Comparison of Aspect Ratio Effects on Neoclassical Tearing Modes Between DIII-D and NSTX

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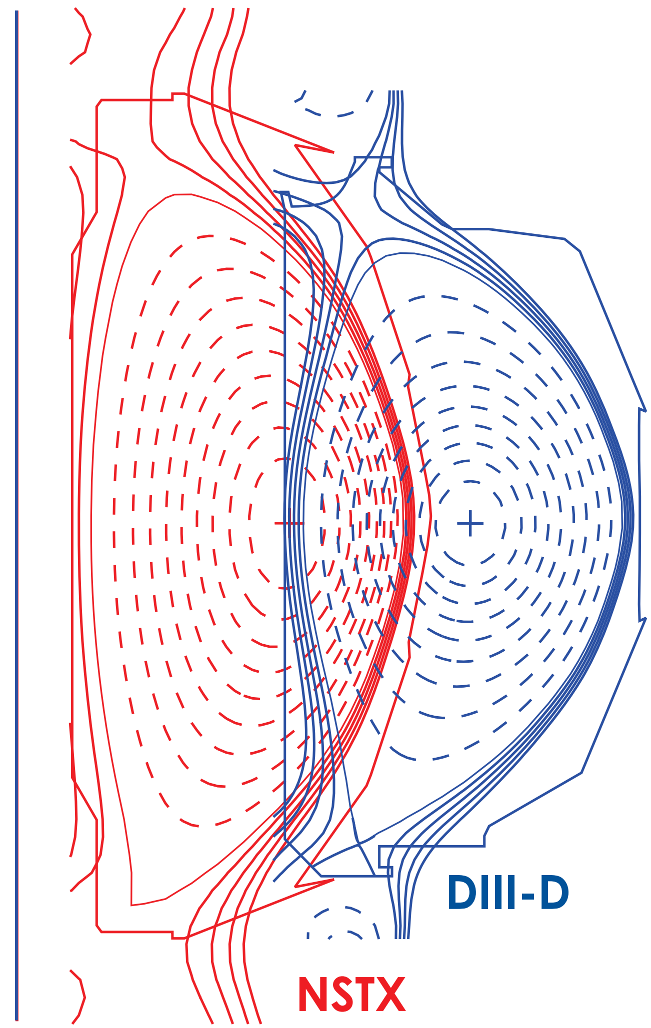

Aspect Ratio R/a = 1.4, 2.7

DIII-D NATIONAL FUSION FACILITY

NSTX

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Key Parameter at Issue is Local Inverse Aspect Ratio ε

- $\varepsilon \approx r/R_o$ at rational surface $q=m/n$
  - ★ approximately $(R_{OUT} - R_{IN})/(R_{IN} + R_{OUT})$
  - ★ rigorously $(B_{IN} - B_{OUT})/(B_{IN} + B_{OUT})$ is used here
    ... a 14% effect in NSTX
    ... 0.3% effect in DIII-D

- ε explicitly comes into...
  - ★ destabilizing bootstrap drive $\propto \varepsilon^{1/2}$, fraction of trapped particles
  - ★ stabilizing small island size $\propto \varepsilon^{1/2} \rho_{\theta i}$, ion banana width, for example
  - ★ relative size of stabilizing curvature $\propto \varepsilon^{3/2}$

Neoclassical Tearing Modes are Sustained by the Balance of the Sum of the Stabilizing Δ' and the Good Curvature with the Destabilizing Helically Perturbed Bootstrap Current

- **Modified Rutherford equation (MRE) for island growth or decay**

normalized growth rate

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + 6.35 r D_R/w + \varepsilon^{1/2}\frac{rL_q}{L_{pe}}\beta_{\theta e}\left[\frac{1}{w} - \frac{w_{small}^2}{3w^3}\right] \approx 0 \text{ is “balanced”}$$

stabilizing classical tearing index

destabilizing bootstrap

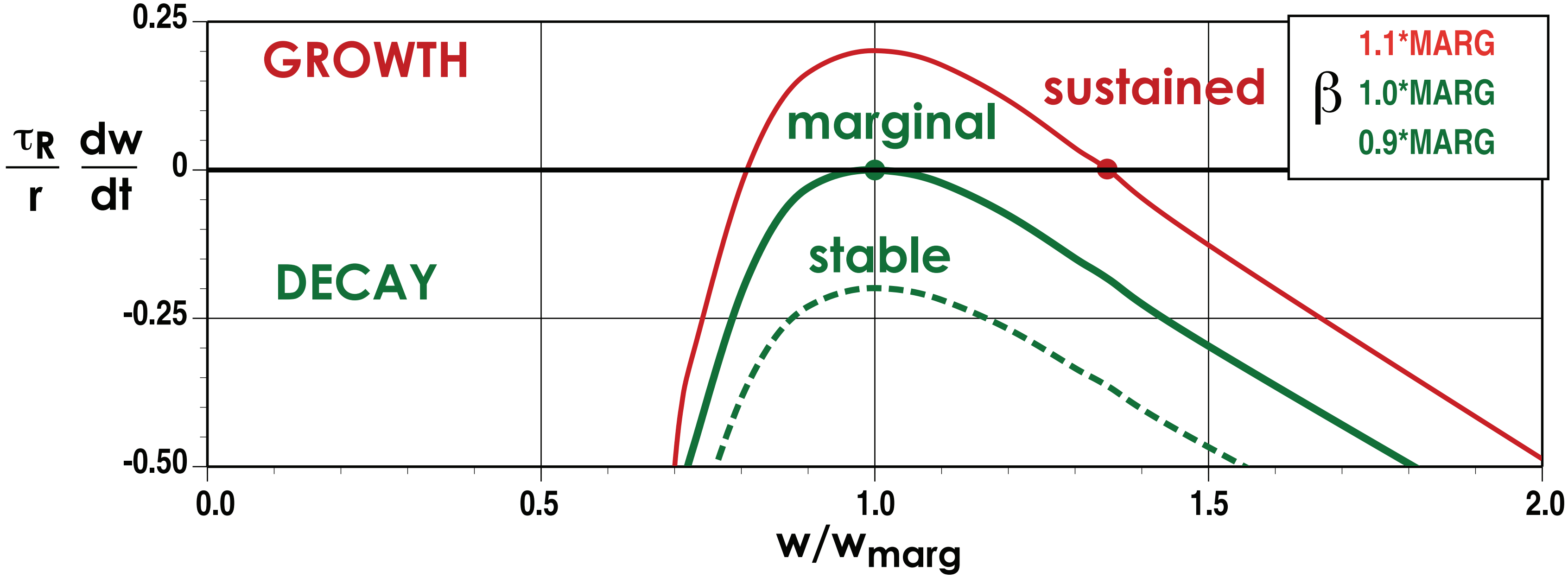
lumped small island stabilizing effects

stabilizing effect of good average magnetic field curvature with $D_R \approx -(q^2-1)(L_q^2/rL_p)\,\beta$ the “resistive interchange parameter”

