Abstract

The resistive wall mode (RWM) can be stabilized by maintaining the plasma toroidal rotation frequency (ω_ϕ) above a critical rotation frequency (Ω_{crit}). Recent experiments on NSTX seek to determine Ω_{crit} and rotation profile effects through actively braking plasma rotation by the application of external magnetic fields. Results from these experiments indicate that maintaining ω_ϕ at the q = 2 surface above $\omega_A/4q^2$ is a necessary condition for RWM stability where ω_A is the local Alfven frequency. This result is in agreement with a theoretical model derived from a drift-kinetic energy principle. Similarity experiments with DIII-D are being performed to examine the aspect ratio dependence of the Ω_{crit} scaling. When ω_ϕ at the q = 2 surface drops below Ω_{crit}, the growth of internal kink/ballooning modes can prevent the RWM from terminating the discharge. A small beta collapse which drops Ω_{crit}, accompanies this mode growth allowing a recovery of RWM rotational stabilization while maintaining $\beta_N > \beta_N^{no\text{-}wall}$.

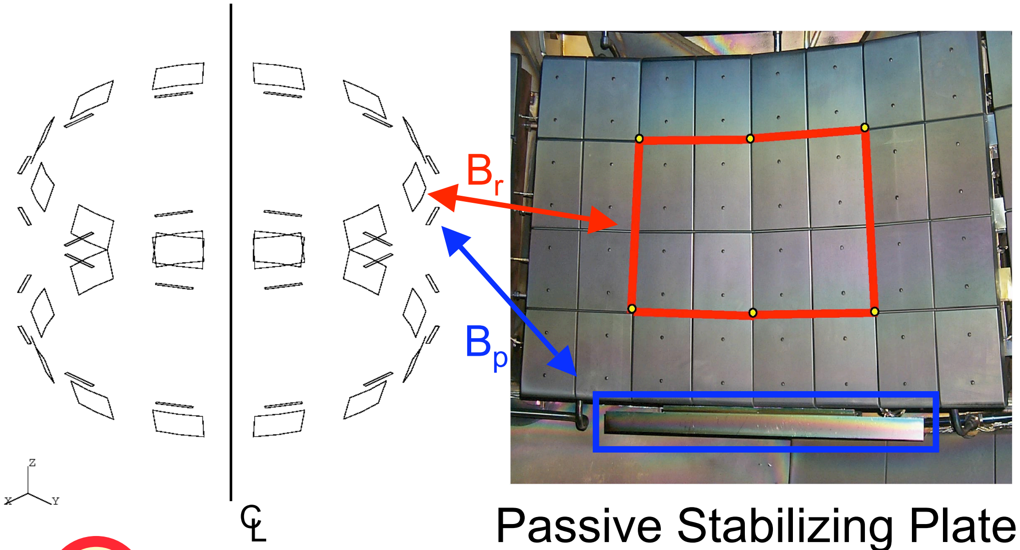
*Work supported by U.S. DOE contracts DE-FG02-99ER54524 and DE-AC02-76CH03073

RWM Can Limit Sustainable Pressure in Current and Future Fusion Devices

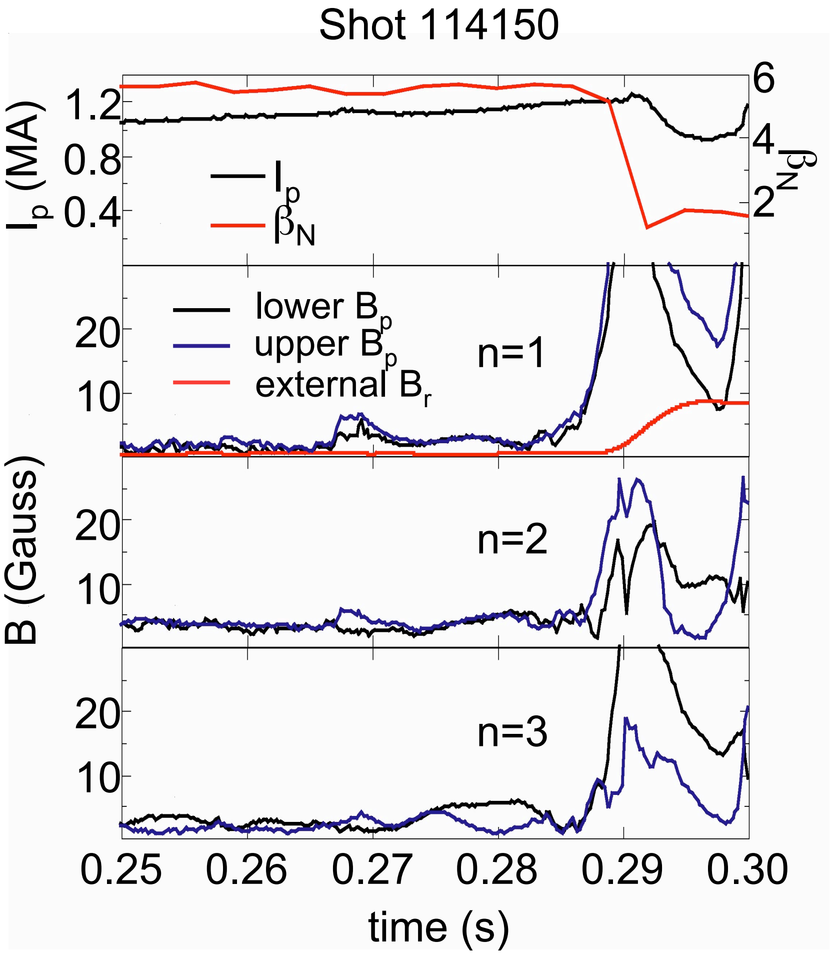
- Current fusion experiments which operate with $\beta_N > \beta_N^{\text{no-wall}}$ experience RWMs
- RWM can be stabilized by plasma rotation
  - Feedback control has also been demonstrated
- Future devices will have low rotation so may be more susceptible to RWMs
  - Understanding of the critical rotation required for RWM stability is important to design these devices correctly
- RWM can be stabilized by combination of toroidal rotation and dissipation
  - several dissipation mechanisms have been proposed
    - sound wave
    - ion Landau damping
    - Alfven continuum
  - rotation can affect dissipation strength
  - critical rotation frequency (Ω_{crit}) is minimum rotation required for stability

Internal Sensor Array Used for RWM Detection

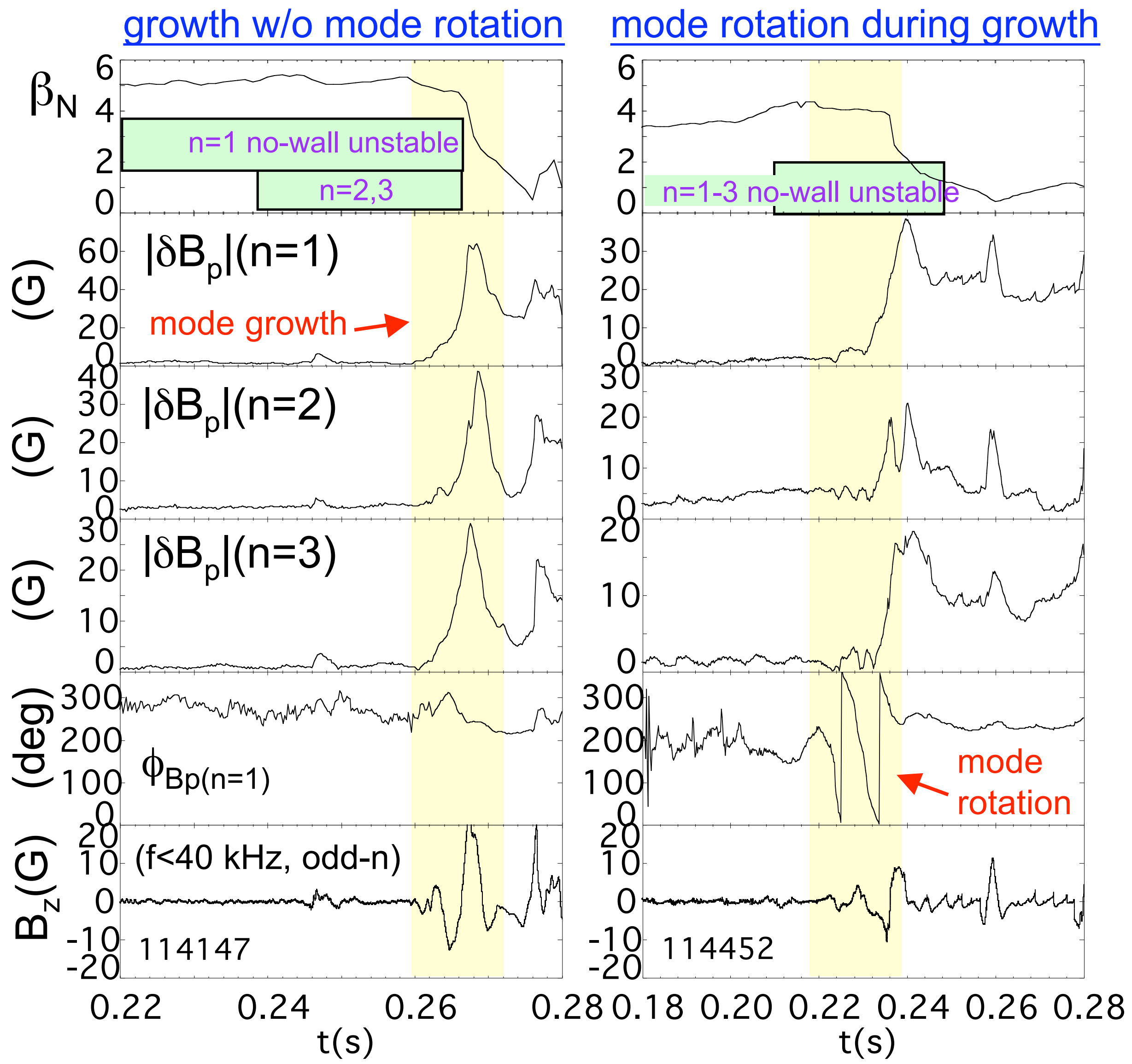
- Internal toroidal arrays of B_p and B_r sensors installed
  - 5 kHz digitization rate
  - instrumented to detect n = 1 - 3
- Measured coil currents used for background subtraction
  - ~2 Gauss noise level achieved
  - allows real time mode detection
- SVD mode detection is robust



