Modifications to Ideal Stability by Kinetic Effects for Disruption Avoidance

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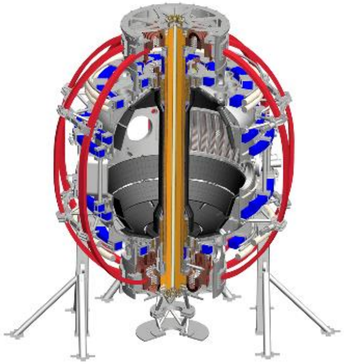


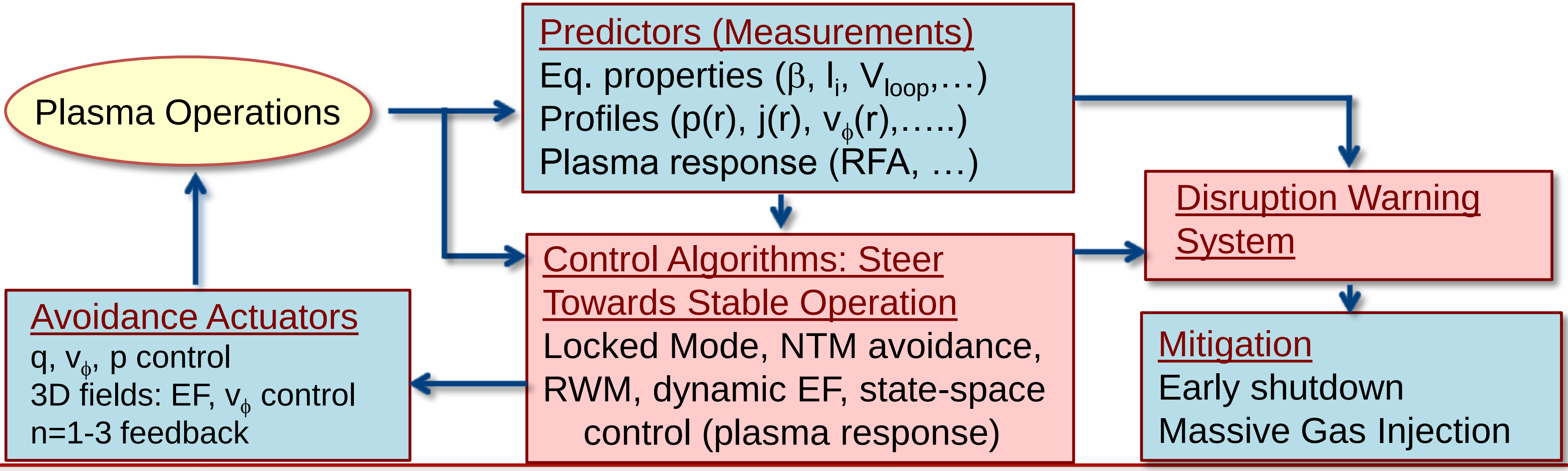
Abstract

Marginal stability points of global modes during high beta operation in NSTX can be found by computing kinetic modifications to ideal magnetohydrodynamic limits on stability. Calculations with the DCON code for nearly five thousand experimental equilibria show that the no-wall beta limit decreased with increasing aspect ratio and increasing broadness of the pressure profile, which has implications for NSTX-U. Kinetic modification to ideal limits calculations for several discharges as computed using the MISK code predict a transition from damping of the mode to growth as the time approaches the experimental time of marginal stability to the resistive wall mode. The main stabilization mechanism is through rotational resonances with the ion precession drift motion of thermal particles in the plasma, though energetic particles also contribute to stability. To determine RWM marginal stability for use in disruption avoidance, ideal stability limits need to be modified by kinetic effects in order to reproduce experimental marginal stability points. Guided by the full calculations, reduced stability models are investigated to inform automated disruption characterization and prediction analyses presently being developed using NSTX data for application to NSTX-U.

Near 100% disruption avoidance is an urgent need for ITER; NSTX-U is planning a disruption avoidance system

- 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)

- Disruption prediction by multiple means will enable avoidance via profile or mode control or mitigation by MGI



Plasma Operations

Predictors (Measurements)
Eq. properties (β, l_i, V_{loop},…)
Profiles (p(r), j(r), v_ϕ(r),…..)
Plasma response (RFA, …)

Control Algorithms: Steer Towards Stable Operation
Locked Mode, NTM avoidance, RWM, dynamic EF, state-space control (plasma response)

Avoidance Actuators
q, v_ϕ, p control
3D fields: EF, v_ϕ control
n=1-3 feedback

Disruption Warning System

Mitigation
Early shutdown
Massive Gas Injection

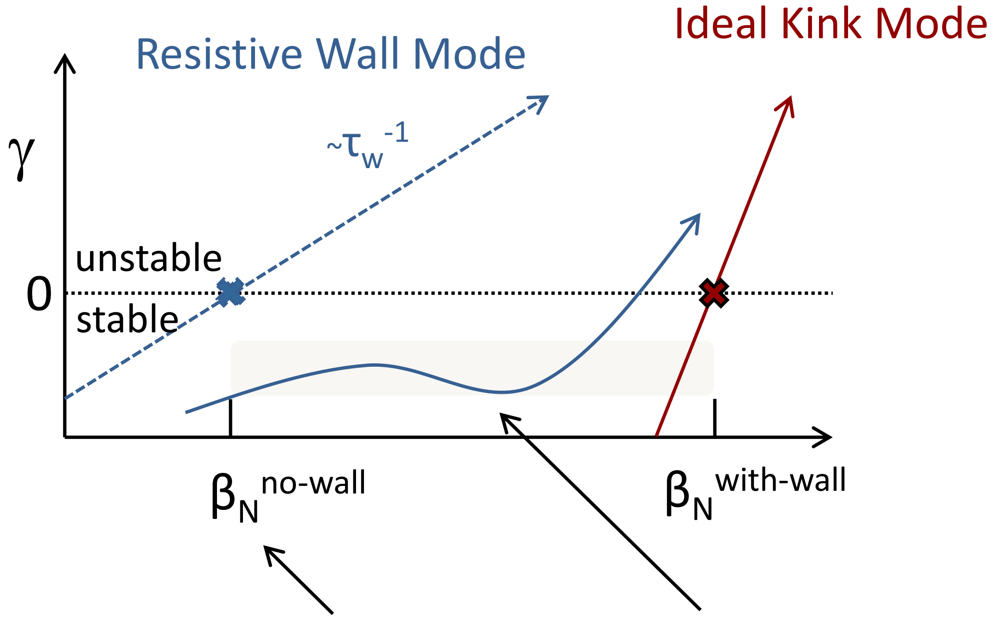
RWM dispersion relation evaluated with ideal and kinetic components allows for passive stabilization of the RWM

Resistive Wall Mode (RWM)
fluid dispersion relation:

$$\boxed{\gamma_f \tau_w = -\frac{\delta W_\infty}{\delta W_b}}$$

τ_w^{-1} is slow enough for <u>active</u> stabilization (feedback)

However, experiments operate above the no-wall limit <u>without active control</u>!



Ideal Stability

Kinetic Effects

$$\boxed{(\gamma - i\omega_r)\,\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}}$$

[B. Hu et al., Phys. Rev. Lett. 93, 105002 (2004)]

Passive stabilization

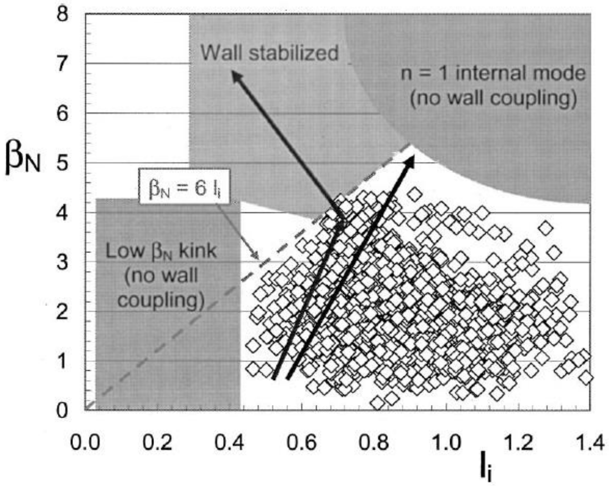
Collisional dissipation

Rotational stabilization

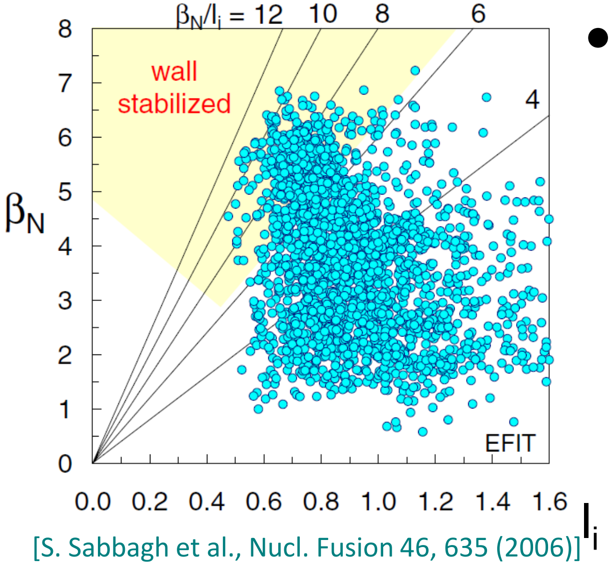
Models with scalar "critical rotation" for stability could not explain experiments

