Comparison of measured and calculated beta limits in DIII-D steady-state scenario discharges

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An understanding of the limits on $q\beta_N$ is a key to improving the prospects for steady-state advanced tokamak discharges

- Steady state: requires a large bootstrap current fraction $f_{BS} \propto \beta_P \propto q\beta_N$.
- Advanced tokamak scenario under study:
  - Moderately high q (including $q(0)$, q_{min}, q_{95}) to optimize f_{BS}.
    - $1.5 < q_{min} < 3$, $q_{95} \approx 5$.
  - High β_N to increase f_{BS} and for:
    - Fusion gain ($\propto \beta\tau_E \propto (\beta_N/q)(H_{89}/q^{\alpha})$).
    - Efficiency of off-axis electron cyclotron current drive (ECCD).
  - Low density:
    - For relevant collisionality and efficient ECCD.
    - Requires effective pumping of H-mode divertor exhaust. Presently in DIII-D, this requires an up/down asymmetric shape.

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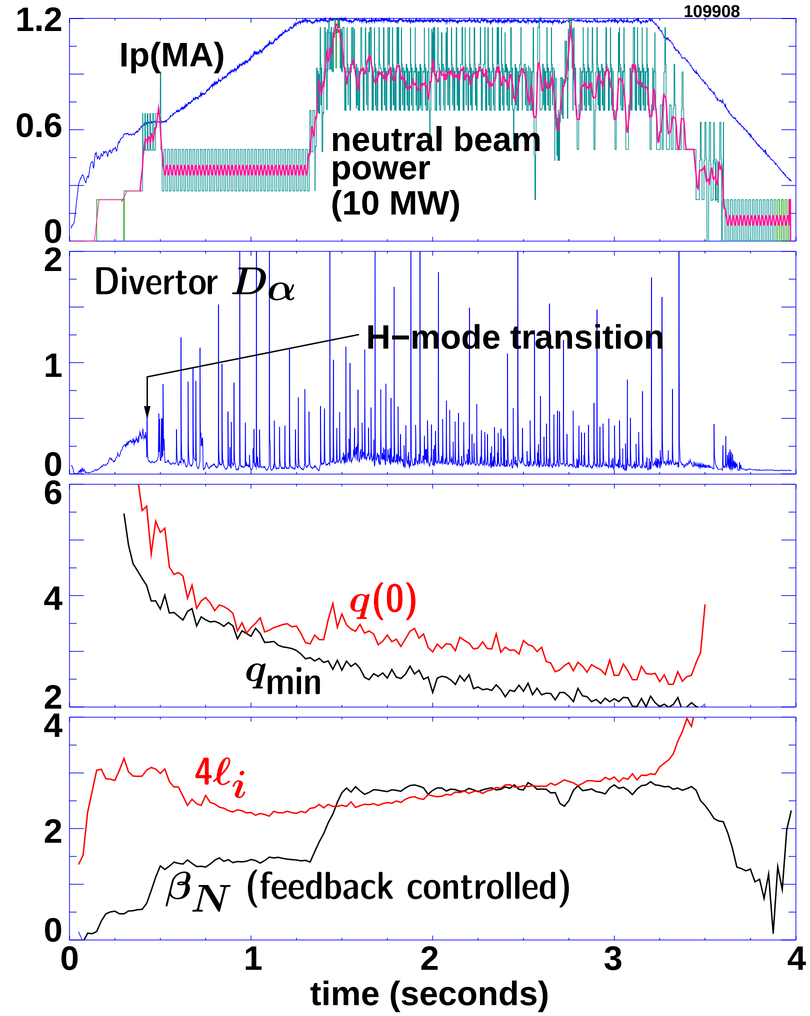
Measured and predicted β_N limits decrease as q_{min} increases in present DIII-D discharges

- Tools for these experiments:
  - Discharges with $q_{min} > 2.5$.
  - A measurement of the no-wall $n = 1$ β_N limit.
- Measured no-wall β_N limit increases:
  - With lower q_{min} values.
  - With up/down double-null divertor symmetry.
  - With lower toroidal field ($\approx q_{95}$) values.
- Measurements agree with modeling of equilibria with P and J profiles typical of the experiment.
- Modeling including the DIII-D vessel wall, finds that an advanced tokamak scenario with a broad pressure profile can have $f_{BS} > 0.95$, $\beta_N > 6$ and stability to $n = 1$.

