Progress on Tokamak Disruption Event Characterization and Forecasting Research and Expansion to Real-Time Application

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A broadened disruption prediction and avoidance analysis is progressing for ITER and future tokamaks

**Motivation:** Disruption prediction/avoidance is a critical need

- **Why?** A disruption stops plasma operation, might cause device damage
- A highest priority DOE FES (Tier 1) initiative - present “grand challenge” in tokamak stability research:
  - Can be done! (JET: < 4% disruptions with carbon wall)
  - ITER disruption allowance: < 1 - 2% (energy + E&M loads); << 1% (runaways)

**Outline**

- Disruption Event Characterization and Forecasting (DECAF) approach
- Overview of DECAF results, disruption event chains, early forecasting
- Initial multiple-device, large database analysis, forecasting performance
- Physics support research: i.e. KSTAR high $\beta_N$, $\Delta’$, ~100% non-inductive CD
- Recent focus on real-time design and implementation on KSTAR
DECAF is a logical, physics-based paradigm that meets all disruption predictor requirement metrics.

Disruption predictor must:

- Predict SPECIFIC pre-disruptive phenomena → link to control
- Provide CONTINUOUS variable quantifying proximity (& can GENERATE triggers)
- Provide SUFFICIENT LEAD TIME for mitigation or avoidance
- Be EXTRAPOLABLE to new device (e.g. ITER) prior to operation
- Be REAL-TIME calculable

D. Humphreys, et al., PoP 22 (2015) 021806
DECAF follows disruption event framework (de Vries) to provide understanding of disruption chains → automates it.

JET disruption event chains

- JET disruption event chain analysis performed by hand, desire to automate
- General code DECAF: automates event chain process, provides disruption warning signals, being validated against databases from multiple devices
DECAF is structured to ease parallel development of disruption characterization, event criteria, and forecasting.

- Physical event modules encapsulate disruption chain events
- Development focused on improving these modules
- Structure eases parallel development incl. real-time
- Physical events are objects in physics modules
  - e.g. VDE, LOQ, RWM are objects in “Stability”
  - Python “objects” having attributes and methods
  - Carry metadata, event forecasting criteria, event linkages, etc.
DECAF is structured to ease parallel development of disruption characterization, event criteria, and forecasting.

- Physical event modules encapsulate disruption chain events. **Examples:**
  - GWL: Greenwald limit
  - IPB: Island power balance
  - LON: Low density
  - HLB: H-L back-transition
  - MHD: MHD
  - BIF: Bifurcation
  - LTM: Locked mode
  - VDE: Pressure peaking
  - PRP: Low q
  - LOQ: RWM and Kinetic RWM forecasting
  - RKM: Not at requested \( I_p \)
  - RWM: Wall proximity control
  - IPR: Disruption

**Tokamak databases**
- Code control workbooks
- Main data structure
- Output processing
- DECAF database

**Physical event modules**
- Density Limits
- Confinement
- Stability
- Tokamak dynamics
- Power/current handling
- Technical issues
DECAFE connected to databases from multiple machines, expanding analysis

- **Analysis**
  - Density limits
  - Ideal, kinetic, resistive MHD stability
  - Rotating MHD, etc.

<table>
<thead>
<tr>
<th>Device / Capability</th>
<th>KSTAR</th>
<th>MAST</th>
<th>NSTX</th>
<th>DIII-D</th>
<th>AUG, TCV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full database access (required!)</strong></td>
<td>Yes (MDSplus)</td>
<td>Yes (UDA)</td>
<td>Yes (MDSplus)</td>
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<tr>
<td><strong>Database analysis</strong></td>
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<tr>
<td><strong>Equilibrium analysis</strong></td>
<td>Magnetic, Kinetic + MSE</td>
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<td><strong>Stability</strong></td>
<td>Ideal, Resistive Kinetic MHD</td>
<td>Ideal (so far)</td>
<td>Ideal, kinetic MHD (resistive)</td>
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<tr>
<td><strong>shot*seconds (for kinetic analysis)</strong></td>
<td>~ 3,880 (2016-2018)</td>
<td>2,667 (est) (M5 - M9 runs)</td>
<td>2,000 / year (est)</td>
<td></td>
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</tr>
</tbody>
</table>

- Now, full access interface to AUG database; expanding to others
- 100 shot LTM disruption database by V. Klevarova analyzed for AUG
DECAF now connected to databases from multiple machines, expanding analysis

- **Analysis**
  - Density limits
  - Ideal, kinetic, resistive MHD stability
  - Rotating MHD, etc.

