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Active Resistive Wall Mode Stabilization in Low Rotation, High Beta NSTX Plasmas

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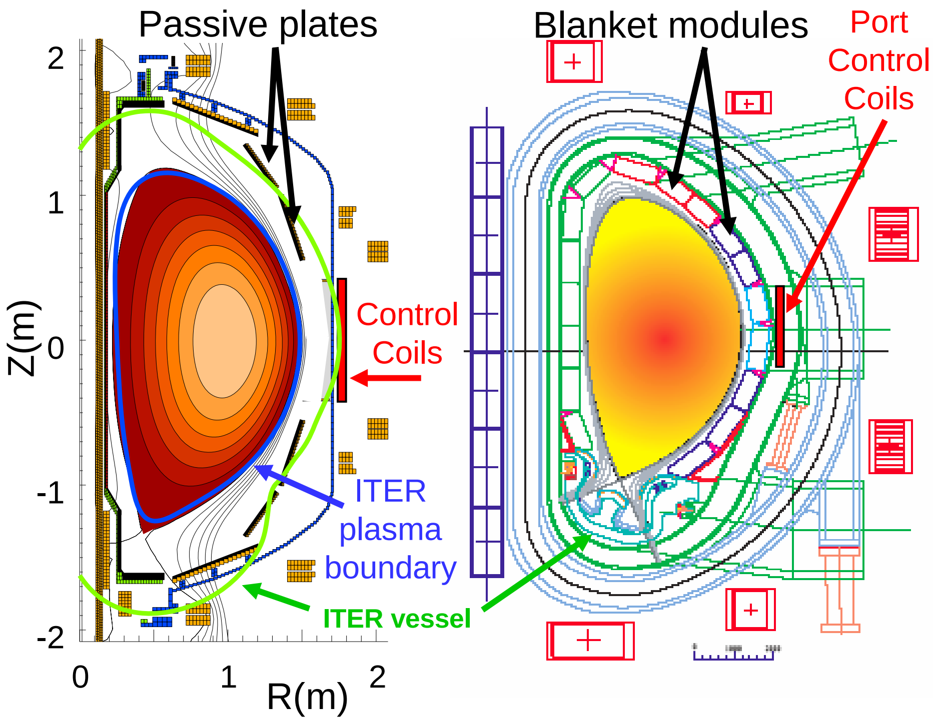
11th Workshop on Active Control of MHD Stability
Active MHD Control in ITER

November 7, 2006
PPPL - Princeton, NJ

Physics understanding and control of pressure-amplified error fields, unstable RWMs reduce performance risks for ITER

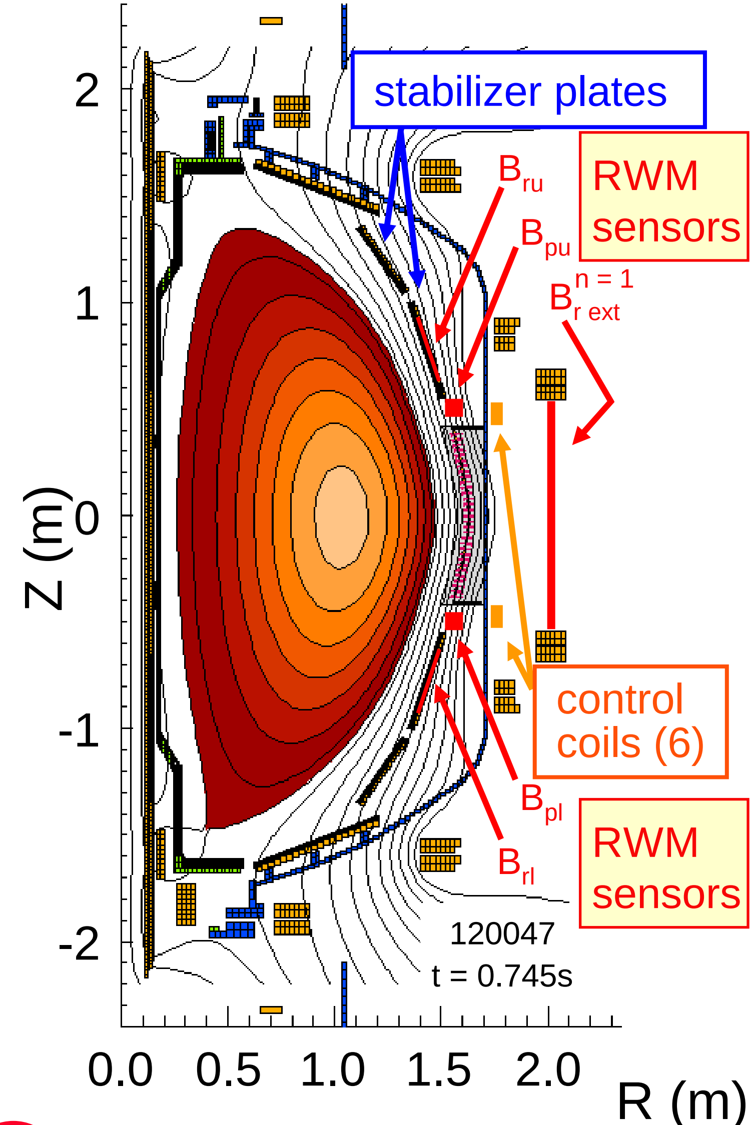
- **RWM active stabilization**
  - RWM control demonstrated
  - RWM actively stabilized in slowly rotating plasmas
- **Plasma rotation control**
  - Sustained rotation by real-time reduction of amplified error field
  - Reduced rotation by non-resonant magnetic braking
  - Quantitative understanding of momentum dissipation

NSTX / ITER RWM control



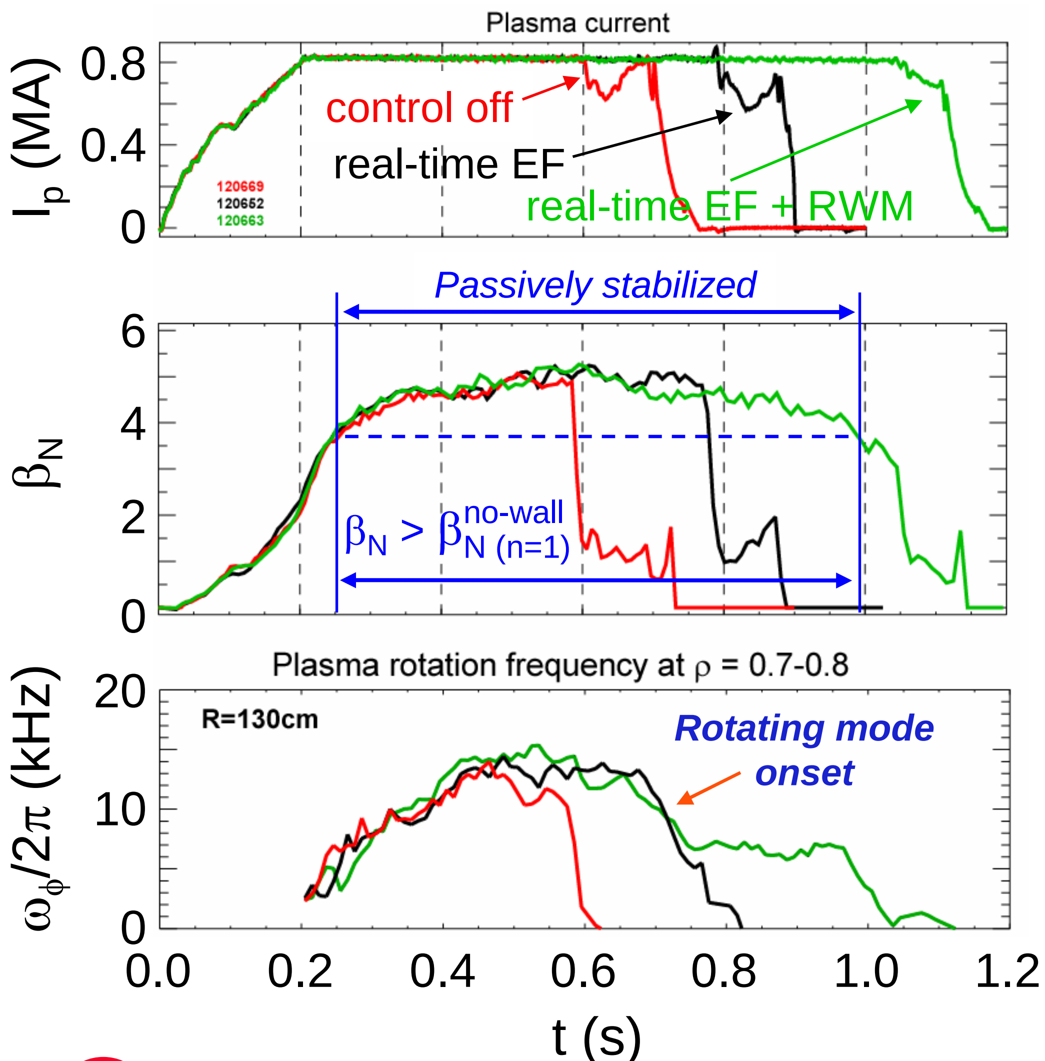
Advantage: low aspect ratio, high β plasmas provide high leverage on theory to uncover key tokamak physics

