

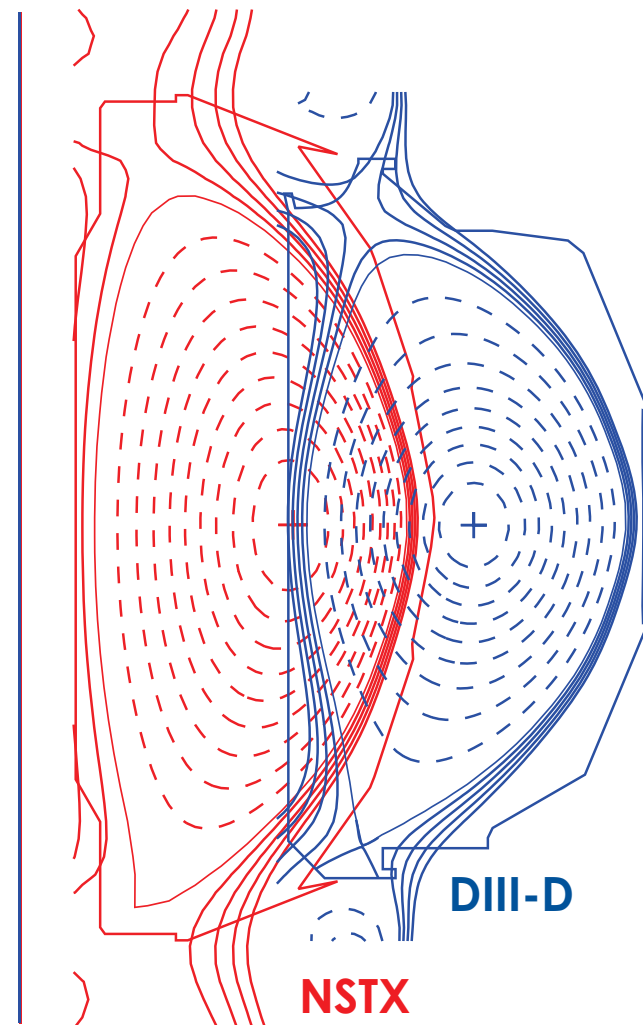
# Comparison of Aspect Ratio Effects on Neoclassical Tearing Modes Between DIII-D and NSTX

by

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Aspect Ratio  $R/a = 1.4, 2.7$



# Key Parameter at Issue is Local Inverse Aspect Ratio $\varepsilon$

- $\varepsilon \approx r/R_0$  at rational surface  $q=m/n$ 
  - ★ approximately  $(R_{OUT} - R_{IN})/(R_{IN} + R_{OUT})$
  - ★ rigorously  $(B_{IN} - B_{OUT})/(B_{IN} + B_{OUT})$ 
    - ... a 14% effect in NSTX
    - 0.3% effect in DIII-D
- $\varepsilon$  explicitly comes into...
  - ★ destabilizing bootstrap drive  $\propto \varepsilon^{1/2}$ , fraction of trapped particles
  - ★ stabilizing small island size ( $\propto \varepsilon^{1/2} \rho_{\theta i}$ ?)
  - ★ relative size of stabilizing curvature ( $\propto \varepsilon^{3/2}$ )

# Neoclassical Tearing Modes are Sustained by the Balance of the **Sum of the Stabilizing $\Delta'$ and Good Curvature** with the **Destabilizing Helically Perturbed Bootstrap Current**

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

normalized growth rate

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

stabilizing classical tearing index

destabilizing bootstrap

lumped small island stabilizing effects

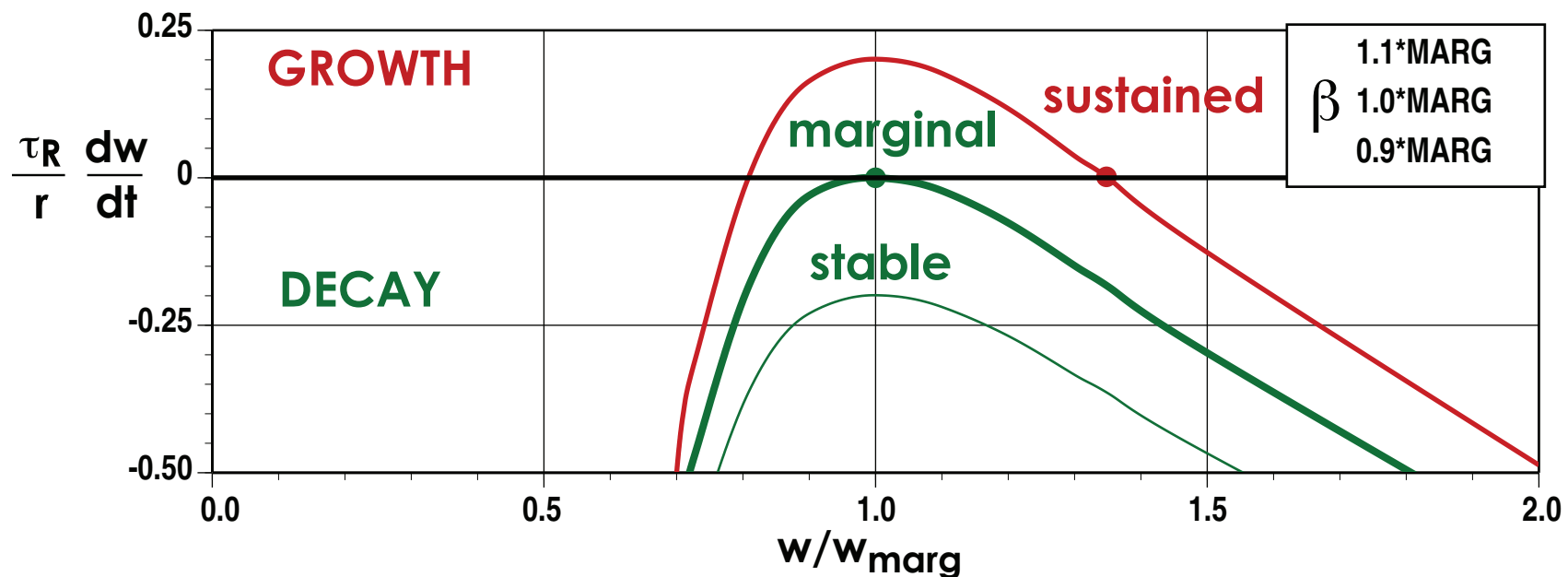
stabilizing effect of good average magnetic field curvature with  $D_R \approx - (q^2 - 1) (L_q^2 / r L_p) \beta$  the "resistive interchange parameter"

