Optimization of the Safety Factor Profile for High Noninductive Current Fraction Discharges in DIII-D

by
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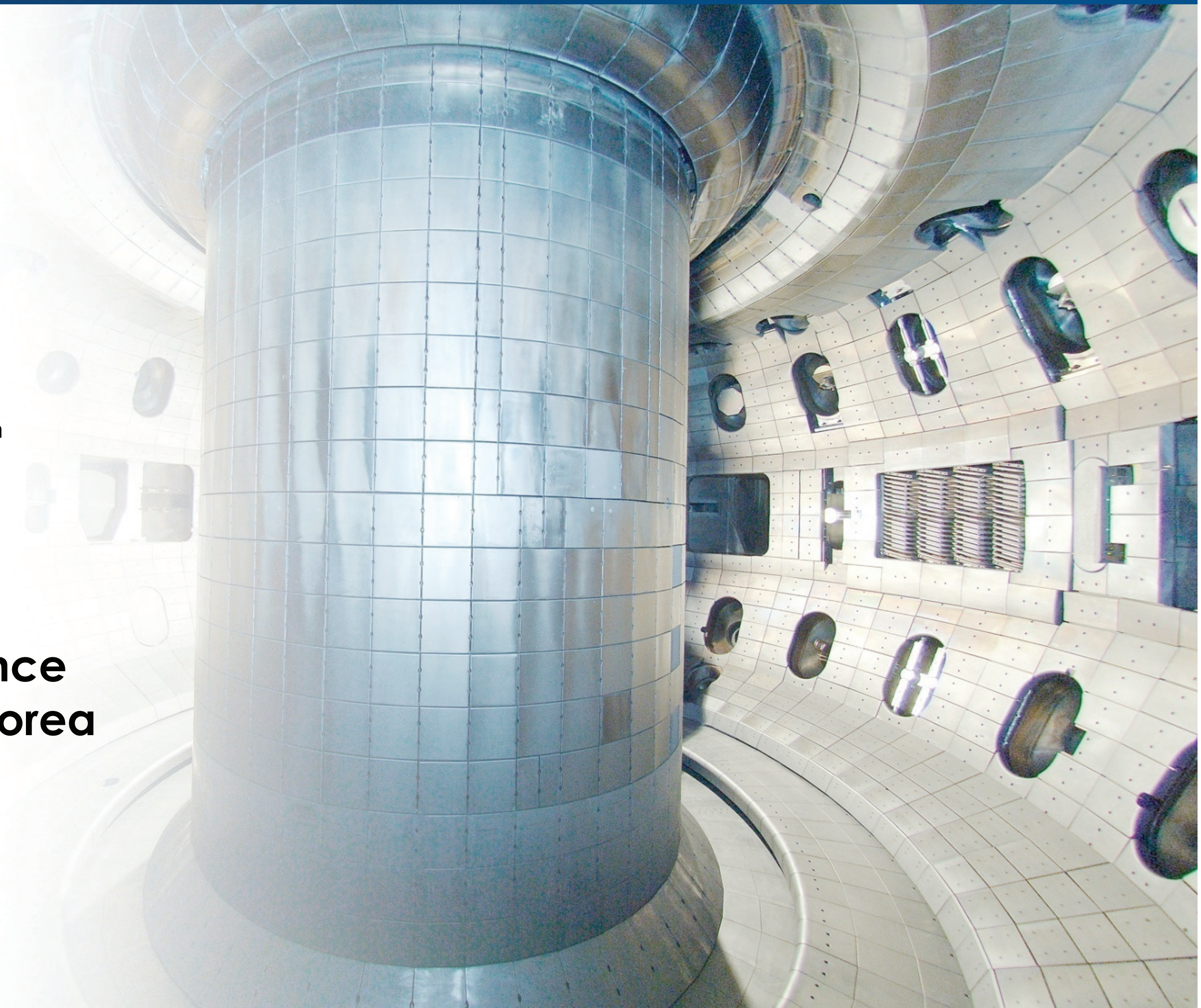

Presented at the Twenty-third IAEA Fusion Energy Conference Daejeon, Republic of Korea

October 11-16, 2010

DIII-D
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Introduction

In a Steady-State Tokamak the q Profile is Closely Coupled to Both Transport Coefficients and Noninductive Current Sources

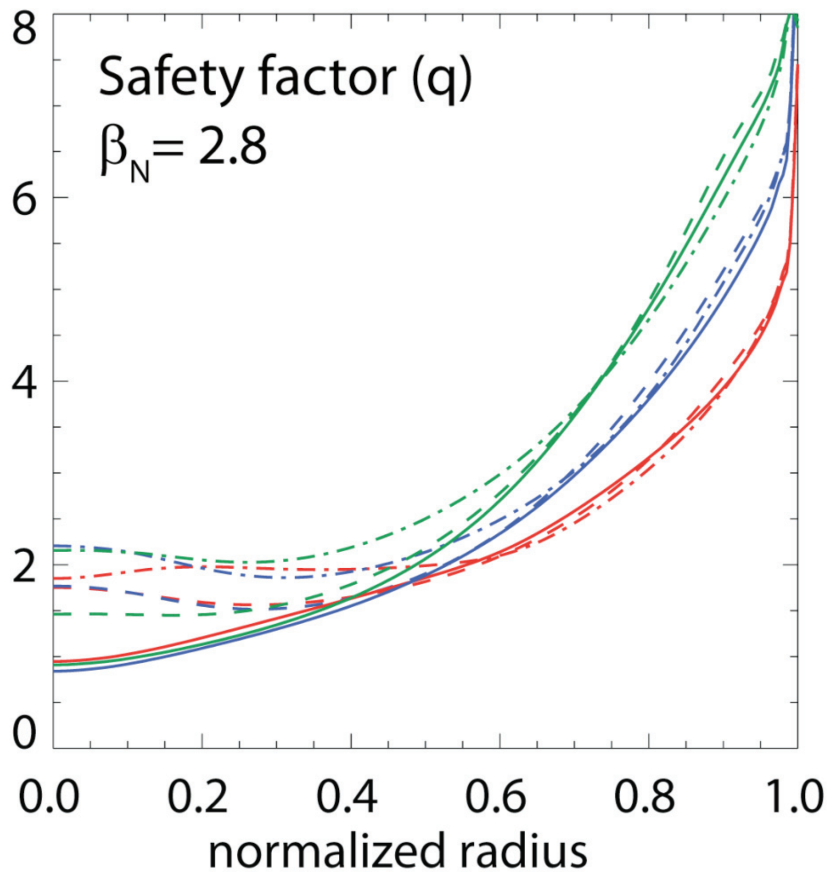
- **Bootstrap: depends on n, T profiles, local q**

$$\langle\langle J_{BS}B\rangle\rangle = -\frac{Fq}{B_{T0}\rho}\left[T_e\frac{\partial n_e}{\partial\rho}L_{31} + n_e\frac{\partial T_e}{\partial\rho}(L_{31}+L_{32}) + T_i\frac{\partial n_i}{\partial\rho}L_{31} + n_i\frac{\partial T_i}{\partial\rho}(L_{31}+\alpha L_{34})\right]$$

