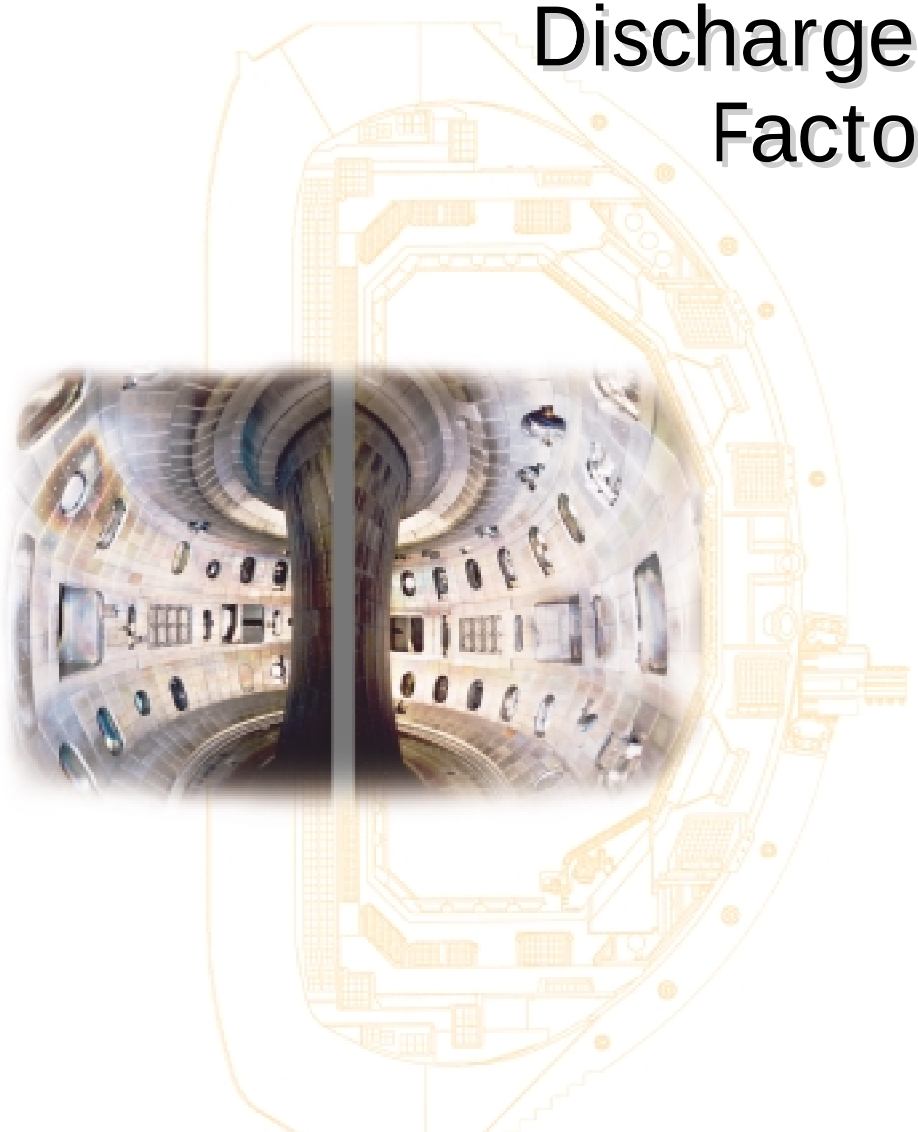
Dependence of Achievable β_N on Discharge Shape and Edge Safety Factor in DIII–D Steady-State Scenario Discharges



by
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GENERAL ATOMICS

Motivation

Motivation: high β_N is an important component of the self-consistent parameter set for a steady-state, advanced tokamak discharge

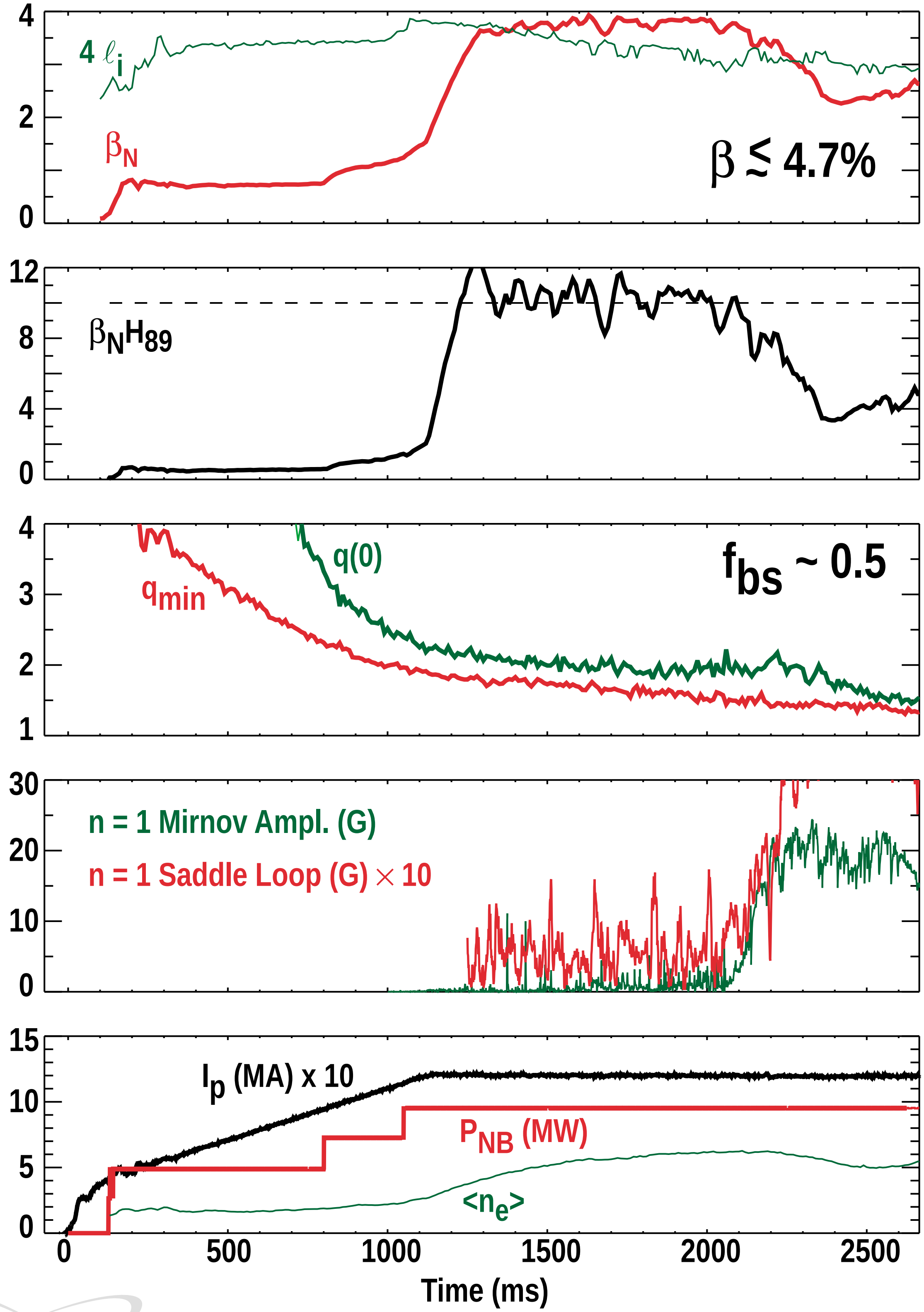
- High $\beta\tau_E \propto (\beta_N/q)(H_{89}/q^\alpha)$ for fusion power output.
- High bootstrap fraction $f_{BS} \propto \beta_P \propto q\beta_N$ for steady state.
- Optimum discharge has relatively high q (including $q(0)$, q_{min}, q_{95}) for f_{BS}, high β_N for power output.
- High β_N enhances off-axis ECCD efficiency.
- Low density required for efficient electron cyclotron current drive (ECCD).
- Low density requires pumping of H-mode divertor exhaust.