# Neoclassical Tearing Modes are Sustained by the Balance of the **Sum of the Stabilizing $\Delta'$ and Good Curvature** with the **Destabilizing Helicallly Perturbed Bootstrap Current**

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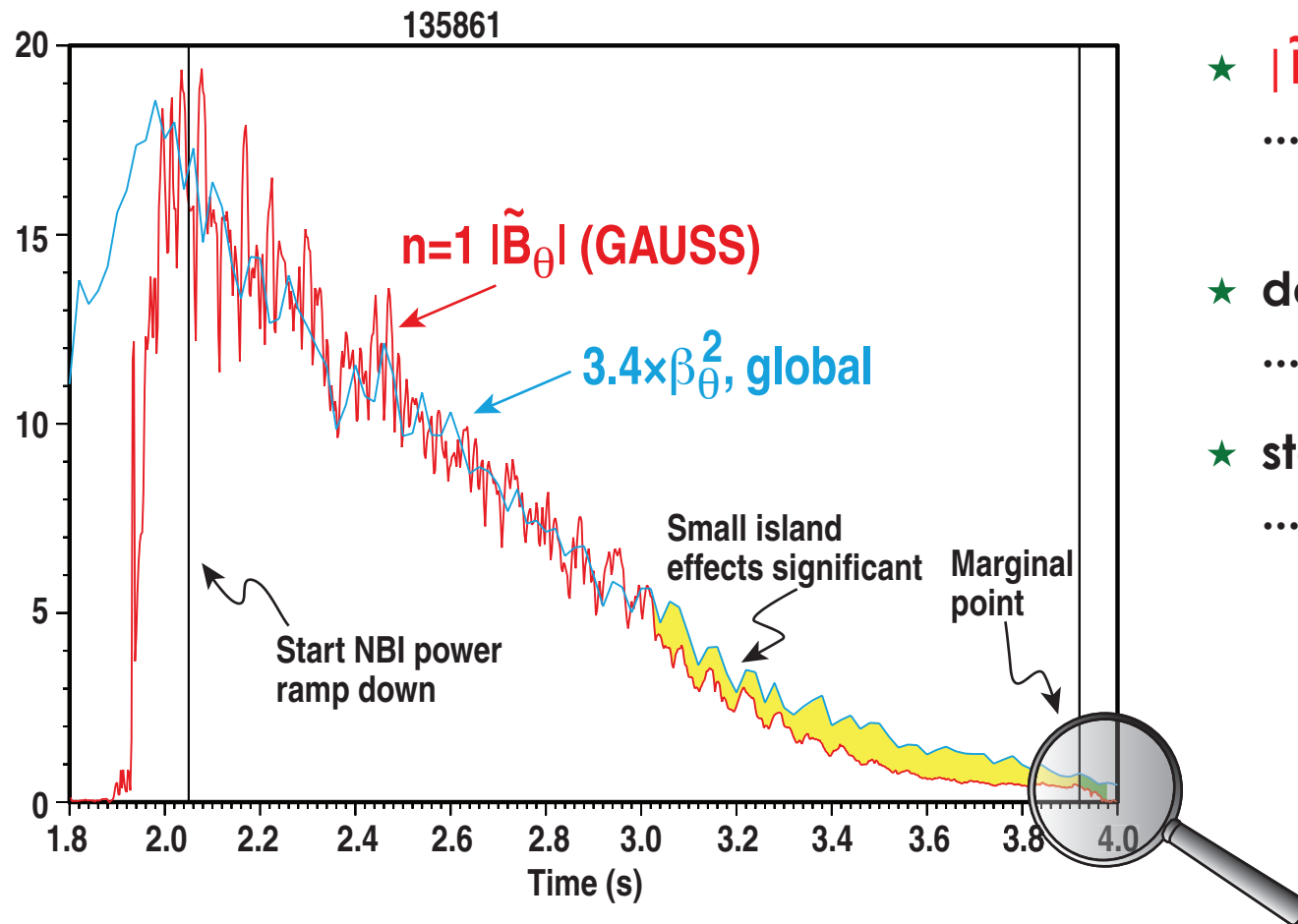
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# DIII-D Exhibits Large Hysteresis in Beta Between n=1 NTM Excitation and Self-Stabilization (“Marginal Point”)

