U.S. DEPARTMENT OF ENERGY | Office of Science

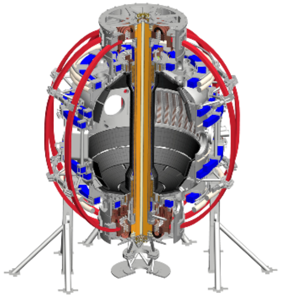
NSTX-U

Aspect ratio dependence of tearing stability

Lucas Morton

3DSP Meeting
11/14/2016

ORAU



Multi-device comparison can test aspect ratio dependences in modified Rutherford equation

La Haye *et al*, PoP **19,** 062506 (2012)

- Terms vary in different ways

$$D_R \propto \epsilon^2 \beta_\theta$$

$$1.22^{-1}\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + C_R \frac{r D_R}{w} + \varepsilon^{1/2}\frac{r L_q}{L_{pe}}\beta_{\theta e}\left[\frac{1}{w} - \frac{w_{small}^2}{3w^3}\right]$$

$$\epsilon = r/R_0$$

$$w_{small}^2 \propto \epsilon\ ?$$

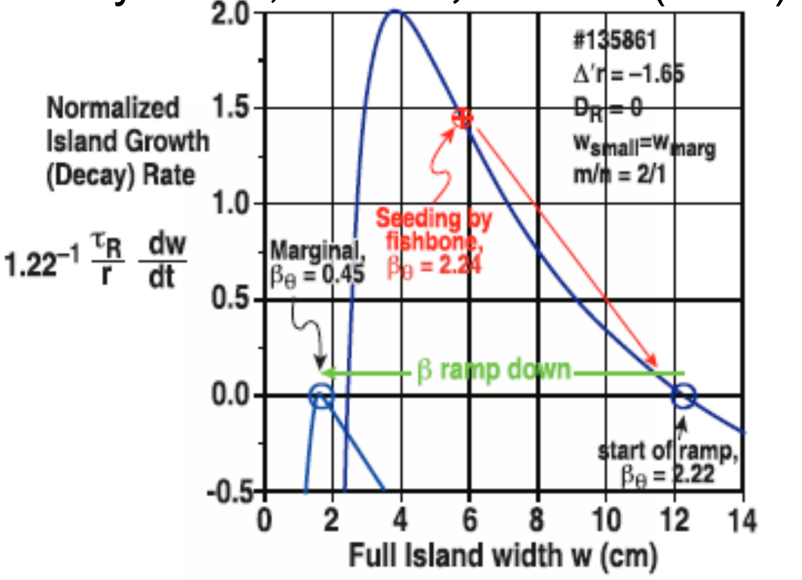


FIG. 9. Evaluation of the MRE for DIII-D $m/n = 2/1$ case of #135861 from Fig. 3. Fitting at the marginal point with the D_R term neglected. The same fitting parameters are used for the saturated mode at the start of the NBI ramp at higher beta (except $w_{small} \propto \beta_\theta^{1/2}$ assumed). And in red, the initially growing island width seeded by a fishbone (at similar beta to the start of the ramp) is noted.

The modified Rutherford equation (MRE) defines a model for neoclassical tearing mode evolution

- Adds geometric (curvature) and kinetic (bootstrap) effects to classical instability

Normalized 'growth' rate

Interchange (curvature) stabilization

Neoclassical bootstrap destabilization

$$1.22^{-1} \frac{\tau_R}{r} \frac{dw}{dt} = \Delta' r + C_R \frac{r D_R}{w} + \varepsilon^{1/2} \frac{r L_q}{L_{pe}} \beta_{\theta e} \left[\frac{1}{w} - \frac{w_{small}^2}{3 w^3} \right]$$

Classical stability (current gradient drive)

Scales as w^{-1} for large w

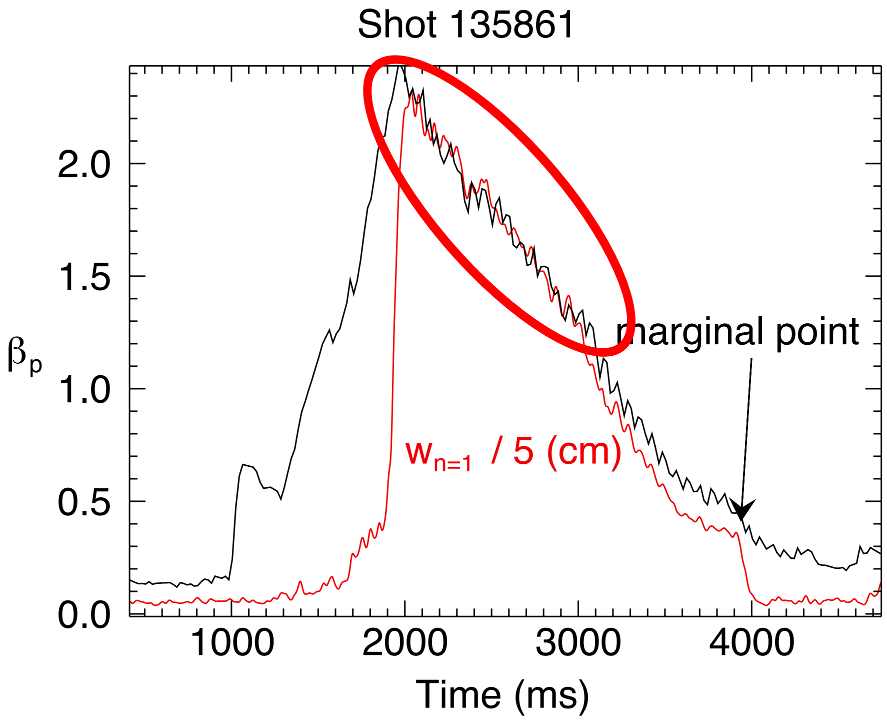
Goes to zero at $w = 0$

Neoclassical tearing modes follow MRE: large island limit

- At large island width, $w \propto \beta/\Delta'$
  - Assuming $\dot{w}$ 'small'
  - Curvature small in DIII-D

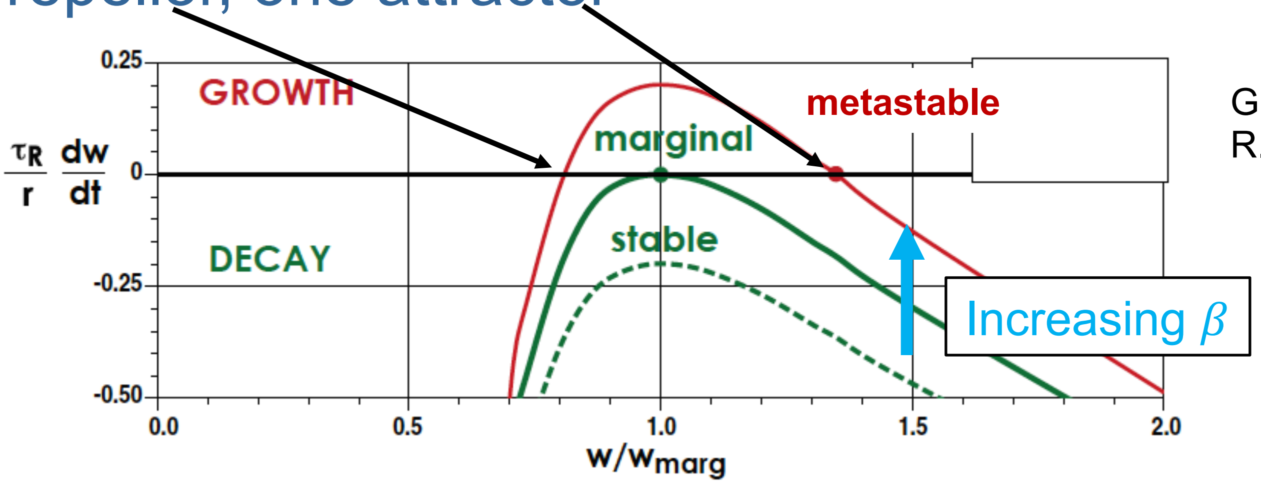
$$1.22^{-1}\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + C_R\frac{rD_R}{w} + \varepsilon^{1/2}\frac{rL_q}{L_{pe}}\beta_{\theta e}\left[\frac{1}{w} - \frac{w_{small}^2}{3w^3}\right]$$

Slow β ramp-down experiment on DIII-D



MRE has bifurcation in solutions

- Two (non-zero) solutions over w for $\dot{w} = 0$ for large β
  - One repellor, one attractor