Background

Optimization of β_N was sought within the constraints of the advanced tokamak scenario

- Prior to upper divertor baffle installation (1999), $\beta_N H_{89} \approx 10$, $\beta_N \approx 3.7$ sustained in $\kappa = 2$, $\delta = 0.9$ shape.
- Achievable β_N (≈ 3.4) reduced in lower elongation, triangularity ($\kappa = 1.7$, $\delta = 0.7$) shape compatible with pumping after divertor baffle installation (2000).
- 1999-2000 operation at $B_T = 1.6$T for ECCD.
- Data set shows a dependence of the achievable β_N on the shape parameter $S = (I/aB)q_{95}$.
- Leads to 2001 investigation of the effect of variation in shape and q_{95} (by changing B_T) on achievable β_N.

HIGH NORMALIZED PERFORMANCE (~10) SUSTAINED FOR 5 τ_E IN $\kappa = 2$, $\delta = 0.9$ SHAPE



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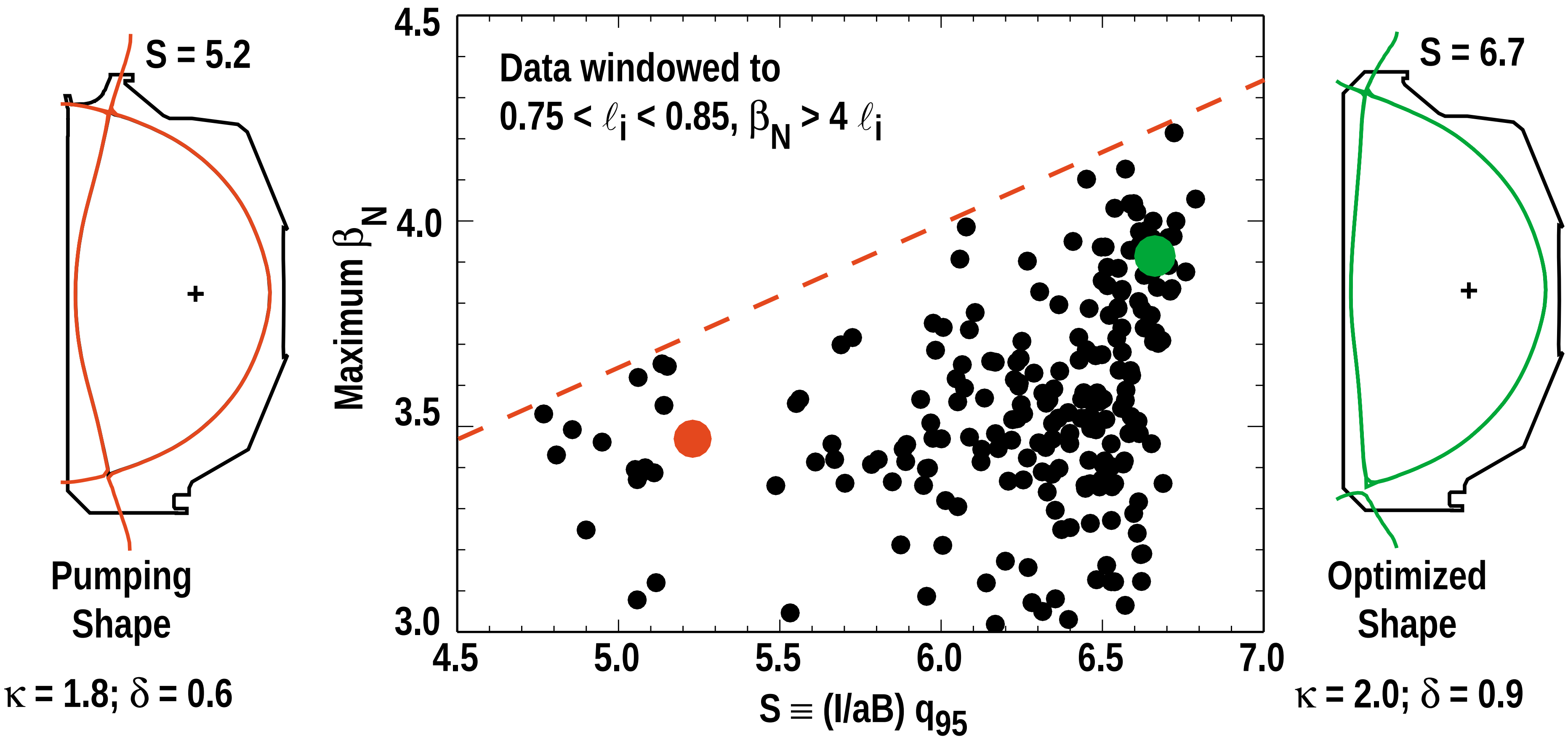
OBSERVED β_N LIMIT HAS A SIGNIFICANT DEPENDENCE ON PLASMA SHAPE

- Comparison between shapes available before and after divertor baffle installation



- Experimental scans at constant I/aB

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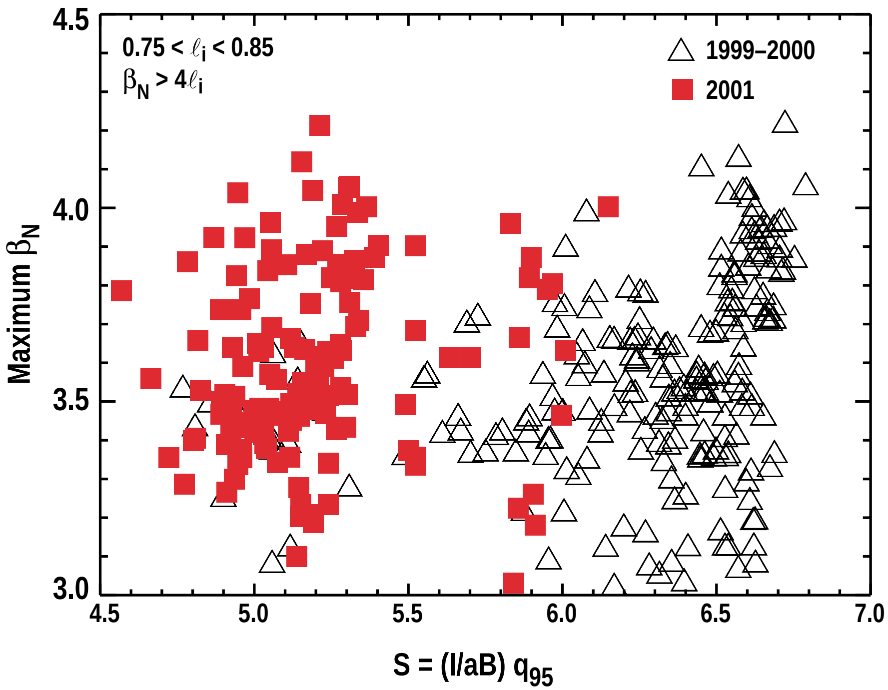
Experimental results

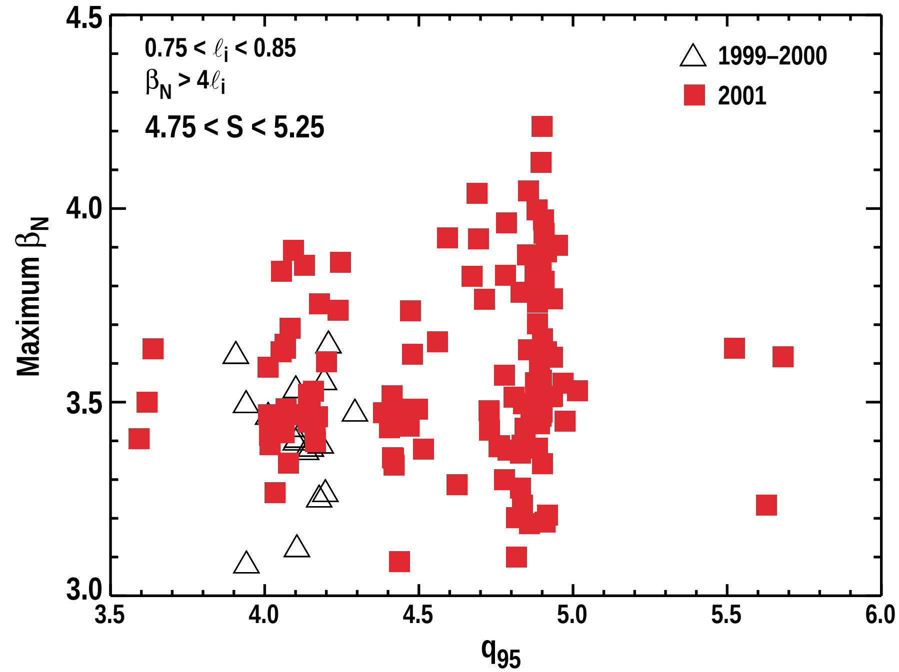
Experimentally achievable β_N increased at higher q_{95}