Neoclassical Tearing Modes are Sustained by the Balance of the Sum of the Stabilizing Δ' the and Good Curvature with the Destabilizing Helically Perturbed Bootstrap Current

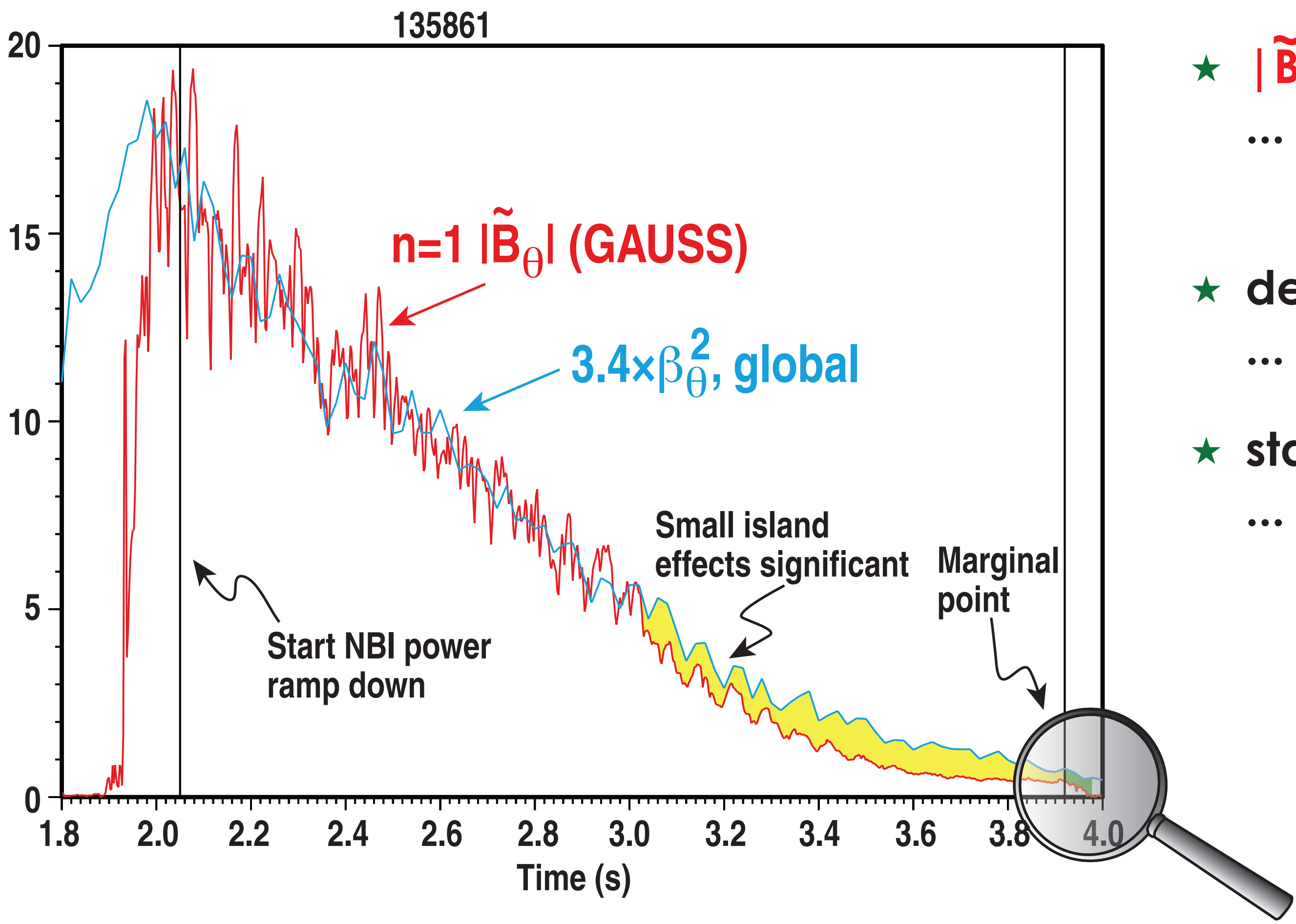
- **Modified Rutherford equation (MRE) for island growth or decay**
  - ★ **operationally, decrease beta to reach the marginal point ... island will stabilize**

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + 6.35 r D_R / w + \varepsilon^{1/2}\frac{rL_q}{L_{pe}}\beta_{\theta e}\left[\frac{1}{w} - \frac{w_{small}^2}{3w^3}\right] \approx 0 \text{ is “balanced”}$$



DIII-D Exhibits Large Hysteresis in Beta Between n=1 NTM Excitation and Self-Stabilization ("Marginal Point")

