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Macroscopic Stability (MHD) Physics in NSTX

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For the NSTX Research Team

DOE Mid-Term Review of Major MFE Facilities

September 21st, 2006

Gaithersburg, MD

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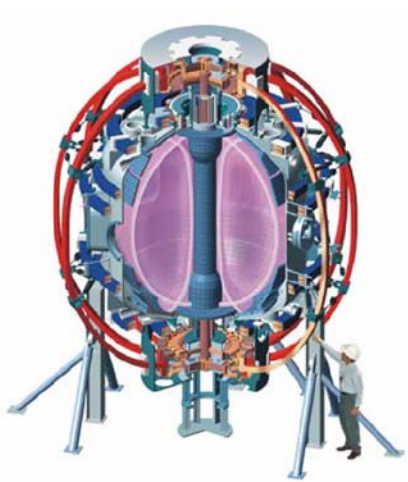

Culham Sci Ctr
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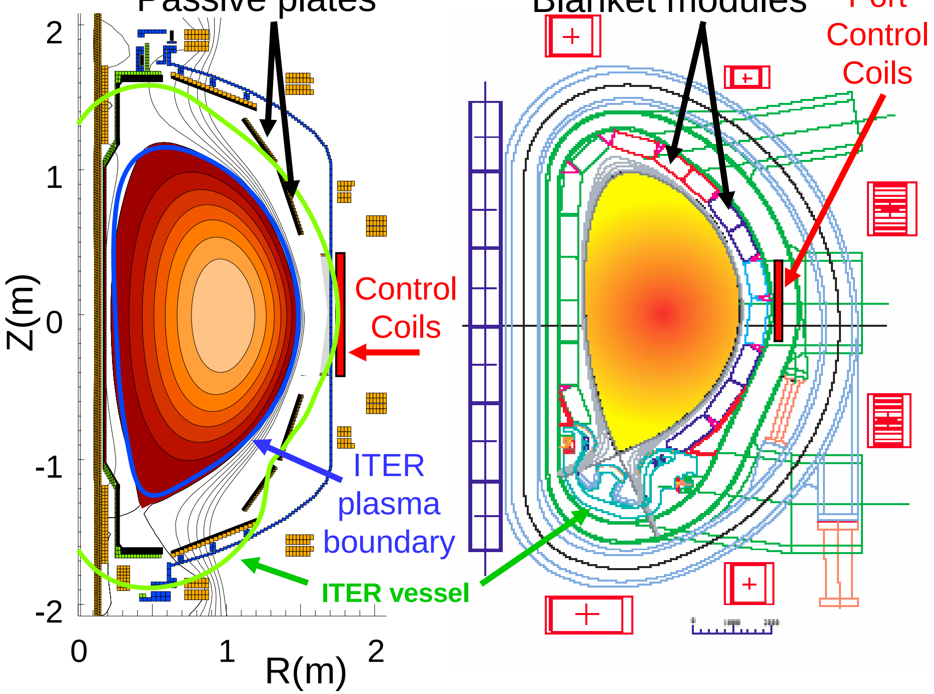
IPP, Garching
ASCR, Czech Rep

NSTX is conducting world-leading MHD physics research addressing critical fusion program issues

- Great progress
  - Key research topics
  - Milestones reached ahead of schedule
  - High-level publications and invited talks
- Flexible research plan has adapted to program needs
  - Addressing relevant physics for ITER, CTF, KSTAR

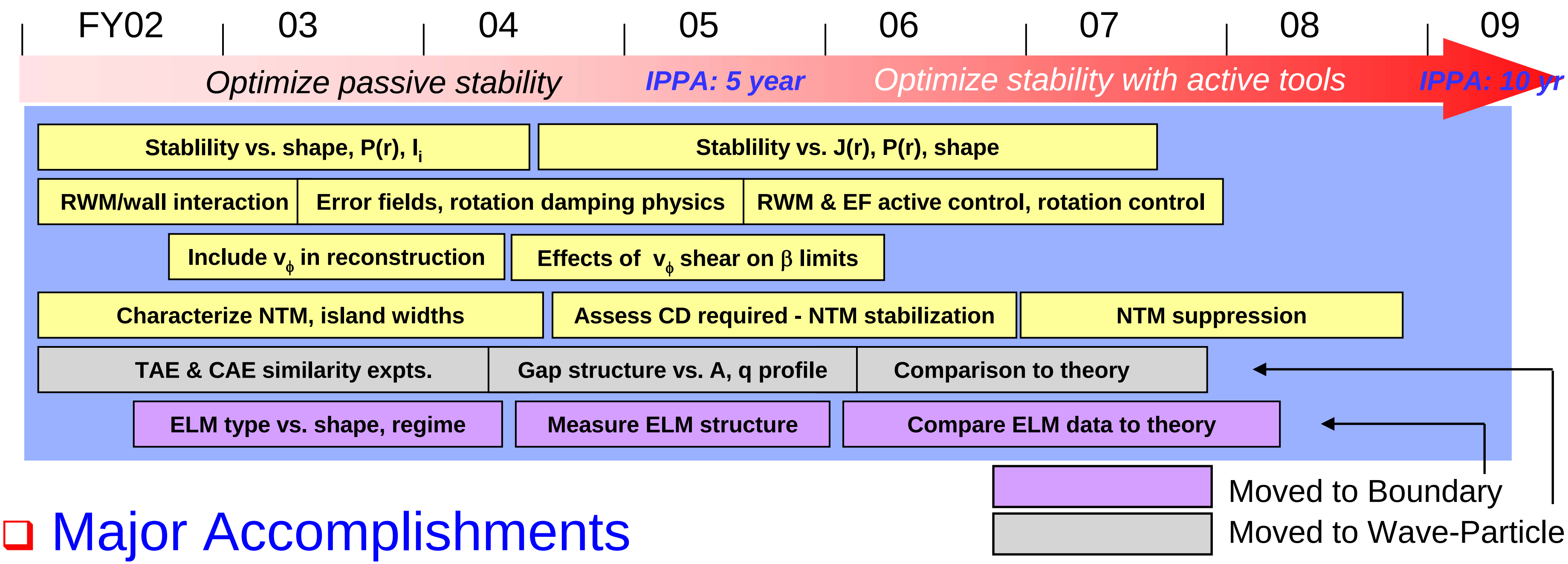
NSTX / ITER RWM control



Advantage: low aspect ratio, high β provides high leverage to uncover key tokamak physics (e.g. RWM control, rotation damping, high elongation)

MHD Research Ahead of Schedule, now Addressing Advanced Goals

(Timeline from 5 Yr Plan)