RWM Active Feedback System Installed on NSTX



- Stabilizer plates for kink mode stabilization
  - Operation at $\beta_N/\beta_N^{no\text{-}wall} > 1.5$ for pulse >> τ_{wall} at highest $\beta_N > 6$
- External midplane control coils closely coupled to vacuum vessel
- Internal sensors can detect $n = 1 – 3$ RWM
  - Unstable $n = 1 – 3$ RWMs already observed in NSTX (Sabbagh, et al., NF **46** (2006) 635.)
  - $n > 1$ RWM studied during $n = 1$ active stabilization

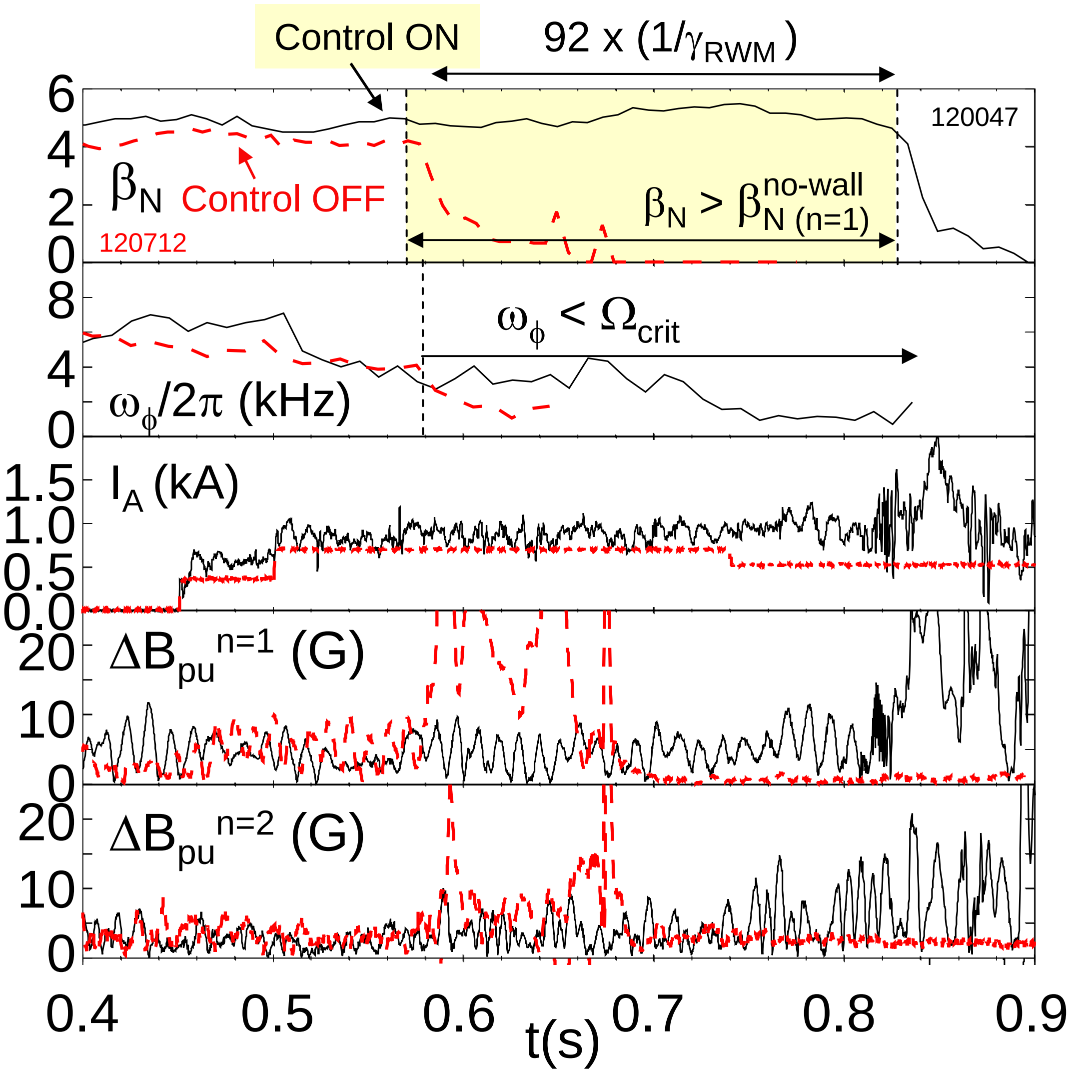
Dynamic error field correction increases pulse length in strongly rotating plasmas



- Real-time correction of known error field (EF)
  - yields higher rotation
  - yields longer pulse
- Combined real-time EF correction + n = 1 RWM feedback yielded best result
  - Toroidal rotation, ω_ϕ, increase or saturation at long pulse lengths - first time for NSTX

J.E. Menard, et al., APS 2006

RWM actively stabilized at low, ITER-relevant rotation



- First such demonstration in low A tokamak
  - Long duration > $90/\gamma_{RWM}$
  - Exceeds DCON $\beta_N^{no\text{-}wall}$ for n = 1 and n = 2
  - n = 2 RWM amplitude increases, mode remains stable while n = 1 stabilized
  - n = 2 internal plasma mode seen in some cases
- Plasma rotation ω_ϕ reduced by non-resonant n = 3 magnetic braking
  - Non-resonant braking to accurately determine RWM critical rotation

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

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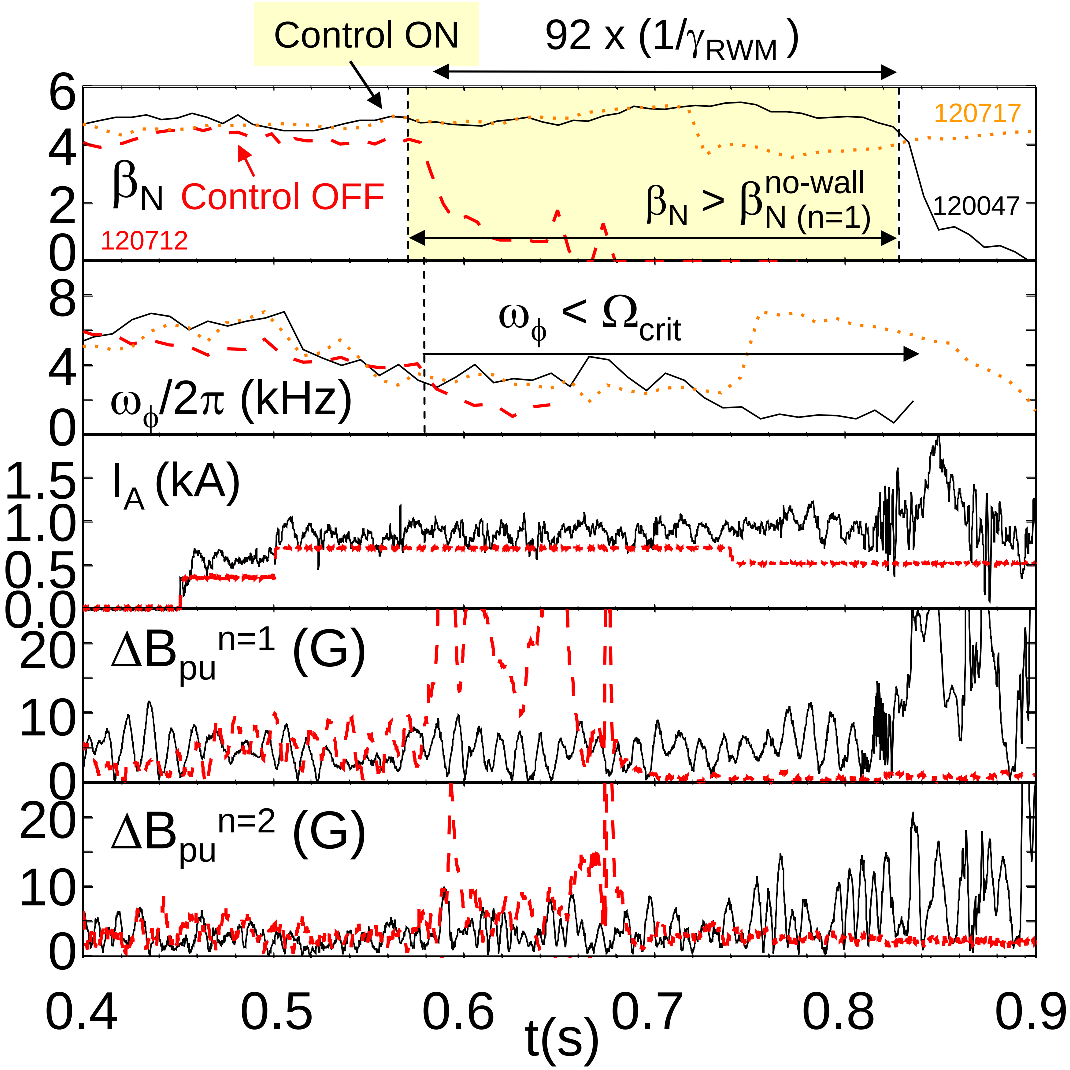

