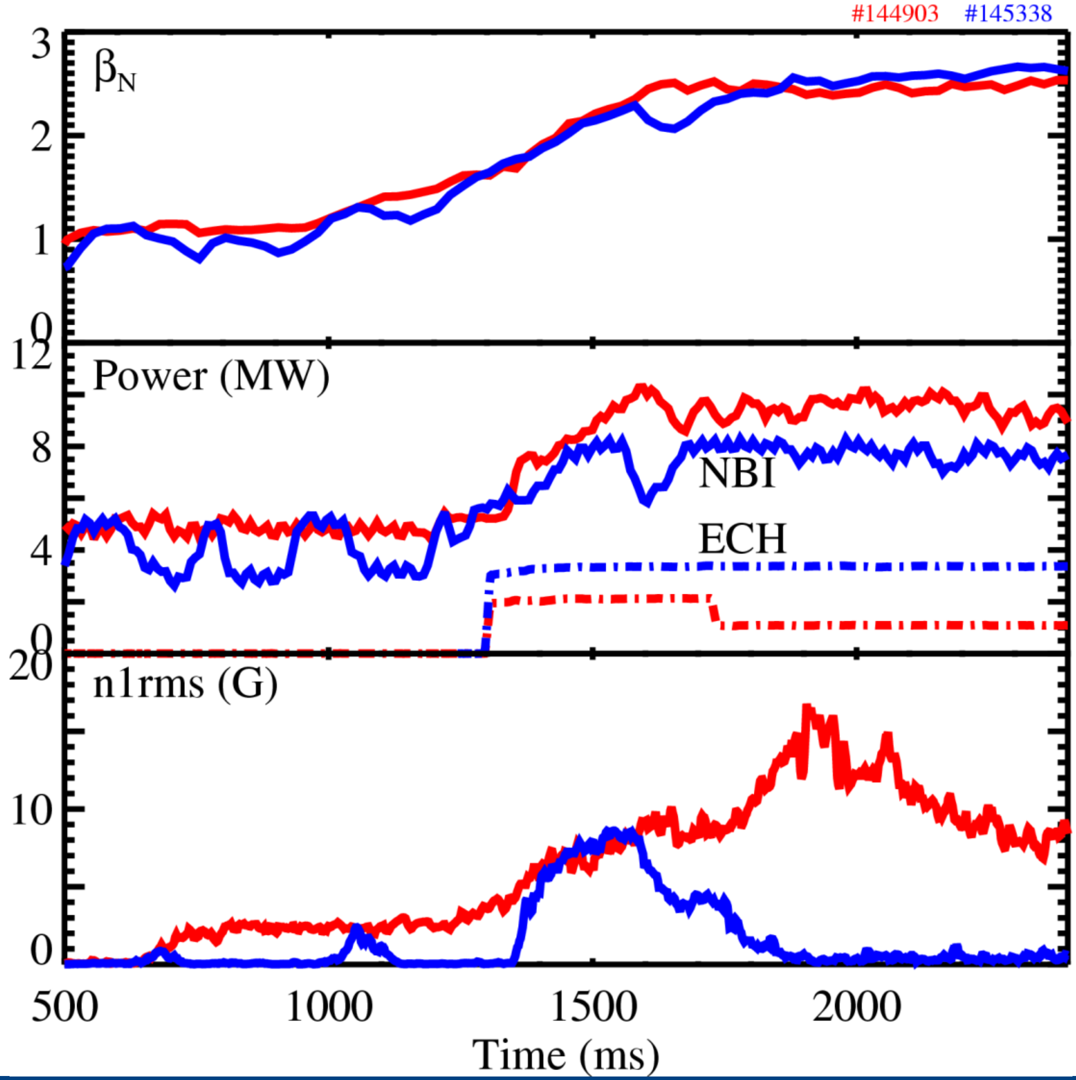
H-mode Startup with ECCD (2 Gyrotrons) Resulted in Stable AI Discharge with Zero Net torque Throughout

- **Modest ECH power allowed 2/1 to be reduced sufficiently to allow stable operation at β_N~2.5**
  - Unknown whether additional sources would have suppressed mode completely
  - Unknown whether plasma remains stable if remove ECCD later in discharge
- **Sustained for max duration of 210RT beam**
- **Note, no obvious 3/2 or 4/3 mode present**
  - Is this a 2/1 AI plasma?
    - In which case, what happens if actually stabilize 2/1?



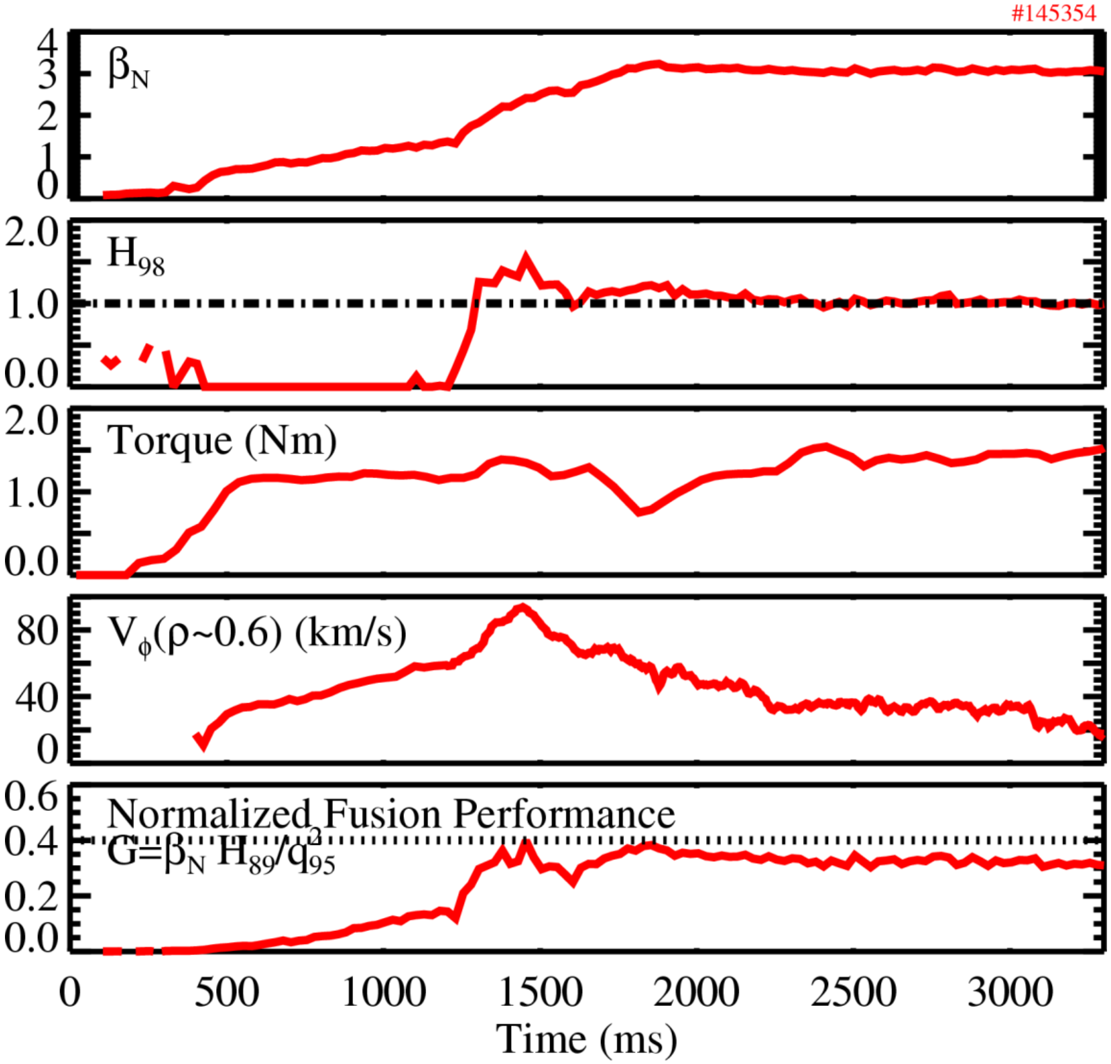
Reproduced Low Torque Reference, and with All 6 Gyrotrons, NTM Completely Suppressed