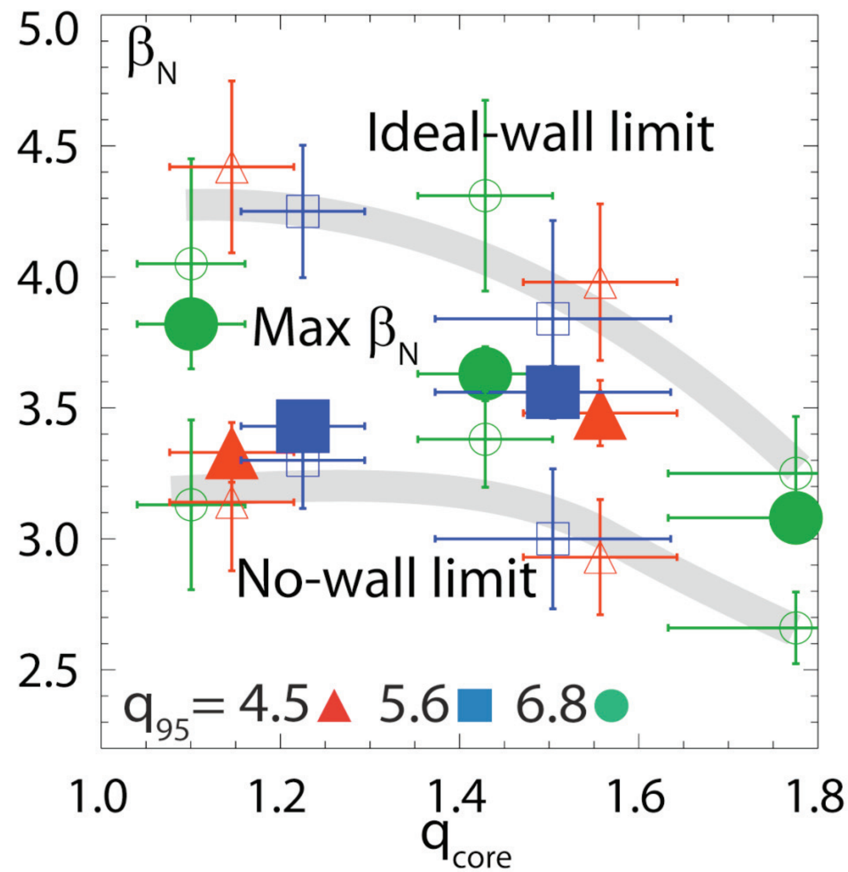
- **Transport: depends on the q profile and determines the n, T profiles**
- **Steady-state: at high f_{BS}, the q profile is largely determined by the J_{BS} profile**
- **Stability limit:**
  - Limits on pressure depend on the q profile
  - Reducing n, T gradients increases the β_N limit
- **Presently this complex interdependence is difficult to understand using only models**

n, T Profiles were Measured vs q Profile at β_N = 2.8 and at the Maximum P_{beam}, then J_{BS}, f_{BS}, J_{NI}, f_{NI} were Calculated

- $q_{min} \approx$ 1, 1.5, 2, $q_{95} \approx$ 4.5, 5.6, 6.8
- Measured and calculated profiles averaged during phase of approximately constant β_N

