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Kinetic Resistive Wall Mode Stabilization in Tokamaks and Initial Results from NSTX-U*

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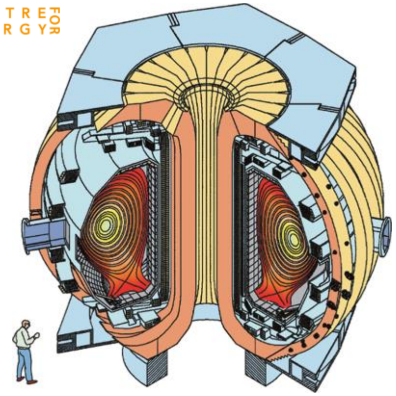

KTH Research Seminar

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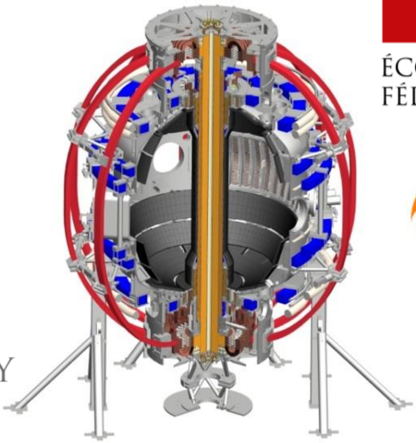
Stockholm, Sweden



V1.2

**This work supported by the US DOE contract DE-AC02-09CH11466, DE-FC02-04ER54698, and DE-FG02-99ER54524*

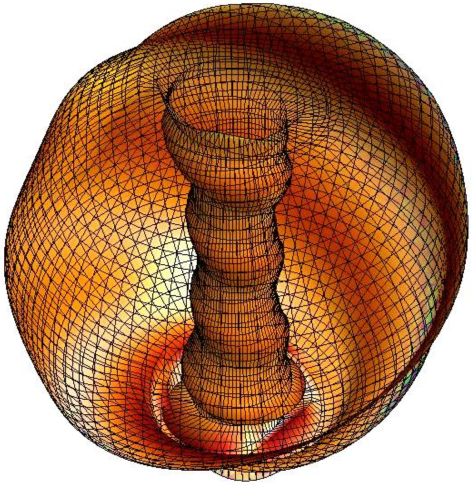
Outline

- Importance of global MHD stability and early RWM theory
- Experimental inconsistencies provoking new understanding
- Kinetic RWM stability physics summary
- Corroborative experiments in stable and unstable plasmas in NSTX and DIII-D, and implications for ITER
- NSTX-U: Plan aimed toward understanding confinement in ST, disruption avoidance, etc; initial device operation

The research shown here verified understanding of resistive wall mode (RWM) stability physics using kinetic MHD theory

- ❑ **Importance: Strongly growing RWMs cause disruptions**
  - ❑ Also cause large stored energy collapse (minor disruption) with ΔWtot ~ 60% (~ 200 MJ in ITER)
    - For comparison, large ELMs have ΔWtot ~ 6% (20 MJ in ITER)
  - ❑ RWM: a global kink/ballooning mode with growth rate, rotation slowed by conducting wall (~ $1/\tau_{wall}$)
  - ❑ RWM typically doesn't occur when strong tearing modes (TM) appear
    - But, what happens when TMs are avoided / controlled (as is planned for ITER)?
  - ❑ RWM evolution is also dangerous as it can itself trigger TMs

Experimental RWM reconstruction in NSTX

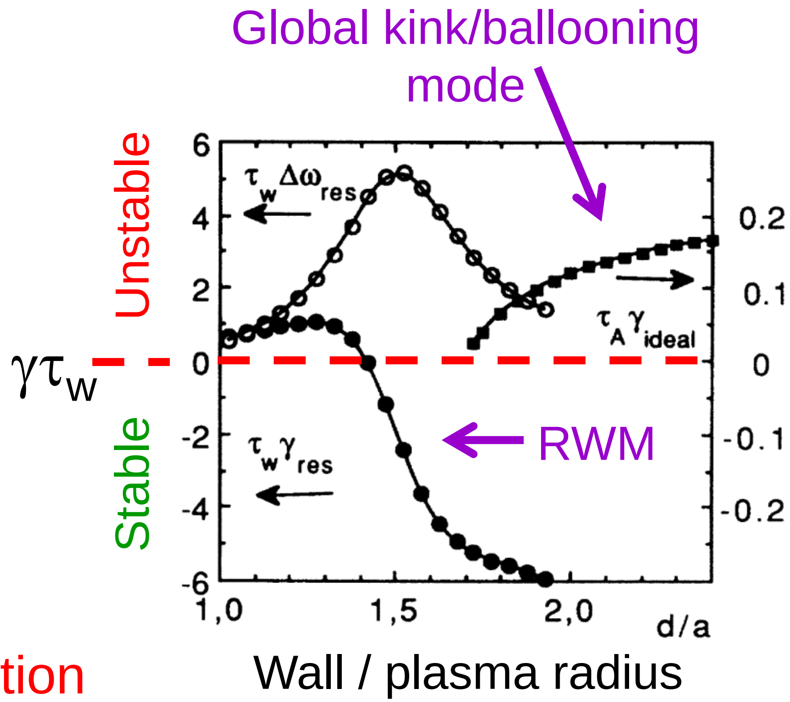


(S.A. Sabbagh, et al., Nucl. Fusion **46** (2006) 635)

RWM stability physics must be understood to best assess techniques for **disruption avoidance**

Early theoretical investigations provided initial hypotheses for global kink/ballooning/RWM mode stabilization physics

- ❑ Conducting wall stabilizes global kink/ballooning mode
  - ➔ Bondeson and Ward, PRL **72** (1994) 2709
  - ❑ Global kink growth rate ~ $1/\tau_{\mathrm{Alfven}}$ ~ μs
  - ❑ Mode transforms into slower growing resistive wall mode (RWM)



- ❑ RWM physical characteristics
  - ❑ Growth rate γ_{RWM} ~ $1/\tau_{\mathrm{wall}}$ ~ ms
  - ❑ RWM *less stable* when wall is closer
  - ❑ RWM stabilized at plasma critical rotation of a few % of Alfven speed

➔ Early experiments looked to determine the plasma critical rotation speed

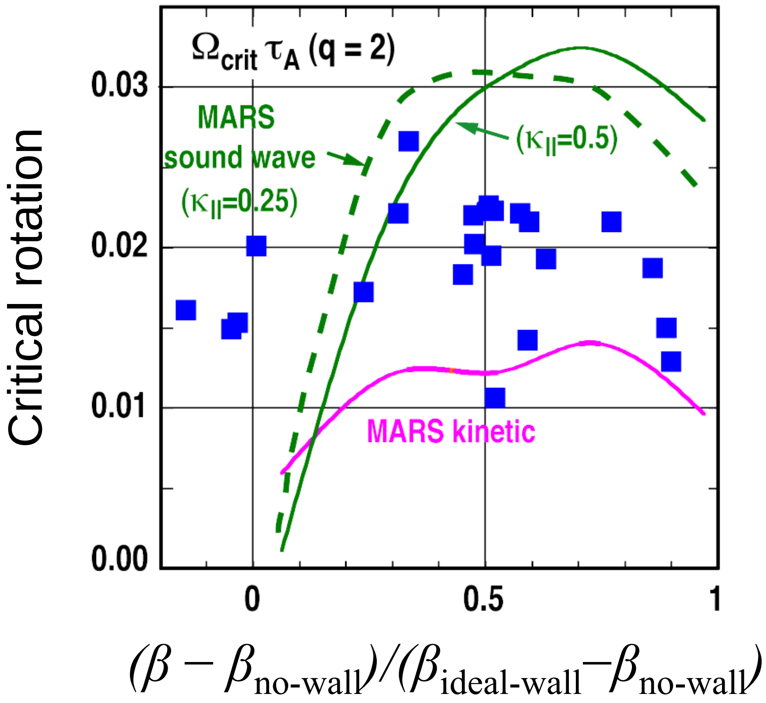
- Experiments initially found consistency with critical rotation at few % of V_A

Therefore, early global mode stabilization physics models related to plasma rotation were investigated

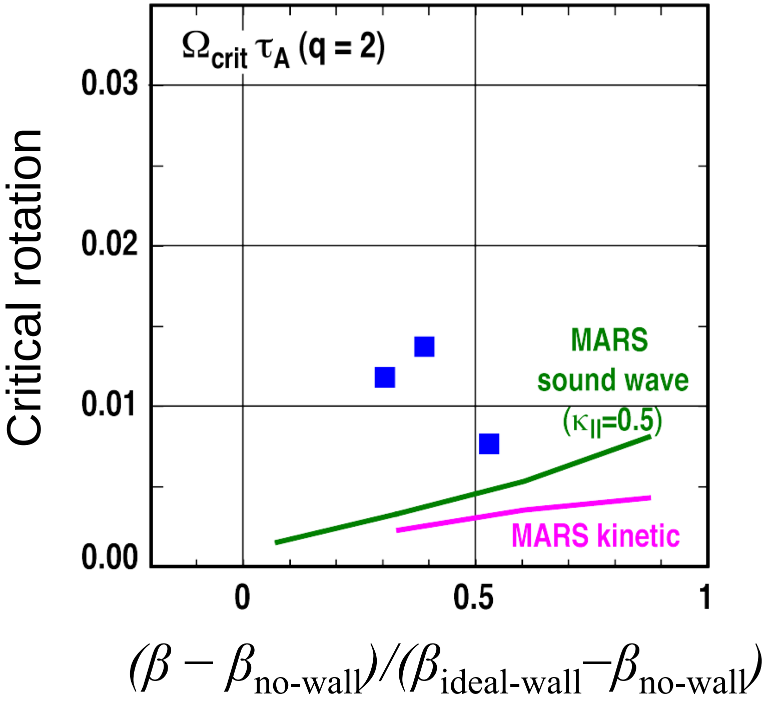
- ❑ Ideal MHD stabilization physics
  - ❑ Sound wave continuum damping
    - Bondeson, et al., PRL **72** (1994) 2709
    - Betti, et al., PRL **74** (1995) 2949
    - Y. Liu, et al., **45** (2005) 1131
  - ❑ Shear Alfven resonance damping
    - Bondeson, et al., PRL **72** (1994) 2709
    - Zheng, et al., PRL **95** (2005) 255003
- ❑ Non-ideal MHD stabilization physics
  - ❑ Resistive layer damping
    - Finn, Phys. Plasmas **2** (1995) 3782
    - Gimblett & Hastie, Phys. Plasmas **7** (2000) 258
  - ❑ Viscous boundary layer damping
    - Fitzpatrick & Aydemir NF **36** (1996) 11
- ❑ Kinetic stabilization physics
  - ❑ Parallel viscous force model for sound wave damping
    - Chu, et al., Phys. Plasmas **2** (1995) 2236
  - ❑ Semi-kinetic model: mode resonance with thermal ion bounce motion
    - Bondeson & Chu (Phys. Plasmas **3** (1996) 3013
    - Bondeson, Y. Liu, PPCF **45** (2003) A253

Early theory did not find general quantitative agreement with experimental RWM marginal stability

Low internal inductance plasma



Moderate internal inductance plasma



- ❑ Low-l_i plasma yields $\Omega_{crit}\,\tau_A \sim 0.02$ with weak β dependence
- ❑ Moderate-l_i scenario yields significantly lower Ω_{crit}

➔ **Kinetic damping** generally underestimates Ω_{crit}

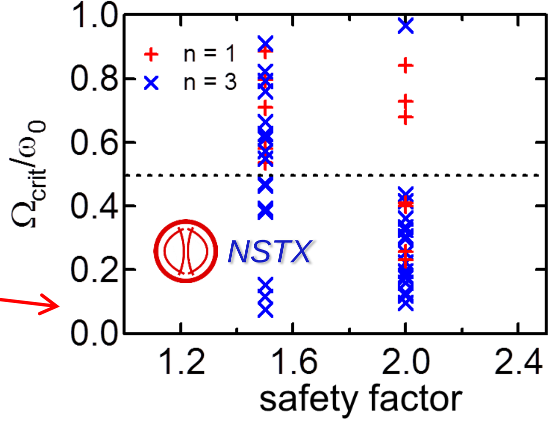
- R. LaHaye, …, Y. Liu, H. Reimerdes, et al., NF **44** (2004) 1197
- H. Reimerdes, J. Bialek, M.Chance, …, Y.Liu, et al., NF **45** (2005) 368

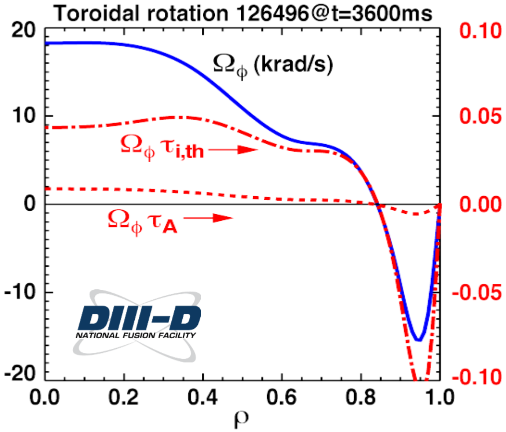
MARS code: Y. Liu

Key transitional period 2006–08: Several experiments showed key inconsistencies with early stability physics models

- Results from earlier critical rotation experiments using resonant magnetic braking ($n = 1$ field) rescinded – explained by torque bifurcation, not RWM (Garofalo, et al., IAEA Fusion Energy Conference (FEC) 2006, paper EX/7-1Ra)

- New hypotheses were now needed to explain mode stabilization physics – *that is where this story begins…*
  - NSTX using non-resonant ($n = 3$) magnetic braking by NTV yielded a growing RWM instability (Sabbagh, et al., PRL **97** (2006) 045004) and <u>did not</u> produce torque bifurcation (Sontag, Sabbagh, et al. NF **47** (2007) 1005)
  - DIII-D with balanced NBI: RWM stable at plasma rotation less than 1% V_A (Reimerdes PPCF **49** (2007) B349)
  - NSTX: Berkery/Sabbagh showed RWM instability at <u>higher</u> plasma rotation (Sabbagh IAEA FEC 2008 paper EX/5-1; Berkery, et al. PRL **104** (2010) 035003





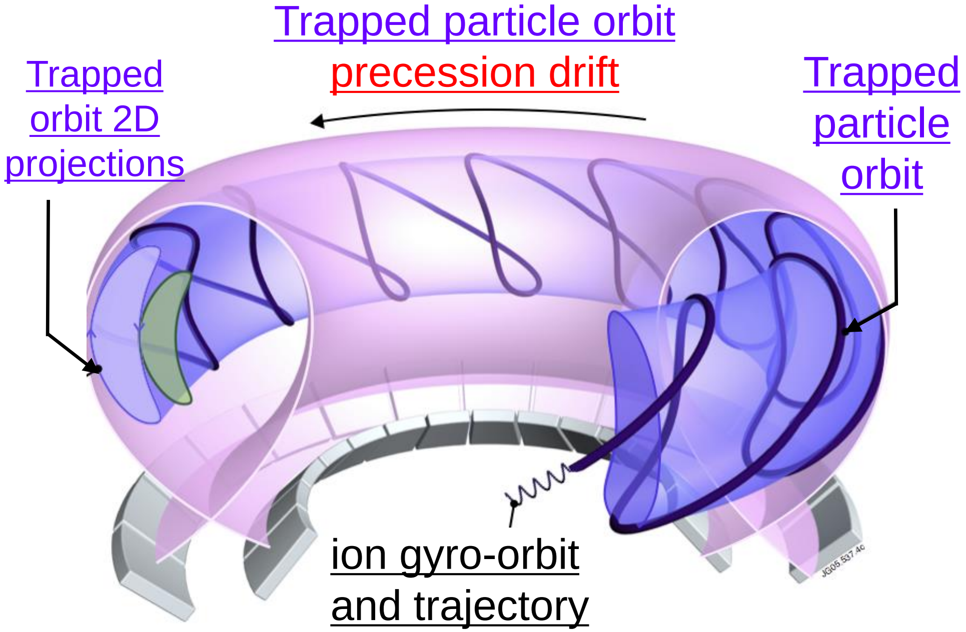
➔ Conclusion: simple critical rotation hypothesis is NOT sufficient to explain stability, new theory needed

Drift kinetic theory energy functional (Hu/Betti) includes key precession drift resonance as stabilizing mechanism

- Kinetic modification to ideal MHD

$$\gamma\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_{wall} + \delta W_K}$$

- Stability depends on
  - Trapped / circulating ions, trapped electrons
  - Particle collisionality
  - Energetic particle (EP) population
  - Integrated ω_ϕ profile matters!!! : broad rotation resonances in δW_K



(Fig. adapted from R. Pitts et al., Physics World (Mar 2006))

(Hu, Betti, et al., PoP **12** (2005) 057301)

plasma integral over particle energy

$$\delta W_K \propto \int \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - {}^{3}\!/_{2}\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle\omega_D\rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma}\right]\hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}}\, d\hat{\varepsilon}$$

← EP integral component is dominated by precession drift term

precession drift

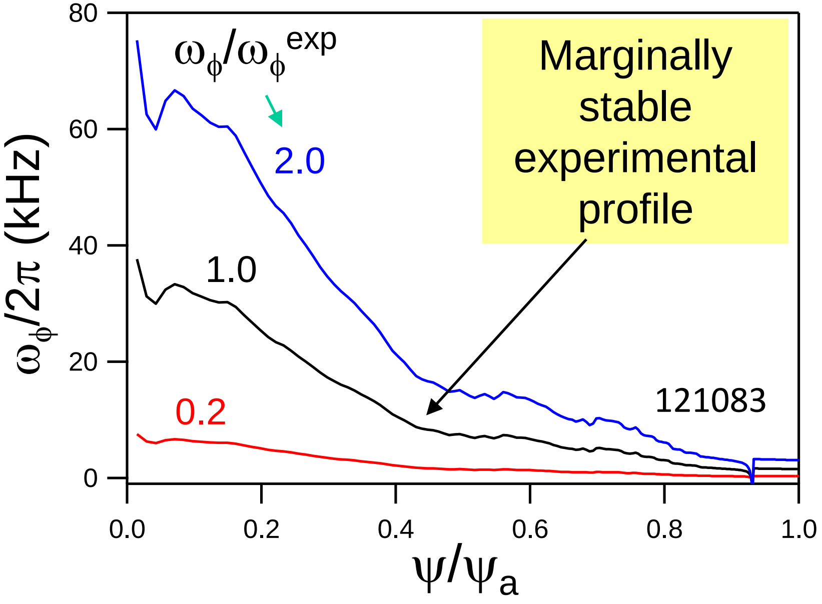
bounce

collisionality

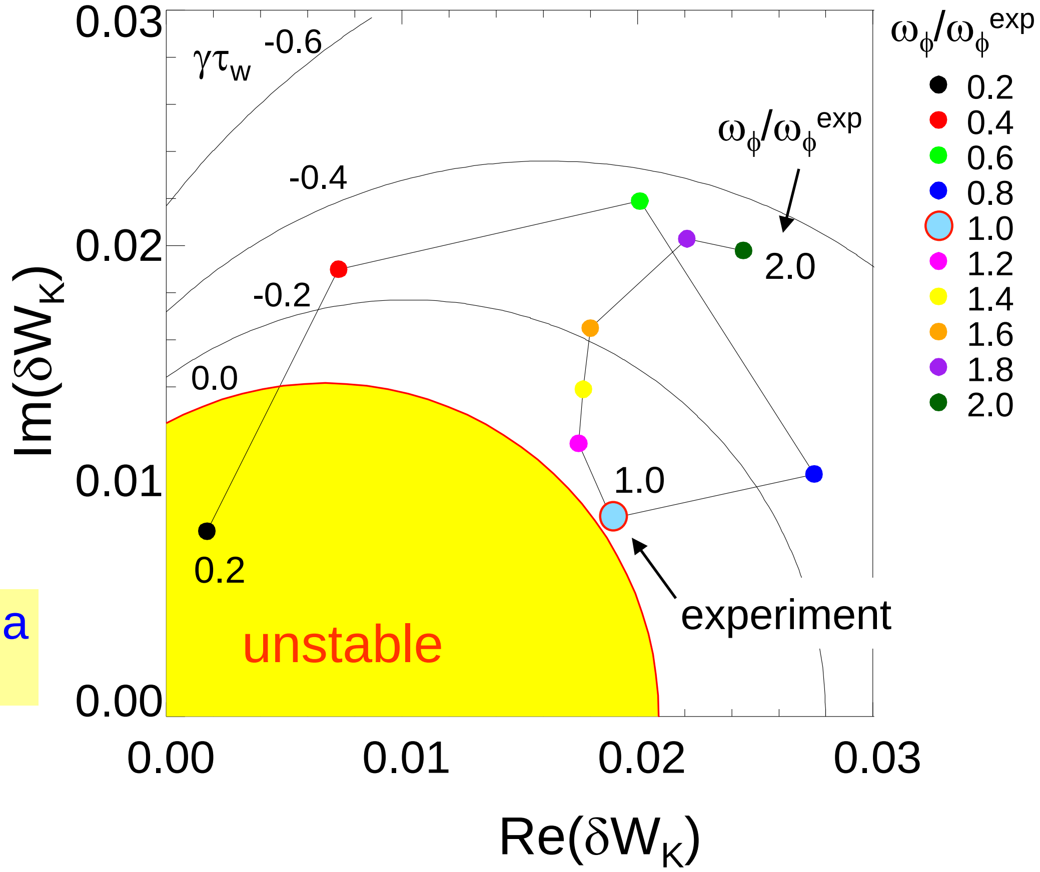
ω_ϕ profile (enters through ExB frequency)

Kinetic modifications show decrease in RWM stability at relatively high ω_ϕ – consistent with experiment (**MISK** code)

Theoretical variation of ω_ϕ



RWM stability vs. V_ϕ (contours of $\gamma\tau_w$)

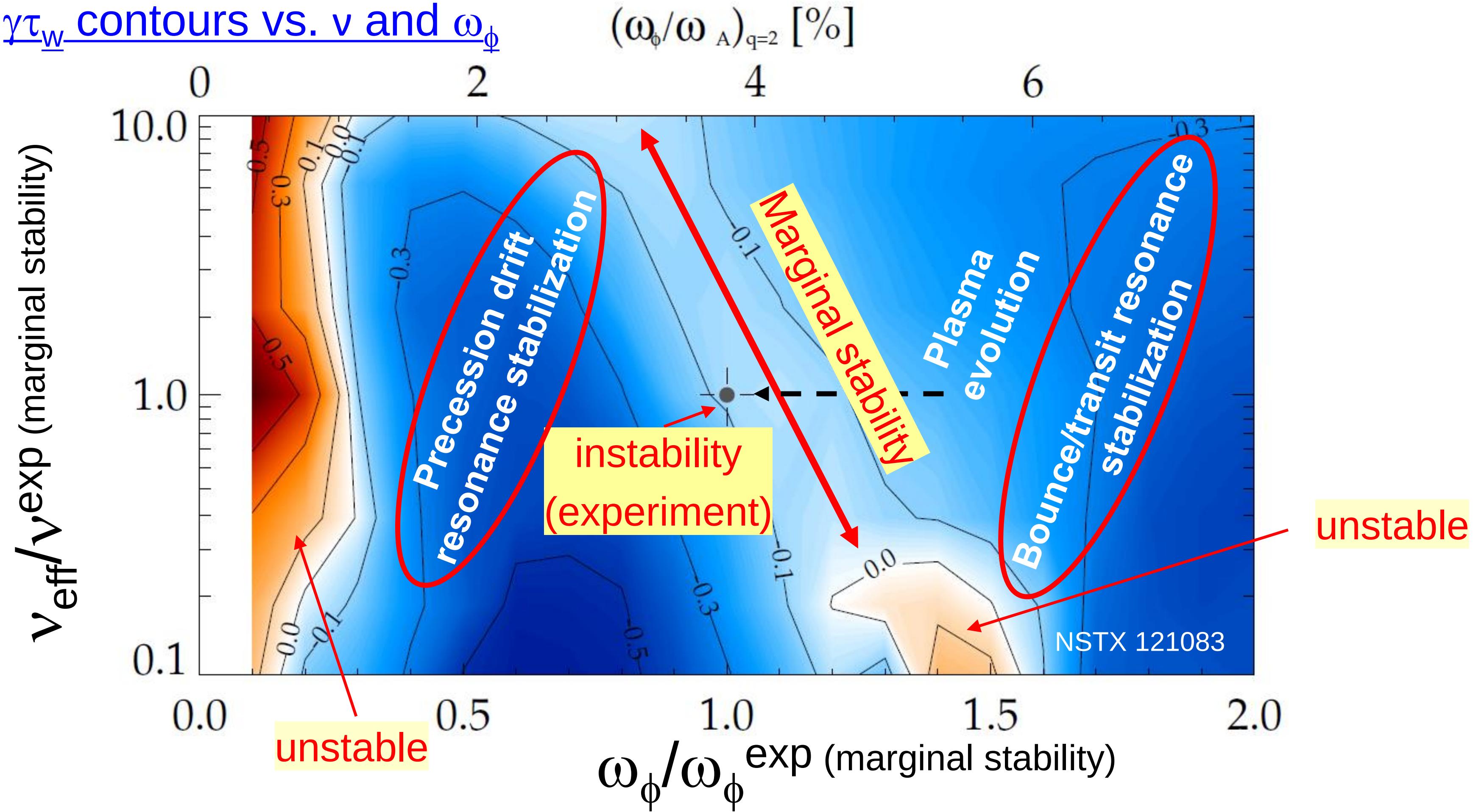


- Marginal stable experimental plasma reconstruction, rotation profile ω_ϕ^{exp}
- Variation of ω_ϕ away from marginal profile increases stability
- Unstable region at low ω_ϕ

