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

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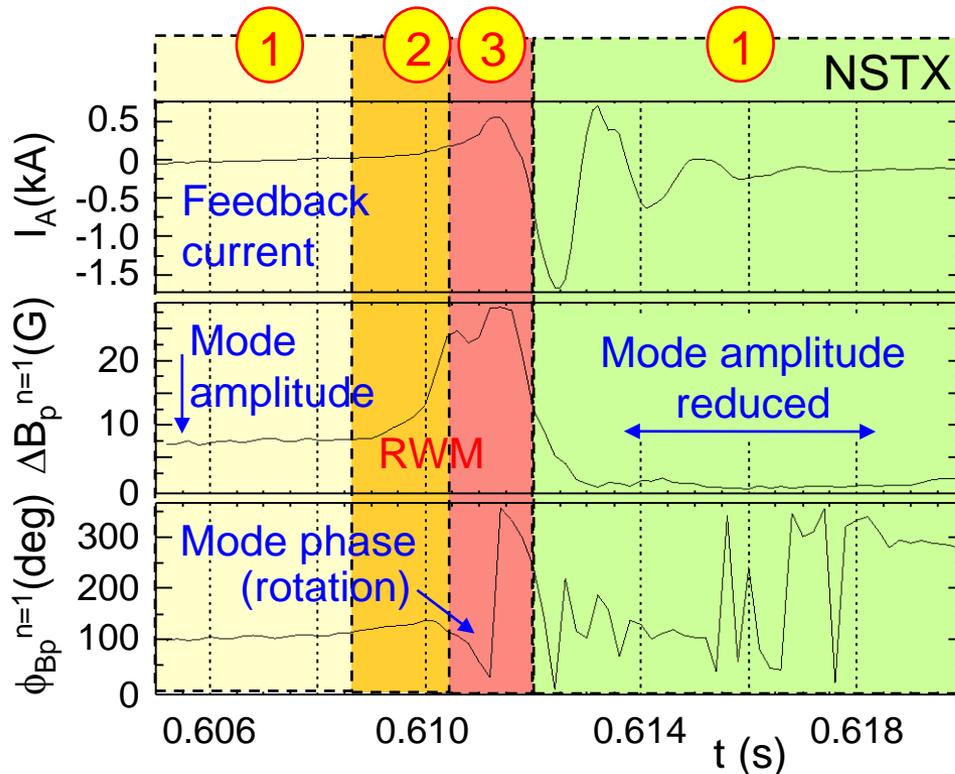
Near 100% disruption avoidance is an urgent need for ITER, FNSF, and future tokamaks

- 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

Increase success of disruption PAM by exploiting more opportunities/actions to avoid/mitigate disruption

EXAMPLE: active RWM feedback control



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

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

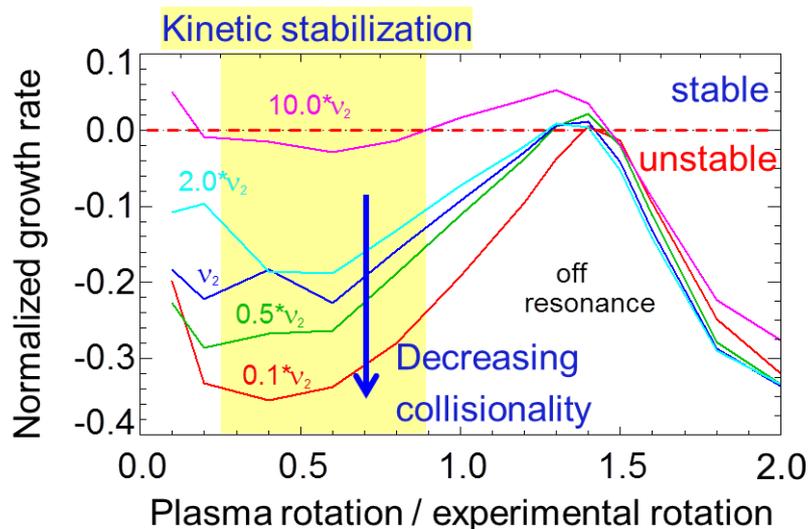
Potential actions Time periods

- Prediction (1-2)
 - Measure stability
 - Theory-based predictions
- Avoidance (2-3)
 - Profile control
 - Active instability control
- Mitigation (3)
 - Impurity injection
 - Controlled shutdown

