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RWM Stabilization and Control Research on NSTX

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Workshop on Active Control of MHD Instabilities
November 18, 2007
Columbia University
New York, NY

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Controlling RWMs and understanding stabilization is critical for future high performance tokamaks

Motivation

- Resistive Wall Mode (RWM) growth leads to beta collapse, disruption
- High reliability control needed for future burning plasma devices (at low or high plasma rotation, ω_ϕ)

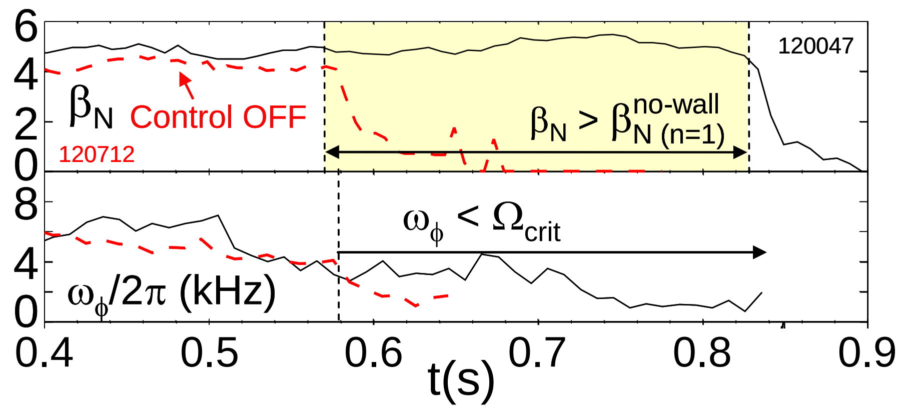
Outline

- Active RWM Control
- RWM Stabilization Characteristics

RWM active control research emphasized in 2007

- Increase reliability and understanding of RWM active control
  - Analysis of RWM control system performance
  - RWM control experiments using expanded magnetic sensor combinations
  - Variations for improved control

Active n = *1* RWM control in NSTX (2006)

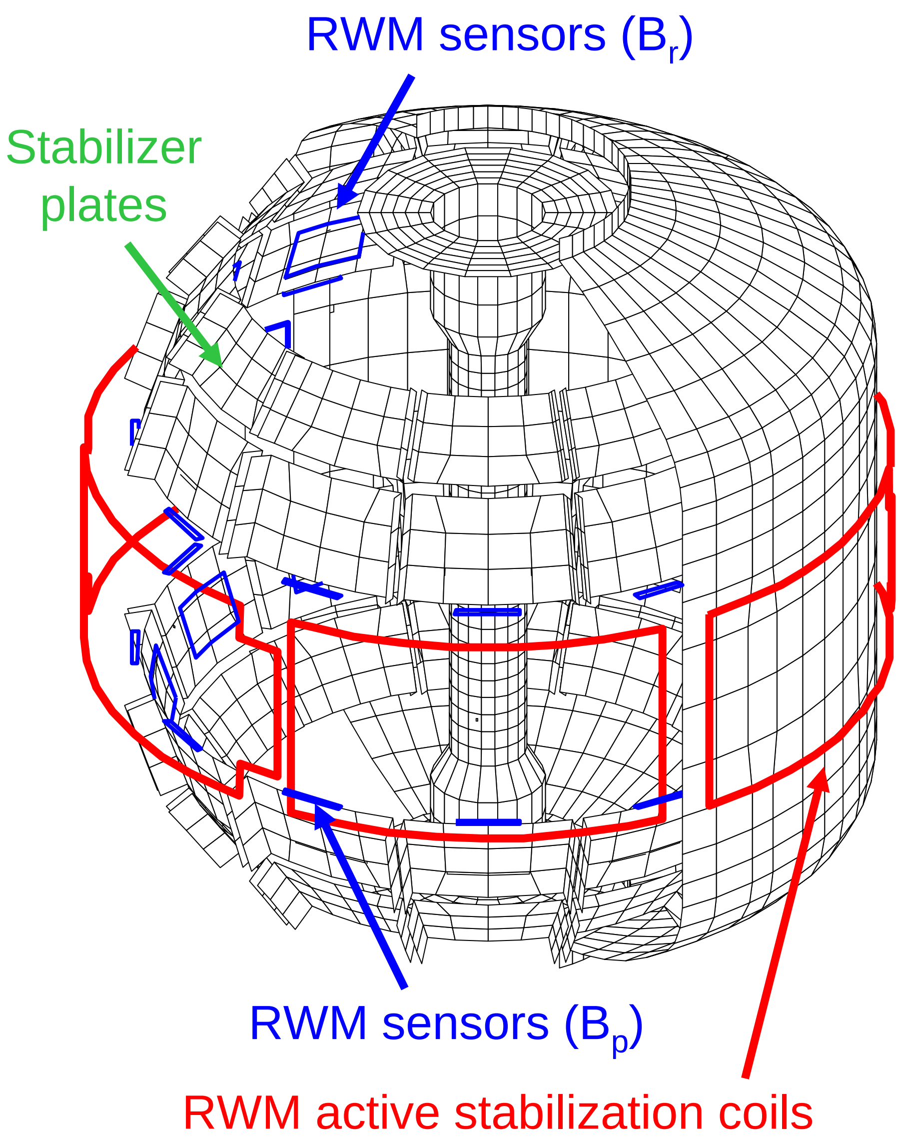


- Upper B_p sensors for feedback
- Non-resonant magnetic braking
- n = 2 RWM amplitude rises, remains stable while n = 1 stabilized
- Plasma $\beta_N > 5.5$ reached

S.A. Sabbagh, et al., PRL **97** (2006) 045004.

RWM control system uses expanded sensor set

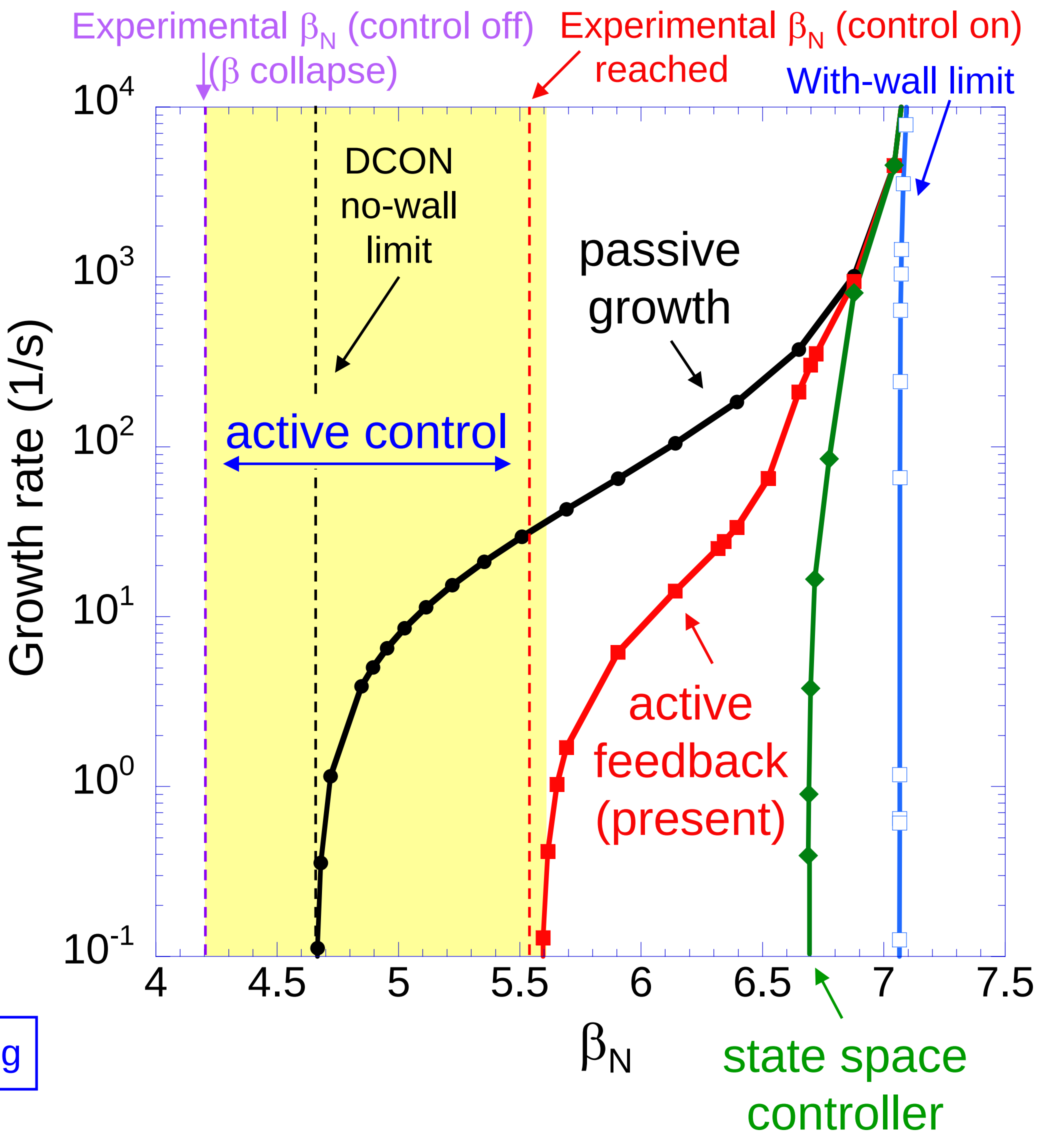
- Stabilizer plates for kink mode stabilization
- External midplane control coils closely coupled to vacuum vessel
- Varied sensor combinations used for feedback
  - 24 upper/lower B_p: (B_{pu}, B_{pl})
  - 24 upper/lower B_r: (B_{ru}, B_{rl})
- Midplane n = 1 B_r sensors
  - Outboard of control coil
  - Not used for feedback to date



