Ideal MHD stability scaling with aspect ratio, shaping, and q

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Outline

- Will describe systematic computational studies of aspect ratio dependence of ideal stability limits

- Search for possible aspect ratio "invariants" of ideal stability, identify scalings which are not A-invariant

- This work is motivated by the predicted and observed increase in β_N and κ limits at low A

Example:

  – Typical NSTX plasma aspect ratio A = 1.3-1.5
    - Achieved $\beta_N \geq 6.5$, $\beta_N / l_i > 10$
    - Sustained $\beta_N > 5$, $\kappa > 2.5$ at $l_i \approx 0.6$ for several τ_J

References: 1. Phys. Plasmas, Vol. 11, No. 2, February 2004, page 639
2. PPPL Report 3779, February 2003

Scope of computational studies:

1. Find optimized ***no-wall*** stability limit vs. A
   - All cases stable to n=1-3 kink and $n=\infty$ ballooning
   - f_{BS} = 50%, κ=2, δ=0.45, up-down symmetric & limited
   - No local BS current over-drive
   - No H-mode - edge p′ and $J_{||}$ profiles → 0 at boundary

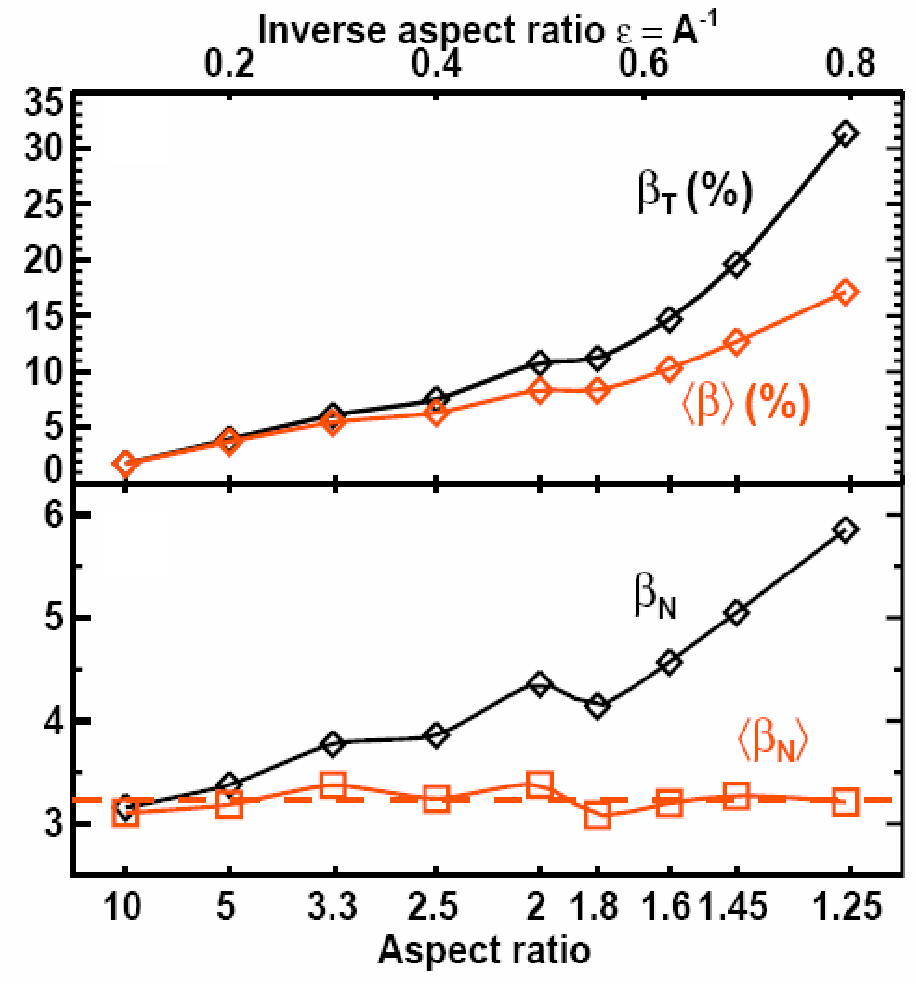
2. Study ***no-wall*** limits vs. shaping and q at fixed low-A
   - Squareness fixed at 0 for all scans treated here