Status and Initiatives in these areas are shown in remainder of talk

Disruption Prediction / Detection: Status

Kinetic RWM stability may increase at lower v



- Theoretically-based prediction

- e.g. kinetic RWM theory - tested against experiment (NSTX, DIII-D)

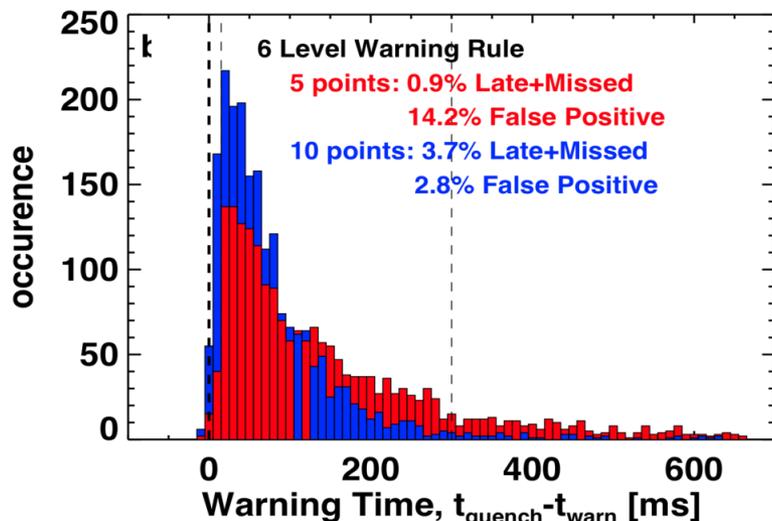
J.W. Berkery, et al., PRL **104** (2010) 035003

J.W. Berkery, et al., PRL **106** (2011) 075004

- MHD Spectroscopy

- Used to measure global plasma stability in DIII-D and NSTX, not yet used routinely

Disruption warning system assessment



- Disruption Warning System

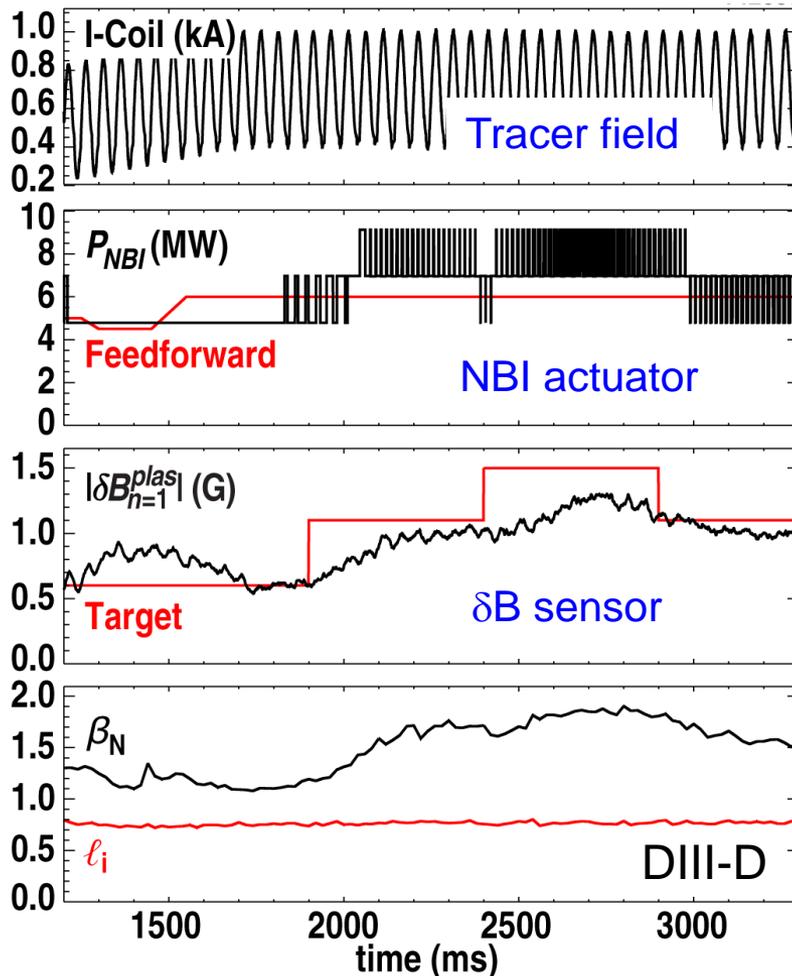
- Some implementations exist (e.g. on DIII-D, JET)