$q_{\mathrm{min}} > 2.5$ during high β_N phase is achieved with an early H-mode transition

- Increased T_e in H-mode slows rate of current penetration.



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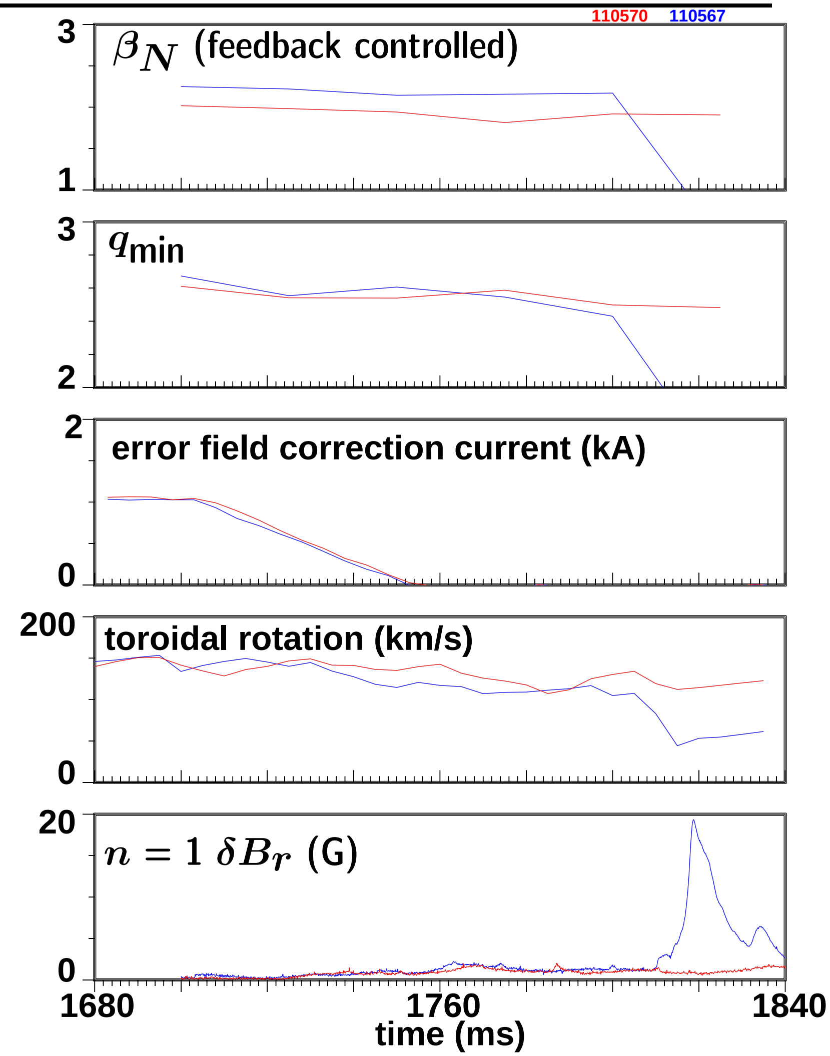
The experimental measurement of the no-wall β_N limit is made by observing the effect on toroidal rotation and stability as the correcting current for nonaxisymmetric error fields is removed

- For β_N above the no-wall limit, the drag on toroidal rotation is enhanced because of the plasma response to the nonaxisymmetric error fields.
- Rotation decreases significantly to below the critical level for $n = 1$ resistive wall mode stabilization.



