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# Wall Stabilized High Beta Operation in NSTX and Active Stabilization Plans

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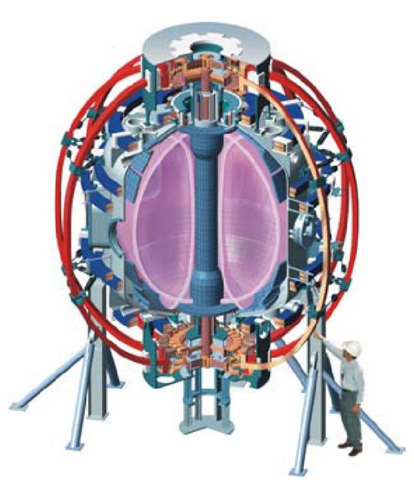

**ITPA MHD Topical Group Meeting #5**
8-10 November 2004
Lisbon, Portugal

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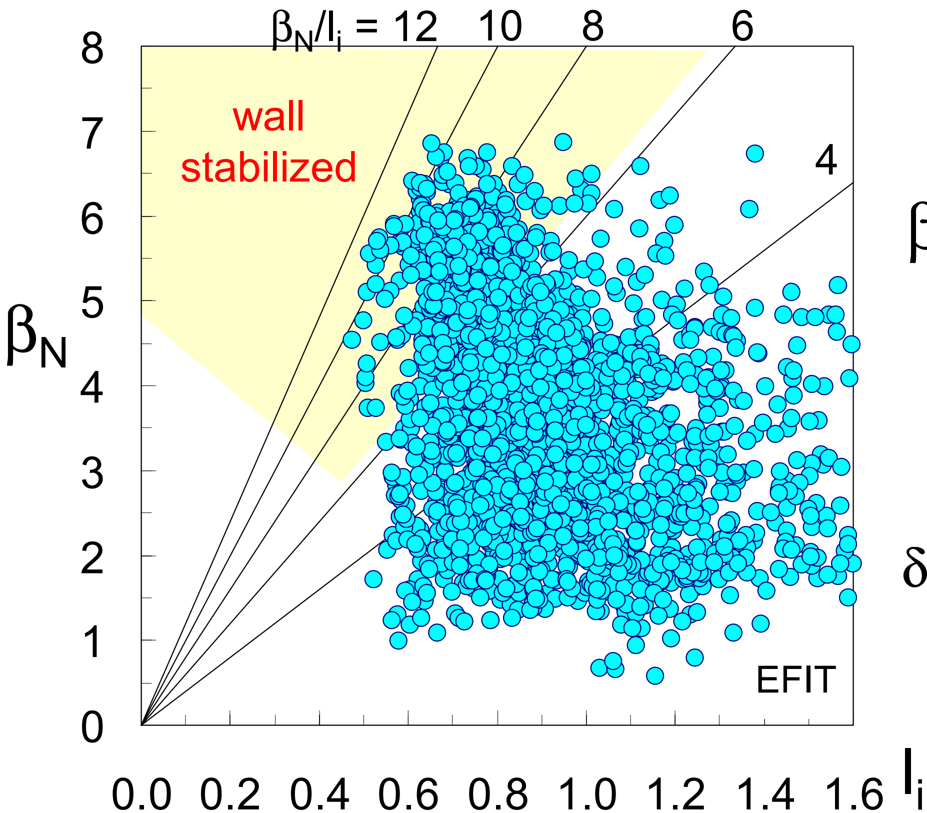
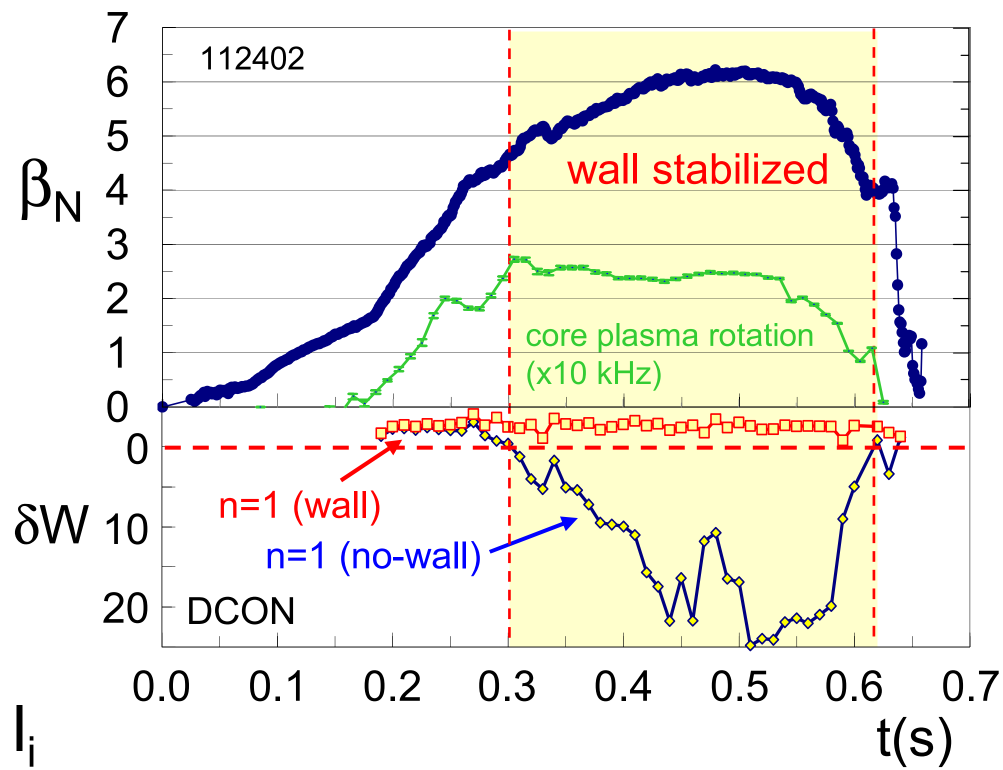
NSTX

# Wall stabilization physics understanding is key to sustained plasma operation at maximum β

- High $\beta_t$ = 39%, $\beta_N$ = 6.8 reached




- Operation with $\beta_N/\beta_N^{no\text{-}wall}$ > 1.3 at highest $\beta_N$ for pulse >> $\tau_{wall}$



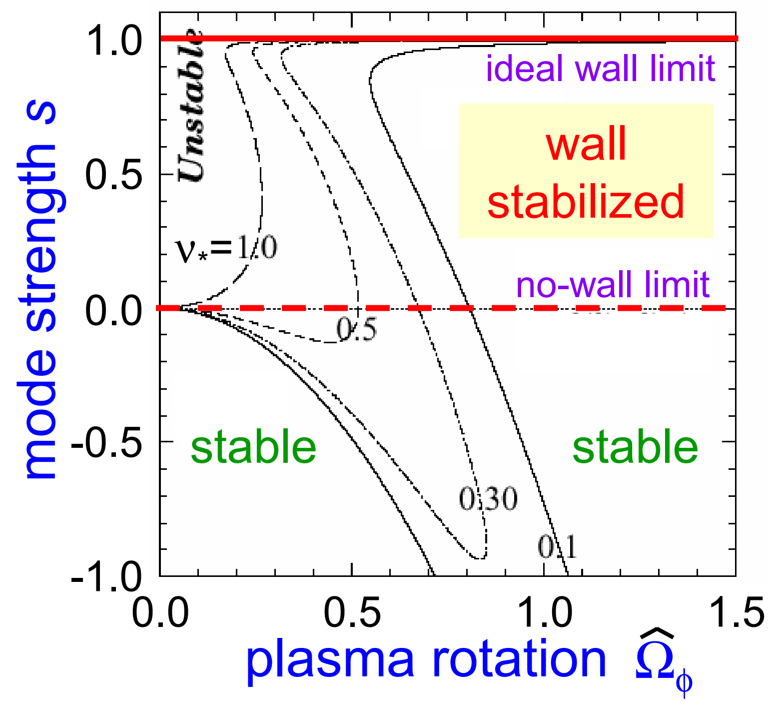

- Global MHD modes can lead to rotation damping, $\beta$ collapse
- Physics of sustained stabilization is applicable to ITER

