Progress Toward Fully Noninductive Discharge Operation in DIII-D Using Off-Axis Neutral Beam Injection

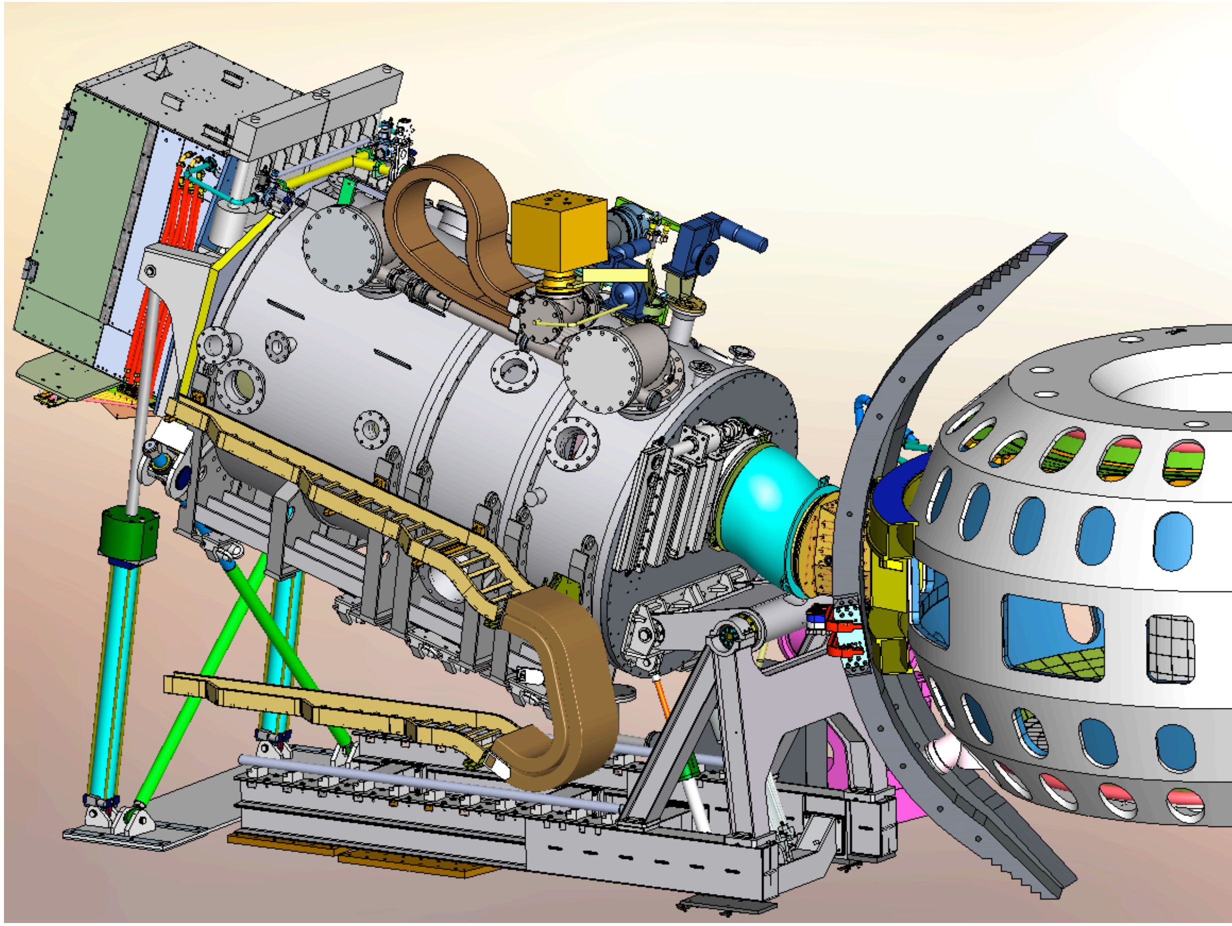
by

J.R. Ferron

With

C. Holcomb[1], J. Park[3], F. Turco[4], T. Luce[2], T. Petrie[2], R. Buttery[2], RP. Politzer[2], M. Lanctot[1], J. Hanson[3], M. Okabayashi[5], Y. In[6], W. Heidbrink[7],. R. La Haye[2], A. Hyatt[2], T. Osborne[2], L. Zeng[7], E. Doyle[8], T. Rhodes[8], A. Garofalo[2], M. Makowski[1], M. Van Zeeland[2]

[1]Lawrence Livermore National Laboratory
[2]General Atomics
[3]Oak Ridge National Laboratory
[4]Columbia University
[5]Princeton Plasma Physics Laboratory
[6]FAR TECH Inc.
[7]Univiersity of California, Irvine
[8]University of California, Los Angeles



Presented at the

54th Annual APS Meeting
Division of Plasma Physics
Providence, Rhode Island

October 29 — November 2, 2012

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

The Need for Economical Fusion Power Motivates Steady-state Tokamak Operation at High Plasma Pressure

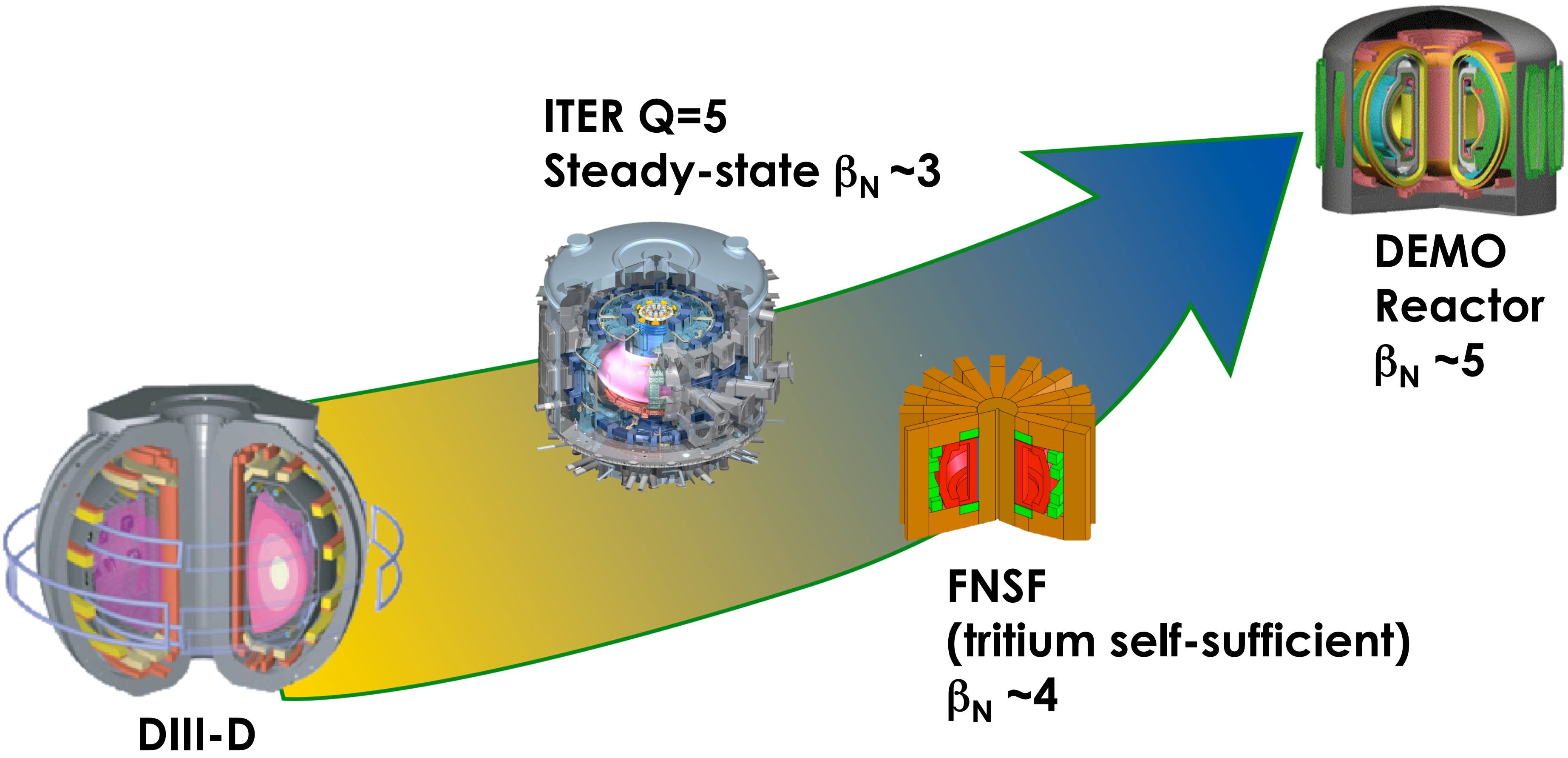
- **Steady-state: 100% of the current driven noninductively, f_{NI} = 1**

- **Large bootstrap current fraction $f_{BS} \propto q_{95}\beta_N$**
  - Minimize the external current drive power
- **High fusion gain ~ $\beta_N H/q_{95}^2$**

→ **High pressure (β_N)**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

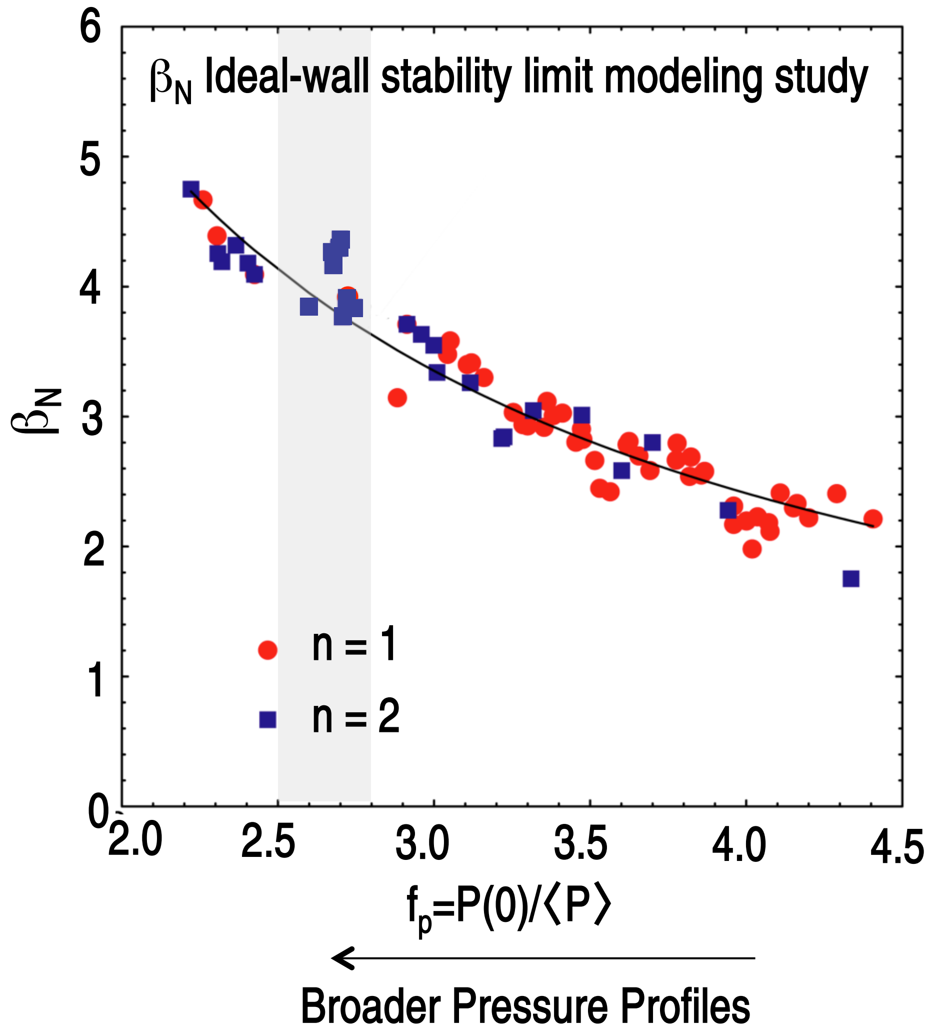
Future Steady-state Devices are Envisioned at Increasing Values of β_N



The DIII-D program aims to establish the physics basis for steady-state operation at $\beta_N = 5$

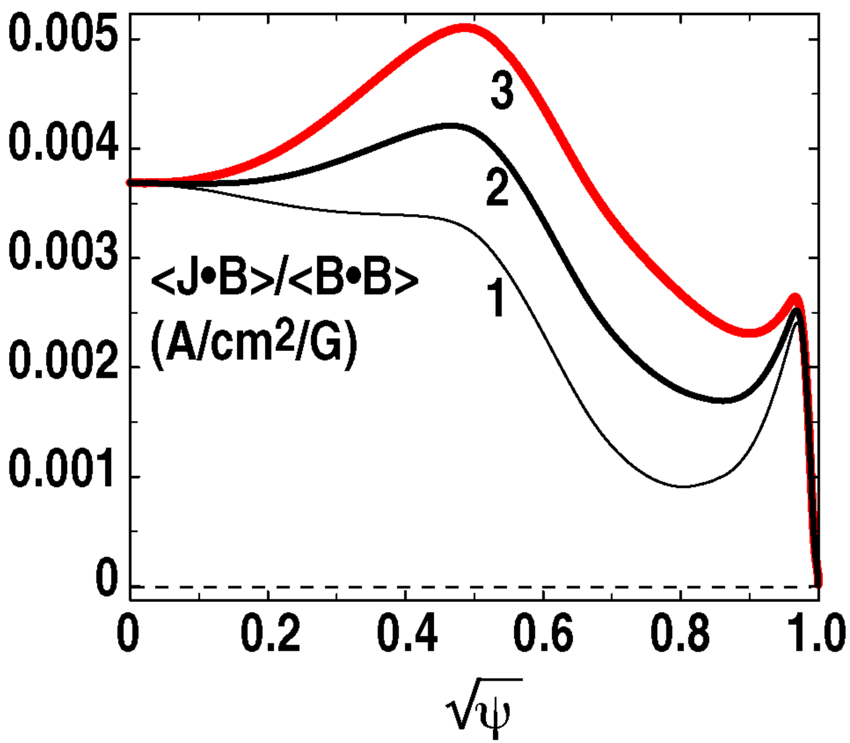
Broad Pressure Profiles Lead to MHD Stability at High β_N

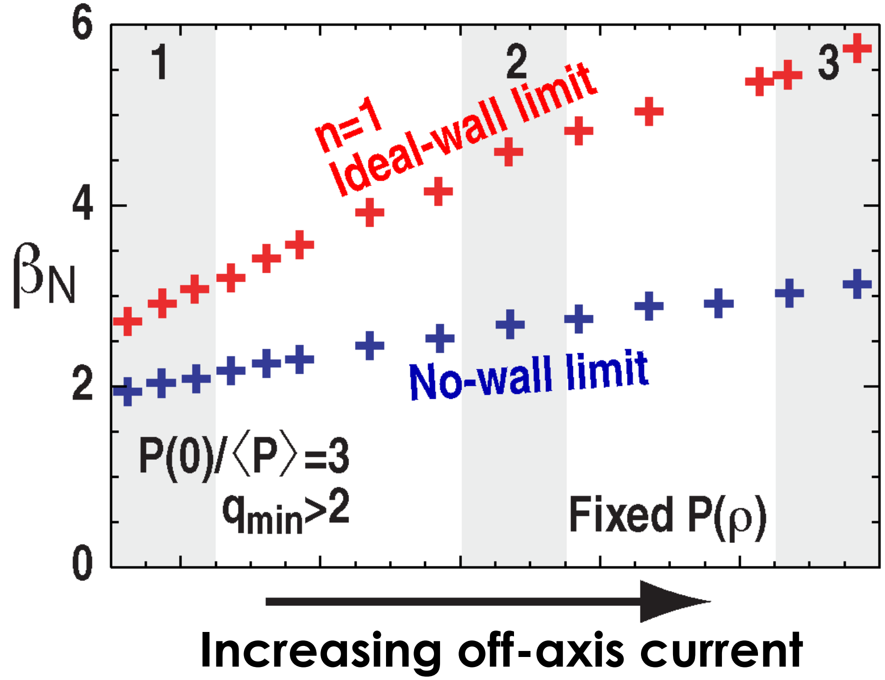
- **Low-n, ideal-wall β_N stability limit increases with pressure profile width**