[S. Sabbagh et al., Nucl. Fusion 50, 025020 (2010)]

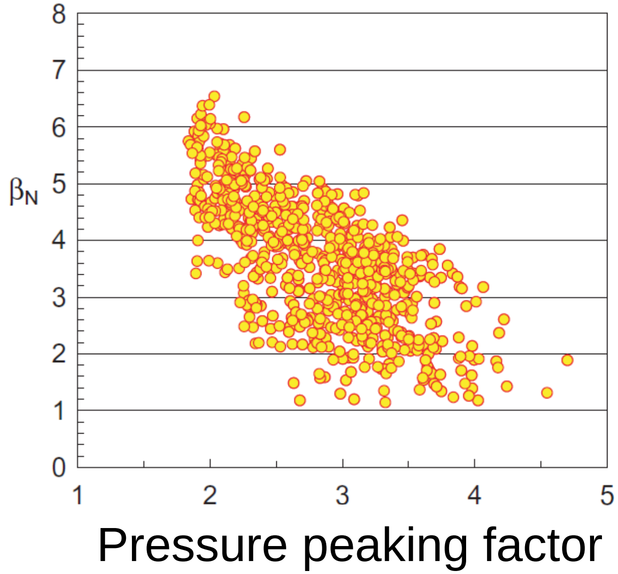
NSTX steadily progressed above the no-wall limit, adding improved active control, understanding of passive stability



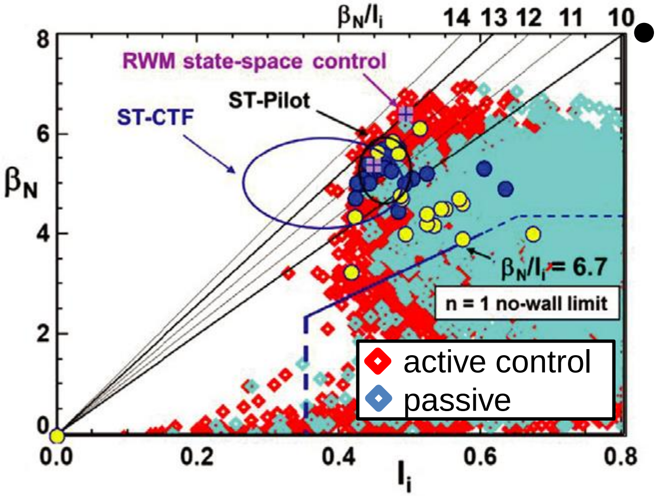
[S. Sabbagh et al., Phys. Plasmas 9, 2085 (2002)]



[S. Sabbagh et al., Nucl. Fusion 46, 635 (2006)]



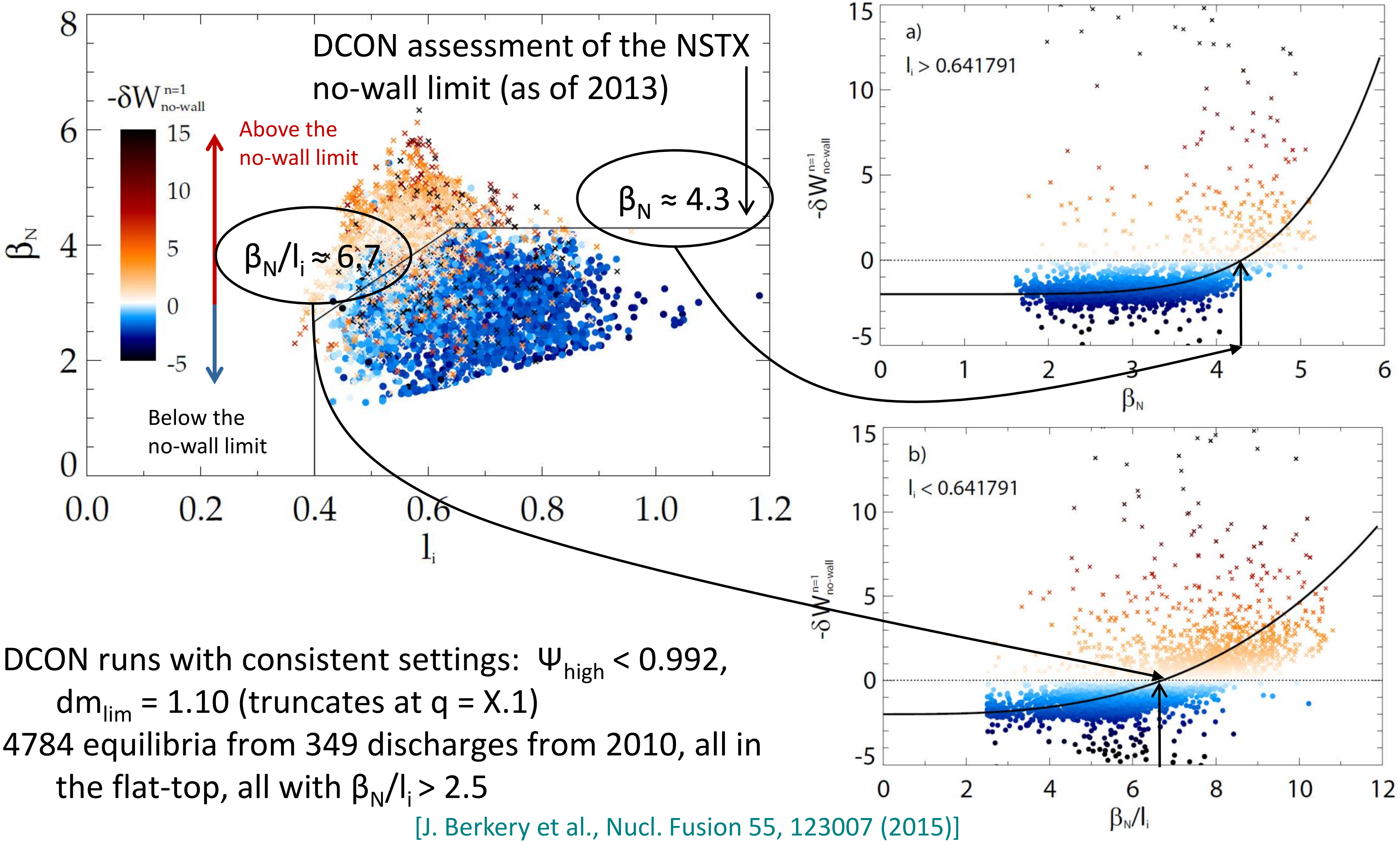
[S. Sabbagh et al., Nucl. Fusion 44, 560 (2004)]



[S. Sabbagh et al., Nucl. Fusion 53, 104007 (2013)]

- Active control
  - Dual sensor ($B_p + B_r$) proportional gain
  - State space control with model of conducting structures and plasma mode
- Passive stability
  - Kinetic effects in the RWM dispersion relation
  - Stabilizing rotational resonances between particles and mode

New, expansive DCON calculations confirm previous assessment of the NSTX ideal n=1 no-wall limit



DCON assessment of the NSTX no-wall limit (as of 2013)

Above the no-wall limit

Below the no-wall limit

$\beta_N \approx 4.3$

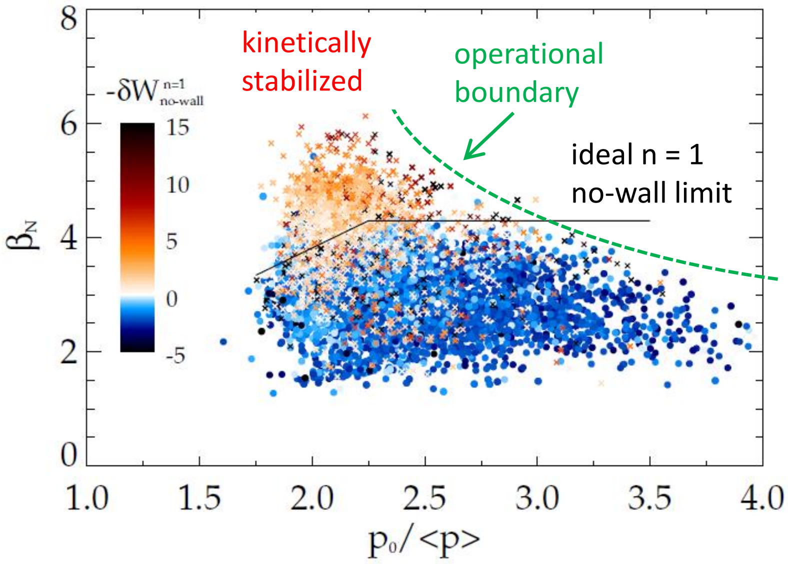
$\beta_N/l_i \approx 6.7$

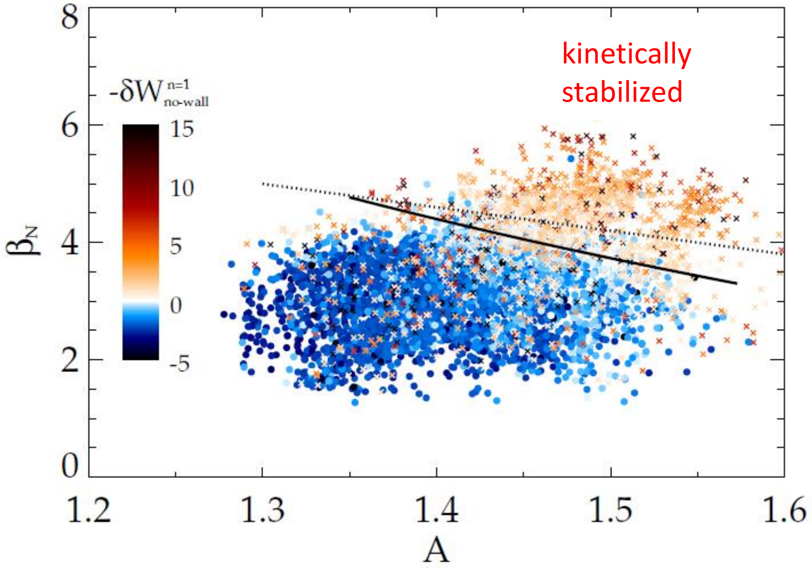
DCON runs with consistent settings: $\Psi_{high} < 0.992$, $dm_{lim} = 1.10$ (truncates at q = X.1)

