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Resistive Wall Mode Research in NSTX

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University of Wisconsin Research Conference

Madison, Wisconsin - February 5th, 2007

Resistive Wall Mode Research in NSTX has Progressed to Address Advanced Topics, support Future Devices

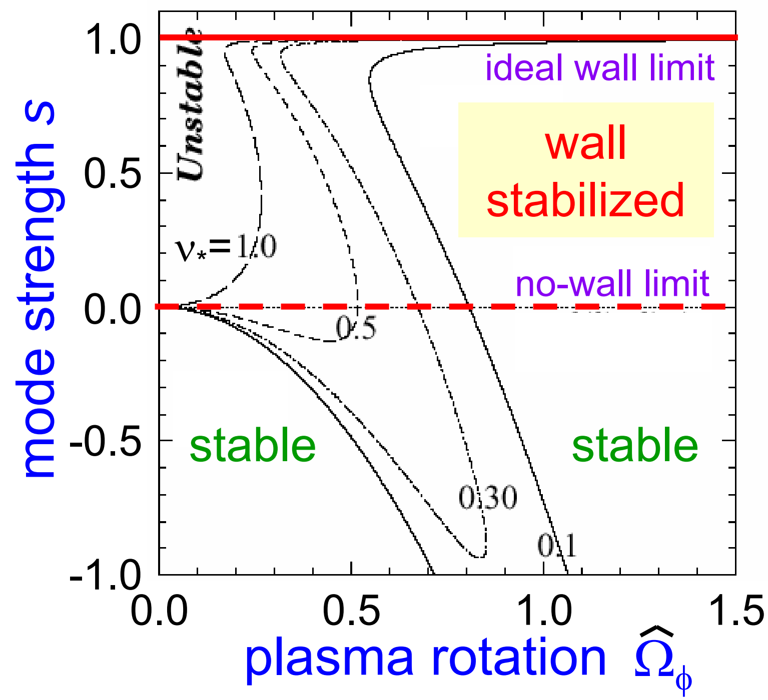
- **Motivation**
  - Global MHD modes, including the resistive wall mode (RWM), limit plasma pressure (β), fusion power
  - RWM stabilization highly desired in fusion reactors to maximize fusion power ($\sim \beta^2$)
- **Outline**
  - Plasma operation in wall-stabilized, high beta regime
  - RWM detection – unstable toroidal mode numbers $n > 1$
  - Passive RWM stabilization in rotating plasmas
  - Active RWM stabilization in low rotation plasmas (ITER relevant)
  - Plasma rotation damping due to non-axisymmetric fields
  - RWM stabilization system physics design for future devices

RWM - branch of the ideal kink/ballooning mode coupled to wall

- **RWM stabilization**
  - Kink/ballooning mode poses hard limit to plasma pressure (β)
  - Conducting wall, plasma rotation stabilizes kink, leads to RWM
  - Passive / active RWM stabilization can increase β limit
- **Analysis tools**
  - EFIT – equilibrium reconstruction
  - DCON – ideal MHD stability
  - VALEN – RWM stability, system design

Fitzpatrick-Aydemir (F-A) stability curves

Phys. Plasmas **9** (2002) 3459

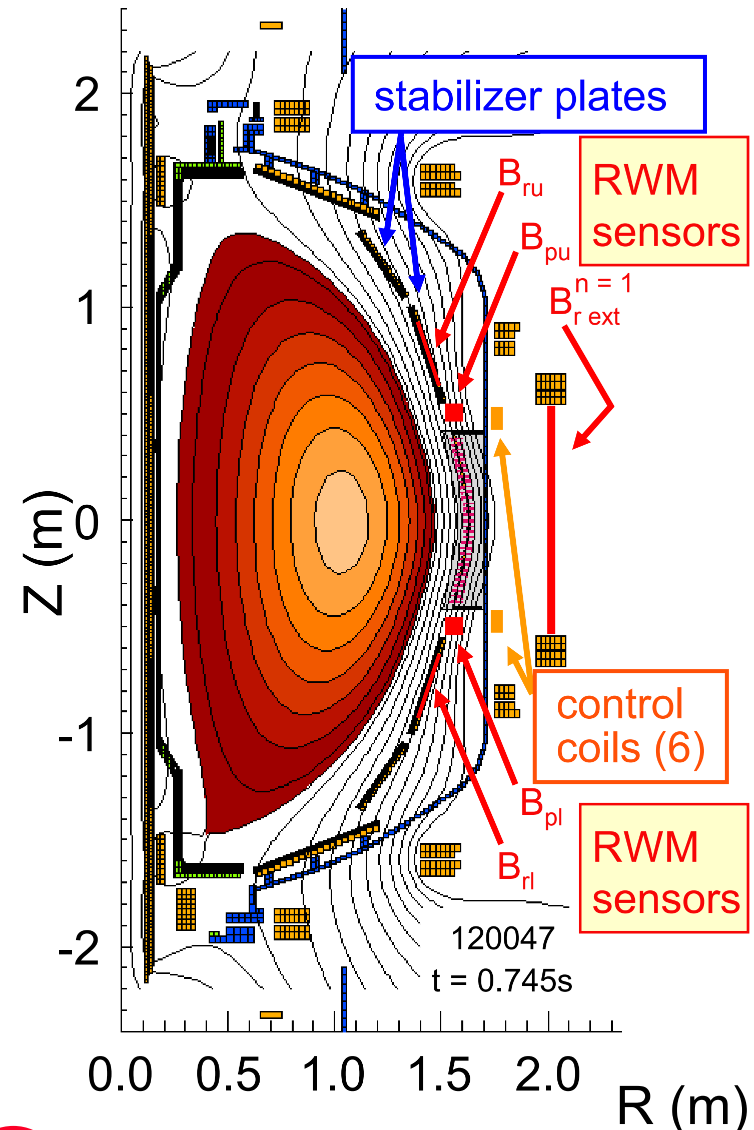


$$\left[\left(\hat{\gamma}-i\hat{\Omega}_{\phi}\right)^{2}+\nu_{*}\left(\hat{\gamma}-i\hat{\Omega}_{\phi}\right)+(1-s)(1-md)\right]\left(S_{*}\hat{\gamma}+(1+md)\right)=\left(1-(md)^{2}\right)$$

plasma inertia — dissipation — mode strength — wall response — wall/edge coupling

$S_* \sim 1/\tau_{wall}$

NSTX is equipped to detect and stabilize kinks, RWM



Machine

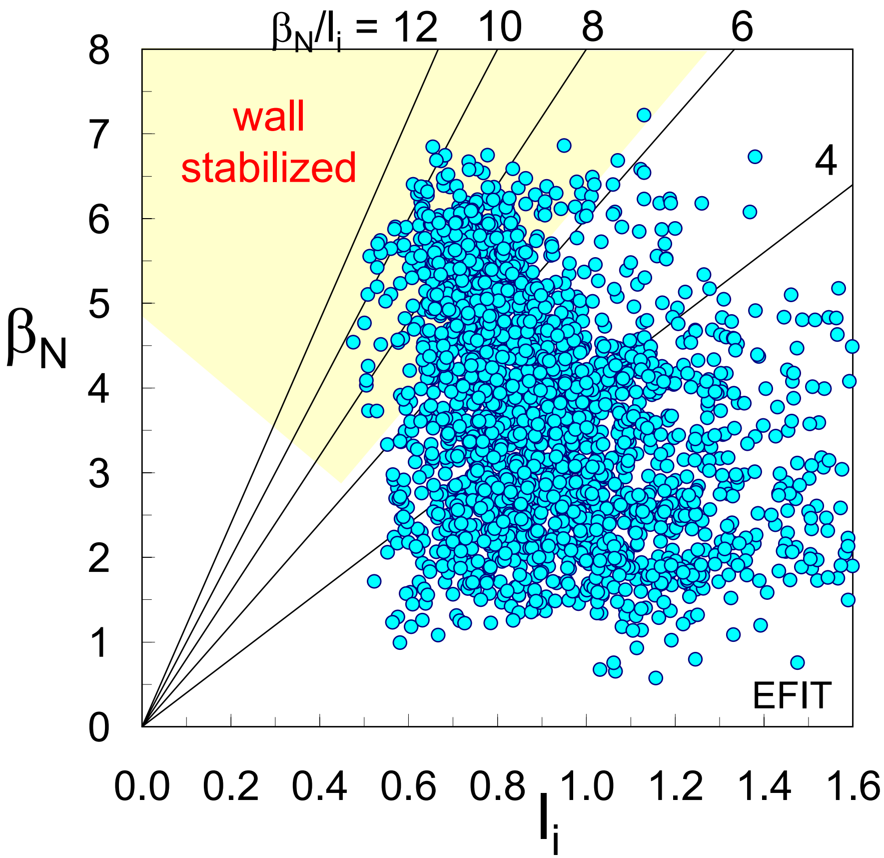
Aspect ratio	≥ 1.27
Elongation	≤ 3.0
Triangularity	≤ 0.8
Plasma Current	≤ 1.5 MA
Toroidal Field	≤ 0.6 T
NBI	≤ 7 MW

- Stabilizer plates for kink mode stabilization
- External midplane control coils closely coupled to vacuum vessel
- Internal sensors can detect n = 1 – 3 RWM

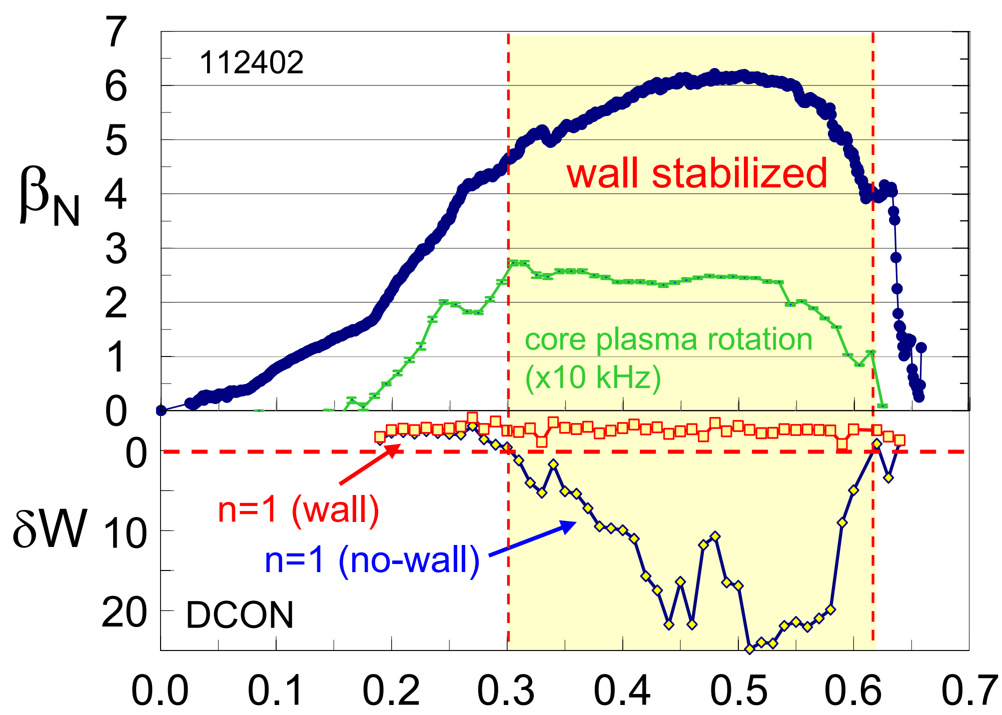
NSTX

Kink stabilization by wall and RWM passive stabilization by rotation allows sustained plasma operation at maximum β

- High β_t = 39%, β_N = 7.2 reached



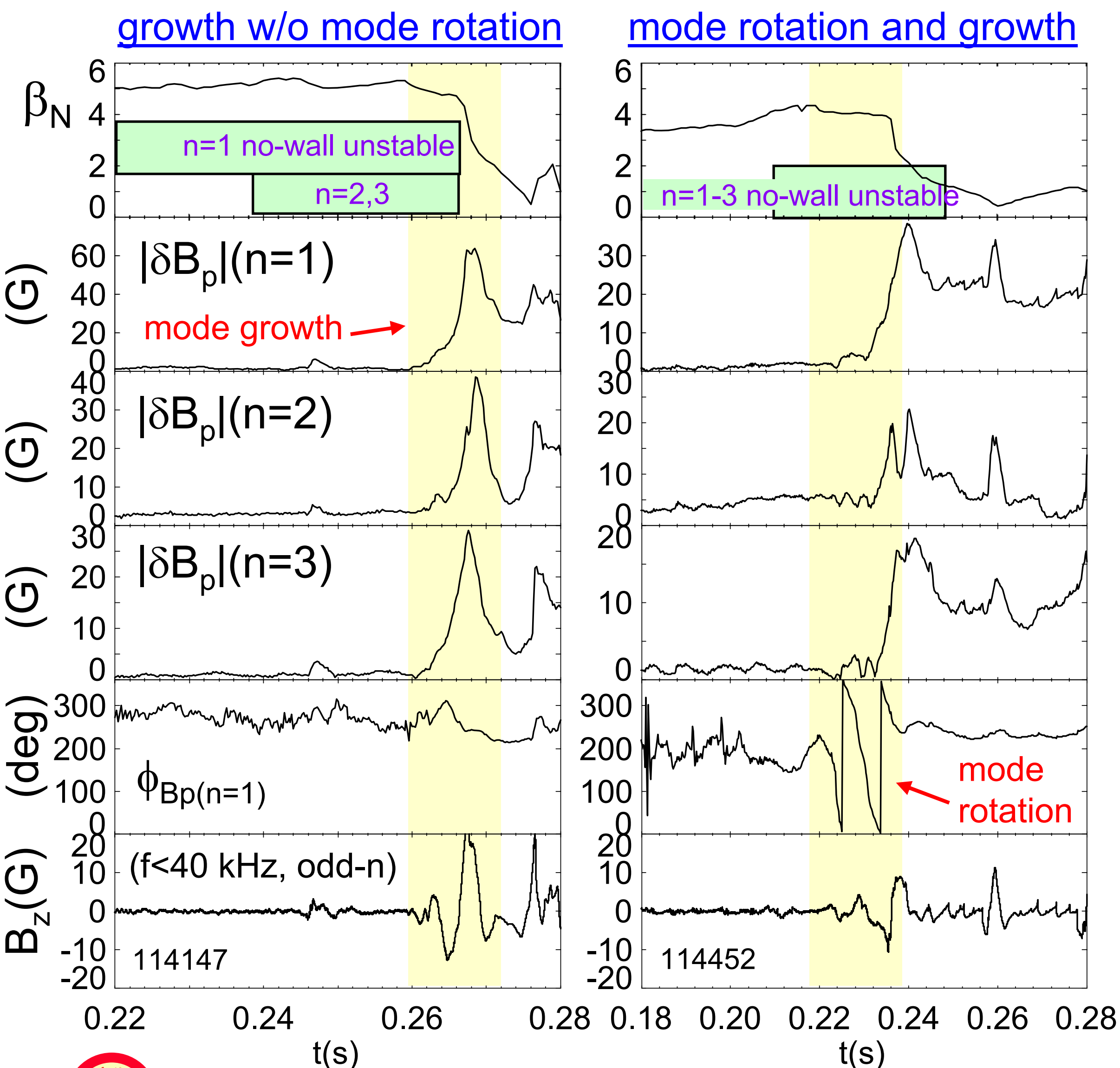
- Operation with $\beta_N/\beta_N^{no\text{-}wall}$ up to 1.5 at highest β_N for pulse >> τ_{wall}, ~ τ_{cr}



*(Sabbagh, et al., NF **46** (2006) 635.)