Broad Current Profiles Also Improve MHD Stability at High β_N

Modeling study





Increased off-axis current ⇨

- Better coupling to the wall for improved wall stabilization
- Increased q_{min} (for fixed q_{95})

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Off-Axis Neutral Beam Injection Is Enabling Improved Access to Fully Noninductive Plasma Regimes

Experimental results

- **Broader current profile:**
  improved access to q_{min} above 2
- **Broader pressure profiles with β_N up to 3.3**
  increase of calculated ideal MHD stability limits: $\beta_N > 4$
- **Thermal confinement as expected for H-mode;**
  total pressure limited by enhanced fast ion transport at high q_{min}

Models of next step parameter regimes for DIII-D

- **Fully noninductive solutions at $\beta_N = 4\text{-}5$, $q_{min} > 2$:**
  parameter regime relevant to ITER through DEMO

Off-Axis Neutral Beam Injection Is Enabling Improved Access to Fully Noninductive Plasma Regimes

Experimental results

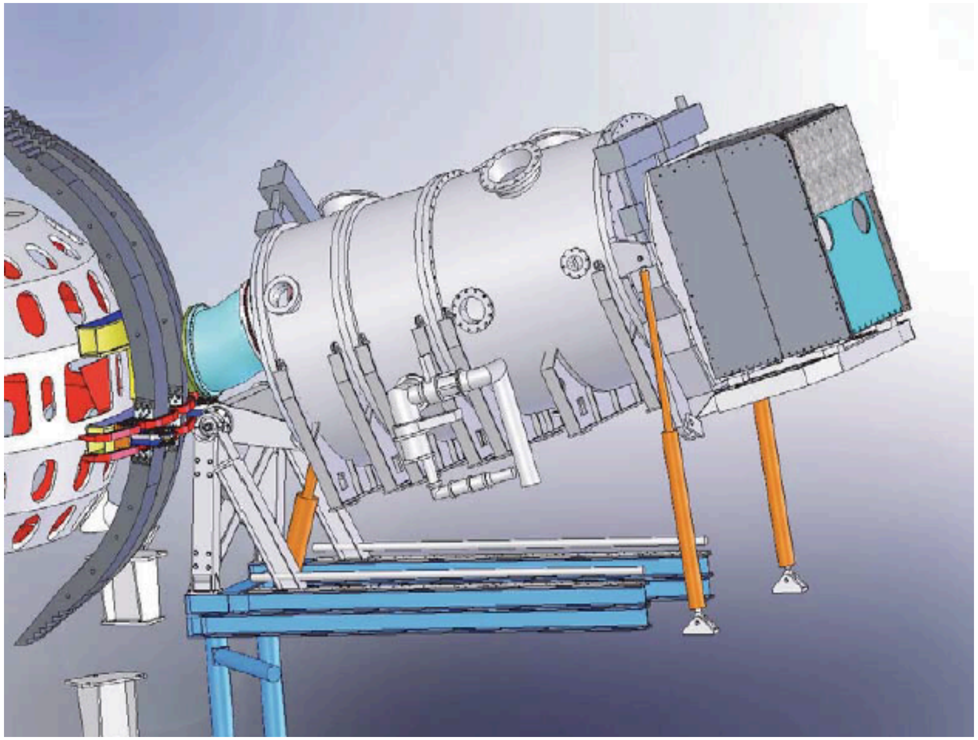
- **Broader current profile:**
  improved access to q_{min} above 2
- Broader pressure profiles with β_N up to 3.3
  increase of calculated ideal MHD stability limits: $\beta_N > 4$
- Thermal confinement as expected for H-mode;
  total pressure limited by enhanced fast ion transport at high q_{min}

Models of next step parameter regimes for DIII-D

- Fully noninductive solutions at β_N = 4-5, $q_{min} > 2$:
  parameter regime relevant to ITER through DEMO

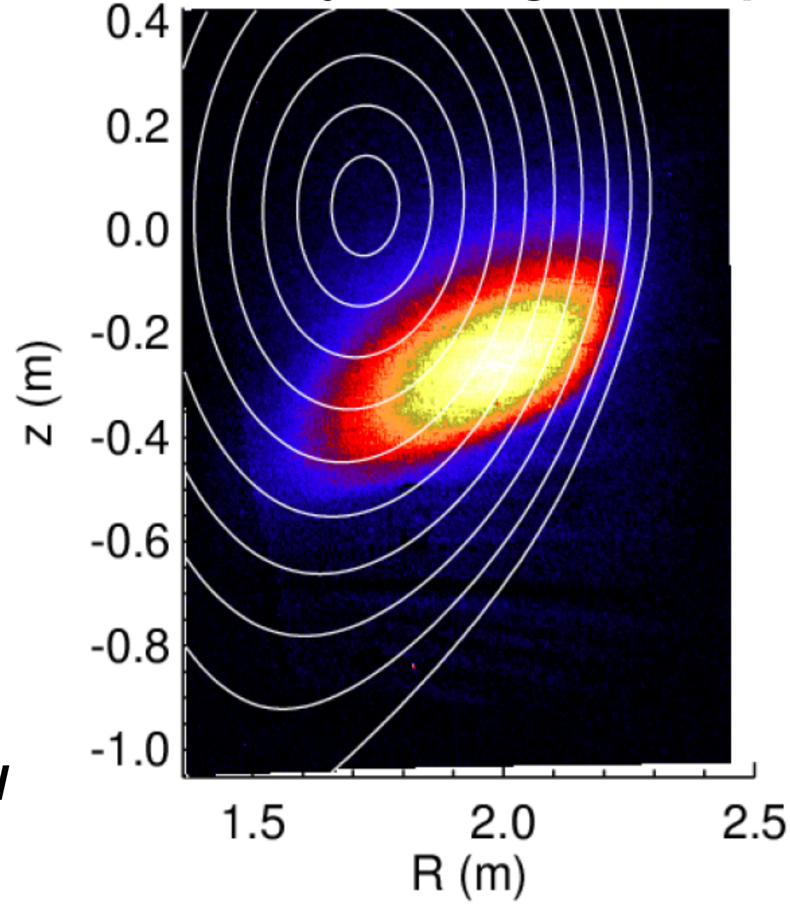
One DIII-D Beamline has been Modified for Downward Vertical Steering to Provide Substantial Off-axis Current Drive

- **Beamline Tilt : 0-16.4°**



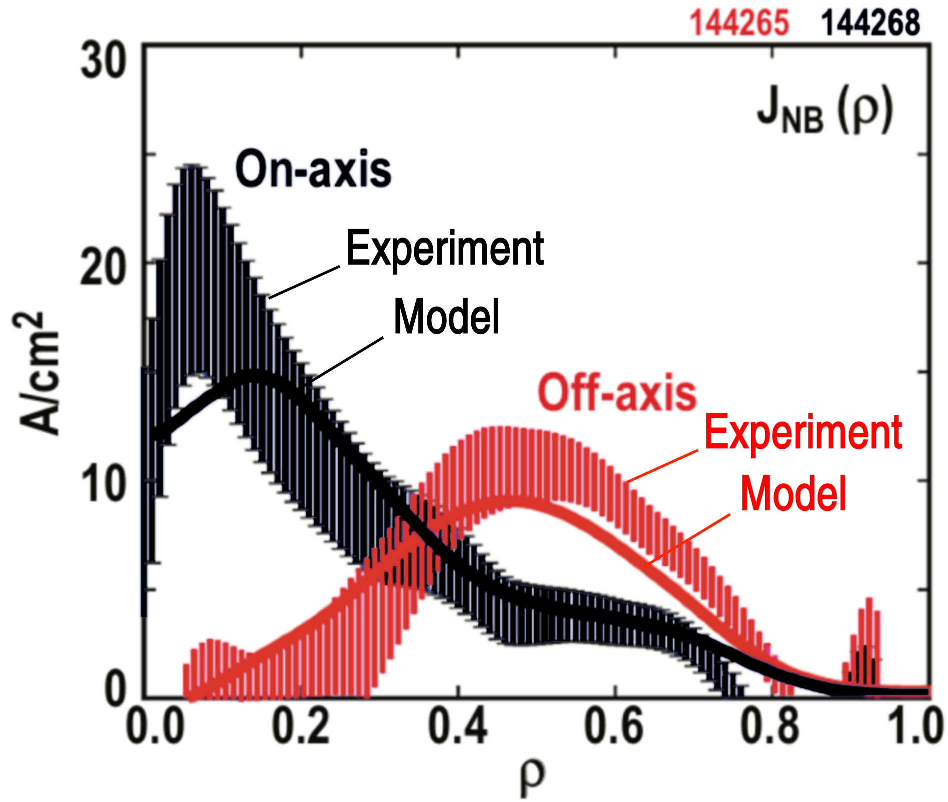
- **Maximum total co-injected power 14.1 MW**
- **Maximum off-axis injected power 5 MW**

- **Beam into plasma D_α image at maximum tilt angle verifies injection geometry**



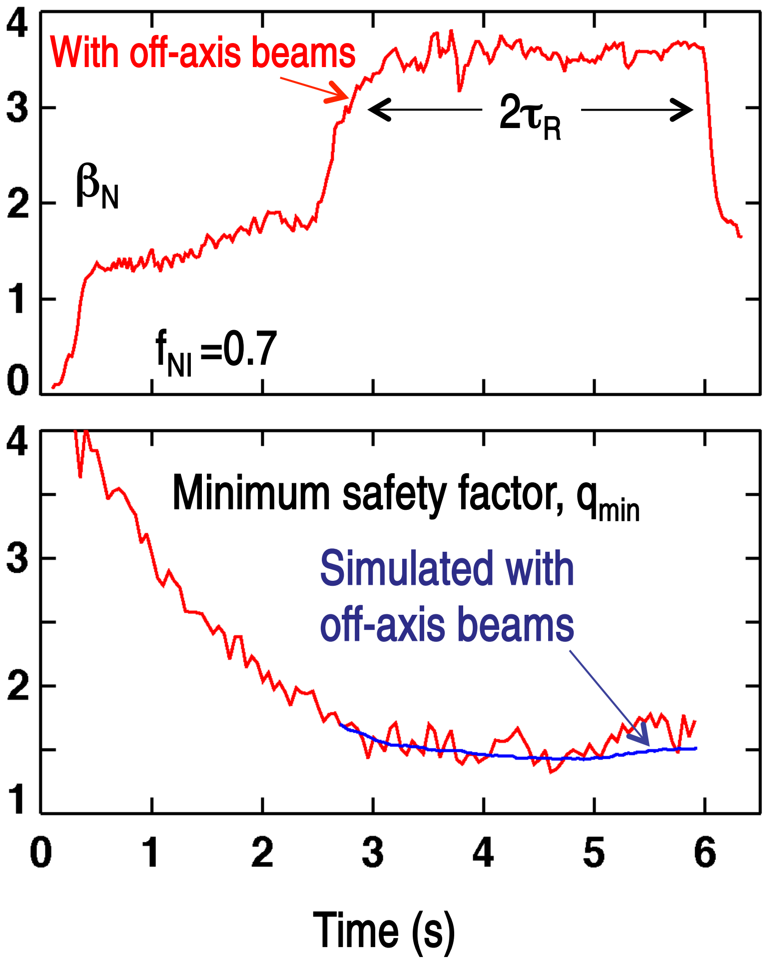
Measured Off-axis NBCD In Low β_N Discharges Is Consistent with Classical Modeling

- β_N = 1.5, H-mode discharge with no coherent MHD
- Clear hollow NBCD profile
- Peak NBCD at ρ ~ 0.5
- Good agreement with modeling with β_N up to 2.3

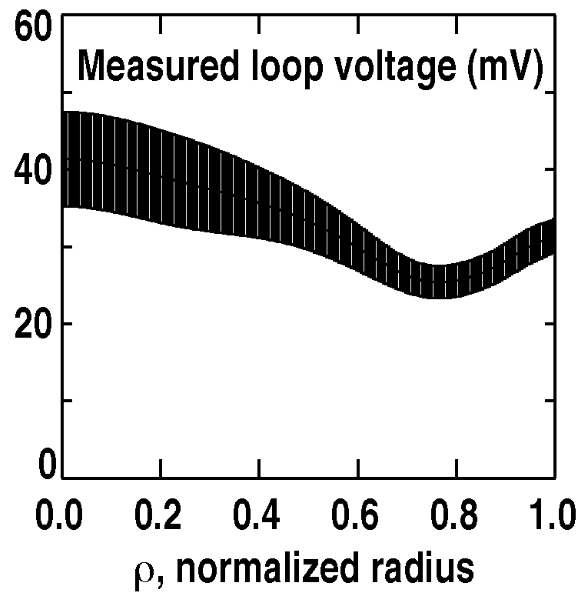


J.M. Park IAEA 2012, EX/P2-13

With Off-axis Injection, the Current Profile is Stationary for Twice the Current Relaxation Time at q_{min}=1.5

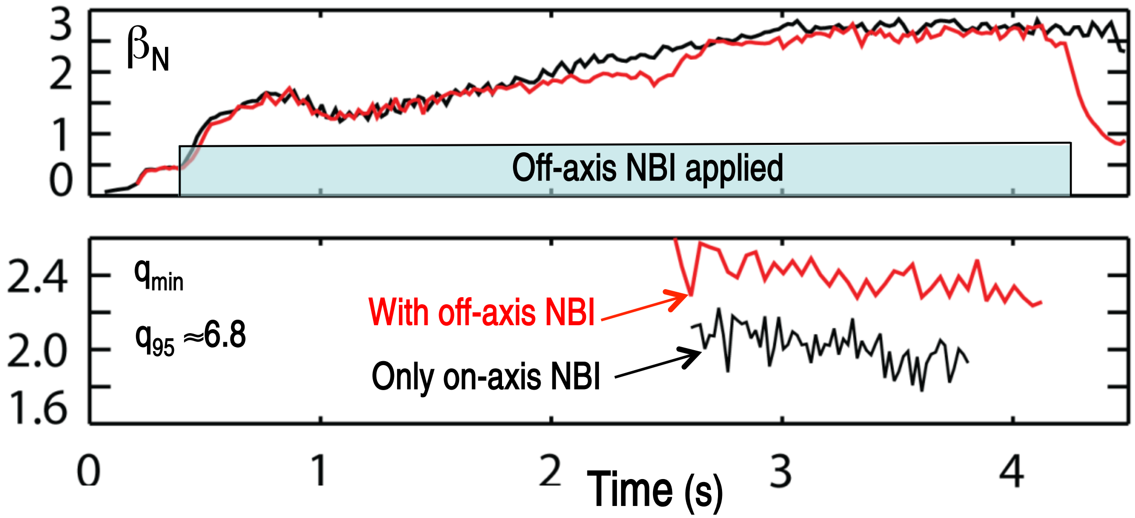


- Reduced $J_{NBCD}(0)$, low J_{ohmic}
- Does not evolve to sawtooth or n = 1 tearing mode unstable profiles for $2\tau_R$, unlike with only on-axis NBI
- $\beta_N H_{89}/q_{95}^2$ = 0.3 sufficient for ITER steady-state mission

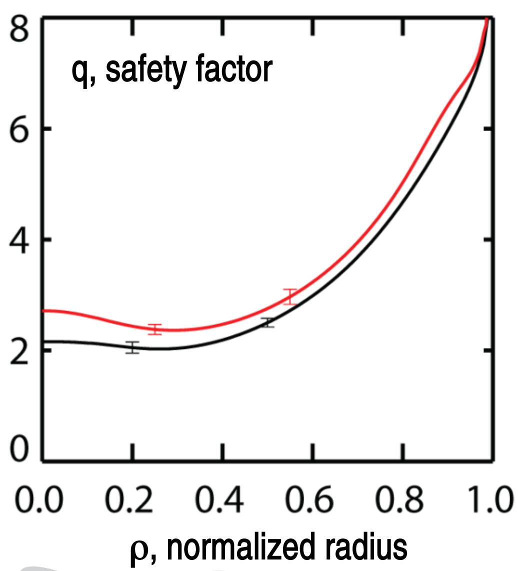


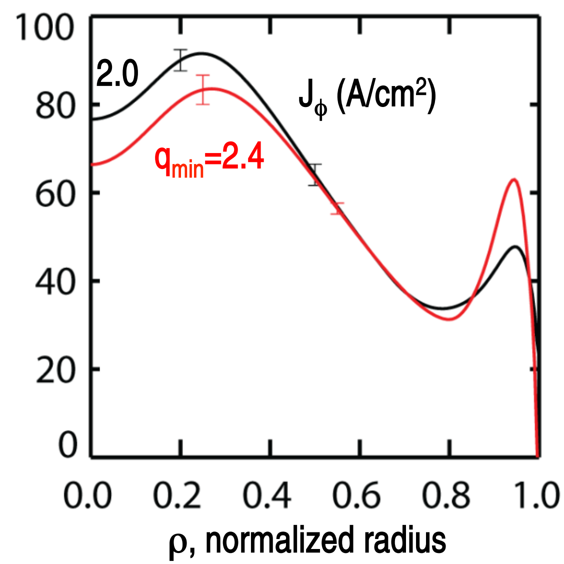
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

