Fully Noninductive Scenario Development in DIII-D Using New Off-Axis Neutral Beam Injection

by

C.T. Holcomb

With

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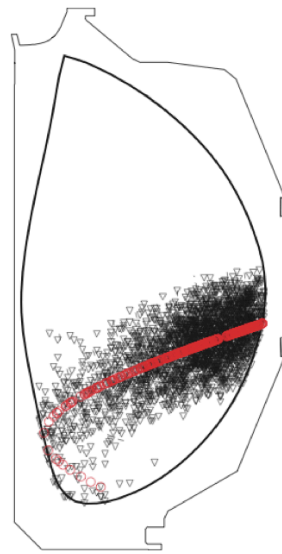

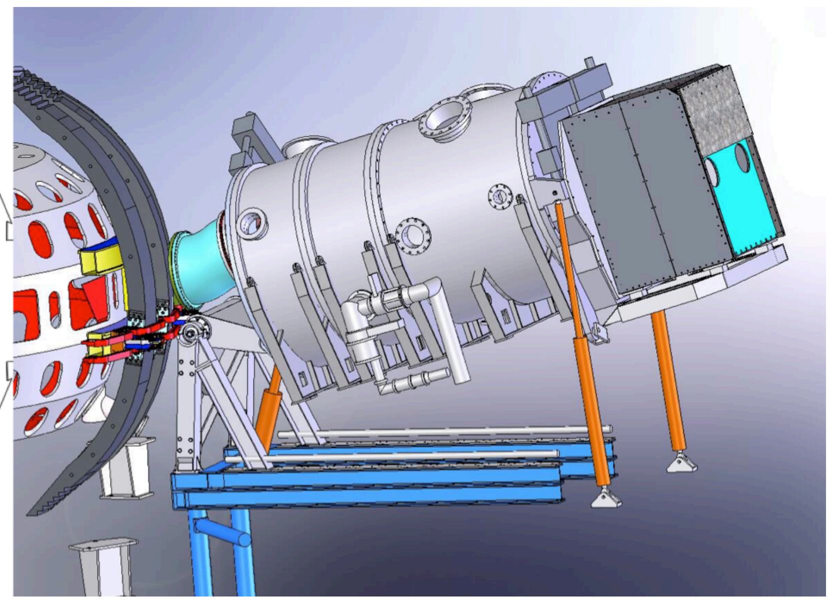

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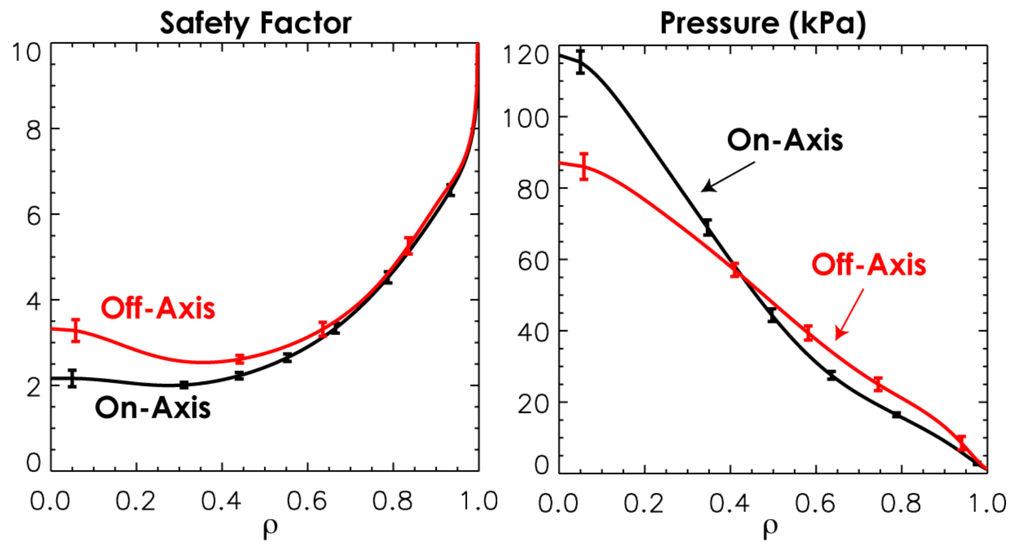
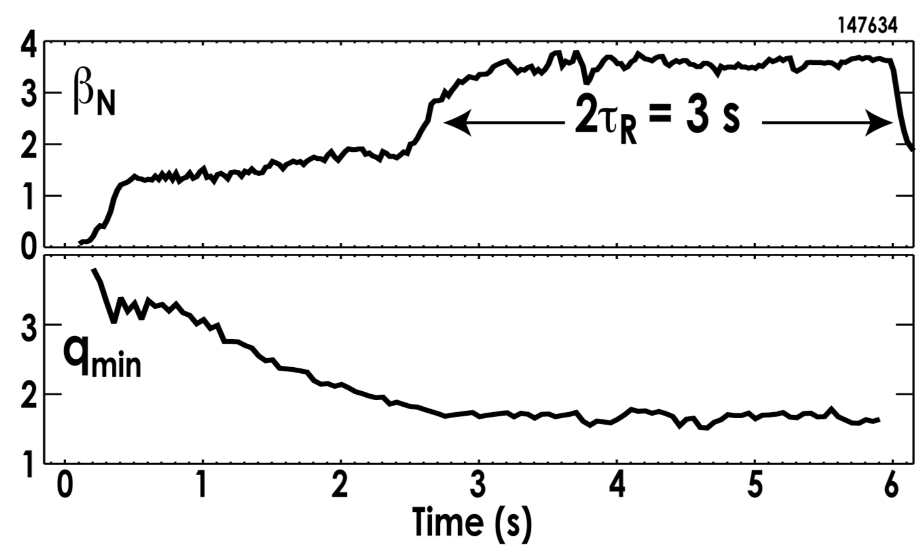
Main Results: DIII-D is Using Off-Axis NBI to Develop Elevated q_{min} Scenarios for High β_N, Steady State Operation

Improves access to q_{min}>2 & broad profiles having higher β_N stability limits



Nearly stationary q_{min}≈1.5 scenario projecting to Q=5 in ITER stable for 2 current profile relaxation times at β_N=3.5



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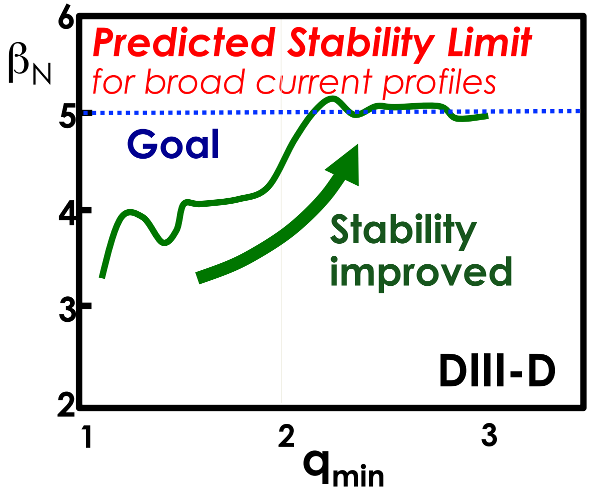
Steady State Operation Needs Motivate Broad Current Profiles & High q_{min}

Need High Bootstrap Current Fraction ∝ $q\beta_N$

Need High β_N Stability:



Need High Fusion Gain∝$\beta_N H/q_{95}^2$, So Low q_{95}

Broad, Off-Axis Current Density & High q_{min}

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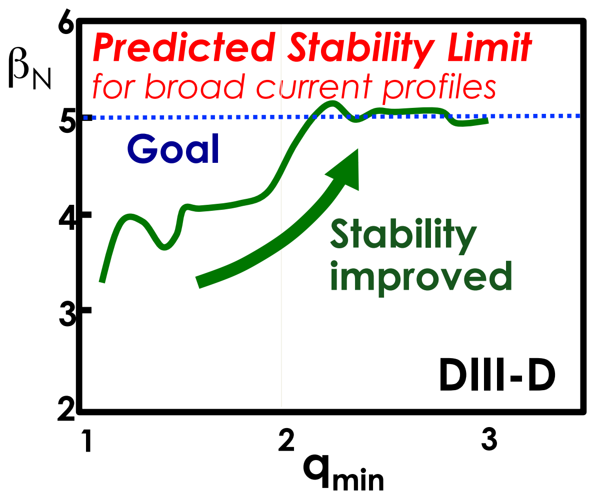
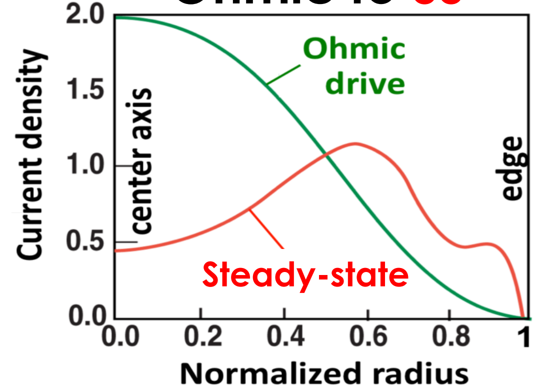


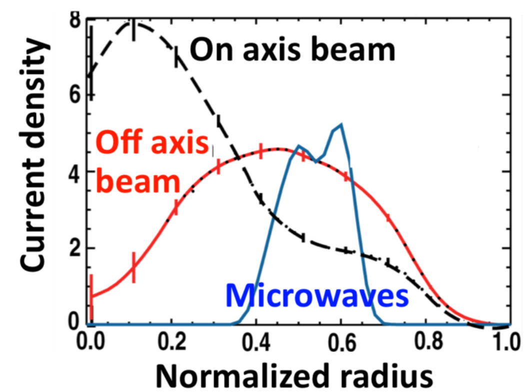
Need High Fusion Gain∝$\beta_N H/q_{95}^2$, So Low q_{95}