S.A. Sabbagh, J.W. Berkery, et al., IAEA Fusion Energy Conference (FEC) 2008 (paper EX/5-1)

MISK calculations for NSTX consistent with RWM destabilization at intermediate plasma rotation; stability altered by collisionality

$\gamma\tau_w$ contours vs. ν and ω_ϕ



Precession drift resonance stabilization

Marginal stability

Plasma evolution

Bounce/transit resonance stabilization

instability (experiment)

unstable

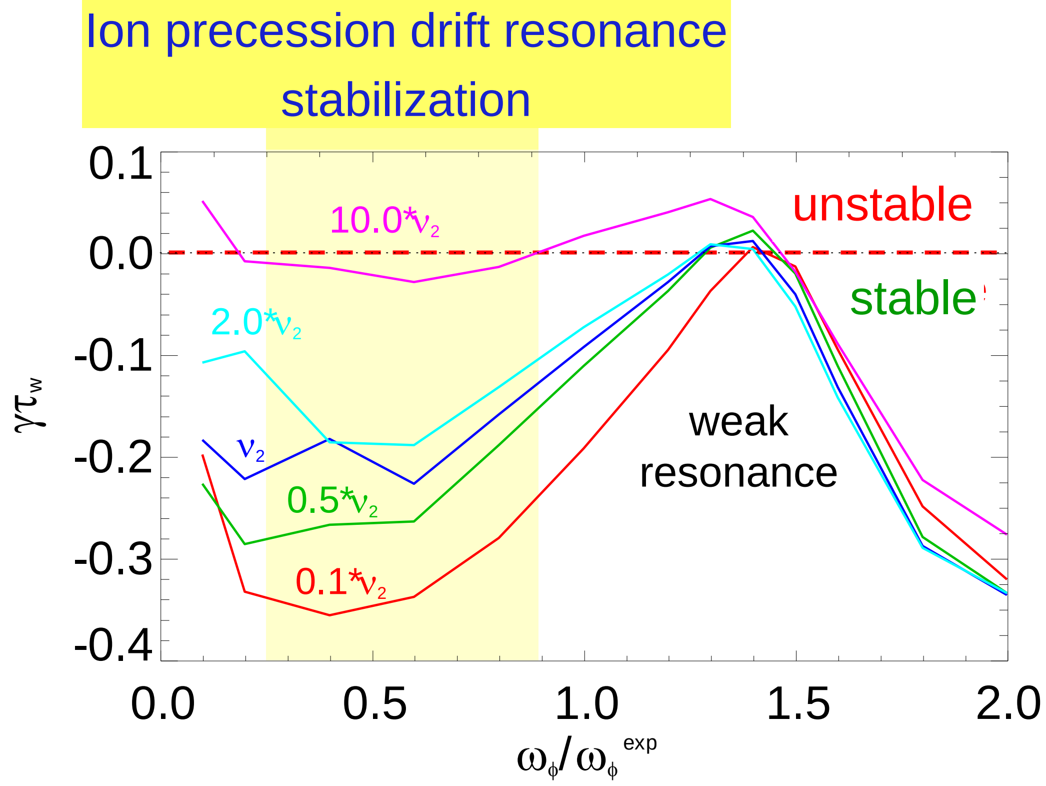
unstable

NSTX 121083

- ❑ Destabilization appears between precession drift resonance at low ω_ϕ, bounce/transit resonance at high ω_ϕ
- ❑ Destabilization moves to increased ω_ϕ as ν decreases

J.W. Berkery, et al., PRL **104** (2010) 035003
S.A. Sabbagh, et al., NF **50** (2010) 025020

Kinetic modifications completely change the understanding and scaling of mode stability at reduced collisionality



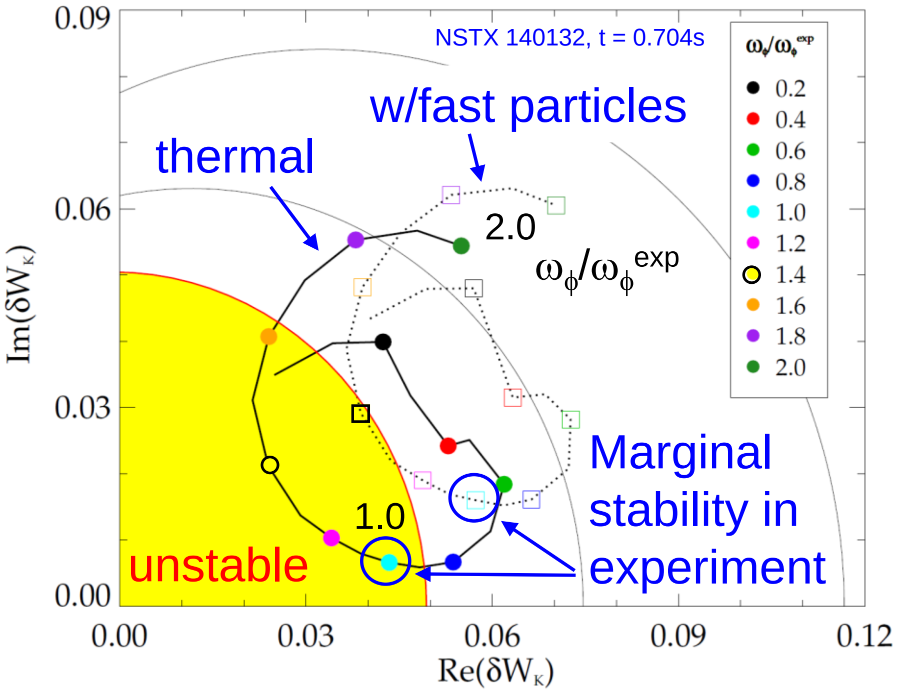
- Past models/ideas
  - Collisions provide mode stabilization
  - So, stability decreased with decreasing ν
  - Unfavorable for ITER

- Present model
  - Collisions spoil broad stabilizing resonances
  - Mode stabilization vs. ν depends on ω_ϕ
    - At strong resonance: mode stability **increases** with decreasing ν

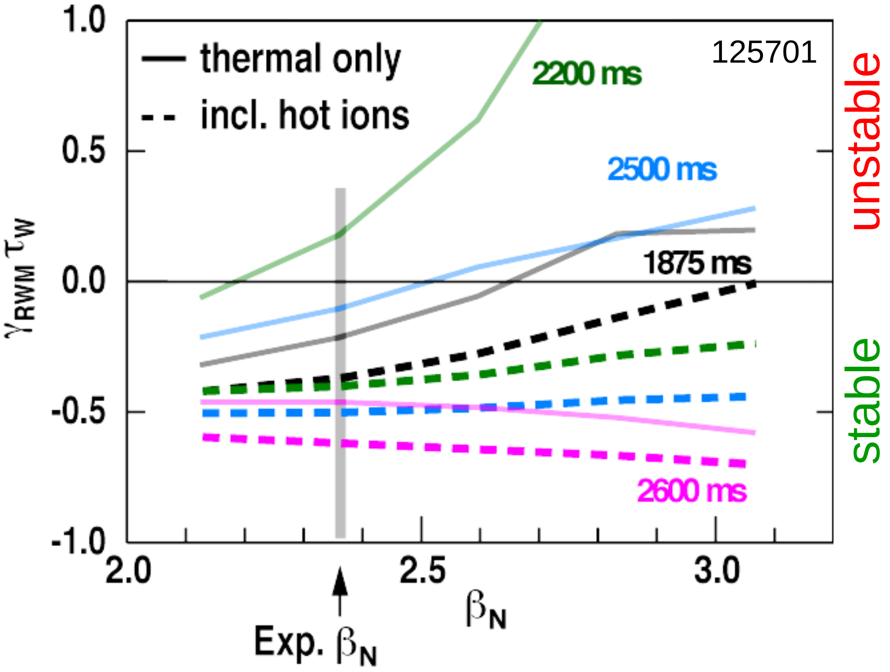
- J.W. Berkery, S.A. Sabbagh, et al., Phys. Rev. Lett. **106** (2011) 075004
- J.W. Berkery, S.A. Sabbagh, et al., Phys. Plasmas **21** (2014) 056112

Further kinetic RWM analysis showed importance of fast particles to refine quantitative marginal stability evaluation

Stability vs. ω_ϕ (contours of $\gamma\tau_w$) - NSTX



Stable rotation profile scan - DIII-D



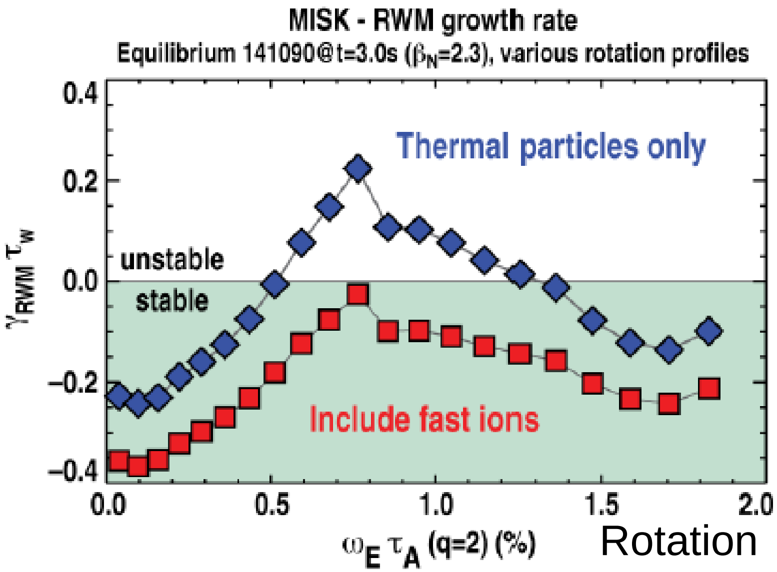
- Rotation profile scans in NSTX and DIII-D
- Inclusion of fast particles more accurately determines mode stability

- Reimerdes, et al., APS 2008
- Sabbagh, Berkery, et al., APS DPP 2010 GI2.00001(invited talk)
- Berkery, Sabbagh, et al., PoP **21** (2014) 056112

Kinetic RWM calculations for DIII-D are consistent with MHD spectroscopy results when energetic particles are included

❑ Technique

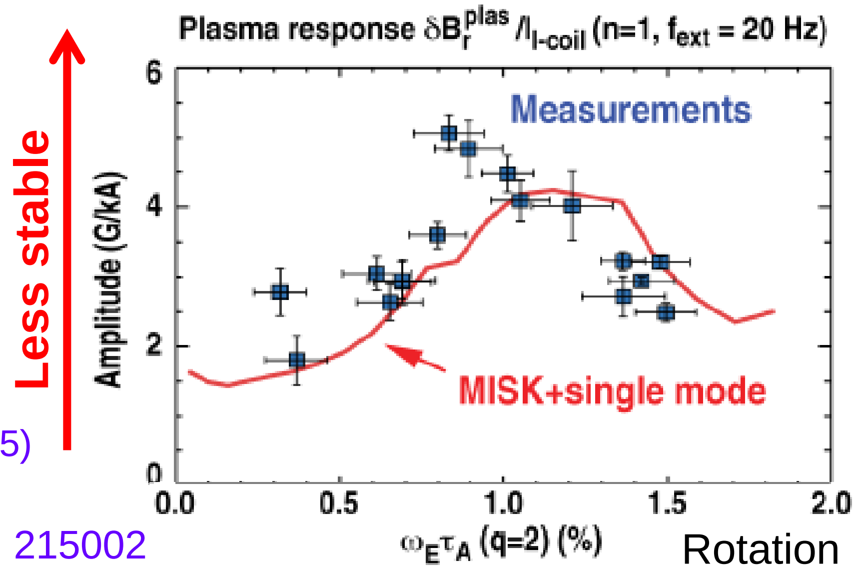
- ❑ Low frequency MHD spectroscopy measures resonant field amplification (RFA) of applied *n*=1 field
  - ➔ H. Reimerdes, *et al*., PRL **93** (2004) 135002
- ❑ Yields RWM growth rate in a stable plasma



❑ Results show

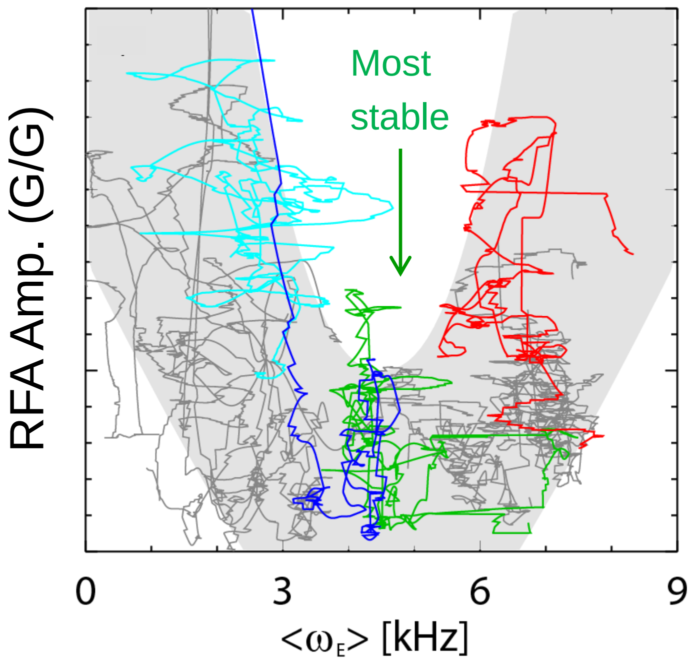
- ❑ Kinetic model requires fast ions to explain experimental stability
- ❑ Plasma rotation dependence of RFA matches kinetic RWM theory
  - Similar finding in NSTX plasmas
  - Recently re-confirmed in DIII-D

(Wang, Lanctot, Liu, *et al*., PRL **114** (2015) 145005)

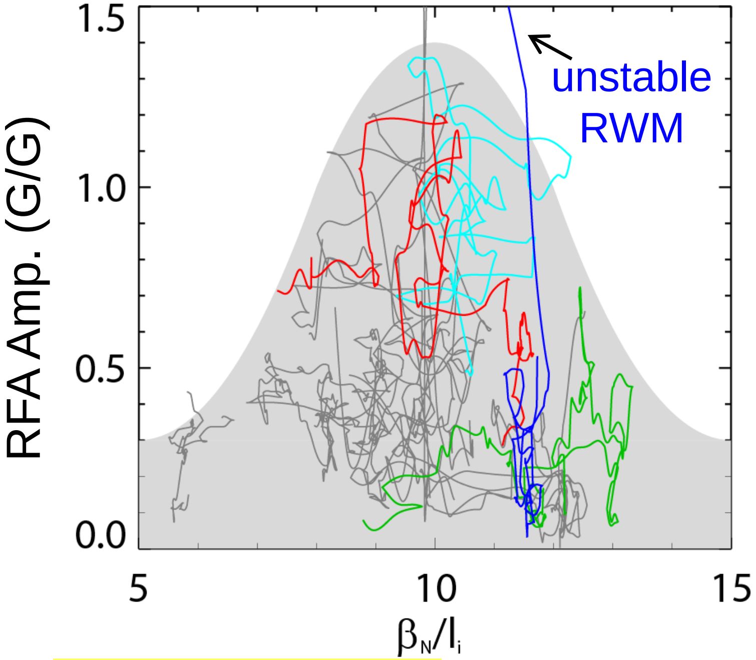


Reimerdes, Berkery, …, Sabbagh *et al*., PRL **106** (2011) 215002

Experiments directly measuring global stability using MHD spectroscopy (RFA) understood by kinetic RWM theory


RFA vs. rotation (ω_E)

Less stable


Resonant Field Amplification vs. β_N/l_i

- **Stability vs. rotation**
  - Largest stabilizing effect from ion precession drift resonance with ω_ϕ

Minimize $|<\omega_D> + \omega_E|$

$$\delta W_k \sim \frac{1}{\langle \omega_D \rangle + \omega_E - i\nu_{eff}}$$

(trajectories of 20 experimental plasmas)

- **Stability vs. β_N/l_i**
  - decreases up to $\beta_N/l_i = 10$, ***increases*** at higher β_N/l_i
  - Consistent with kinetic resonance stabilization

S. Sabbagh, et al., NF **53** (2013) 104007

J. Berkery, et al., PoP **21** (2014) 056112

2014: Dedicated DIII-D experiments directly probed RWM marginal stability boundary, compared to NSTX results

DIII-D High β_N, q_{min} plasmas

- Candidates for steady-state, high β_N operation
- Can have high probability of significant RWM activity with $q_{min} > 2$
  - RWMs and TMs cause strong β collapses in 82% of a database of 50 shots examined, with an average of 3 collapses every 2 shots
  - RWMs cause collapse 60% of the time, TMs 40% of the time
- Employ high $q_{min} > 2$ to avoid 2/1 TM instability (TM precludes RWM)
  - Used ECCD control of 3/1 TM to provide further control of strong n = 1 TMs
- Unique 1 ms resolution of ω_ϕ and T_i measurement captures profile detail in timescale < RWM growth time

S.A. Sabbagh, J.W. Berkery, J. Hanson, et al. APS DPP Invited Talk VI2.0002 (2014)

NSTX

- Strong RWM drive: Maximum $\beta_N > 7$, $\beta_N / l_i > 13.5$
- Strong TMs eliminated by high elongation (> 2.6) or Li wall conditioning

2014: Kinetic RWM marginal stability boundaries were directly probed over wide range of plasma rotation profiles

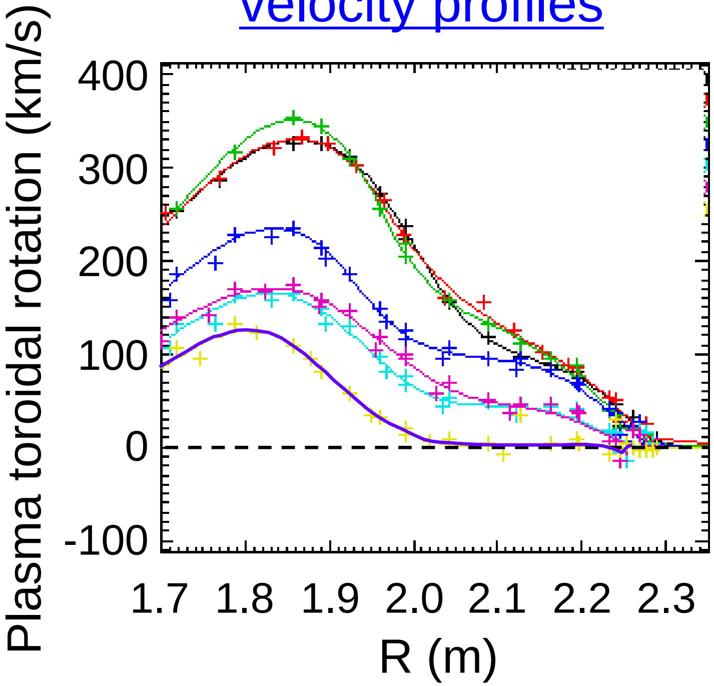
- RWM marginal stability examined for major and minor disruptions

1. Found at high β_N and high rotation

2. Found at high β_N and low rotation
   - Low rotation expected in ITER

3. At moderate β_N and high rotation with increased profile peaking
   - similar loss of profile broadness might easily occur in ITER

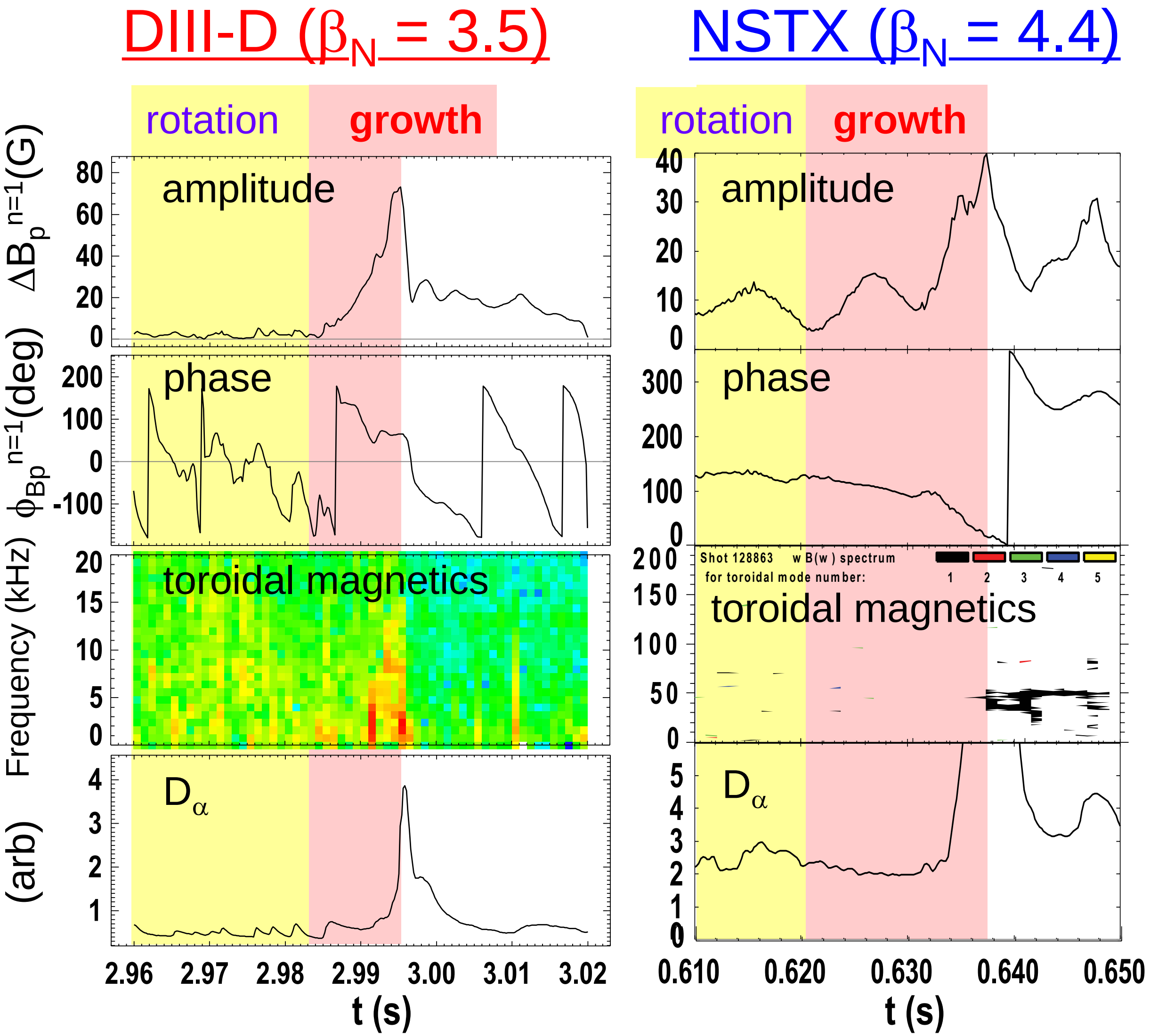
Wide range of DIII-D toroidal plasma velocity profiles



S.A. Sabbagh, J.W. Berkery, J. Hanson, et al. APS DPP Invited Talk VI2.0002 (2014)