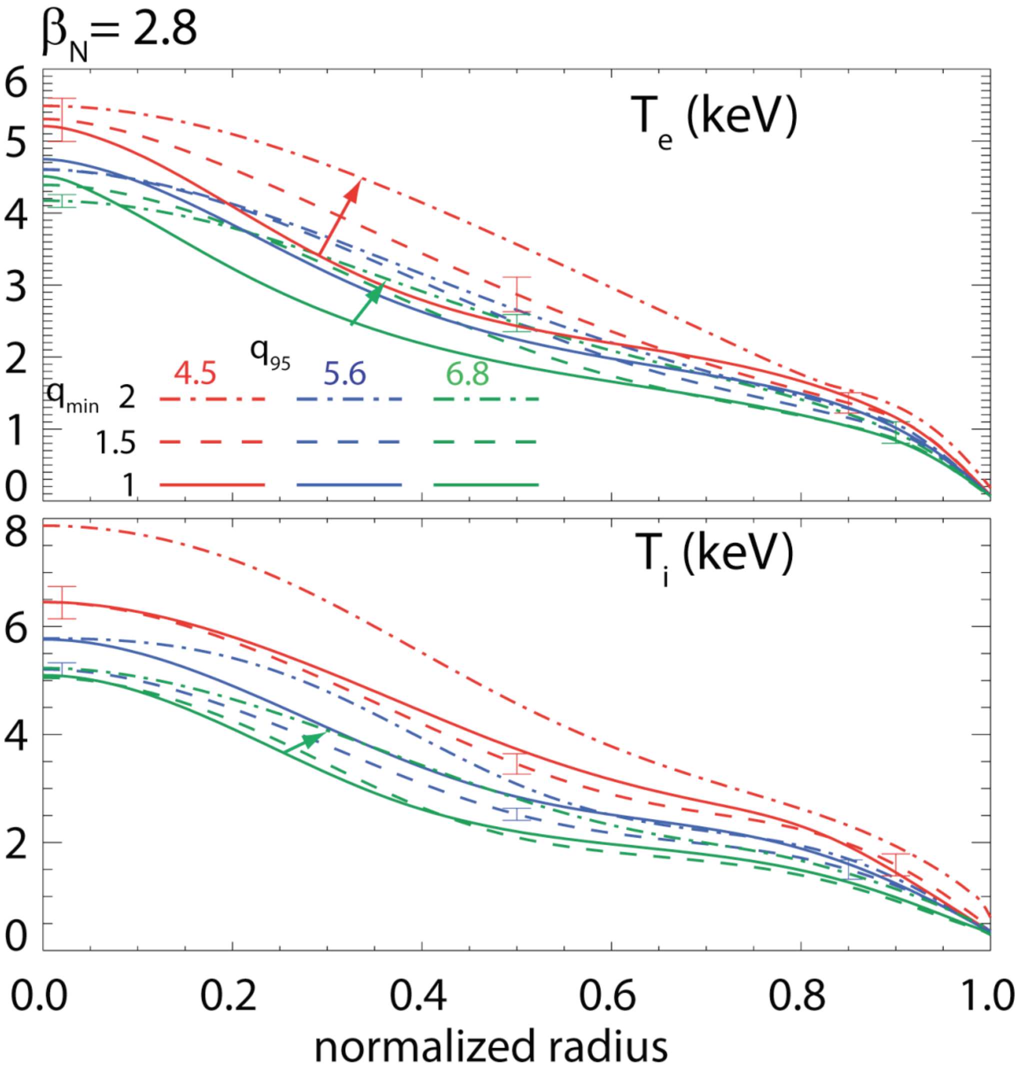


- Maximum β_N close to the calculated ideal-wall n = 1 stability limit

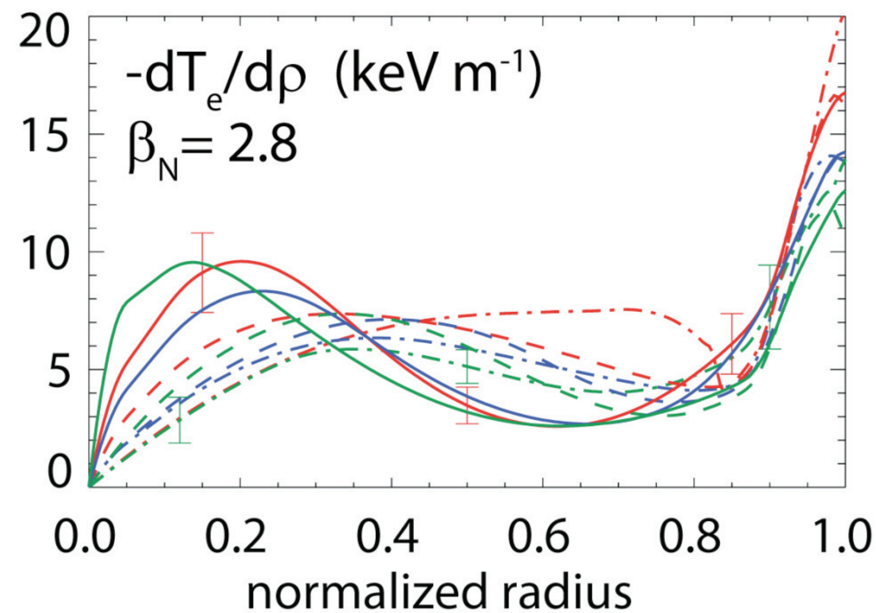


Temperature and Density Profiles

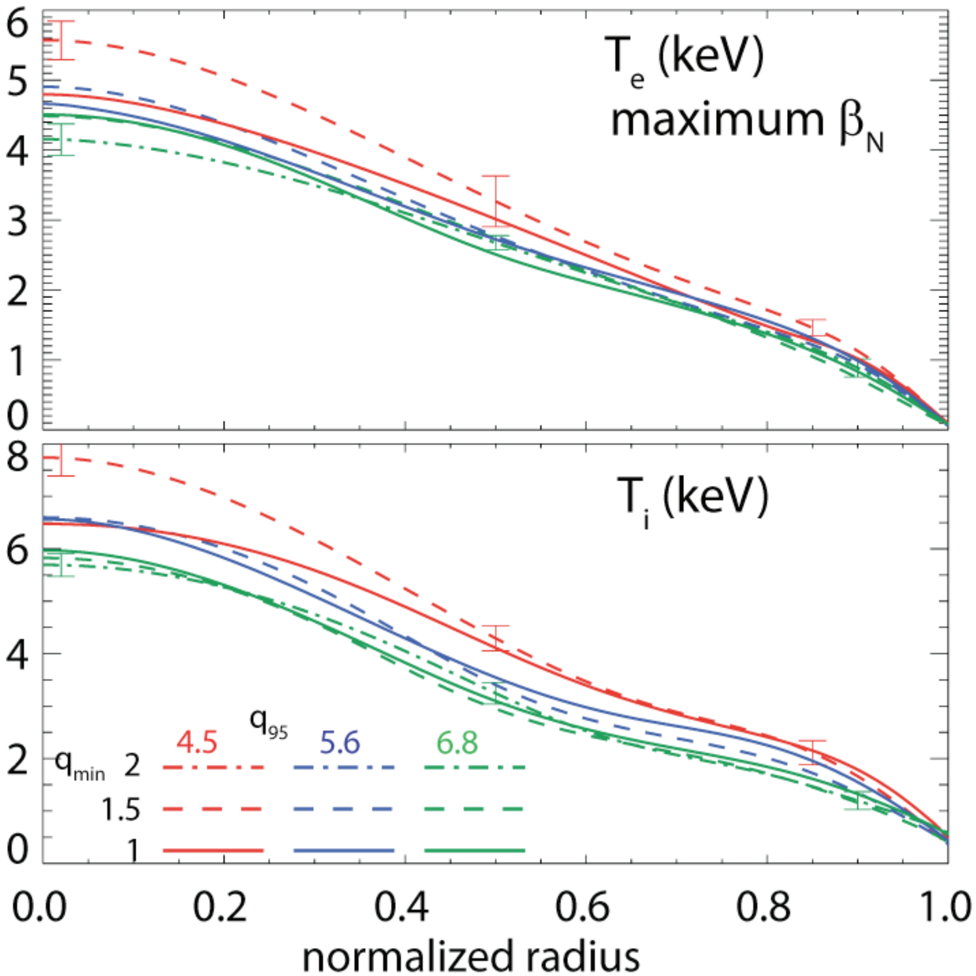
T_e and T_i Profiles Broaden as q_{min} is Increased (β_N = 2.8)



- **T_e, T_i increase as q_{95} is decreased**
- **$dT_e/d\rho$, $dT_i/d\rho$ increase in the H-mode pedestal as q_{95} decreases**

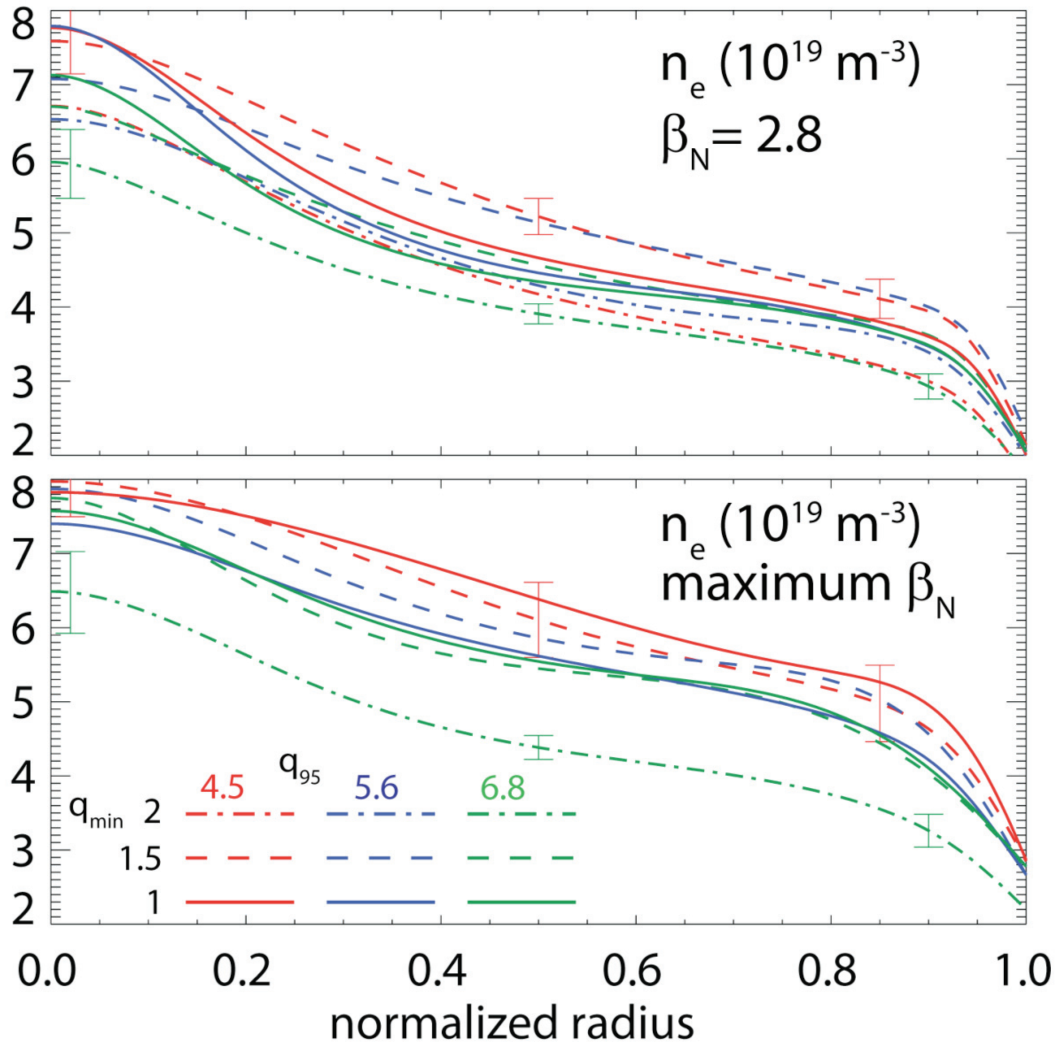


At the Maximum Achieved β_N, the Temperature Profiles are Nearly Independent of q_{min}



- **Profiles at $q_{min} \approx 1$ and ≈ 1.5 are significantly broader at higher β_N**
- **Temperature dependence on q_{95} is still present**

Pumping of the Particle Exhaust in the Divertor Results in Low Pedestal Density and Peaked Density Profiles