- **Slight increase in performance without 2/1 NTM, but largely offset by increased use of EC power**
  - Similar β_N for similar combined NBI+ECH



β_N~3.2, Approaching ITER Q=10 Equivalent Achieved with Torque~1 Nm, H98~1.1, G~0.38

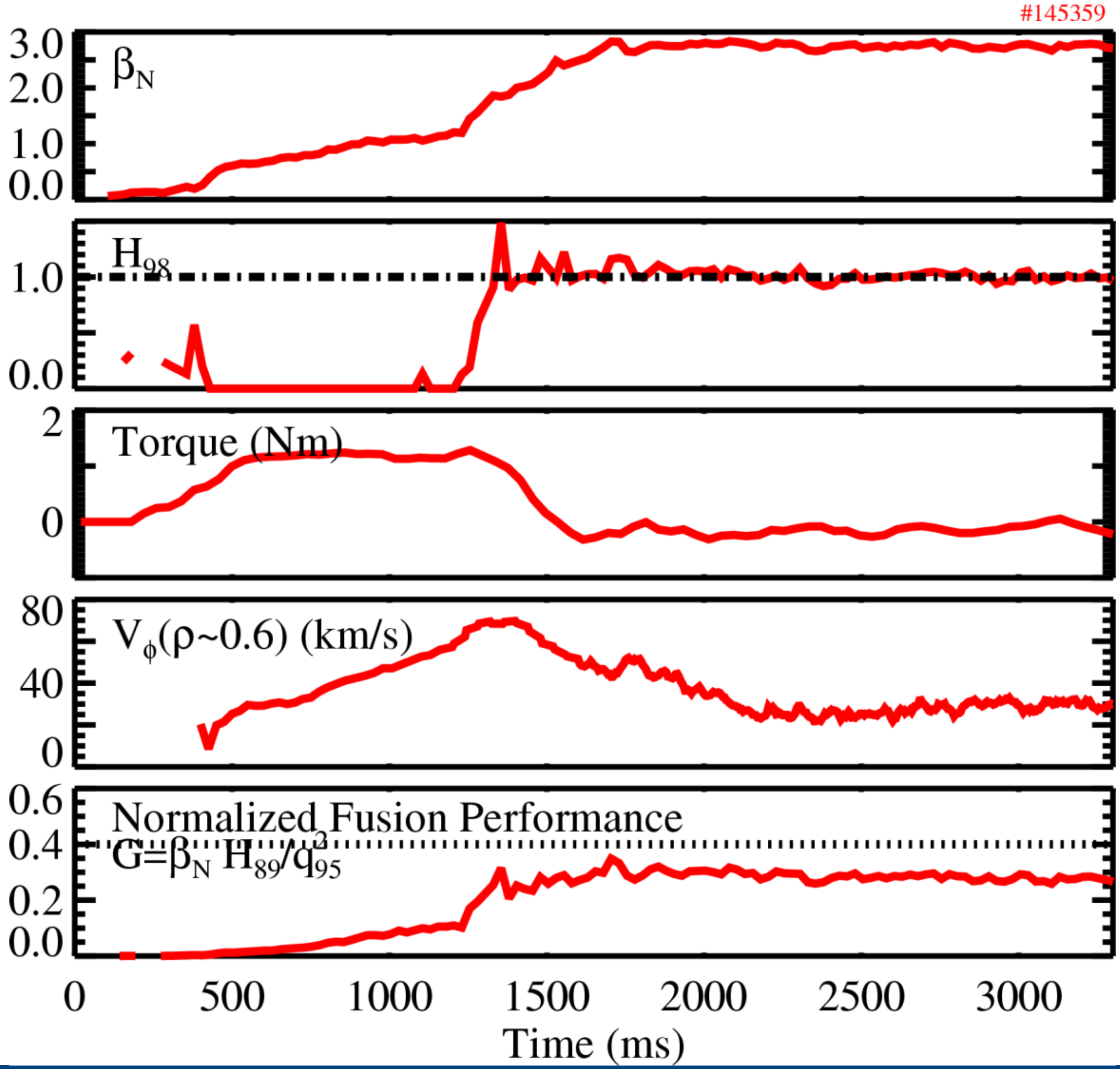
- **1 Nm in DIII-D drives approximately the same rotation as ITER beams (30+ Nm)**
  - Scaling for moment of inertia and confinement
- **H98>~1**
- **Normalized fusion performance, G~0.38**
  - G~0.4 is ITER Q=10 equivalent



Also Achieved Higher Fusion Performance with Net Torque~0 Nm at Higher Current, q95~4