Passive Stabilizing Plate



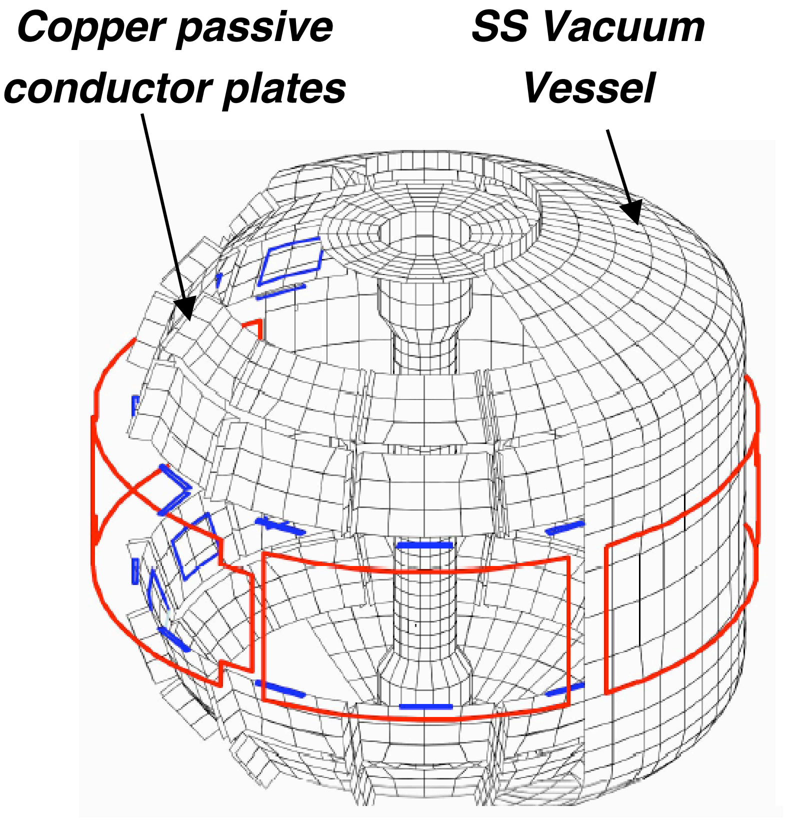
Unstable RWM Dynamics Follow Theory



- Unstable n=1-3 RWM observed*
  - ideal no-wall unstable at high β_N
  - n > 1 theoretically less stable at low A
- F-A theory / experiment show
  - mode rotation can occur during growth
  - growth rate, rotation frequency ~ 1/τ_{wall}
    - << edge Ω_ϕ > 1 kHz
  - RWM phase velocity follows plasma flow
  - n=1 phase velocity not constant due to error field
- Low frequency tearing modes absent

**S.A. Sabbagh, et al., IAEA FEC 2004 paper EX/3-2; submitted to NF*

New Coils and Power Supplies Provide Greater Flexibility to Study Ω_{crit}

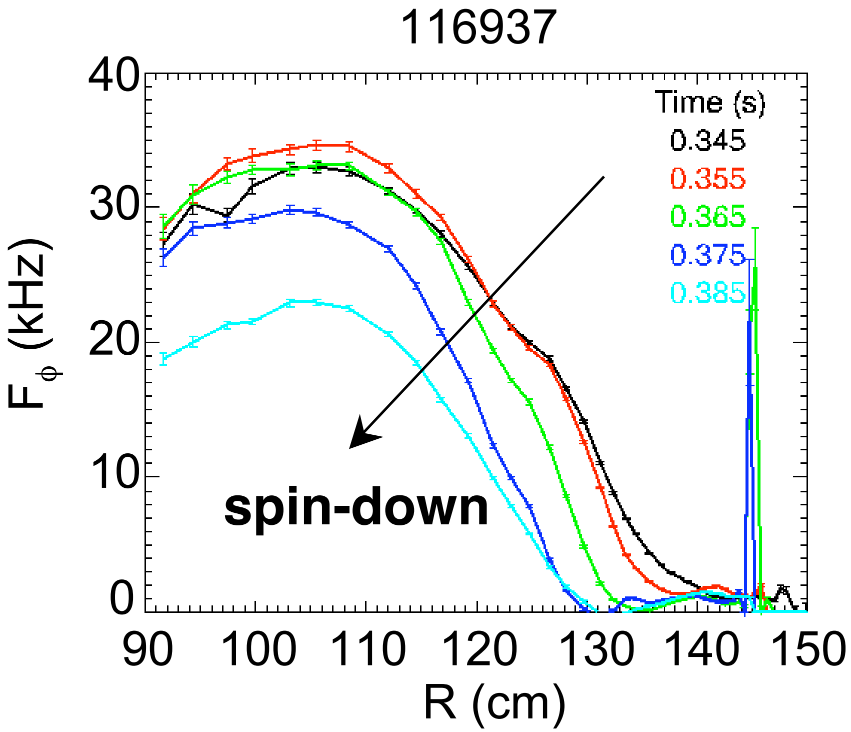


VALEN Model of NSTX (J. Bialek)

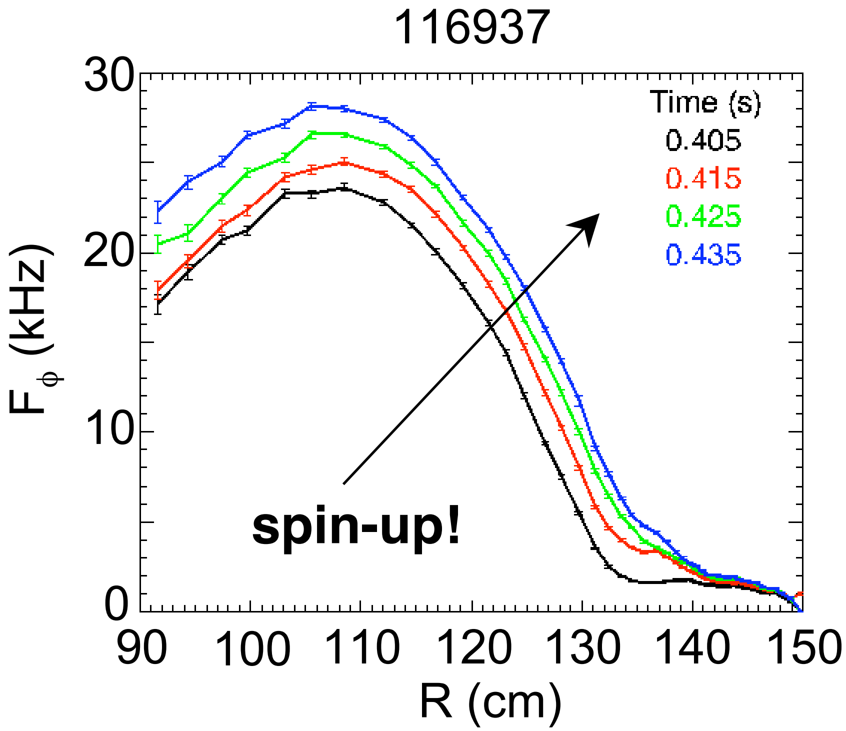
6 ex-vessel midplane control coils

- RWM/EF coil and SPA capabilities:
  - 3 opposing coil pairs in anti-series (n=1,3)
    - n=2 interconnection also possible
  - 3 independent SPA circuits - 3.3 kA, 7.5 kHz
  - Can produce 10-15 G n=1 resonant $B_\perp$ at q=2
- Uses for NSTX:
  - investigate Ω_{crit} profile by perturbing ω_ϕ
  - investigate RFA
  - investigate error field correction
  - future active RWM stabilization

External Field Application Allows Rotation Control



n=3 DC (1.1kA) external field applied

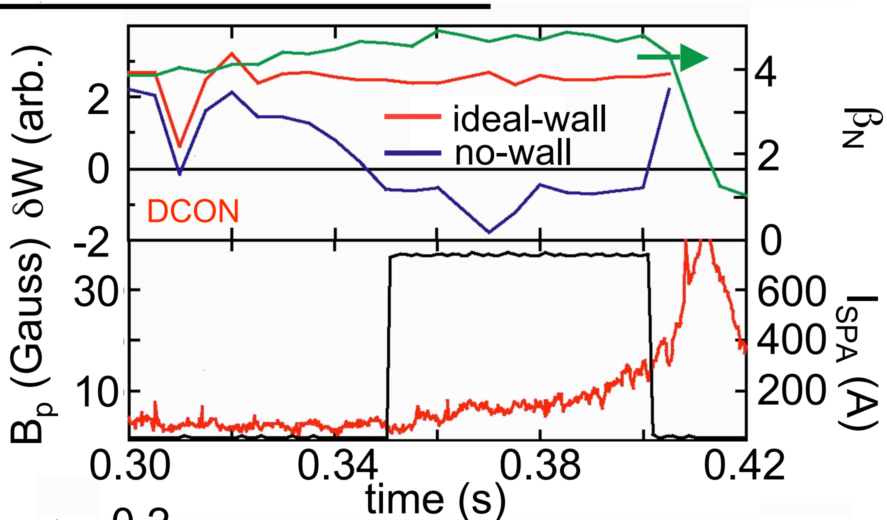


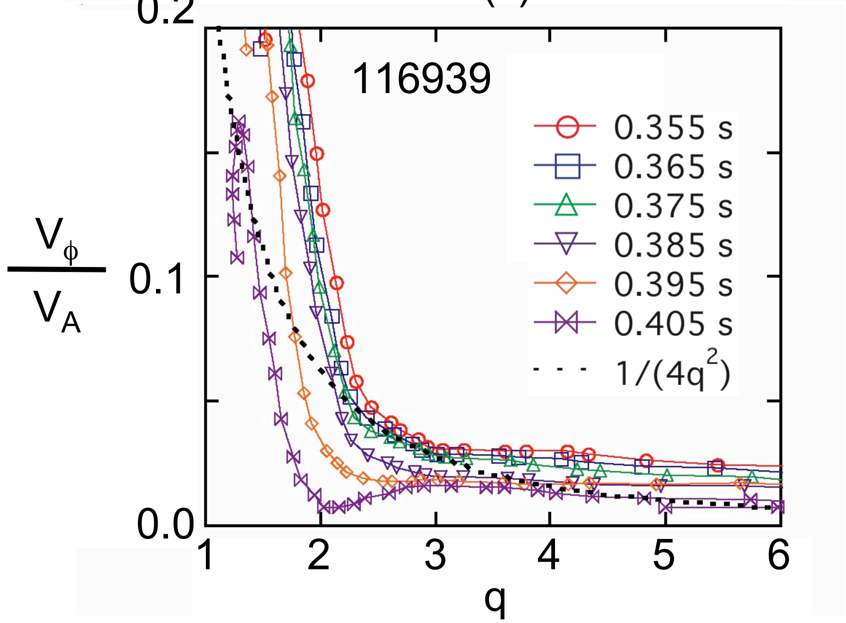
external field shut down

- Control over rotation allows more careful examination of the rotation profile effects on RWM stability