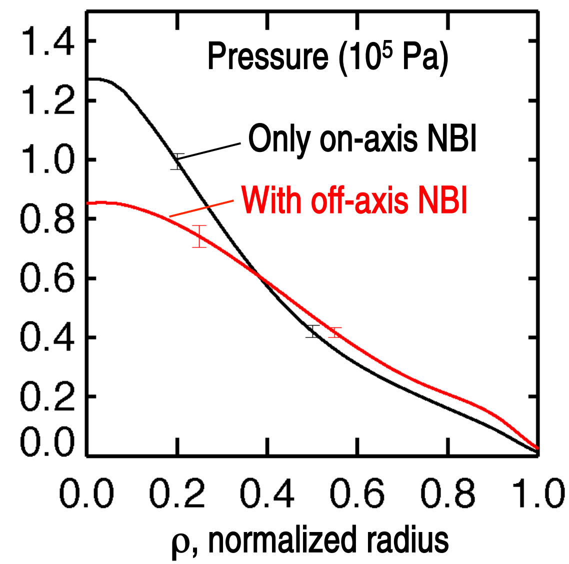
With Off-Axis Injection, q_{min} can be Maintained Above 2



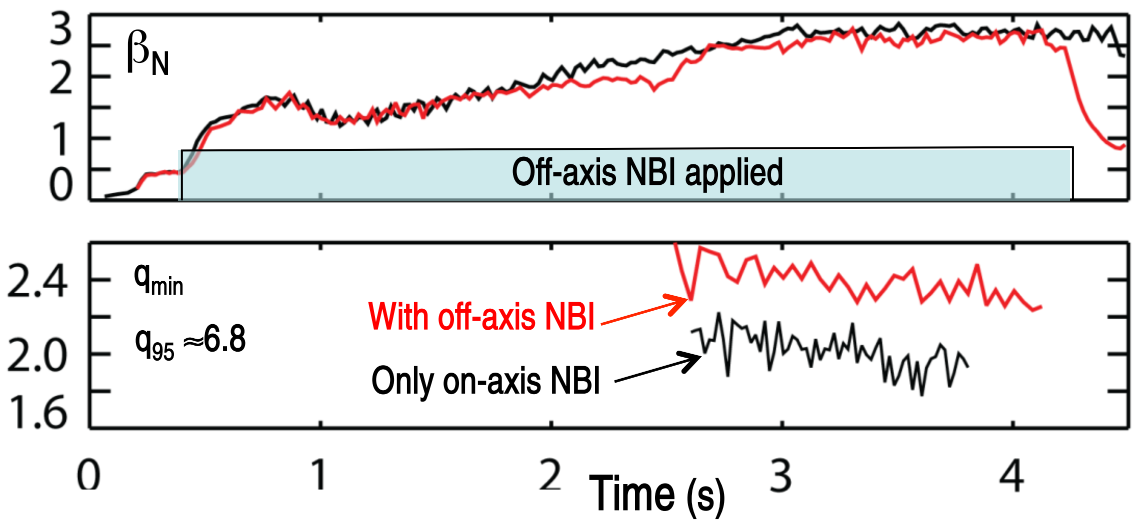
- **Current density shifts outward as q_{min} increases**
- **Pressure profile broadens**



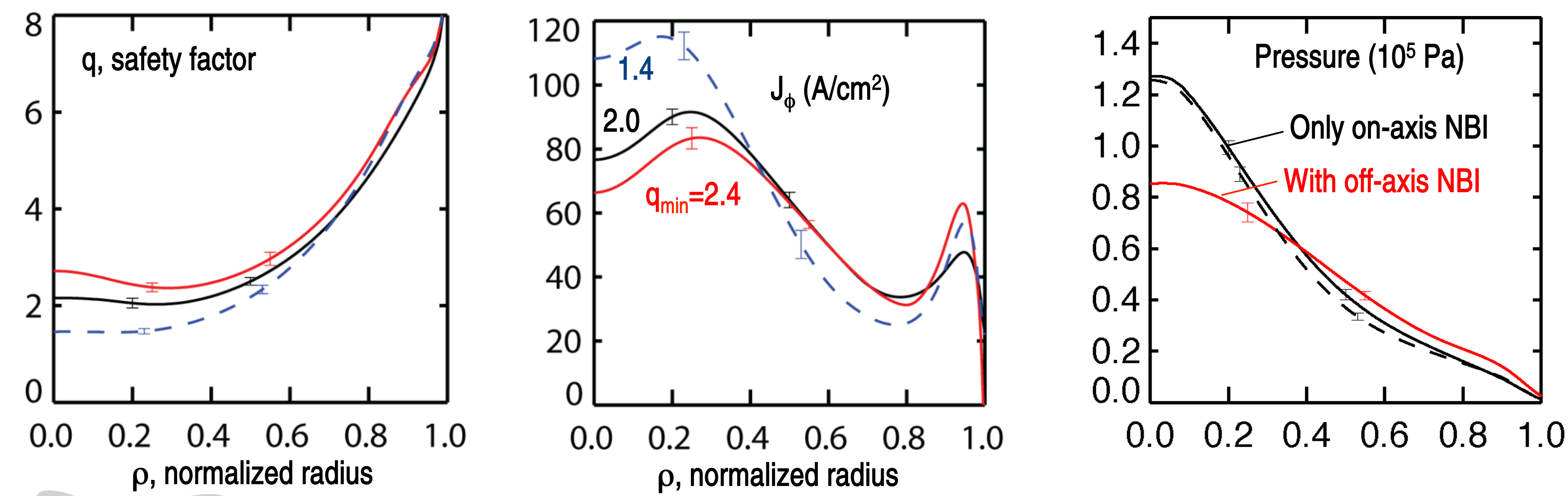




With Off-Axis Injection, q_{min} can be Maintained Above 2



- **Current density shifts outward as q_{min} increases**
- **Pressure profile broadens**



Off-Axis Neutral Beam Injection Is Enabling Improved Access to Fully Noninductive Plasma Regimes

Experimental results

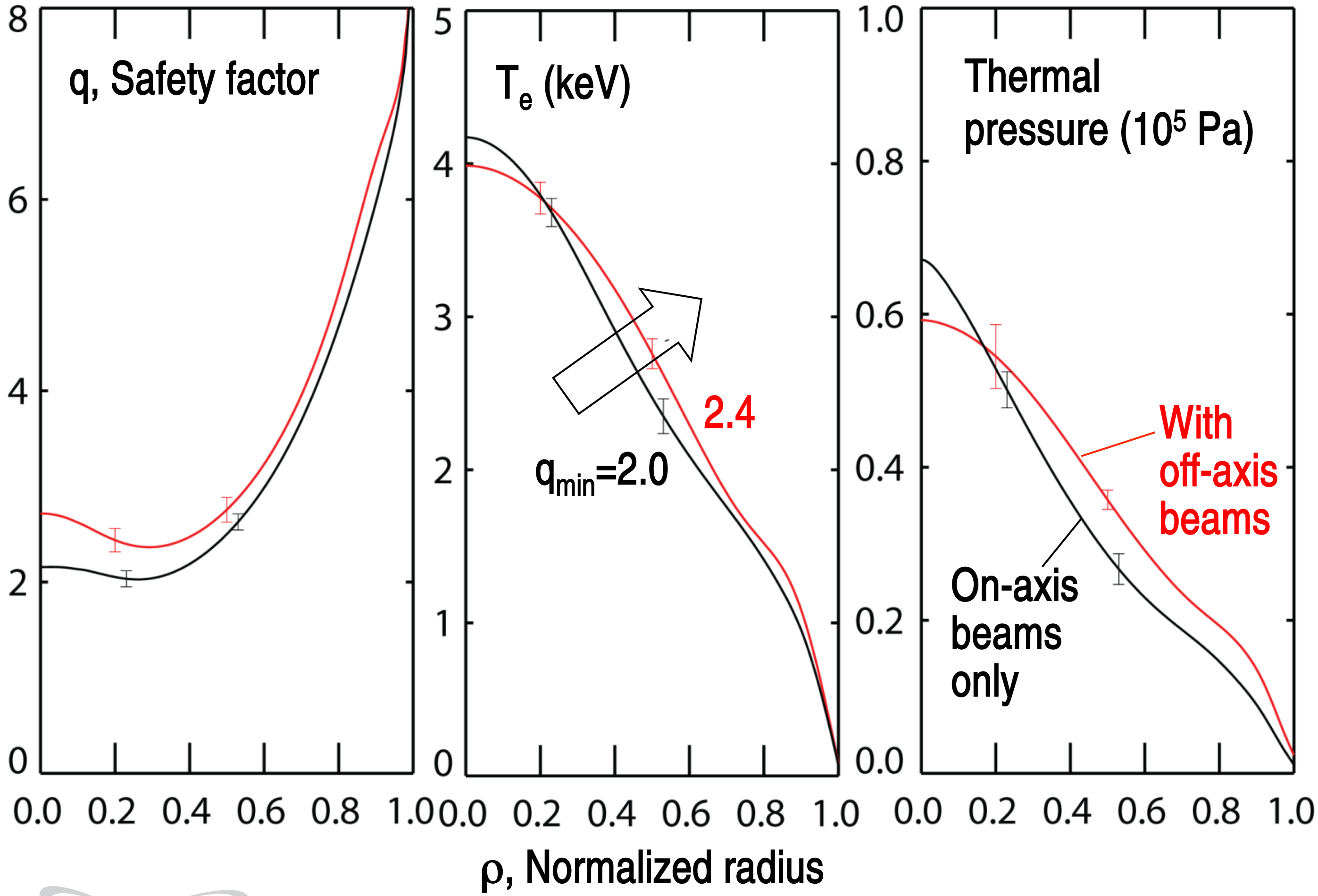
- ✓ **Broader current profile:**
  improved access to q_{min} above 2
- **Broader pressure profiles with β_N up to 3.3**
  increase of calculated ideal MHD stability limits: $\beta_N > 4$
- **Thermal confinement as expected for H-mode;**
  total pressure limited by enhanced fast ion transport at high q_{min}

Models of next step parameter regimes for DIII-D

- **Fully noninductive solutions at β_N = 4-5, $q_{min} > 2$:**
  parameter regime relevant to ITER through DEMO

The Thermal Pressure Profile Broadens with Increasing q_{min}

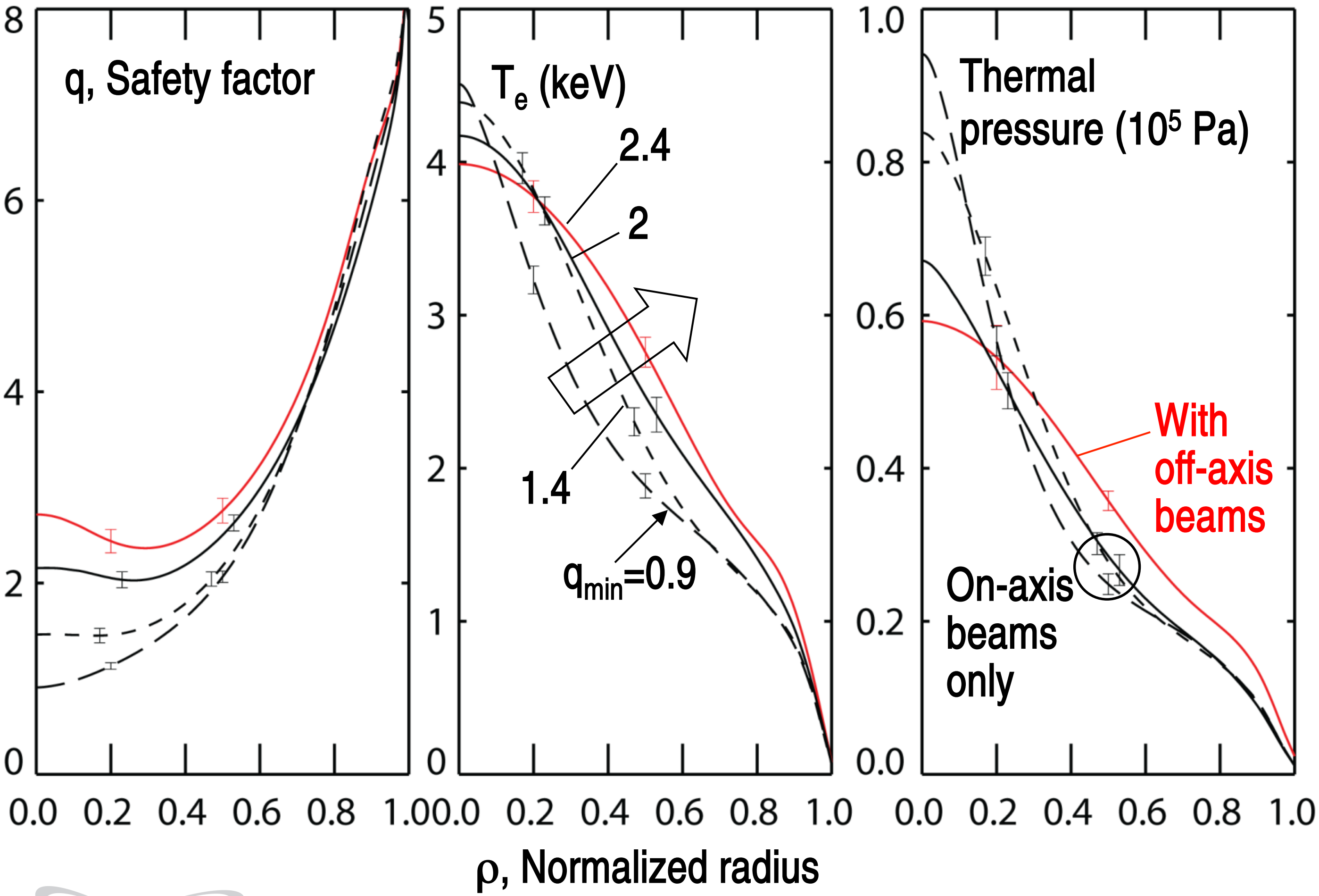
- T_e profile broadens with increasing q_{min}
- Also broadening of T_i and n_e profiles