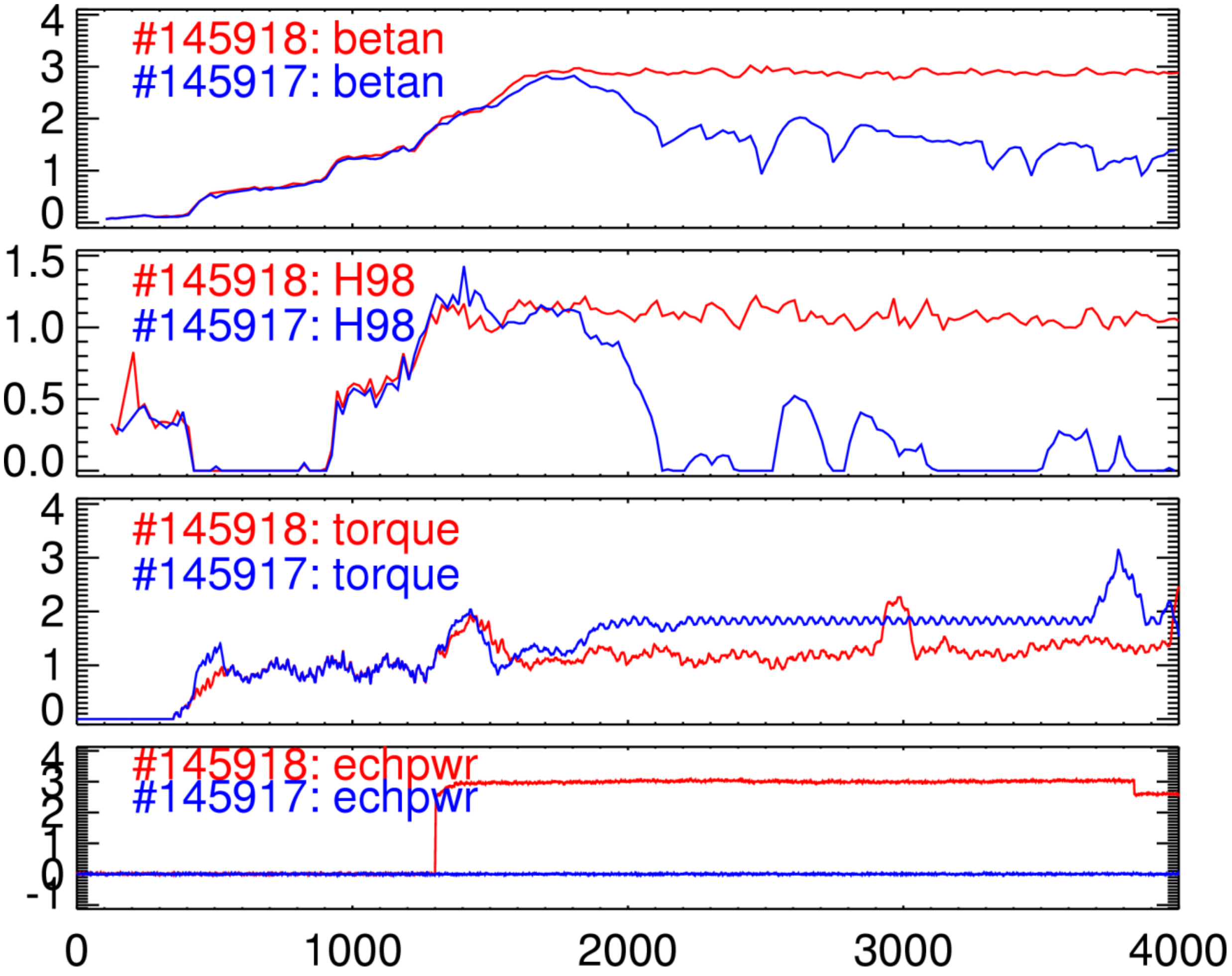
- Torque stepped down from 1 Nm in startup phase back to 0

- β_N~2.7, H98~1, G~0.32



High β_N~3, Torque~1 Nm, H98~1 Achieved Using Central ECH (no q=2 ECCD)

- **Previous results needed ECCD at q=2 to operate at high beta and low torque**
- **Most recent results still required EC power, but insensitive to deposition location or heating vs current drive**
  - **Here, ρ_{ECH} ~ 0.3 and configured for heating**



QH Mode May Be an ITER-relevant ELM Avoidance Scheme

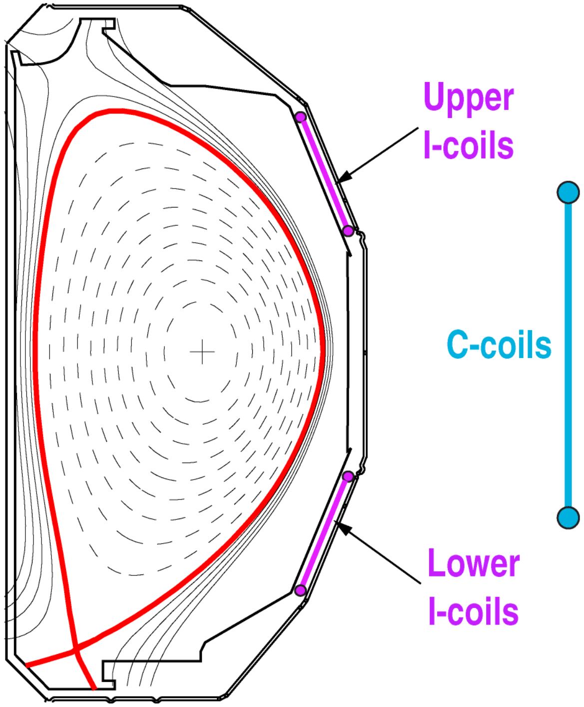
- **QH mode has a saturated (or stationary) edge mode instead of ELMs**
  - Observed on all 4 large divertor tokamaks
  - Traditionally observed with ctr-NBI

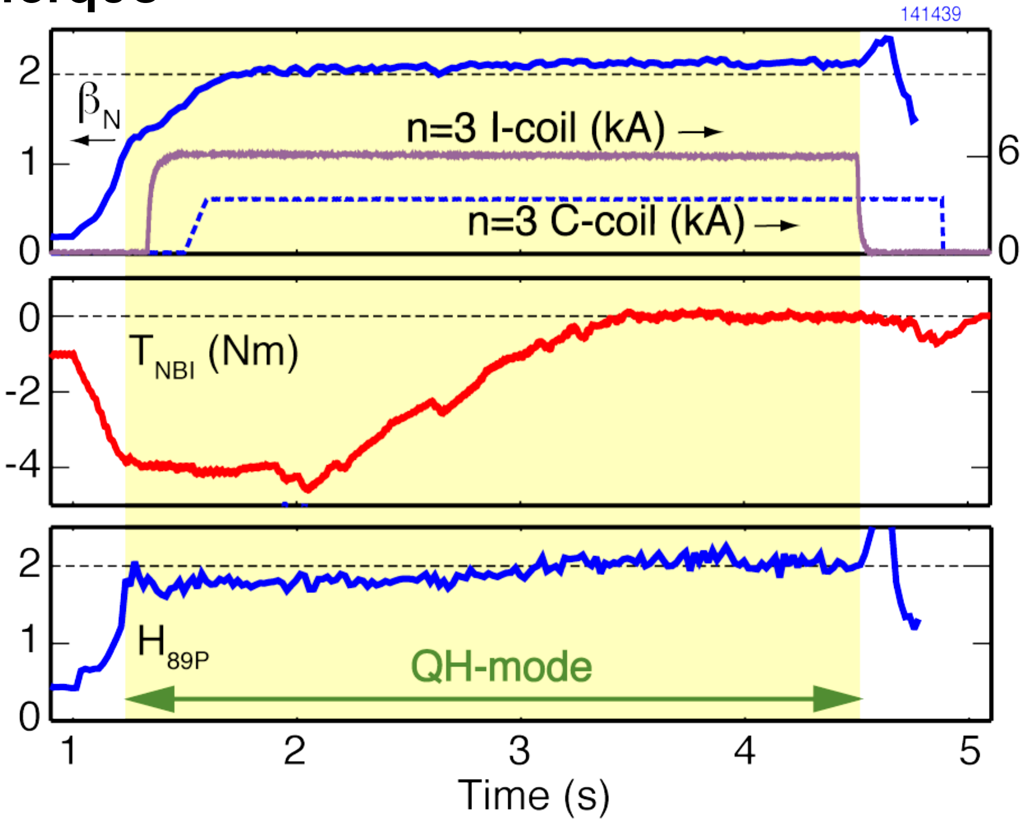
- **Recent results have used the plasma response to non-axisymmetric (*n*=3) magnetic fields to supply the edge rotation in the counter direction believed necessary for QH mode in the absence of external torque input**

