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Macroscopic Stability (MHD) Physics in NSTX

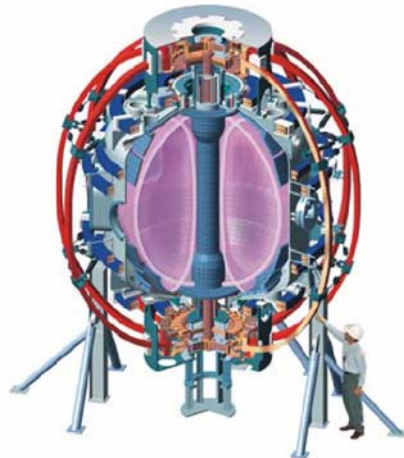
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For the NSTX Research Team

DOE Mid-Term Review of Major MFE Facilities

September 21st, 2006
Gaithersburg, MD



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

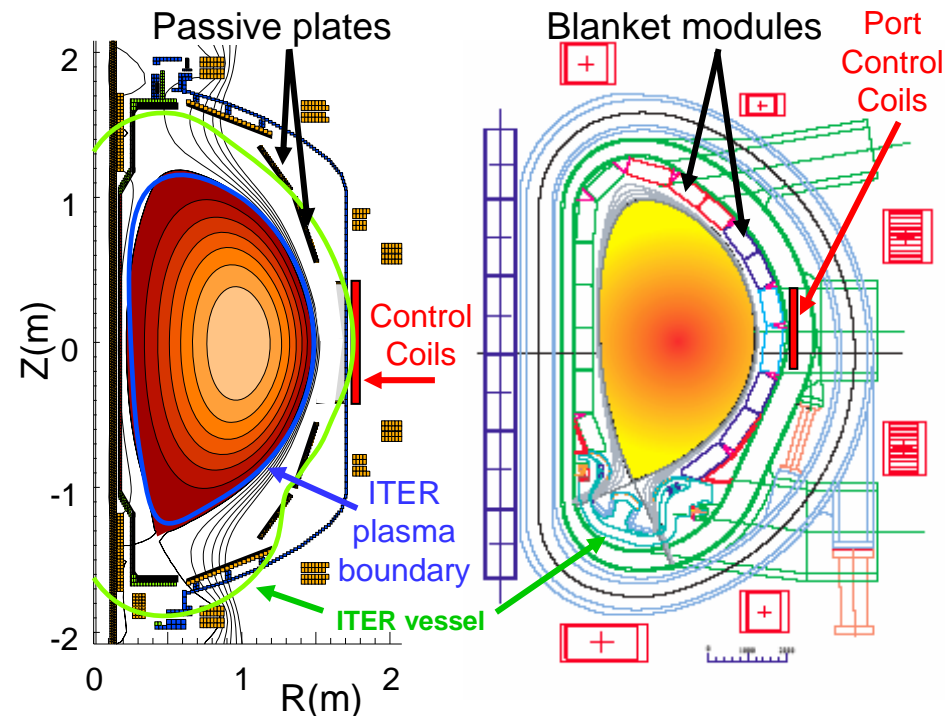
□ Great progress

- 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

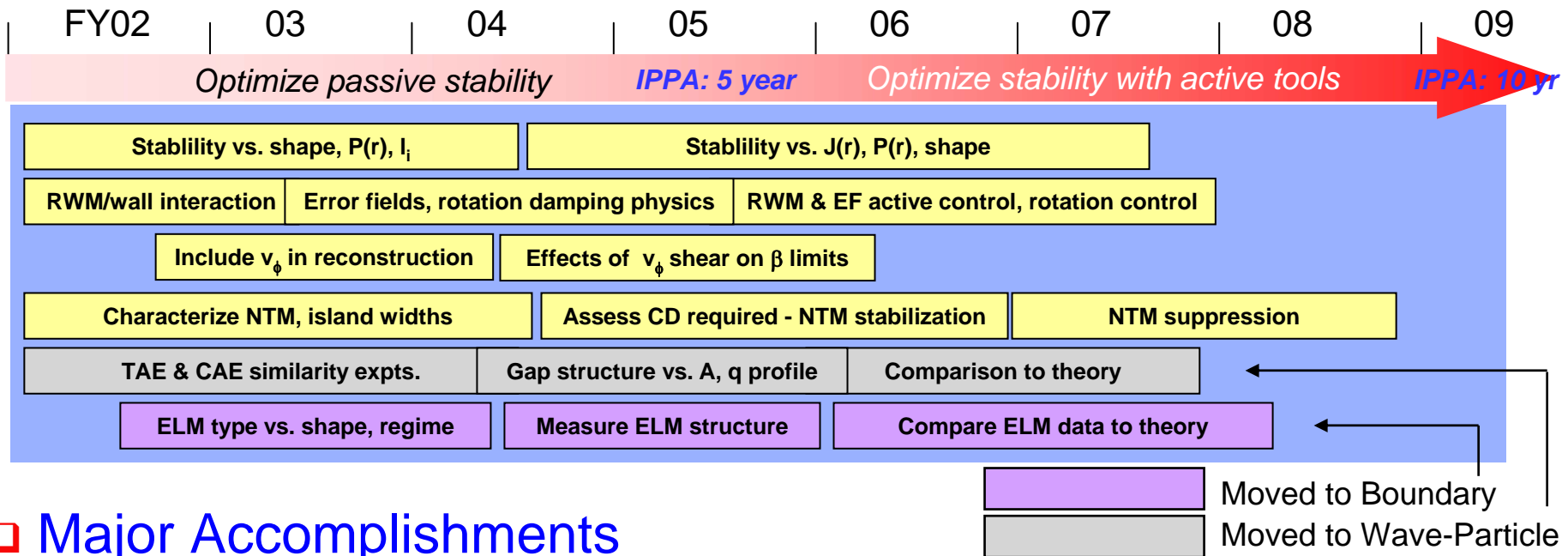


Advantage: low aspect ratio, high β provides high leverage to uncover key tokamak physics (e.g. RWM control, rotation damping, high elongation)

MHD Research Ahead of Schedule, now Addressing

Advanced Goals

(Timeline from 5 Yr Plan)