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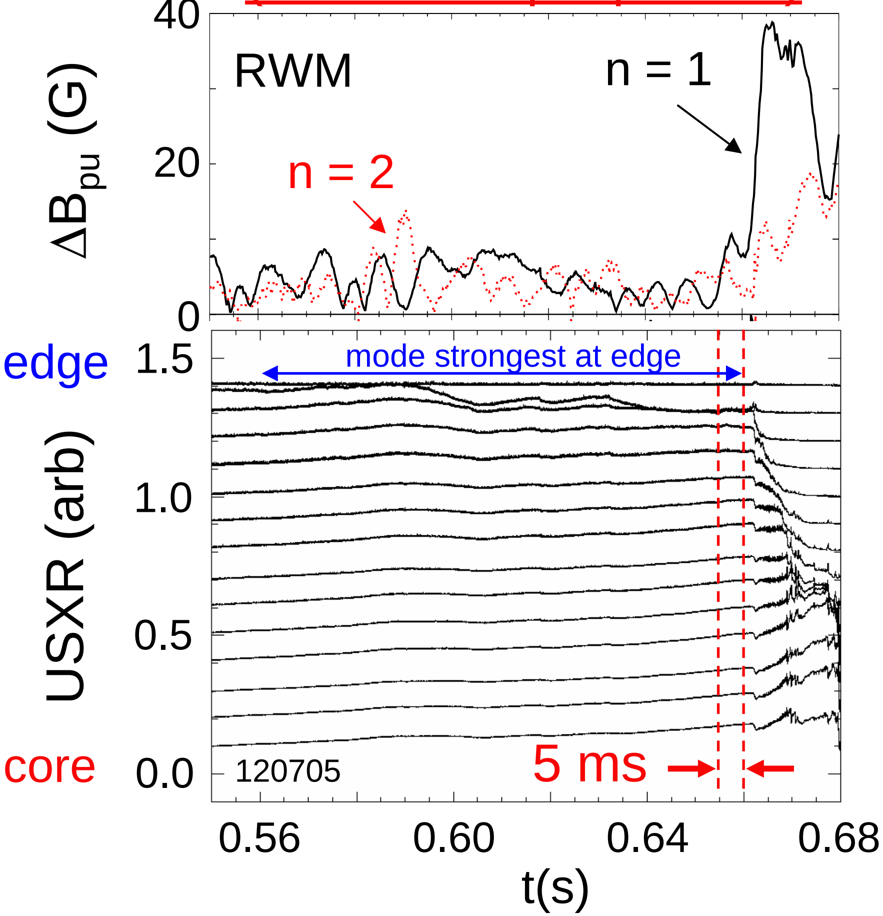
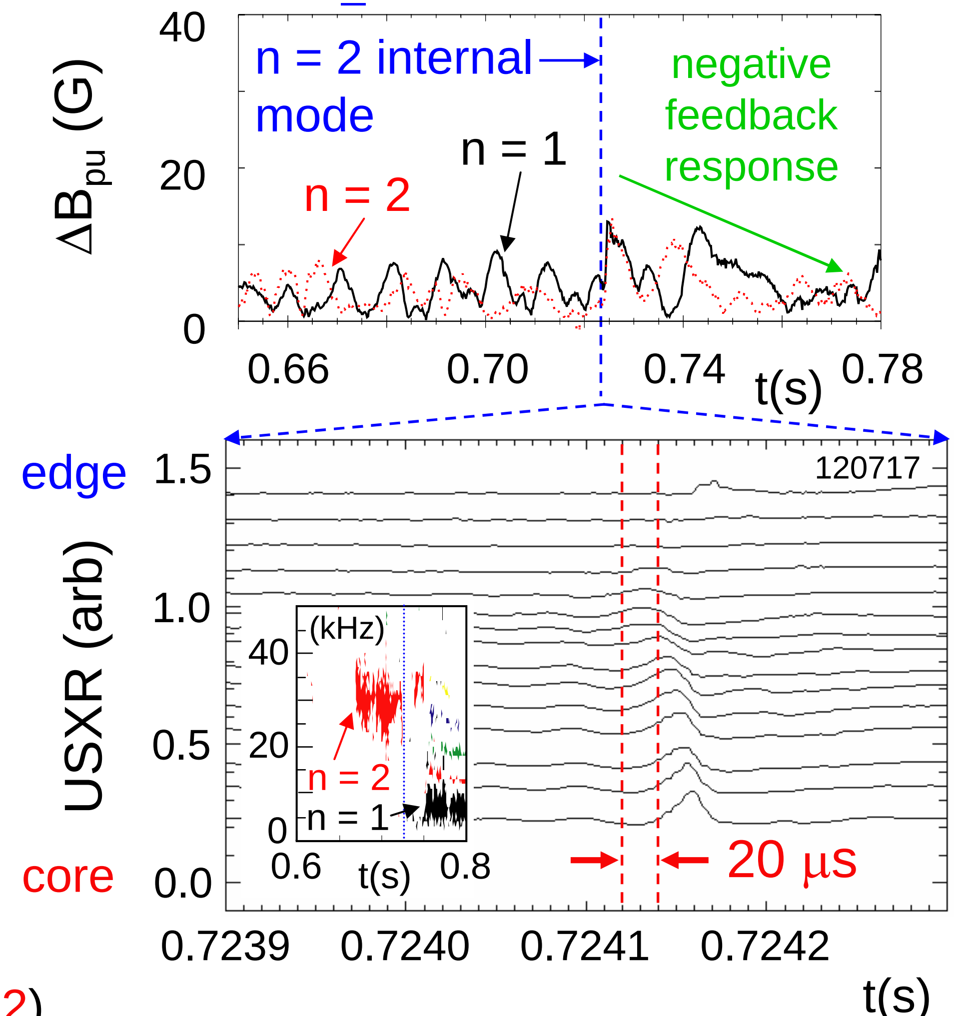
n = 2 RWM does not become unstable during n = 1 stabilization

Control OFF
(RWM disrupts plasma)