Resonant Field Amplification Observed With Application of External n = 1

- Resonant field amplification (RFA) when $\beta_N > \beta_{N\ \text{no-wall}}$
  - amplification of external perturbations by *stable* RWM
  - predicted by theory*
  - Ideal MHD stability δW from DCON (A.H. Glasser)
- RFA observed until rotation braking destabilizes mode
  - unstable growth after significant rotation damping
  - edge rotation remains stabilizing
  - low rotation at multiple low-order rational q surfaces

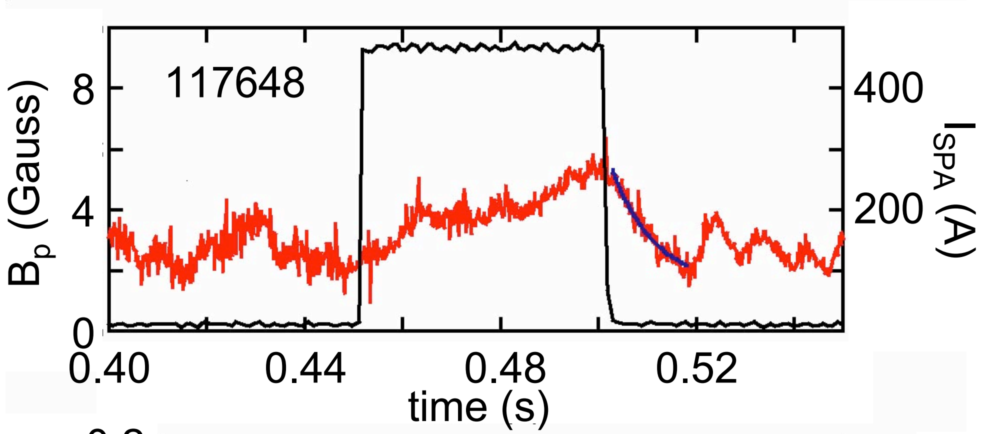


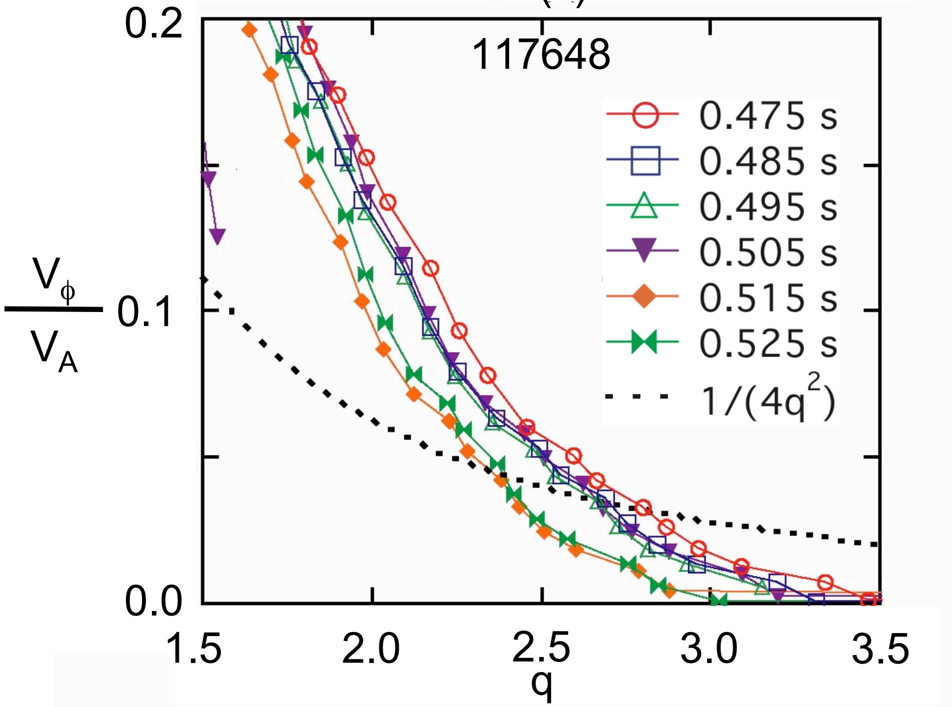


*Boozer, A.H., Phys. Rev. Lett., **86** 5059 (2001)

RFA Decays When External Field Turned Off Before RWM Destabilization

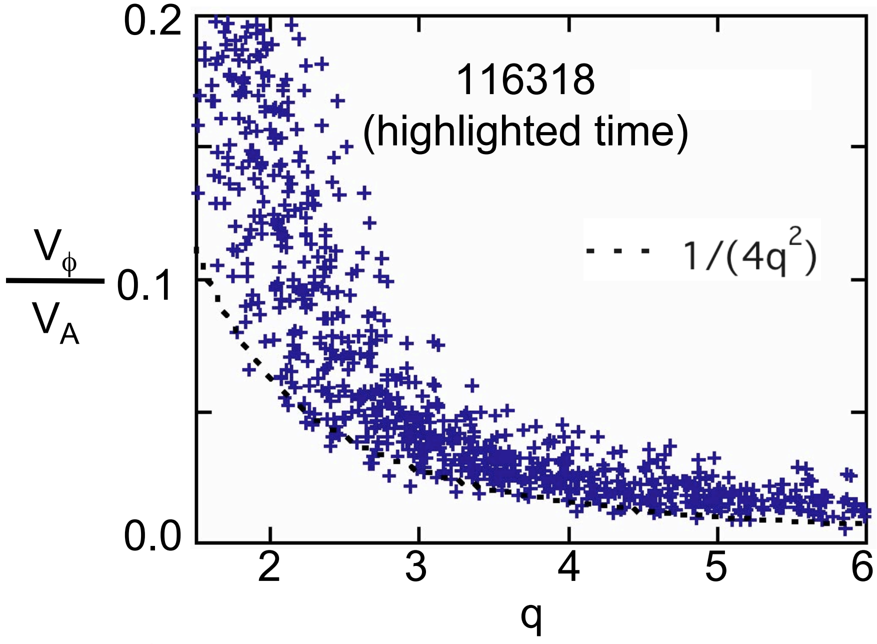
- rotation remains high at some low-order rational q surfaces
  - near zero rotation outside q = 3 (ψ_N ~ 0.65)
- field amplitude below threshold
  - ~20 Gauss causes unstable mode growth and disruption
- 9.1 ms decay time measured

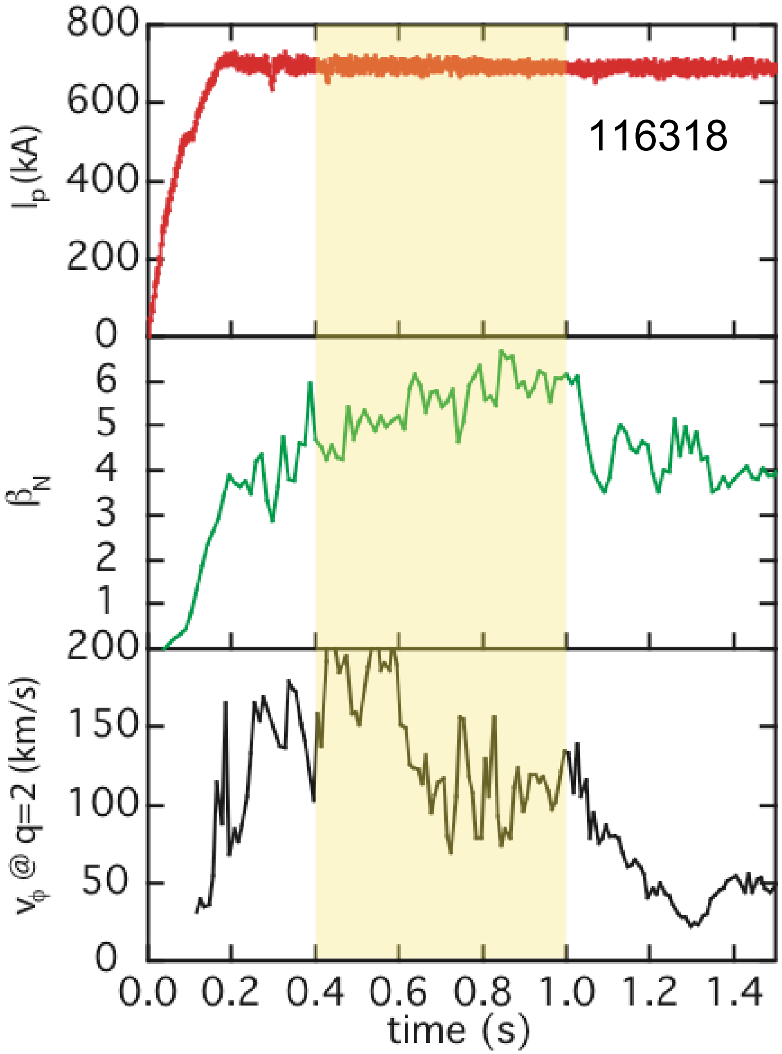




High Toroidal Rotation Across Entire Profile Allows Sustained High β_N

- Entire rotation profile stays high during high-β period
  - ❑ Alfven speed normalization & q dependence from drift-kinetic theory
- Trend observed in numerous discharges