Neoclassical Torque from 3D Fields Can Replace NBI Torque for QH-mode Access

- **Previously, QH-mode required significant NBI torque**
  - Minimum pedestal velocity shear necessary for QH-mode, consistent with theory predictions [Burrell et al., PRL (2009)]
- **Counter-Ip torque from nonresonant magnetic fields (NRMFs) enables QH-mode in plasmas with zero-net NBI torque**

  [Garofalo et al., NF (2011)]





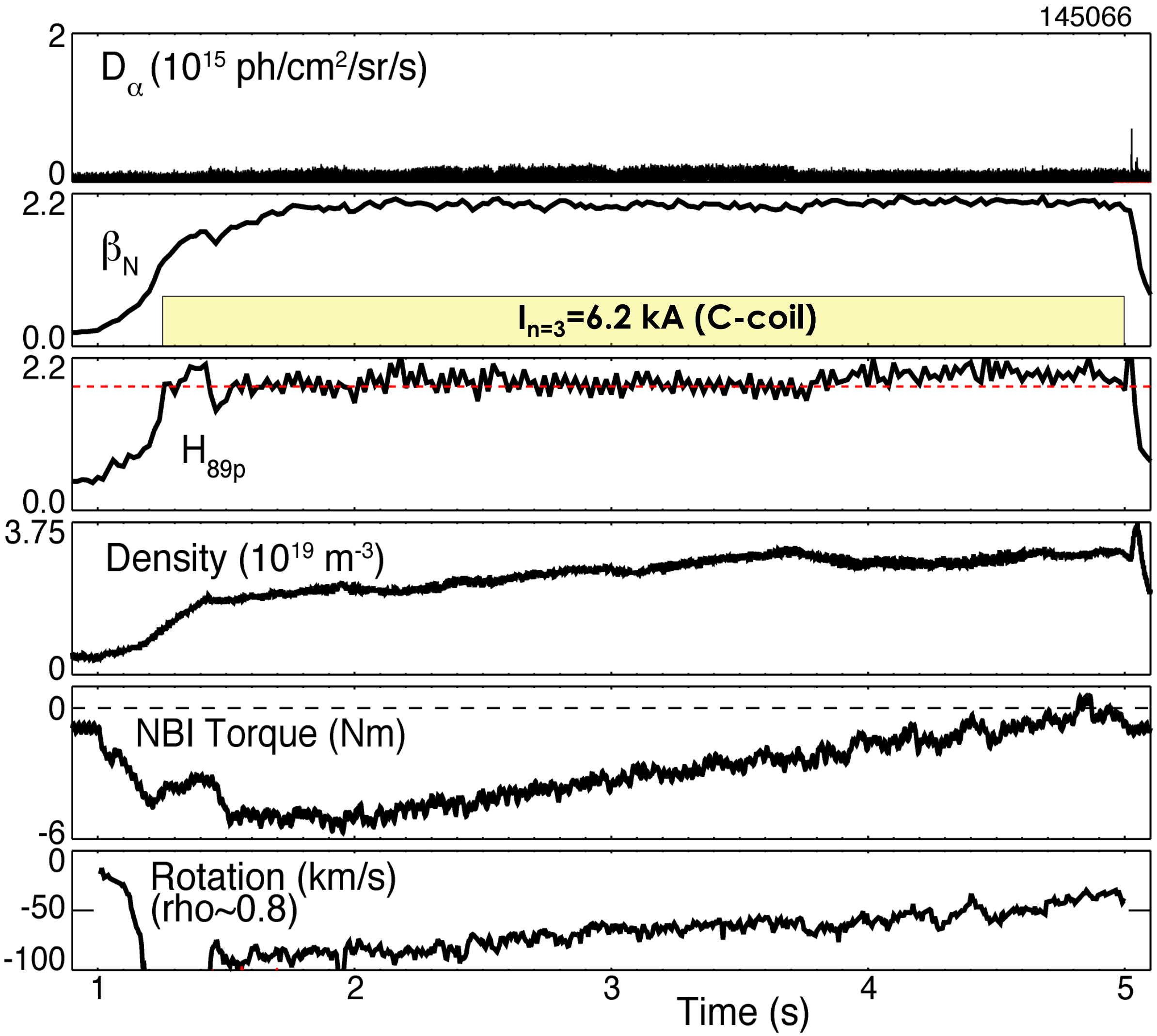
➠ **Path toward QH-mode in self-heated burning regime**

Recent Experiments Aimed at Testing ITER-like NBI Torque and External Coils for 3D fields

- **C-coil only maintains QH-mode with zero-net NBI torque**

- **Confinement improves at low NBI torque**

- **Large counter-rotation obtained with zero-net NBI torque**

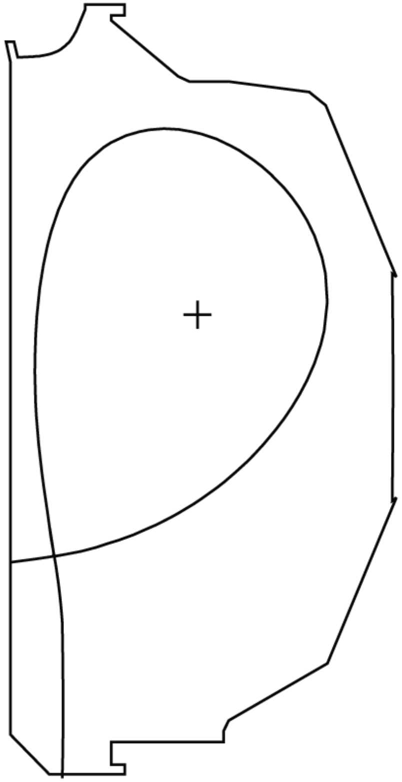


Divertor Experiments Seek to Validate Basic Scalings and Look for Impact on Pedestal and Core Performance