- **At β_N = 2.8:**
  - Density gradient locally peaked near ρ = 0.2
  - Density gradient largest at q_{min} = 1
- **At the maximum β_N, profile is broader and pedestal density is higher**

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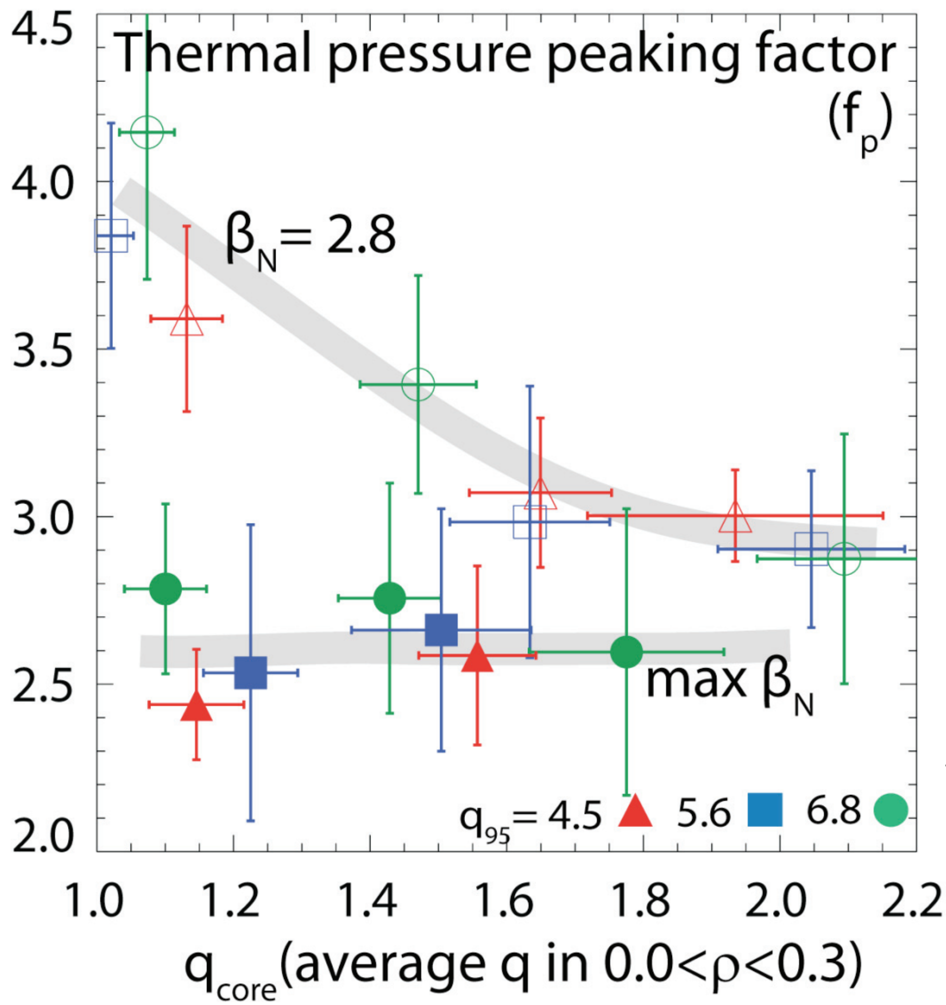
The Scaling of the Thermal Pressure Peaking Factor Summarizes the Changes in the n, T Profiles with q_{min} and β_N



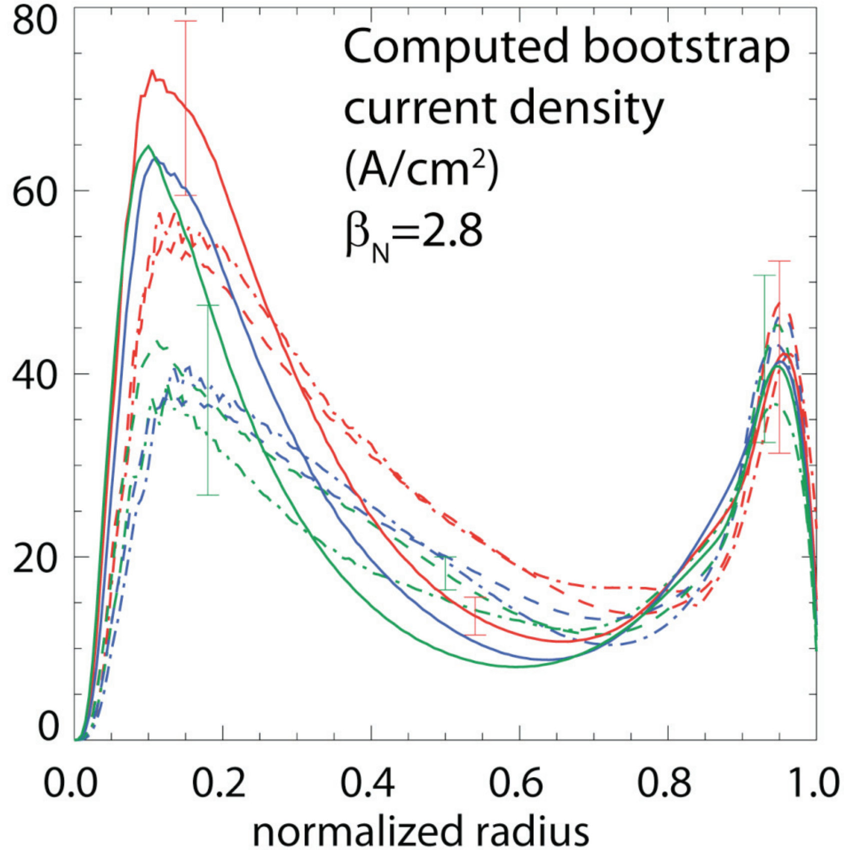
- **At β N = 2.8 pressure is less peaked at higher values of qcore**
- **Pressure peaking is significantly reduced at the maximum β_N**
  - Little dependence on the q profile as all n, T profiles are relatively broad

$$f_p = [n_e(0)T_e(0) + n_i(0)T_i(0)] / \langle n_e T_e + n_i T_i \rangle$$

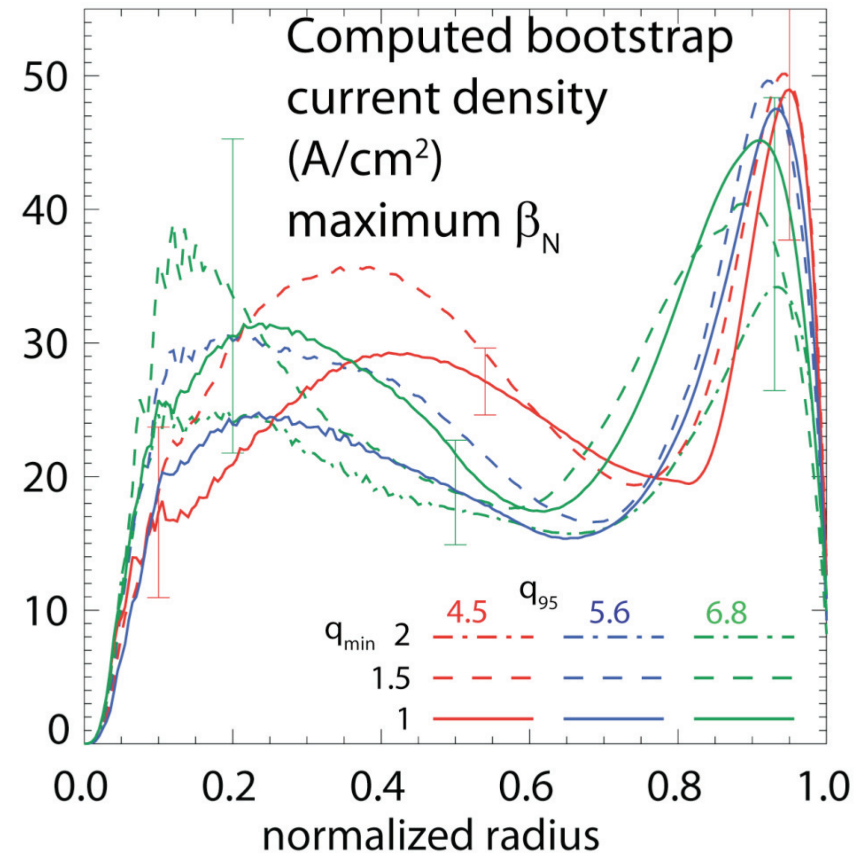
Calculated Bootstrap Current

At $\beta_N = 2.8$, J_{BS} is Peaked Near $\rho = 0.1$
At Maximum β_N, the J_{BS} Profile is Significantly Broadened

