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Aspect Ratio Considerations for Resistive Wall Mode Stabilization

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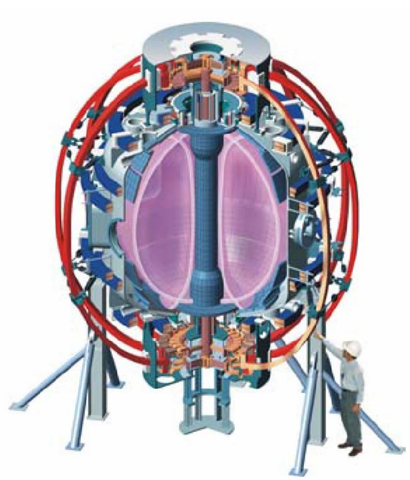

IEA Workshop 59: Shape and Aspect Ratio Optimization for High Beta, Steady-State Tokamak
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General Atomics, San Diego, CA

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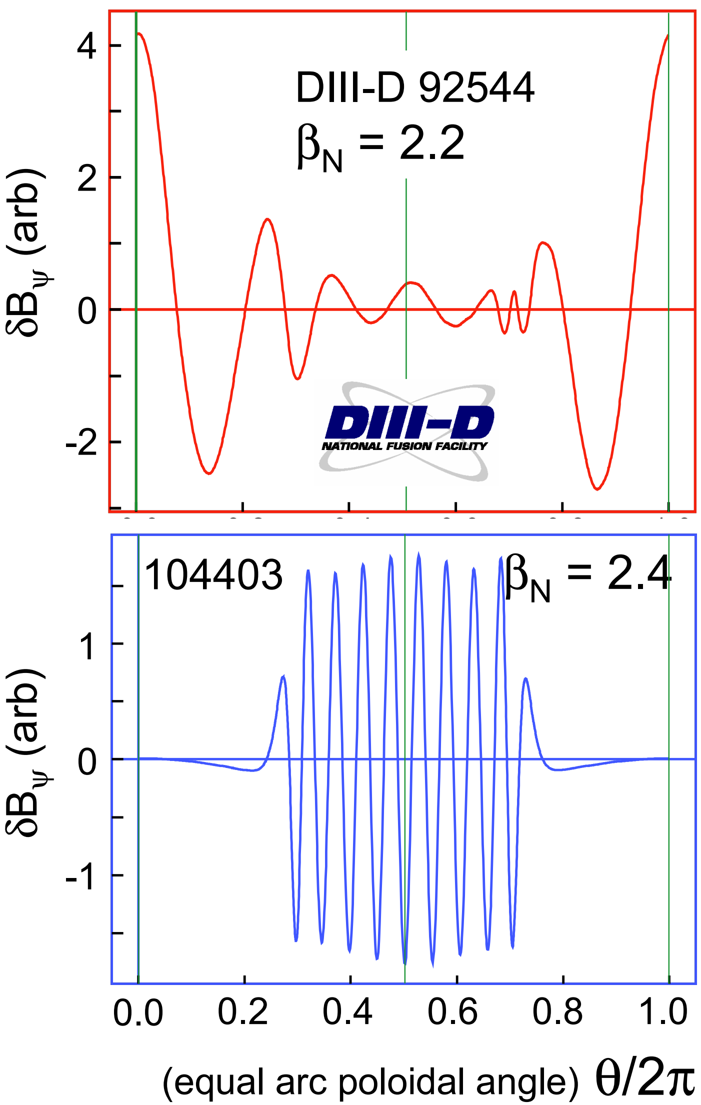
NSTX

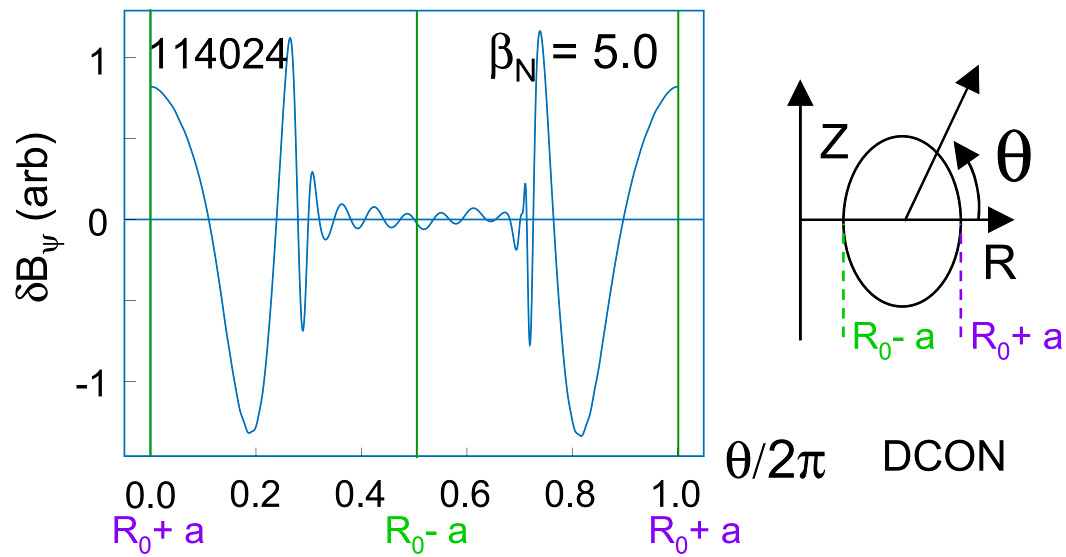
Physics study of global MHD mode stabilization at low A provides understanding for all A, including ITER

- **Motivation**
  - Study / optimize high β stability of low A, spherical tokamak
  - Low A, high q challenges theory and code benchmarking
  - Compare data from various A devices to test theory

- **Key Topics**
  - Kink and RWM stabilization at low A; mode characteristics
  - Toroidal rotation damping physics
  - Critical plasma rotation frequency for stabilization, Ω_{crit}
  - Resonant field amplification (RFA)
  - Rotation effects on equilibrium at low A