- Strong inverse dependence of β_N vs. pressure peaking factor*
- Time-evolved DCON analysis performed between shots on request

Unstable RWM dynamics follow simple theory

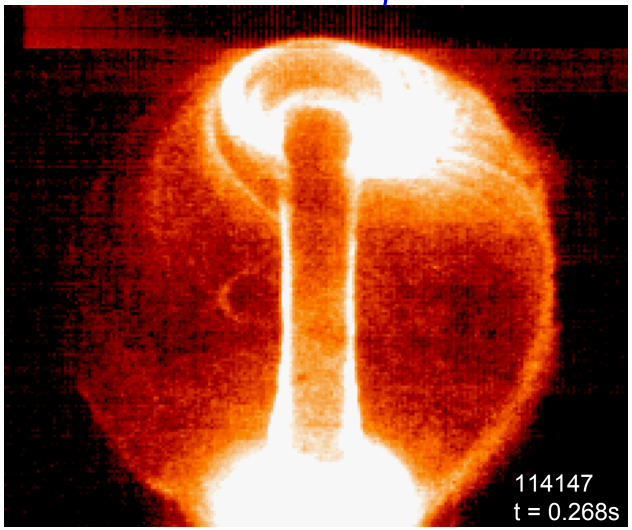


- Unstable n=1-3 RWM observed
  - ideal no-wall unstable at high β_N
  - n > 1 theoretically less stable at low A
- F-A theory / experiment show
  - mode rotation can occur during growth
  - growth rate, rotation frequency ~ $1/\tau_{wall}$
    - << edge Ω_ϕ > 1 kHz
  - RWM phase velocity follows plasma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

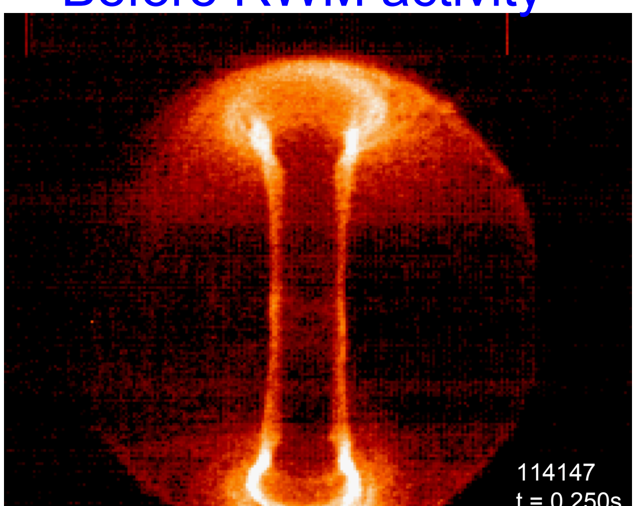
(Sabbagh, et al., NF **46** (2006) 635.)

Theoretical RWM reconstructed from experimental data

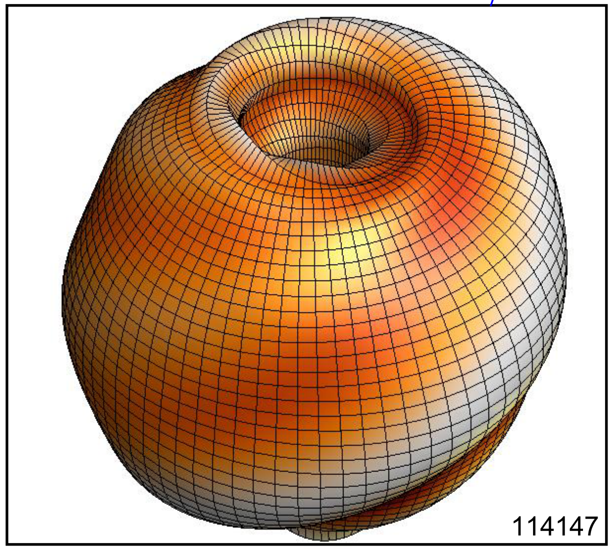
RWM with ΔB_p = 92 G



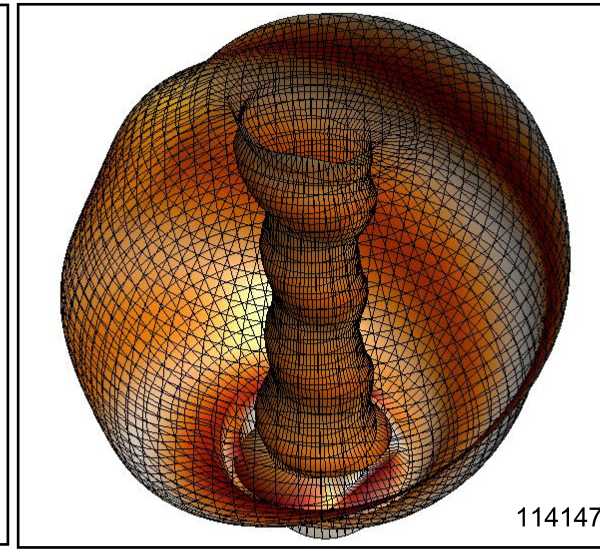
Before RWM activity



Theoretical ΔB_ψ (x10) with n=1-3 (DCON)



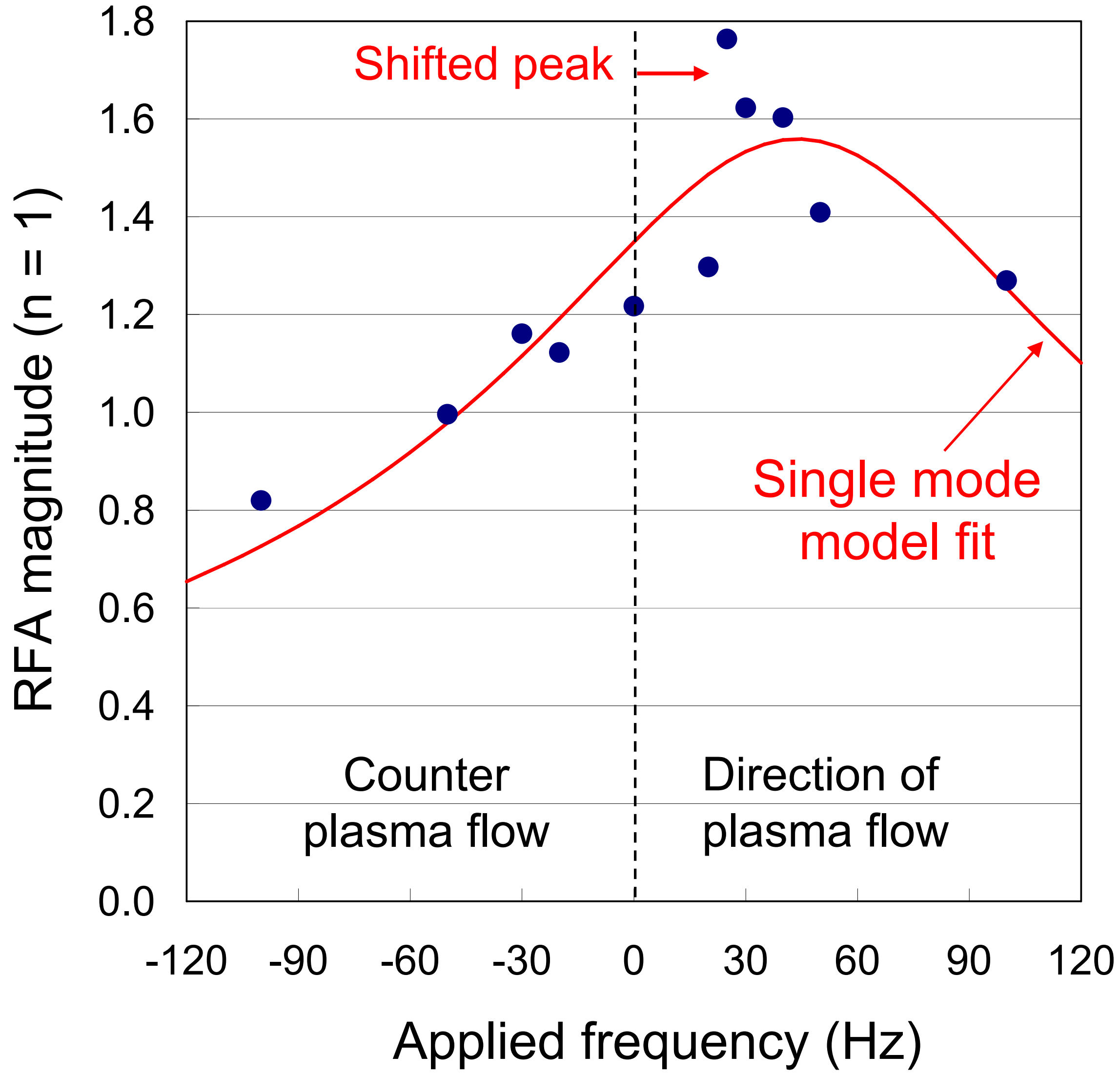
(exterior view)



(interior view)

- Visible light emission, USXR is toroidally asymmetric during RWM
- DCON theory + data reconstructs mode
  - uses experimental equilibrium reconstruction
  - includes n = 1 – 3 mode spectrum
  - uses relative amplitude / phase of n spectrum measured by RWM sensors

Resonant field amplification (RFA) magnitude dependent on applied field frequency



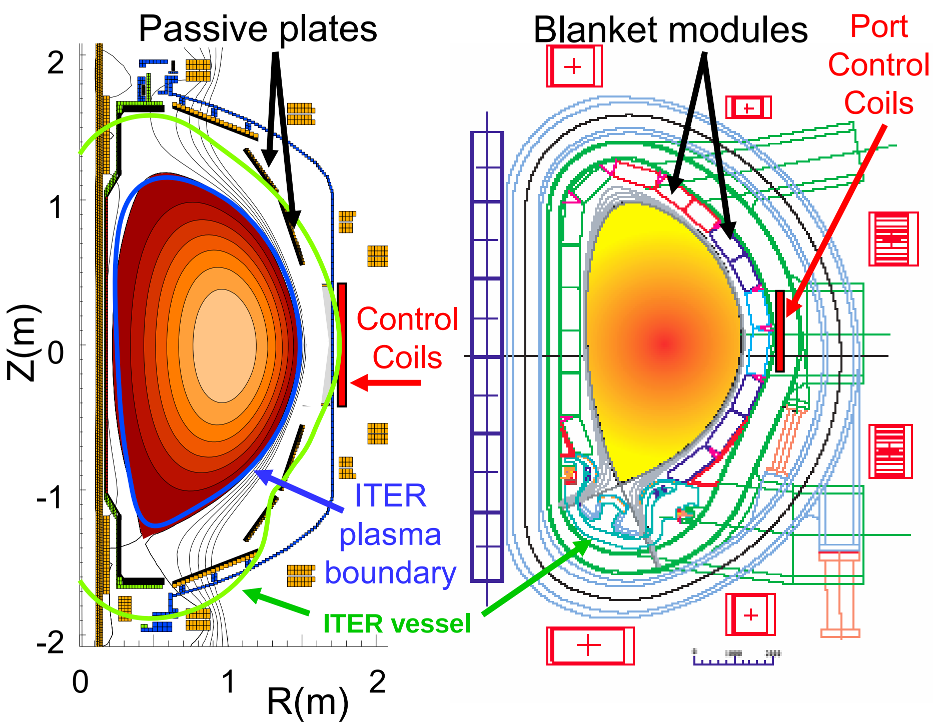
$$RFA = \frac{B_{plasma}}{B_{applied}}$$

- Applied field phased to create traveling wave in toroidal direction
- Peak in RFA shifted in the direction of plasma flow
  - Peak near 30 Hz
  - Expected by RWM theory / experiment
    - Observed in DIII-D (H. Reimerdes, NF 45 (2005) 368.)