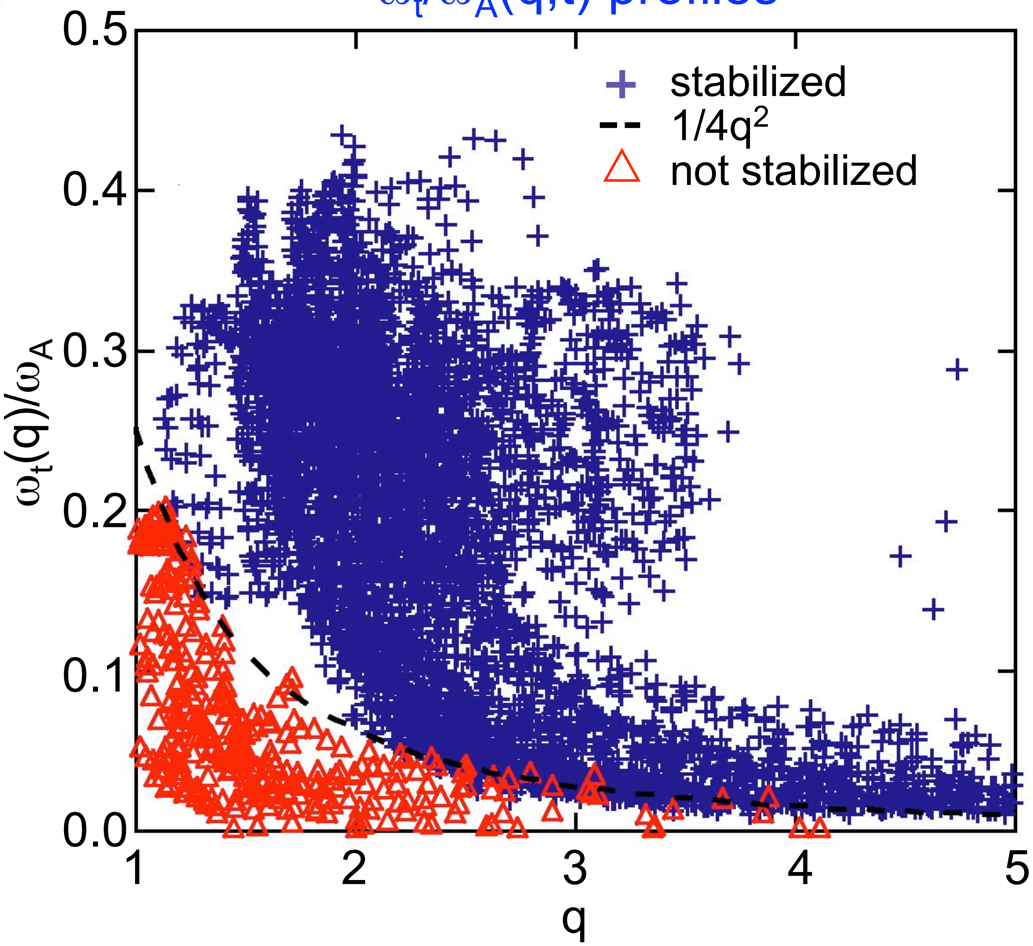


2004 Data Supports $1/q^2$ Scaling of Critical Rotation Frequency

- Scaling from two stability classes:
  - stabilized ⇒ no RWM for t >> τ_{wall} when $\beta_N > \beta_{N\ \text{no-wall}}$
  - not stabilized ⇒ collapse after a few τ_{wall} when $\beta_N > \beta_{N\ \text{no-wall}}$
- Bondeson-Chu drift-kinetic model* agrees with observed scaling
  - trapped particle effects weaken stabilizing ion Landau damping
  - toroidal inertia enhancement becomes more important
  - Alfven continuum damping gives:

$$\Omega_{crit} \equiv \frac{\omega_t}{\omega_A} = \frac{1}{4q^2}$$

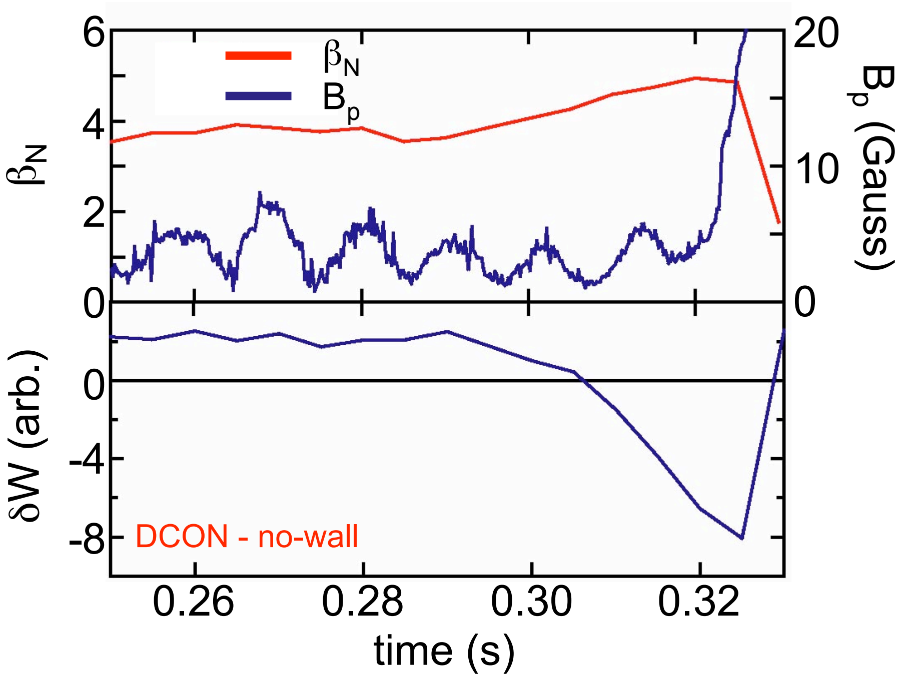
$\omega_t/\omega_A(q,t)$ profiles

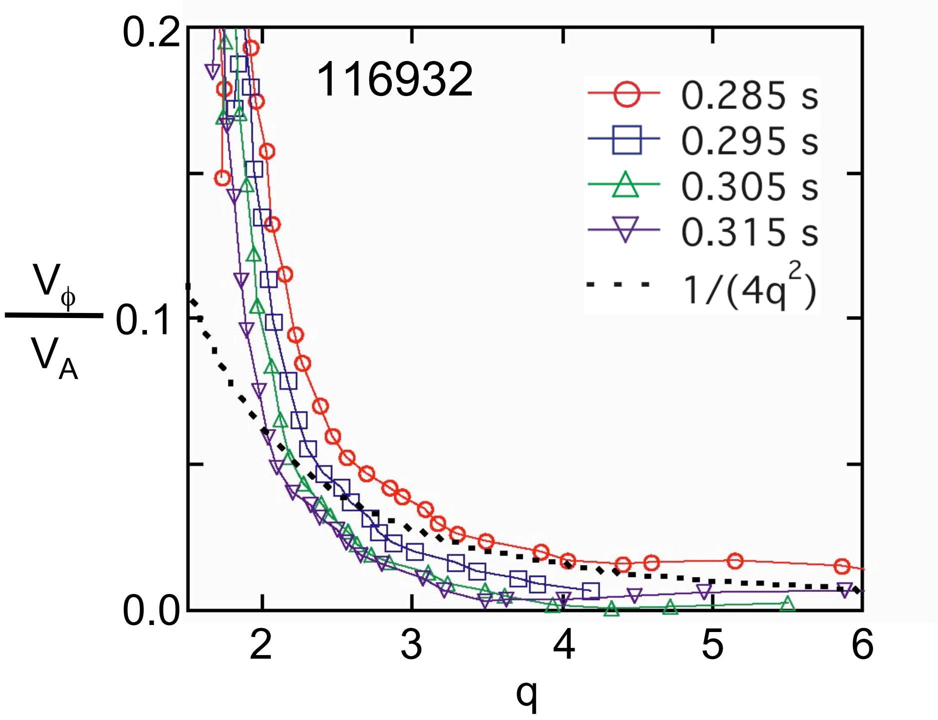


*Bondeson, A., Chu, M.S., Phys. Plasmas **3** 3013 (1996) & Sontag, A.C., et al., Phys. Plasmas **12** 056112 (2005)

High Core Rotation Insufficient to Stabilize RWM

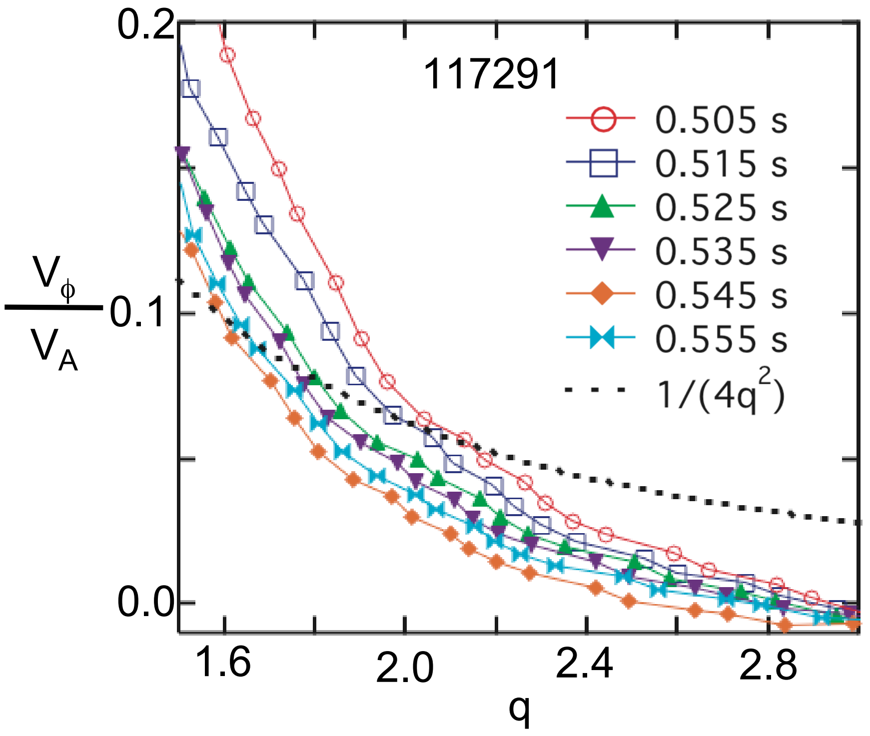
- Low edge rotation when no-wall limit exceeded
- RWM growth causes further rotation damping
    - ~15 Gauss threshold after which collapse is inevitable
- Important question: What is the critical rotation profile?