- 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

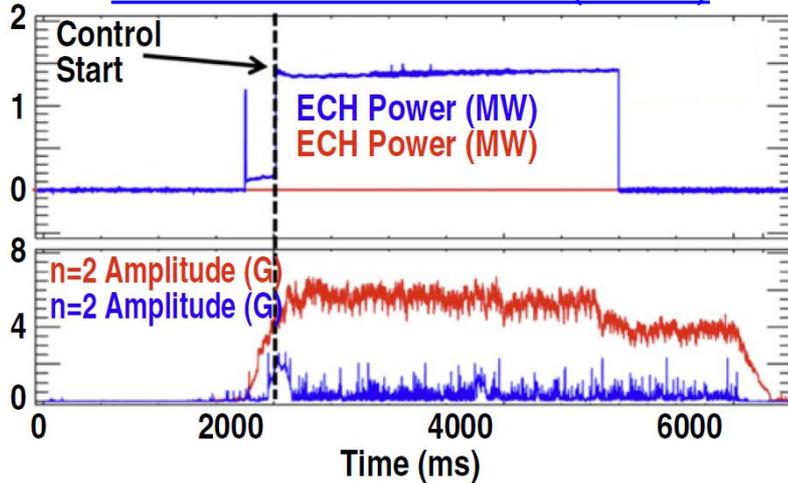
- Demonstrate general effectiveness of MHD spectroscopy in r/t stability prediction
- Develop predictions based on large data-driven statistics (incl. JET)
- Non-magnetic mode diagnosis, especially detection of internal modes

• Disruption Warning System

- Introduce additional real-time measurements, theoretical models to further improve performance
- Implement on major US tokamaks, (potentially international devices as well)