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

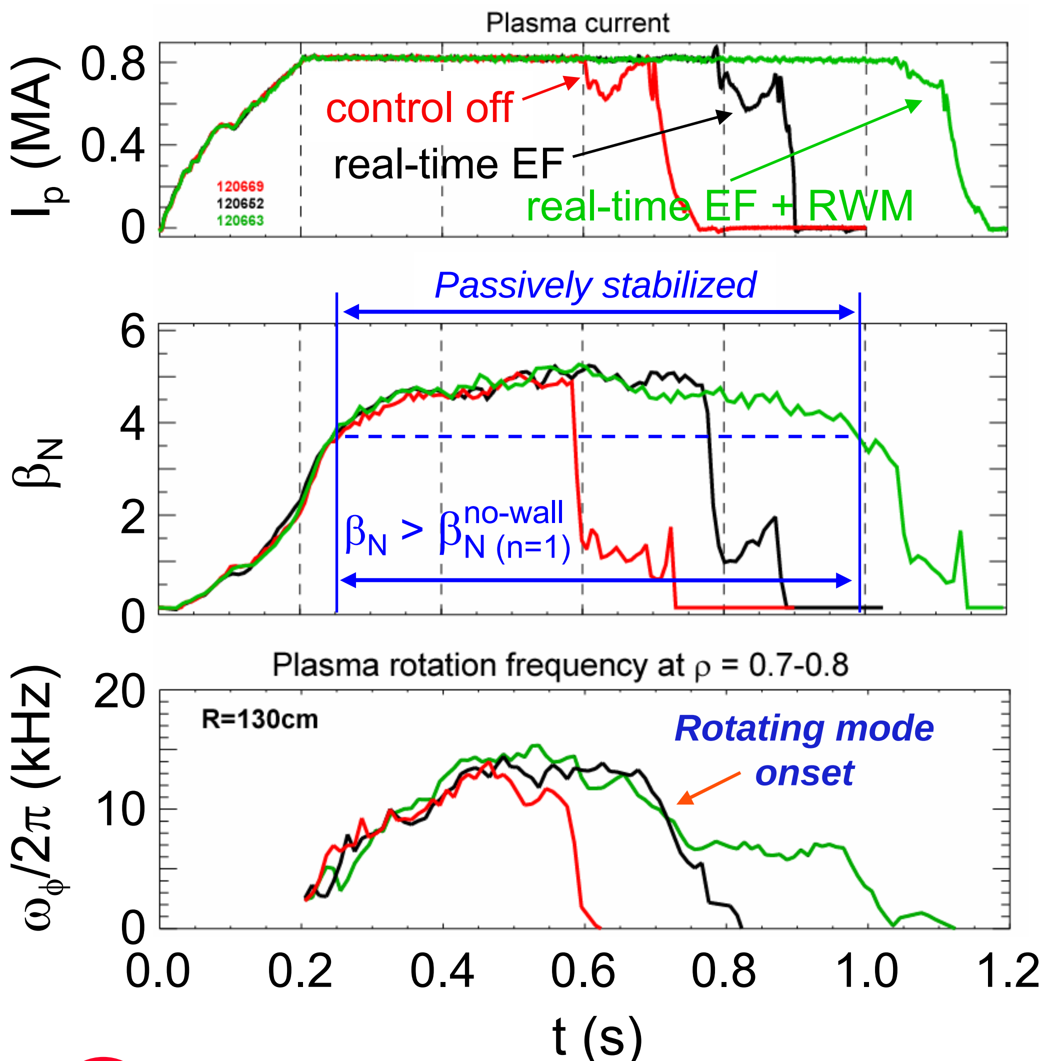
NSTX / ITER RWM control



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

NSTX

Dynamic error field correction increases pulse length by maintaining plasma rotation

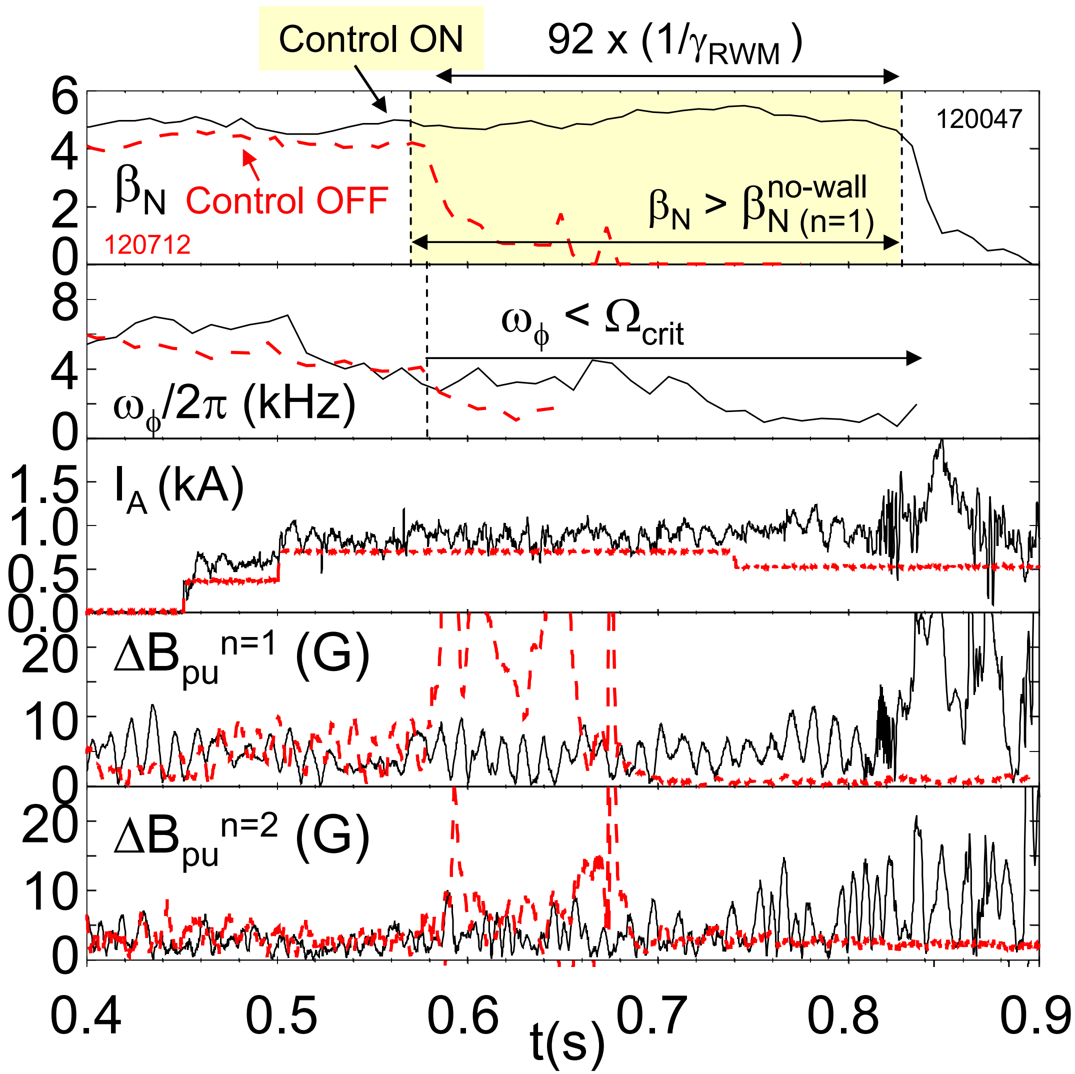


- Real-time correction of known error field (EF)
  - yields higher rotation
  - yields longer pulse
- Combined real-time EF correction + n = 1 RWM feedback yielded best result
  - Toroidal rotation, ω_ϕ, increase or saturation at long pulse lengths - first time for NSTX

J. Menard, APS 2006

NSTX

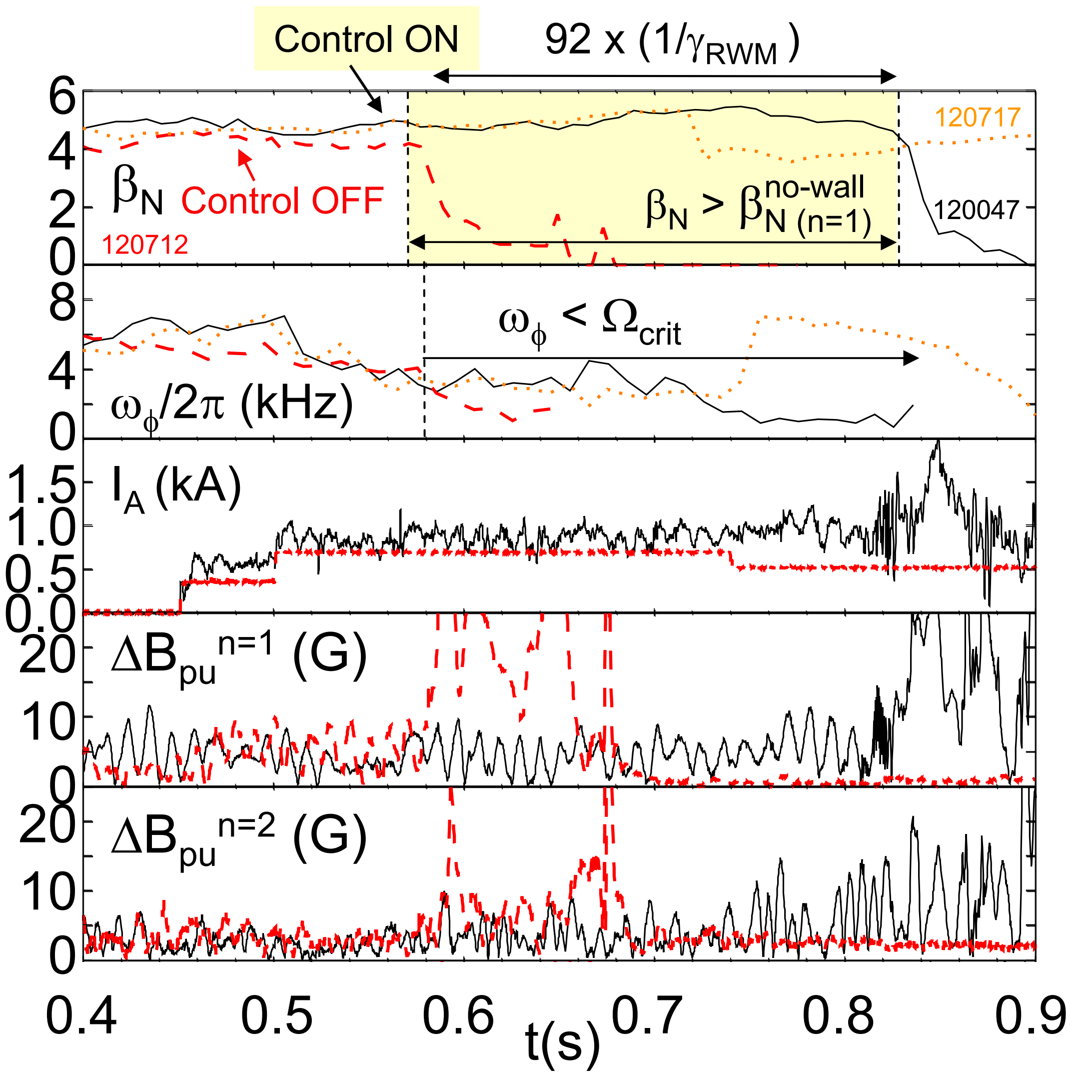
RWM actively stabilized at low, ITER-relevant rotation



- First such demonstration in low A tokamak
  - Long duration > $90/\gamma_{RWM}$
  - Exceeds DCON $\beta_N^{no-wall}$ 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.)

RWM actively stabilized at low, ITER-relevant rotation



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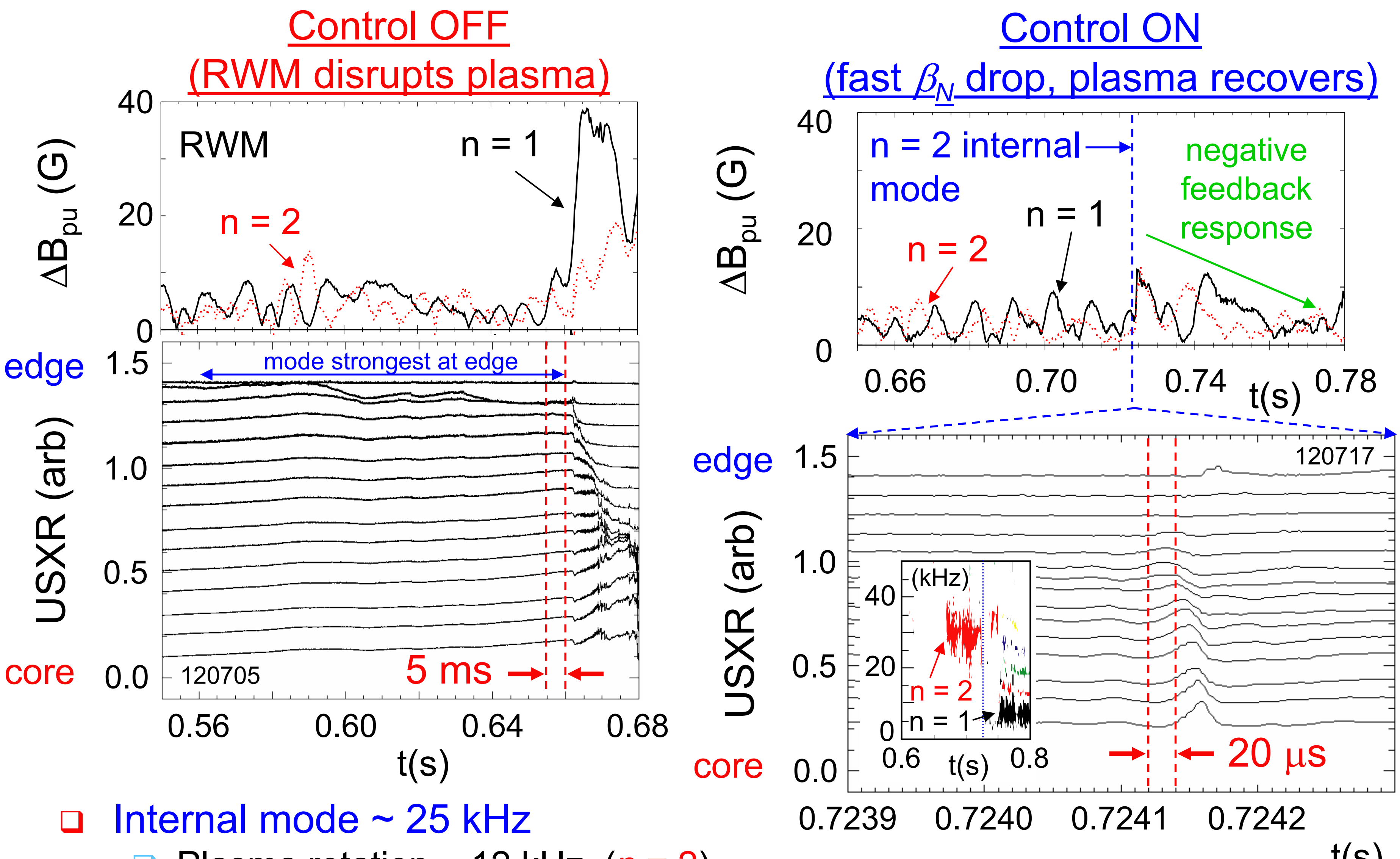
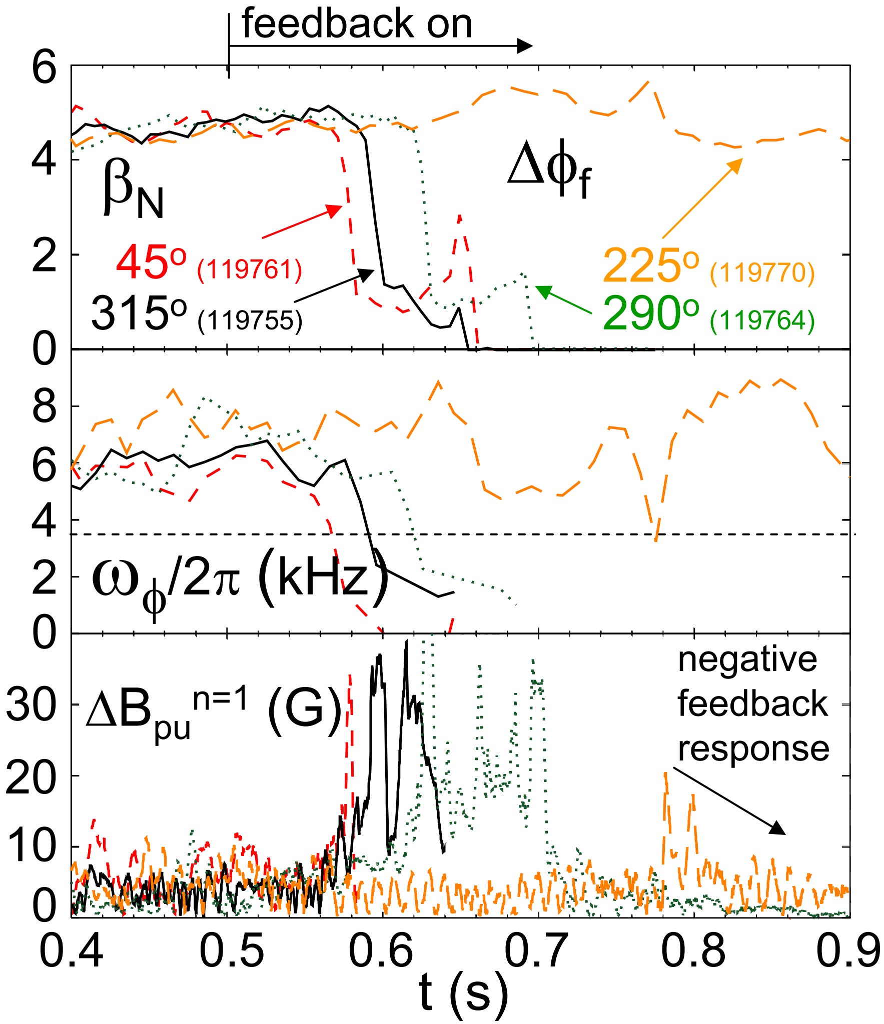
NSTX

