Disruptions in the High-$\beta$ Spherical Torus NSTX

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Disruptions Are a Critical Issue for the Tokamak/ST Line of Fusion Systems

• Phases and consequences:
  – Thermal quench can lead to excessive PFC thermal loading.
  – Current quench can lead to large eddy current forces/moments on in-vessel structures or the chamber itself.
  – Combined, the thermal and current quench phases can lead to the generation of potentially damaging runaway electron beams.
  – If vertical motion of the plasma column occurs, then large halo current loading of in-vessel structures can result.

• Strategies to address this problem include development of…
  – operations regimes and control techniques to avoid disruptions,
  – recovery techniques when the plasma has become unstable,
  – disruption detection, and rapid discharge shut-down methods once a disruption is deemed imminent,
  – improved understanding of disruption effects.
Outline

Talk Addresses Three Aspects of Disruptions

- Neutron Emission
- $\delta B_{P,n=1}$
- $I_{HC}$

Graphical data showing trends in $I_P$, $\beta_N$, $q^*$, and neutron emission over time.
 Outline
Talk Addresses Three Aspects of Disruptions

1: Conditions with minimal disruptivity
Determine desirable operating points for next step STs.

Neutron Emission

$\delta B_{P,n=1}$

$I_{HC}$

$[\text{MA}]$

$[G, 10^{13} \text{ s}^{-1}]$

$[\text{kA}]$

$[\text{time [s]}]$
Outline

Talk Addresses Three Aspects of Disruptions

1: Conditions with minimal disruptivity

Determine desirable operating points for next step STs.

2: Disruption detection

Improve the basis for triggering mitigation systems.
Outline
Talk Addresses Three Aspects of Disruptions

1: Conditions with minimal disruptivity
Determine desirable operating points for next step STs.

2: Disruption detection
Improve the basis for triggering mitigation systems.

3: Disruption halo currents.
Better understand the dynamics of, and mechanical loading from, these currents.
1: Conditions with minimal disruptivity
Global Kink Stability: Strong Shaping, Broad Profiles, and Rotation are Key For Avoiding Disruptions in NSTX

Definition of Disruptivity:
Select a Portion of Operating Space For Analysis
Disruptivity = # of Disruptions / Discharge Time

Sample all NSTX H-mode discharges since 2007, every 33.3 ms, for these studies

\[ q^* = \varepsilon \pi a B_r \left(1 + \kappa^2 \right) / \mu_0 I_p \]
Global Kink Stability: Strong Shaping, Broad Profiles, and Rotation are Key For Avoiding Disruptions in NSTX

\[ q^* = \varepsilon \pi a B_T \left(1 + \kappa^2\right) / \mu_0 I_P \]

\[ S = q_{95} I_P / a B_T \propto \varepsilon \left(1 + \kappa^2\right) f(\kappa, \delta, \varepsilon, ...) \]
Global Kink Stability: Strong Shaping, Broad Profiles, and Rotation are Key For Avoiding Disruptions in NSTX
Global Kink Stability: Strong Shaping, Broad Profiles, and Rotation are Key For Avoiding Disruptions in NSTX

Relationship between stability and rotation at high-$\beta_N$ can non-monotonic:

• due to resonances in the kinetic RWM stabilization effects.

See Berkery, et al., EX/P8-07
When Global Stability Limits are Avoided, Rotating Core n=1 Modes Often Limit Performance

• Mode onset at $t \approx 800$ msec.
  – Locks at $t \approx 860$ ms, followed by disruption
• Initial rotation is with the $q=2$ surface.
  – First the core rotation is damped
  – Then the total rotation is reduced.
• Analysis of soft X-ray data shows a coupled eigenfunction:
  – $m/n=1/1$ core kink
  – $m/n=2/1$ magnetic island
• Similar, but not identical, to “long-lived mode” on MAST.
Maintaining Elevated $q_{\text{min}}$ Helps Avoid Core $n=1$ Kink/Tearing Modes

**Experiment**

Database of 139 H-mode discharges
MSE constrained reconstructions

68 discharges with no observable trigger
$q_{\text{min}}$ at onset typically $<1.25$

71 discharges with ELM or EPM trigger
$q_{\text{min}}$ up to 1.5 at onset

**Theory**

Linear Growth Rate vs. $q_0$
Representative NSTX H-Mode Equilibria for Triggerless Onset Mode
(from M3D-C1, Breslau NF 2011)
Maintaining Elevated $q_{\text{min}}$ Helps Avoid Core n=1 Kink/ Tearing Modes

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**Summary (1)**

Disruptions are best avoided in NSTX when

- Plasma is strongly shaped
- $q^*$ maintained above ~2.7
- Pressure and current profiles are broad.
- Rotation is maintained
- $q_{\text{min}}$ is kept elevated

These conditions do not eliminate need for active control, but rather provide situations when control is likely to be most successful.
Talk Addresses Three Aspects of Disruptions

1: Conditions with minimal disruptivity
- Strong shaping, broad profiles,
- Sustained rotation, and elevated $q_{\text{min}}$

2: Disruption detection

3: Disruption halo currents.
- Dominant structure of the halo current is a single toroidally localized lobe,
- Which can make up to 8 toroidal revolutions.