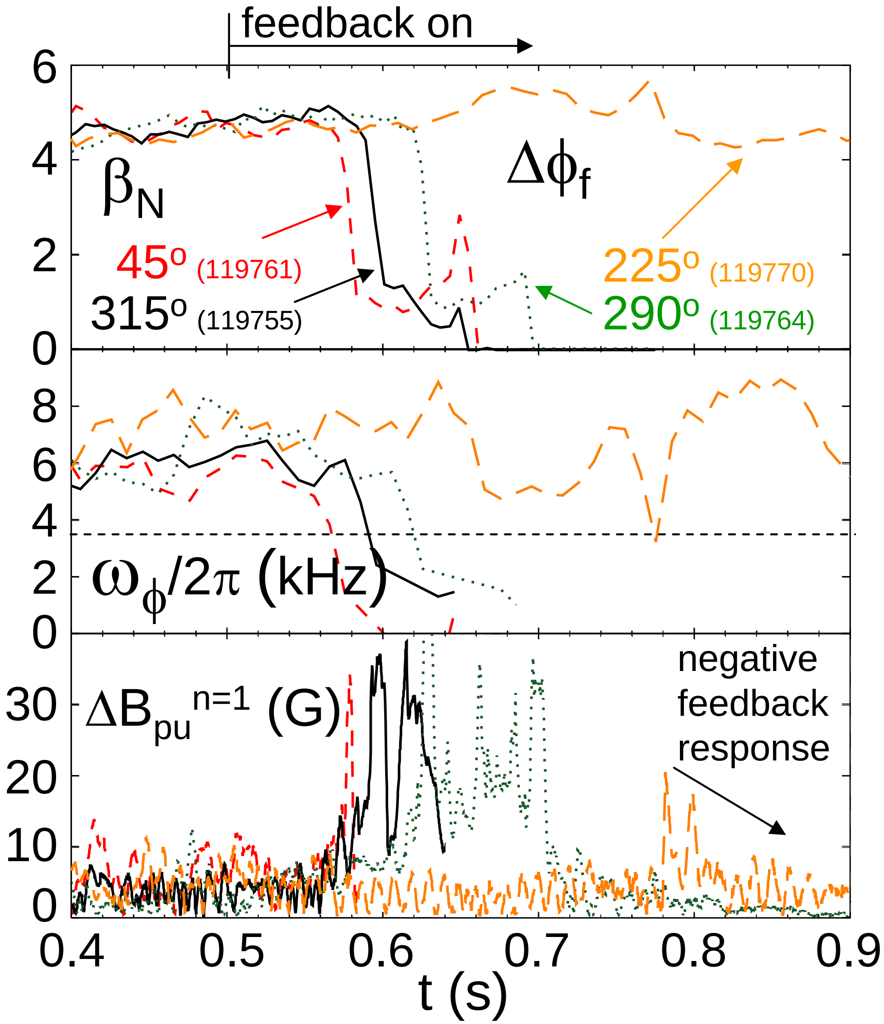
Control ON
(fast β_N drop, plasma recovers)



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

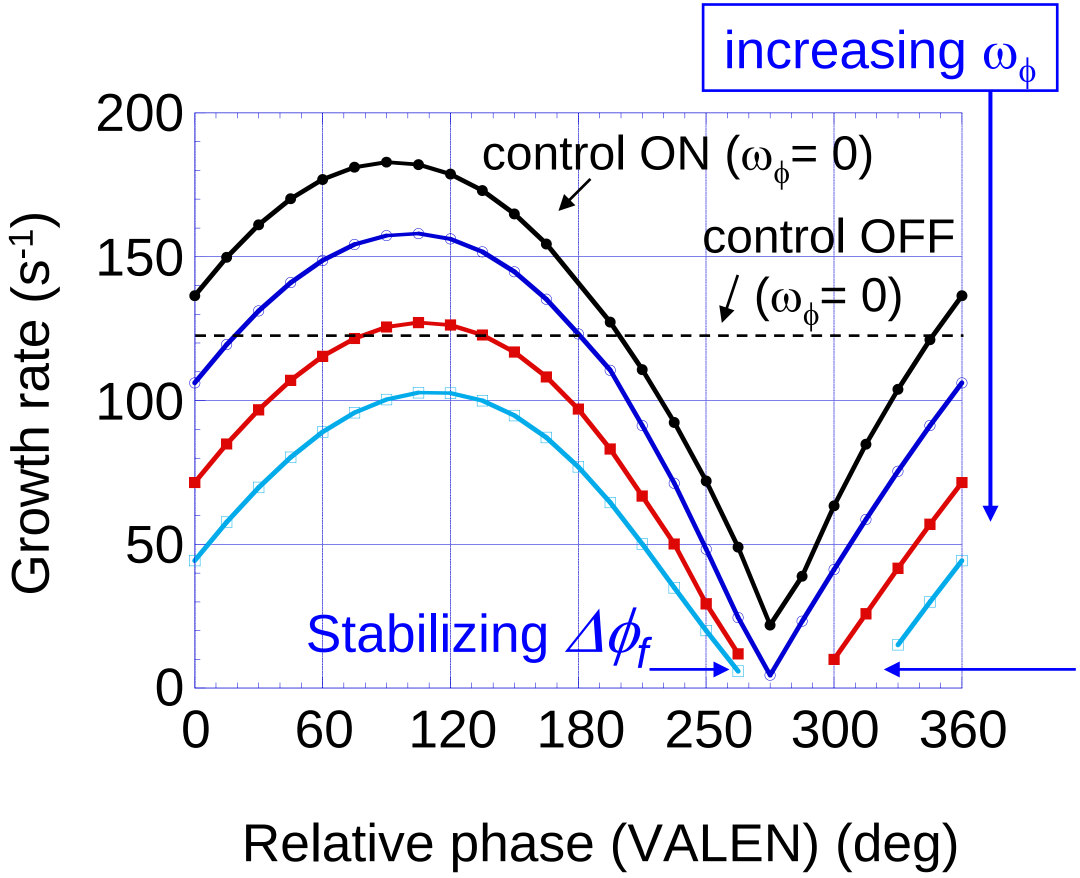
NSTX

Varying relative phase shows positive/negative feedback



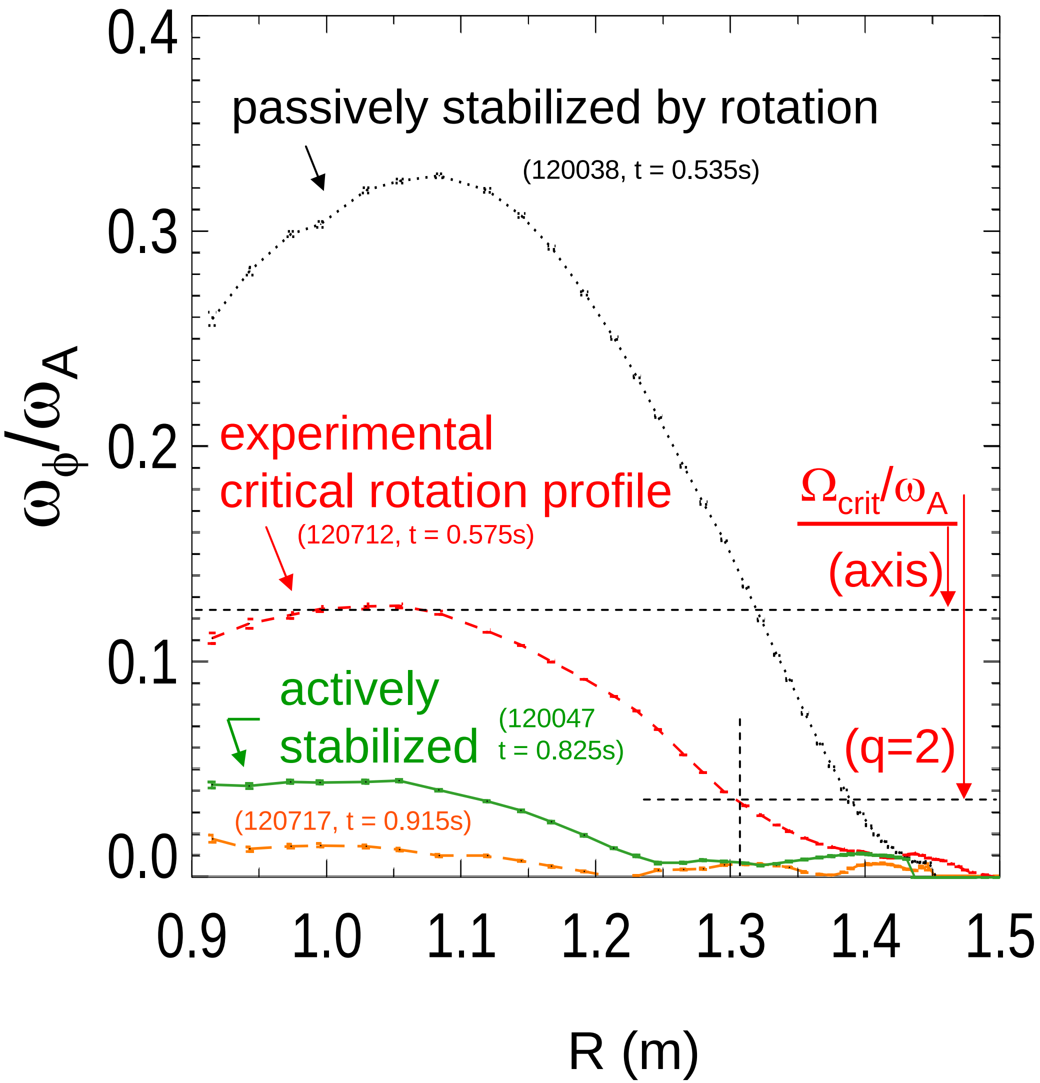
- Feedback on n = 1 RWM
  - Control current has relative phase $\Delta\phi_f$ to measured ΔB_p
- Phase scan shows superior settings for negative feedback
  - Pulse length increases
  - Internal plasma mode seen at $\Delta\phi_f$ = 225°, damped feedback system response
- Gain scan also performed
  - Sufficiently high gain showed feedback loop instability