# Theory provides framework for wall stabilization study

- This talk: Resistive Wall Mode physics
  - RWM toroidal mode spectrum
  - Critical rotation frequency, $\Omega_{crit}$
  - Toroidal rotation damping
  - Resonant field amplification (RFA)
  - Active stabilization system design
- Theory
  - Ideal MHD stability – DCON (Glasser)
  - Drift kinetic theory (Bondeson – Chu)
  - RWM dynamics (Fitzpatrick – Aydemir)

Fitzpatrick-Aydemir (F-A) stability curves

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

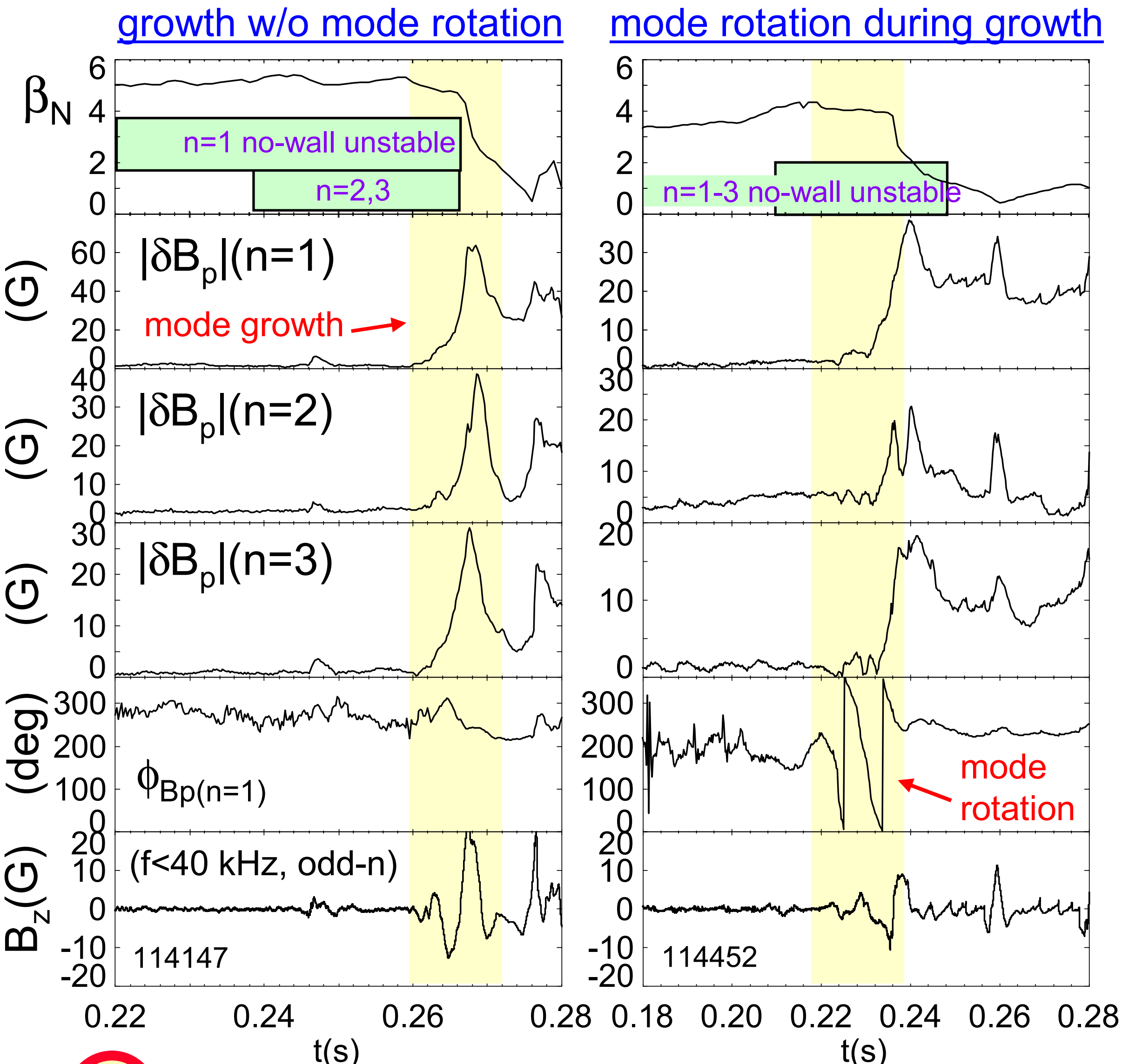



$$\left[\left(\hat{\gamma} - i\hat{\Omega}_\phi\right)^2 + \nu_*\left(\hat{\gamma} - i\hat{\Omega}_\phi\right) + (1-s)(1-md)\right]\left(S_*\hat{\gamma} + (1+md)\right) = \left(1-(md)^2\right)$$

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

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

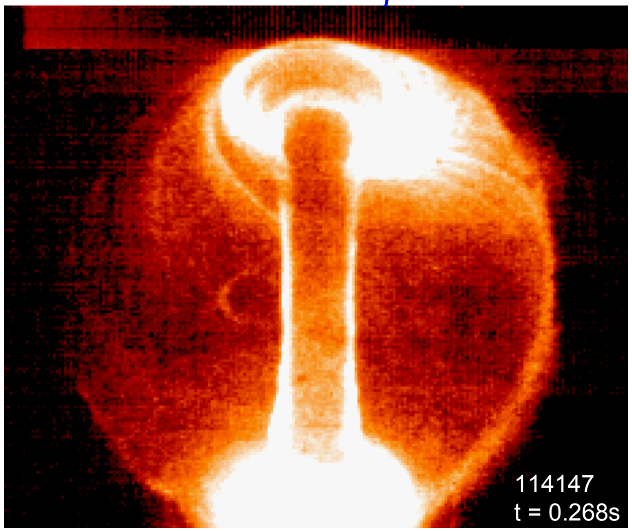
# Unstable RWM dynamics follow theory



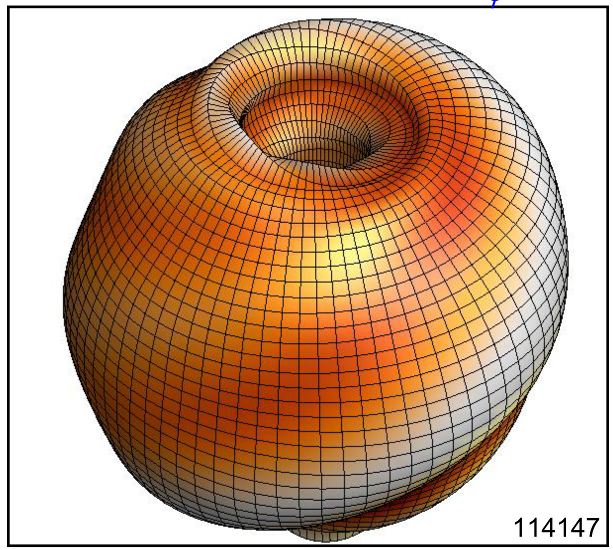

- Unstable n=1-3 RWM observed
  - ideal no-wall unstable at high $\beta_N$
  - n > 1 theoretically less stable at low A
- F-A theory / experiment show
  - mode rotation can occur during growth
  - growth rate, rotation frequency ~ $1/\tau_{wall}$
    - << edge $\Omega_\phi$ > 1 kHz
  - RWM phase velocity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