3. Study ***ideal-wall*** limits vs. A at f_{BS} = 99%
   - All cases stable to n=1-6 kink and $n=\infty$ ballooning
     - Requires ideal wall at b_{wall} / a = 1.1
   - J profile perfectly aligned with J_{BS}, need 1% on-axis seed current
   - Elongation increased (and l_i decreases) as A → 1
     - All κ's stable with ideal wall at b_{wall} / a = 1.1

4700 JSOLVER fixed-boundary equilibria + DCON & PEST-I

No-wall stability at f_{BS}=50%, κ=2, δ=0.45

Expect $\beta_T \sim A^{-1/2}(1+\kappa^2)\,\beta_N^2 / f_{BS}$



← β_T increases 10-fold as A=10 → 1.25

← Low A separates β_T from $\langle\beta\rangle \equiv 2\mu_0\langle p\rangle/\langle B^2\rangle$ (Troyon)

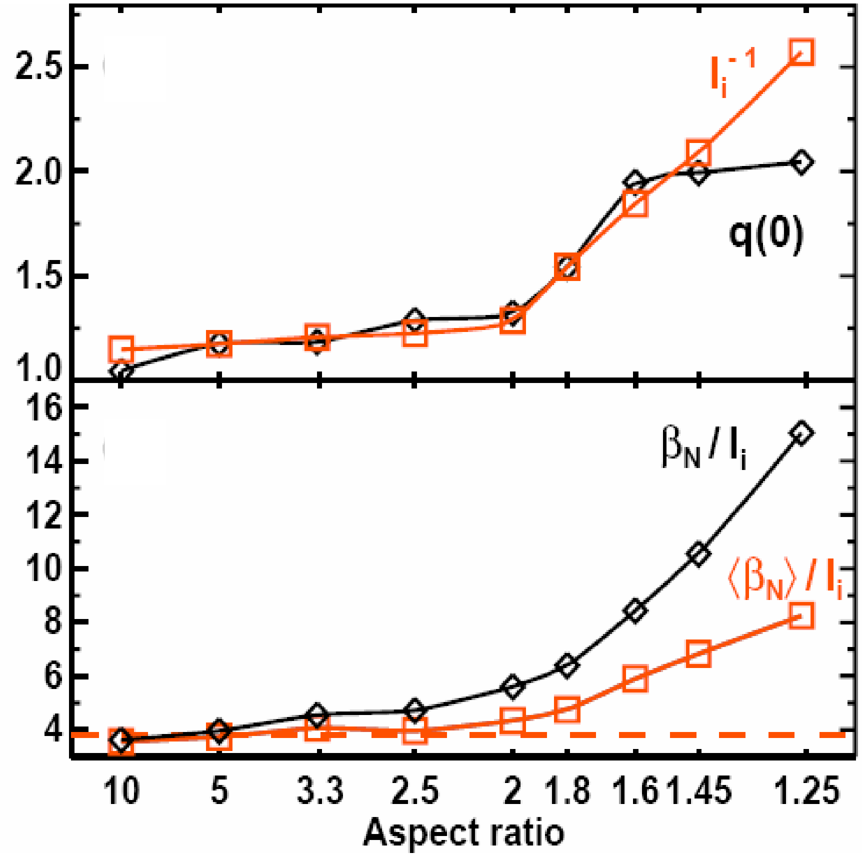
← β_N increases ≈ 2-fold as A=10 → 1.25

← $\langle\beta_N\rangle \approx 3.2$ nearly invariant

$\langle\beta_N\rangle \equiv \langle\beta\rangle$(%) a(m) B_T(T) / I_P(MA)

Troyon's original scaling apparently extends to low-A

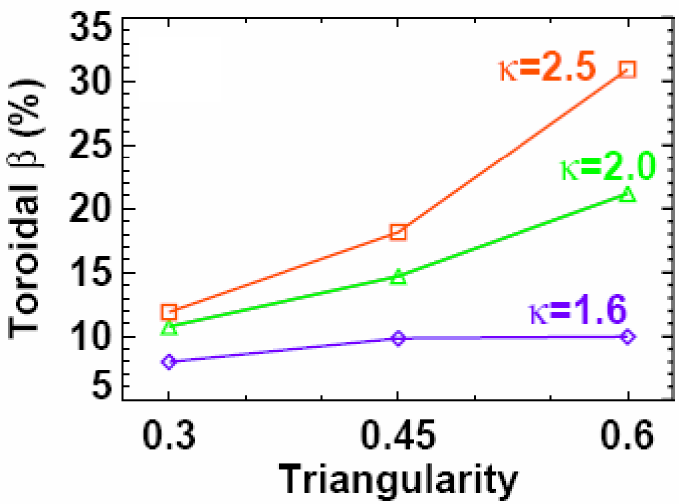
No-wall stability at f_{BS}=50%, κ=2, δ=0.45