4784 equilibria from 349 discharges from 2010, all in the flat-top, all with $\beta_N/l_i > 2.5$

[J. Berkery et al., Nucl. Fusion 55, 123007 (2015)]

The ideal no-wall limit is estimated through dependence on internal inductance, pressure peaking, aspect ratio





[J. Berkery et al., Nucl. Fusion 55, 123007 (2015)]

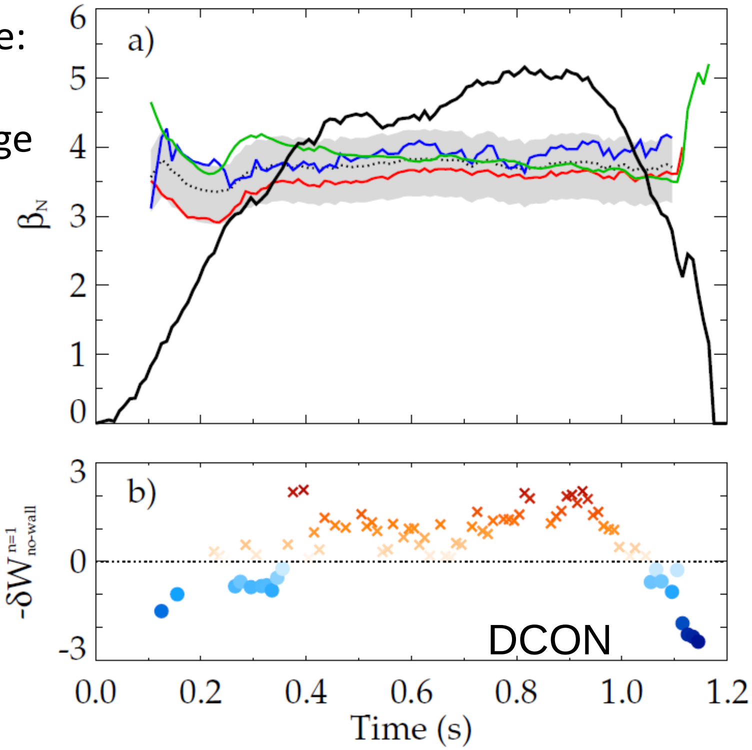
$\beta_N = 6.7 l_i$

$\beta_N = 1.9111(p_0/\langle p\rangle)$

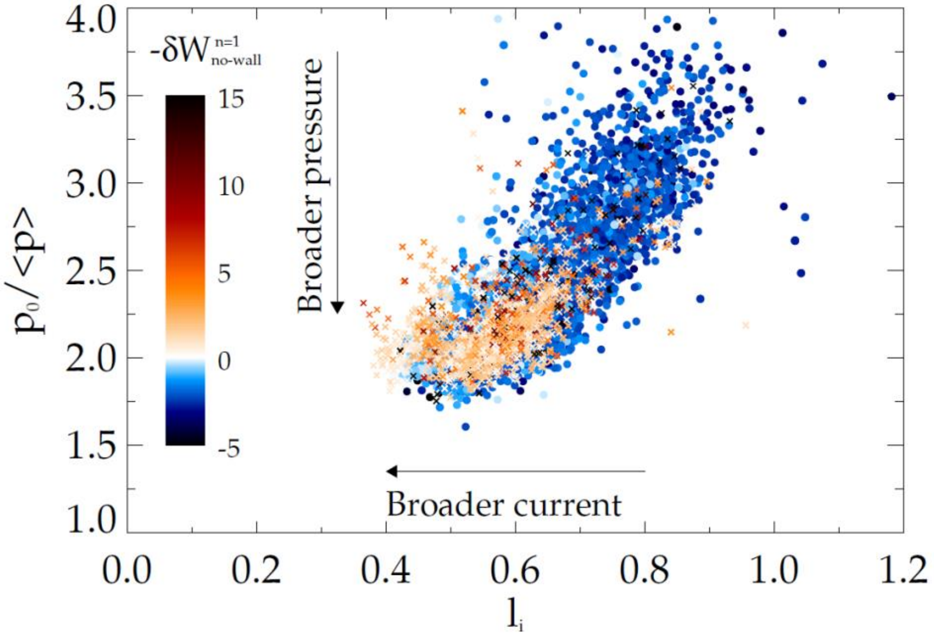
$\beta_N = 14(A^{-1}-0.4)$

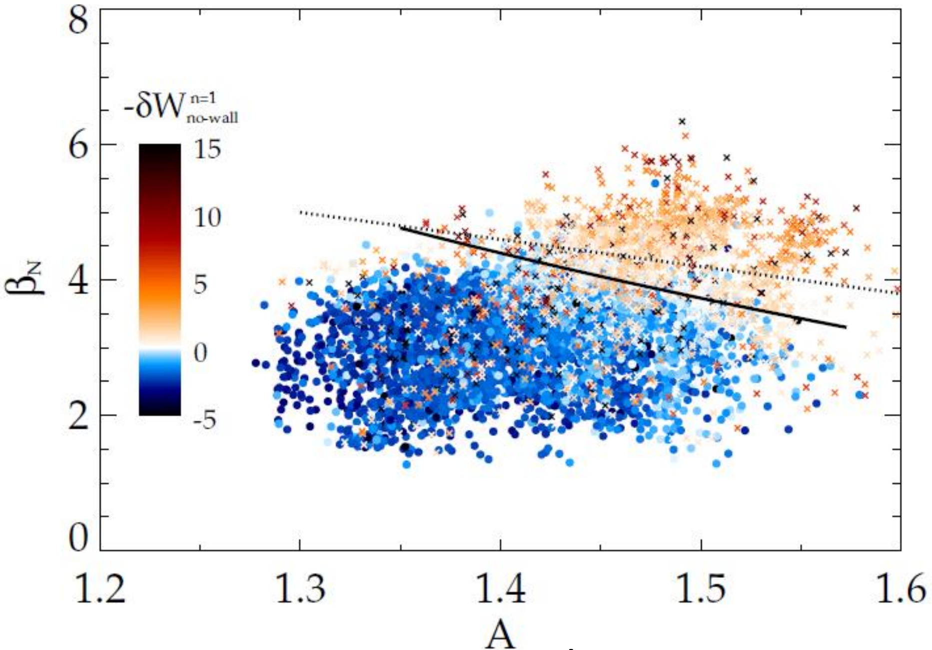
Composite estimate

Example: NSTX discharge 138556



No-wall limit dependencies on internal inductance, pressure peaking, and aspect ratio have implications for NSTX-U





<u>New neutral beams:</u>

Broader current and pressure profiles

<u>New center stack:</u>

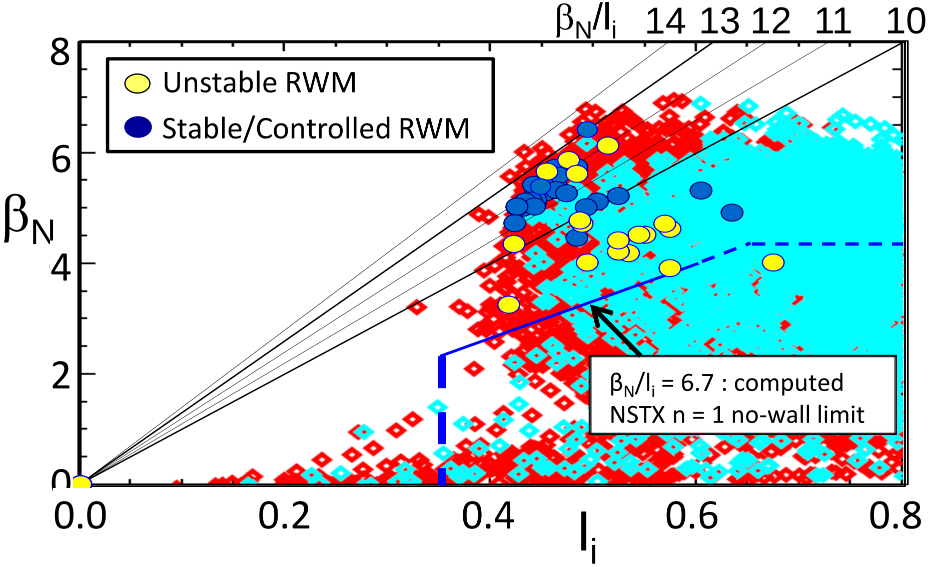
Larger aspect ratio

(NSTX-U: ~2x higher B_T, I_p, P_{NBI} and ~5x pulse length vs. NSTX)