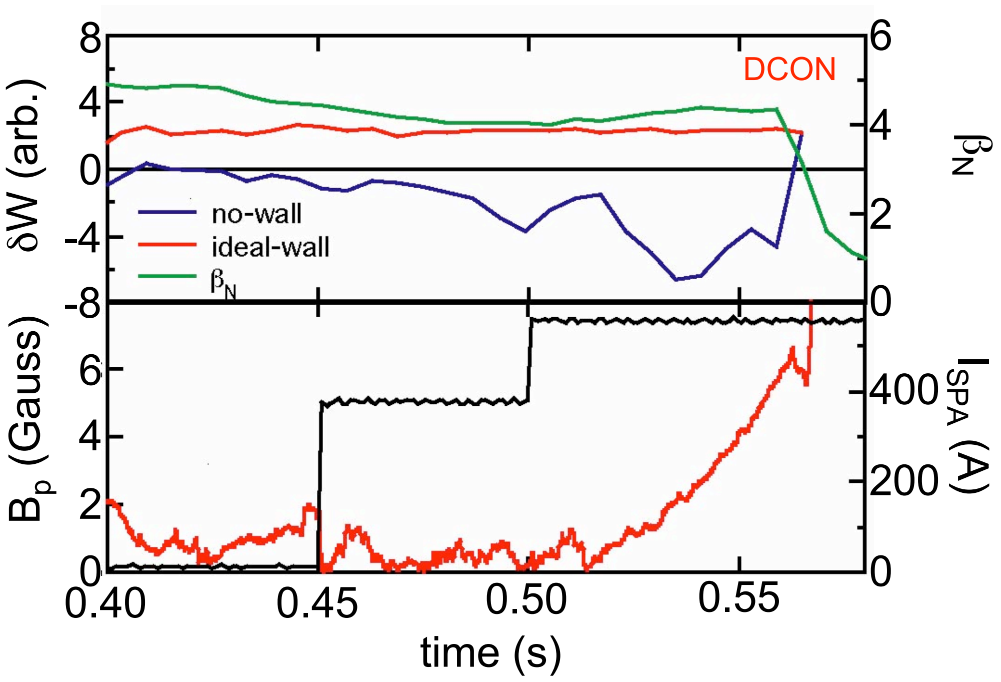




Rotation on Higher Order Rational Surfaces Not Required for RWM Stabilization

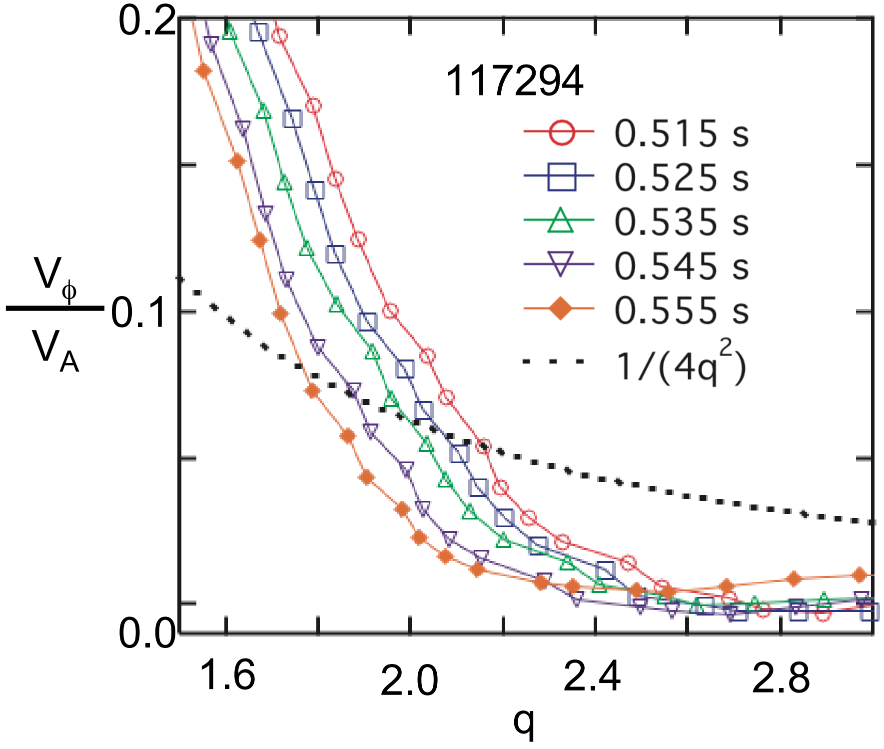
- Plasma remains RWM stable with near zero rotation outside q = 3
  - ❑ Stable with near zero rotation outside ψ_N = 0.62
  - ❑ growth coincides with low rotation inside of q = 2

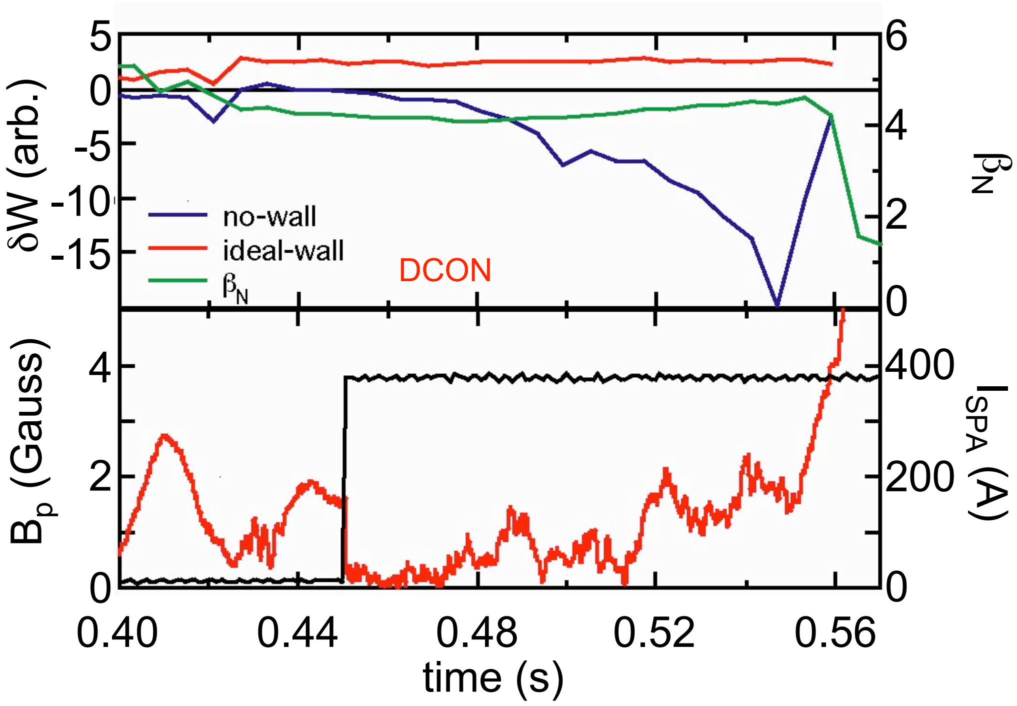




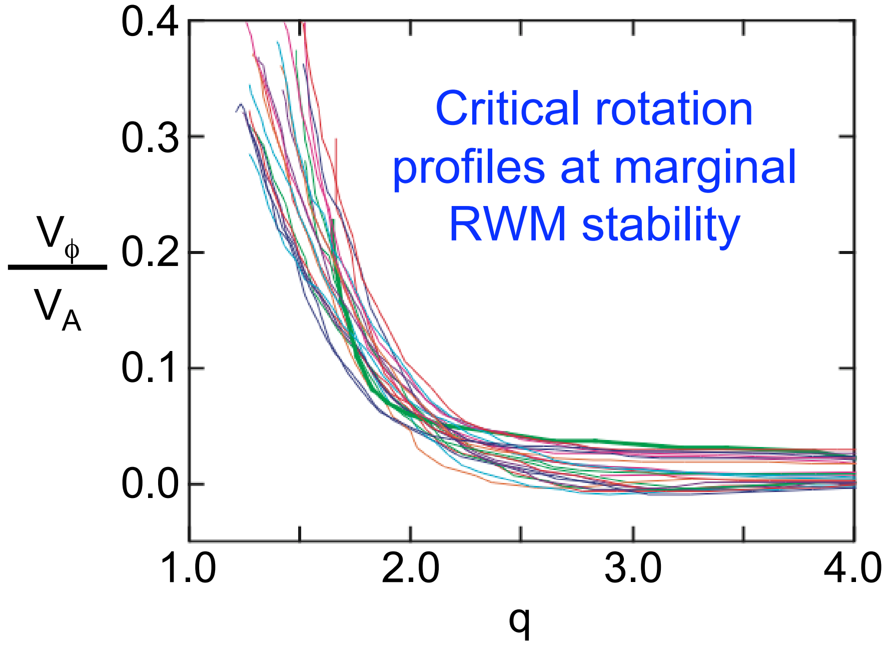
Similar Discharges Survive Longer With Lower Rotation @ q = 2 Surface

- No unstable growth until ~ 20 ms after rotation drops at q = 2
- Higher δW & lower applied field than 117291
  - factors beyond rotation at q = 2 need consideration

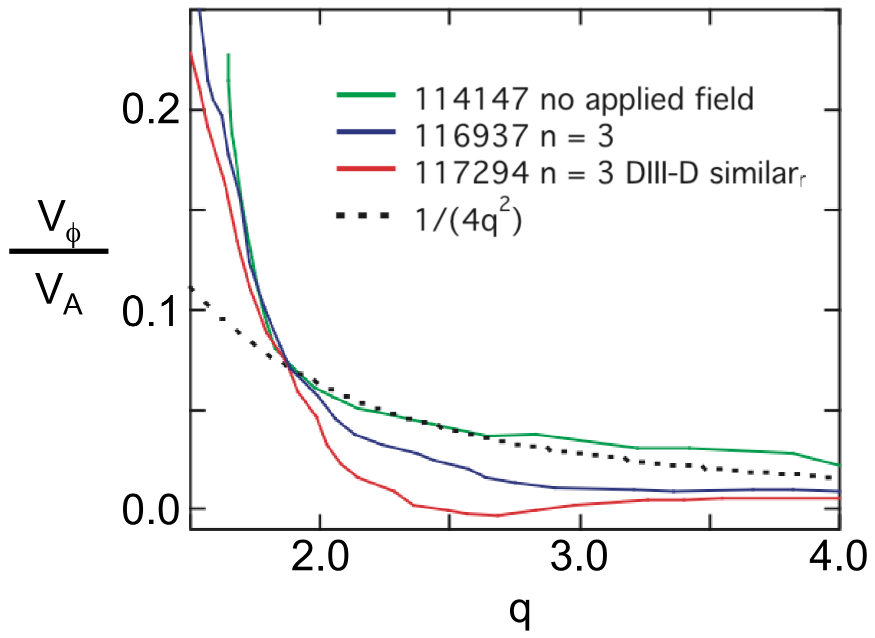




Significant Variation Observed in Marginal Rotation Profiles



Critical rotation profiles at marginal RWM stability



- Each case is last profile before unstable RWM growth observed
- Shot with no applied field has entire profile near or above $1/4q^2$
- n=3 applied field used to alter rotation profile
  - rotation in edge of plasma suppressed
- q = 2 region appears significant but not definitive