Major Accomplishments

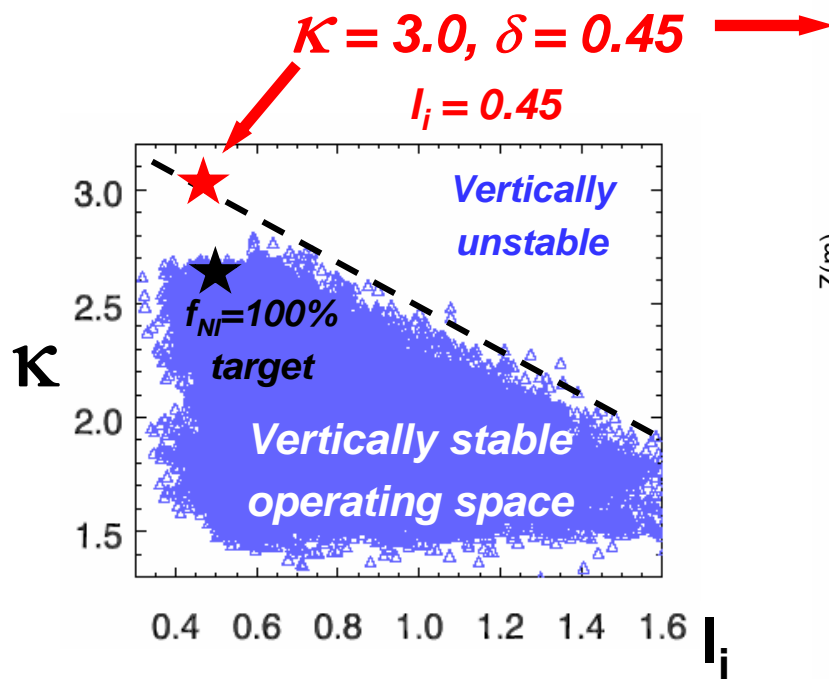
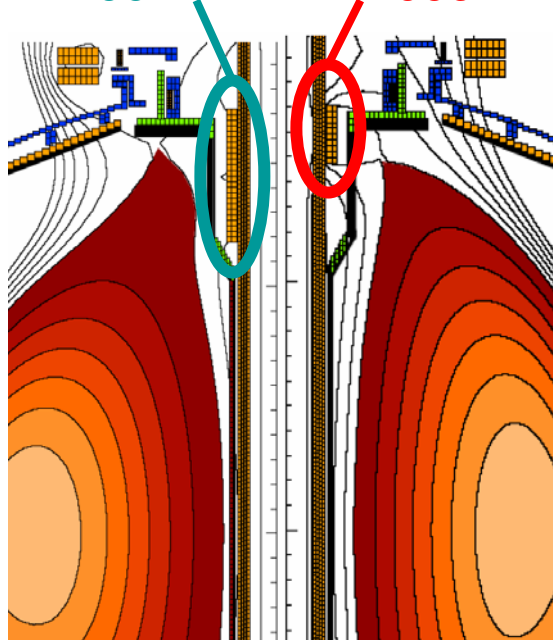
- ❑ RWM active stabilization at low rotation (ITER-relevant) (Sabbagh, PRL **97** (2006) 045004)
- ❑ Observed plasma rotation damping by NTV physics (Zhu, PRL **96** (2006) 225002)
- ❑ Unstable $n = 1 - 3$ RWM observed (Sabbagh, NF **46** (2006) 635)
- ❑ RWM critical rotation speed depends on V_ϕ profile, 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, $P(r)$, I_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)



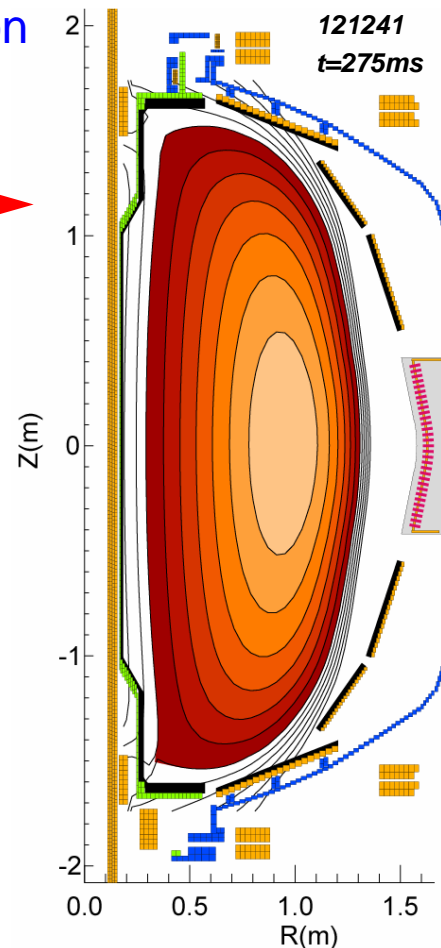
Extreme elongation at low I_i opens possibility of higher β_P , f_{BS} operation at high β_T