- **For fixed midplane temperature (fixed power flow?), one expects:**
  - Divertor target temperature to scale with $1/[R_{target}]^2$ from basic geometry
  - Divertor target temperature to scale with $1/[L_{||}]^{0.57}$, where $L_{||}$ is the parallel path length from the midplane to the divertor

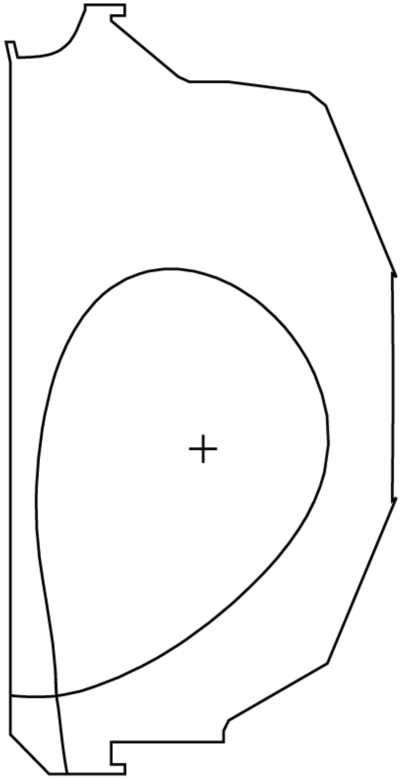
- **BUT, one can turn the argument around and assume fixed divertor temperature and look for the impact on the pedestal and core parameters**

Three Basic Shapes used in the Divertor Shaping Experiment



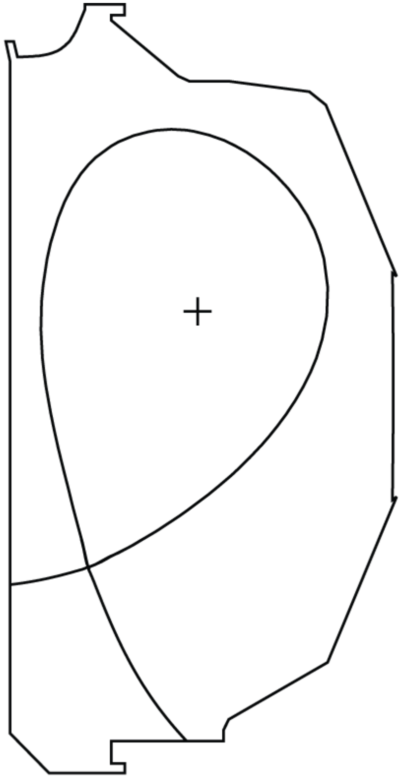
$R_{TAR} = 1.20$ m

$L_{||}$ (mid) $\simeq$ 40 m



$R_{TAR} = 1.21$ m

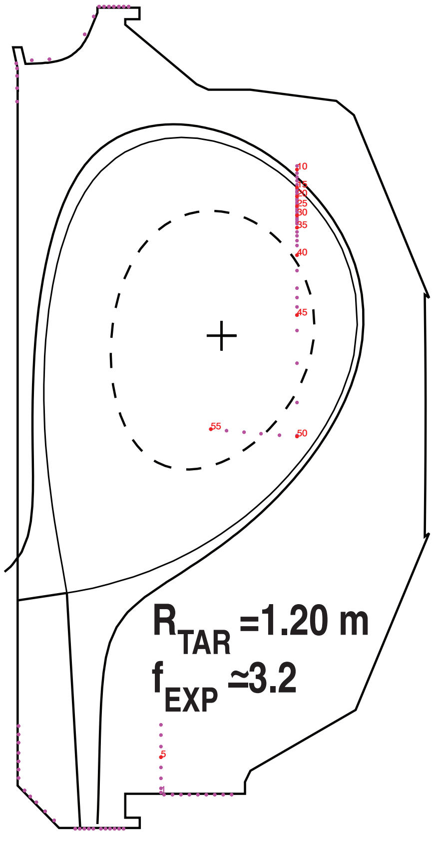
$L_{||}$ (mid) $\simeq$ 32 m



$R_{TAR} = 1.64$ m

$L_{||}$ (mid) $\simeq$ 36 m

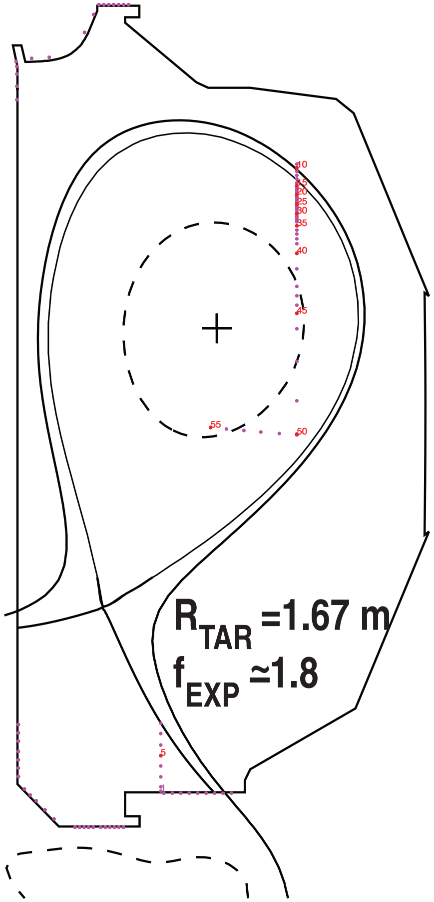
The Base Case for the R_{TAR} Comparison Have Similar Plasma Properties