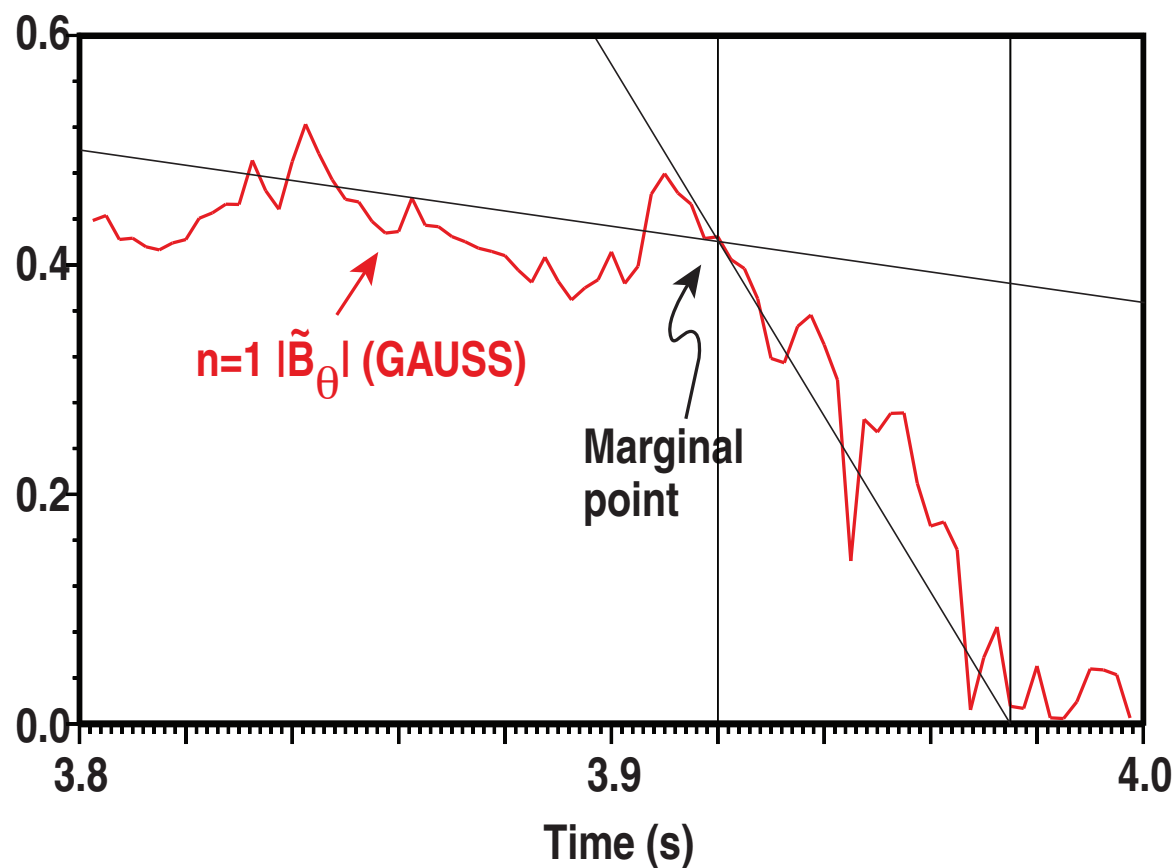
- NBI power ramped down after n=1 mode (here m=2) saturates



- ★  $|\tilde{B}_\theta| \propto \beta_\theta^2$   
... signature of an NTM  
– as  $w \propto \beta_\theta$
- ★ deviates  
... small island effects
- ★ stabilizes  
... marginal point

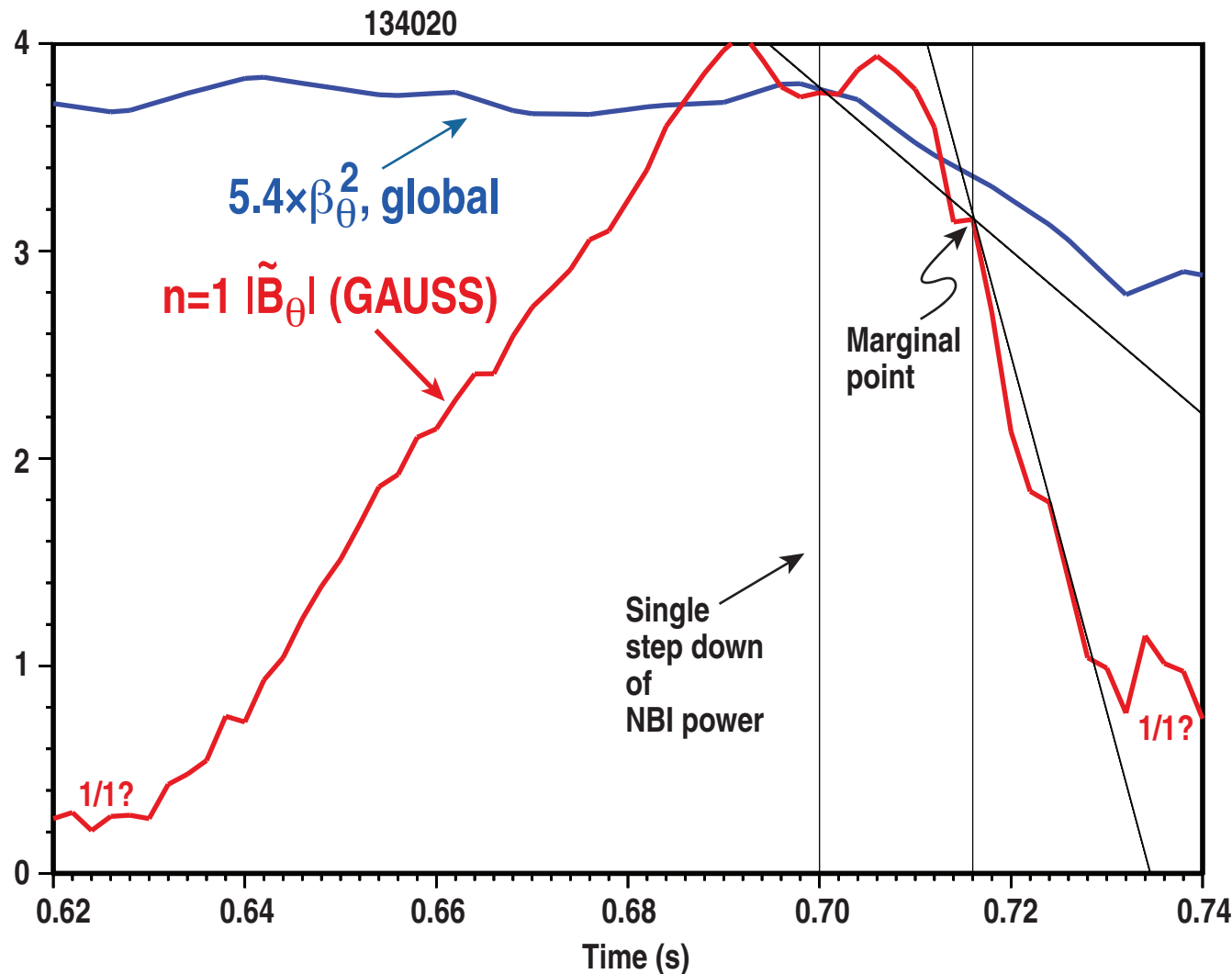
# DIII-D Exhibits Large Hysteresis in Beta Between n=1 NTM Excitation and Self-stabilization (“Marginal Point”)