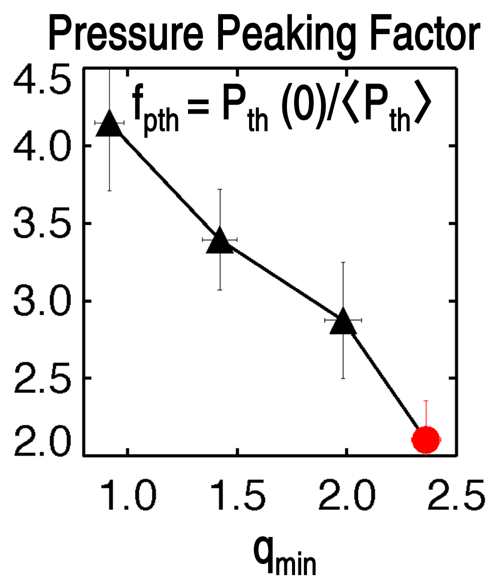
β_N = 2.7
q_{95} = 6.8
B_T = 2 T

The Thermal Pressure Profile Broadens with Increasing q_{min}

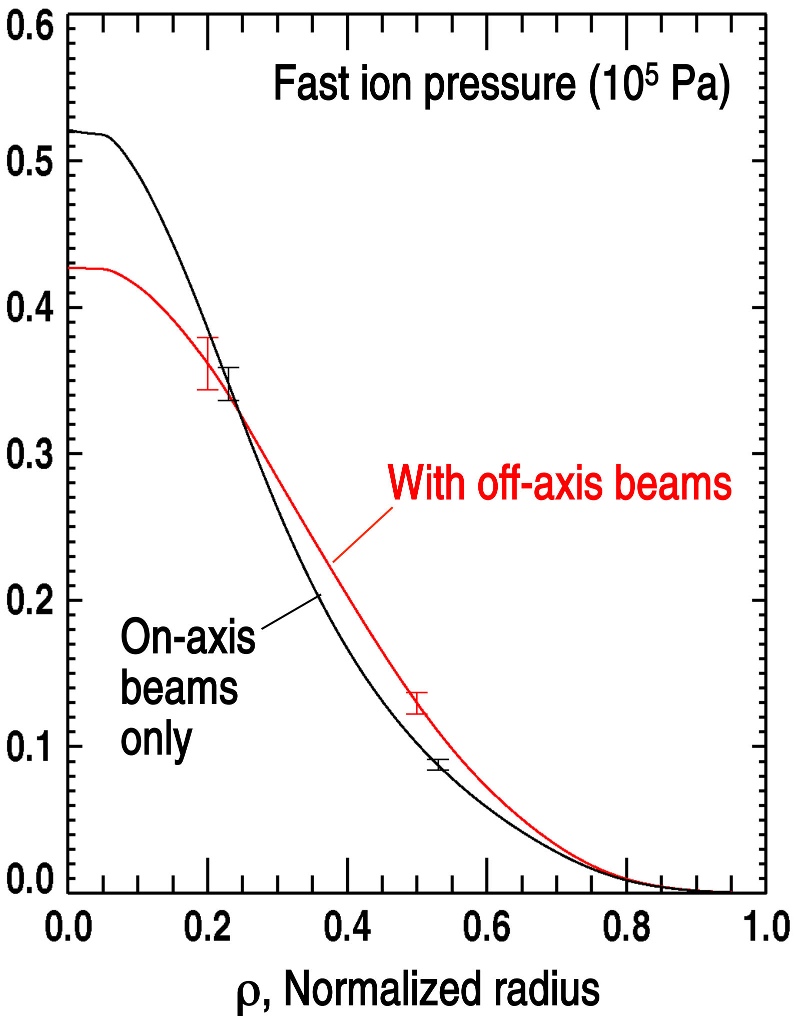
- T_e profile broadens with increasing q_{min}
- Also broadening of T_i and n_e profiles



$\beta_N = 2.7$
$q_{95} = 6.8$
$B_T = 2$ T

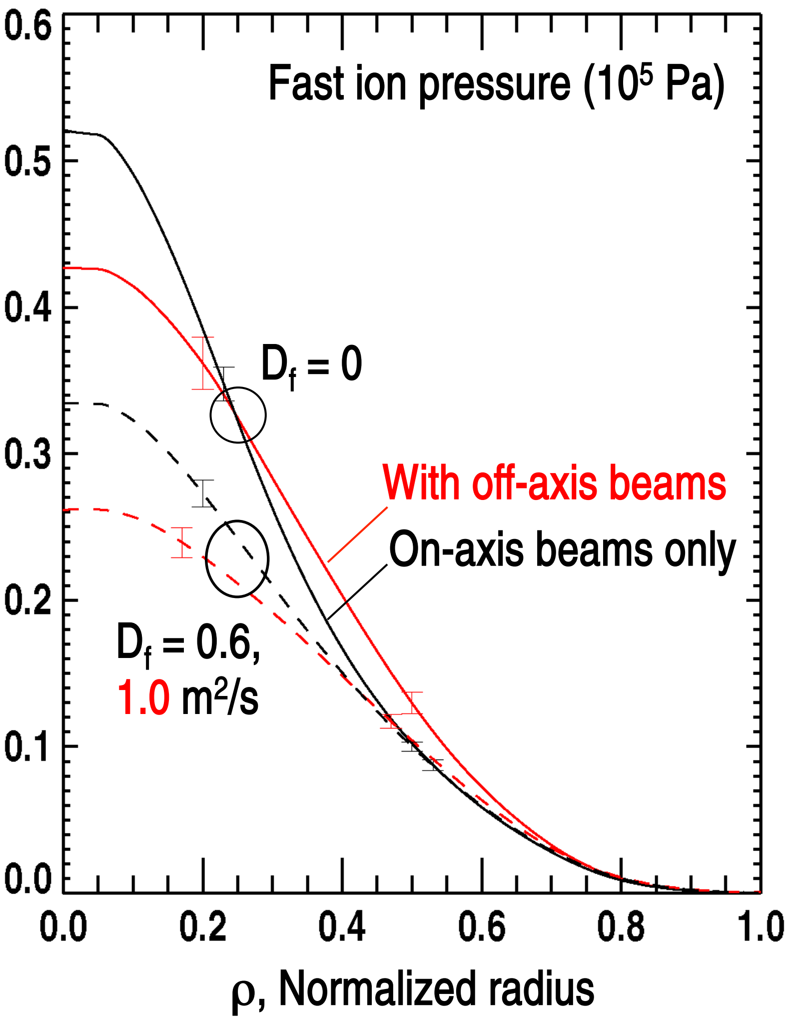


Off-Axis Injection Results in a Broader Calculated Fast Ion Pressure Profile



- **Two otherwise identical discharges**
  - One has 45% beam power off-axis
- **q_{min} = 1.1**

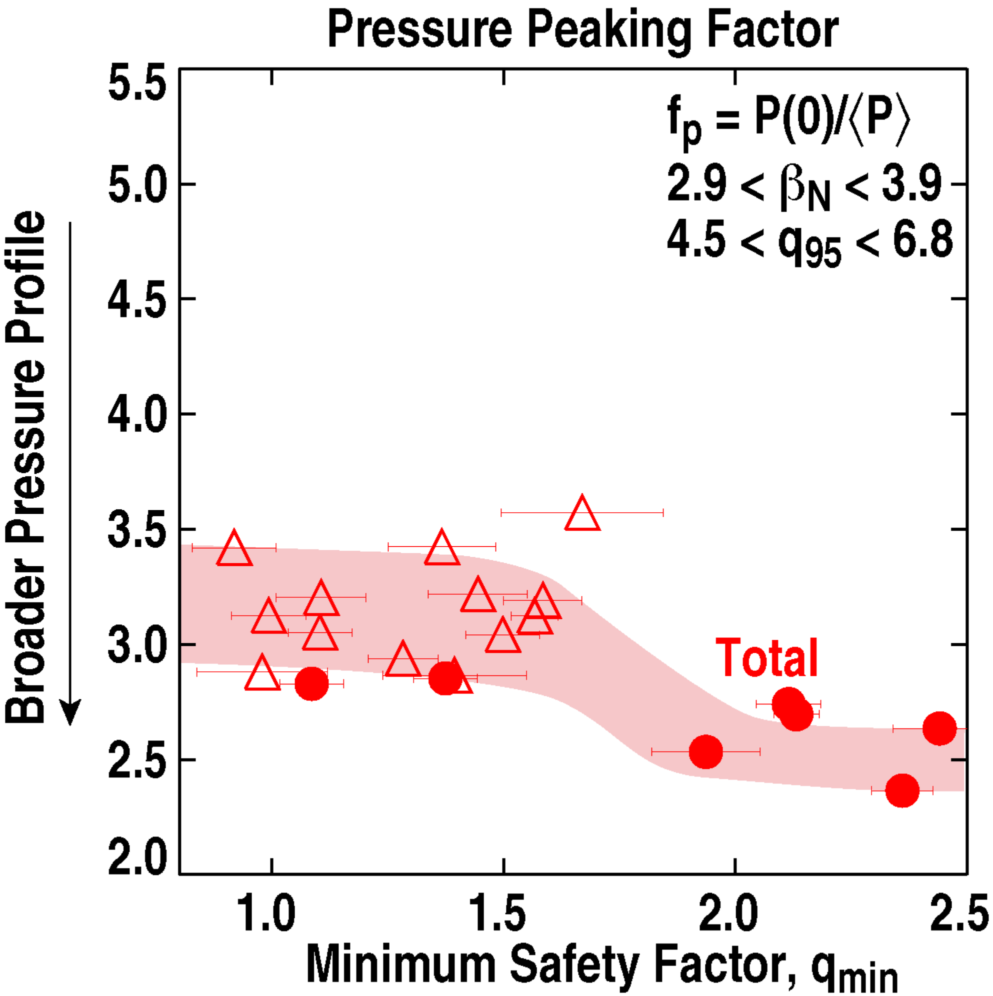
Off-Axis Injection Results in a Broader Calculated Fast Ion Pressure Profile



- **Two otherwise identical discharges**
  - One has 45% beam power off-axis
- **q_{min} = 1.1**
- **Computed fast ion stored energy plus measured thermal energy exceeds value from equilibrium reconstruction**
  - Fast ion diffusion (D_f) added to model
  - Diffusion probably not the completely correct model; introduces uncertainty

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Discharges with off-Axis Beam Injection and q_{min} > 2 Have the Lowest Pressure Peaking Factors

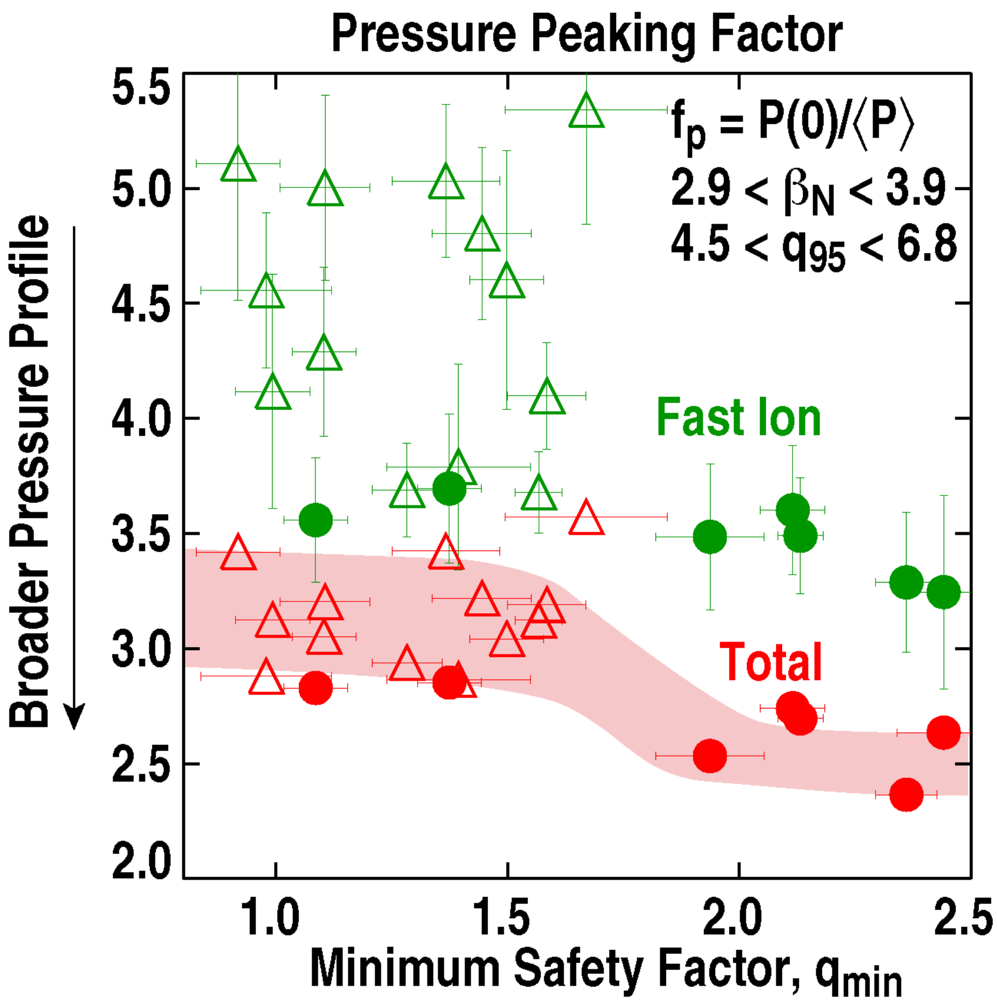


- At fixed q_{min}, discharges with off-axis injection have the least peaked pressure profiles

● With off-axis beams

△ On-axis only

Discharges with off-Axis Beam Injection and $q_{min} > 2$ Have the Lowest Pressure Peaking Factors

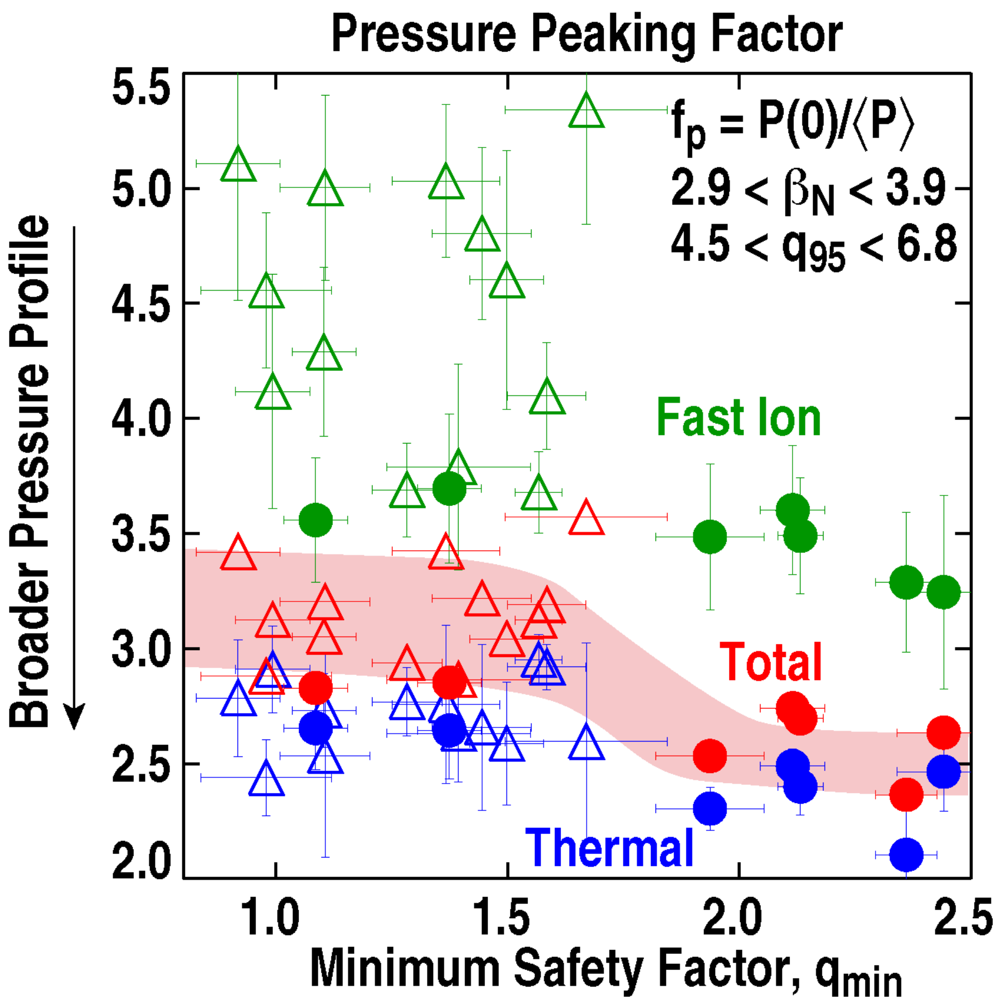


- At fixed q_{min}, discharges with off-axis injection have the least peaked pressure profiles

● With off-axis beams

△ On-axis only

Discharges with off-Axis Beam Injection and q_{min} > 2 Have the Lowest Pressure Peaking Factors