- ❑ 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 2004 2005

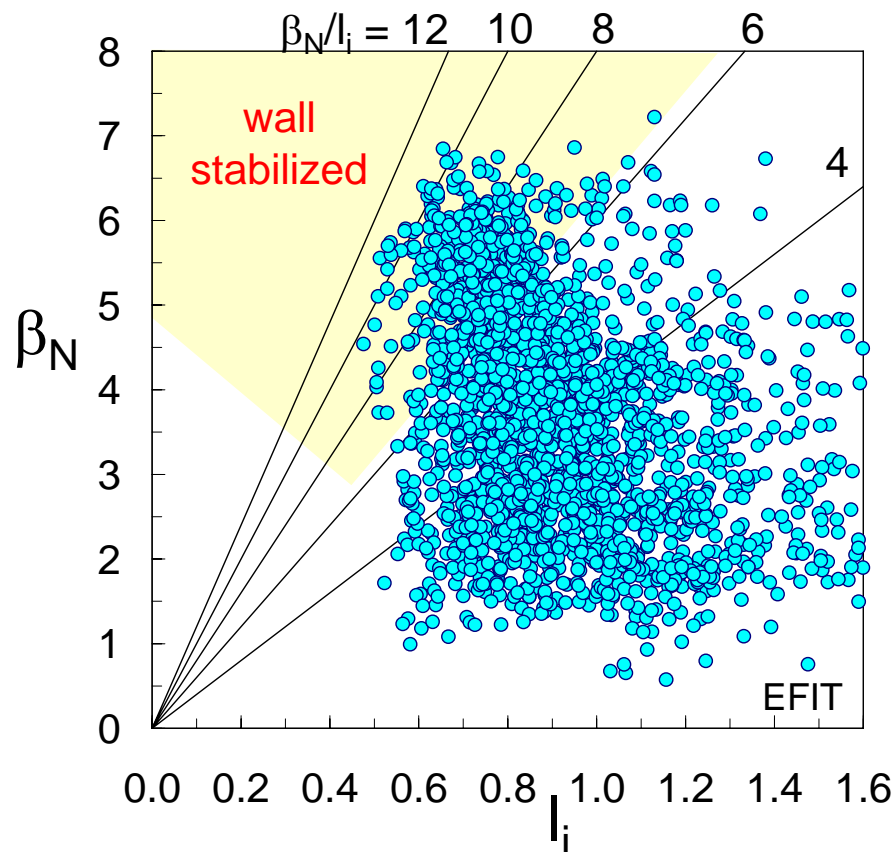


(Gates, et al., PoP **13** (2006) 056122.)
(Gates, et al., NF **46** (2006) 17.)

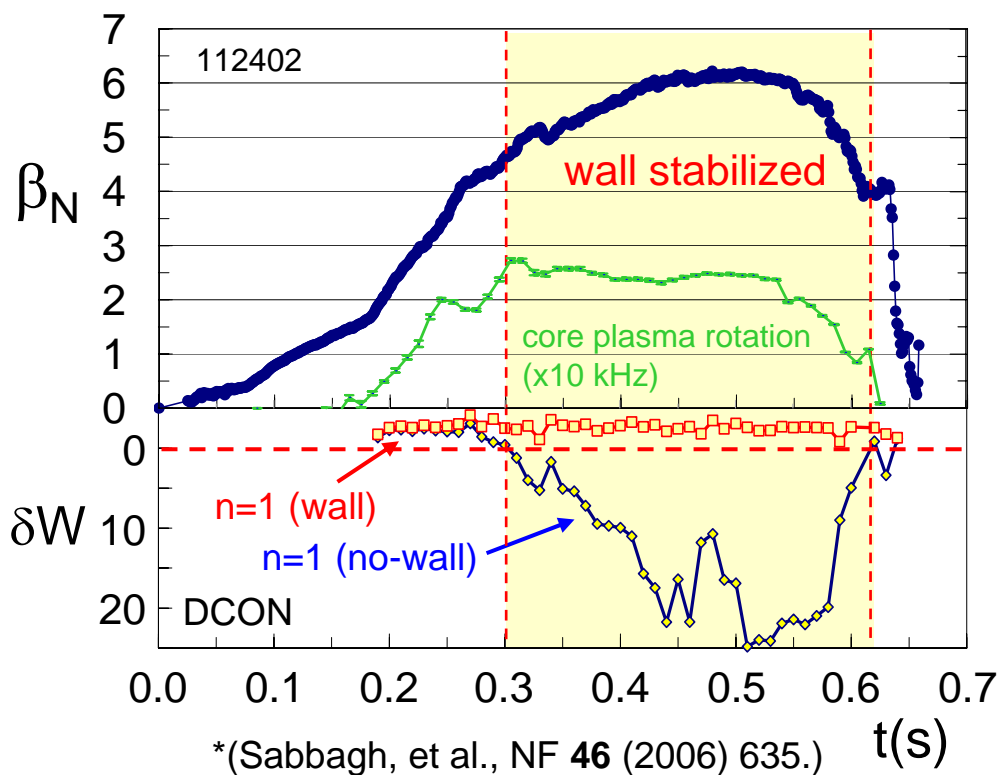


Kink stabilization by wall and RWM passive stabilization by rotation allows sustained plasma operation at maximum β

- High $\beta_t = 39\%$, $\beta_N = 7.2$ reached

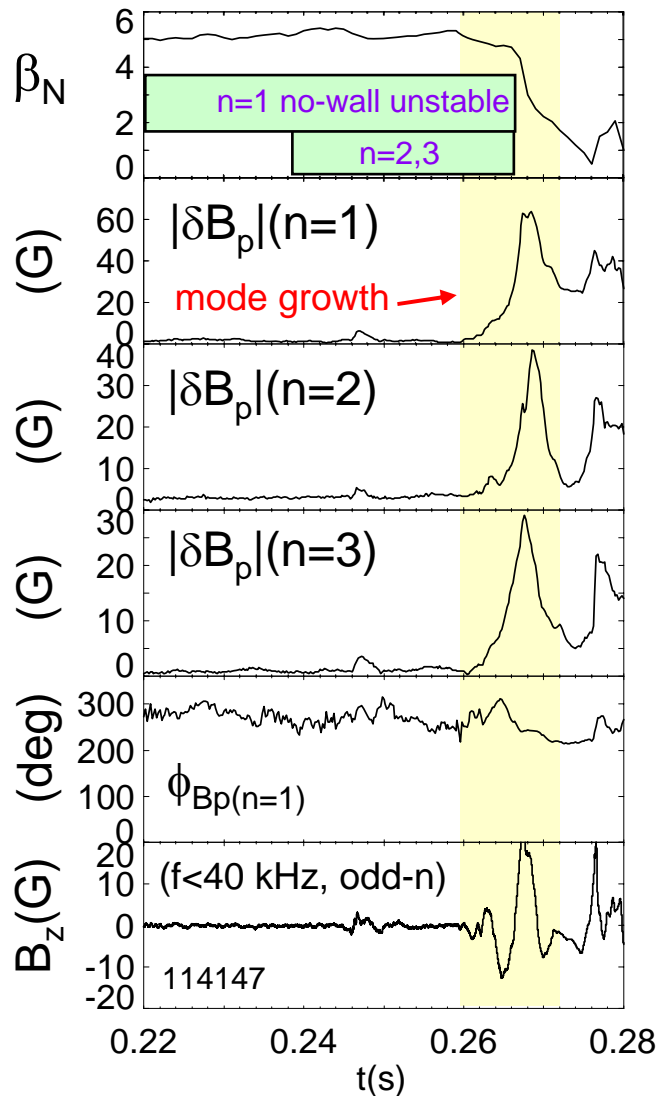


- Operation with $\beta_N/\beta_N^{no-wall}$ up to 1.5 at highest β_N for pulse $\gg \tau_{wall}, \sim \tau_{cr}$



- 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)