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- Now, full access interface to AUG database; expanding to others
- 100 shot LTM disruption database by V. Klevarova analyzed for AUG

AUG (100 shot LTM database)

Equation: $y = 1.0004x + 0.003$

$R^2 = 1$

- Presently ~50 TB stored
DECAF MHD events utilize history of 15 criteria to define time evolving disruption warning level.

DECAF automated MHD objects:
- MHD-n1
- MHD-n2
- MHD-n3
- BIF-n1
- BIF-n2
- LTM-n1
- LTM-n2

"quasi-steady state (O)"

DECAF “heat map” (for MHD):
- Locked mode > 25G
- Core plasma rotation < 6 kHz
- Decreasing plasma rotation
- High amplitude
  - f below bifurcation
- Very low f mode

Key notables of MHD warning:
- "Safe"/"unsafe" MHD periods found
- Early, slow warning level evolution
  - Locked mode amplitude important, but warning comes in very late
- Mode frequency below bifurcation, decreasing plasma rotation key
DECAF provides an **early disruption forecast** - on **transport timescales** – giving potential for disruption avoidance.

- **DECAF event chain**

  - MHD-n1: (0.490s)
  - BIF-n1: (+.005s)
  - LTM-n1: (+.045s)
  - PRP: (+.068s)
  - IPR: (+.073s)
  - WPC: (+.073s)
  - DIS: (+.077s)
  - VDE: (+.080s)

- **DECAF event chain reveals physics**
  - Rotating MHD slows, bifurcates, and locks
  - Then, plasma has an H-L back-transition (pressure peaking warning PRP) before DIS
  - **Important**: Early warning occurs in apparently SAFE region of operating space!

- **NSTX**

- **Disruption forecast level**

- **Safe**
Example: DECAF shows plasma parameters of VDE event can occur far from those of DIS event

- Largest portion of detected VDE events appear at \((l_i, \kappa)\) with very small portion of DIS events detected.
DECAF MHD events also produce early disruption warnings for KSTAR

**DECAF automated MHD objects**

- **MHD-n1**
- **MHD-n2**

**DECAF “heat map” (for MHD)**

- Plasma rotation profile and dynamics
- Decreasing $\beta_N$
- High amplitude mode
- Very low frequency mode

- **Warning level**
- **Safe**

- **Mode locking at reduced plasma rotation**
- **Key notables of MHD warning**
- “Safe”/“unsafe” MHD periods
- Early disruption warning (300 ms) ➔ on transport timescale
New “reduced” locked tearing mode event being created, aimed for real-time use / comparison

- Using pickup coils and partial saddle loops
- Compare to full FFT approach
- Warning level criteria
  - Pickup coil amplitude > 5 T/s
  - Low zero-crossing measured frequency < 5 kHz
  - High mode identified saddle loops amplitude > 20 G
New DECAF edge localized mode event created to start examining correlations to other MHD

- **DECAF ELM event**
  - Presently determines ELM triggering times, along with frequency and relative amplitude

- **Near-term-goals**
  - Determine greater understanding between ELM triggering and more deleterious MHD excitation

- **Compatible with real-time use**
A density limit model has been examined in DECAF based on power balance in an island

- Local island power balance limit
  - Power balance in island between Ohmic heating and radiated power loss
  - If radiated power at the island exceeds the input power ($P_{\text{loss}} > P_{\text{input}}$), island grows

**Power density balance:**

$$n_e n_D L_D(T_e) + \sum n_e n_Z L_Z(T_e) < \eta j^2$$

![Diagram showing power balance in an island](image)

Initial assessment of density limit model shows correlation with MHD events

Magnetic spectrogram (toroidal array)

- Greenwald limit
  - Near 0.9 when mode starts (range 0.75 – 1.05)
- Rad. island power balance
  - Near 1.0 when mode starts (range 0.60 – 1.50) → next step: reduce range
Limited event chain analysis of large databases evolves initial performance of disruption prediction