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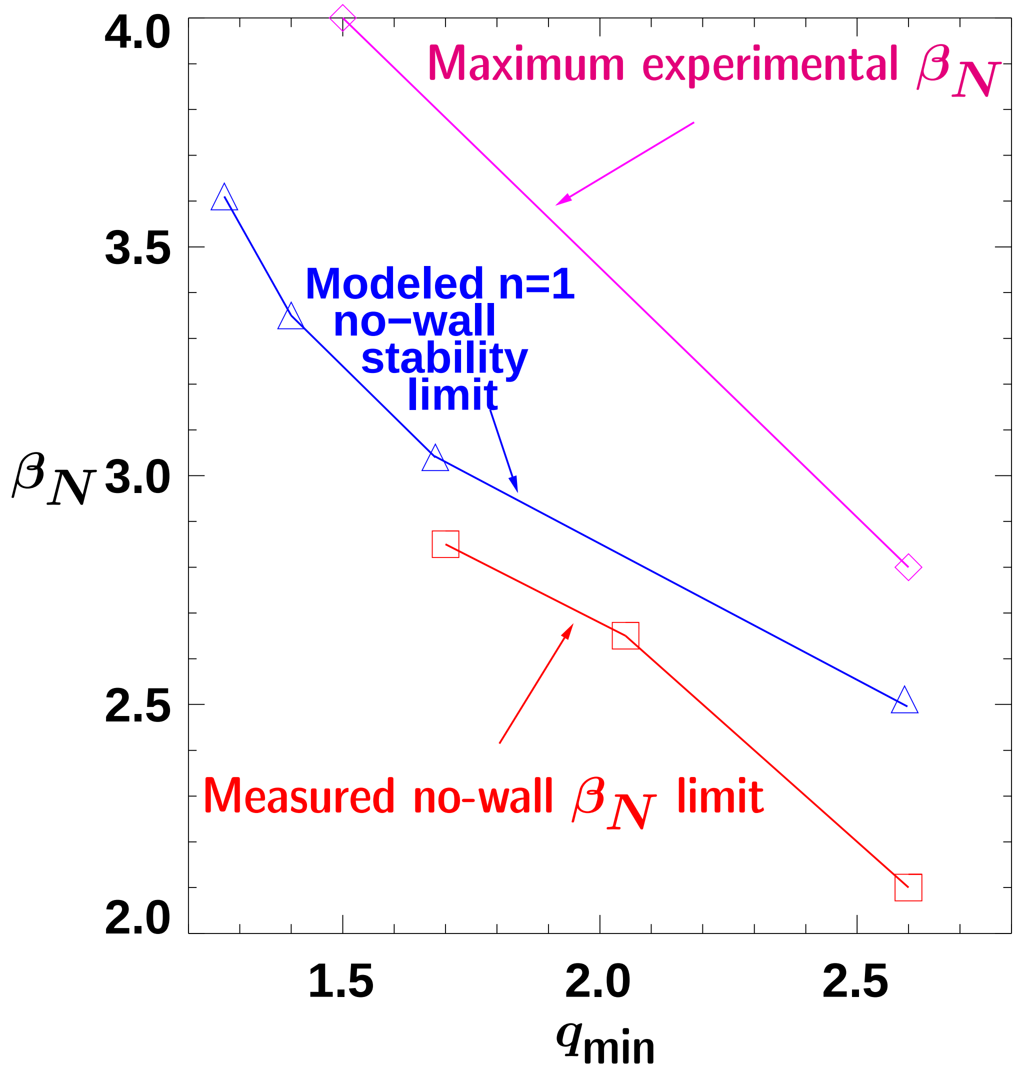
Measured no-wall β_N limit and maximum experimental β_N decrease as $q_{\rm min}$ increases

- Trend is the same for the $n = 1$ no-wall stability limit calculated for model equilibria.
- The predicted stability limit depends on the H-mode edge pedestal pressure gradient and current density.