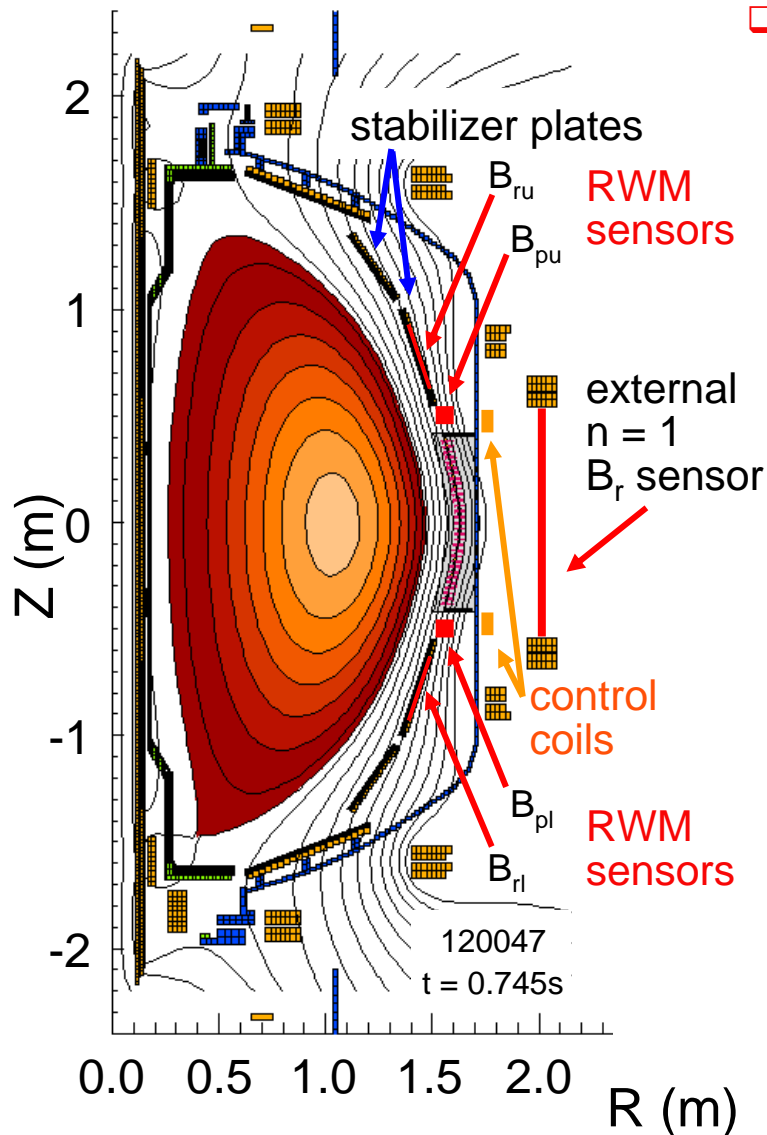
 - ❑ measurable mode rotation can occur during growth
 - ❑ growth rate, rotation frequency $\sim 1/\tau_{wall}$
 - \ll edge $\Omega_\phi > 1$ kHz
 - ❑ RWM phase velocity follows plasma flow