R_{TAR} =1.20 m

f_{EXP} ≃3.2

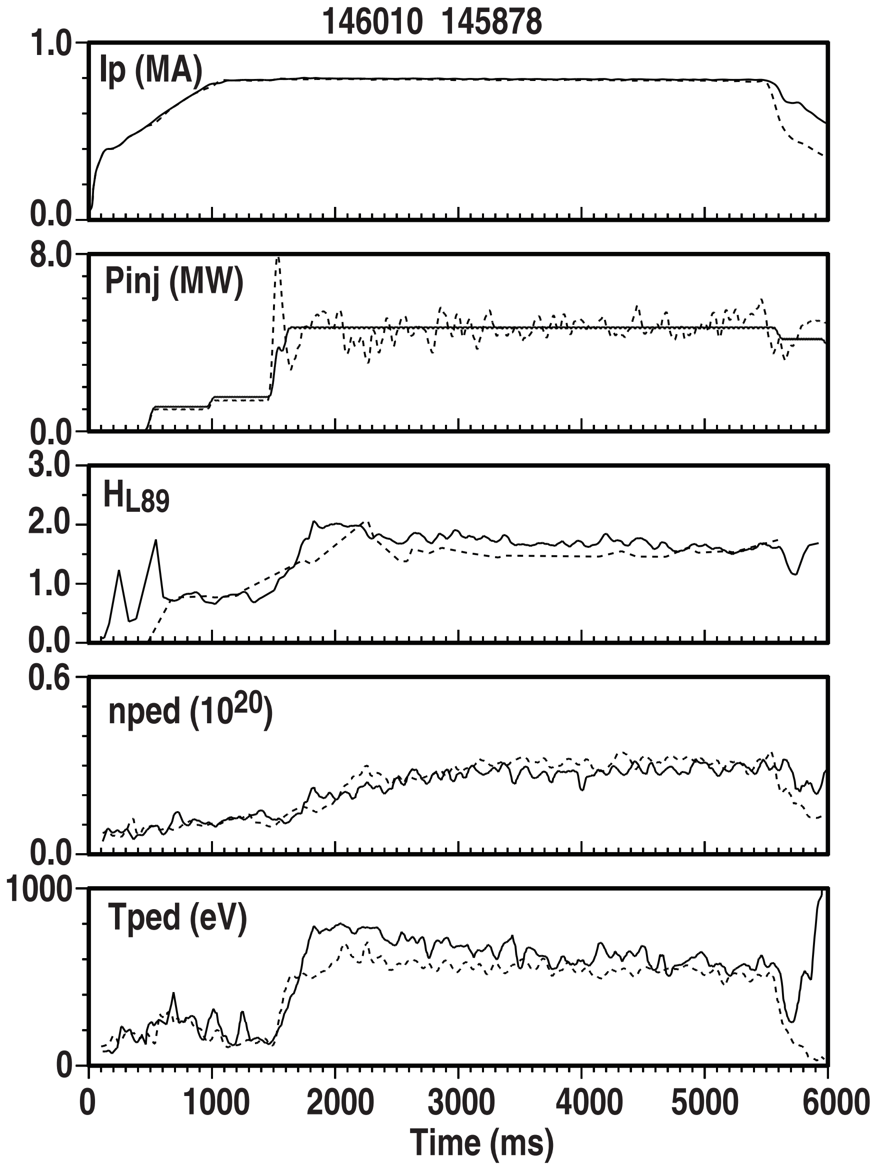
146010



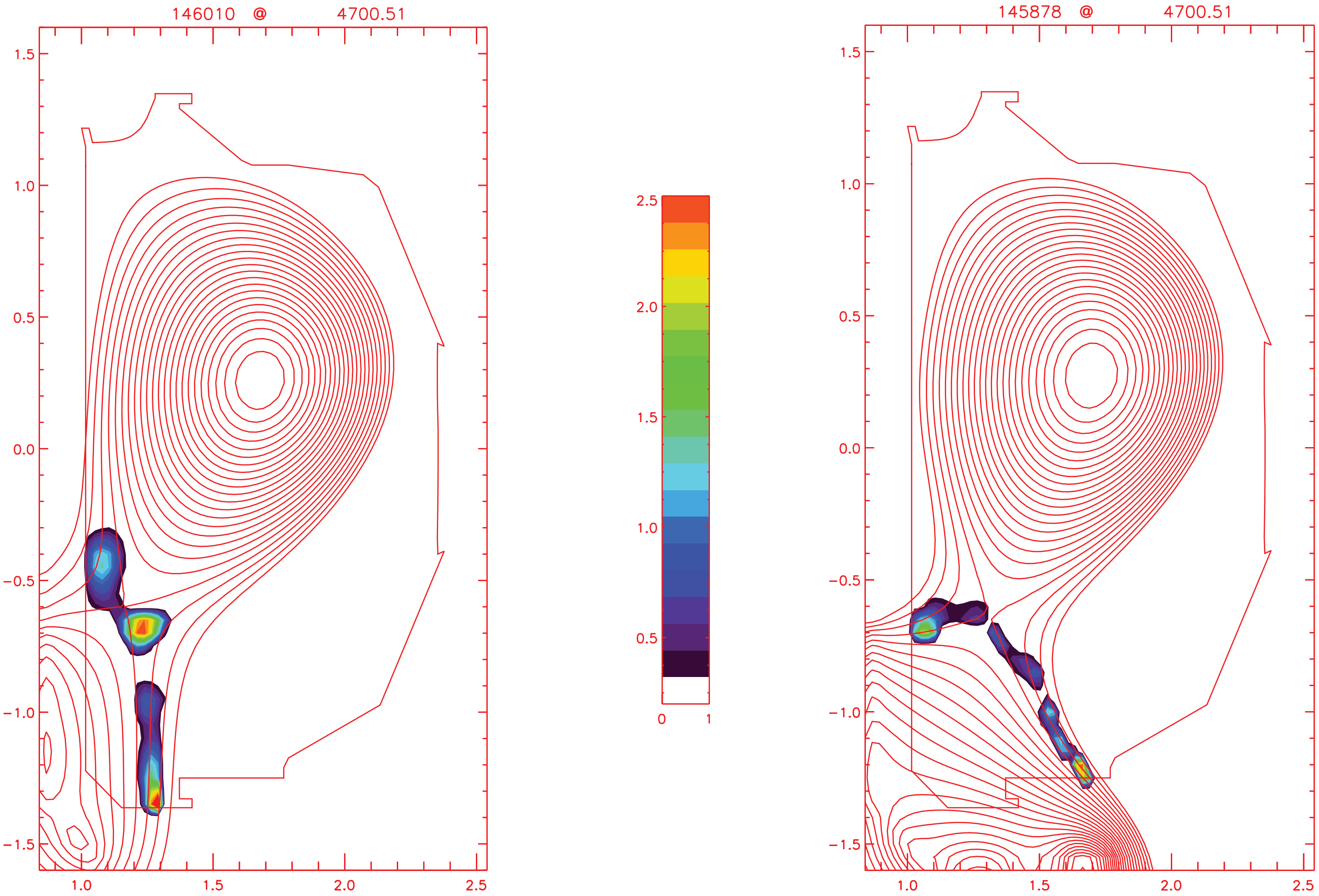
R_{TAR} =1.67 m

f_{EXP} ≃1.8

145878



The Time-averaged Emissivity Along the Outer Divertor Leg is Markedly Different in These Attached Plasmas