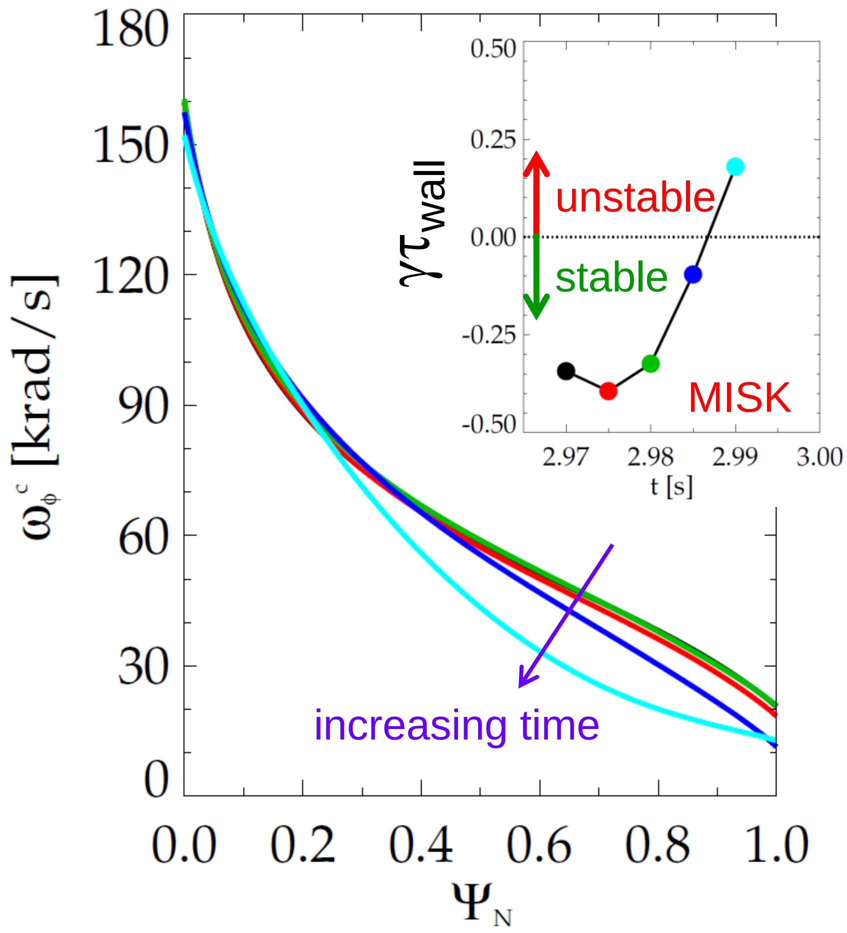
1. Comparison of RWM growth and dynamics in high β_N shots with high plasma rotation

- Elements
  - RWM rotation and mode growth observed
  - No strong NTM activity
  - Some weak bursting MHD in DIII-D plasma
    - Alters RWM phase
  - No bursting MHD in NSTX plasma

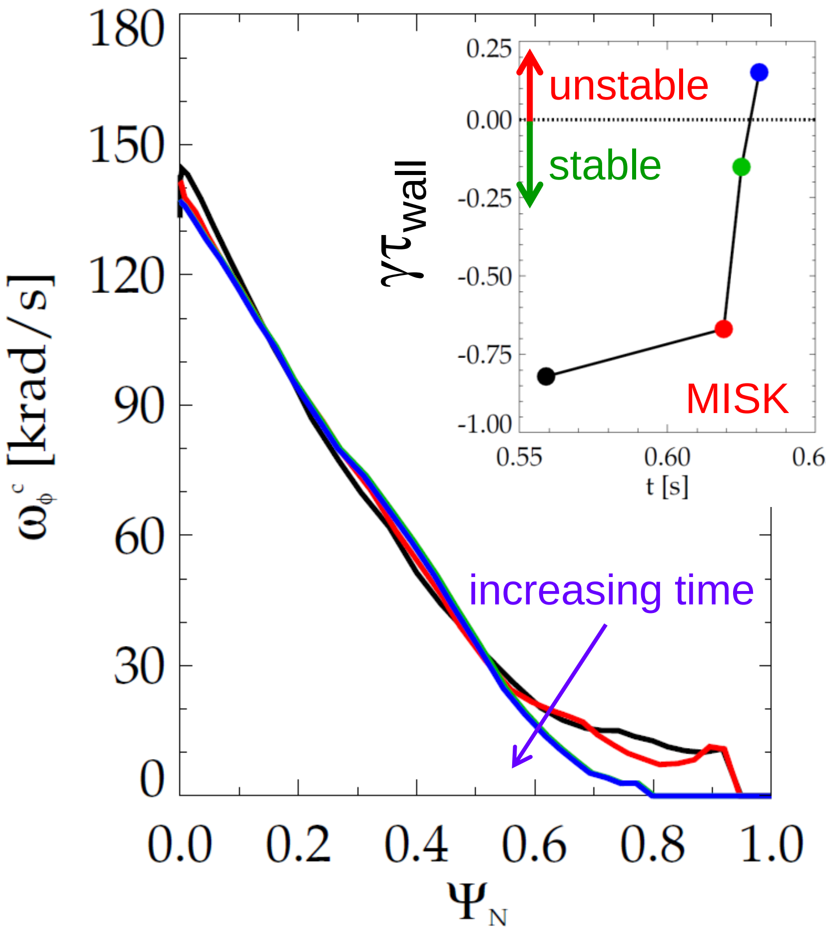


Evolution of plasma rotation profile leads to linear kinetic RWM instability as disruption is approached

DIII-D (minor disruption)



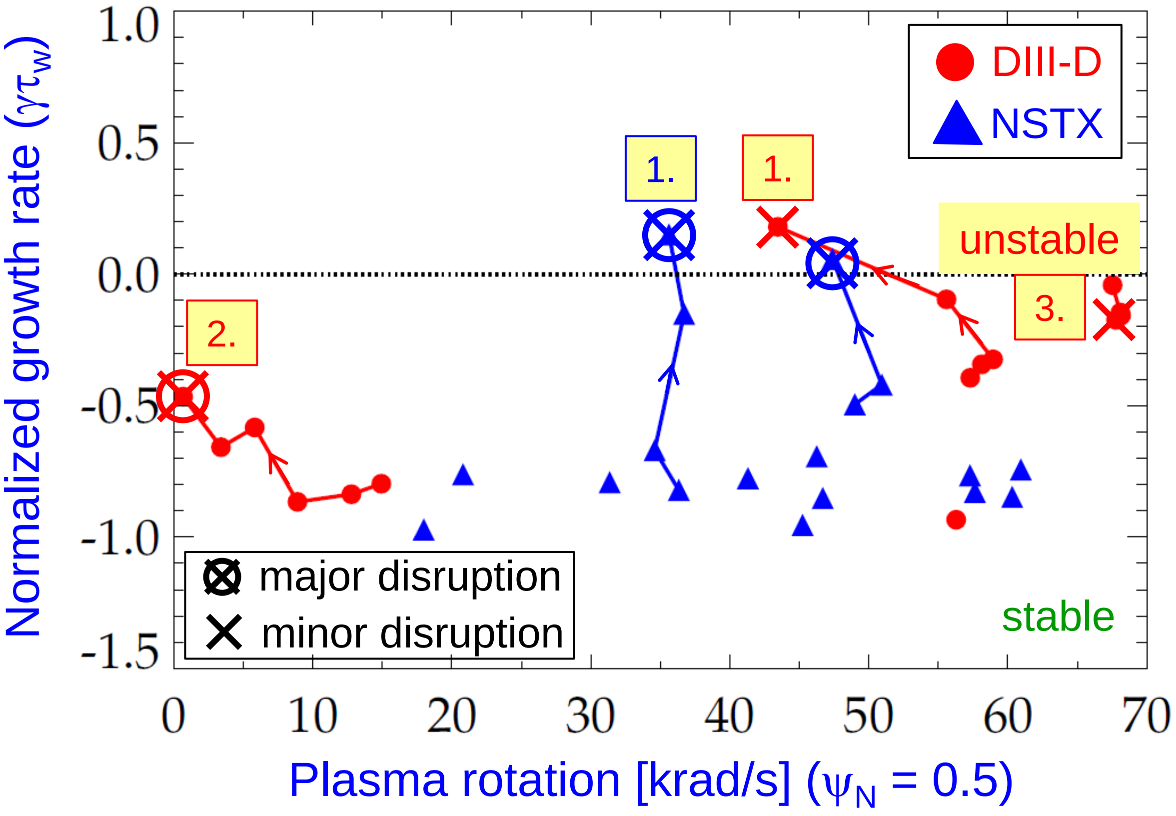
NSTX (major disruption)



Kinetic RWM stability analysis evaluated for DIII-D and NSTX plasmas

- Summary of results
  - Plasmas free of other MHD modes can reach or exceed linear kinetic RWM marginal stability

Kinetic RWM stability analysis for experiments (MISK)



S.A. Sabbagh, J.W. Berkery, J. Hanson, et al. APS DPP Invited Talk VI2.0002 (2014)

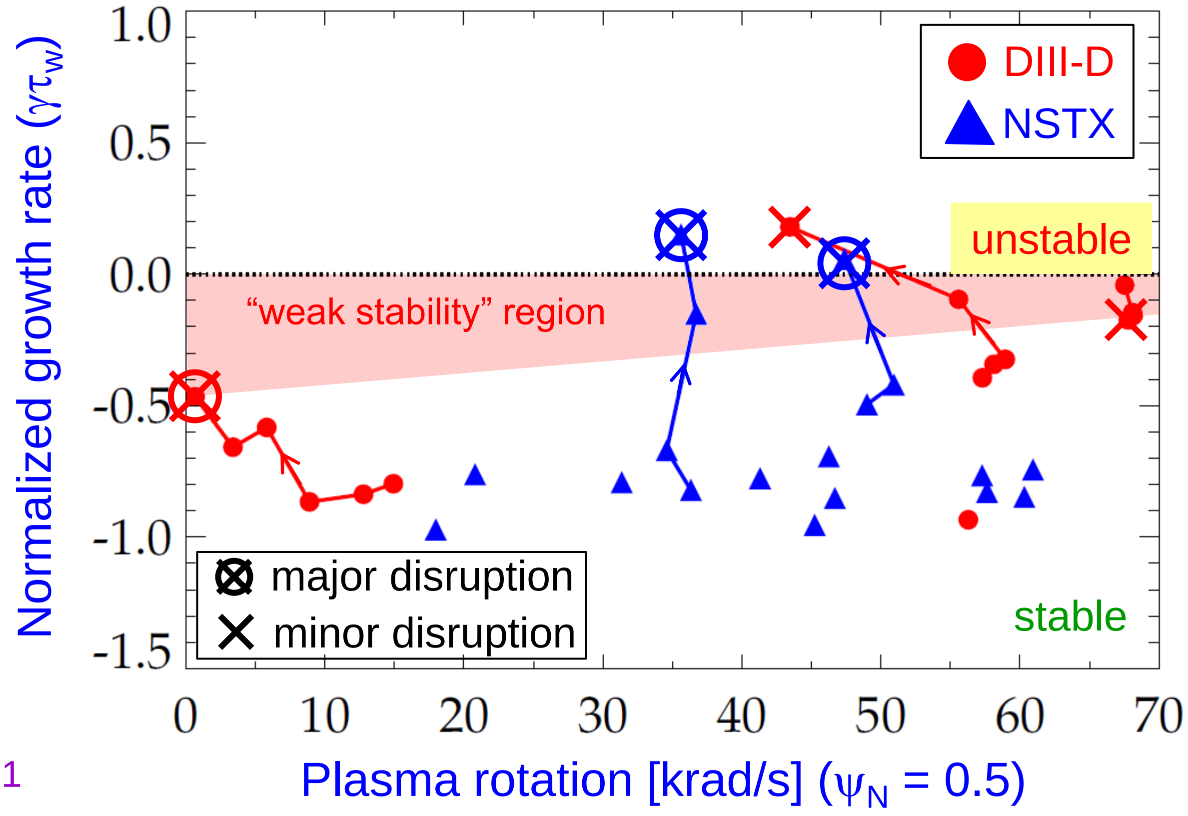
Kinetic RWM stability analysis evaluated for DIII-D and NSTX plasmas

- Summary of results
  - Plasmas free of other MHD modes can reach or exceed linear kinetic RWM marginal stability
  - Bursting MHD modes can lead to non-linear destabilization before linear stability limits are reached

    - Present analysis can quantitatively define a "weak stability" region below linear instability

Strait, et al., PoP **14** (2007) 056101

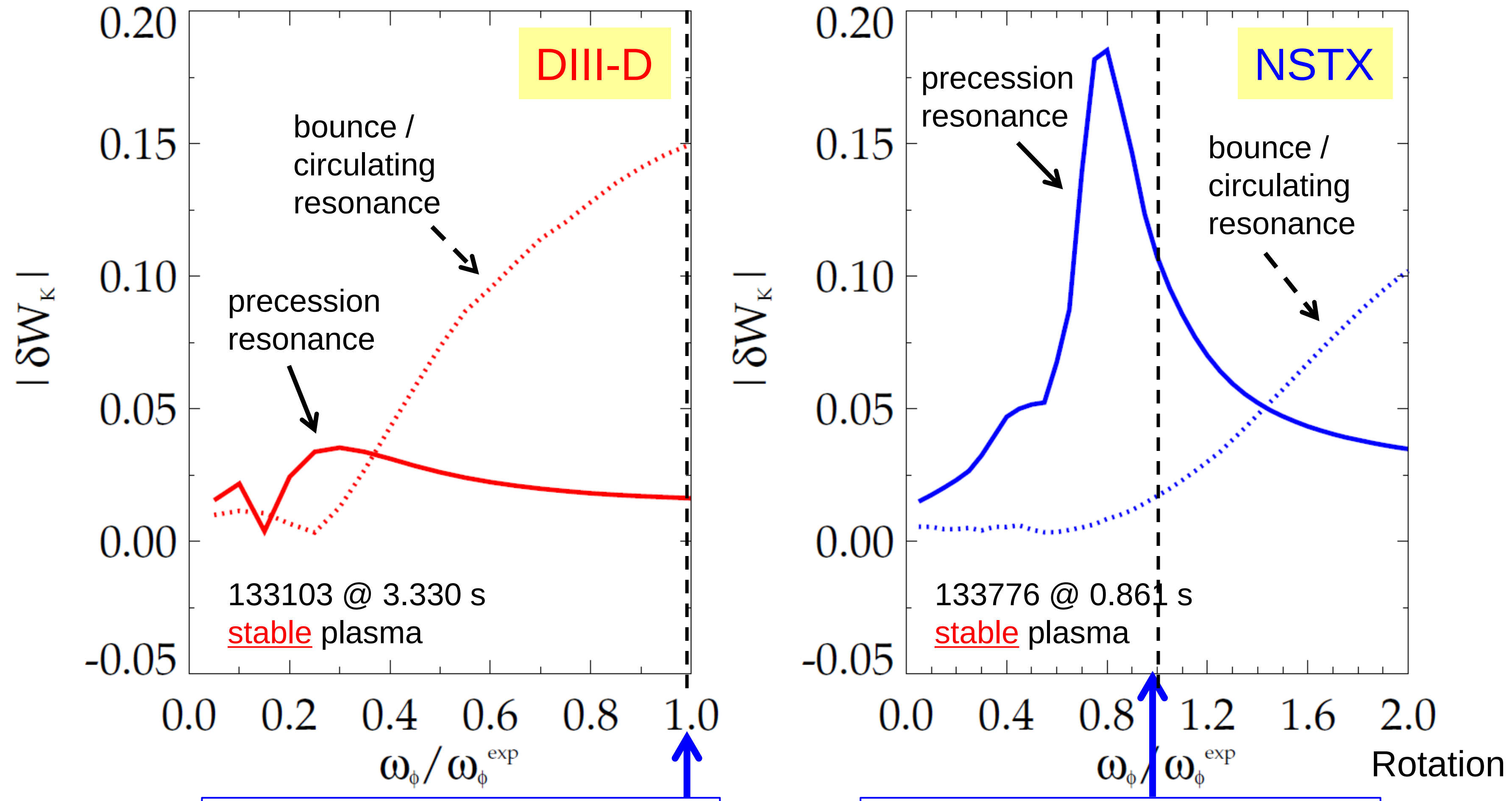
Kinetic RWM stability analysis for experiments (MISK)



S.A. Sabbagh, J.W. Berkery, J. Hanson, et al. APS DPP Invited Talk VI2.0002 (2014)

Bounce resonance stabilization dominates for DIII-D vs. precession drift resonance for NSTX at similar, high rotation

$|\delta W_K|$ for trapped resonant ions vs. scaled experimental rotation (MISK)

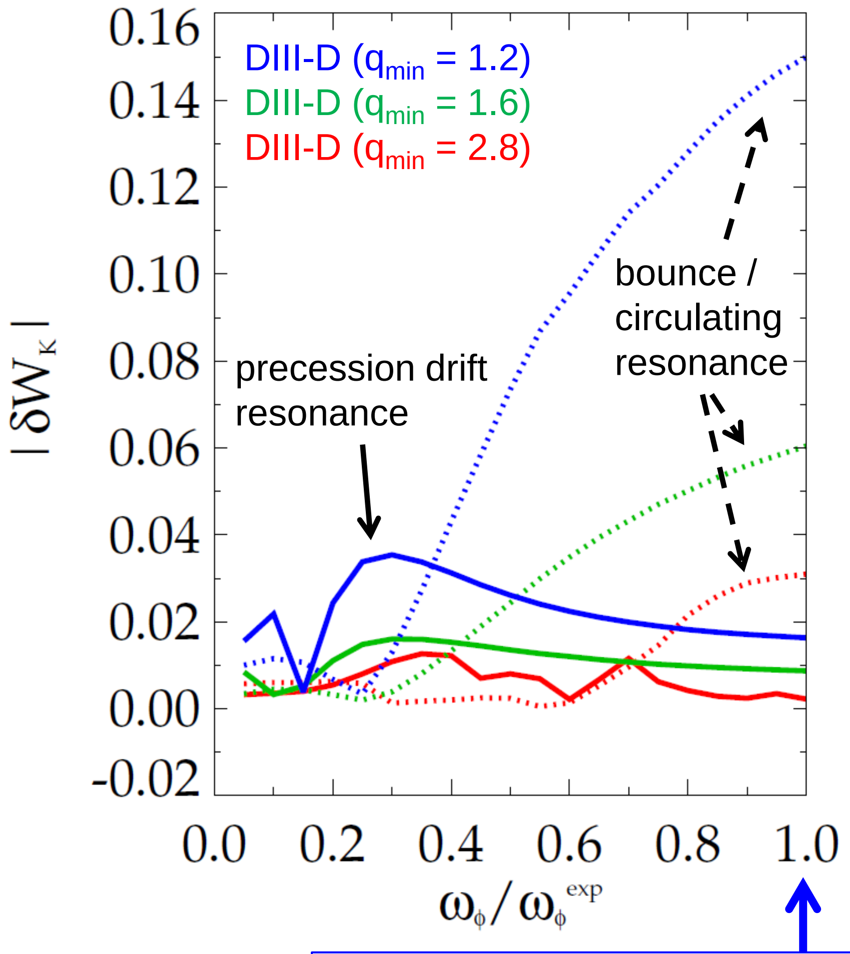


DIII-D experimental rotation profile

NSTX experimental rotation profile

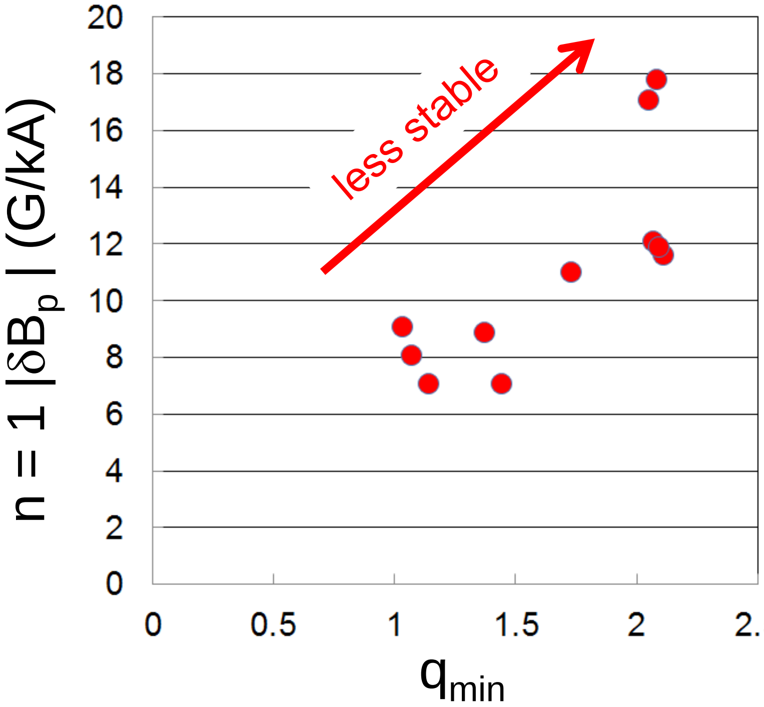
Reduced RWM stability measured in DIII-D plasmas as q_{min} is increased is consistent with kinetic RWM theory

$|\delta W_K|$ for trapped resonant ions vs. scaled experimental rotation (MISK)



DIII-D experimental rotation profile

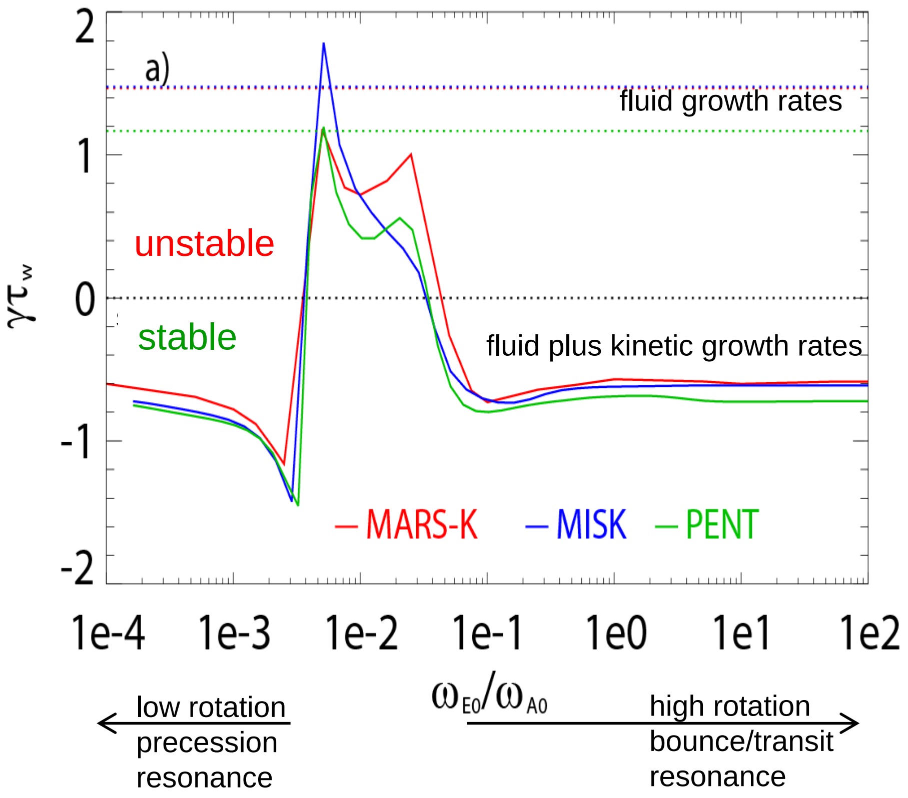
Measured plasma response to 20 Hz, n = 1 field vs q_{min}



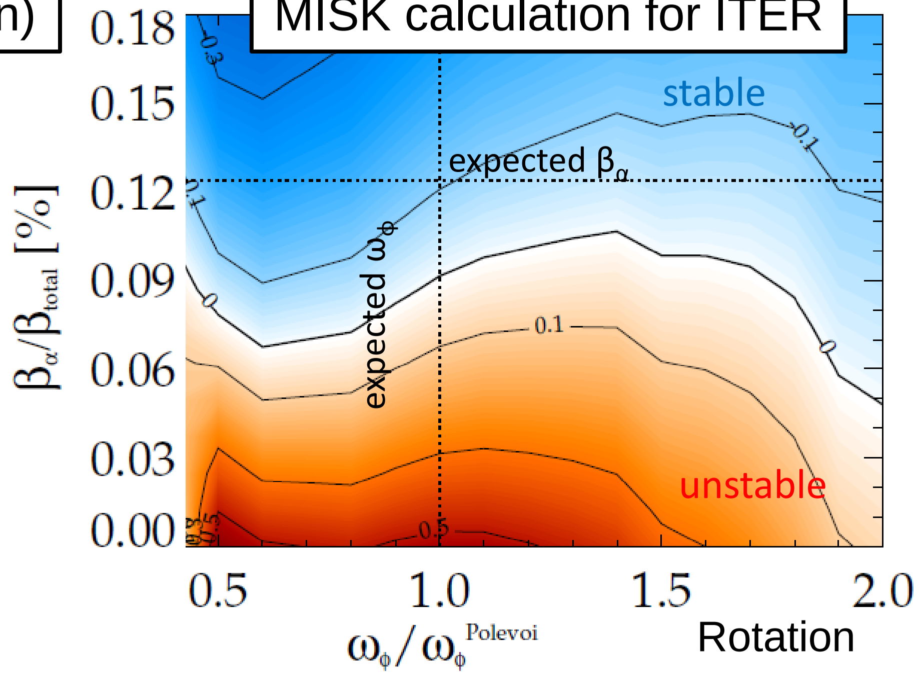
- Bounce resonance dominates precession drift resonance for all q_{min} examined at the experimental rotation