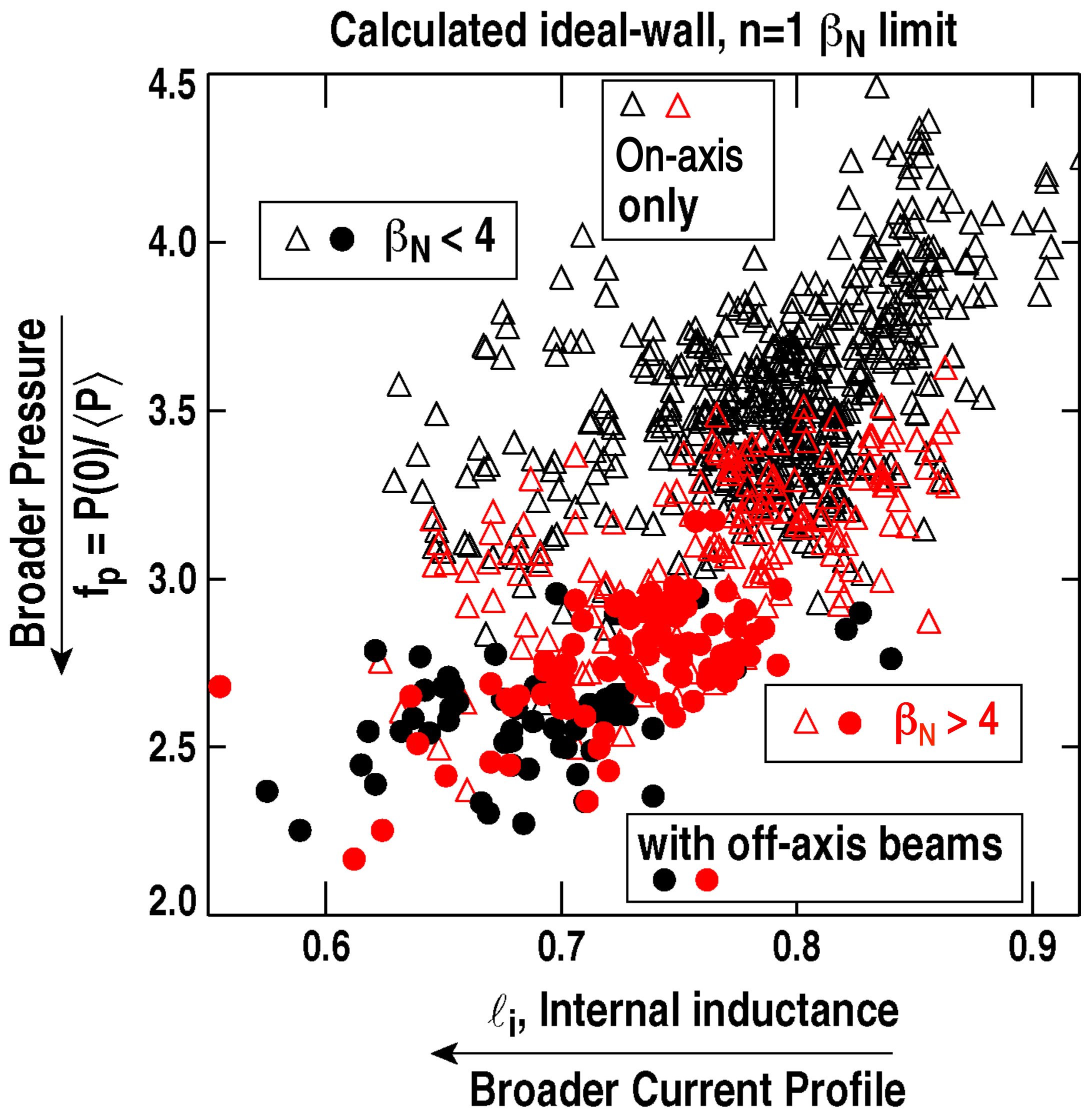


- At fixed q_{min}, discharges with off-axis injection have the least peaked pressure profiles

● With off-axis beams

△ On-axis only

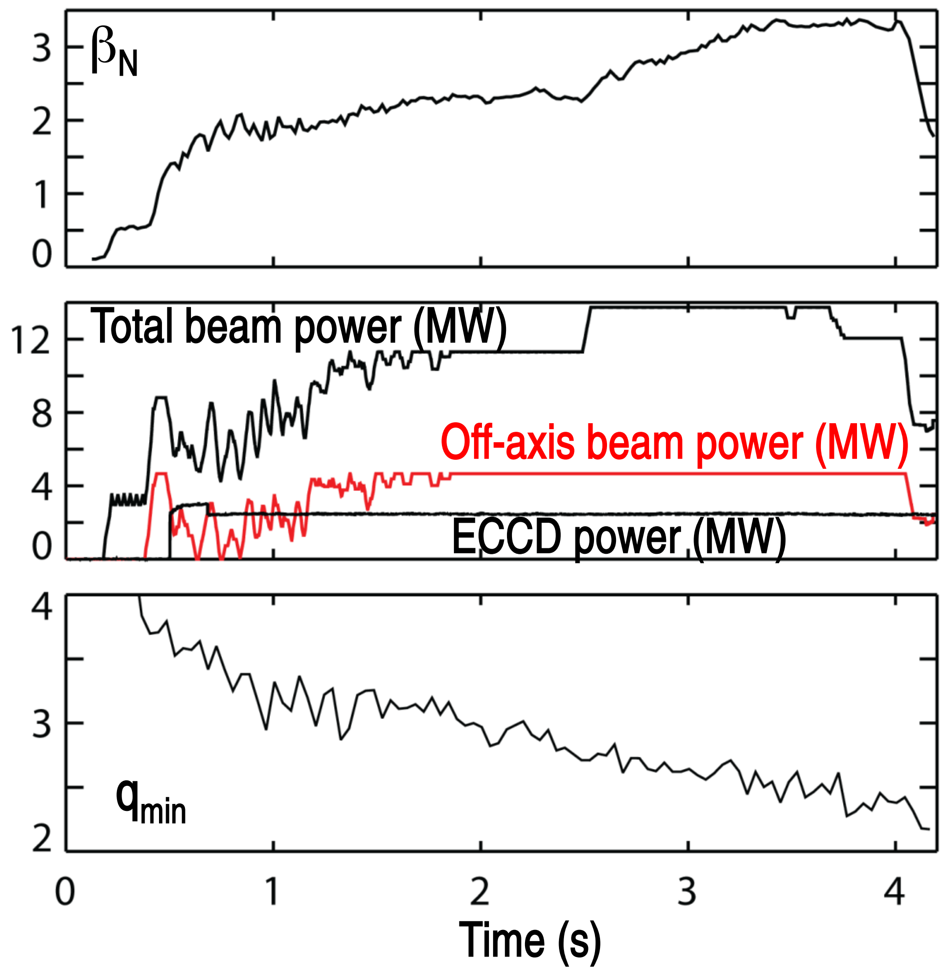
Broader Pressure Profiles Combined with Increased Off-axis Current at High q_{min} Result in Higher Calculated β_N Limits



- At q_{min} > 2, current density peaked off-axis couples to the conducting wall to improve stability
- Ideal MHD, low-n β_N limit with wall stabilization included
- Many time slices per shot

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

At q_{min} >2, the Maximum Achieved $\beta_N \approx 3.3$ is Limited by the Available Power, Not Stability



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

Off-Axis Neutral Beam Injection Is Enabling Improved Access to Fully Noninductive Plasma Regimes

Experimental results

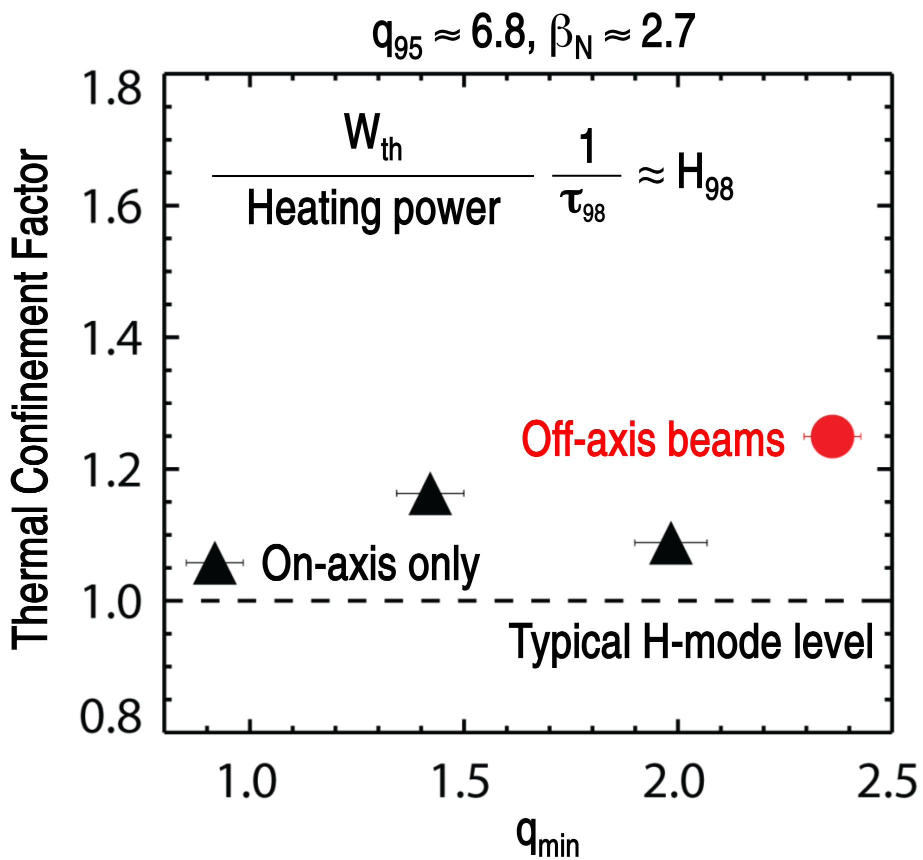
- ✓ Broader current profile:
  improved access to q_{min} above 2
- ✓ Broader pressure profiles with β_N up to 3.3
  increase of calculated ideal MHD stability limits: $\beta_N > 4$
- Thermal confinement as expected for H-mode;
  total pressure limited by enhanced fast ion transport at high q_{min}

Models of next step parameter regimes for DIII-D

- Fully noninductive solutions at β_N = 4-5, $q_{min} > 2$:
  parameter regime relevant to ITER through DEMO

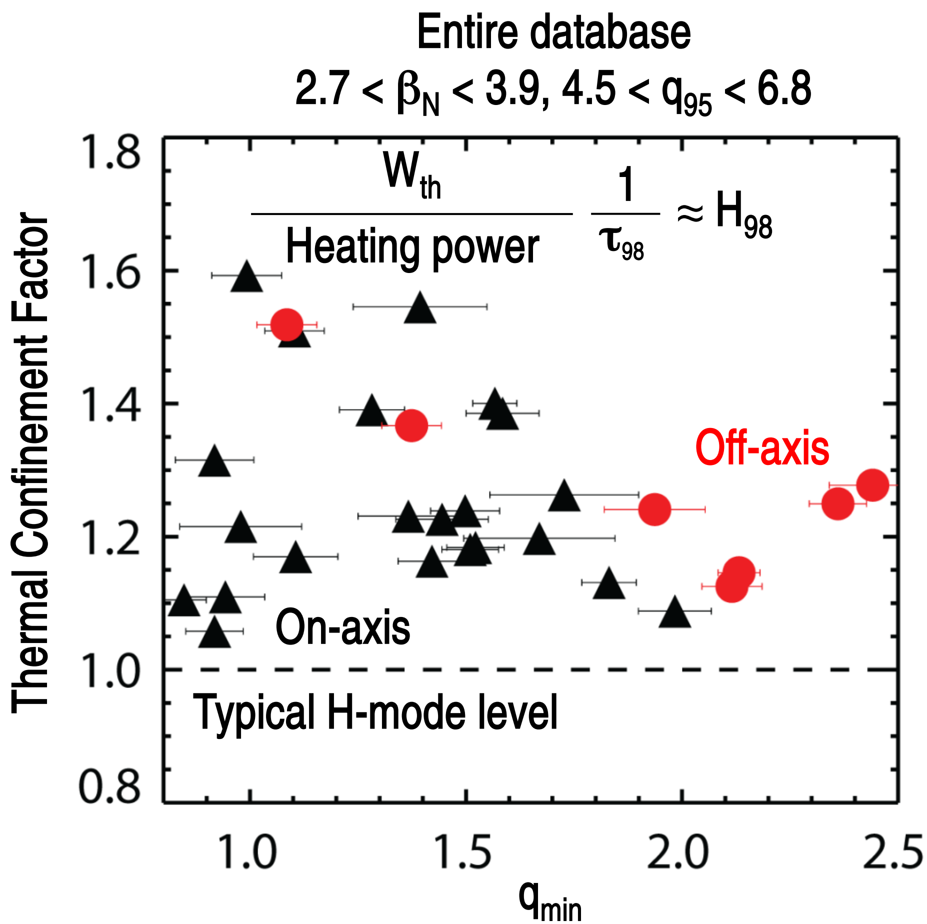
Steady-State Scenario Discharges Have Thermal Confinement Above the Level Expected for a Typical H-Mode

- **No systematic decrease observed with off-axis injection or as q_{min} increases**



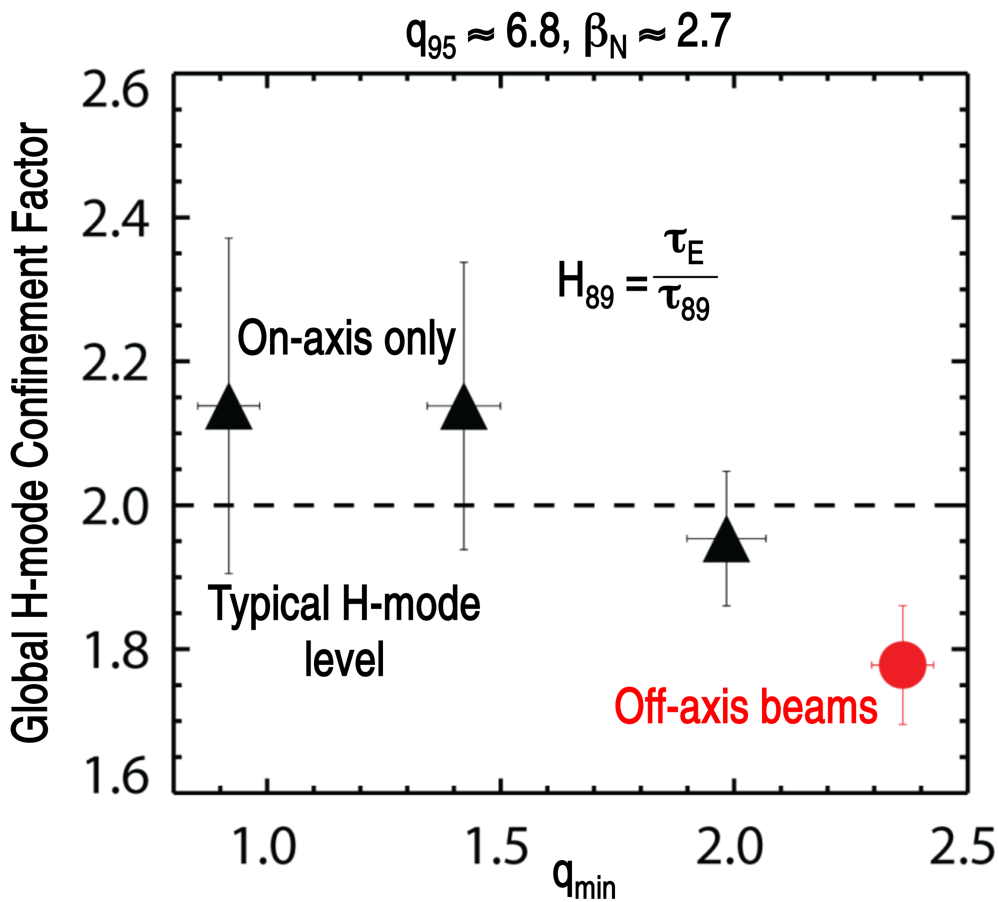
Steady-State Scenario Discharges Have Thermal Confinement Above the Level Expected for a Typical H-Mode

- **No systematic decrease observed with off-axis injection or as q_{min} increases**



Highest q_{min} Plasmas Have Global (Thermal+Fast Ion) Confinement Below the Typical H-mode Level