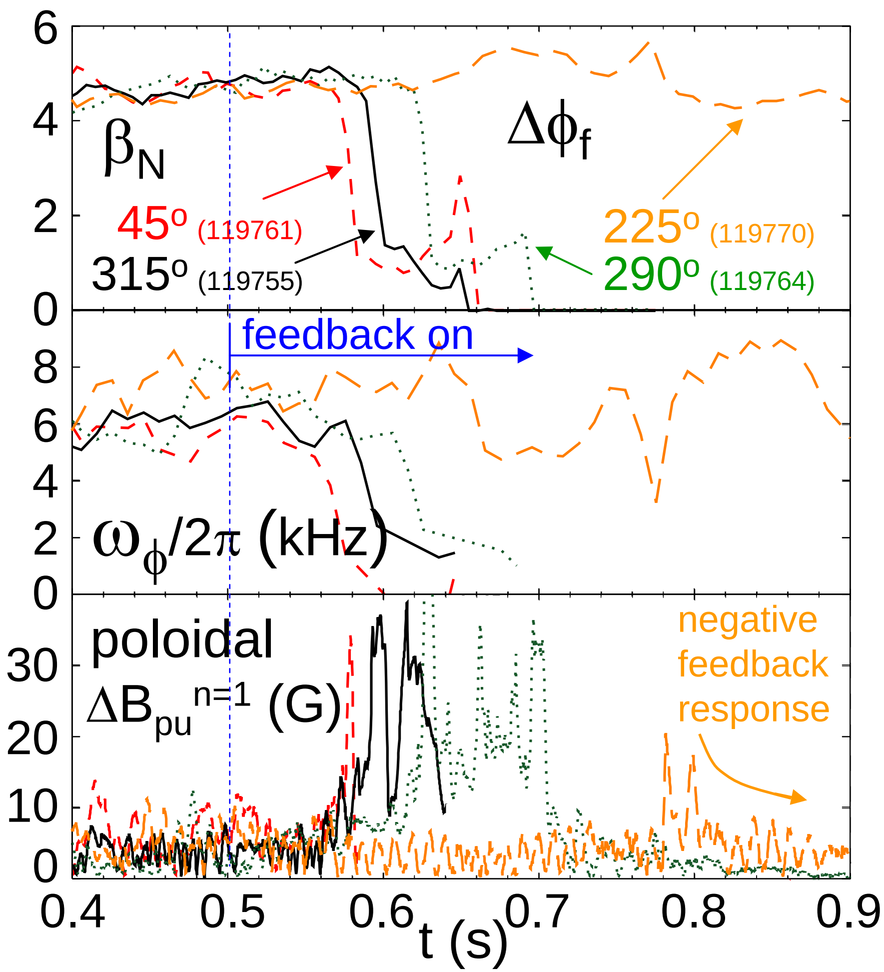
VALEN code reproduces B_{pu} sensor feedback performance

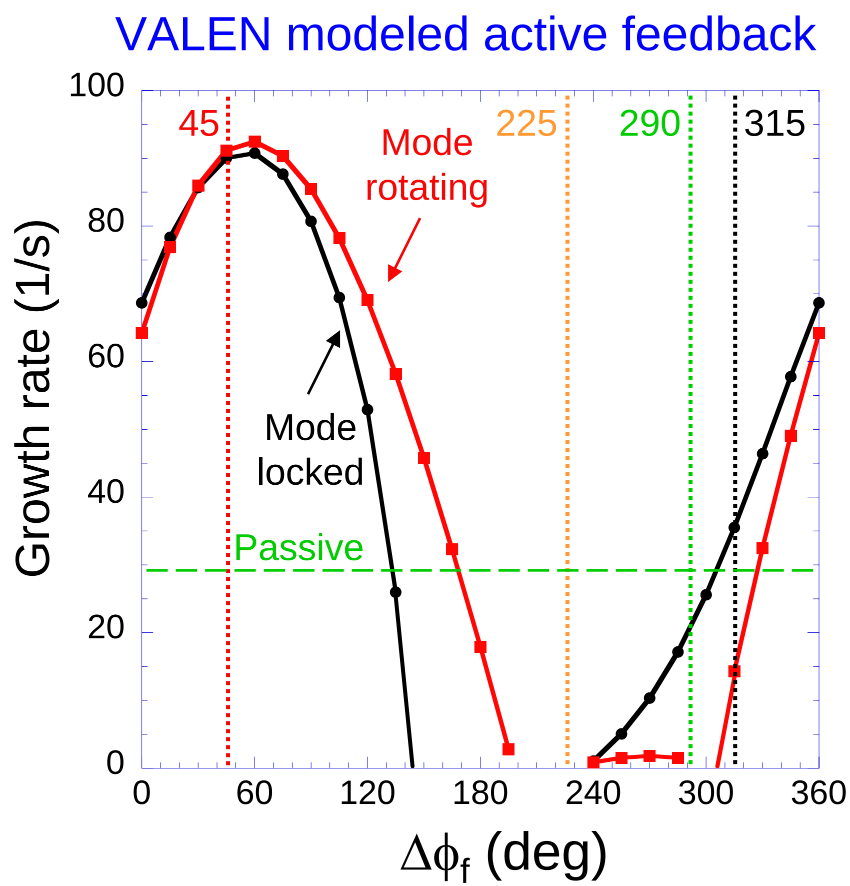
- **New model simulates experiment**
  - Upper B_p sensors located as on device
  - Compensation of control field from sensors
  - Experimental equilibrium reconstruction (including MSE data)
  - Proportional gain
- **Advanced feedback control may significantly improve future performance**
  - Optimized state-space controller with B_{pu} sensors may stabilize $\beta_N/\beta_N^{wall} < 95\%$