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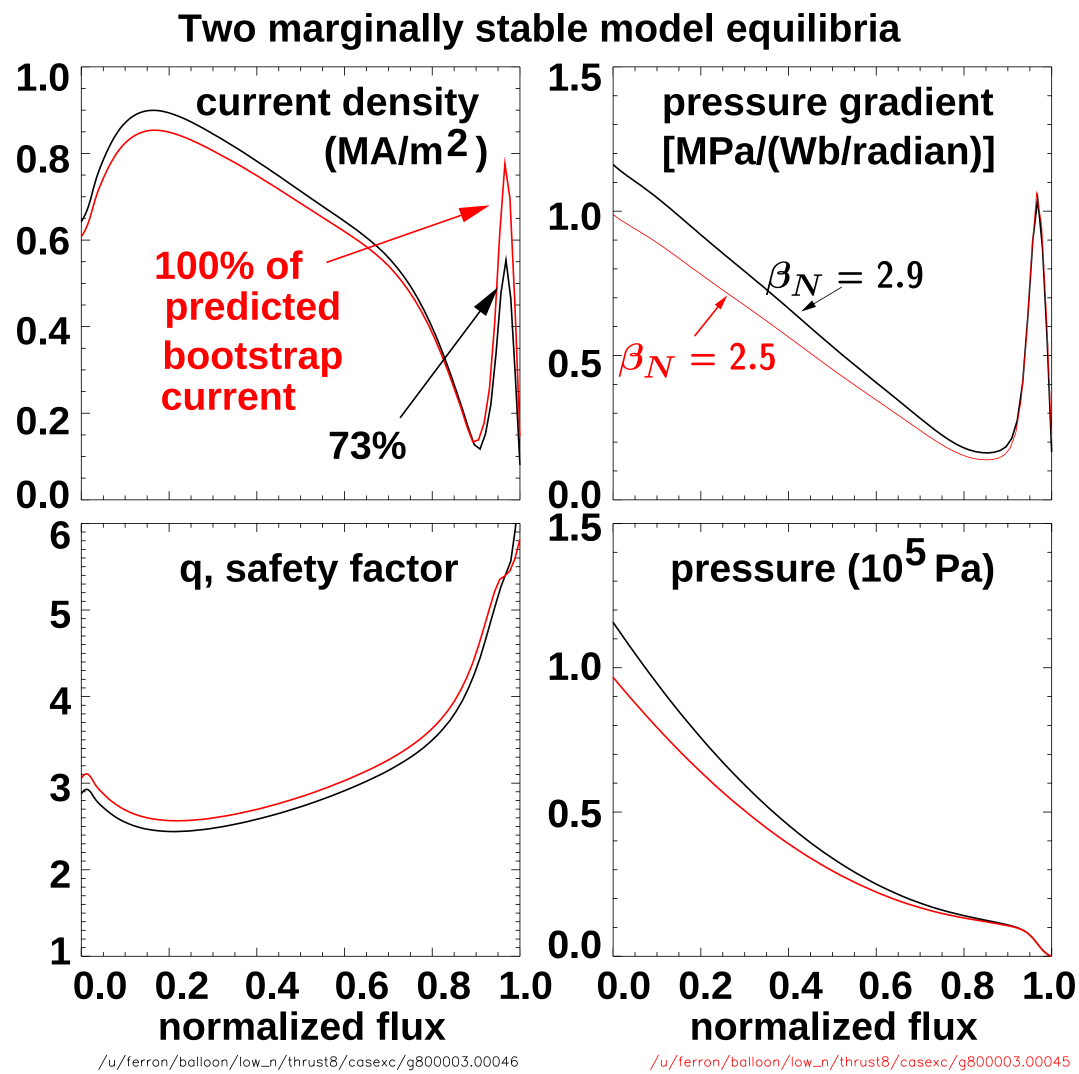
Increasing the modeled current density in the H-mode pedestal reduces the predicted β_N limit

- 100% of predicted bootstrap current: β_N limit ≈ 2.5
- 73% of predicted bootstrap current: β_N limit ≈ 2.9
- Motivates new diagnostic for the edge-region current profile.
- Also important: P'_{edge} peak value, width and shape of P'_{edge} profile.