Broad, Off-Axis Current Density & High q_{min}

Goal: Move from Ohmic to SS



Flexible, Matched DIII-D Tools



Steady State Operation Needs Motivate Broad Current Profiles & High q_{min}

Need High Bootstrap Current Fraction $\propto q\beta_N$

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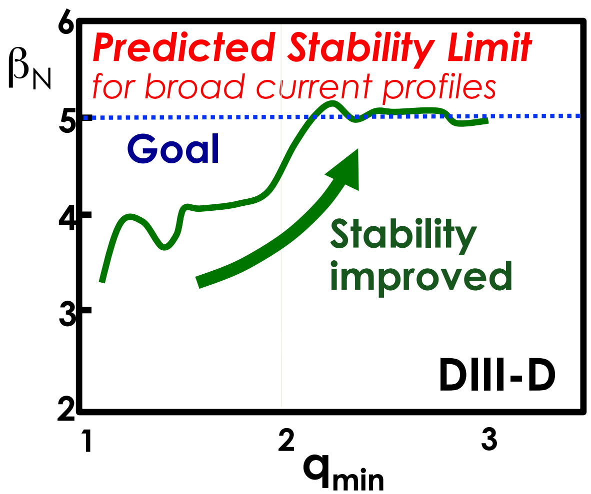

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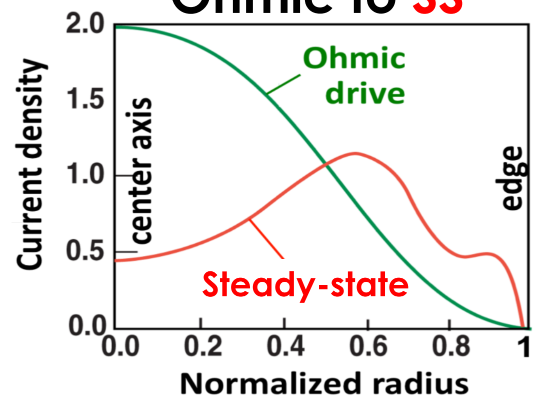

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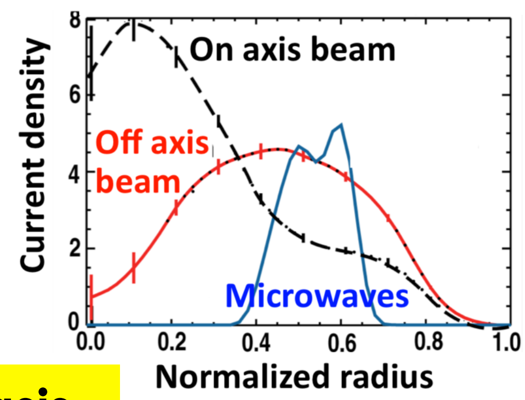

DIII-D is Developing the Physics Basis of Steady State Operation

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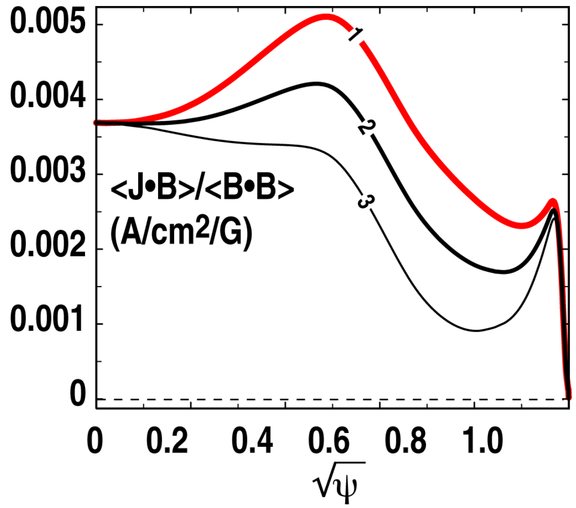
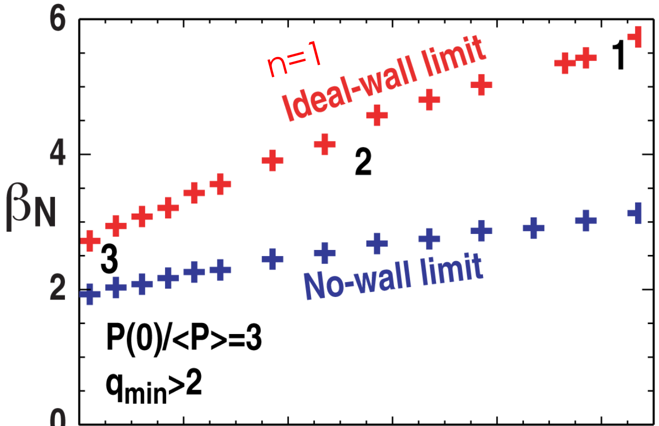
Modeling Shows Both Broad Current and Broad Pressure Profiles Are Important for Raising the Ideal-Wall β_N Limit

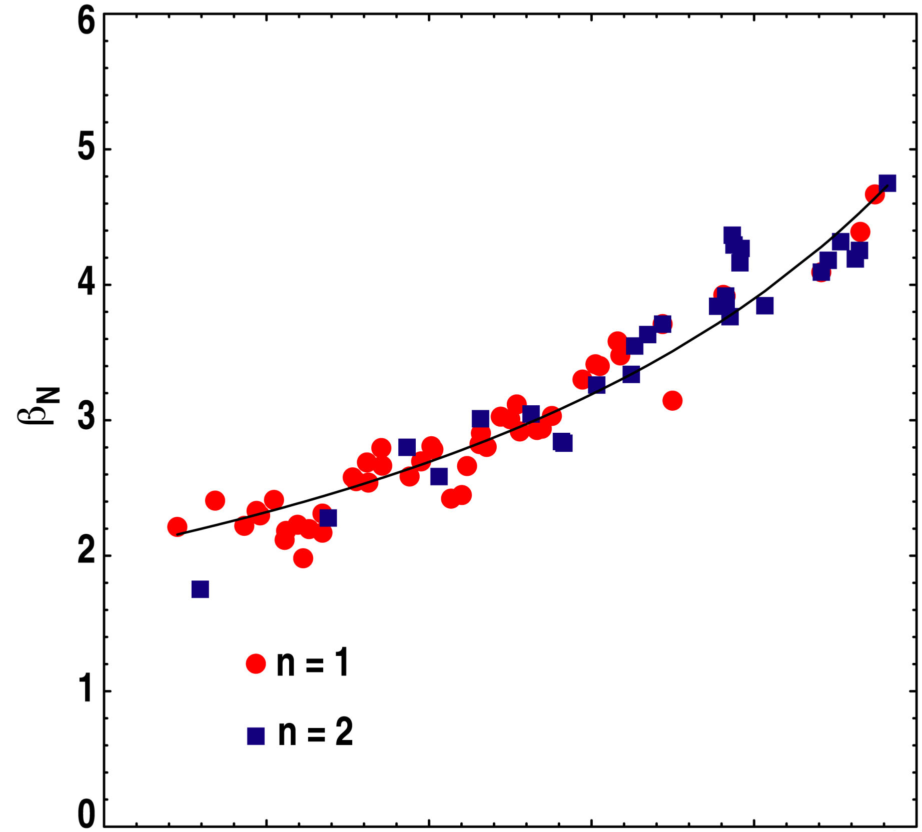
Corsica/DCON Modeling: 2 Separate Studies





More off-axis current

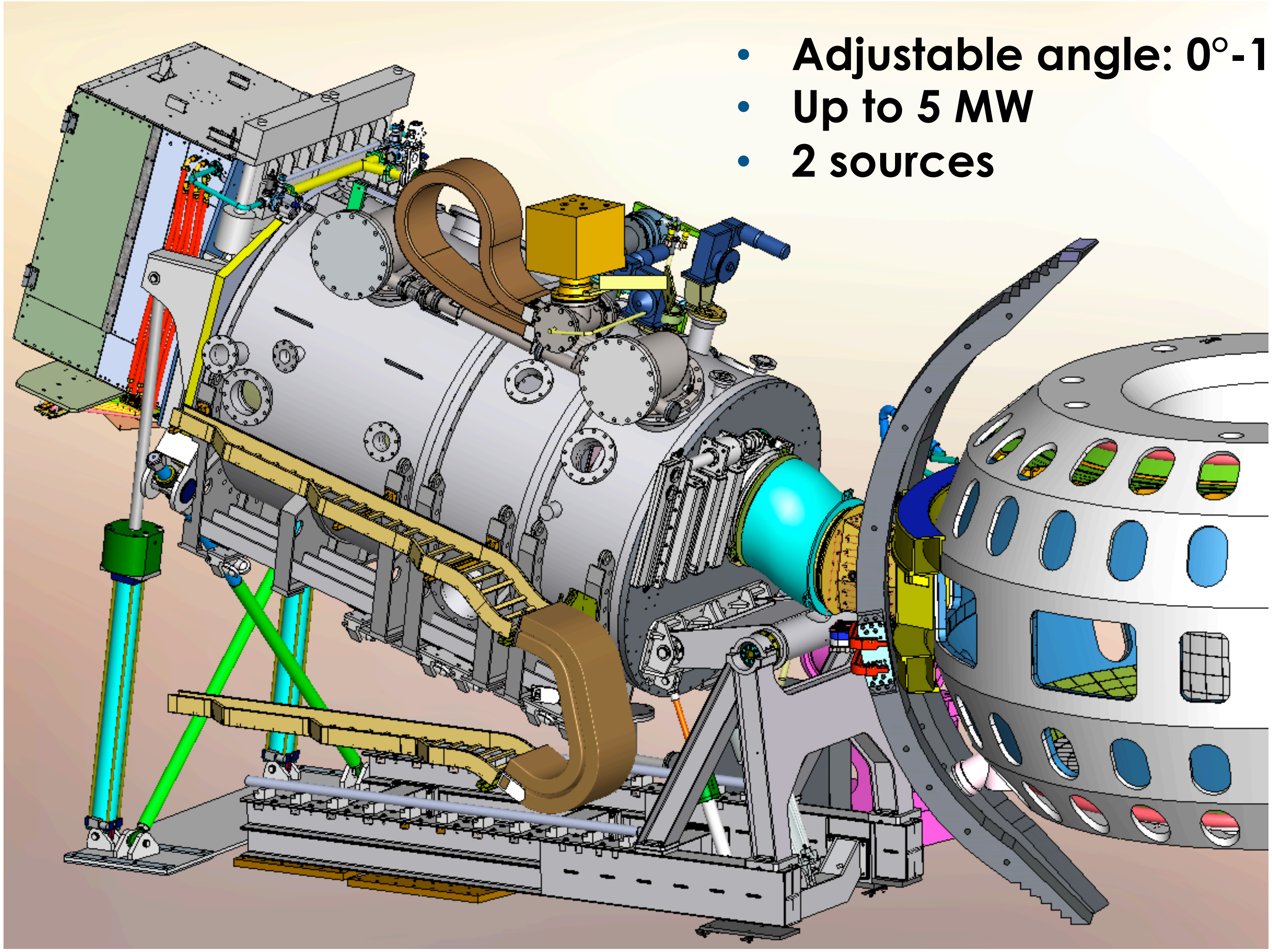
(fixed $p(\rho)$)