Low A kink mode amenable to stabilization at high β_N

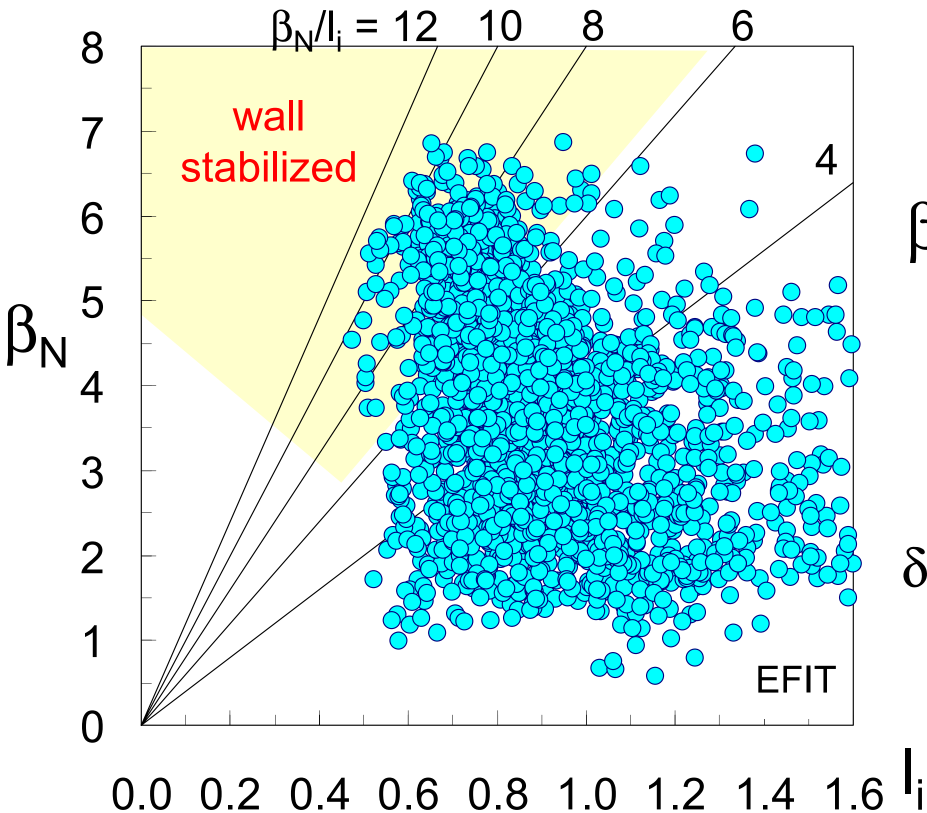




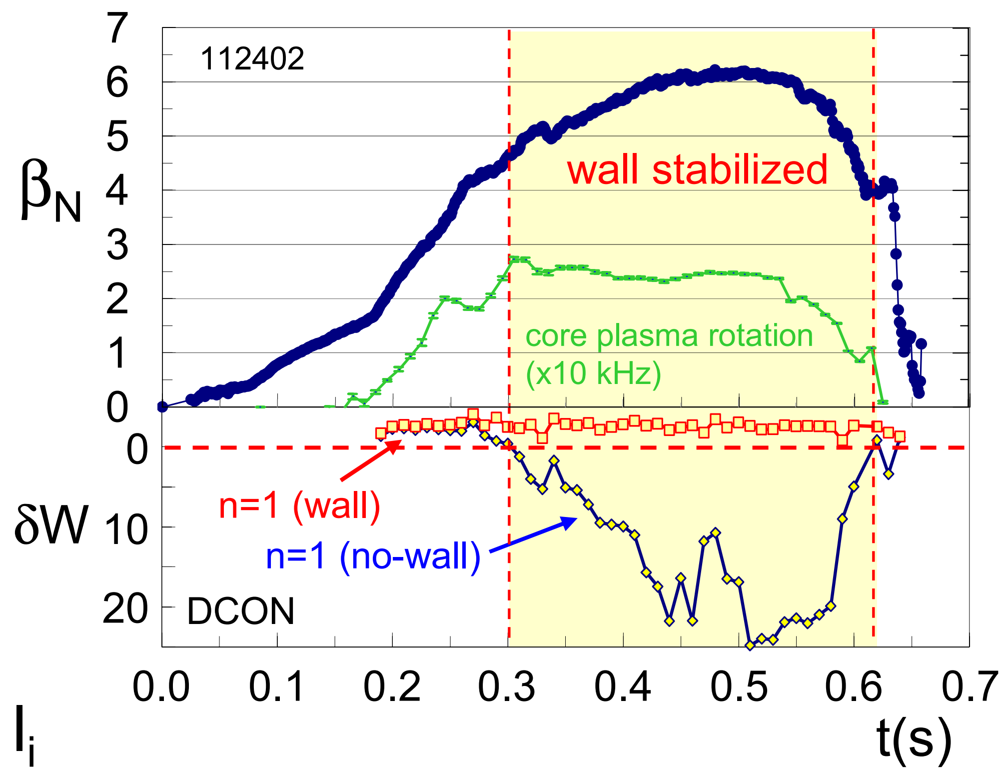
- Higher A ~ 3.1 (DIII-D); β_N = 2.2 (above $\beta_N^{no-wall}$)
  - Maximum amplitude on outboard side; relatively long poloidal wavelength
  - Strong wall coupling; effective wall stabilization
- Lower A ~ 1.4 (NSTX)
  - β_N = 2.4:
    - Minimum amplitude on outboard side; short poloidal wavelength inboard side
    - Weak wall coupling; ineffective wall stabilization
  - β_N = 5.0 (above $\beta_N^{no-wall}$)
    - Mode balloons out and can be effectively stabilized

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

- High β_t = 39%, β_N = 6.8 reached

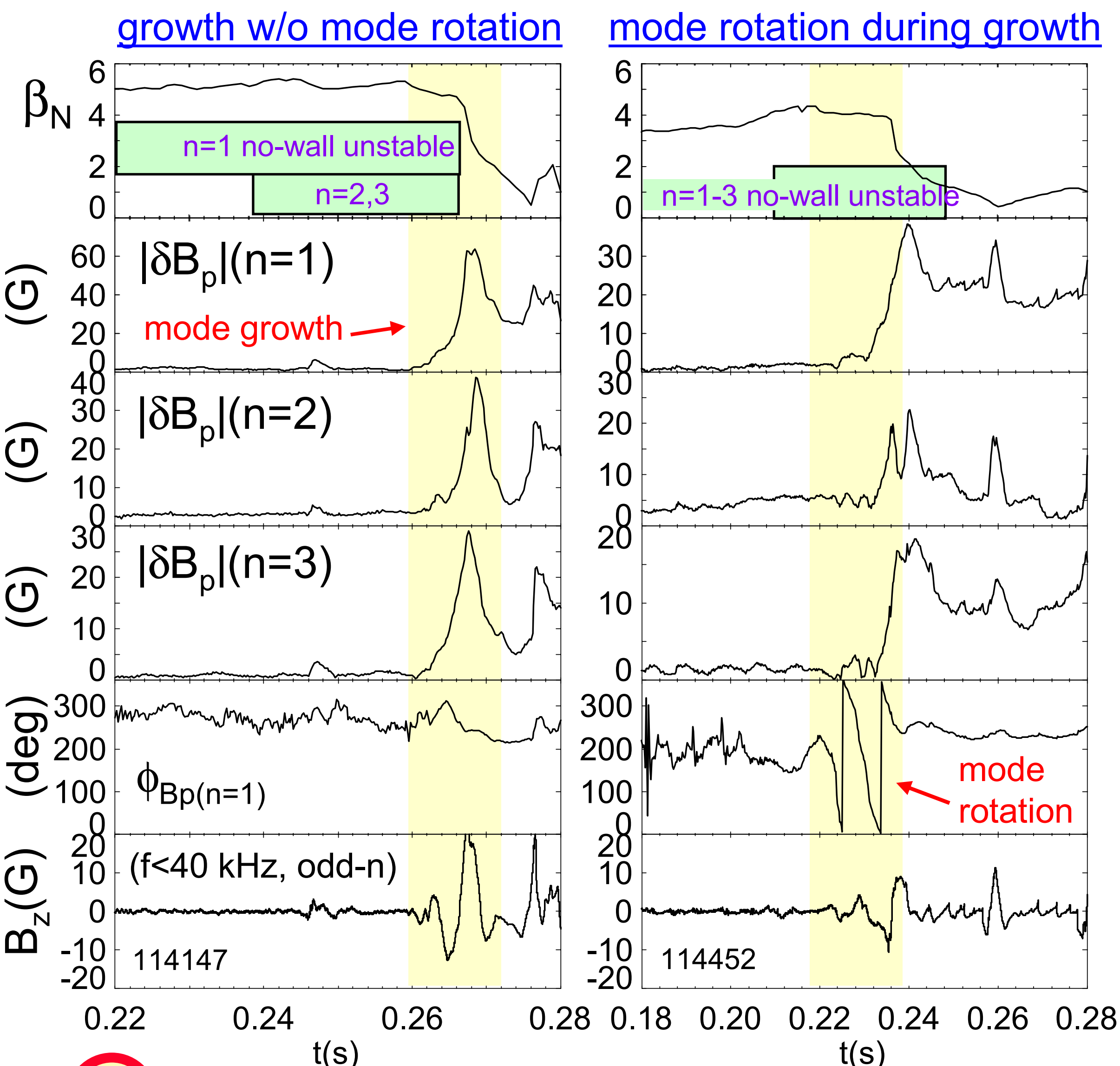


- Operation with $\beta_N/\beta_N^{no\text{-}wall}$ > 1.3 at highest β_N for pulse >> τ_{wall}



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

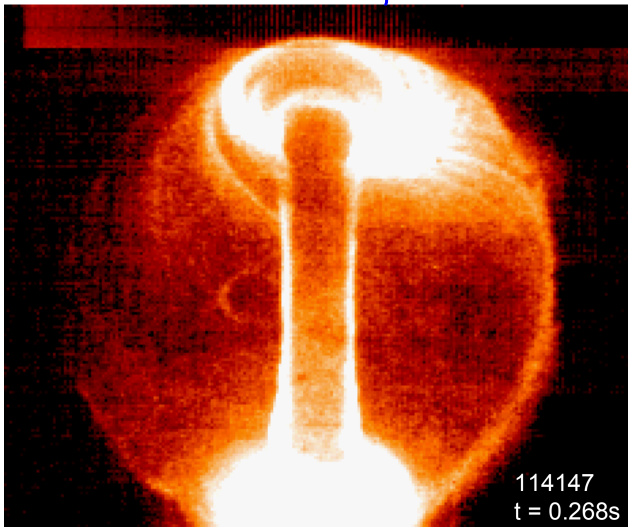
Unstable n = 1-3 RWM observed



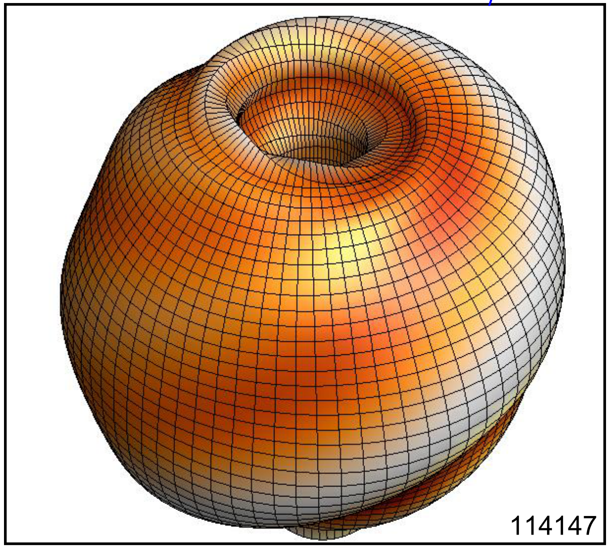
- n > 1 theoretically more prominent at low A
- Fitzpatrick-Aydemir (F-A) theory / experiment show
  - mode rotation can occur during growth
  - growth rate, rotation frequency ~ $1/\tau_{wall}$
    - << edge Ω_ϕ > 1 kHz
  - RWM phase velocity follows plasma flow
  - n=1 phase velocity not constant due to error field
- Low frequency tearing modes absent