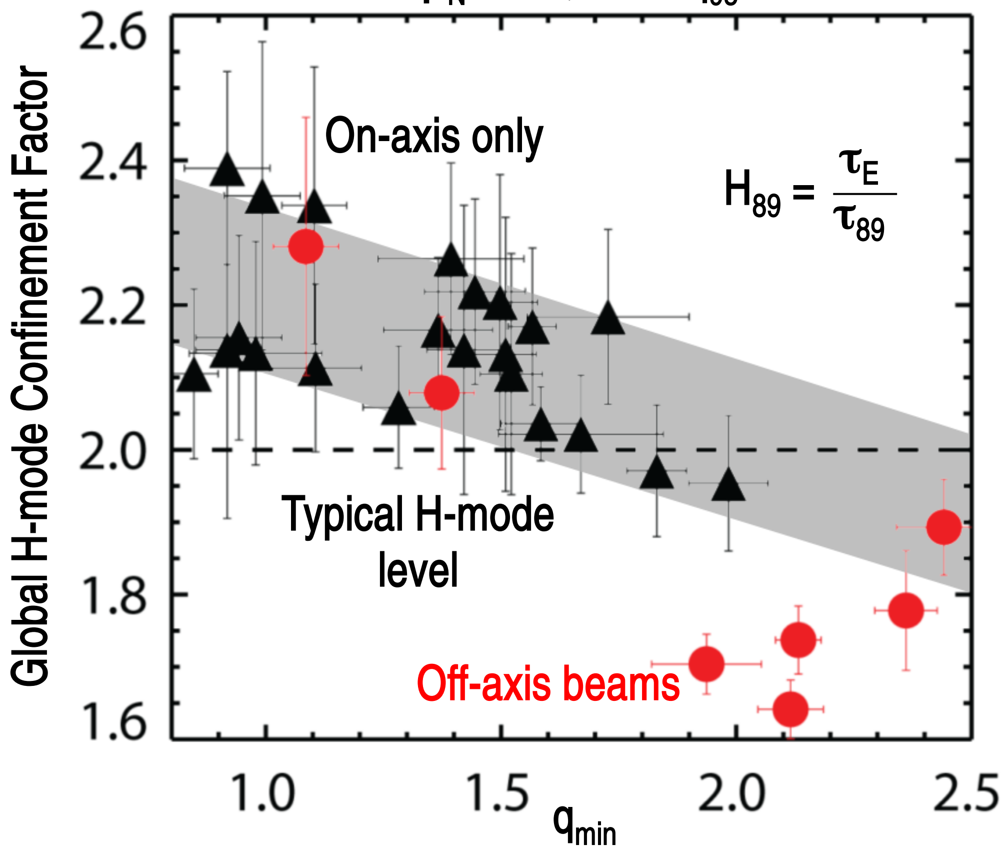
- **Implies increased fast ion transport as q_{min} increases**
  - Because thermal confinement shows no q_{min} scaling



Highest q_{min} Plasmas Have Global (Thermal+Fast Ion) Confinement Below the Typical H-mode Level

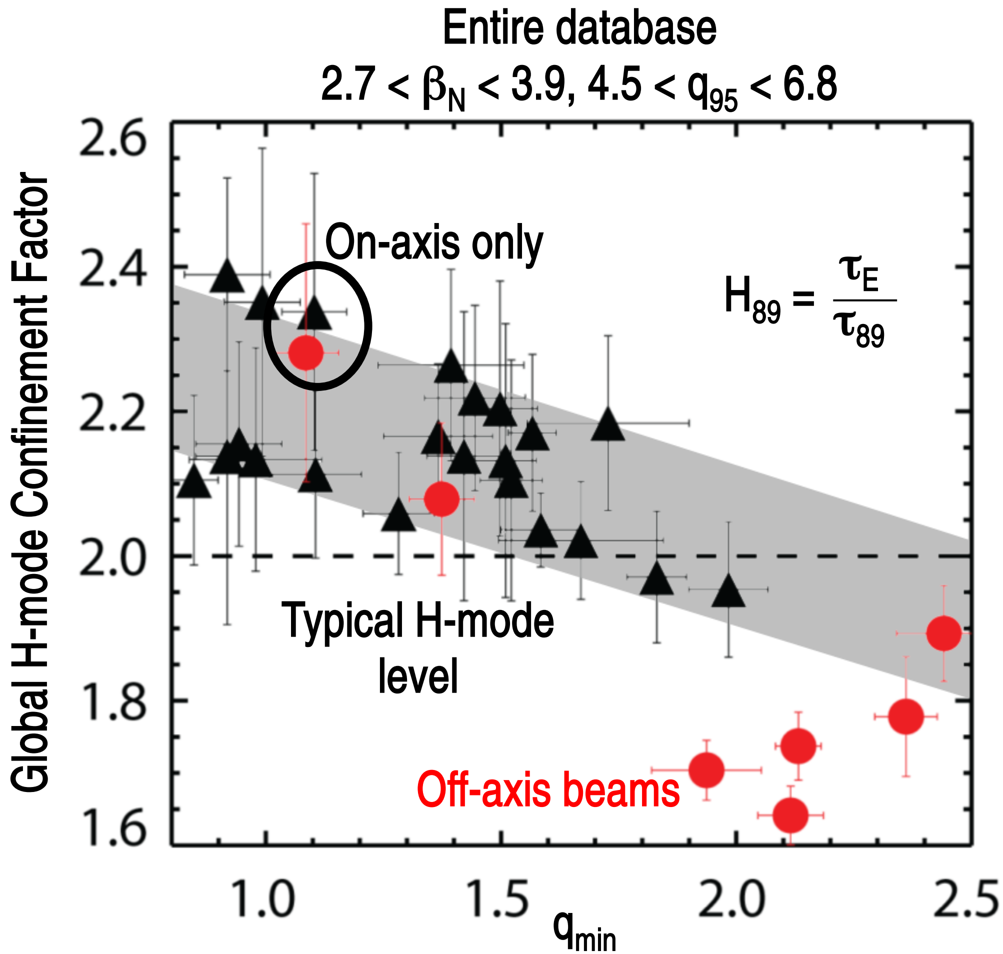
- **Implies increased fast ion transport as q_{min} increases**
  – Because thermal confinement shows no q_{min} scaling

Entire database
$2.7 < \beta_N < 3.9$, $4.5 < q_{95} < 6.8$

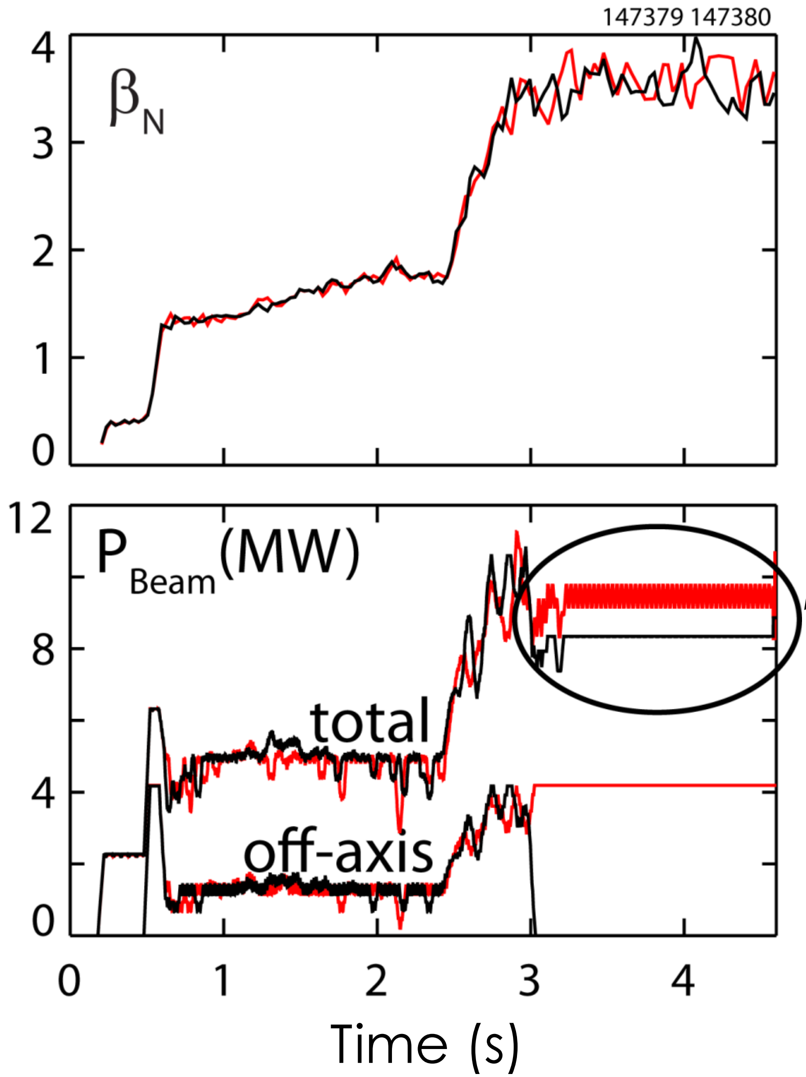


Highest q_{min} Plasmas Have Global (Thermal+Fast Ion) Confinement Below the Typical H-mode Level

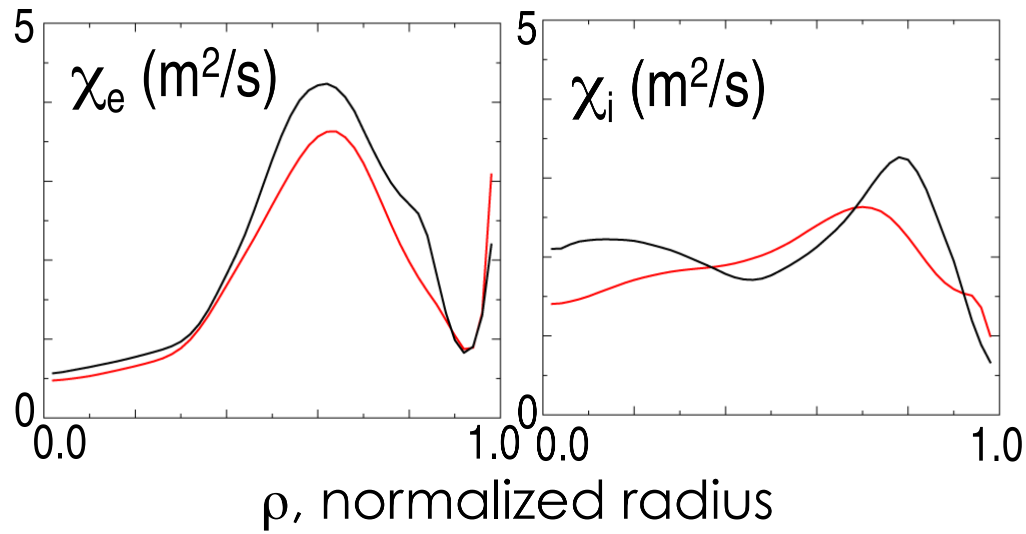
- **Implies increased fast ion transport as q_{min} increases**
  - Because thermal confinement shows no q_{min} scaling



A Change in Beam Injection Location to Off-axis Accounts for Only a Small Reduction in Confinement



- **Discharges with equal β_N, $q_{min} \approx 1.1$**
- **Discharge with off-axis injection requires 13% more neutral beam power**
  - τ_E reduced by 10% (including P_{ECCD})
  - H_{89} (≈2.3) $\propto \tau_E \sqrt{P}$ reduced by 5%
- **Injection in region with higher χ_e,χ_i closer to the boundary**

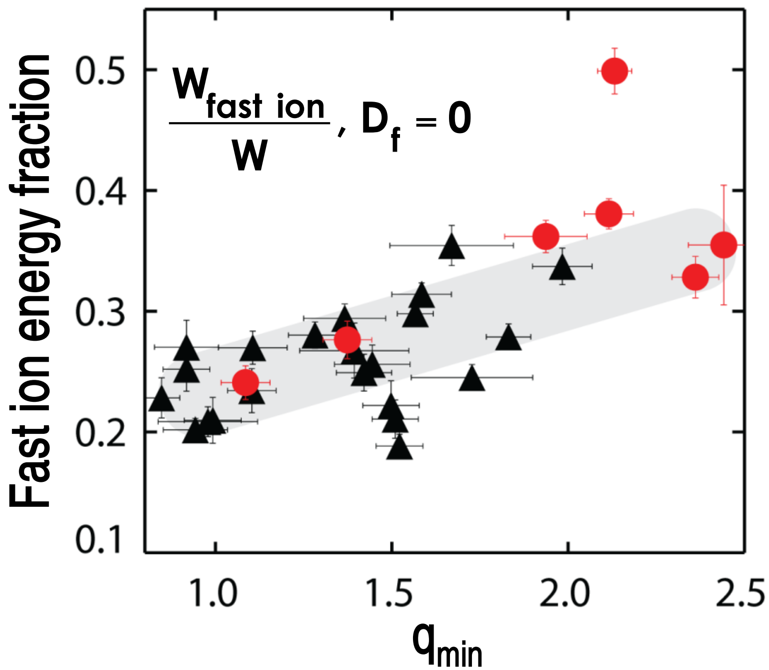


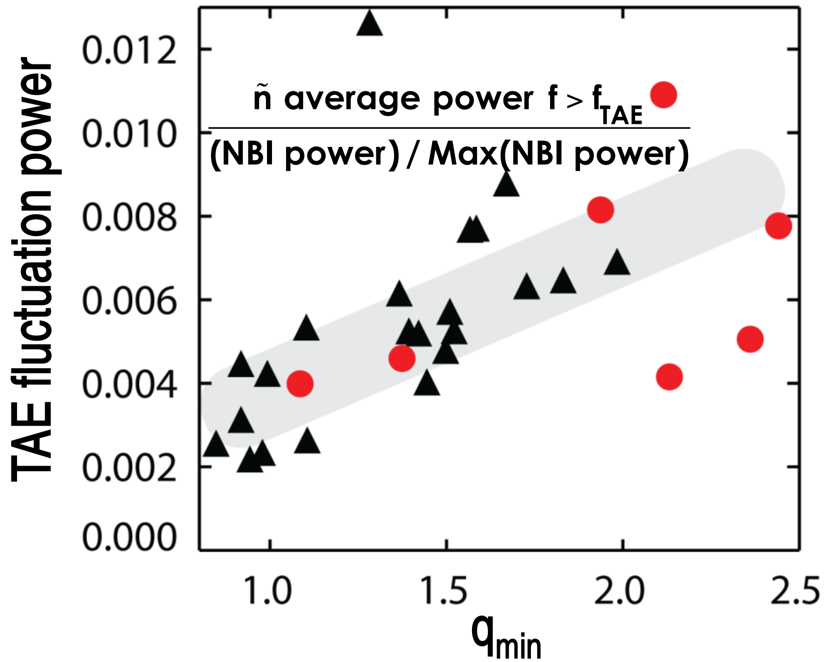
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Increased Fast Ion Loss at High q_{min} May be a Result of Increased Fluctuation Power in the Alfvén Eigenmode Frequency Range

- Calculated fast ion stored energy fraction increases with q_{min} ⇒ instability drive

- Fluctuation power in Alfvén Eigenmode frequency range generally increases with q_{min}





Off-Axis Neutral Beam Injection Is Enabling Improved Access to Fully Noninductive Plasma Regimes

Experimental results

✓ **Broader current profile:**
improved access to q_{min} above 2

✓ **Broader pressure profiles with β_N up to 3.3**
increase of calculated ideal MHD stability limits: $\beta_N > 4$

✓ **Thermal confinement as expected for H-mode; total pressure limited by enhanced fast ion transport at high q_{min}**

Models of next step parameter regimes for DIII-D

- **Fully noninductive solutions at β_N = 4-5, $q_{min} > 2$: parameter regime relevant to ITER through DEMO**

Off-Axis Neutral Beam Injection Is Enabling Improved Access to Fully Noninductive Plasma Regimes