VALEN-3D analysis demonstrates optimal relative phase $\Delta\phi_f$ for RWM active control



- First VALEN-3D analysis with both active and passive stabilization (ω_ϕ > 0)
- Unfavorable $\Delta\phi_f$ drives mode growth
- Stable range of $\Delta\phi_f$ increases with increasing ω_ϕ
- Optimal $\Delta\phi_f$ for active stabilization at ω_ϕ = 0 bracketed by results with ω_ϕ > 0.

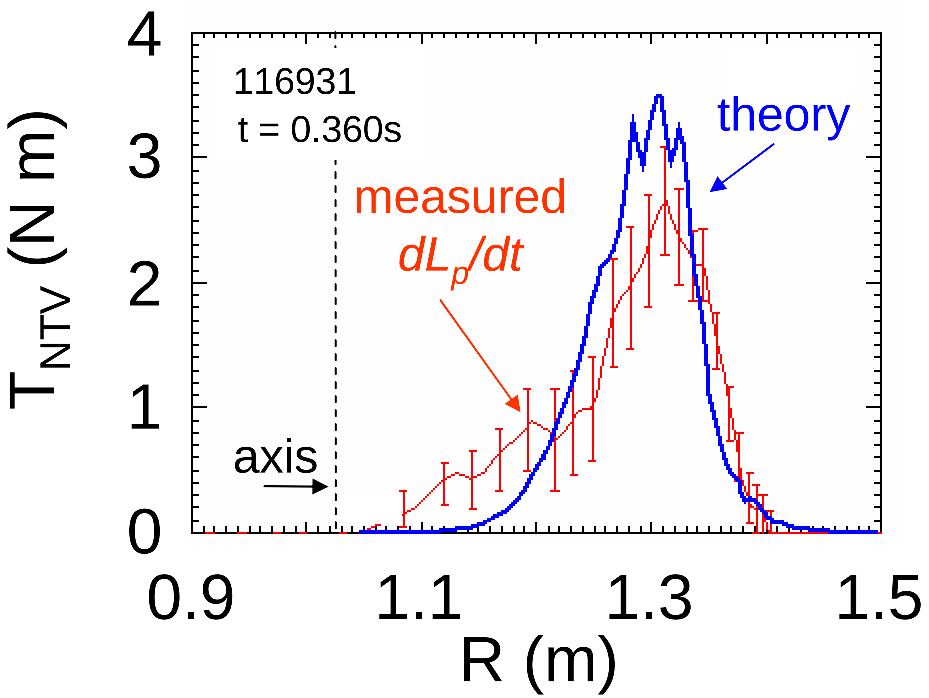
Rotation reduced far below RWM critical rotation profile



- Rotation typically fast and sufficient for RWM passive stabilization
  - Reached $\omega_\phi/\omega_A = 0.48|_{axis}$
- Non-resonant n = 3 magnetic braking used to slow entire profile
  - The $\omega_\phi/\omega_A < 0.01|_{q = 2}$
  - The $\omega_\phi/\Omega_{crit} = 0.2|_{q = 2}$
  - The $\omega_\phi/\Omega_{crit} = 0.3|_{axis}$
  - Less than ½ of ITER Advanced Scenario 4 $\omega_\phi/\Omega_{crit}$ (Liu, et al., NF **45** (2005) 1131.)
- Rotation profile responsible for passive stabilization, not just single radial location

Observed rotation decrease follows NTV theory

n = 3 applied field configuration



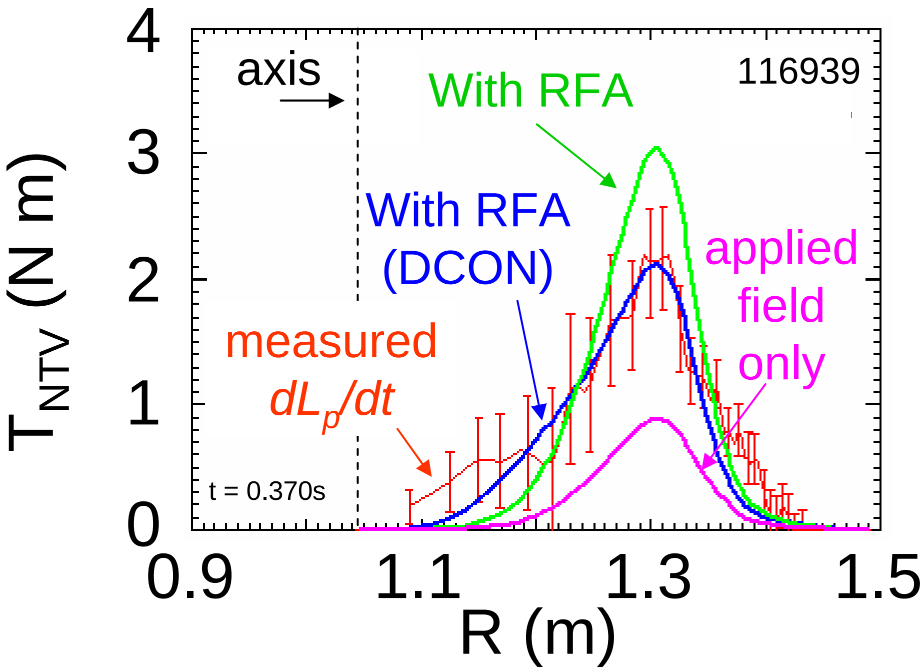
(Zhu, et al., PRL **96** (2006) 225002.)

- First quantitative agreement using full neoclassical toroidal viscosity theory (NTV)
  - Due to plasma flow through non-axisymmetric field
  - Computed using experimental equilibria
  - Trapped particle effects, 3-D field spectrum important
- Viable physics for simulations of plasma rotation in future devices (ITER, CTF)
  - Scales as $\delta B^2(p_i/\nu_i)(1/A)^{1.5}$
  - Low collisionality, ν_i, ITER plasmas expected to have higher rotation damping