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

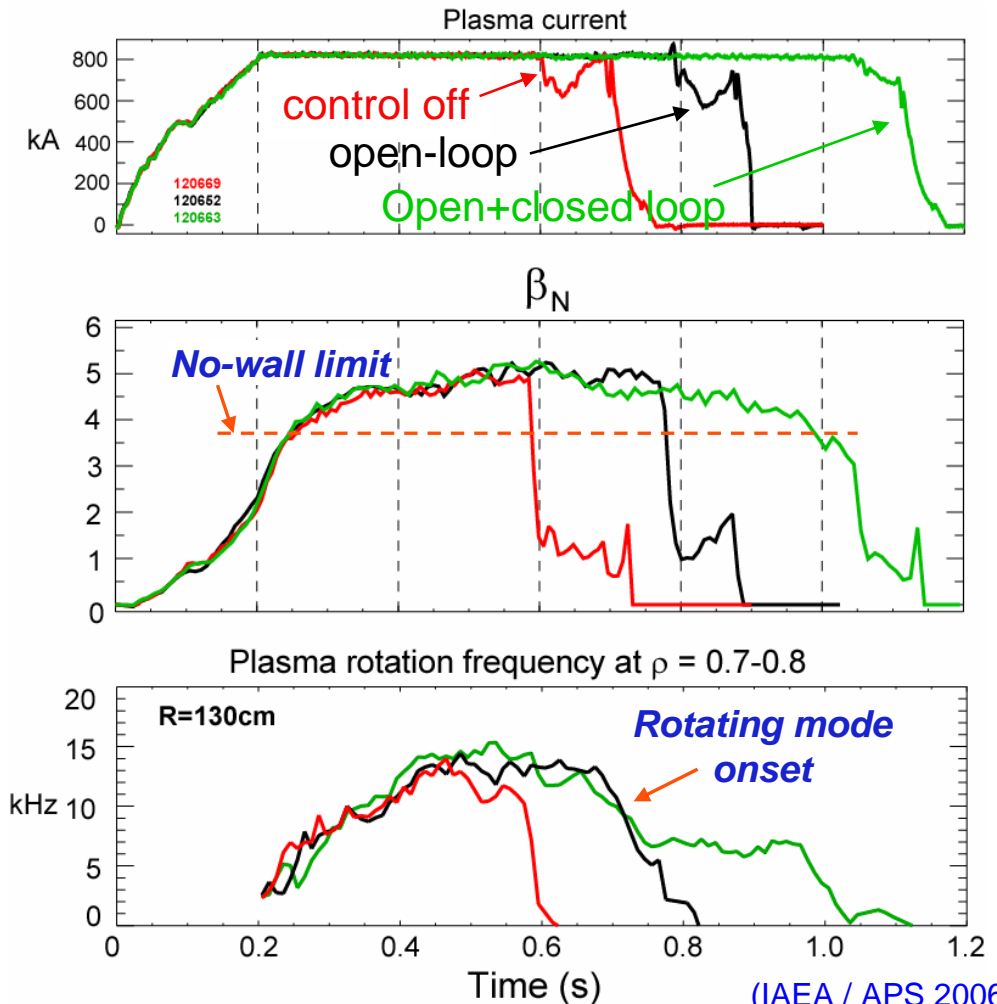


NSTX

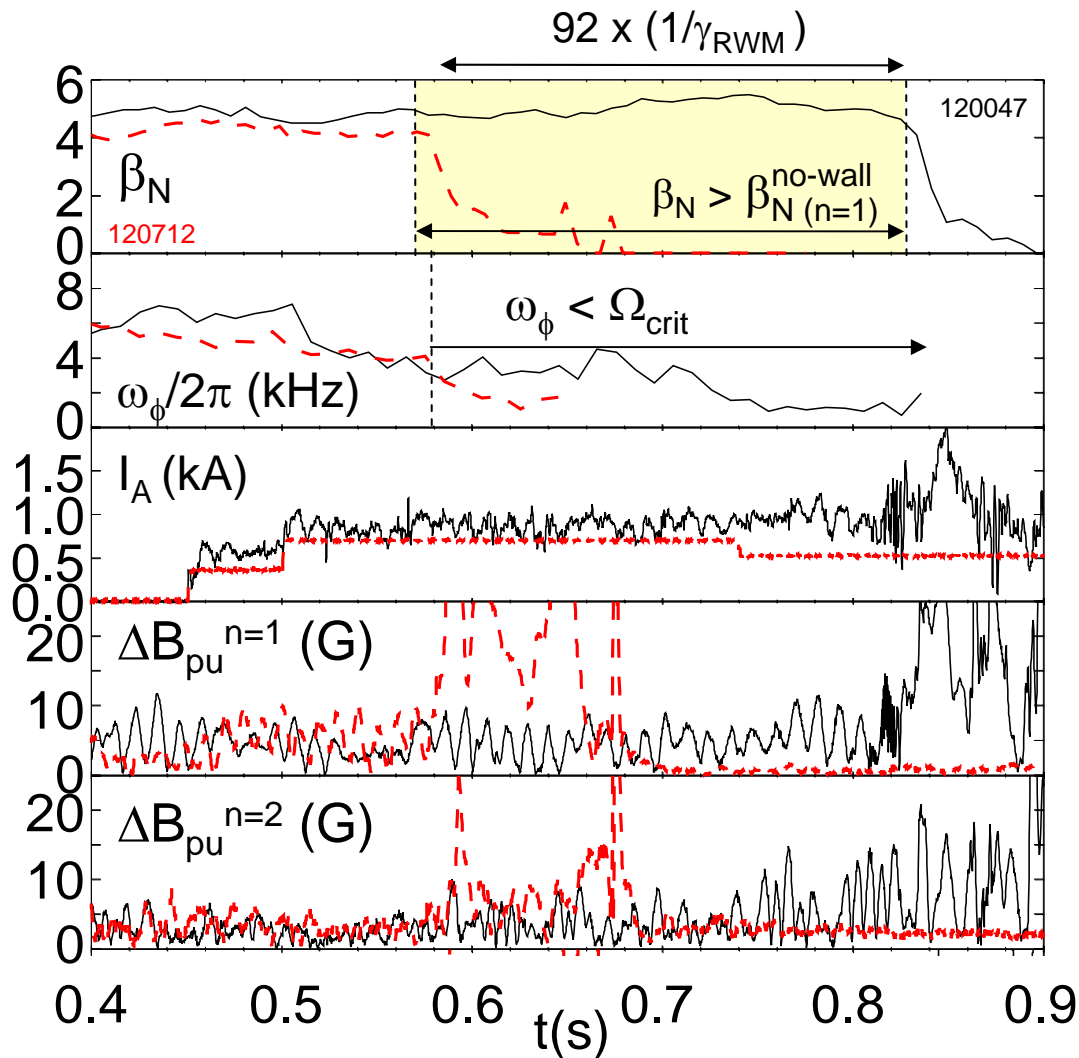
RWM active control system, rotation control installed



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



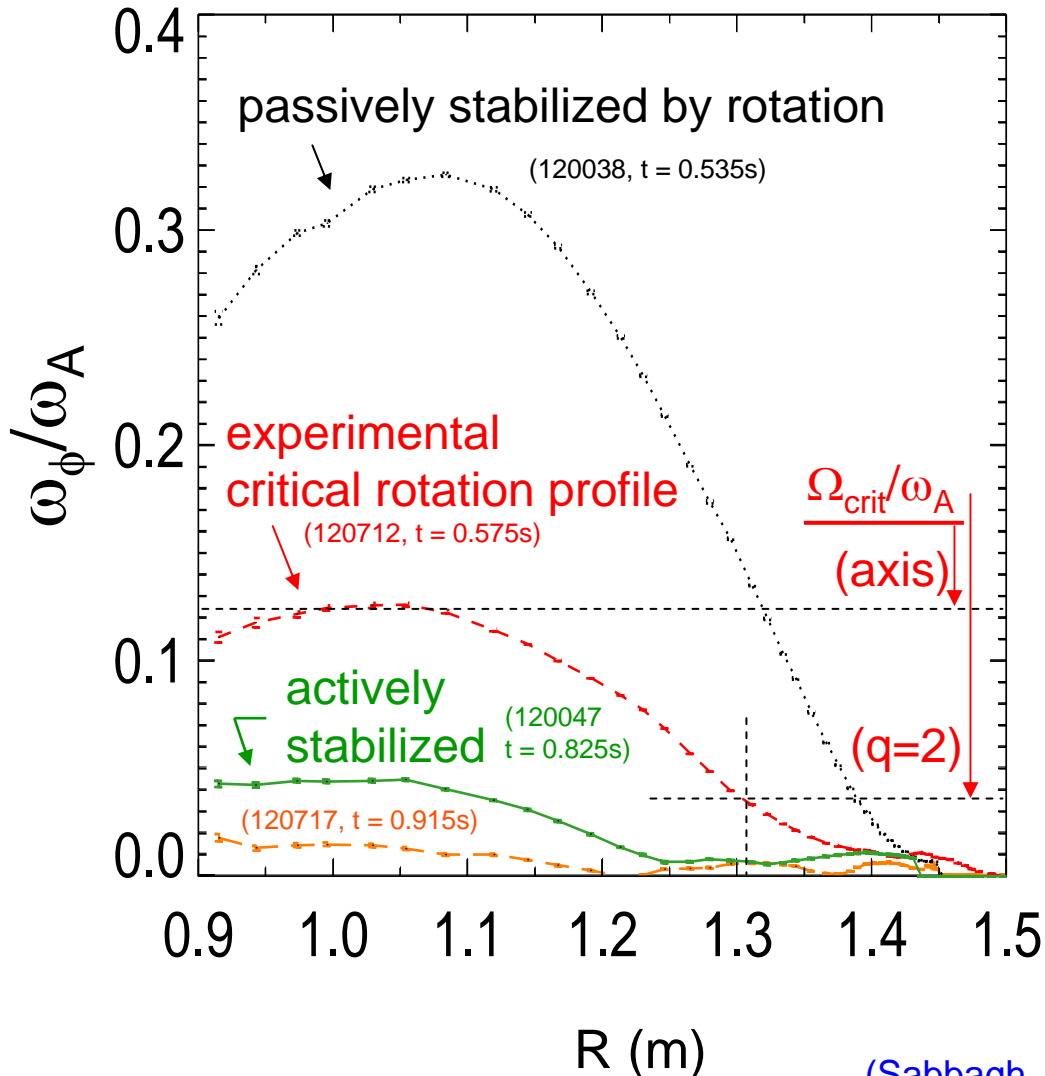
RWM stabilized at ITER-relevant rotation for $\sim 90/\gamma_{\text{RWM}}$



