Critical Need for Disruption Prediction, Avoidance, and Mitigation in Tokamaks

S.A. Sabbagh[1], N. Commaux[2], N. Eidietis[3], S.P. Gerhardt[4], B. Granetz[5], J.M. Hanson[1], V. Izzo[6], E. Kolemen[4], R. La Haye[3], J.E. Menard[4], R. Raman[7], M. Walker[3]

[1]Columbia. U., [2]ORNL, [3]General Atomics, [4]PPPL, [5]MIT, [6]UCSD, [7]U. Washington

presented at the

PPPL Workshop on the Theory and Simulation of Disruptions

Princeton Plasma Physics Laboratory

July 11th, 2014

Near 100% disruption avoidance is an urgent need for ITER, FNSF, and future tokamaks

- This is the new “grand challenge” in tokamak stability research
  - Can be done! (JET: < 4% disruptions w/C wall, < 10% w/ITER-like wall)
    - ITER disruption rate: < 1 - 2% (energy load, halo current); << 1% (runaways)
  - Disruption prediction, avoidance, and mitigation (*PAM*) is multi-faceted, best addressed by focused, national effort (multiple devices/institutions)
  - Serves FES strategic planning charge; pervades 3 of 5 ReNeW themes
- Strategic plan summary: Utilize and expand upon successes in stability and control research – synergize elements
  - Add focused, incremental support for US research programs to show near 100% disruption PAM success using quantifiable figures of merit
  - Leverage upgraded facilities with heightened focus on disruption PAM
- Leverage US university expertise, international collaborations
  - e.g. JET high power operation, KSTAR long-pulse operation above ideal MHD stability limits, US university scientists, post-docs, and students

A relatively modest incremental investment will greatly enhance quantifiable progress

Disruption PAM research is critically important – it pervades 3 of 5 ReNeW Themes

Key PAM extrapolations

reduced collisionality

- Theme 1: Burning Plasmas in ITER
  - Thrust 2: Control transient events in burning plasmas
- Theme 2: Creating Predictable, High-Performance, Steady-State Plasmas
  - Thrust 5: Expand the limits for controlling/sustaining fusion plasmas
  - Thrust 6: Develop predictive models for fusion plasmas, supported by theory, challenged with experimental measurement

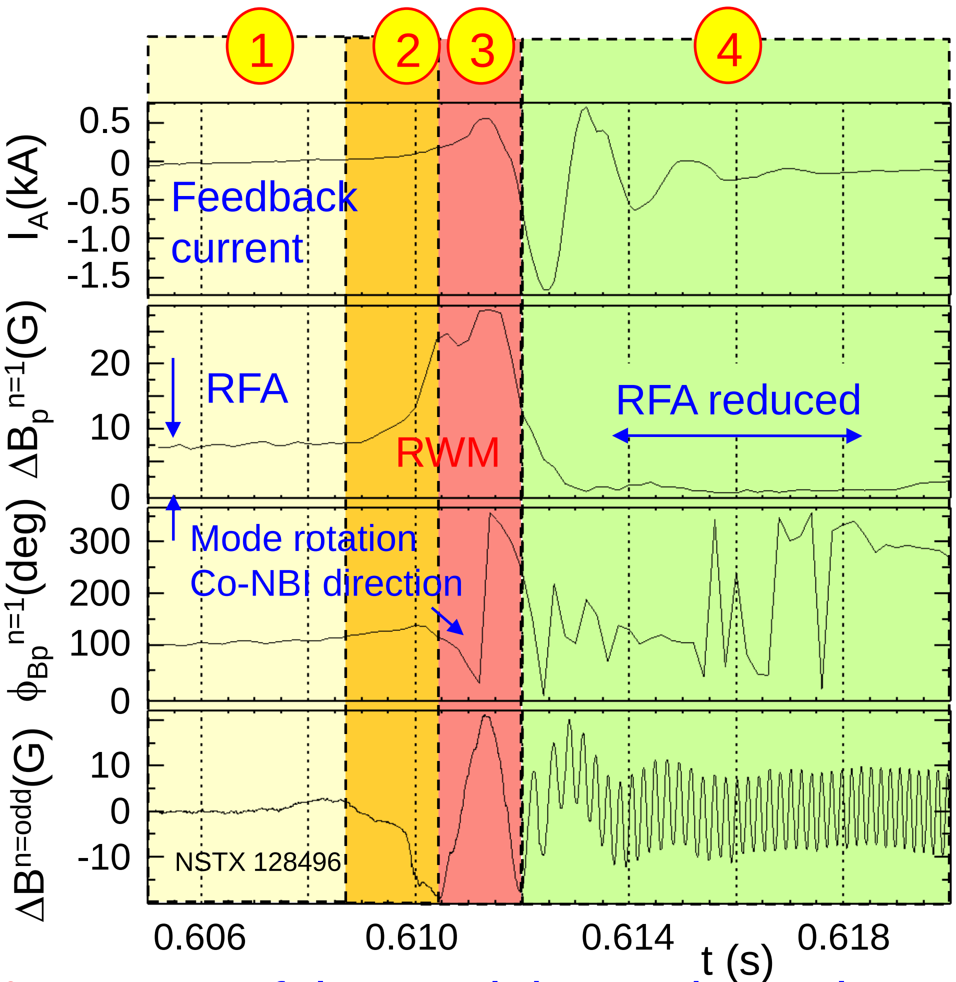
+ non-inductive sustainment

- Theme 5: Optimizing the Magnetic Configuration
  - Thrust 16: Develop the ST to advance fusion nuclear science
    - Element 3: "…*understanding of ST confinement and stability at fusion-relevant parameters*"
    - *Element 4: "Implement and understand active and passive control techniques to enable long-pulse disruption-free operation…"*
    - *Element 5: "Employ …beams, …waves, particle control, core fueling techniques to maintain the current and control the plasma profiles."*

+ high β, profile control

Highly successful disruption PAM needs to exploit several opportunities/actions to avoid/mitigate disruption

Example: Active RWM control in NSTX



- Successful control, but action only taken during mode growth (period 2)

1 Pre-instability
- RFA to measure stable γ
- Profile control to reduce RFA

2 Instability growth
- Profile control to reduce RFA
- Active instability control

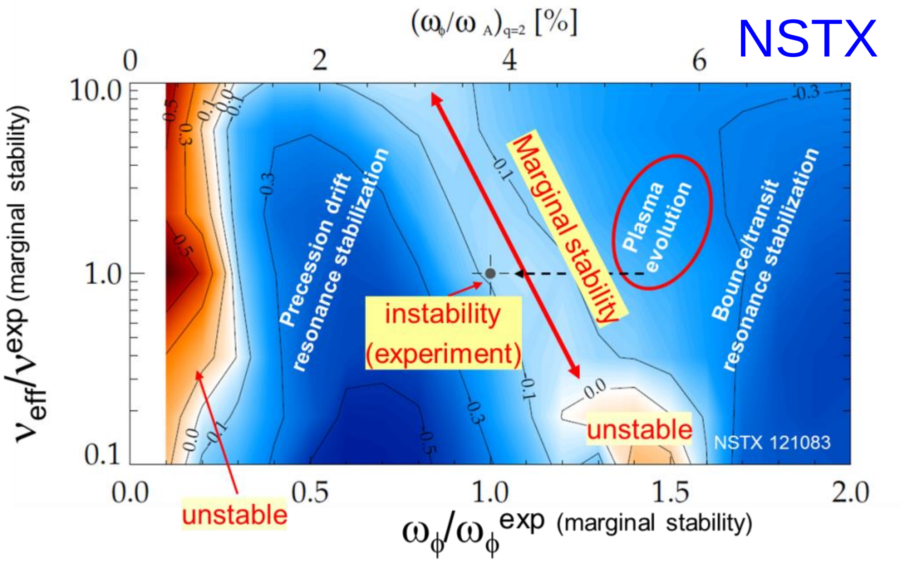
3 Large amplitude instability
- Active instability control
- Controlled shutdown/mitigation