O. Katsuro-Hopkins et al., this meeting



Varying relative phase shows positive/negative feedback



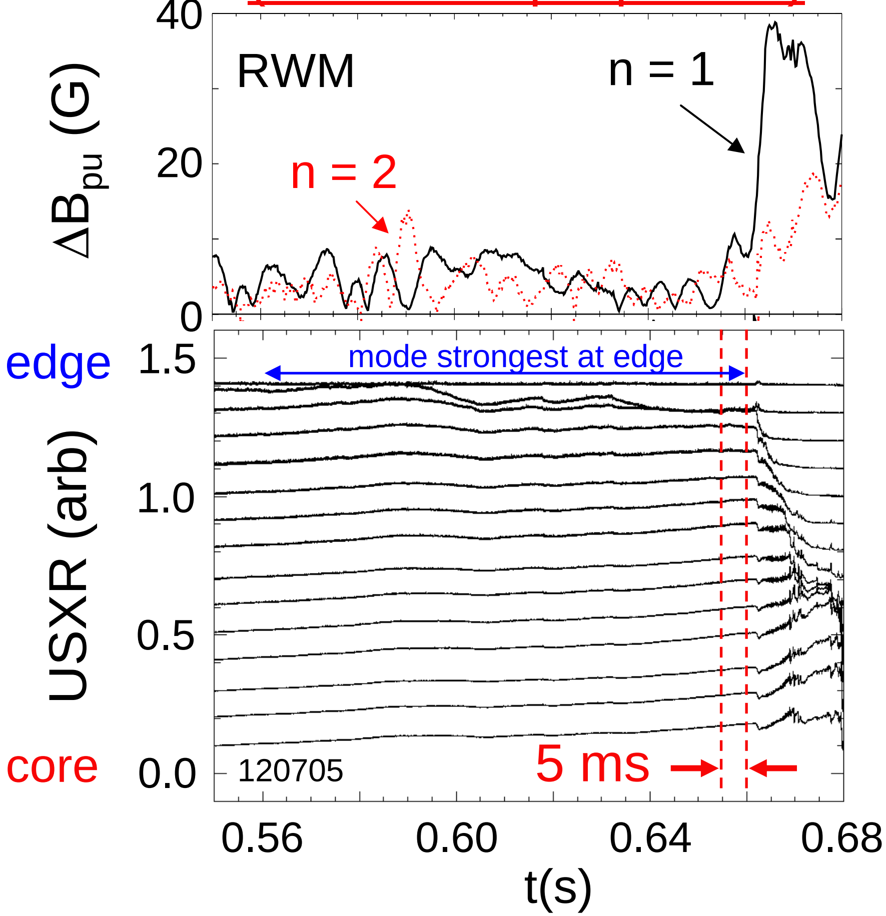


- Feedback control current has relative phase $\Delta\phi_f$ to measured ΔB_{pu}
  - Internal plasma mode seen at $\Delta\phi_f = 225^o$, damped feedback system response
- Phase scan shows superior settings for negative feedback
  - Agreement between theoretical and experimental feedback behavior

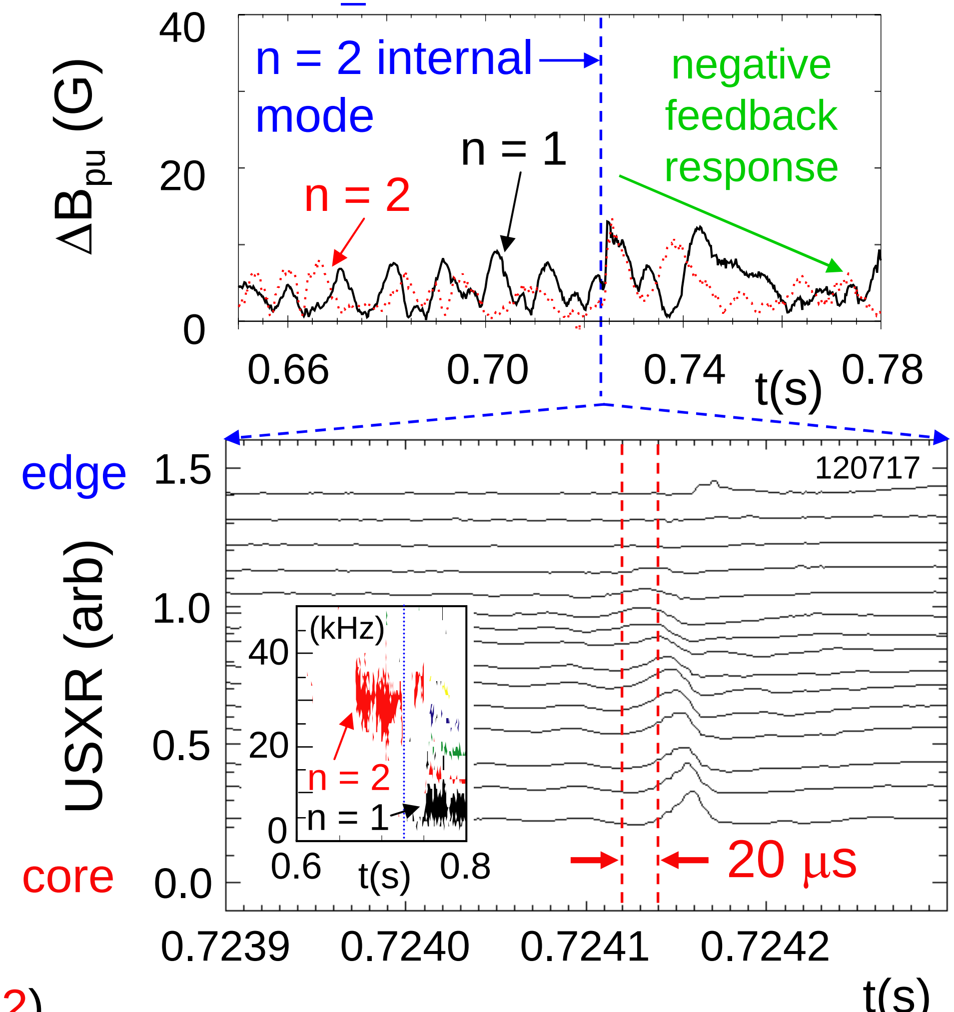
NSTX

n = 2 RWM does not become unstable during n = 1 stabilization

Control OFF
(RWM disrupts plasma)