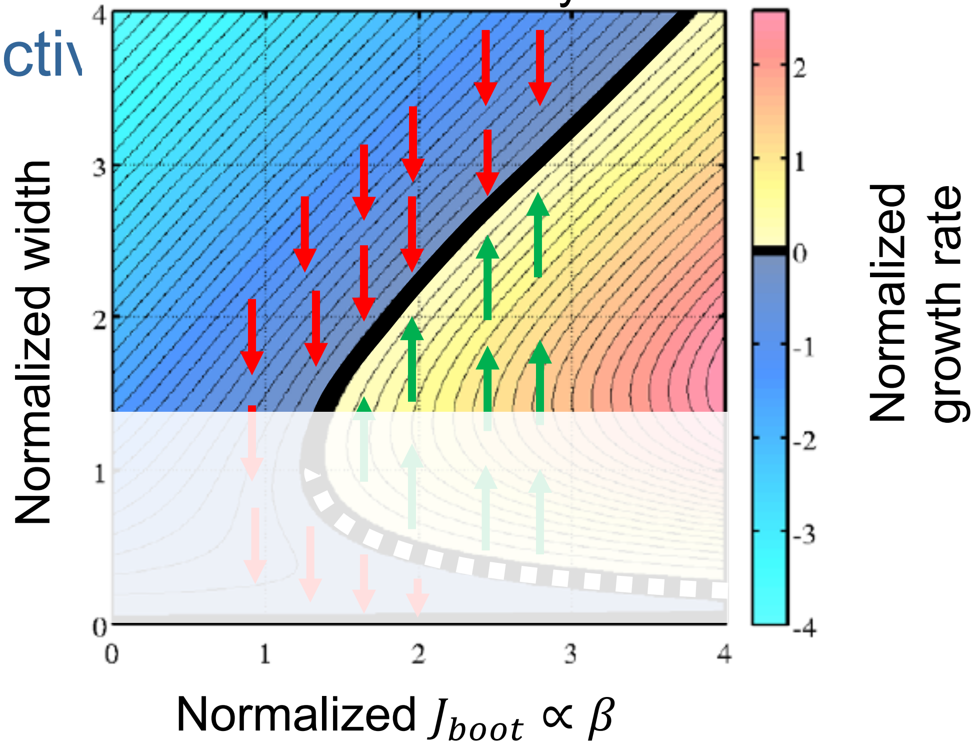
Graphic courtesy of R. La Haye

- No (non-zero) solutions at low β
  - Solutions merge, disappear at 'marginal point'

Solutions to MRE can be represented graphically

- Attractor: →|←
  - ‘Stable’ branch (from perspectiv equilibrium)
- Repellor: ←|→
  - ‘Unstable’ branch

D. L. Rayburn, PhD thesis, Princeton University 2011



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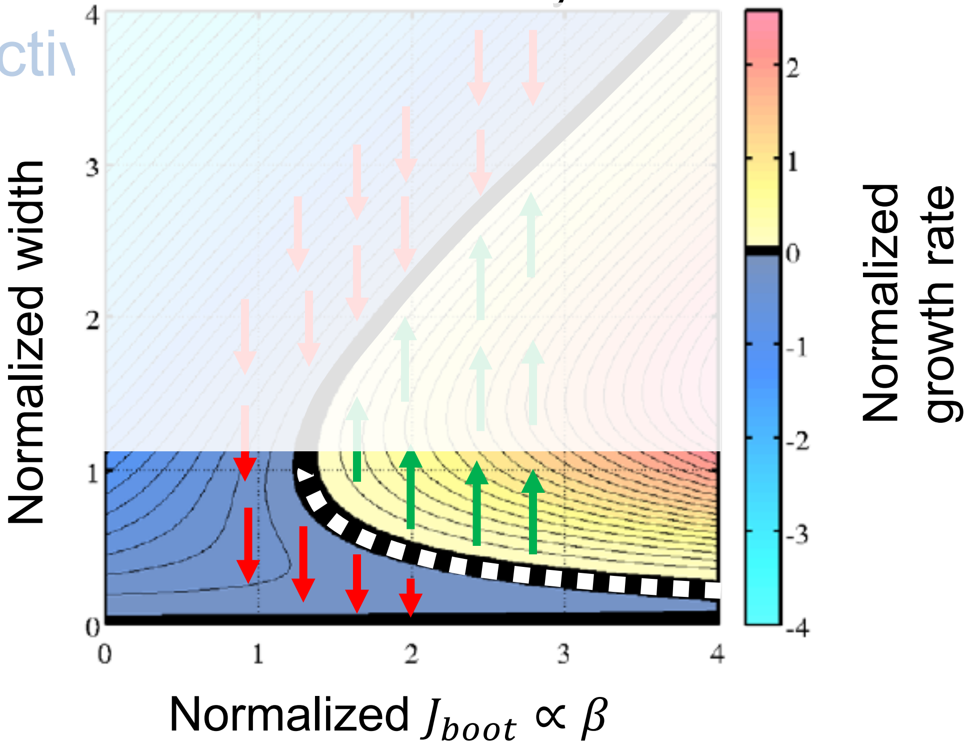
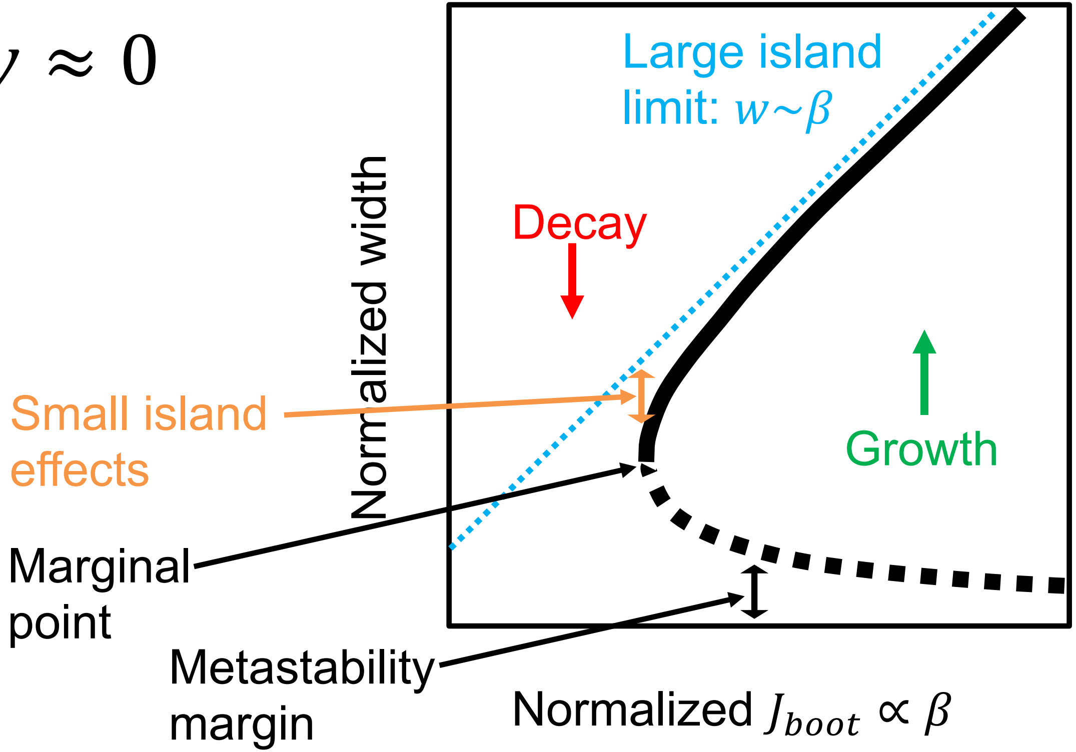


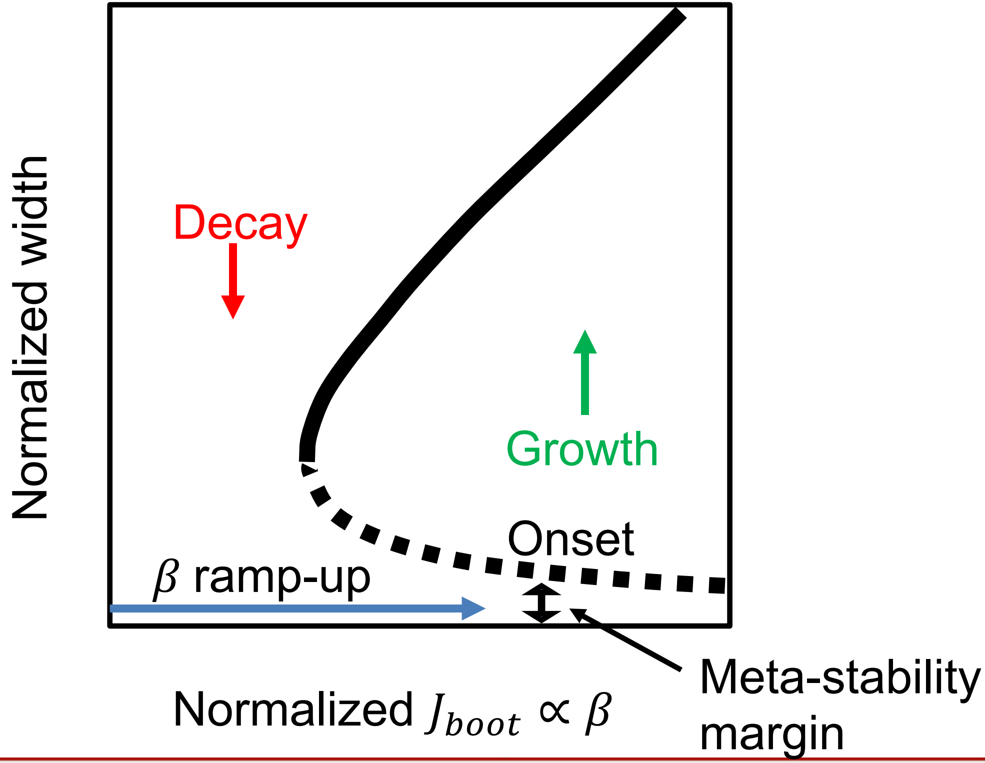
Solutions to MRE can be represented graphically

- Simplify to stability boundary for qualitative picture
- Keep in mind: $\dot{w} \approx 0$