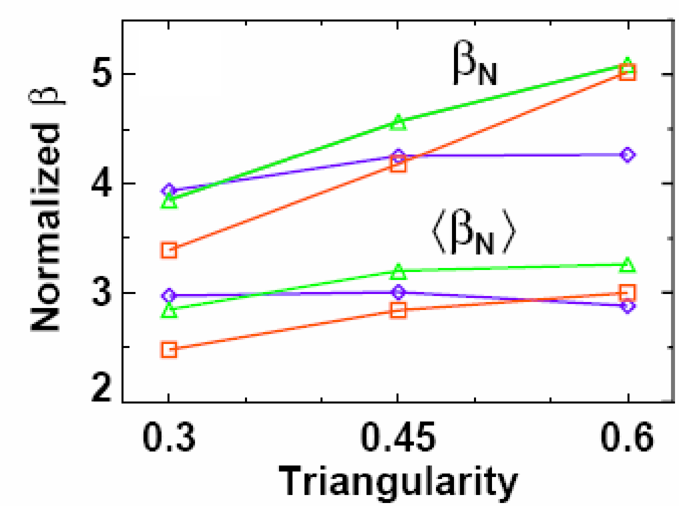


- ← Optimum $l_i \approx 0.8$ for A > 2
  - l_i drops to 0.4 as A → 1.25
- ← Optimum q(0) ≈ 1.2 for A > 2
  - q(0) increases to 2 as A → 1.25
- ← β_N / l_i → 16 as A → 1.25
  - Clearly $\beta_N / l_i \approx 4$ not A-invariant
- ← $\langle\beta_N\rangle / l_i$ also not A-invariant

No A-invariant β_N / l_i value has been found for the no-wall limit

No-wall stability at f_{BS}=50%, A=1.6





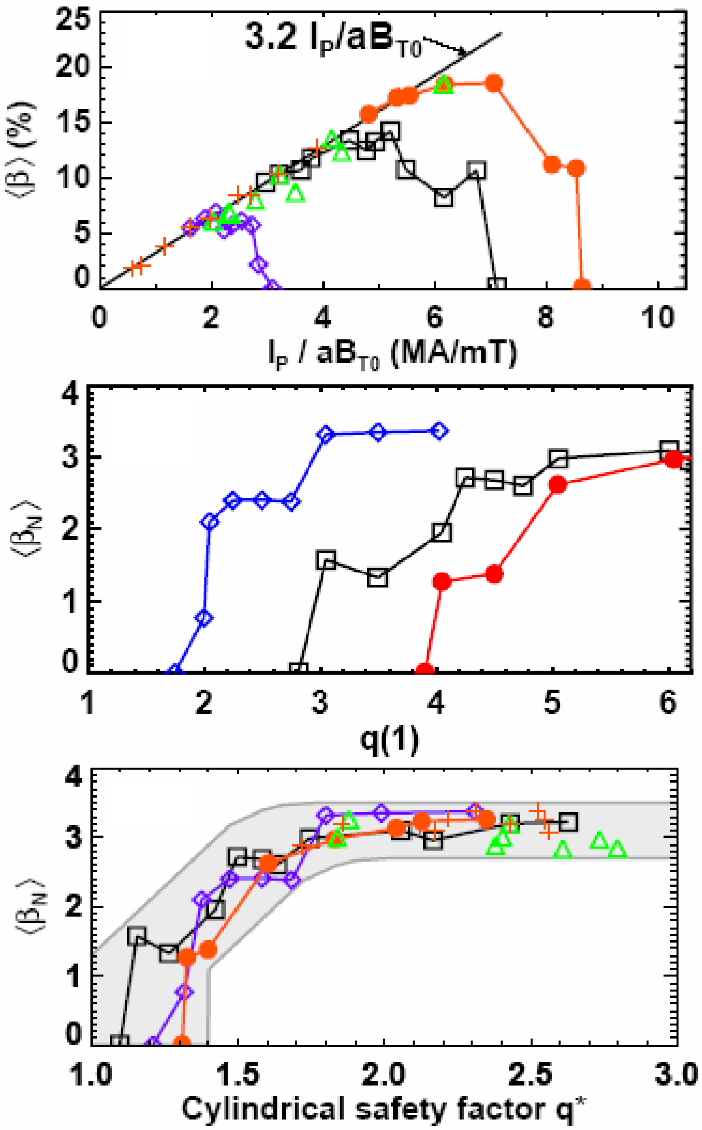
← β_T limit can increase 3-fold as κ increases from 1.6 to 2.5
- Only 1.5 × increase with κ at δ = 0.3
- **High δ <u>essential</u> for highest stable β_T**