Camera shows scale/asymmetry of theoretical RWM

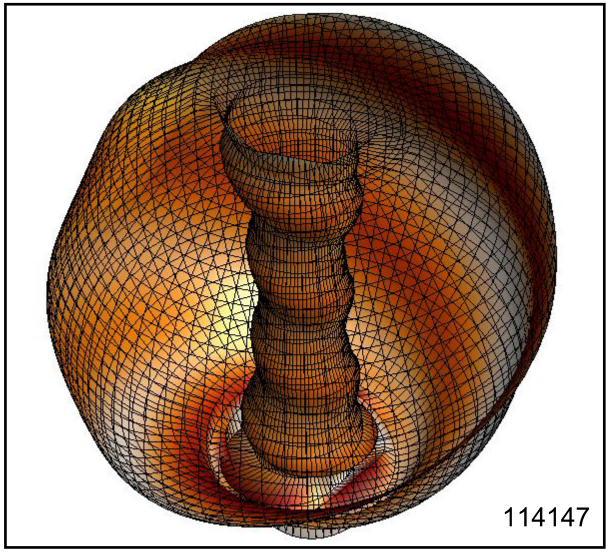
RWM with ΔB_p = 92 G



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

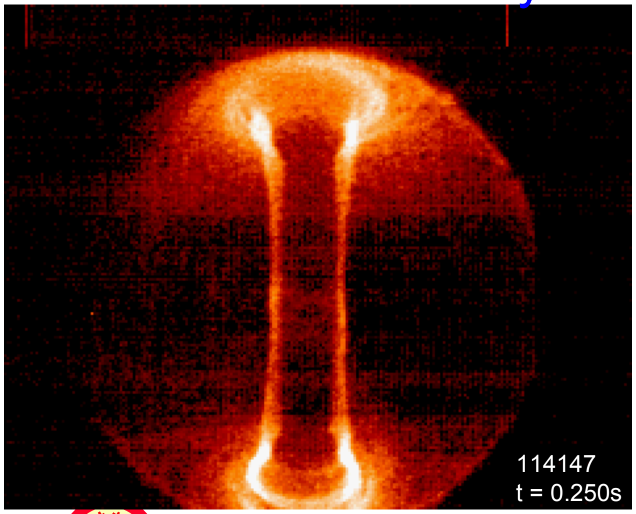


(exterior view)



(interior view)

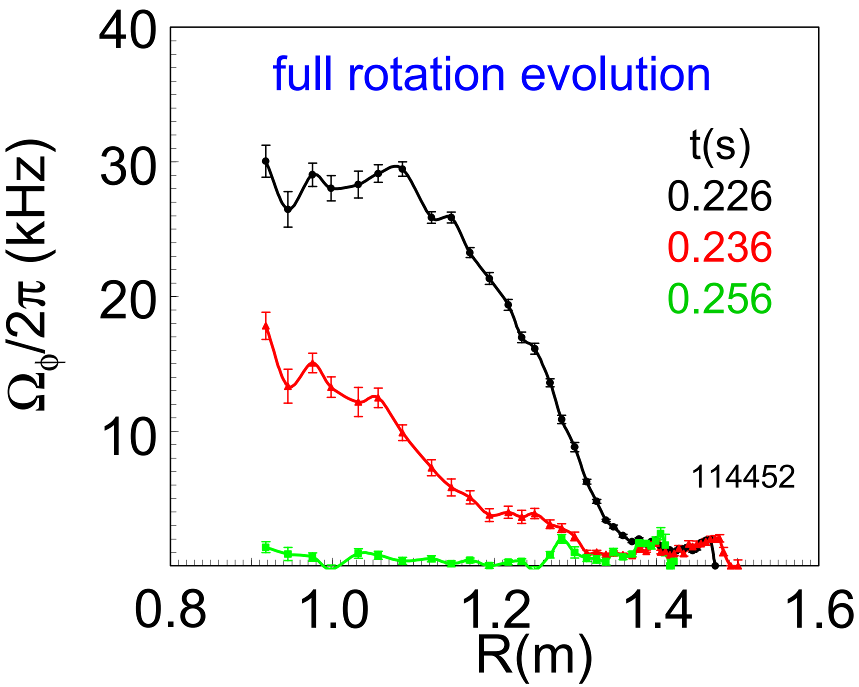
Before RWM activity

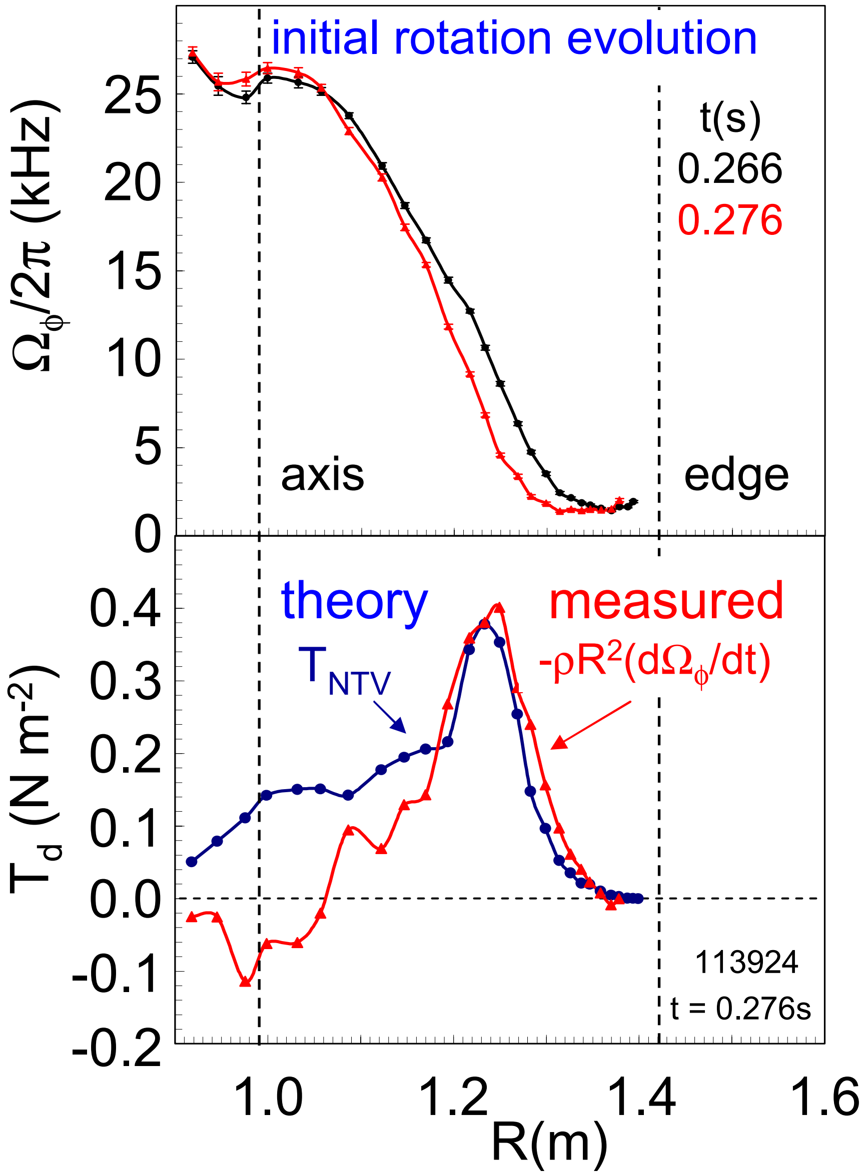


- Visible light emission is toroidally asymmetric during RWM
- DCON theory computation displays mode
  - uses experimental equilibrium reconstruction
  - includes n = 1 – 3 mode spectrum
  - uses relative amplitude / phase of n spectrum measured by RWM sensors

Plasma rotation damping described by NTV theory

- Neoclassical toroidal viscosity (NTV)
- 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)