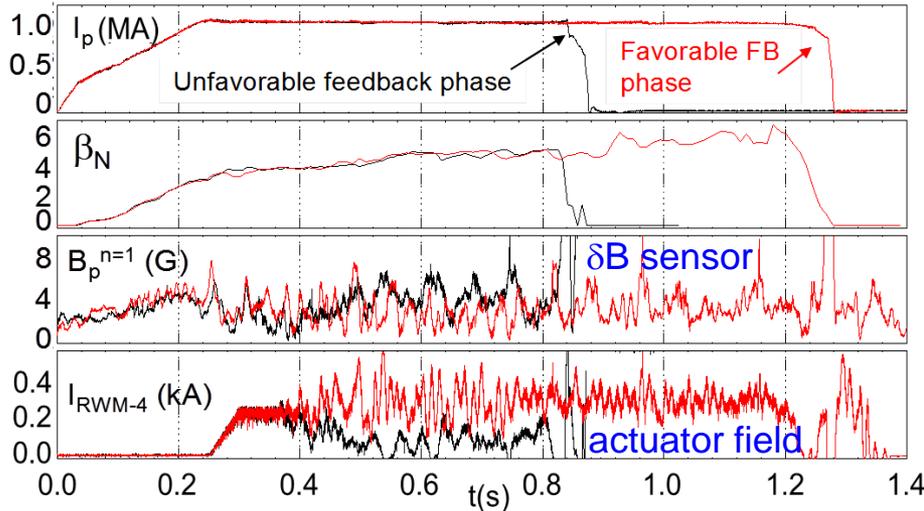
Disruption Avoidance: Status

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

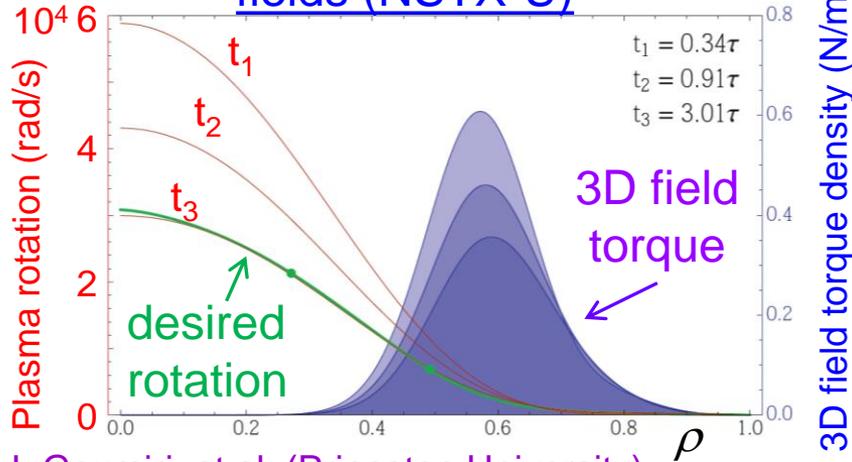
- Physics-based, state-space algorithms, sensors, and magnetic/ECCD actuators have shown significant successes for RWM / NTM control

- 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

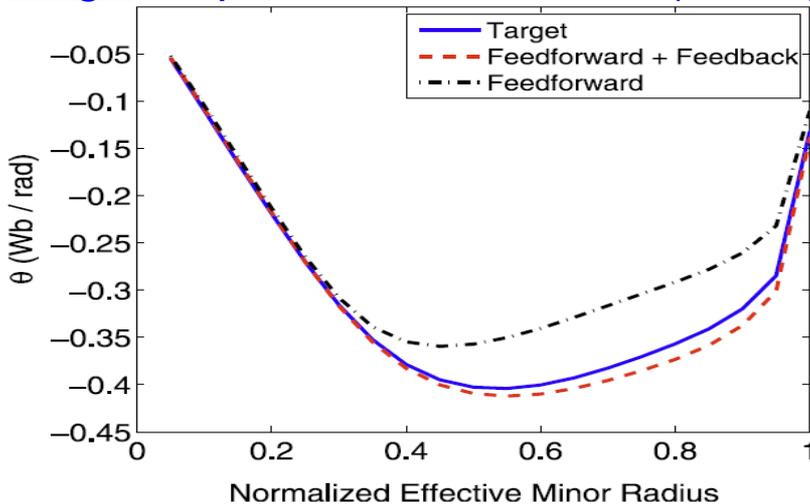
Disruption Avoidance: Initiatives

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



I. Goumiri, et al. (Princeton University)

Magnetic profile control tested (DIII-D)

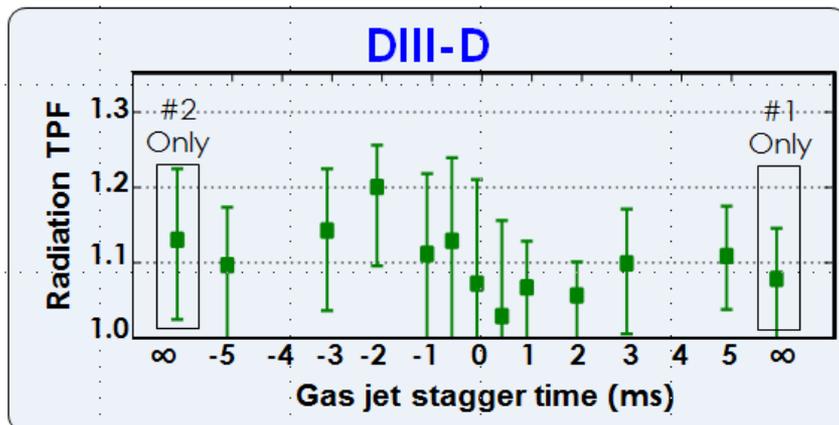
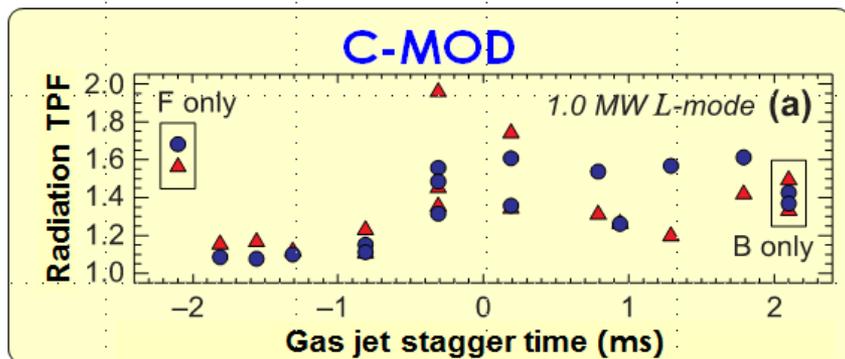