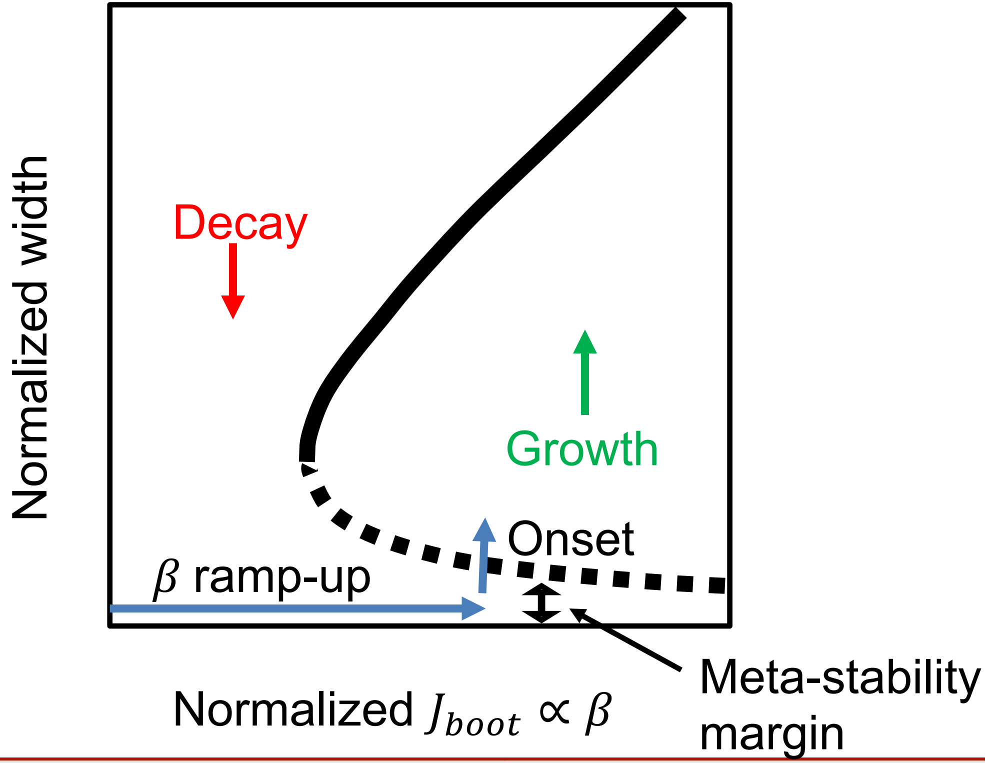
Trajectories during β ramp up/down exhibit hysteresis

1. Ramp-up: $w = 0$



Trajectories during β ramp up/down exhibit hysteresis

1. Ramp-up: $w = 0$
2. Onset: something 'kicks' mode over boundary



Trajectories during β ramp up/down exhibit hysteresis

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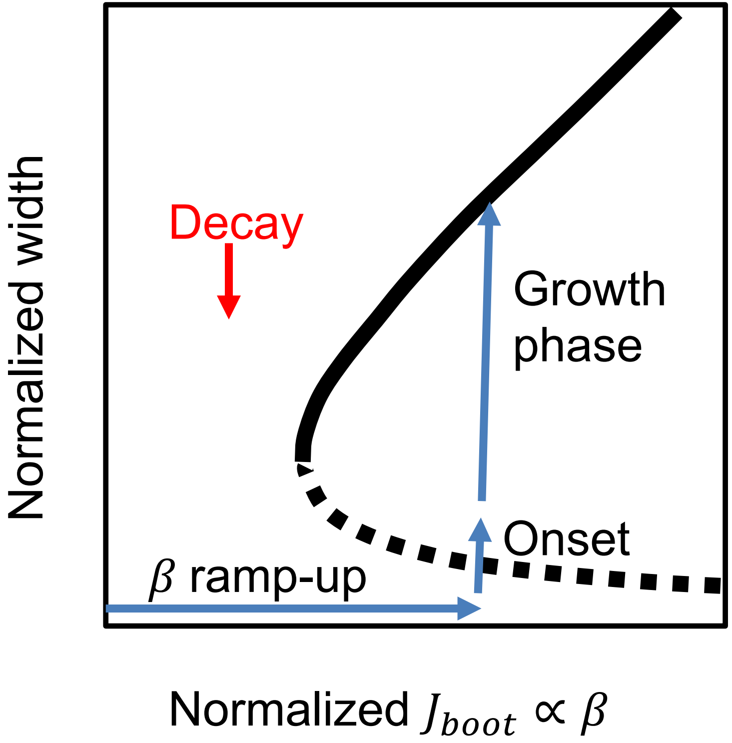

Trajectories during β ramp up/down exhibit hysteresis

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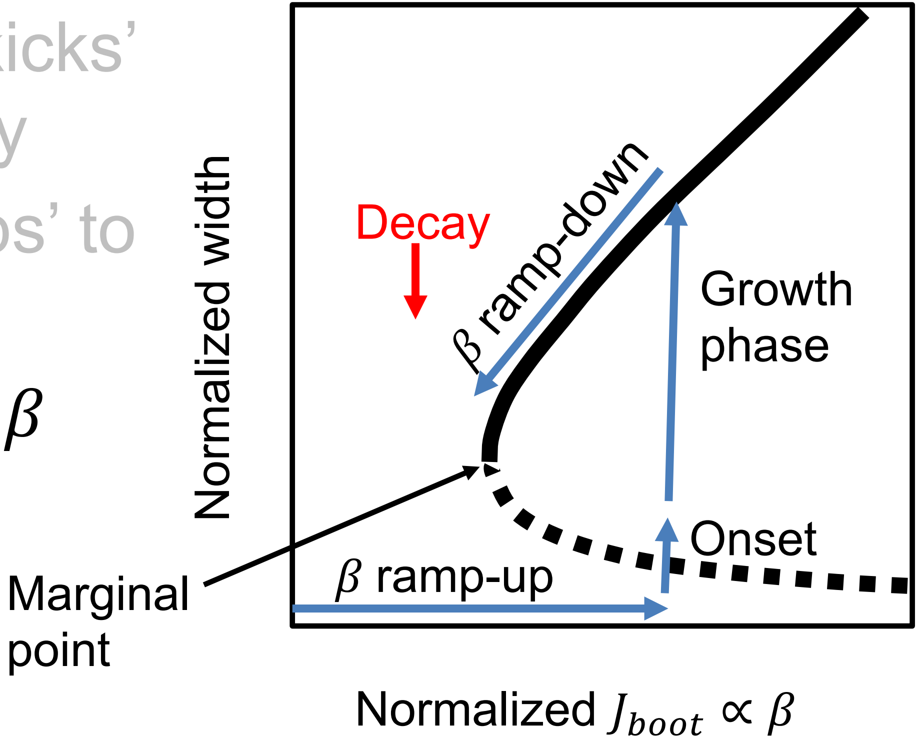
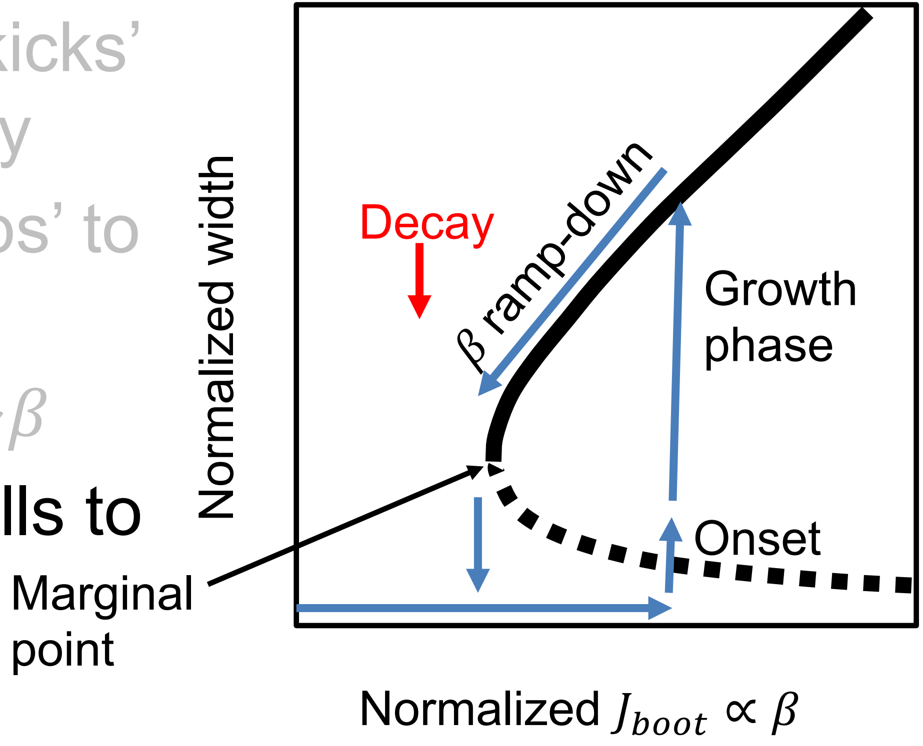
4. Saturated state: $w{\sim}\beta$