Pressure-driven RFA increases NTV at high β_N

n = 1 applied field configuration

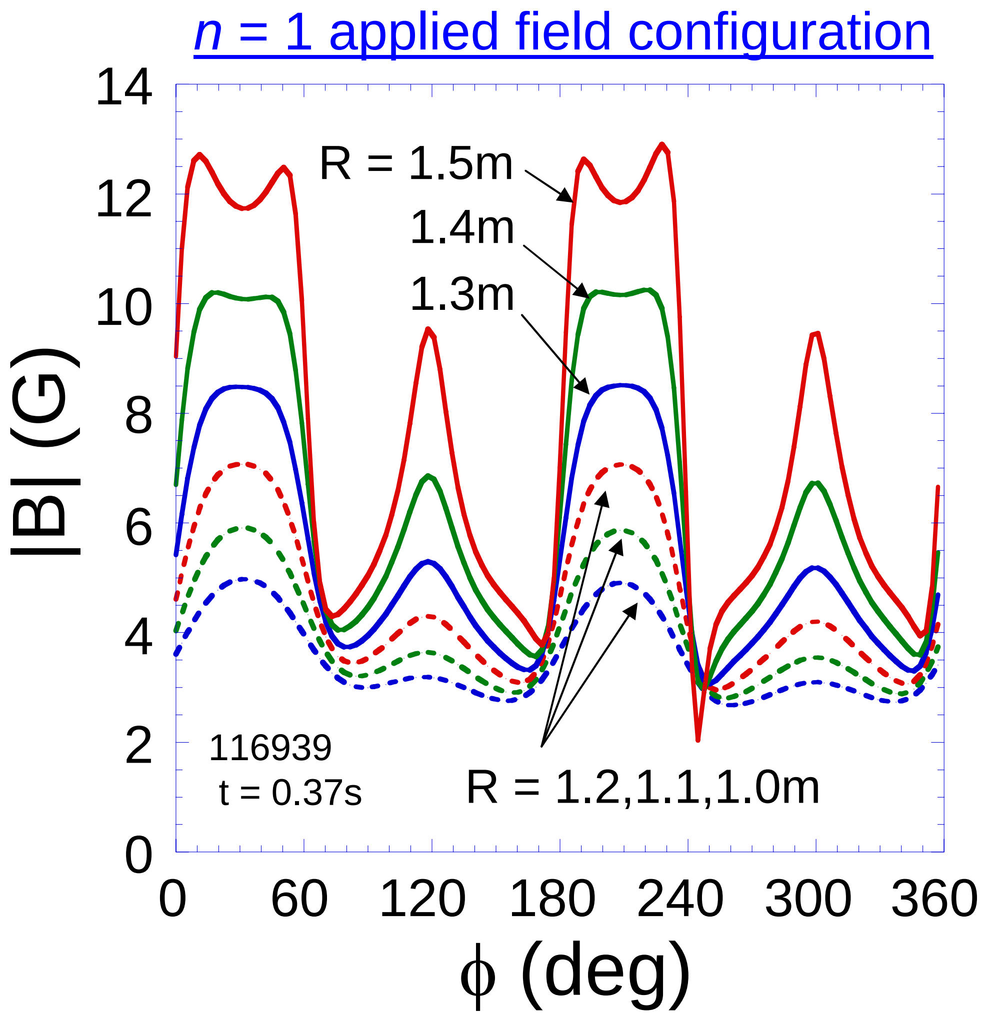
($\beta_N > \beta_N^{no\text{-}wall} = 4.4$)

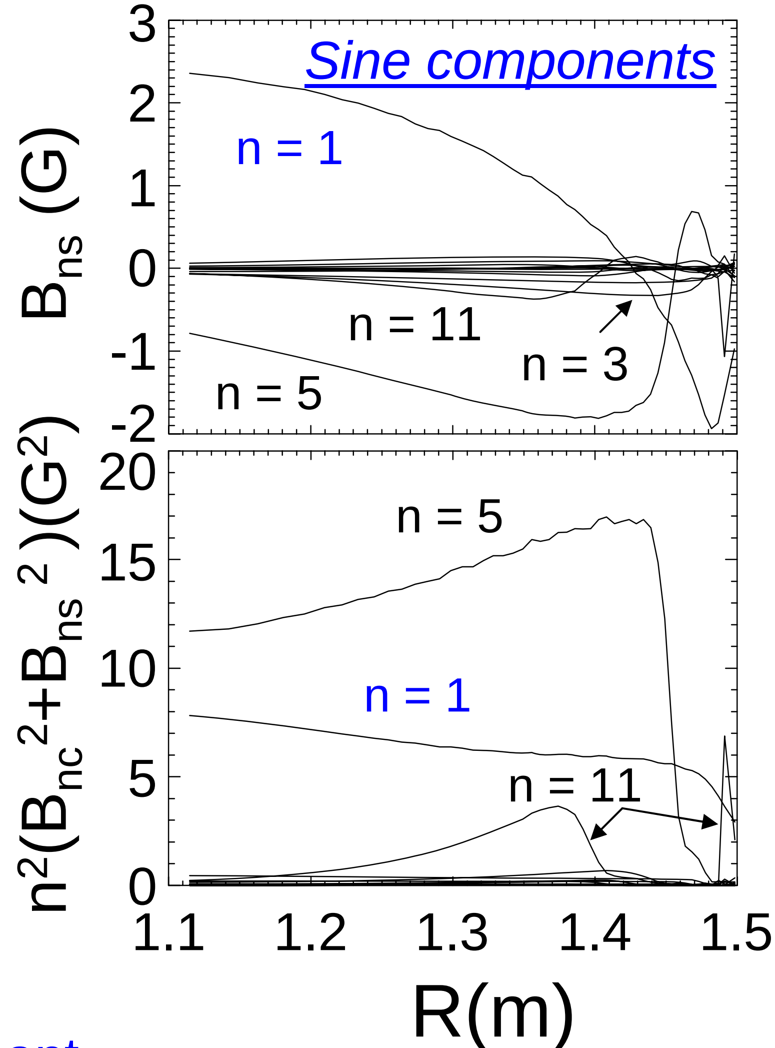


(Zhu, et al., PRL **96** (2006) 225002.)

- Resonant field amplification (RFA) increases applied field when $\beta_N > \beta_N^{no\text{-}wall}$
  - n = 1 has strongest RFA
- Measured RFA, or unstable RWM field yields increase in NTV rotation damping
  - Torque due to applied field alone does not match experiment as well
- Computation based on applied field, or DCON computed mode spectrum
  - DCON eigenfunction yields slightly broader profile, better experimental agreement

Accurate NTV calculation requires broad applied |B| spectrum



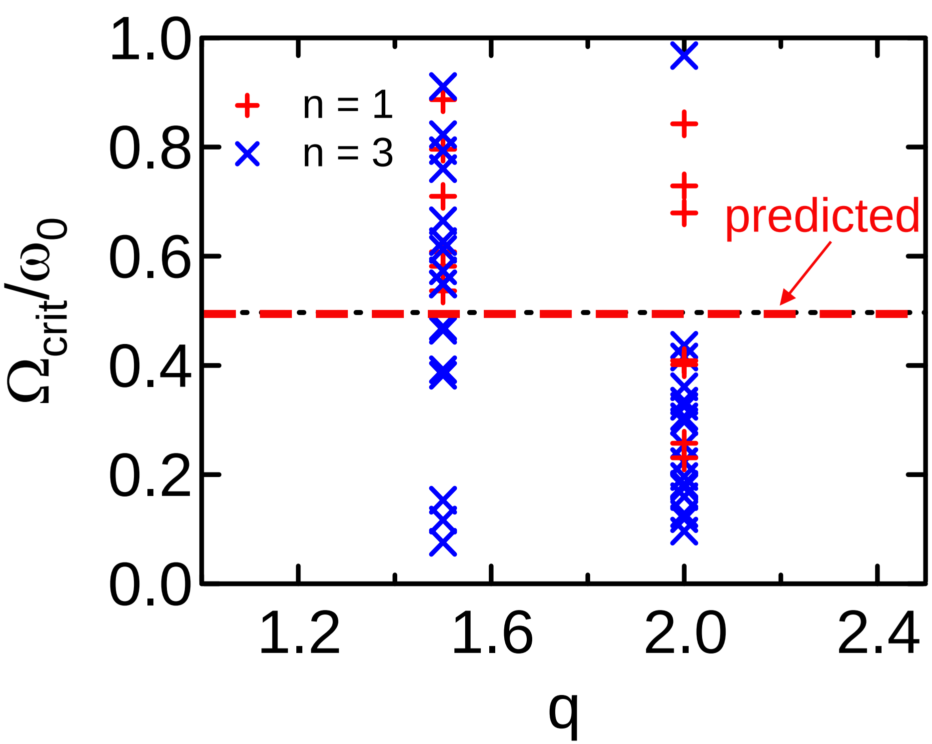


- *n* = 3 configuration has *n* = 3, 9 dominant

Ω_{crit} not correlated with Electromagnetic Torque 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 or further into core at q = 1.5
  - Same result for n = 1 and 3 applied field configuration

NSTX Ω_{crit} Database



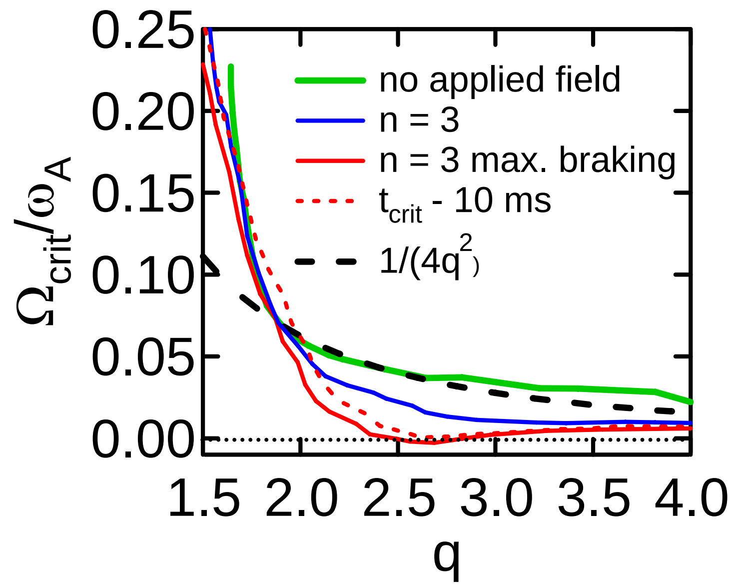
($\omega_0 \equiv$ steady-state plasma rotation)

