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

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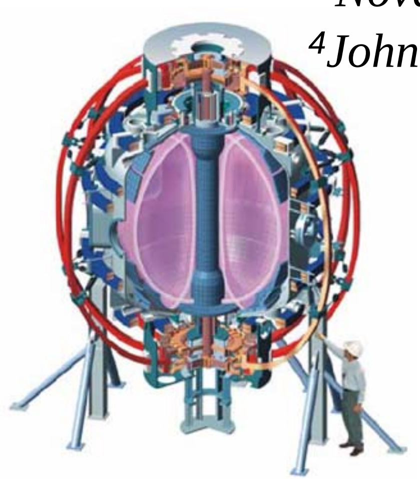

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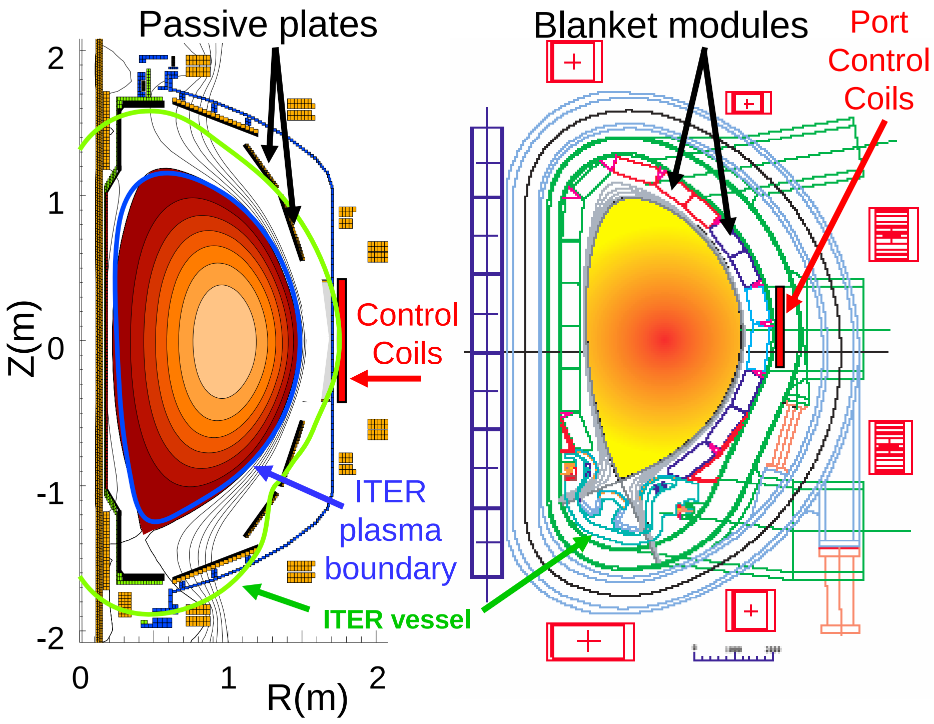
Experiments in 2006 examined RWM physics and stabilization at ITER-relevant rotation

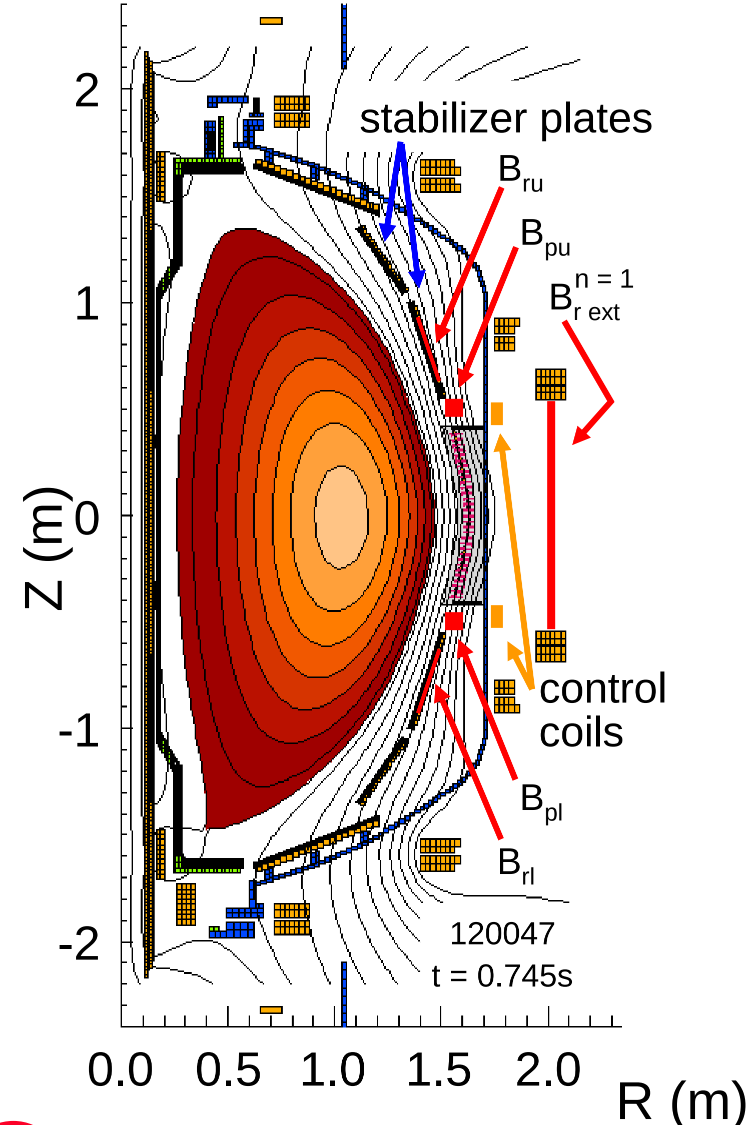
- RWM active stabilization
  - New control system installed
  - RWM control demonstrated
  - RWM actively stabilized in slowly rotating plasmas
- Plasma rotation control
  - Sustained rotation by real-time reduction of amplified error field
  - Reduced rotation by non-resonant magnetic braking