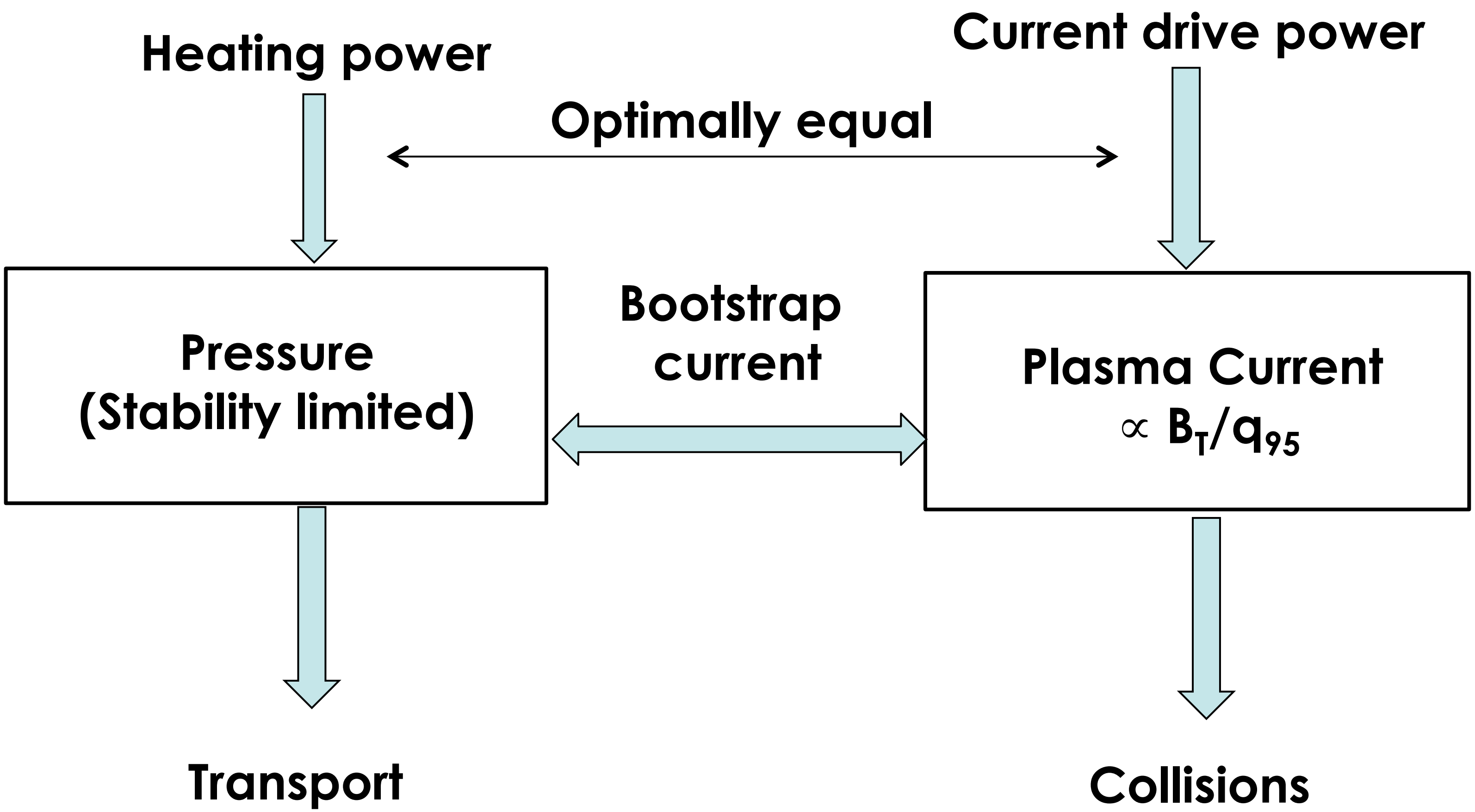
Experimental results

- Broader current profile:
  improved access to q_{min} above 2
- Broader pressure profiles with β_N up to 3.3
  increase of calculated ideal MHD stability limits: $\beta_N > 4$
- Thermal confinement as expected for H-mode;
  total pressure limited by enhanced fast ion transport at high q_{min}

Models of next step parameter regimes for DIII-D

- **Fully noninductive solutions at β_N = 4-5, $q_{min} > 2$:**
  parameter regime relevant to ITER through DEMO

At a Steady-State Operating Point, The Heating and Current Drive Input Powers Balance Transport and Collisional Losses



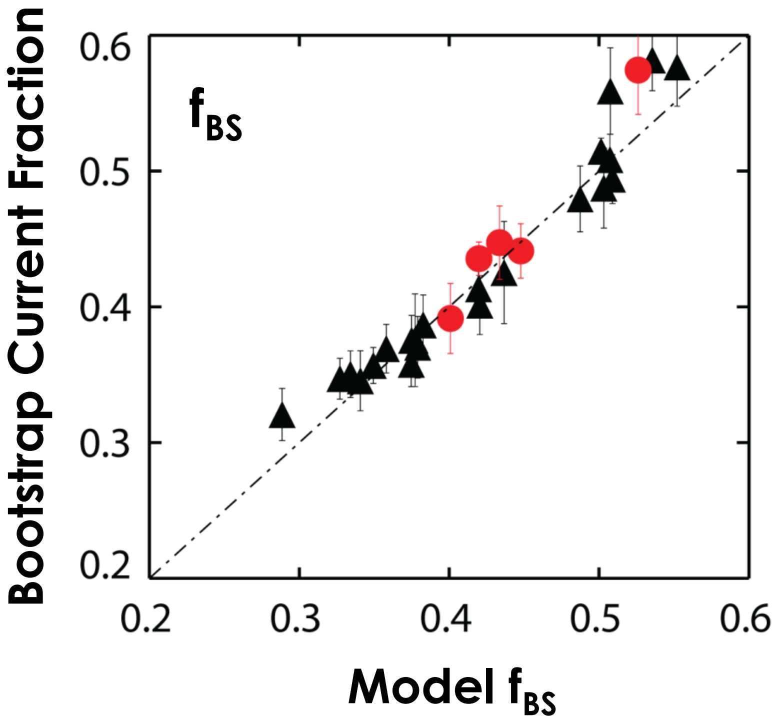
- Goal: find externally selectable parameters so that f_{NI} is exactly 1
- β_N, q_{95}, B_T, n, external current drive profile

Extrapolation from DIII-D Steady-state Scenario Discharges Allows Scaling to f_{NI} = 1 without use of a Transport Model

- H_{98} confinement scaling ⇒ pressure
- Current sources from fits of the database to theory-based models
- Typical experimental profile shapes reflected in fitting coefficients
- Inputs f_p, H_{98}, Z_{eff} chosen to match the database

$$f_{BS} = \beta_{Nthermal}(Aq_{core}f_{pi}^{B} + Cq_{95}f_{po}^{D})$$

q_{core} = average $q(0.0 < \rho < 0.3)$



Extrapolation from DIII-D Steady-state Scenario Discharges Allows Scaling to f_{NI} = 1 without use of a Transport Model

- **H_{98} confinement scaling ⇒ pressure**
- **Current sources from fits of the database to theory-based models**
- **Typical experimental profile shapes reflected in fitting coefficients**
- **Inputs f_p, H_{98}, Z_{eff} chosen to match the database**

$$f_{BS} = \beta_{Nthermal}(Aq_{core}f_{pi}^{B} + Cq_{95}f_{po}^{D})$$

q_{core}= average $q(0.0 < \rho < 0.3)$

$$f_{NBCD} \propto P_B \frac{T_e}{n_e}\frac{q_{95}}{B_T} f(T_e, n_e, Z_{eff}, E_B, geometry, ...)$$

$$f_{ECCD} \propto P_{EC} \frac{T_e}{n_e}\frac{q_{95}}{B_T} f(geometry)$$

Extrapolation from DIII-D Steady-state Scenario Discharges Allows Scaling to f_{NI} = 1 without use of a Transport Model

- H_{98} confinement scaling ⇒ pressure
- Current sources from fits of the database to theory-based models
- Typical experimental profile shapes reflected in fitting coefficients
- Inputs f_p, H_{98}, Z_{eff} chosen to match the database

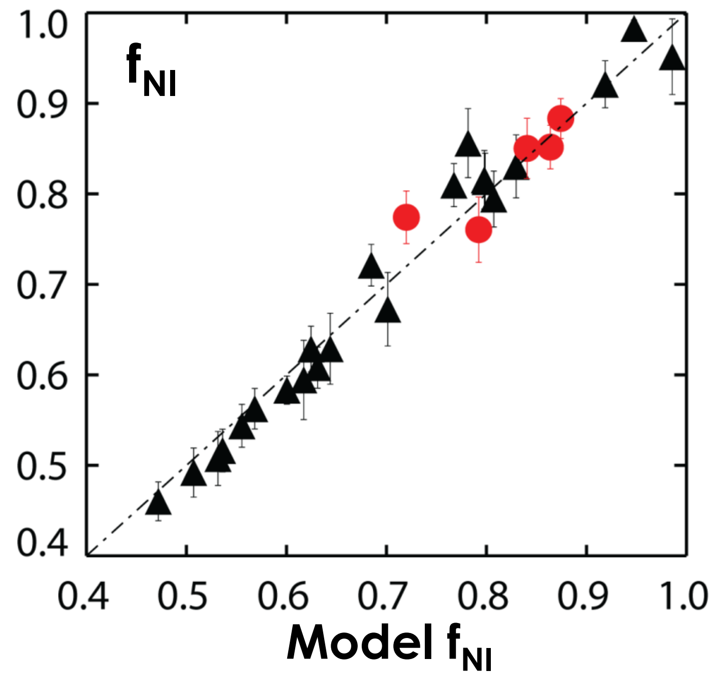
$$f_{BS} = \beta_{Nthermal}(Aq_{core} f_{pi}^{B} + Cq_{95} f_{po}^{D})$$

q_{core} = average $q(0.0 < \rho < 0.3)$

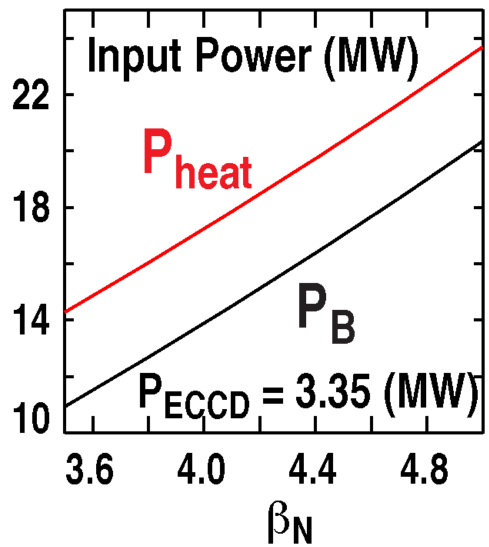
$$f_{NBCD} \propto P_B \frac{T_e}{n_e} \frac{q_{95}}{B_T} f(T_e, n_e, Z_{eff}, E_B, geometry, \ldots)$$

$$f_{ECCD} \propto P_{EC} \frac{T_e}{n_e} \frac{q_{95}}{B_T} f(geometry)$$

$$\boxed{f_{NI} = f_{BS} + f_{NBCD} + f_{ECCD}}$$



At the f_{NI} = 1 Operating Point, the Current Drive Input Power Exactly Matches the Losses Resulting from Transport

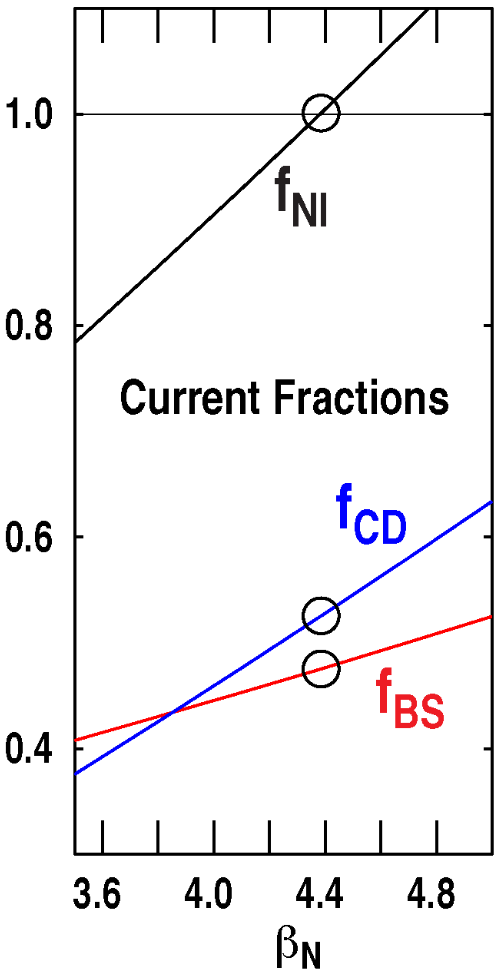


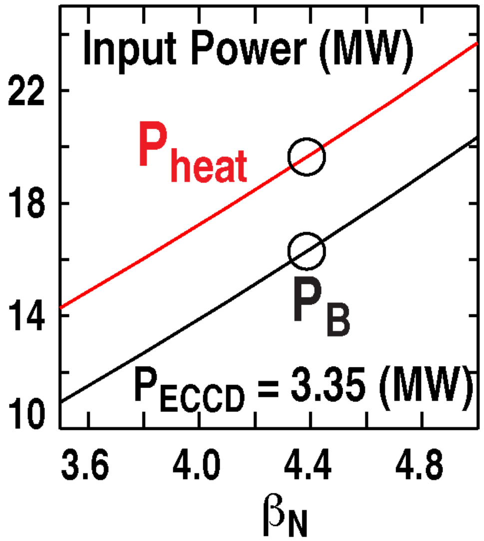
- β_N scanned to find f_{NI} = 1

n_e=4.7x10^{19} m^{-3} B_T=1.75T H_{98}=1.2 q_{95}=5.75

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

At the f_{NI} = 1 Operating Point, the Current Drive Input Power Exactly Matches the Losses Resulting from Transport



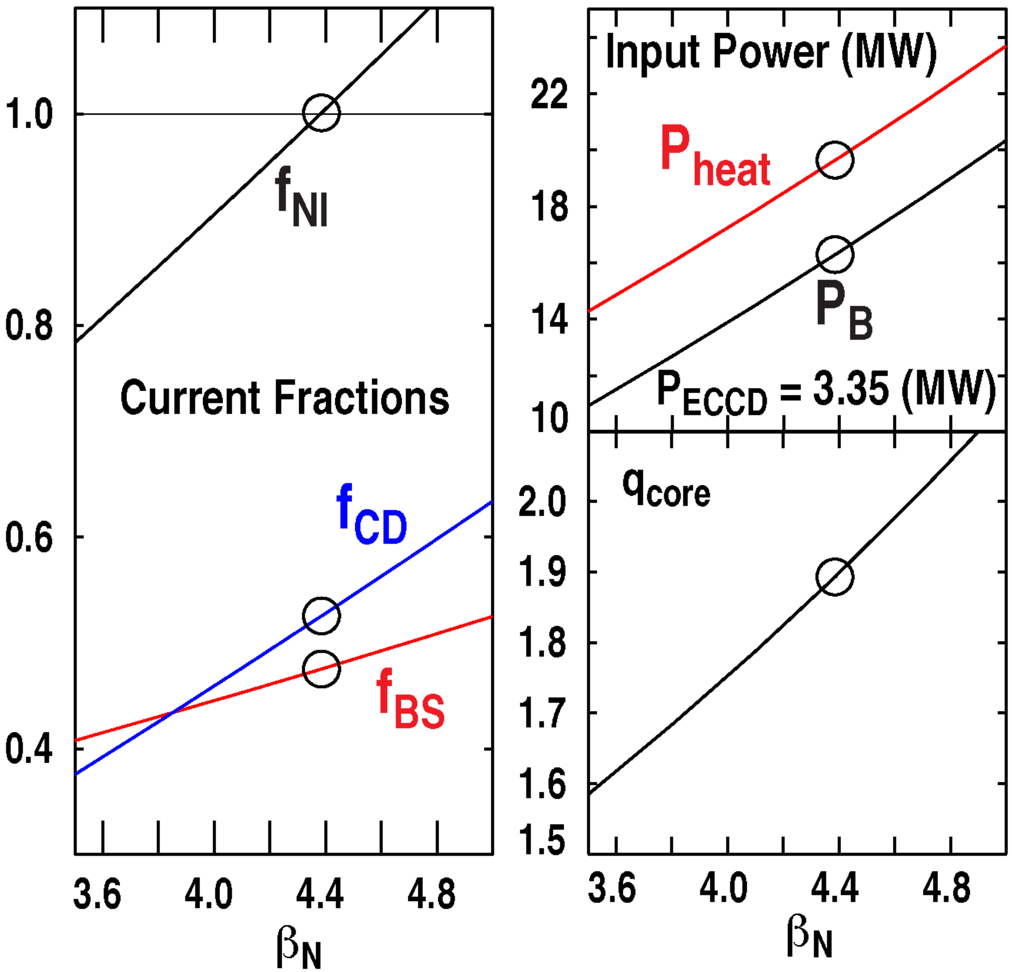


- β_N scanned to find f_{NI} = 1
- Constraint: $P_{heating} = P_{CD}$

$n_e = 4.7 \times 10^{19}\ m^{-3}$ $B_T = 1.75T$ $H_{98} = 1.2$ $q_{95} = 5.75$

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

At the f_{NI} = 1 Operating Point, the Current Drive Input Power Exactly Matches the Losses Resulting from Transport