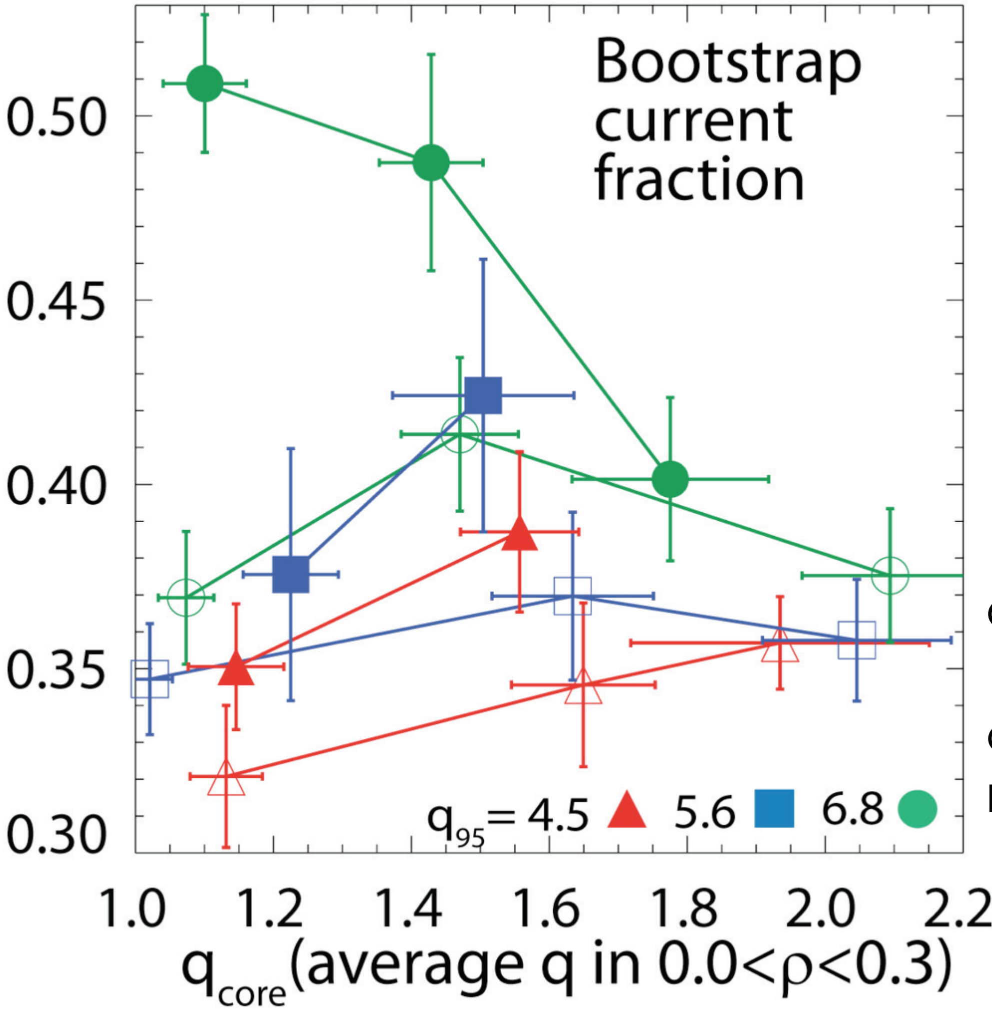
- **q_{min} = 1: peaked $n_e \rightarrow$max J_{BS}**
- **H-mode pedestal: no systematic variation of J_{BS} with q_{min} or q_{95}**
  - $\partial/\partial\rho$ larger at lower q_{95} but $J_{BS} \propto q$



- **Both temperature and density profiles broader at max β_N**
- **H-mode pedestal: J_{BS} profile width increases with q_{95}**



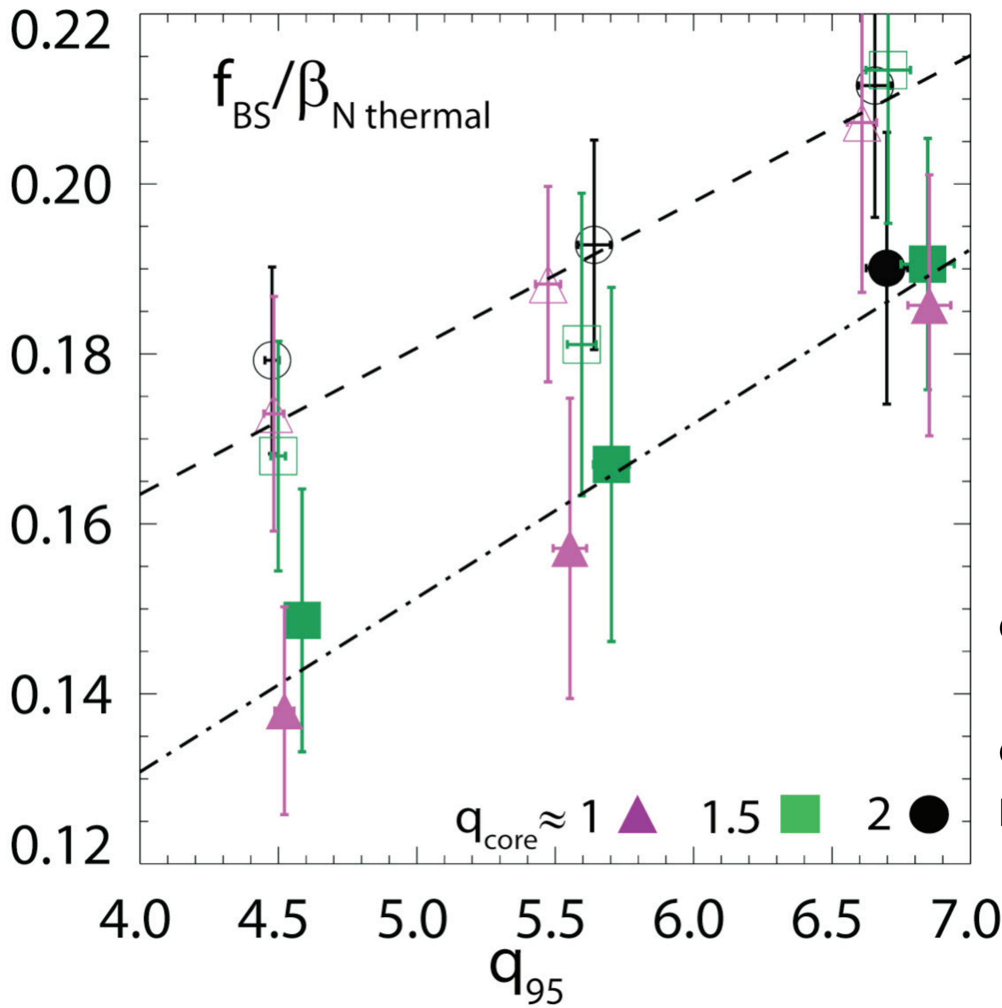
The Dependence of f_{BS} on q_{core} is Comparable to the Dependence on q_{95}



open: β_N = 2.8
closed: max β_N

- **f_{BS} is maximum at the largest values of q_{95} and β_N**
- **Reduced f_{BS} at highest q_{core}: n, T profile broadening and low achieved β_N**