NSTX

NTV Torque depends on aspect ratio, n, q

- Neoclassical toroidal viscosity (NTV) theory
  (K.C. Shaing et al., Phys. Fluids **29** (1986) 521)

$$T_{NTV} = R\frac{\pi^{1/2} p_i}{v_{t_i}}\left(\Omega_\phi - \Omega_{\text{mode}}\right)\varepsilon^2 \sum_{m,n\neq 0}\left(\frac{\delta B_r^{mn}}{B_\phi}\right)^2 \frac{1.365 n^2 q}{1.182 + 1.365\left|m - nq\right|}$$

dominant m:

$$T_{NTV} = R\frac{\pi^{1/2} p_i}{v_{t_i}}\left(\Omega_\phi - \Omega_{\text{mode}}\right)\varepsilon^2 n^2 q \left(\frac{\delta B_r}{B_\phi}\right)^2$$

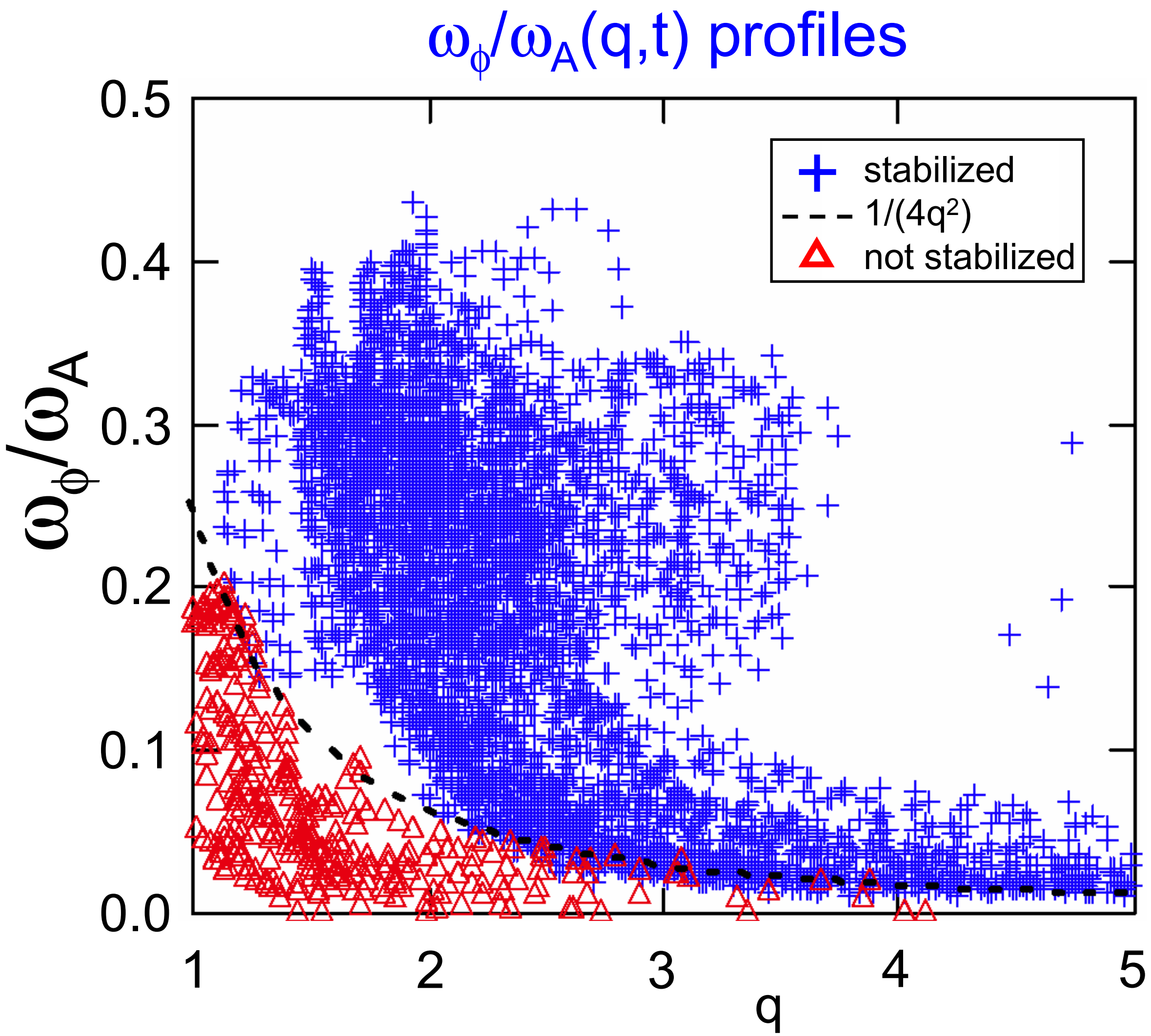
measured $T_i^{0.5}$ profile

measured rotation profile

- *n*, *q* (profile) variation can be considered in a single machine
- ε = 1/A variation can be made between machines

Experimental Ω_{crit} follows Bondeson-Chu theory

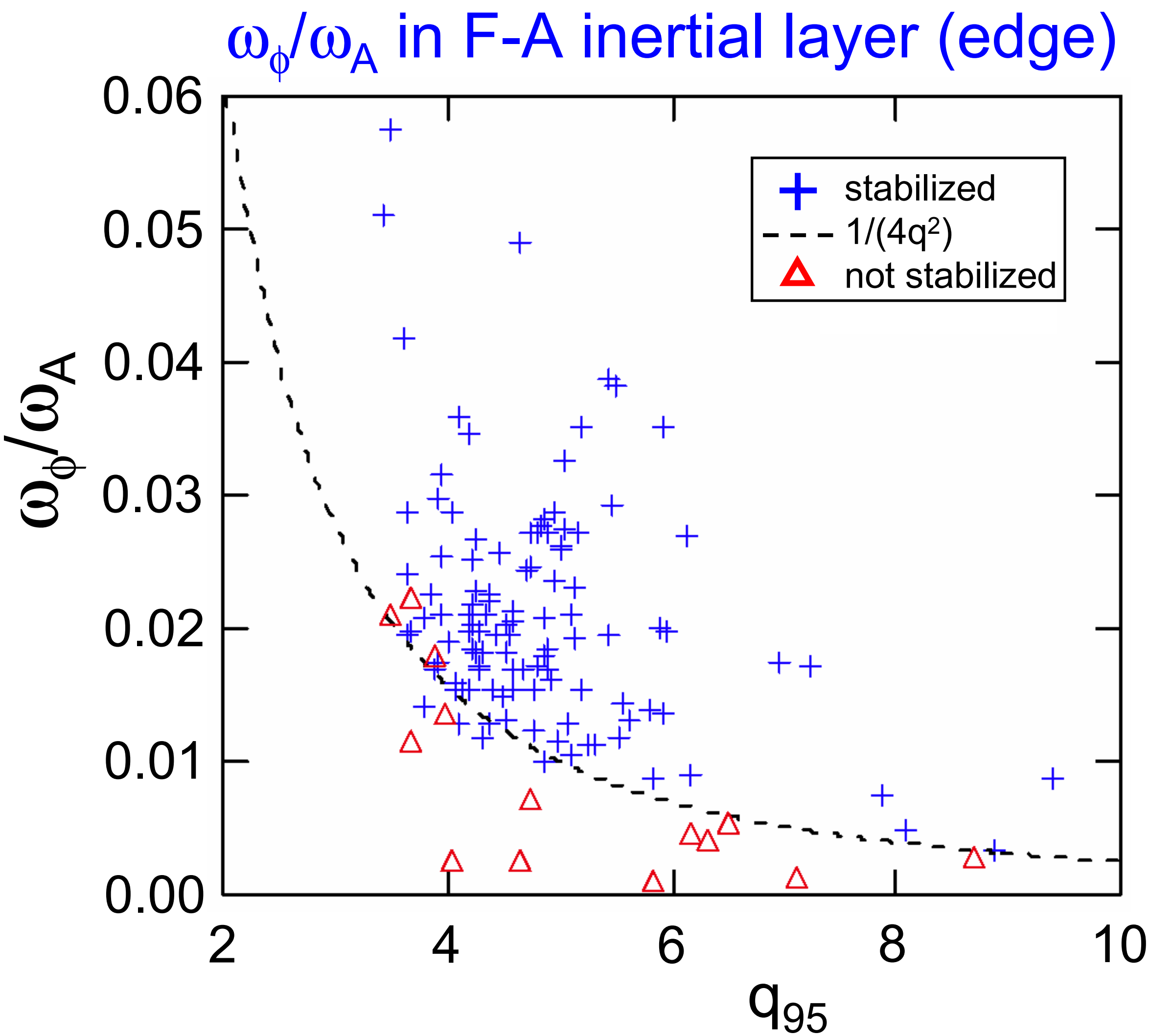
Phys. Plasmas **8** (1996) 3013



- **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 yields $\Omega_{crit} = \omega_A/(4q^2)$
- Neoclassical effect: Is there an $\varepsilon^{0.5}$ scaling?

