Dependence of Bootstrap Current, Stability, and Transport on the Safety Factor Profile in DIII-D Steady-State Scenario Discharges

Chris Holcomb[1]

With
J. Ferron[2], A. White[3], T. Luce[2], P. Politzer[2],
F. Turco[3], J. DeBoo[2], T. Petrie[2], C. Petty[2],
R. La Haye[2], A. Hyatt[2], T. Rhodes[4],
L. Zeng[4], E. Doyle[4]

[1]Lawrence Livermore National Laboratory
[2]General Atomics
[3]Oak Ridge Institute for Science & Education
[4]University of California, Los Angeles

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This Work Tests the Dependence of the Bootstrap Current on Choice of Target Safety Factor (q) Profile

Important for Achieving Steady-State Development Goals

1. Fully noninductive operation with a high bootstrap current fraction $f_{BS} \equiv I_{BS}/I_P \propto \beta_P \propto q\beta_N$
2. Avoid local noninductive "overdrive" $J_{NI} > J_{TOTAL}$ (incompatible with steady-state)
3. Achieve sufficient fusion gain $G \sim \beta_N H_{89}/q_{95}^2$ (G=0.3 for ITER Q=5 operation)

- Conventional approach has been to try to maximize f_{BS} by targeting high q_{min} and β_N with q_{95} set by a trade-off with G

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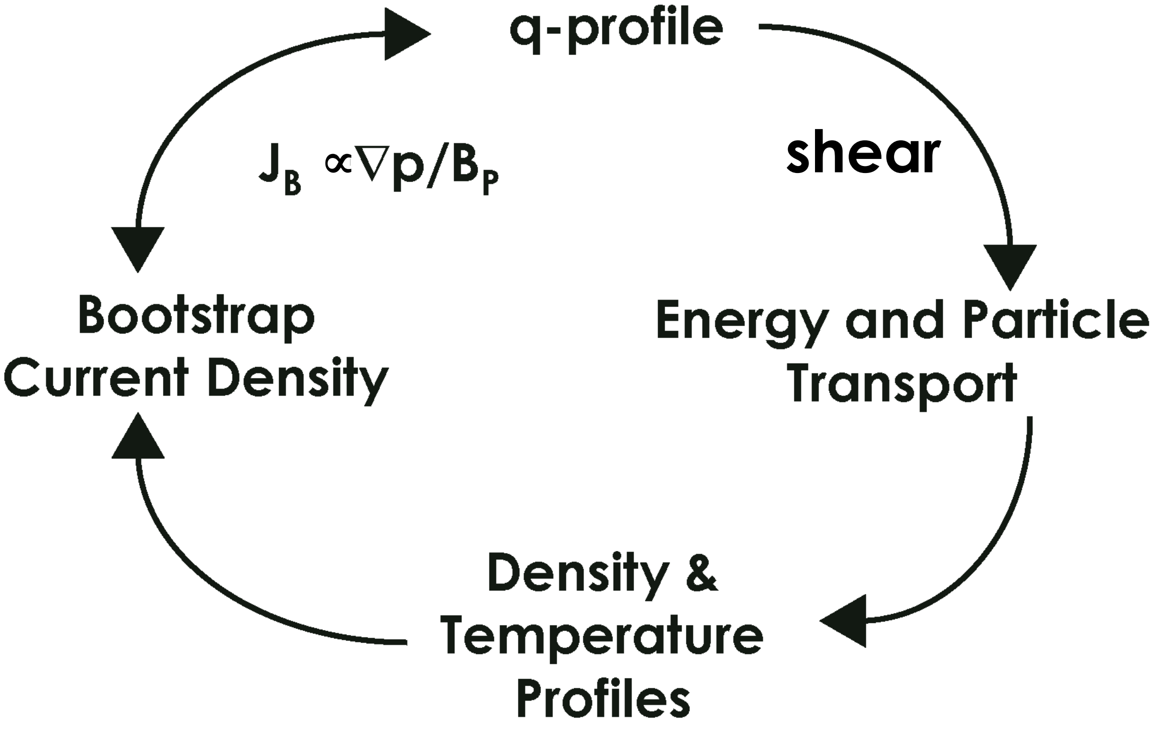
There is a Recursive Relationship Between Target q-Profile and J_{BS} at high f_{BS}



q-profile

shear

Energy and Particle Transport

Density & Temperature Profiles

Bootstrap Current Density

$J_B \propto \nabla p/B_P$

- Limits our ability to predict J_{BS}
- Experiment designed to vary q and measure resulting profiles

Experiment Produced Nine Different q-Profiles With $q_{min} \approx 1.1, 1.5, 2$ and $q_{95} \approx 4.5, 5.6, 6.8$

- q_{95} adjusted by I_P at fixed B_T
- First scan at fixed β_N=2.8 and second scan pushed β_N to maximum limited by stability or confinement
- Measured q, density and temperature profiles
- Calculated Bootstrap Current Density using '99 Sauter formula in ONETWO transport code

$$\frac{\left\langle J_{BS} \bullet B \right\rangle}{B_{T0}} = -\frac{F}{B_{T0}}\left[T_e \frac{dn_e}{d\psi}\left(L_{31}\right) + n_e \frac{dT_e}{d\psi}\left(L_{31} + L_{32}\right) + T_i \frac{dn_i}{d\psi}\left(L_{31}\right) + n_i \frac{dT_i}{d\psi}\left(L_{31} + \alpha L_{34}\right)\right]$$