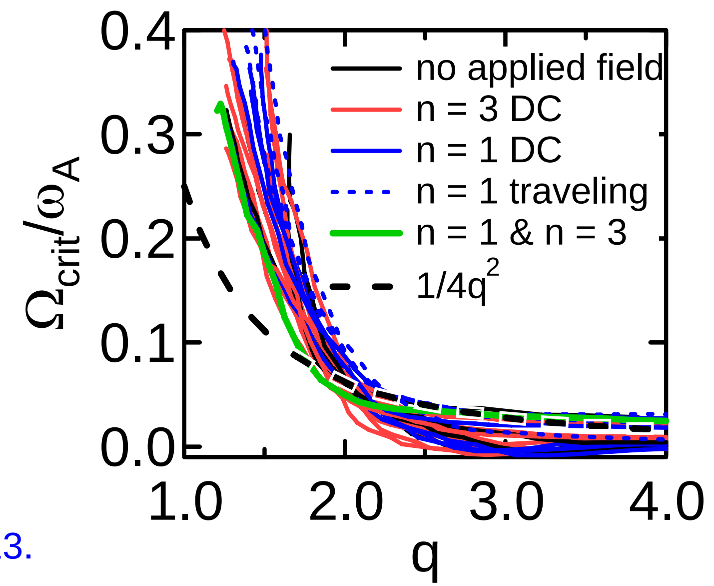
A.C. Sontag, et al., IAEA 2006

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

Rotation profile shape important for RWM stability

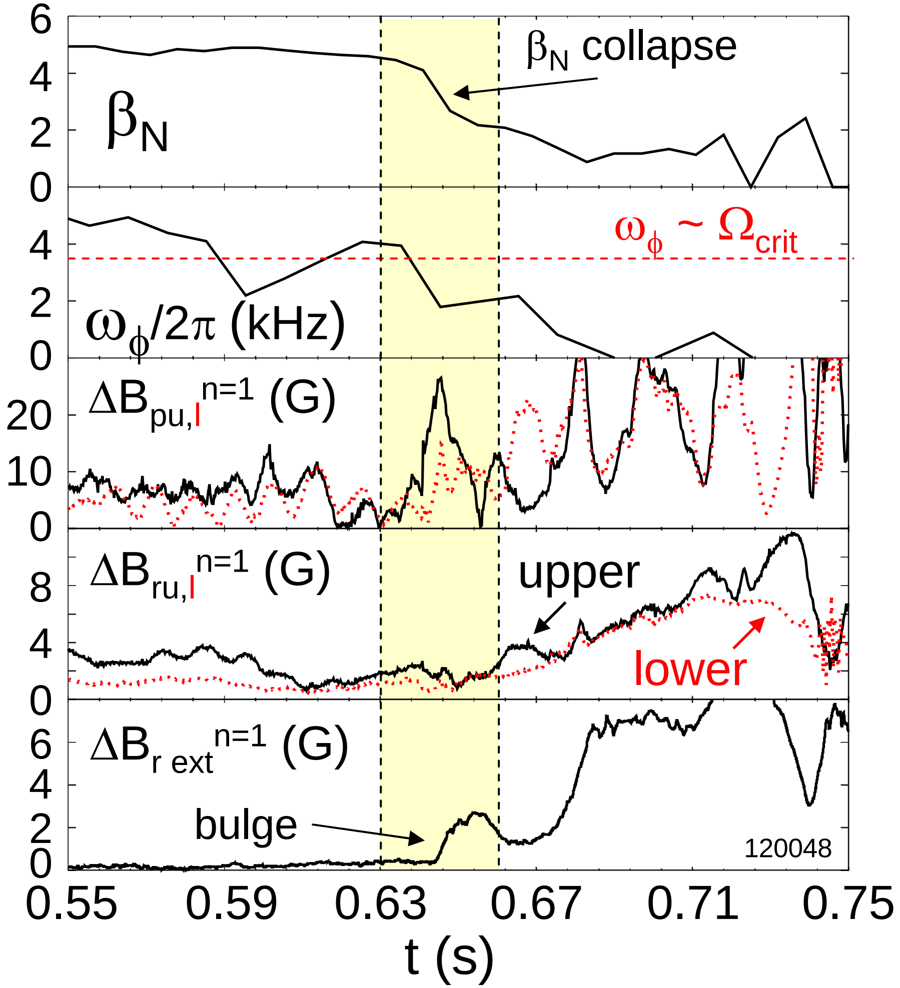
- Benchmark profile for stabilization is
  $\omega_c = \omega_A / 4q^2$ *
  - predicted by Bondeson-Chu semi-kinetic theory**
- n = 3 braking field ***reduces*** Ω_{crit} profile
- High rotation outside q = 2.5 not required for stability
  - Zero rotation at single q can be stable
- Scalar Ω_{crit}/ω_A 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.

RWM may change form and grow during active control



- Poloidal $n = 1$ RWM field decreases to near zero
  - Radial field increasing
- Subsequent growth of poloidal RWM field
  - *Asymmetric* above/below midplane
- Radial sensors show RWM bulging at midplane
  - midplane signal increases, upper/lower signals decrease
  - Theory: may be due to other stable ideal $n = 1$ modes becoming less stable

Future research will assess using combined sensors for optimization

NSTX begins RWM active stabilization research relevant to ITER, CTF and beyond

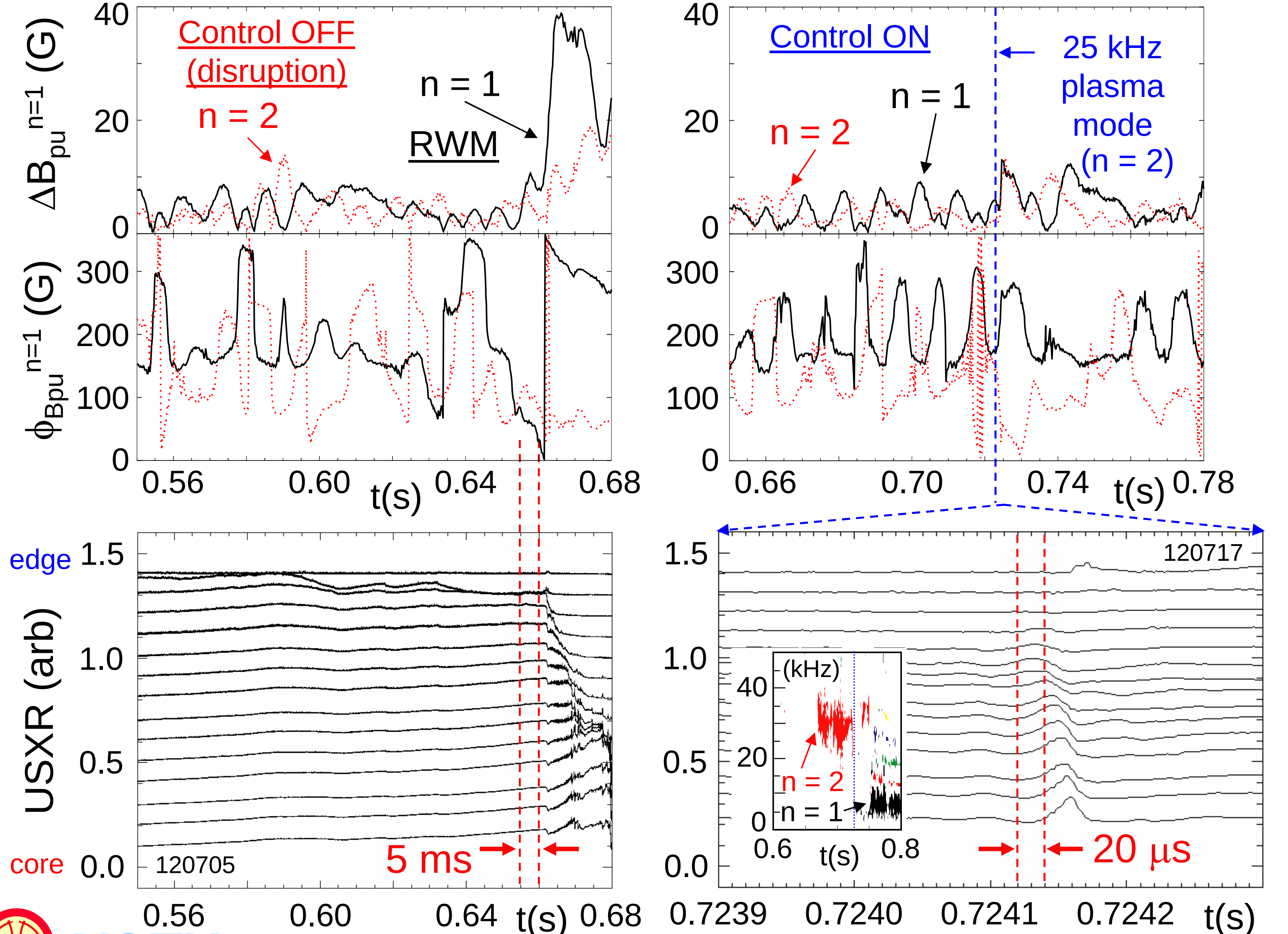
- First demonstration of RWM active stabilization in high β, low A tokamak plasmas with ω_ϕ significantly less than Ω_{crit}
  - In the predicted range of ITER
  - Positive and negative RWM feedback demonstrated by varying feedback gain and relative phase
- Stability of $n = 2$ RWM observed during $n = 1$ RWM stabilization
  - $n = 1,2$ plasma mode sometimes observed; fast β collapse, recovery
- Plasma rotation reduction by non-resonant applied field; follows neoclassical toroidal viscosity theory
  - Full NTV calculation yielding quantitative agreement to experiment ; general momentum transport relevance
- Results continue to support Ω_{crit} as profile; scalar insufficient