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



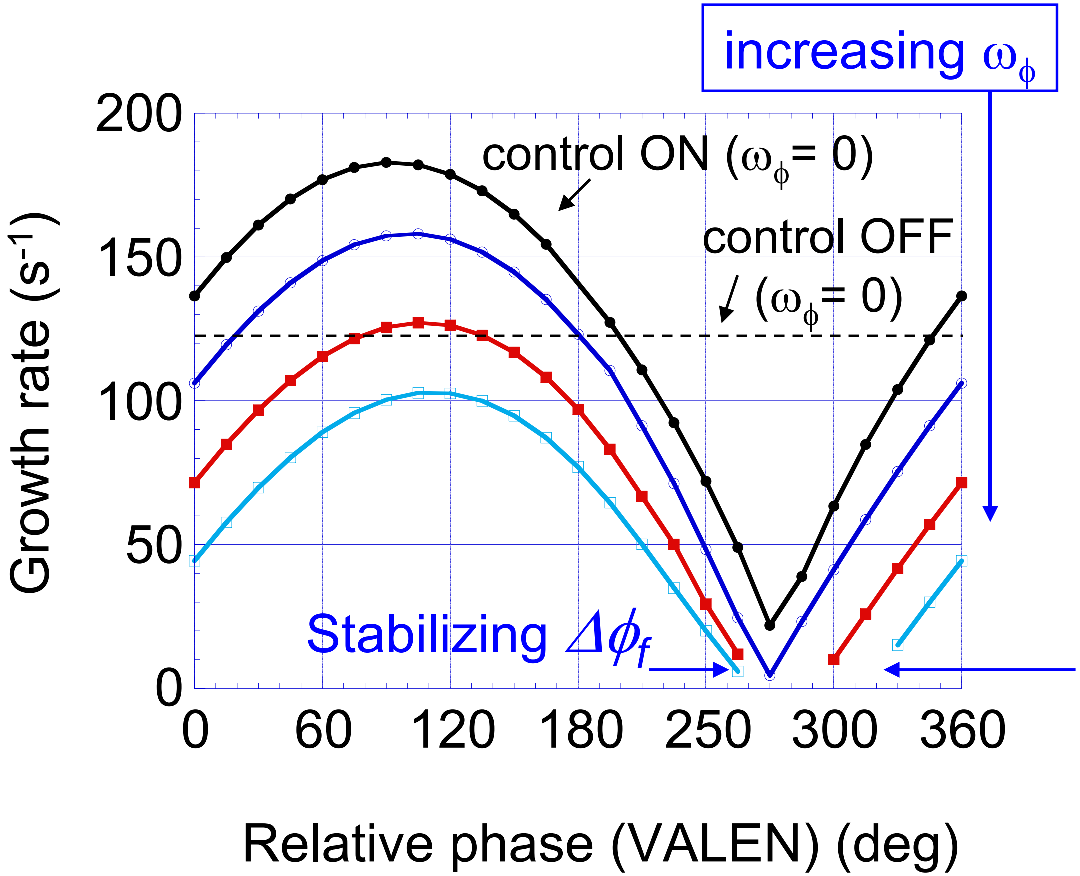
- Internal mode ~ 25 kHz
  - Plasma rotation ~ 12 kHz (n = 2)

Varying relative phase shows positive/negative feedback



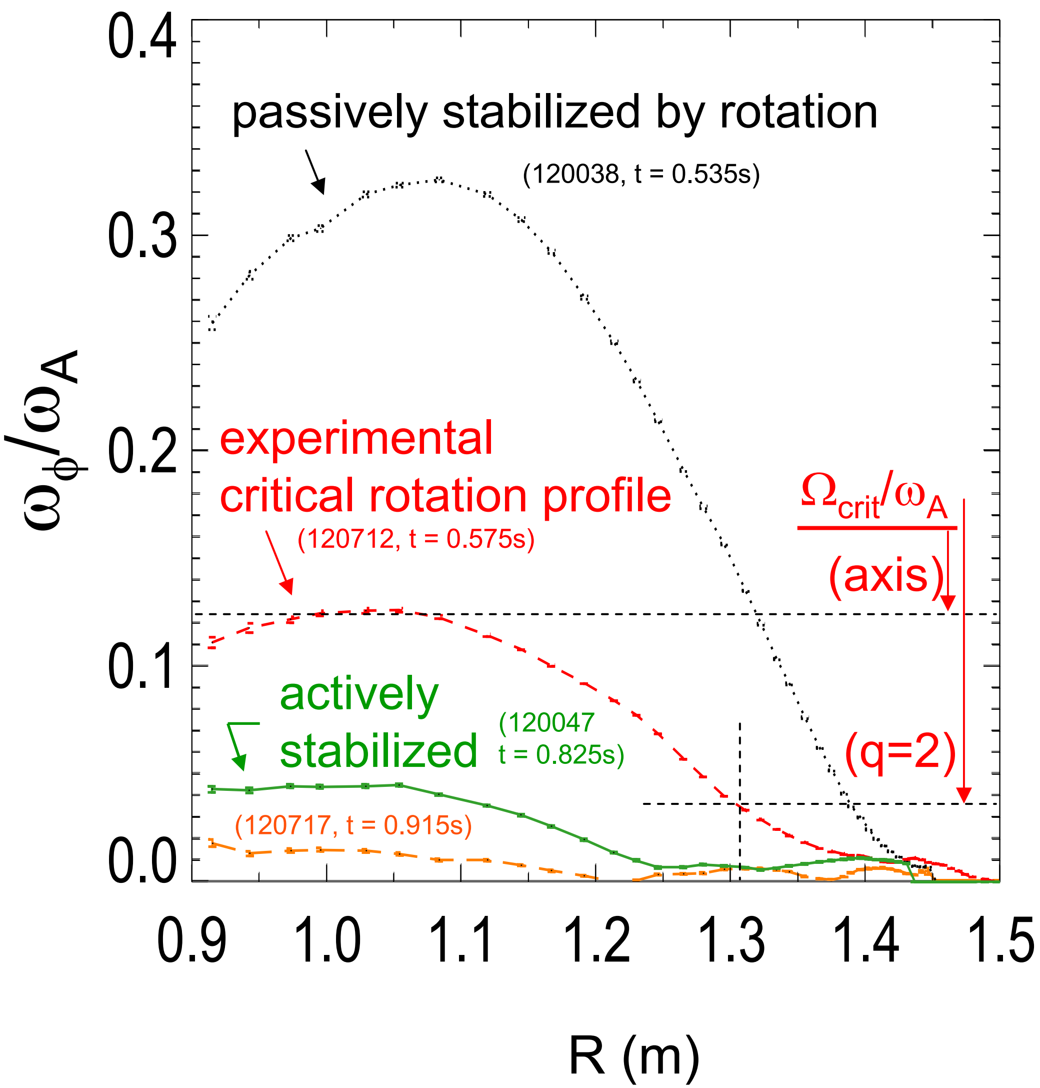
- Feedback on n = 1 RWM
  - Control current has relative phase $\Delta\phi_f$ to measured ΔB_p
- Phase scan shows superior settings for negative feedback
  - Pulse length increases
  - Internal plasma mode seen at $\Delta\phi_f$ = 225°, damped feedback system response
- Gain scan also performed
  - Sufficiently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

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



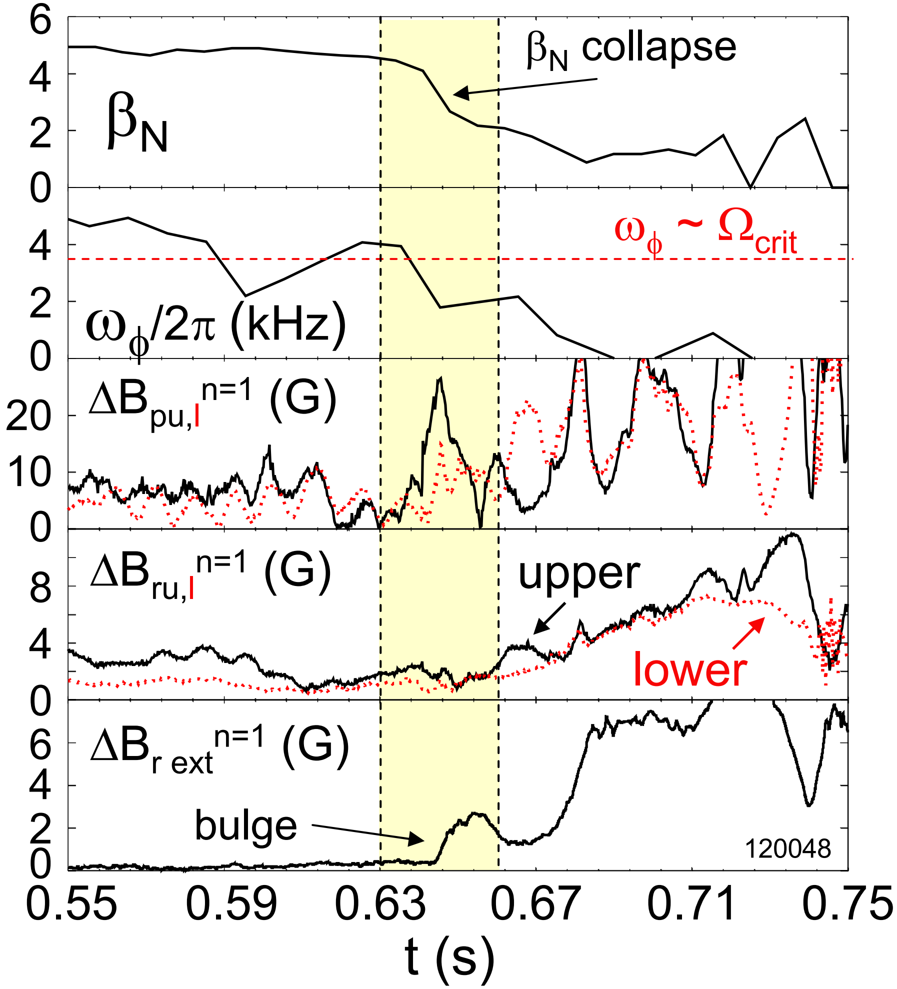
- First VALEN analysis with both active and passive stabilization ($\omega_\phi > 0$)
- Unfavorable $\Delta\phi_f$ drives mode growth
- Stable range of $\Delta\phi_f$ increases with increasing ω_ϕ
- Optimal $\Delta\phi_f$ for active stabilization at $\omega_\phi = 0$ bracketed by results with $\omega_\phi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