- NBI power ramped down after n=1 mode (here m=2) saturates



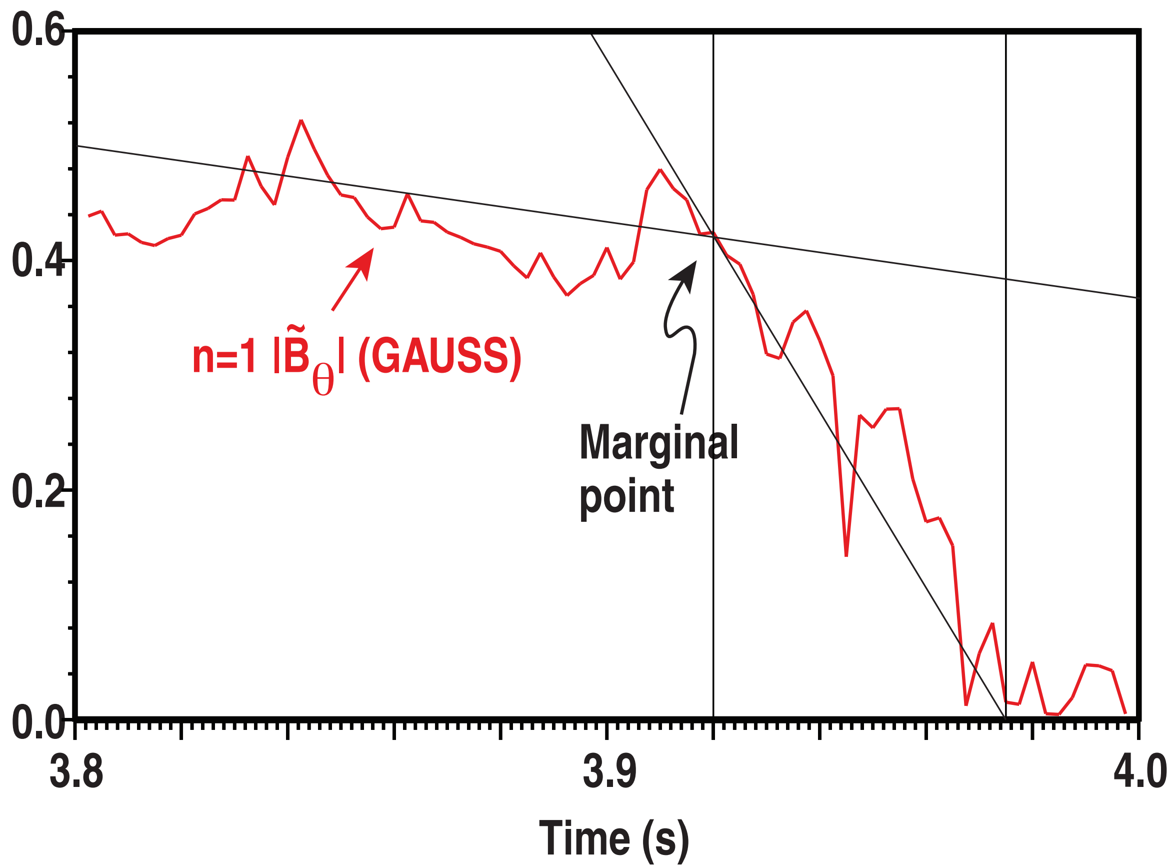
★ $|\tilde{B}_\theta| \propto \beta_\theta^2$
... signature of an NTM
– as $w \propto \beta_\theta$

★ deviates
... small island effects

★ stabilizes
... marginal point

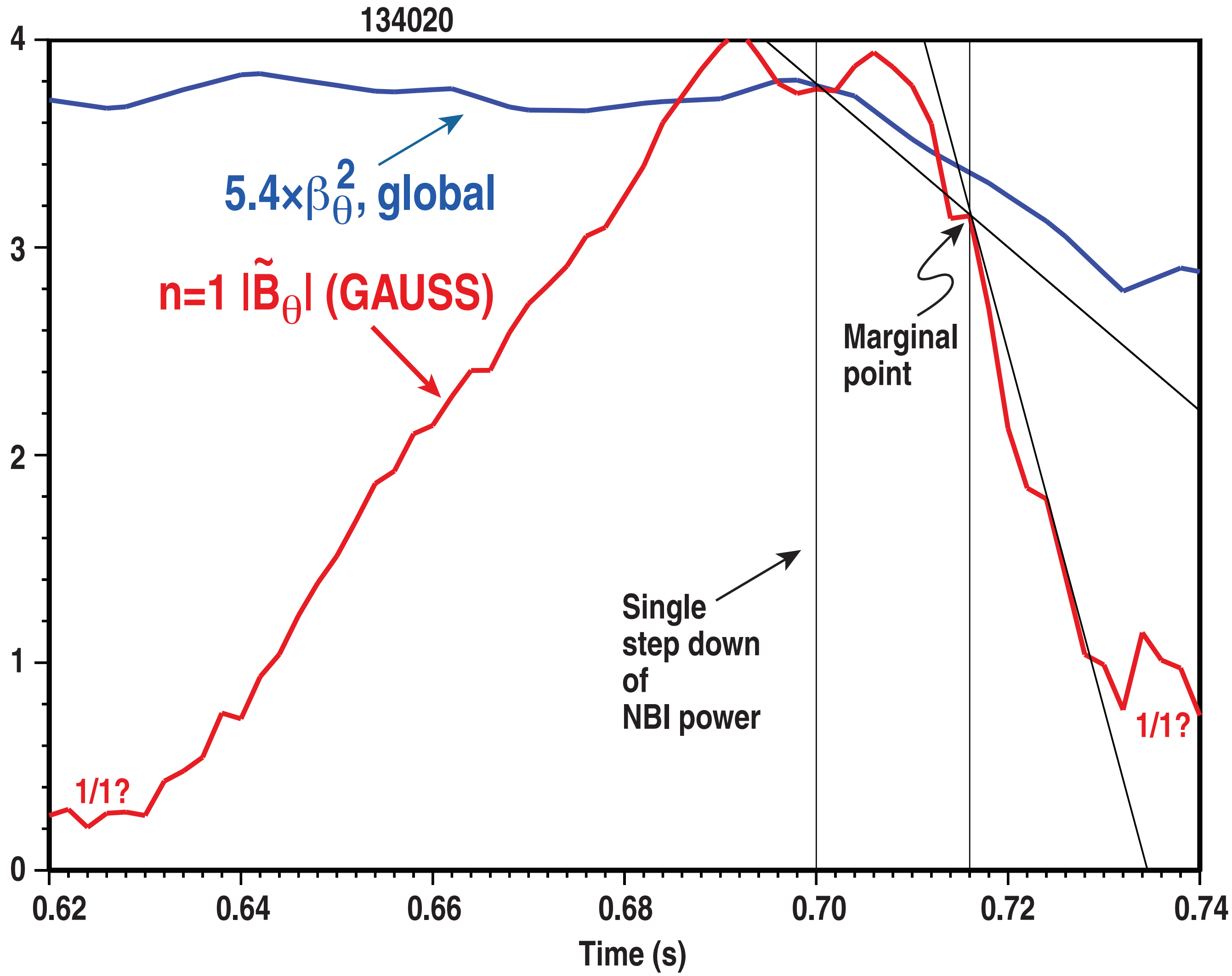
DIII-D Exhibits Large Hysteresis in Beta Between n=1 NTM Excitation and Self-stabilization ("Marginal Point")

- At marginal point dw/dt ≈ 0 at w ≈ w_{marg}
  - ★ beta below marginal point has dw/dt < 0 for all w



NSTX Exhibits Little Hysteresis in Beta Between n=1 NTM Excitation and Self-Stabilization ("Marginal Point")

- NBI power stepped down after m=2, n=1 mode saturates
  - ★ mode wanes, then stabilizes