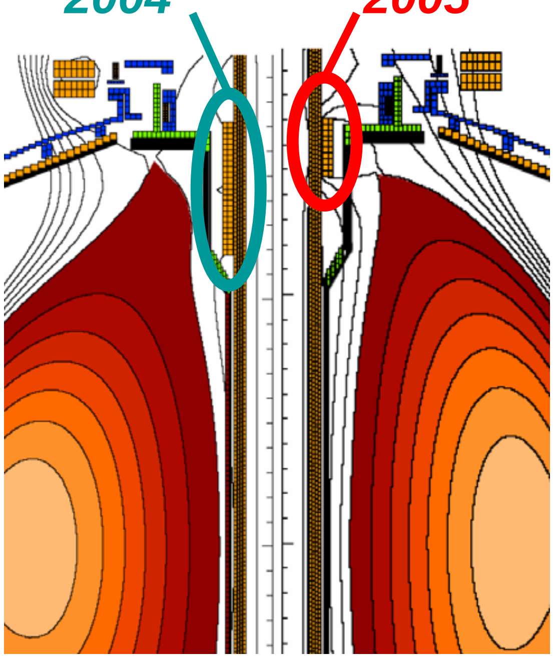
Major Accomplishments

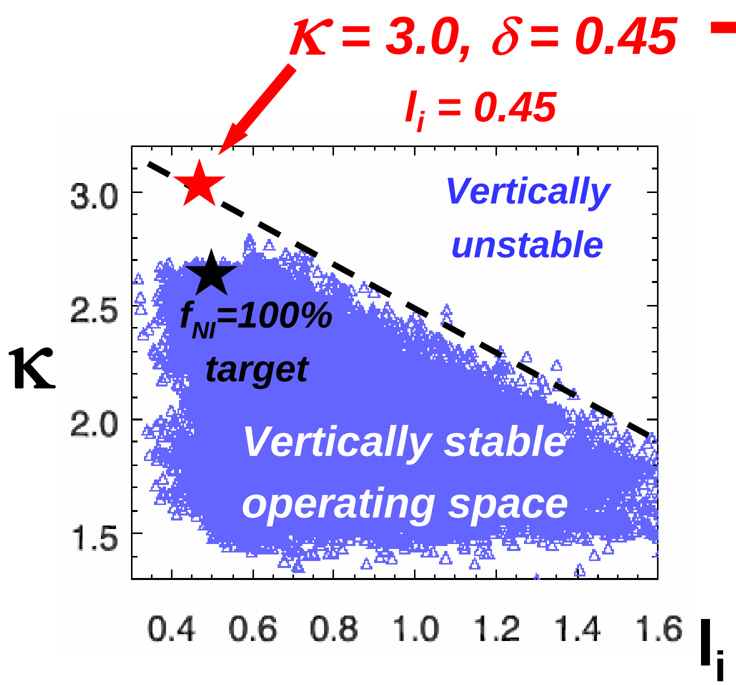
- RWM active stabilization at low rotation (ITER-relevant) (Sabbagh, PRL **97** (2006) 045004)
- Observed plasma rotation damping by NTV physics (Zhu, PRL **96** (2006) 225002)
- Unstable n = 1 – 3 RWM observed (Sabbagh, NF **46** (2006) 635)
- RWM critical rotation speed depends on V_ϕ profile, q; A (Sontag, PoP **12** (2005) 056112) (Reimerdes, PoP **13** (2006) 056107)
- Rotation + ω^* effects may provide 1/1 mode saturation (Menard, NF **45** (2005) 539)
- Stability vs. shape, P(r), l_i studied (Gates, PoP **13** (2006) 056122) (Sabbagh, NF **44** (2004) 560; Menard, PoP 11 (2004) 639)
- V_ϕ, flux-isotherm, MSE in equilibrium reconstructions (Sabbagh, NF **46** (2006) 635)

Extreme elongation at low l_i opens possibility of higher β_P, f_{BS} operation at high β_T

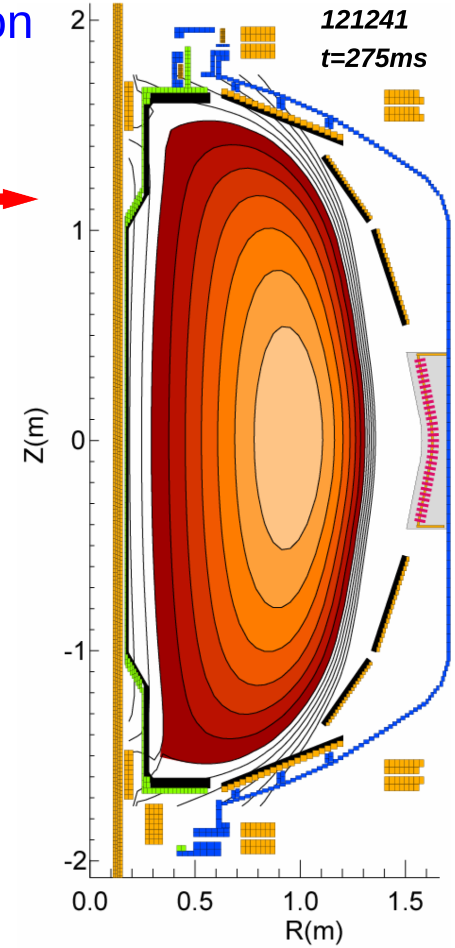
- Five-year plan shape target already reached
- Sustained $\kappa \geq 2.8$ (reached $\kappa = 3$) for many τ_{WALL} using rtEFIT isoflux control
  - Allowed by divertor coil upgrade in 2005, **no** in-vessel vertical position control coils
- Stability analysis of new operational regime under investigation
- High κ research important for CTF design studies

Divertor coil upgrade



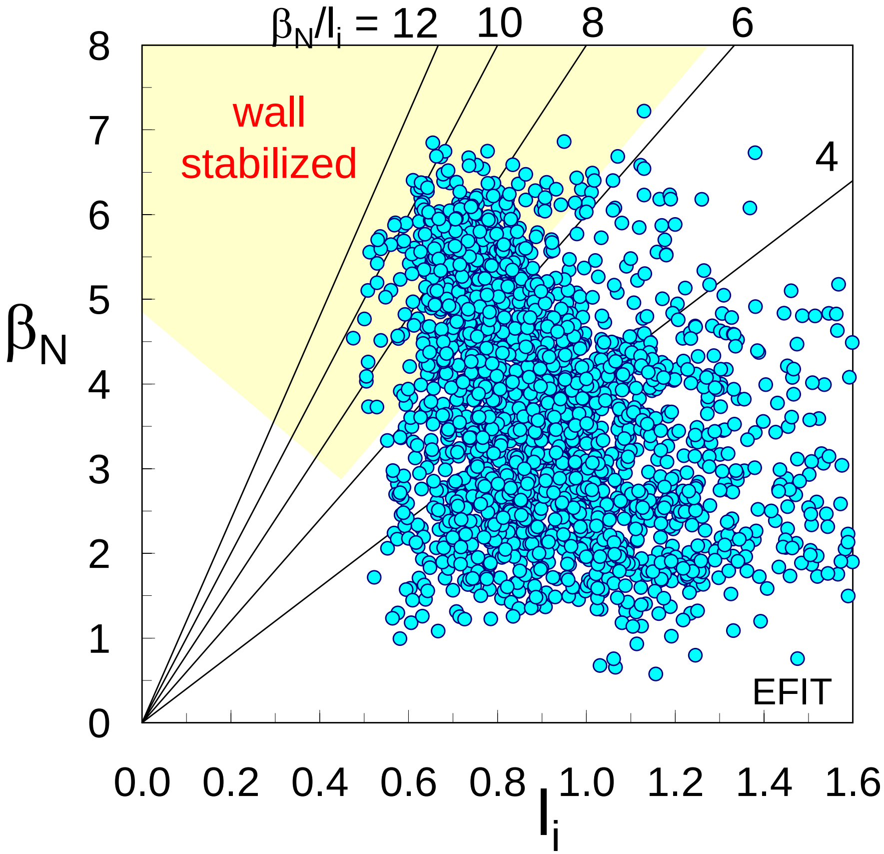


(Gates, et al., PoP **13** (2006) 056122.)
(Gates, et al., NF **46** (2006) 17.)

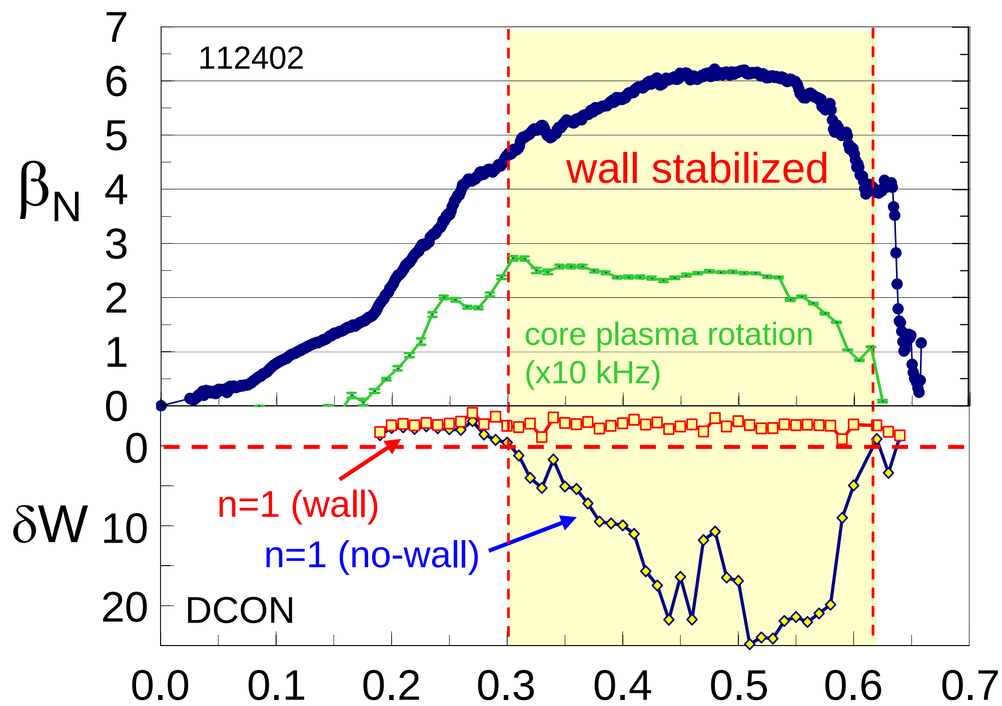


Kink stabilization by wall and RWM passive stabilization by rotation allows sustained plasma operation at maximum β