Ω_{crit} follows F-A theory with neoclassical viscosity

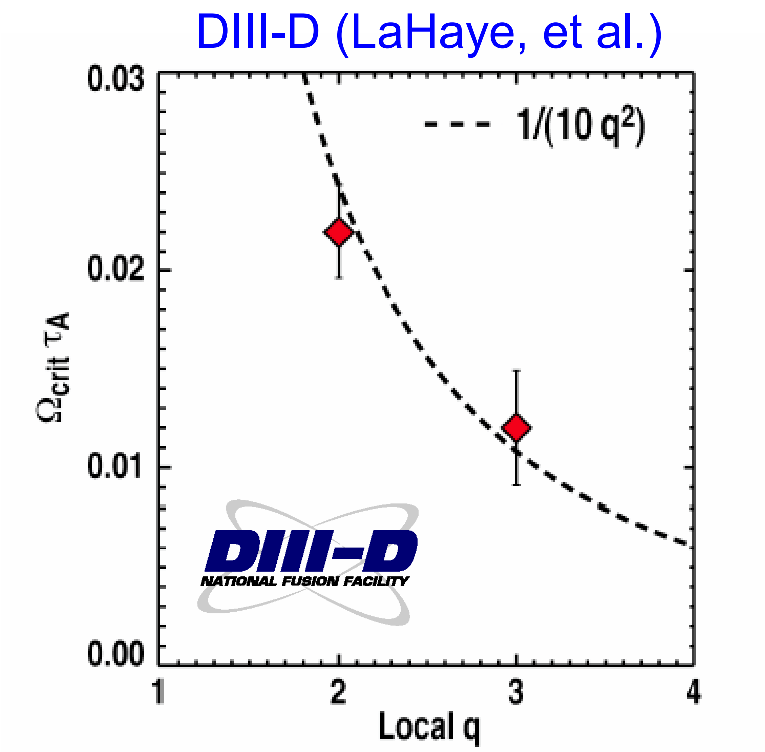
(K. Shaing, PoP 2004)



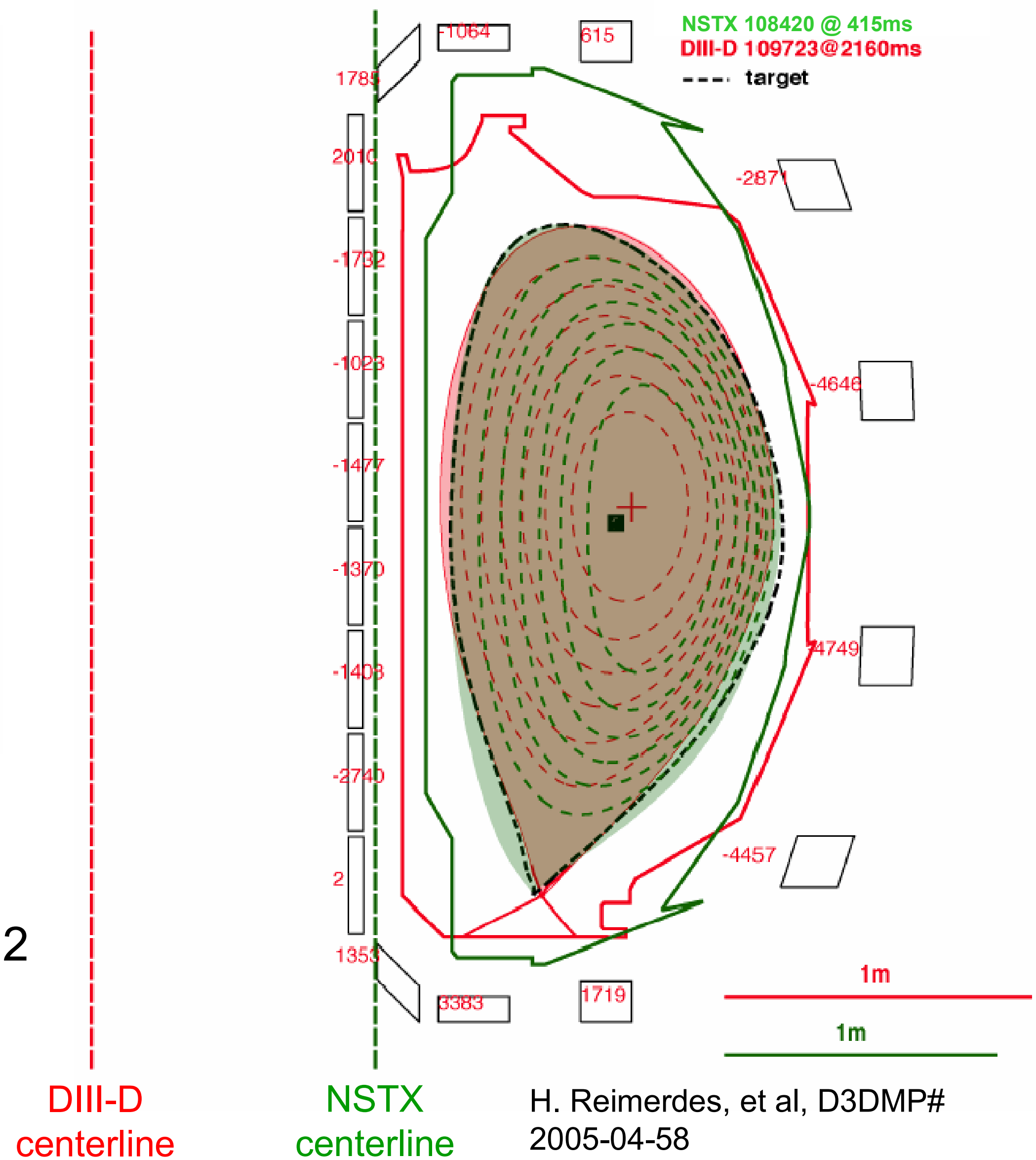
- **Experimental Ω_{crit}**
  - stabilized points: $\beta > \beta_N^{no\text{-}wall}$ (DCON)
  - points not stabilized cannot maintain $\beta > \beta_N^{no\text{-}wall}$
  - regions separated by $\omega_\phi/\omega_A = 1/(4q^2)$
- **F-A Theory**
  - Standard F-A theory yields $\Omega_{crit} \sim 1/q$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

> - $\Omega_{crit} \sim \varepsilon/q^2$ or $\varepsilon^{0.25}/q^2$ depending on RWM dissipation strength

DIII-D/NSTX RWM experiment to investigate q, A effects



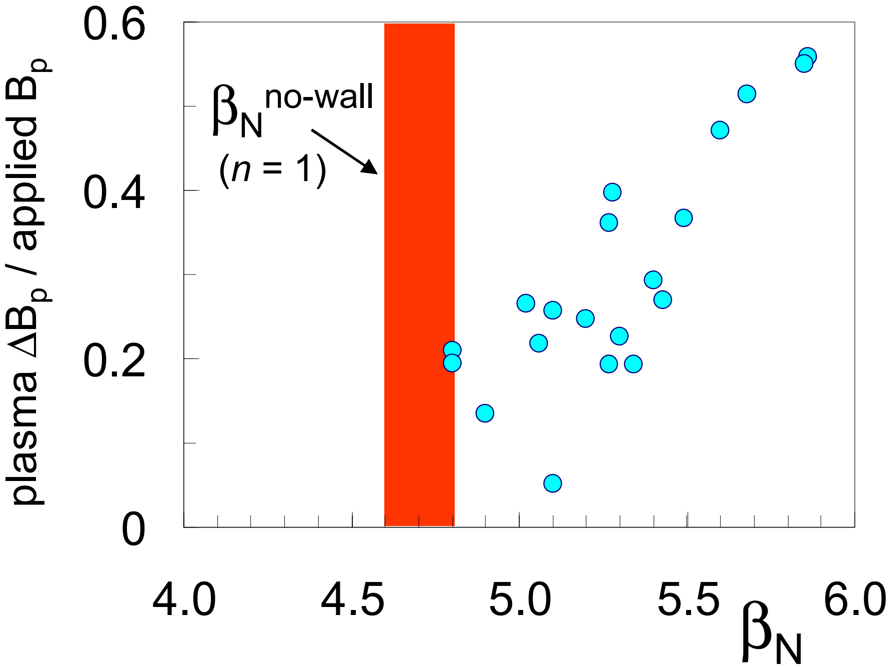
- RWM physics in similar shape
- q and A dependence of
  - Ω_{crit} : A scaling ~ factor 1.2 – 2.2
  - Toroidal rotation damping
  - Resonant field amplification