NSTX

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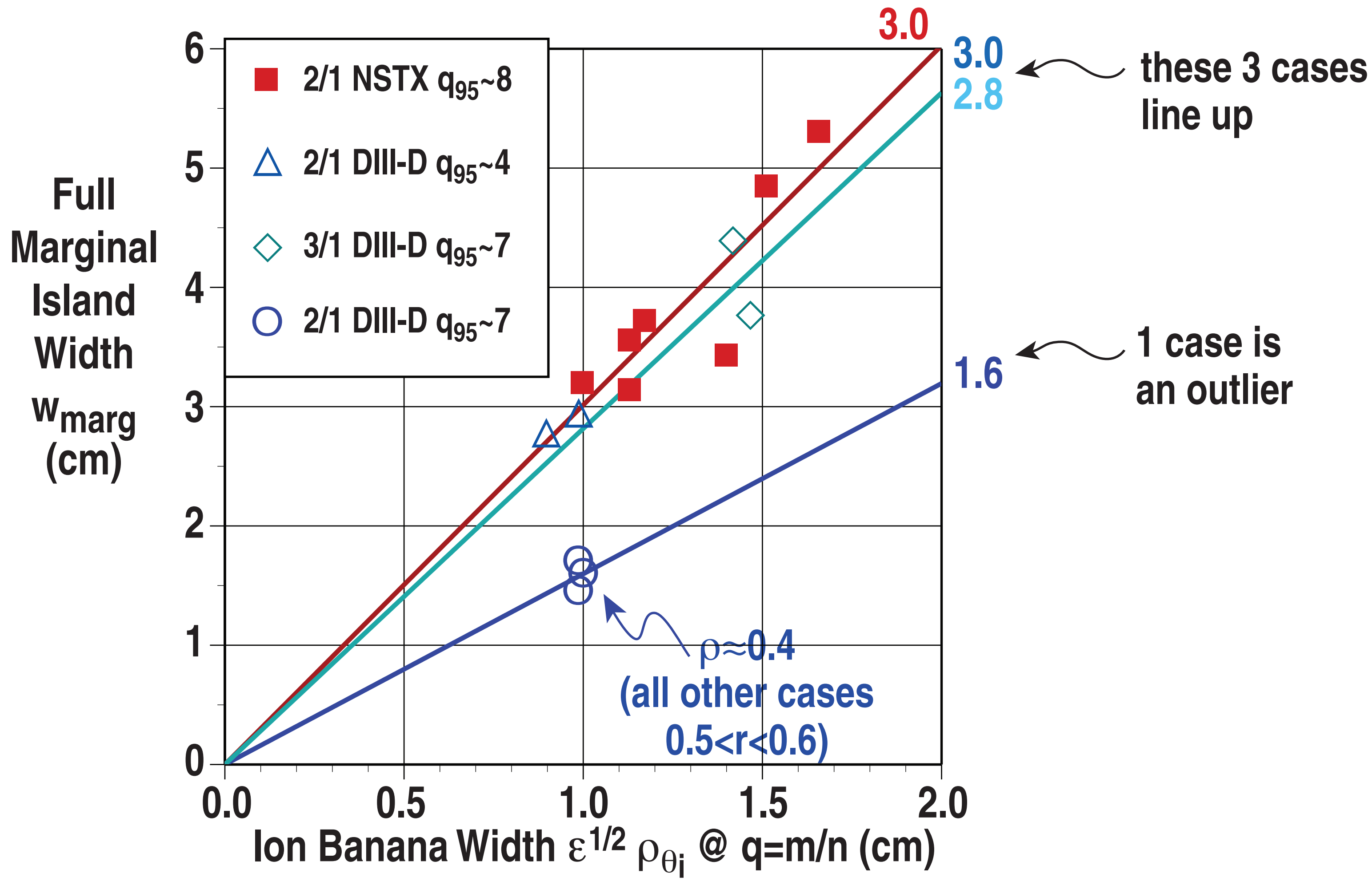
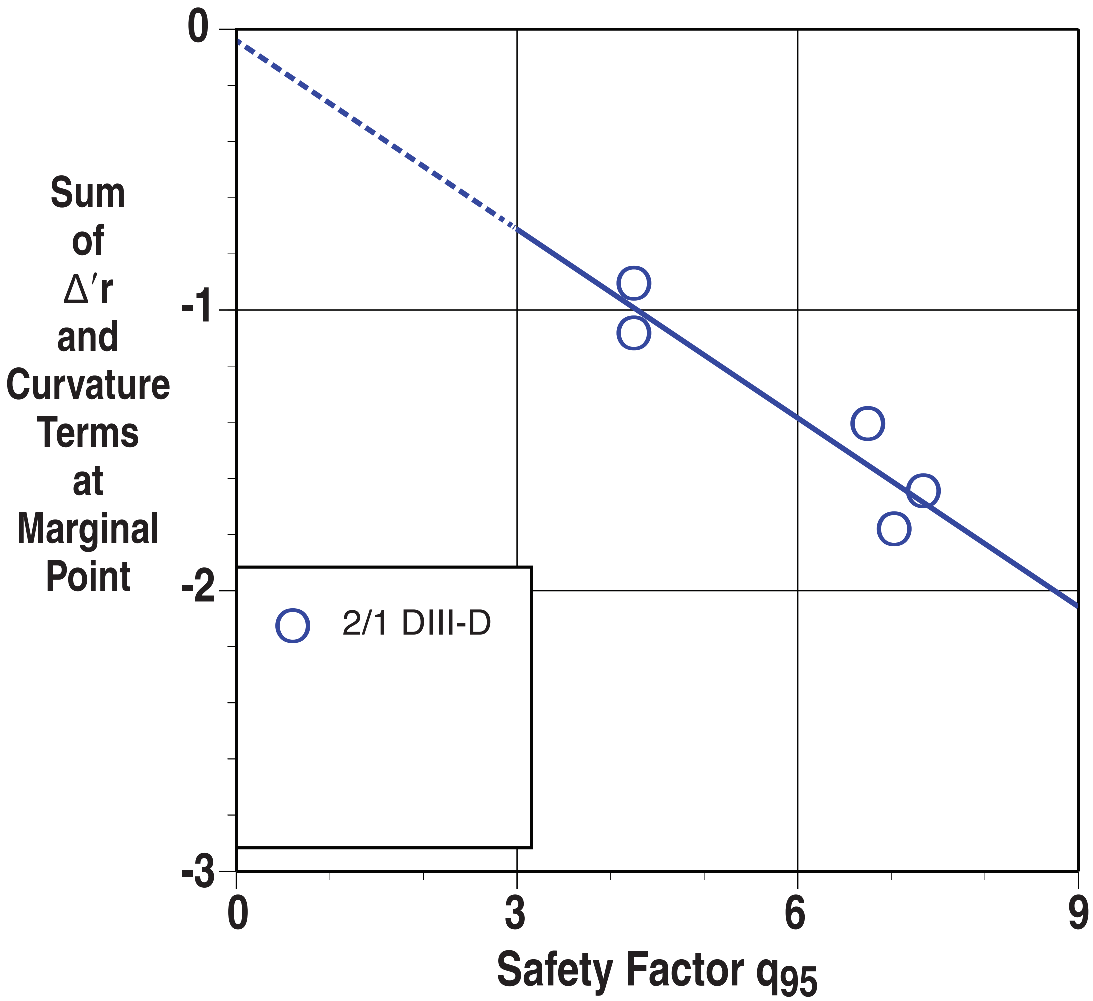
Measure of the Marginal Island Width Gives Information on Small Island Stabilizing Physics that in Part Governs Onset