- **First such demonstration in low A tokamak**
 - Exceeds DCON $\beta_N^{\text{no-wall}}$ 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

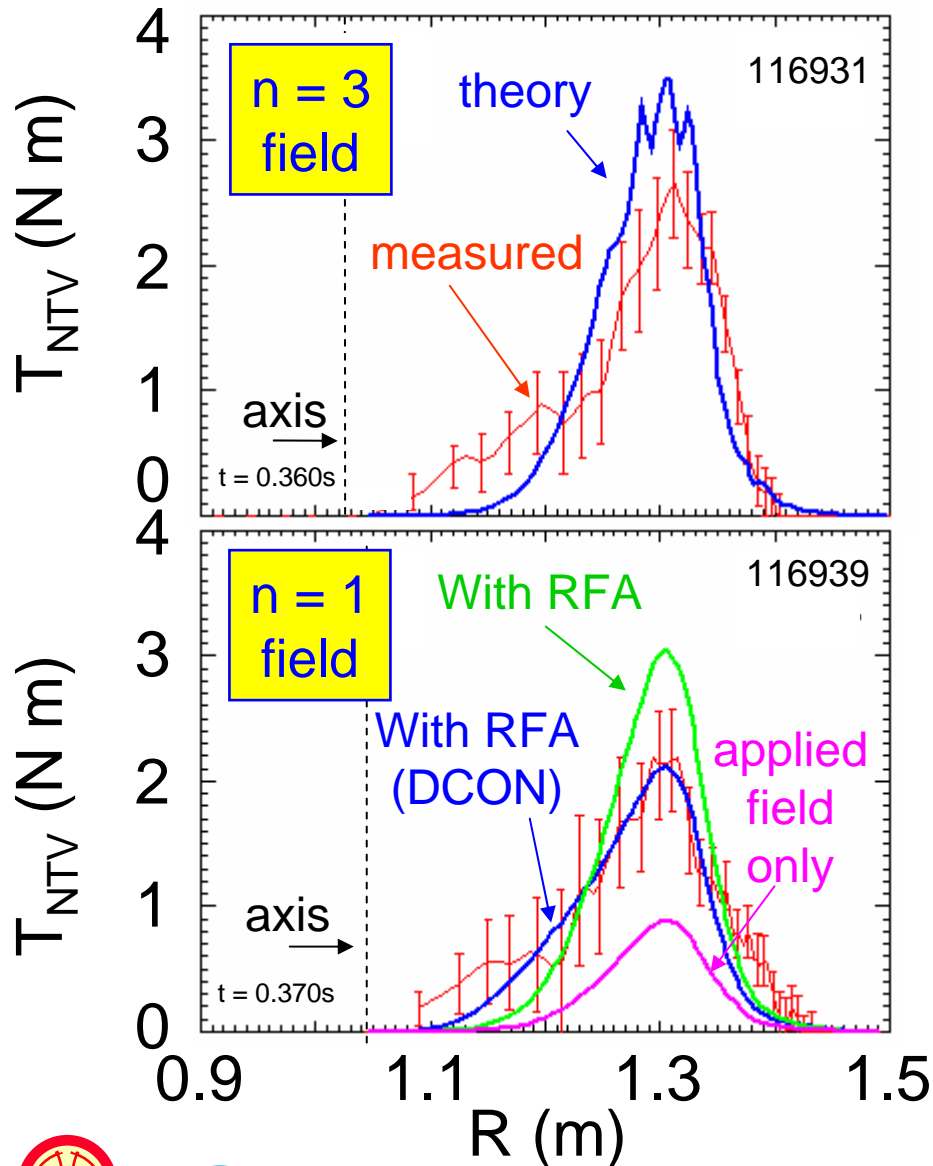


- Rotation typically fast and sufficient for RWM passive stabilization
 - Reached $\omega_\phi/\omega_A = 0.48|_{\text{axis}}$
- Non-resonant $n = 3$ magnetic braking used to slow entire profile
 - The $\omega_A/\Omega_{\text{crit}} = 0.2|_{q=2}$
 - The $\omega_A/\Omega_{\text{crit}} = 0.3|_{\text{axis}}$
 - Rotation less than $\frac{1}{2}$ of ITER predicted $\omega_\phi/\Omega_{\text{crit}}$ (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)

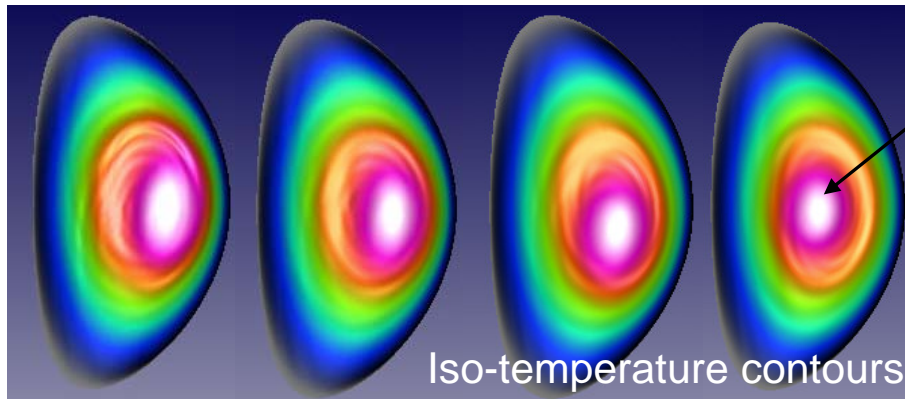
(Zhu, et al., PRL **96** (2006) 225002.)
Columbia U. thesis dissertation