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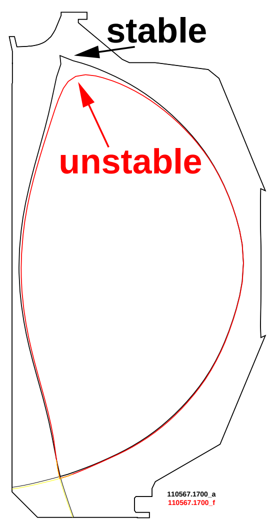
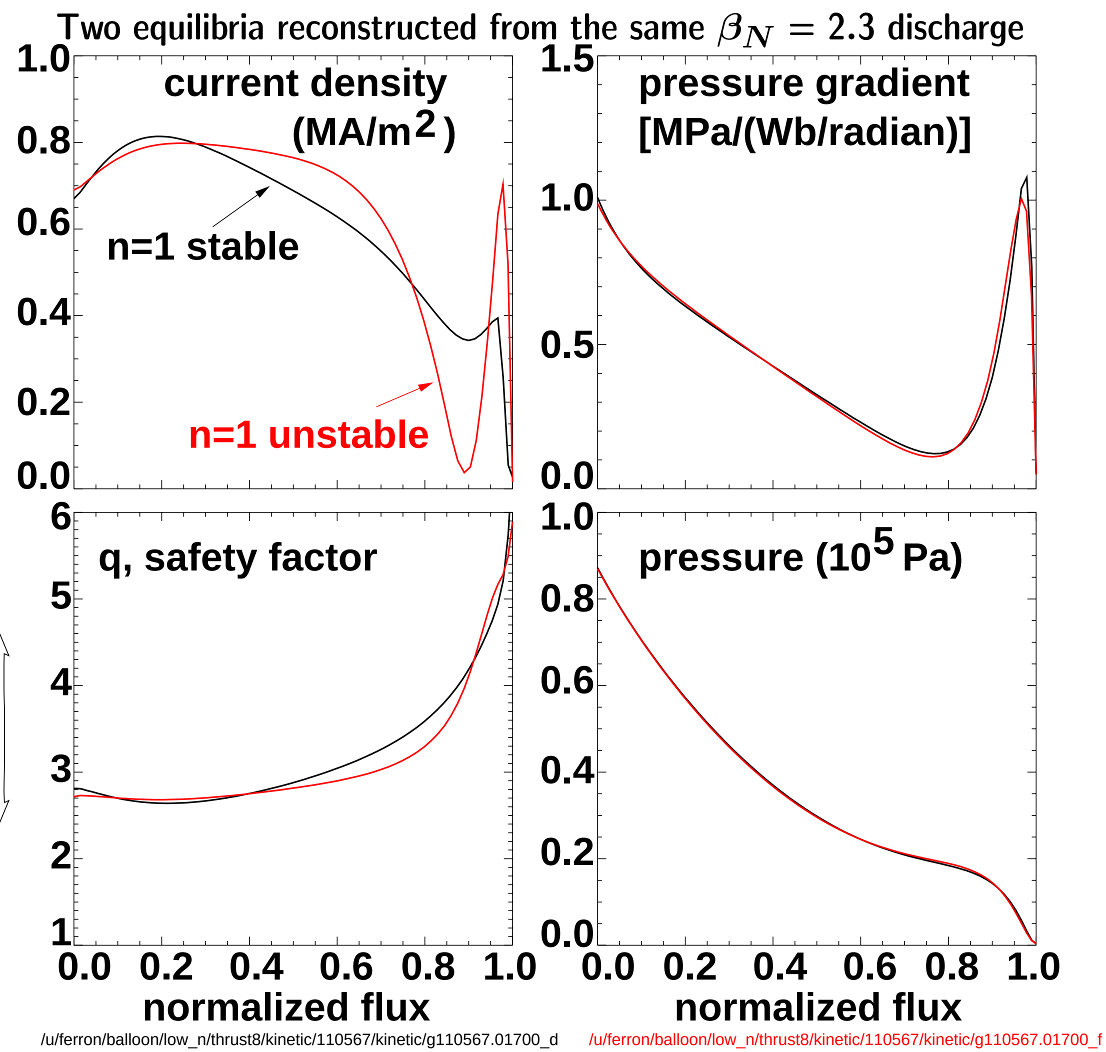
Stability analysis of equilibria reconstructed from experimental data does not identify the no-wall β_N limit with the resolution observed in the $q_{\min} > 2.5$ discharges

- Experiment: $\beta_N \leq 2$ stable, $\beta_N \geq 2.2$ unstable.
- Analysis: Within uncertainties, both stable and unstable reconstructed equilibria can be found in the range $1.8 \leq \beta_N \leq 2.6$.
- Primary uncertainties: discharge up/down symmetry, pedestal region J.