4 Instability conversion or saturation
- Profile control to damp mode

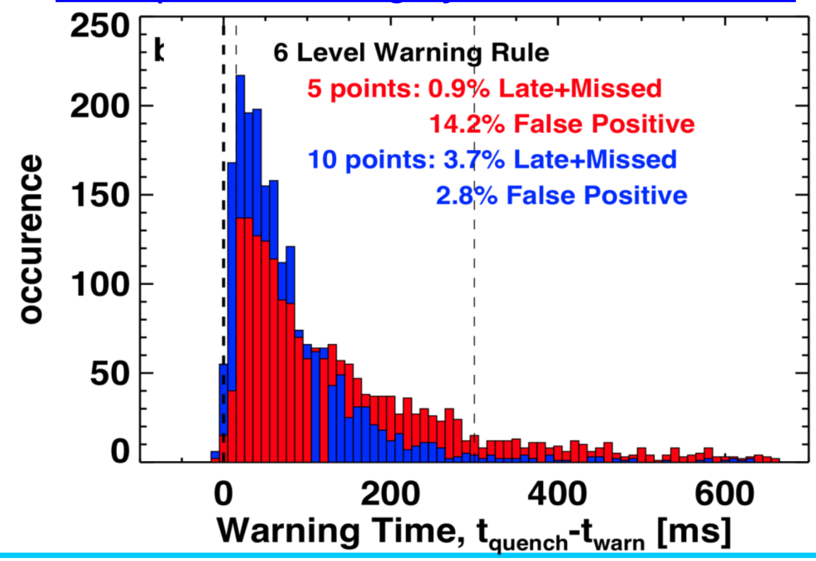
S.A. Sabbagh, et al., Nucl. Fusion **50** (2010) 025020

Disruption Prediction / Detection: Status

Kinetic RWM stability theory matches experiment



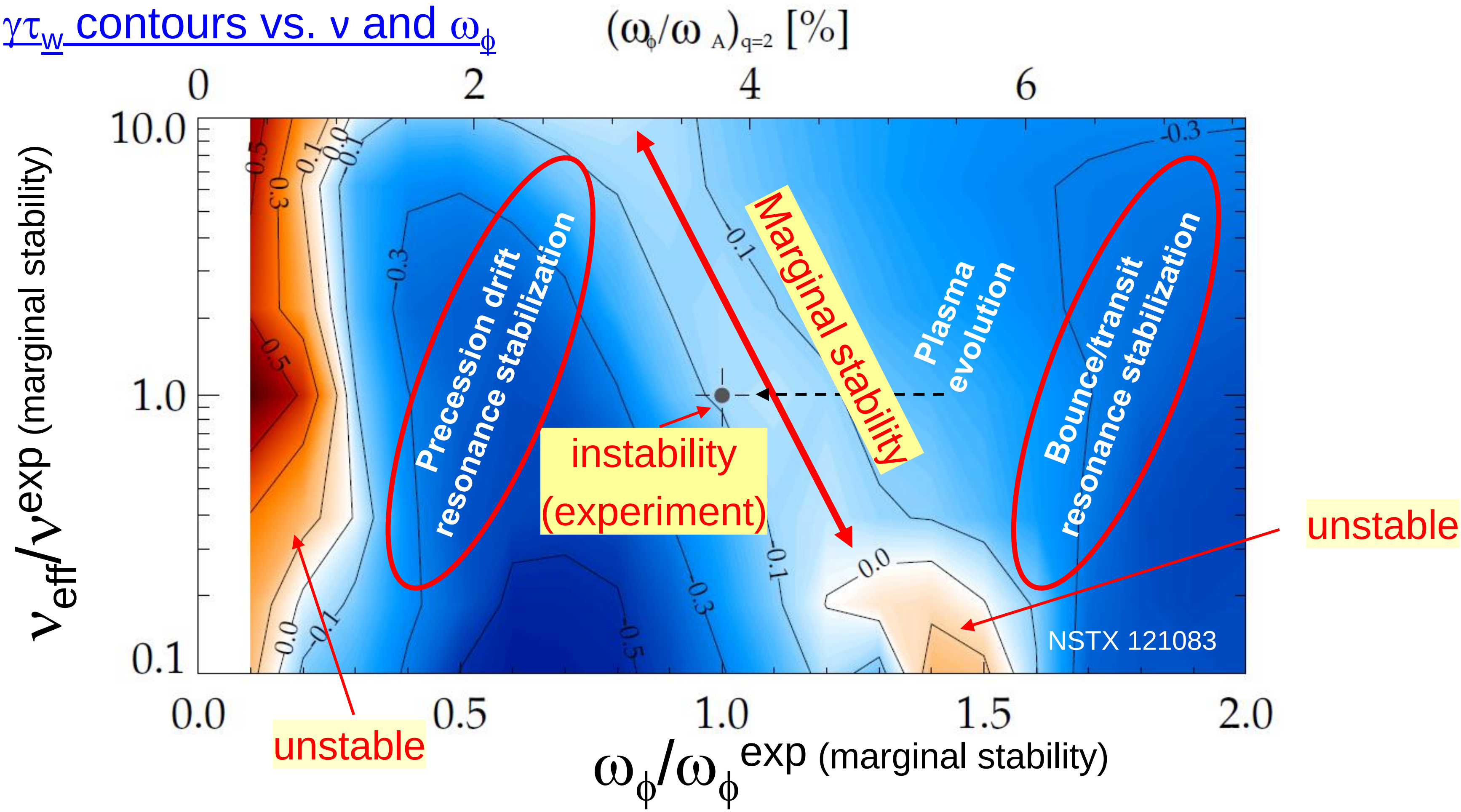
Disruption warning system assessment



- Theoretically-based prediction
  - e.g. kinetic RWM theory - tested against experiment (NSTX, DIII-D)
    J.W. Berkery, et al., PRL **104** (2010) 035003
    J.W. Berkery, et al., PRL **106** (2011) 075004
  - Recent experiments comparing detailed stability / mode dynamics results between NSTX and DIII-D
- MHD Spectroscopy
  - Used to measure global plasma stability in DIII-D and NSTX, not yet used routinely
- Disruption Warning System
  - Some implementations exist (e.g. on DIII-D, JET)
  - Recent analysis, highly successful in disruption prediction with low % of false positives when applied to NSTX database
    S.P. Gerhardt, et al., NF **53** (2013) 063021

