Disruption event characterization and forecasting of global and tearing mode stability for tokamaks

J.W. Berkery, S.A. Sabbagh, Y.S. Park, J.H. Ahn, Y. Jiang, and J.D. Riquezes
Columbia University

S.P. Gerhardt¹, C.E. Myers¹, T. Blanken², F. Felici², C. Galperti³, H. Reimerdes³

¹PPPL, ²Eindhoven University of Technology, ³École Polytechnique Fédérale de Lausanne

Theory and Simulation of Disruptions Workshop
Princeton, NJ
July 19, 2017

*This work is supported by the US DOE contracts DE-AC02-09CH11466 and DE-FG02-99ER54524
Outline

• The Disruption Event Characterization And Forecasting (DECAF) code
  – Contains various physical event modules with warning algorithms

• A reduced kinetic model for resistive wall mode stability
  – Complex calculation reduced for speed, performs well

• Identification of rotating MHD
  – Tracks characteristics that lead to disruption: rotation bifurcation, mode lock
Disruption event chain characterization capability continues as next step in disruption avoidance plan

- Approach to disruption prevention
  - Identify disruption event chains and elements
  - Predict events in disruption chains
  - Cues disruption avoidance systems to break event chains
    - Attack events at several places with active control to prevent disruption
  - Builds upon both physics and control successes of NSTX
    - Presently expanding analysis on data from other tokamaks (DIII-D, KSTAR, TCV)

Disruption Event Characterization And Forecasting (DECAF) code is structured to ease parallel development

- **Physical event modules**
  - Present grouping follows work of deVries [P.C. de Vries et al., Nucl. Fusion 51, 053018 (2011)]
  - BUT, easily appended or altered

- **Warning algorithms**
  - Present approach follows [S.P. Gerhardt et al., Nucl. Fusion 53, 063021 (2013)]
  - More flexible: arbitrary number of tests, thresholds, and user-defined levels and warning points

RWM and tearing mode stability
Several of the more than 50 planned disruption chain events are currently implemented in DECAF:

<table>
<thead>
<tr>
<th>Disruption chain event</th>
<th>Points</th>
<th>Test Criteria</th>
<th>Test Thresholds</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenwald limit</td>
<td>GWL</td>
<td>Greenwald density limit</td>
<td>[0.90, 0.95, 0.99]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td>Low density (error field)</td>
<td>LON</td>
<td>Decrease in line density (10^{14} \text{ cm}^3/\text{s}) too large</td>
<td>[-10.0, -20.0, -30.0]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Line density (10^{14} \text{ cm}^3) too low</td>
<td>[0.3, 0.2, 0.1]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td>Vertical stability control</td>
<td>VSC</td>
<td>Axis position (m)</td>
<td>[0.05, 0.075, 0.10]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axis velocity (m/s)</td>
<td>[3.93, 6.54, 9.01]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Excessive ZdZdt (m/s²)</td>
<td>[0.20, 0.41, 0.84]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td>Resistive wall mode</td>
<td>RWM</td>
<td>(B_p^{n=1}) lower component (G) too large</td>
<td>[10, 20, 30]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td>Low edge q</td>
<td>LOQ</td>
<td>Safety factor (q_s) too low</td>
<td>[3.0, 2.5, 2.0]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td>Sawtooth</td>
<td>SAW</td>
<td>Safety factor (q_{95}) too low</td>
<td>[3.0, 2.5, 2.0]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Safety factor (q_0) too low</td>
<td>[1.05, 1.00, 0.95]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td>High pressure peaking</td>
<td>PRP</td>
<td>Excessive (p_0/\langle p \rangle)</td>
<td>[3.5, 4.0, 4.5]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td>Plasma current request</td>
<td>IPR</td>
<td>(</td>
<td>I_p^{req} - I_p</td>
<td>/I_p^{req}</td>
</tr>
<tr>
<td>Wall proximity control</td>
<td>WPC</td>
<td>Inner gap (m) too small</td>
<td>[0.03, 0.02, 0.01]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outer gap (m) too small</td>
<td>[0.03, 0.02, 0.01]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper gap (m) too small</td>
<td>[0.03, 0.02, 0.01]</td>
<td>[1, 2, 3]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bottom gap (m) too small</td>
<td>[0.03, 0.02, 0.01]</td>
<td>[1, 2, 3]</td>
</tr>
</tbody>
</table>

Accomplished by reading in >50 scalar and profile measurements plus derived and modelled quantities; continued development to improve results.
DECAF uses a range of analyses, from multiple signal comparisons to more sophisticated physics models to declare events.

- Ex. DECAF analysis on single NSTX discharge
  - Example: RWM $B_p^{n=1}$ threshold 30G ($\delta B/B_0 \sim 0.67\%$)

Disruption event chain

\[
\begin{align*}
&\text{RWM} & (0.717s) \\
&\text{VSC} & (0.724s) \\
&\text{WPC} & (0.729s) \\
&\text{LON} & (0.731s) \\
&\text{IPR} & (0.736s) \\
&\text{LOQ} & (0.747s) \\
&\text{DIS} & \ldots
\end{align*}
\]
DECAF uses a range of analyses, from multiple signal comparisons to more sophisticated physics models to declare events

- Ex. DECAF analysis on single NSTX discharge
  - Example: RWM $B_p^{n=1}$ threshold 30G ($\delta B/B_0 \sim 0.67\%$)

- Tests can be combined with “warning points”
  - Ex: VSC uses $Z$, $dZ/dt$, and $ZdZ/dt$