J.E. Barton, et al., Nucl. Fusion **52** (2012) 123018

- **Advanced profile control**
 - Significant opportunities using NBI, 3D fields, and innovative core fueling / momentum injection techniques
See R. Raman talk
- **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

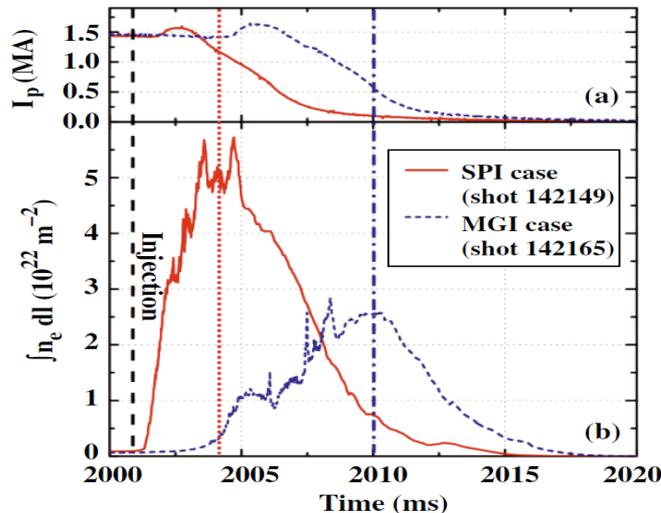
- ❑ Can cause intense melting / erosion
- ❑ Innovative ideas now being tested to reduce RE beam

• Induced Halo Currents

- ❑ Vessel forces associated with halo current asymmetry and rotation are key ITER concern now

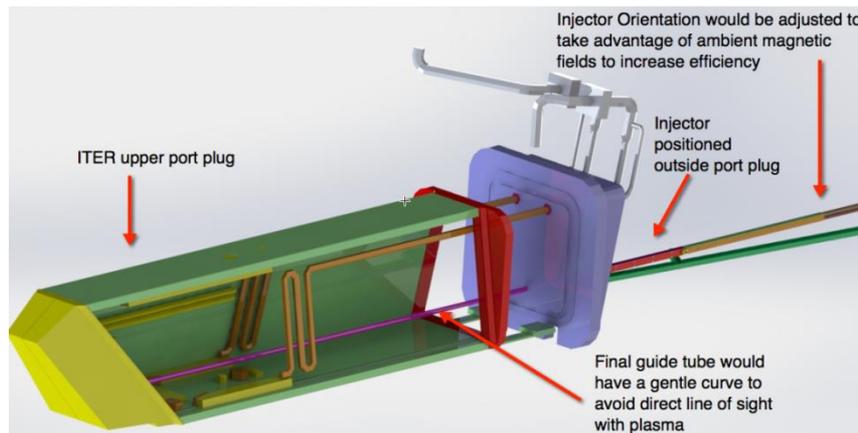
Disruption Mitigation: Initiatives

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.

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**

Supporting Slides Follow

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

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)	$\leq 5\%$	$\leq 1-2\%$	$\leq 1-2\%$	$\ll 1\%$
Prediction success	$\geq 95\%$	$\geq 98\%$	$\geq 98\%$	$\sim 100\%$
Mitigation performance	$\leq 1/10$	$\leq 1/10$	$\leq 1/2$	$\leq 2\text{ MA}$

Compatible with “response time” of $\leq 20\text{ms}$?

minimum requirement
substantial melting still likely