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

$\gamma\tau_w$ contours vs. ν and ω_ϕ

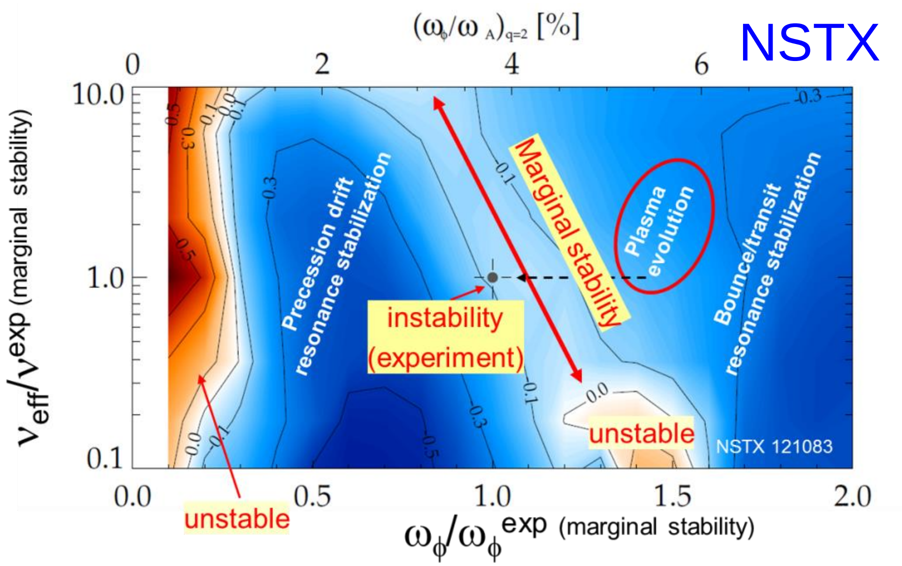


- Destabilization appears between precession drift resonance at low ω_ϕ, bounce/transit resonance at high ω_ϕ
- Destabilization moves to increased ω_ϕ as ν decreases

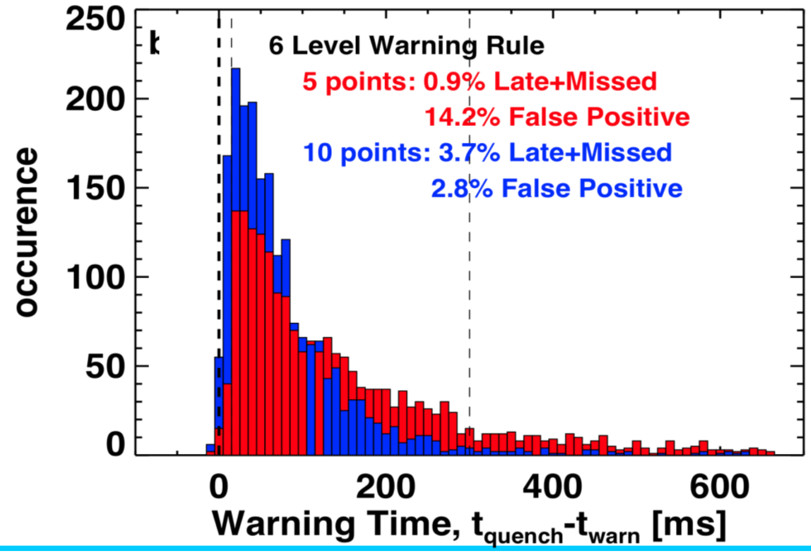
J.W. Berkery, et al., PRL **104** (2010) 035003
S.A. Sabbagh, et al., NF **50** (2010) 025020

Disruption Prediction / Detection: Status

Kinetic RWM stability theory matches experiment



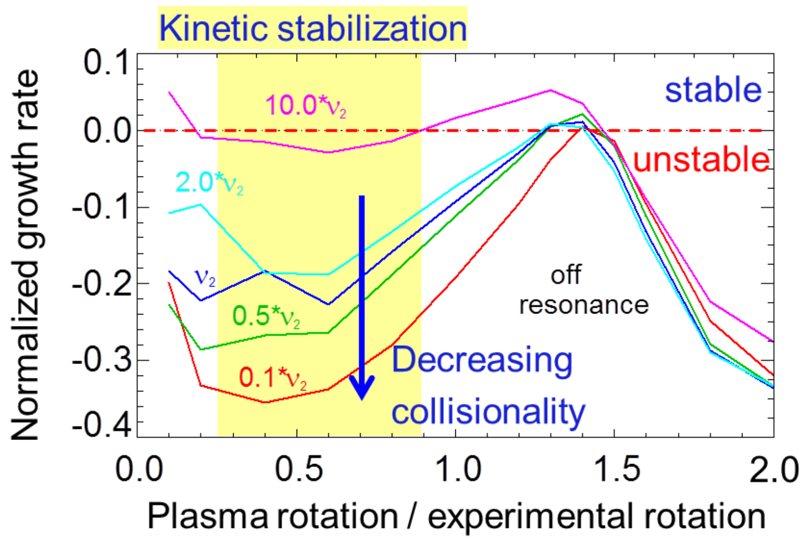
Disruption warning system assessment



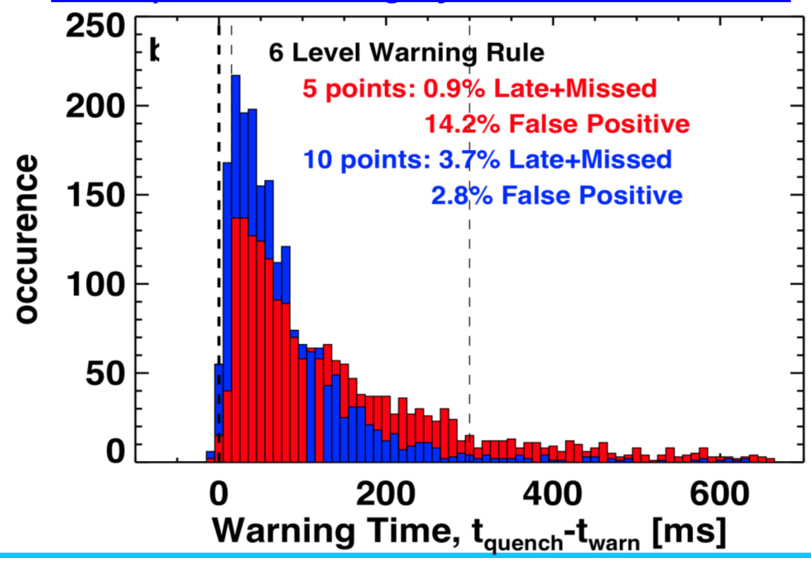
- Theoretically-based prediction
  - e.g. kinetic RWM theory - tested against experiment (NSTX, DIII-D)
    J.W. Berkery, et al., PRL **104** (2010) 035003
    J.W. Berkery, et al., PRL **106** (2011) 075004
  - Recent experiments comparing detailed stability / mode dynamics results between NSTX and DIII-D
- MHD Spectroscopy
  - Used to measure global plasma stability in DIII-D and NSTX, not yet used routinely
- Disruption Warning System
  - Some implementations exist (e.g. on DIII-D, JET)
  - Recent analysis, highly successful in disruption prediction with low % of false positives when applied to NSTX database
    S.P. Gerhardt, et al., NF **53** (2013) 063021