Active RWM control remains vitally important to minimize performance risk in ITER

- Agreement does not yet exist regarding Ω_{crit}, RWM stabilization physics in low-rotation plasmas
- Observed inverse dependence of Ω_{crit} on ν_i indicates lower ITER collisionality may require a higher degree of RWM active stabilization (see talk by A. Sontag, this meeting)
- Similar inverse dependence of plasma momentum dissipation on ν_i in NTV theory indicates ITER plasmas will be subject to higher viscosity, greater ω_ϕ reduction
- Strong δB^2 dependence of quantitatively verified NTV theory shows that error fields, resonant field amplification, ELMs need be minimized to maximize stabilizing ω_ϕ
- Pressure, q, and ω_ϕ profiles unknown for burning plasma. RWM (and ELM, error field) control reduces performance risk

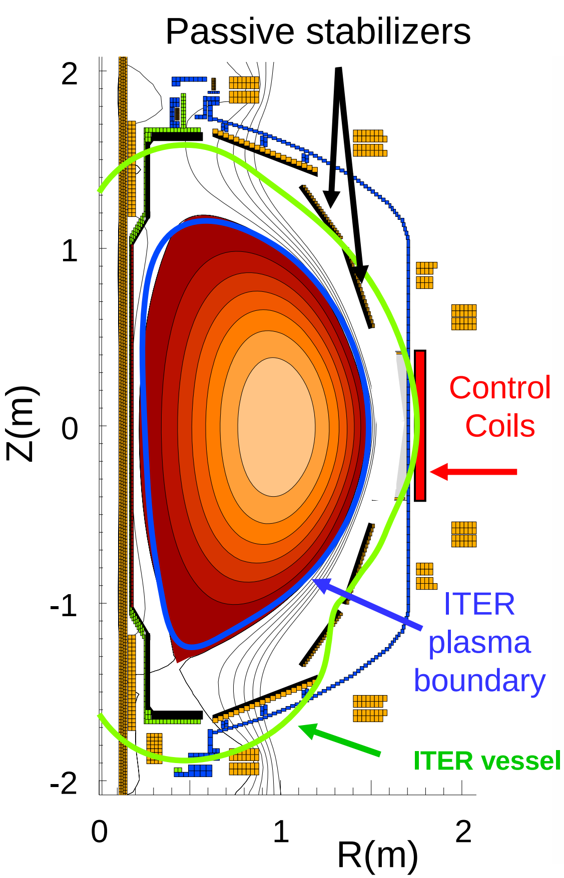
Extra slides

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

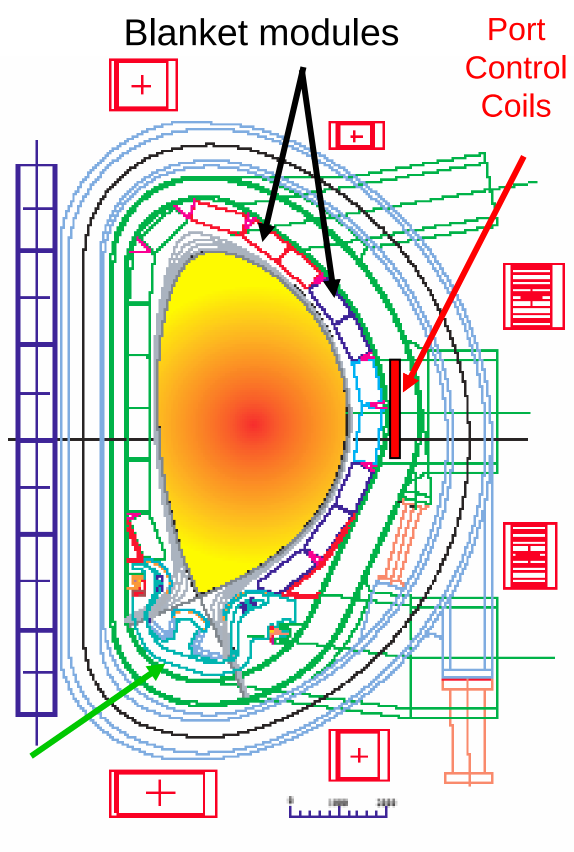


NSTX global MHD mode stabilization hardware similar to designs for next-step tokamaks

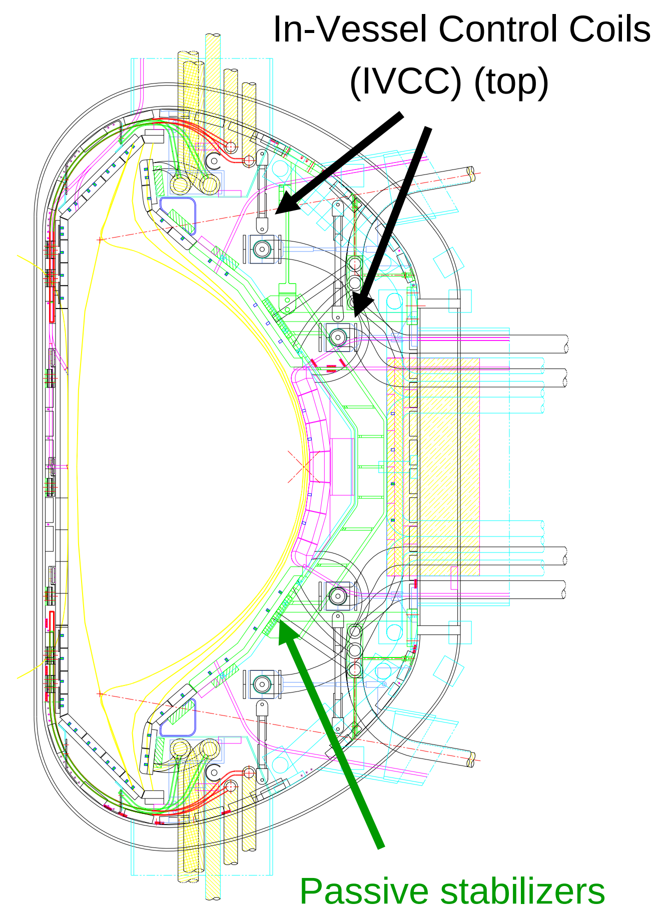
NSTX



ITER



KSTAR



- ITER: Midplane port control coils, blanket
- KSTAR: Midplane control coil, passive plate geometry with midplane gap