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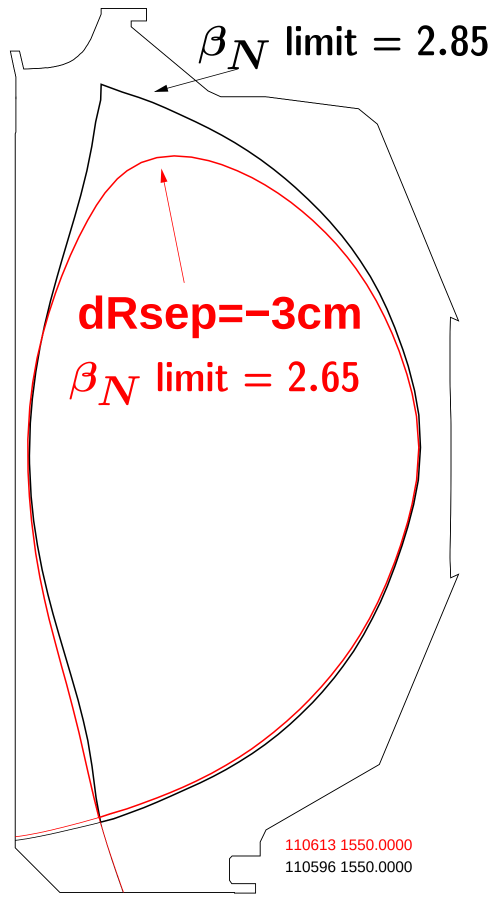
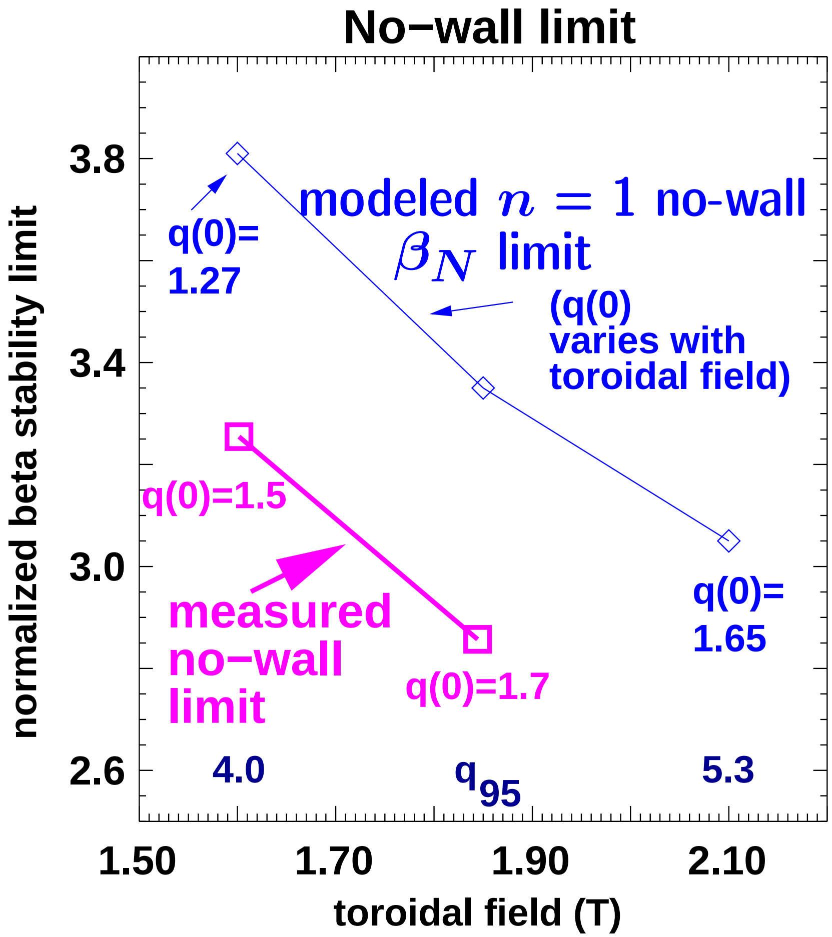
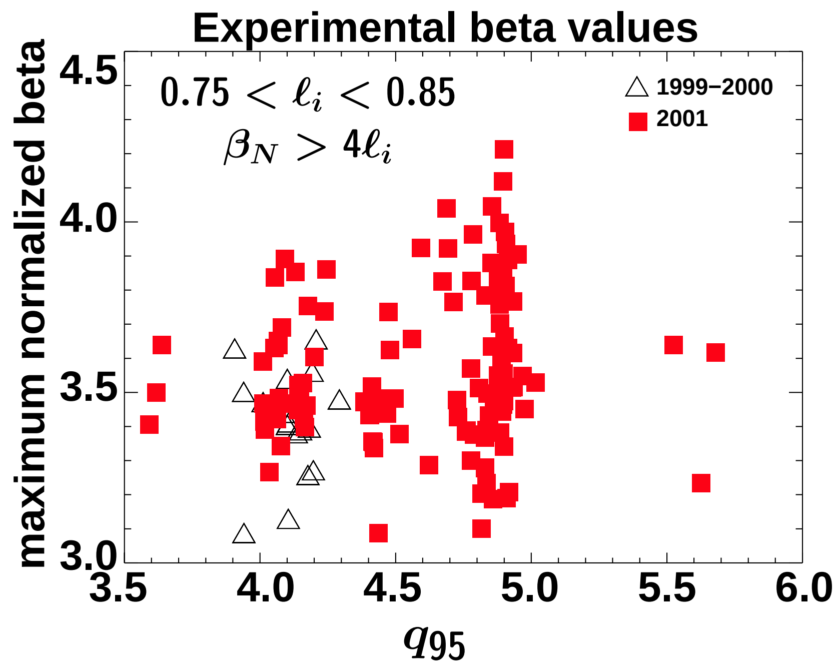
Measured $n = 1$ no-wall β_N limit is higher in a symmetric double-null shape