NSTX / ITER RWM control



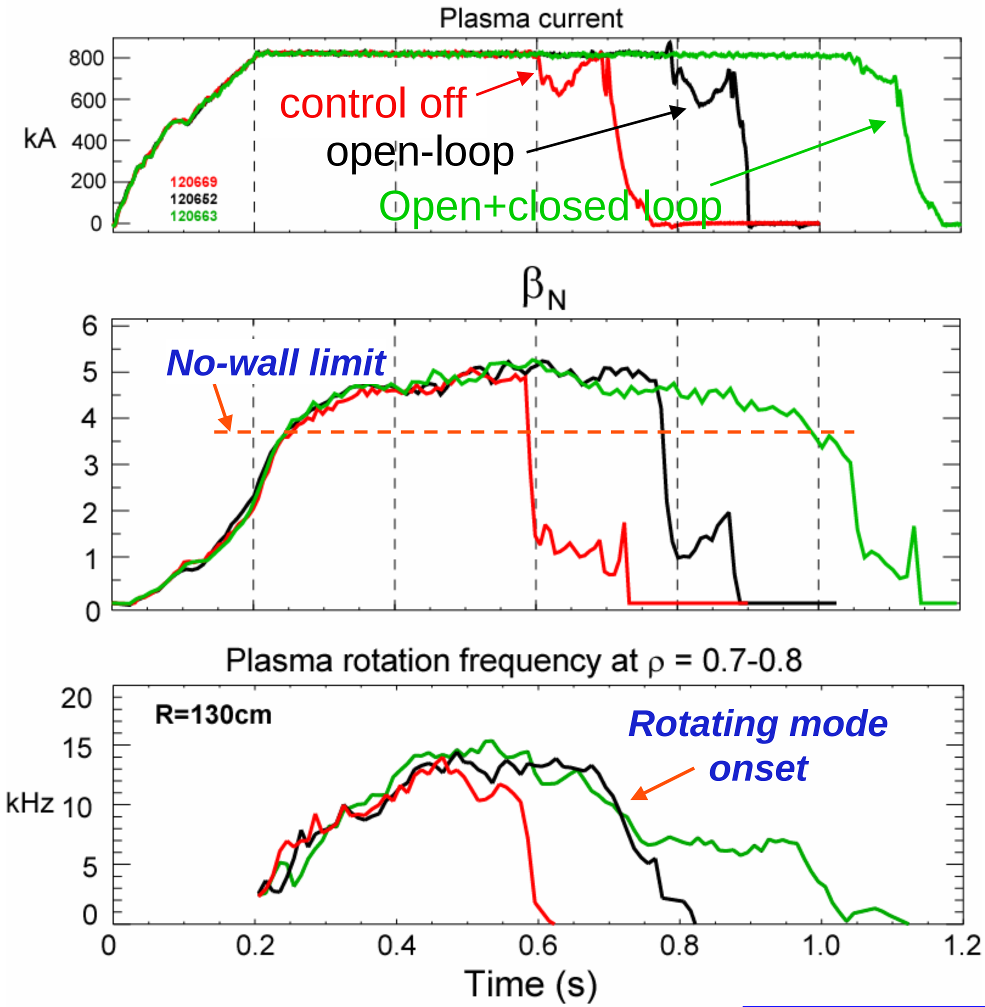
Advantage: low aspect ratio, high β provides high leverage to uncover key tokamak physics for ITER (e.g. RWM control, momentum dissipation)

RWM Active Feedback System Installed on NSTX



- Stabilizer plates for kink mode stabilization
- External midplane control coil closely coupled to vacuum vessel
  - Similar to ITER port plug designs
- 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 = 1active stabilization

Dynamic error field correction (DEFC) increases pulse length in strongly rotating plasmas