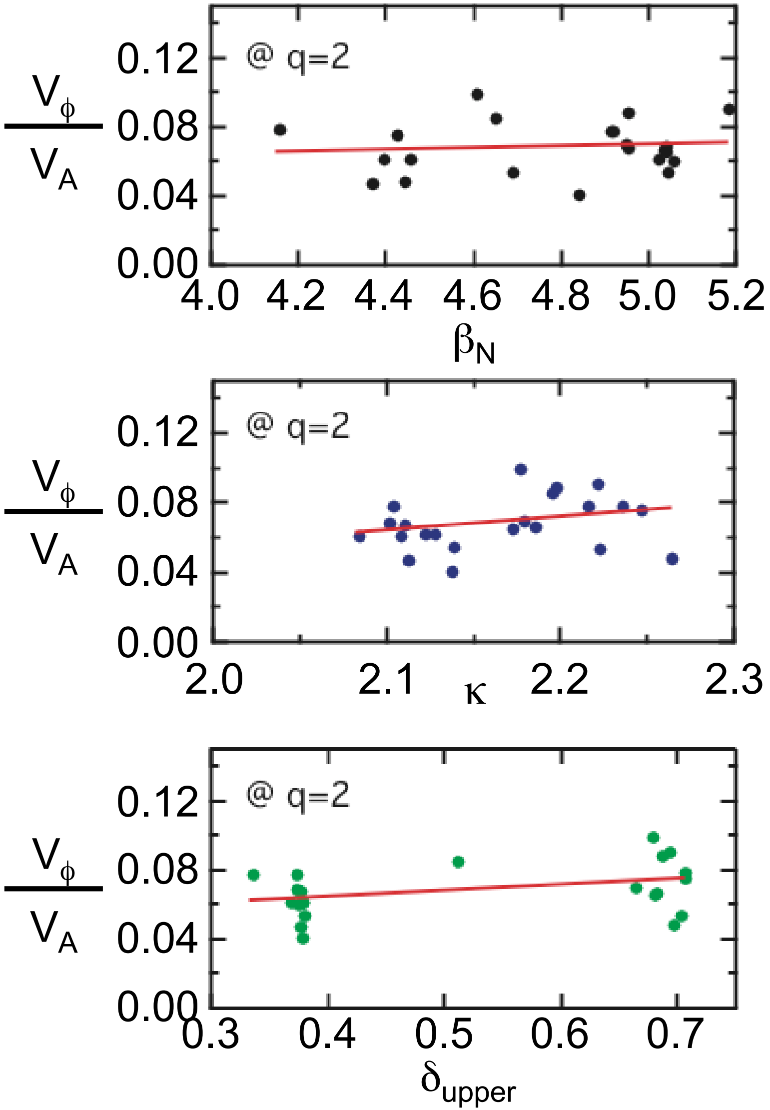
NSTX

Marginal Stability Shows Weak Dependence on Plasma Parameters

- Rotation shows no scaling with β
  - no-wall limit varies significantly shot-to-shot
  - need to check against C_β

$$C_\beta = \frac{\beta - \beta_{no\ wall}}{\beta_{ideal\ wall} - \beta_{no\ wall}}$$

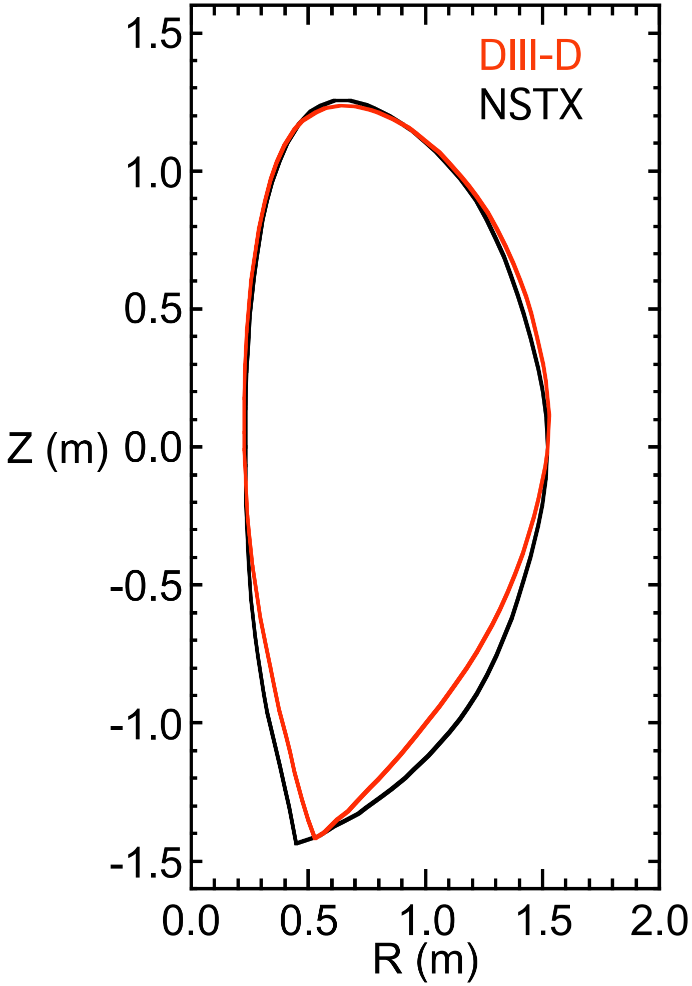
- Weak variation with plasma shape
  - need to normalize out influences of shape on no-wall limit



NSTX

DIII-D Shape Reproduced to Examine A Scaling of Ω_{crit}

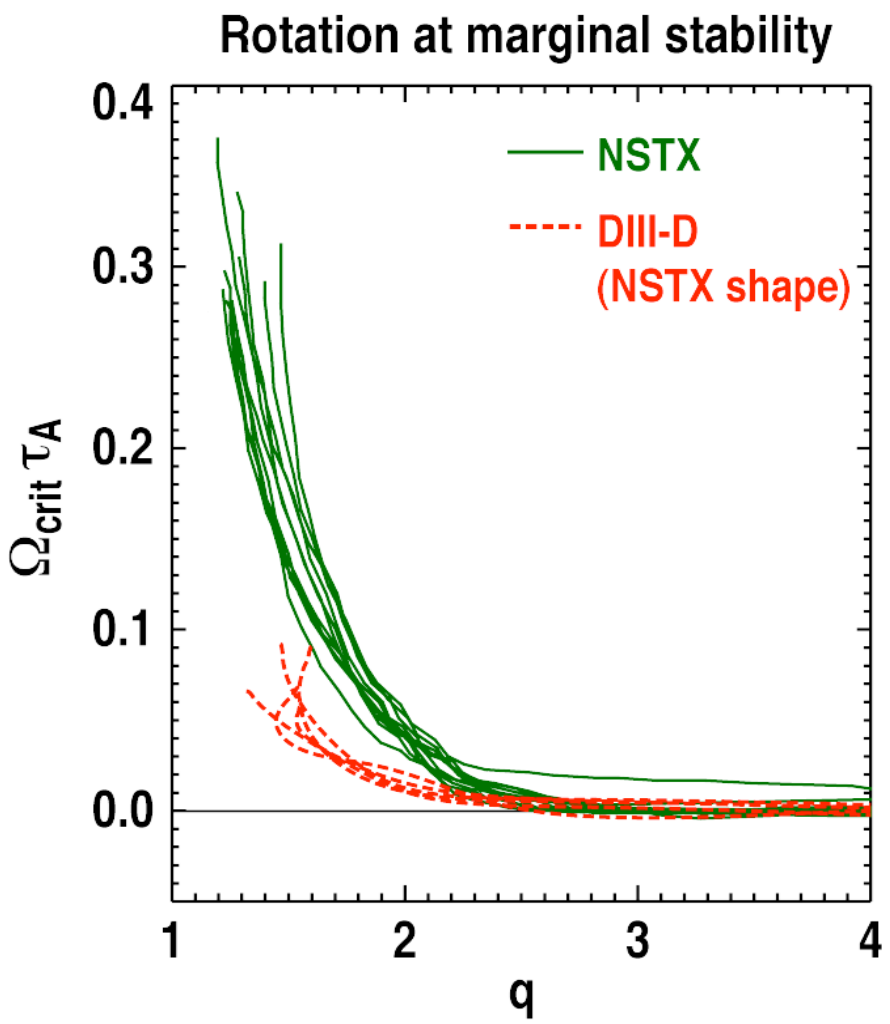
- Including neoclassical viscous dissipation in RWM dispersion relation* leads to inverse aspect ratio dependence of Ω_{crit}
- Previous comparisons used different techniques to determine Ω_{crit}
  - Active braking on NSTX allows more straightforward comparison
- DIII-D shape matched in NSTX with $\beta_N > \beta_N^{no\text{-}wall}$
  - q & β scans performed



*Shaing, K.C., Phys. Plasma **11** 5525 (2004)

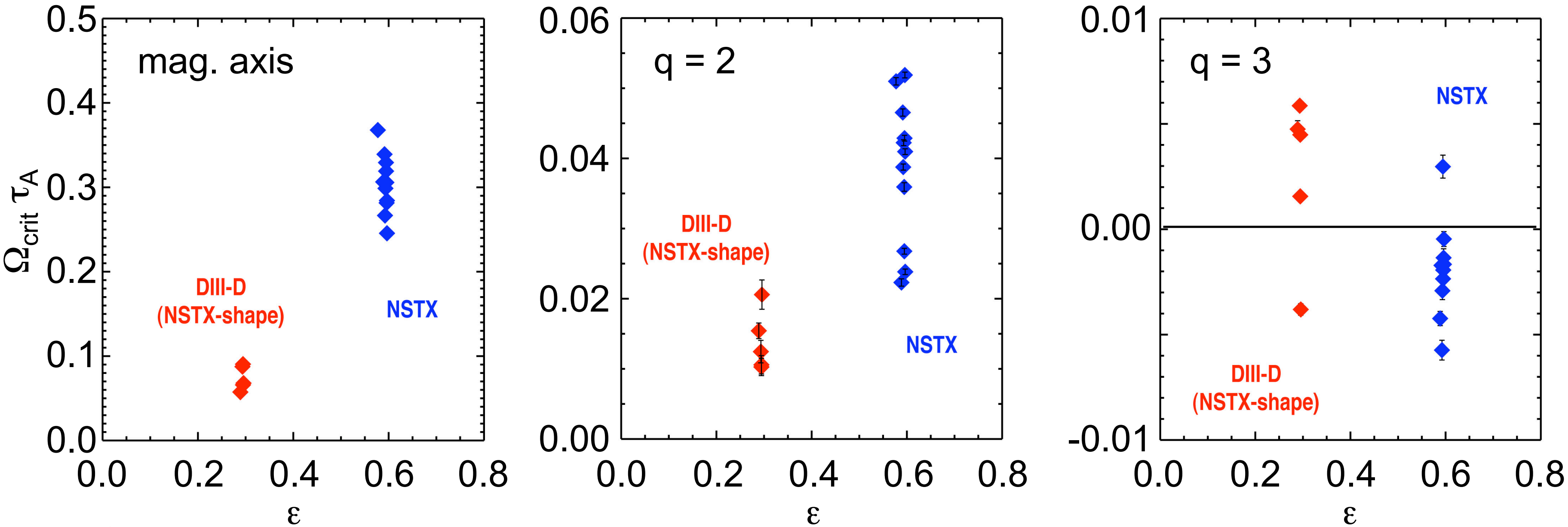
More Rotation Required for RWM Stability in NSTX