Key analysis codes MARS-K and MISK were brought into agreement in $\gamma\tau_w$ vs ω_E for analysis of ITER

Code benchmarking (growth rate vs. rotation)



MISK calculation for ITER



- J.W. Berkery, Y. Liu, … S.A. Sabbagh et al. Phys. Plasmas **21** (2014) 052505

MARS-K code/analysis: Y. Liu, Z. Wang

- ❑ Case: β_N = 2.9 (20% > no-wall limit – advanced scenario)
- ❑ Alpha particles are required for RWM stabilization at all ω_ϕ
- ❑ Near RWM marginal stability at $\beta_\alpha/\beta_{total}$ = 0.1 at expected rotation

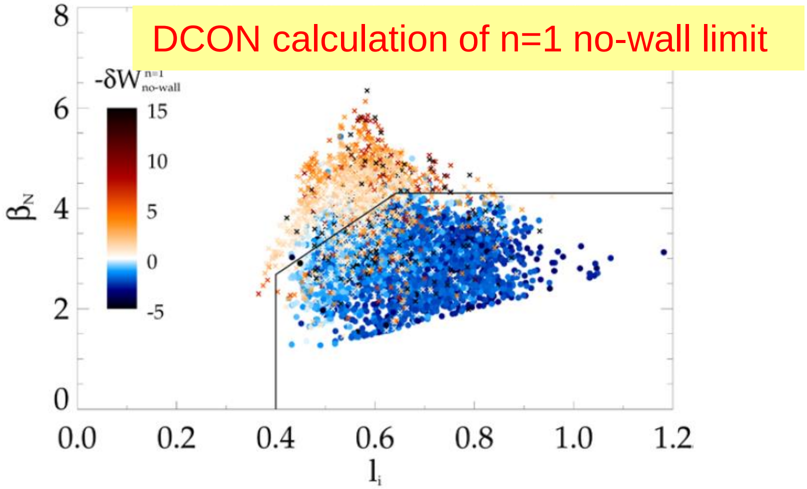
NSTX-U is building on past strength, creating an arsenal of capabilities for disruption avoidance (available / future)

Predictor/Sensor (CY available)	Control/Actuator (CY available)	Modes	REFER TO
Rotating and low freq. MHD (n=1,2,3) 2003	Dual-component RWM sensor control (closed loop 2008)	NTM RWM	- Menard NF 2001 - Sabbagh NF 2013
Low freq. MHD spectroscopy (open loop 2005); Kinetic RWM modeling (2008)	Control of β_N (closed loop 2007)	Kink/ball RWM	- Sontag NF 2007 - Berkery (2009–15) - Gerhardt FST 2012
r/t RWM state-space controller observer (2010)	Physics model-based RWM state-space control (2010)	NTM, RWM Kink/ball, VDE	- Sabbagh IAEA 2010 - Sabbagh NF 2013 - THIS TALK
Real-time V_ϕ measurement (2016)	Plasma V_ϕ control (NTV 2004) (NTV + NBI rotation control closed loop ~ 2018-19)	NTM Kink/ball RWM	- Podesta RSI 2012 - Zhu PRL 06 - THIS TALK
Reduced kinetic RWM stabilization (2016) (aimed at real-time)	Safety factor, l_i control (closed loop ~ 2018-19)	NTM, RWM Kink/ball, VDE	- Berkery, NF 2015 (+ THIS TALK) - D. Boyer, NF 2015
MHD spectroscopy (real-time) (in 5 Year Plan)	Upgraded 3D coils (NCC): improved V_ϕ and mode control (in 5 Year Plan)	NTM, RWM Kink/ball, VDE	- NSTX-U 5 Year Plan

A reduced kinetic RWM model in new Disruption Event Characterization And Forecasting (DECAF) code

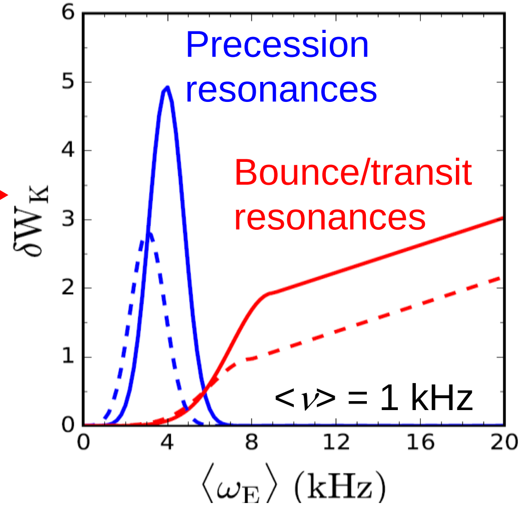
Elements: mode growth rate calculation

- Ideal component δW
  - Equilibrium quantities including l_i, $p_0/\langle p \rangle$, A, used in beta limit models for δW_b, δW_{inf} →


DCON calculation of n=1 no-wall limit

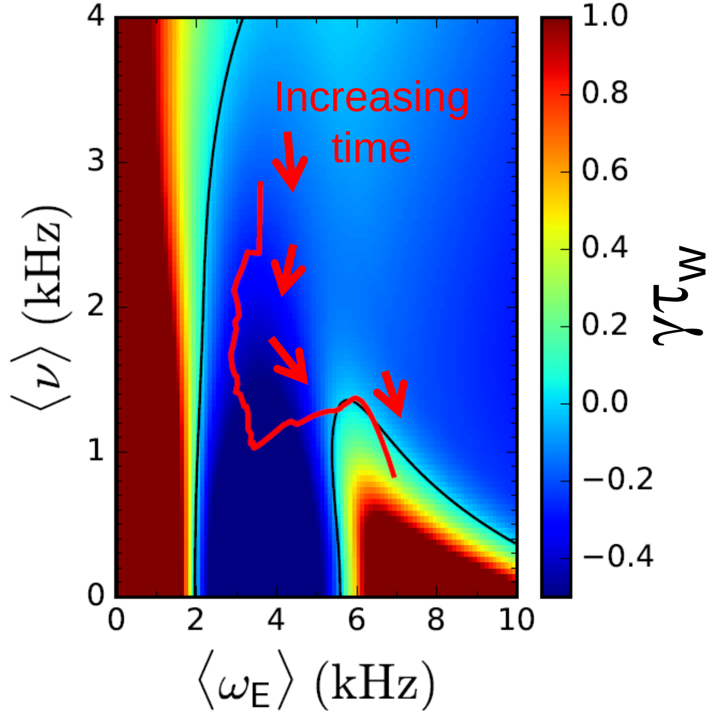
J.W. Berkery, S.A. Sabbagh, R.E. Bell, *et al.*, NF **55** (2015) 123007

- Kinetic component δW_k
  - Functional forms (mainly Gaussian) used to reproduce precession and bounce/transit resonances →
  - Height, width, position of peak depend on collisionality

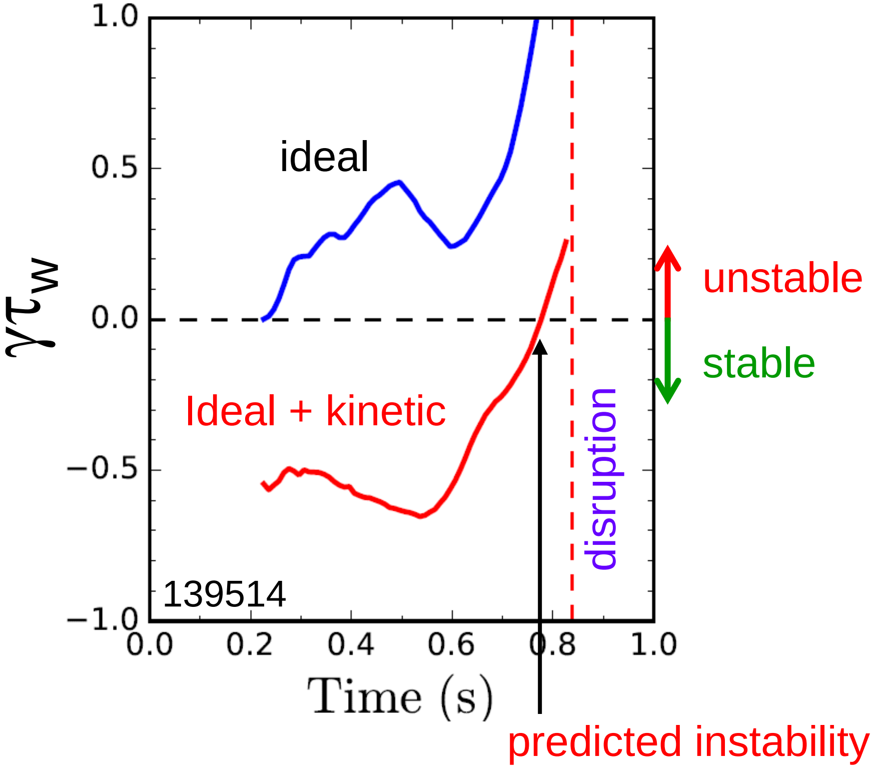


Reduced kinetic RWM model in DECAF results in a calculation of $\gamma\tau_w$ vs. time for each discharge

$\gamma\tau_w$ contours vs. ν and ω_ϕ



Normalized growth rate vs. time

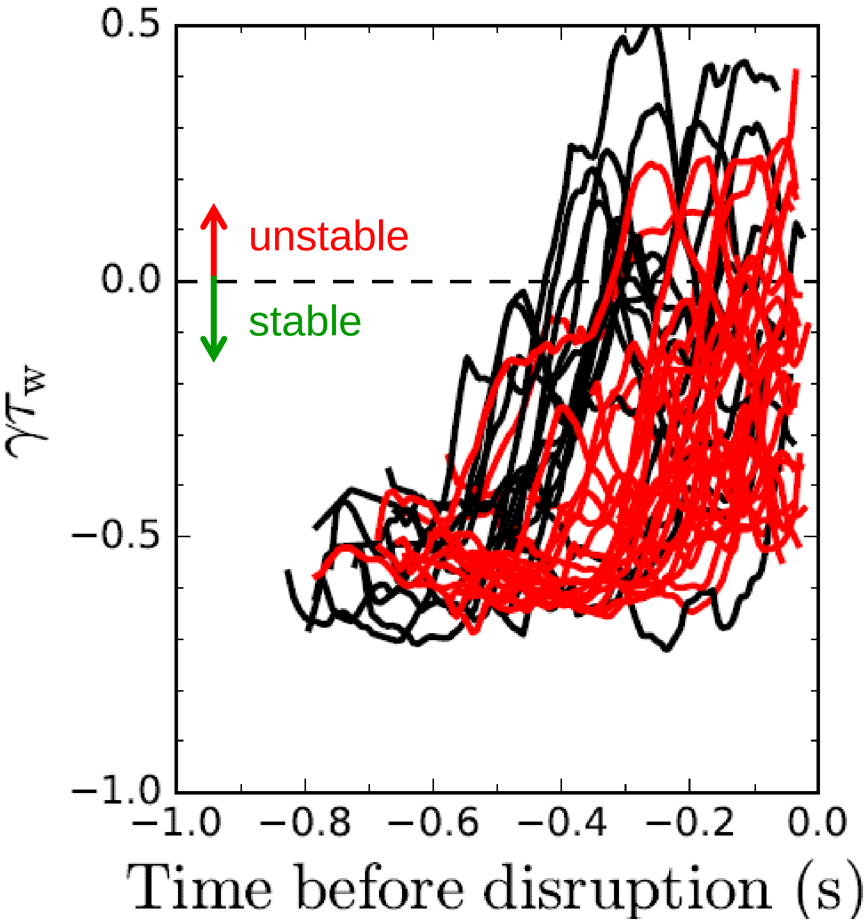


- Favorable characteristics
  - Stability contours CHANGE for each time point (last time point shown left frame)
  - Possible to compute growth rate prediction in real time

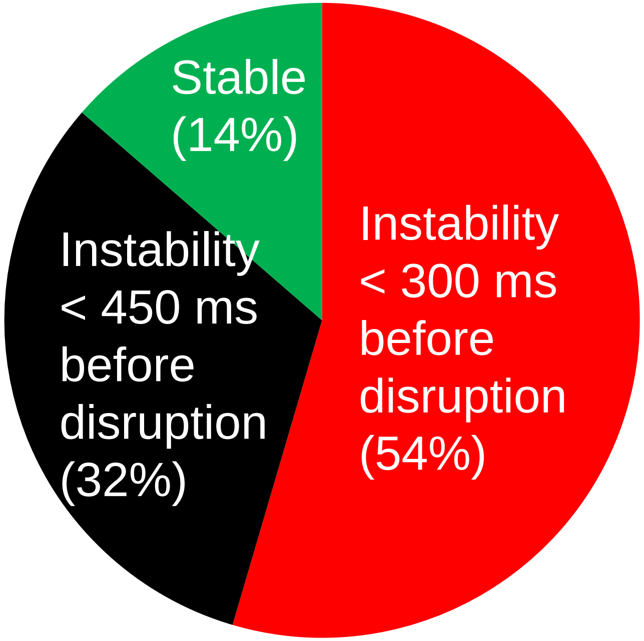
J.W. Berkery, S.A. Sabbagh, R. Bell, *et al.*, submitted to Phys. Plasmas (2017)

DECAF reduced kinetic model results initially tested on a database of NSTX discharges with unstable RWMs

Normalized growth rate vs. time



Predicted instability statistics (44 shots)



- 86% of shots are predicted unstable
- 54% predicted unstable < 300 ms (approx. $60\tau_w$) before current quench
- 32% predicted unstable < 450 ms before current quench
    - Mostly earlier cases are minor disruptions

State space rotation controller designed for NSTX-U using non-resonant NTV and NBI to maintain stable profiles

- Momentum force balance – ω_ϕ decomposed into Bessel function states

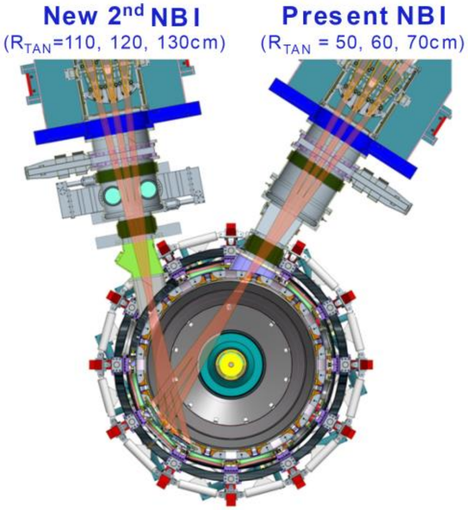
$$\sum_i n_i m_i \left\langle R^2 \right\rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho}\right)^{-1} \frac{\partial}{\partial \rho}\left[\frac{\partial V}{\partial \rho}\sum_i n_i m_i \chi_\phi \left\langle \left(R\nabla\rho\right)^2 \right\rangle \frac{\partial \omega}{\partial \rho}\right] + T_{NBI} + T_{NTV}$$

- Neoclassical Toroidal Viscosity (NTV) torque:

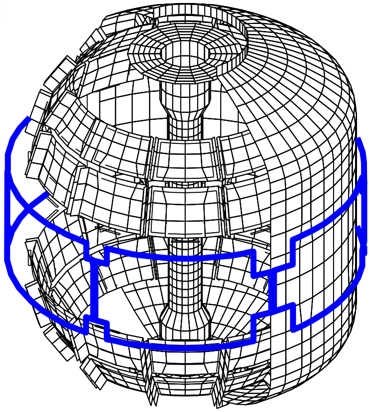
$$T_{NTV} \propto K \times f\left(n_{e,i}^{\;K1} T_{e,i}^{\;K2}\right) g\left(\delta B\left(\rho\right)\right)\left[I_{coil}^{\;2}\omega\right]$$

Momentum Actuators

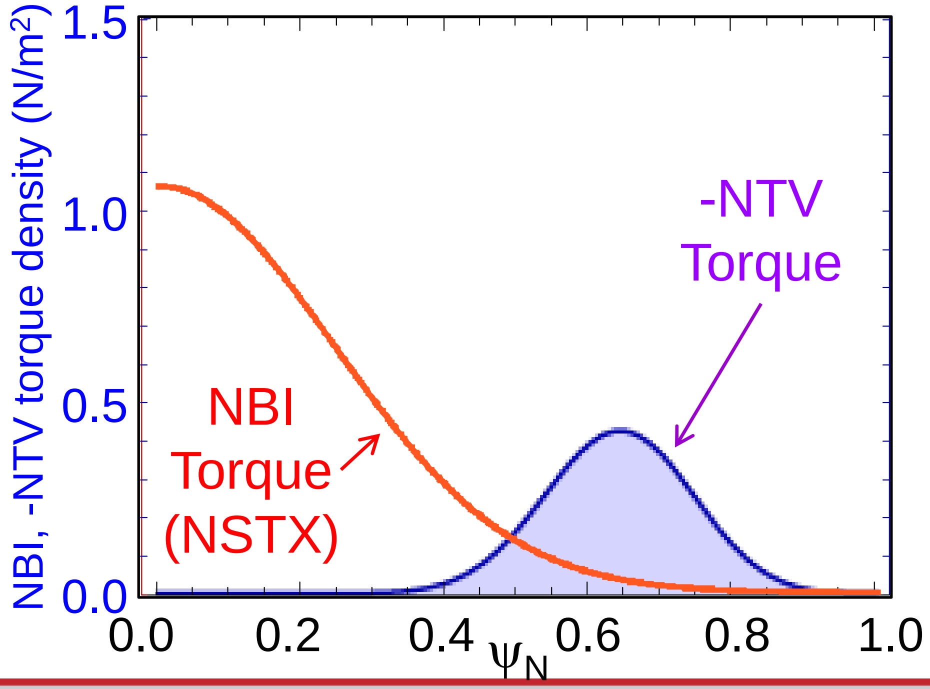
New NBI
(broaden rotation)



3D Field Coil
(shape ω_ϕ profile)



NBI and NTV torque profiles for NSTX-U



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Momentum Actuators

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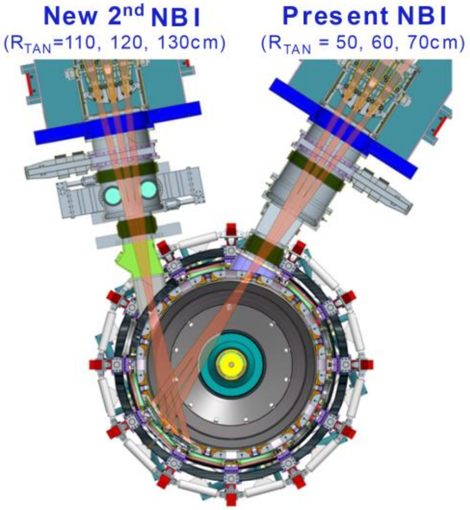
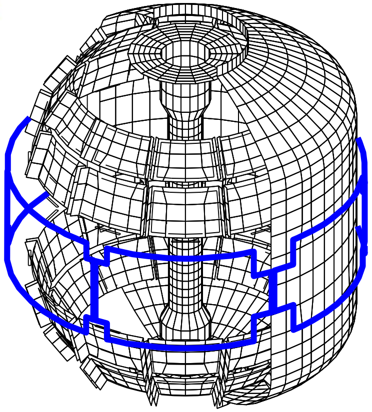
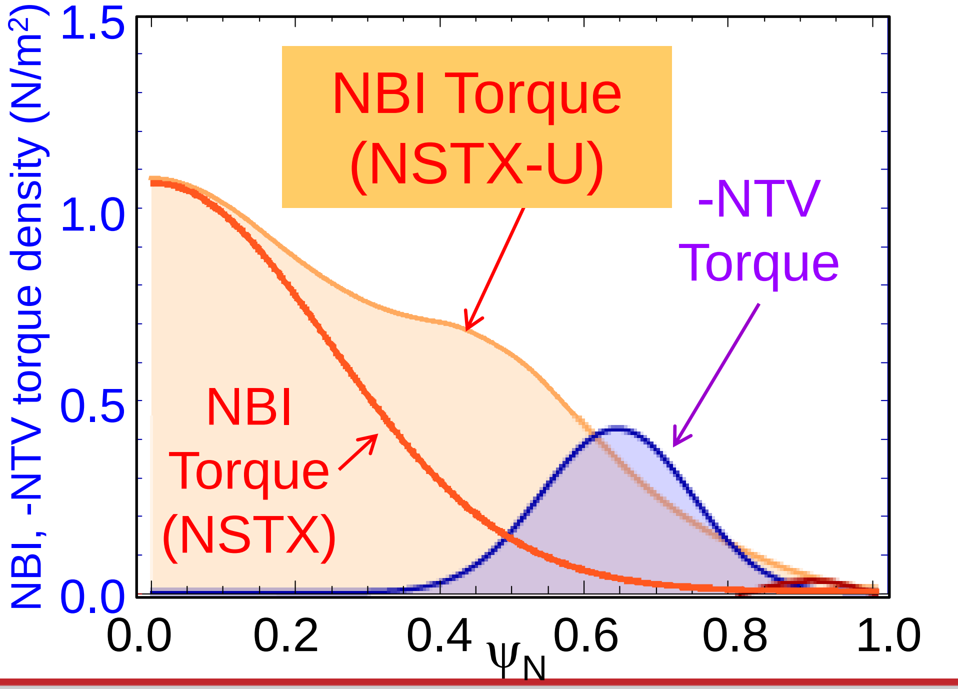
3D Field Coil (shape ω_ϕ profile)

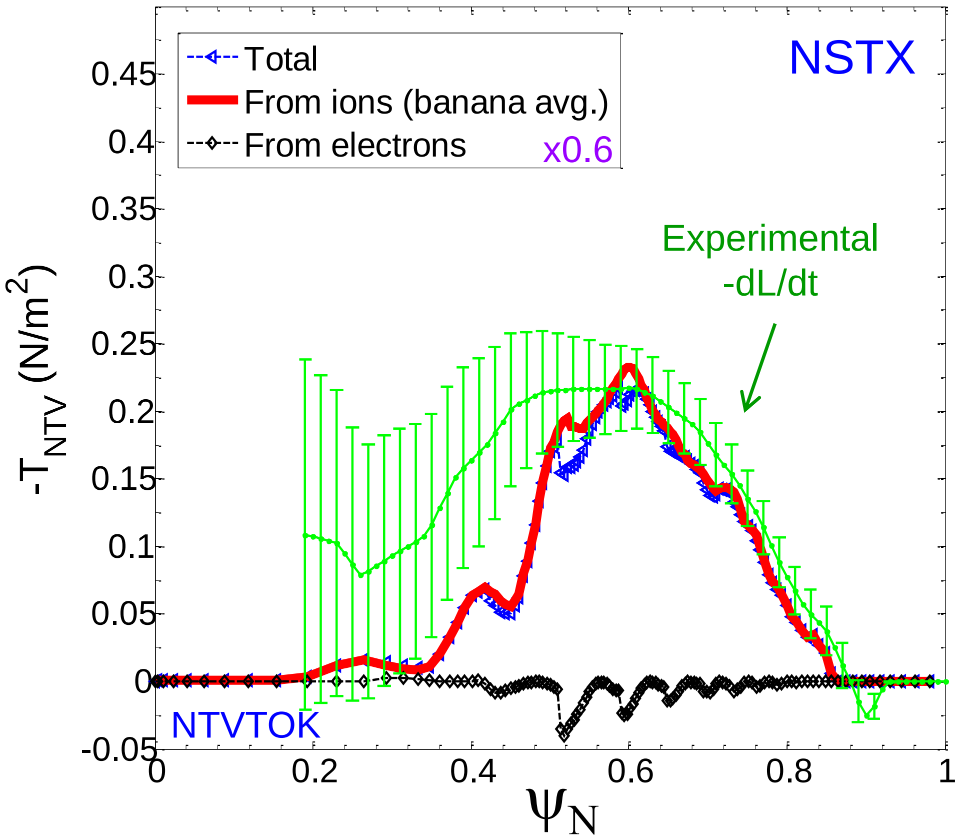




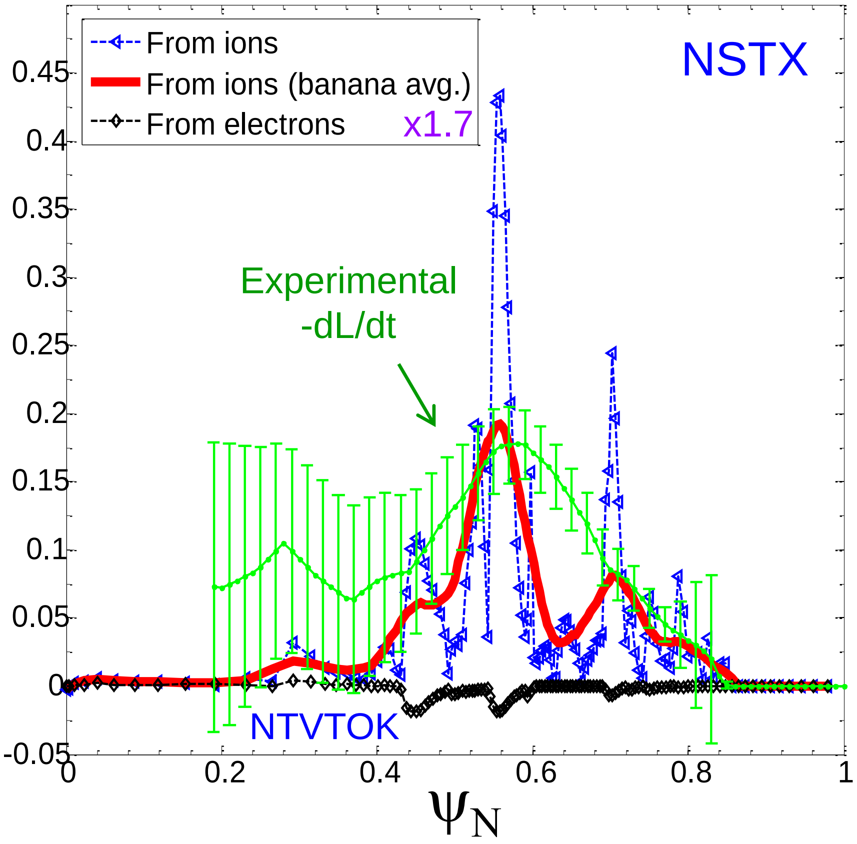
NBI and NTV torque profiles for NSTX-U



NTV physics studies for rotation control: measured NTV torque density profiles quantitatively compare well to theory



n = 3 coil configuration



n = 2 coil configuration

- T_{NTV} (theory) scaled to match *peak* value of measured *-dL/dt*
  - Scale factor ((*dL/dt*)/T_{NTV}) = 1.7 and 0.6 for cases shown above – O(1) agreement