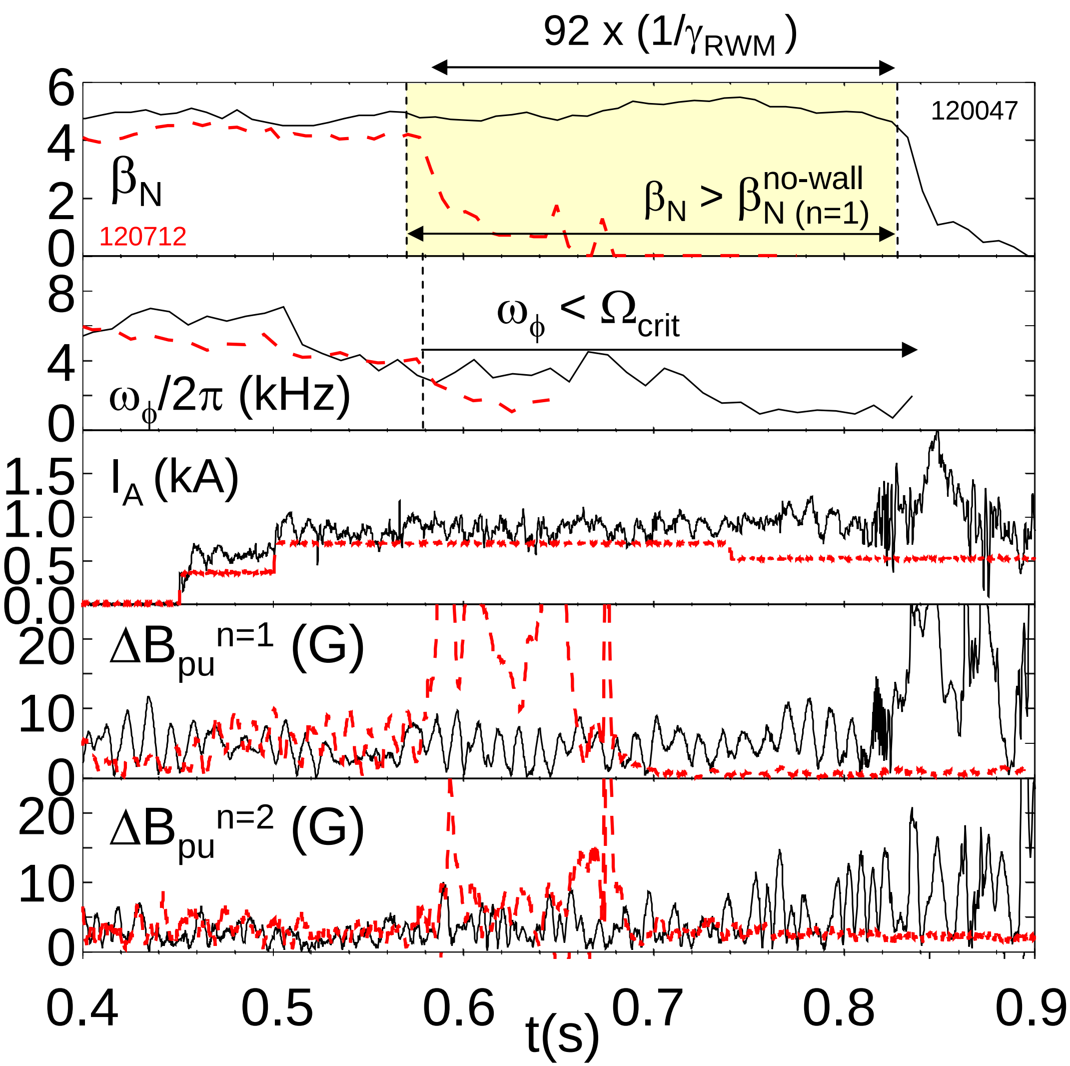


- Open-loop control of error field amplified by *stable* RWM
  - yields higher rotation
  - yields longer pulse
- Combination of open + closed loop control yielded best result
  - Rotation increase or saturation at long pulse lengths - first time in NSTX

see OV/2-4 Menard

NSTX

RWM stabilized at ITER-relevant rotation for ~ 90/γ_{RWM}



- First such demonstration in low A tokamak
  - 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
    - Multi-mode research – connection to RWM stabilization in RFPs

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

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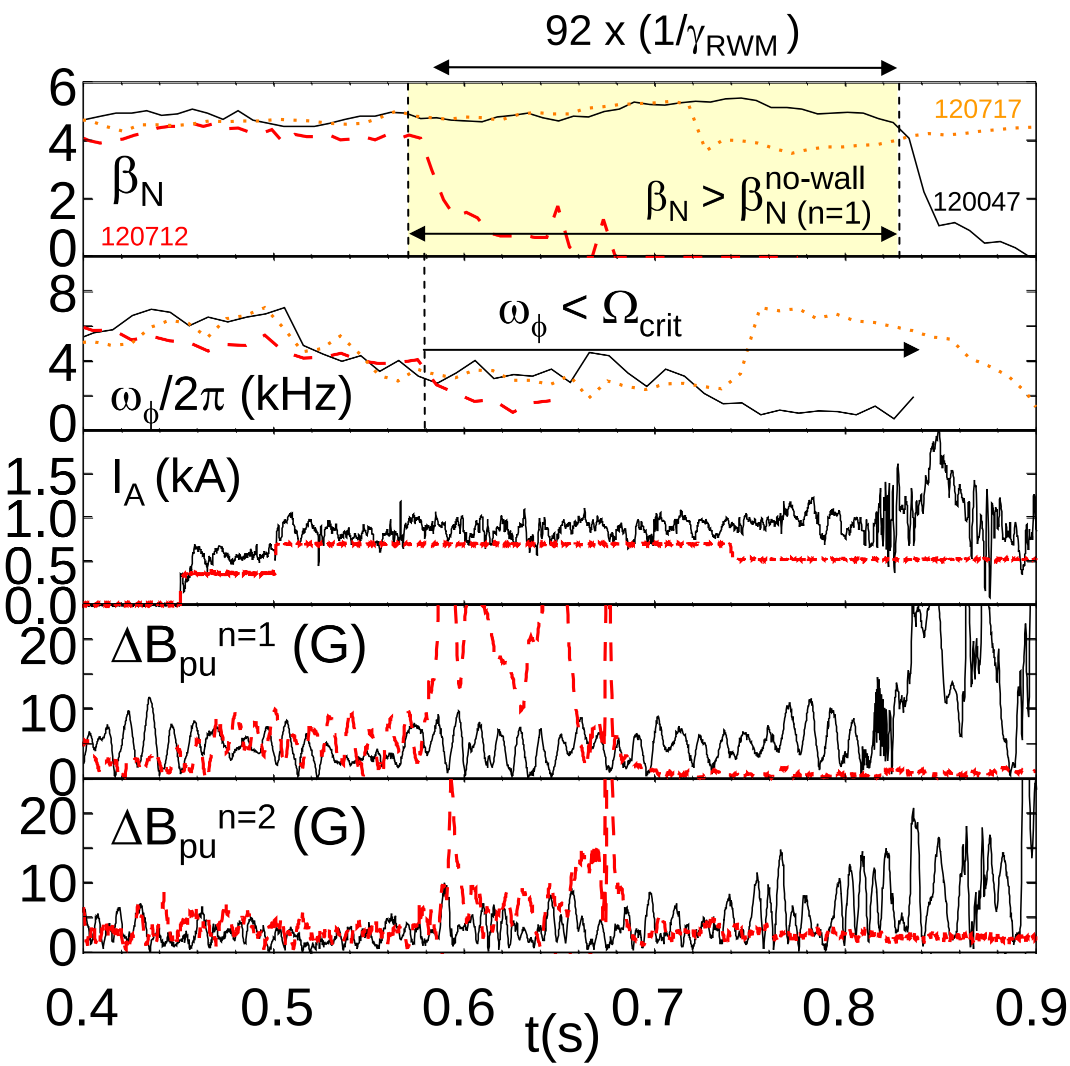