- High β_t = 39%, β_N = 7.2 reached



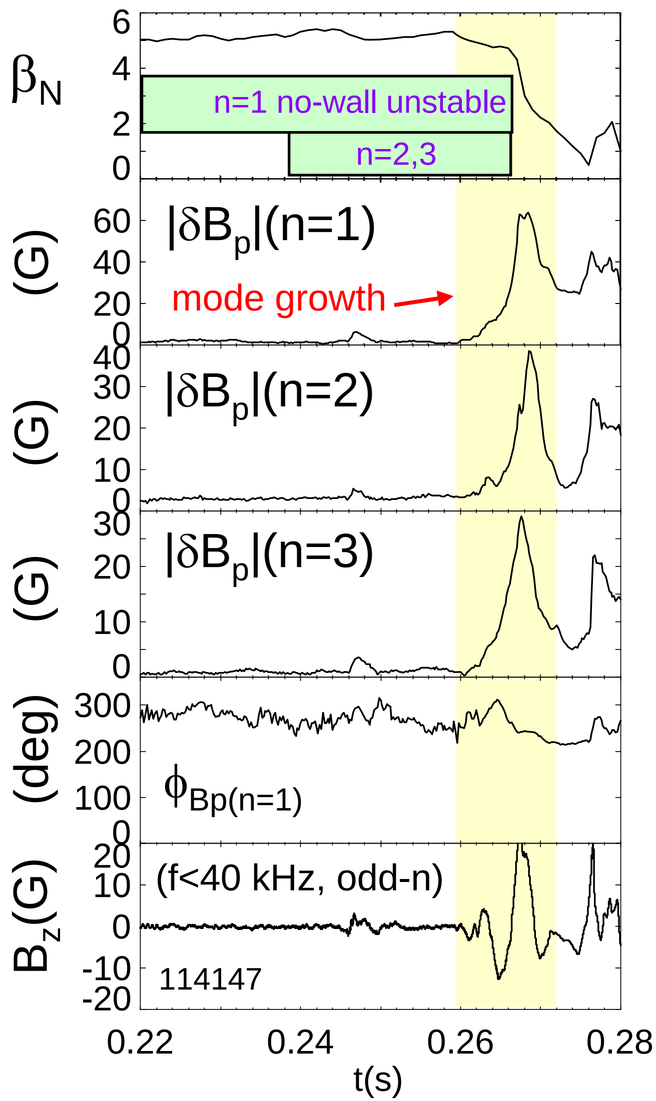
- Operation with $\beta_N/\beta_N^{no\text{-}wall}$ up to 1.5 at highest β_N for pulse >> τ_{wall}, ~ τ_{cr}



*(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 with n = 1 - 3 observed

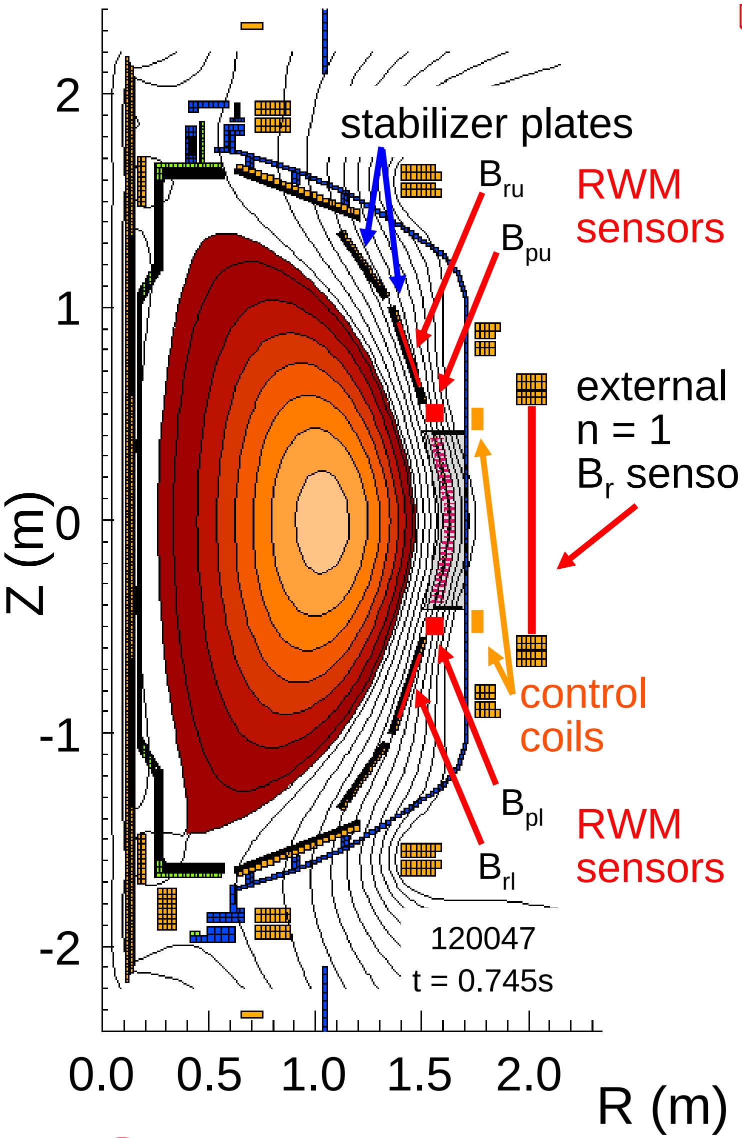


- First such identification in a tokamak device
- Toroidal mode number n > 1 theoretically less stable at low A
  - n > 1 physics important for advanced tokamak operation
- Unstable RWM dynamics follow theory

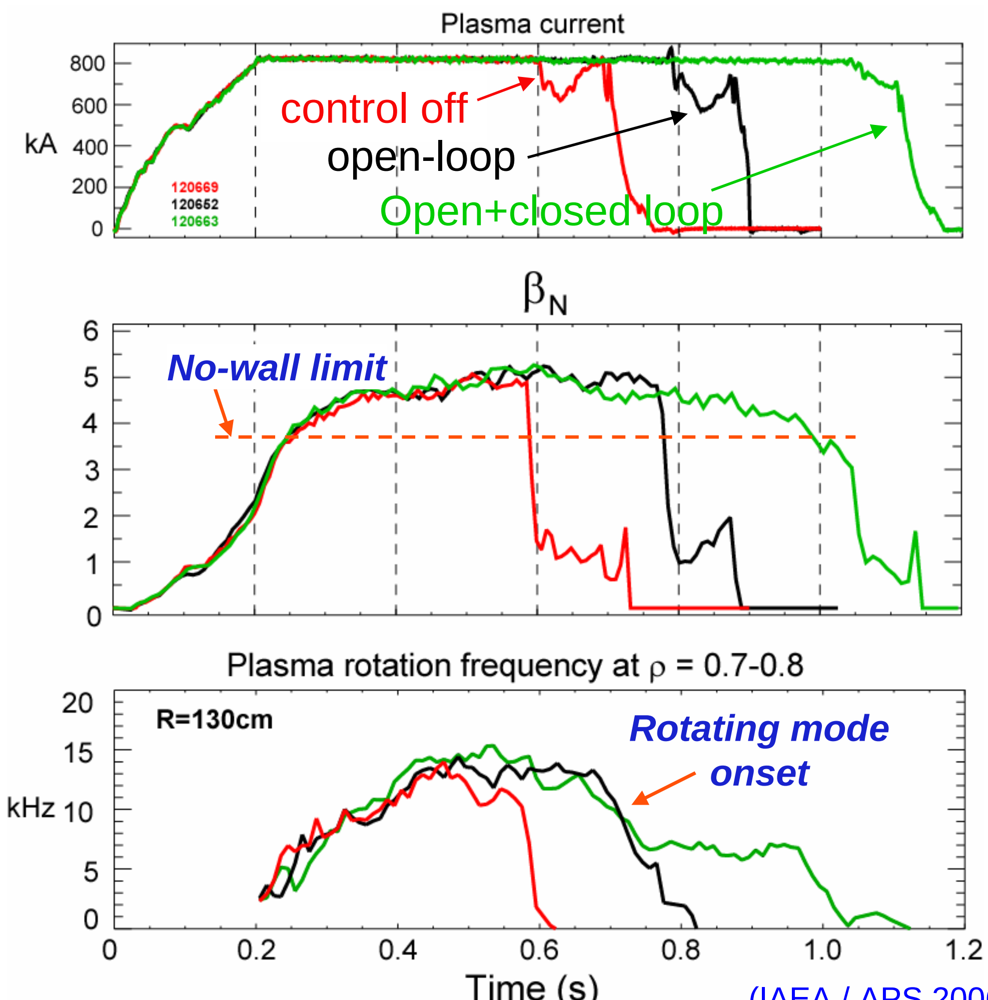
  (Fitzpatrick, Phys. Plasmas **9** (2002) 3459)
  - measurable mode rotation can occur during growth
  - growth rate, rotation frequency ~ $1/\tau_{wall}$
    - << edge Ω_ϕ > 1 kHz
  - RWM phase velocity follows plasma flow