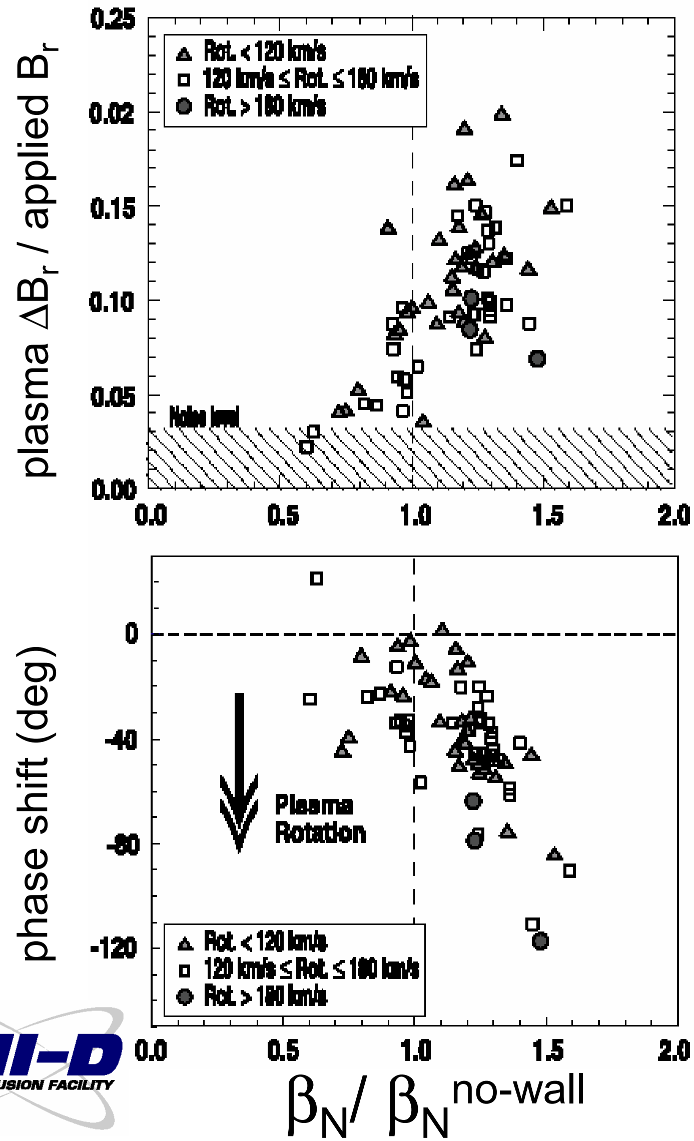
H. Reimerdes, et al, D3DMP# 2005-04-58

Resonant Field Amplification increases at high β_N

NSTX



DIII-D

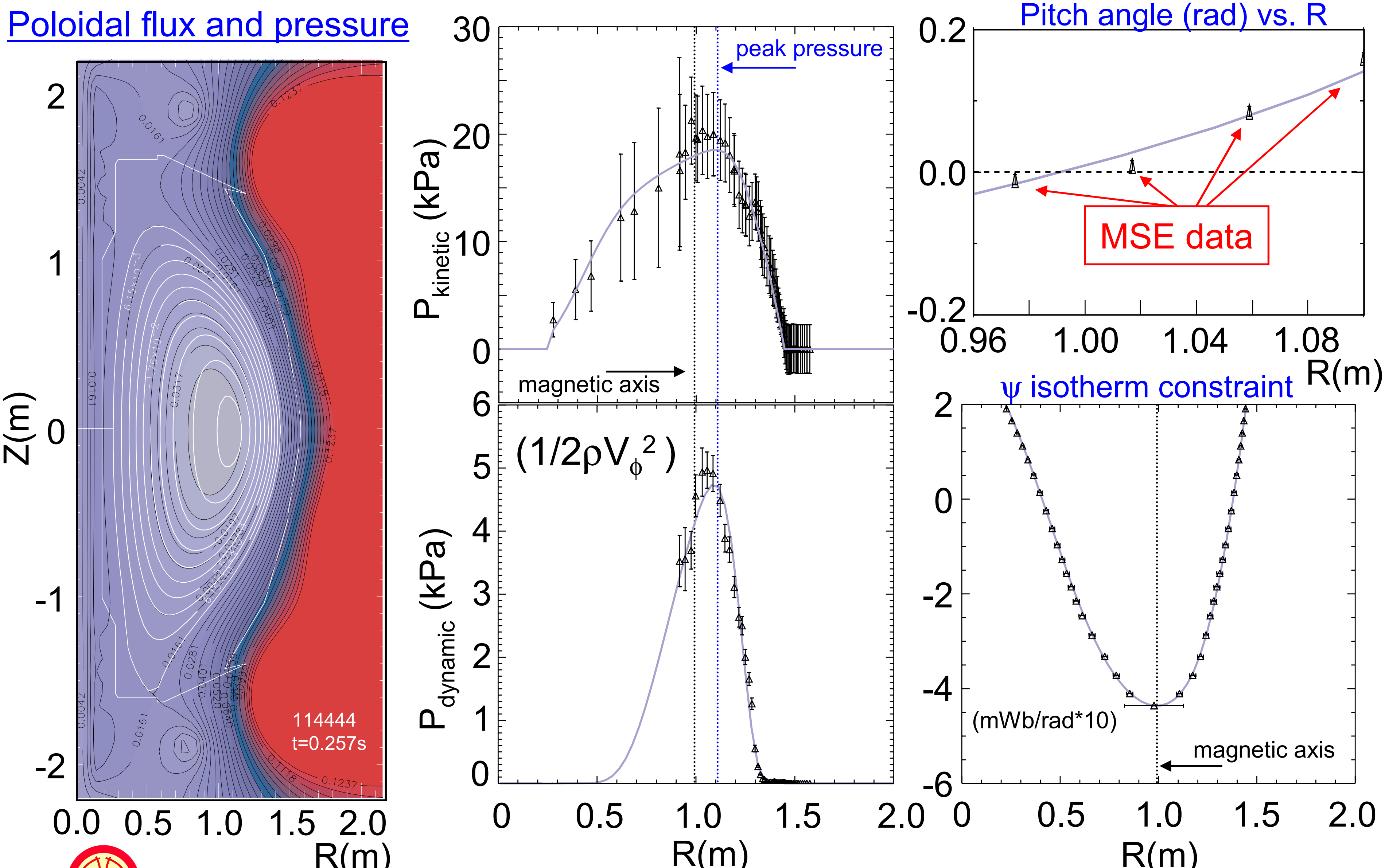


- Plasma response to applied field from initial RWM stabilization coil pair
  - AC and pulsed n = 1 field
- RFA increase consistent with DIII-D
- Stable RWM damping rate of $300s^{-1}$ measured in NSTX, similar to DIII-D