- Empirically, marginal island width three times ion banana width
  - ★ except outlier is DIII-D 2/1 mode closer to axis at higher q95

Helically Perturbed Bootstrap Term with Small Island Effects Yields Sum of Stabilizing Terms in Balanced MRE

- Evaluated at the marginal point $w = w_{marg}$



★ m/n=2/1 in DIII-D shows greater stability at larger q_{95}

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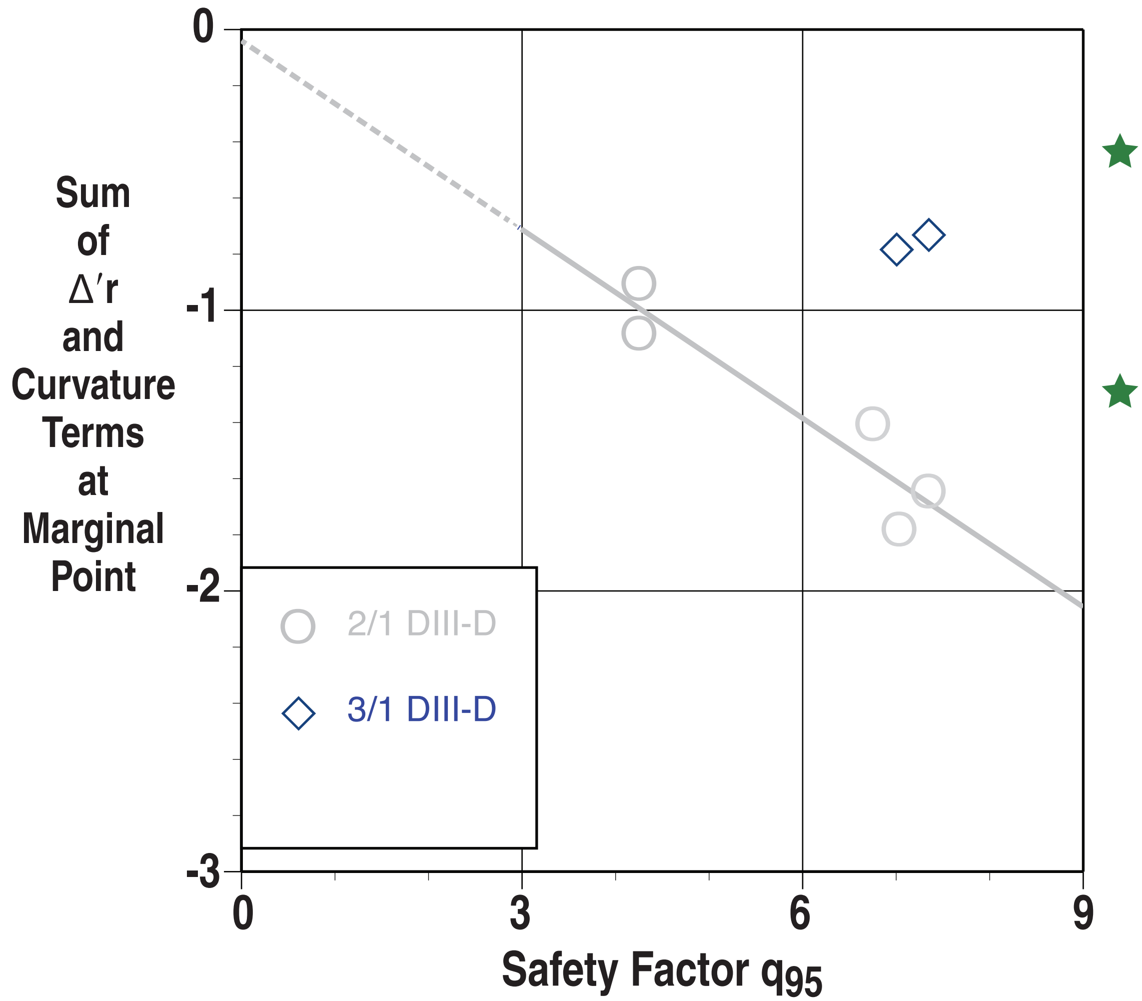

★ m/n=2/1 in DIII-D shows greater stability at larger q_{95}

★ m/n=3/1 in DIII-D less stable then 2/1 (at high q95) ... beta at marg higher

Helically Perturbed Bootstrap Term with Small Island Effects Yields Sum of Stabilizing Terms in Balanced MRE