2: Disruption detection
Warning Times Defined With Respect to the Current Quench

**False Positive:**
Warning more than 300 ms in advance of current quench.

**Late Warning:**
Warning later than 10 ms before the current quench.

\[ \frac{R_{ITER}}{R_{NSTX}} \cdot 10\, ms = 72\, ms \]
Instability Detection

- n=1 perturbation inferred from array of 24 in-vessel poloidal field sensors
  - Useful for detecting resistive wall modes, locked modes

Model Comparison

- Often a significant drop in neutron emission proceeding a disruption.
- Estimate the neutron emission from a simple slowing down model.
  - $T_e$, $Z_{eff}$, $n_e$ are inputs.
Single Threshold Tests Form a Basis For Disruption Prediction

Instability Detection

• n=1 perturbation inferred from array of 24 in-vessel poloidal field sensors
  • Useful for detecting resistive wall modes, locked modes

Examined Many Threshold-Based Disruption Indicators

• MHD Equilibrium and Stability
  – Vertical motion indicators
  – n=1 perturbed fields
  – $F_P = p_0/\langle p \rangle$, $l_i$, $q_{95}$, $q^*$
  – Boundary-wall gaps

• Transport indicators for comparisons to simple models
  – Neutron rate
  – Stored energy
  – Loop voltage

• Other
  – Line-average density transients
  – Rotation and rotation shear
  – Radiated power / Input Power
  – Deviations of $I_P$ from request
Developed a Method to Combine These Tests For Improved Prediction

- No one of these diagnostic tests could serve as a stand alone disruption indicator.
  - Must combine the tests in some fashion.
- Common way to combine data is to use neural nets.
  - Here explore an alternative system.
- Algorithm summary:
  - Take a series of ~15 threshold tests like those previously described.
  - For each test, assign a number of “points” for various thresholds, for instance:
    - 1 point if the n=1 amplitude exceeds 10 G,
    - 2 points for 15 G
    - 3 points for 20 G
  - Evaluate tests at each time-slice, then sum the points from threshold tests to form an “aggregate” point total.
  - Declare a disruption warning if the aggregate total exceeds a chosen value.
  - May not yet be optimized.
Compound Threshold Tests Can Predict Most Disruptions.

Warning Level: 5 Points

~2100 Discharges

Tuned To Minimize Late Warnings
<1% late warning
~15% false positive
Compound Threshold Tests Can Predict Most Disruptions.

Warning Level: 5 Points
Warning Level: 8 points
≈2100 Discharges

Tuned To Minimize Late Warnings
<1% late warning
≈15% false positive

Tuned To Minimize Late Warnings + False Positives
≈2% late warning
≈4% false positive

(False positive count dominated by near-disruptive MHD events)
Compound Threshold Tests Can Predict Most Disruptions.

The vast majority of NSTX disruptions have detectable precursors. Both raw diagnostic data and comparisons to simple models can contribute to prediction. A simple combination of disruption tests can produce high-fidelity prediction.

Tuned To Minimize Late Warnings
<1% late warning
~15% false positive

Tuned To Minimize Late Warnings + False Positives
~2% late warning
~4% false positive
(False positive count dominated by near-disruptive MHD events)

Summary (2)
Talk Addresses Three Aspects of Disruptions

1: Conditions with minimal disruptivity
- Strong shaping, broad profiles, sustained rotation, and elevated $q_{min}$ are key to avoiding disruptions.

2: Disruption detection
- Simple combination of signal checks can predict most disruptions.

3: Disruption halo currents.

3: Disruption halo currents.
Talk Addresses Three Aspects of Disruptions

Halo currents:
- When vertical position control is lost, the plasma can come in contact with the divertor or first wall.
- Currents then flow between the plasma and the vessel, PFCs, or divertor structures, leading to mechanical loading of structures.

Currents can be toroidally asymmetric:
- When toroidally localized, forces are concentrated.
- Those asymmetries can rotate toroidally, potentially in mechanical resonance with in-vessel structures.