← β_N limit increases from 3.5 to 5.5 with increasing δ at κ = 2.5
- **Much weaker $\beta_N(\delta)$ variation at low κ**

← $\langle\beta_N\rangle$ nearly invariant w.r.t. shape
- **But, $\langle\beta_N\rangle$ → 2.5 at highest κ, lowest δ**

High δ is required to take full advantage of high κ at low A
Similar result found in numerous previous studies at higher A

q scaling of the no-wall current limit:



← $\langle\beta\rangle(\%) \leq 3.2\ I_N \equiv I_P/aB_T$ for all scans

- **$\langle\beta\rangle$ scales linearly with I_N only above some critical "edge" q (below some I_N)**
- Current limit → kink unstable at β=0

← Edge q limit is not an A-invariant

- **A=3.3, κ=2.0, δ=0.45**
- **A=1.6, κ=2.0, δ=0.45**
- **A=1.6, κ=2.5, δ=0.60**

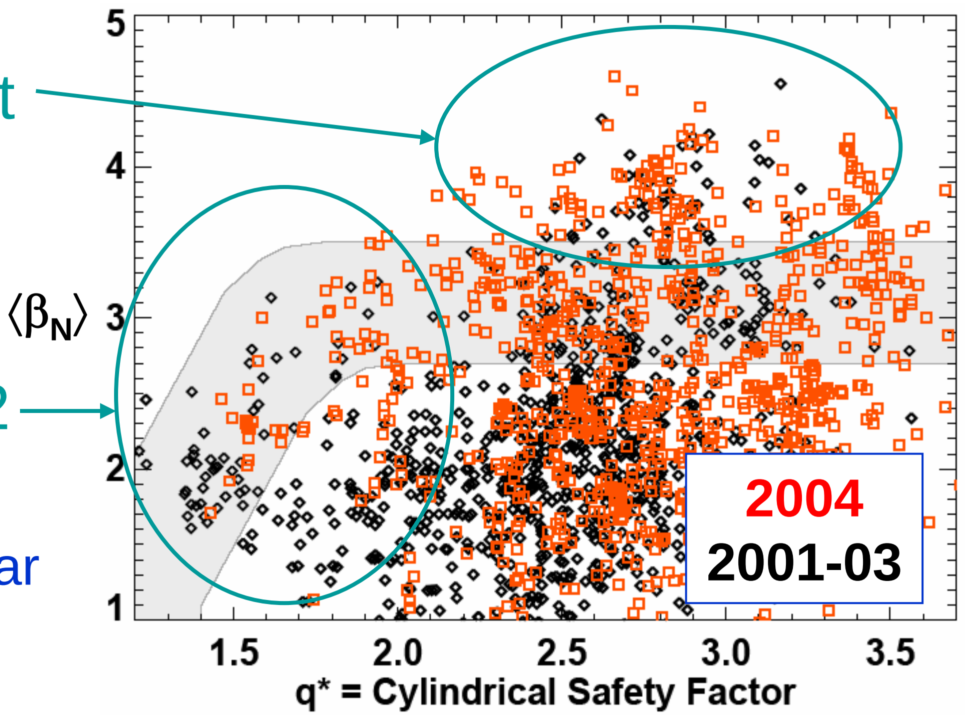
← $\langle\beta_N\rangle$ and $q^* \equiv \varepsilon(1+\kappa^2)\ \pi\ /\ \mu_0 I_N$ define no-wall stability space in a more aspect ratio invariant form:

- $\langle\beta_N\rangle$ decreases for $q^* < 2$
- $\langle\beta_N\rangle$ → 0 as q^* → 1 for all cases studied