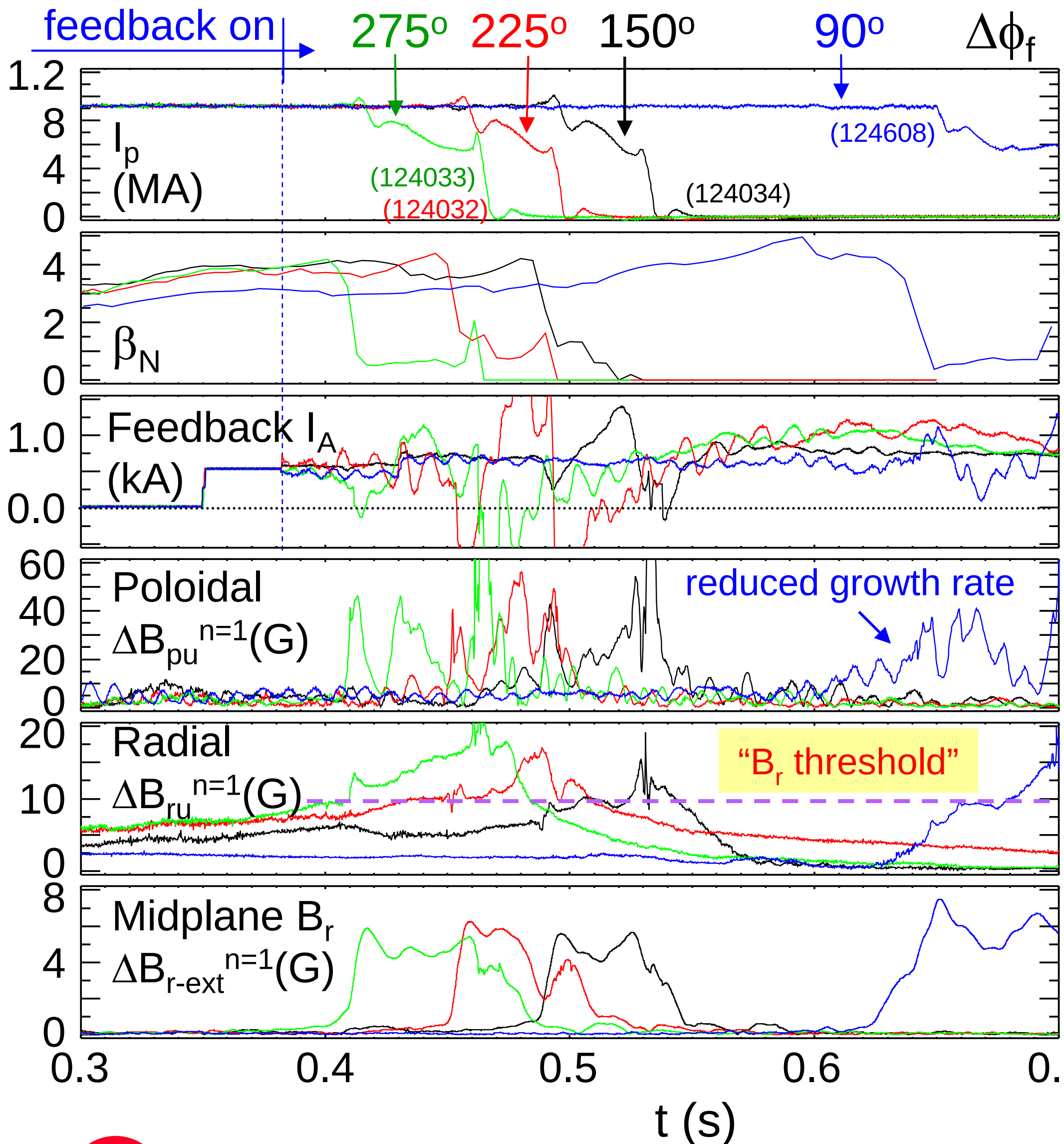


Control ON
(fast β_N drop, plasma recovers)



- Internal mode ~ 25 kHz
  - Plasma rotation ~ 12 kHz (n = 2)

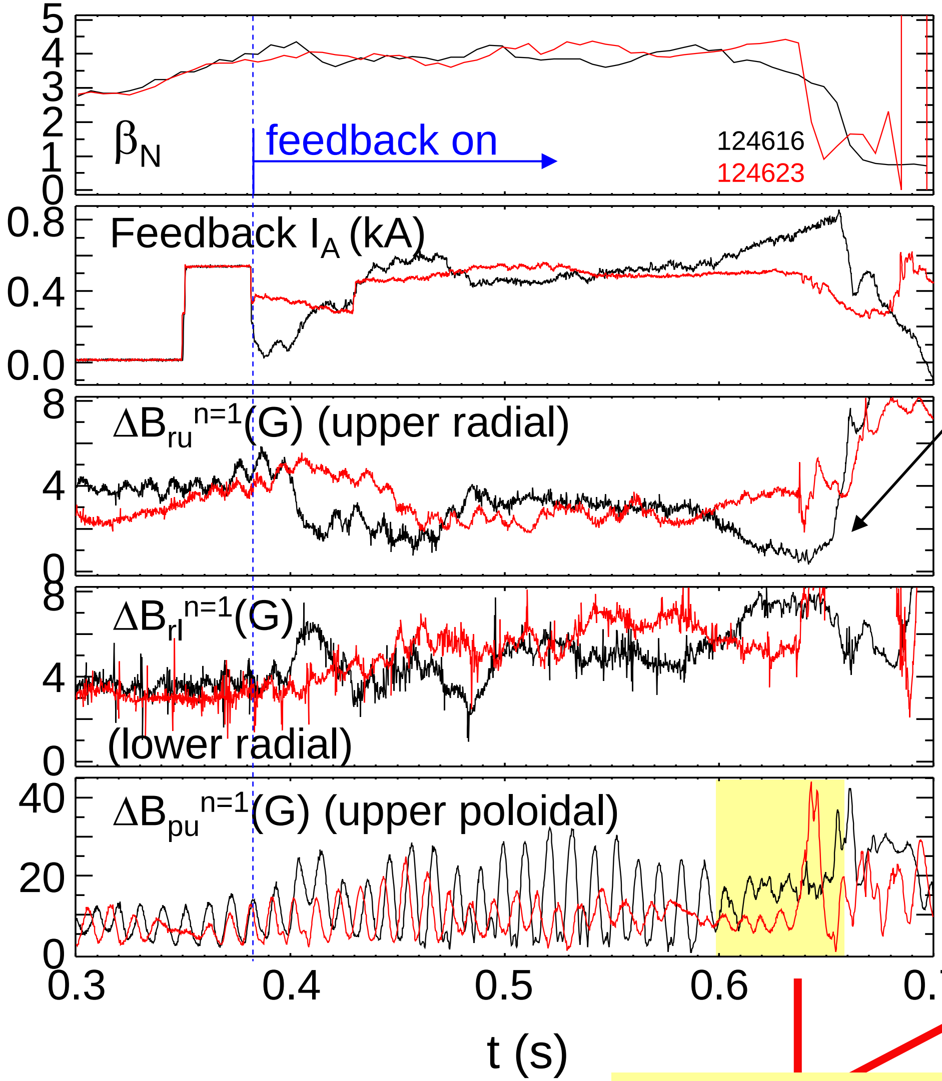
Combination of upper/lower B_p sensors used to improve control



- Feedback phase scan using B_{pu} and B_{pl}
  - Best phase shown 90°, not optimal configuration
    - Reduction in $\Delta B_{pu}^{n=1}$ growth rate
  - Spatial phase offset between upper/lower B_p sensor flux can improve feedback
- Control using B_{pu} and B_{pl} also reduces ΔB_r
  - Correlation of β_N collapse and $\Delta B_{ru}^{n=1}$ amplitude
  - Suggests that feedback on ΔB_r may allow mode control