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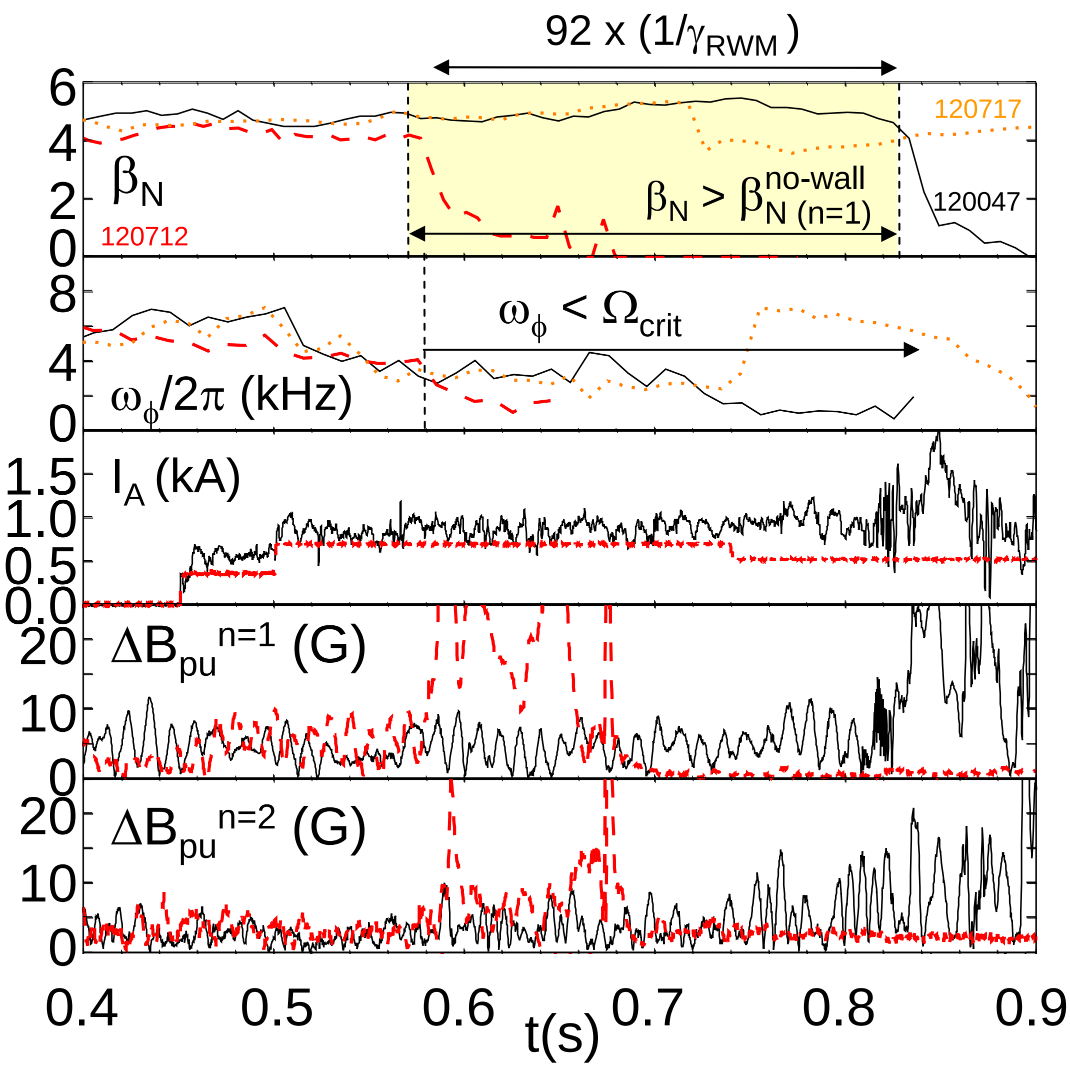