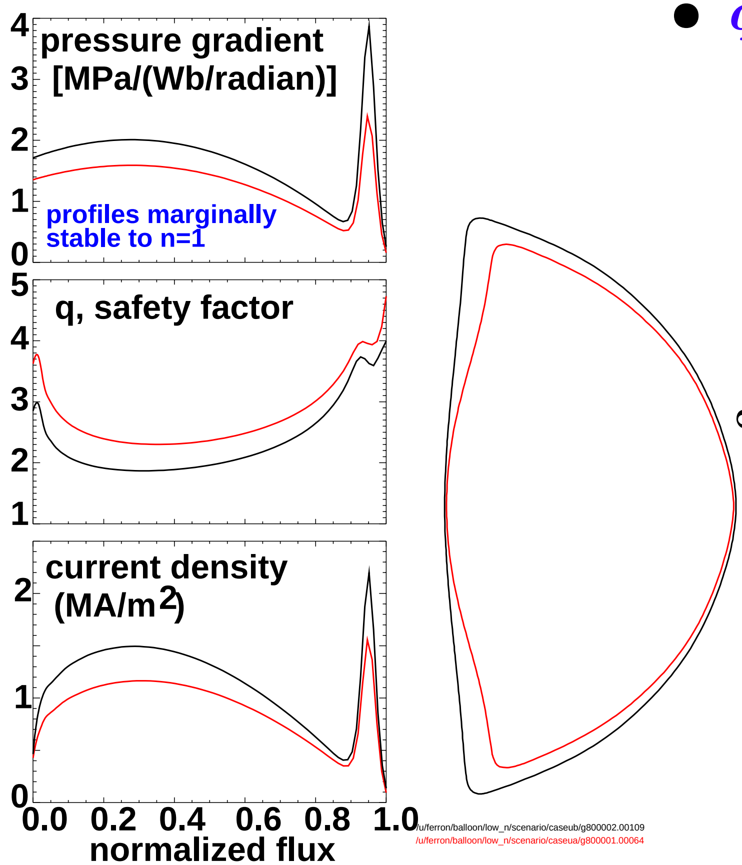
Measurement of the no-wall β_N limit versus B_T (or q_{95}) is consistent with the trend predicted by modeling