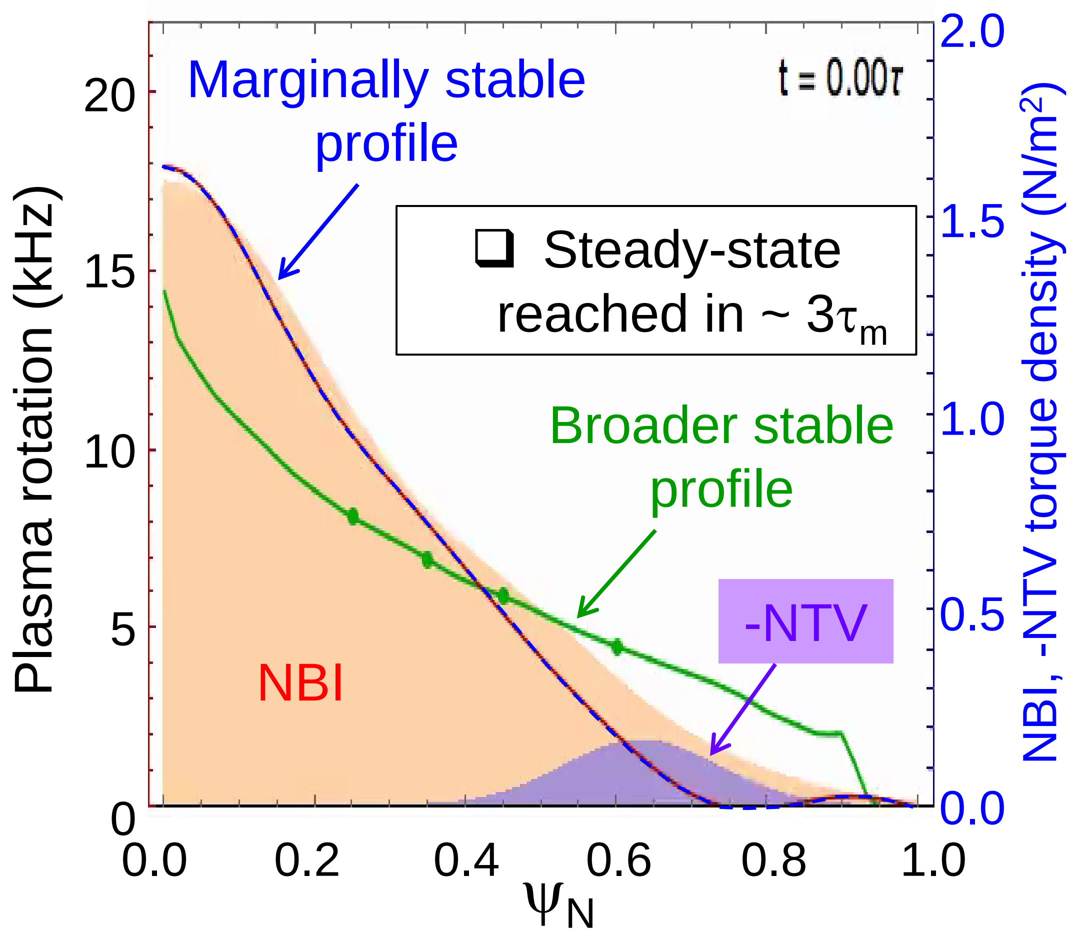
For NTV experiment/theory see: W. Zhu, S.A. Sabbagh, R.E. Bell, et al., PRL **96** (2006) 225002

Also, see recent NTV review paper: K.C. Shaing, K. Ida, S.A. Sabbagh, et al., Nucl. Fusion **55** (2015) 125001

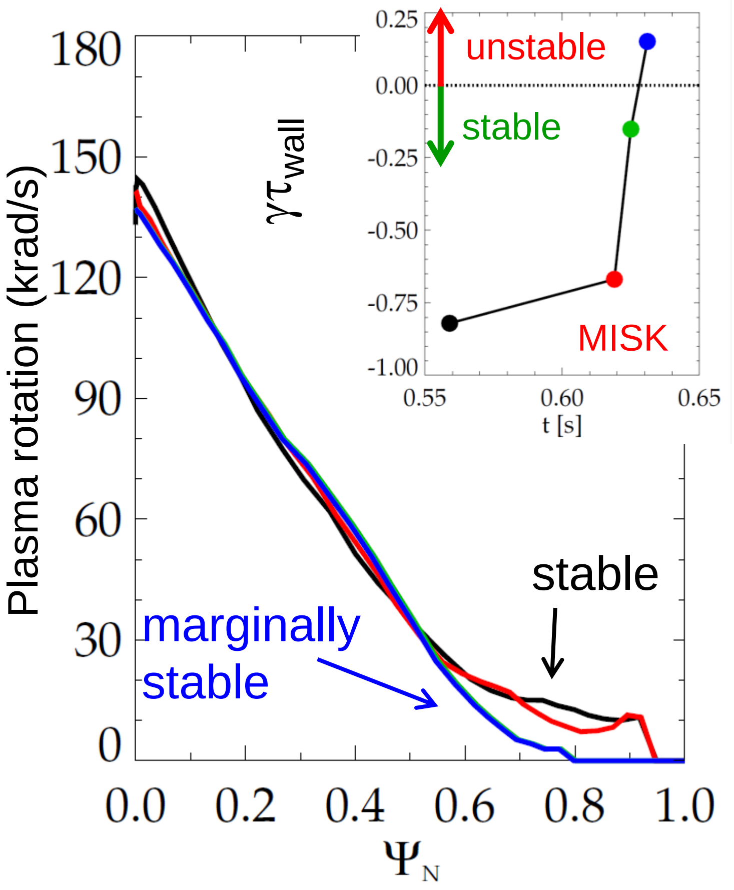
Application of kinetic RWM physics understanding from present research will now be used for disruption avoidance

Planned rotation control in NSTX-U

(actuators: 6 NBI sources, n = 3 NTV)


- ☐ Steady-state reached in ~ $3\tau_m$

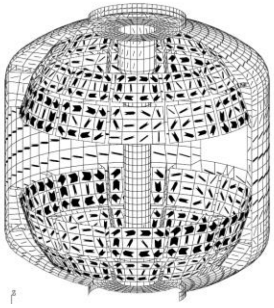
Recall:
NSTX (major disruption)



I. Goumiri, C. Rowley, S.A. Sabbagh, et al. Nucl. Fusion **56** (2016) 036023

Model-based RWM state space controller including 3D model of plasma and wall currents used at high β_N

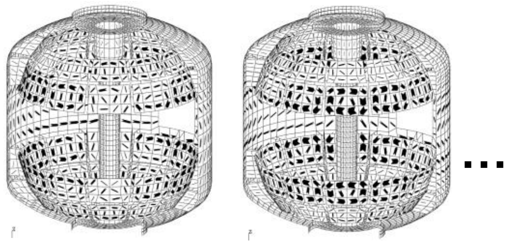
Full 3-D model ~3000+ states



Balanced truncation

State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)



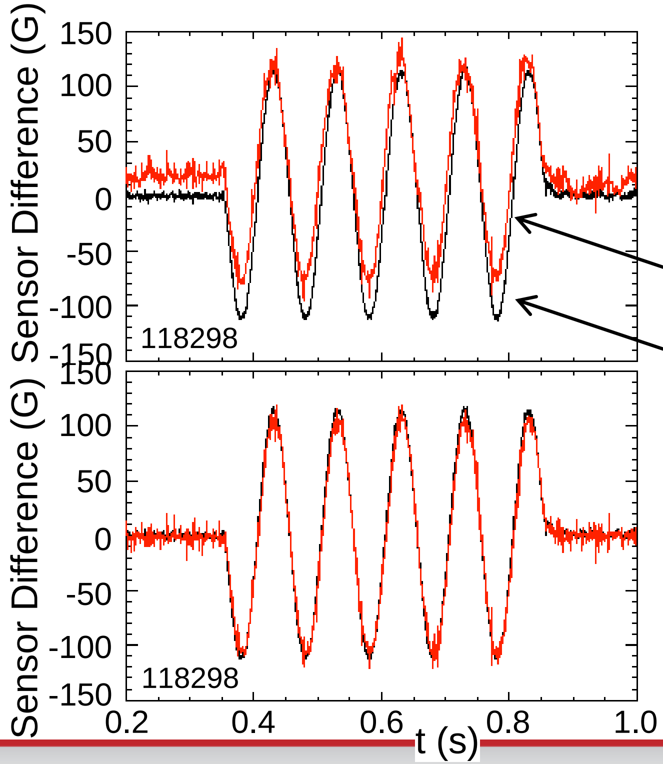
$(\hat{x}_1, \hat{x}_2)$ $\hat{x}_3$ $\hat{x}_4$

Controller reproduction of n = 1 field in NSTX

- ❑ Controller model can compensate for wall currents
  - ❑ Includes linear plasma mode-induced current model (DCON)
- ❑ Includes plasma response model

  A. Boozer, Phys. Plasmas **10** (2003) 1458
- ❑ Straightforward inclusion of multiple modes (n = 1, or n > 1)
- ❑ Potential to allow control coils to be moved further from plasma, and be shielded (e.g. for ITER)

  O. Katsuro-Hopkins, et al., NF **47** (2007) 1157



5 states used

Controller (observer)

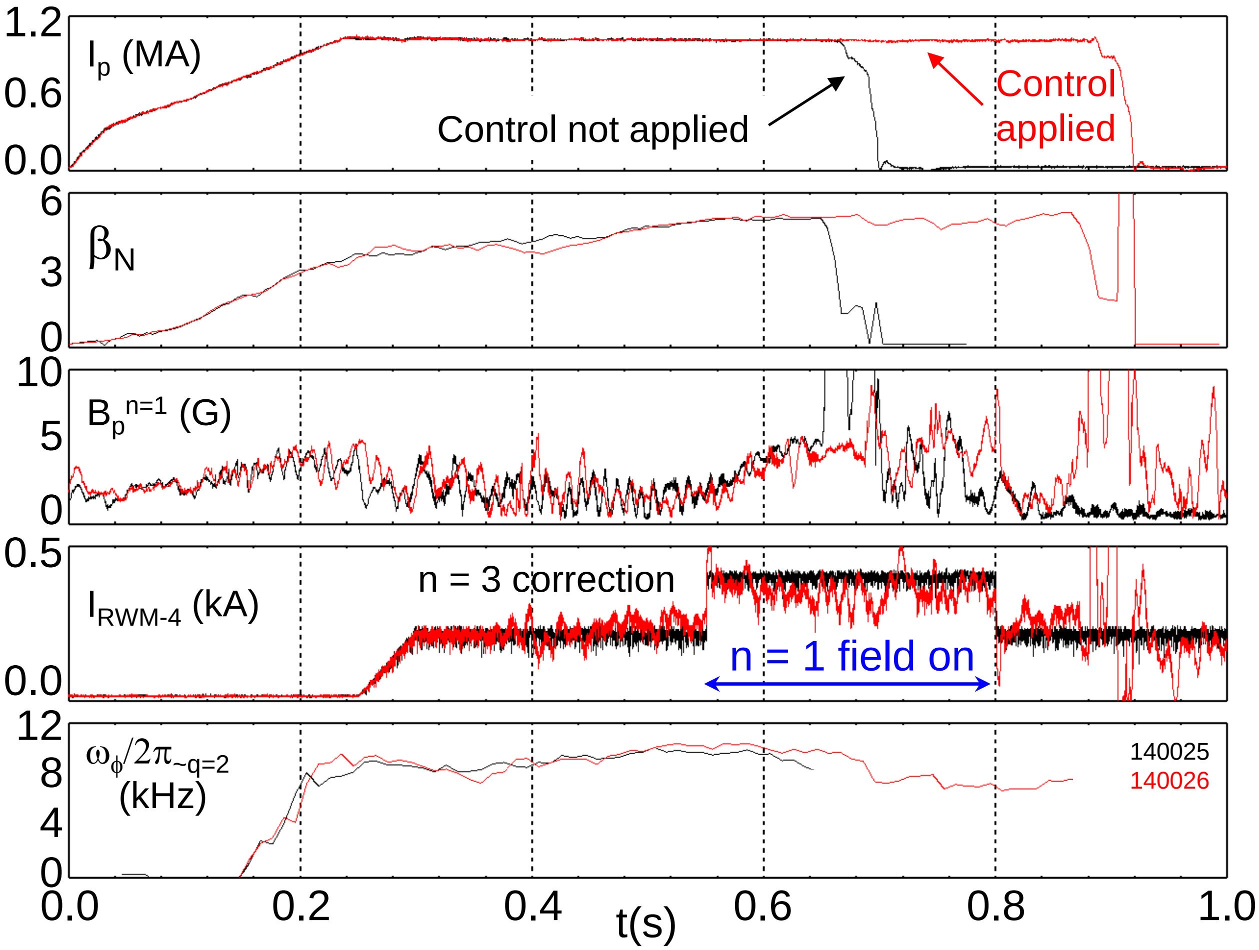
Measurement

10 states used

(only wall states used)

NSTX RWM state space controller sustains otherwise disrupted plasma caused by DC n = 1 applied field

RWM state space feedback (12 states)



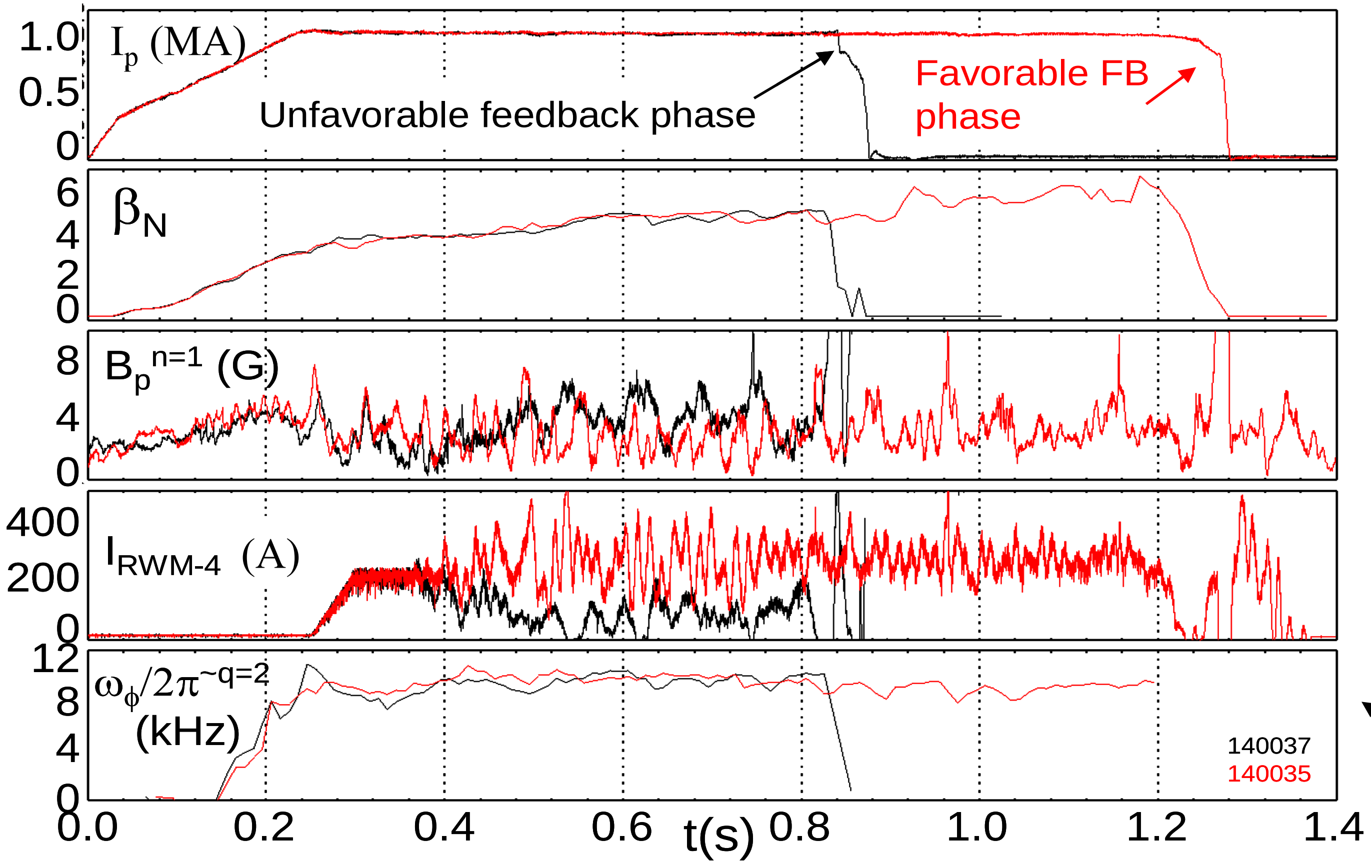
- n = 1 DC applied field test
  - Generate resonant field amplification, disruption
  - Use of RWM state space controller sustains discharge
- RWM state space controller sustains discharge at high β_N
  - Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13

S. Sabbagh et al., IAEA FEC (2010) Paper EXS/5-5

S. Sabbagh et al., Nucl. Fusion **53** (2013) 104007

NSTX RWM state space controller sustains high β_N, low l_i plasma – available for NSTX-U with independent coil control

RWM state space feedback (12 states)



NSTX Experiments (from 2010)

- n = 1 applied field suppression
  - Suppressed disruption due to n = 1 field
- Feedback phase scan
  - Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13

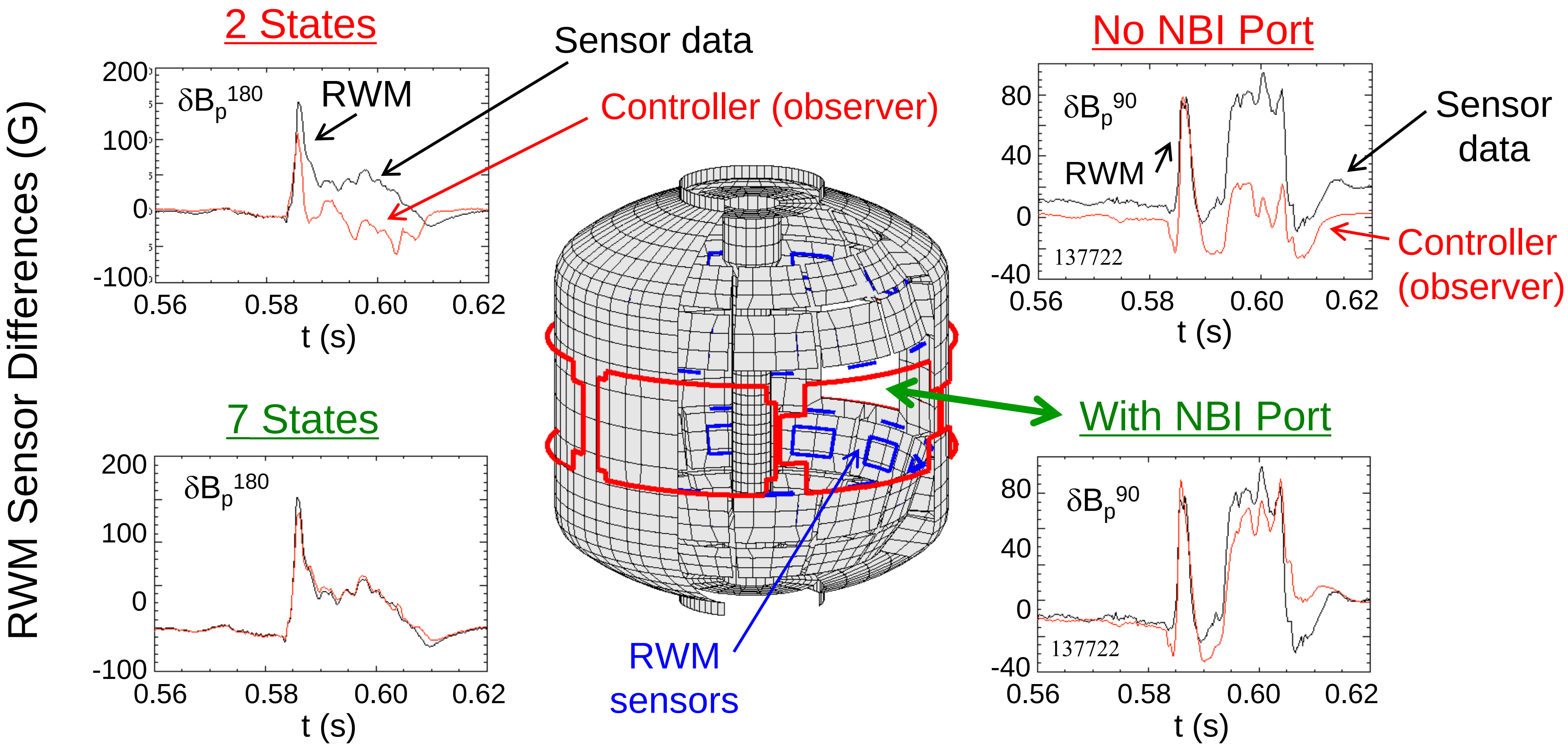
S. Sabbagh et al., IAEA FEC (2010) Paper EXS/5-5

S. Sabbagh et al., Nucl. Fusion **53** (2013) 104007

Open-loop comparisons between measurements and RWM state space controller show importance of states and model

A) Effect of Number of States Used

B) Effect of 3D Model Used



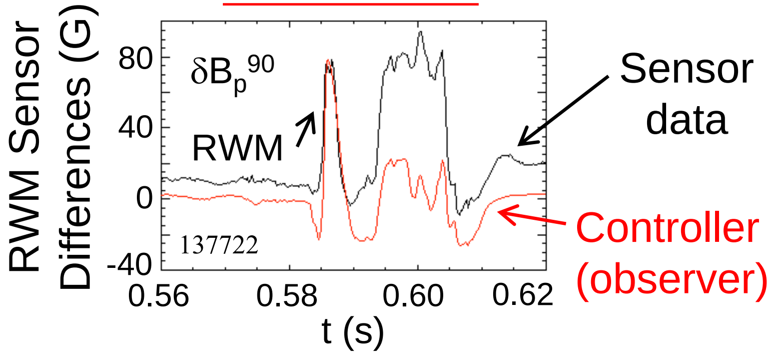
- ❑ Improved agreement with sufficient number of states (wall detail)
- ❑ 3D detail of model important to improve agreement

In addition to active mode control, the NSTX-U RWM state space controller can be used for real-time disruption warning

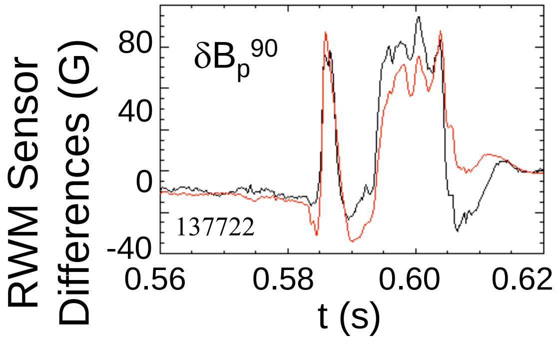
- The controller "observer" produces a physics model-based calculation of the expected sensor data – a synthetic diagnostic
- If the real-time synthetic diagnostic doesn't match the measured sensor data, a r/t disruption warning signal can be triggered
  - Technique will be assessed using new Disruption Event Characterization and Forecasting (DECAF) code