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

RWM active control system, rotation control installed

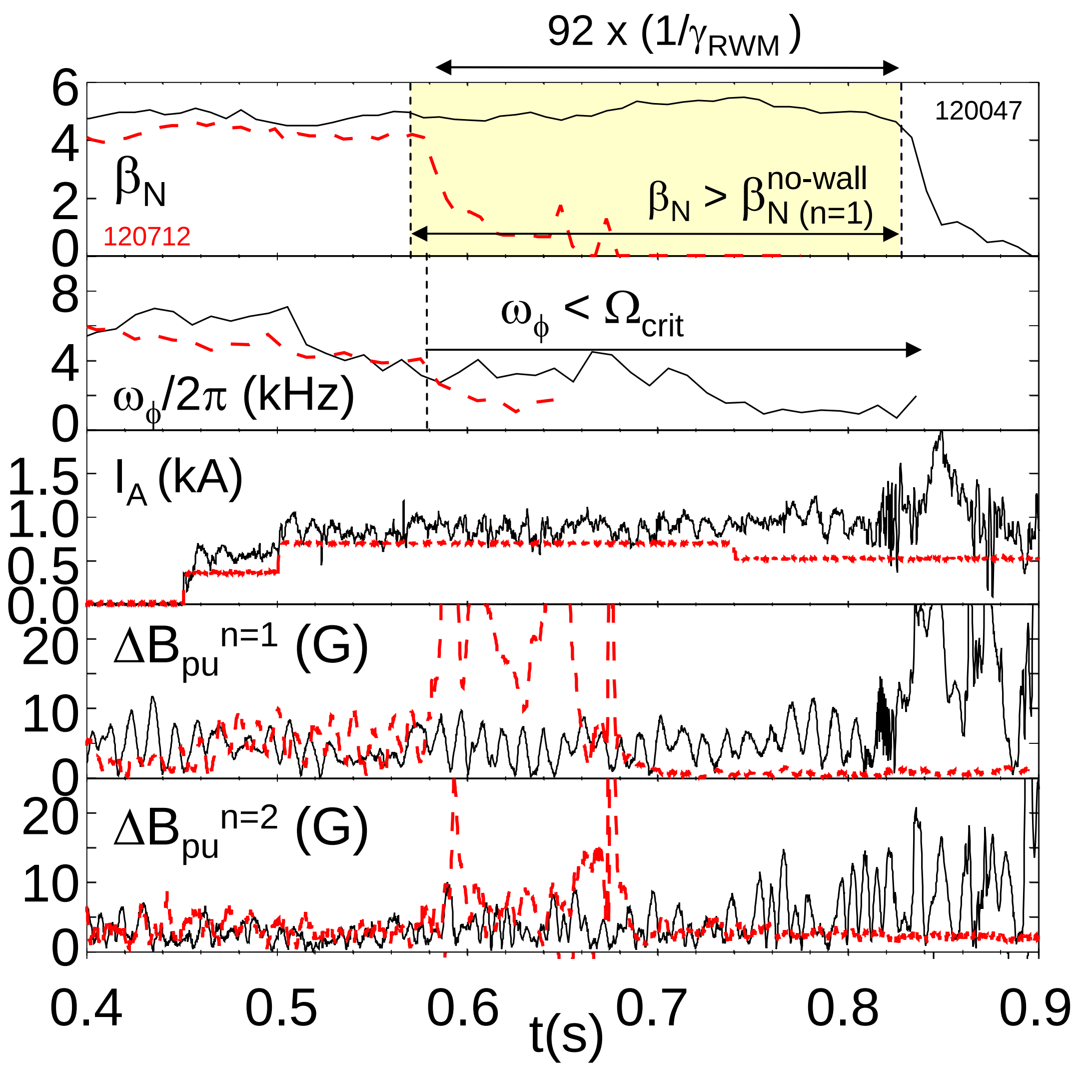


- Dynamic error field correction (DEFC) increases pulse length
  - Combination of open + closed loop control yielded best result



(IAEA / APS 2006)

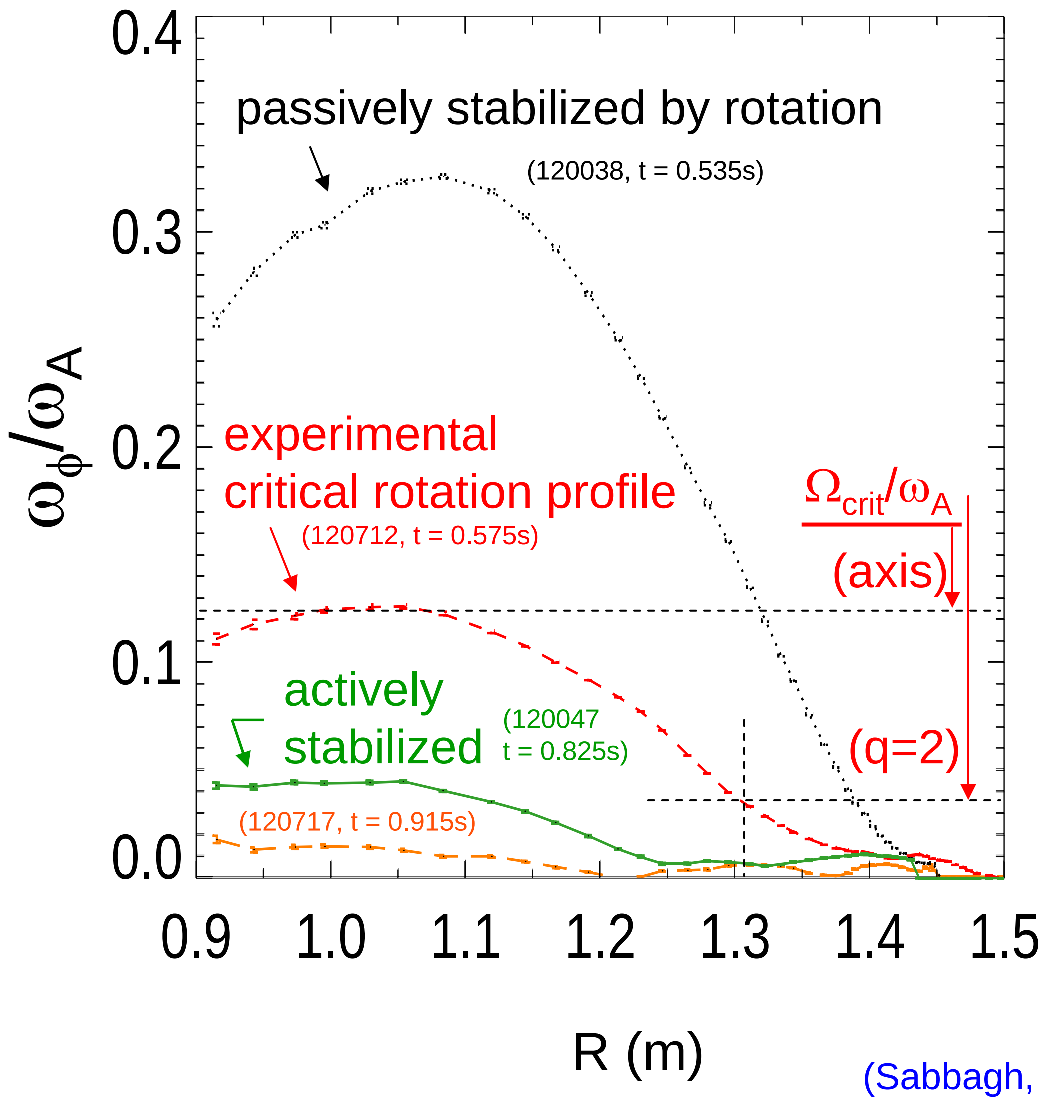
RWM stabilized at ITER-relevant rotation for ~ $90/\gamma_{RWM}$