- $\beta_N = 4.1$ sustained at $B_T = 1.85$T in $\kappa = 1.8$, $\delta = 0.7$ shape (compared to $\beta_N = 3.4$ at $B_T = 1.6$T).
- Improvement over β_N in the older higher elongation, triangularity shape.
- Provides a satisfactory β_N value for an ECCD target.
- No improvement in β_N was found by varying the discharge shape near the pumping geometry.
- β_N limited, high performance phase terminated by instability:
  - Resistive wall modes (RWM).
  - ELMs
  - Neoclassical tearing modes (NTM) at $m/n = 2/1$.
- Maximum β_N:
  - Up to $5.5\ell_i$.
  - Above the ideal, no-wall $n = 1$ limit.
  - In some cases, close to the ideal-wall limit.

EXPERIMENTAL STUDIES INDICATE β_N INCREASES WITH INCREASING q_{95}

- Increasing DRSEP causes a drop in the shape parameter $S = (I/aB)\, q_{95}$ and q_{95} itself
- 1999-2000 studies indicated variation of RWM β limit with shape parameter and q_{95}





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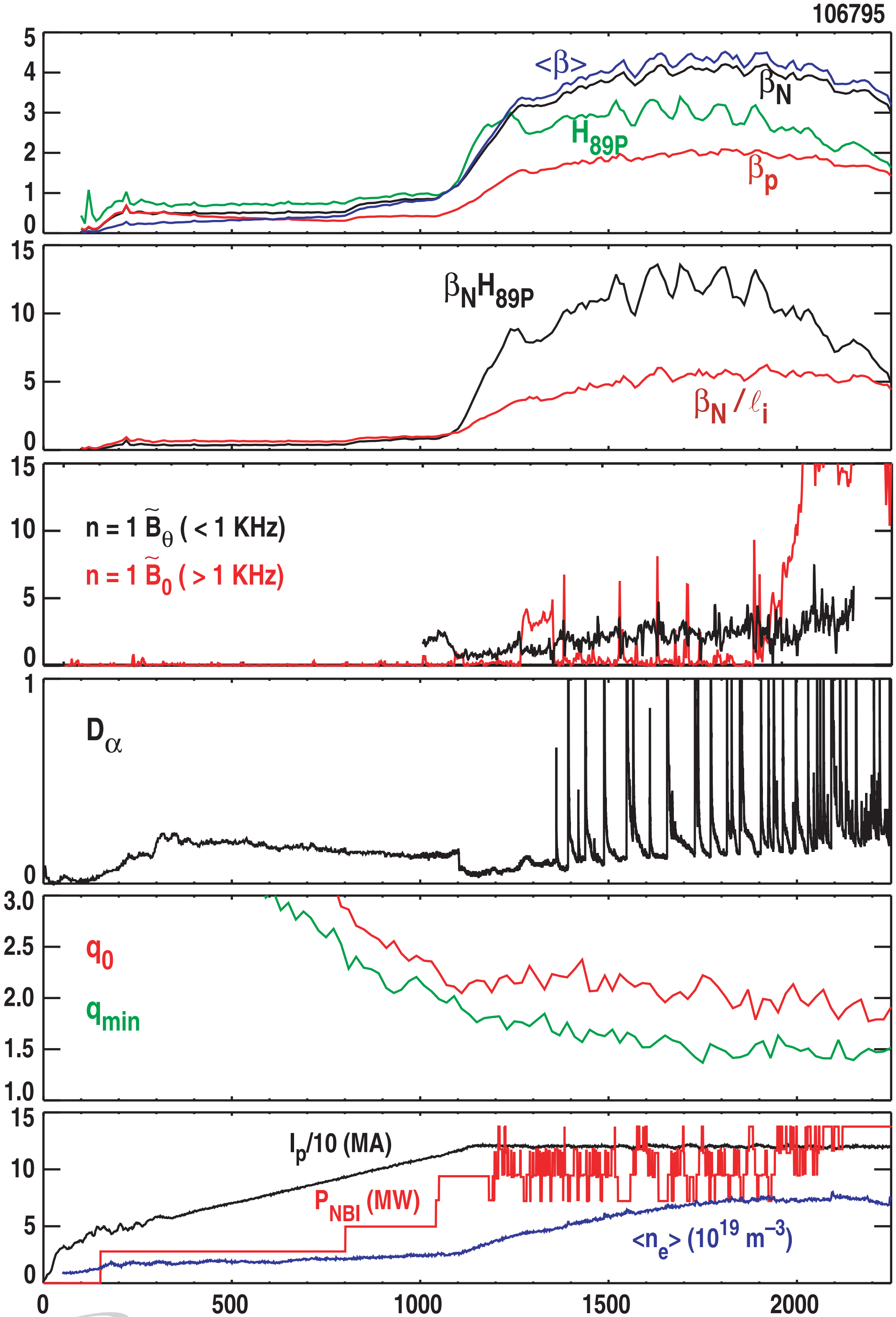
CONDITIONS CONDUCIVE TO HIGH f_{BS} AND HIGH $\beta\tau$ (β_N = 4, H_{89} = 3 WITH q_{min} > 1.5) SUSTAINED FOR $5\tau_E$