# Camera shows scale/asymmetry of theoretical RWM

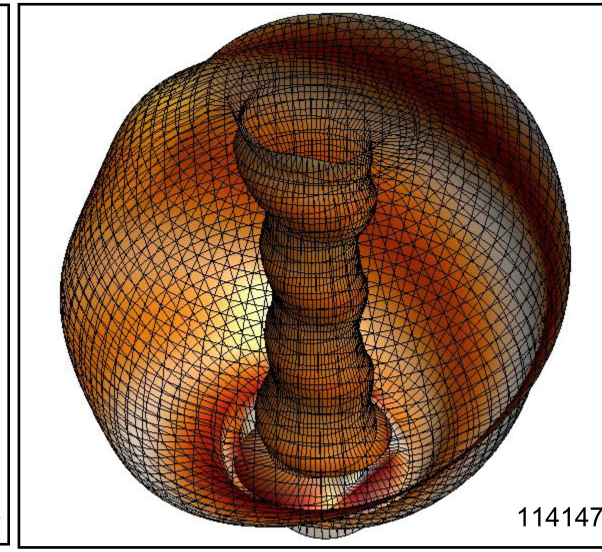
RWM with $\Delta B_p$ = 92 G




Theoretical $\Delta B_\psi$ (x10) with $n$=1-3 (DCON)

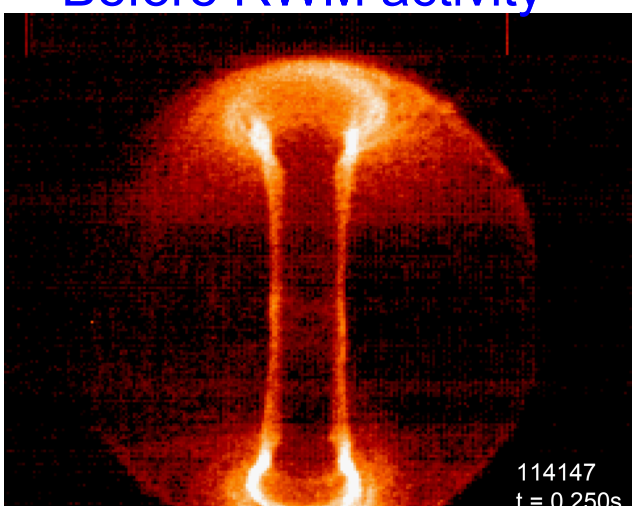



(exterior view)




(interior view)

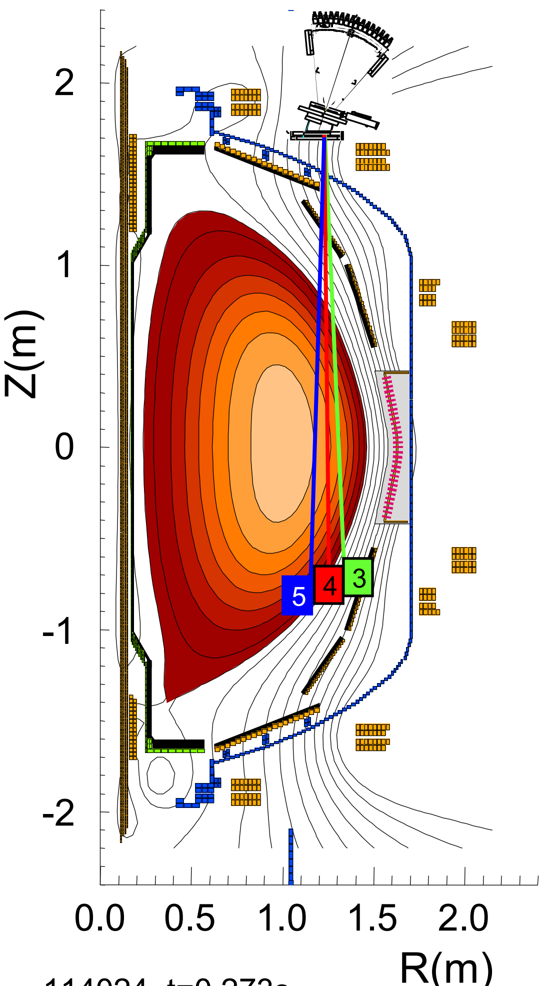
Before RWM activity



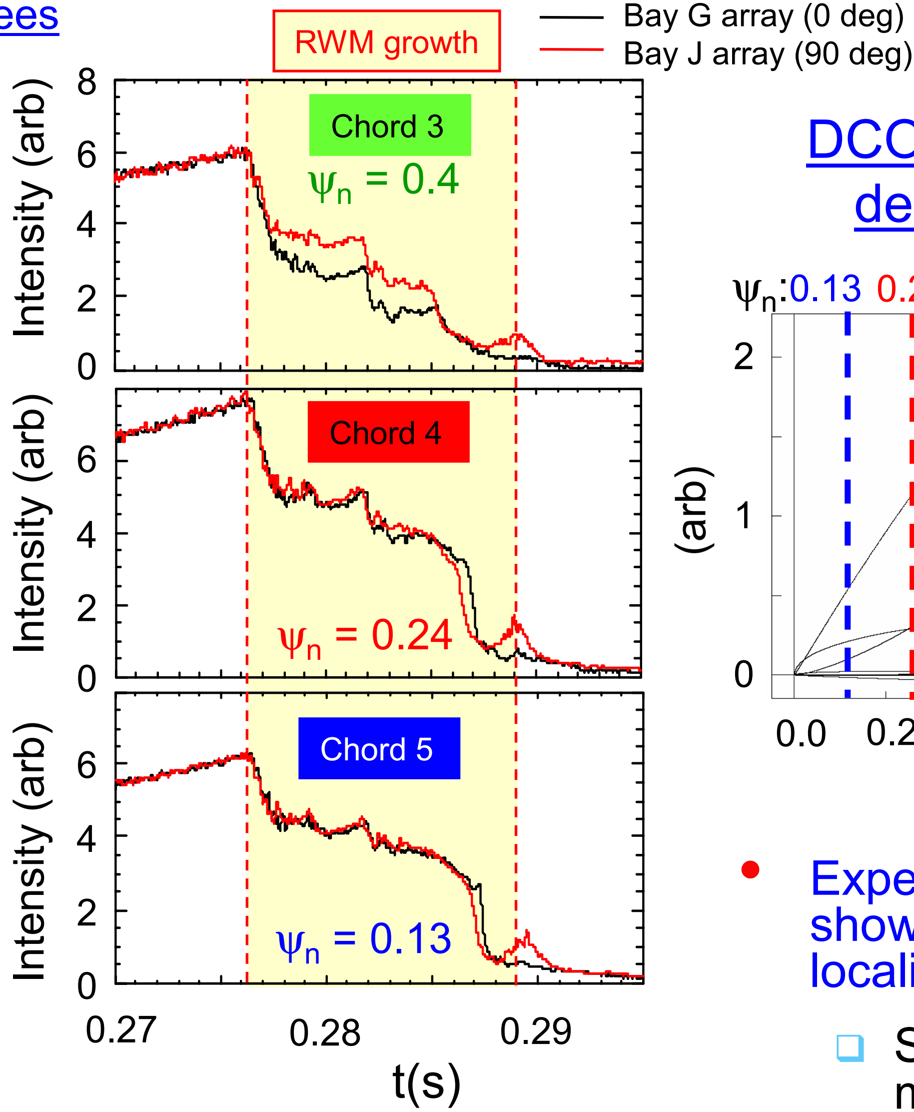

- Visible light emission is toroidally asymmetric during RWM
- DCON theory computation displays mode
  - uses experimental equilibrium reconstruction
  - includes $n$ = 1 – 3 mode spectrum
  - uses relative amplitude / phase of $n$ spectrum measured by RWM sensors