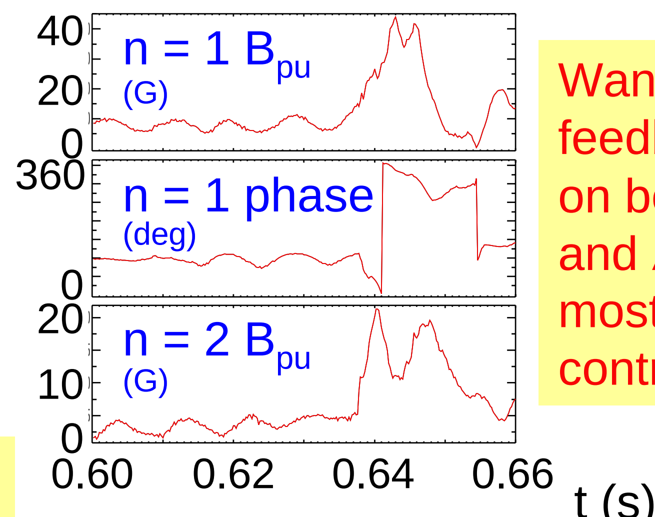
NSTX

Feedback on B_r sensors alone insufficient for control



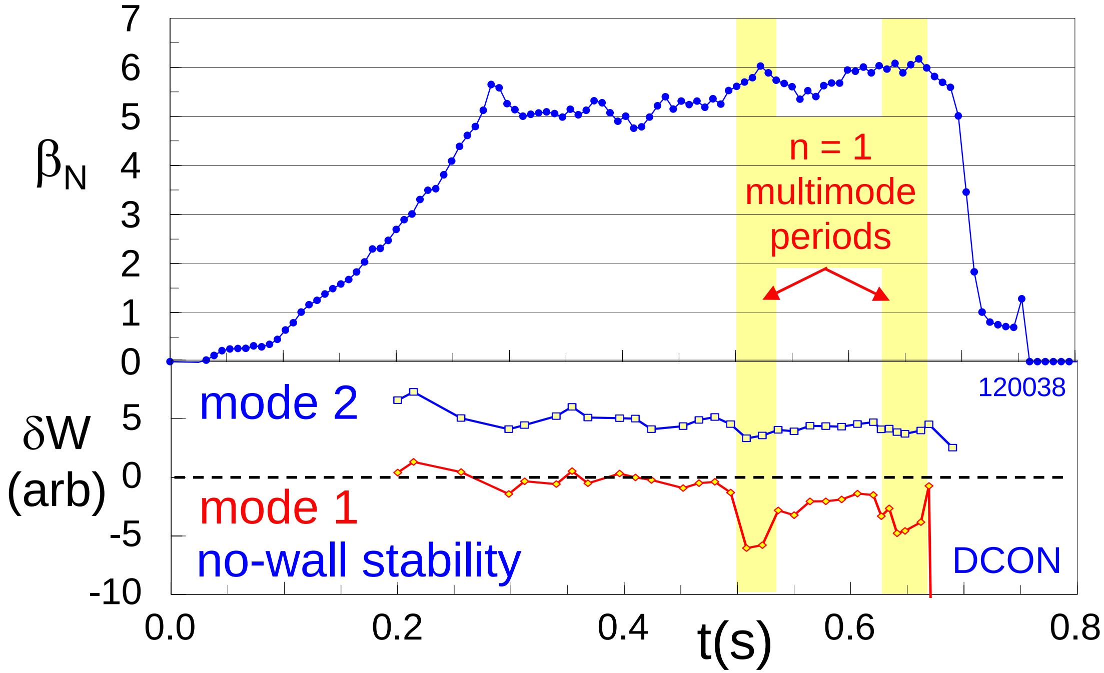
unstable RWM

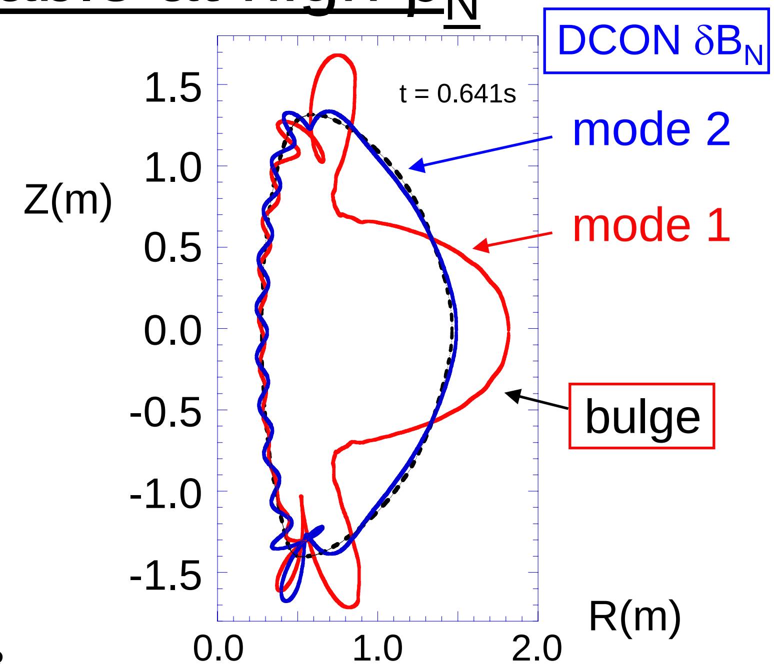
- Feedback on ΔB_{ru} alone
  - Clear initial drop in ΔB_{ru}
  - Continued drop in ΔB_r and *increase* in ΔB_{rl} (also ΔB_{pu})
  - leads to β_N collapse
- Feedback on ΔB_{ru} and ΔB_{rl}
  - Controlled, steady ΔB_{ru}, ΔB_{rl}
  - rapid RWM growth, rotation: β_N collapse

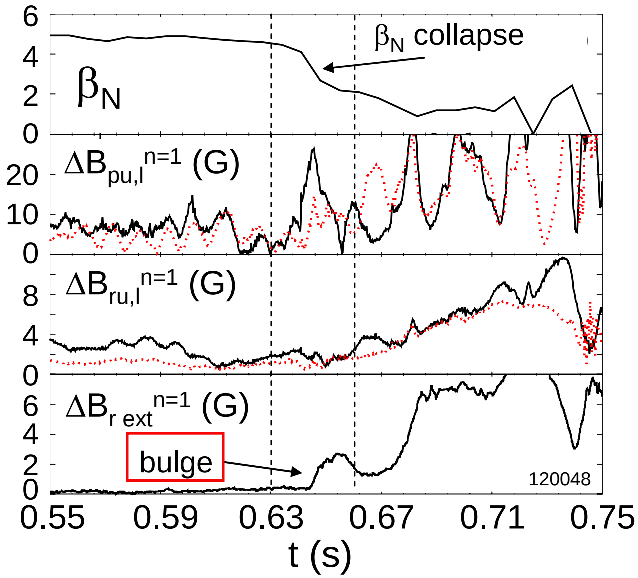


Want feedback on both ΔB_r and ΔB_p for most reliable control

Multimode theory applicable at high β_N







- Boozer multimode criterion for n = 1 met at high β_N (PoP 10 (2003) 1458.)
  - $|\delta W|$ smallest for 2nd n = 1 eigenfunction
- Multiple n > 1 RWM also observed in NSTX

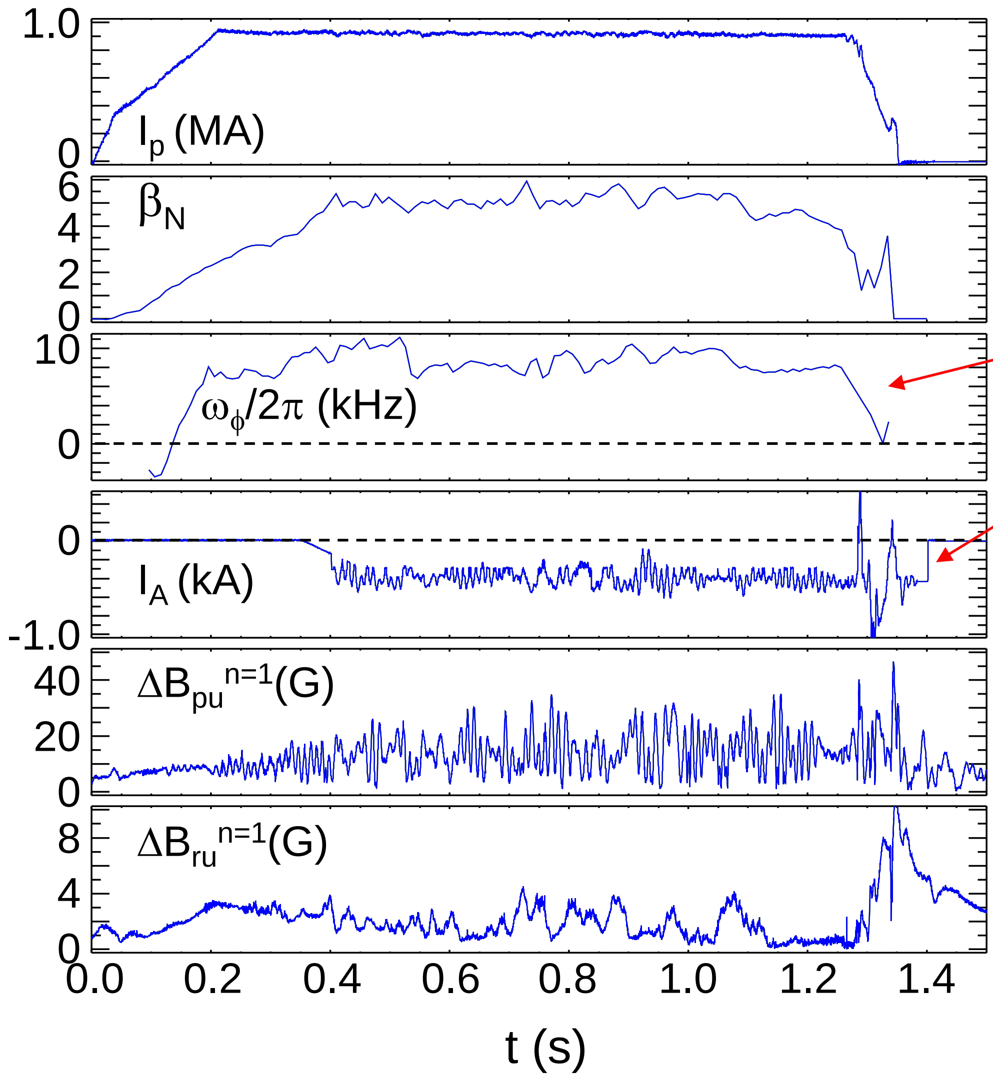
(Sabbagh, et al., Nucl. Fusion **46** (2006) 635.)