Effect of 3D Model Used

No NBI Port



With NBI Port



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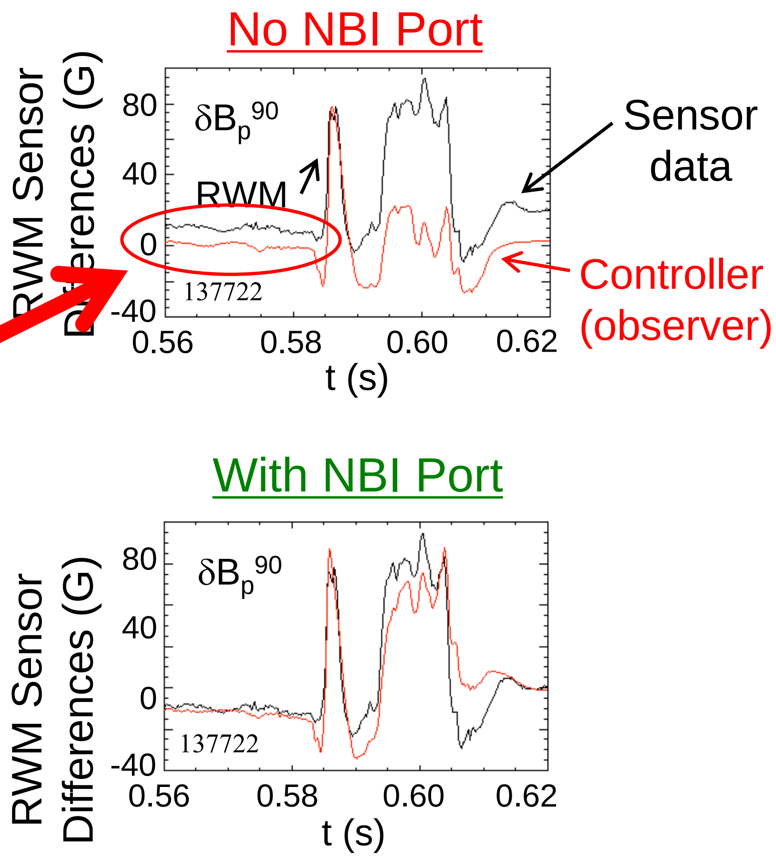
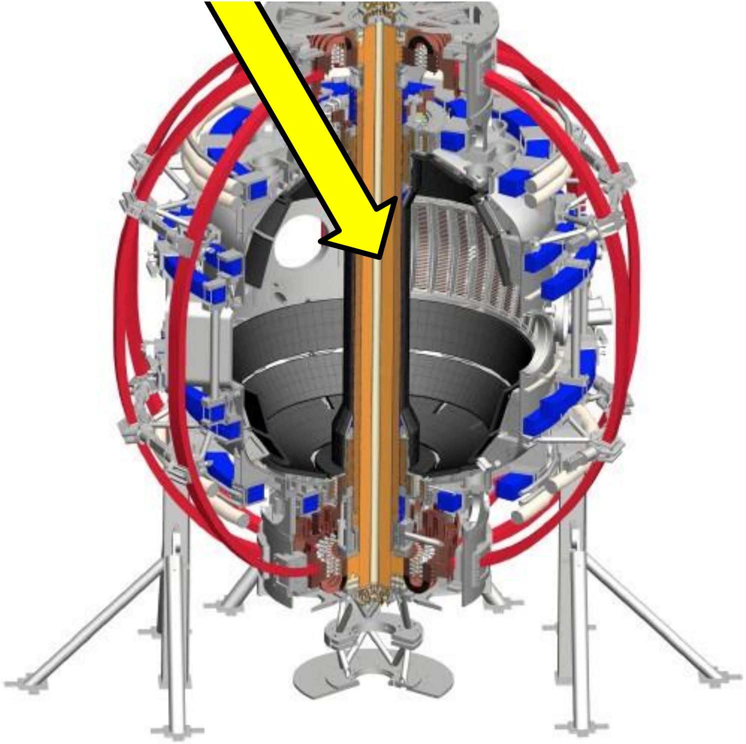
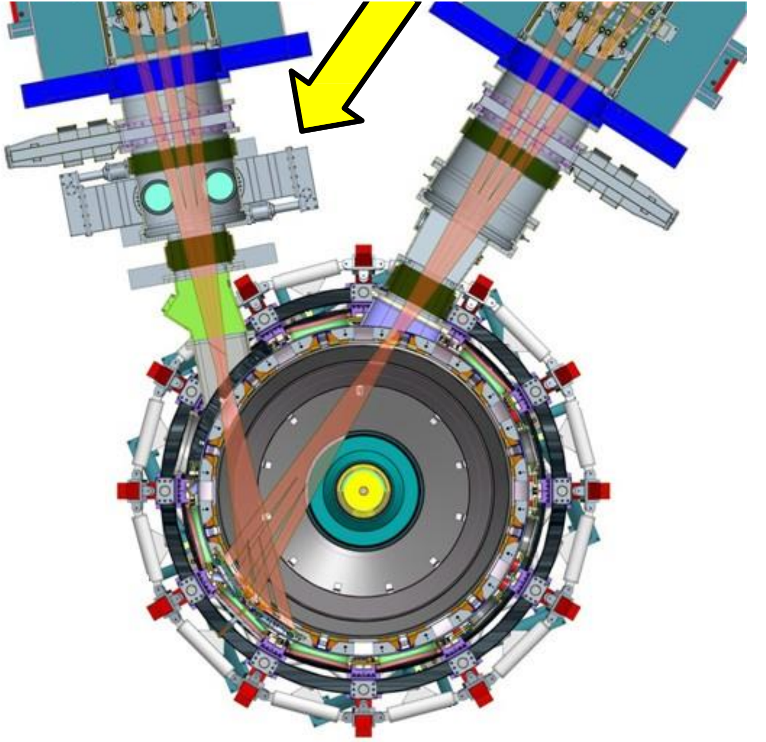


NSTX-U will access new physics with 2 major new tools

1. New Central Magnet



2. Tangential 2nd Neutral Beam



Higher T, low ν^* from low to high β

→ Unique regime, study new transport and stability physics

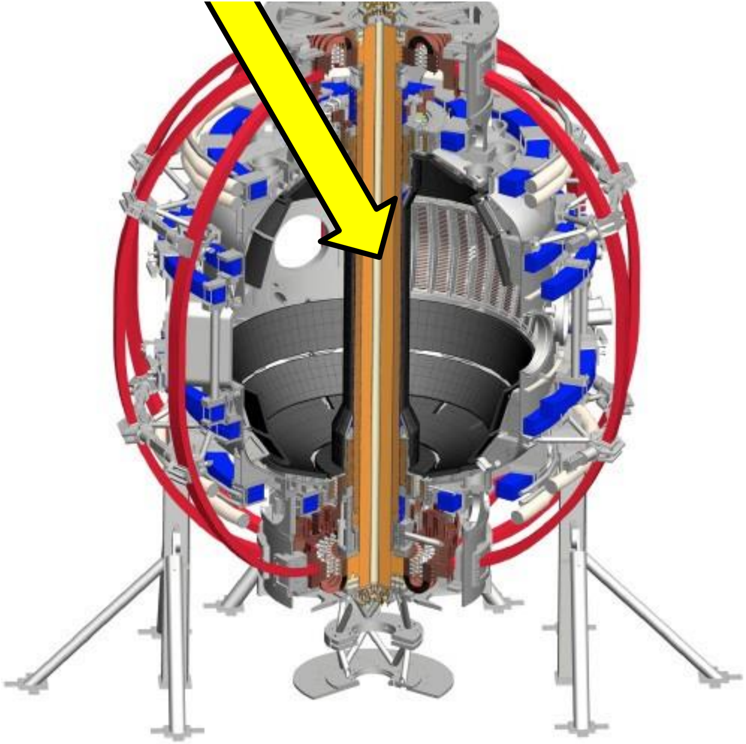
Full non-inductive current drive

→ Not demonstrated in ST at high-β_T

Essential for any future steady-state ST

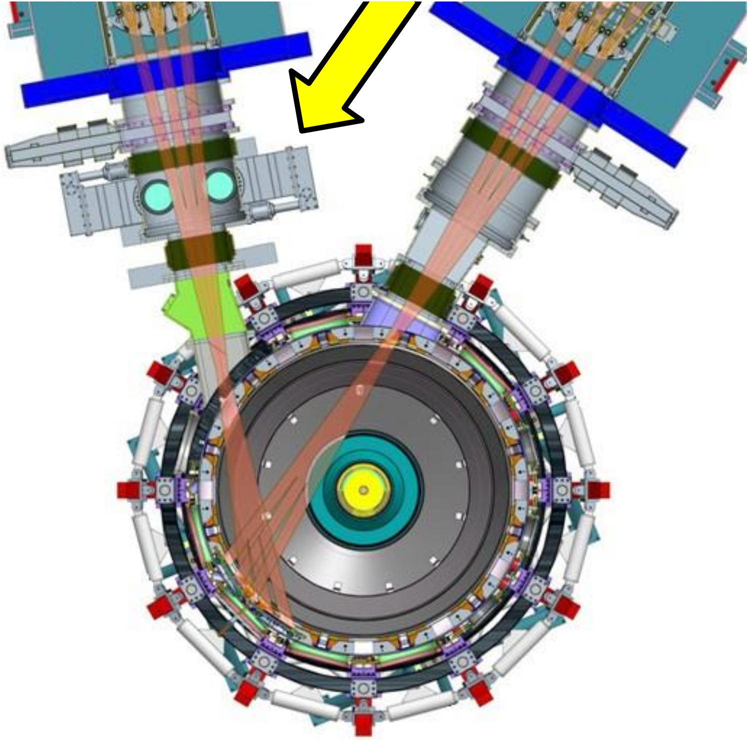
NSTX-U designed for major performance boost

1. New Central Magnet



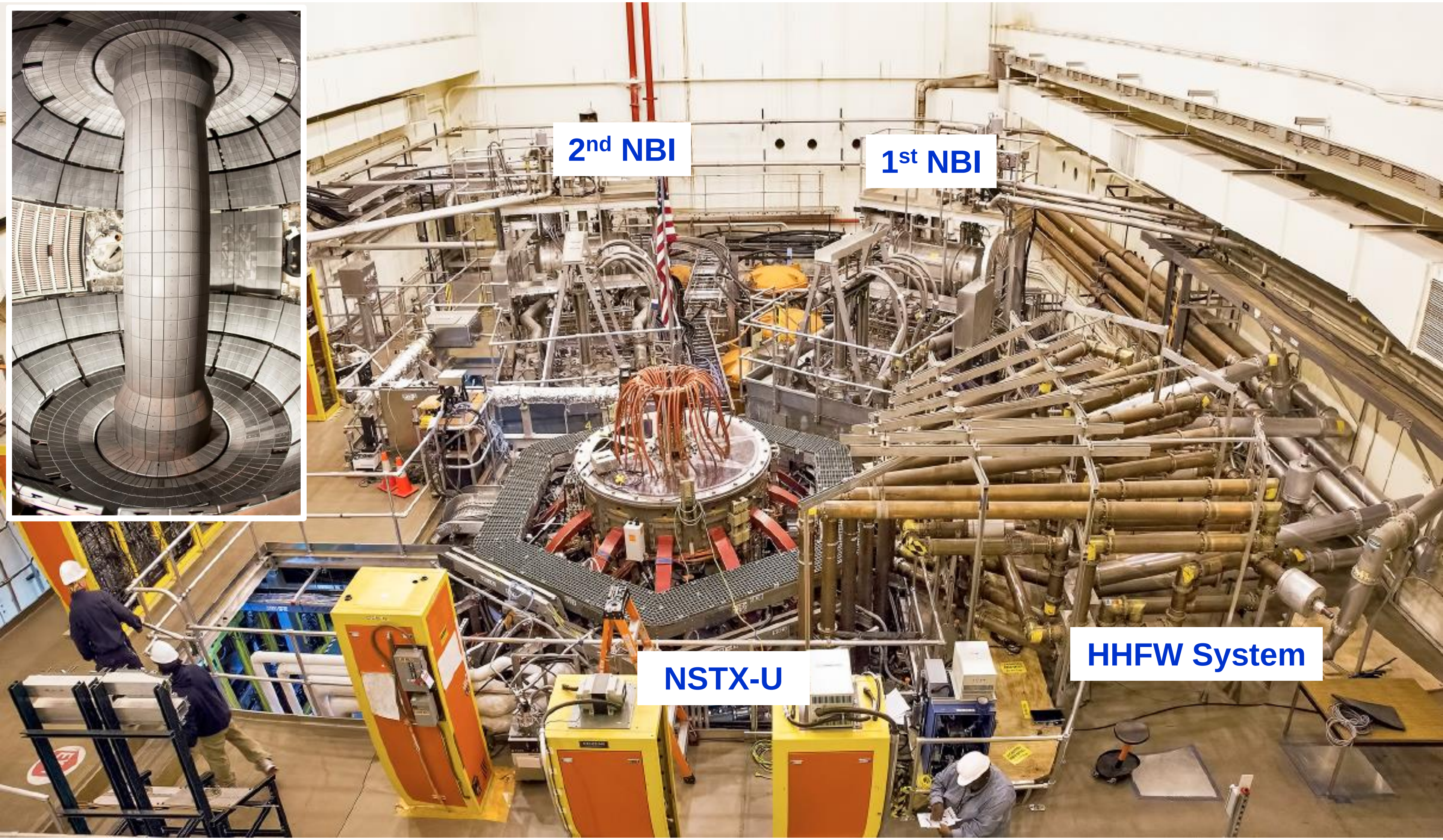
- ➢2 × toroidal field (0.5 → 1T)
- ➢2 × plasma current (1 → 2MA)
- ➢5 × longer pulse (1 → 5s)

2. Tangential 2nd Neutral Beam



- ➢2 × heating power (5 → 10MW)
  - Tangential NBI → 2 × current drive efficiency
- ➢4 × divertor heat flux (→ ITER levels)
- ➢Up to 10 × higher $nT\tau_E$ (~MJ plasmas)

NSTX Upgrade Device and Test Cell – Interior (inset) and Aerial View



NSTX-U will address key physics questions in first 3 years leveraging unique capabilities

Establish ST physics / scenarios:

Confinement vs. β , collisionality

Sustain high β w/ advanced control

Non-inductive start-up, ramp-up

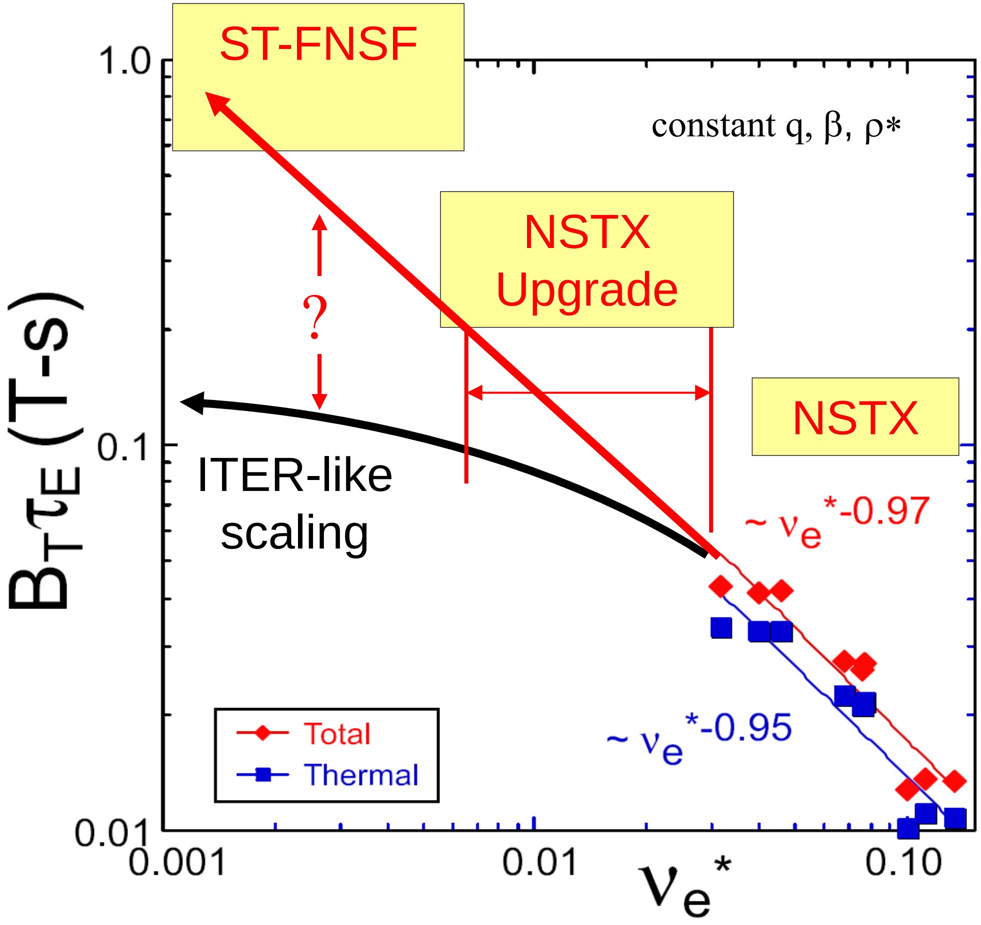
Mitigate high heat fluxes

Test high-Z divertor, Li vapor shielding

- **What role do electromagnetic effects play in electron energy transport?** (High β, lower ν^*)
- **Can fast-ion instabilities be predicted and controlled for ITER and beyond?** (Vary v_f/v_A, β_f, anisotropy)
- **Can ST operate disruption-free near with-wall limit, aiming to be 100% non-inductive?**
  - Only ST in world capable of this research critical for steady-state FNSF / Pilot Plant
- **What physics determines SOL heat flux width?** (Low-A, 2× I_P , Li wall)
- **How do advanced divertors and Li impact edge transport, scenarios?**

NSTX / MAST confinement increased at higher T_e (!)

Will confinement trend continue, or look like conventional A?



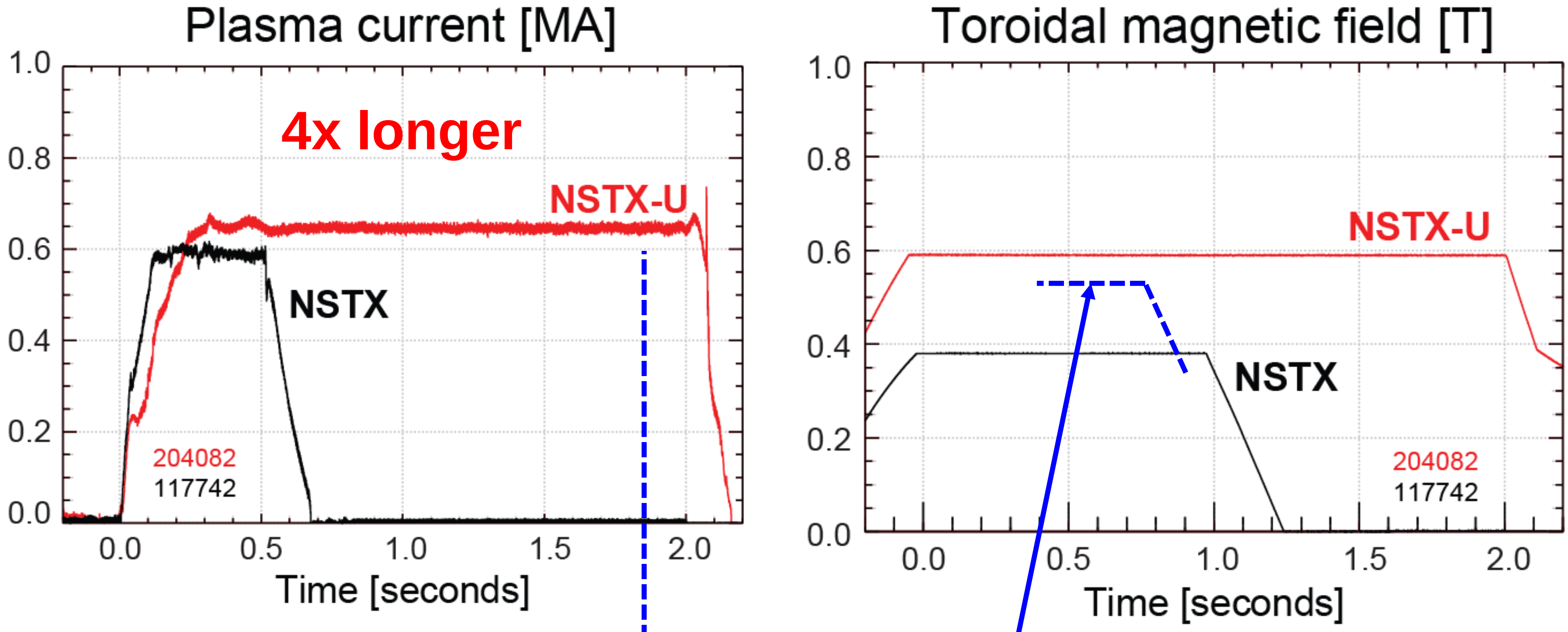
Normalized electron collisionality $\nu_e^* \propto n_e / T_e^2$

Favorable confinement results could lead to more compact ST reactors

Low ν^* → need higher plasma current, toroidal field, heating power, density control

NSTX-U has surpassed maximum pulse duration and magnetic field of NSTX

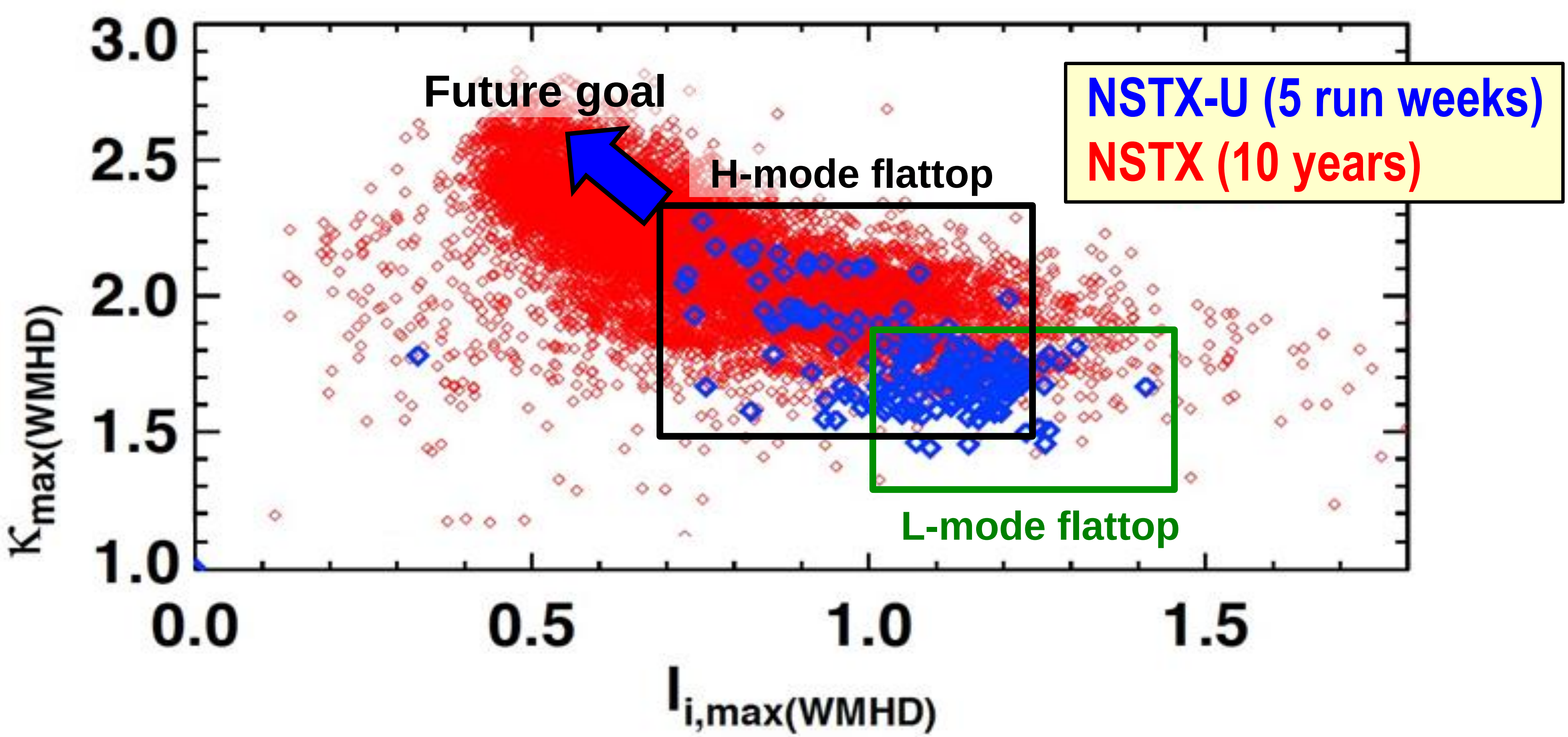
Compare similar **NSTX** / **NSTX-U** Boronized L-modes, P_{NBI}=1MW