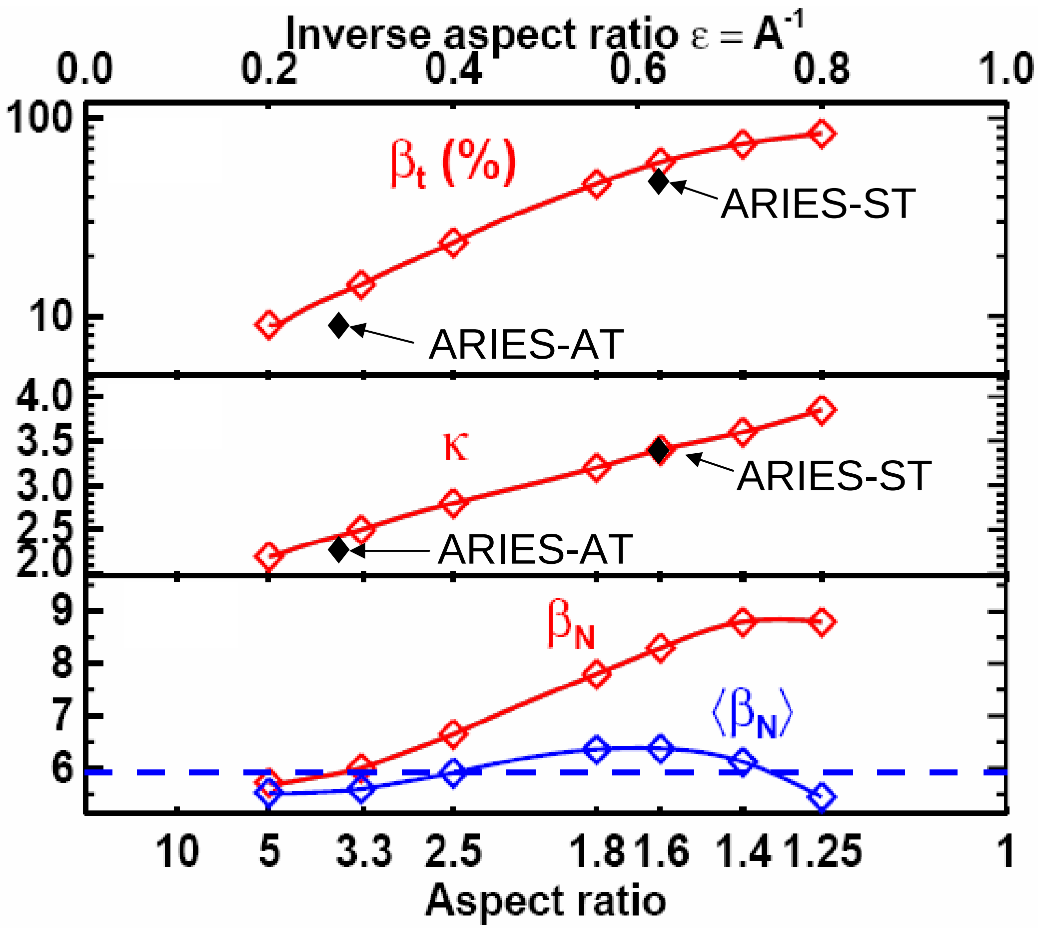
NSTX stability data compared to scalings:

- Highest-β_N shots are H-mode
  - **H-mode profiles → $\langle\beta_N\rangle \leq$ 3.5 for optimized *n*=1 no-wall limit**
    - 10% above limit for L-mode profiles
- Many shots above no-wall limit
  - Plasma rotation + close-fitting passive plates stabilize RWM
- **MAX**($\langle\beta_N\rangle$) decreases for $q^* < 2$
  - Appears to hold for κ = 1.8-2.4
  - Will test at high κ + high δ this year