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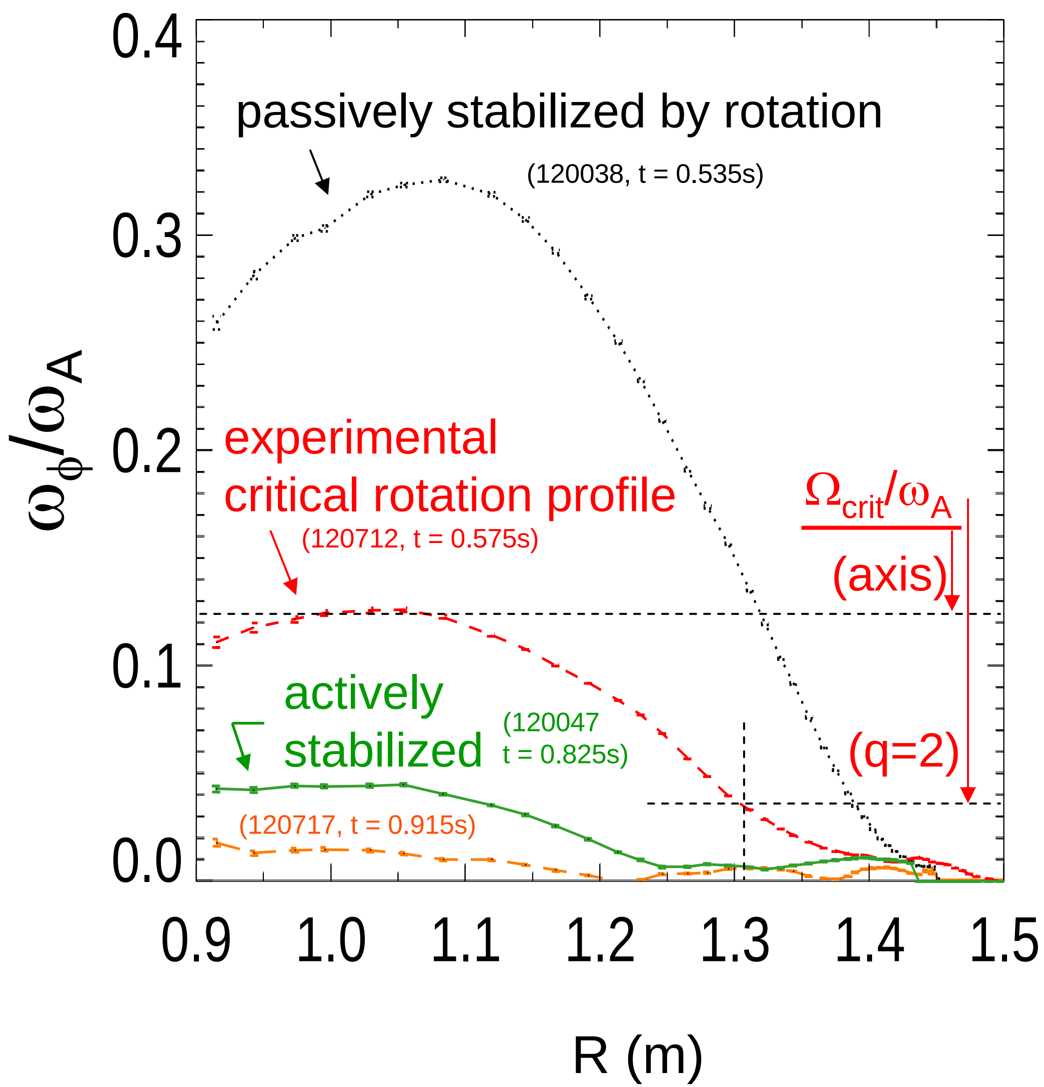
    - Multi-mode research – connection to RWM stabilization in RFPs
  - n = 2 internal plasma mode seen in some cases
- Plasma rotation ω_ϕ reduced by non-resonant *n* = 3 magnetic braking
  - Non-resonant braking to accurately determine RWM critical rotation

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

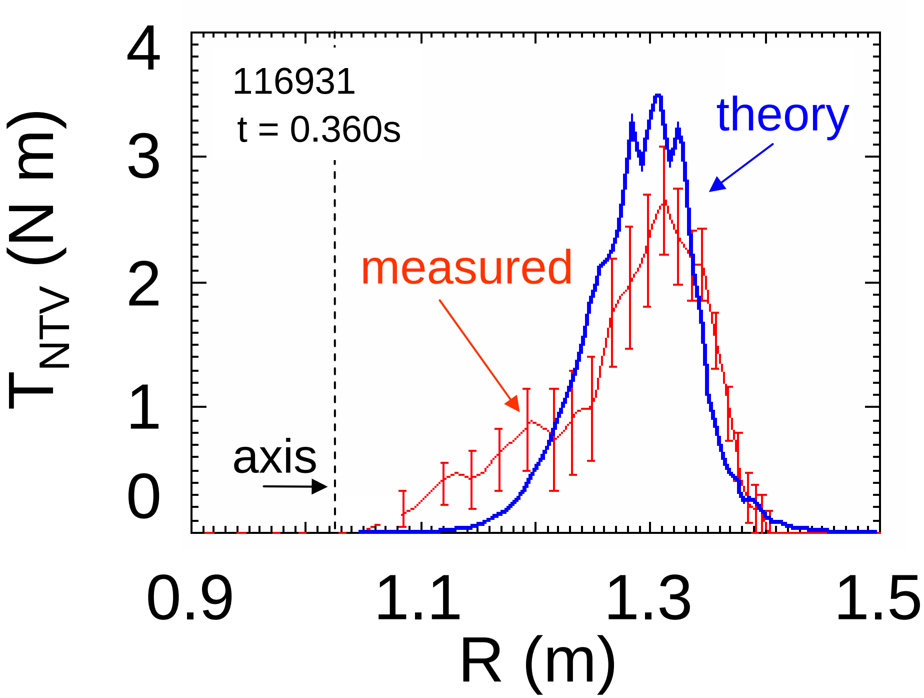
Rotation reduced far below RWM critical rotation profile



- 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 $\omega_\phi/\Omega_{crit} = 0.2|_{q = 2}$
  - 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
  - see paper EX/7-2Rb Sontag