Broader Pressure

(fixed $q(\rho)$)

In 2010-2011, One Beamline Was Modified to Allow Off-Axis Injection



- Adjustable angle: 0°-16.5°
- Up to 5 MW
- 2 sources

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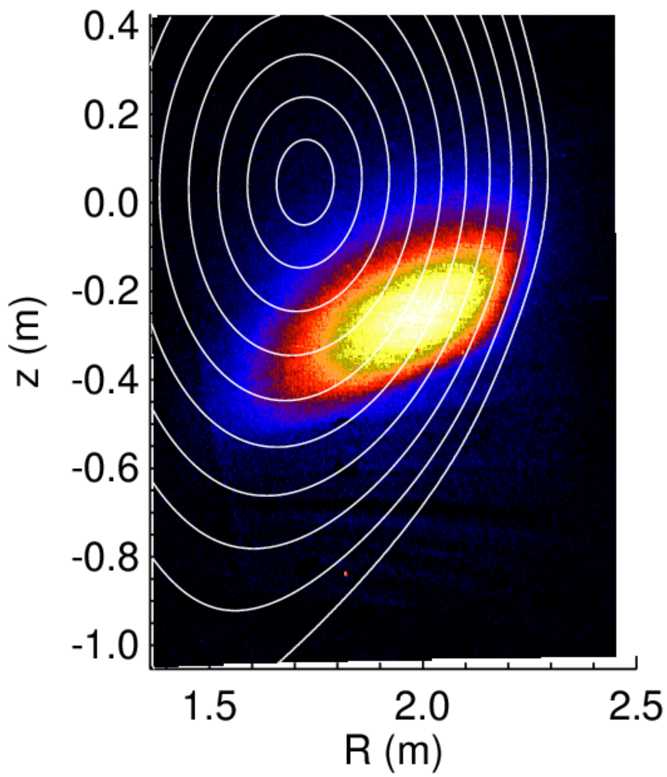
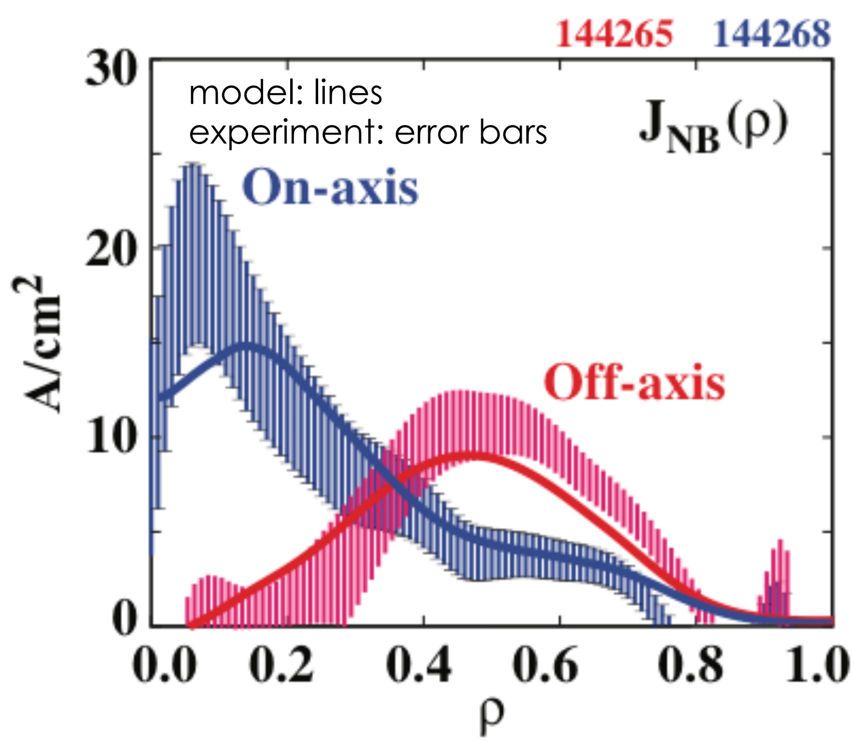
Measurements of NBCD in MHD-Free *H*-modes Agree With Classical Model Predictions

Dα imaging of off-axis beams confirmed geometry & power for inclusion in NUBEAM model

- $\beta_N < 2.3$, monotonic q, q_0~1.1
- Measure $J_{NBI}=J_{tot}-J_{BS}-\sigma_{neo}d\psi/dt$
- No obvious anomaly related to microturbulence
- See poster, EX/P2-13





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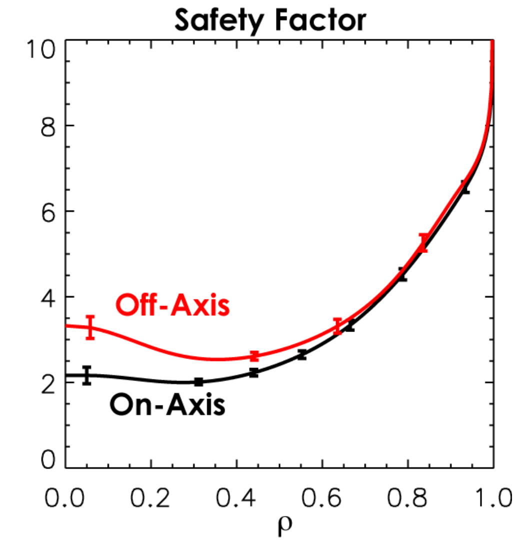
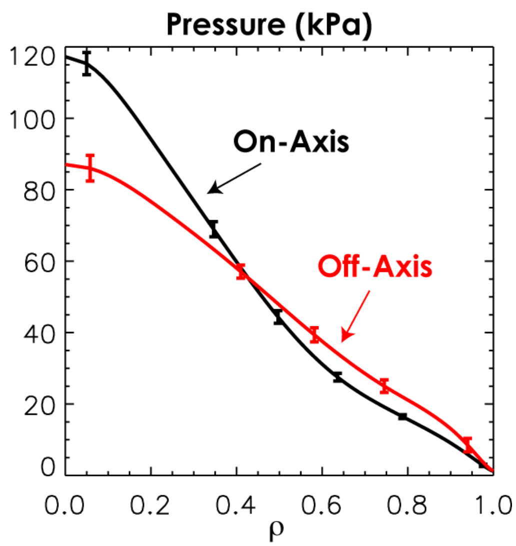
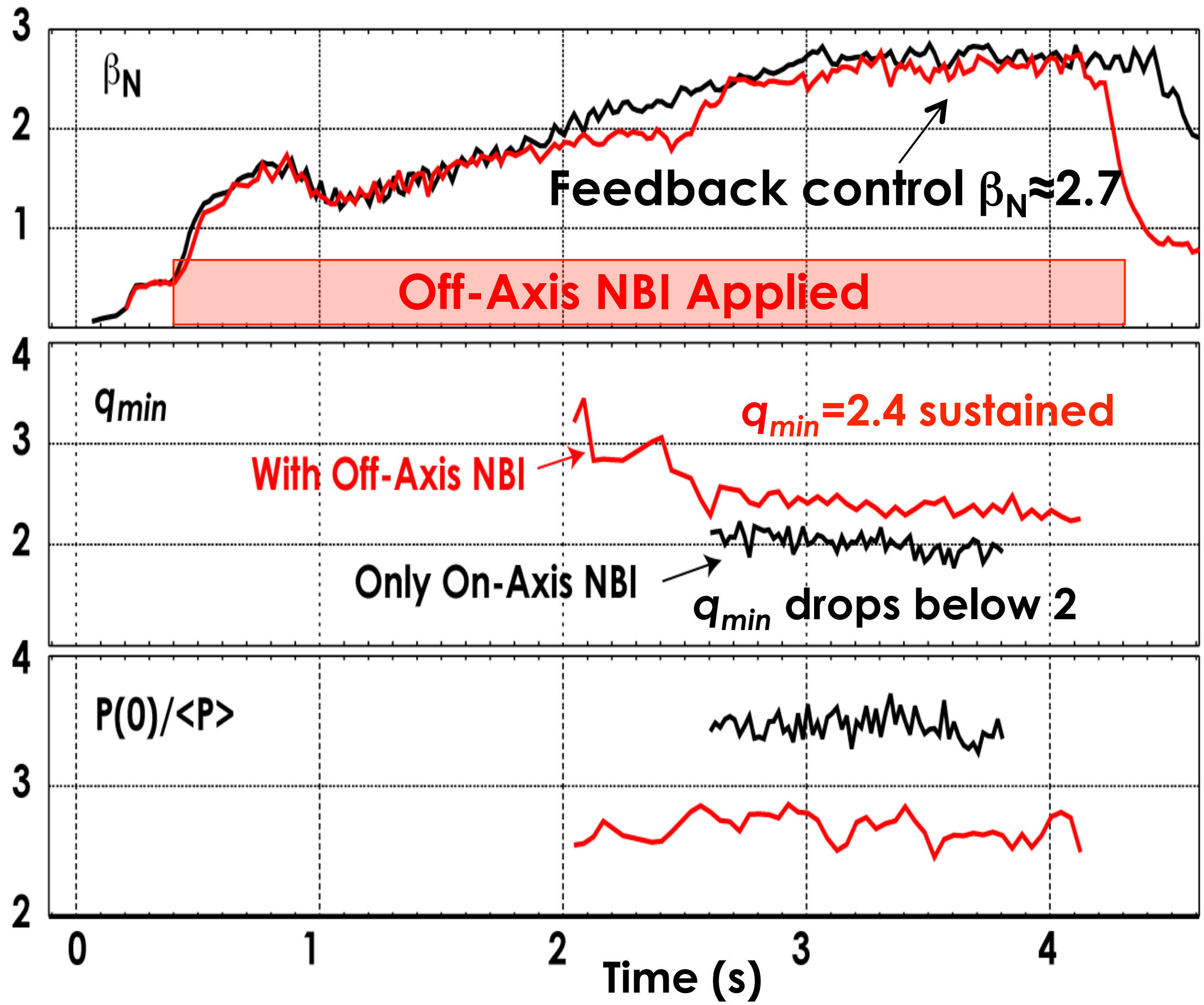
q_{min} > 2 Sustained With Broader Pressure Profile Using Off-Axis NBI and Additional ECCD Power