# Soft X-ray emission shows toroidal asymmetry during RWM

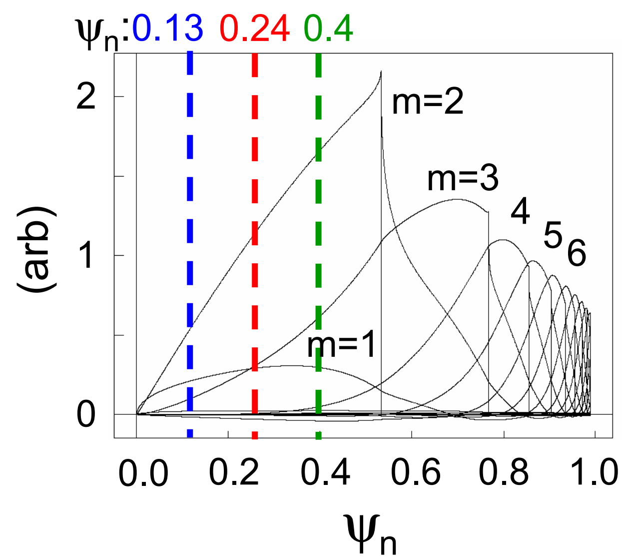
USXR separated by 90 degrees




114024, t=0.273s
$\beta_N = 5$



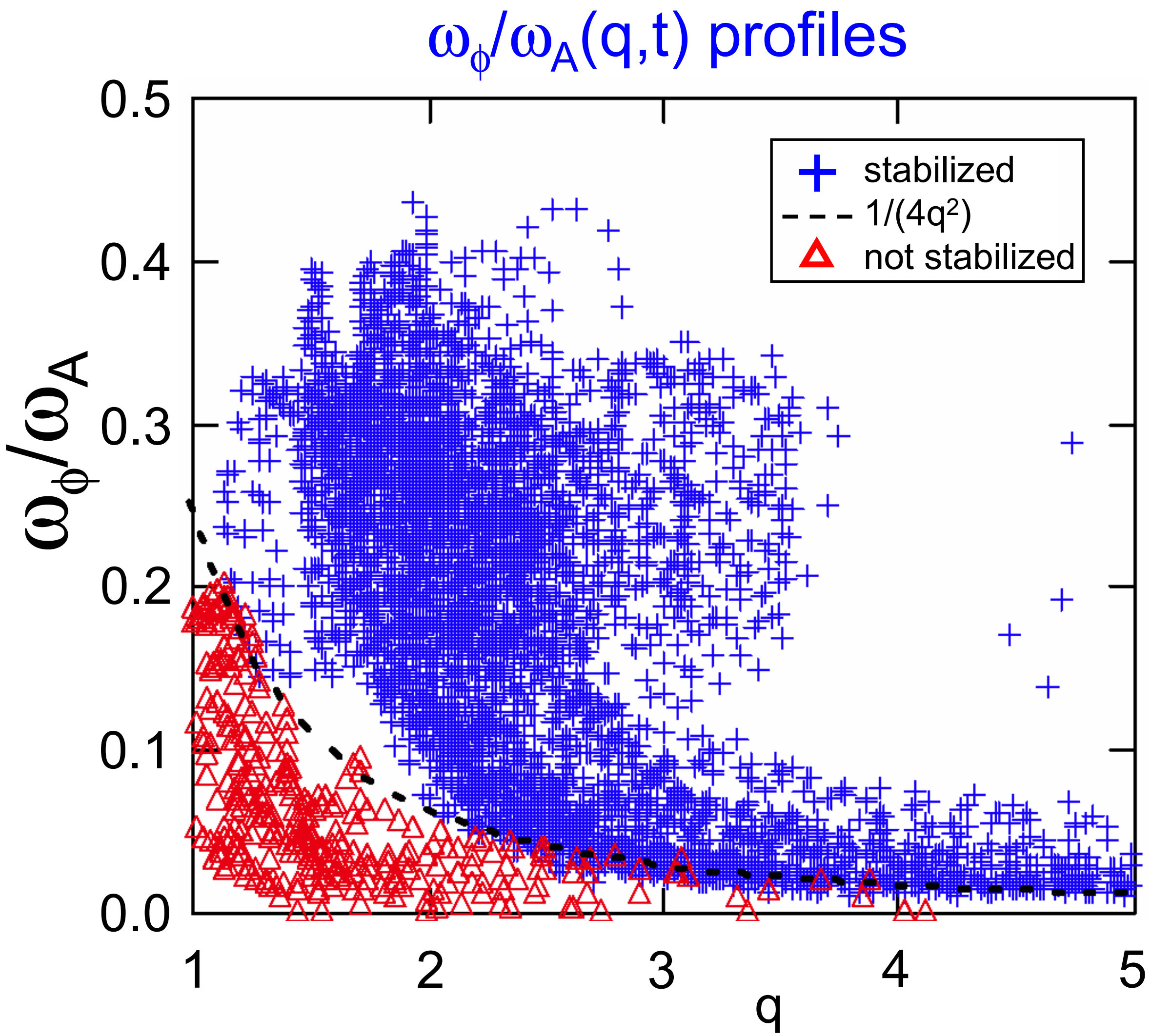

DCON $n$ = 1 mode decomposition




- Experiment / theory show RWM not edge localized
  - Supported by measured $\Delta T_e$