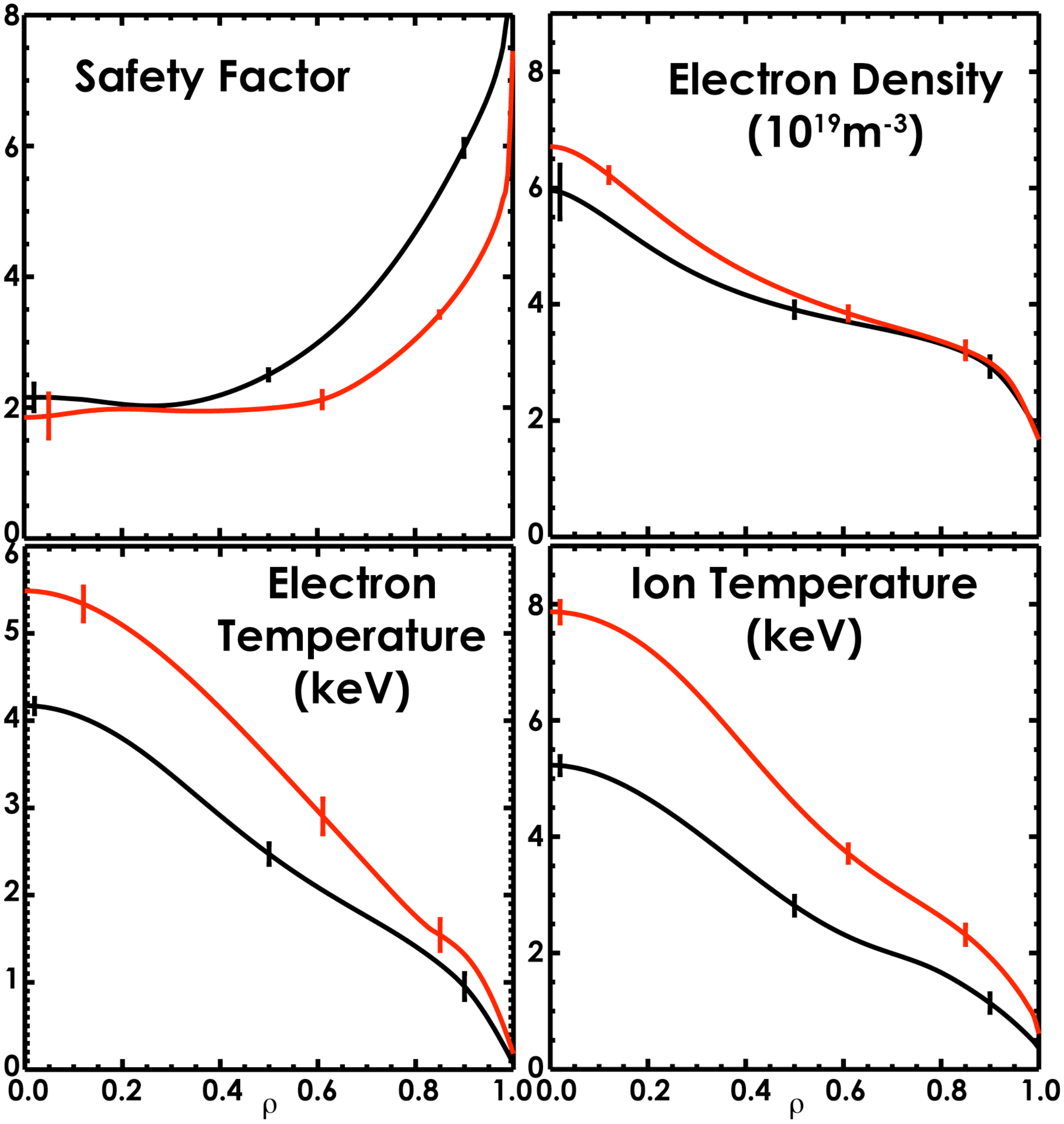
- Compared all quantities averaged over few hundred to ~1000 ms for better statistics

q-Profile Variation at $\beta_N = 2.8$ Led to Systematic Differences in Measured Density and Temperature

		q_{95}	
		4.5	6.8
q_{min}	2	136837	136835
	1.1		

Variation with q_{95}:

n_e, T_e, T_i higher at low q_{95} (q_{min}≈2 shown here)



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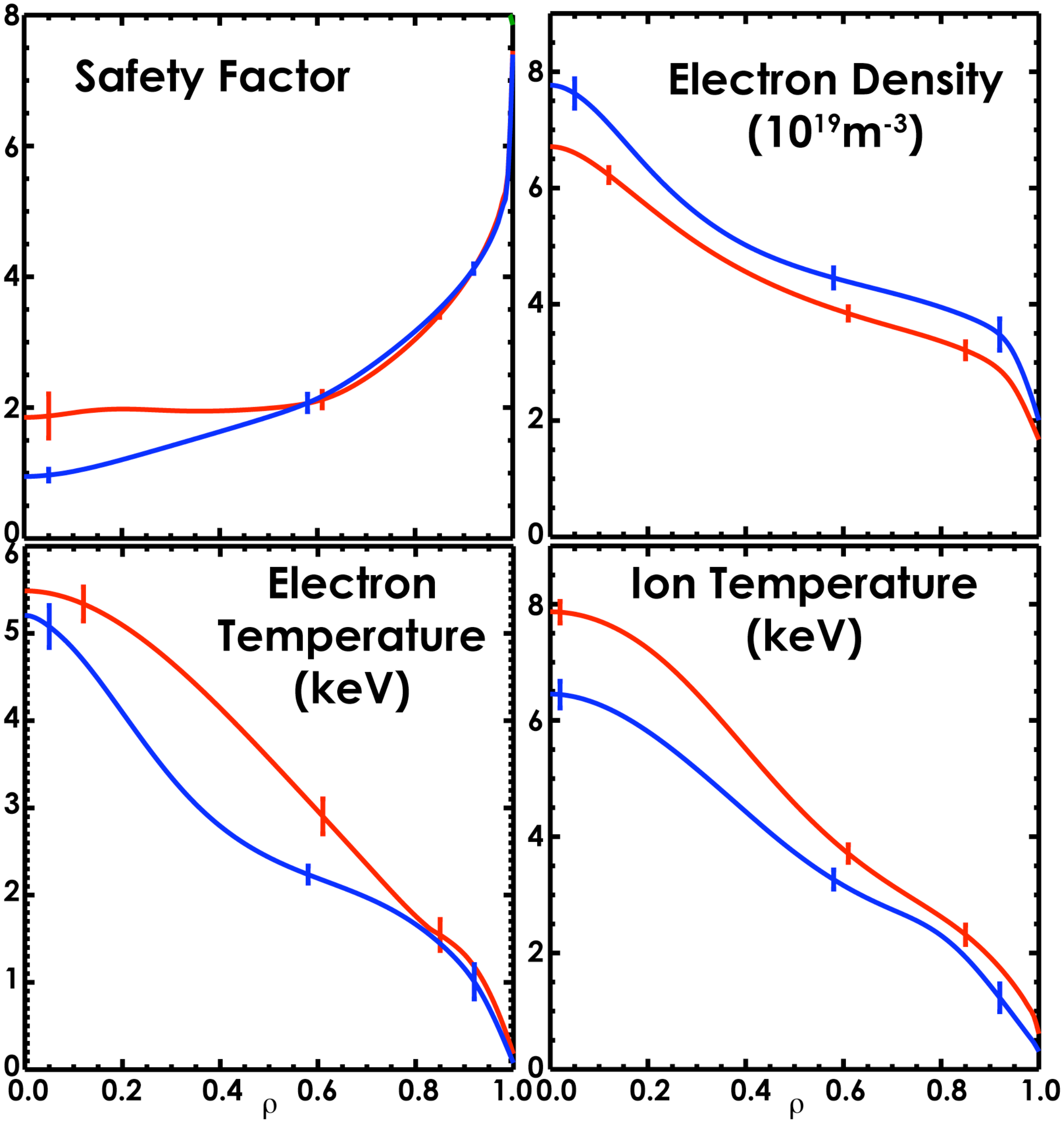
		q_{95}	
		4.5	6.8
q_{min}	2	136837	
	1.1	136854	