- 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
  - 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

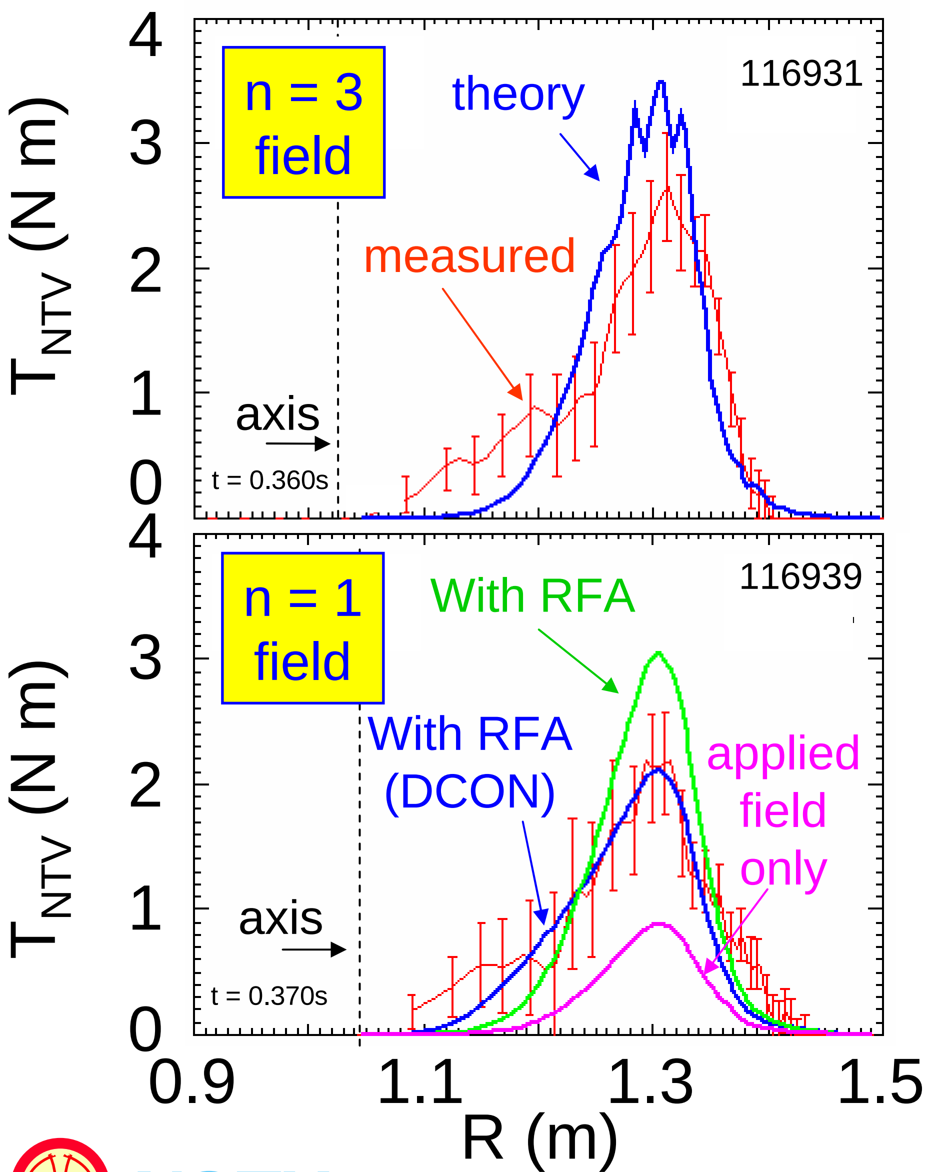


- Rotation typically fast and sufficient for RWM passive stabilization
  - Reached $\omega_\phi/\omega_A = 0.48|_{axis}$
- Non-resonant n = 3 magnetic braking used to slow entire profile
  - The $\omega_A/\Omega_{crit} = 0.2|_{q = 2}$
  - The $\omega_A/\Omega_{crit} = 0.3|_{axis}$
  - Rotation less than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

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

*(Sontag, et al., PoP **12** (2005) 056112.)

Observed plasma rotation braking follows NTV theory



- First quantitative agreement using full neoclassical toroidal viscosity theory (NTV)
  - Due to plasma flow through non-axisymmetric field
  - Trapped particle effects, 3-D field spectrum important
- Pressure-driven resonant field amplification (RFA) increases damping at high beta
  - Included in calculations
  - Based on applied field, or DCON computed mode spectrum
- Viable physics for simulations of plasma rotation in future devices (ITER, CTF, KSTAR)

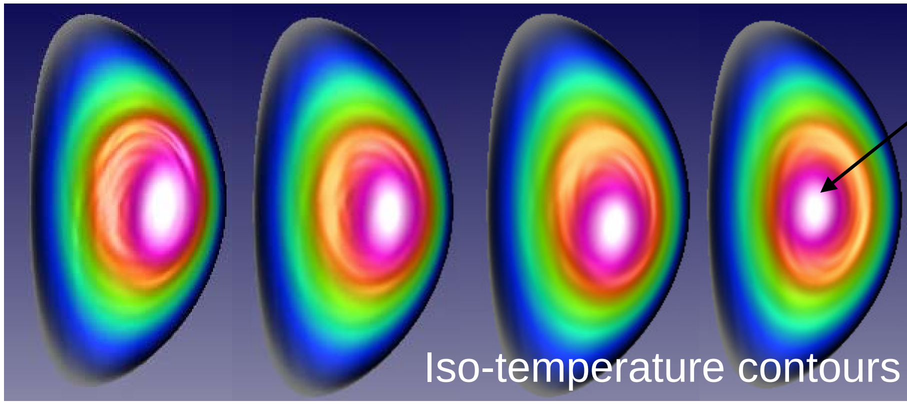
(Zhu, et al., PRL **96** (2006) 225002.)
Columbia U. thesis dissertation

Combination of rotation and two-fluid effects may explain experimentally observed saturated 1/1 mode

Saturation with hot spot pulled away from x-point

Co-injection
w/ 2-fluid

M_A=+0.3



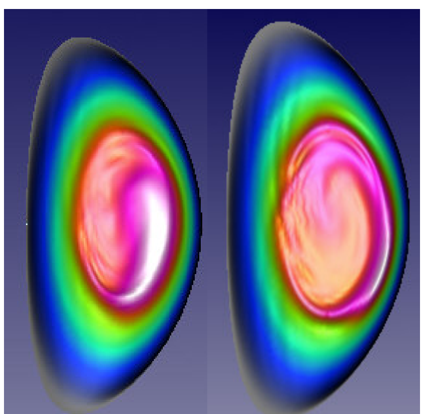
Displaced core
"hot-spot"

Nonlinear 2-fluid MHD simulations
(M3D)

Mode crashes faster than single-fluid MHD

Counter injection
w/ 2-fluid

M_A=-0.3



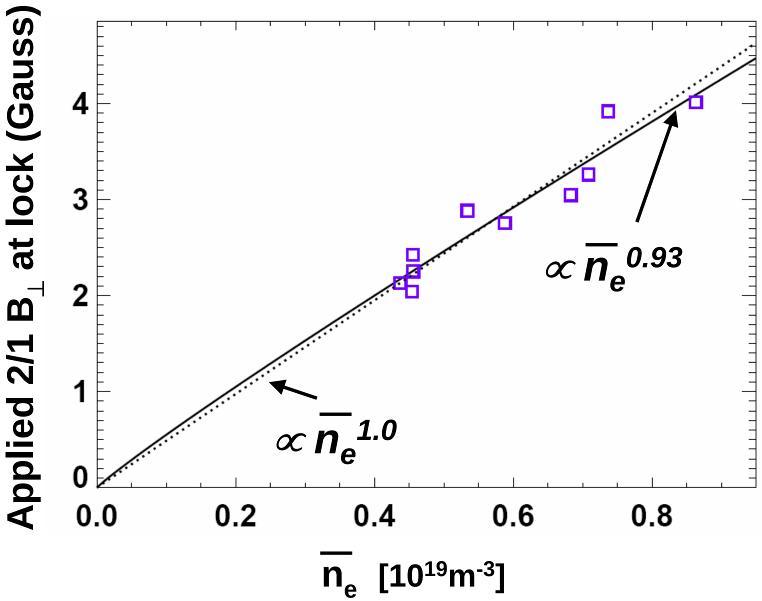
- Sawtooth stabilization physics critical for ITER
- Rotational and kinetic stabilization effects are amplified at high β and M_A
- Sustained high rotational shear can cause 1/1 saturation in simulations, but shear is greatly reduced by NTV in experiments

(Menard, et al., NF **45** (2005) 539.)