Observed rotation decrease follows NTV theory

n = 3 applied field configuration

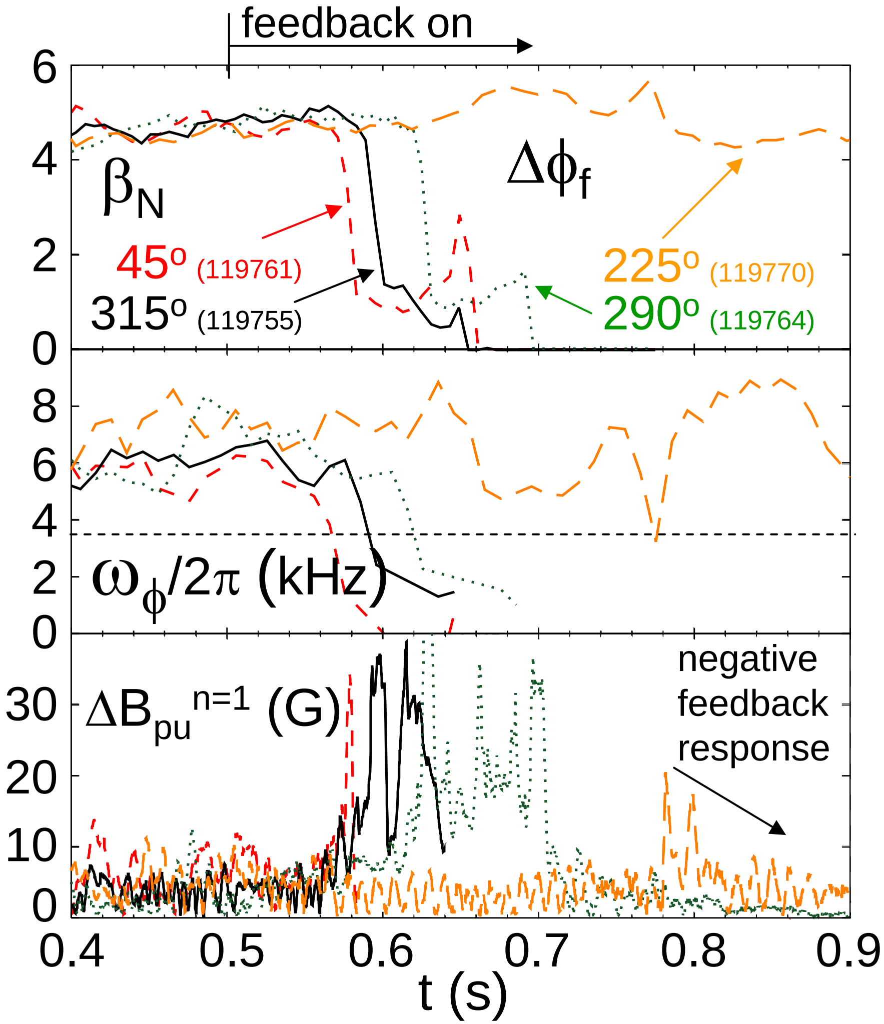


(Zhu, et al., PRL **96** (2006) 225002.)

- 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, KSTAR)
  - Scales as $\delta B^2 (T_i/\nu_i)(1/A)^{1.5}$
  - Low ν_i ITER plasmas will have higher rotation damping

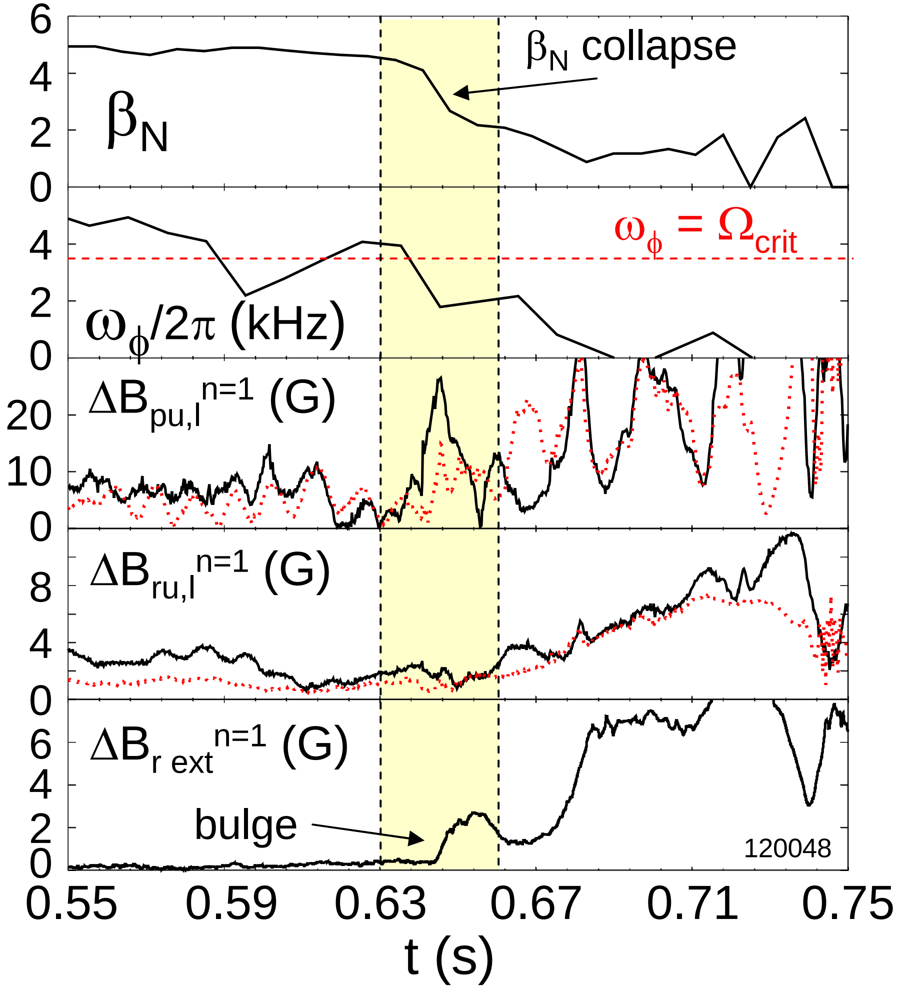
see EX/7-2Rb Sontag

Varying relative phase shows positive/negative feedback



- RWM active feedback on n = 1
  - Control current relative phase, $\Delta\phi_f$
- 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