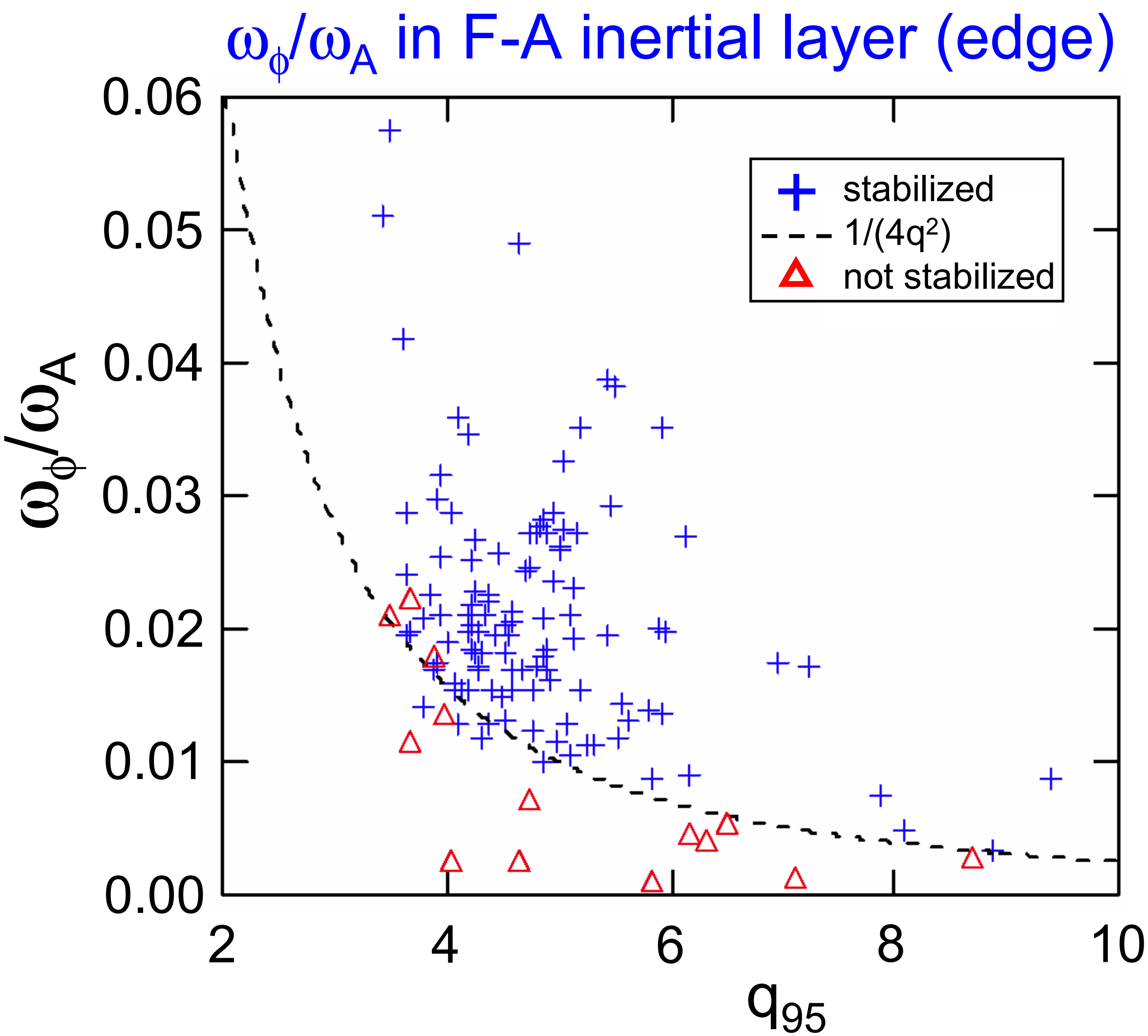
# Experimental $\Omega_{crit}$ follows Bondeson-Chu theory

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




- **Experimental $\Omega_{crit}$**
  - 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 $\Omega_{crit} = \omega_A/(4q^2)$

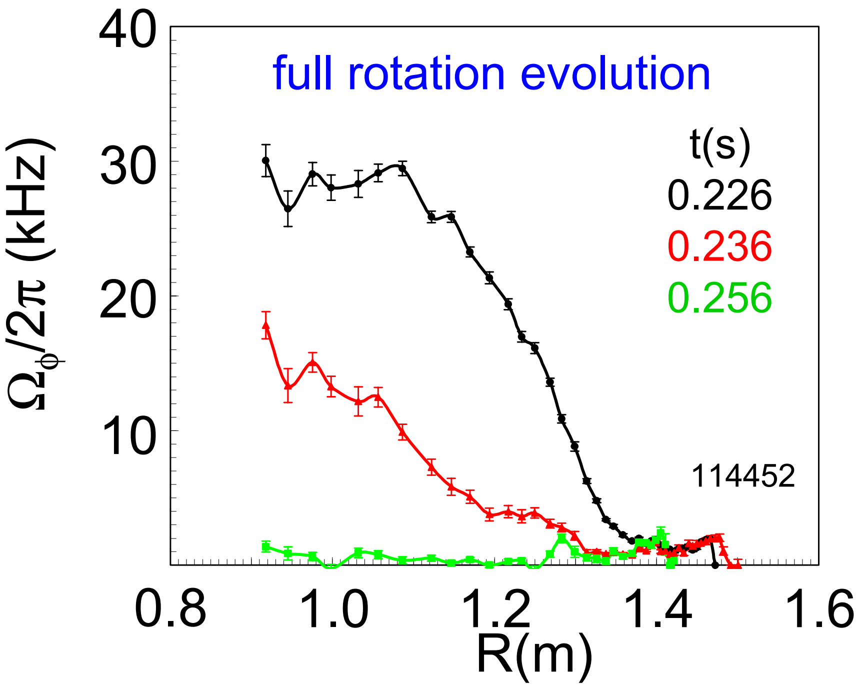
# $\Omega_{crit}$ follows F-A theory with neoclassical viscosity

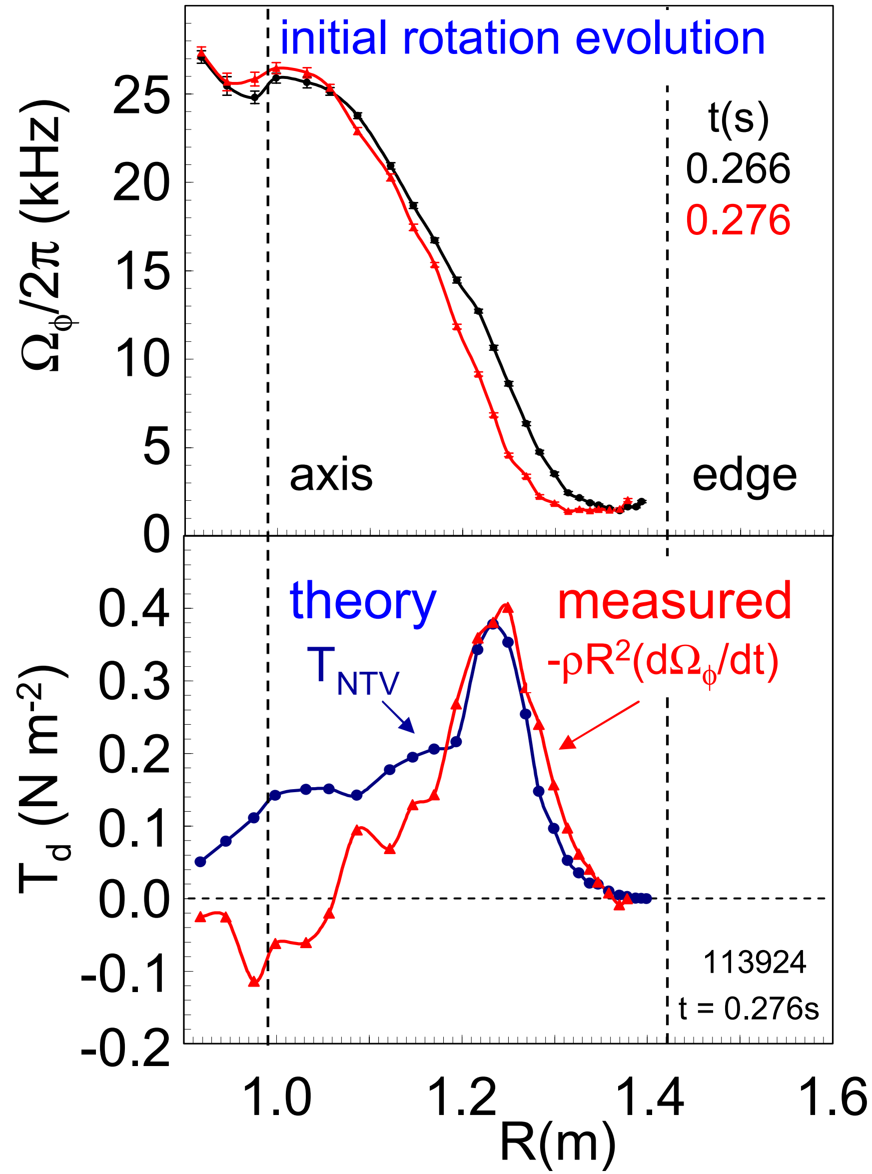



- **Experimental $\Omega_{crit}$**
  - stabilized points: $\beta > \beta_N^{no\text{-}wall}$ (DCON)
  - points not stabilized cannot maintain $\beta > \beta_N^{no\text{-}wall}$
  - regions separated by $\omega_\phi/\omega_A = 1/(4q^2)$
- **F-A Theory**
  - Standard F-A theory has $\Omega_{crit} \sim 1/q$
  - neoclassical viscosity includes toroidal inertia enhancement (K. Shaing, PoP 2004)
    - yields $\Omega_{crit} \sim 1/q^2$