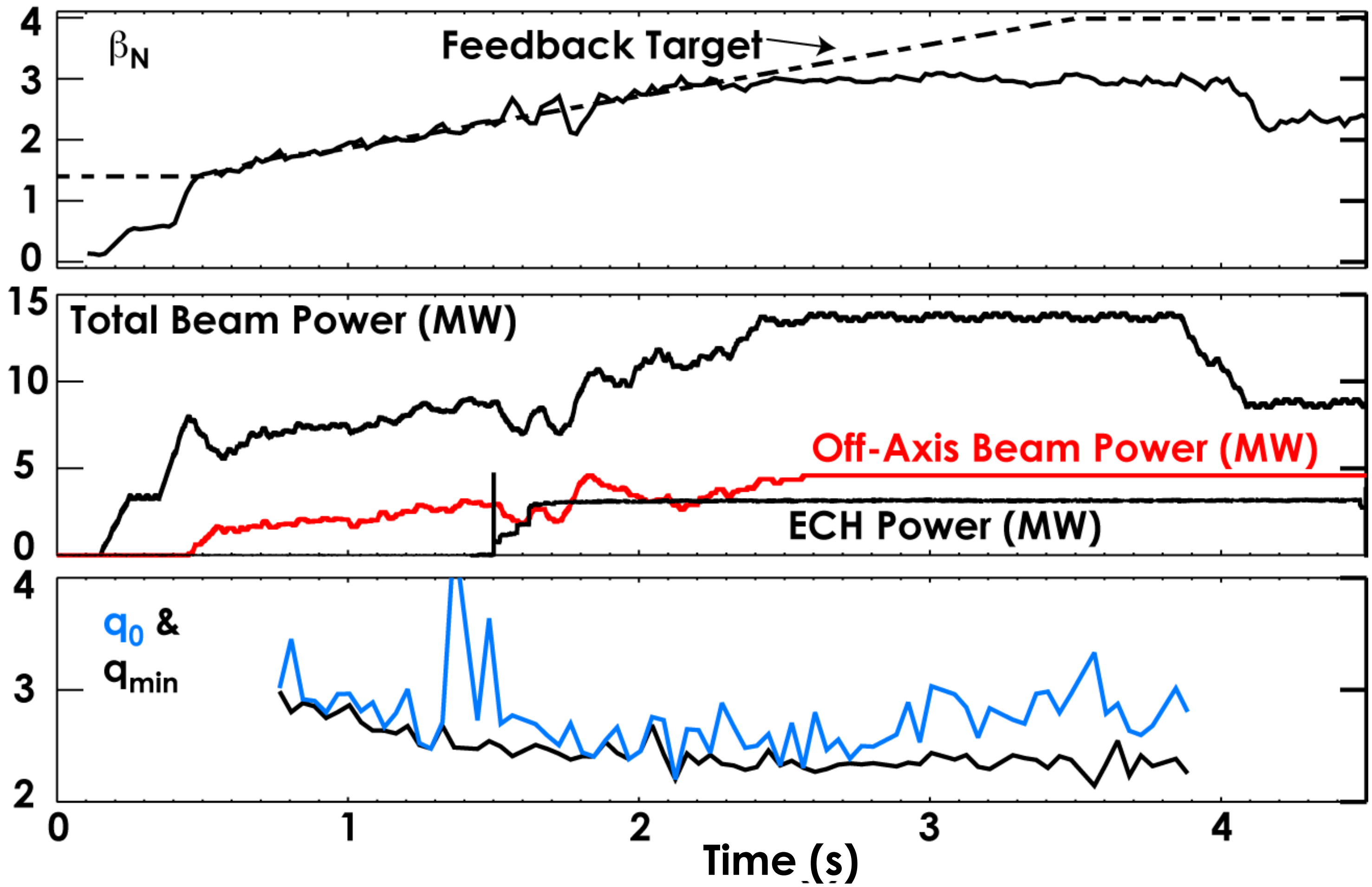




Shots 136835, 144476

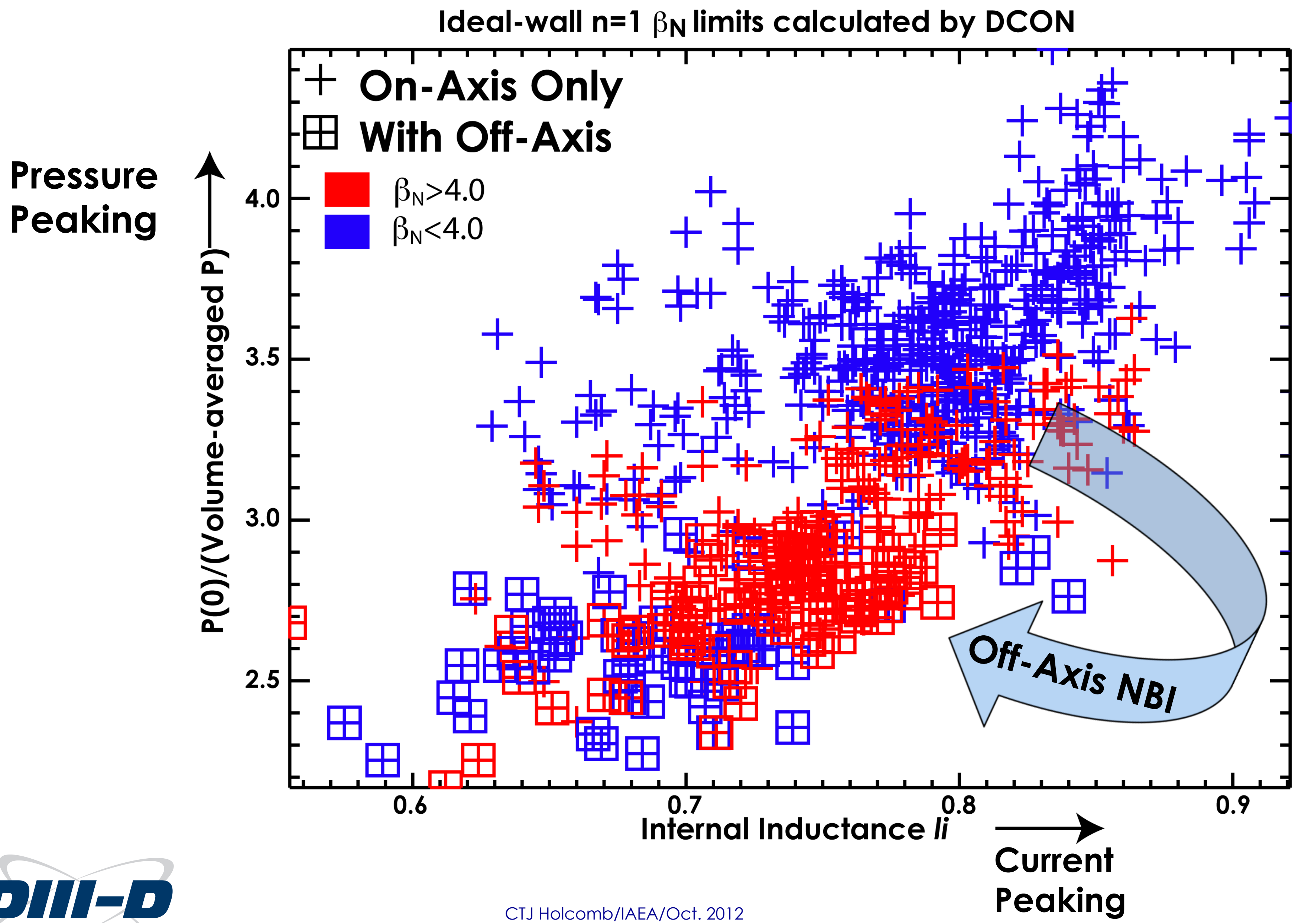
Experiment to Push to High β_N: With q_{min}>2, β_N≈3.2 Was Achieved & Limited By Available Power, Not Stability

- **No ideal modes**
- **Tearing modes**
  - 2/1 nonexistent
  - 3/1 avoided by optimizing discharge evolution
  - 7/2 & 5/2 reduce τ_E by ~15% when present



Shot 146821

Ideal MHD Stability Analysis of Experimental Equilibria Shows Accessing Broader Profiles Raised the β_N Limit