- Comparison of marginal profiles in similar shaped discharges
- Low rotation edge doesn't affect stability
- NSTX has higher rotation throughout region which determines stability



Similarity Experiment is Examining RWM Stability Variation with A

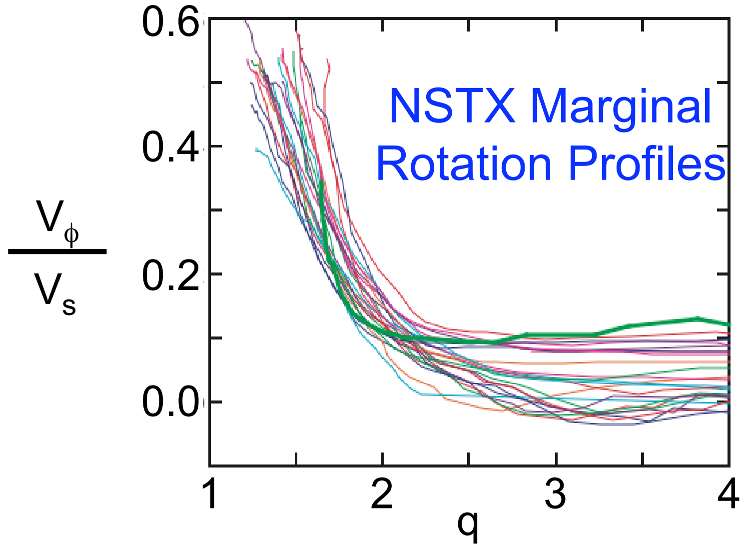
- Profile effects being studied
  - NSTX has higher rotation at q = 2 and in the core
  - very low rotation at q = 3 ⇒ Ω_{crit} cannot depend on q = 3
- Large data spread (especially NSTX)
  - subjectivity in determining start of unstable growth
  - 10 ms averaging time for rotation measurement



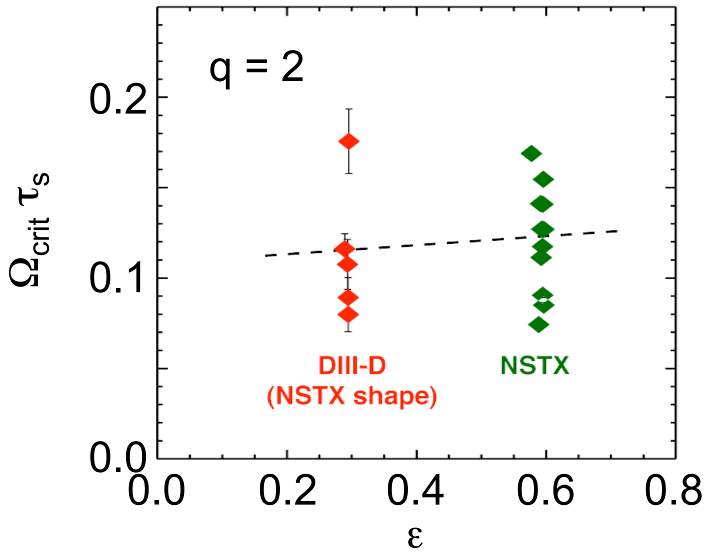
Sound Speed Normalization Removes Aspect Ratio Dependence

- Coupling to sound waves is one possible dissipation mechanism
  - depends on sound speed

$$V_s = \sqrt{\frac{kT_e + \gamma kT_i}{m_i}}$$

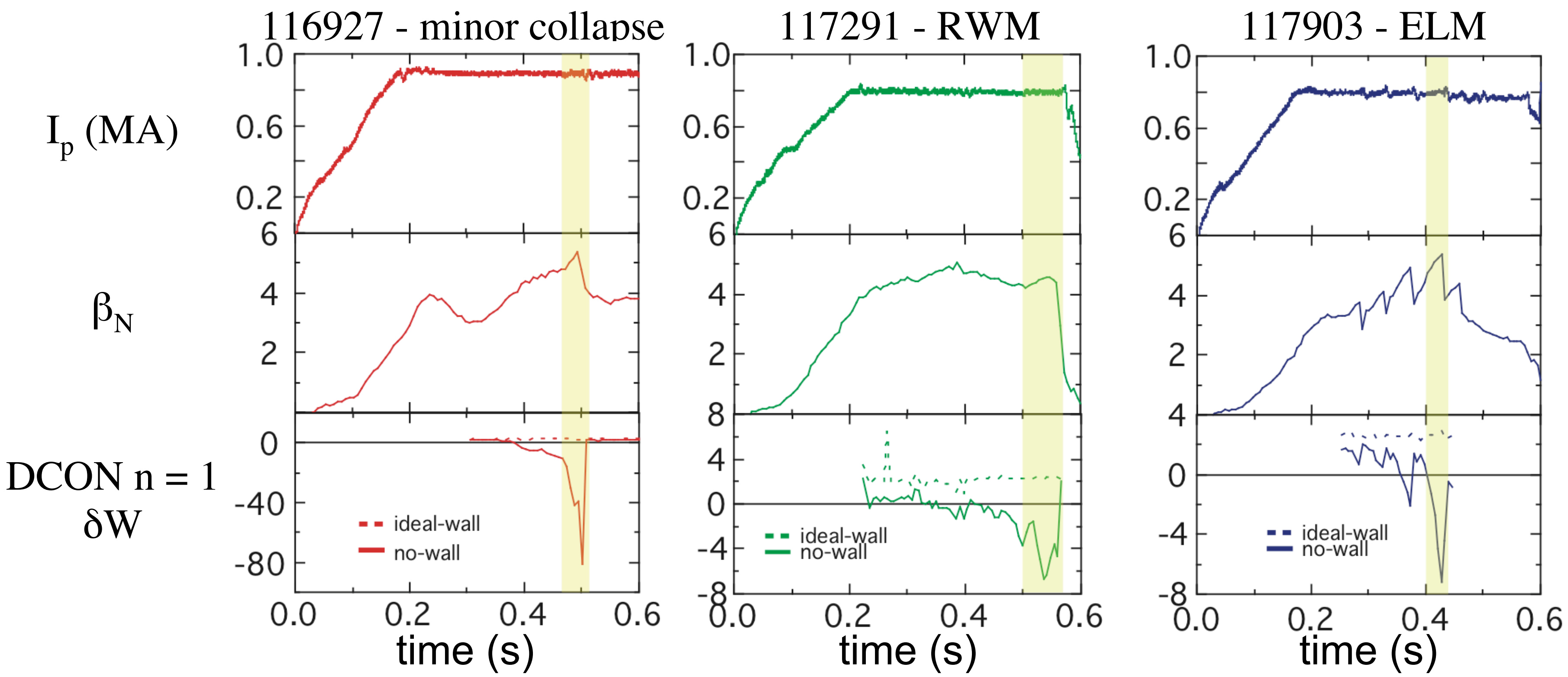


- Critical rotation variation at q = 2 reduced with V_s normalization
  - consistent with significant dissipation due to sound waves



Numerical calculations of relative magnitudes of sound and Alfven wave dissipation needed

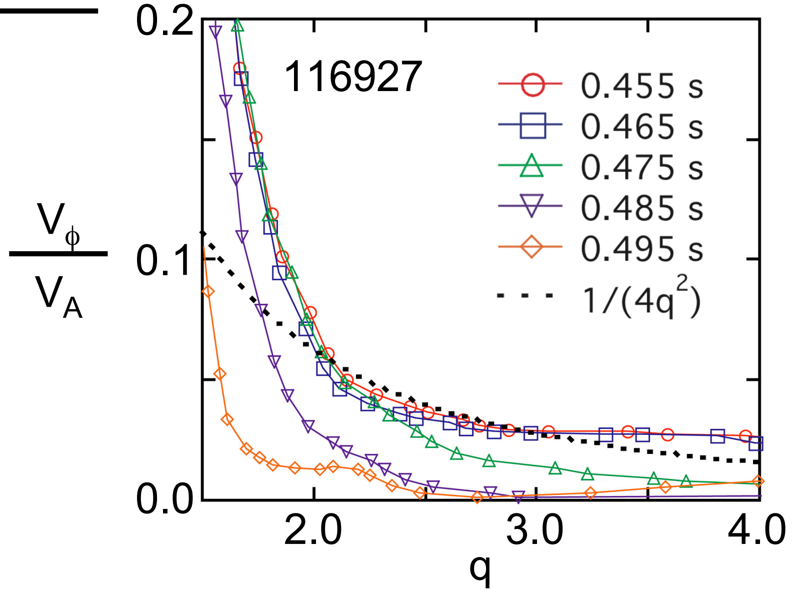
Minor β Collapse Has Effects on Plasma Similar to Both RWM and ELM