- Multiple n = 1 modes may explain observations
  - Upper/lower sensor phases do not always match single mode
  - Poloidal deformation of mode during feedback (mode “non-rigidity”)

S.A. Sabbagh, et al., PRL **97** (2006) 045004.

NSTX

Feedback control modifications used successfully at moderate ω_ϕ



- NSTX record pulse length at I_p = 0.9 MA
  - Feedback used combined upper/lower B_p sensors with spatial phase offset
  - Moderate plasma rotation keeps ΔB_r in check
  - n = 3 DC field phased to best maintain ω_ϕ
- Next steps toward further control reliability
  - Feedback on upper and lower arrays of both B_r and B_p sensors
  - Determine optimal sensor spatial phase offsets
  - Test reliability at further reduced plasma rotation

J.E. Menard, et al., this meeting

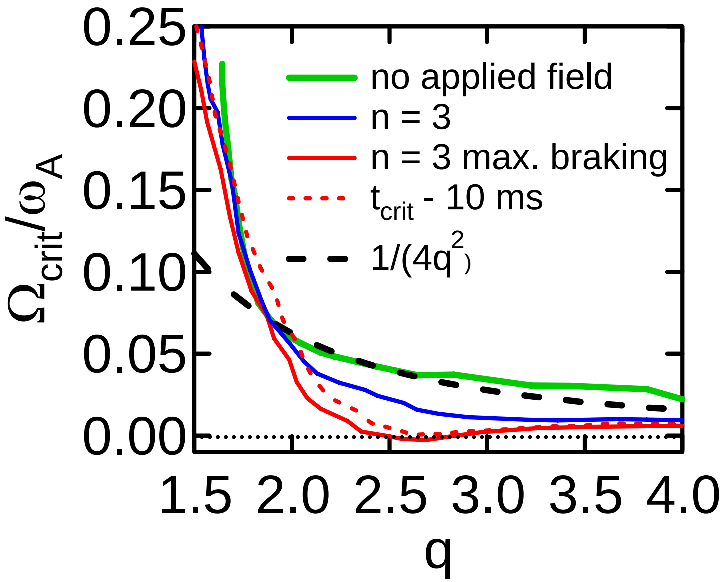
NSTX

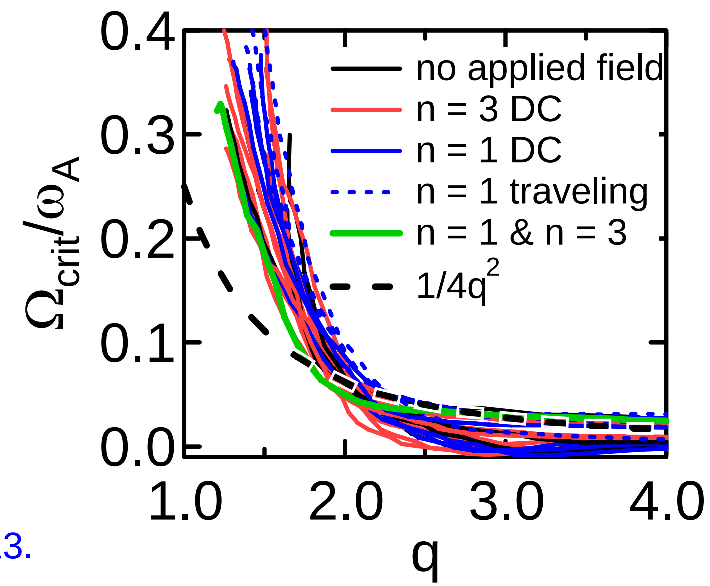
RWM passive stabilization characteristics more clear

- Scalar plasma rotation at q = 2 not adequate to describe RWM marginal stability
  - Concluded a few years ago on NSTX, further evidence in 2007
- RWM can go unstable at various levels of plasma rotation, various profile shapes
- RWM stability at low rotation profile not yet found unless
  - internal rotating mode with frequency ~ ω_ϕ present
  - active RWM control applied
- Some integral of plasma rotation, convolved with other plasma profile(s), apparently required to describe stabilization
- Role of Alfven frequency in description of stability criteria not yet well established in NSTX
  - Experiments showing stability at very low Ω_{crit}/ω_A may suggest that ω_A is simply not a useful scaling variable
  - Ion collisionality profile appears to alter Ω_{crit}

Significant variation of rotation profile shape at Ω_{crit}

- Benchmark profile for stabilization is $\omega_c = \omega_A/4q^2$ *
  - predicted by Bondeson-Chu semi-kinetic theory**
- n = 3 braking field *reduces* Ω_{crit} profile
  - Contrary to simple loss of torque balance hypothesis
- High rotation outside ~~q = 2.5~~ q = 2.0 not required for stability
  - Zero rotation at single q can be stable
- Scalar Ω_{crit}/ω_A at q = 2 , > 2 not a reliable criterion for stability
  - consistent with distributed dissipation mechanism