Disruption Prediction / Detection: Status

Kinetic RWM stability may increase at lower ν



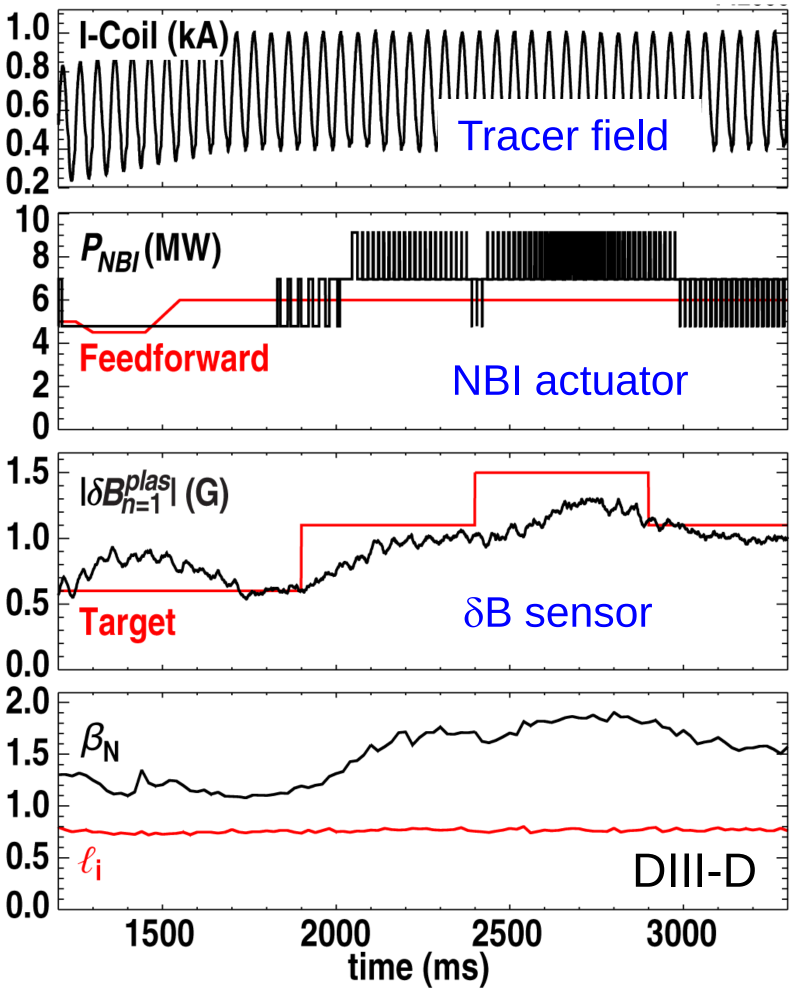
Disruption warning system assessment



- Theoretically-based prediction
  - e.g. kinetic RWM theory - tested against experiment (NSTX, DIII-D)
    J.W. Berkery, et al., PRL **104** (2010) 035003
    J.W. Berkery, et al., PRL **106** (2011) 075004
  - Recent experiments comparing detailed stability / mode dynamics results between NSTX and DIII-D
- MHD Spectroscopy
  - Used to measure global plasma stability in DIII-D and NSTX, not yet used routinely
- Disruption Warning System
  - Some implementations exist (e.g. on DIII-D, JET)
  - Recent analysis, highly successful in disruption prediction with low % of false positives when applied to NSTX database
    S.P. Gerhardt, et al., NF **53** (2013) 063021

Disruption Prediction / Detection: Initiatives

First real-time β_N control using measured field amplification

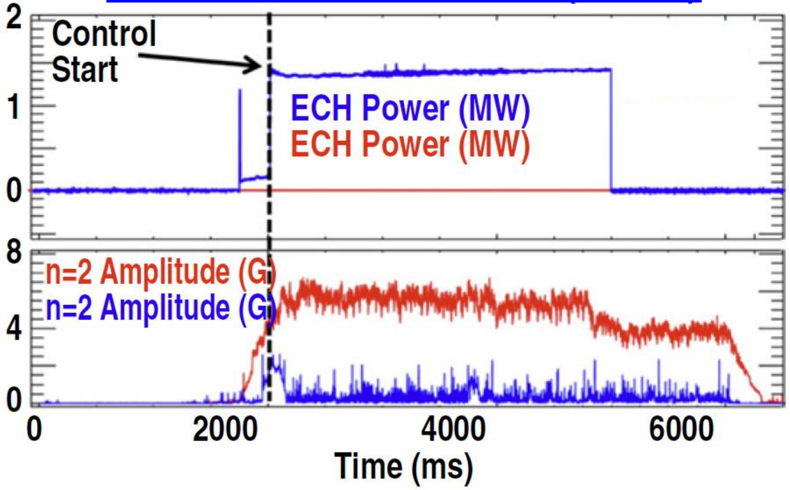


J.M. Hanson, et al., Nucl. Fusion **52** (2012) 013003

- **Physics models**
  - Real-time (r/t) ideal MHD calculations (DCON), simplified models of kinetic MHD stabilization physics
  - Utilize results from non-linear MHD codes
  - Expand real-time MHD mode control models, more general plasma response
- **Measurements**
  - Demonstrate general effectiveness of MHD spectroscopy in r/t stability prediction
  - Develop predictions based on large data-driven statistics (incl. JET)
  - Non-magnetic mode diagnosis, especially detection of internal modes
- **Disruption Warning System**
  - Introduce additional real-time measurements, theoretical models to further improve performance
  - Implement on major US tokamaks, (potentially international devices as well)

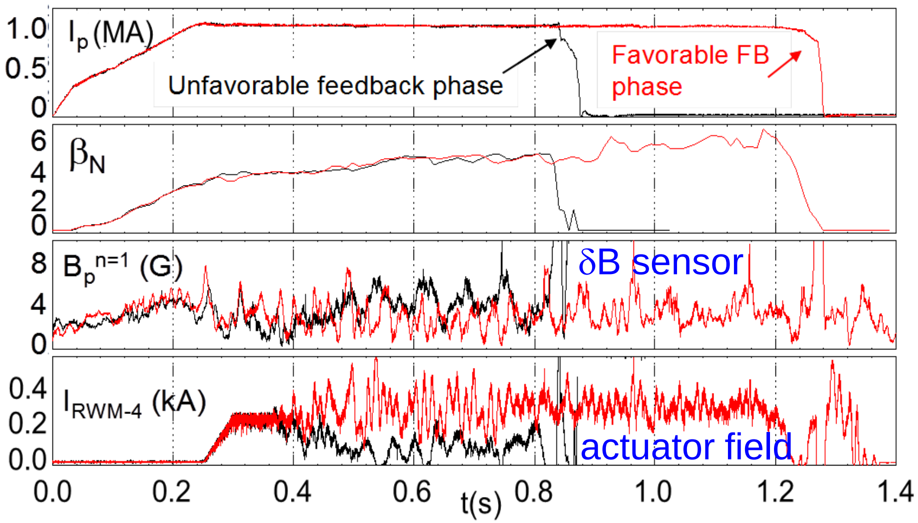
Disruption Avoidance: Status

Advanced NTM Control (DIII-D)