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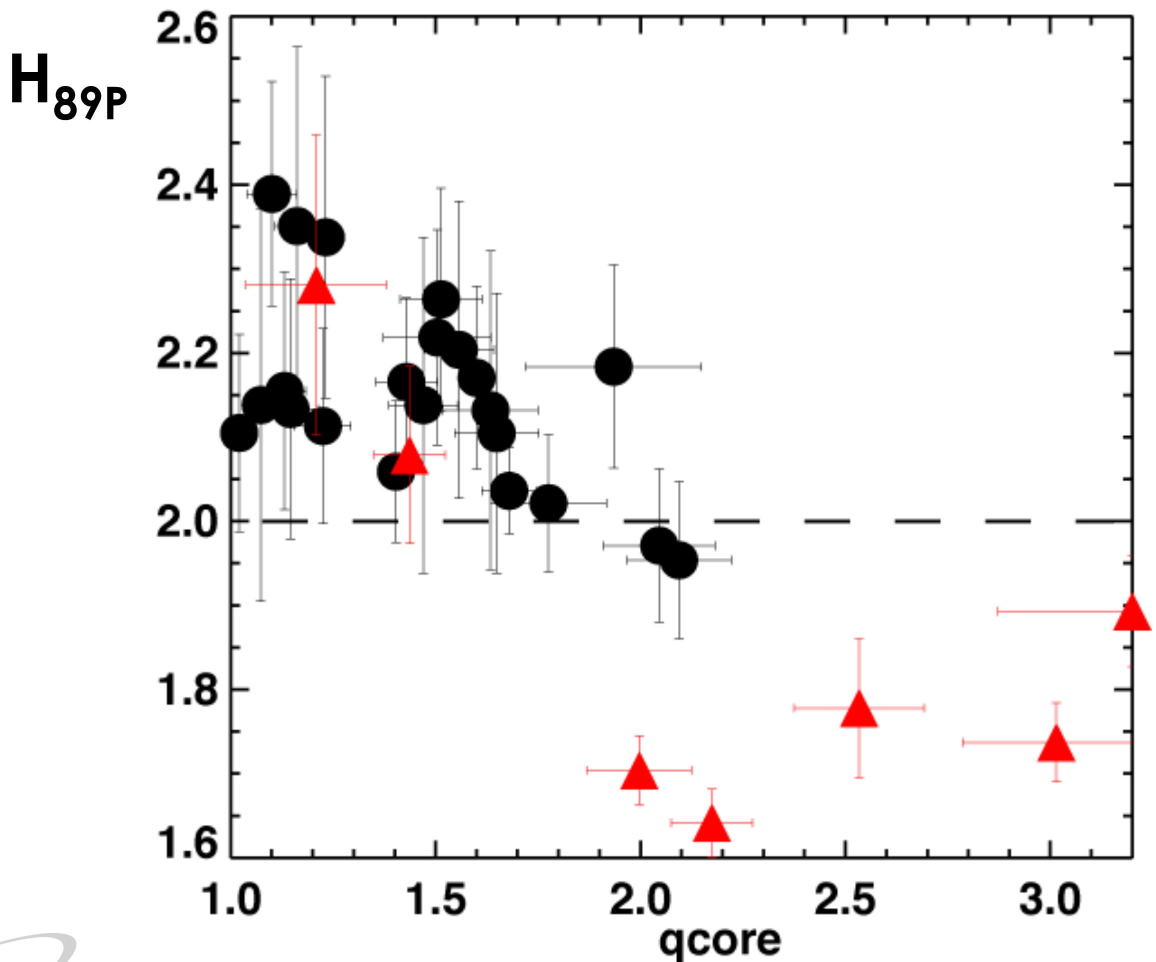
Highest q_{min} Plasmas Have H_{89} < 2: Less Than Typical *H*-Mode Global Confinement

● No off-axis beams used
▲ Off-axis beams used
"*qcore*" is average of *q* from ρ = 0-0.3



H_{89} includes thermal + fast ion energy

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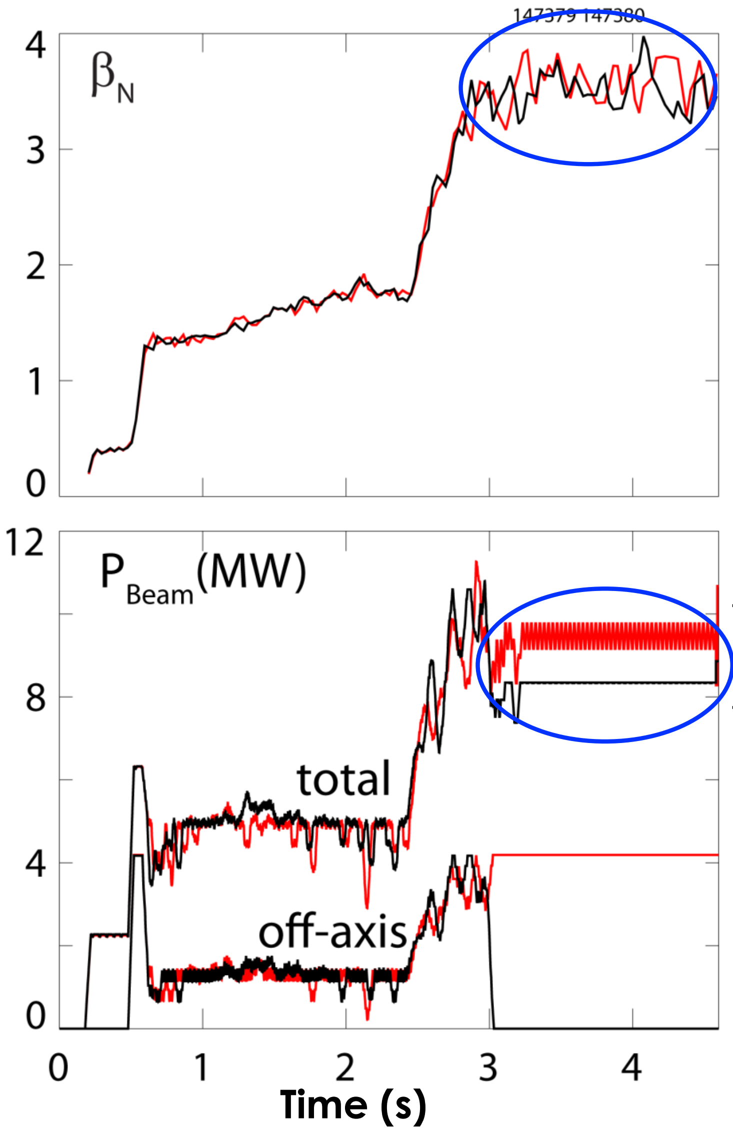
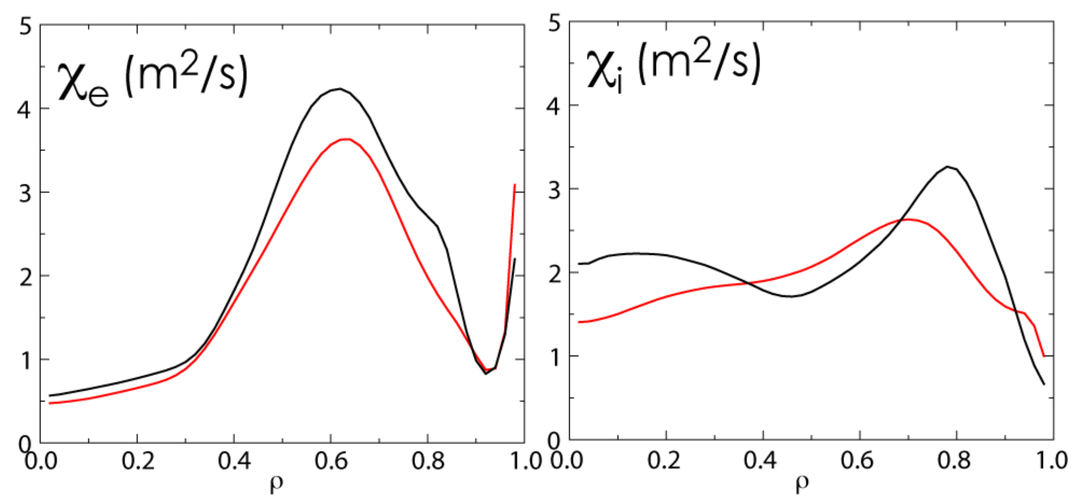
Off-Axis Injection Itself Results in Only a Small Reduction in Confinement Time



- **2 discharges compared at *equal* β_N**
- **Both with $q_{min} \approx 1.1$**

- **Discharge with all on-axis injection requires 10% less total power**
  - Off-axis injection reduced τ_E by 10%
  - H_{89} ($\approx$2.3) reduced by 5%
  - Puts power at radius with higher χ



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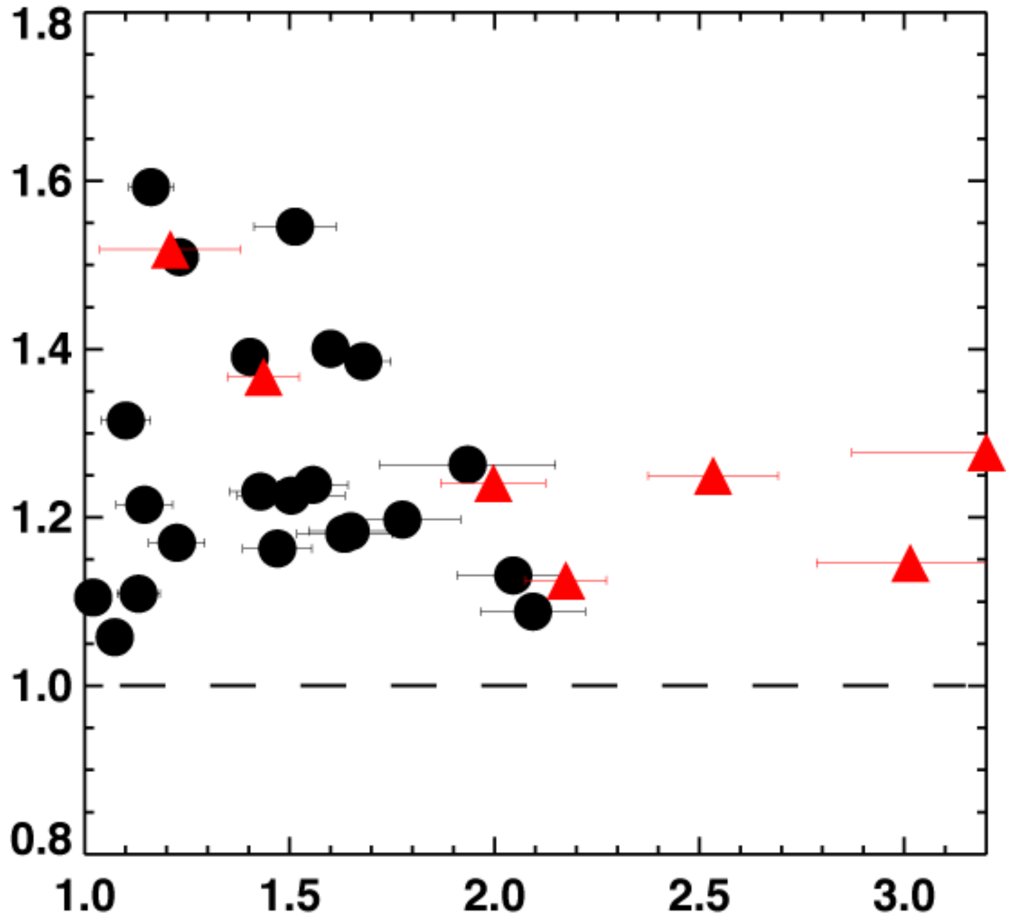
High q_{min} Plasmas With Off-Axis NBI Have H_{98} > 1: Typical *H*-Mode Level Thermal Confinement