- β_N scanned to find f_{NI} = 1
- Constraint: $P_{heating}$= P_{CD}

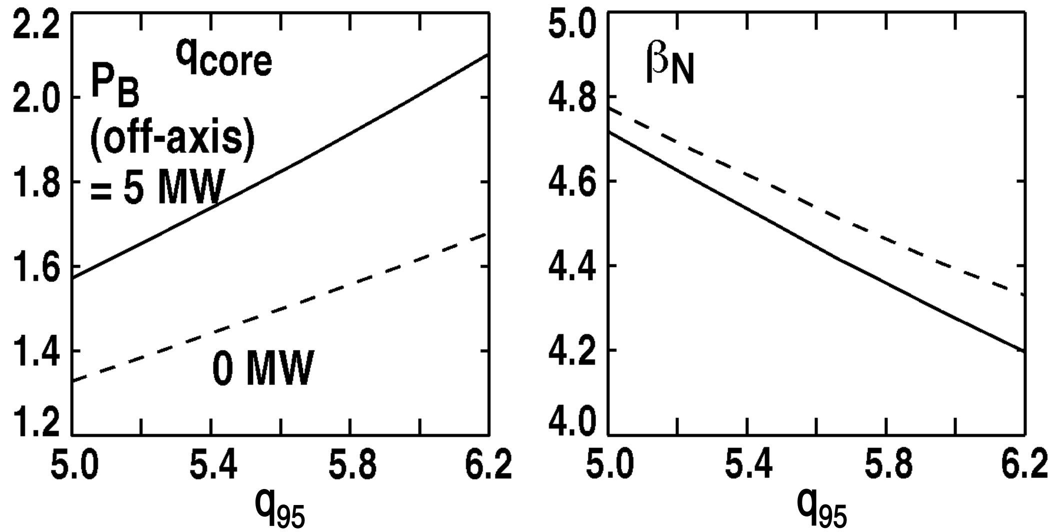
- $f_{BS} \approx f_{CD} \approx 0.5$
- f_{BS} scales more slowly than β_N
- Increase in fast ion stored energy with P_B

n_e=4.7x10^{19} m^{-3} B_T=1.75T H_{98}=1.2 q_{95}=5.75

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Projected f_{NI} = 1 Operating Points in DIII-D have $\beta_N > 4$

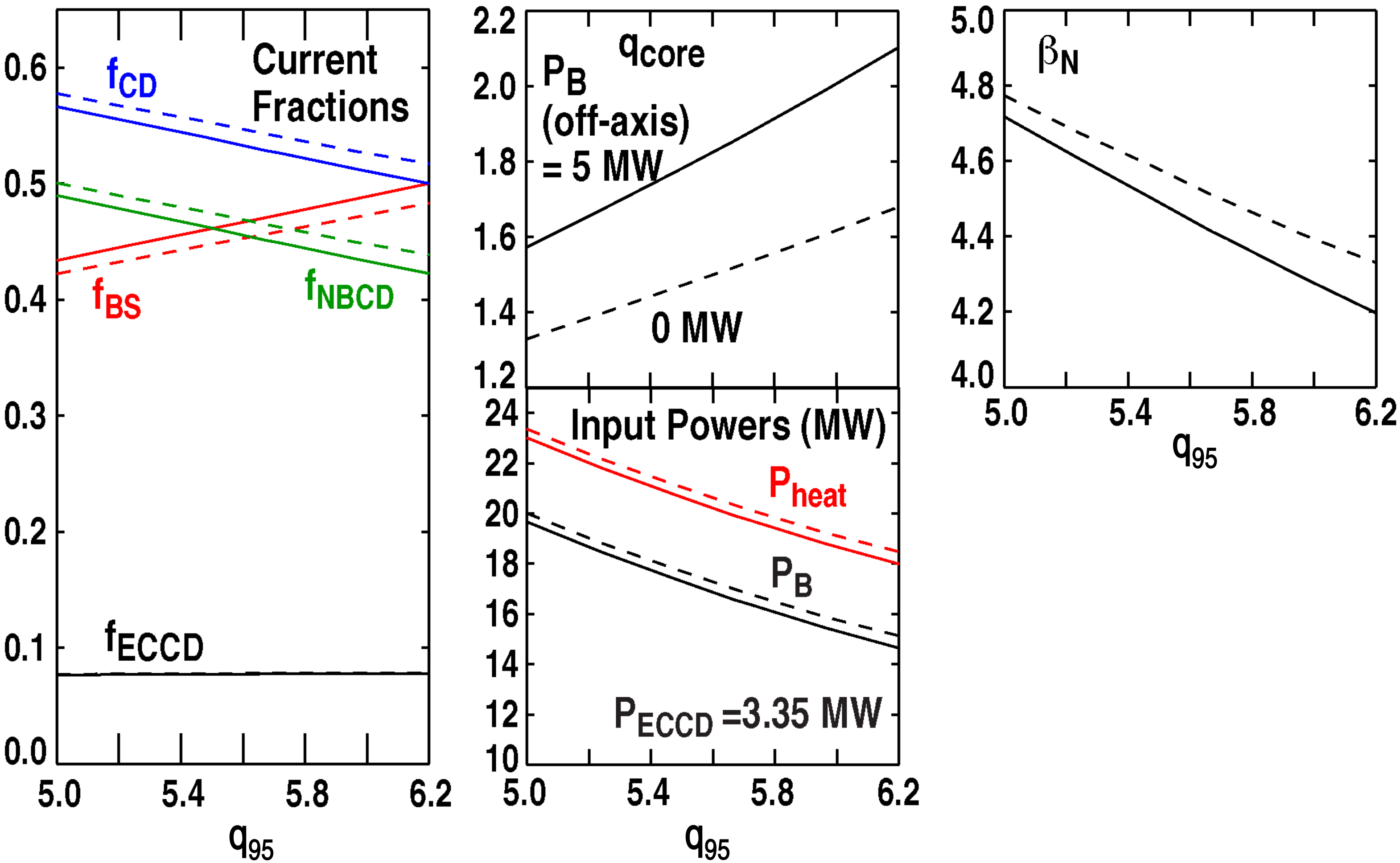
- **q_{core} increases with off-axis injection**



$n_e = 4.7 \times 10^{19}$ m^{-3}
B_T = 1.75 T
H_{98} = 1.2

Projected f_{NI} = 1 Operating Points in DIII-D have $\beta_N > 4$

- q_{core} increases with off-axis injection



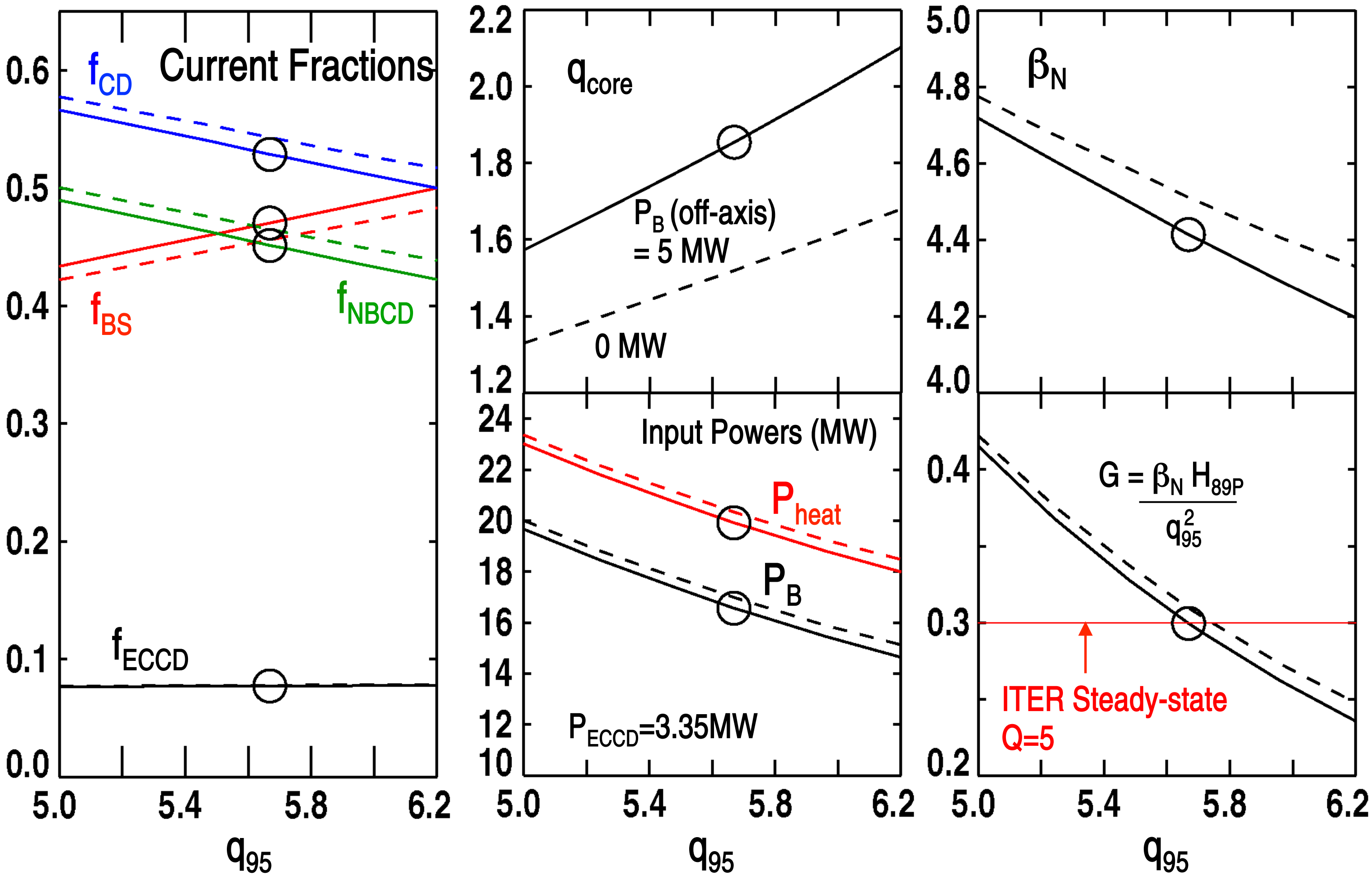
$n_e = 4.7 \times 10^{19}$ m^{-3}

B_T = 1.75 T

H_{98} = 1.2

Projected f_{NI} = 1 Operating Points in DIII-D have $\beta_N > 4$

- **Compromise between reduced current drive power and increased fusion gain to choose q_{95}**

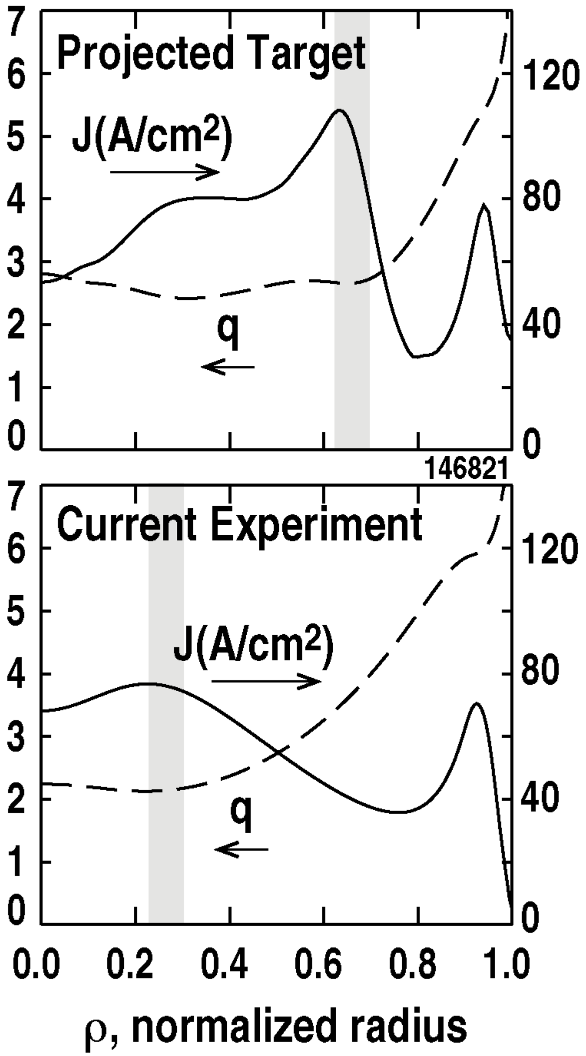


$n_e = 4.7 \times 10^{19}\ m^{-3}$

B_T = 1.75 T

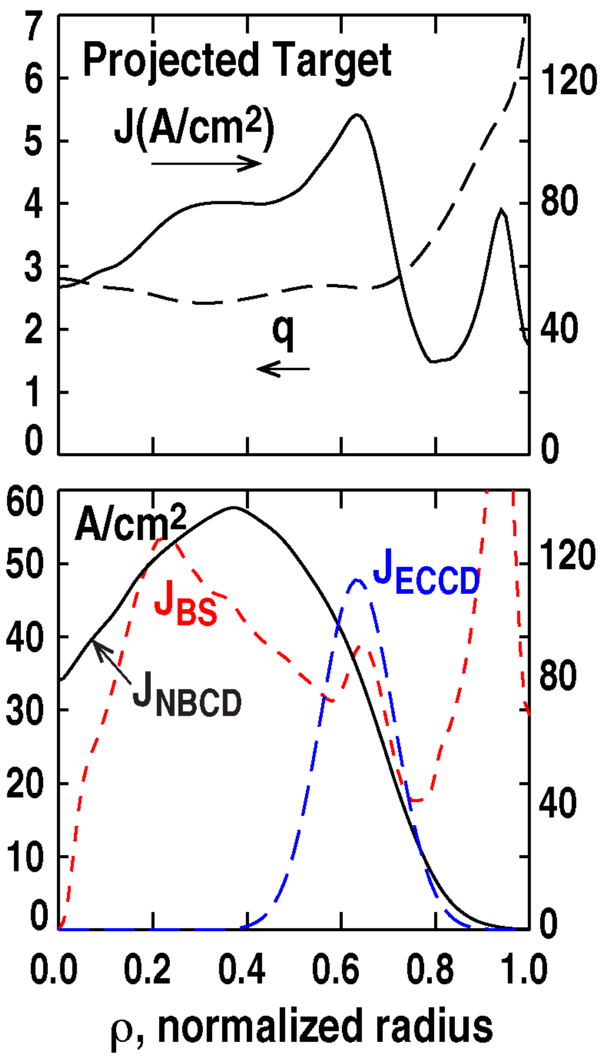
H_{98} = 1.2

An MHD Stable Solution at β_N = 5 is Projected with Optimum use of the Full Set of DIII-D Heating and Current Drive Tools



- **TGLF transport model ⇒ T_e, T_i profiles**
  - Accounts for P(0)/⟨P⟩ changes with heating power
- **Utilizes increased current drive flexibility from proposed upgrades**
  - 9 MW ECCD absorbed power
  - Second off-axis beamline
  - Beam energy 75-100 keV
- **Off-axis ECCD, off-axis beam injection provides current drive for large $\rho(q_{min})$**
  - Current profile broader than in present experiments
  - Retains broad pressure profile

An MHD Stable Solution at β_N = 5 is Projected with Optimum use of the Full Set of DIII-D Heating and Current Drive Tools



- **TGLF transport model ⇒ T_e, T_i profiles**
  - Accounts for P(0)/⟨P⟩ changes with heating power
- **Utilizes increased current drive flexibility from proposed upgrades**
  - 9 MW ECCD absorbed power
  - Second off-axis beamline
  - Beam energy 75-100 keV
- **Off-axis ECCD, off-axis beam injection provides current drive for large $\rho(q_{min})$**
  - Current profile broader than in present experiments
  - Retains broad pressure profile

f_{NI} = 1 Solutions in DIII-D at $\beta_N \geq 4$ are Accessible Using Off-axis Neutral Beam and Electron Cyclotron Current Drive

- **Broader current and pressure profiles are obtained with off-axis neutral beam injection**
  - Increases in predicted ideal-wall β_N limits
- **Achieving high β_N with $q_{min} > 2$ will require optimizing for good τ_E**
  - Requires understanding of fast ion transport at high q_{min} or compensation with higher thermal confinement
- **Anticipated $\beta_N \approx 5$ operating point is well-placed to inform ITER, FNSF, and DEMO steady-state solutions**