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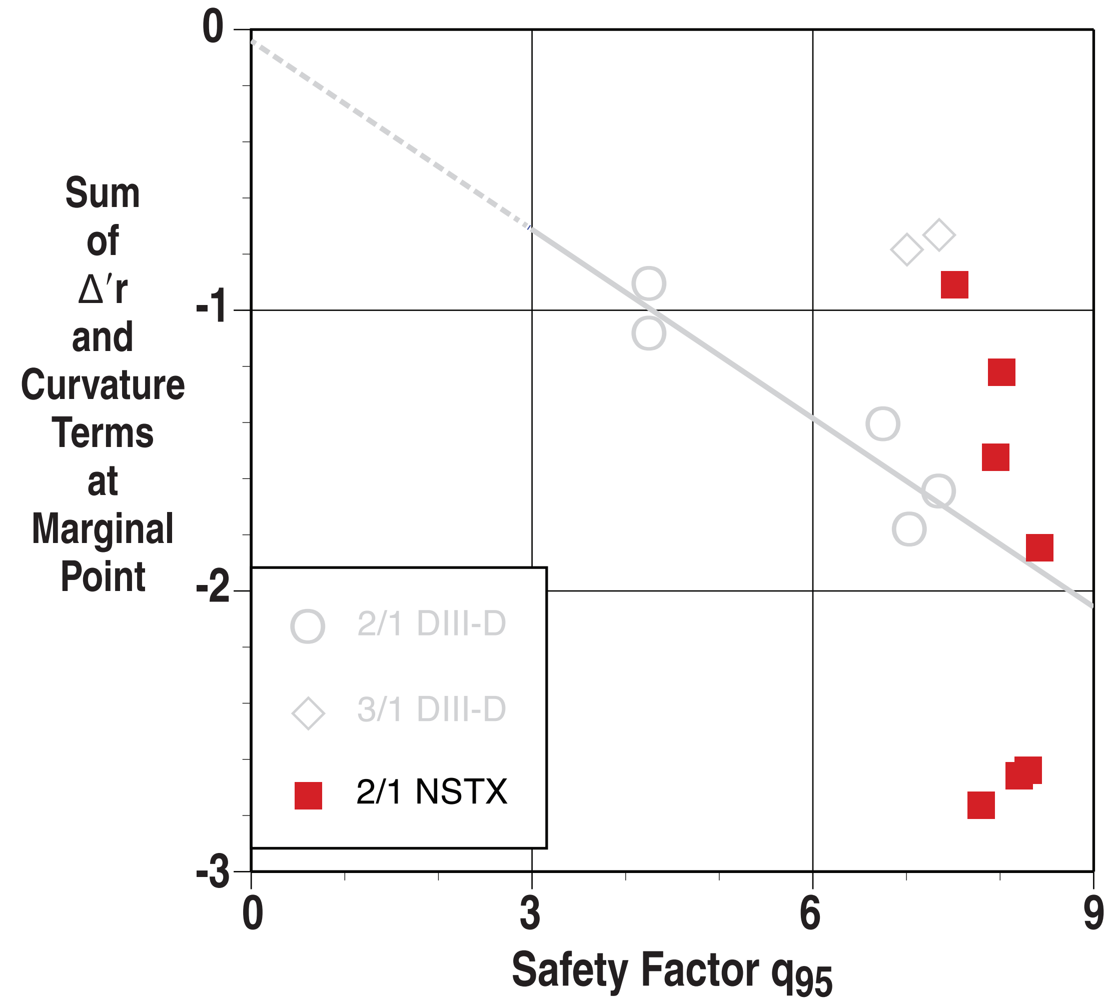


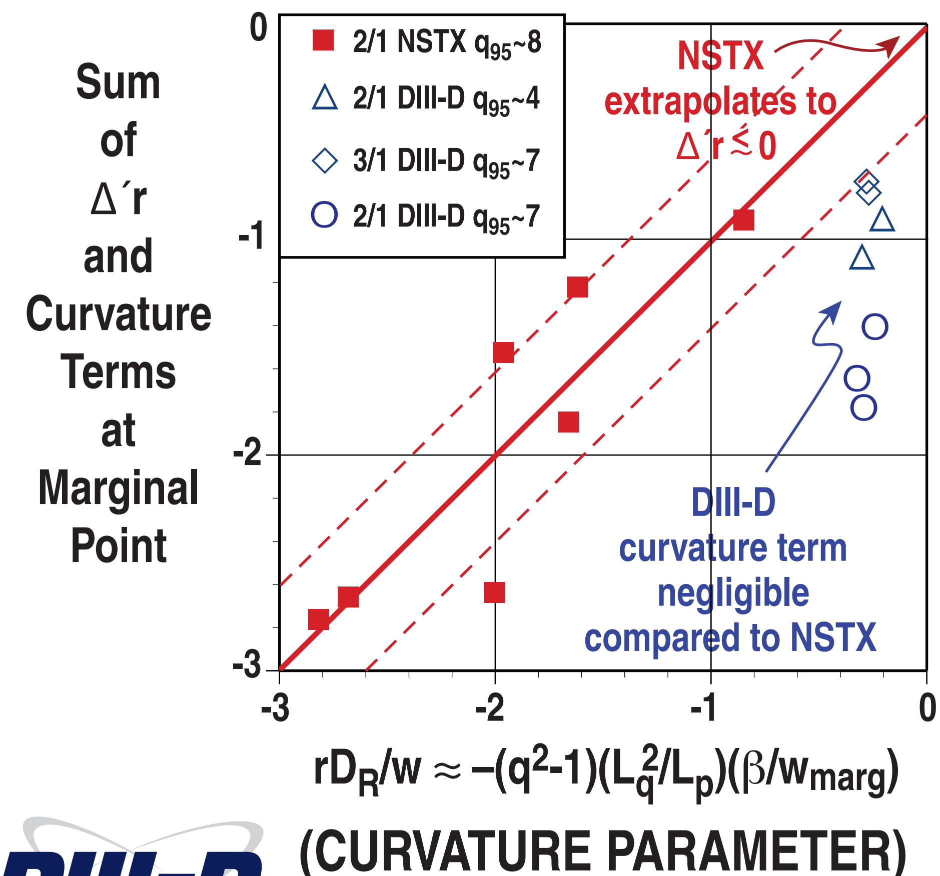
★ m/n=2/1 in DIII-D shows greater stability at larger q_{95}

★ m/n=3/1 in DIII-D less stable then 2/1 (at high q_{95}) … beta at marg higher

★ m/n=2/1 in NSTX shows wide variation … a “hidden variable” in stability
  – i.e. in curvature term

Stabilizing Field Curvature is Indeed the Hidden Variable in NSTX

- Good correlation with curvature parameter for NSTX
  - ★ suggests curvature term dominates over Δ'
    - ... little hysteresis in NSTX beta explained
      - – curv term $\propto \beta$ and bootstrap term $\propto \beta_{\theta e}$ scale together and "delicately balanced"



- DIII-D curvature term negligible compared to that in NSTX
  - ★ stabilizing term dominated by Δ'
    - ... large hysteresis in beta

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Conclusions on n=1 NTM Physics Between DIII-D and NSTX

- Marginal island width three times ion banana width
  - ★ except 1 of 3 DIII-D cases an outlier