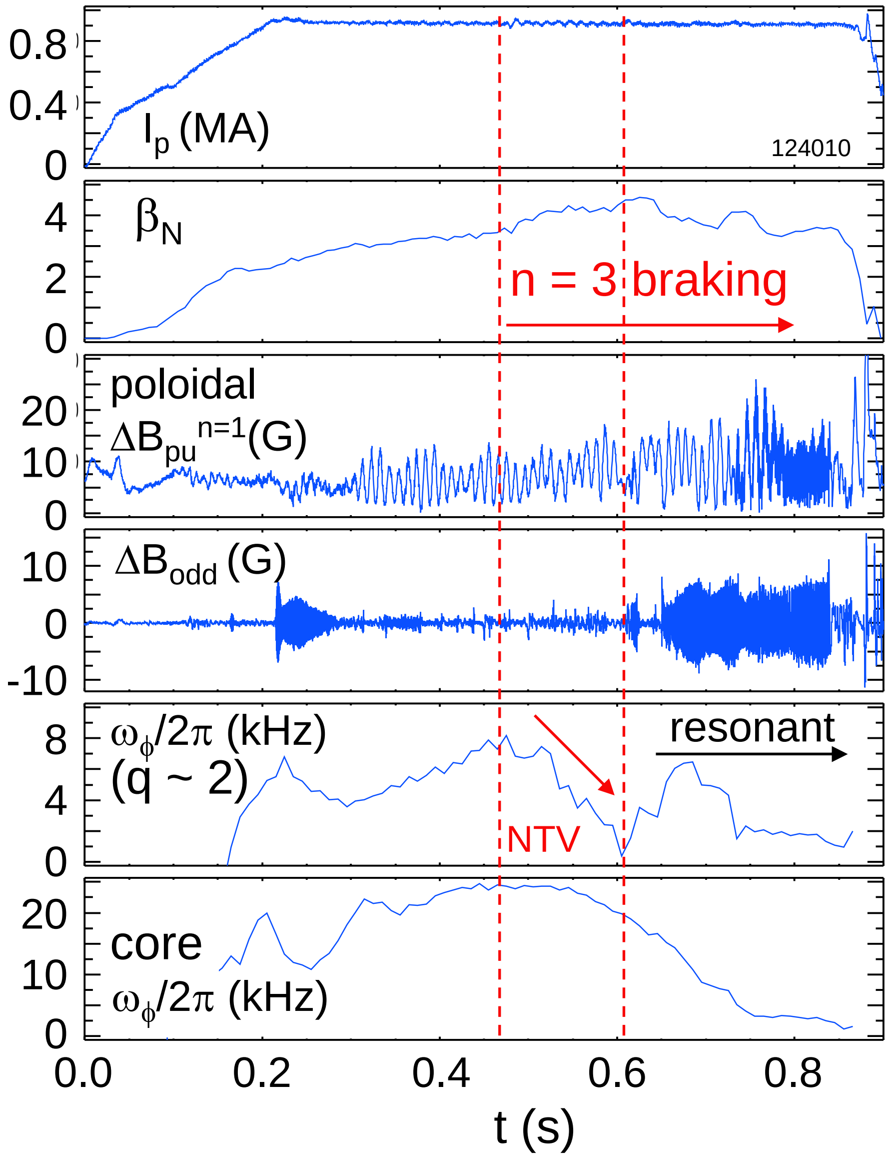


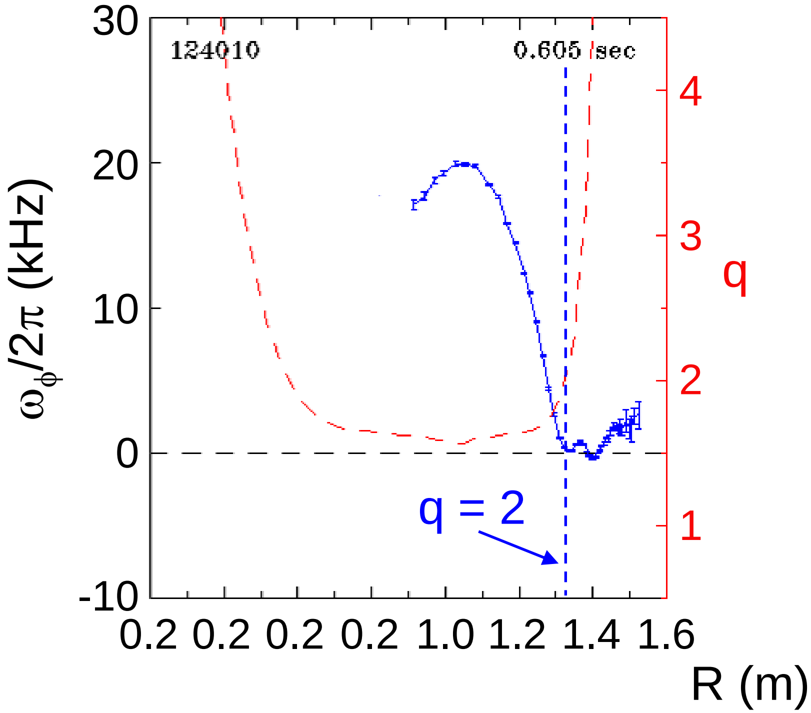


*A.C. Sontag, et al., Phys. Plasmas **12** (2005) 056112.

A. Bondeson, M.S. Chu, Phys. Plasmas **3 (1996) 3013.

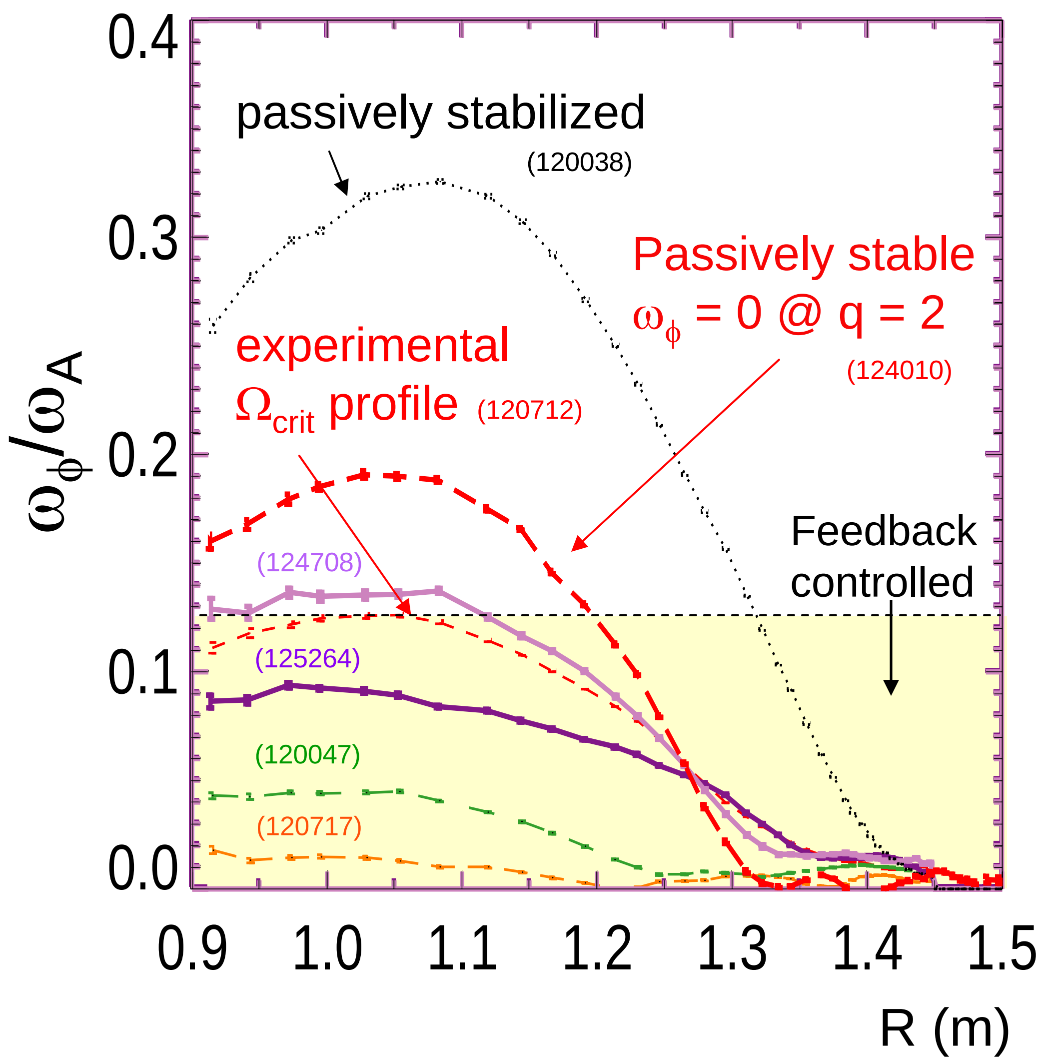
Plasma with zero rotation at q = 2 stable without feedback