RWM may change form and grow during active control

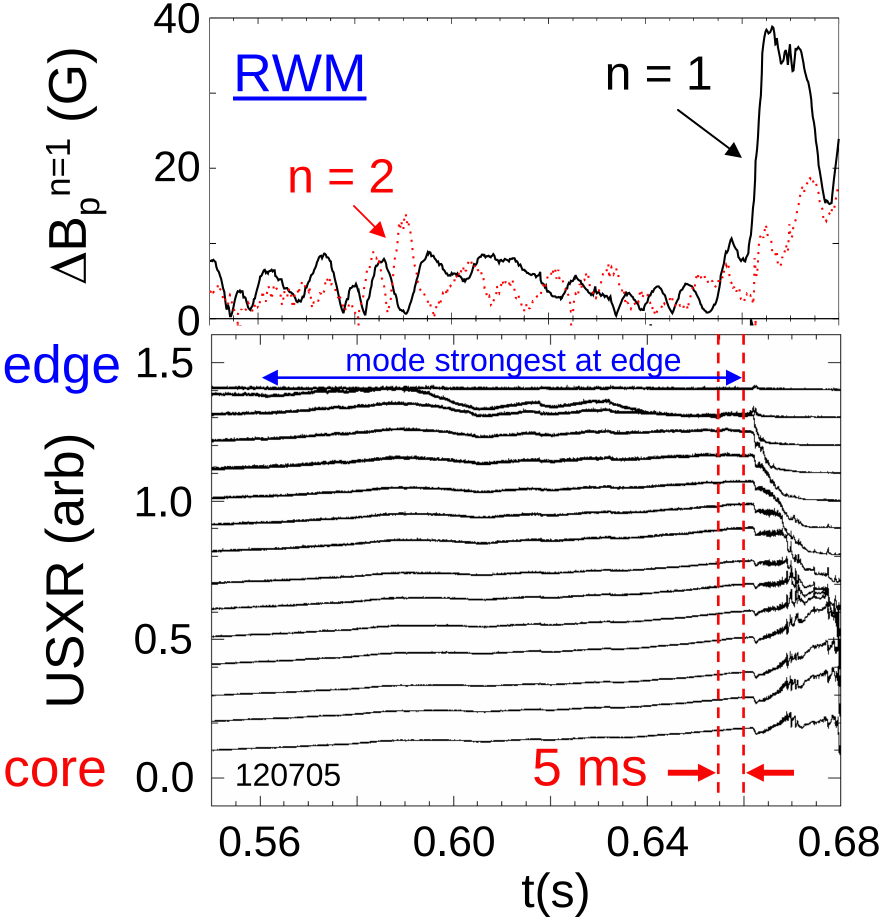


- Poloidal n =1 RWM field decreases to near zero
  - Radial RWM field increasing
- Subsequent growth of poloidal RWM field
  - *Asymmetric* above/below midplane
- Midplane radial sensor shows RWM bulging
  - Upper/lower radial sensors show decrease, while midplane sensor increases
  - Theory: may be due to stable ideal *n* = 1 modes becoming less stable (e.g. *q* evolution)

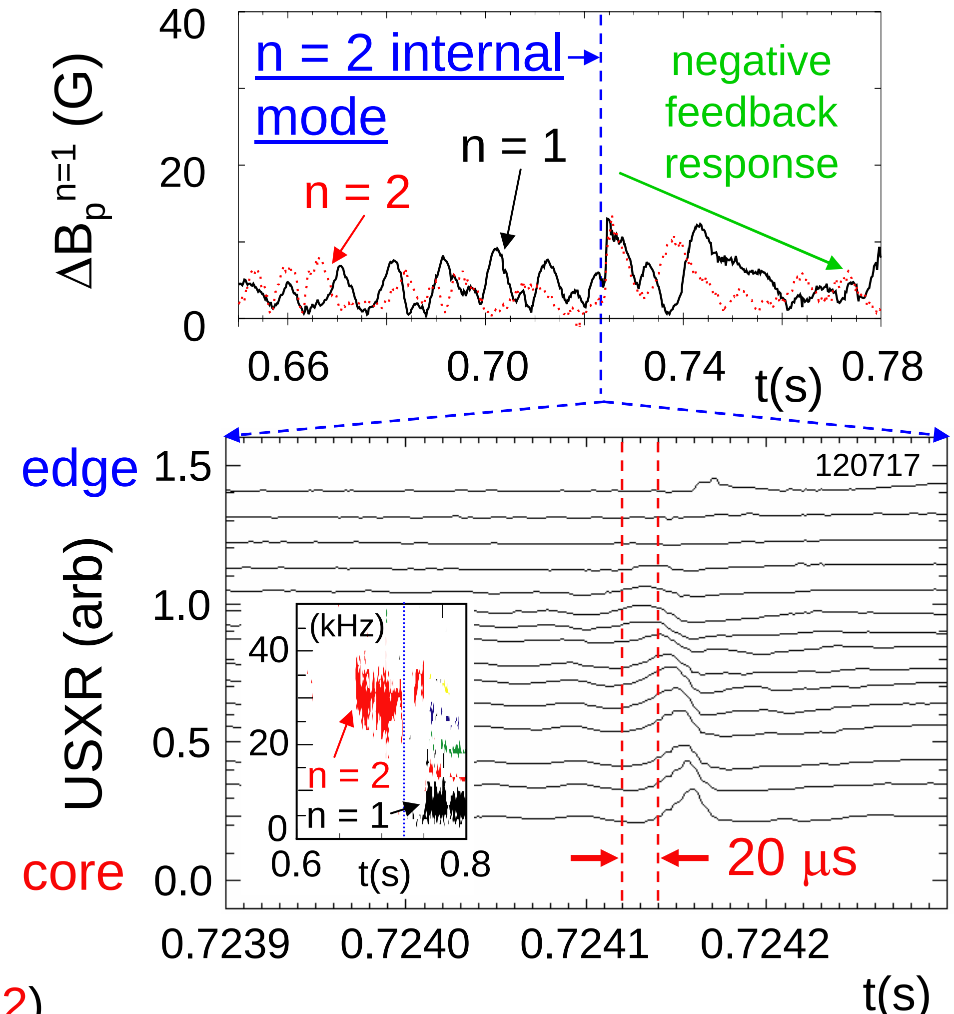
Future research will assess using combined sensors for optimization