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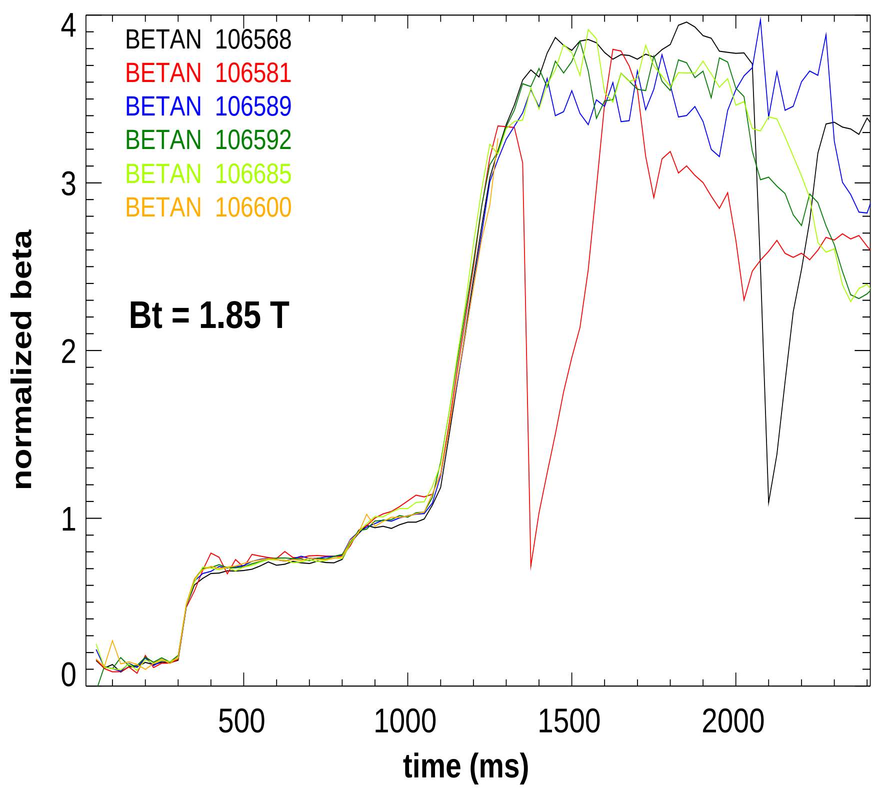
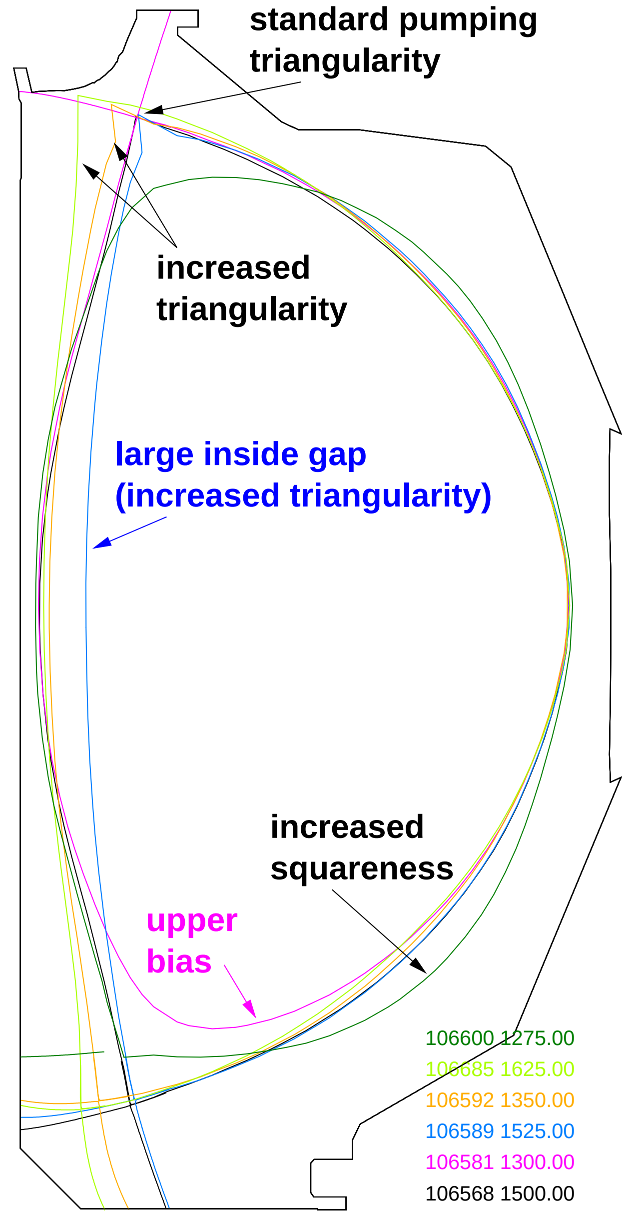
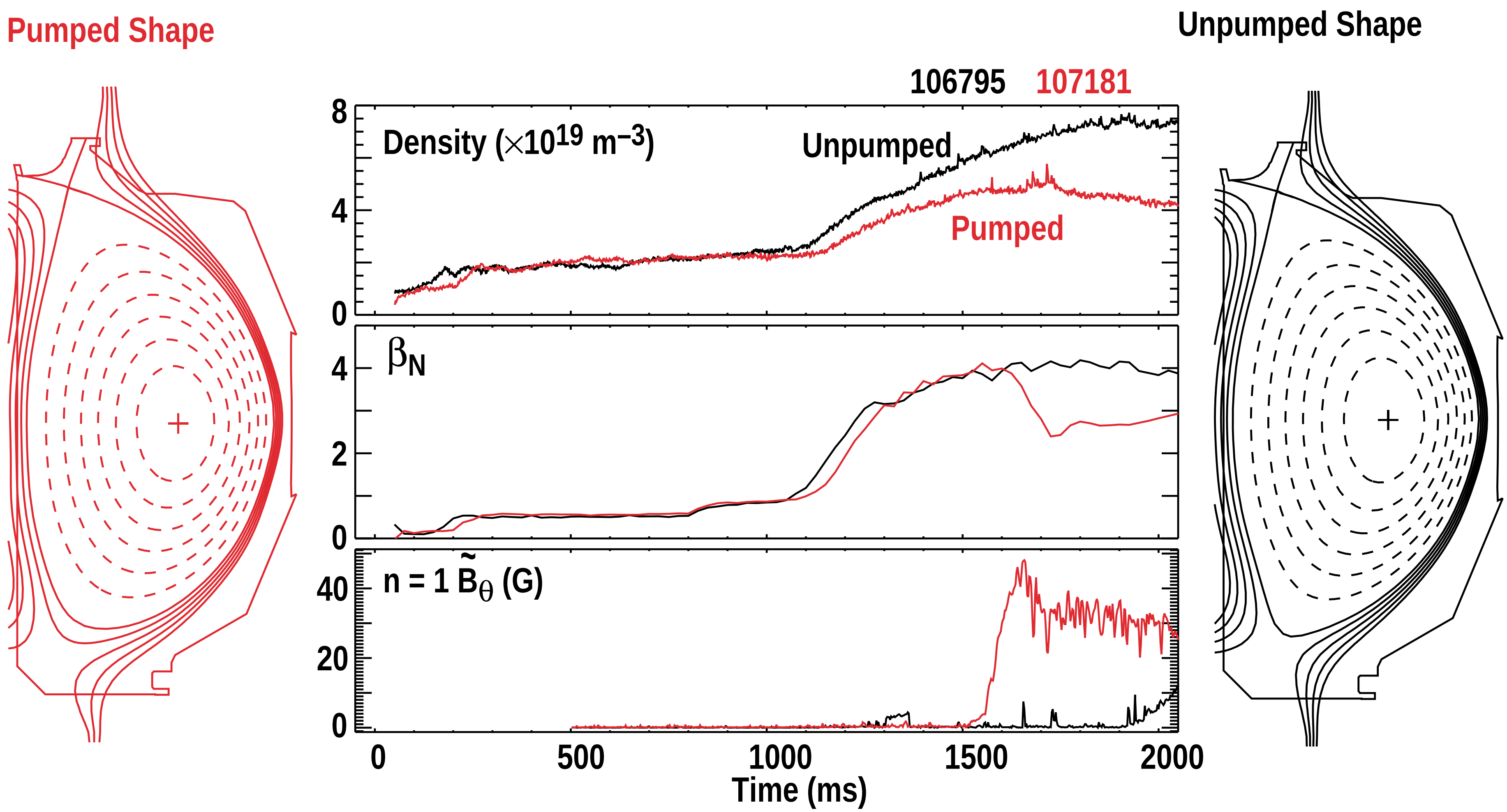
No systematic variation in β_N resulted from many small variations about the standard pumping shape

- No opportunity to optimize most shapes.
- Further analysis and modeling comparison required.