NSTX

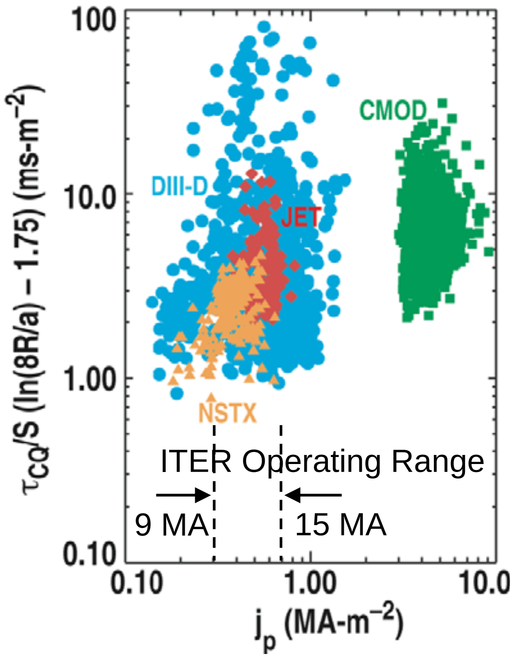
Program adaptation to support ITPA / ITER locked mode threshold and disruption studies

(1) Locked mode threshold



- NSTX contributing low-A, low B data
  - density scaling nearly linear, similar to higher-A
  - Will contribute B, q scaling data for ITER size scaling

(2) Disruption studies



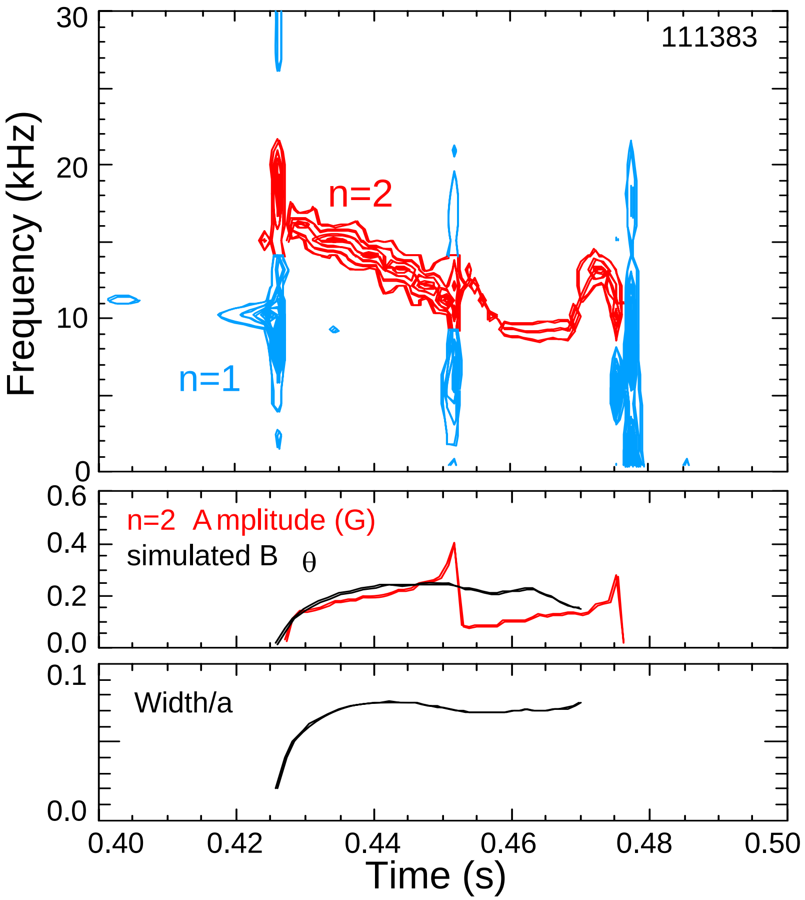
(GA report A25385)

- NSTX data contributes dependence of current quench time, τ_{CQ} on A
  - Important test of theory for ITER, CTF
  - τ_{CQ} independent of plasma current density when A dependence of plasma inductance is included

Low A, high β favorable for NTM seeding / stabilization study

- NTM seeding from large sawteeth could greatly reduce ITER β-limit
- Several modes (e.g. sawteeth*, RWMs**) seed other MHD modes
  - Large q = 1 radius, high β, mode coupling at low-A makes seeding process easier
  - NTM stabilization effects amplified at low-A (GGJ $\propto \varepsilon^{3/2}$) – NTM less deleterious
- Adaptation: Priority given to study most deleterious modes in 2004 – 2006
  - NTM study planned 2007 - 2008
  - Exploit 12 channel MSE, reflectometer, fast multi-filter USXR capabilities
  - 2007 - 2008 plans for NTM suppression by EBW subsequently delayed

Sawtooth excitation of n = 2

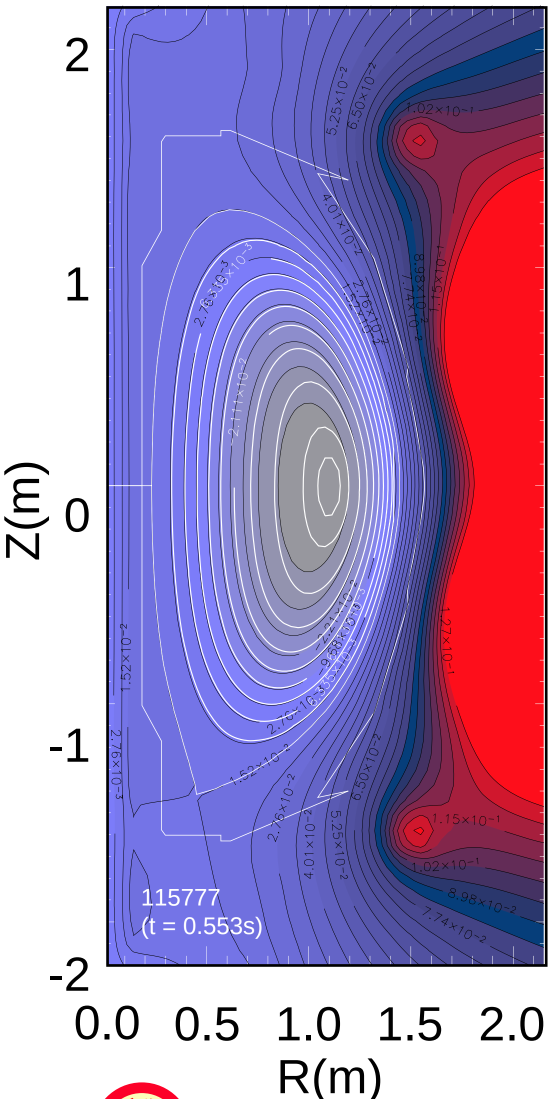


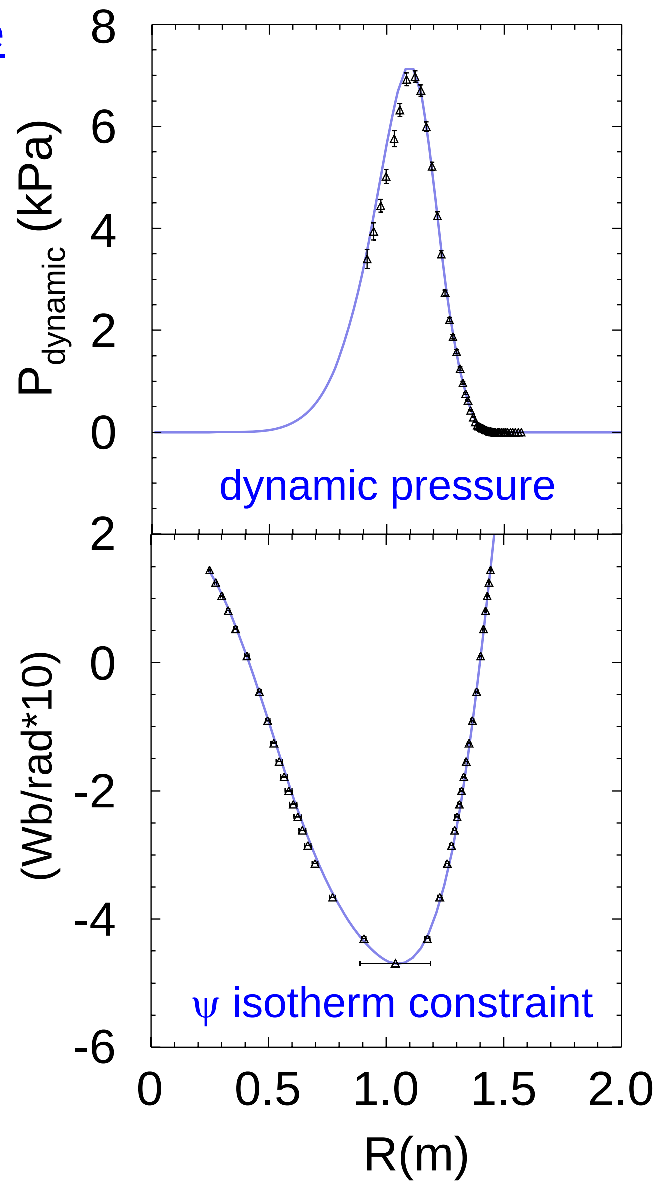
- Sawtooth excites n = 2, but n = 2 can decrease post-crash