Variation with q_{min}:

n_e higher and more peaked

T_e more peaked

T_i lower

(q_{95}≈4.5 shown here)

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q-Profile Variation at β_N = 2.8 Led to Systematic Differences in Measured Density and Temperature

		q_{95}	
		4.5	6.8
q_{min}	2	136837	136835
	1.1	136854	136853

Variation with q_{95}:

n_e, T_e, T_i higher at low q_{95}

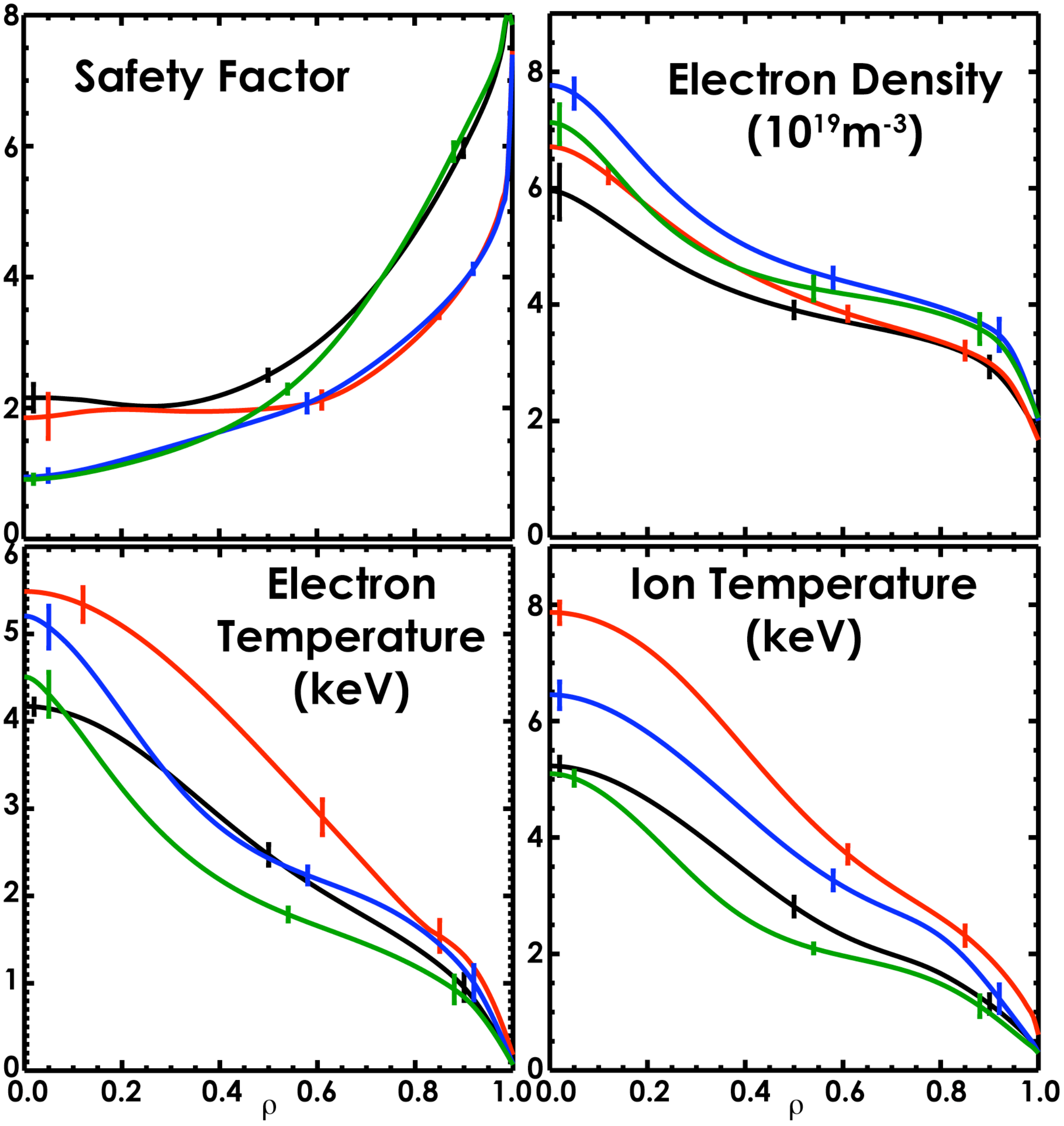
Variation with q_{min}:

n_e higher and more peaked

T_e more peaked

T_i lower

These dependencies hold true in general in β_N=2.8 data set (4 of 9 points in q-scan shown)



