Development and Experimental Qualification of Novel Disruption Prevention Techniques on DIII-D

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Comprehensive disruption prevention must cover the full range of control regimes

Disruption Control

Regimes:

1. Continuous Prevention:
   - Nominal scenario
   - Regulate perform.
   - Catch & Subdue
   - Temp. lower performance
   - Return to target if stable

2. Asynchronous Avoidance:
   - Controllability Limit
   - Controlled Plasma Parameter ($l$, $\beta$, $I_p$, etc.)

3. Emergency Avoidance:
   - Rapid Controlled Shutdown, Mitigation: the last resort

"disruption" = loss of control

(1) Should catch 99%+ of disruptions!

The Disruption Free Protocol:

- To qualify ITER-scalable, comprehensive disruption control in routine operations

- Large-scale piggybacks to complement experiments: >40% run days in ’19
Comprehensive disruption prevention must cover the full range of control regimes.

**Disruption Control Regimes:**

1. **Continuous Prevention:**
   - Controllability Limit
   - Controlled Plasma Parameter ($l_i, \beta, I_p$, etc.)
   - Nominal scenario
   - Regulate performance
   - Catch & Subdue
   - Temp. lower performance
   - Return to target if stable
   - Controlled Plasma Parameter

2. **Asynchronous Avoidance:**
   - Rapid Controlled Shutdown
   - Mitigation: the last resort

3. **Emergency Avoidance:**
   - Proximity Controller
   - Continuously regulate stability vs performance

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Proximity Controller

Continuous disruption prevention must cover the full range of control regimes.
A new proximity-to-instability control architecture has been developed for DIII-D in FY 2020

- **Threshold instability value for applying action**
  - Allows setting margin of stability

- **Generalized architecture maps stability metrics to requested changes in plasma targets**
  - Shape, I_p, β...
  - Tunable PIDs, gains

- **Output target mods combined, weighted by problem importance**
Proximity-to-instability control architecture maps real-time stability metrics to modified scenario targets

**Stability Models:**
- VDE $\gamma$-Est.
- $\Delta^*$-Est., ML TM...
- Div Heat Flux
- A(M)MS Response
- Mode |Ampl. |, $f_{\text{RHD}}$
- Interpretable ML
- More tools needed!

**Avoidance Handling:**
- VDE
- Ideal, $\beta$, GW limits
- Tearing Modes
- Locked Modes
- Stable Ops Space Monitoring
- Unintended ELM
- Radiative Collapse
- H-L Back-transition

**Target Mods:**
- $K, \delta, \zeta$
- $n_e$
- $\beta_N$
- $l_i$
- $q_{95}$
- $j, j_{CD}$
- EFC
- Rot.
- $f_{\text{rad}}$

**Other Control Categories:**
- Discharge Shape
- Density Control
- Profile Control
- Alternate:
  - Ip & Vloop
  - Neutral Beams
  - ECH/ECCD
  - RMP

**Real-time target changes sent to actuator controllers**

**Settings map metrics to scenario targets**

**Physics-problem focused**

**Uses real-time stability metrics**
Proximity-to-instability control architecture maps real-time stability metrics to modified scenario targets

Ex: VDEs

Uses real-time stability metrics

Physics-problem focused

Settings map metrics to scenario targets

Real-time target changes sent to actuator controllers

Stability Models:
- VDE $\gamma$-Est.
- $\Delta'$-Est., ML TM...
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Interpretable ML

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- Ideal, $\beta$, GW limits
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Target Modds:
- $K$, $\delta$, $\zeta$
- $n_c$
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Proximity controller applied for robust VDE prevention using real-time VDE-\(\gamma\) estimator for shape target feedback

- VDE reliably prevented until Proximity Controller disabled
  - Example: pre-shot K-target ramp to induce VDE

- **Real-time VDE-\(\gamma\) estimators:** rigid motion, or ML-based models

[Graphs and diagrams showing Ip, K, Limit, and Threshold with red and blue lines indicating Prox. Ctrl on and off, and adjusted time (blue).]
Robust control is a requirement for safe operations near stability limits

- Operational limits are limited by physics & control
- Robustly controllable VDE growth-rates assessed in recent experiments
- Robust control at $\gamma \sim 800-850$ /s for $\geq 3$ s

![Graph showing magnetic limiter threshold and control](image-url)
Future integration with include Interpretable ML, MHD Spectroscopy planned for experiments in 2021

- **Integrating with Interpretable ML [1]**
  - DPRF: Disruption Prevention via Random Forests [1]
  - Contribution factors ($f_c$) map to controllable params
  - Scale by overall disruptivity

**Example:**

$$\Delta \kappa = PID \left[ f_{danger} \cdot f_{\kappa-\text{contrib}} \cdot \text{sign} \left( \frac{d\kappa}{dt} \right) \left( \frac{\Delta \kappa_{\text{target}}}{\Delta f_{\kappa-\text{contrib}}} \right) \right]$$

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- **Active Multi-Mode Spectroscopy Demonstrated Offline [2-3]**
  - Continuous monitoring of closest-to-unstable modes
  - Real-time version ready for upcoming experiments

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Figure adapted from T. Liu NF [2]
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- **Rapid Controlled Shutdown**
  - 2nd-to-last resort before mitigation

**Controlled Plasma Parameter**

\[(l, \beta, I_p, \text{etc.})\]
Qualifying fast, emergency shutdown after large $n=1$ tearing, locked modes for effectiveness on DIII-D

- Applied shutdown survey recipe$^1$:
  - $dI_p/dt \sim 2-3$ MA/s, sustained $P_{\text{NBI}} \sim 2-3$ MW

- Metric of success is lower final $I_N$ ($W_m \sim I_p^2 \sim I_N^2$)

Example emergency shutdown:

After high B-dot or LM (Div and Lim)

\[
I_N = I_p / aB_t
\]

$N = 10^1$

$12$ J. Barr/ITER FEC 2020/May 14$^{th}$, 2021

[1] J.L. Barr et al. IAEA FEC 2018
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![Graph showing % Shots and \( I_N \) vs. \( I_p/aB_t \)]

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**Transitioning to limited topology for emergency shutdown dramatically reduces LM disruption risk on DIII-D**

- After LM is detected, shape modification immediately applied.

- Despite common use and improvements, ITER will likely require multiple prevention tools to improve these rates.

**Focus on LM trips:**

**Limited Shutdown:**
- After LM detected:
  - $I_N = I_p / aB_t$
  - N = 18

**Diverted Shutdown:**
- After LM detected:
  - $I_N = I_p / aB_t$
  - N = 31

[1] J.L. Barr et al. IAEA FEC 2018
Warm, helical plasma core generation is a promising technique for emergency shutdown / alternate mitigation

- Novel emergency shutdown technique for long current quench durations
  - DIII-D high-Ip discharges (~1.7MA+)
  - Improves confinement after thermal quench

- Helical structure induced after thermal quench with large applied 3-D fields
  - Reconstructed with dual Soft X-ray Imaging
  - Consistent with ECE, TS

- Can modify current quench alongside Ne injection
  - Can extend current quench to ~100ms
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Conclusions: DIII-D is developing, testing, and qualifying control tools for comprehensive disruption avoidance

- DIII-D Disruption Free Protocol: initiative for qualifying comprehensive disruption prevention tools

- Novel Proximity-to-Instability controller implemented for real-time scenario mod’s to maintain stability, applied for robust VDE prevention

- The effectiveness of emergency shutdown for disruption prevention is being rigorously quantified

- Novel technique generates warm, helical core after thermal quench to significantly slow current quench