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

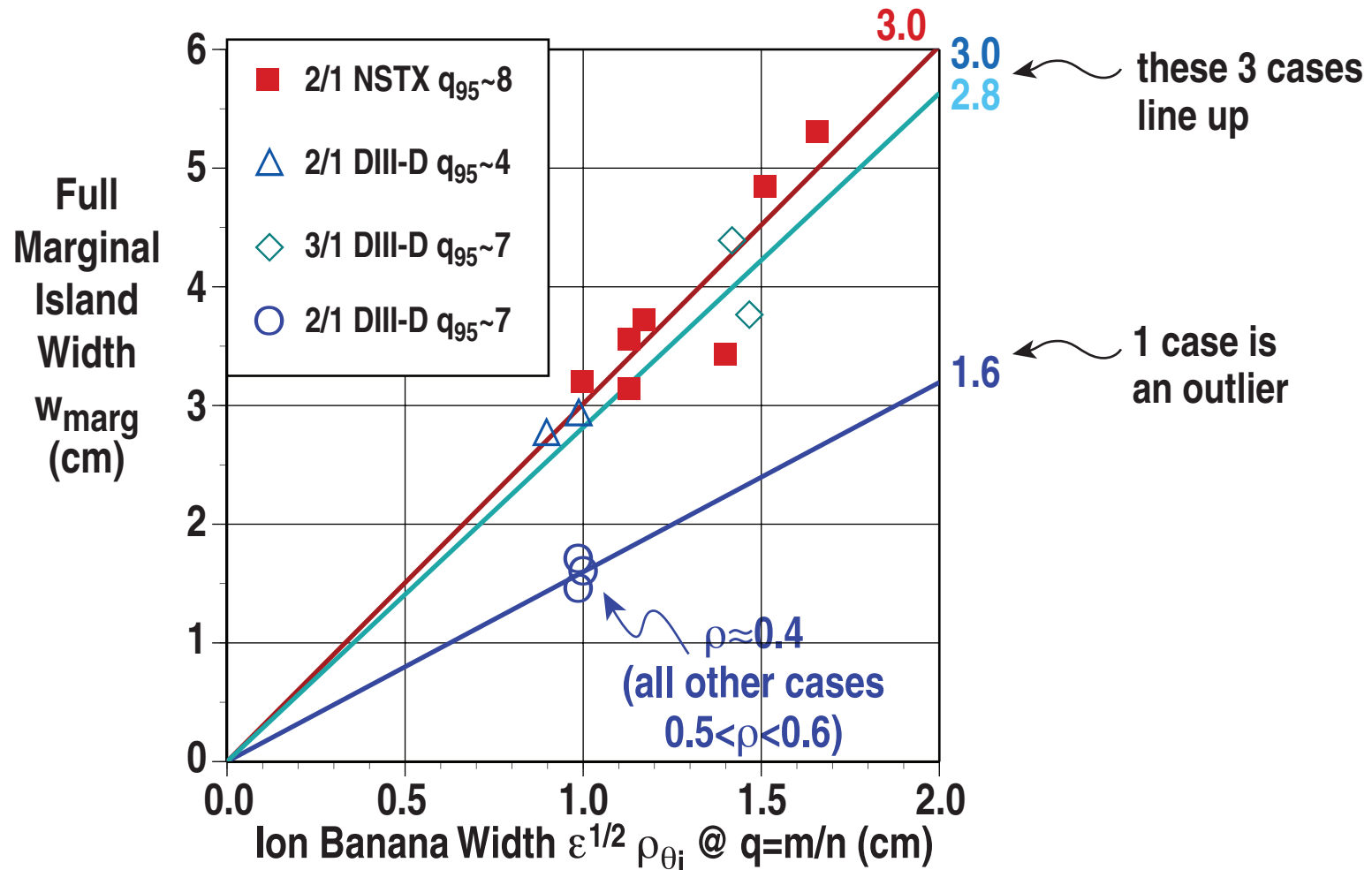


# NSTX Exhibits Little Hysteresis in Beta Between n=1 NTM Excitation and Self-Stabilization (“Marginal Point”)

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



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