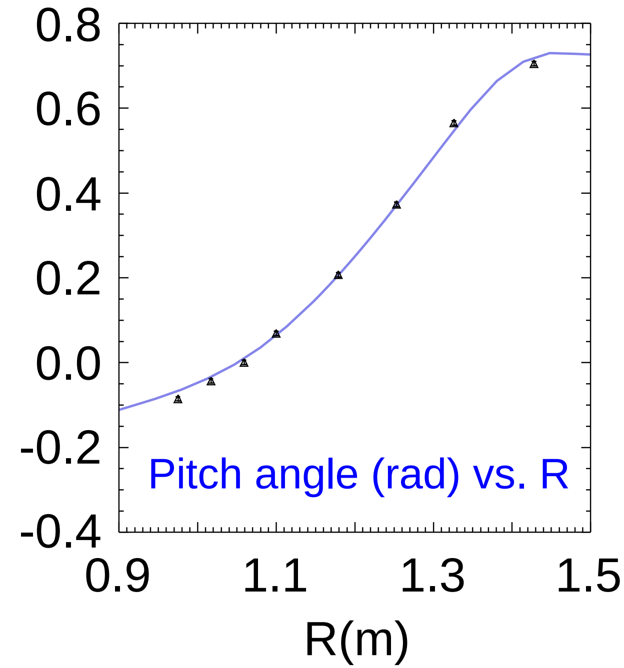
*Fredrickson, et al., Bull. Am. Phys. Soc. 2004
Sabbagh, et al., NF **44 (2004) 560.

Plasma rotation, ψ-isotherm, MSE included in reconstructions

Poloidal flux and pressure







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

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

Significant progress in MHD research, ahead of program milestones

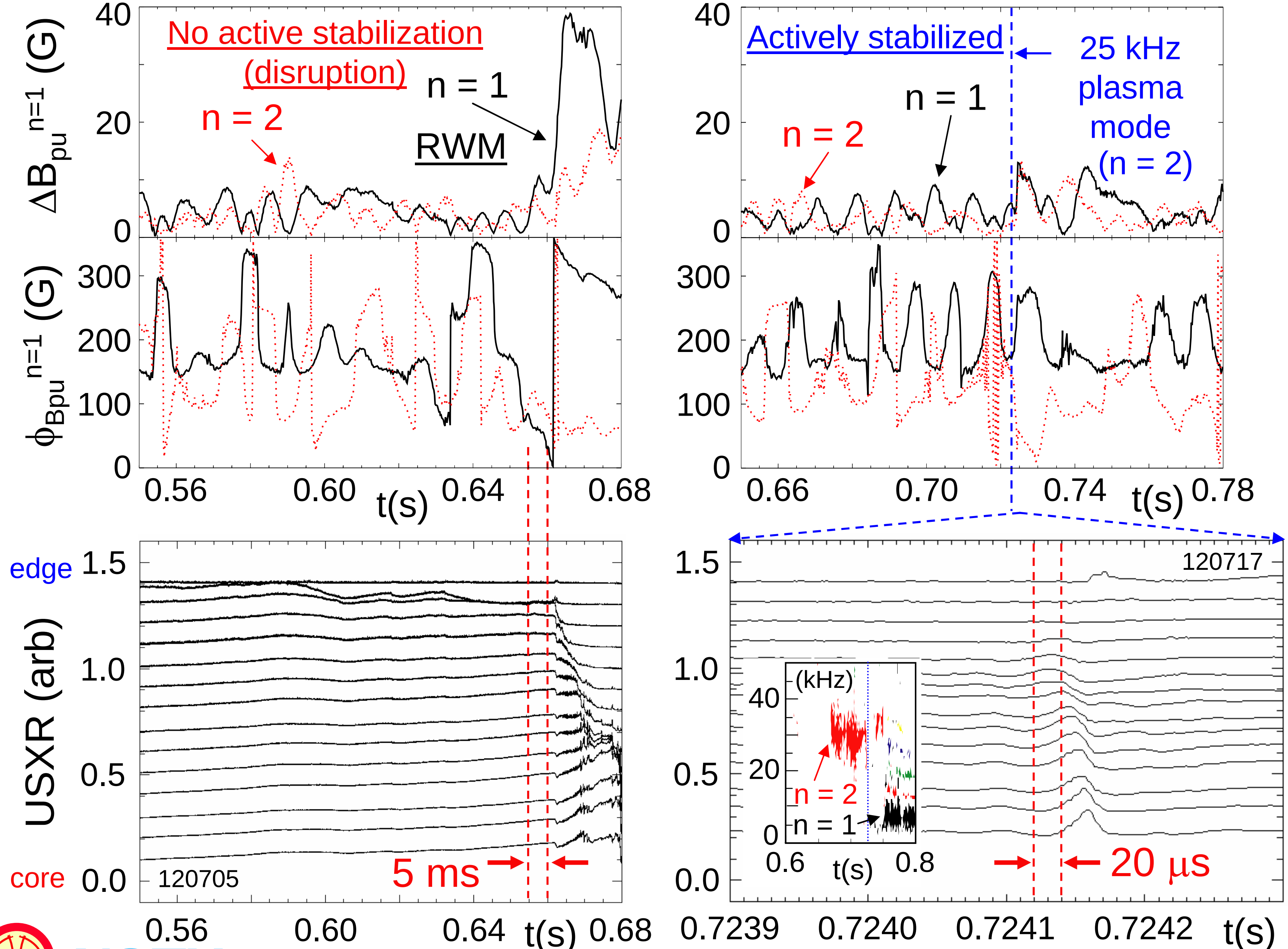
- Advanced progress in research
  - Stability space vs. l_i, F_p, κ established; record κ beyond 5 year plan
  - Extensive RWM physics research, yielding novel observations and theory/experimental comparisons
  - RWM active stabilization demonstrated at low rotation (ITER-relevant)
  - First full NTV calculation, quantitative agreement with experiment
  - 1/1 mode saturation may be explained by rotation + two-fluid effects
- Adaptation to technical/program changes
  - Machine modified to study high elongation for CTF and beyond
  - Precise, non-resonant plasma rotation control for ITER relevance
  - Contribution to ITPA locked mode threshold scaling and disruption I_p quench-rate studies, supports ITER, CTF
  - Performed RWM joint experiment with DIII-D, JET – supports ITPA (Reimerdes, PoP **13** (2006) 056107.)