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

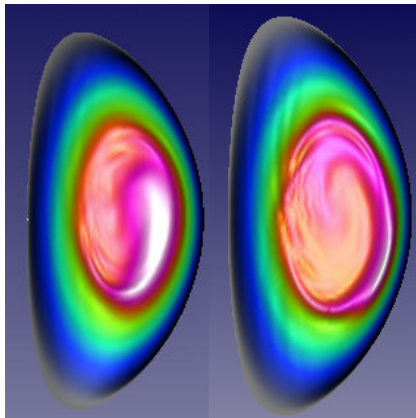
“hot-spot”

← **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

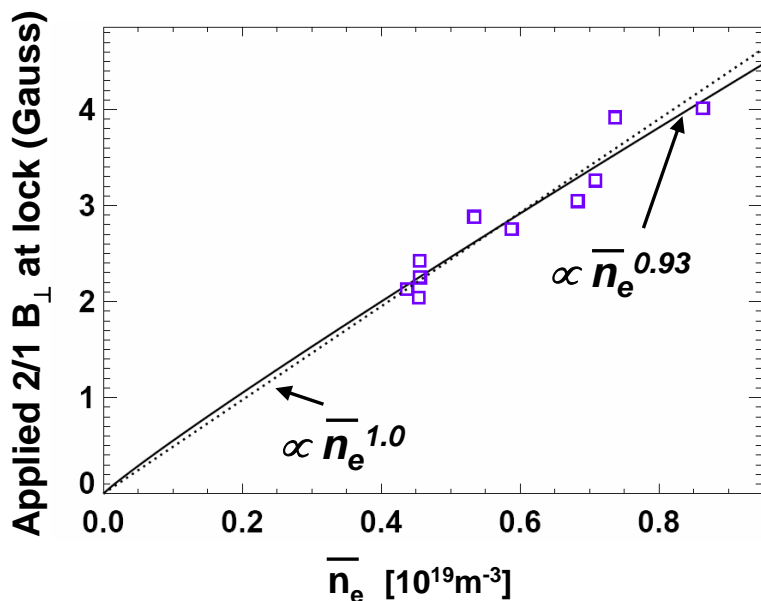
(Menard, et al., NF **45** (2005) 539.)



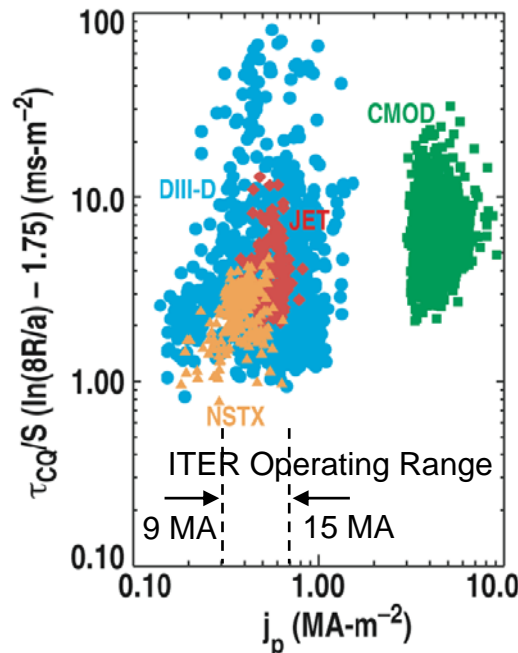
NSTX

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

(1) Locked mode threshold



(2) Disruption studies



(GA report A25385)

❑ 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

❑ 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



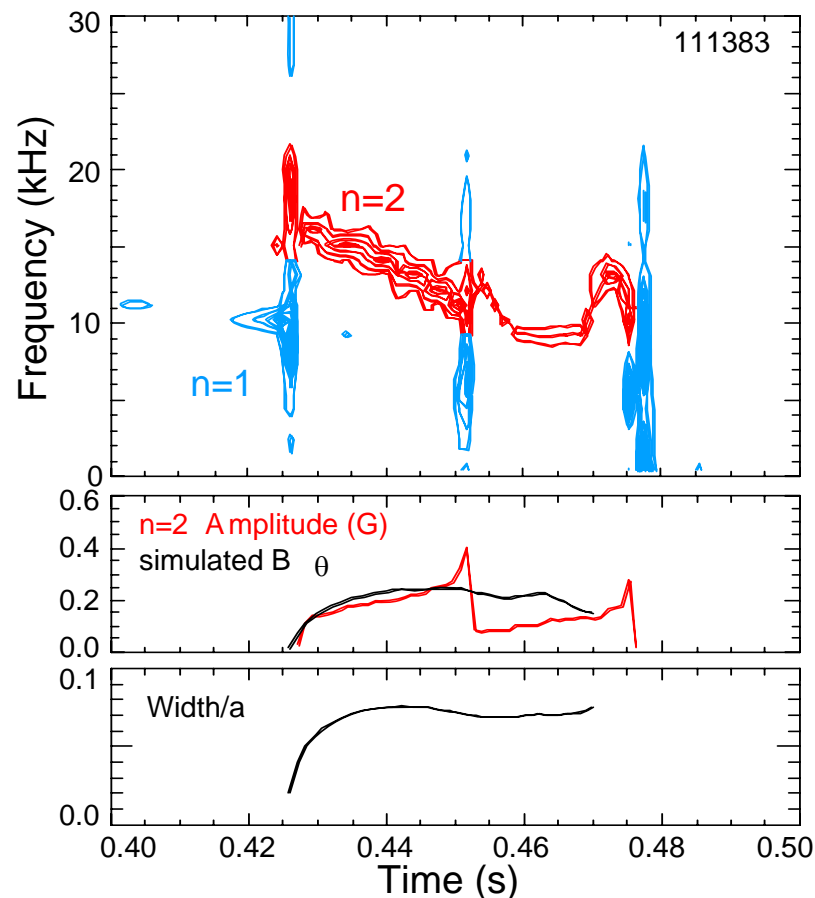
Low A, high β favorable for NTM seeding / stabilization study