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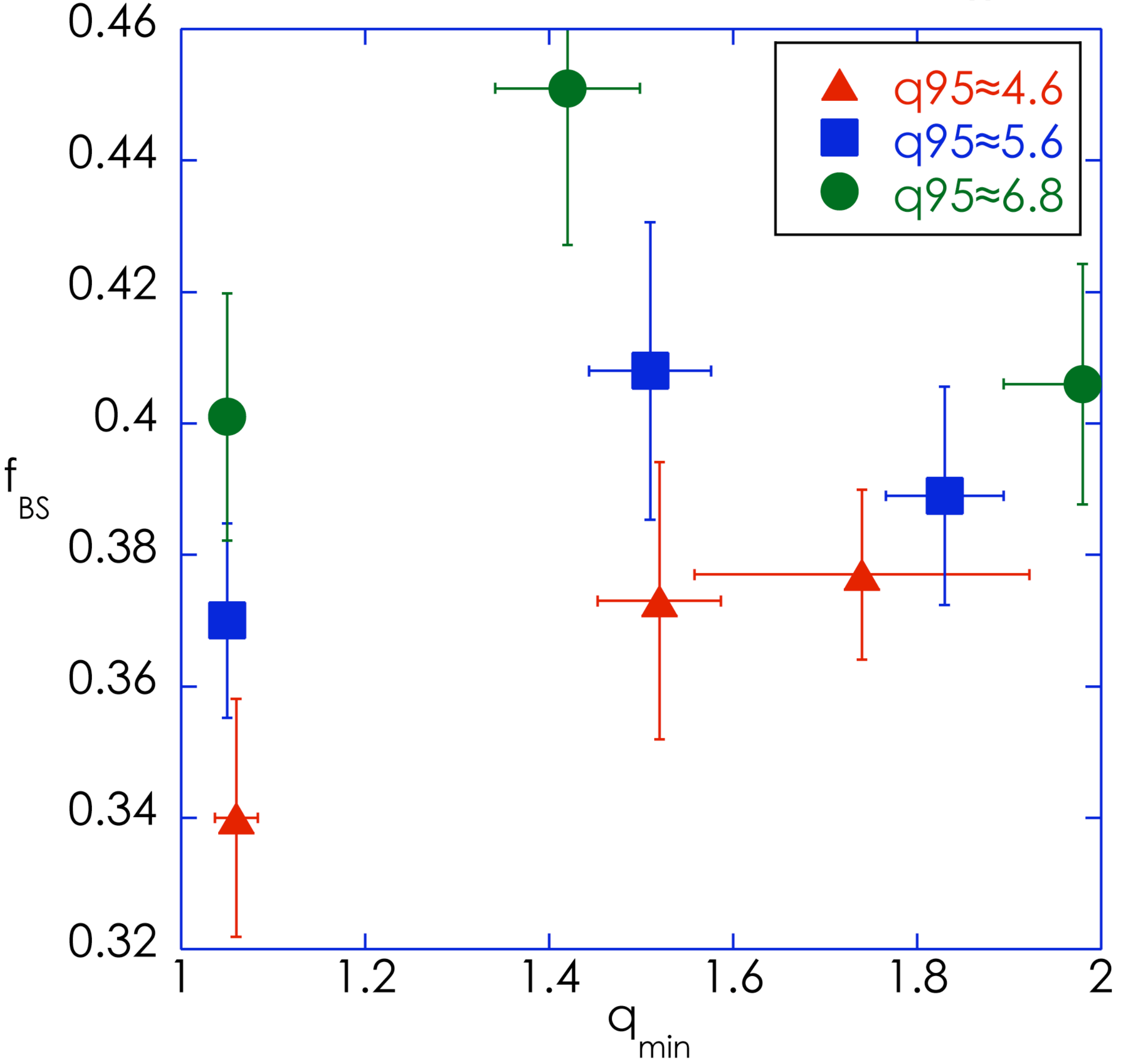
At $\beta_N = 2.8$, the Bootstrap Fraction Increased With q_{95} in Agreement With $f_{BS} \propto q\beta_N$ Scaling

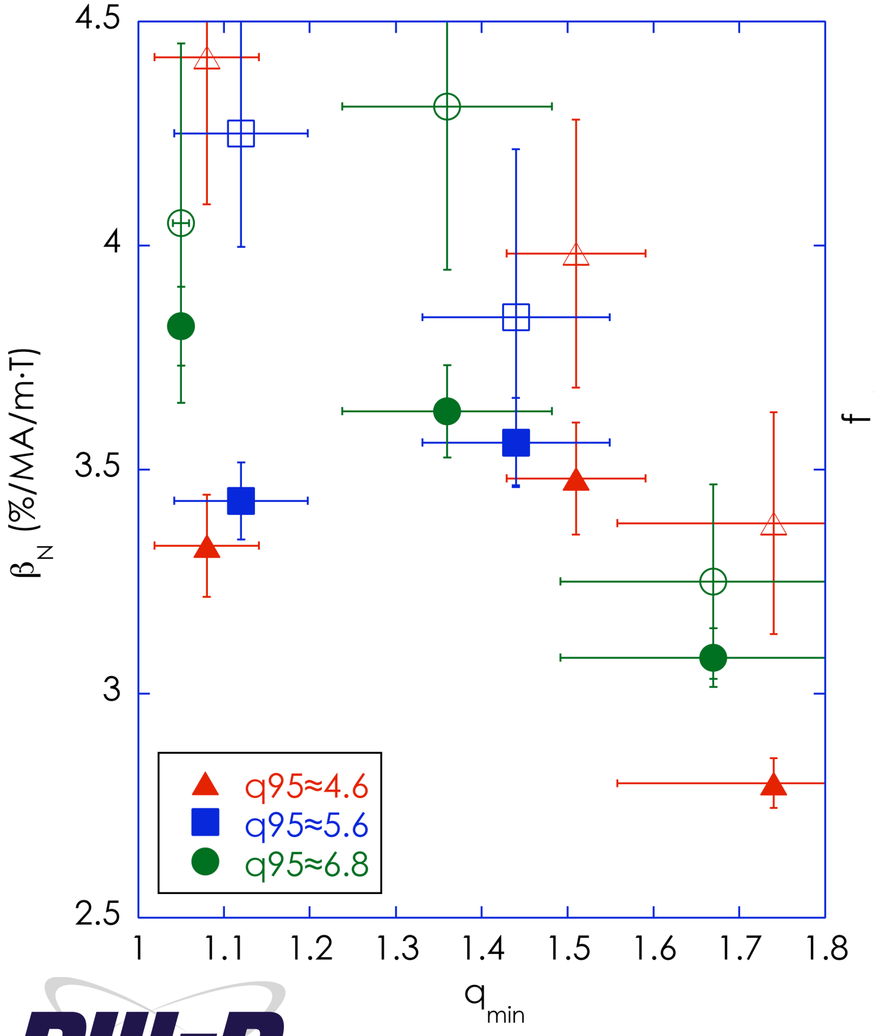
- **Bootstrap Fraction leveled off or dropped with q_{min} above ~1.5**
- **This is contrary to expected $q\beta_N$ scaling**