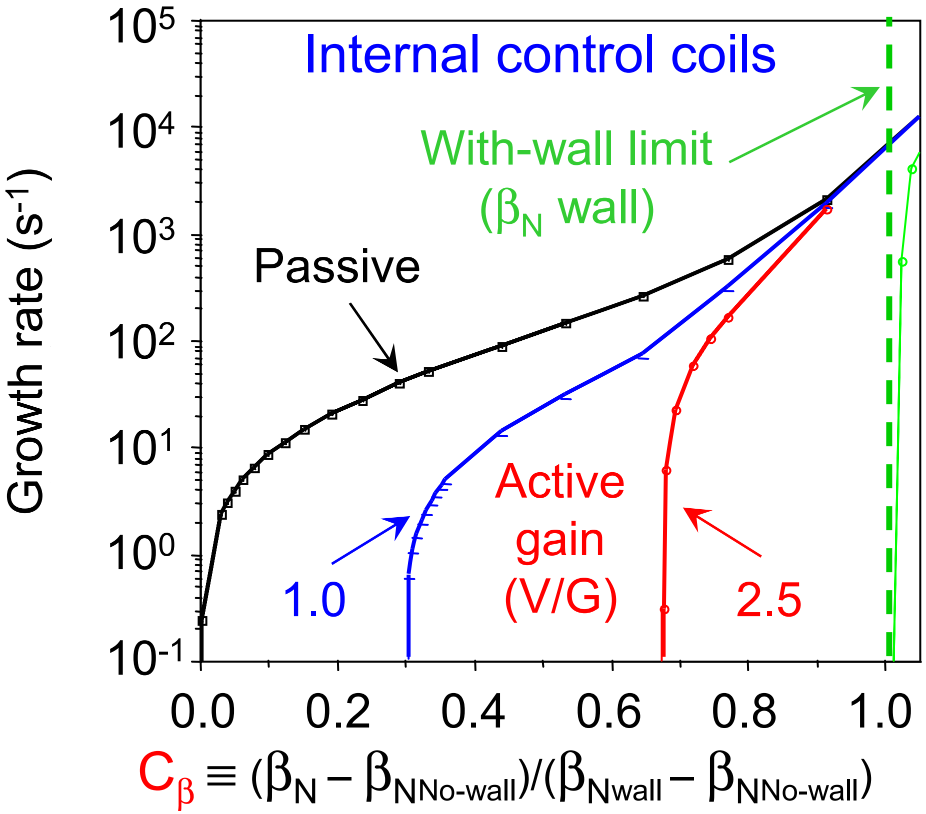
DIII-D NATIONAL FUSION FACILITY

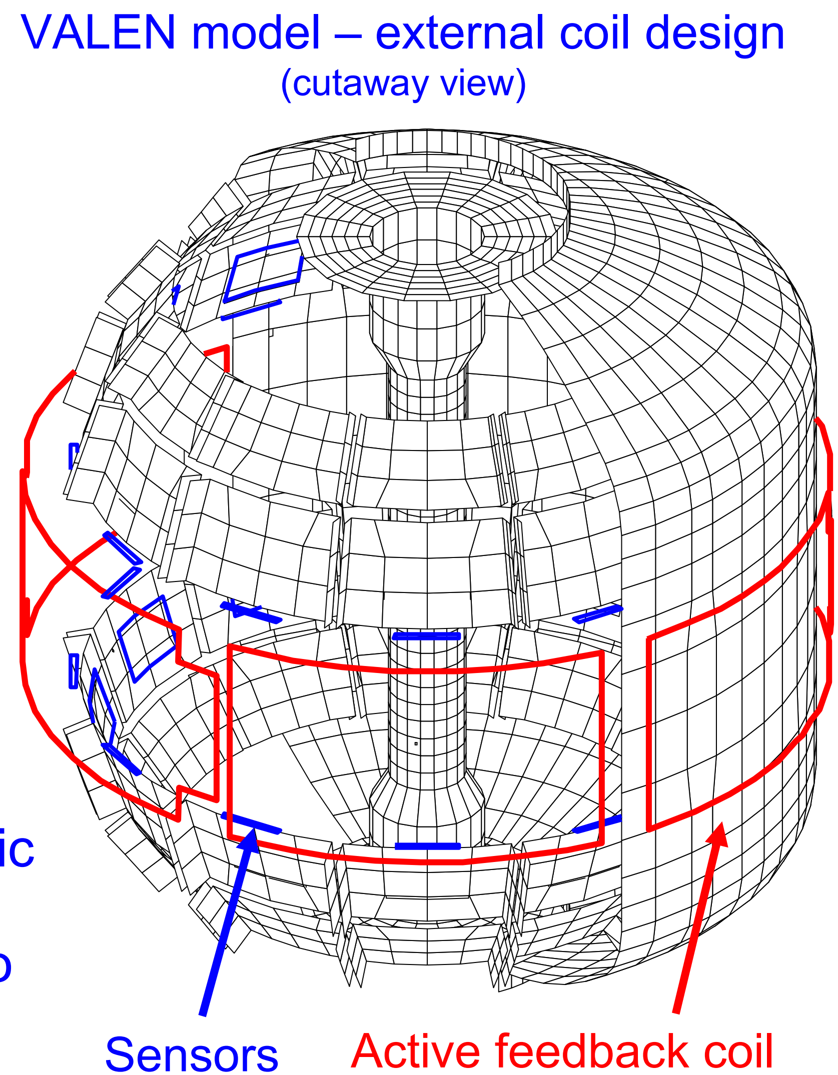
NSTX

Peak pressure shifts significantly off axis: low A, high V_ϕ



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

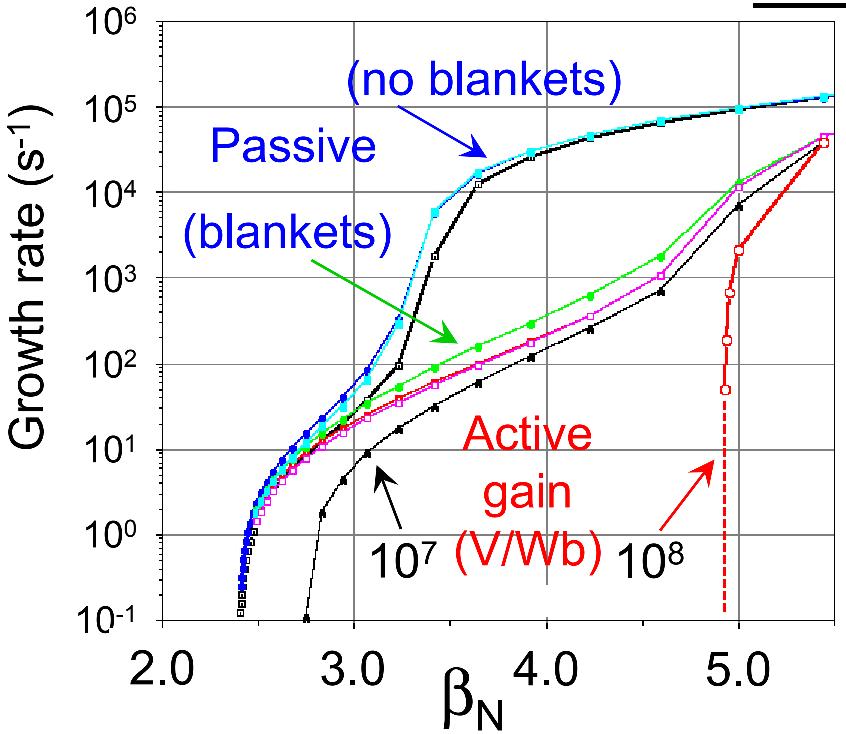




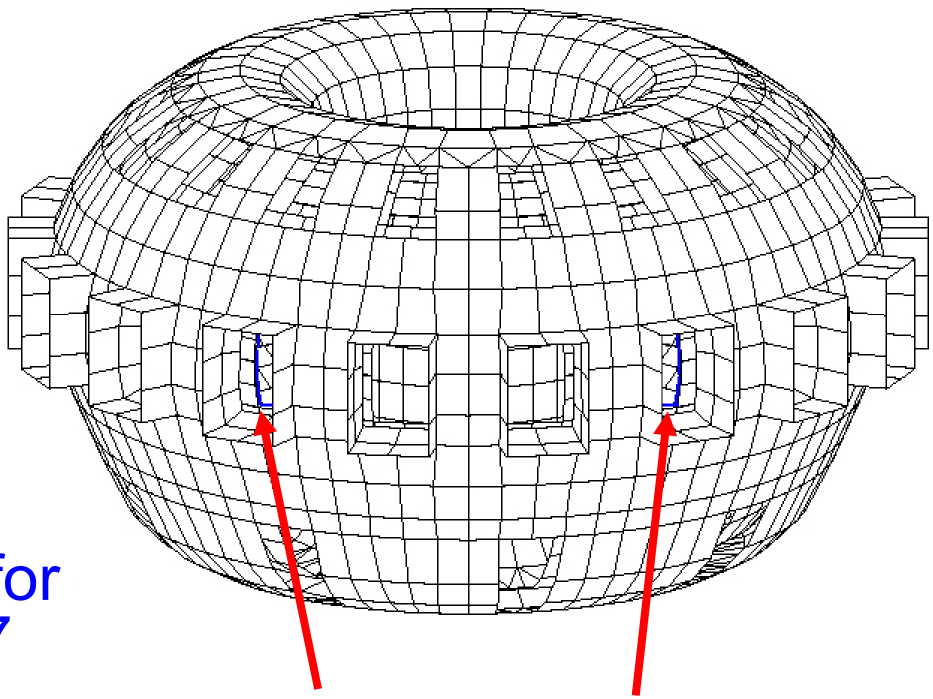
- Control coil / sensor design with realistic geometry
- Internal control coil design computed to reach C_β = 94%

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

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 $\beta_N = 2.7$
- Proposed improvement raises maximum stable β_N to near 5 (!)