E. Kolemen, et al., Nucl. Fusion **54** (2014) 073020

Model-based RWM control (NSTX)

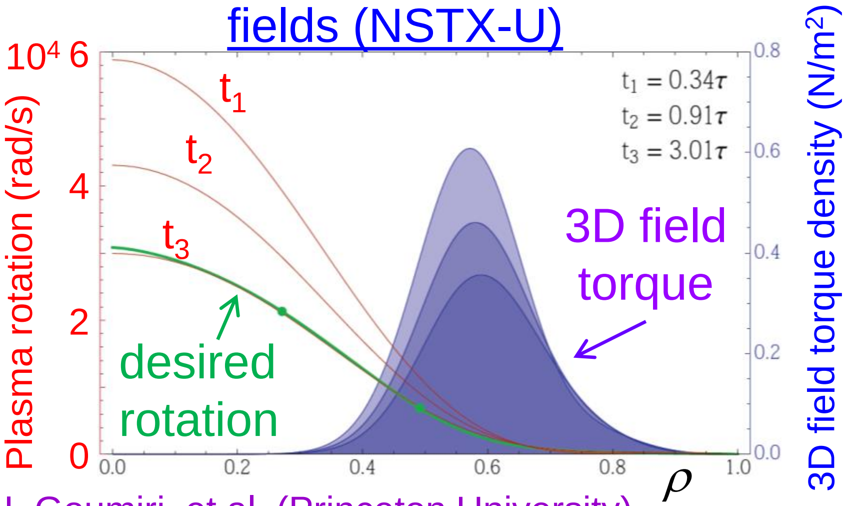


S.A. Sabbagh, et al., Nucl. Fusion **53** (2013) 104007

- Advanced profile control algorithms
  - Being implemented, but profile control is still a relatively untapped opportunity
- Active mode control
  - Physics-based, state-space algorithms, sensors, and magnetic/ECCD actuators have shown significant successes for RWM / NTM control
- MHD spectroscopy (direct stability measurement)
  - Not yet generally used for disruption avoidance
  - Real-time use for disruption avoidance will be significantly enhanced by profile control

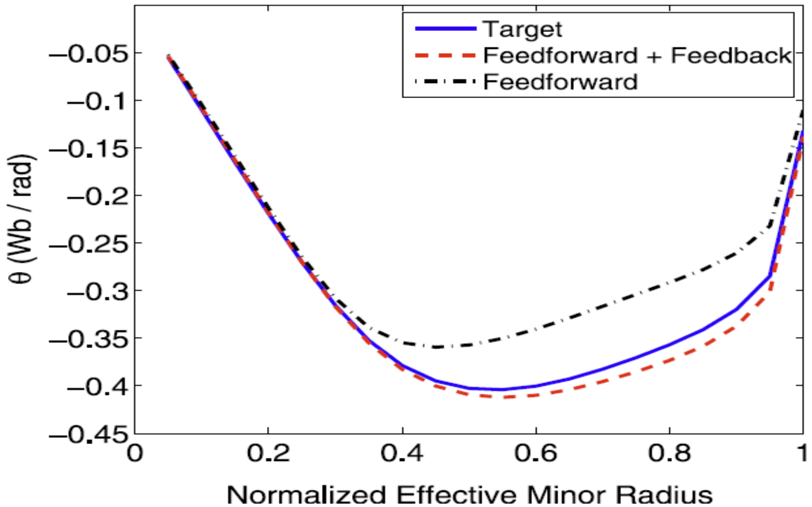
Disruption Avoidance: Initiatives

Plasma rotation controller using 3D fields (NSTX-U)



I. Goumiri, et al. (Princeton University)

Magnetic profile control tested (DIII-D)

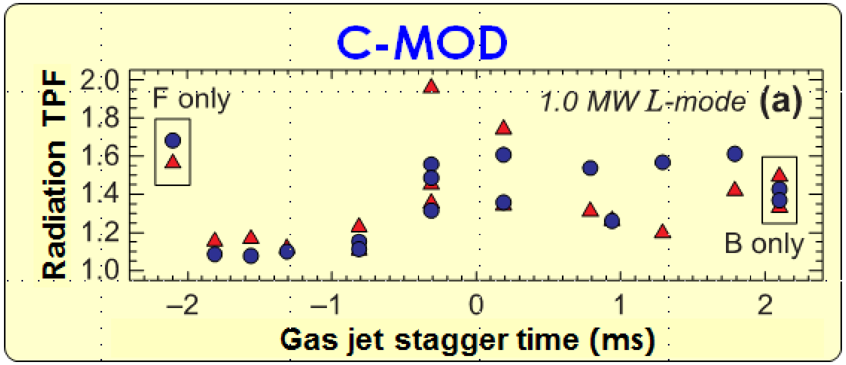


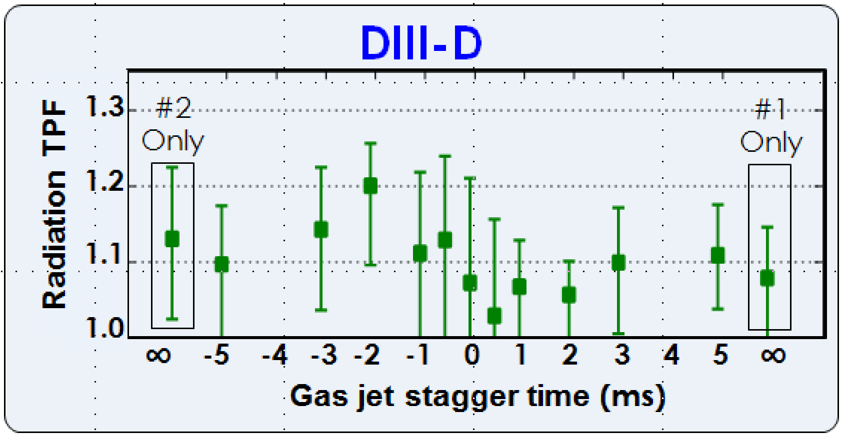
J.E. Barton, et al., Nucl. Fusion **52** (2012) 123018