$\bar{n}_e/n_G \approx 0.35$

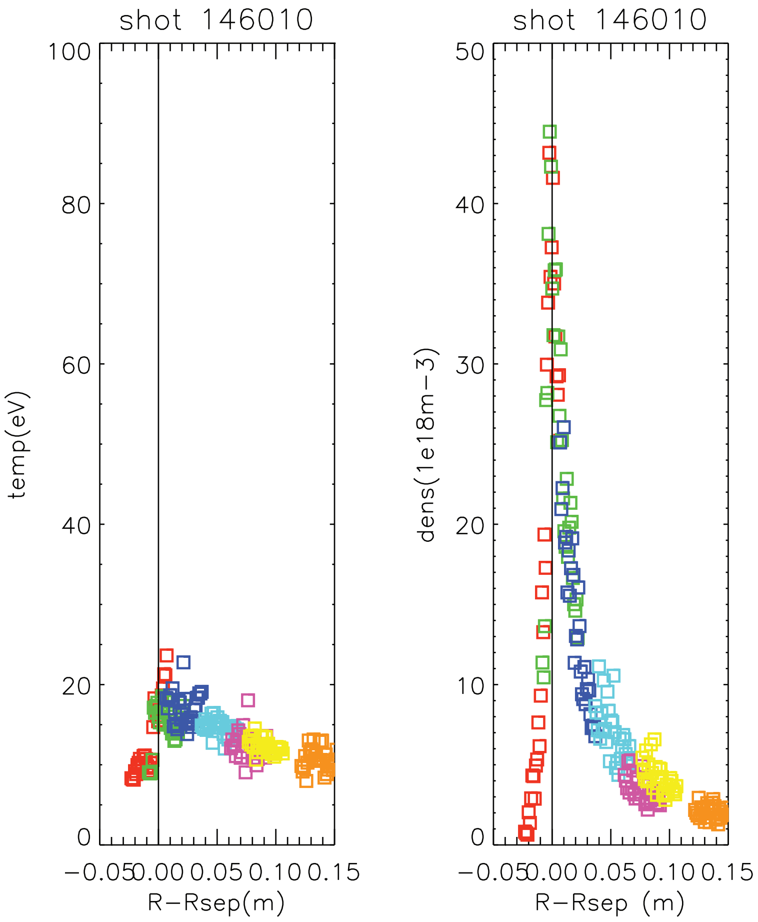
$P_{RAD}/P_{IN} \simeq 0.38$

$\bar{n}_e/n_G \approx 0.38$

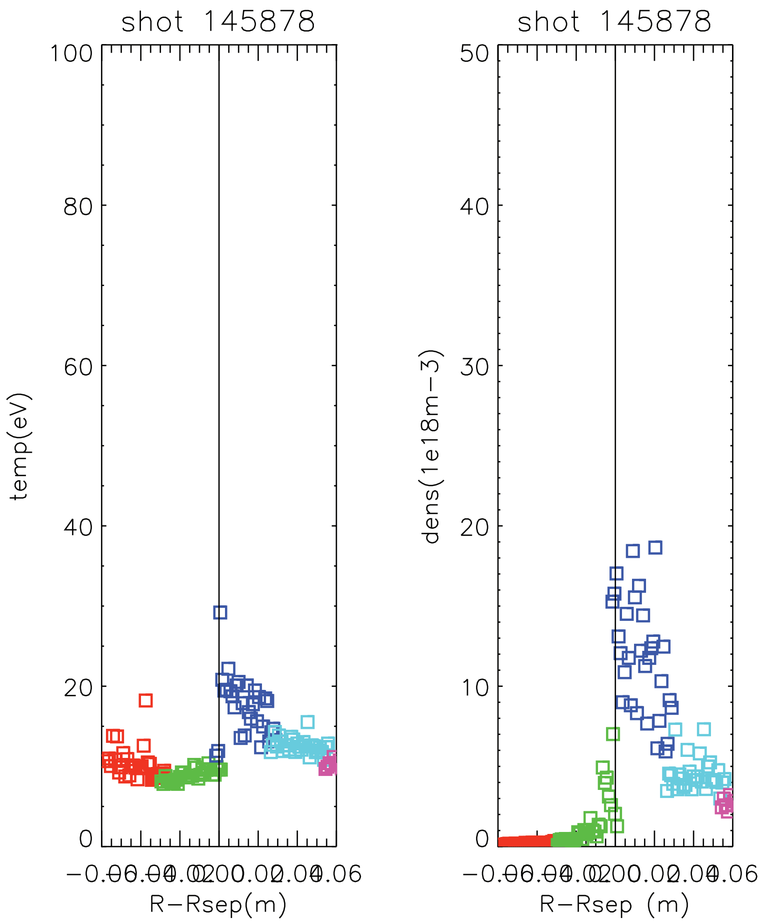
$P_{RAD}/P_{IN} \simeq 0.43$

Electron Density and Temprature at the Outer Target During H-mode Do Not Show the Expected Behaviors

$$\left.\begin{array}{l} T_{TAR} \propto 1/R_{TAR}^2 \\ n_{TAR} \propto R_{TAR}^2 \end{array}\right\} \longrightarrow$$ **Expect ~2× differences**



$R_{TAR} = 1.20$ m



$R_{TAR} = 1.67$ m

Current Profile Control Has Demonstrated Impressive Closed-Loop Results

- **Primary motivations are:**
  - Feedback control to explore suitability of target current profiles for advanced scenario operation
  - Provide reproducible target conditions to clearly distinguish effects of variations in the high performance phase

- **Two approaches were successfully demonstrated on DIII-D this year**
  - System identification approach will be discussed by Moreau in IOS-6.1 talk
  - Model-based control results discussed here

First-principles Model-based Current Profile Control

- **Why Current Profile Control?**
  - Effect on steady-state operation, MHD stability and confinement.
- **Why Model-based Control?**
  - The high dimensionality and nonlinearity of the system dynamics, and the strong coupling between magnetic and kinetic variables, motivate the design of a model-based, multi-variable controller that takes into account the dynamic responses of both magnetic and kinetic profiles to the different actuators.
- **Why First-principles Control?**
  - The model can be expanded/modified as our system understanding improves. New physics can be easily incorporated into the model.
  - No need for a system identification experiment for each scenario of interest. Model can be more easily adapted to different scenarios.
  - The high dimensionality and nonlinearity of the system can be preserved in the model, overcoming limitations of linearized models.