Bootstrap Current Fraction, β_N=2.8

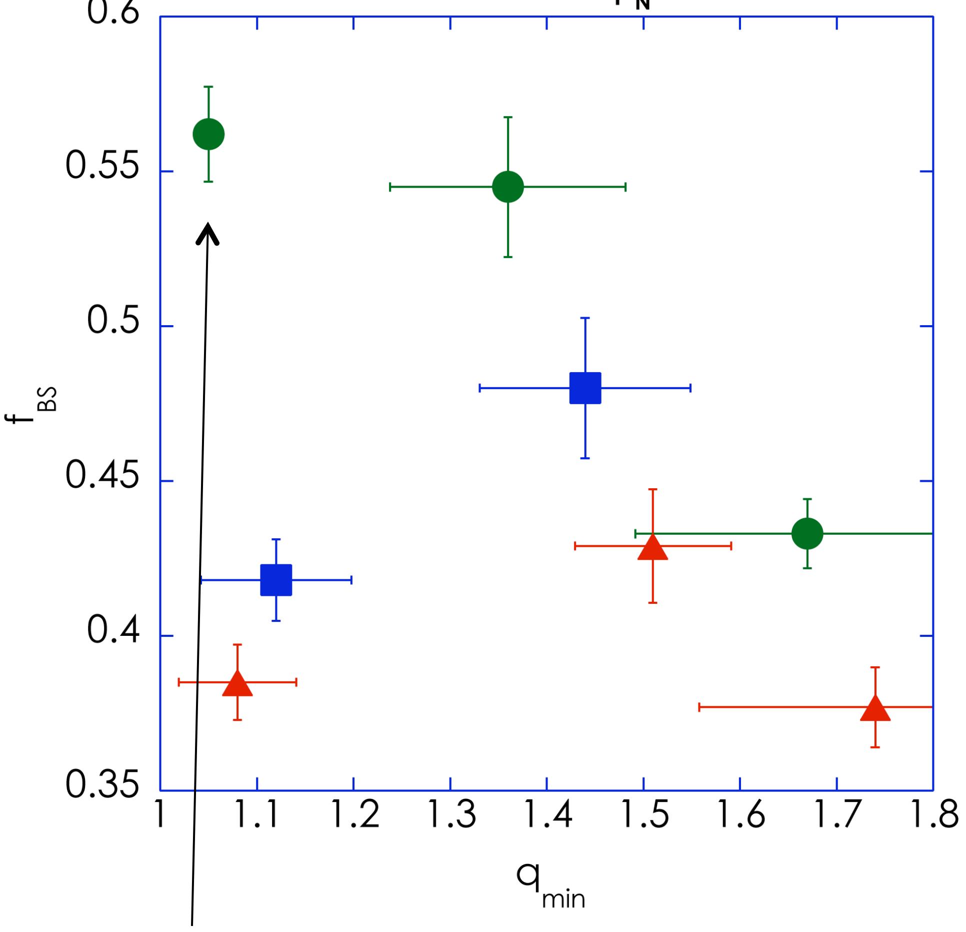


Increased Stability at Lower q_{min} Resulted in Highest Achieved β_N and f_{BS} Occurring at $q_{min} \approx 1.1$

Achieved β_N (Closed Symbols) and *n*=1 Ideal-Wall Limit from DCON (Open Symbols)