- ❑ 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

*Fredrickson, et al., Bull. Am. Phys. Soc. 2004

**Sabbagh, et al., NF 44 (2004) 560.

Sawtooth excitation of $n = 2$

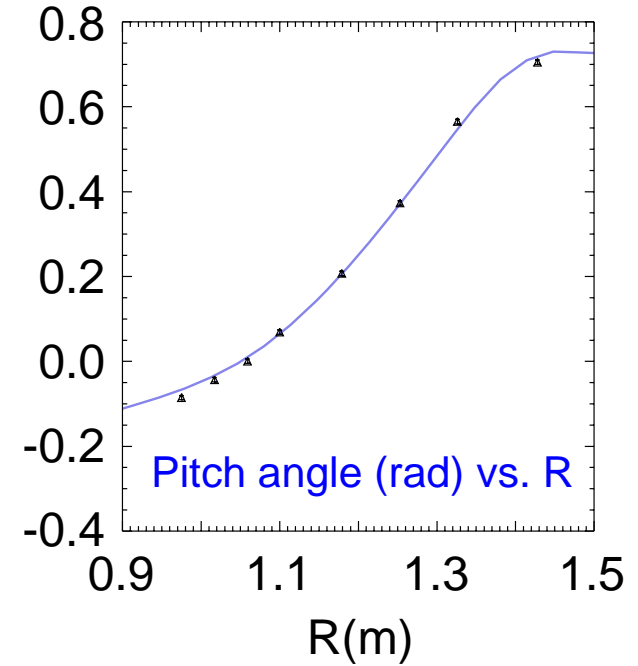
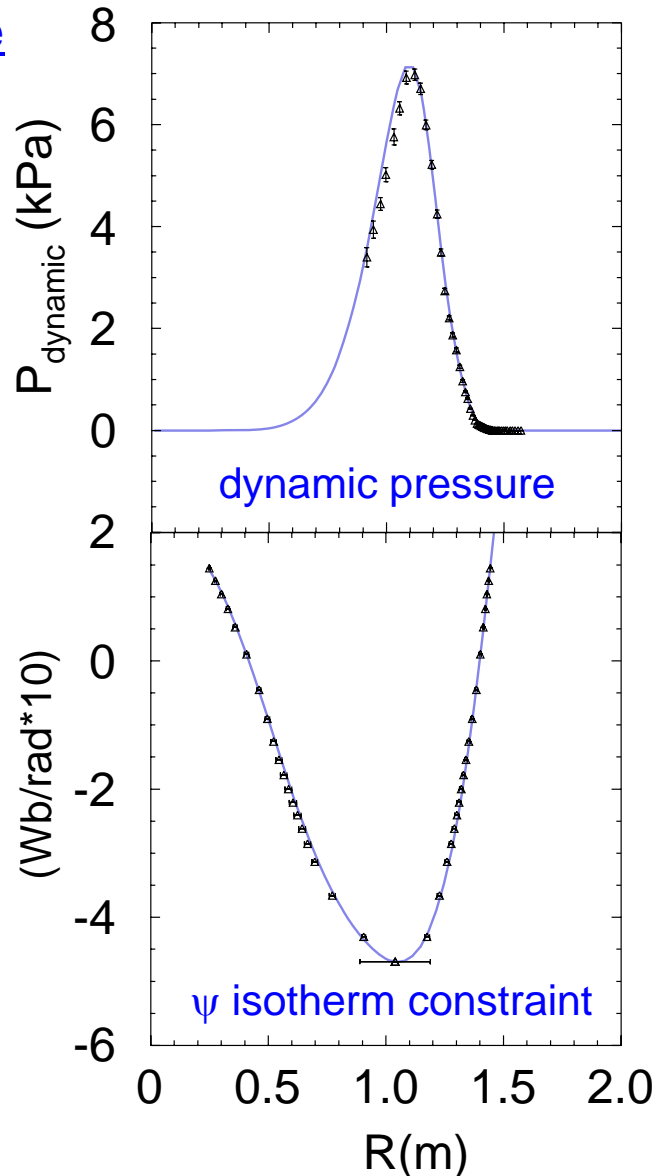
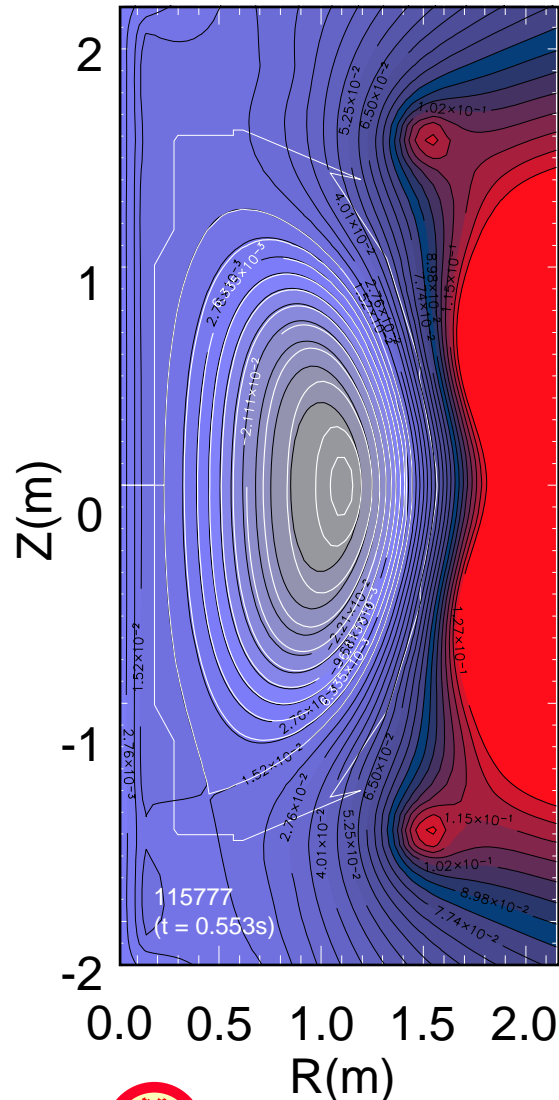


- ❑ Sawtooth excites $n = 2$, but $n = 2$ can decrease post-crash



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. I_p , 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 (results published in PoP)

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