First-principles Model-based Current Profile Control

- **Our Approach to Control-oriented Modeling:**
  - A first-principle model of current profile evolution in response to auxiliary heating and current drive systems (NBI, ECH, ECCD), line-averaged density and electric field due to induction was developed for an L-mode plasma.

$$\frac{\partial\psi}{\partial t} = \frac{\eta(T_e)}{\mu_o\rho_b^2\hat{F}^2}\frac{1}{\hat{\rho}}\frac{\partial}{\partial\hat{\rho}}\left(\hat{\rho}\hat{F}\hat{G}\hat{H}\frac{\partial\psi}{\partial\hat{\rho}}\right) + R_o\hat{H}\eta(T_e)\frac{\left\langle \bar{j}_{NI}\cdot\bar{B}\right\rangle}{B_{\phi,o}}$$

Diffusivity Control

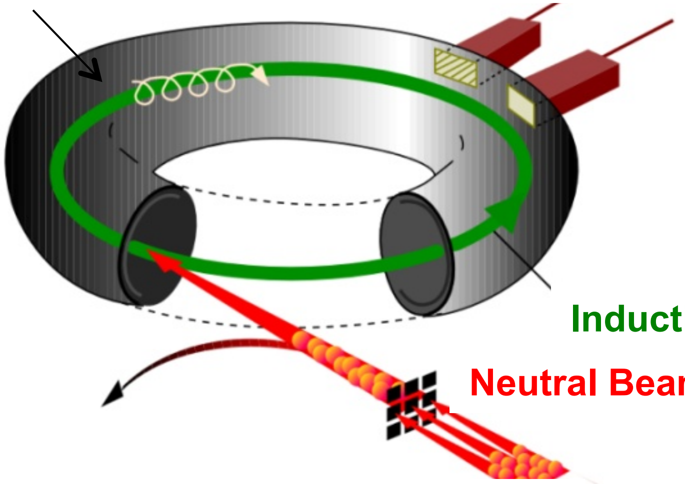
Interior Control

Magnetic diffusion equation

$$\left.\frac{\partial\psi}{\partial\hat{\rho}}\right|_{\hat{\rho}=0} = 0$$

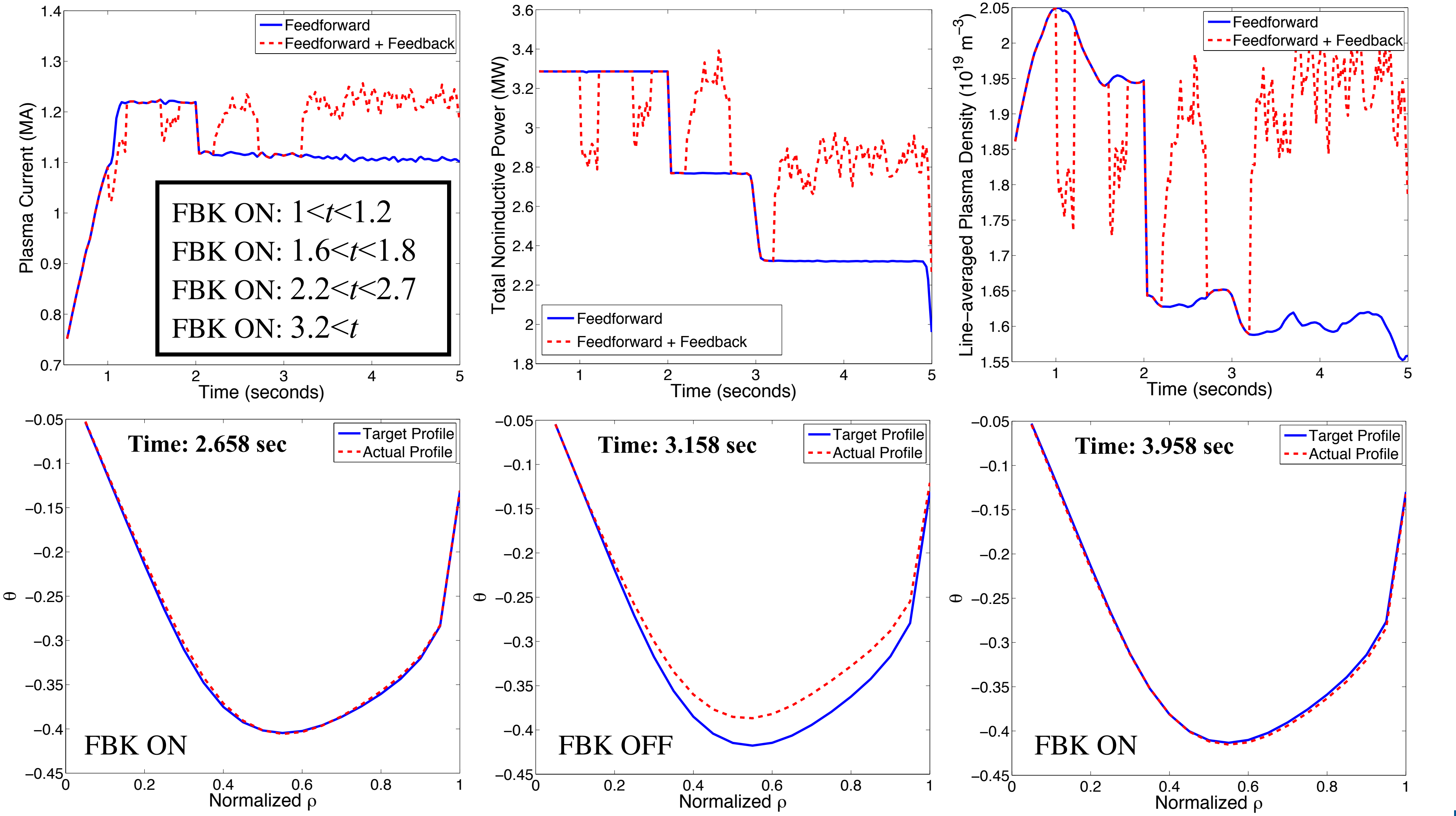
Boundary Control

$$\left.\frac{\partial\psi}{\partial\hat{\rho}}\right|_{\hat{\rho}=1} = -\frac{\mu_o}{2\pi}\frac{R_o}{\hat{G}\big|_{\hat{\rho}=1}\hat{H}\big|_{\hat{\rho}=1}}I(t)$$



Y. Ou, T.C. Luce, E. Schuster, J.R. Ferron, M.L. Walker, C. Xu, and D.A. Humphreys, “Towards Model-based Current Profile Control at DIII-D,” *Fusion Engineering and Design* 82 (2007) 1153–1160.

First-principles Model-based Current Profile Control



Disturbance is artificially introduced at *t*=2.2 sec.

Plans for “October” run period

- **DIII-D management identified 3 areas of focus for this 3 week run**
  - ITER baseline scenario (especially n=1 tearing stability)
  - QH mode (focus on fusion performance metric and co-NBI startup)
  - Performance extension in steady state scenario with off-axis NBI
- **Additional experiments will be done in the following areas**
  - Correction of TBM fields with coils
  - Pellet pacing of ELMs
  - Runaway channel control