<table>
<thead>
<tr>
<th>Vertical stability control</th>
<th>VSC</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axis position (m)</td>
<td></td>
<td>[0.05, 0.075, 0.10] [1,2,3]</td>
</tr>
<tr>
<td>Axis velocity (m/s)</td>
<td></td>
<td>[3.93, 6.54, 9.01] [1,2,3]</td>
</tr>
<tr>
<td>Excessive $ZdZdt$ (m/s$^2$)</td>
<td></td>
<td>[0.20, 0.41, 0.84] [1,2,3]</td>
</tr>
</tbody>
</table>
DECAF detects disruption chain events when applied to dedicated 45 shot NSTX RWM disruption database

- RWM $B_p^{n=1}$ threshold $30G$ ($\delta B/B_0 \sim 0.67\%$)
- 60% within $14\tau_w$ of disruption time ($\tau_w = 5$ ms)

- Identifying common chains of events can provide insight to cue avoidance systems
  - 5 (out of theoretically 56) two-event combinations followed 77% of RWM cases
    (those that occurred within $14\tau_w$ of DIS)

IPR: Plasma current request not met
RWM: RWM event warning
VSC: Vertical stability control
LOQ: Low edge q warning

(WPC: Wall proximity control, PRP: Pressure peaking)
Outline

• The Disruption Event Characterization And Forecasting (DECAF) code
  – Contains various physical event modules with warning algorithms

• A reduced kinetic model for resistive wall mode stability
  – Complex calculation reduced for speed, performs well

• Identification of rotating MHD
  – Tracks characteristics that lead to disruption: rotation bifurcation, mode lock
Goal is to forecast mode growth rate in real-time using reduced models of the full kinetic MHD stability calculation

\[(\gamma - i\omega_r)\tau_w = -\frac{\delta W_{\infty} + \delta W_K}{\delta W_b + \delta W_K}\]

\[
\delta W_K \sim \frac{1}{\langle \omega_D \rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E}
\]

• Gaussian functions used for resonances
  – Coefficients selected to reflect NSTX experience

DECAF contains modeled kinetic quantities for generation of time-evolving stability boundaries

Normalized growth rate vs. time

- Stability diagram shows trajectory of a discharge towards unstable regions

\[ C_\beta = \frac{(\beta_N - \beta_{N\text{no-wall}})}{(\beta_{N\text{with-wall}} - \beta_{N\text{no-wall}})} \]

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

Normalized growth rate vs. time

![Normalized growth rate vs. time](image)

Predicted instability statistics (45 shots)

- Instability within 100 ms of minor disruption (33%)
- Instability < 320 ms before disruption (44%)
- Stable (16%)
- (7%) False positives

Minor disruptions are not false positives!


Text: Minor disruptions are not false positives!
Reduced kinetic model distinguishes between stable and unstable NSTX discharges

- 84% unstable discharges are predicted unstable
- 10/13, or 77%, of stable cases are stable in the model
- Model is successful in first incarnation - development continues to improve forecasting performance

Tradeoff: missed vs. early warnings
Outline

• The Disruption Event Characterization And Forecasting (DECAF) code
  – Contains various physical event modules with warning algorithms

• A reduced kinetic model for resistive wall mode stability
  – Complex calculation reduced for speed, performs well

• Identification of rotating MHD
  – Tracks characteristics that lead to disruption: rotation bifurcation, mode lock
Essential new step for DECAF analysis of general tokamak data: Identification of rotating MHD (e.g. NTMs)

- **Initial goals**
  - Create portable code to identify existence of rotating MHD modes
  - Track characteristics that lead to disruption
    - e.g. rotation bifurcation, mode lock

- **Approach**
  - Apply FFT analysis to determine mode frequency, bandwidth evolution
  - Determine bifurcation and mode locking

**Magnetic spectrogram of rotating MHD in NSTX**

- NSTX “stable periods” — enhanced by high elongation ($\kappa \sim 2.7$), lithium wall conditioning
- NSTX-U: rotating MHD more common (lower $\kappa \sim 2.3$, no lithium)
DECAF rotating MHD analysis identifies the state of the modes found

- Fast Fourier transforms used to find mode peak frequency within a time interval
- Presently adding phase matching and SVD algorithms to DECAF to determine mode numbers, track strongest modes
- General algorithm with ability to process multi-machine data
The characterization algorithm shows that the expected bifurcation and locking events can be automatically found.

- Algorithm written looks for a “quasi-steady state” period, a potential bifurcation, and possible mode locking.

![Graph showing frequency vs. time with mode status and DECAF mode status](image_url)

- Mode frequency
- Bifurcates
- Odd-n peak frequencies
- Lock
- NSTX shot 138854
- NSTX-U shot 204202
Example of expansion to multiple machines: DECAF now being tested on TCV tokamak data

DECAF events implemented:

- IPR (\(I_p\) not meeting request)
- GWL (Greenwald density limit)
- VSC (Vertical stability control)

TCV advantage:
Excellent real-time measurement and control capabilities

Next: radiated power, more real-time MHD signals...

\[\text{C. Galperti et al., IEEE TNS 64, 1446 (2017)}\]
Conclusions and next steps

• The DECAF code characterizes chains of events leading to disruption
  – Expanding set of modules and warnings used to analyze data sets

• A reduced kinetic model for resistive wall mode stability
  – Complex calculation reduced for speed, performs well

• Algorithm for identifying rotating MHD can find frequency, bifurcation points, locking times

• Next steps
  – Significant expansion of events and continued improvement of accuracy
  – Starting DECAF analysis on other tokamaks (DIII-D, KSTAR, TCV available)