$\beta_N \sim 4$ HAS BEEN ACHIEVED WITH THE UPWARD SHAPE BIAS REQUIRED TO MAINTAIN DENSITY CONTROL



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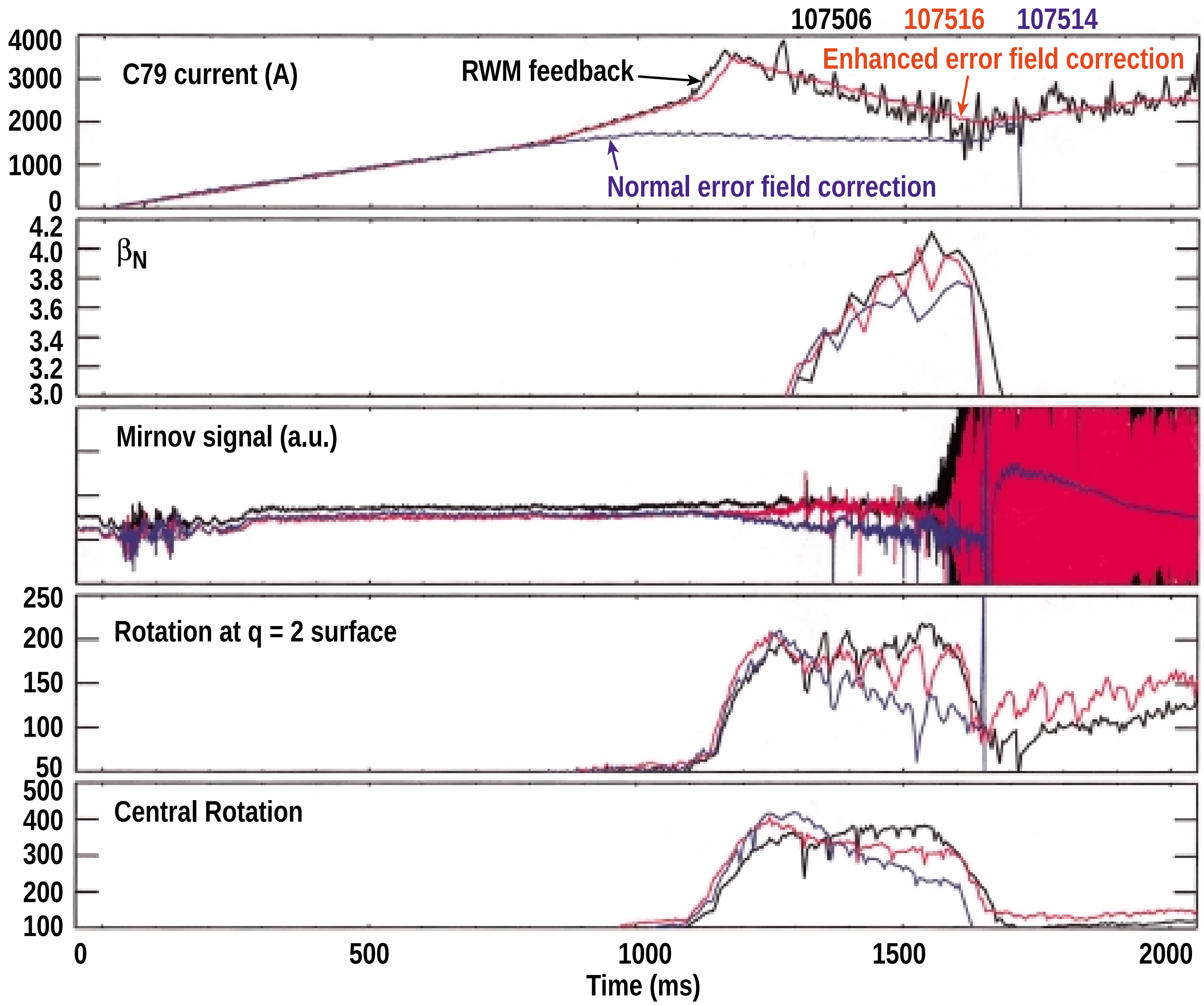
ERROR FIELD CORRECTION AND RWM FEEDBACK STABILIZATION HAVE ALSO BEEN SUCCESSFUL IN IMPROVING THE ACHIEVABLE β_N



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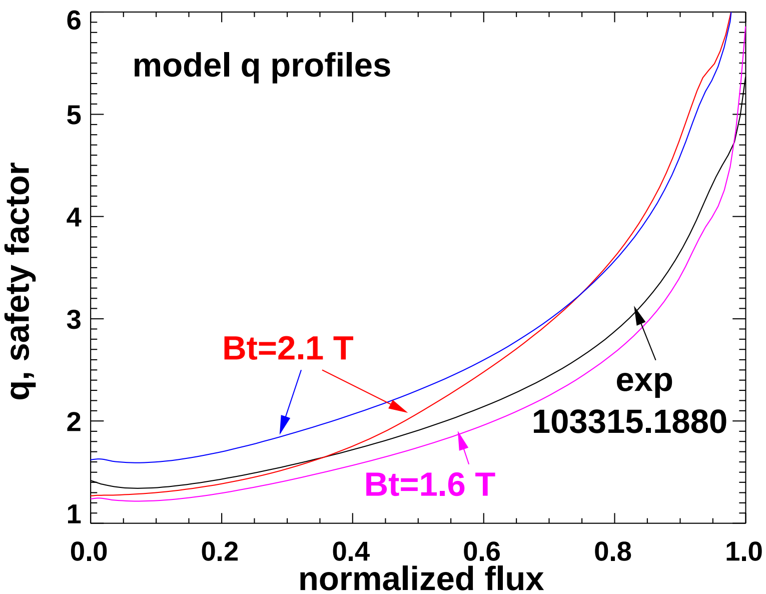
Modeling of no-wall limit

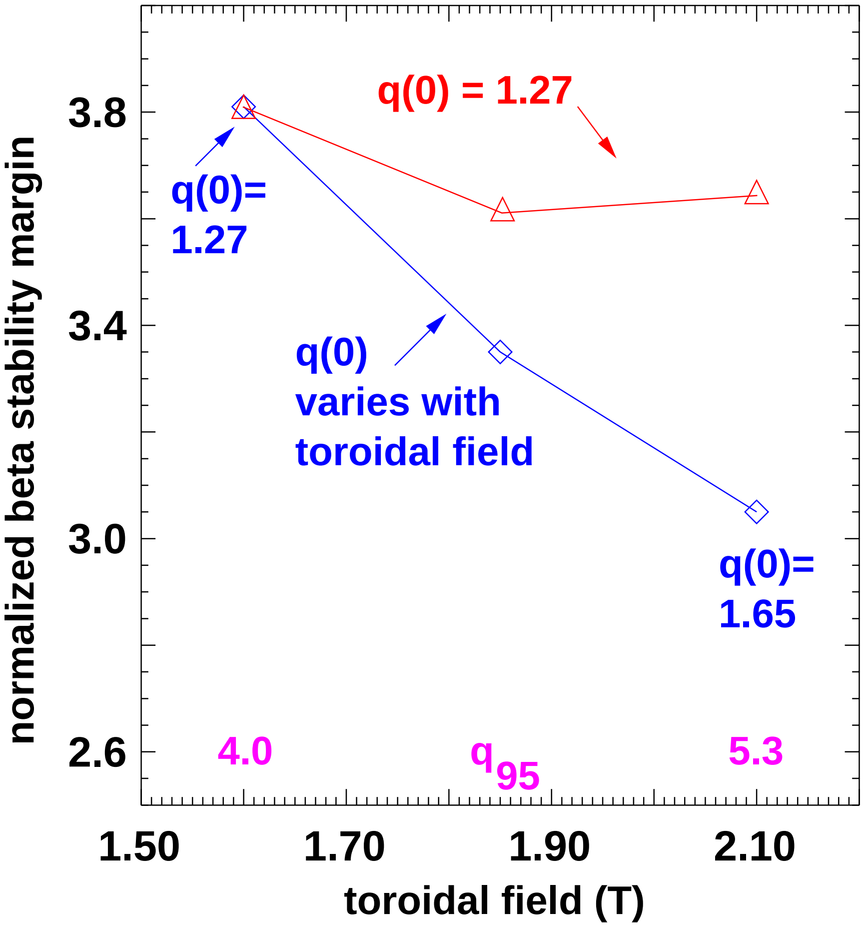
Modeling based on ideal $n = 1$ no-wall theory cannot account for the changes in β_{N} observed in the experiment

- In contrast to the experiment, the predicted no-wall $n = 1$ limit:
  - Decreases as q_{95} increases.
    - Scan of B_{T} at constant shape.
    - Change in I_{p} at constant shape.
  - Is lower in the higher elongation, triangularity shape.
- Modeling also predicts that the no-wall $n = 1$ limit:
  - Is optimized at lower $q(0)$.
  - Is not strongly dependent on details of the pressure gradient profile shape.
- Modeling:
  - Equilibria computed with the code TOQ.
  - Current and pressure gradient profiles modeled from measured experimental profiles.
  - Ideal stability computed with GATO with or without a conformal wall or a wall at the DIII-D vessel position.