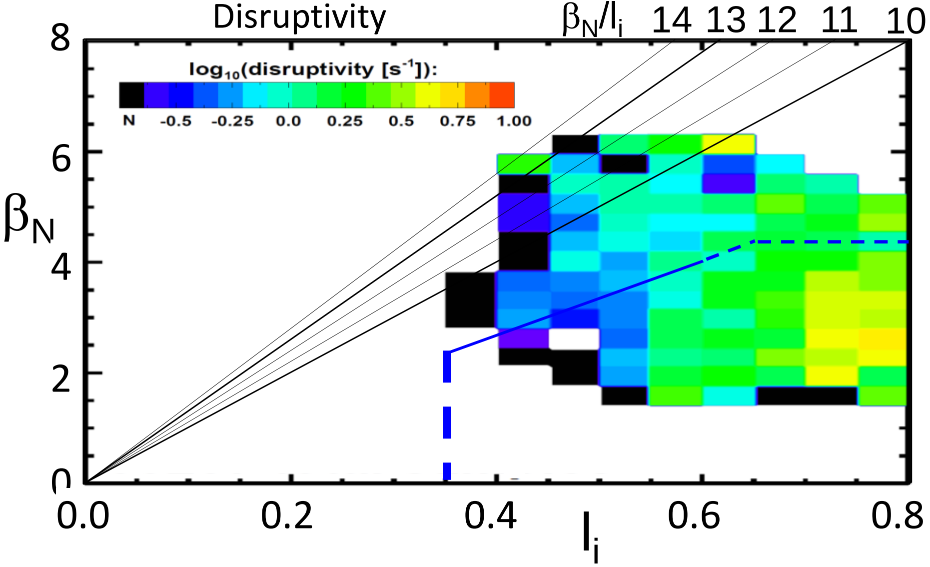
- Both new capabilities mean NSTX-U no-wall beta limit should be lower than NSTX
- <u>BUT</u> ideal stability is, of course, not the full picture! Kinetic effects must be included…

[J. Berkery et al., Nucl. Fusion 55, 123007 (2015)]

NSTX reaches high β_N, low l_i range of next-step STs and the highest β_N/l_i is not the least stable



[S. Sabbagh et al., Nucl. Fusion 53, 104007 (2013)]



[S. Gerhardt et al., Nucl. Fusion 53, 043020 (2013)]

- NSTX can reach high β, low l_i range where next-step STs aim to operate
  - High β_N for fusion performance, high non-inductive fraction for continuous operation
    - High bootstrap current fraction -> Broad current profile -> Low $l_i = \langle B_p^2 \rangle / \langle B_p \rangle_\psi^2$
  - Unfavorable for ideal stability since low l_i reduces the ideal n = 1 no-wall beta limit
- The highest β_N/l_i is not the least stable in NSTX
  - In the overall database of NSTX disruptions, disruptivity deceases as β_N/l_i increases
  - Passive stability of the resistive wall mode (RWM) must be explained

[J. Berkery et al., Phys. Plasmas 21, 056112 (2014)]

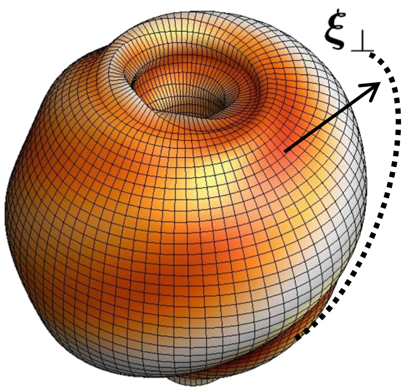
Kinetic effects arise from the perturbed pressure, are calculated in MISK from the perturbed distribution function

Force balance:

$$\boxed{\rho\frac{d\mathbf{v}}{dt} = \mathbf{j}\times\mathbf{B} - \boldsymbol{\nabla}\cdot\mathbb{P}}$$

leads to an energy balance:

$$\boxed{\underbrace{-\frac{1}{2}\int \rho\omega^2|\boldsymbol{\xi}_\perp|^2 d\mathbf{V}}_{\text{Kinetic Energy}} = \frac{1}{2}\int \boldsymbol{\xi}_\perp^* \cdot \left[\underbrace{\tilde{\mathbf{j}}\times\mathbf{B_0} + \mathbf{j_0}\times\tilde{\mathbf{B}} - \boldsymbol{\nabla}\tilde{p}_F}_{\text{Fluid terms}} - \boldsymbol{\nabla}\cdot\tilde{\mathbb{P}}_K\right] d\mathbf{V}}$$



Change in potential energy due to perturbed kinetic pressure is:

$$\boxed{\delta W_K = -\frac{1}{2}\int \boldsymbol{\xi}_\perp^* \cdot \left(\boldsymbol{\nabla}\cdot\tilde{\mathbb{P}}_K\right) d\mathbf{V}}$$

δW_K is solved in MISK by using $\tilde{f}$ from the drift kinetic equation for $\tilde{\mathbb{P}}_K$

~ Plasma Rotation

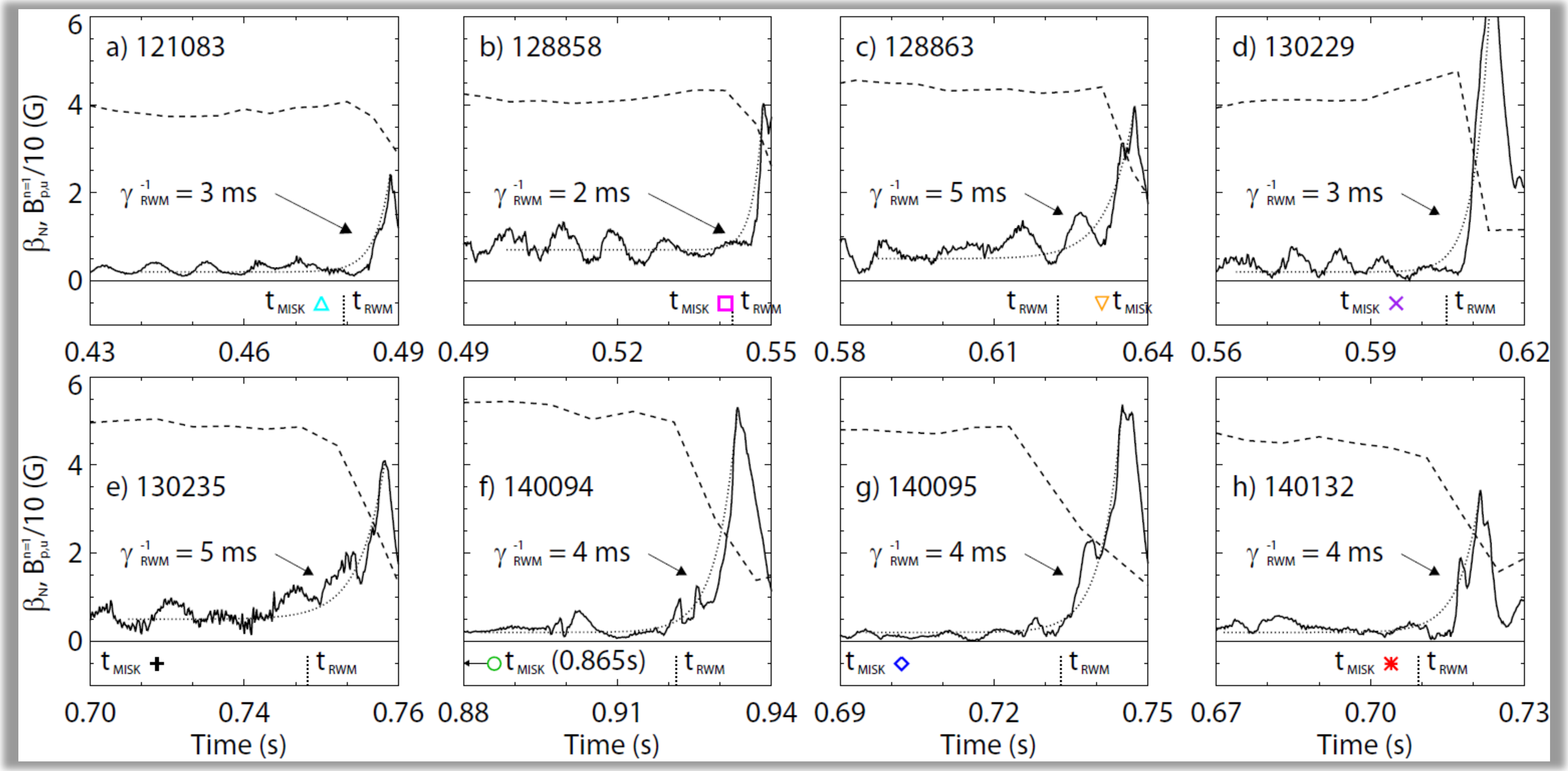
$$\boxed{\omega_E \approx \omega_\phi - \omega_{*i}}$$