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

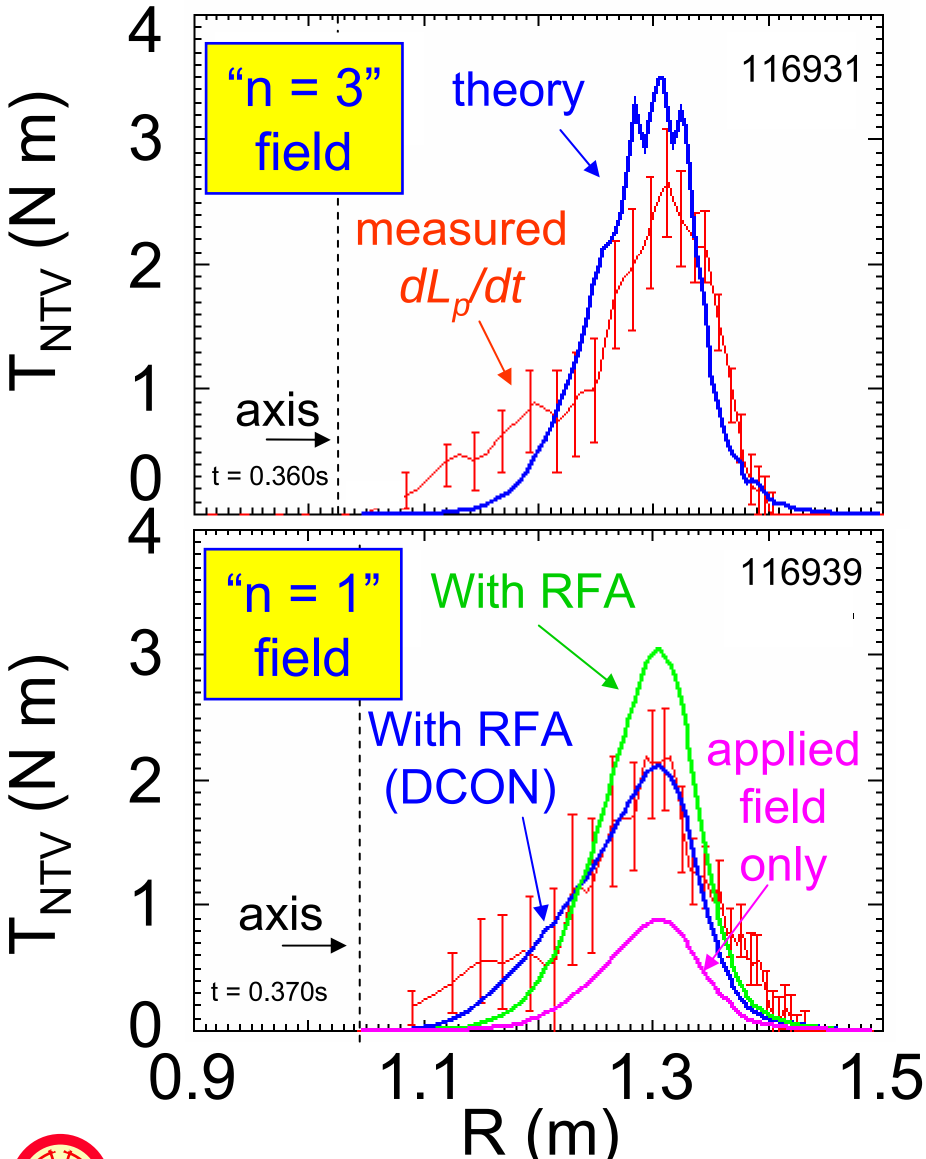
RWM may change form and grow during active control



- 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 (multimode analysis next step)

Future research will assess using combined sensors for optimization

Observed rotation decrease follows NTV theory

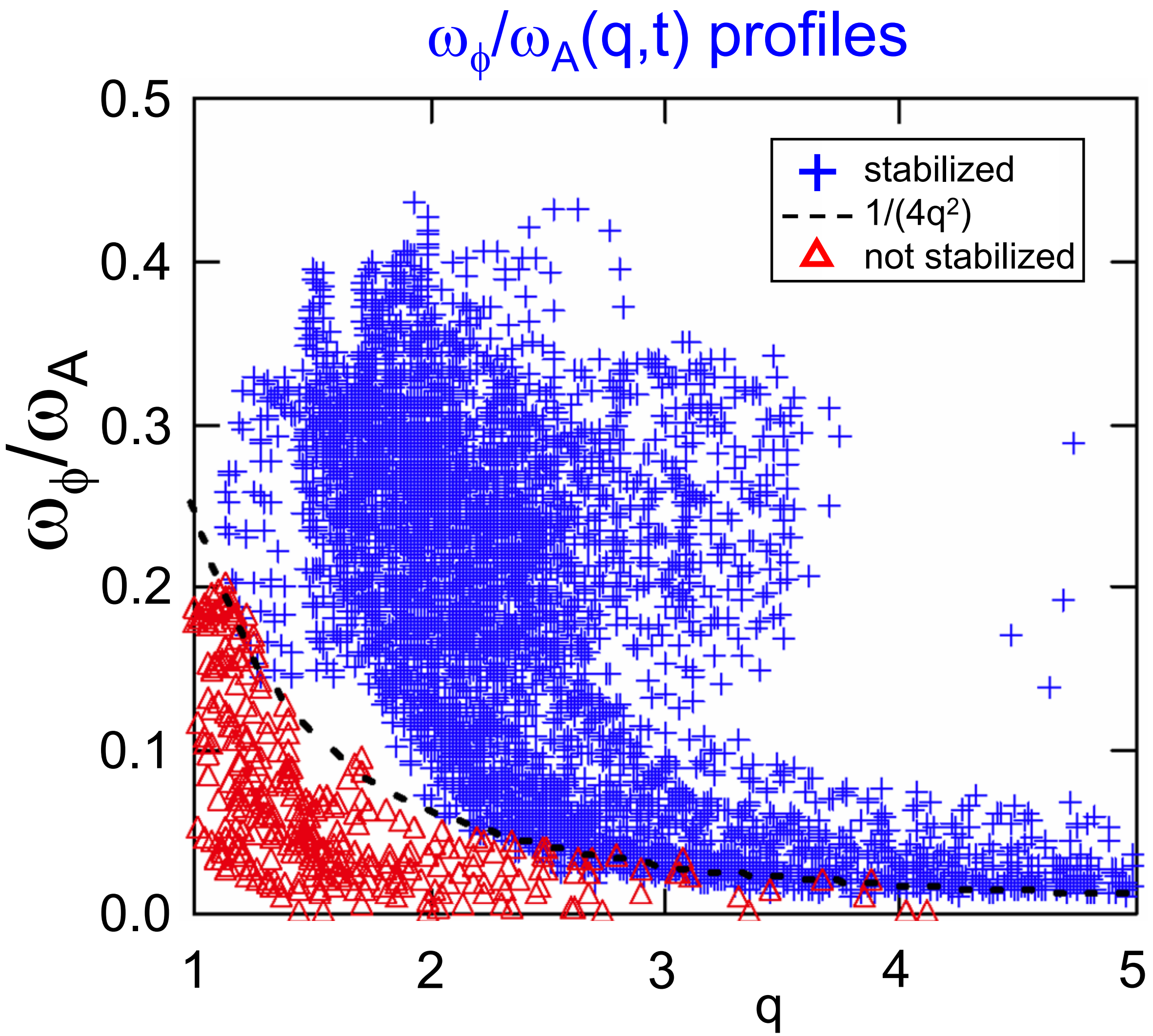


- First quantitative agreement using full neoclassical toroidal viscosity theory (NTV) (K.C. Shaing, UW)
  - Due to plasma flow through non-axisymmetric field
  - Computed using experimental equilibria
  - Trapped particle effects, 3-D field spectrum important
- Viable physics for simulations of plasma 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

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

Experimental Critical Rotation Frequency for RWM passive stabilization, Ω_{crit}, follows Bondeson-Chu theory

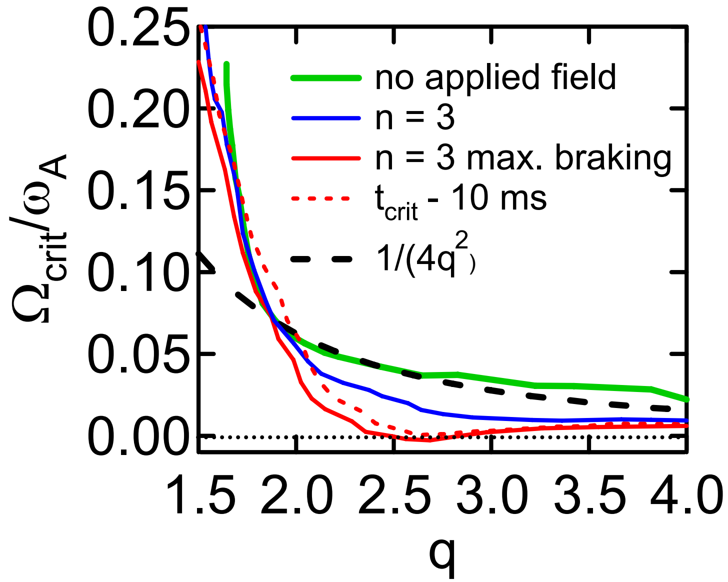
Phys. Plasmas **8** (1996) 3013

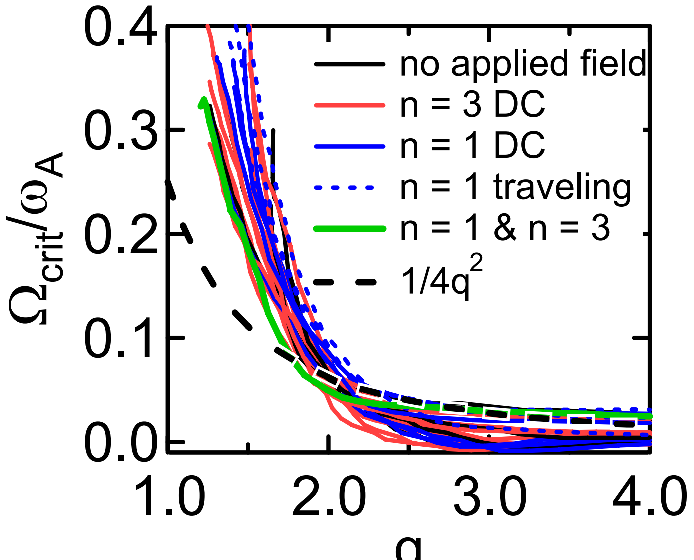


- Experimental Ω_{crit}
  - stabilized profiles: $\beta > \beta_N^{no\text{-}wall}$ (DCON)
  - profiles not stabilized cannot maintain $\beta > \beta_N^{no\text{-}wall}$
  - regions separated by $\omega_\phi/\omega_A = 1/(4q^2)$
- Drift Kinetic Theory
  - Trapped particle effects significantly weaken stabilizing ion Landau damping
  - Toroidal inertia enhancement more important
    - Alfven wave dissipation yields $\Omega_{crit} = \omega_A/(4q^2)$

RWM critical rotation profile shape can be altered

- Benchmark profile for stabilization is $\omega_c = \omega_A/4q^2$ *
- n = 1,3 braking used to reduce rotation
- 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
  - investigating trapped particle precession as stabilization physics at low rotation (B. Hu and R. Betti, PRL **93** (2004) 105002.)



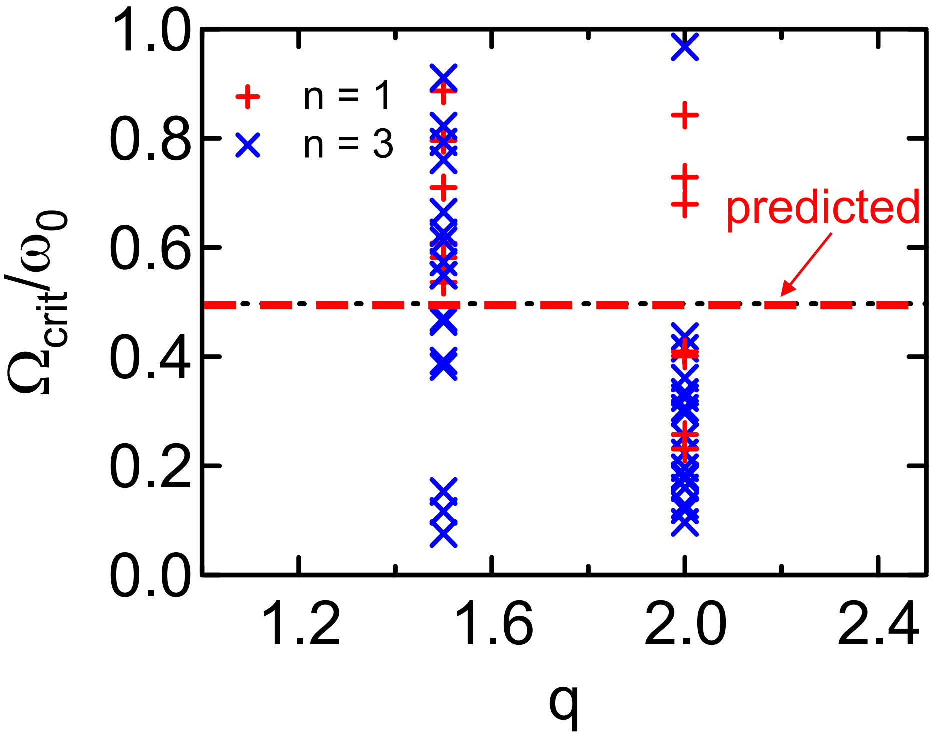


*A.C. Sontag, et al., Phys. Plasmas **12** (2005) 056112.
*A. Bondeson, M.S. Chu, Phys. Plasmas **3** (1996) 3013.

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)

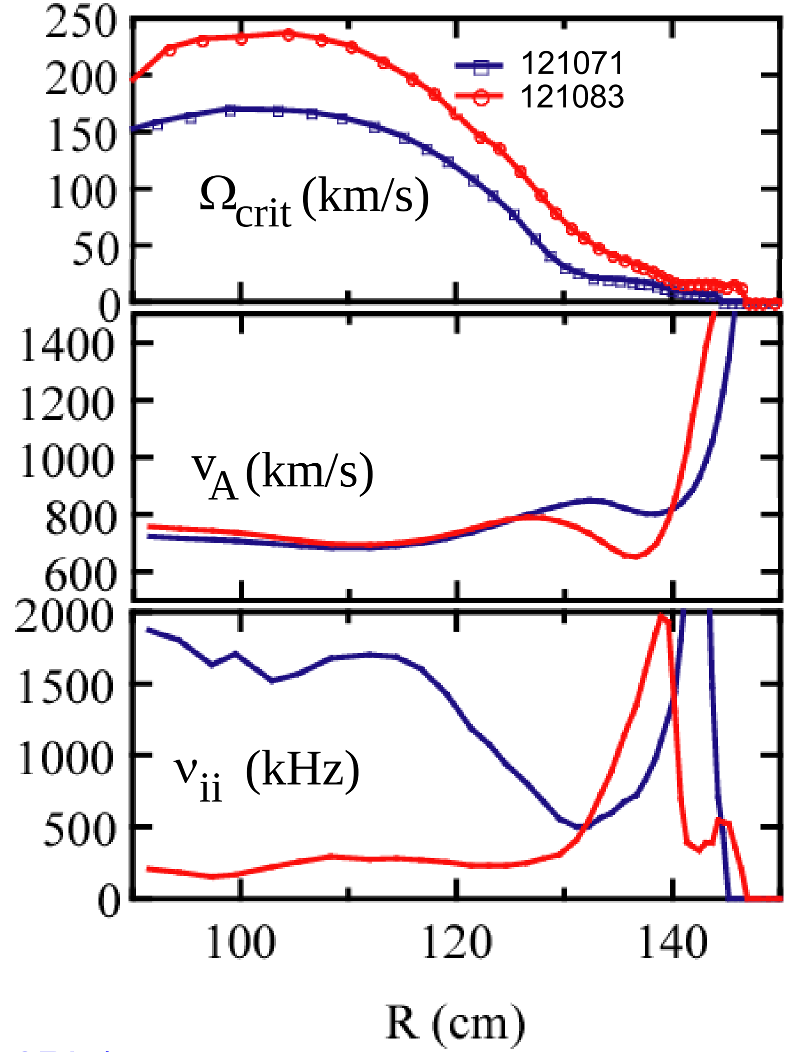
A.C. Sontag, IAEA 2006 paper EX/7-2Rb.