● No off-axis beams used
▲ Off-axis beams used
"*qcore*" is average of *q* from

"Direct H98Y2"=

$$\frac{\dfrac{W_{thermal}}{P_{input}}}{\tau_{98Y2}}$$



H_{98} includes only thermal stored energy

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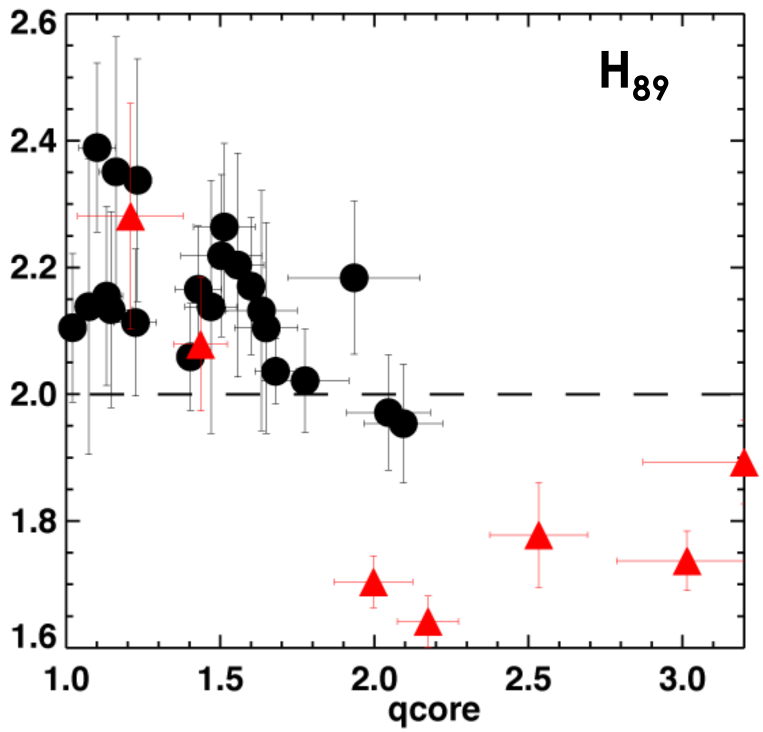
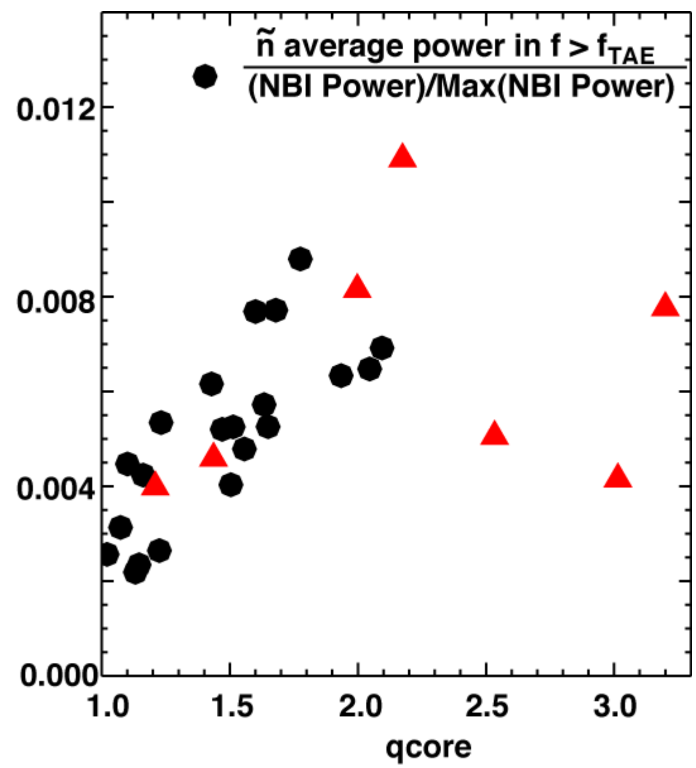
Enhanced Fast Ion Transport May Contribute to Lower H_{89} at the Highest q_{min}

● No off-axis beams used
▲ Off-axis beams used
"*qcore*" is average of *q* from ρ=0-0.3



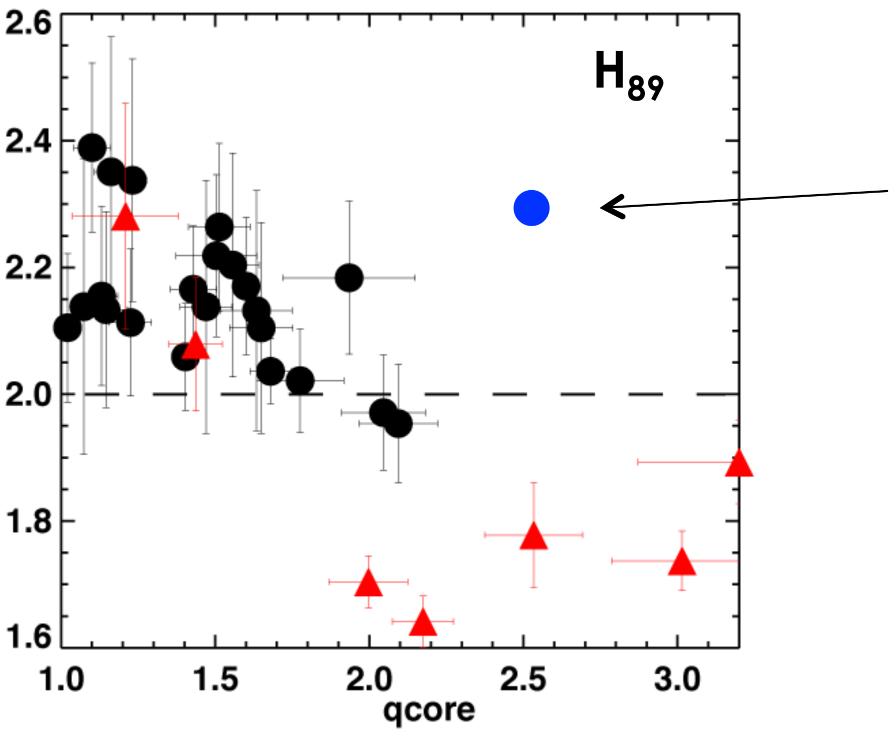
Fluctuation power in Alfvén Eigenmode frequency range generally increases with *qcore*



- At high *qcore*, total stored energy computed by ONETWO transport code exceeds that measured by EFIT unless anomalous fast ion transport is included

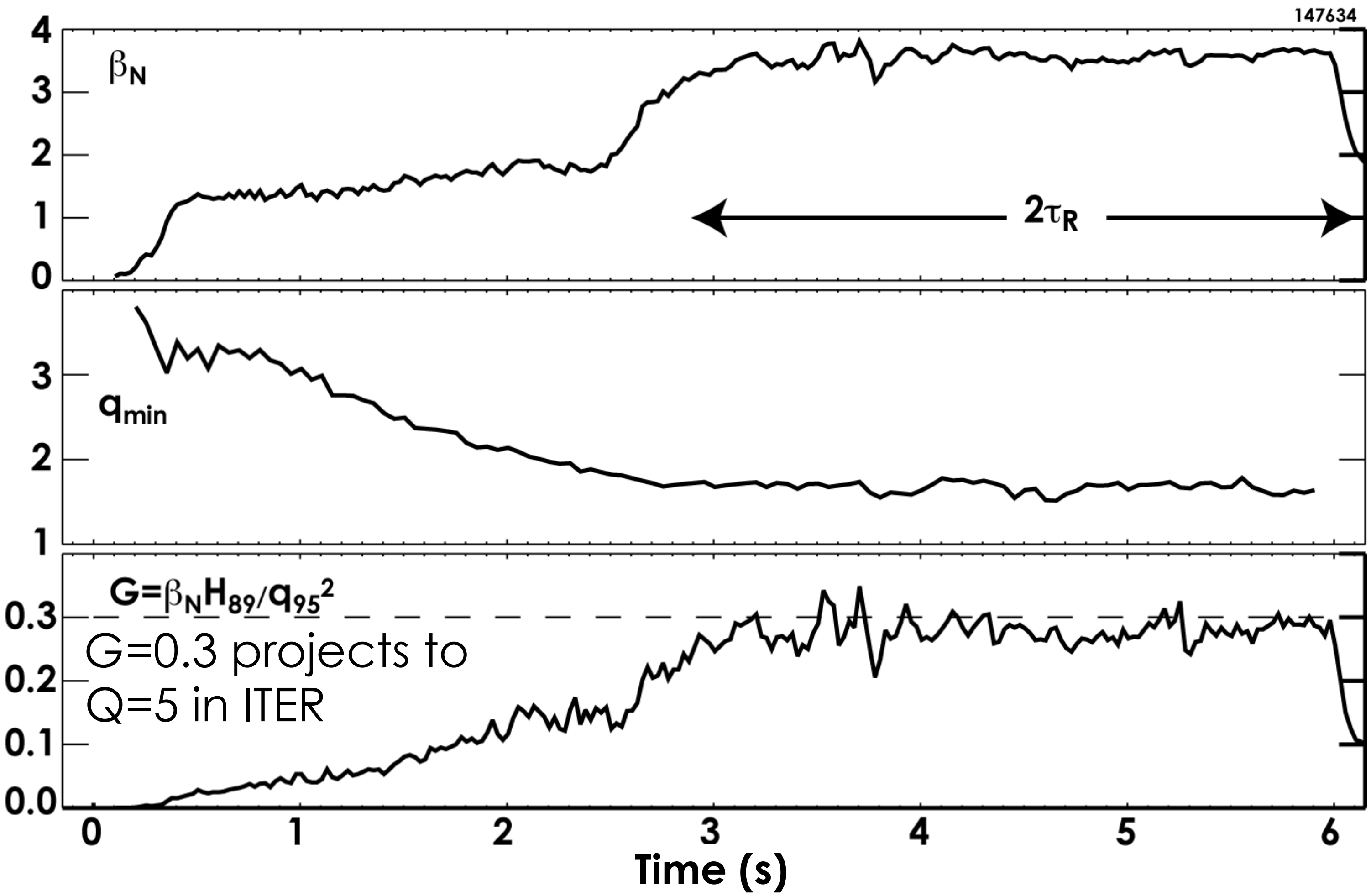
Exceptions With q_{min}>2, H_{89}>2, and High β_N Do Exist