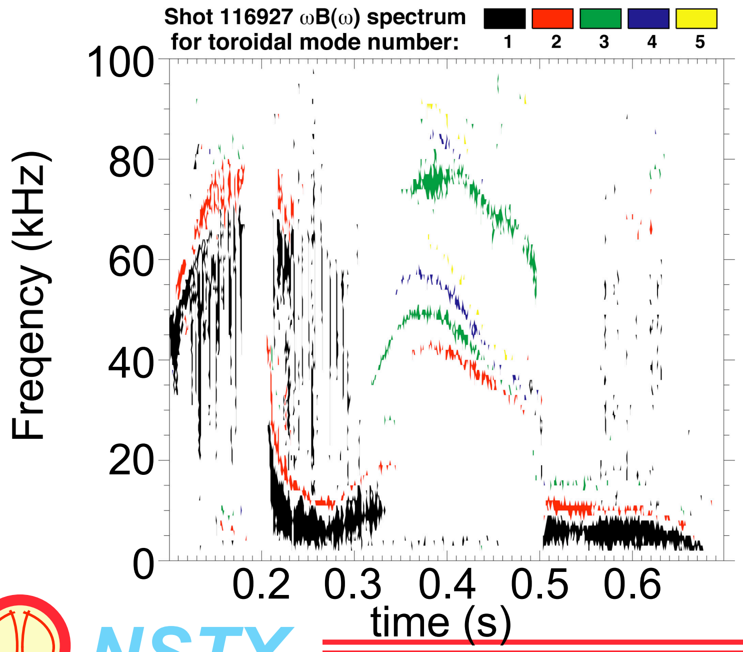


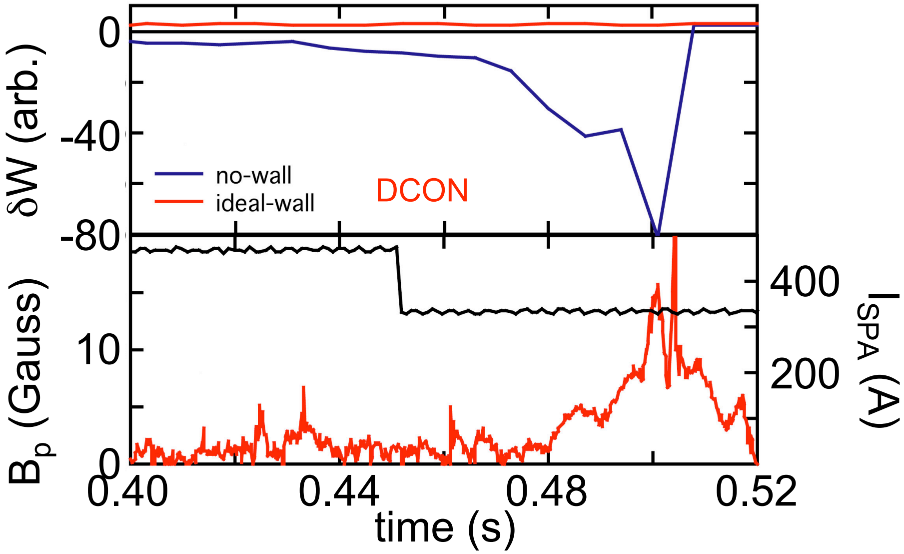
- RWM leads to disruption
- Type I ELM causes β drop, but plasma recovers
- Minor collapse has smaller β drop than RWM, but no recovery
  - ❑ *must examine in more detail to classify this collapse*

RWM Characteristics Observed During Smaller β collapses

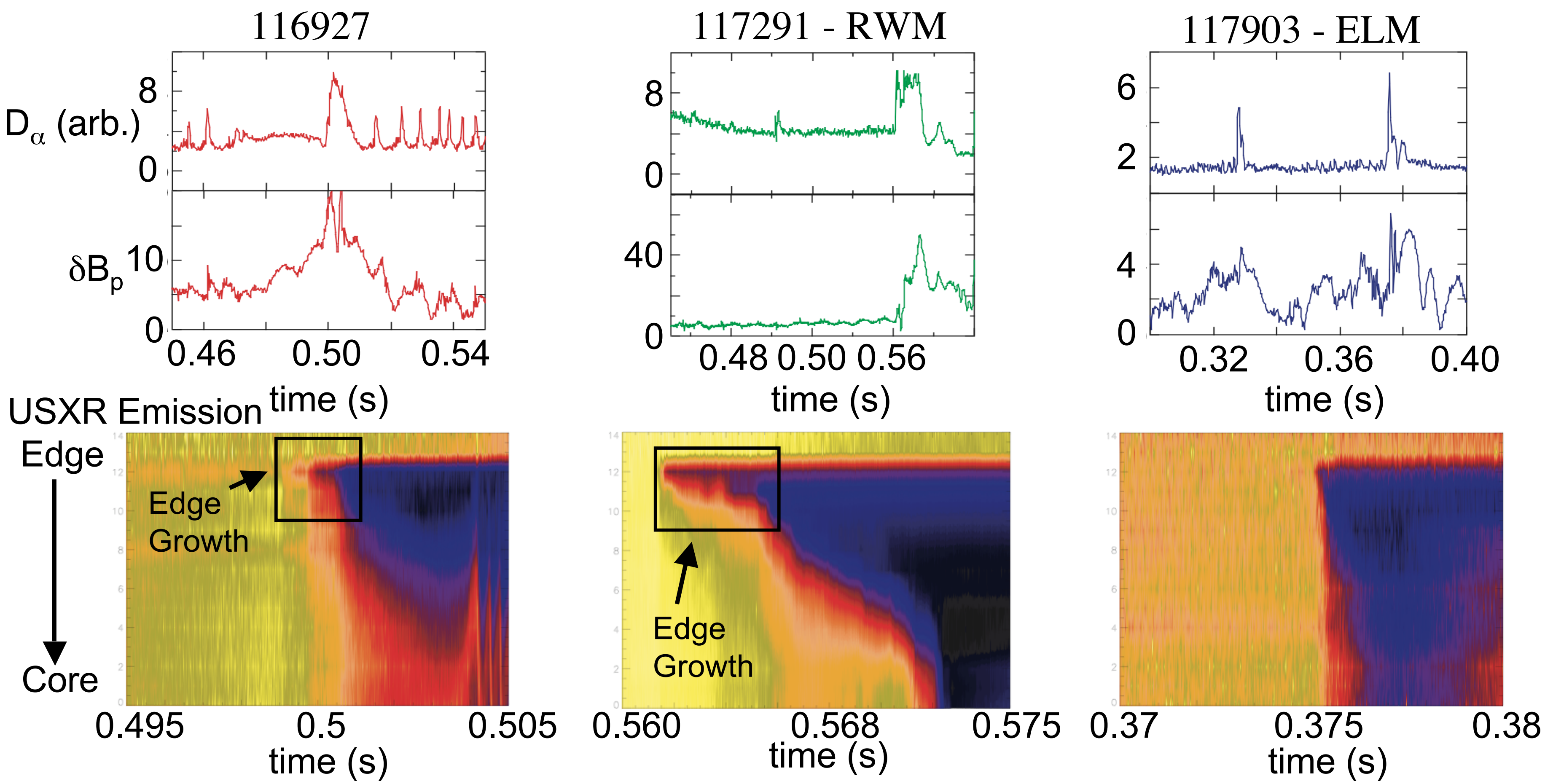
- Typical RWM causes disruption
- Some smaller collapses could be due to non-disruptive RWM
  - slow mode growth observed in internal sensors
  - growth rate and onset consistent with RWM
    - ~ 10 ms growth time
    - low rotation well inside q = 2
- Growth of tearing mode removes unstable drive







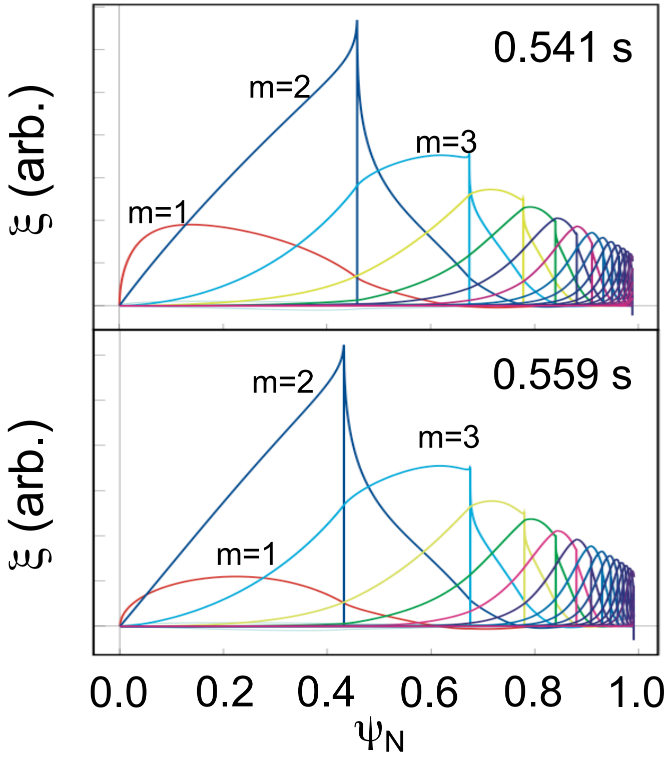
Minor β Collapse Dynamics Support RWM

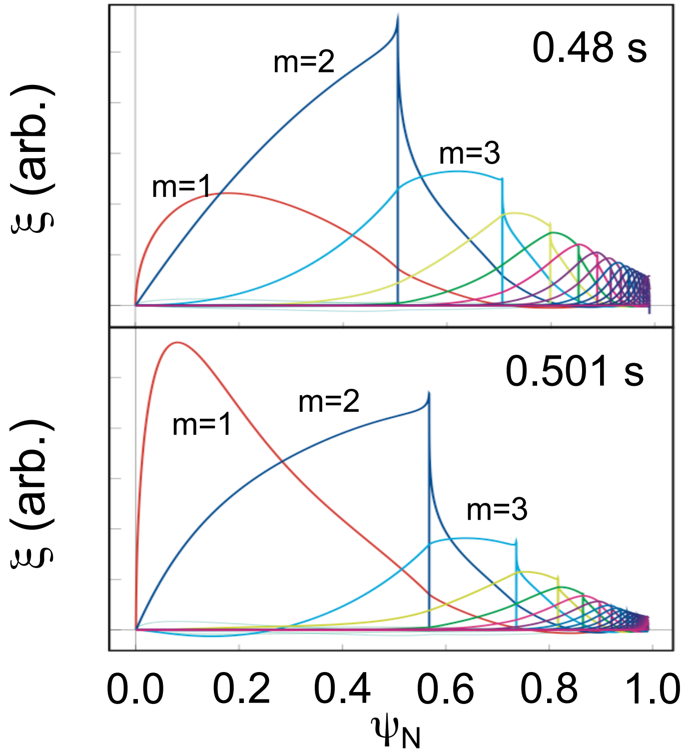


- SXR data shows initial mode growth at edge then slow penetration
  - high δW for 116927 causes faster growth than 117291
- ELM much more rapid than both 116927 & 117291

NSTX

DCON Shows Mode Structure Internalizing


117291 Poloidal Mode Eigenfunctions


116927 Poloidal Mode Eigenfunctions

- 116927 becomes Mercier unstable in core
- Large internal perturbation provides ideal trigger for tearing mode
  - reduction in β removes unstable drive for RWM

Summary

- Active coils allow detailed study of RWM physics
  - ❑ rotation control
  - ❑ RFA studies - MHD spectroscopy
- Examining rotation profile effects indicates rotation at outer q surfaces not required for RWM stability
  - ❑ RWM stable discharges produced with low or negative rotation outside q = 3
  - ❑ core rotation (inside q = 1.5) alone cannot stabilize RWM
- DIII-D similarity study under way to determine aspect ratio effects on RWM stability
  - ❑ low-A requires higher rotation
  - ❑ V_s normalization removes aspect ratio dependence
- Growth of internal modes can halt RWM collapse
  - ❑ internal kink/ballooning modes can trigger tearing modes, removing unstable drive for RWM

Reprints