The Commonly Used Scaling $f_{BS} \propto \beta_P \propto \beta_N q_{95}$ is not the Best Description of the Results

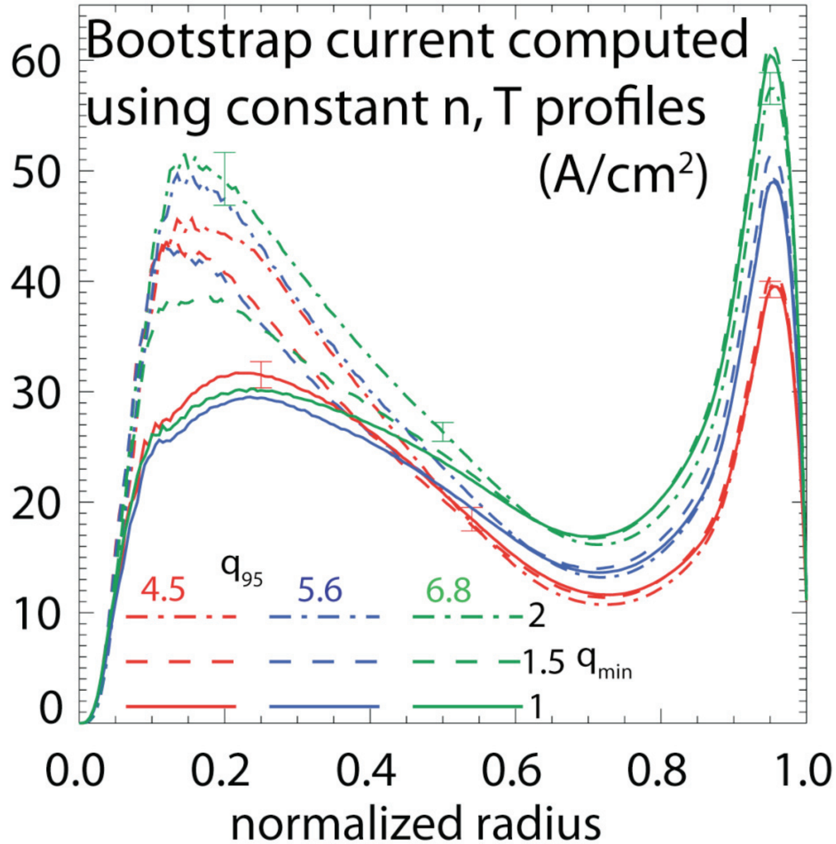


- **Offset at q_{95} = 0: q_{core} important**
- **Max β_N points below β_N = 2.8 data: reflects n, T profile changes**

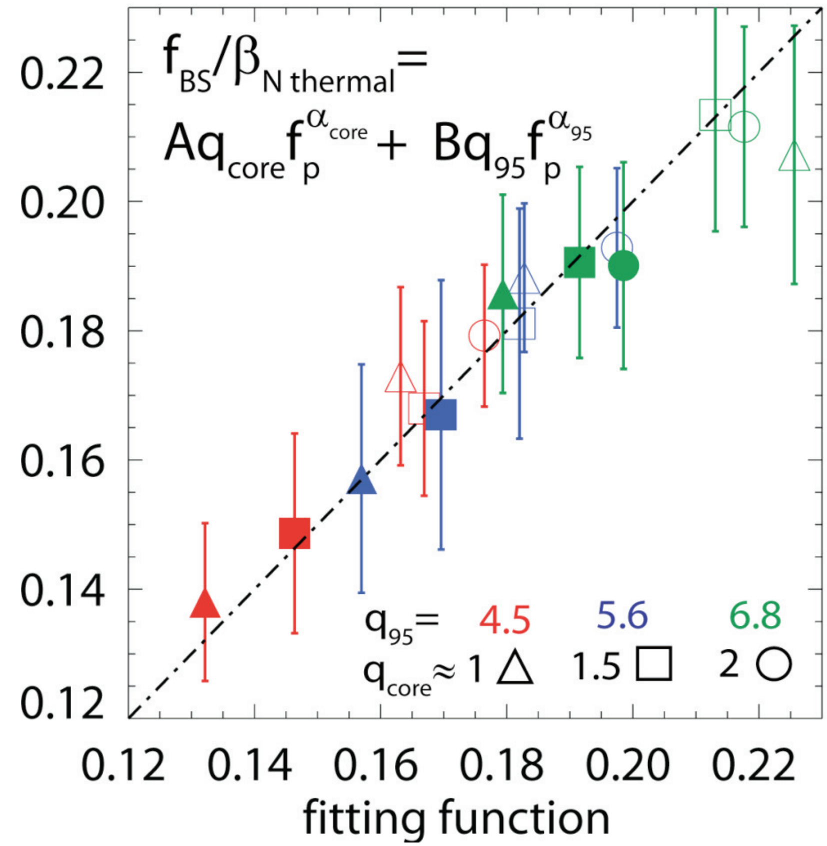
open: $\beta_N = 2.8$
closed: max β_N

Scaling Function $f(q_{core}, q_{95}, f_p)$ Reflects the Observed Dependence of f_{BS}/β_N on q, n, T Profiles

- **Test case illustrates $J_{BS} \propto$ (local q value)**
  - Differs from experiment J_{BS} profiles
- **Plasma divides into two regions:**
  - Inner half: $J_{BS} \propto q_{core}$
  - Outer half: $J_{BS} \propto q_{95}$



- **Two regions → scaling function with separate q_{core} and q_{95} terms**
- **Opposite scaling of ∇n,∇T with f_p in the inner and outer regions**
  - Opposite signs for α_{core} and α_{95}