Bootstrap Current Fraction at Maximum Achieved β_N

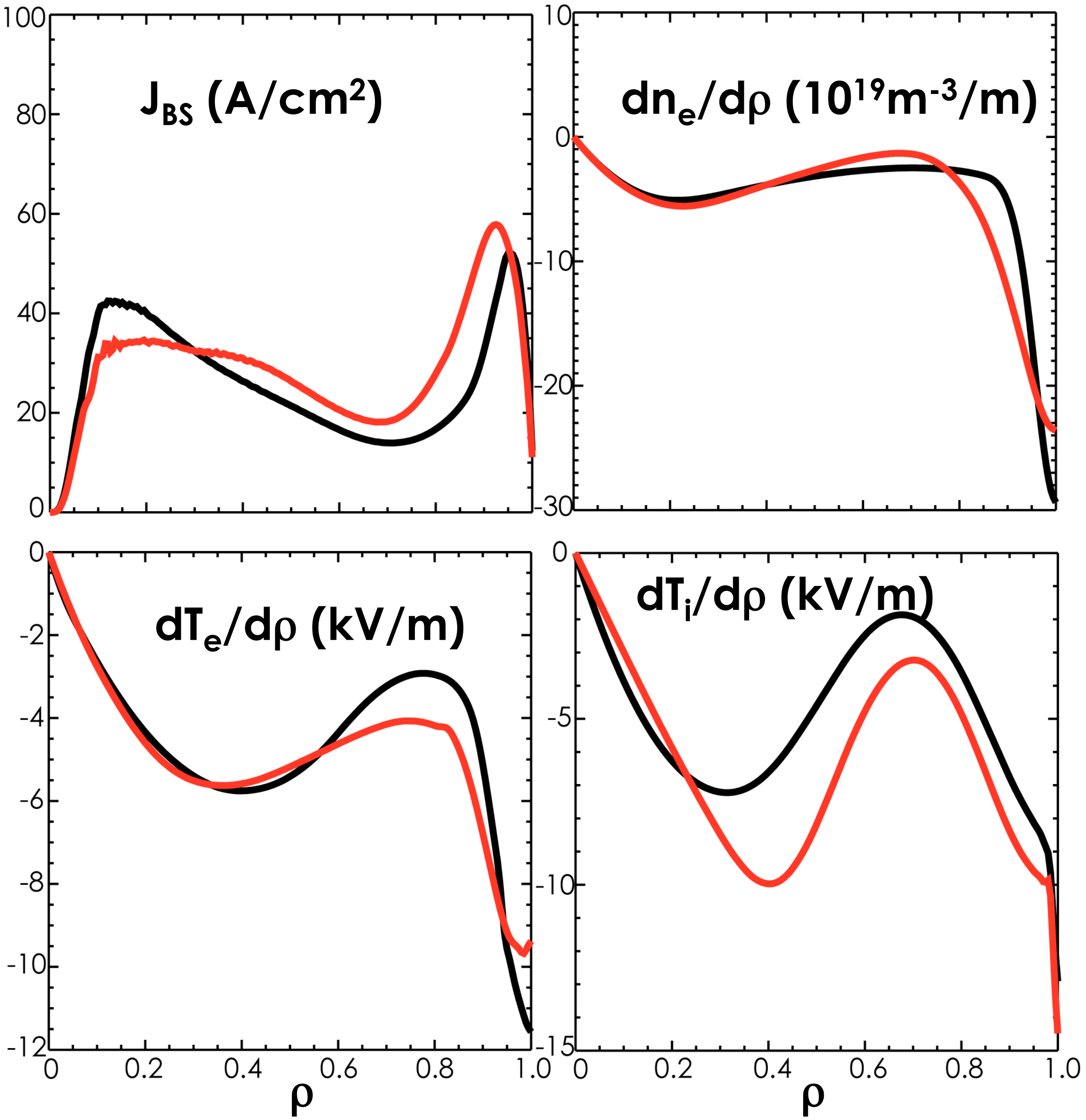


Lowest q_{min}, $q_{95} \approx 6.8$ discharge had ~10% higher H_{89} than all others

Increasing β_N Broadened J_{BS} By Increasing ∇T_e and ∇T_i at Larger Radius

- This example, 2 shots: $q_{95}=5.6$, $q_{min}\approx1.5$

  $\beta_N \approx 2.8 \rightarrow 3.6$
- Similar broadening with β_N for all q-profiles
- Broadening favorable for avoiding local noninductive current overdrive near $\rho\sim0.2$
- For some q profiles, $dn_e/d\rho$ changed as well