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

Increased Ion Collisionality Leads to Decreased Ω_{crit}

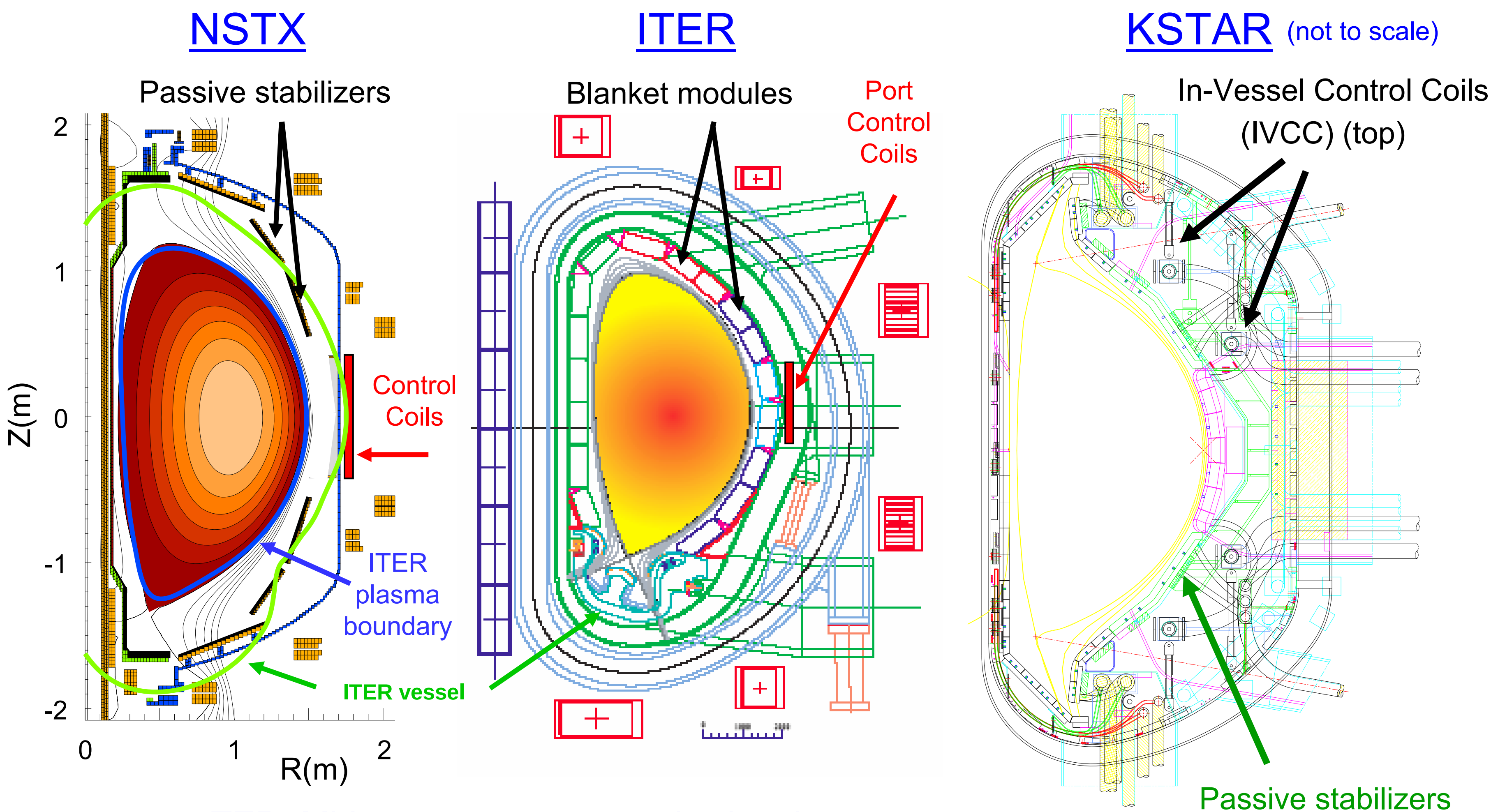
- Plasmas with similar v_A
- Consistent with neoclassical viscous dissipation model
  - at low γ, increased ν_i leads to lower Ω_{crit}
    (K. C. Shaing, Phys. Plasmas **11** (2004) 5525.)
- ITER plasmas with lower ν_i may require higher degree of RWM active stabilization

Future research aims to uncover critical RWM stabilization physics to confidently scale to new devices (NSTX FY09 Milestone)



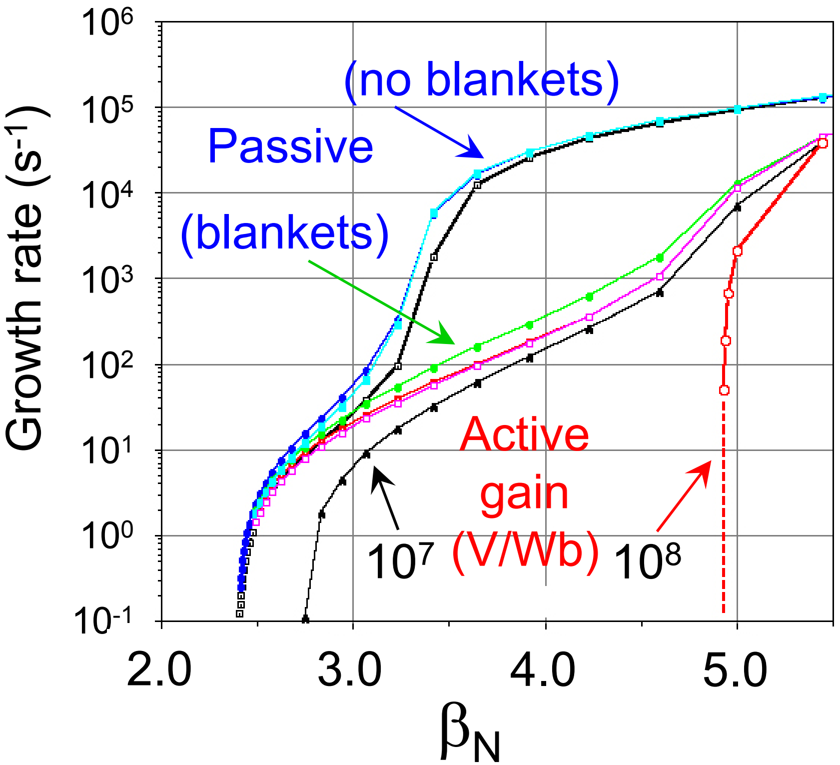
(Sontag, et al., IAEA FEC 2006 paper EX/7-2Rb.)

NSTX RWM stabilization research applied to next-step tokamaks

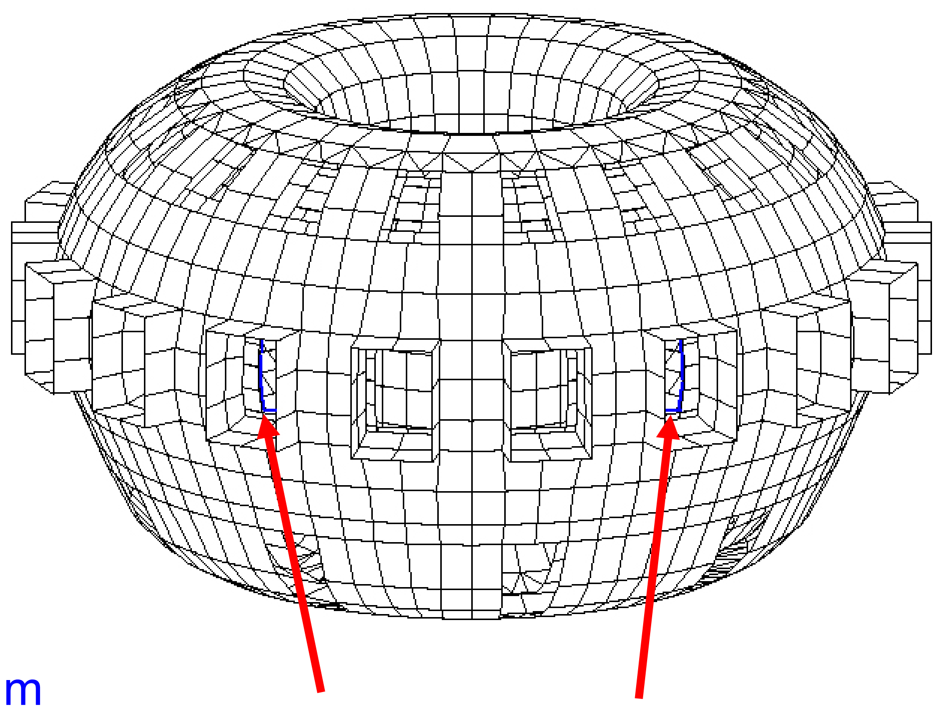


- ITER: Midplane port control coils, blanket
- KSTAR: Midplane control coil, passive plate geometry with midplane gap

ITER active coil modification can significantly raise stable β_N



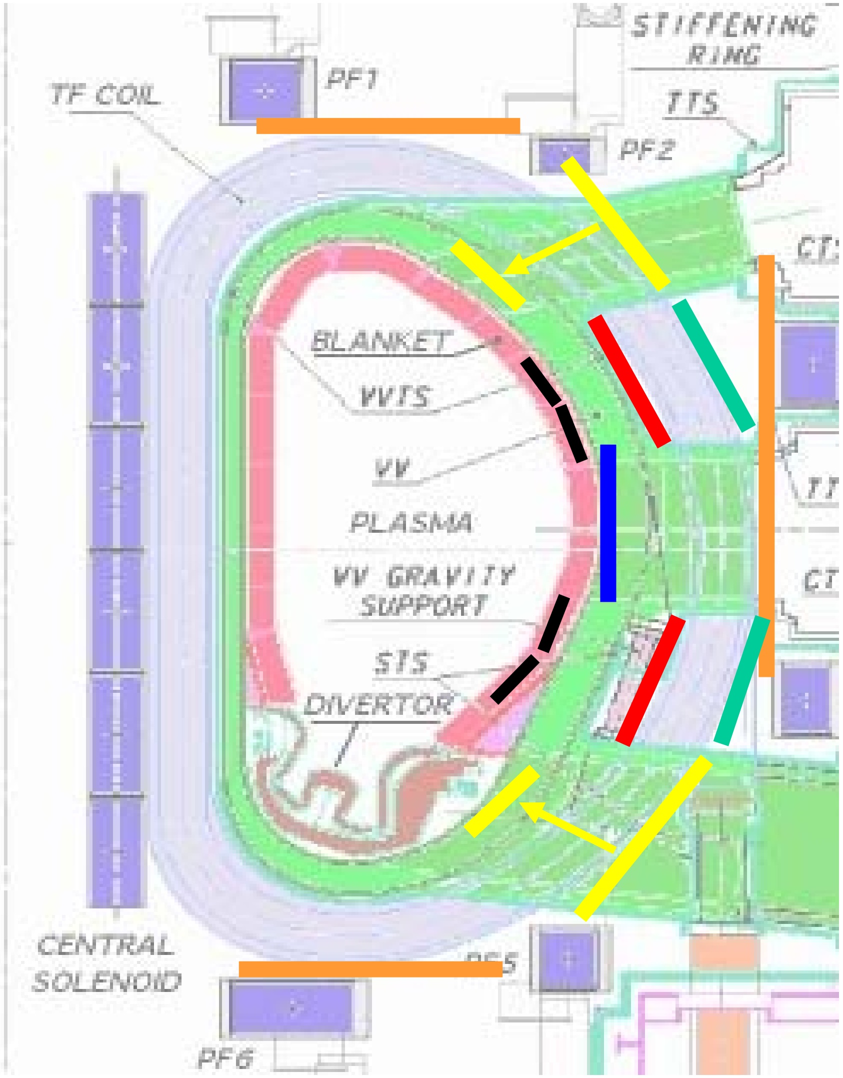
VALEN dual-wall vessel / blanket model
(full view)



Active feedback coil modification
(coils in ports)

- Original external coil design for ITER stabilizes up to β_N = 2.7
- Proposed improvement raises maximum stable β_N to near 5
- Dual-wall vacuum vessel and blanket used in VALEN model

ITER non-axisymmetric coil designs being studied by USBPO for combined ELM, RWM, error field control



J. Menard, USBPO MHD group leader

- RWM: G. Navratil, J. Bialek (CU)
- ELM: T. Evans (GA)
- Error field: M. Schaffer (GA)