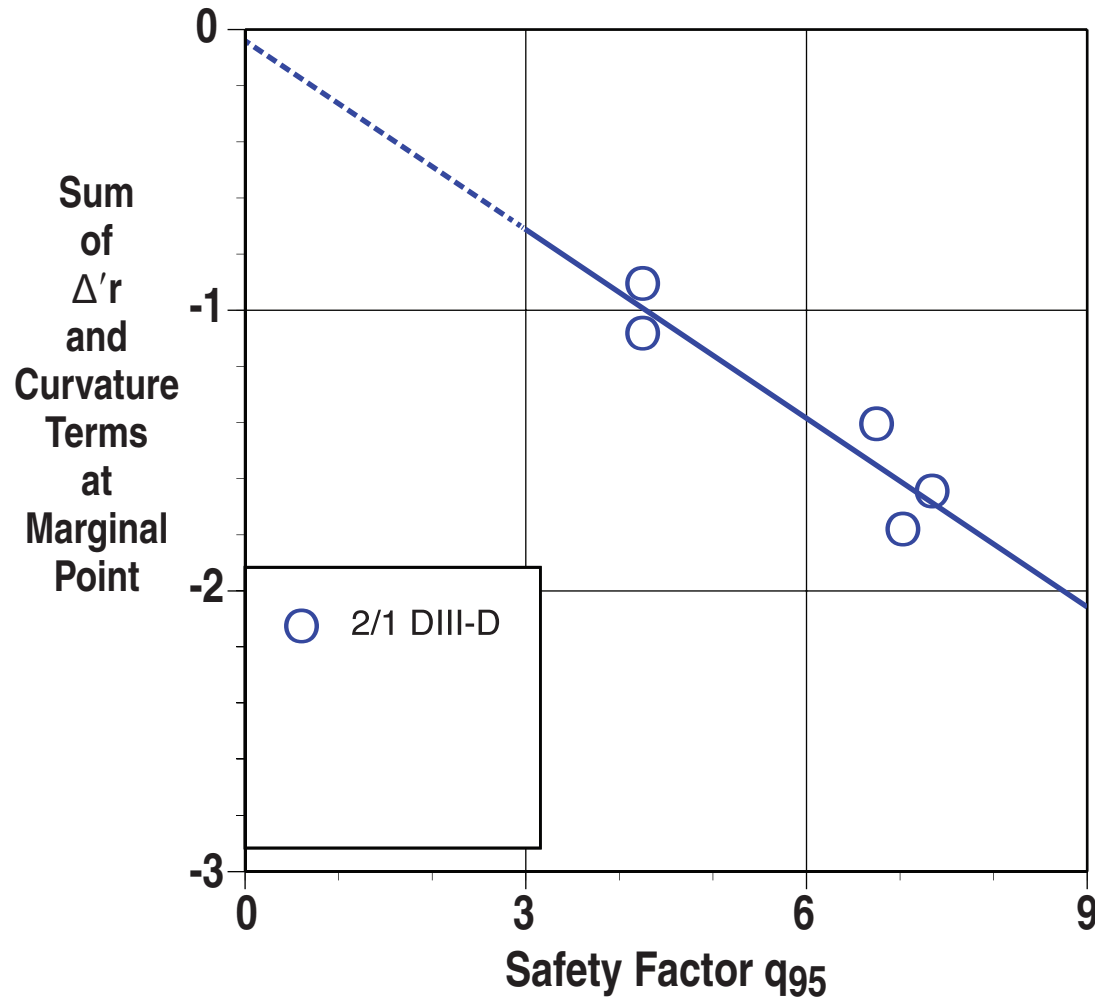


- Empirically, marginal island width three times ion banana width
  - ★ except outlier is DIII-D 2/1 mode closer to axis at higher  $q_{95}$



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

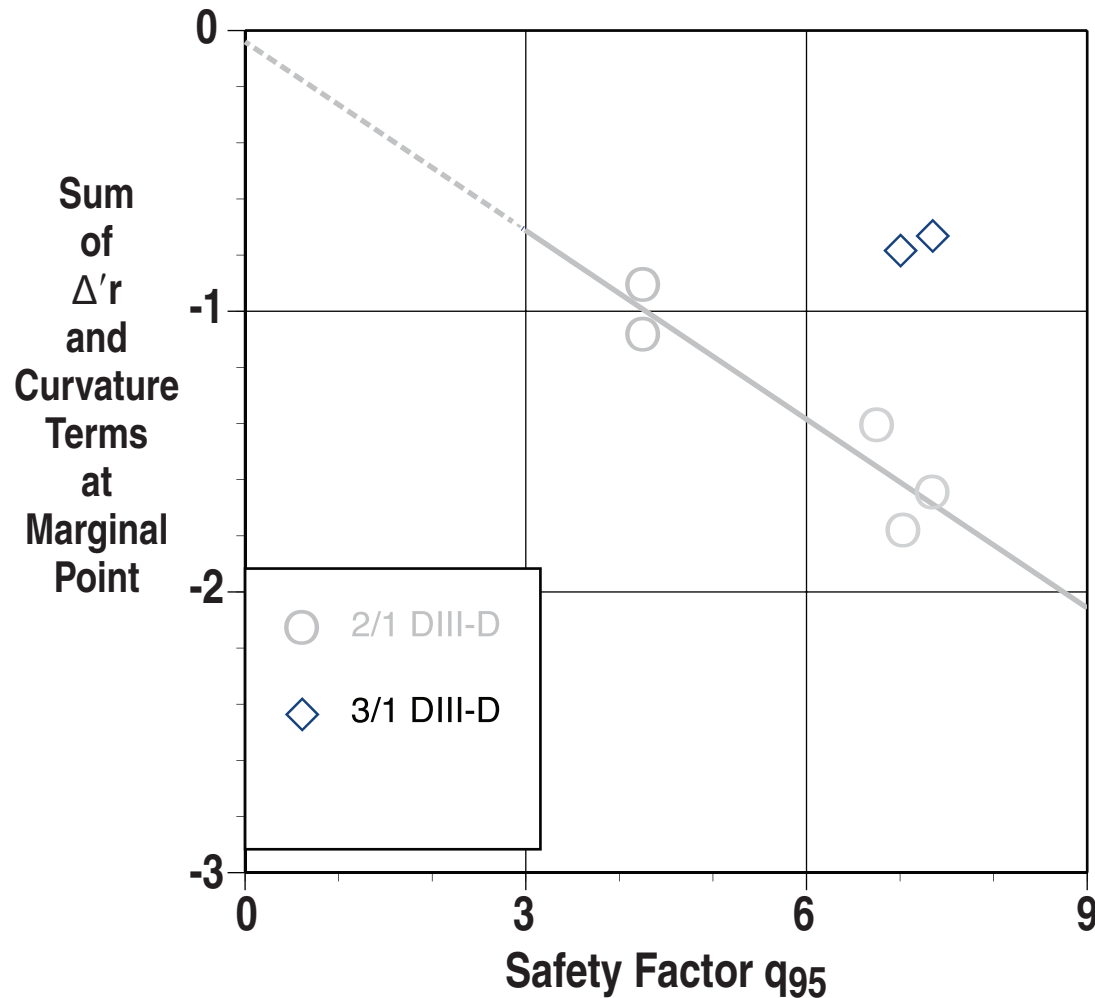
- Evaluated at the marginal point  $w=w_{\text{marg}}$