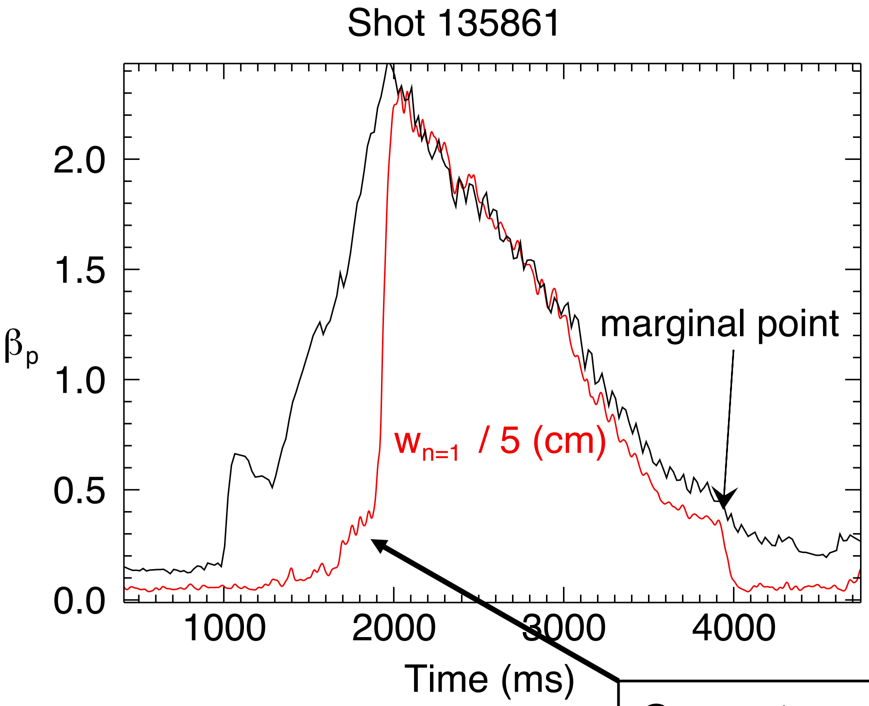


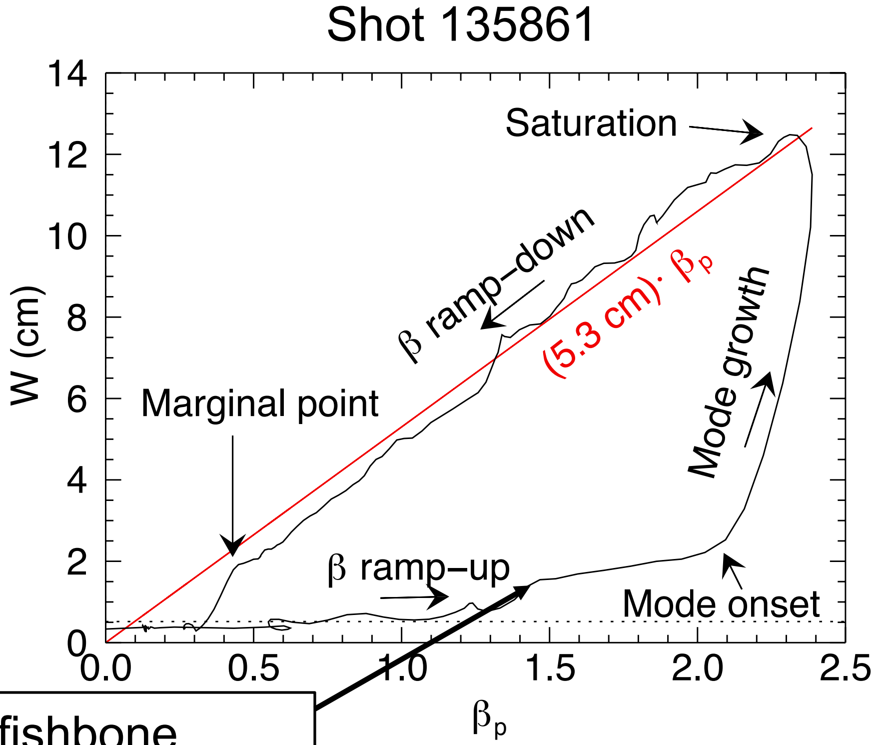
Trajectories during β ramp up/down exhibit hysteresis

1. Ramp-up: $w = 0$
2. Onset: something 'kicks' mode over boundary
3. Growth: mode 'jumps' to upper branch
4. Saturated state: $w \sim \beta$
5. Marginal point: w falls to zero
   – Loss of 'equilibrium'



Hysteresis loop seen in DIII-D experiments

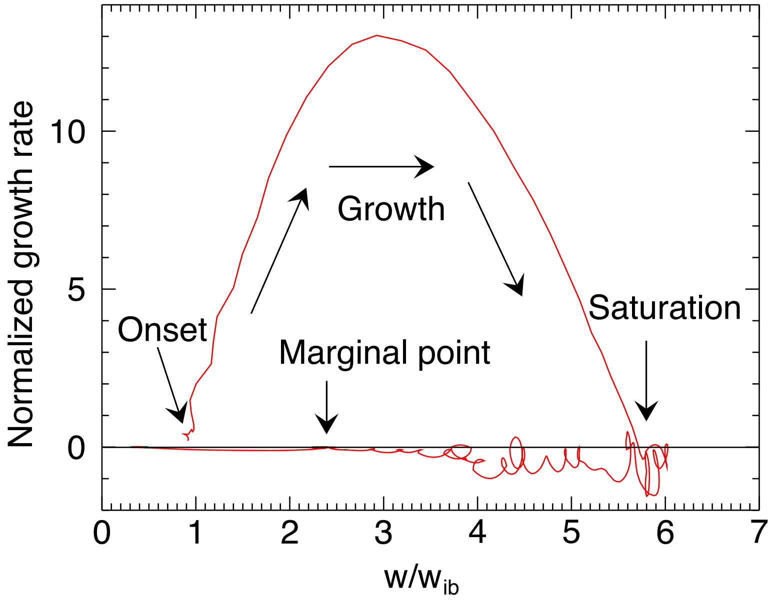




Caveat: m=1 fishbone activity in n=1 RMS

Evaluation of MRE using special points

- Maximum, saturated width
  - Relates bootstrap + curvature to Δ'
  - Neglect small-island-width terms
- Peak growth rate
  - Relates bootstrap/curvature to τ_r
  - Need to get τ_r correct
- Marginal point
  - Address small-island-width terms



Multi-device comparison can test aspect ratio dependences in modified Rutherford equation

La Haye *et al*, PoP **19,** 062506 (2012)

- Terms vary in different ways
  - With ϵ, in addition to β

$D_R \propto \epsilon^2 \beta_\theta$

$$1.22^{-1} \frac{\tau_R}{r} \frac{dw}{dt} = \Delta' r + C_R \frac{r D_R}{w} + \varepsilon^{1/2} \frac{r L_q}{L_{pe}} \beta_{\theta e} \left[\frac{1}{w} - \frac{w_{small}^2}{3w^3} \right]$$

$\epsilon = r/R_0$

$w_{small} \propto \epsilon^{-1/2}$?

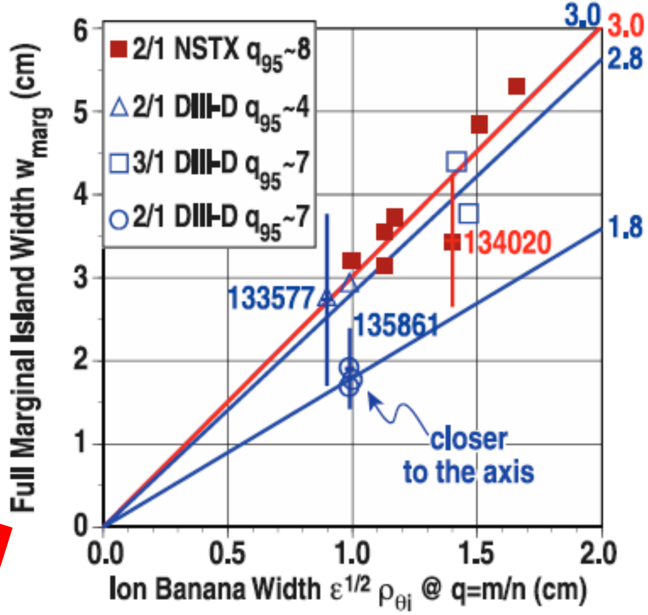
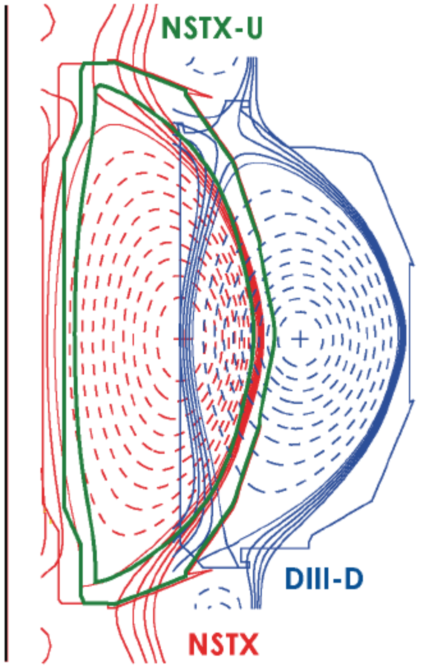


FIG. 5. Full marginal island width at outboard midplane $q = m/n$ versus local ion banana width. NSTX and two of three DIII-D cases have a ratio of about 3 while the one of three DIII-D cases that is closer to the magnetic axis (smaller local inverse aspect ratio magnetic field variation) is closer to a ratio of 2.