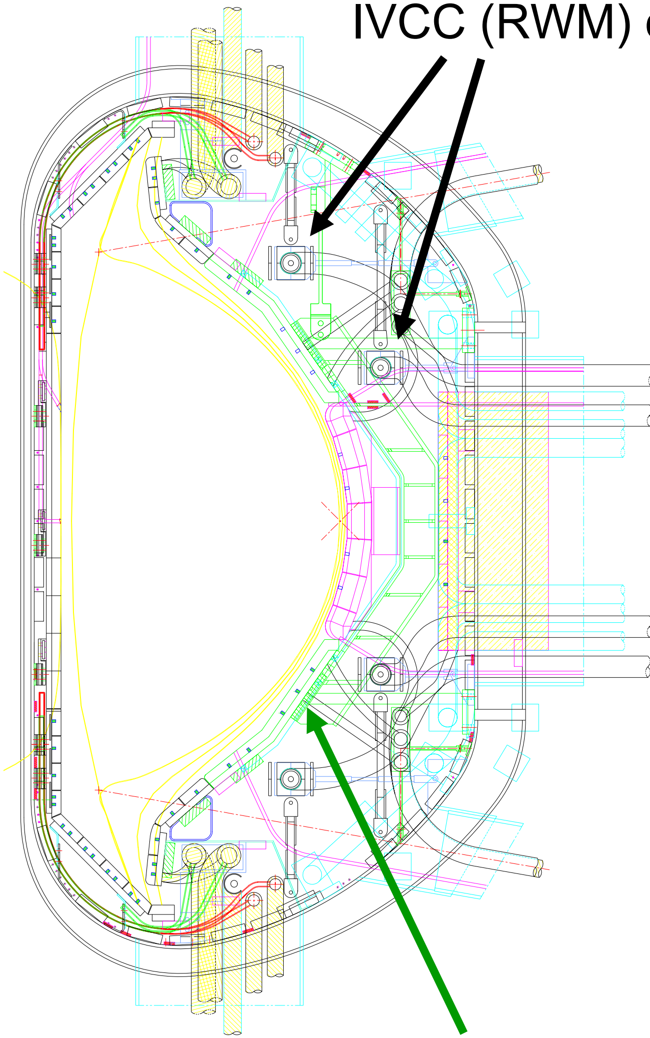
Coil position considerations

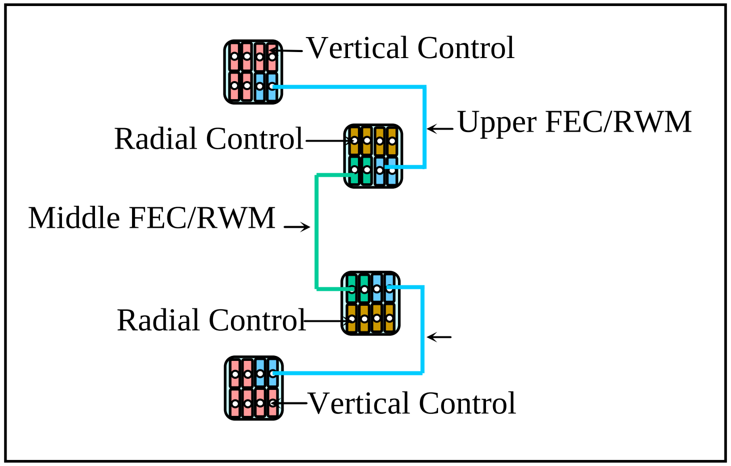
1. **Present error field correction coils**
2. **Mid-plane port-plug RWM coils**
3. ~~**ELM coils on vessel, inside TF**~~
4. **ELM coils in blanket modules**
5. **ELM coils on TF, near mid-plane**
6. **ELM coils on upper/lower ports**

Extension of work performed by M. Becoulet (CEA), et al. presented at IAEA-FEC 2006: Paper IT/P1-29

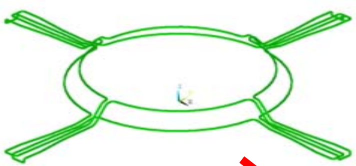
KSTAR active stabilization system now modeled

IVCC (RWM) coils

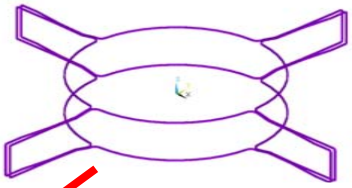


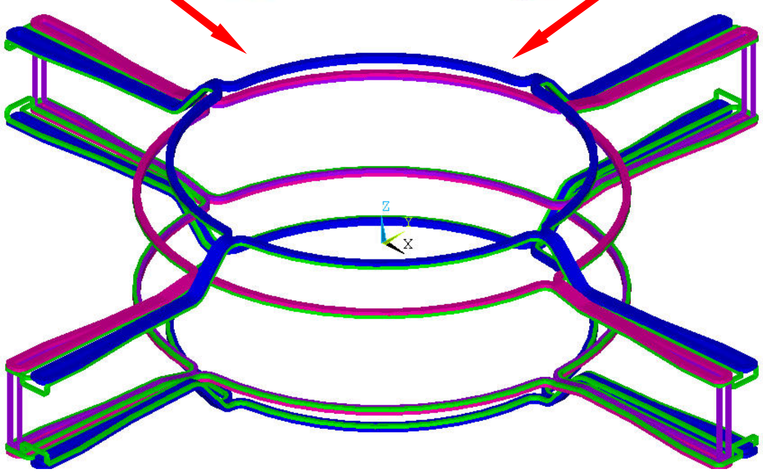


top IVCC (RWM) coil



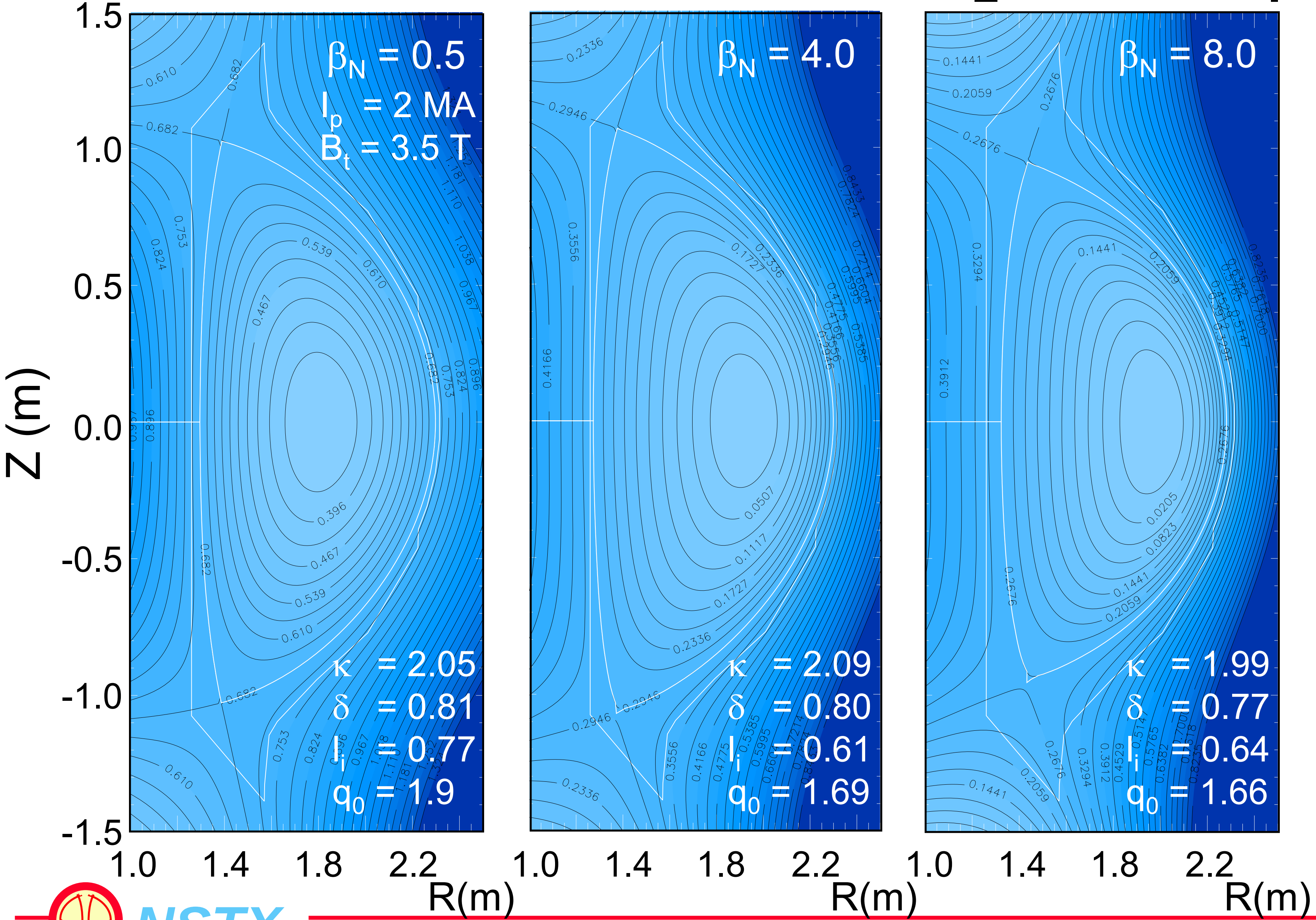
middle IVCC (RWM) coil



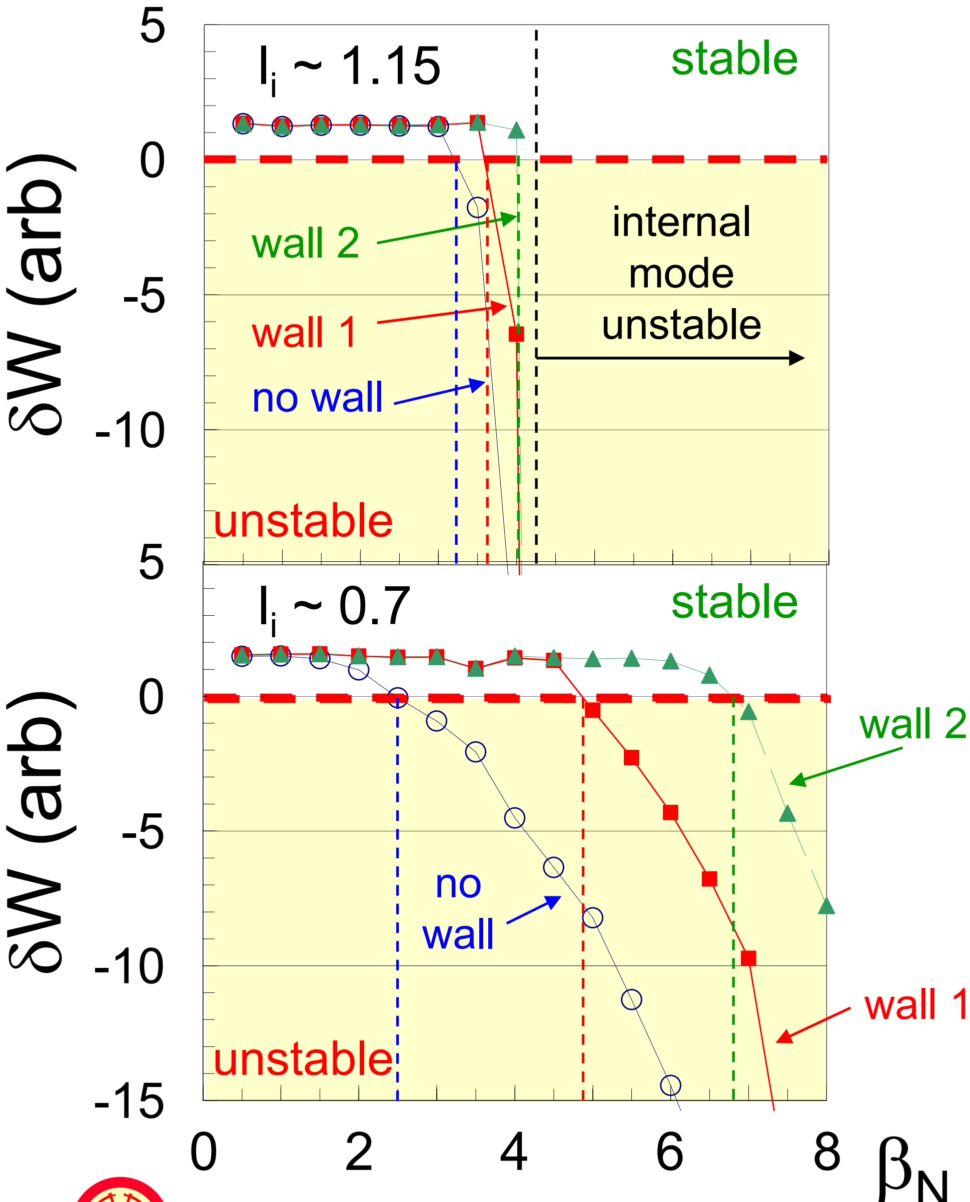


Passive stabilizer (bottom)

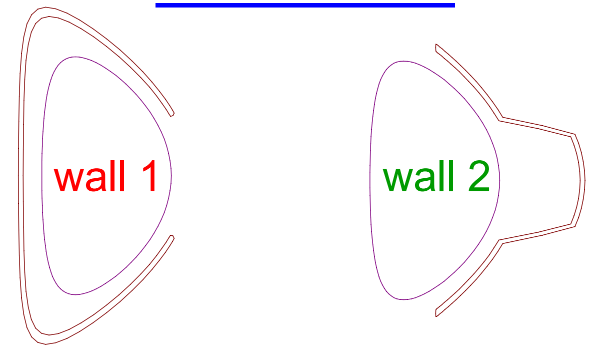
KSTAR flux contours and parameters for β_N scan at low l_i



KSTAR equilibrium has large wall-stabilized region at low l_i



walls used

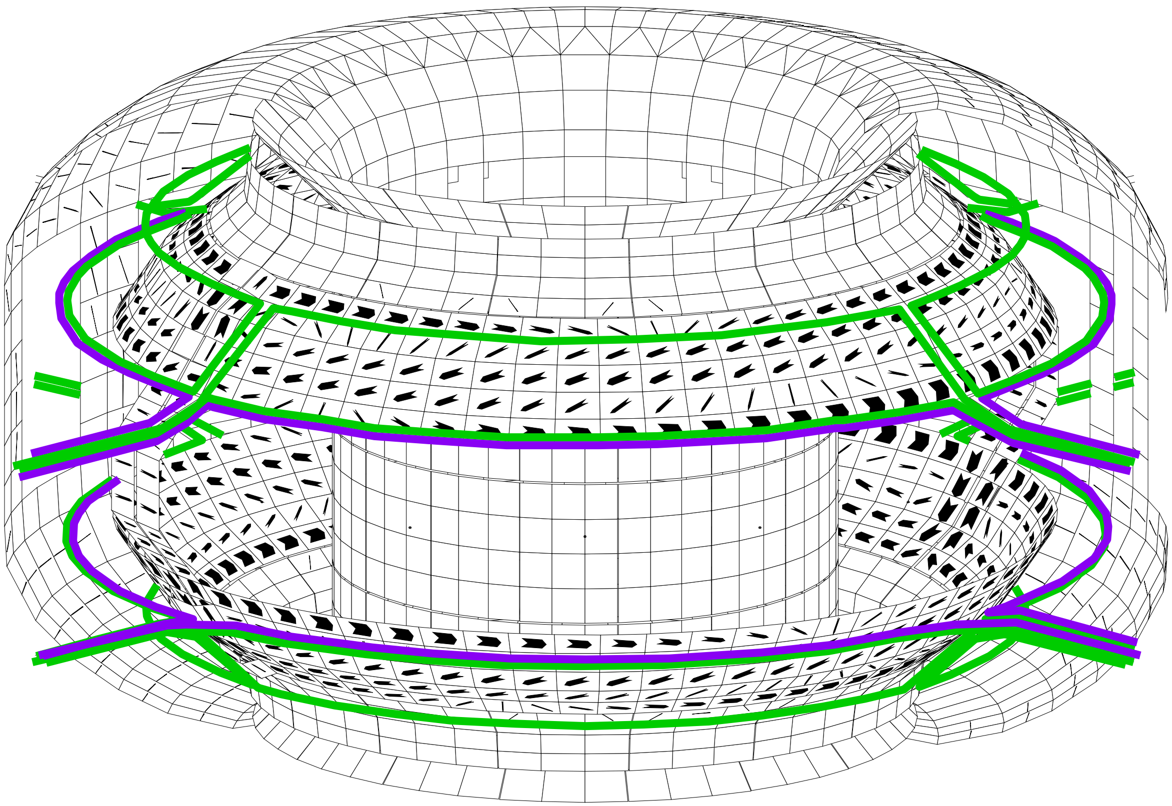


- High l_i: narrow stability window
  - No-wall β_N limit = 3.2
  - With-wall β_N limit = 3.6 – 4.0
  - Internal mode β_N limit = 4.3
- Low l_i: wide stability window
  - No-wall β_N limit = 2.5
  - With-wall β_N limit = 4.85 – 6.8