Precession Drift

Collisionality

$$\boxed{\delta W_K = \sum_{l=-\infty}^{\infty} 2\sqrt{2}\pi^2 \int\!\!\int\!\!\int \left[|\langle H/\hat{\varepsilon}\rangle|^2 \frac{(\omega-\omega_E)\frac{\partial f}{\partial \hat{\varepsilon}} - \frac{n}{Ze}\frac{\partial f}{\partial \Psi}}{\langle\omega_D\rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E - \omega}\right] \frac{\hat{\tau}}{m_j^{\frac{3}{2}} B}\left|\frac{v_\parallel}{v}\right| \hat{\varepsilon}^{\frac{5}{2}} d\hat{\varepsilon}\, d(v_\parallel/v)\, d\boldsymbol{\Psi}}$$

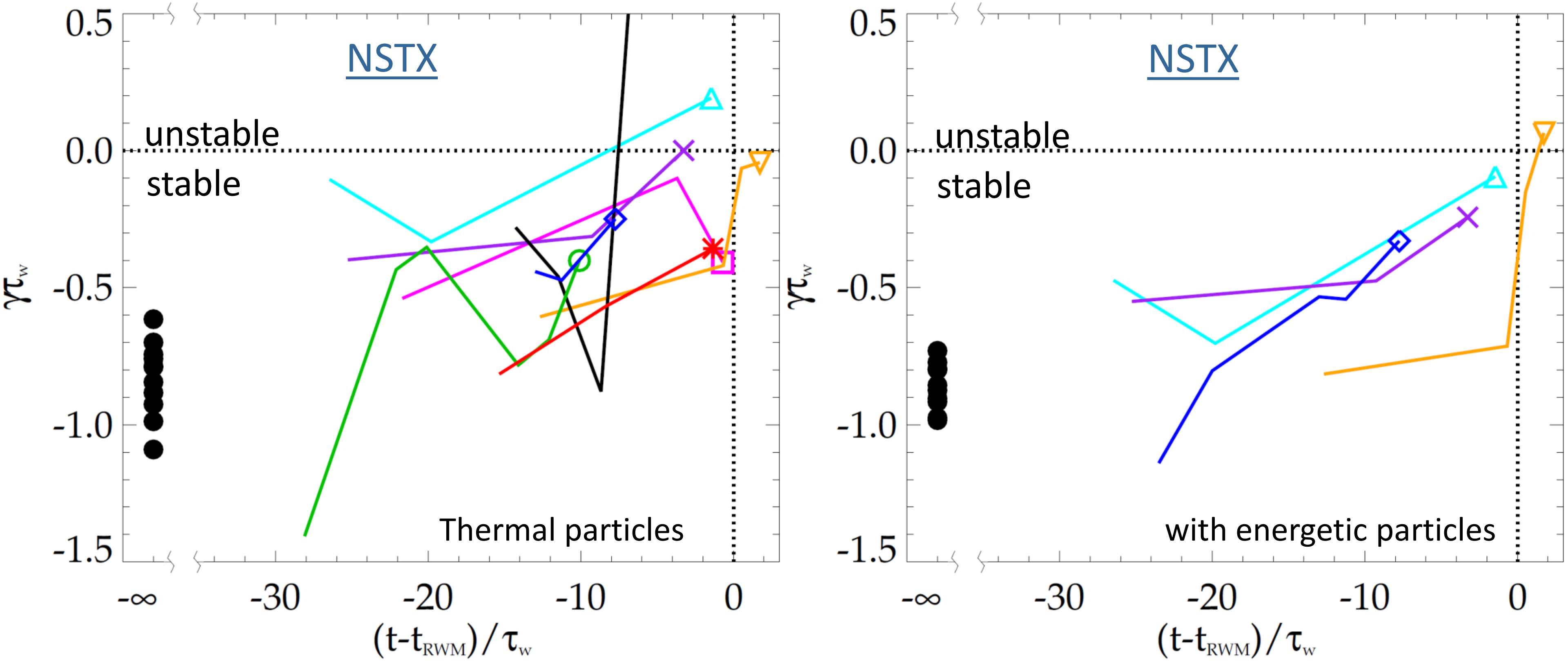
MISK calculations are grounded in validation against unstable experimental plasmas



- MISK calculations (at t_{MISK}) include kinetic effects, have been tested against many marginally stable NSTX experimental cases

[J. Berkery et al., Nucl. Fusion 55, 123007 (2015)]

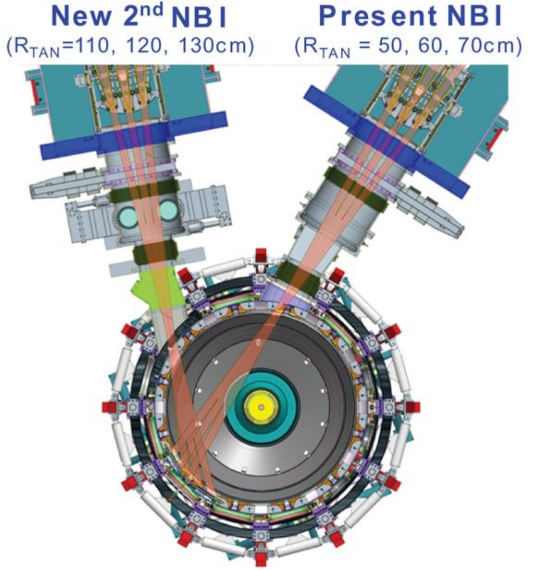
MISK calculations generally reproduce the approach towards marginal stability seen in experiments



- In each case, the calculations trend towards instability ($\gamma\tau_w = 0$) as the time approaches the time of experimental RWM instability growth
  - Twelve equilibria from discharges with no RWM show no trend and are more stable in the calculations

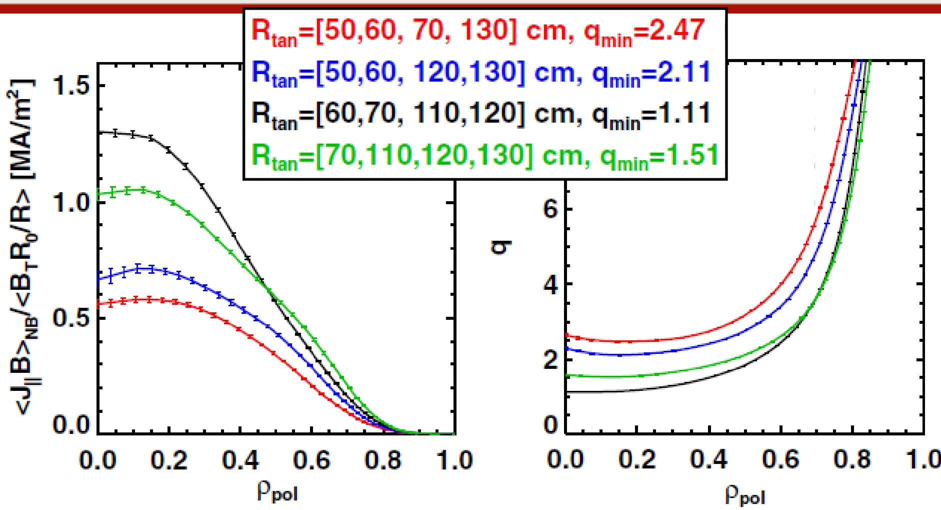
[J. Berkery et al., Nucl. Fusion 55, 123007 (2015)]

NSTX-U has new capabilities that impact stability or can be utilized for disruption avoidance

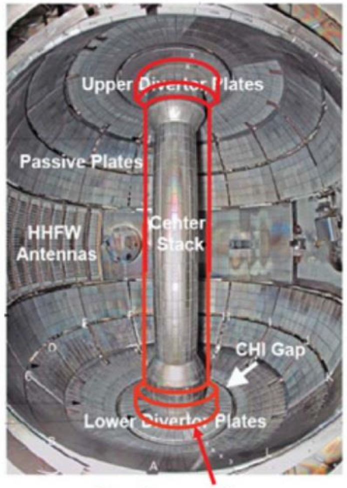


New neutral beams:

- Higher power
- Broader current and pressure profiles



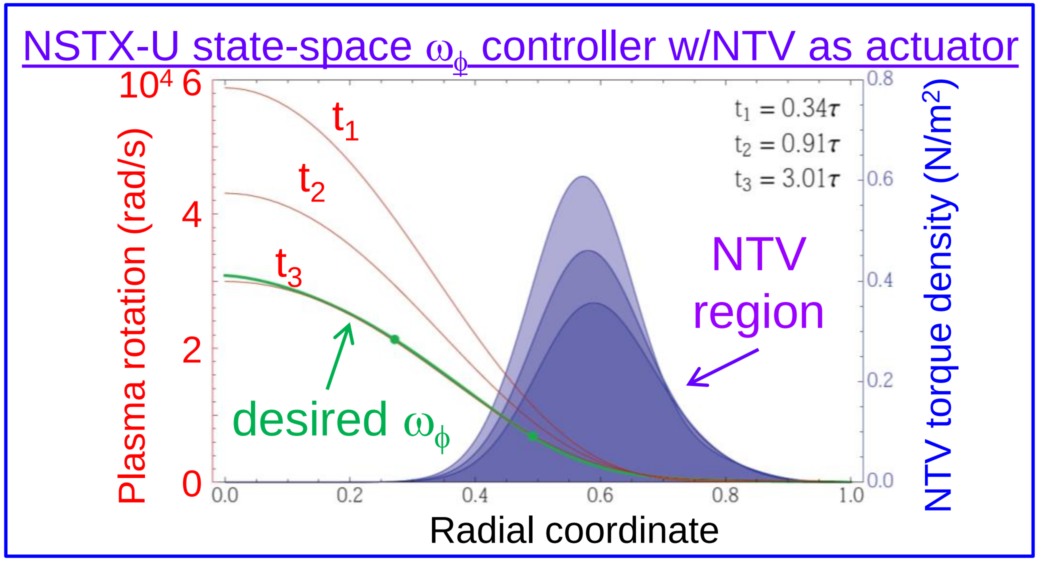
[S.P. Gerhardt *et al.*, Nucl. Fusion 52, 083020 (2012)]