- Equilibrium reconstruction with MSE and flux-isotherm constraint
- Rotation braking physics evolves
  - Non-resonant n = 3 (NTV), then additional braking seen at resonant surfaces

Plasma rotation speed, profile altered to examine stability



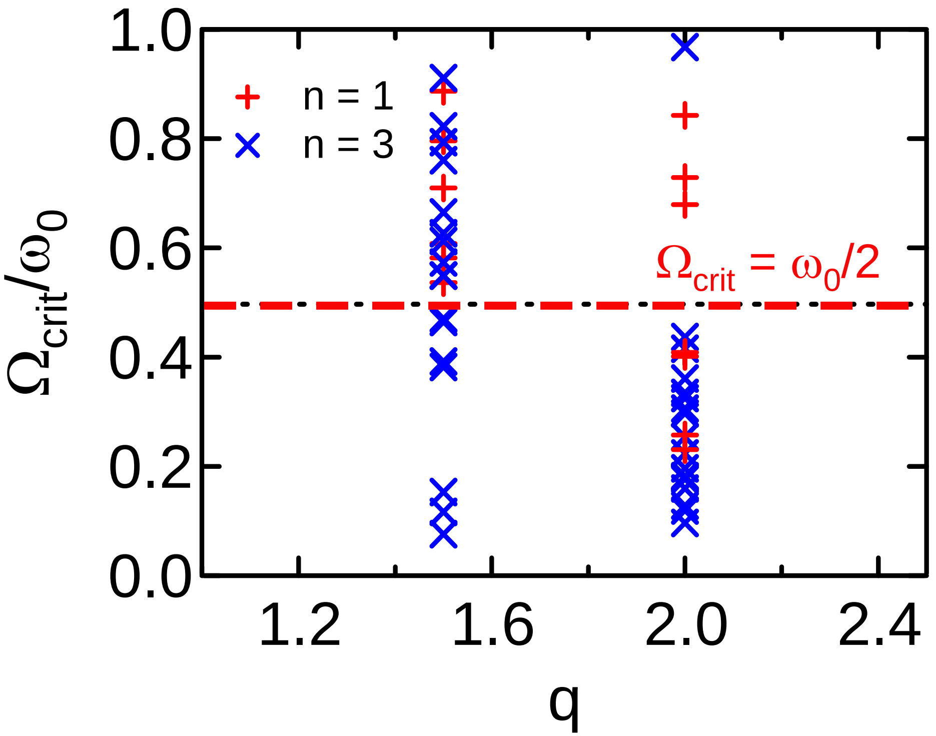
- High rotation typically stable, but not always
  - Apparent RWM observed at high core rotation
  - Need to understand instability mechanism
- Stability at intermediate rotation depends on profile
  - Passively stable plasma with $\omega_\phi = 0$ at $q = 2$ has slower edge and faster core rotation
- No reliable stable state at low rotation with feedback off
  - Increase number of low rotation plasmas in future research

NSTX

Ω_{crit} not correlated with simple torque balance model

- Rapid drop in ω_ϕ when RWM unstable may seem similar to ‘forbidden bands’ model
  - theory: drag from electromagnetic torque on tearing mode*
  - Rotation bifurcation at $\omega_0/2$ predicted
- No bifurcation at $\omega_0/2$ observed
  - no correlation at q = 2
  - Similar result for n = 1 and 3 applied field configuration

NSTX Ω_{crit} Database



($\omega_0 \equiv$ steady-state plasma rotation)

*R. Fitzpatrick, Nucl. Fusion **33** (1993) 1061.

Increased Ion Collisionality Leads to Decreased Ω_{crit}

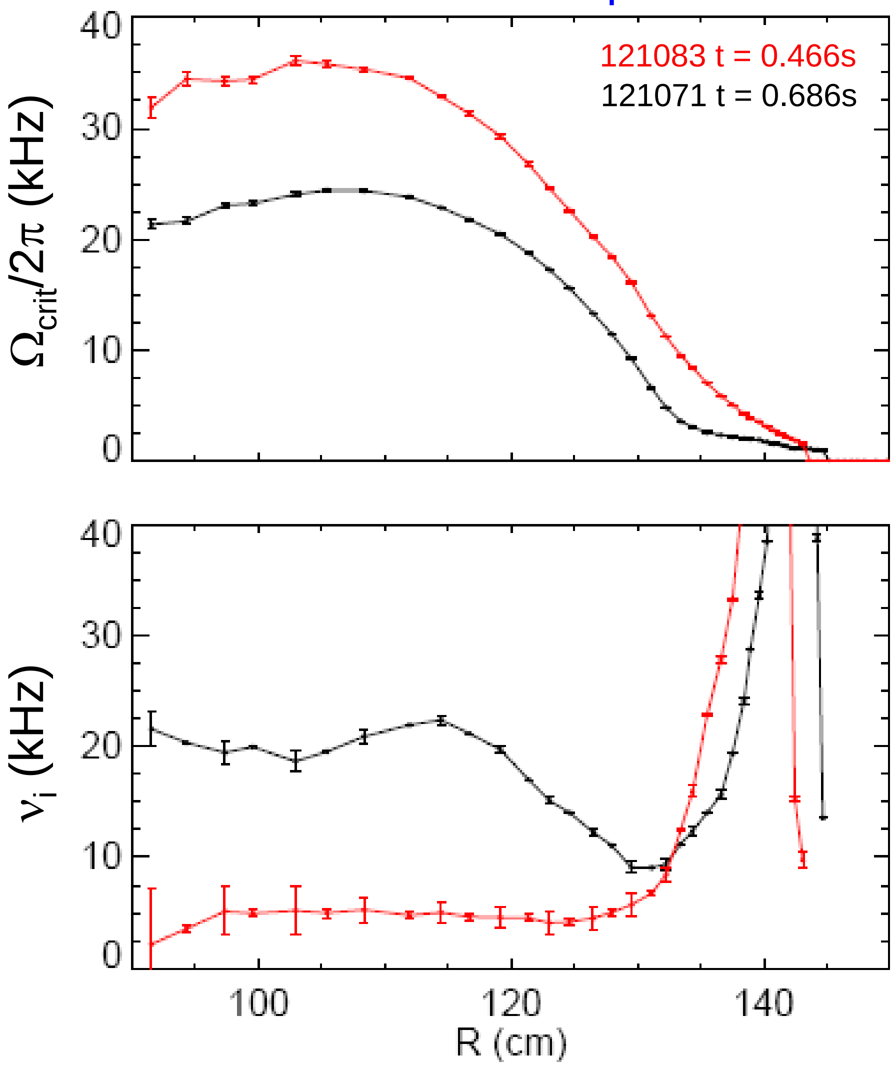
- Plasmas with similar v_A
- Consistent with neoclassical viscous dissipation model
  - at low γ, increased ν_i leads to lower Ω_{crit}
  - dissipation $\eta \sim \nu_i$ in high dissipation limit
    (K. C. Shaing, Phys. Plasmas **11** (2004) 5525.)

$$|\Omega_{crit}| > ((1 - d/d_c)/4 + (1 - d/d_c)^2/\eta^2)^{1/2}$$

wall parameters   dissipation

(A. C. Sontag, et al., Nucl. Fusion **47** (2007) 1005.)

Critical rotation profiles



NSTX research moves toward reliable active RWM control and stabilization physics understanding

- Active feedback on upper and lower arrays of both B_r and B_p RWM sensors as key next step for reliability
  - Determine optimal feedback/sensor configuration at reduced plasma rotation
  - Examine potential role of multiple modes
- Passive stabilization physics not yet determined, however
  - Scalar Ω_{crit} is insufficient; full ω_ϕ profile may play a role
  - Simple torque balance model $\Omega_{crit} = \omega_\phi/2$ insufficient
  - Destabilization / loss of control possible in all rotation ranges
  - Role of ω_A not yet well established
  - Ion collisionality profile appears to alter Ω_{crit}