Future plans (2007 – 2008) for MHD research build upon present results

- Investigation of extreme elongation regime for CTF, stability studies with greater detail of J(r) from expanded MSE
- RWM / DEFC research targeting active stabilization needs for USBPO, ITER, CTF, KSTAR
- RWM research program leveraging joint experiments (ITPA) for needed physics understanding of kink/RWM stabilization
- Further attention to ITPA / ITER disruption needs (e.g. B, q scaling of locked mode threshold, thermal quench and halo current peaking studies)
- Characterization of NTM at low A, high β and assessment of current drive needs for stabilization

Reference Slides Follow
(Not part of main presentation)

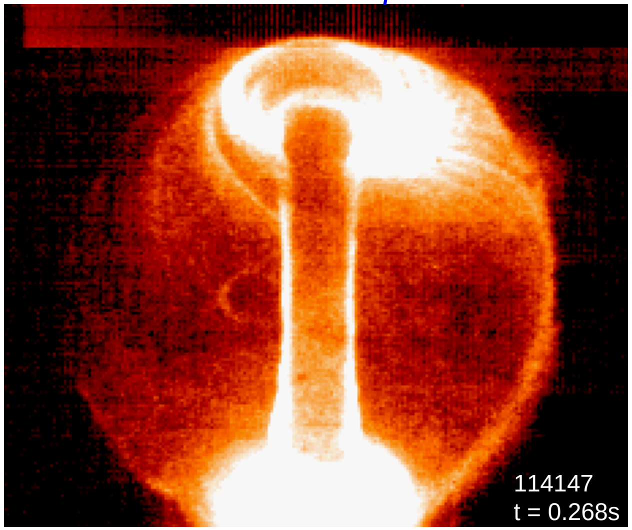
n = 2 RWM does not become unstable during n = 1 stabilization



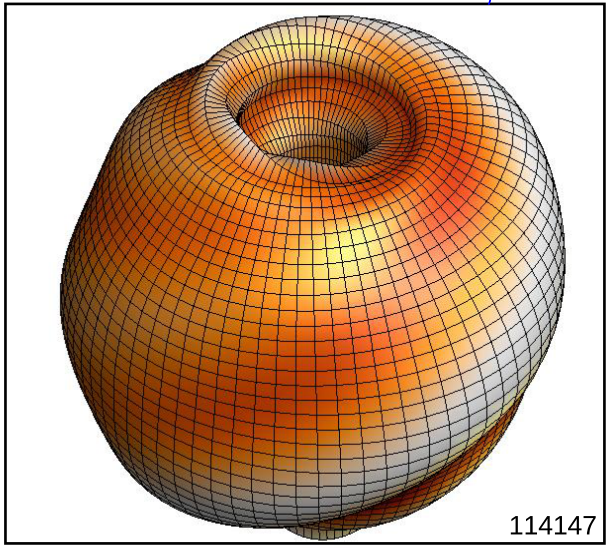
(Sabbagh, et al., PRL **97** (2006) 045004.)

Theoretical RWM reconstructed from experimental data

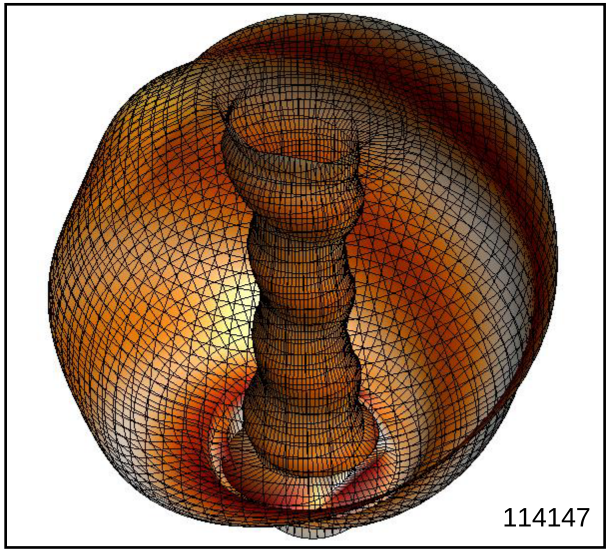
RWM with ΔB_p = 92 G



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

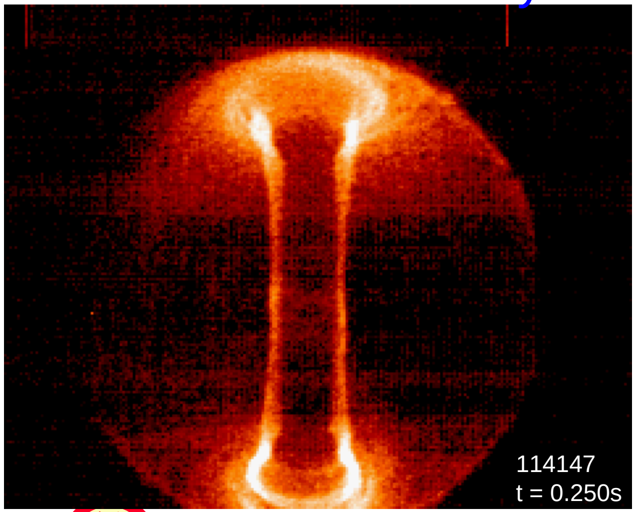


(exterior view)



(interior view)

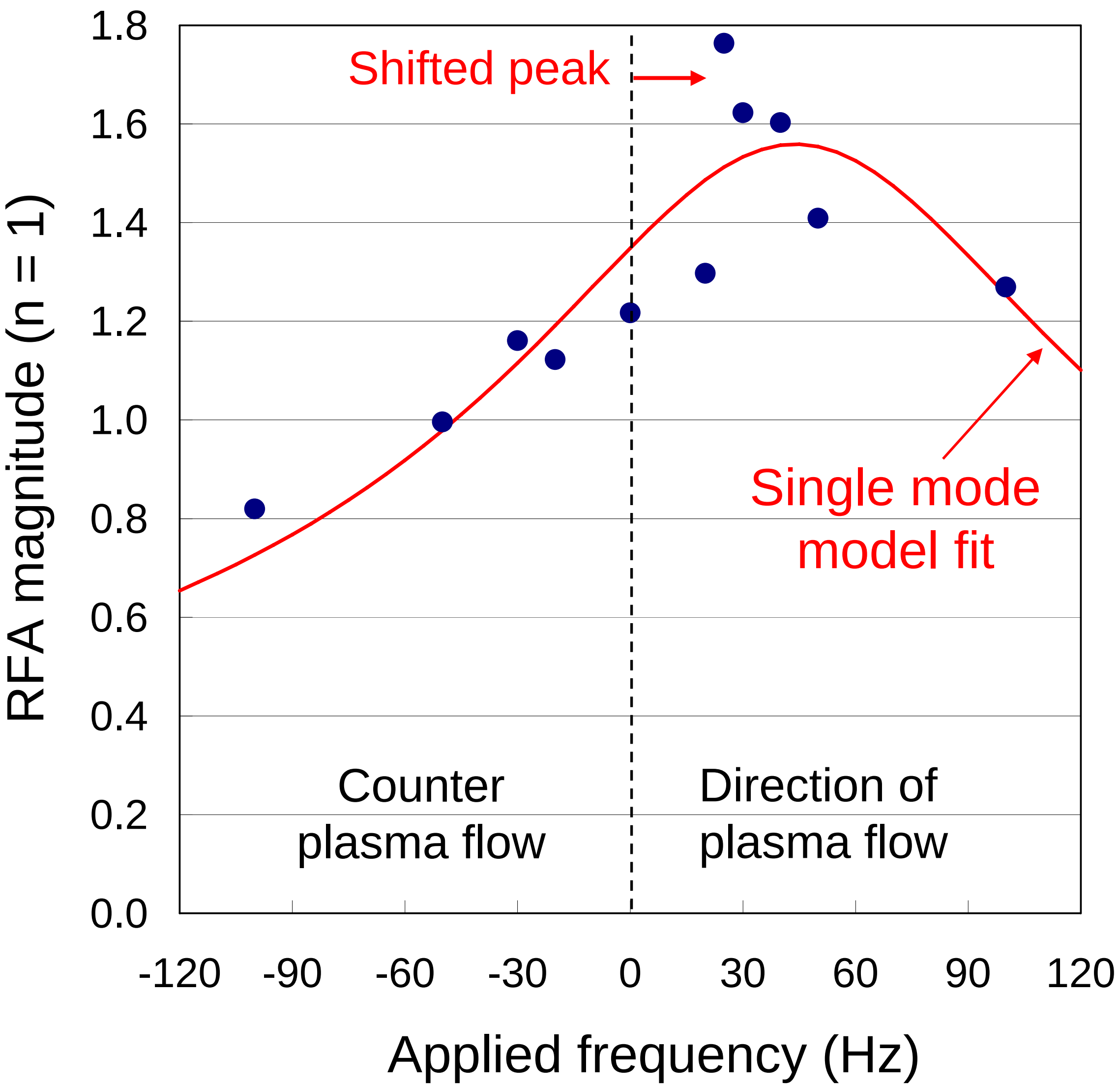
Before RWM activity



- Visible light emission, 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

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

MHD Spectroscopy: 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 35 Hz
  - Expected by RWM theory / experiment
    - Observed in DIII-D (H. Reimerdes, NF 45 (2005) 368.)

(Sabbagh, et al., APS 2005)