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

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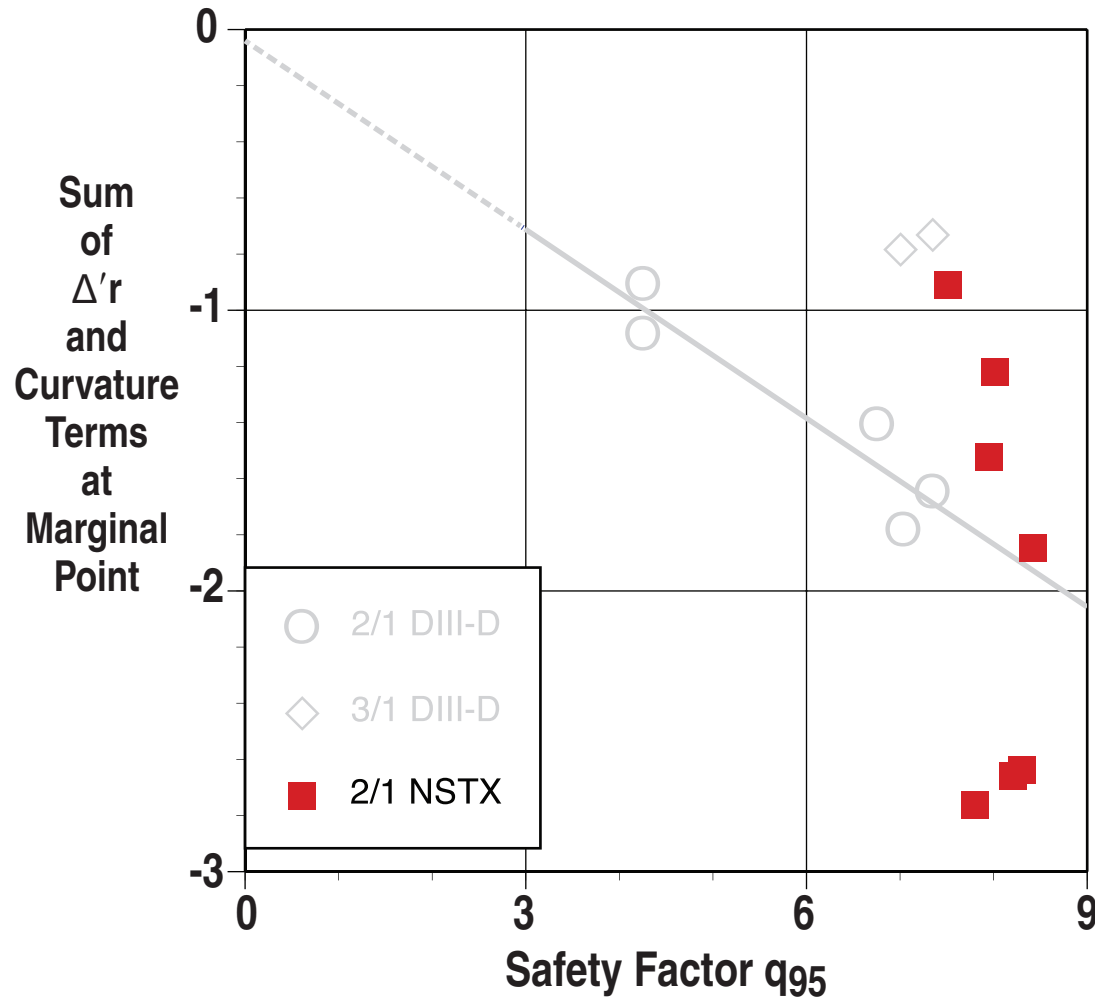


★  $m/n=2/1$  in DIII-D shows greater stability at larger  $q_{95}$

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

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

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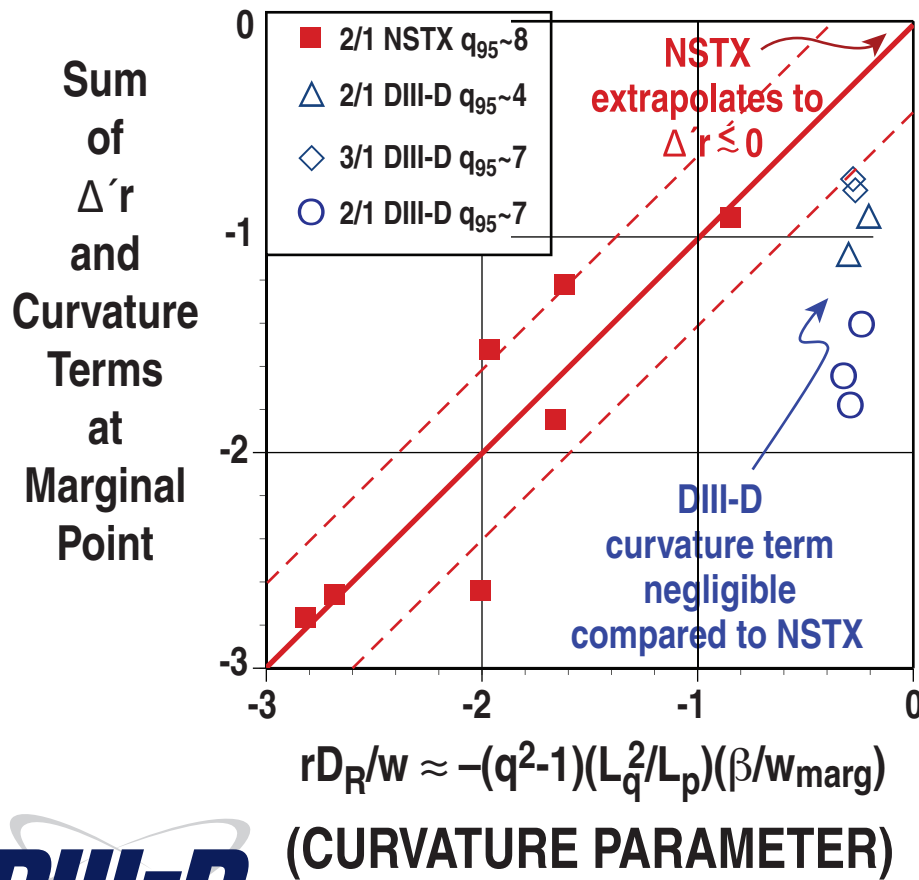
★  $m/n=2/1$  in DIII-D shows greater stability at larger  $q_{95}$

★  $m/n=3/1$  in DIII-D less stable than 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