A = 1.3–1.6, κ = 1.5–2.5
δ = 0.3–0.8, l_i = 0.5–1.7



β limits of wall-stabilized scenarios with $f_{BS} \rightarrow 100\%$



← β_T increases 8-fold as A=5 → 1.25

- Factor of 2 from lower A

← Low A requires high κ to achieve reactor-relevant β_T

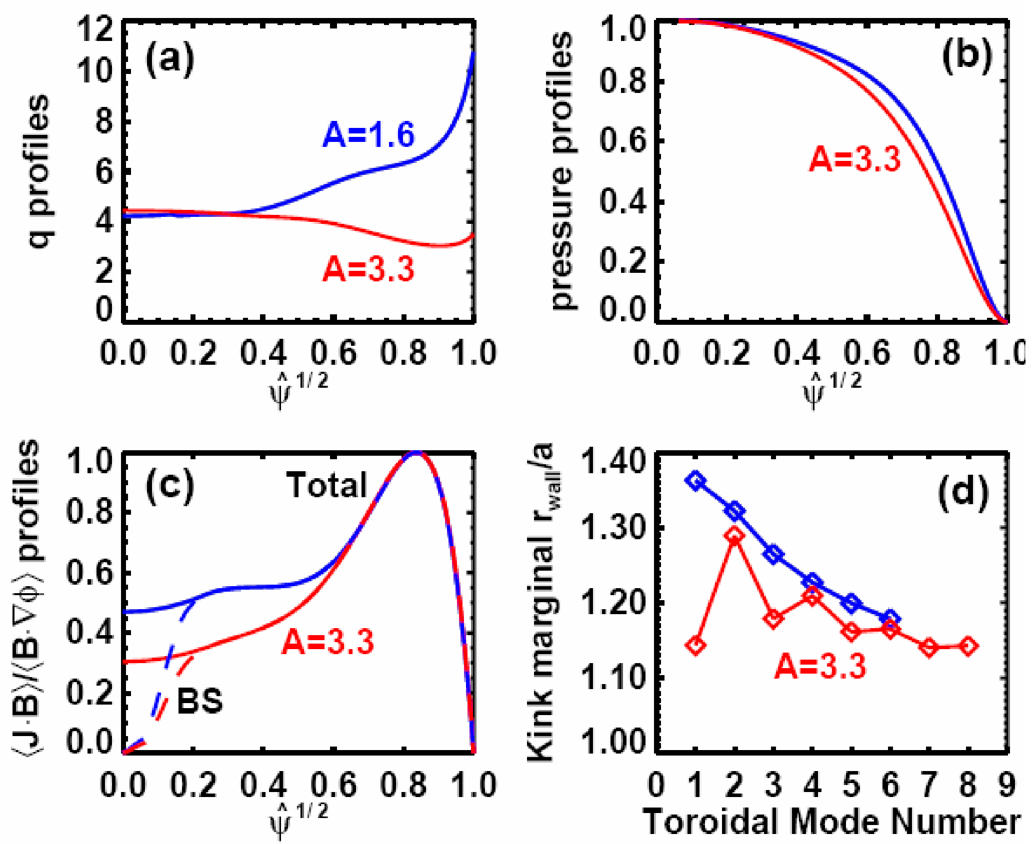
← β_N increases ≈ 1.5 × as A=5 → 1.25

← $\langle\beta_N\rangle = 6 \pm 0.5$ w/ ideal wall (only valid for this wall position)

***n* = 0-6 modes stable with ideal wall at 1.1 × minor radius →**

Active control (or rotation for RWM) required for plasma stability

Profiles of wall-stabilized scenarios with f_{BS} → 100%



(a) Low-A has monotonic shear, higher-A is reversed-shear
- Central q ≈ 4 for both cases

(b) Optimal *p* profiles very broad with peaking factor = 1.4

(c) Current density profiles very hollow with l_i = 0.15-0.3
- Small on-axis ext. CD required

(d) Intermediate to high-*n* kink modes set β limit

Overall, wall stabilization and optimized profiles can double the toroidal β and bootstrap current fraction → efficient & steady-state

Summary

- For fixed shape κ=2, δ=0.45 and f_{BS}=50%, the no-wall β_N limit doubles from 3 to 6 as A → 1

- A volume-average $\beta_N \equiv \langle\beta_N\rangle$ (Troyon) limit of 3-3.5 is an approximate aspect ratio invariant
  – High δ is required at high κ to maximize benefit of high κ
  – $\langle\beta_N\rangle$ and q^* good variables to parameterize current limit
  – NSTX data consistent with current limit scaling for $q^* < 2$

- For reactor scenarios with f_{BS}=99%, the ideal-wall β_N limit increases from 6 to 9 as A → 1
  – Results strongly dependent on constraints:
    - Wall position, *n* and *T* profiles, elongation, etc.