3: Disruption halo currents.
Strongly Non-Axisymmetric Halo Currents Detected in the NSTX Lower Divertor

- Measurements from an array of instrumented tiles
  - Same poloidal angle
  - Distributed toroidally
- Infer strong toroidal asymmetry, often with significant rotation, at locations where currents enter the divertor floor.
Dominant Structure of the Halo Current is a Rotating Toroidally Localized Lobe of Current

max($J_{HC}$) min($J_{HC}$)
Dominant Structure of the Halo Current is a Rotating Toroidally Localized Lobe of Current

\[ f(t, \phi) = f_0 + f_1 \cos^2(\frac{f_4}{2} (\phi - f_2 - f_3 t)/2) \]

Fits applied during small time windows of width 0.1 ms
Dominant Structure of the Halo Current is a Rotating Toroidally Localized Lobe of Current

\[ f(t, \phi) = f_0 + f_1 \cos^2 f_4 \left( \phi - f_2 - f_3 t \right) / 2 \]
Halo Currents Become Symmeterized In the Final Phase of the Disruption

- Tendency is seen to some extent for virtually all halo current occurrences
- Utilize a regularized filament model for the reconstruction.
  - Find currents in a grid of toroidal filaments that provides best fit to magnetics measurements.
  - Includes vessel eddy currents.
  - Does not satisfy $\nabla p = J \times B$
- Period of late halo current axisymmetry corresponds to near or complete loss of closed surface geometry
Halo Currents Become Symmeterized In the Final Phase of the Disruption
# of Rotations is Observed to Scale Inversely with Halo Current Magnitude

- Compute the rotation dynamics during time when the halo current is >25% of its maximum.
- Compare to the time average of the maximum halo current magnitude.
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Summary (3)
- Dominant halo current pattern is a toroidally localized lobe of current.
- Up to 8 toroidal revolutions have been observed.
- # of revolutions scales inversely with halo current magnitude.
Summary

• Recipe for minimal disruptions includes strong shaping, broad profiles, maintained rotation, and sufficiently elevated $q_{\text{min}}$.
  – Sustaining these optimal scenario characteristics is a critical topic for NSTX-Upgrade research. [Menard FTP/3-4]

• Disruptions in NSTX are generally detectable, and a simple means of combining single threshold tests can predict most disruptions.
  – Encouraging for the detectability and mitigatability of disruptions in next-step ST devices.

• The dominant halo current pattern is a toroidally localized lobe, which has been observed to make up to 8 toroidal transits.
  – Lower loading in cases with many revolutions may, if confirmed in additional devices, alleviate the problem of HC rotation to some extent.
Halo Current Patterns Can Be Highly Variable in Space and Time

Large Halo Currents: max(I_{HC}) \sim 300 \text{ kA},
Little Rotation

Reduced Currents: max(I_{HC} \sim 150 \text{ kA}),
Seemingly Erratic Rotation

Observations

- Structure best described as a single lobe of current.
- Rotation, when it occurs, is typically in the counter-direction, except for short bursts.
Monitoring of $n=1$ and $n=0$ Perturbations Provides Foundation for Disruption Warning

- $n=1$ perturbation inferred from array of 24 in-vessel poloidal field sensors
  - Useful for detecting resistive wall modes, locked modes

- Estimate $\frac{dZ_P}{dt}$ from two toroidal loops on outboard side of plasma, above and below midplane.
  - $Z_P$ from fluxes
  - $dZ_P/dt$ from voltages

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<th>% Late Warning</th>
<th>% False Positive</th>
<th>% No Trigger</th>
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<td>1</td>
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<td>0.2</td>
<td>15</td>
<td>4</td>
<td>3</td>
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B_p>5.00 G  
B_p>10.0 G  
2525 discharges

Z_p*dZ_p/dt>0.05  
Z_p*dZ_p/dt>0.20  
3556 discharges
Comparison of Diagnostic Signal to Simple Models Can Provide Useful Indicators

- Often a significant drop in neutron emission proceeding a disruption.
- Estimate the neutron emission from a simple slowing down model.
  - $T_e$, $Z_{\text{eff}}$, $n_e$ are inputs.

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<tr>
<td>0.4</td>
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- Often an increase in loop voltage proceeding the disruption. Process:
  - Estimate $T_e$ from ITER-98 scaling and measured $n_e$, $B_T$, $I_p$, $P_{\text{inj}}$, ...
  - Use these to calculate expected bootstrap and beam driven currents.
  - Use these to calculate inductive current and then loop voltage.