- Advanced profile control
  - Significant opportunities using NBI, 3D fields, and innovative core fueling / momentum injection techniques
    - Reactor-class CT injection 2 mg D_2 @ 20 Hz → same momentum as 69 MW NBI @ 500 keV (R. Raman, FESAC 2014)
- Active mode control
  - Generalize RWM, NTM control: improve performance, prove over long-pulse
- Greater utilization of real-time physics models/ MHD spectroscopy
  - Utilize real-time guidance from stability gradients to steer away from instability
- Computational simulations
  - Develop to test control algorithms to make faster progress
- Disruption Warning Systems
  - Increase and more intelligently use input, prioritize multiple actuators

Disruption Mitigation: Status

Multiple injectors do not reduce radiation toroidal asymmetry





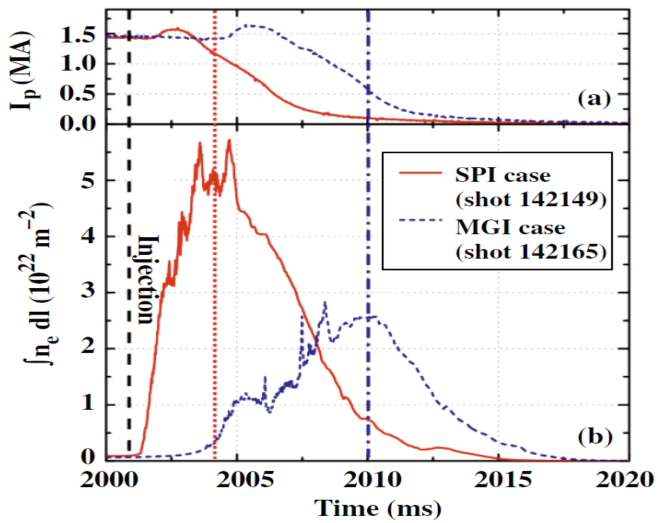
N. Eidietis, et al., DIII-D 5 Year Plan talk (2014)

Effort being made to support ITER mitigation system final design review (2017)

- Heat and radiation loads
  - Massive Gas Injection has demonstrated partial success
  - …but gas penetration too slow / requires MHD mixing to reach core
  - Radiation asymmetries could cause first wall melting – magnitudes differ across devices
- Runaway Electron Generation
  - Can cause intense melting / erosion
  - Innovative ideas now being tested to reduce RE beam
- Induced Halo Currents
  - Vessel forces associated with halo current asymmetry and rotation are key ITER concern now

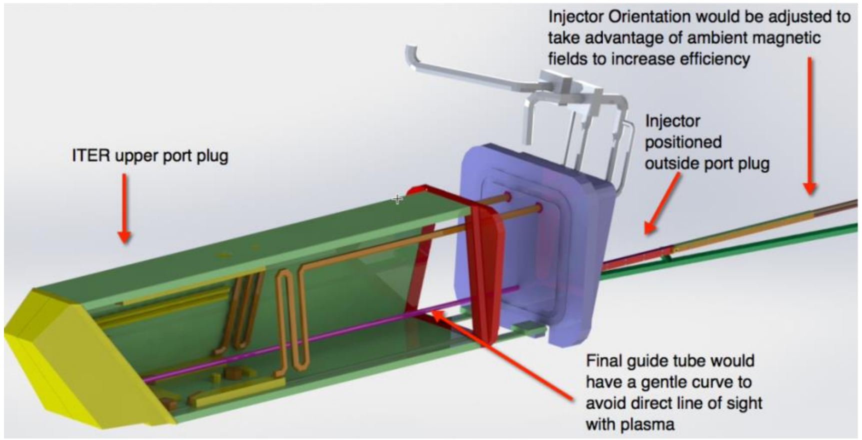
Disruption Mitigation: Initiatives

Shattered Pellet Injector results (DIII-D)



N. Commaux, et al., Nucl. Fusion **51** (2011) 103001

Electromagnetic Particle Injector in ITER (schematic)