Dedicated DIII-D experiments can match NSTX-U tearing discharges already run

- Match shaping (except R/a), $q_{95} \approx 7$, $I_p \approx 0.9$ MA
  - $B_T \approx 1.44$ T (DIII-D) vs. 0.65 (NSTX-U) for q_{95} matching
- Get growth, saturation, marginal point
- Tearing stability is high priority topic in MSG
  - Exp's on DIII-D will provide complimentary data for NSTX-U



Aspect Ratio R/a = 1.4, 1.7, 2.7

‘Leapfrog’ NSTX-U MSG XP1544

- XP1544 approved but not run
  - “Make contact with NSTX for n=1 tearing stability”
- PPPL / GA collaboration on core stability
  - Previously published study

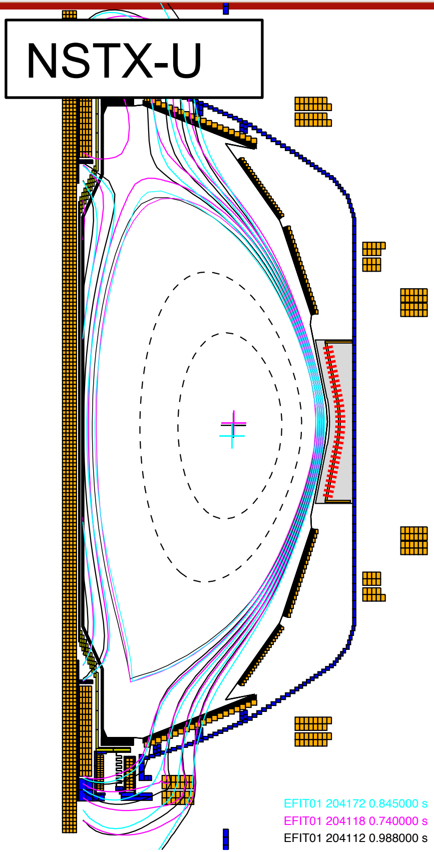
R. J. La Haye, R. J. Buttery, S. P. Gerhardt, S. A. Sabbagh, D. P. Brennan, *“Aspect ratio effects on neoclassical tearing modes from comparison between DIII-D and National Spherical Torus Experiment”*
PoP **19,** 062506 (2012)

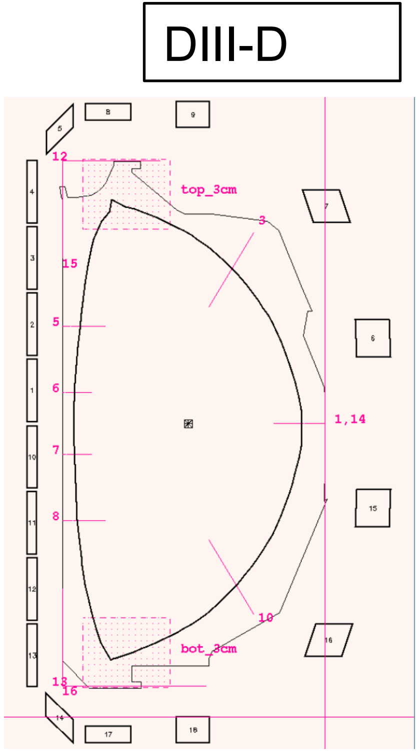
	DIII-D	NSTX-U	NSTX
R/a	3.1	1.7	1.4
Growth rate	!!!	✓	✓
Saturated size	!!!	✓	✓
Marginal point	!!!	✗	✓

XP 1544

DIII-D shot developed from target 135861

- Near q_{95}, I_p targets
- Improving shape matching
  - Increased inner gap at midplane
    - Increases elongation
  - Adjusted B_T to match q_{95}

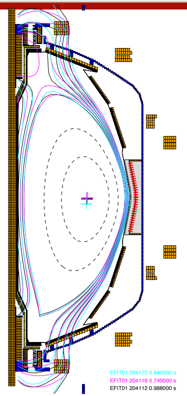




Courtesy R. La Haye

Tearing mode activity observed in NSTX-U initial operations

- **H-mode**
- **All high β_N**
- **All growing n=1 tearing during flattop**
- **Little/no CHERS**
- **No MSE**
- **Did have Thomson**



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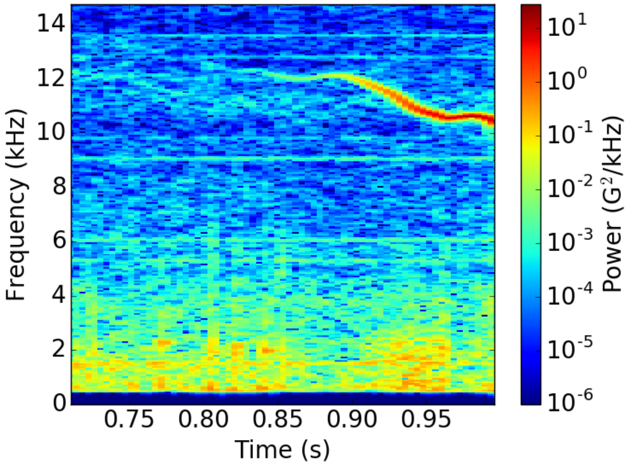

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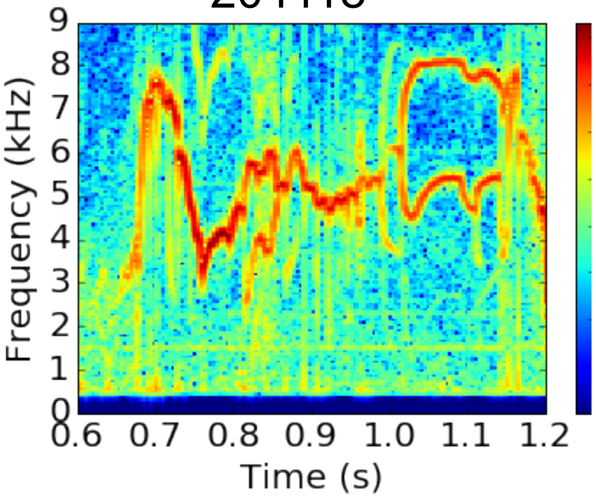

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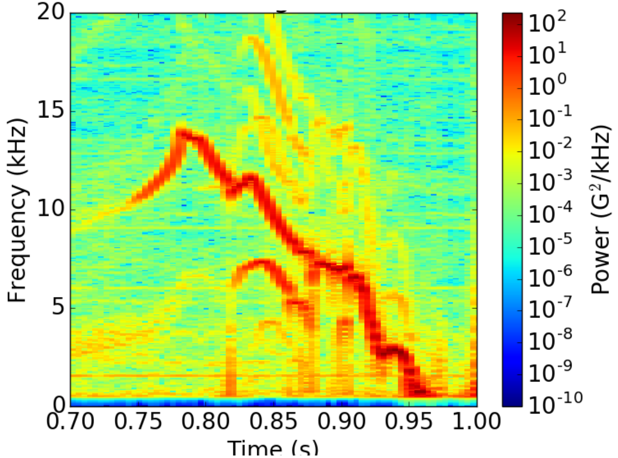
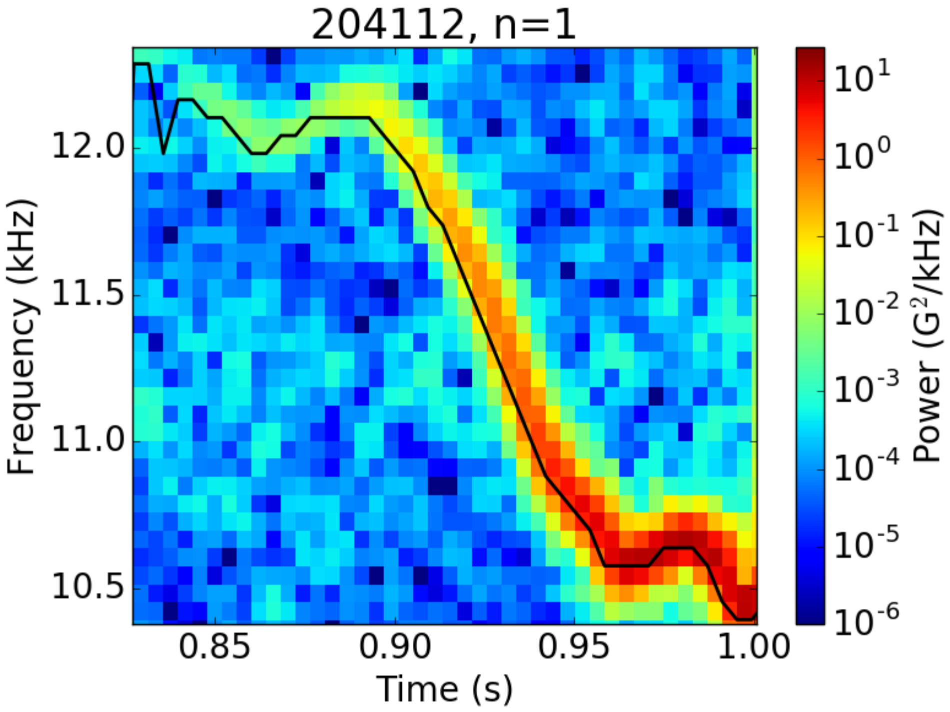