NSTX-U L-mode duration exceeds longest NSTX H-mode

NSTX-U B_T > highest NSTX B_T

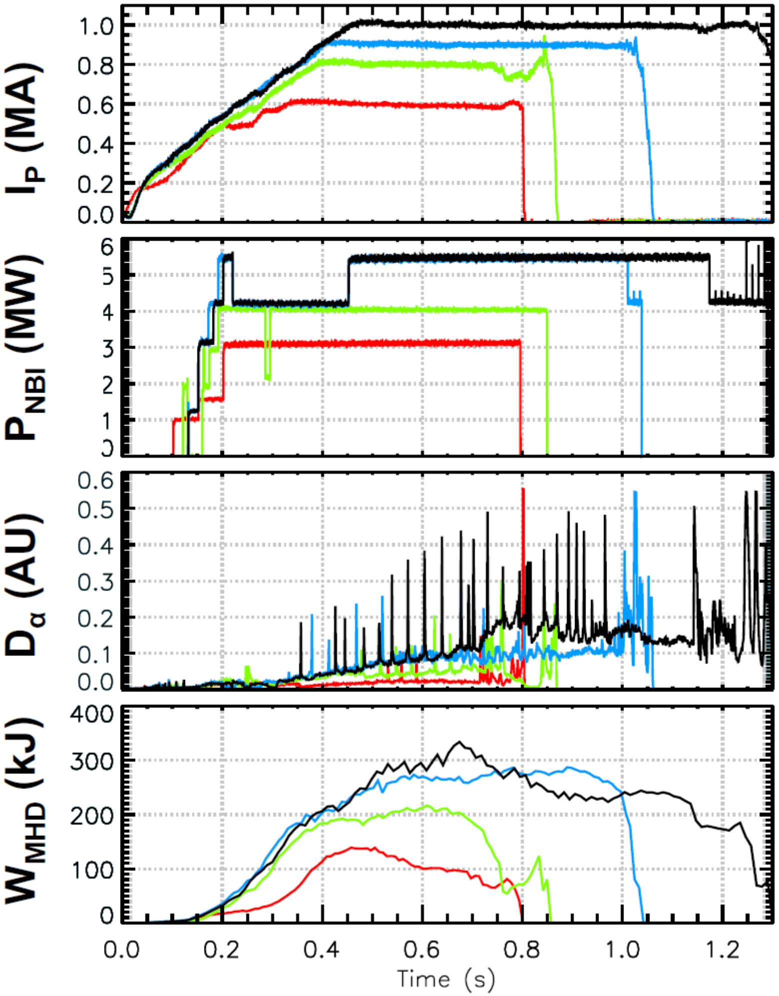
Accessed high elongation κ using progressively earlier H-mode and heating + optimized EFC



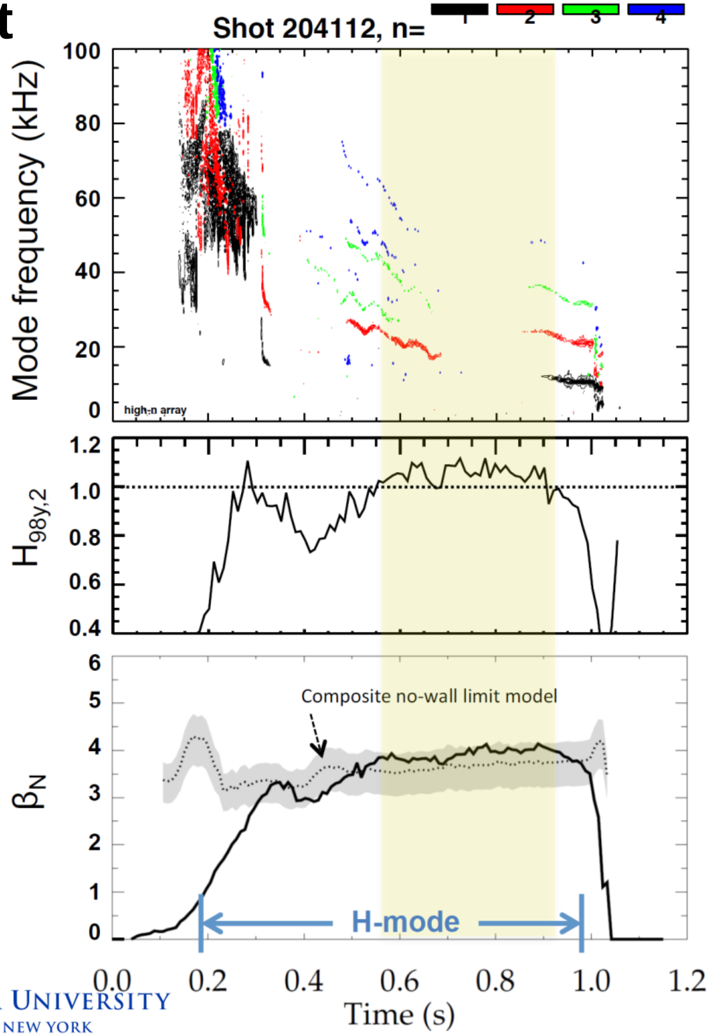
- **Goal: Internal inductance l_i = 0.5-0.7 → κ = 2.4-2.7**

Recovered ~1MA H-modes that reached / exceeded the ideal n = 1 no-wall limit

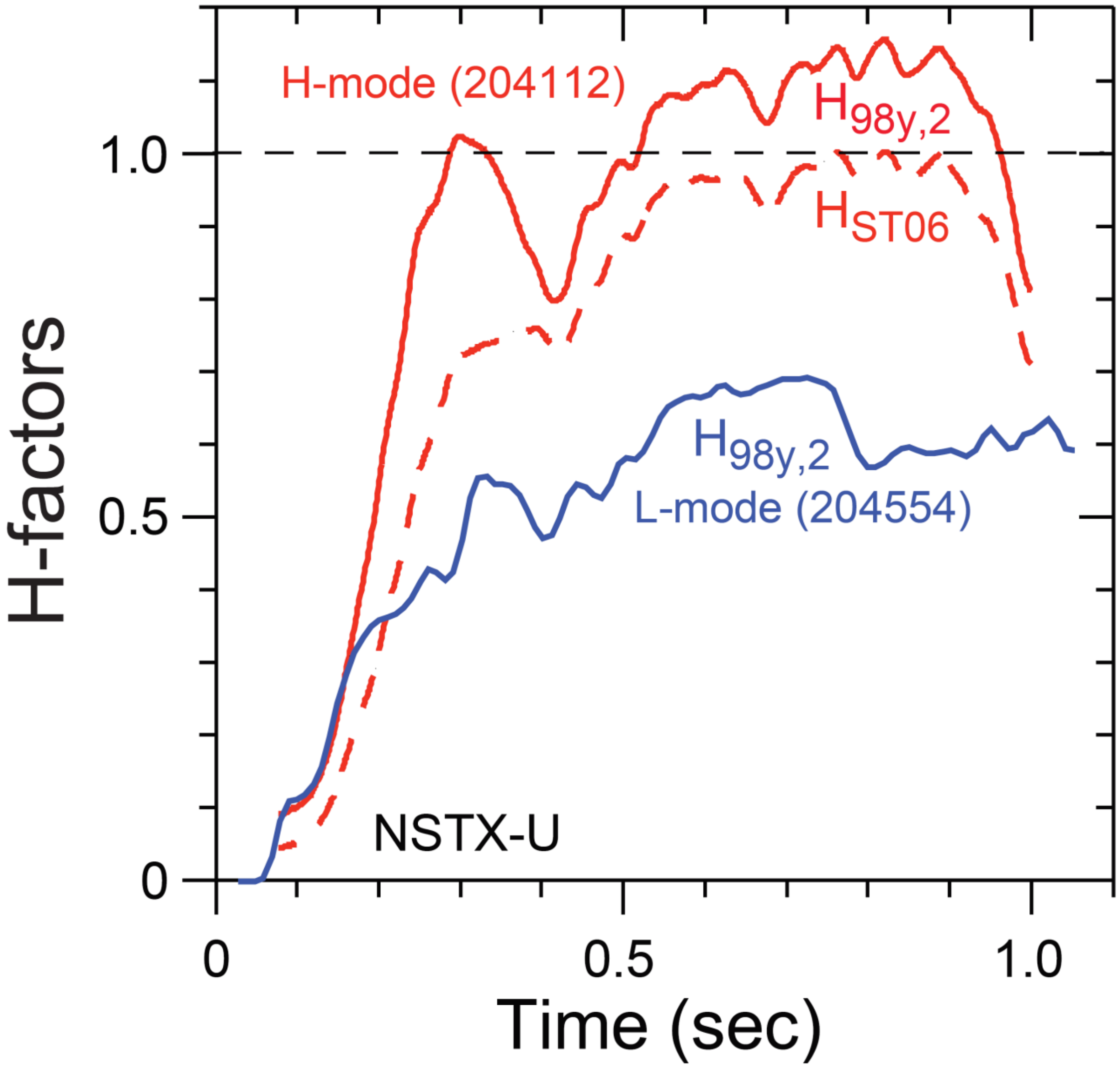
202946 – no EFC 204112 – EFC v2
203679 – EFC v1 204118 – EFC v2



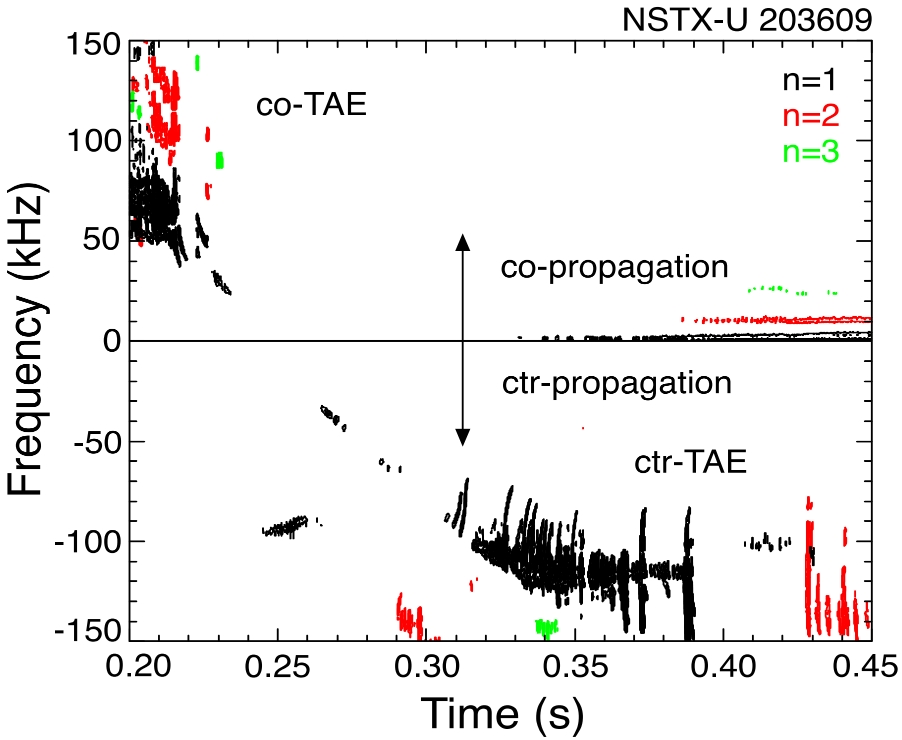
$H_{98} \geq 1$, β_N ~ 3.5-4 ≥ n=1 no-wall limit



H-mode confinement > ITER scaling, consistent with ST scaling (so far) – need higher I_P, B_T to test



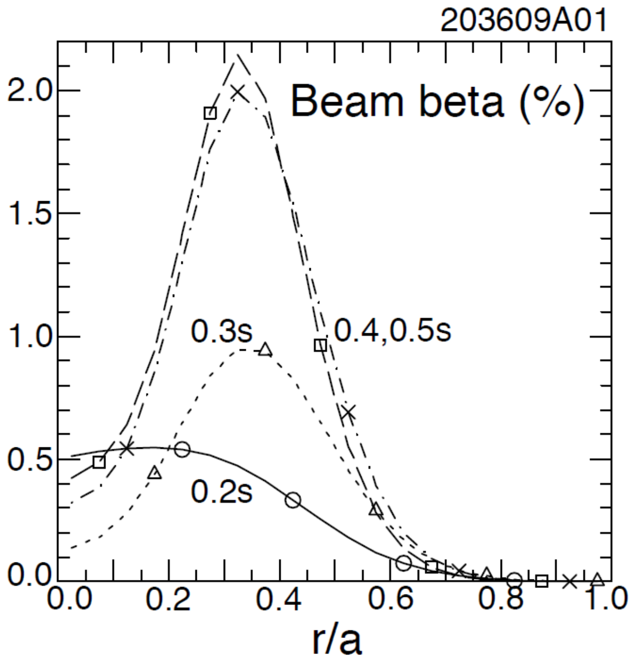
Most tangential NBI generates counter-propagating Toroidal Alfvén Eigenmodes (TAEs)



- Counter-propagating TAE predicted for **hollow** fast-ion profiles

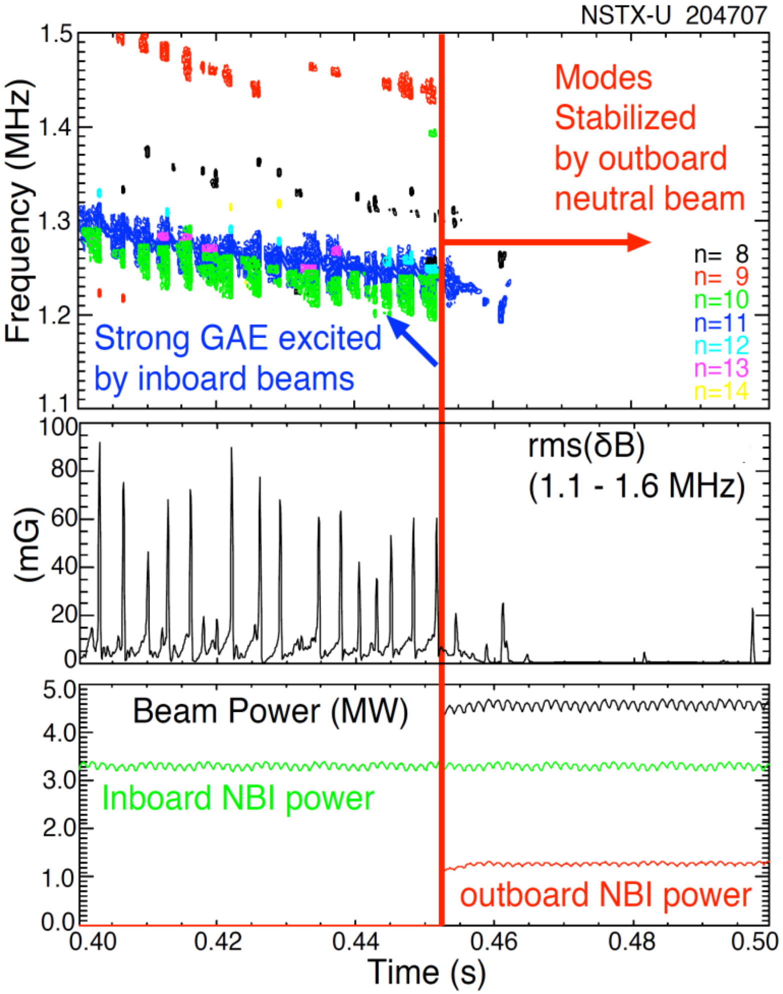
H.V. Wong, H. Berk, Phys. Lett. A ***251*** *(1999) 126.*

- TRANSP: As current builds up beam fast-ion beta profile predicted to become hollow

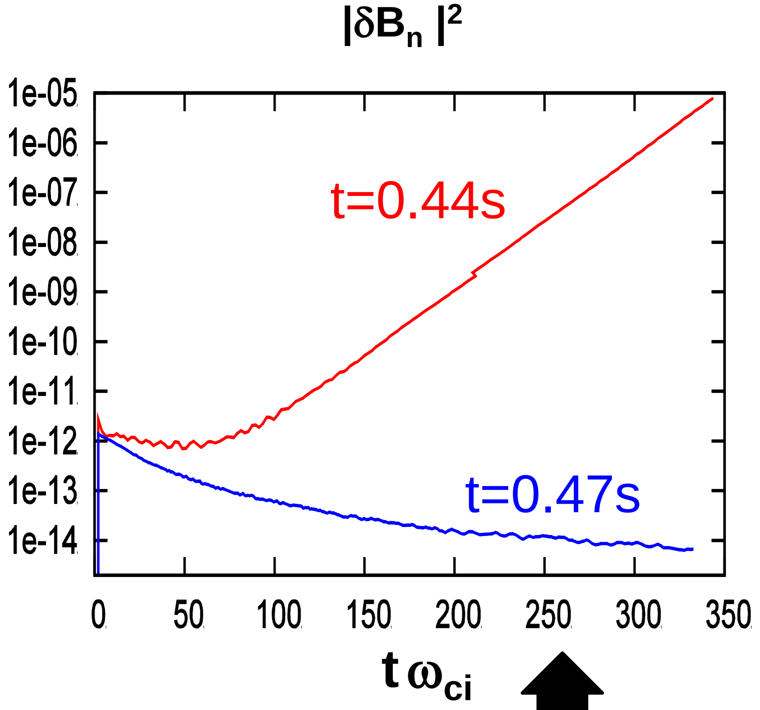


- **1st evidence of off-axis NBI in NSTX-U**

Tangential 2nd neutral beam suppresses Global Alfven Eigenmode (GAE) – consistent with simulation



HYM code simulation of #204707, n=10



- HYM code: growth of n=10 counter-GAE from 1st NBI
- HYM: suppression of n=10 counter-GAE by 2nd NBI
- Most unstable *n*-number, mode ω consistent with HYM

New 2nd NBI already powerful tool for fast-ion mode physics

NSTX-U had scientifically productive 1st year

- Achieved H-mode on 8th day of 10 weeks of operation
- Surpassed magnetic field and pulse-duration of NSTX
- Matched best NSTX H-mode performance at ~1MA
- Identified and corrected dominant error fields
- Exceeded the n = 1 ideal MHD no-wall beta limit
- Injected up to 12MW NBI power into armor by end of run
- Discovered new 2nd NBI modifies several fast-ion modes
- Implemented techniques for controlled plasma shut down, disruption detection, commissioned new tools for mitigation

- 2016 run ended prematurely due to fault in divertor PF coil
  - Coil forensics, Extent of Condition → new coil fab, other repairs
  - Aim to resume plasma operation during 2018 – but timing still TBD

Research established verified understanding of kinetic MHD theory to determine global mode stability in tokamaks

- ❑ Early theory did not find general agreement with experimental global mode (RWM) marginal stability; simple “critical rotation” hypothesis inadequate
- ❑ Drift kinetic theory modification to ideal stability criterion can explain mode stability results in experiments when precession drift physics is included
- ❑ Computed kinetic RWM marginal stability limits can describe disruptive limits in plasmas free of other MHD modes
- ❑ Stabilization physics complementarity found: at similar high rotation, kinetic RWM stabilization physics dominated by ion precession drift resonance in NSTX, and bounce orbit resonance in DIII-D
- ❑ Unification of theoretical understanding and joint experimental verification allows stability research to progress to next step: disruption avoidance
  - ❑ Expanded use of present theory for disruption prediction
  - ❑ Disruption avoidance via plasma rotation profile control

- Berkery, Sabbagh, et al. submitted to PoP (2017)

- Goumiri, Rowley, Sabbagh, et al. NF **56** (2016) 036023

Goals for future NSTX-U operation

- Increase field to 0.8-1T, current to 1.6-2MA, extend flat-top duration (H-mode) to 2-5s
- Characterize 2nd beam: heating, current drive, torque / rotation profiles, fast-ion instabilities
- Characterize and forecast events leading to disruptions; demonstrate disruption-free operation
- Assess energy confinement, pedestal height/structure, edge heat-flux width
- Push toward full non-inductive current drive
- Test advanced divertor heat flux mitigation

Supporting Slides Follow

Modification of Ideal Stability by Kinetic theory (MISK code) has sufficiently broad physics to determine RWM stability

(Hu, Betti, et al., PoP **12** (2005) 057301)

Energy balance

$$\underbrace{-\frac{1}{2}\int \rho\omega^2|\boldsymbol{\xi}_\perp|^2 d\mathbf{V}}_{\text{Kinetic Energy}} = \frac{1}{2}\int \boldsymbol{\xi}_\perp^* \cdot \left[\underbrace{\tilde{\mathbf{j}}\times\mathbf{B_0} + \mathbf{j_0}\times\tilde{\mathbf{B}} - \boldsymbol{\nabla}\tilde{p}_F}_{\text{Fluid terms}} - \boldsymbol{\nabla}\cdot\tilde{\mathbb{P}}_K\right] d\mathbf{V}$$

δW_K is solved numerically by using $\tilde{f}$ from the drift kinetic equation to solve for $\tilde{\mathbb{P}}_K$

Change in potential energy due to perturbed kinetic pressure is:

$$\delta W_K = -\frac{1}{2}\int \boldsymbol{\xi}_\perp^* \cdot \left(\boldsymbol{\nabla}\cdot\tilde{\mathbb{P}}_K\right) d\mathbf{V}$$

$$\delta W_K = \sum_{l=-\infty}^{\infty} 2\sqrt{2}\pi^2 \int\!\!\int\!\!\int \left[|\langle H/\hat{\varepsilon}\rangle|^2 \frac{(\omega-\omega_E)\frac{\partial f}{\partial \varepsilon} - \frac{n}{Ze}\frac{\partial f}{\partial \Psi}}{\langle\omega_D\rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E - \omega}\right] \frac{\hat{\tau}}{m_j^{\frac{3}{2}} B} \left|\frac{v_\parallel}{v}\right| \hat{\varepsilon}^{\frac{5}{2}} d\hat{\varepsilon}\, d(v_\parallel/v)\, d\boldsymbol{\Psi}$$

Precession drift resonance

Bounce orbit resonances

Collisionality

~ Plasma Rotation

$$\omega_E \approx \omega_\phi - \omega_{*i}$$

Plasma response to external n=1 field is determined by the RWM damping rate γ_{RWM} and mode rotation frequency ω_{RWM}

- **Dependence of the plasma response δB_{plas} on the frequency ω_{ext} of an externally applied n=1 field described by single mode model**

  H. Reimerdes *et al*., PRL (2004)

  – Perturbed field at wall:

$$\delta B_s = \frac{M^*_{sc}}{i\omega_{\mathrm{ext}}\tau_{\mathrm{W}} - \gamma_0\tau_{\mathrm{W}}} I_{\mathrm{c}}$$

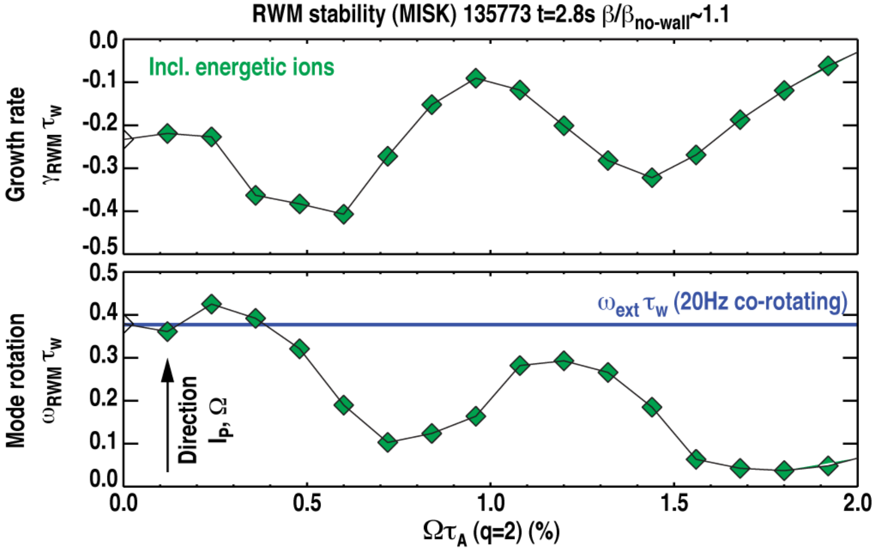
  – Plasma response at wall:

$$\delta B_{s,\mathrm{plas}} = \frac{M^*_{sc}\left(\gamma_0\tau_{\mathrm{W}}+1\right)}{\left(i\omega_{\mathrm{ext}}\tau_{\mathrm{W}} - \gamma_0\tau_{\mathrm{W}}\right)\left(i\omega_{\mathrm{ext}}\tau_{\mathrm{W}}+1\right)} I_{\mathrm{c}}$$