- First test on large, general database
- Analysis with only 5 DECAF events tested for 10,094 discharges with disruptions (NSTX)
  - Events used: VDE, GWL, LOQ, IPR, DIS
- Performance (Model 3)
  - 91.2% true positives (warning occurs)
  - 8.7% false negatives (no warning)
    - Somewhat high number of false negatives expected: only 5 DECAF events are used in this large database analysis
- In 5,909 shots, vertical instability is part of the disruption chain

DECAF Disruption Forecasting Performance Evolution

ITER need

5 events
~10^4 shots*s
(general database)

~10 events, ~10^2 shots*s
(earlier forecasting)

~10 events, ~10^2 shots*s
(initial event validation)

Model tested

greater realism
DECAF is fueled by coordinated research that continues to validate/develop physics models, e.g.:

- **Resistive MHD**
  - Detection / forecasting: available magnetic diagnostics, plasma rotation
  - Forecasting: starting examination of MRE ➔ start with $\Delta'$ evaluation

- **Density limits**
  - Detection: rad. power, global empirical limit
  - Forecasting: starting examination of rad. island power balance model

- **Global MHD**
  - Detection: available magnetic diagnostics, plasma rotation, equilibrium
  - Forecasting: Kinetic MHD model has high success in NSTX, DIII-D

- **Physics analysis / experiments to build DECAF models**
  - Interpretive and “predict-first” TRANSP analysis of KSTAR long-pulse, high beta plasmas with high non-inductive fraction
Classical tearing stability index, $\Delta'$, computed at $q = 2$ surface using outer layer solutions

- At higher $q_{95}$, $\Delta'$ is mostly positive predicting unstable classical tearing mode
  - Indicates neoclassical effects, additional physics needed to reproduce XP
  - **KEY POINT:** Conclusions regarding $\Delta'$ evolution can be made!
    - Recent paper with MRE evaluation ➔ Y.S. Park, et al., NF 60 (2020) 056007

*A.H. Glasser PoP (2016)*
A database of high-non-inductive fraction plasmas is important for disruption forecasting; NICF ~ 75% in KSTAR

- TRANSP analysis of experimental plasmas
- Non-inductive fraction
  - Beam-driven
  - Bootstrap
- Non-inductive fraction is key for stable high beta steady state operation
“Predict-first” KSTAR TRANSP analysis shows expected high performance plasmas at > 80% NICF

Predicted high non-inductive current fraction (NICF) current profiles

- High non-inductive current fraction predicted for 6.5, 7.5, 8.5 MW NBI
- The $\beta_N$ ranges from 3.0 – 3.5; based on KSTAR plasmas with NICF ~70%
- Aim to generate a significant database of long pulse, high NICF plasmas in 2020-2021 KSTAR runs for disruption prediction studies
Machine learning approaches are now coupling to DECAF to compute sub-elements of computations.

**Determination of ideal MHD no-wall stability limit by DL NN**

(2019 Marseille conference)

![Contour plot showing probability distribution predicted by neural network](image)

**Determination of ideal MHD stability function by non-linear random forest regression**

(2019 IAEA ML conference)

![Scatter plot showing linear correspondence with some spread](image)

**Figure 1:** $\beta_n$ vs $l_i$ decision boundary. The contour plot shows the probability distribution predicted by the neural network.


FES/ACSR Advancing Fusion with Machine Learning - Research Needs Workshop (May 2019)
Disruption prediction and avoidance research on KSTAR moving to real-time application

1. Disruption forecasting physics analysis expansion

2. Implementation of real-time diagnostic capabilities

3. Real-time implementation of DECAFS analysis and sensor input
   - Plasma control system (PCS) code specifications written for 10 DECAFS events – process continues

4. Real-time control leveraging real-time DECAFS analysis and sensors
   - Initial specification for model-based control in the PCS is written; interfaces to DECAFS events being made

Next slides
KSTAR DPA grant research “fills in” the desired real-time (r/t) diagnostic capability for r/t DECAF

- Real-time measurement of rotating / locking MHD
  - < 300 kHz; Data collected during Jan/Feb 2020 run

- Real-time and offline Motional Stark Effect - IN FINAL DESIGN
  - “offline” MSE background polychromometer system, \( Z_{\text{eff}} \) profile
  - Real-time implementation of MSE; includes \( \delta B \) profile measurement