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</tr>
<tr>
<td>9</td>
<td>5</td>
<td>2</td>
<td>37</td>
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\[ S_N, \text{Meas./Model}<0.70 \]
\[ S_N, \text{Meas./Model}<0.50 \]
3366 discharges

\[ V_{\text{loop}}, \text{Meas./Model}<4.00 \]
\[ V_{\text{loop}}, \text{Meas./Model}<9.00 \]
3411 discharges
1D Disruptivity vs. Engineering and Equilibrium Parameters

- Figures show disruptivity (top, blue), and sample distribution (bottom, red)

**Key results**
- Rapid increase in disruptivity at higher current
- Rapid decrease in disruptivity at higher power

**Key results**
- Some decrease in disruptivity at higher $\beta_N$
- Rapid decrease in disruptivity at higher $q$ or shaping
Sustained Rotation Helps to Avoid Disruptions

**Absolute Frequency**

- $F_{T,\text{core}}$ vs. Disruptivity [s$^{-1}$] (Core)
- $F_{T,\text{mid-radius}}$ vs. Disruptivity [s$^{-1}$] (Mid-Radius, near $q=2$)

**Normalized Frequency**

- $V_A = \left| B_0 \right| \sqrt{\frac{\mu_0}{2}} \bar{n}_e m_p$
- $F_A = \frac{V_A}{2\pi R_0}$

- $\log_{10}(\text{# Instances})$ for Core: 49227 samples
- $\log_{10}(\text{# Instances})$ for Mid-Radius: 49142 samples

- $\log_{10}(\text{# Instances})$ for Core: 49230 samples
- $\log_{10}(\text{# Instances})$ for Mid-Radius: 49145 samples

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NSTX-U

Small Changes in Early Gas Fuelling Have a Profound Impact on Early Disruptions

Discharge where incorrect fueling leads to the $q=3$ surface locking as soon as it enters the plasma (132847).

Fuelling was modified in 132850, resulting in longer pulse (comparison of 132847 and 132850).

Stability not from avoiding the early mode, but rather preventing it from slowing the plasma too much.
Break Disruption Rate Statistics into Four Times During the Discharge

**Total # of Shots**

Generally increased in later campaigns due to operational benefits of lithium PFC conditioning.

Drop in # of good conditions in 2009 related to need to clean up residual lithium carbide from previous run campaign.

**Disruption Rate**

**Ramp-Up:**
Disruptions before start of flat-top were always uncommon.

**Early Flat-top:**
Disruptions within 250 ms after the start of flat-top
Often coincide with MHD modes forming as rational surfaces enter the plasma locking to the wall

**Late Flat Top:**
RWMs, Locked Modes, H->L back transitions

**Ramp-Down:**
Includes deliberately ramped down cases, and instances where the solenoid current was reached and the PS software reversed the loop voltage.
Large Losses of Stored Energy and Plasma Current Commonly Proceed NSTX Disruptions

![Graph of # of Disruptions vs. W_{MHD,D} [kJ]](a)

- Bar charts showing the number of disruptions versus MHD energy release ($W_{MHD,D}$) with bins for Ramp-Up, Early Flat-Top, Late Flat-Top, and Ramp-Down.

![Graph of # of Disruptions vs. QR_{80-20} [MA/s]](b)

- Bar charts showing the number of disruptions versus QR_{80-20} with bins for Ramp-Up, Early Flat-Top, Late Flat-Top, and Ramp-Down.

![Graph of # of Disruptions vs. W_{MHD,D} / W_{MHD,MP}]](a)

- Histogram showing the number of disruptions versus the ratio of MHD energy release to MHD energy profile with bins for Ramp-Up, Early Flat-Top, Late Flat-Top, and Ramp-Down.

![Graph of # of Disruptions vs. I_{P,D} / I_{P,MP}]](b)

- Histogram showing the number of disruptions versus the ratio of plasma current to plasma current profile with bins for Ramp-Up, Early Flat-Top, Late Flat-Top.
# of Rotations is Observed to Scale Inversely with Halo Current Magnitude

- Compute the rotation dynamics during time when the halo current is >25% of its maximum.
- Compare to the time average of the maximum halo current magnitude.

Summary (3)
- Dominant halo current pattern is a toroidally localized lobe of current.
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Fits Reveal Dynamics of the Halo Currents
(Case With Steady Rotation)

**Halo Current Amplitudes**
- From instantaneous cosine power fits ($f_1$)
- From windowed fits ($f_1$: solid, $f_0$:dashed)
- $\max(J_{HC})$, $\min(J_{HC})$

**Rotation Frequency**
- From “windowed cosine power” fits
- From differentiating phase of simple $n=1$ fits:
  $I_{HC} = f_{n=1} + f_{n=1} \cos(\phi - \phi_{n=1})$

**Full Width at Half Maximum:**
- From instantaneous cosine power fits
- From windowed fits

**Peaking Factor**
- From “windowed cosine power” fits
- From raw data
Fits Reveal Dynamics of the Halo Currents (Case With Erratic Rotation)

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From instantaneous cosine power fits ($f_1$)
From windowed fits ($f_1$: solid, $f_0$:dashed)

**max($J_{HC}$)**

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**Rotation Frequency**

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$$I_{HC} = f_{n=1} + f_{n=1} \cos(\phi - \phi_{n=1})$$

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