Outline of new center-stack (CS)

New center stack:

- Higher current, field yields lower collisionality
- Test physics at larger aspect ratio


NSTX-U state-space ω_ϕ controller w/NTV as actuator

[S.A. Sabbagh *et al.*, IAEA FEC paper EX/1-4 (2014)]

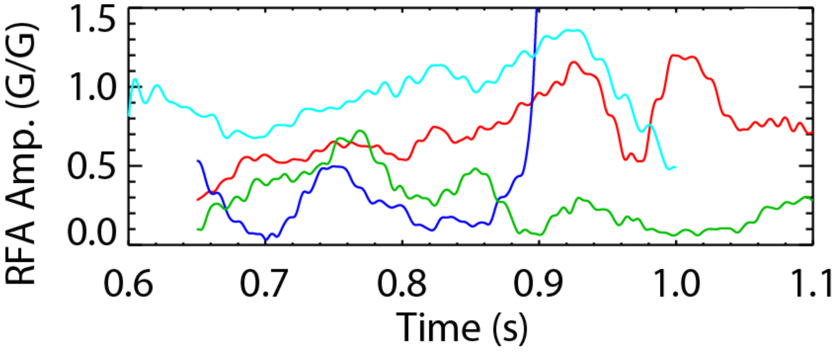
NSTX-U has evolving capabilities for disruption prediction/avoidance

Sensor/predictor (CY available)	Control/Actuator (CY available)
Low frequency MHD (n=1,2,3): 2003	Dual-component RWM sensor control (closed loop: 2008)
Low frequency MHD spectroscopy (open loop: 2005)	Control of β_N (closed loop: 2007)
r/t RWM state-space controller observer (2010)	Physics model-based RWM state-space control (2010)
Real-time rotation measurement (2016)	Plasma rotation control (NTV rotation control open loop: 2003) (+NBI closed loop ~ 2017)
Kinetic RWM stabilization initial real-time model (2016-17)	Safety factor control (closed loop ~ 2016-17)
MHD spectroscopy (real-time) (in NSTX-U 5 Year Plan)	Upgraded 3D coils (NCC) (in NSTX-U 5 Year Plan)

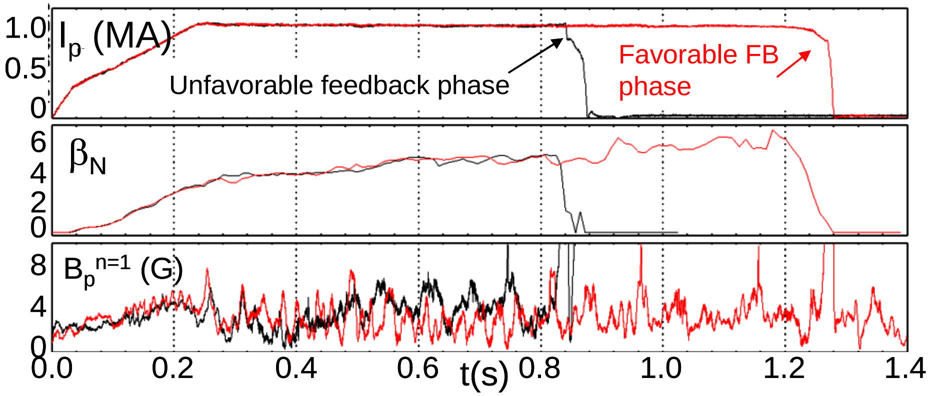
+ New Disruption Event Characterization and Forecasting code

Real-time MHD spectroscopy, active control, or kinetic physics can be used for disruption avoidance in NSTX-U

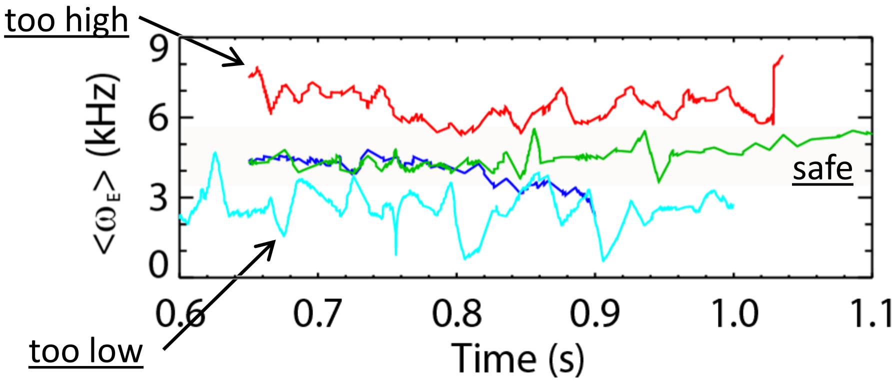
- MHD Spectroscopy
  - Use real-time MHD spectroscopy while varying ω_ϕ and β_N to predict disruptions
  - Disadvantage: plasma stability can change when kinetic profiles change, but MHD spectroscopy is limited in frequency



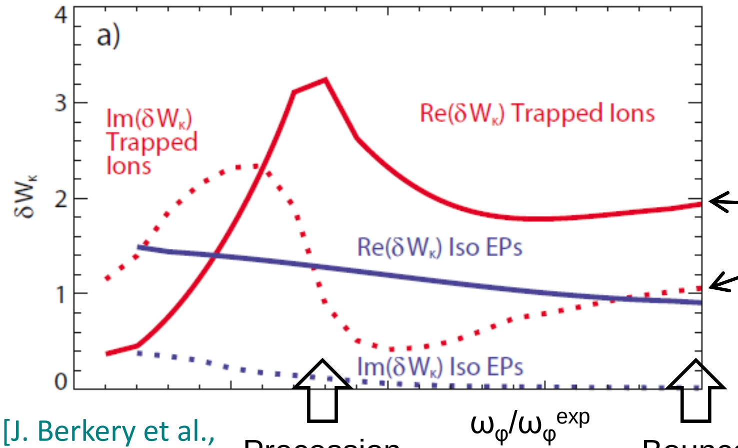
- Active Control
  - Combined Br + Bp feedback reduces n = 1 field amplitude, improves stability
  - RWM state space controller sustains low l_i, high β_N plasma



- Kinetic Physics
  - Need real-time control of plasma rotation to stay in favorable kinetic stability range
  - Evaluate simple physics criteria for global mode marginal stability in real-time ($<\omega_E>$ on resonance)



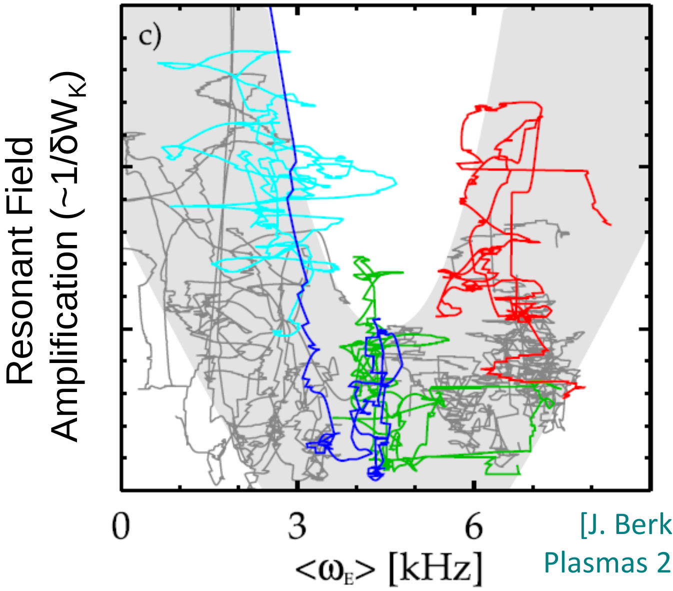
Reduced RWM kinetic stability model for disruption prediction



[J. Berkery et al., Phys. Plasmas 17, 082504 (2010)]

Precession

Bounce



[J. Berkery et al., Phys. Plasmas 21, 056112 (2014)]