(DCON: A.H. Glasser, LANL)

KSTAR configuration set up in VALEN-3D

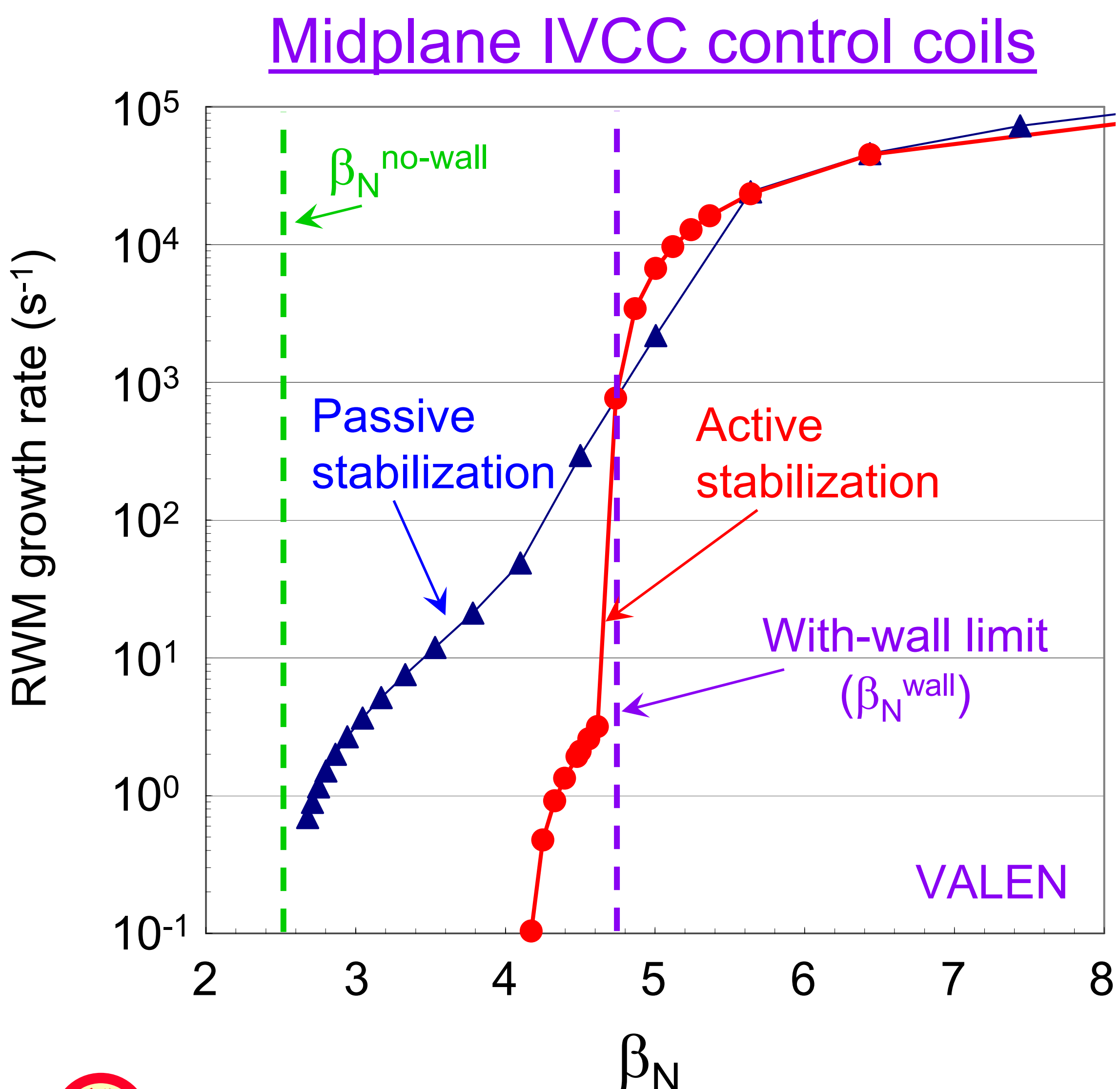
n = 1 RWM passive stabilization currents



IVCC (RWM) control coils
(upper,middle,lower)

- Conducting hardware modeled
  - Vacuum vessel
  - Center stack backplates
  - Divertor backplates
  - Passive stabilizer (PS)
  - PS Current bridge
- Stabilization currents dominant in SP
  - 40 times less resistive than nearby conductors

Active control may sustain 73% margin above $\beta_N^{no\text{-}wall}$



- Slow mode sets actively stabilized C_β = 0.73 in low l_i equilibria
  - Stabilized to β_N = 4.17
  - Passive growth time of 15 ms at β_N = 4.2
  - Active feedback gain not optimized
- Computed β_N limits
  - $\beta_N^{no\text{-}wall}$ = 2.56
  - β_N^{wall} = 4.76

Future study to optimize and implement advanced control algorithms

$$C_\beta \equiv \frac{(\beta_N - \beta_N^{no\text{-}wall})}{(\beta_N^{wall} - \beta_N^{no\text{-}wall})}$$

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

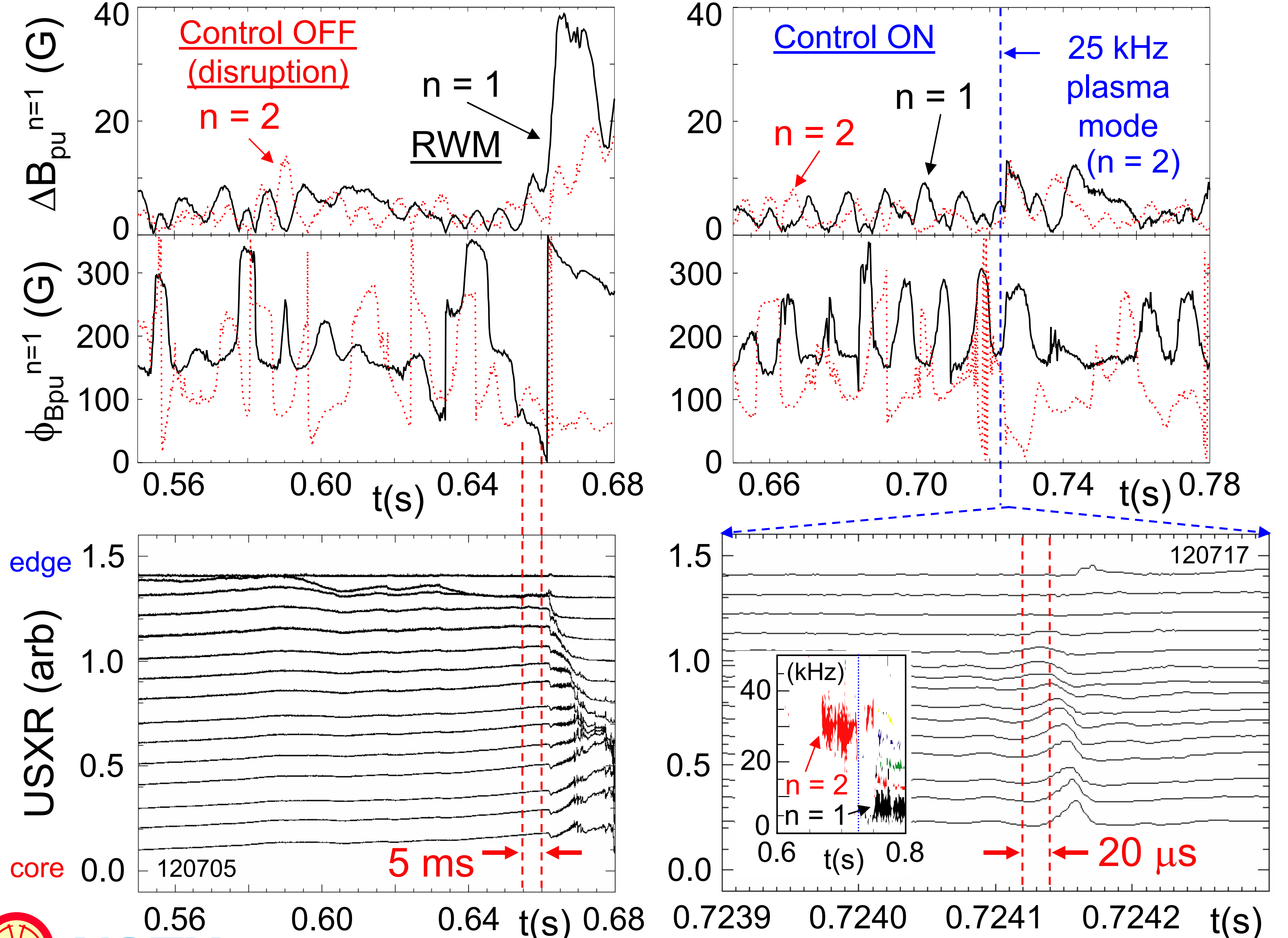
- First demonstration of RWM active stabilization in high β, low A tokamak plasmas with ω_ϕ significantly less than Ω_{crit}
  - In the predicted range of ITER
  - Positive and negative RWM feedback demonstrated by varying feedback gain and relative phase
- Stability of n = 2 RWM observed during n = 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

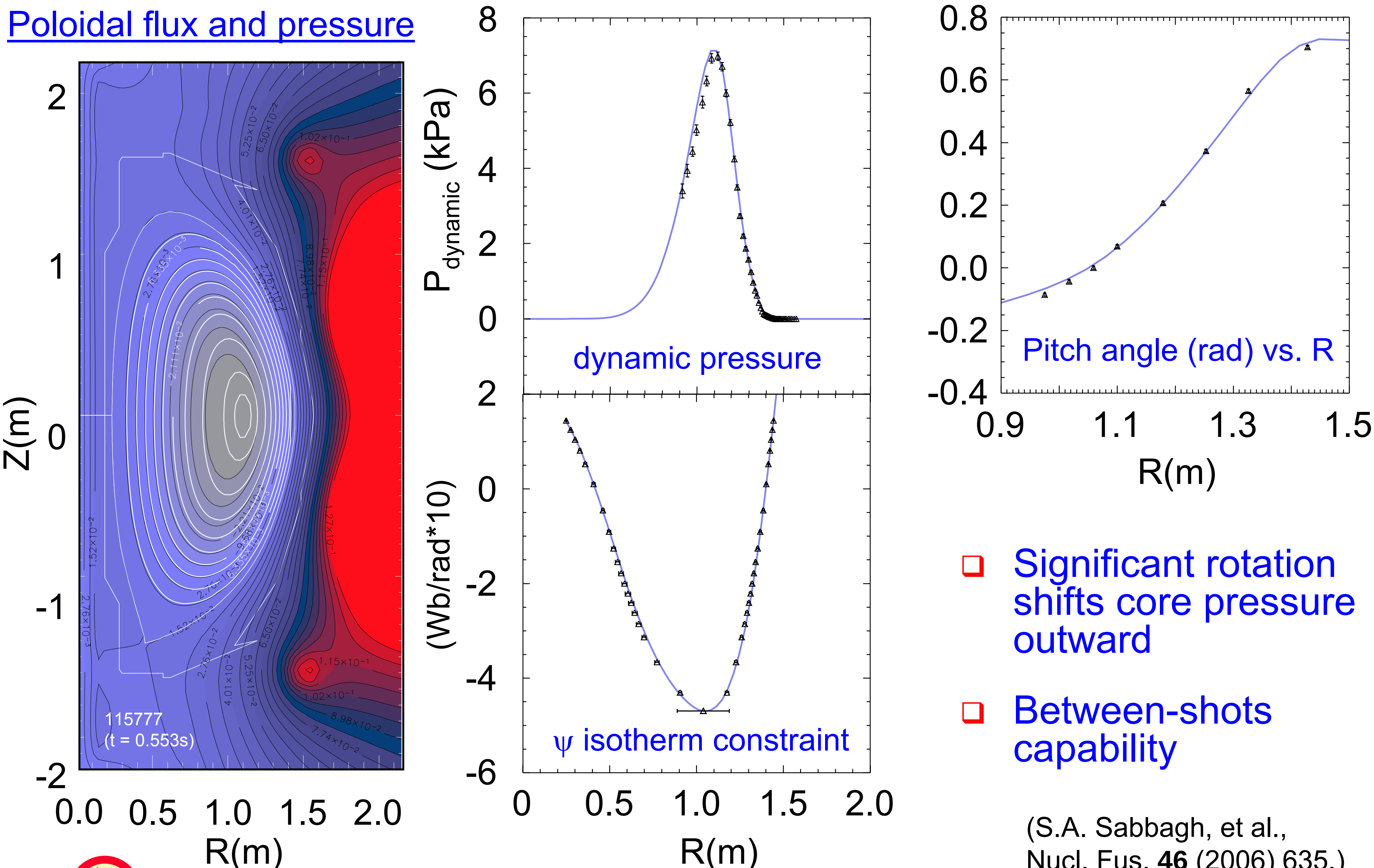
- Agreement does not yet exist regarding Ω_{crit}, RWM stabilization physics in low-rotation tokamak plasmas
- Observed inverse dependence of Ω_{crit} on ν_i indicates lower ITER collisionality may require a higher degree of RWM active stabilization
- Similar inverse dependence of plasma momentum dissipation 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



Plasma rotation, ψ-isotherm, MSE included in reconstructions



- Significant rotation shifts core pressure outward
- Between-shots capability

(S.A. Sabbagh, et al., Nucl. Fus. **46** (2006) 635.)