# Plasma rotation damping described by NTV theory

- Neoclassical toroidal viscosity (NTV) ~ $\delta B^{2} * T_i^{0.5}$
- Rapid, global damping observed during RWM
  - Edge rotation ~ 2kHz maintained
  - Low frequency tearing modes absent

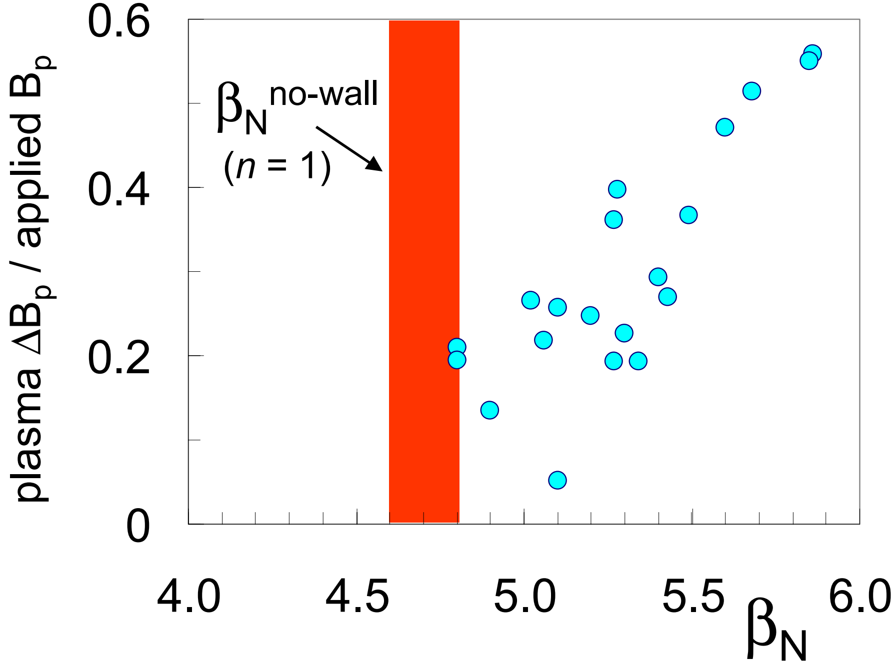


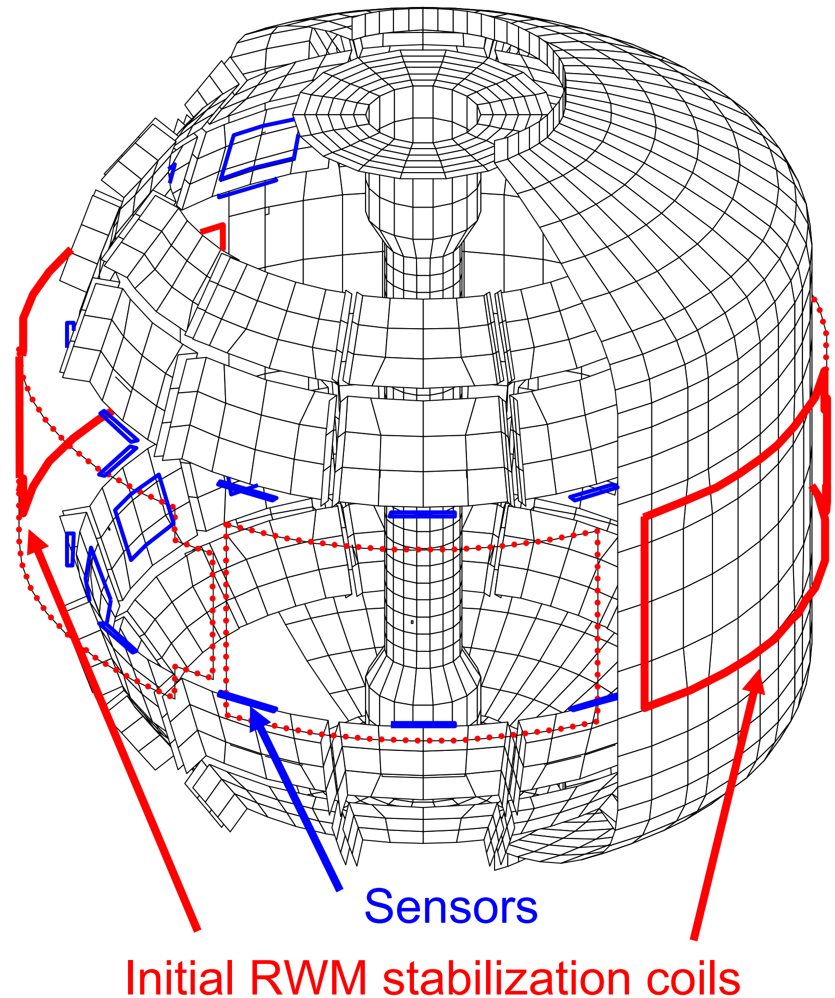




- Evolution detail differs for other modes
  - no momentum transfer across rational surfaces
  - no rigid rotor plasma core (internal 1/1 mode)