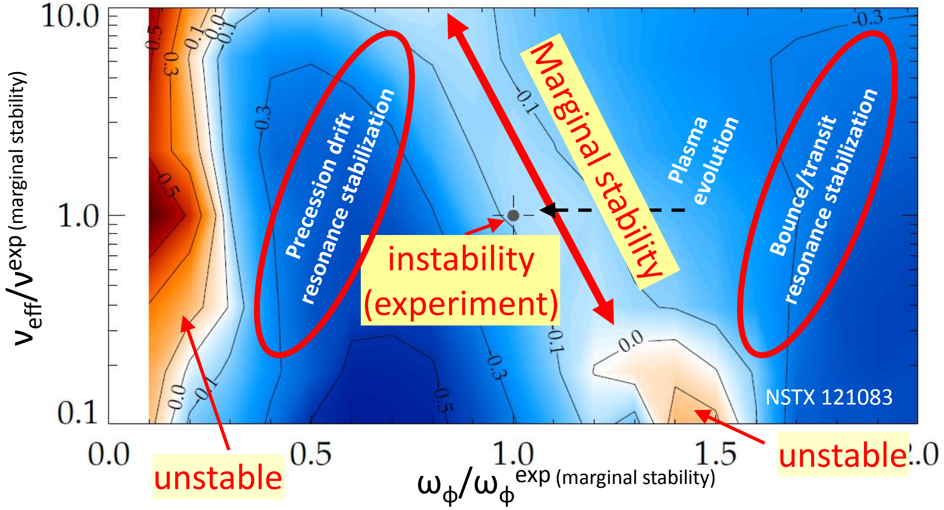
$$
\begin{aligned}
Re(\delta W_K) &= c_1 \beta_{\rm EP}/\beta_{\rm thermal} + F(\omega_\phi, \nu) \\
Im(\delta W_K) &= 0 + F(\omega_\phi, \nu)
\end{aligned}
$$

Simple expression for $\delta W_K = F(\omega_\phi)$ will approximate these curves, with simple expressions for precession and bounce frequencies… and with collisionality

[J. Berkery et al., Phys. Rev. Lett. 104, 035003 (2010)]

$\gamma\tau_w$ contours vs. ν and ω_ϕ

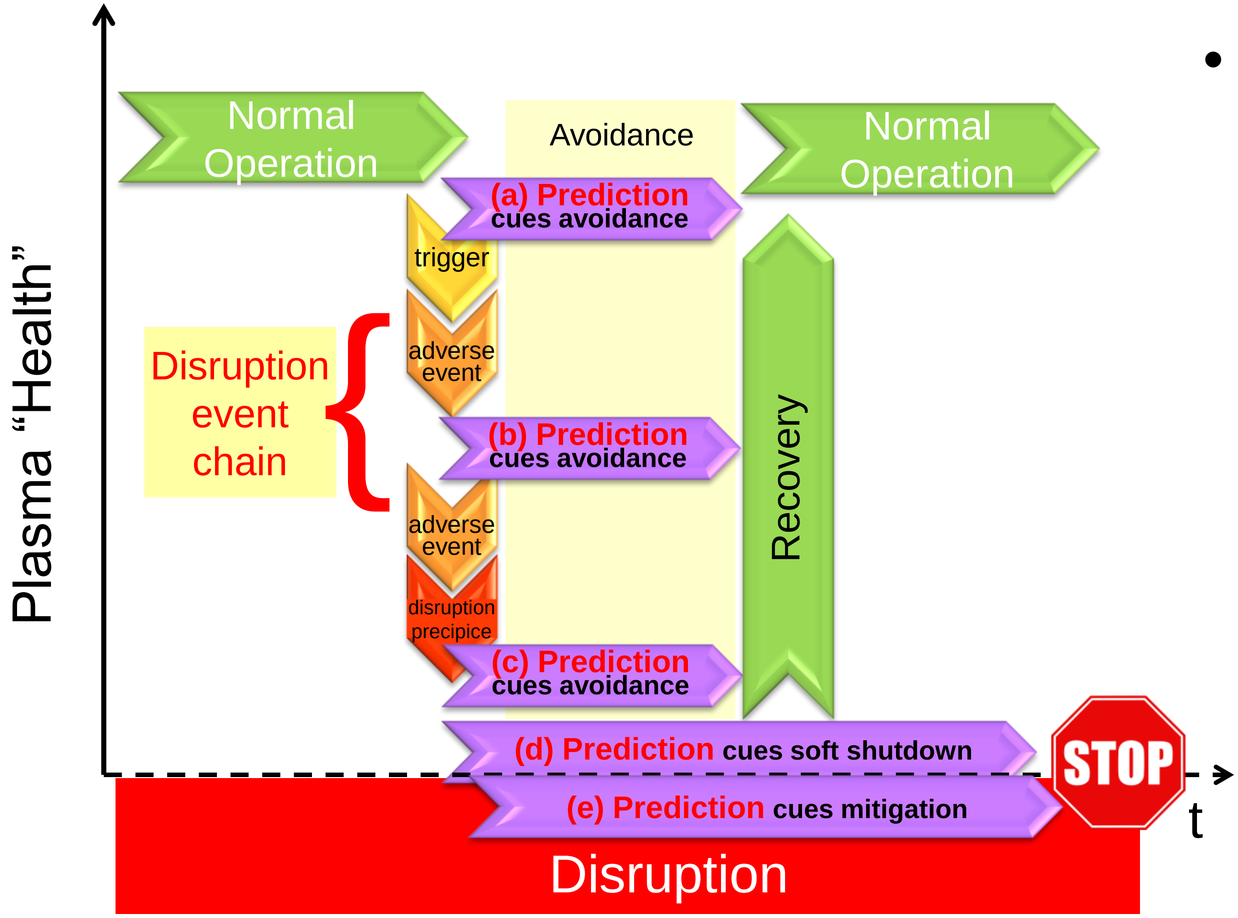
MISK code



Simplified analytical models with both rotation and collisionality dependencies have been proposed as well.

[J.W. Berkery et al., Phys. Plasmas 18, 072501 (2011)], [Y.Q. Liu et al., Phys. Plasmas 16, 056113 (2009)]

Disruption event chain characterization capability started for NSTX-U

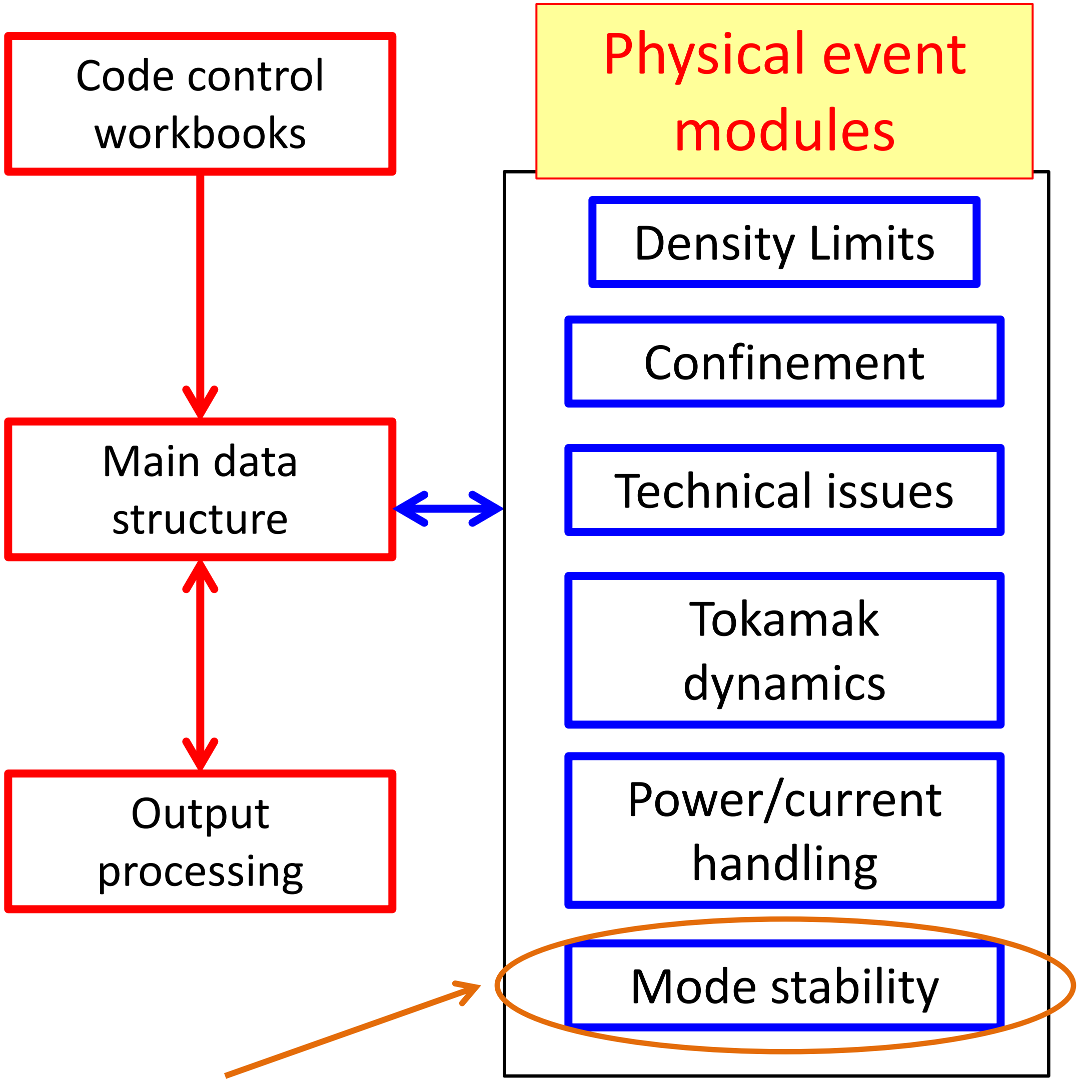


[DOE report on Transient events (2015 - in final preparation)]