    ... comparison to w_d, w_{pol}, w_{banana} theory in progress

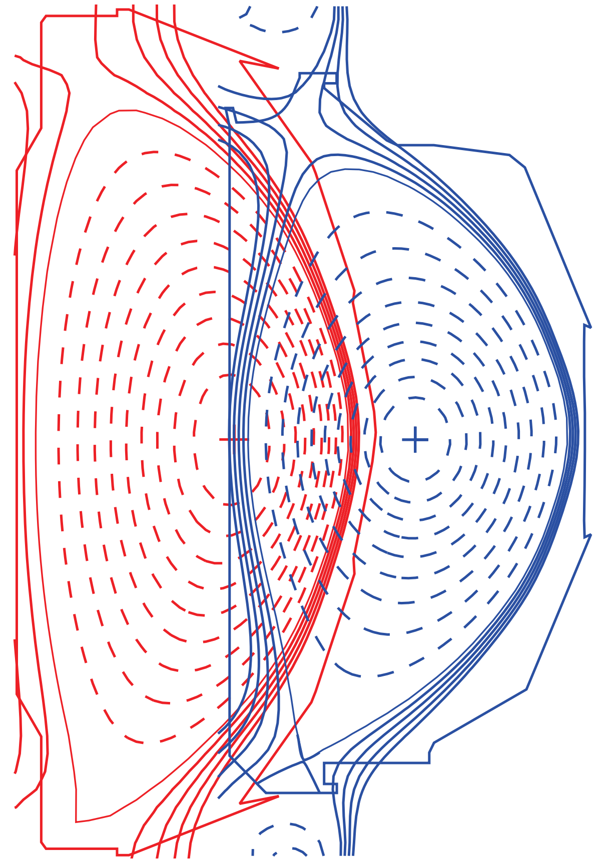
- MRE balance in NSTX by stabilizing curvature
  - ★ DIII-D by stabilizing Δ'

    ... explains different hysteresis between beta at onset and beta at marginal condition

    ... comparison to NIMROD code in progress

- Advantage at low aspect ratio
  - ★ curvature effect relatively greater

    ... thus less susceptibility to NTMs



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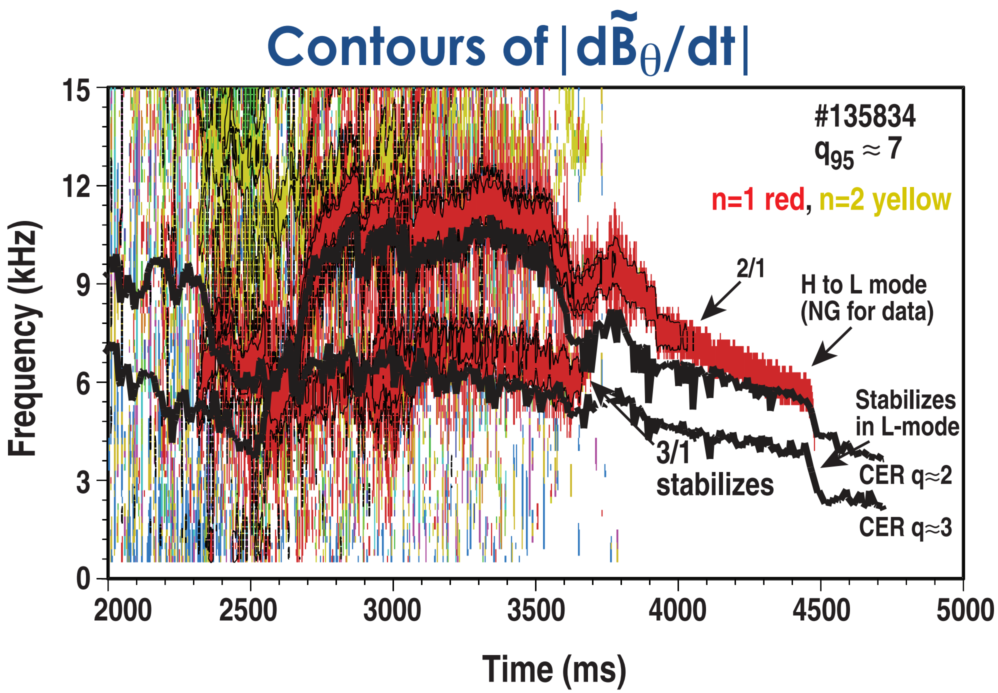
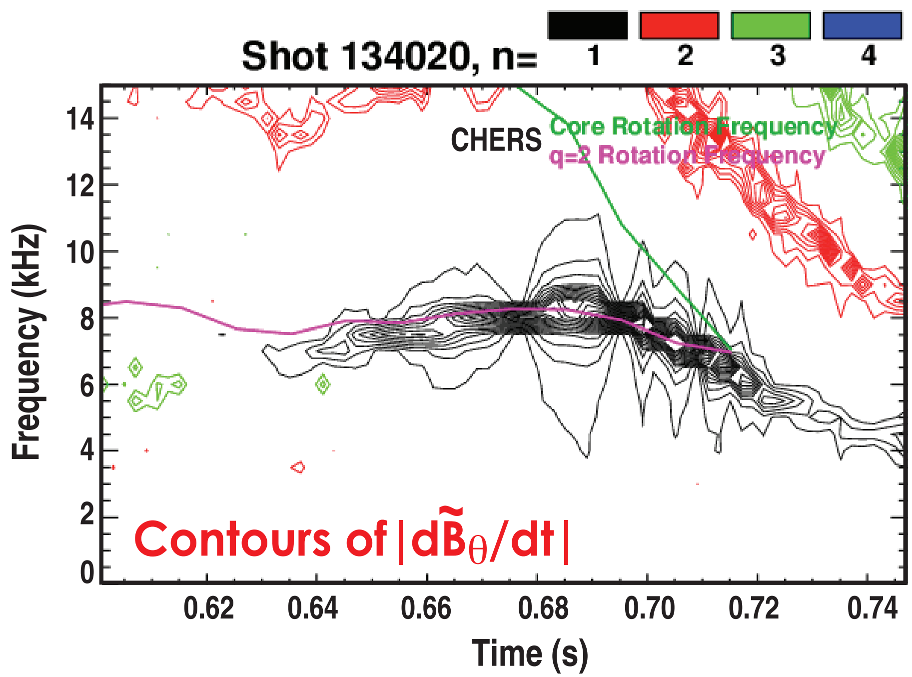
BACK UPS

Experimental Procedure is: (1) Strike an n=1 Mode, (2) Reduce NBI Power (and Thus Beta), (3) Stay in H-mode Without Mode Locking, and (4) Observe Self-Stabilization

DIII-D: Use gas puffing to stay in H-mode (IP= 0.8 MA, BT = 1.3 or 2.0T to vary q_{95}). Note some hi q_{95} shots initially had both m/n=2/1 and 3/1 modes