● No off-axis beams used
▲ Off-axis beams used
"*qcore*" is average of *q* from ρ=0-0.3



- Transient generation of very broad current profiles with a B_T-ramp, high density, low q_{95} (Garofalo, Phys. Plasmas 2006)
- Comparison in progress to identify most important differences for τ_E

For ITER & FNSF-AT, a Relaxed High q_{min} Constraint May Still Meet the Steady State Mission Goals

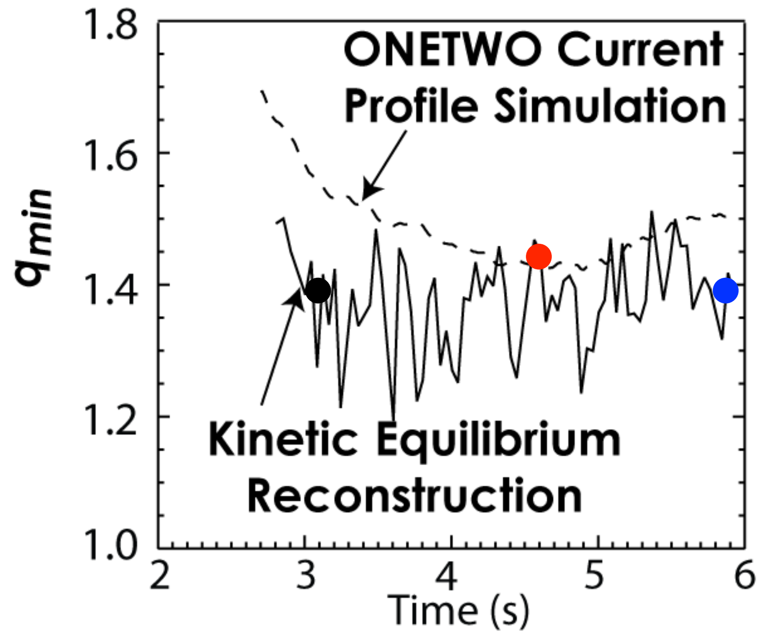


- Off-axis CD maintains quasi-stationary q_{min}≈1.5 scenario with good H_{89}
- Stable to 2/1 modes for 2 current profile relaxation times
- Improves confidence equilibrium will not evolve to unstable state

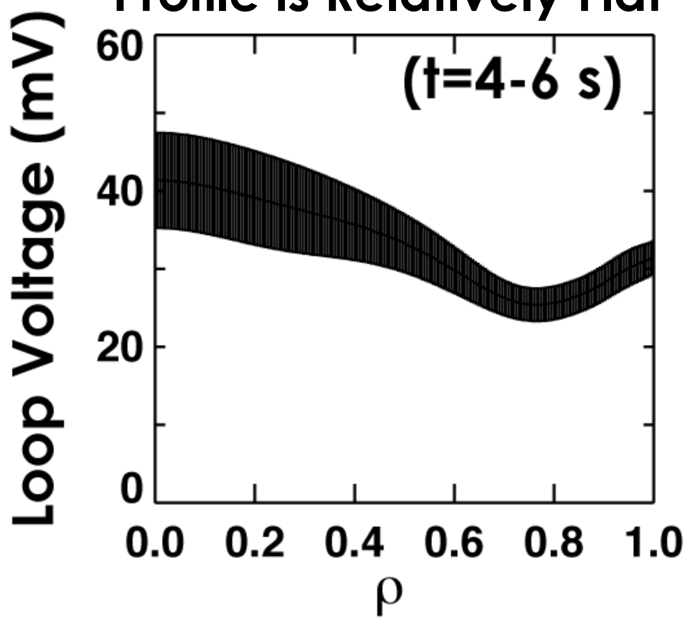
At β_N=3.5, the Current Profile is Nearly Stationary Even With ~25% of I_P Driven Inductively

Current Drive Balance
Bootstrap=50%
NBCD=20%
ECCD=5%
Inductive=25%

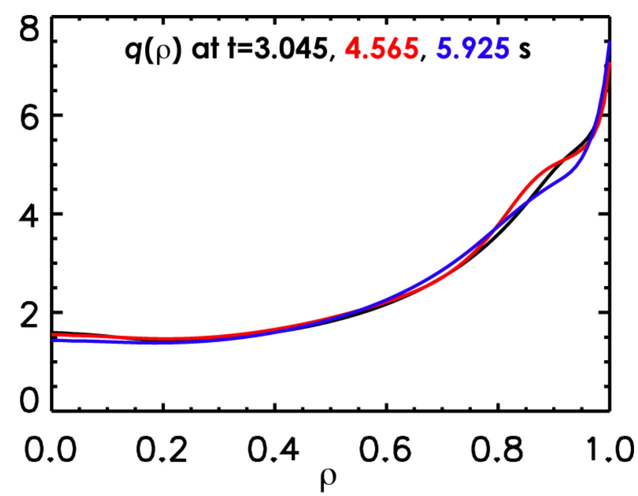
q_{min} Does Not Evolve to 1 in $2\tau_R$



Measured Loop Voltage Profile is Relatively Flat

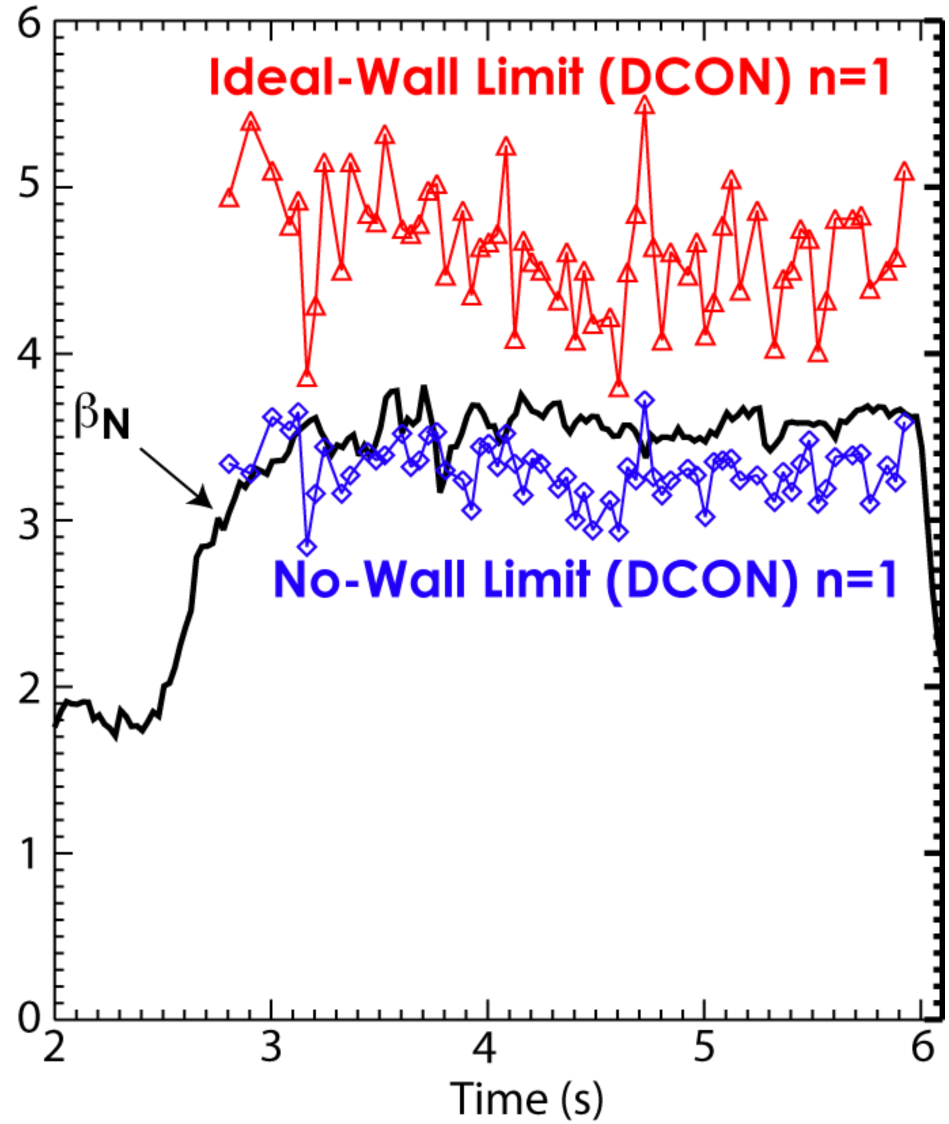


Very Little change in $q(\rho)$



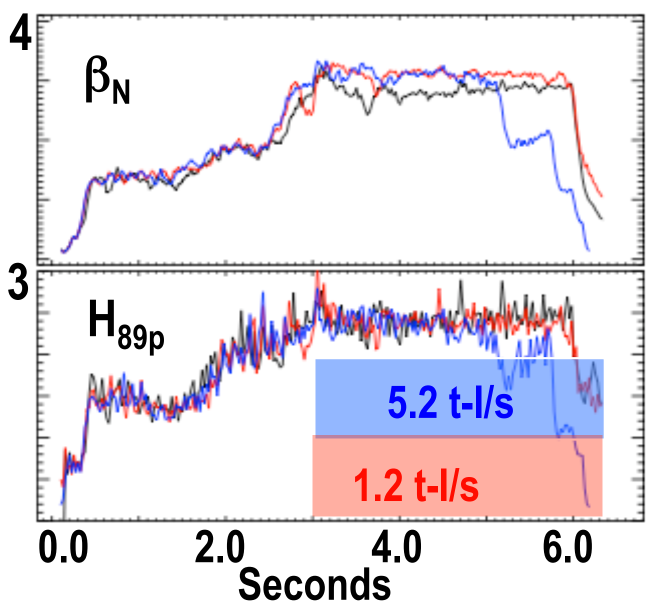
With More Power, q_{min}≈1.5 Scenario Has Margin For Improvement – Higher β_N & Full Noninductive Current Drive