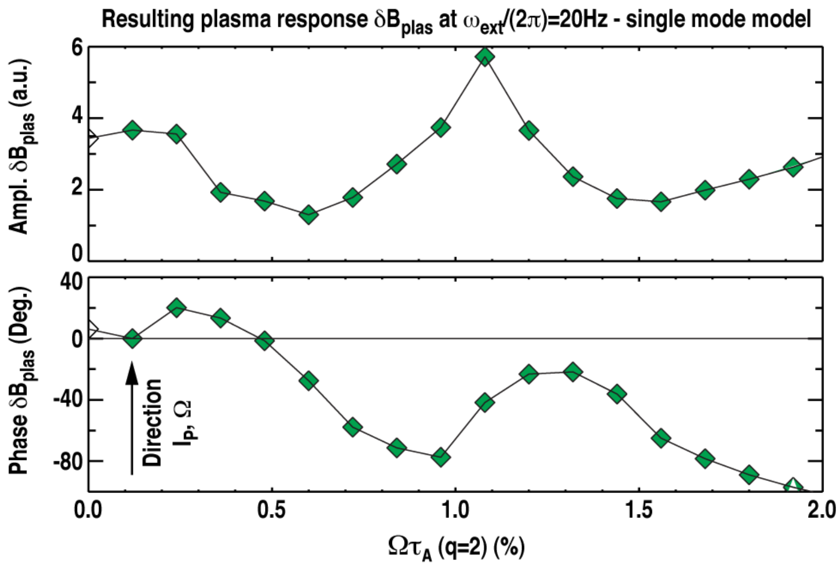
  with complex growth rate

$$\gamma_0=\gamma_{RWM}+i\omega_{RWM}$$

  and coupling coefficient M^*_{SC} between coil c and sensor s

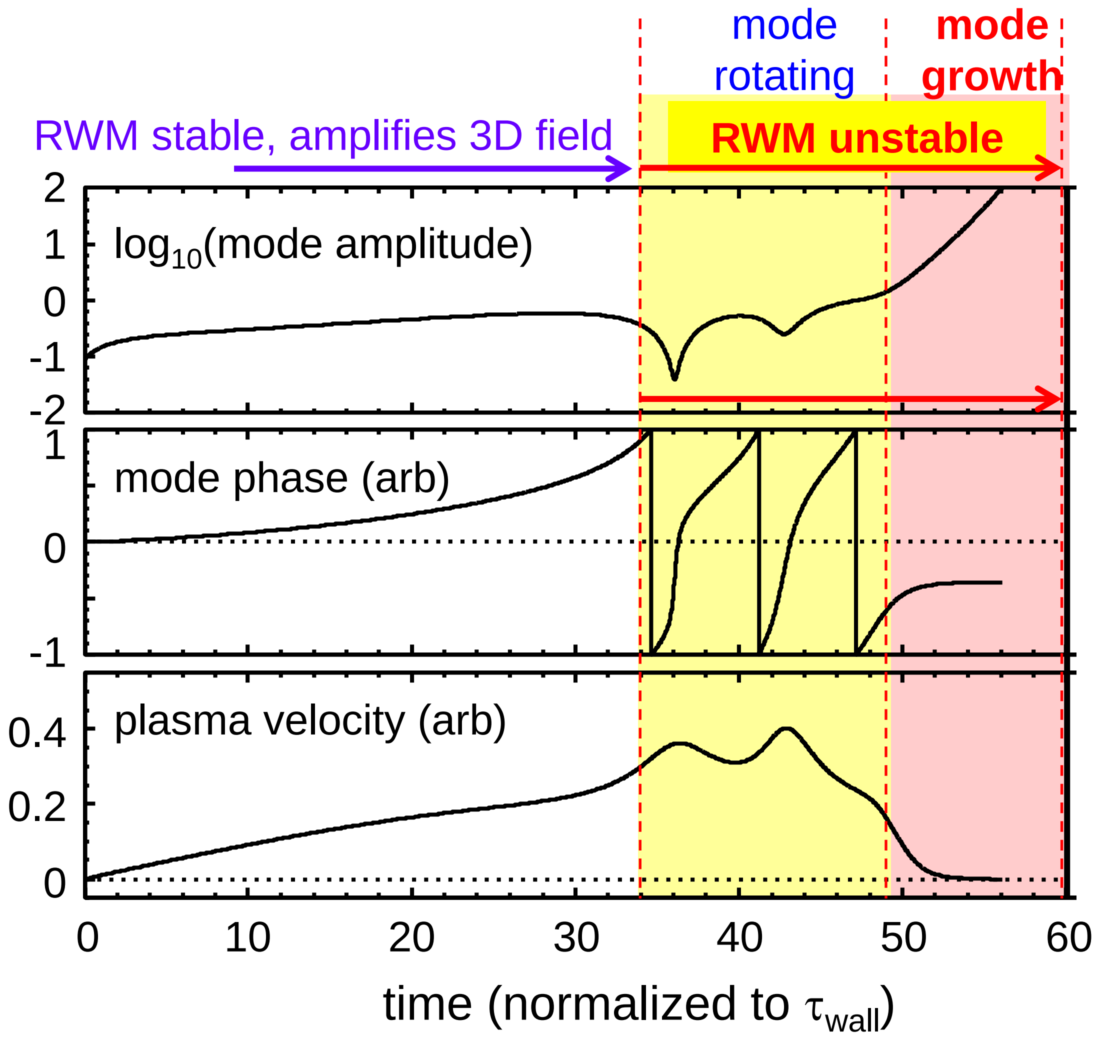


RWM stability (MISK) 135773 t=2.8s $\beta/\beta_{no\text{-}wall}$~1.1



Resulting plasma response δB_{plas} at $\omega_{ext}/(2\pi)$=20Hz - single mode model

A classic, simple RWM model illustrates basic mode dynamics



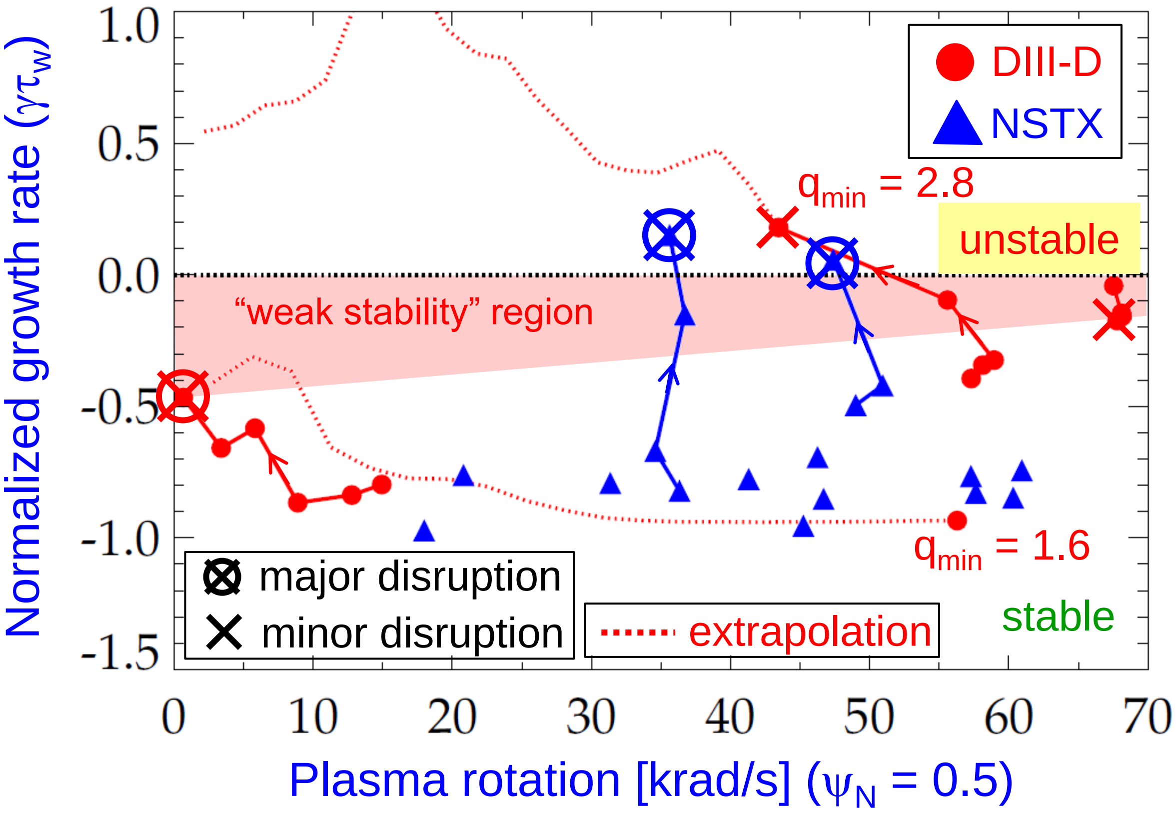
R. Fitzpatrick, Phys. Plasmas **9** (2002) 3459

- ❑ Simulation with error field, and increasing mode drive
- ❑ Stable RWM amplifies error field (resonant field amplification (RFA))
- ❑ When RWM becomes unstable, it first unlocks, rotates in co-NBI direction
  - ❑ Amplitude is not strongly growing during this period
- ❑ Eventually unstable mode amplitude increase causes RWM to re-lock, mode grows strongly
- ❑ RWM growth rate, rotation frequency is $O(1/\tau_{wall})$

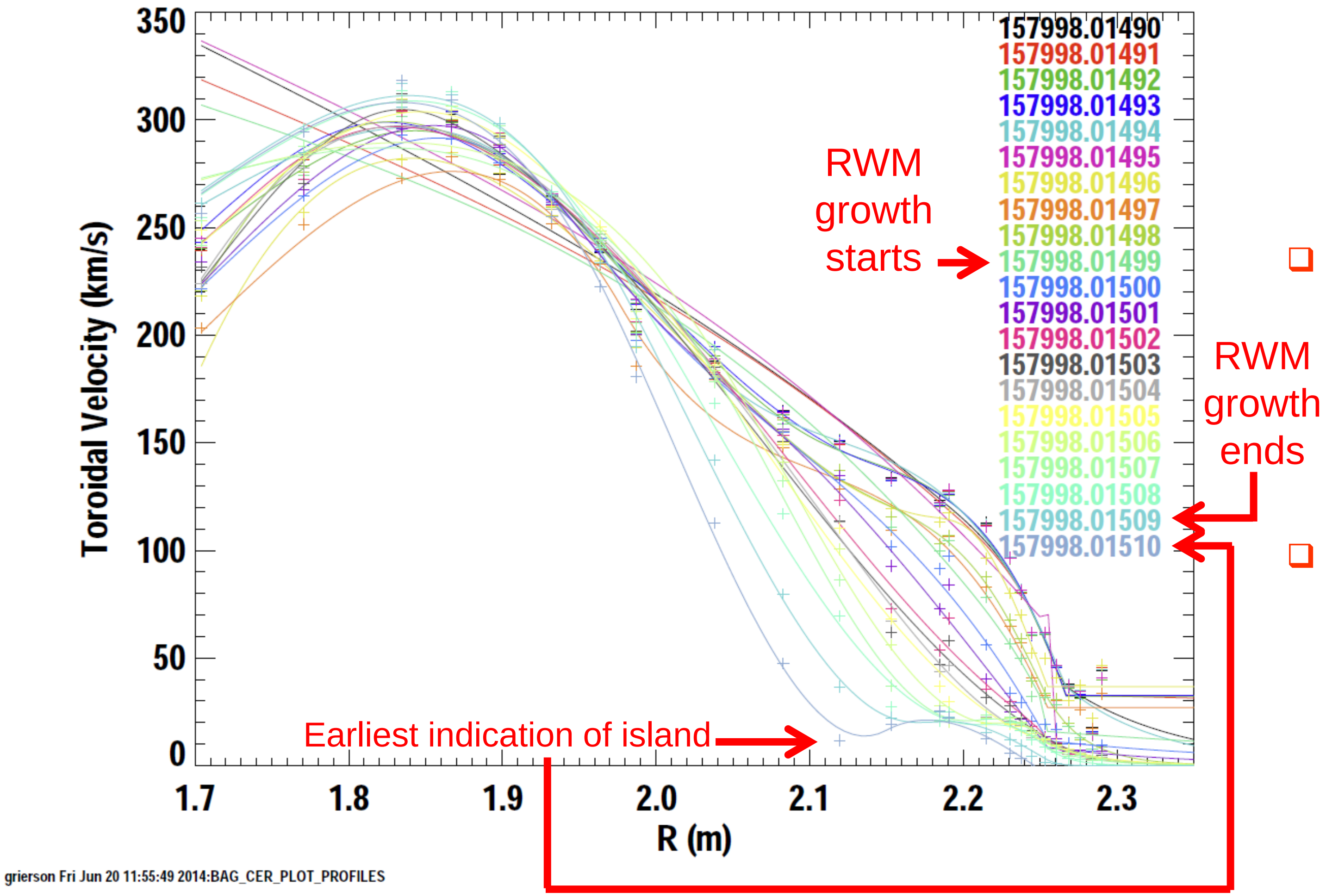
Kinetic RWM stability analysis evaluated for DIII-D and NSTX plasmas

- Summary of results
  - Plasmas free of other MHD modes can reach or exceed linear kinetic RWM marginal stability
  - Bursting MHD modes can lead to non-linear destabilization before linear stability limits are reached
  - Extrapolations of DIII-D plasmas to different V_ϕ show marginal stability is bounded by $1.6 < q_{min} < 2.8$

Kinetic RWM stability analysis for experiments (MISK)



The earliest potential indication of a locking island (from CER) comes after the n = 1 RWM has fully grown



RWM growth starts

RWM growth ends

Earliest indication of island

- 1 ms CER indicates that an island may be forming and locking by 1.510s
- Magnetics show that n = 1 RWM reaches full amplitude by 1.509s
- Conclude that this dynamic is not caused by an island-induced loss of torque balance

Due to benchmarking effort, alterations to both MARS-K and MISK codes produced agreement in all categories

INITIAL RESULT	r_{wall}/a	Ideal $\delta W/-\delta W_\infty$	$\mathrm{Re}(\delta W_k)/\delta W_\infty$	$\mathrm{Im}(\delta W_k)/(\delta W_\infty)$	$\gamma\tau_{wall}$	$\omega\tau_{wall}$	$\delta W_k/-\delta W_\infty$ $(\omega_E = \infty)$
Solov'ev 1 (MARS-K) (MISK)	1.15	1.187 1.122	0.0256 0.0243	-0.0121 0.0280	0.804 0.850	-0.0180 -0.0452	
Solov'ev 3 (MARS-K) (MISK)	1.10	1.830 2.337	0.208 0.371	-0.343 0.0601	0.350 0.232	-0.228 -0.0273	
ITER (MARS-K) (MISK)	1.50	0.682 0.677	141.5 0.665	2.286 -0.548	-0.988 0.0709	0.00019 0.437	
FINAL RESULT							
Solov'ev 1 (MARS-K) (MISK)	1.15	1.187 1.122	0.0218 0.0208	-0.0121 -0.0068	0.803 0.861	0.0180 0.0189	0.157 0.154
Solov'ev 3 (MARS-K) (MISK)	1.10	1.830 2.337	0.0794 0.0892	-0.147 -0.090	0.471 0.374	0.114 0.051	1.98 1.09
ITER (MARS-K) (MISK)	1.50	0.682 0.677	0.241 0.367	-0.046 -0.133	0.817 0.581	0.090 0.202	6.11 6.72

Green = good

State Derivative Feedback Algorithm needed for Current Control

- State equations to advance

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \qquad \vec{u} = -K_c\vec{x} = \dot{I}_{cc}$$

$$\vec{y} = C\vec{x} + D\vec{u}$$

Control vector, *u*; controller gain, K_c

Observer est., *y*; observer gain, K_o

K_c , K_o computed by standard methods (e.g. Kalman filter used for observer)

- ❖ Previously published approach found to be formally “uncontrollable” when applied to current control
- ❖ State derivative feedback control approach

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \qquad \vec{u} = -\hat{K}_c\dot{\vec{x}} \longrightarrow \vec{I}_{cc} = -\hat{K}_c\vec{x}$$

$$\dot{\vec{x}} = ((\mathrm{I} + B\hat{K}_c)^{-1}A)\vec{x}$$

e.g. T.H.S. Abdelaziz, M. Valasek., Proc. of 16th IFAC World Congress, 2005

  - new Ricatti equations to solve to derive control matrices – still “standard” solutions for this in control theory literature

Advance discrete state vector

$$\hat{\vec{x}}_t = A\vec{x}_{t-1} + B\vec{u}_{t-1}; \hat{\vec{y}}_t = C\hat{\vec{x}}_t$$ (time update)

$$\vec{x}_{t+1} = \hat{\vec{x}}_t + A^{-1}K_o(\vec{y}_{sensors(t)} - \hat{\vec{y}}_t)$$ (measurement update)

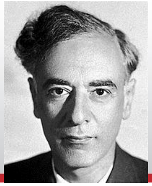
Written into the PCS

- General (portable) matrix output file for operator

The ITPA process greatly aided our unified EU and US effort (example: code benchmarking and implications for ITER)

- ITPA allowed a common basis and goals for research
  - Reimerdes, Sabbagh, Liu were/are ITPA joint experiment leaders/co-leaders
- Significant kinetic RWM analysis code benchmarking effort
  - Two Solov'ev, and ITER Advanced Scenario case tested
  - Leading codes tested: MARS-K, MISK (PENT code written during this process)
- Key components of the analyses separately compared
  - Ideal MHD stability functional δW (with and without stabilizing wall)
  - Kinetic MHD stability functional δW_k (Real & Imaginary components)
- Yielded a direct comparison of kinetic RWM growth rate and natural rotation rate ($\gamma\tau_{wall}$, $\omega\tau_{wall}$)

ITPA joint experiments: MDC-2 Reimerdes, Liu, Sabbagh; and MDC-21: Sabbagh, Liu



Landau

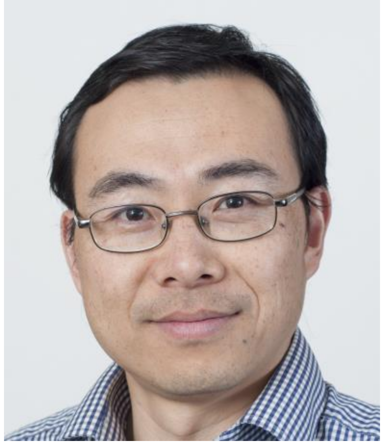
The 2016 Landau-Spitzer Award recipients are greatly thankful for this fine honor

Spitzer

- The awardees especially thank
  - The 2016 Award committee
  - The EPS and the APS
  - Prof. Riccardo Betti (U. Rochester) for his enthusiastic, and selfless nomination

- The awardees
  - Appreciate the joint, collaborative, nature of this research between the EU and US, aided by the ITPA
  - Acknowledge the experimental teams on NSTX and DIII-D; scientific exchanges with JET, JT-60U, RFX, HBT-EP
  - Convey that the research meriting the award comprises an ~decade-long effort

S.A. Sabbagh J.W. Berkery



Y.Q. Liu H. Reimerdes

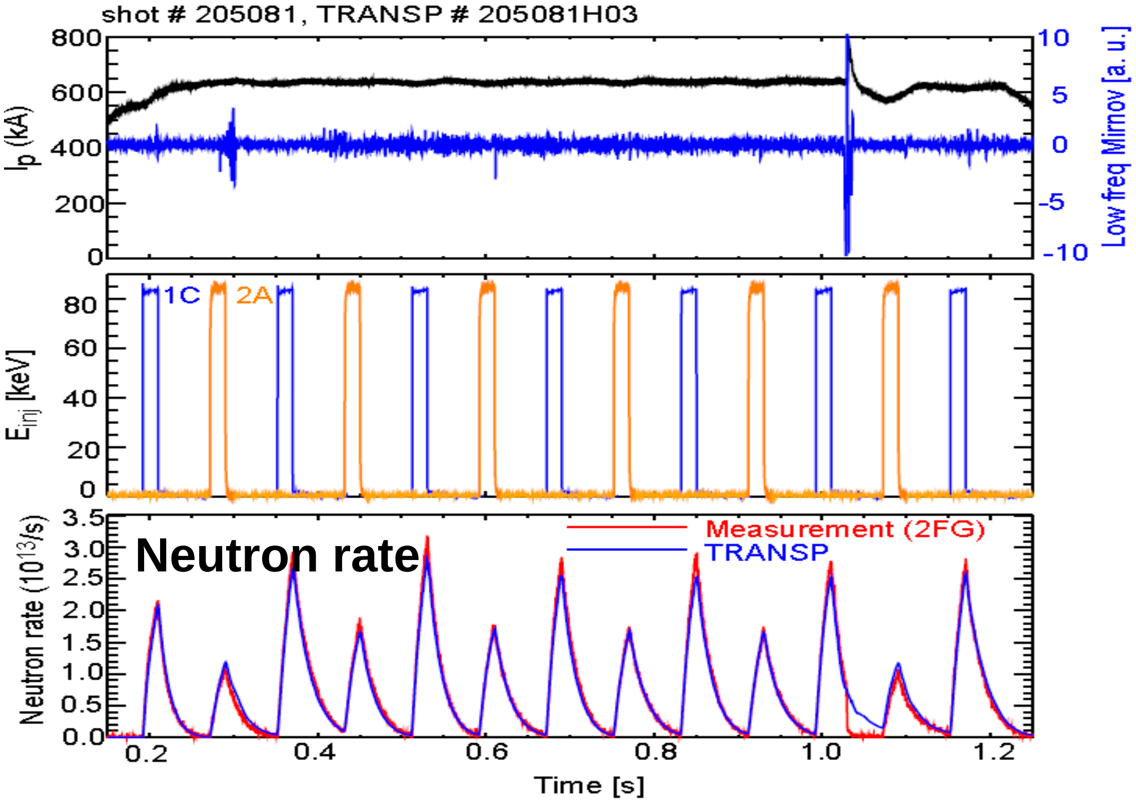
NSTX-U device performance progression

- **1st year:** Limit forces to ½ way between NSTX and NSTX-U, and ½ of the design-point heating of any coil
  - Presently operating at B_T ~ 0.63T
  - Increase to B_T ~ 0.8T after completing engineering analysis
- **2nd year goal:** Full field and current, coil heating to ¾ of limit
- **3rd year goal:** Full capability

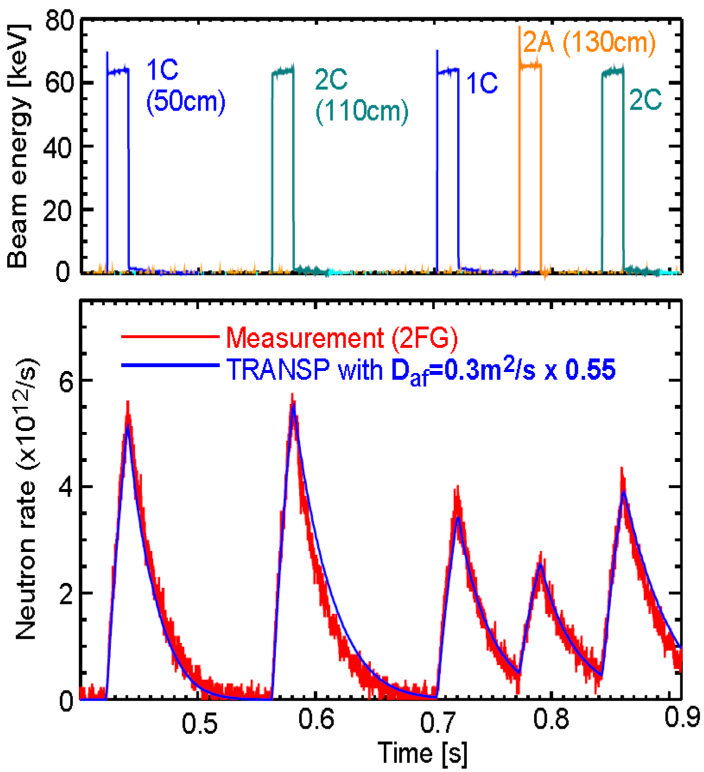
Parameter	NSTX (Max.)	Year 1 NSTX-U Operations	Year 2 NSTX-U Operations	Year 3 NSTX-U Operations	NSTX-U Ultimate Goal
I_P [MA]	1.2	~1.6	2.0	2.0	2.0
B_T [T]	0.55	~0.8 (0.65)	1.0	1.0	1.0
Allowed TF I^2t [MA^2s]	7.3	80	120	160	160
I_P Flat-Top at max. allowed I^2t, I_P, and B_T [s]	~0.4	~3.5	~3	5	5

Fast-ion confinement measured to be at / near predicted values at low total NBI power ~1-2MW

E_{NBI} = 85keV



E_{NBI} = 65keV



- Good agreement between neutron measurement and TRANSP prediction
- Need small anomalous fast ion diffusivity ($D_{af}=0.3m^2/s$) for agreement