see EX/P2-26 Menard

# Resonant Field Amplification increases at high $\beta_N$



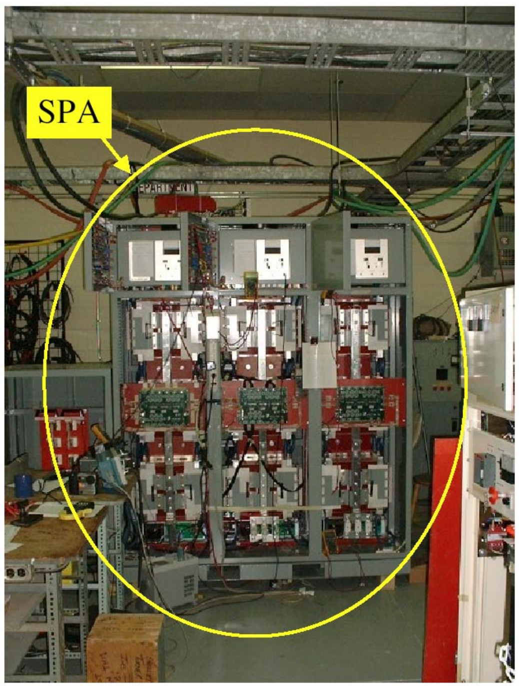



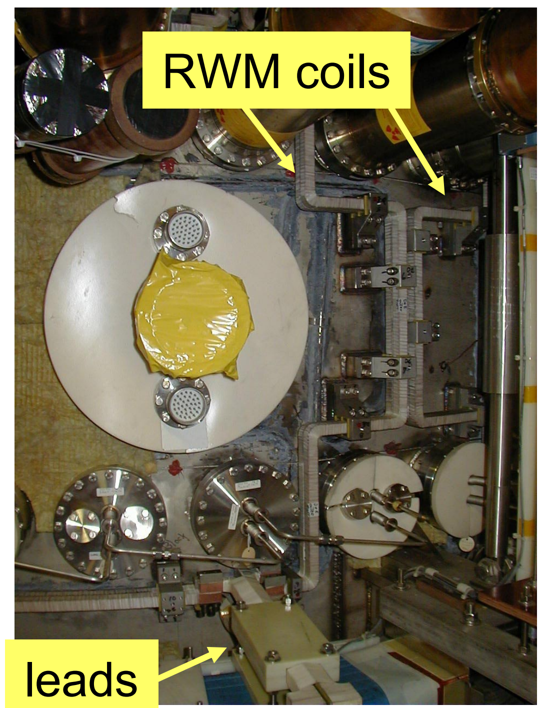

- Plasma response to applied field from initial RWM stabilization coil pair
  - AC and pulsed n = 1 field
- RFA increase consistent with DIII-D
- Stable RWM damping rate of 300$s^{-1}$ measured

Completed coils will be used to suppress RFA, stabilize RWM, sustain high $\beta$

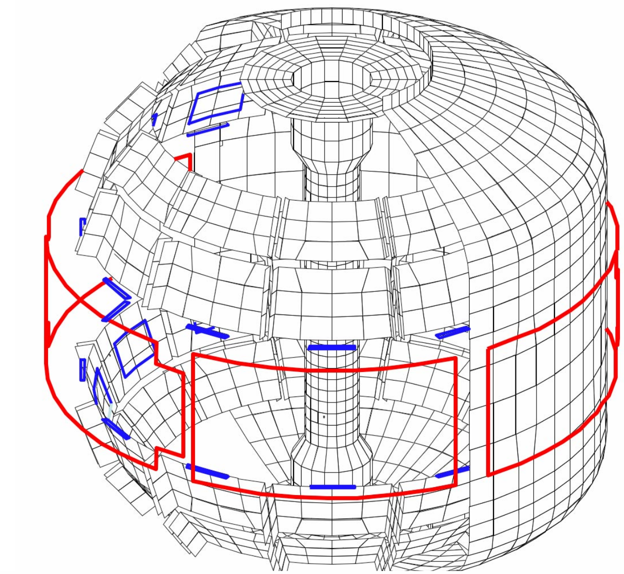
# RWM stabilization system being installed for 2005 run

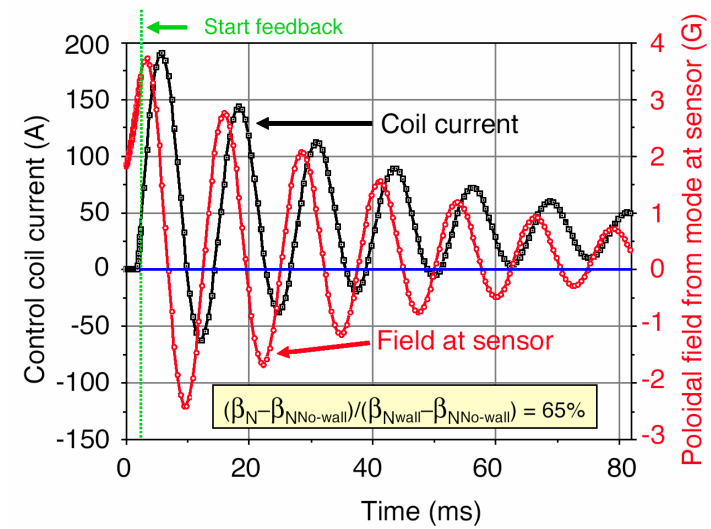
- RWM sensor array used in 2004 experiments
- 6 $B_r$ coils now installed on NSTX
  - Pre-programmed capability in 2005 for RFA suppression / MHD spectroscopy experiments
- 3-channel switching power amplifier (SPA) on-site
- Real-time mode detection and control algorithm development in 2005 for feedback experiments