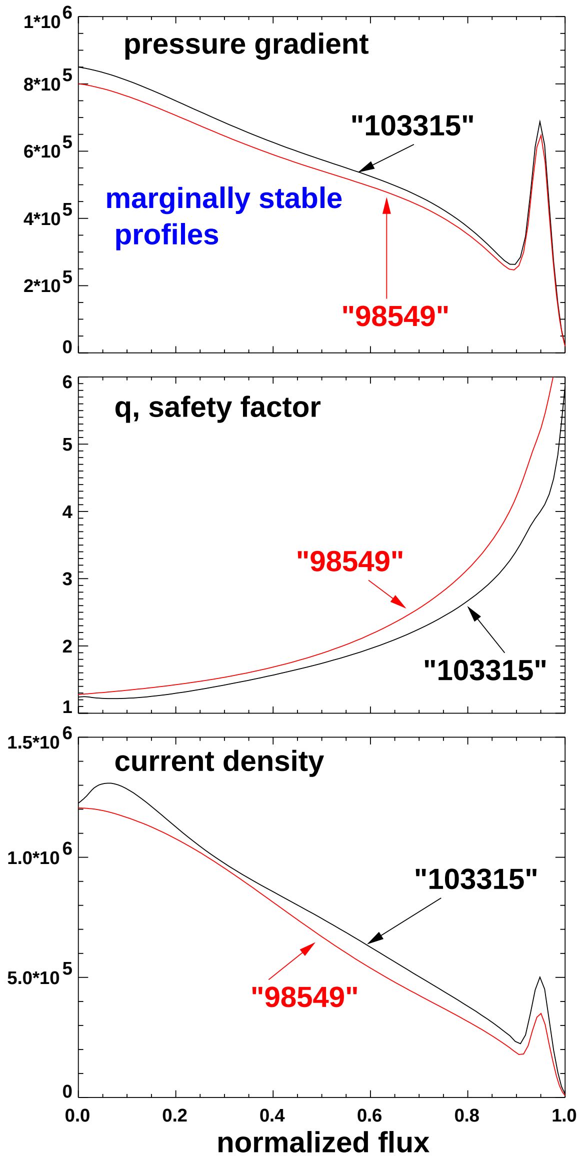
Stability modeling results show that the marginal value of β_N is constant or decreasing as B_T and q_{95} are increased

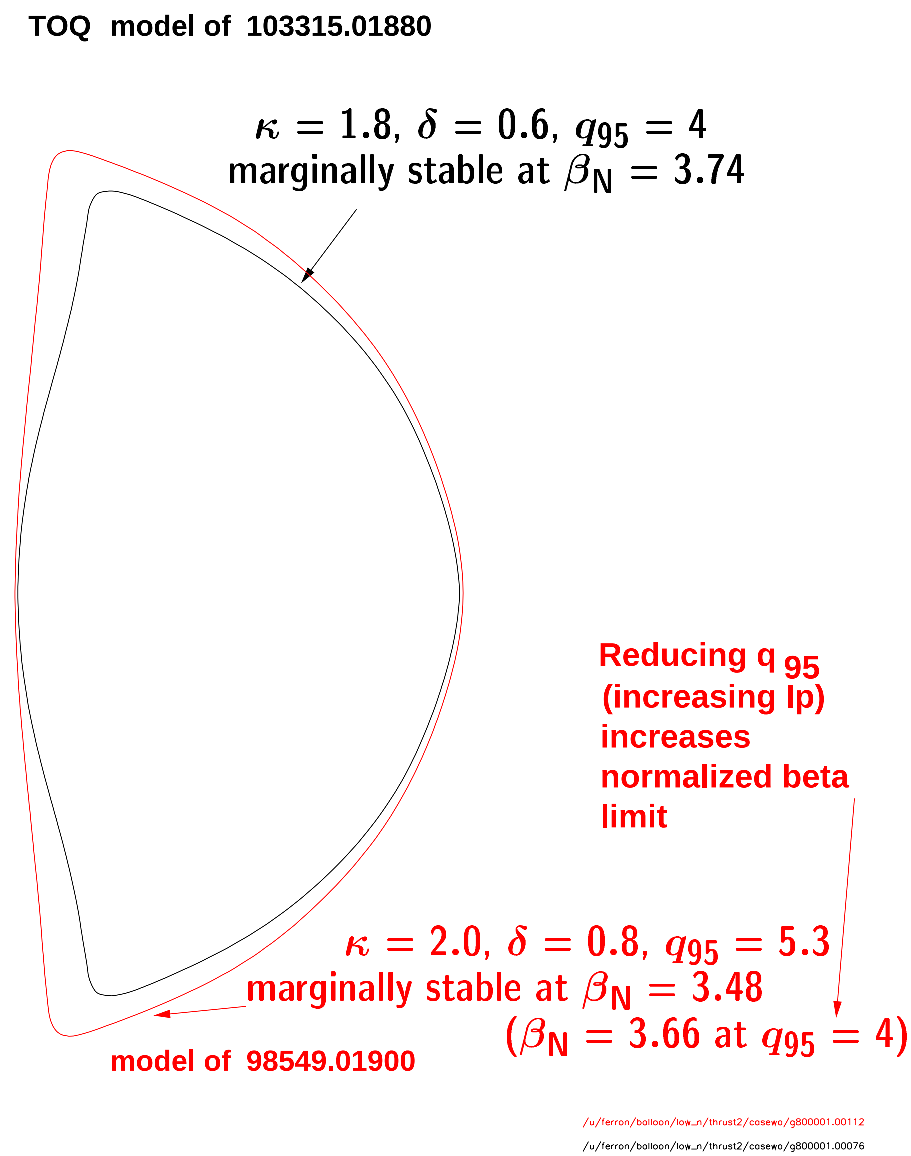
- No-wall β_N limit for $n = 1$ from GATO/TOQ.





No increase in the ideal, no-wall, $n = 1$ stability limit with extra shaping has been found in initial modeling results