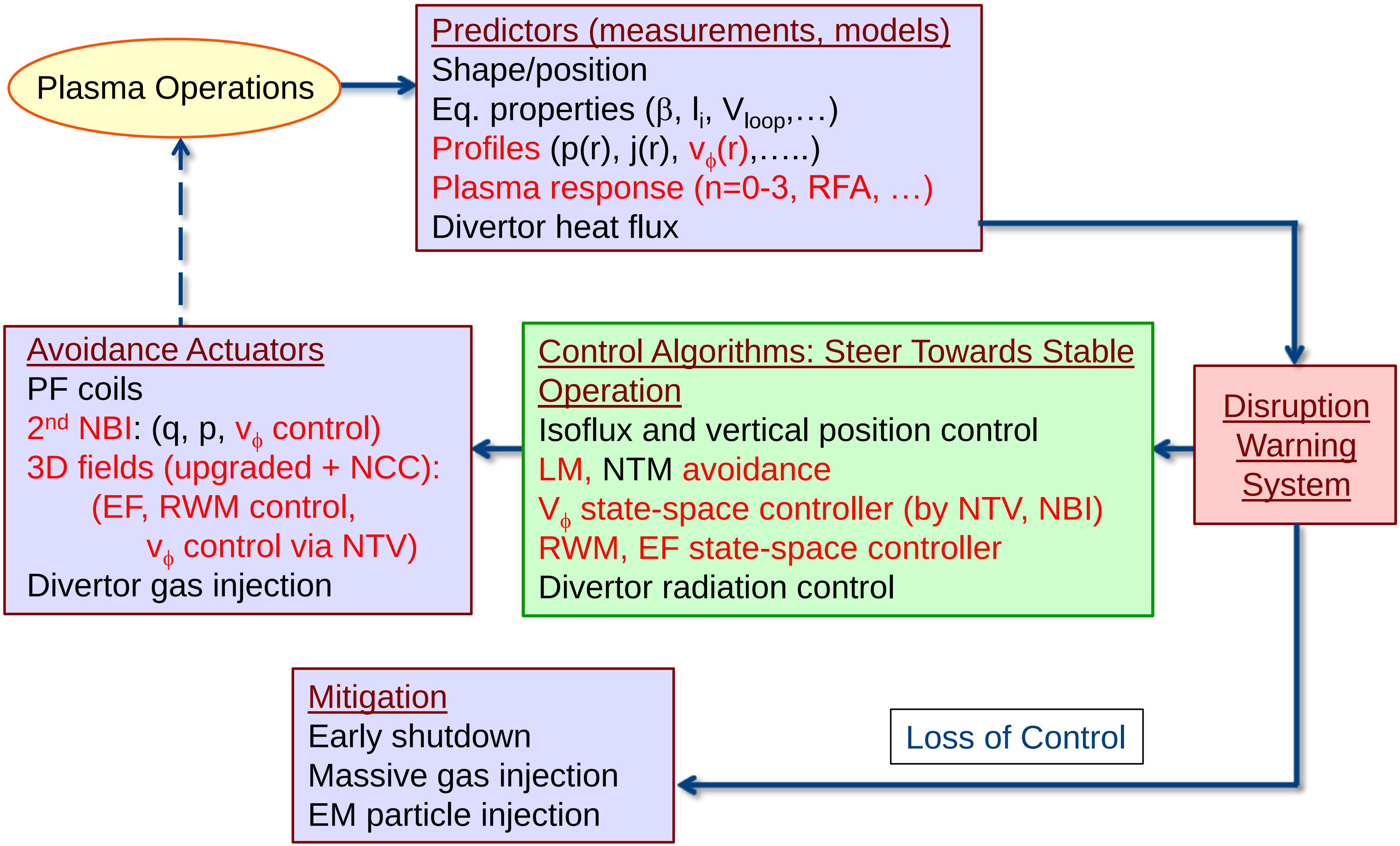


R. Raman, et al., EPS 2014, Paper P5.015

- Massive Gas Injection
  - Understand gas penetration efficiency vs poloidal location (including X-point); spatial distribution of heat / radiation
- Shattered / Shell Pellet Injection
  - promising alternative to MGI
- Halo current diagnosis
  - Expand to understand toroidal asymmetries, rotation, related forces
- Electromagnetic Particle Injection
  - Adequate to meet < 10 ms response time needed for ITER, test on NSTX-U
- Active control of disrupting plasma
  - Reduce impact of halo currents and runaway electrons
- Sacrificial limiters
  - including low-Z liquid metals

Related theoretical modeling needed for extrapolation to ITER, FNSF, etc.

Some elements shown in this talk will be part of a sophisticated disruption PAM system developed in NSTX-U



Building on present program strengths in disruption PAM is the most efficient path for best progress

- Fund a "National Initiative for Disruption Elimination"
  - A unique, world-leading effort with quantifiable objectives, leveraging significant US investment in major facilities and university expertise
  - Funded leaders (including university collaborations) to be responsible for key elements, conduct work as a synergistic team
- Initiative supports incremental elements of disruption PAM in the present, complementary efforts at major US facilities
  - Five-year plan of significantly upgraded NSTX device is shifting focus of stability and control research to disruption PAM
  - Significant and complementary disruption PAM elements exist in DIII-D 5 Year Plan, esp. advanced NTM control and mitigation research
- Leverage international programs
  - Gain experience from JET, utilize KSTAR high β long-pulse plasmas
  - Apply US-developed techniques to high power / long-pulse devices
- Estimated cost of 10 year mission: +$5M/year – $7.5M/year
  - Based on up to 50% increase in present FTEs, and international funding
  - NOTE: includes $3M/year cost of major facility hardware upgrades

Discussion of tactical initiatives for disruption PAM

- FESAC white paper would be most effective by having a prioritized list of research/tools needed to improve disruption PAM

- Discussion: What actions should we take / what new tools do we need to make disruption PAM most effective?

- Follow-up in the white paper with a quantifiable assessment of the effectiveness / readiness of any actions / tools proposed

- Send email to sabbagh@pppl.gov to join group

Supporting Slides Follow

ITER Disruptivity Requirements (Lehnen 2013)

Disruption Mitigation System *requirements*

DT phase (requirements gradually increasing from H/He phase)

	Energy load on divertor target	Energy load on first wall (VDEs)	EM load due to halo currents (VDEs)	Runaway electrons
Disruption rate (Avoidance)	≤ 5 %	≤ 1-2 %	≤ 1-2 %	<< 1 %
Prediction success	≥ 95 %	≥ 98 %	≥ 98 %	~ 100 %
Mitigation performance	≤ 1/10	≤ 1/10	≤ 1/2	≤ 2 MA

Compatible with "response time" of ≤ 20ms?

minimum requirement
substantial melting still likely

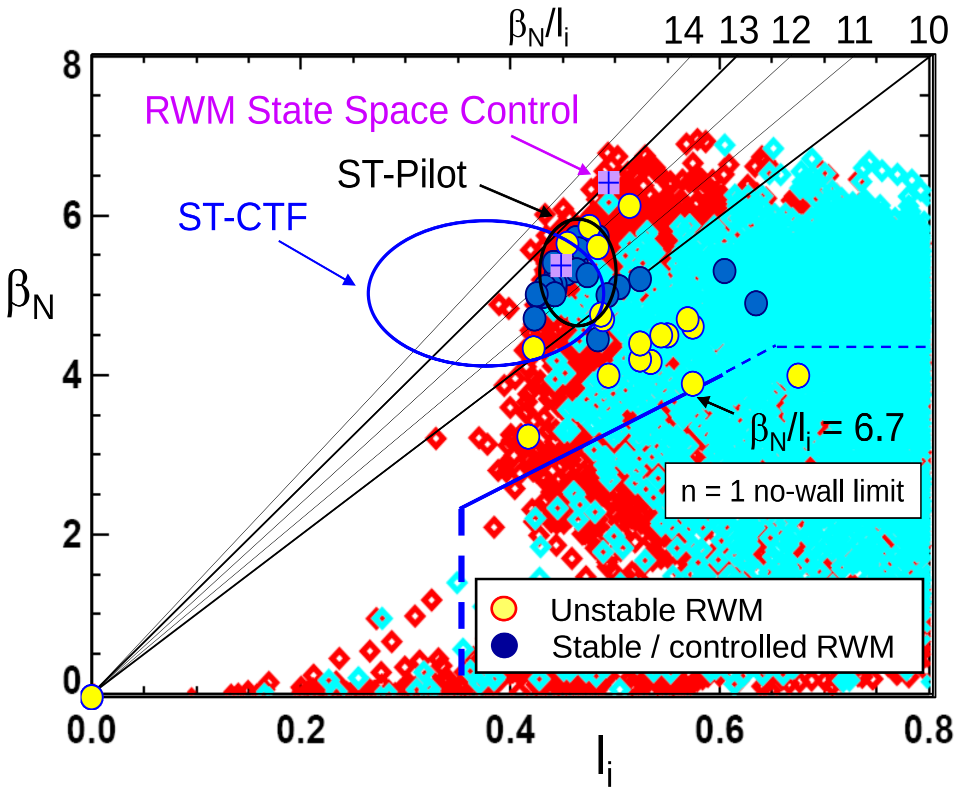
M. Lehnen, ITPA-MHD Topical Group Meeting, Culham 2013