- Real-time plasma rotation profile – 1\textsuperscript{st} system shipped to NFRI
  - Completely new for KSTAR: 8 channels; 1 – 2 kHz time resolution

- Real-time electron temperature profile – IN PROCUREMENT
  - Implement real-time acquisition of heterodyne radiometer system

- Real-time \( T_e \) fluctuation profile – IN PROCUREMENT
  - Implement real-time acquisition to 2-D ECE imaging system
Overall setup for KSTAR real-time diagnostic integration and DECAF analysis for the PCS

- **KSTAR Test Cell / ECE Screen Room**
  - A-to-D (192 ch)
  - Expansion box connected to main ECEI r/t computer

- **Main Diagnostics Room**
  - r/t ECEI and r/t DECAF development computer
  - r/t ECEI computer (includes Te(R) calibrations 73 ch)
  - r/t V φ computer (includes profile calibration 8 ch)
  - r/t MSE computer (includes profile calibration 25 ch)

- **Optical isolation (Dolphin)**

- **PCS Room**
  - r/t ECEI and r/t DECAF development computer
  - r/t MHD computer

- **All software development under GIT version control**
Disruption prediction and avoidance research on KSTAR moving to real-time application

- Real-time MHD analysis computer installed at NFRI
- Designed for connection to plasma control system (PCS)
- Interface to MHD probes built

Real-time magnetic probe data acquired
(14 toroidal probes: \( n = 1 \) rotating field applied)

Offline DECAF analysis of real-time signals

DECAF spectrogram

DECAF mode decomposition

\[ \text{time (s)} \]

\[ \text{frequency (kHz)} \]

\[ \text{0.05 kHz} \]

\[ \text{0.10 kHz} \]

\[ \text{0.20 kHz} \]
KSTAR real-time MHD computer acquired data for 2019 campaign – data quality as good as offline

**Offline data, native code analysis**

**Real-time data, DECAF analysis (offline)**

![Spectrogram](image)

DECAF object decomposition

Frequency (kHz)

Amplitude (G)

Offline data, native code analysis

Real-time data, DECAF analysis (offline)
Analysis of KSTAR real-time MHD computer data compared to simulated FPGA* r/t analysis (I)

DECAF analysis using various inputs

- From simulated FPGA FFTs
- From offline FFTs

- $\Delta t = 3.06$ ms, $\Delta f = 0.31$ kHz (offline analysis set to match FPGA)

*FPGA: field-programmable gate array
DECAF object decomposition of r/t MHD computer data works well on simulated FPGA analysis

DECAF object decomposition

From simulated FPGA FFTs

From offline FFTs
New real-time velocity diagnostic for KSTAR expands design of NSTX-U system (operated in 2016)

- NSTX-U: demonstrated RT analysis for $v_\phi$, $T_i$ (for $T_i > 150$ eV)
  - 4 radial channels, active + backgrd, 5 kHz

- KSTAR: plan for 8 radial channels, ~1kHz sampling rate
  - Assess requirements in FY20 to optimize design & analysis software
  - Re-locate NSTX-U system, interface w/ KSTAR

- Status / plan
  - NSTX-U system shipped to KSTAR (arrival this Wed July 22\textsuperscript{nd} evening)
  - Use data from initial system for final design of new KSTAR system
  - Install new KSTAR system 2021

M. Podesta (PPPL)
Expanding DECAF approach provides a new paradigm for disruption avoidance research

- Multi-device, integrated approach to disruption prediction and avoidance that meets disruption predictor requirement metrics
  - Physics-based “event chain” yields key understanding of evolution toward disruptions needed for confident extrapolation of forecasting, control
  - Present performance on large ($10^4$) databases: 91.2% w/ only 5 Events
  - Full multi-machine databases used (full databases needed!)
  - Innovative use of machine learning started (event analysis, pred. models)
  - Physics analysis, experiments run to understand, create, validate models

- DECAF producing early warning disruption forecasts
  - On transport timescales: guide disruption avoidance by profile control

- Continuing development
  - Improve DECAF forecasting performance run on large database analysis
  - Continue / expand disruption forecasting performance analysis (ITER)
  - Implement DECAF disruption forecasting models in real-time (KSTAR)
Supporting slides follow
Simple island rotation dynamics model presently being constructed to forecast the bifurcation point