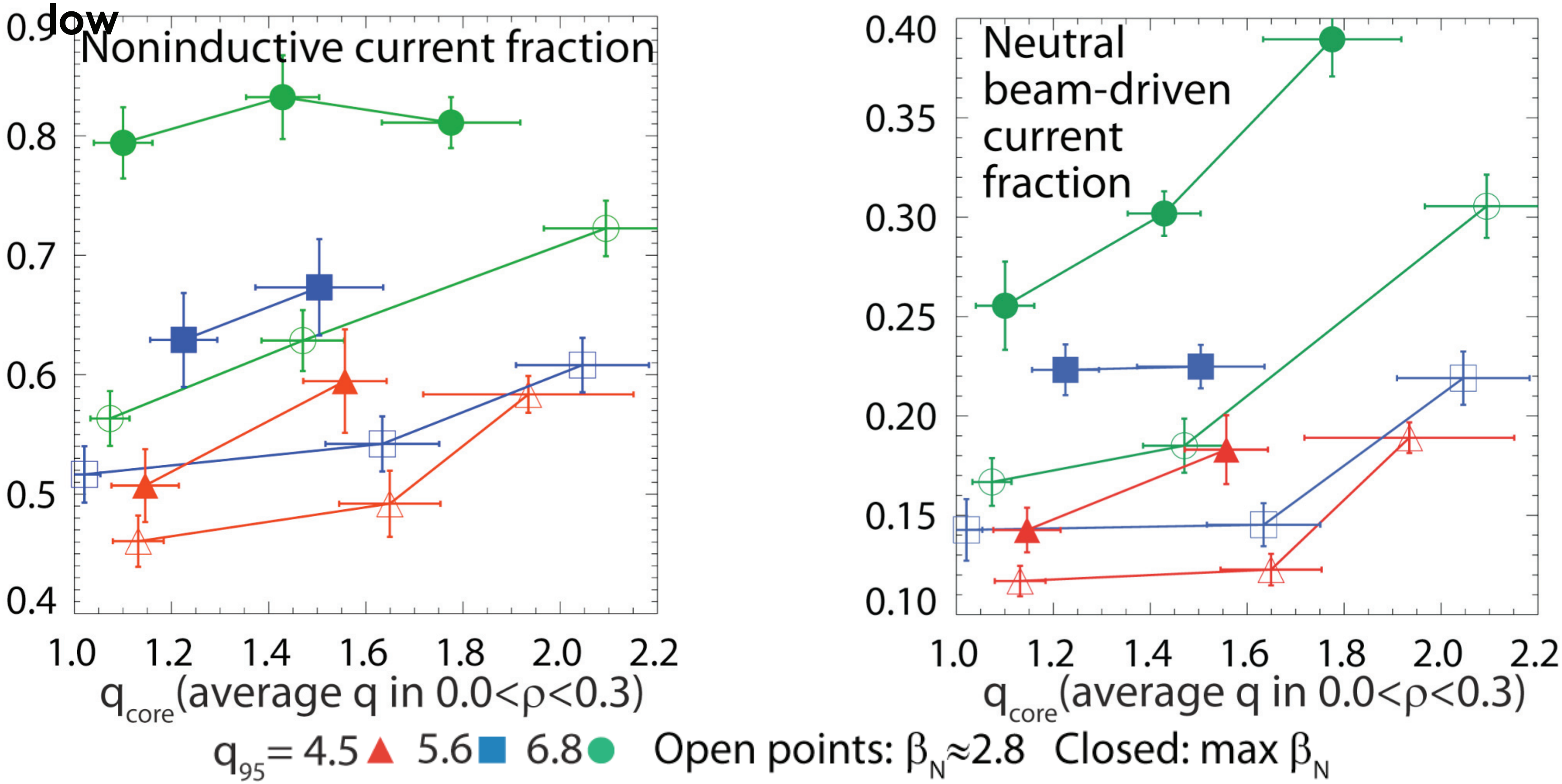


Total Noninductively Driven Current

The Calculated f_{NI} Increases with Both q_{core} and q_{95}

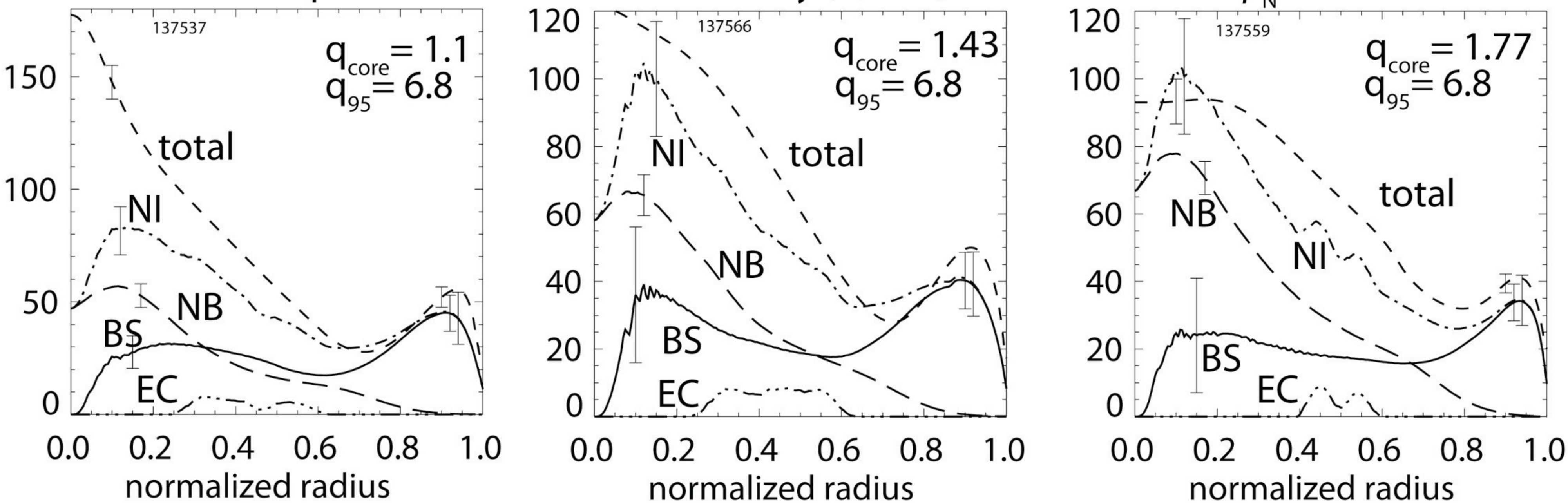
- **Result of combined changes in f_{BS} and f_{NBCD}**
- **One exception: q_{core} = 1.8, q_{95} = 6.8 where max β_N is low**

- **f_{NBCD} increases with q_{core}**
  - Higher T_e, lower n_e



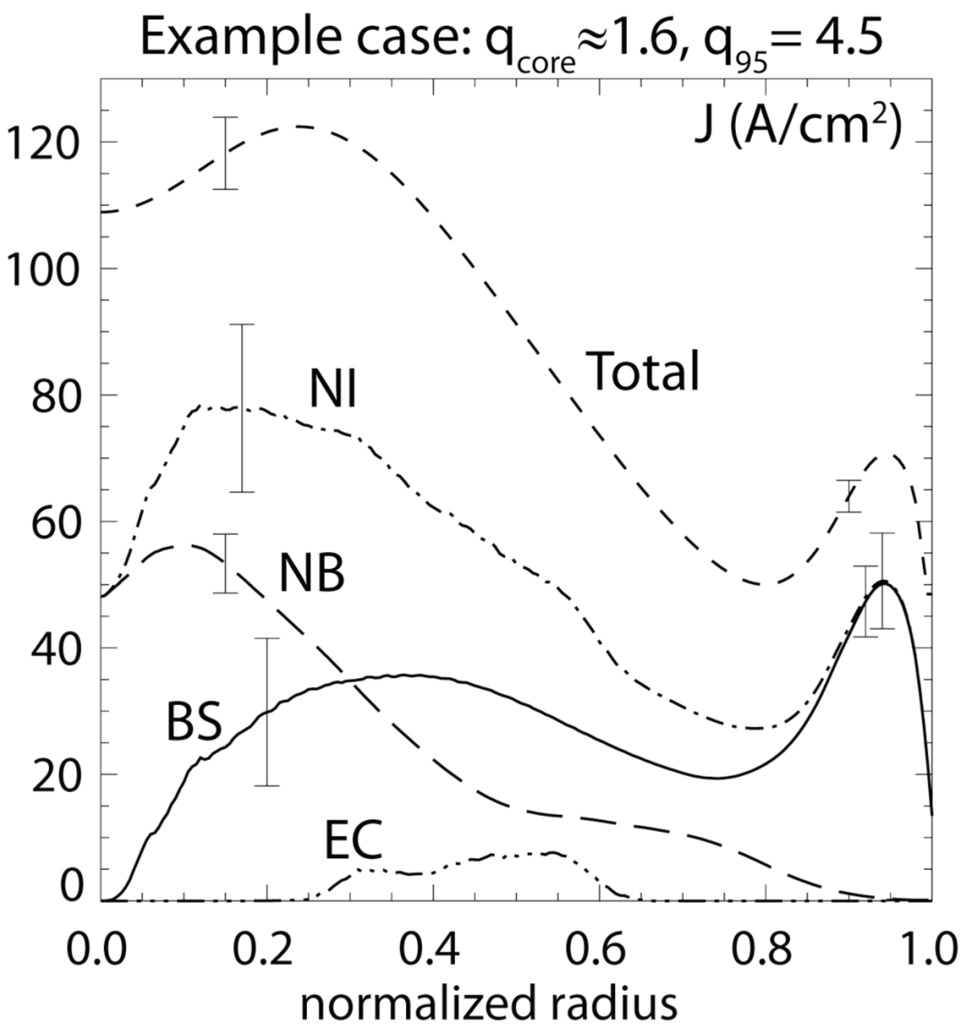
q_{95} = 6.8 Discharges are the Closest to f_{NI} = 1, J_{NI} and J Profile Shapes are Best Matched at $q_{core} \geq 1.4$