- Approach to disruption prevention
  - Identify disruption event chains and elements
  - Predict events in disruption chains
    - Example: RWM marginal stability from kinetic model
    - Attack events at several places
    - Give priority to early events
  - Provide cues to avoidance system to break the chain
  - Provide cue to mitigation system if avoidance deemed untenable

Disruption Event Characterization And Forecasting (DECAF) code written to address the first step – initial test runs started using NSTX data

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



Kinetic RWM analysis will be used in DECAF as a reduced stability model

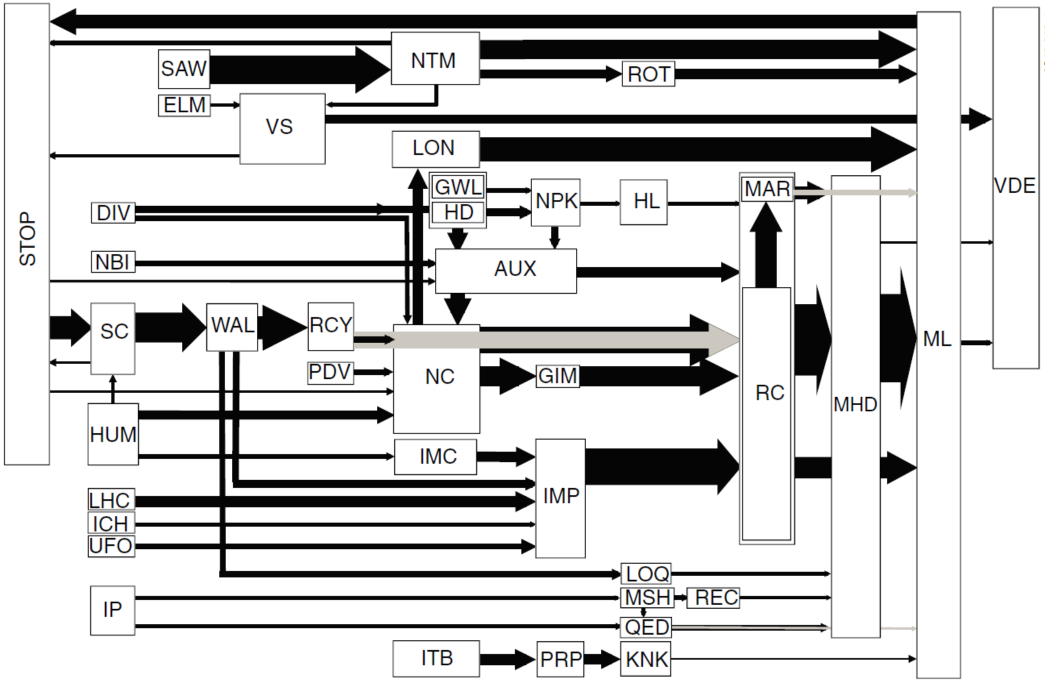
- Physical event modules separated
  - Present grouping follows work of deVries – BUT, easily appended or altered

    [P.C. de Vries et al., Nucl. Fusion 51, 053018 (2011)]
- Warning algorithm
  - Present approach follows work of Gerhardt, et al. – BUT easily appended or altered

    [S.P. Gerhardt et al., Nucl. Fusion 53, 063021 (2013)]
- General idea:
  - Build from successful foundations – BUT keep approach flexible

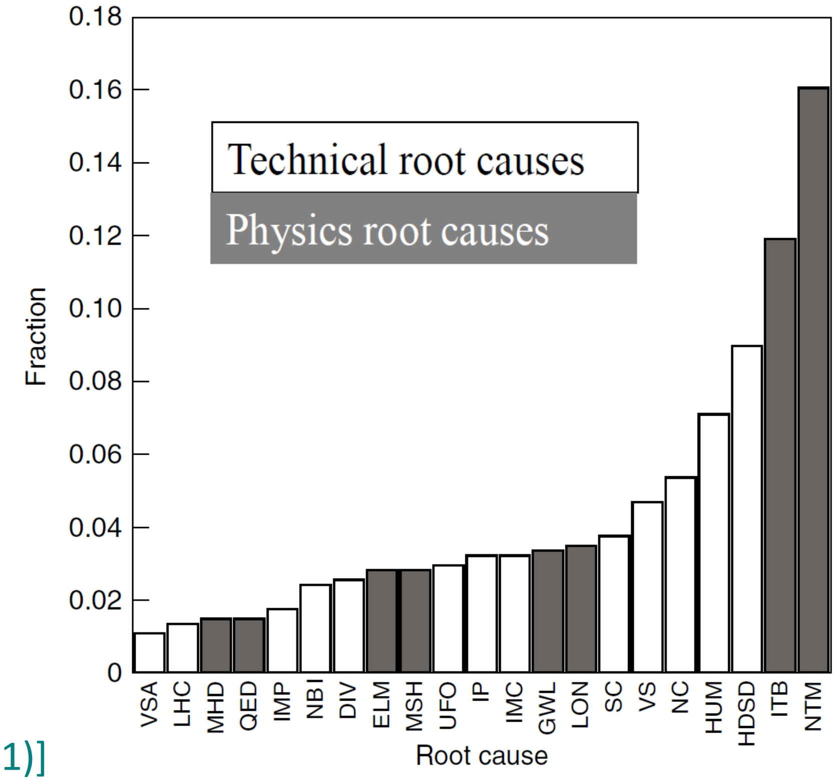
JET disruption event characterization provides framework to follow for understanding / quantifying DPAM progress

JET disruption event chains



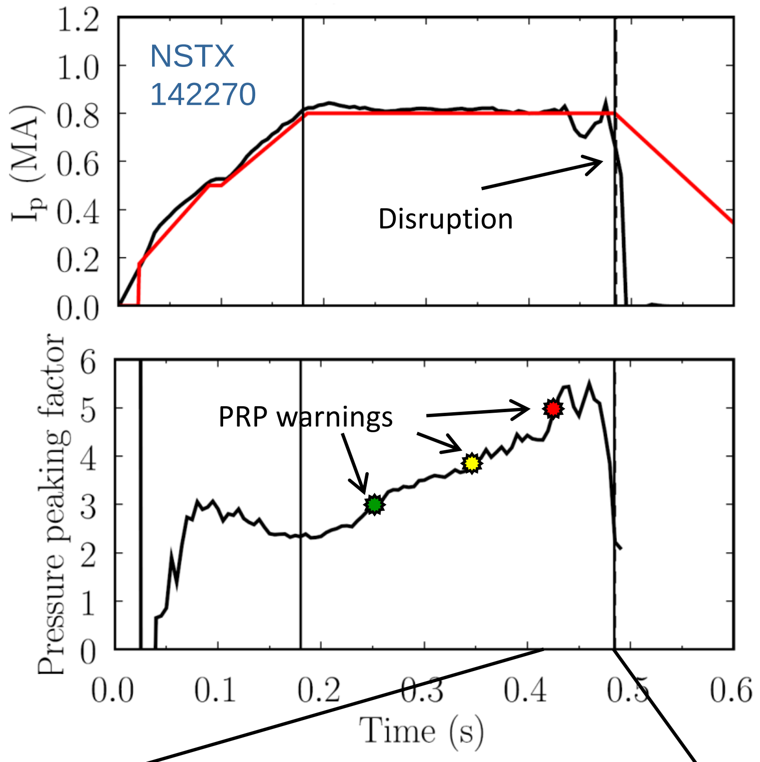
[P.C. de Vries et al., Nucl. Fusion 51, 053018 (2011)]

Related disruption event statistics



P. de Vries disruption event chain analysis for JET performed by hand – need to automate

DECAF code yielding initial results: disruption event chains, with quantitative warnings



Event chain: PRP → VDE → SCL → IPR

Detected at: 0.420s 0.440s 0.475s 0.485s

- 10 physical events are presently defined in code with quantitative warning points
  - – Easily expandable, portable to other tokamaks
- <u>This example:</u> Pressure peaking (PRP) disruption event chain identified by code
  1. (PRP) Pressure peaking warnings identified first
  2. (VDE) VDE condition subsequently found 20 ms after last PRP warning
  3. (SCL) Shape control warning issued
  4. (IPR) Plasma current request not met
- Kinetic RWM stability model will be implemented in (RWM) event

Reduction of plasma disruptivity in NSTX-U will require implementing global stability models

- Ideal stability is necessary, but not sufficient to explain stability
  - Detailed DCON calculations confirm that previous calculations of the no-wall limit for NSTX were relatively accurate

- Stabilizing kinetic resonances between plasma rotation and particle motions explain RWM stability
  - Addition of kinetic effects yields agreement with marginal point in NSTX
  - A real-time estimate of ExB frequency can determine if the plasma rotation is unfavorable and rotation control will return the plasma to a stable state

- Disruption Event Characterization And Forecasting (DECAF) code written to identify disruption event chains
  - Disruption categories and their sequential connections analogous to those used on JET are adopted, with warning algorithm for NSTX-U
  - Reduced marginal stability models from kinetic RWM theory will be implemented in this framework

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See Sabbagh talk Wednesday afternoon (PO6.3) for more info

Or pick up a reprint…