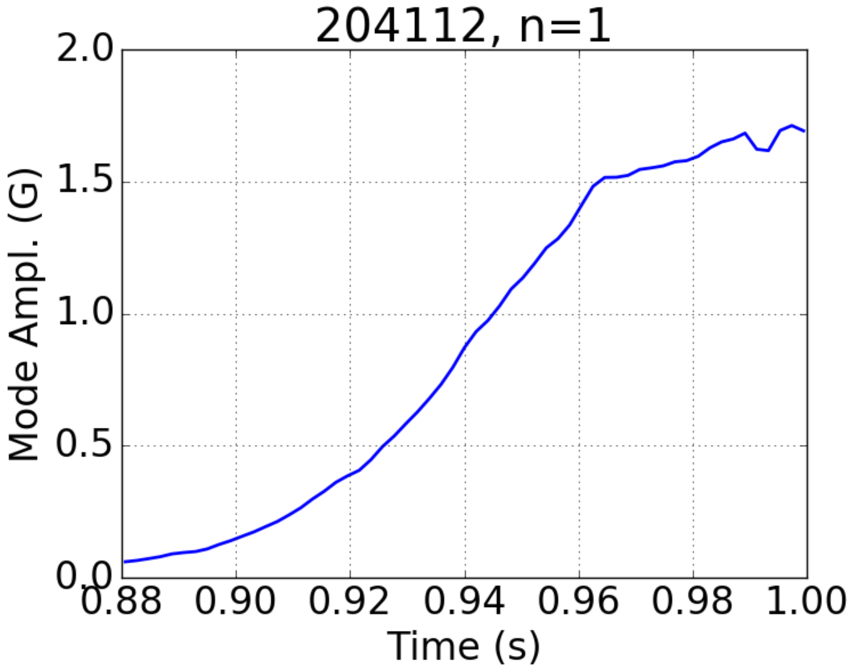
Step 1: Toroidal mode number analysis

- Use cross-phase, amplitude to auto-calibrate coils
  - Assume signal is $B(t, \phi_j) = C_j (B_n e^{i\omega t})$ with $C_j = |C_j| e^{in\phi_j}$
  - Check that nominal ≈ actual phase (correct n)
- Get best estimate of fluctuation:
  - $\hat{B}_n(t) = FFT^{-1}\left(\sum_j \frac{B(\omega, \phi_j)}{C_j}\right)$
- Calculate 'coherence' spectrogram:
  - $\chi(t, \omega) = \frac{\left|\sum_j B(t, \omega, \phi_j)\right|}{\sum_j \left|B(t, \omega, \phi_j)\right|}$

Step 2: Identify mode frequency, amplitude

- Fit Gaussian profile in frequency space for total power

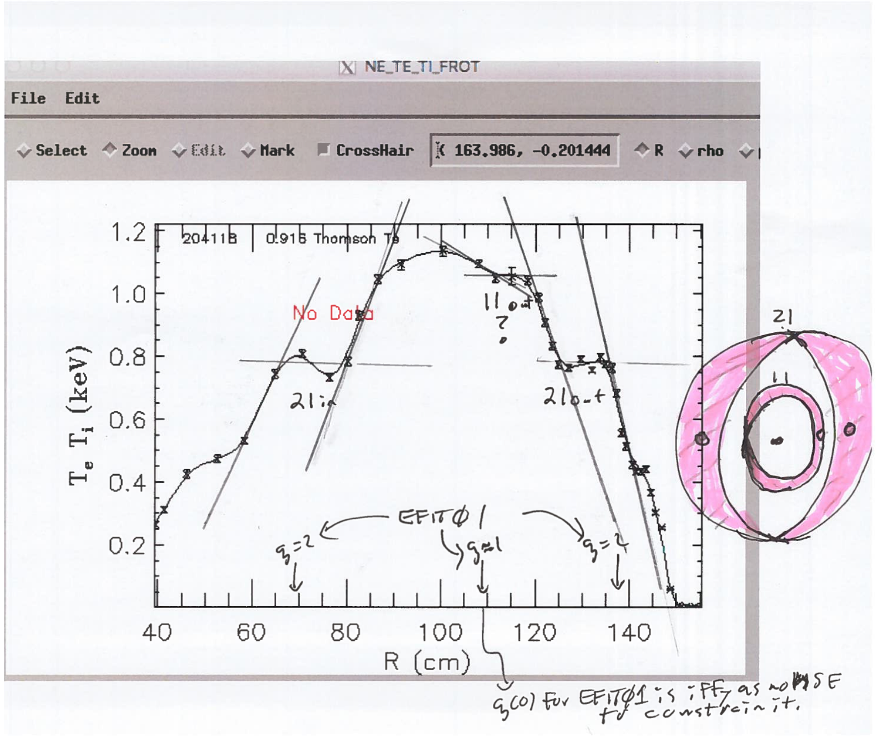




Step 3: Find island width from amplitude

- Use TS (NSTX-U), CHERS (NSTX) as available
- Find width of flat spot
- Calibrate mode amplitude:

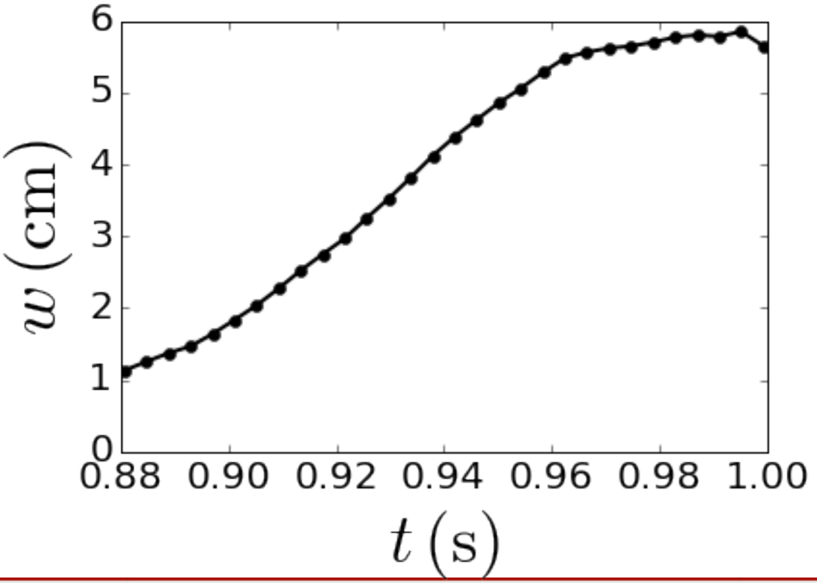
$$-w \propto \sqrt{\frac{\tilde{b}}{B_0}} \rightarrow w = C\sqrt{\tilde{b}}$$



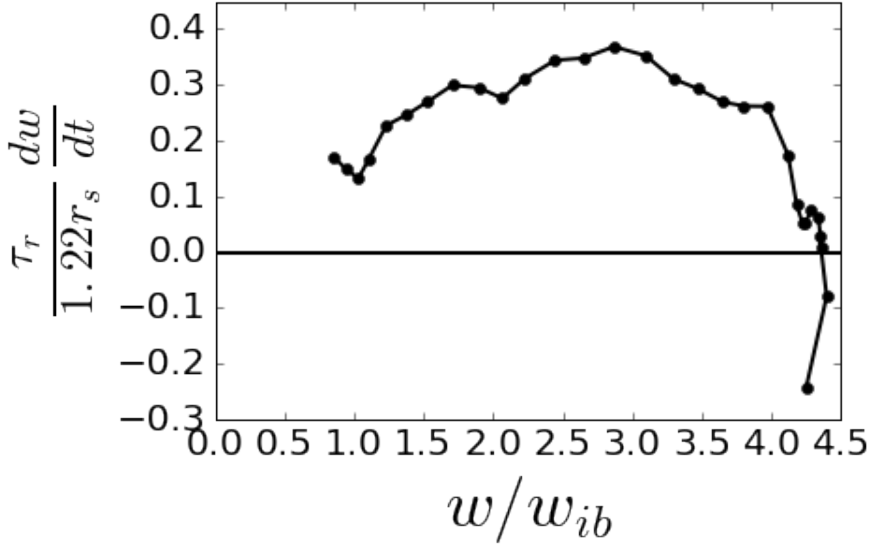
Step 4: Normalized phase diagram

- Growth rate as a function of width
- Normalize to ion banana width, resistive time

