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

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Princeton Plasma Physics Laboratory

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

- **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

- **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.”

Key PAM extrapolations
- reduced collisionality
- + non-inductive sustainment
- + high β, profile control
Highly successful disruption PAM needs to exploit several opportunities/actions to avoid/mitigate disruption

Example: Active RWM control in NSTX

1. **Pre-instability**
   - RFA to measure stable $\gamma$
   - 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

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


**Disruption Prediction / Detection: Status**

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

- Destabilization appears between precession drift resonance at low $\omega_\phi$, bounce/transit resonance at high $\omega_\phi$
  - S.A. Sabbagh, et al., NF 50 (2010) 025020
- Destabilization moves to increased $\omega_\phi$ as $\nu$ decreases
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Kinetic RWM stability may increase at lower $\nu$

Disruption warning system assessment

![Graph showing disruption warning system assessment]

- 6 Level Warning Rule
  - 5 points: 0.9% Late+Missed
  - 14.2% False Positive
  - 10 points: 3.7% Late+Missed
  - 2.8% False Positive

Normalized growth rate

Plasma rotation / experimental rotation

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Disruption Prediction / Detection: **Initiatives**

- **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)

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First real-time $\beta_N$ control using measured field amplification

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J.M. Hanson, et al., Nucl. Fusion **52** (2012) 013003
Disruption Avoidance: Status

Advanced NTM Control (DIII-D)

- 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


S.A. Sabbagh, et al., Nucl. Fusion 53 (2013) 104007
Disruption Avoidance: **Initiatives**

**Advanced profile control**
- Significant opportunities using NBI, 3D fields, and innovative core fueling / momentum injection techniques
  - Reactor-class CT injection 2 mg D₂ @ 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

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

- **t₁ = 0.34τ**
- **t₂ = 0.91τ**
- **t₃ = 3.01τ**

**Magnetic profile control tested (DIII-D)**

I. Goumiri, et al. (Princeton University)

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

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Disruption Mitigation: Status

Multiple injectors do not reduce radiation toroidal asymmetry

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

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

C-MOD

DIII-D
**Disruption Mitigation: Initiatives**

- **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

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**Shattered Pellet Injector results (DIII-D)**

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

**Electromagnetic Particle Injector in ITER (schematic)**


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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

**Predictors (measurements, models)**
- Shape/position
- Eq. properties ($\beta$, $l_i$, $V_{loop}$, …)
- Profiles ($p(r)$, $j(r)$, $v_\phi(r)$, …)
- Plasma response (n=0-3, RFA, …)
- Divertor heat flux

**Avoidance Actuators**
- PF coils
- 2nd NBI: ($q$, $p$, $v_\phi$, control)
- 3D fields (upgraded + NCC): (EF, RWM control, $v_\phi$ control via NTV)
- Divertor gas injection

**Control Algorithms: Steer Towards Stable Operation**
- Isoflux and vertical position control
- LM, NTM avoidance
- $V_\phi$ state-space controller (by NTV, NBI)
- RWM, EF state-space controller
- Divertor radiation control

**Mitigation**
- Early shutdown
- Massive gas injection
- EM particle injection

**Disruption Warning System**

**Loss of Control**
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 $\beta$ 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

<table>
<thead>
<tr>
<th>DT phase (requirements gradually increasing from H/He phase)</th>
<th>Energy load on divertor target</th>
<th>Energy load on first wall (VDEs)</th>
<th>EM load due to halo currents (VDEs)</th>
<th>Runaway electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disruption rate (Avoidance)</td>
<td>≤ 5 %</td>
<td>≤ 1-2 %</td>
<td>≤ 1-2 %</td>
<td>&lt;&lt; 1 %</td>
</tr>
<tr>
<td>Prediction success</td>
<td>≥ 95 %</td>
<td>≥ 98 %</td>
<td>≥ 98 %</td>
<td>~ 100 %</td>
</tr>
<tr>
<td>Mitigation performance</td>
<td>≤ 1/10</td>
<td>≤ 1/10</td>
<td>≤ 1/2</td>
<td>≤ 2 MA</td>
</tr>
</tbody>
</table>

Compatible with “response time” of ≤ 20ms?

minimum requirement substantial melting still likely
Stability control improvements significantly reduce unstable RWMs at low $l_i$ and high $\beta_N$; improved stability at high $\beta_N/l_i$

- 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 $\beta_N/l_i$


Mode stability directly measured in experiments using MHD spectroscopy
- Stability decreases up to $\beta_N/l_i = 10$
- Stability increases at higher $\beta_N/l_i$
- Presently analysis indicates consistency with kinetic stabilization
Model-based RWM state space controller including 3D plasma response and wall currents used at high $\beta_N$ in NSTX

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)


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