Components of the current density (A/cm²) at the maximum β_N



- **J_{BS} profiles at max β_N are roughly uniform while J profile is peaked**
  - Externally driven current (J_{CD}) required at ρ <0.8
  - J_{NBCD} profile aligns well with J inside ρ <0.8
- **Required J_{CD} near the axis is very large for $q_{core} \approx 1$**
- **At the highest q_{core}, possibility of J_{NI} overdrive near the axis**

To Achieve f_{NI} = 1at $q_{95} \approx 5$, Significantly Increased J_{NI} Located Off Axis is Required



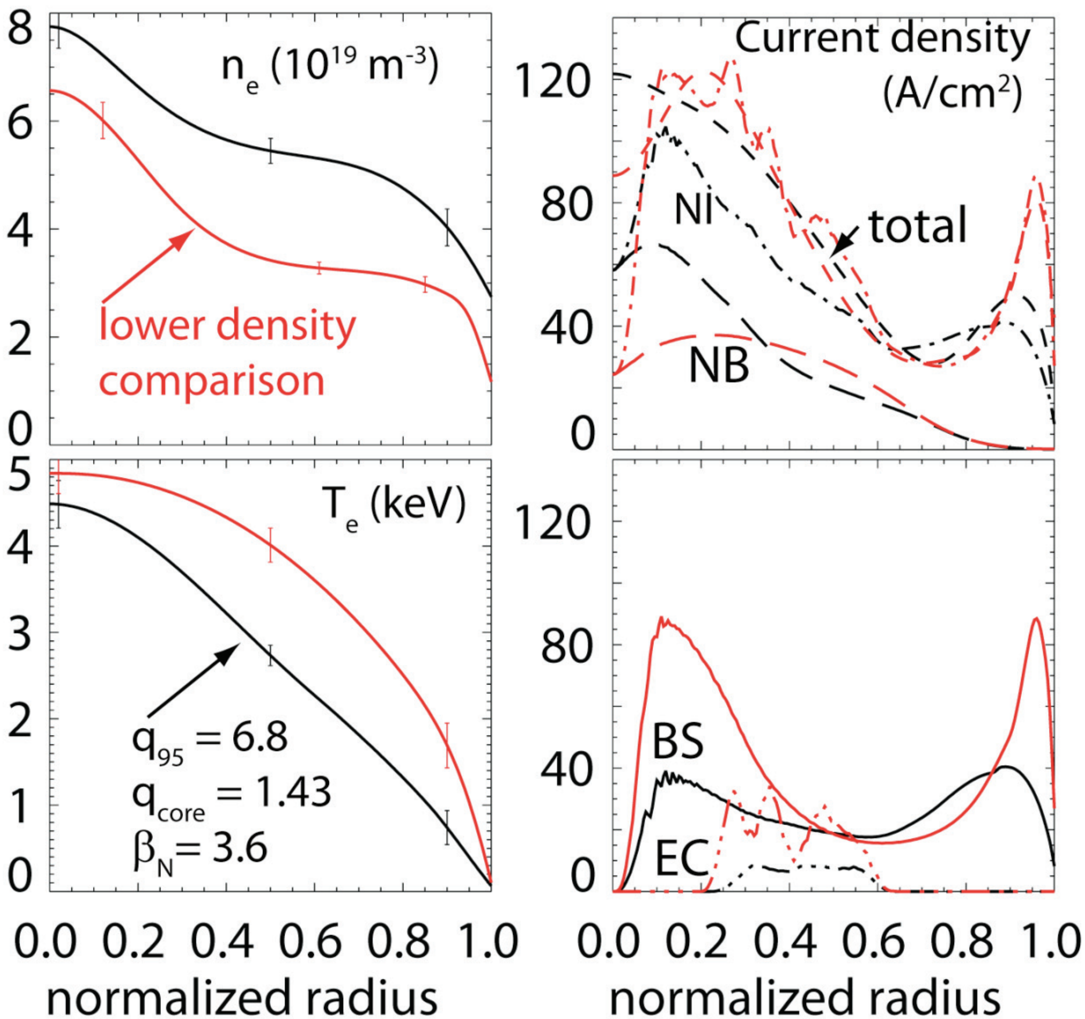
- **$q_{95} \approx 5$ required for sufficient fusion gain in a reactor or for ITER steady-state mission**
- **In this example:**
  $f_{BS} \approx 0.39$, $f_{NI} \approx 0.6$
- **For f_{NI} = 1 in this example (compared to q_{95} = 6.8):**
  - Factor 2 additional J_{NI} is required
  - >factor 3 additional total noninductive current is required

J.R.Ferron et al. , 23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea, 2010, EXS/P2-6

Paths to Higher f_{BS} at Fixed q_{95} are Increased β_N, Increased q_{core} or Increased Gradients

- **Increase β_N limit by broadening P profile**
  - n, T profiles broaden as β_N is increased
    - β_N limits may be higher than calculated
  - Off-axis beam injection to broaden fast ion pressure profile
    - $f_{p\ total}$(here ≈ 3.3) closer to $f_{p\ thermal}$(here ≈ 2.6)
  - Broader P moves gradients and J_{BS} off-axis
- **q_{min} controllable with external CD**
  - Choose high q_{min} to increase J_{BS}, reduce external CD requirement
  - Compatible with off-axis beam injection
- **Increasing gradients (larger f_p) reduces β_N limit**
  - Focus on reduced n_e, increased T_e to increase CD and J_{BS}

Other DIII-D Discharges Have Demonstrated Higher f_{BS} with Decreased n_e^{ped} and Increased T_e



- **Illustrated by comparison to a discharge from a 2008 AT-style discharge with f_{BS} = 0.7, same q profile, β_N = 3.1**
- **Average n_e lower, but still with substantial core density gradient**
- **Higher T_e maintains P_e, J_{BS}**
- **Reduced n_e, increased T_e increases J_{CD}**
- **Possible fast ion diffusion can reduce J_{NBCD}**
  - Curve in red assumes 1 m²/s

Summary

Systematic Dependence of the n_e, T_e, T_i Profile Shapes on the q Profile and β_N Strongly Affects the Bootstrap Current

- **At β_N = 2.8, T_e, T_i profiles broaden with increased q_{min}**
- **Increasing β_N broadens all profiles**
- **At high β_N, core J_{BS}<J with ~uniform profile**
  - No systematic dependence on the q profile
- **Peaked profile of J_{CD} needed so that J_{NI} matches J**
- **q_{95} > 6 is the best choice for f_{NI} = 1 with the present DIII-D external current drive sources**
  - Planned off-axis NBCD, ECCD are good matches to the current drive requirements
- **Path to f_{NI} = 1 at $q_{min} \approx 5$ is increased β_N and T_e, reduced n_e, relatively high q_{min}**