- Start with cylindrical, rigid body model
- Possible model of drag for both a “slip” and a “no slip” condition:

\[ T_{mode} = \frac{k_2 \Omega}{1 + k_3 \Omega^2} \]

R. Fitzpatrick et al., Nucl. Fusion 33 (1993) 1049

- At very low angular speed mode reaches a stable steady state, investigating this in KSTAR
- Collaborating with UW Madison theoreticians to add explicit effect of island size on viscosity, toroidal effects, etc.

\[
\frac{d(I\Omega)}{dt} = T_{aux} - \frac{k_2 \Omega}{1 + k_3 \Omega^2} - \frac{(I\Omega)}{\tau_{2D}}
\]
Predictive TRANSP analysis shows KSTAR design target $\beta_N \sim 5$ can be approached with $f_{NI} \sim 100\%$

- “Predict-first” analysis used to design high-$\beta$, 100% non-inductive current fraction (NICF) experiments for present KSTAR run campaign

- $B_T = 1.5T$
- $\beta_N / l \leq 6$
- $\beta_N / l^i = 5$
- $B_T = 1.7T$
- $B_T = 2.0T$

- Up to 75% NICF already reached in similar plasmas
- NBI $\geq 6.5$ MW in 2018
- By altering $I_P$ and $B_T$ values, $\beta_N > 4$, up to KSTAR design target 5 can be achieved with 100% NICF

See J-H Ahn CO6.00005
DECAF reduced kinetic MHD model provides early forecast of instability boundary to global MHD modes.

Preferences and characteristics:
- Favorable characteristics:
  - Stability contours change for each time point
  - Model allows real-time stability and mode growth rate prediction

Predicted instability statistics:
- 84% of shots are predicted unstable (stringent evaluation)
- 44% predicted unstable < 320 ms (approx. 60\(\tau_w\)) before current quench
- 33% predicted unstable within 100 ms of a minor disruption

DECAF analysis of large databases further supports published results that disruptivity doesn’t increase with $\beta_N$.

- **DECAF analysis of DIS event**
  - Shots analyzed at 10 ms intervals

- **Analysis during $I_p$ flat-top**
  - MAST: 8,902 plasmas analyzed
  - NSTX: 10,432 plasmas analyzed
  - KSTAR: 1,309 plasmas analyzed
Initial analysis of large databases further supports published result that disruptivity doesn’t increase with plasma $\beta$.

- **DECAF analysis of DIS event**
- Similar to a “standard” disruptivity analysis
- Shots analyzed at 10 ms intervals

- **Analysis during $I_p$ flat-top**
  - MAST: 8,902 plasmas analyzed
  - NSTX: 10,432 plasmas analyzed
  - KSTAR: 1,309 plasmas analyzed
Global MHD modes can also be “slow” and allow early warnings for disruptions, potentially allowing avoidance.

- Global MHD (RWM) can also be “slow”
  - Rotating MHD warning level decreases after 0.46s ➔ DANGEROUS for RWM onset!
  - H – L back transition (PRP) drags out time to disruption (> 100 ms – transport timescale)

DECAF event chain

NSTX

DECAF rotating MHD warning level

Safe
New 2nd NBI system installed in KSTAR, may be available for 2020 run campaign

- Geometry of 2nd NBI system is included in TRANSP model
- Available power
  \[ P_{NBI} \approx 1.5 \text{MW/source} \] (conservative)
Clear pressure profile distinction between Internal Transport Barrier and H-mode phases

- ITB phase
  - Safety factor
  - \( t = 2.5\text{s} \)

- H-mode phase
  - Safety factor
  - \( t = 4.8\text{s} \)

- Broad pedestal pressure reconstructed in H-mode is not observed in earlier ITB phase

\[ \Delta \text{data} - \text{fitted} \]

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<th>( t = 4.8\text{s} )</th>
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<td>R (m)</td>
<td>1.8, 1.9, 2.0, 2.1, 2.2, 2.3</td>
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\[ \text{Total Pressure} \]

\[ \text{Total Pressure} \]

\[ \Delta \text{data} - \text{fitted} \]

\[ \beta_n \]

\[ W_{\text{MHD}} \]

\[ t = 2.5\text{s} \]

\[ t = 4.8\text{s} \]

\[ \text{Xp by Jinil Chung} \]