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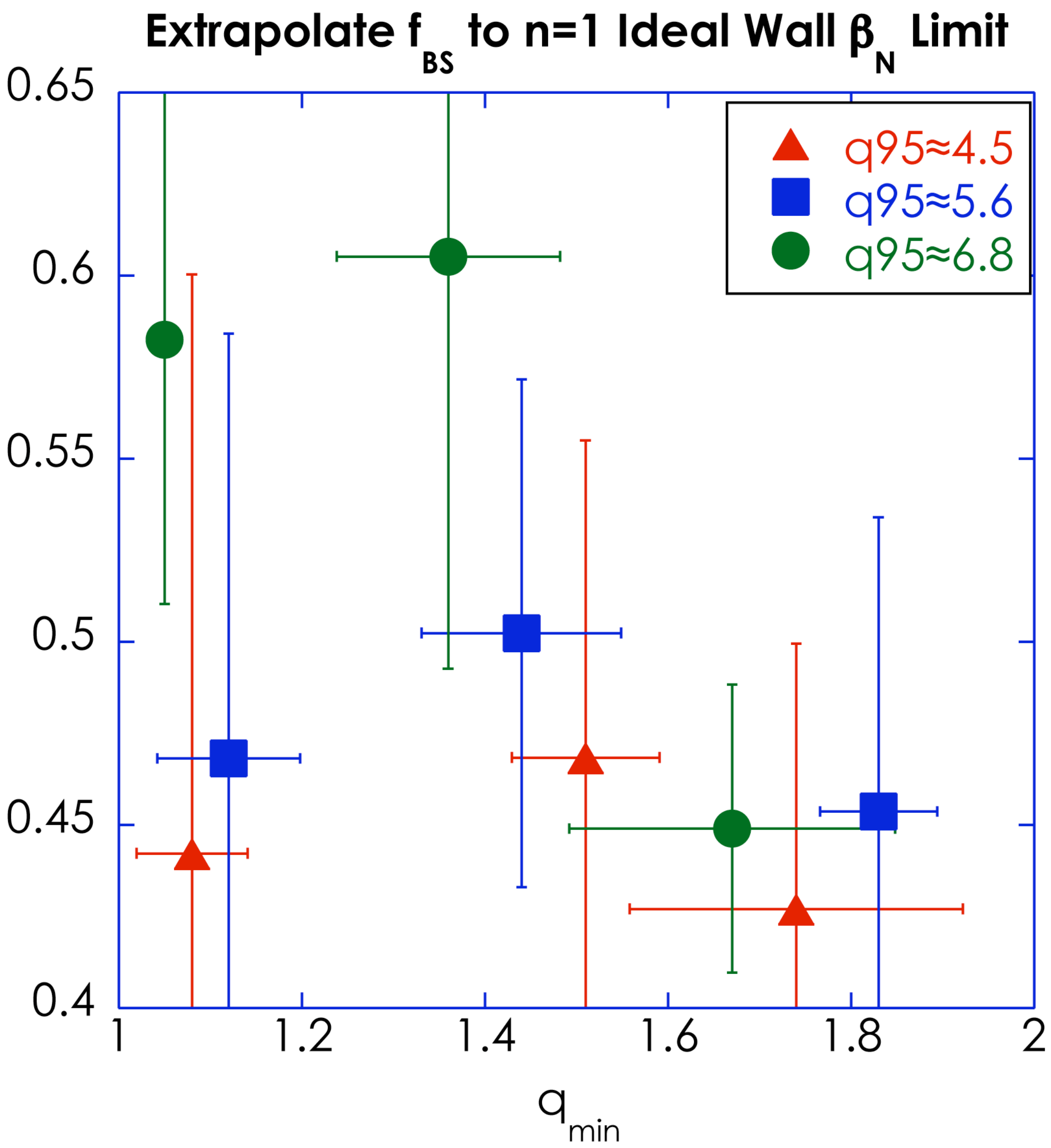
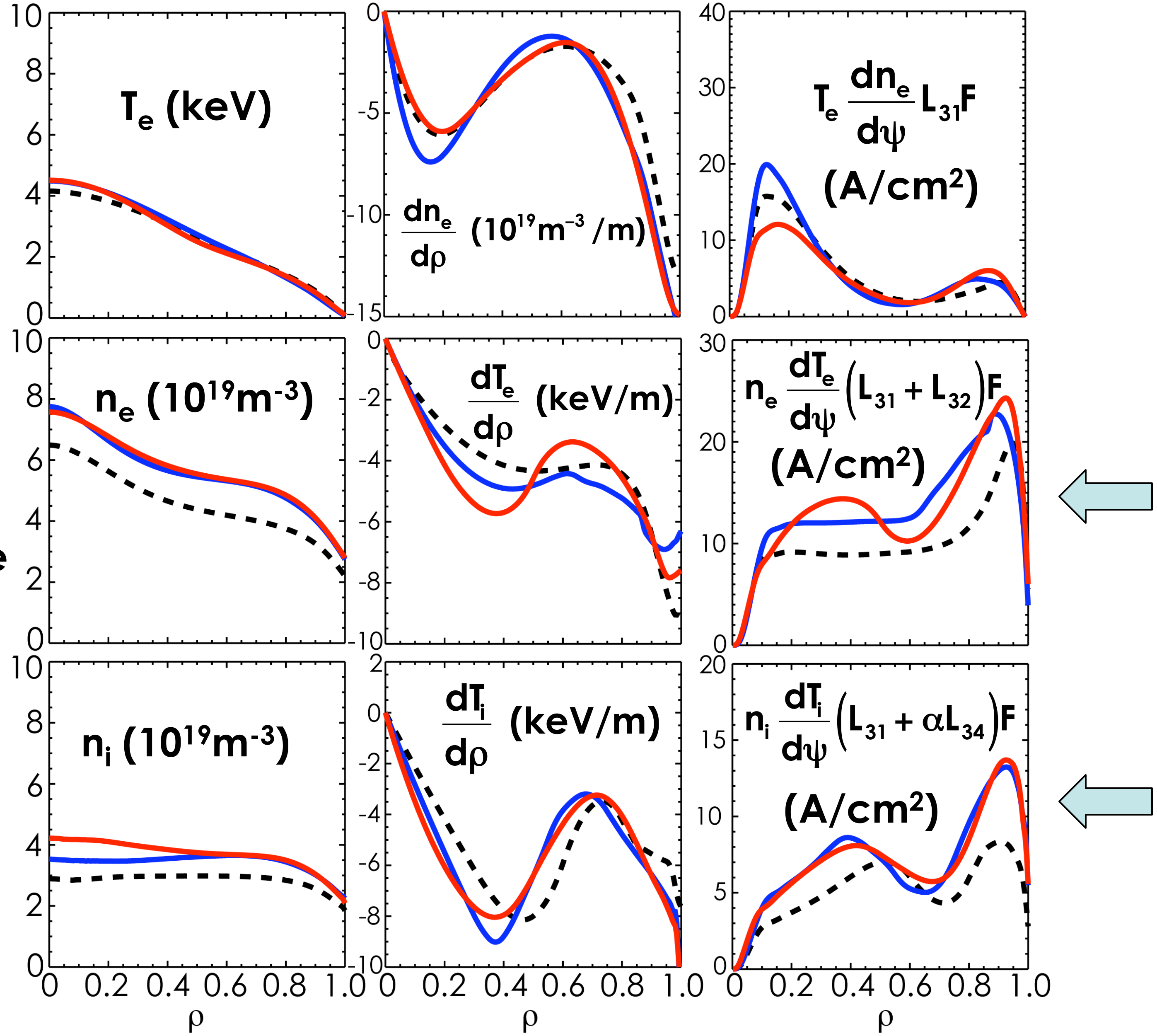
Extrapolating to the *n*=1 Ideal Wall β_N Limit Suggests f_{BS} Maximizes Near $q_{min} \approx 1.5$

- **Measured f_{BS}/β_N decreased going from low to high β_N at "fixed" q-profile**
- **This reflects change in density and temperature profiles with β_N**
- **Used the difference between measured f_{BS}/β_N at low and high β_N to scale to f_{BS} at the calculated ideal wall limit**



Lower f_{BS} at q_{min} > 1.5 Caused Mostly By Lower Density and Lower Temperature Gradients

- **Profiles from 3 shots: q_{95}=6.8, q_{min}≈2 (dash)**
  q_{min}≈1.5
  q_{min}≈1.1
- **β_N pushed to maximum**
- **In each row, first two quantities are leading scale factors of bootstrap terms in 3rd column**