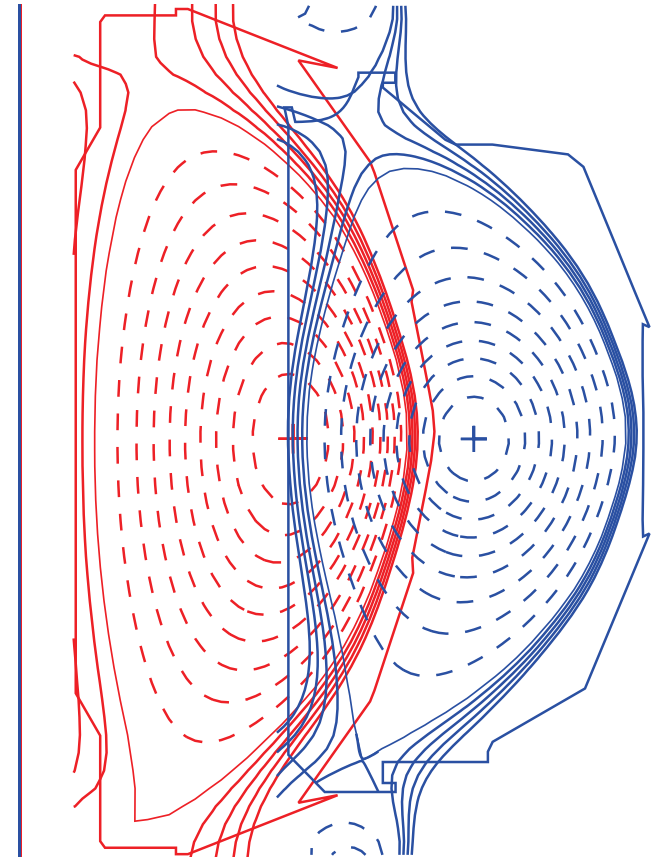
- **Good correlation with curvature parameter for NSTX**
  - ★ suggests curvature term dominates over  $\Delta'$
  - ... little hysteresis in NSTX beta explained
    - curv term  $\propto \beta$  and bootstrap term  $\propto \beta_{\theta e}$  scale together and “delicately balanced”



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

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

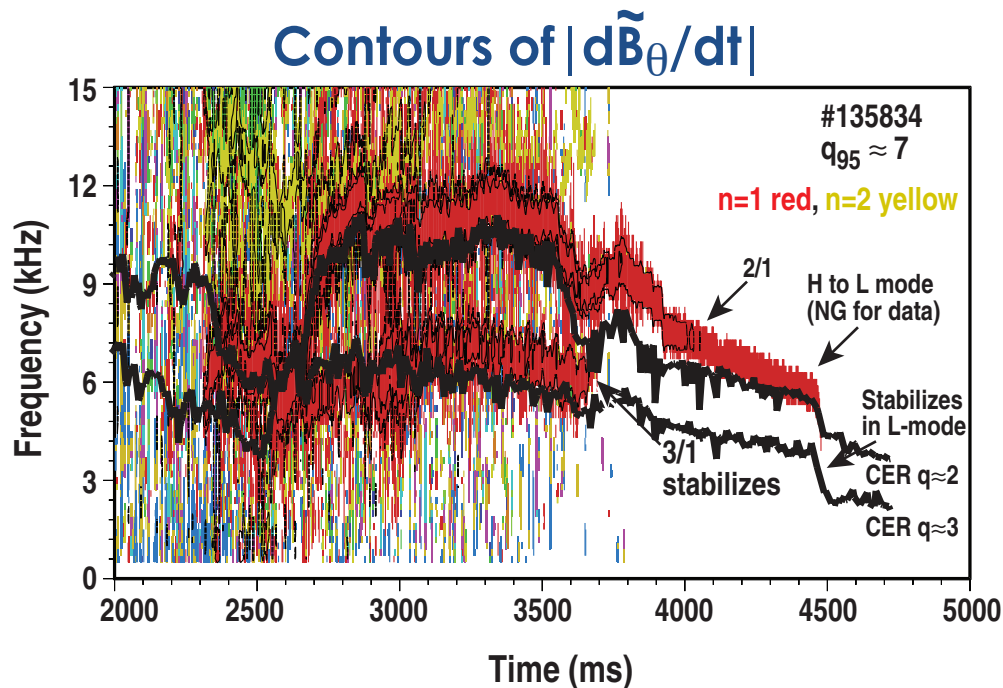
- Marginal island width three times ion banana width
  - ★ except 1 of 3 DIII-D cases an outlier
  - ... comparison to  $w_d$ ,  $w_{pol}$ ,  $w_{banana}$  theory in progress
- **MRE balance in NSTX by stabilizing curvature**
  - ★ DIII-D by negative  $\Delta'$
  - ... explains different hysteresis between beta at onset and beta at marginal condition
  - ... comparison to NIMROD code in progress
- Advantages at low aspect ratio
  - ★ larger ion banana width ( $\propto \epsilon^{1/2}$ )
  - ... stronger small island stabilization
  - ★ curvature effect relatively greater ( $\propto \epsilon^{3/2}$ )
  - ... suggests less susceptible to NTMs