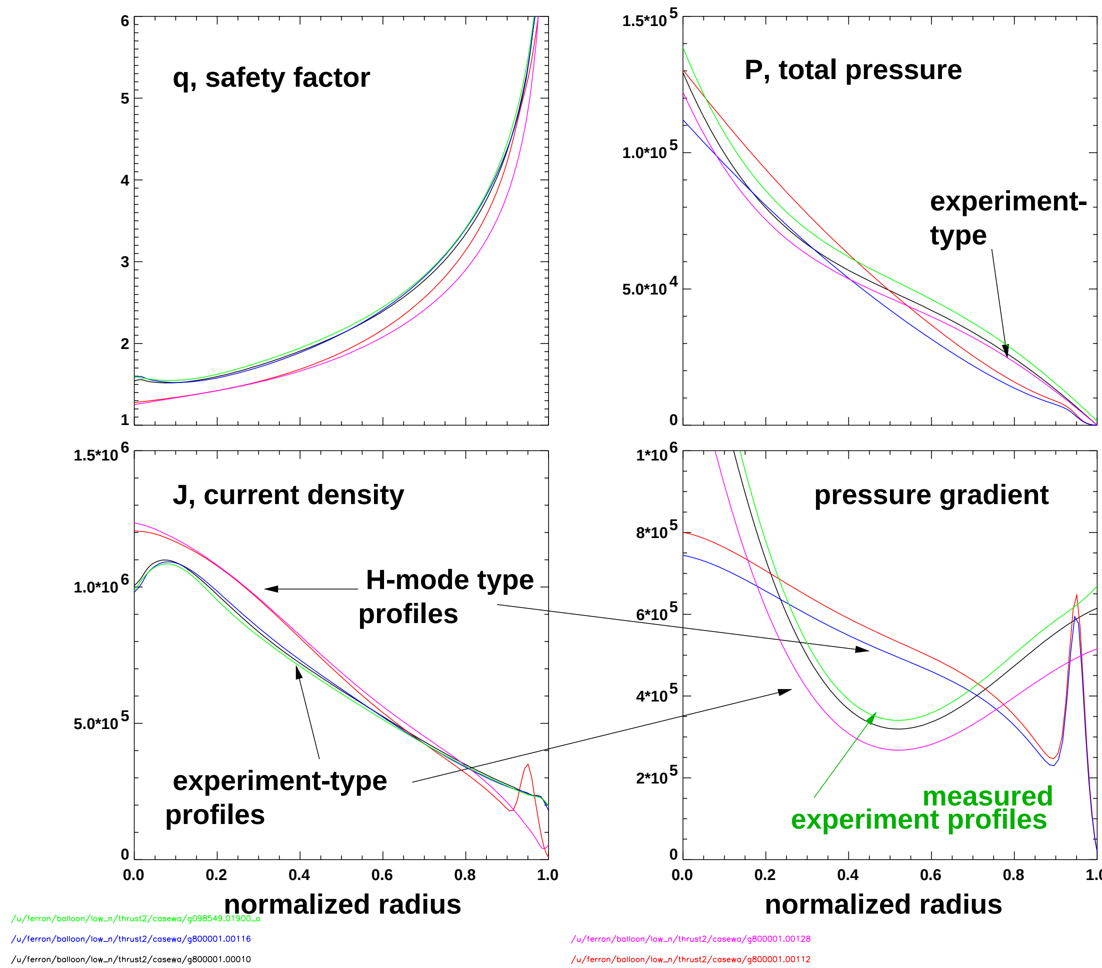




Sensitivity of the β_N limit to the model profiles was studied for the more strongly shaped case

	H-mode type J profile ($q(0) \approx 1.27$)	experiment-type J profile ($q(0) \approx 1.6$)
H-mode P' profile	3.52	3.15
Experiment-type P' profile	3.34	3.62

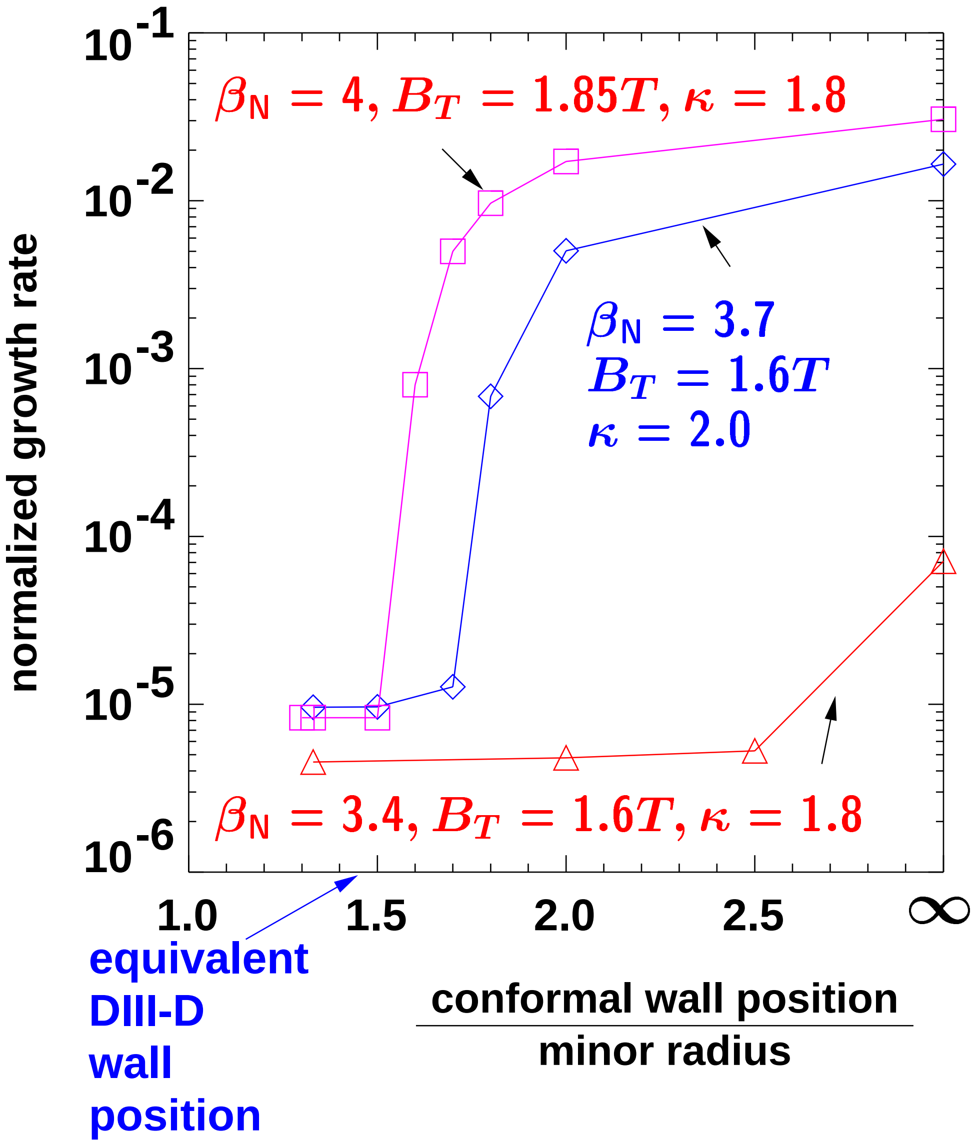
- β_N limit varies by at most 0.5.
- Strongly shaped discharge had an unusually broad pressure profile.



Effect of an ideal wall

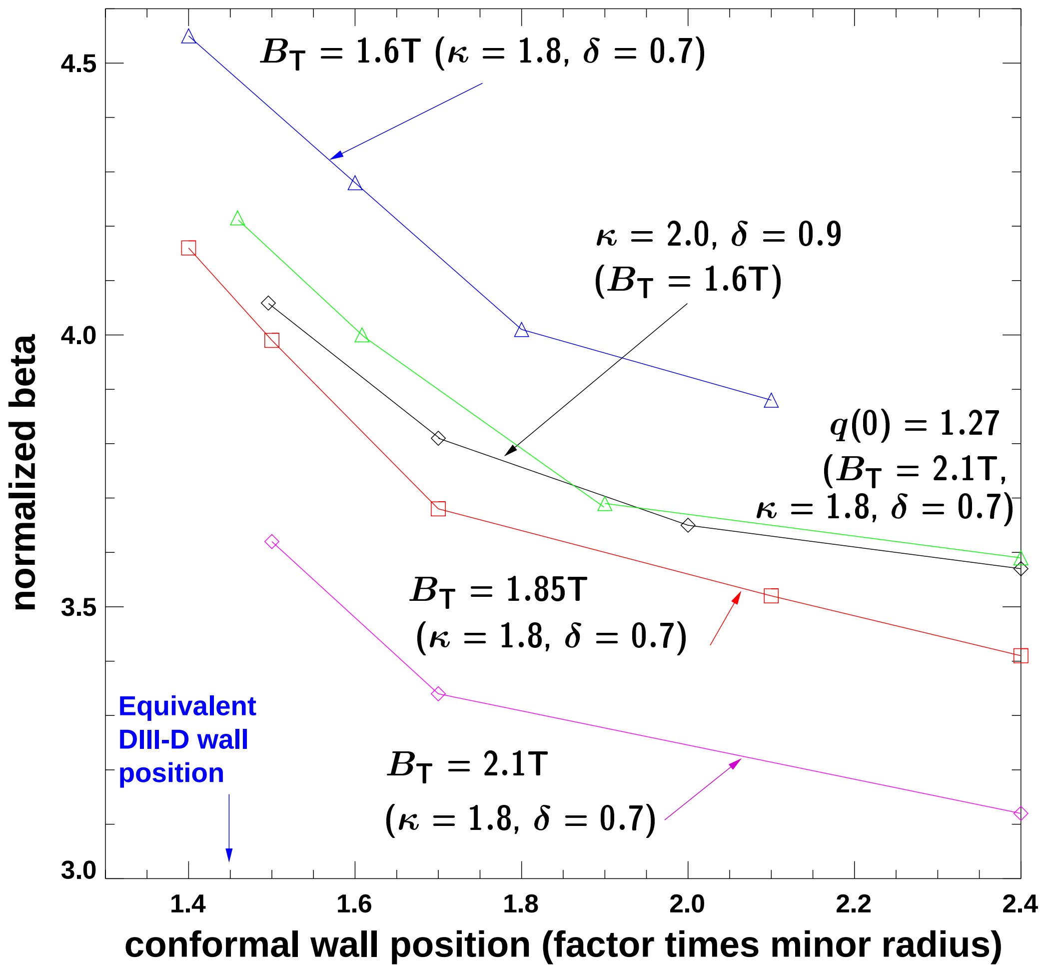
Increases in β_N achieved by exceeding the no-wall limit by a wider margin

- The no-wall limit is exceeded if the ideal wall must be present for stability.
- The more the no-wall limit is exceeded, the closer the stabilizing wall must be to the plasma.