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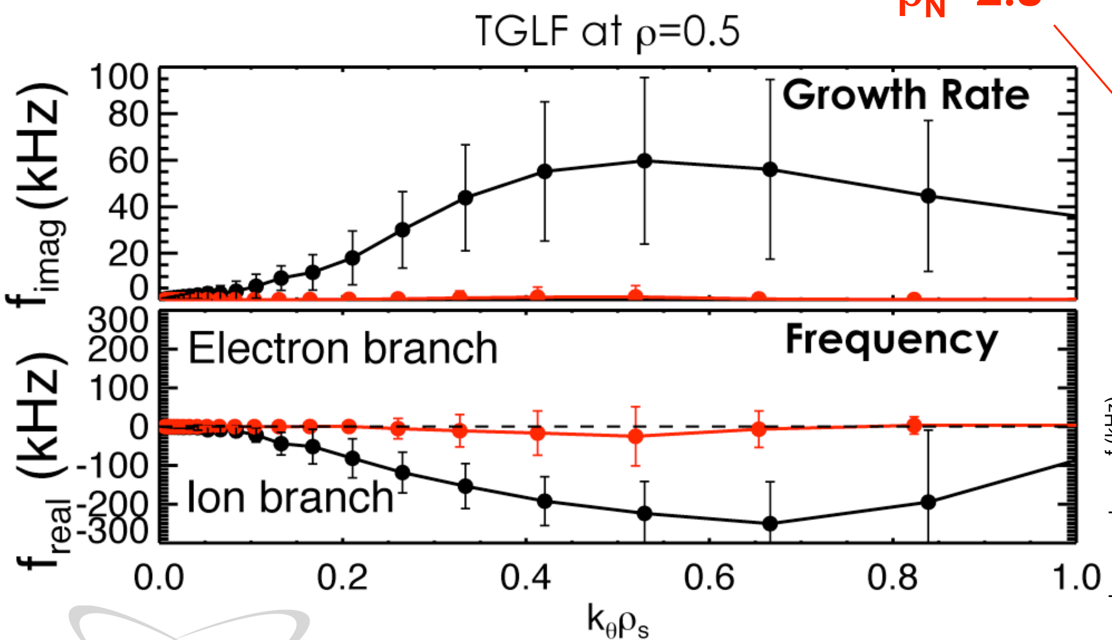
q_{min}>1.5 Had Higher Measured Density Fluctuations and Calculated Growth Rates Than $q_{min}≈1.1$

- **FIR scattering spectrograms of $\tilde{n}$ (k_θ<1 cm^{-1})** →
- **Linear TGLF runs show $q_{min}≈1.1$ was basically stable, $q_{min}≈2$ unstable to ITG type turbulence at mid-radius**

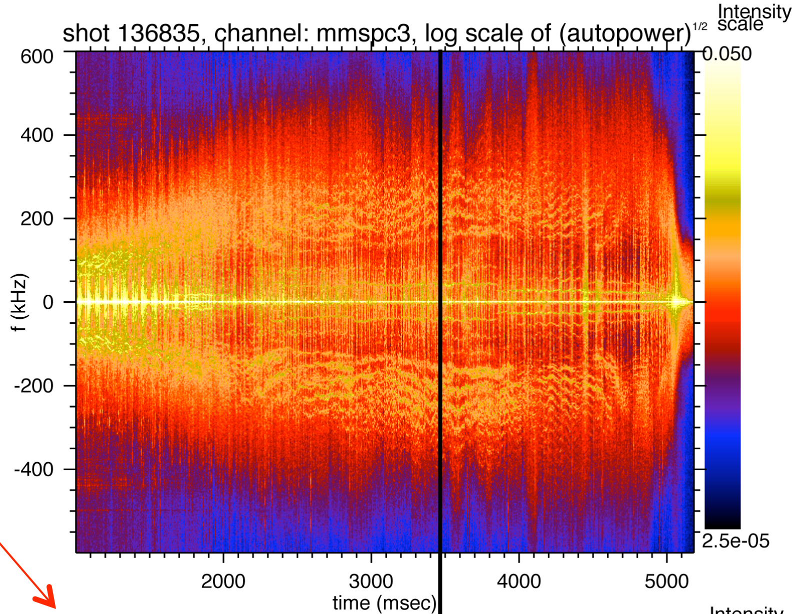
$q_{min}≈2$
$q_{95}=6.8$
$\beta_N=2.8$

$q_{min}≈1.1$
$q_{95}=6.8$
$\beta_N=2.8$

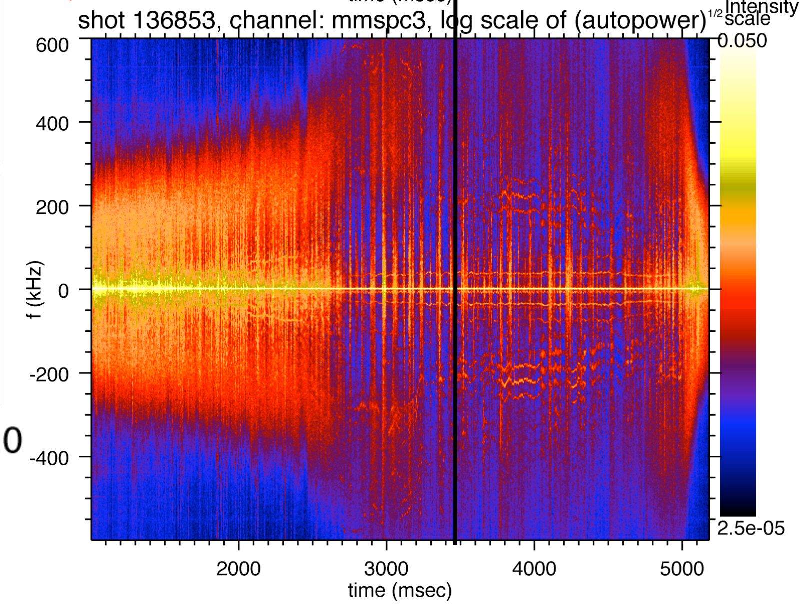
TGLF at ρ=0.5



shot 136835, channel: mmspc3, log scale of (autopower)$^{1/2}$



shot 136853, channel: mmspc3, log scale of (autopower)$^{1/2}$



Summary and Conclusions

- In our scans of q_{min} and q_{95}, the bootstrap current fraction increased with q_{95} but did not continue to increase with q_{min} above about 1.5 as expected by $f_{BS} \propto q\beta_N$

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- New tools (off-axis NBI, more ECCD) may allow access to higher β_N limits and higher bootstrap fractions