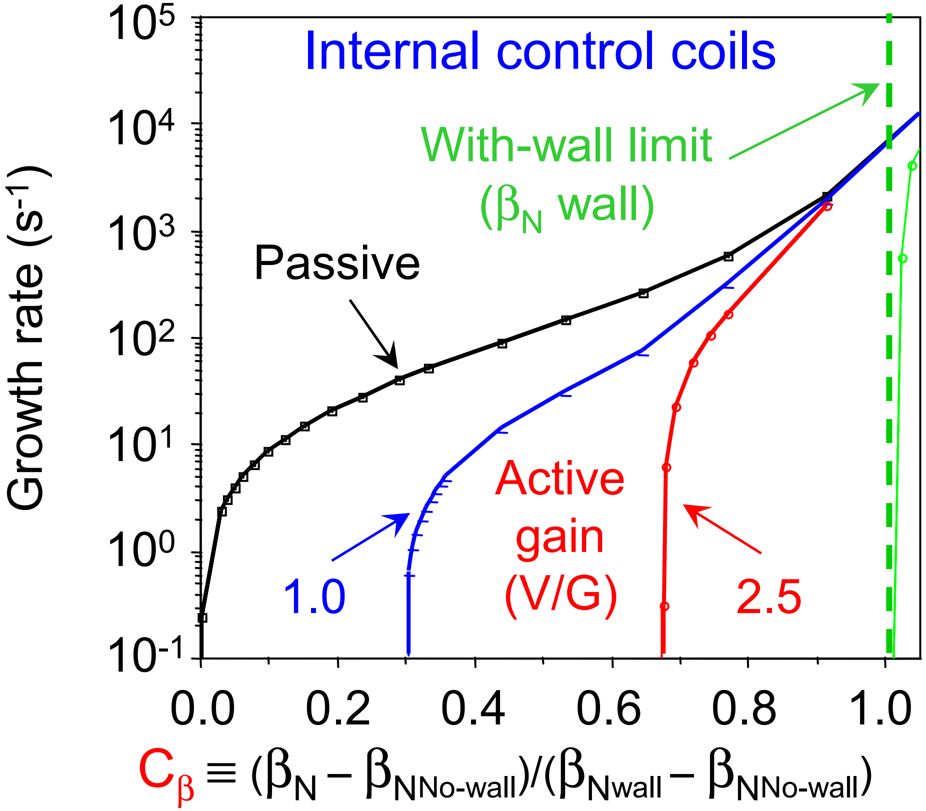



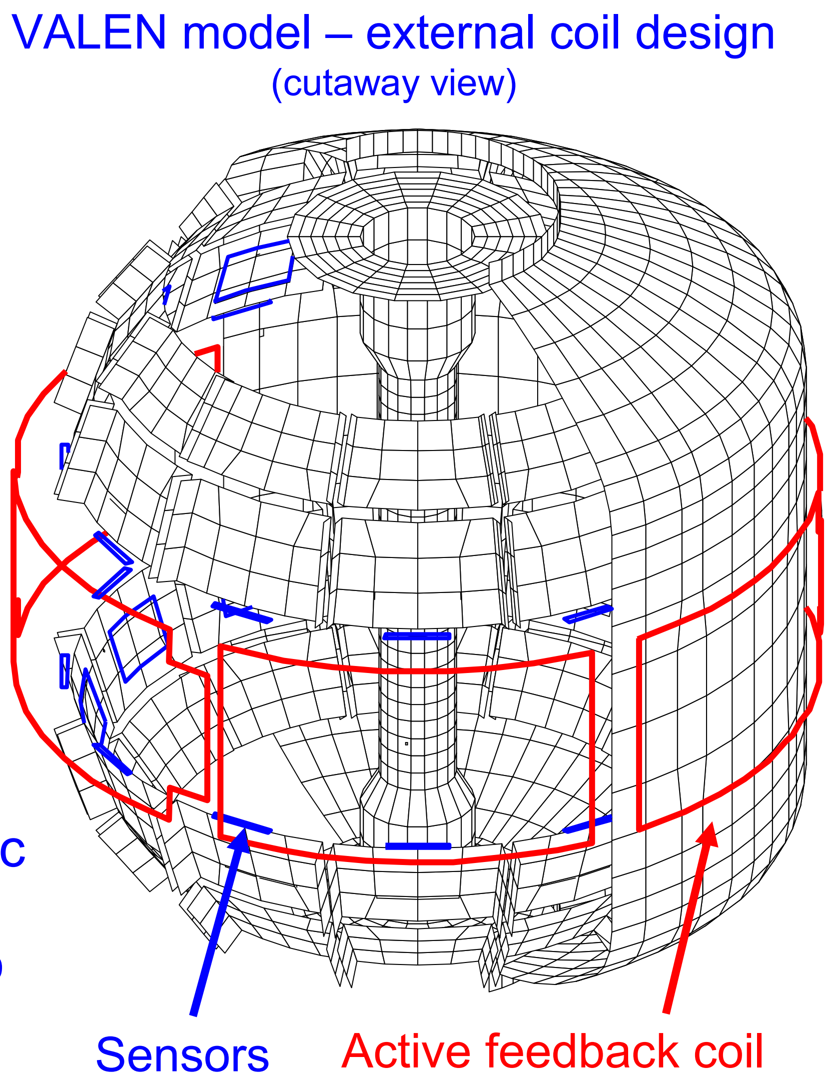

Physics design (VALEN code)





# NSTX control modeling predicts 68% stable margin above $\beta_{Nno\text{-}wall}$ with initial external coil system



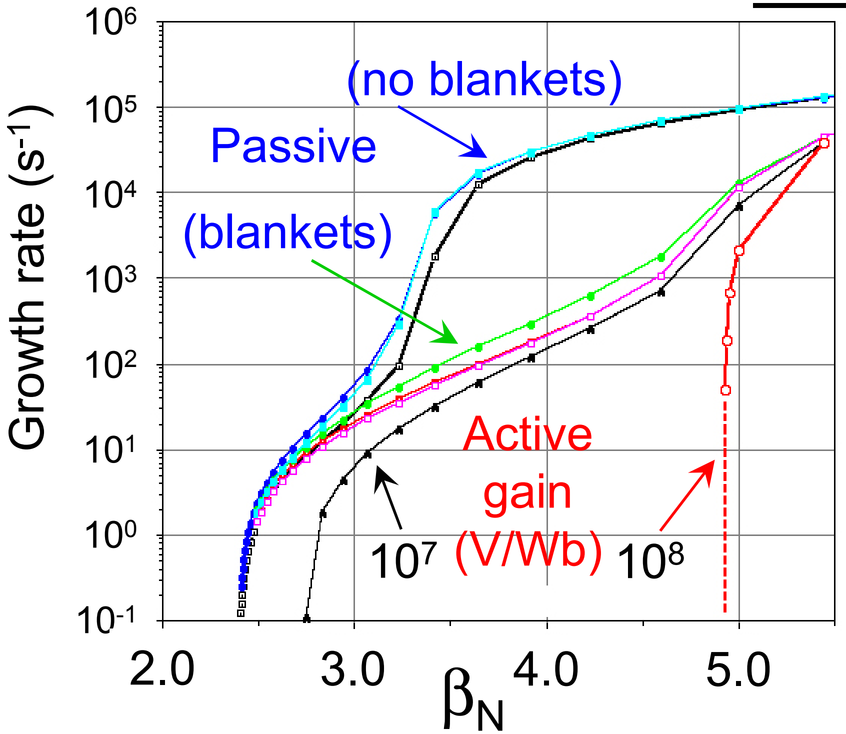




- Control coil / sensor design with realistic geometry
- Internal control coil design computed to reach $C_\beta$ = 94%

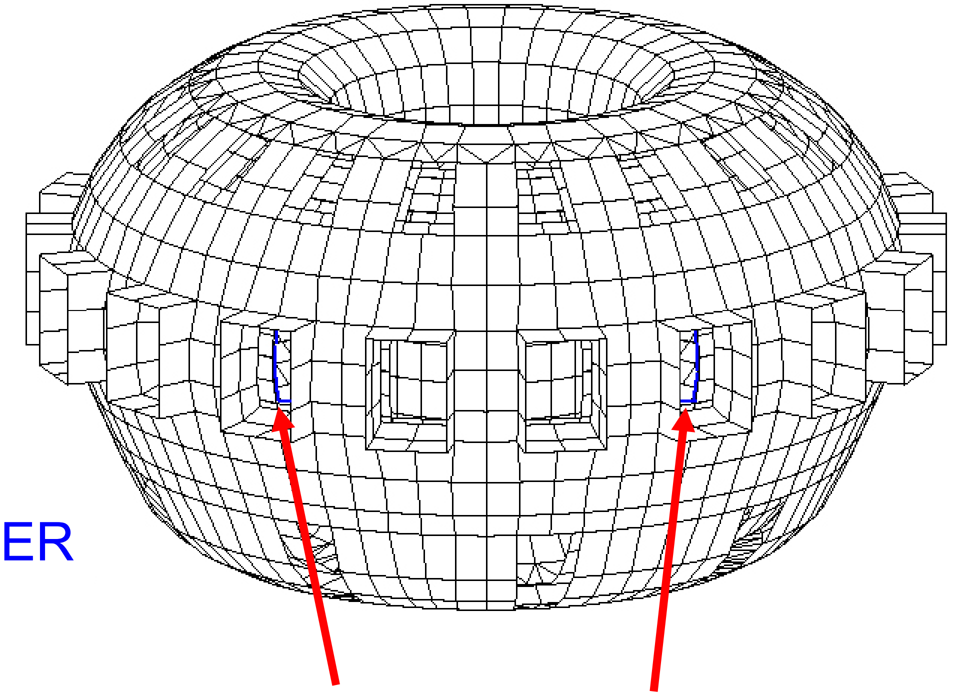
(Equilibria used have $\beta_{Nno\text{-}wall}$ = 5.1; $\beta_{Nwall}$ = 6.9)

NSTX

# ITER active coil modification can significantly raise stable $\beta_N$




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




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

# Wall stabilization research at low aspect ratio illuminates key physics for general high β operation

- Plasma $\beta_t$ = 39%, $\beta_N$ = 6.8, $\beta_N/l_i$ = 11 reached; $\beta_N/\beta_N^{no\text{-}wall} > 1.3$
- Unstable $n$ = 1-3 RWMs measured (n > 1 prominent at low A)
- Critical rotation frequency ~ $\omega_A/q^2$ strongly influenced by toroidal inertia enhancement (prominent at low A)
- Rapid, global plasma rotation damping mechanism associated with neoclassical toroidal viscosity
- Resonant field amplification of stable RWM increases with increasing $\beta_N$ (similar to higher A)
- An active RWM stabilization system is being implemented in 2005
- RWM active stabilization design studies show that significant increase to $\beta_N$ ~ 5 might be achieved and sustained in ITER