NSTX-U



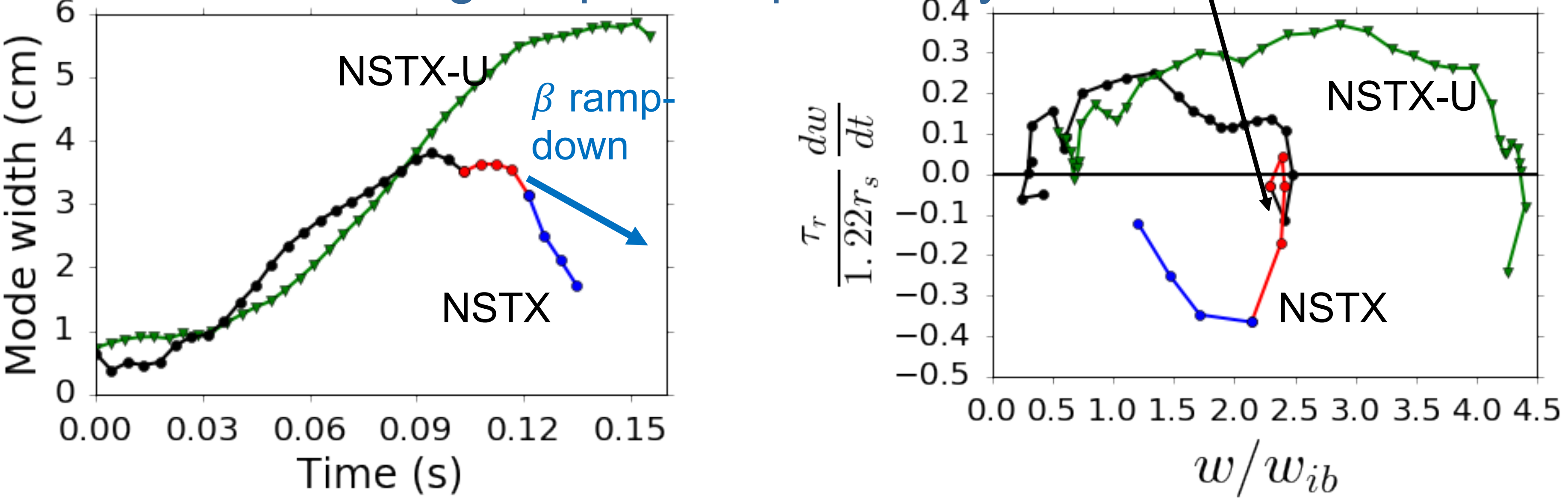
Shot 204112: growth and saturation



Early results from NSTX/NSTX-U comparison

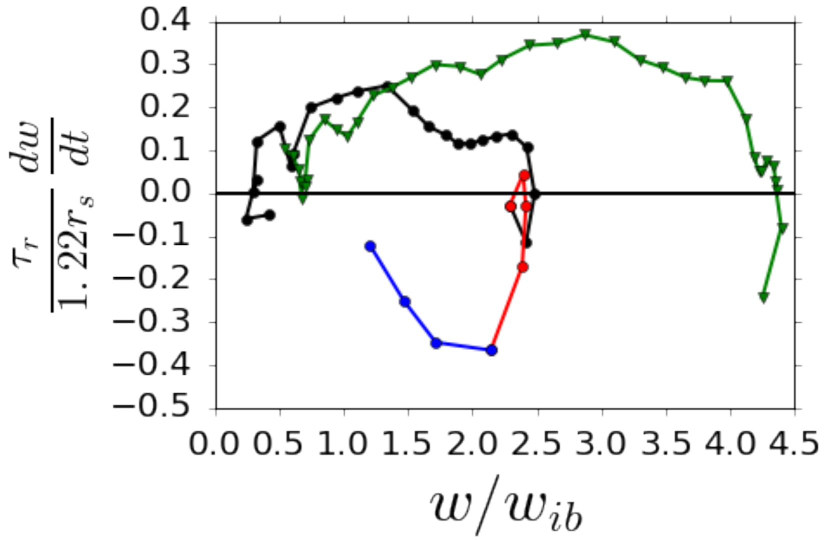
- NSTX-U sees larger, faster-growing $n = 1$ mode
  - Higher B_T & T_e → longer τ_r
  - No NSTX-U marginal point expt'l data yet

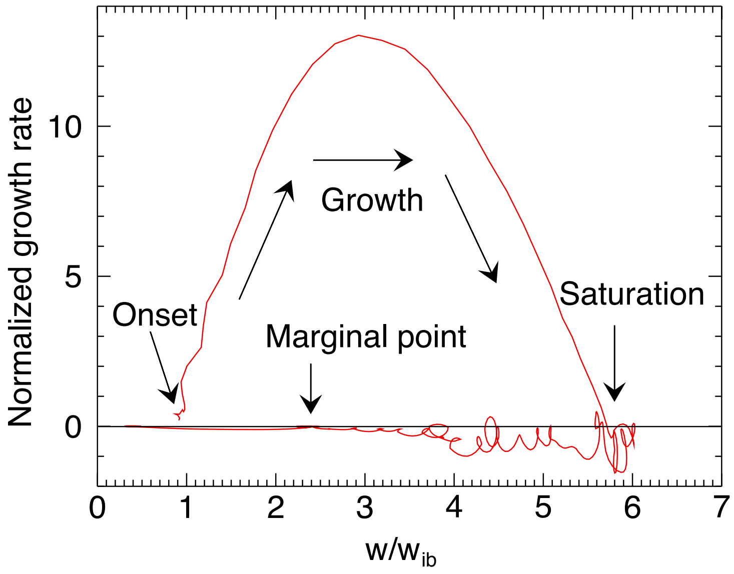
Marginal point ≈ saturated width!



Initial comparison of NSTX(-U), DIII-D

- Trend to larger, faster islands with smaller ϵ
- DIII-D peak growth rate very large
  - Resistive time?





Small aspect ratio → small hysteresis

- Larger ϵ →
  - More bootstrap
  - Smaller ‘small island’ limit

$D_R \propto \epsilon^2 \beta_\theta$

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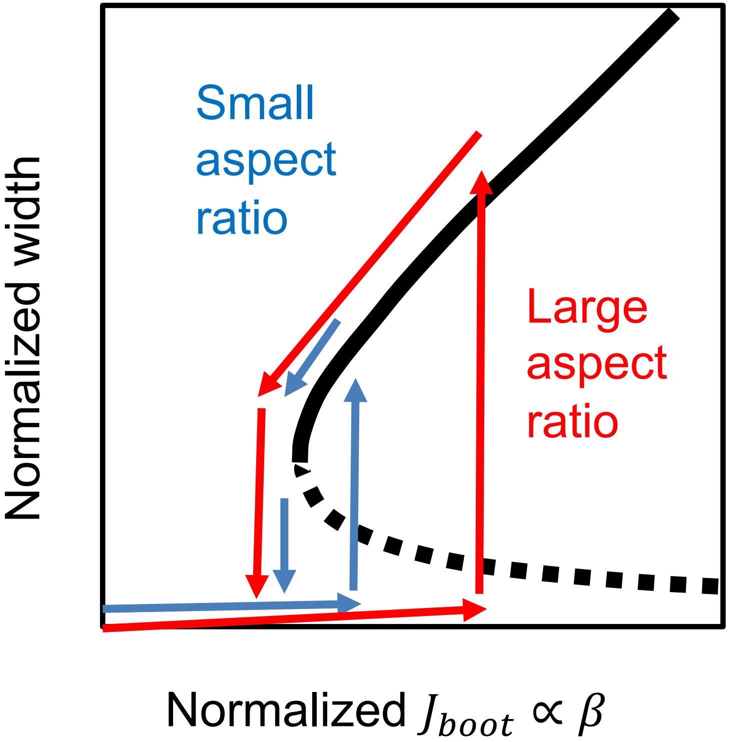

Dedicated DIII-D experiments for the national campaign can match NSTX-U tearing discharges already run

- Match shaping (except R/a), $q_{95} \approx 7$, $I_p \approx 0.9\ \mathrm{MA}$
  - $B_T \approx 1.44\ \mathrm{T}$ (DIII-D) vs. 0.65 (NSTX-U) for q_{95} matching
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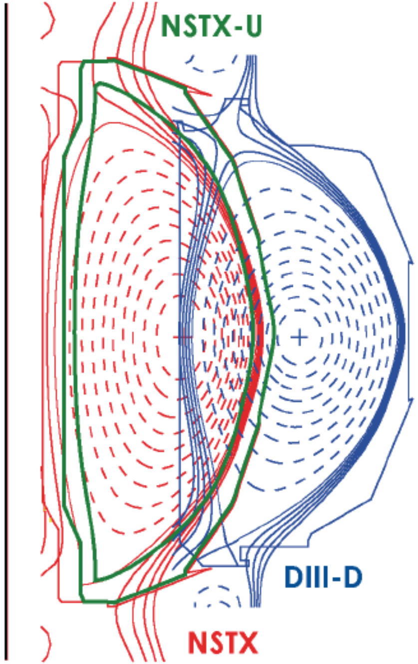