Kink/RWM stabilization research at low aspect ratio illuminates key physics for general high β operation

- Plasma with β_t = 39%, β_N = 6.8, β_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 ~ ω_A/q^2 strongly influenced by toroidal inertia enhancement (prominent at low A)
- Rapid, global plasma rotation damping mechanism associated with neoclassical toroidal viscosity (stronger at low A, high q)
- Resonant field amplification of stable RWM increases with increasing β_N (similar to higher A)
- Plasma rotation at low A can significantly alter core pressure gradients
- Full RWM stabilization coil and MSE diagnostic will be used to study and suppress RFA, actively stabilize RWM, sustain high beta in 2005
    - Will allow thorough comparison with higher aspect ratio DIII-D plasmas

NSTX

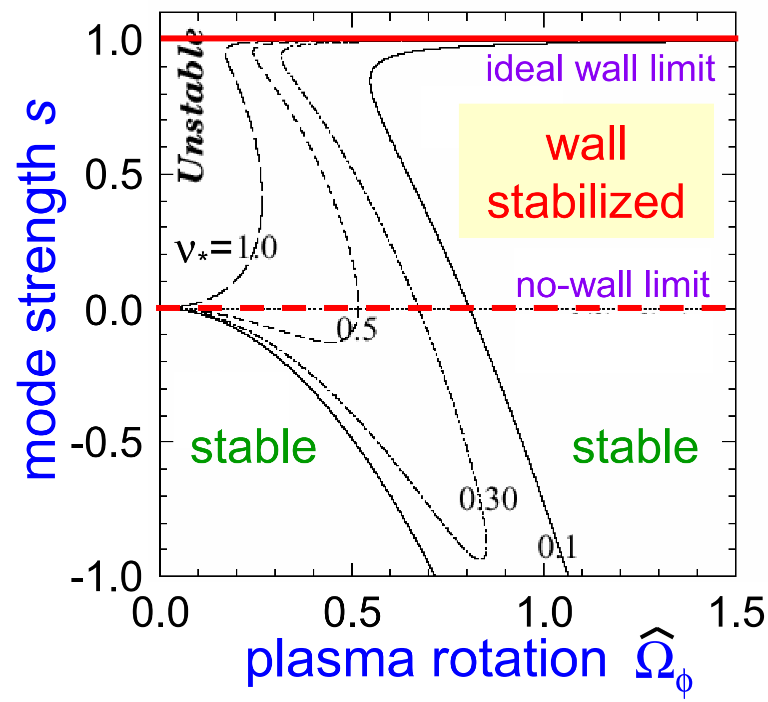
Supporting slides follow

Theory provides framework for wall stabilization study

- **Theory**
  - Ideal MHD stability – DCON (Glasser)
    - arbitrary 2-D geometry
  - RWM passive/active stability – VALEN
    - 3-D geometry
  - Drift kinetic theory (Bondeson – Chu)
    - cylindrical; toroidal expansion
  - RWM dynamics (Fitzpatrick – Aydemir)
    - cylindrical

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

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

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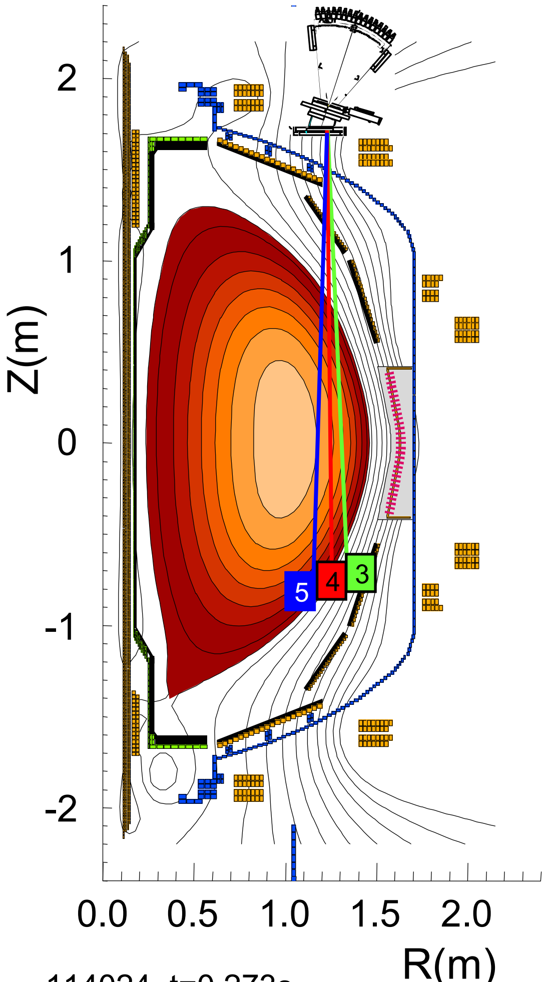
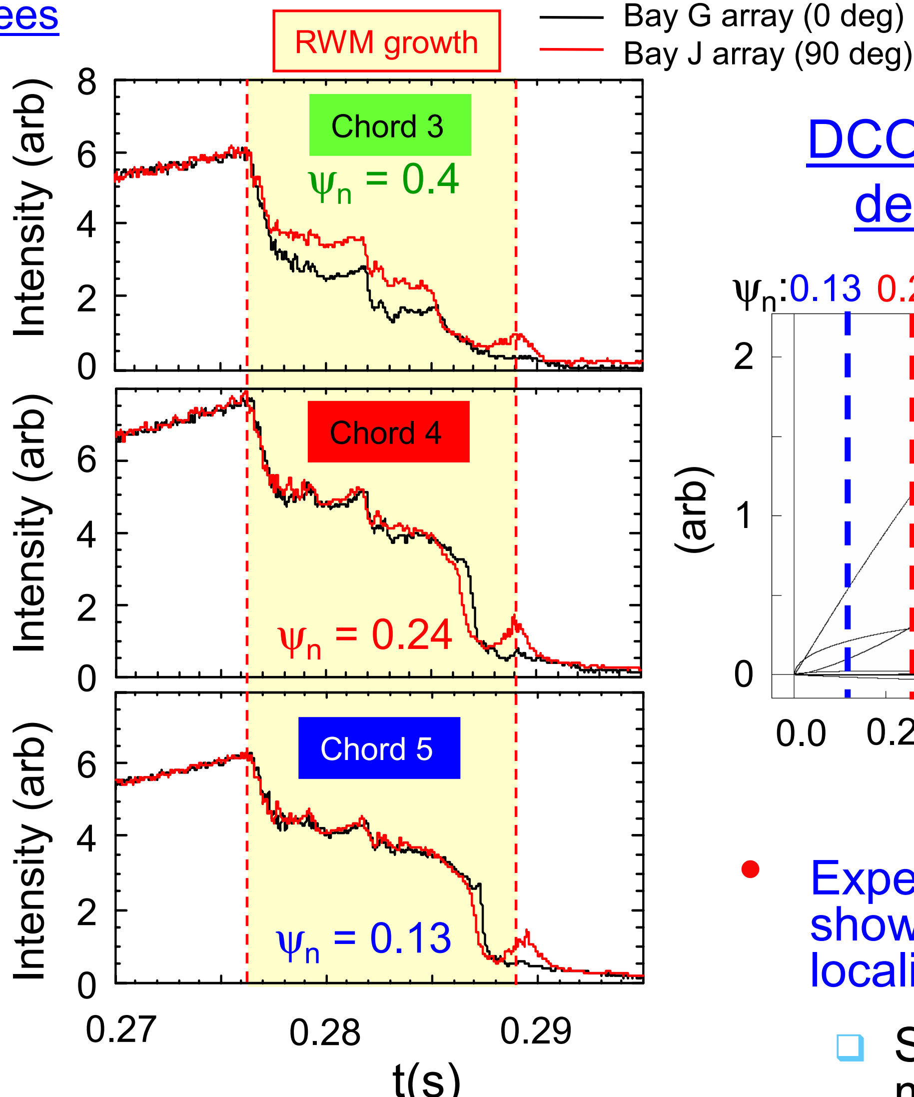
Soft X-ray emission shows toroidal asymmetry during RWM

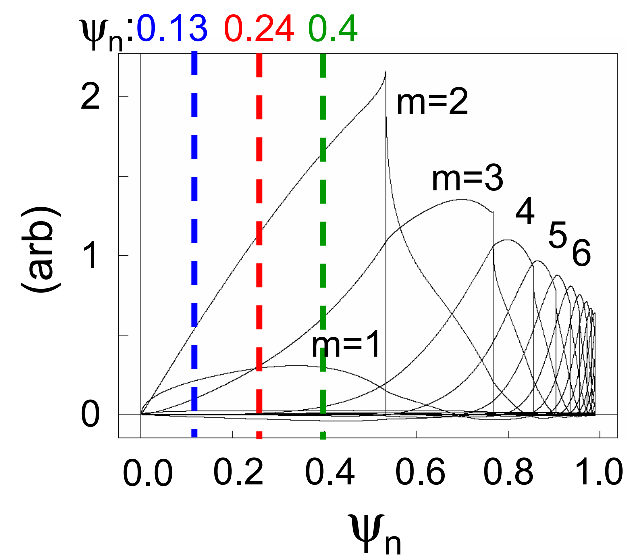
USXR separated by 90 degrees



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



DCON *n* = 1 mode decomposition



- Experiment / theory show RWM not edge localized
  - Supported by measured ΔT_e