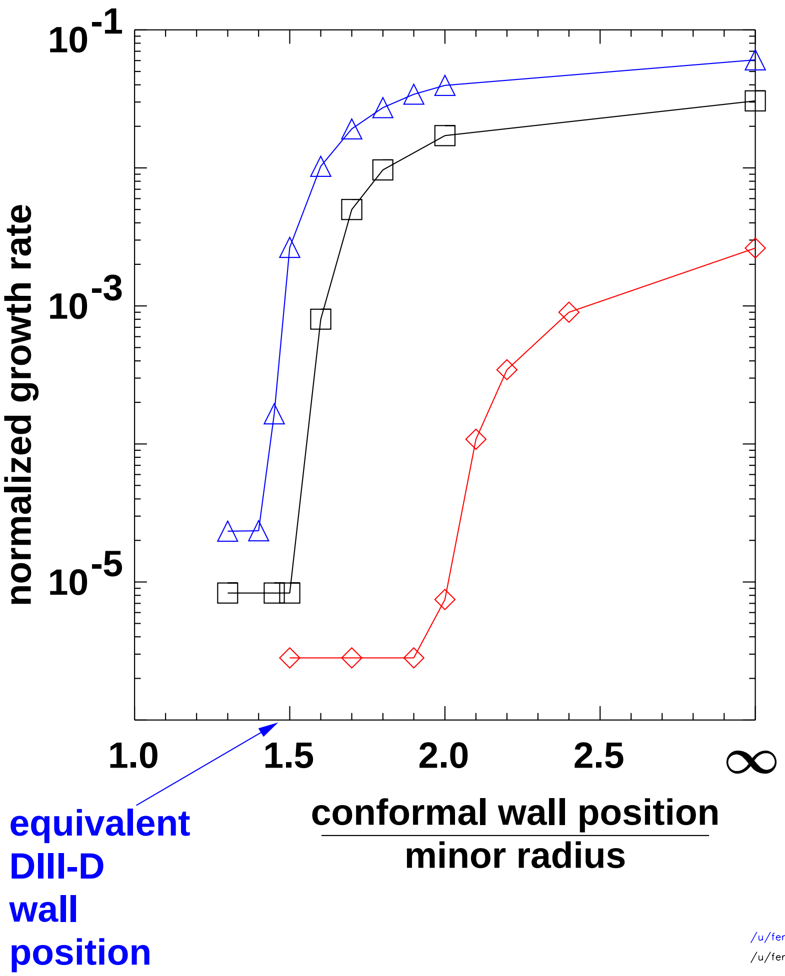
Maximum β_N achievable with an ideal wall determined by modeling stability versus wall position

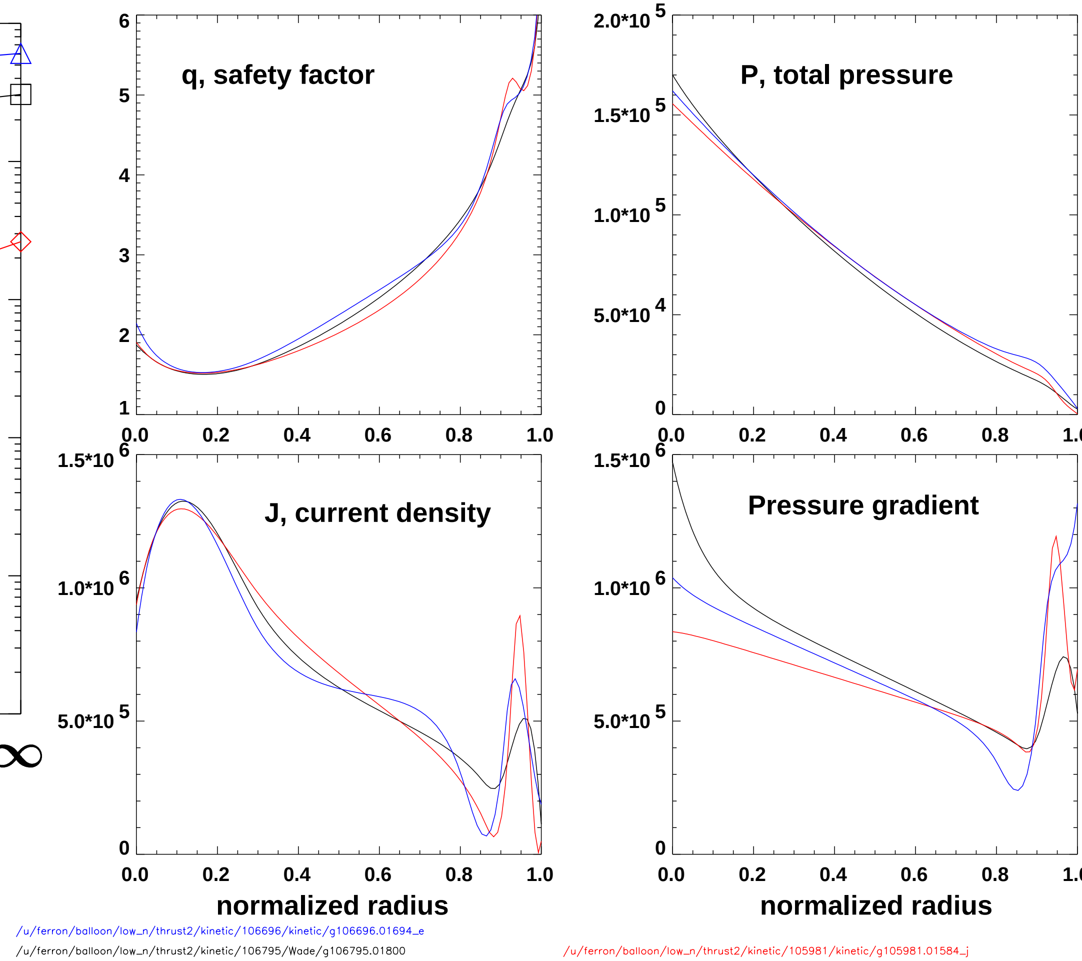
- Little difference in response to change in wall position as shape and B_T (i.e. q_{95}) are varied.



Some experimental discharges with $\beta_N \geq 4$ are near the ideal wall $n = 1$ stability limit

- Effect of wall depends on details of the equilibrium in 3 examples with $\beta_N \geq 4$.





Summary

Summary

- The advanced tokamak steady-state scenario required a method to increase achievable β_{N} in the lower κ, δ pumping shape.
- An increase to $\beta_{\mathrm{N}} > 4$ was achieved by a 15% increase in B_{T}.
  - q_{95} is thought to be the key parameter.
  - Improved error field correction may be an enabling factor.
- The higher β_{N} values cannot be accounted for by an increase in the no-wall β_{N} limit.
- Increase in β_{N} likely results from a closer approach to the ideal wall β_{N} limit.
- Discharges at $q_{95} \approx 5$, $\beta_{\mathrm{N}} \approx 4.1$ appear to be close to the ideal wall limit.
- Further increases in the ideal wall limit appear possible through changes in profiles.