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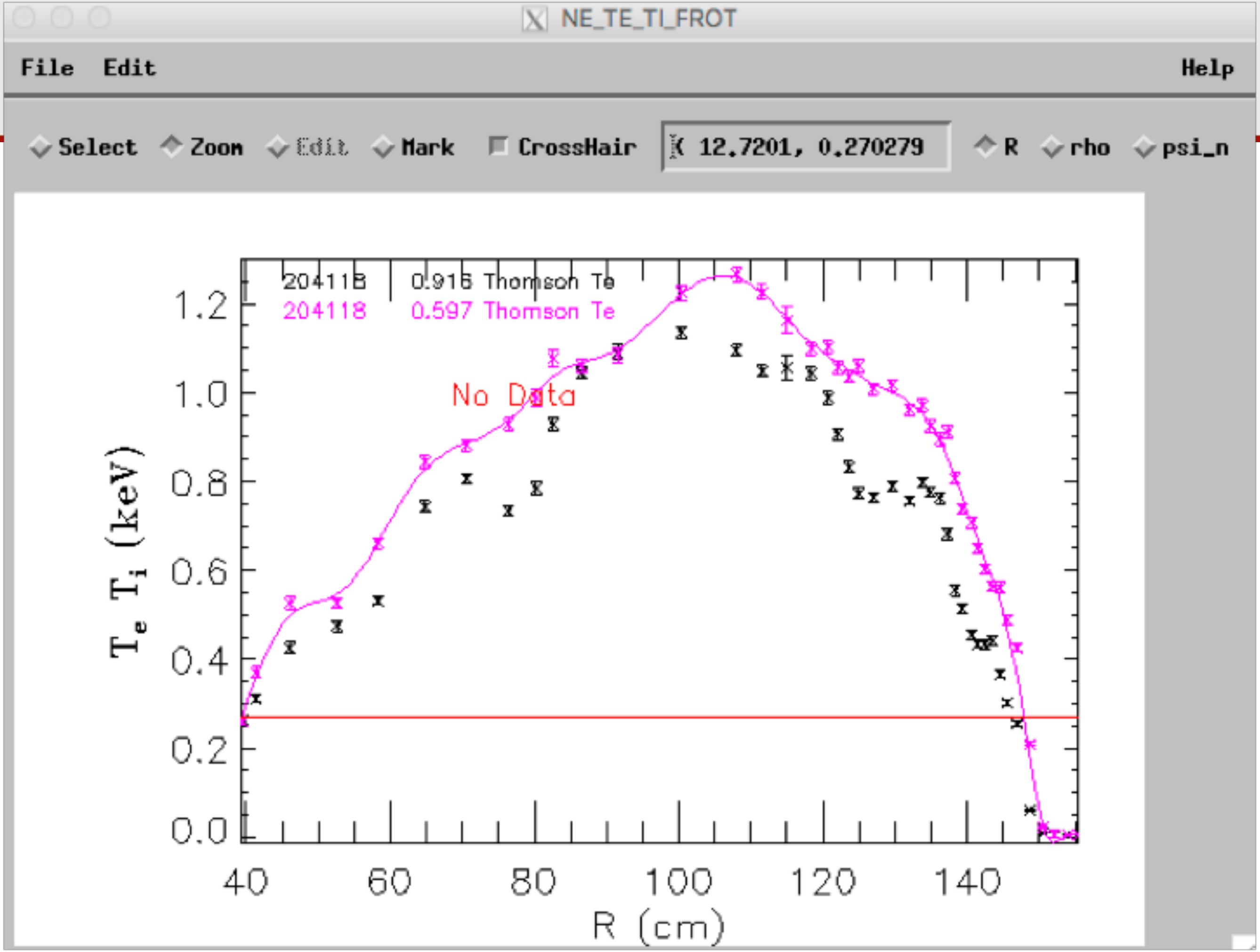
Reserve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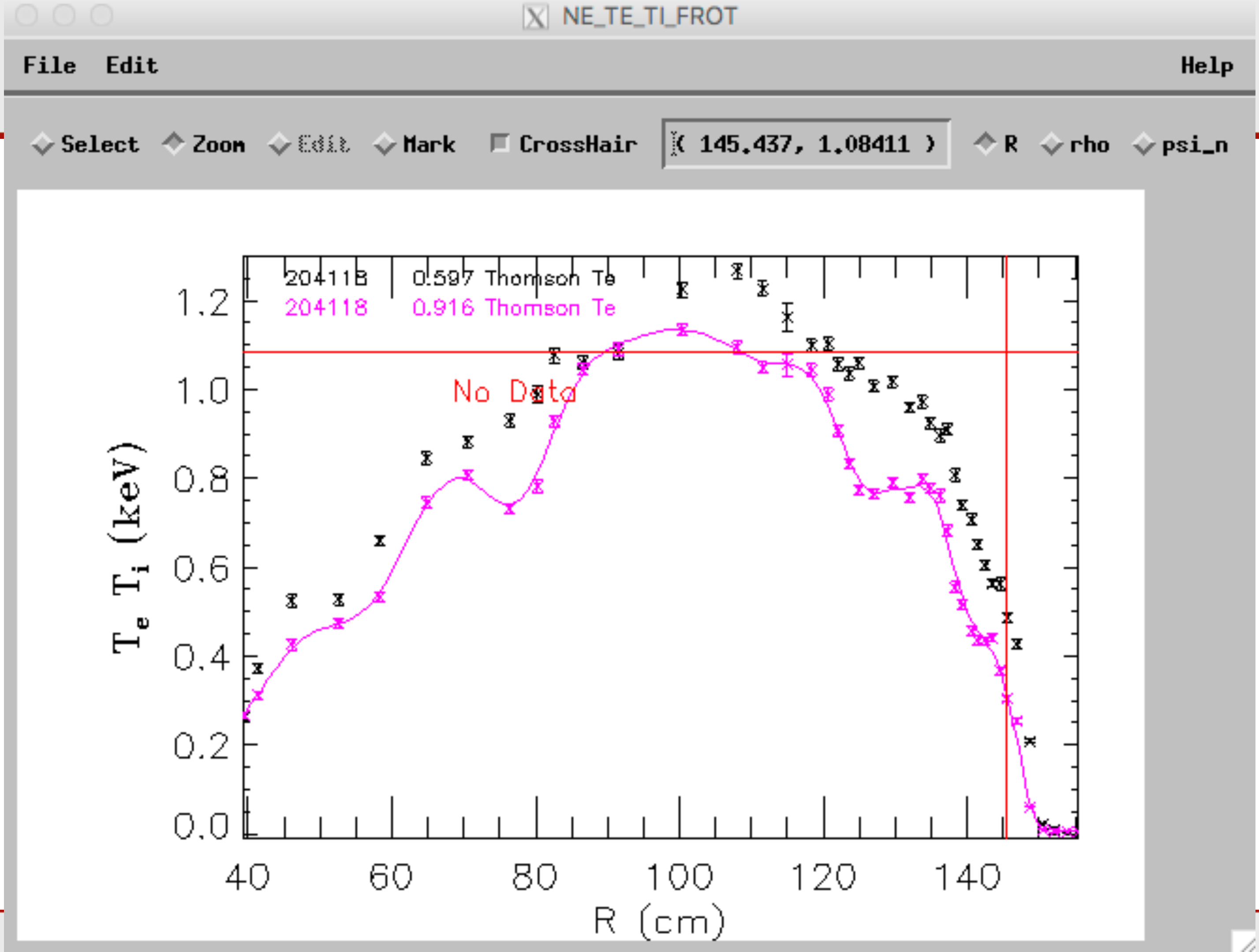
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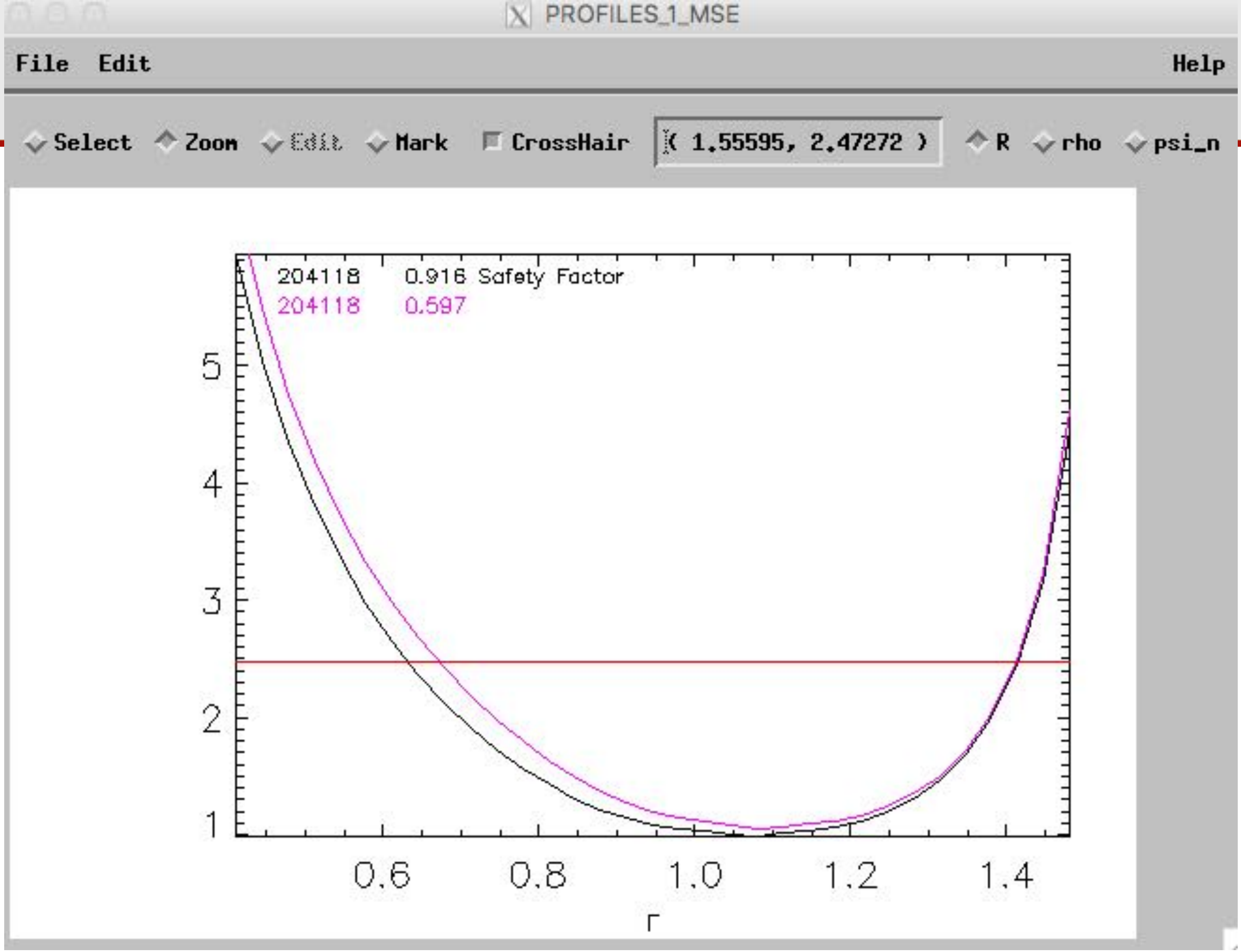
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