Clear differences between RWM and internal plasma mode

No active stabilization (RWM disrupts plasma)



Active stabilization (fast β_N drop, plasma recovers)



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

(USXR: K. Tritz JHU)

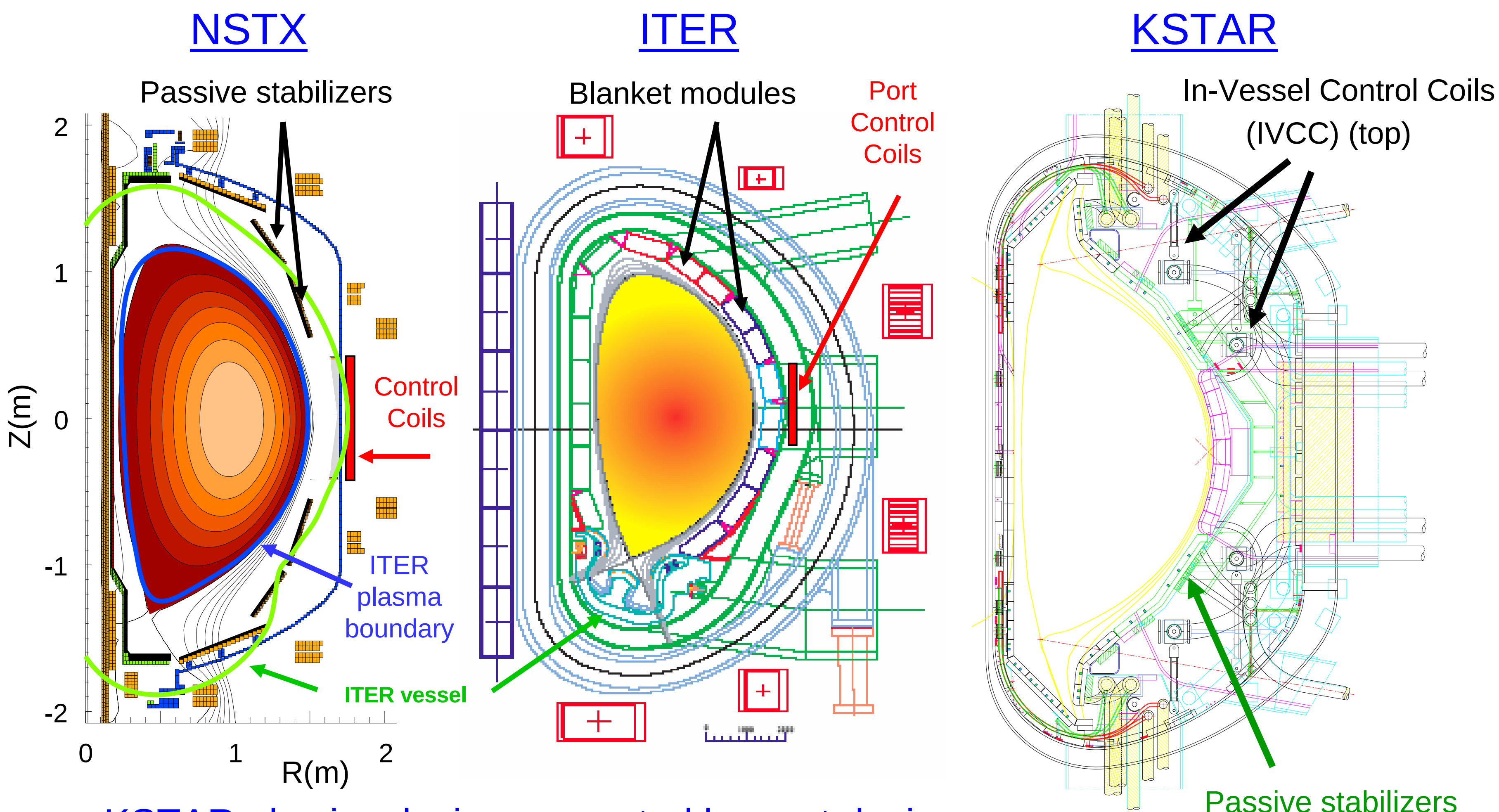
NSTX begins RWM active stabilization research relevant to ITER and beyond

- 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
  - Plasma response to feedback control demonstrated
- Stability of n = 2 RWM demonstrated 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 NTV theory
  - Full NTV calculation yielding quantitative agreement to experiment
  - Key component of RWM stability physics and dynamics; general momentum transport relevance

Additional slides for poster follow

Work slides follow

NSTX begins RWM active stabilization research relevant to ITER, KSTAR, CTF



- KSTAR physics design supported by past design studies, present experiments in NSTX, DIII-D

Close connection to present experiments in NSTX impacts the KSTAR stability physics study

- RWM active stabilization demonstrated in low rotation (ITER-relevant) plasmas (Sabbagh, et al., PRL **97** (2006) 045004)
  - KSTAR with co-NBI should have rotation control for experiments
- Precise plasma rotation control through neoclassical toroidal viscosity (Zhu, et al., PRL **96** (2006) 225002)
  - n = 2 non-resonant magnetic braking possible rotation control option for KSTAR
- Unstable resistive wall mode with toroidal mode number n > 1 observed (Sabbagh, et al., NF **46** (2006) 635)
  - May need to address n > 1 unstable modes in KSTAR at the highest beta or for certain equilibrium profile shapes
- RWM critical rotation speed (H. Reimerdes, et al., PoP **13** (2006) 056107)
  - Dependence on aspect ratio, Alfven speed, ion collisionality – key research topic