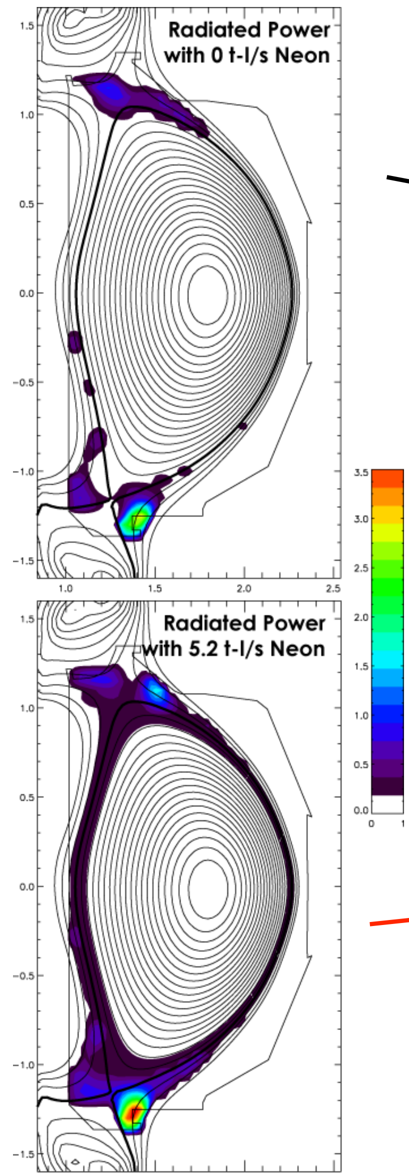
- **13-30% below predicted ideal-wall limit**
- **Residual Ohmic current is peaked – fill in with BS, NB, & EC**
- **Must still avoid pressure peaking that can reduce stability**



q_{min}≈1.5 Scenario Appears Compatible With Radiating Mantle Technique for Divertor Heat Flux Reduction

- Neon injected into private flux region
- P_{RAD} doubles without significant performance degradation





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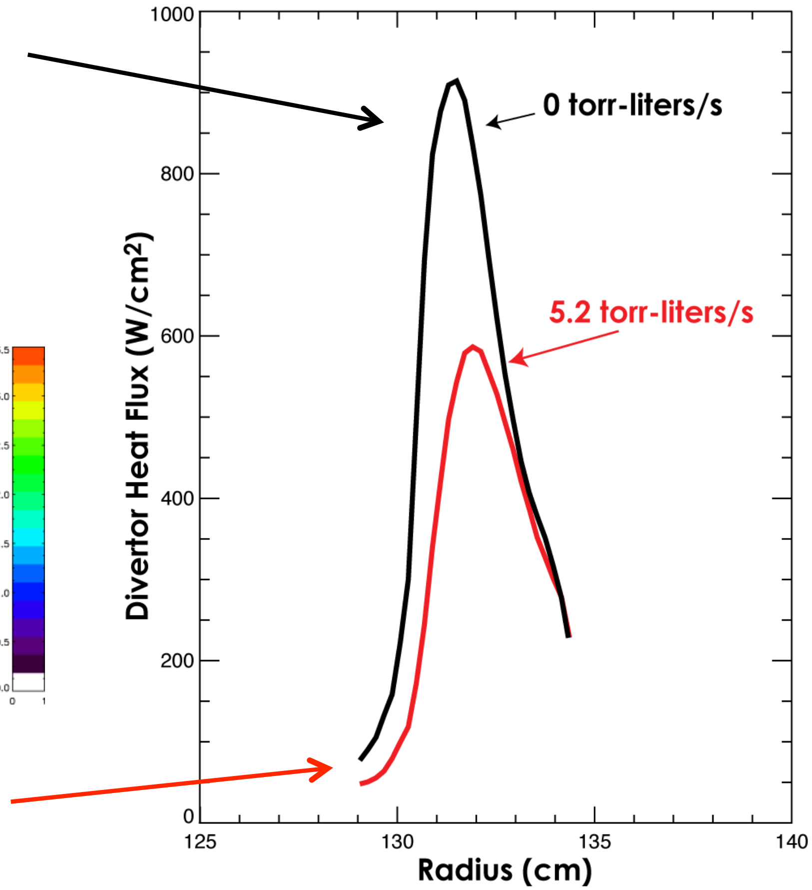
Peak divertor heat flux reduced ~35%



(IR camera measurements)

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Conclusions

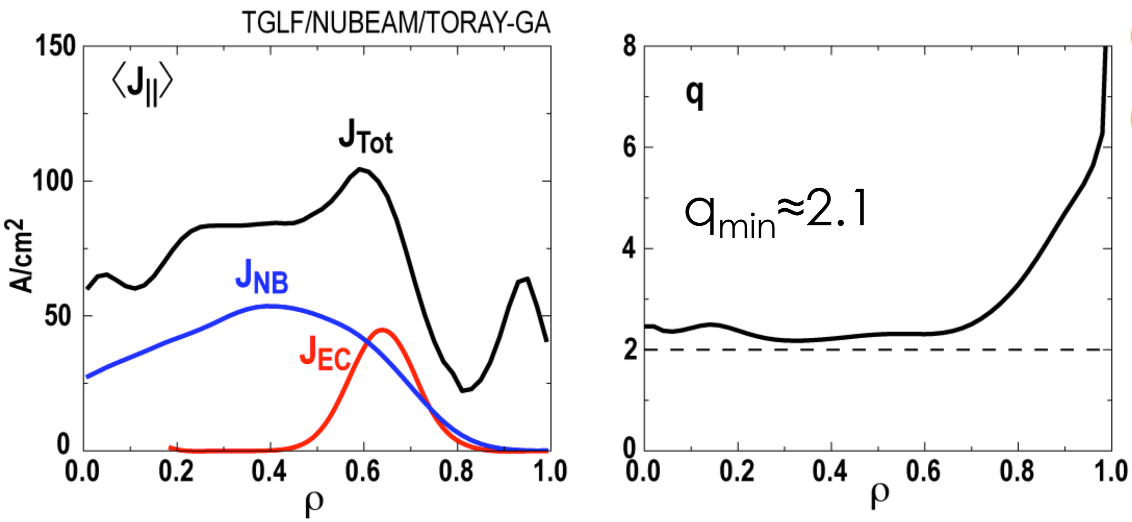
- **Off-axis beams sustain more advanced profiles with better stability**
  - q_{min}>2 with broad pressure: predicted ideal-wall β_N limits increased
  - ITER-sized Q=5 equivalent, ~75% noninductive scenario tested to $2\tau_R$ for tearing stability and is compatible with radiative divertor

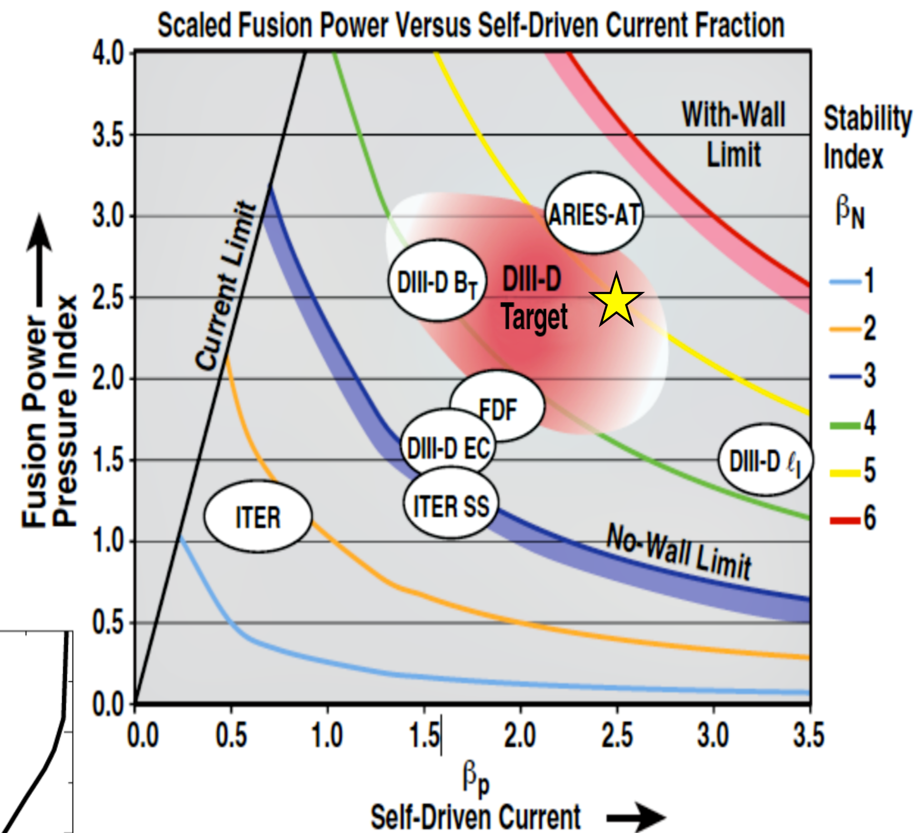
- **Achieving high β_N with q_{min}>2 will require optimizing for good τ_E**
  - Need to explore how to reduce fast ion transport in high q_{min} or compensate with higher thermal confinement, e.g. optimize q-shear
  - Future optimization will benefit from increased heating and current drive power and flexibility

DIII-D Proposed Upgrades Will Enable Optimization of Steady State Scenarios

- **Increased current drive flexibility**
  - 9 MW ECH absorbed
  - 2nd off-axis beamline
  - Beam energy 75-100 keV
- **<u>Integrated Modeling Projection</u>:** ☆

$\beta_N = 4.94$, $f_{NI}=1$, $H_{89}=2.17$





Projected operating point is well placed to inform ITER, FNSF, & DEMO SS solutions