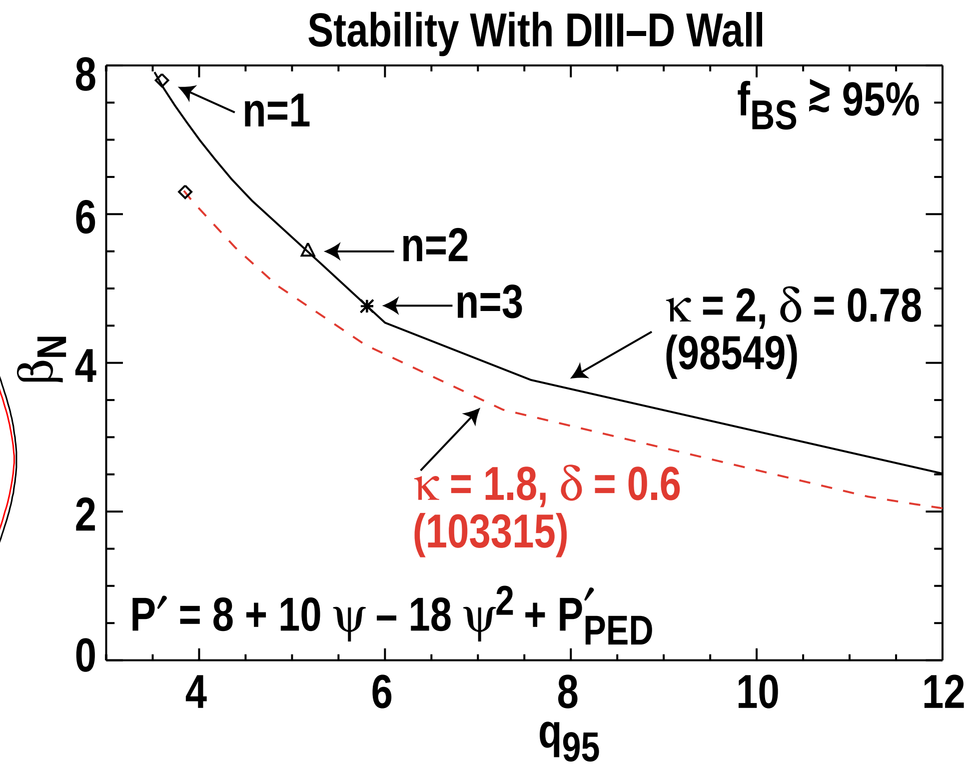
- In the experiment, achievable β_N increases with B_T because of operation closer to the ideal-wall β_N limit.



With the DIII-D conducting wall and broad pressure profiles: model equilibria with self-consistent bootstrap current profiles ($f_{\mathrm{BS}} > 95\%$) are predicted stable to $n = 1$ at $\beta_N > 6$



- $q_{\mathrm{min}} > 2$



- see also Makowski (QP1.061)

Progress has been made in understanding how to optimize $q\beta_N$ in advanced tokamak discharges

- Achievable β_N values are, thus far, lower in discharges with $q_{\text{min}} \approx 2.5$ than in discharges with $q_{\text{min}} \approx 1.5$.
- Measured and predicted no-wall, $n = 1$ β_N limits both show:
  - A decrease as q_{min} or q_{95} increases.
  - An increase with double-null divertor up/down symmetry.
- Details of the H-mode edge pedestal region parameters are important to $n = 1$ stability.
- An advanced tokamak scenario in DIII-D with β_N near 6 and close to 100% bootstrap current is reasonable if the core pressure profile can be broader than in present experiments.