NSTX: Reproducible onset condition using modest L_i evaporation, and mode locking avoided by n=1 and n=3 error field correction (IP = 0.9 MA, BT = 0.44 T, "fixed" q_{95})



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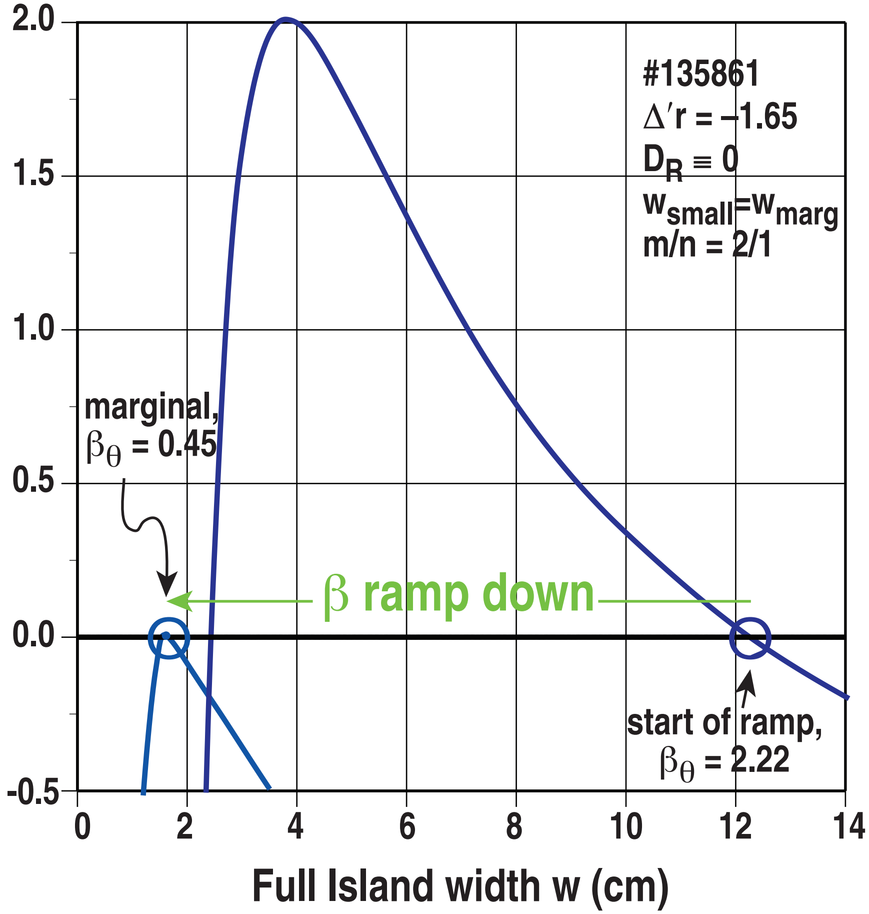
DIII-D Bootstrap Balanced by Δ', Large Hysteresis in β

- Shown is MRE from marginal point worked back in time to start of power ramp down (Δ', profiles all assumed same)

Normalized Island Growth (Decay) Rate

$$\frac{\tau_R}{r}\frac{dw}{dt}$$



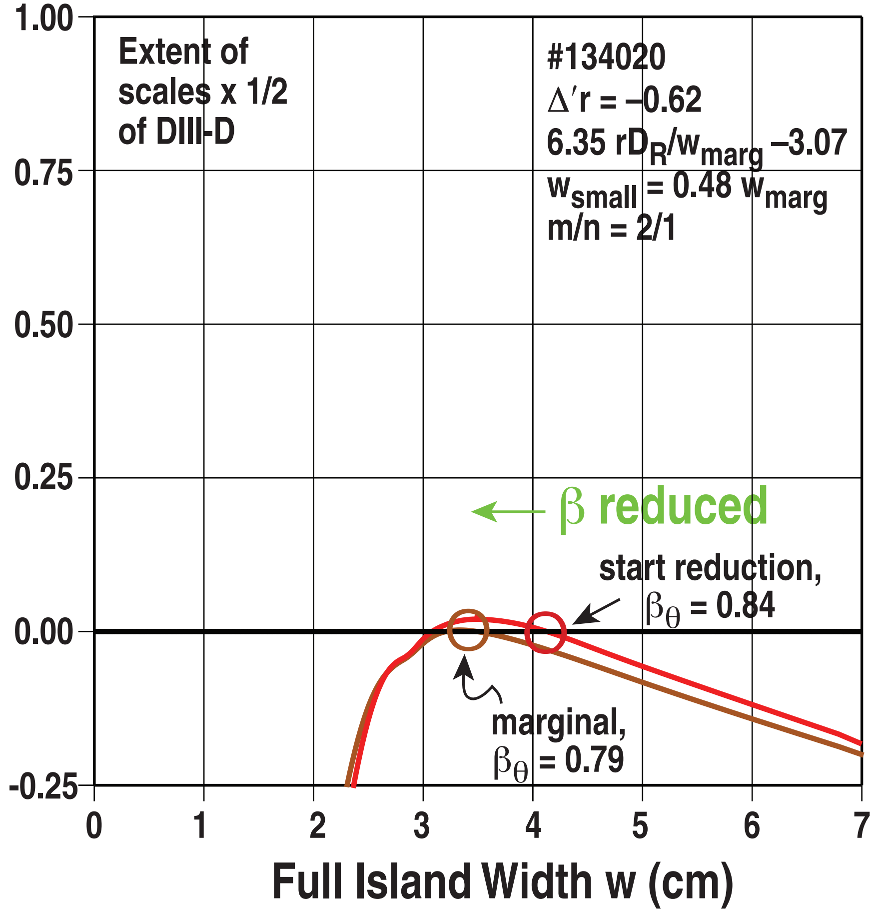
- Neglecting w_{small} & D_R, $\dot{w} = 0$ for...
  - ★ $\frac{w}{r} \approx \frac{\varepsilon^{1/2} L_q \beta_{\theta e}}{L_{pe}(-\Delta' r)}$

NSTX Bootstrap Balanced by Curvature, Small Hysteresis in β

- Shown is MRE from marginal point worked back in time to power step down (Δ', profiles all assumed same)

Normalized Island Growth (Decay) Rate

$$\frac{\tau_R}{r}\frac{dw}{dt}$$



- Neglecting w_{small} & Δ', $\dot{w} = 0$ not determined...

★ $$0 = \frac{6.35\, rD_R}{w} + \frac{\varepsilon^{1/2} r L_q \beta_{\theta e}}{w L_{pe}}$$

... with $D_R \propto \beta$

NSTX

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