iter china eu india japan korea russia usa

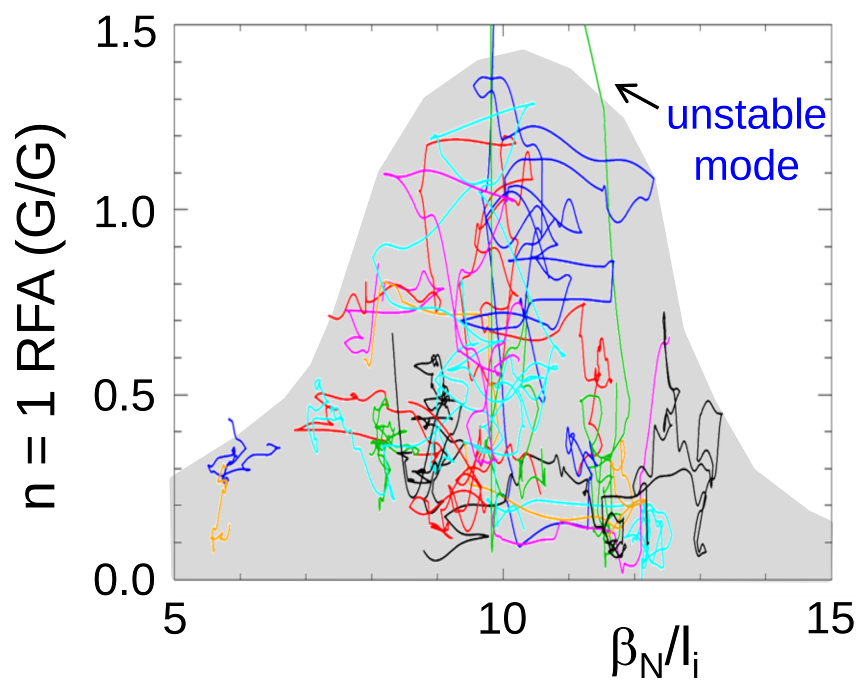
IDM: ITER_D_DSNCCZ

15

Stability control improvements significantly reduce unstable RWMs at low l_i and high β_N; improved stability at high β_N/l_i



Resonant Field Amplification (RFA) vs. β_N/l_i



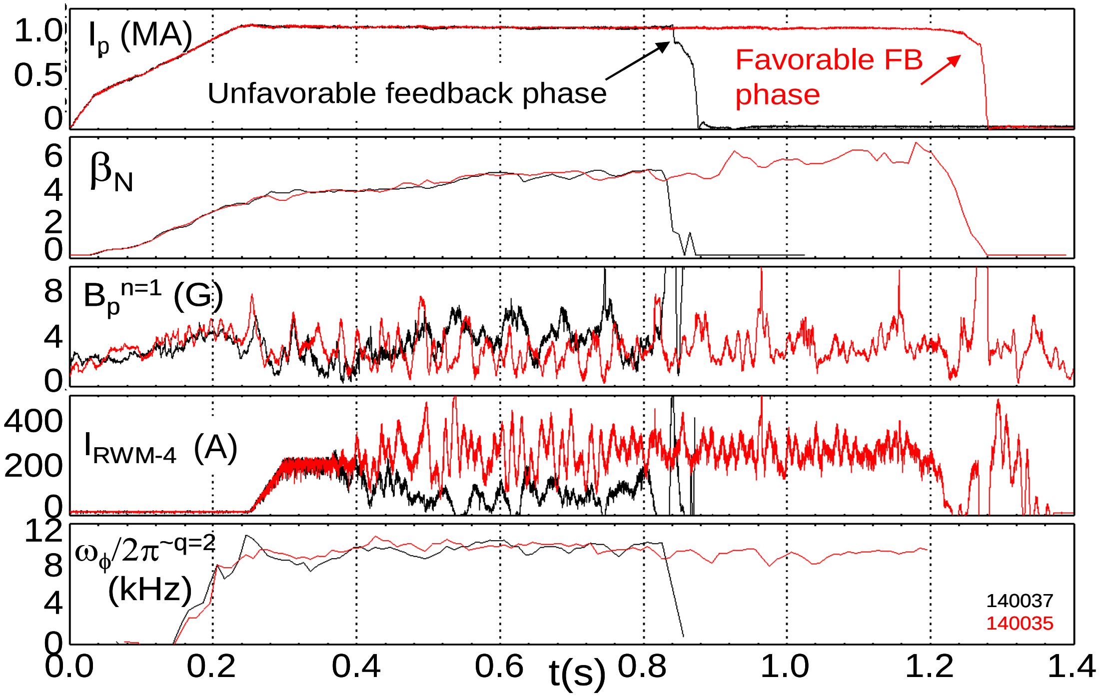
- Disruption probability reduced by a factor of 3 on controlled experiments
  - Reached 2 times computed n = 1 no-wall limit of $\beta_N/l_i = 6.7$
- Lower probability of unstable RWMs at high β_N/l_i

- Mode stability directly measured in experiments using MHD spectroscopy
  - Stability decreases up to $\beta_N/l_i = 10$
  - Stability increases at higher β_N/l_i
  - Presently analysis indicates consistency with kinetic stabilization

S.A. Sabbagh, et al., Nucl. Fusion 2013, J.W. Berkery, et al., PoP 2014

Model-based RWM state space controller including 3D plasma response and wall currents used at high β_N in NSTX

RWM state space controller in NSTX at high β_N

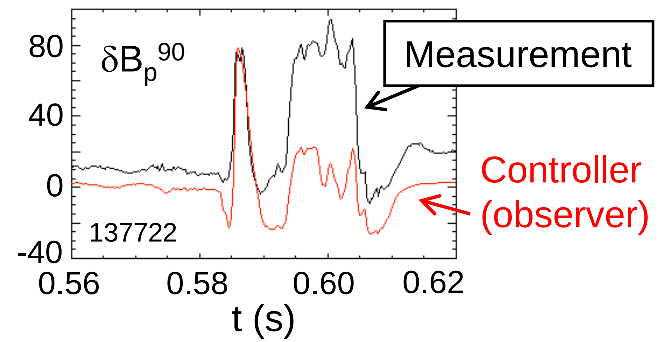


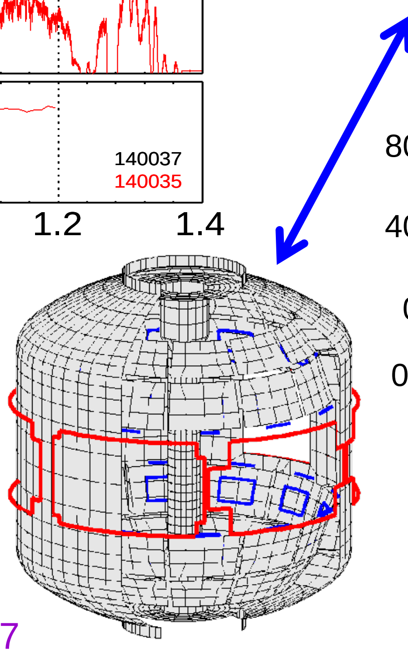
- Potential to allow more flexible control coil positioning
  - May allow control coils to be moved further from plasma, and be shielded (e.g. for ITER)
    Katsuro-Hopkins, et al., NF **47** (2007) 1157

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

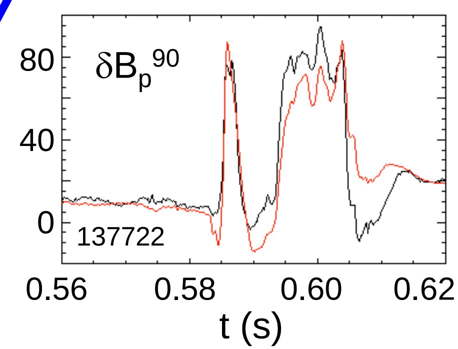
Effect of 3D Model Used

No NBI Port





With NBI Port



- 3D detail of model is important to improve sensor agreement