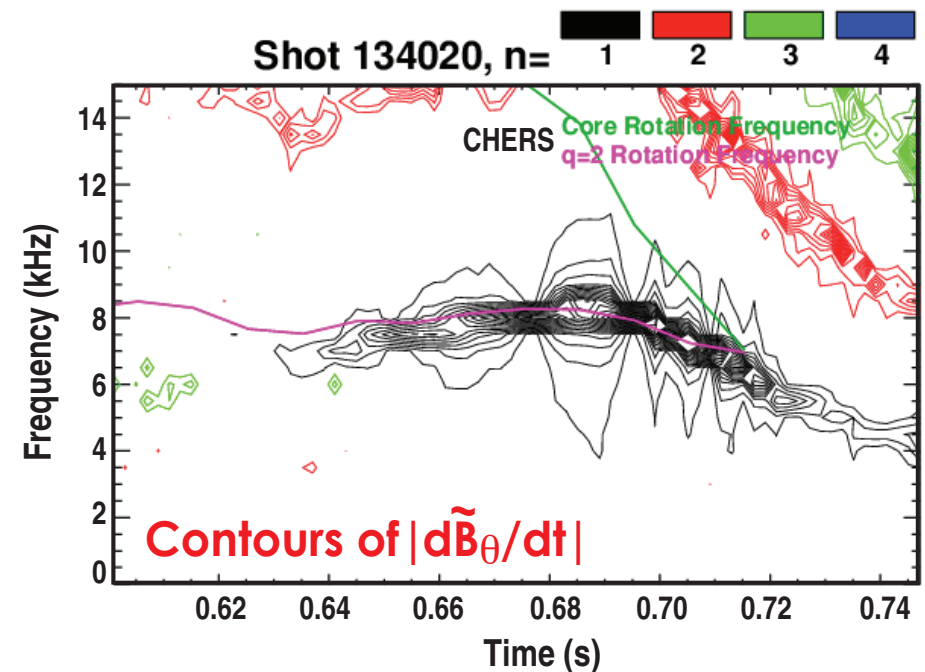
# BACK UPS

# 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”  $q_{95}$ )

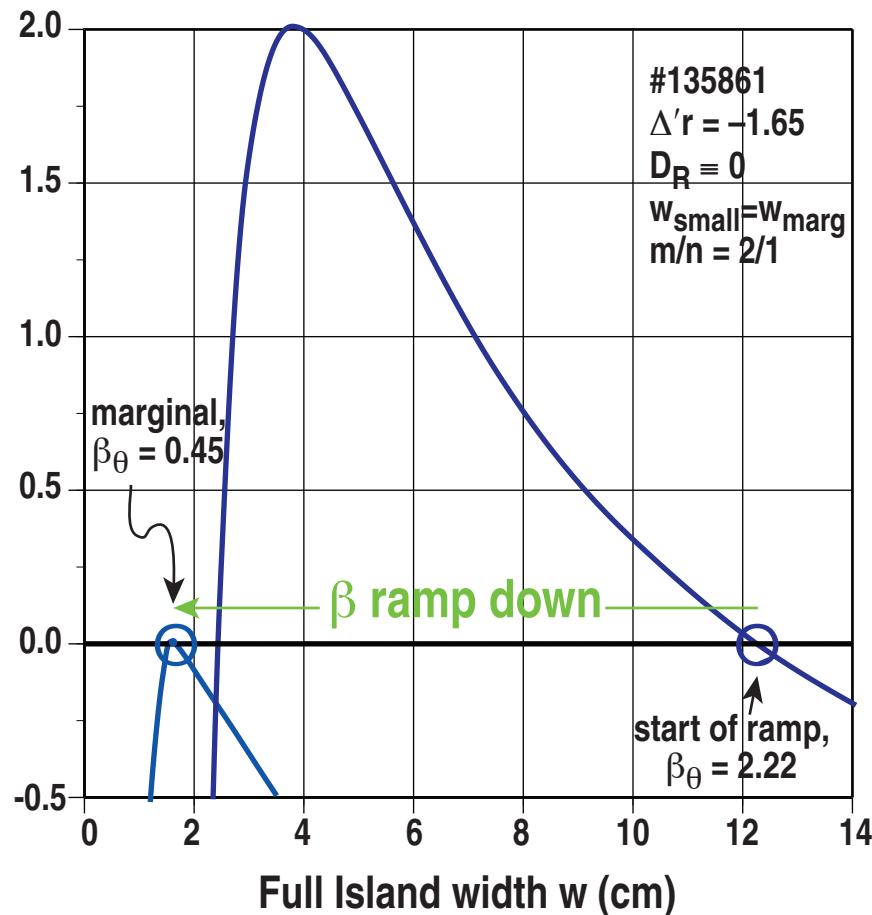


# DIII-D Bootstrap Balanced by $\Delta'$ , Large Hysteresis in $\beta$

- Shown is MRE from marginal point worked back in time to start of power ramp down ( $\Delta'$ , 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...

$$\star \frac{w}{r} \approx \frac{\varepsilon^{1/2} L_q \beta_\theta e}{L_{pe} (-\Delta'r)}$$

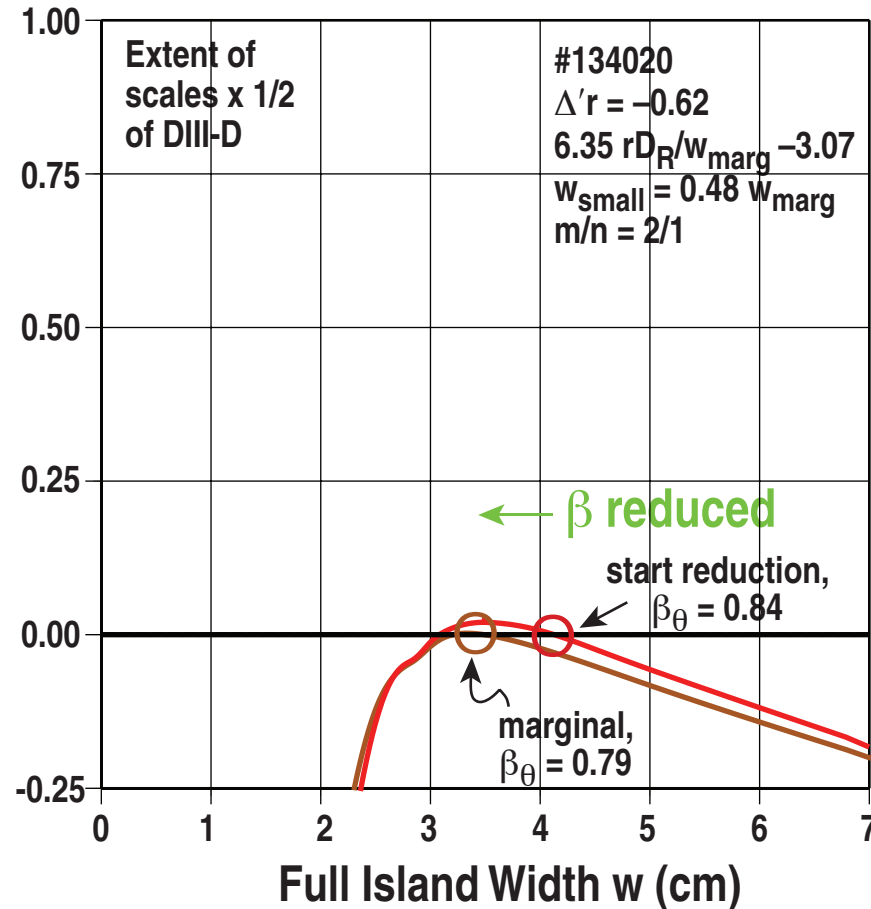


# NSTX Bootstrap Balanced by Curvature, Small Hysteresis in $\beta$

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

Normalized Island Growth (Decay) Rate

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



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

$$\star 0 = \frac{6.35 r D_R}{w} + \frac{\epsilon^{1/2} r L q \beta_{\theta} e}{w L p e}$$

... with  $D_R \propto \beta$