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Disruptivity and Density Limits in MAST and other Tokamaks

J.W. Berkery

S.A. Sabbagh, Y.S. Park, J.H. Ahn, Y. Jiang, J.D. Riquezes, J.M. Bialek

Department of Applied Physics, Columbia University, New York, NY

R.E. Bell, M.D. Boyer, L. Delgado-Aparicio, B.P LeBlanc, Z.R. Wang

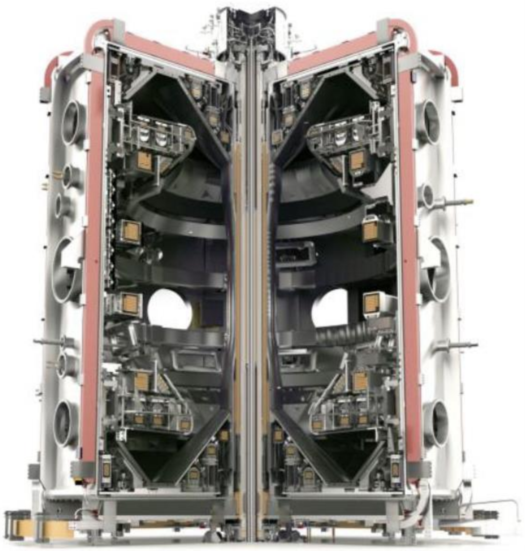
Princeton Plasma Physics Laboratory, Princeton, NJ

C. Ham, J. Hollocombe, A. Kirk,
L. Kogan, A. Thornton

Culham Centre for Fusion Energy,
UKAEA, Abingdon, UK

H. Reimerdes

Ecole Polytechnique Fédérale
de Lausanne,
Lausanne,Switzerland



Columbia University
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Density limits and other parameter ranges of disruptivity are illuminated with DECAF code studies of multiple tokamaks

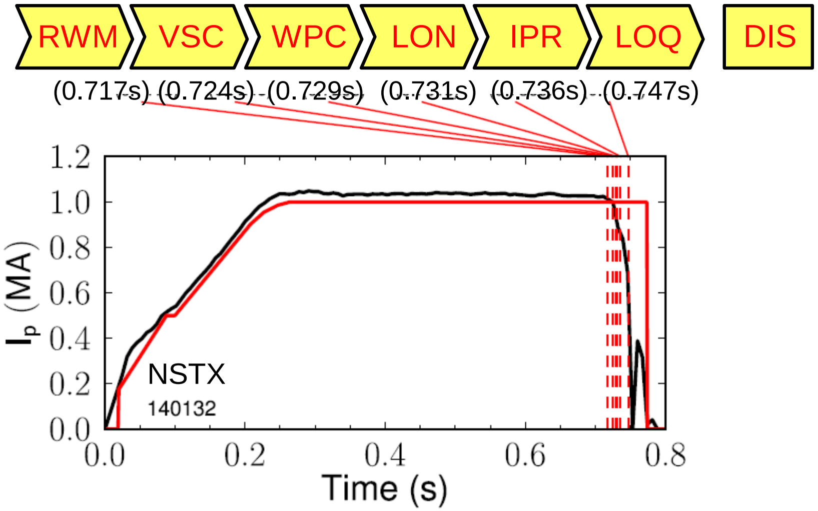
- DECAF code used to automatically detect disruptions in MAST database
  - MAST plasmas have high disruptivity above the Greenwald limit, and at low q_{95}
- Disruptivity plots (or more generally, Event Probability plots) give insight into causes of disruption
  - The large number of analyses in DECAF combined with large databases from multiple machines will make this an extremely powerful tool
- Local island power balance limit has been proposed to explain density limits
  - Evaluation of this physics, while not easy, is possible and may be useful for disruption warning

The Disruption Event Characterization And Forecasting (DECAF) code

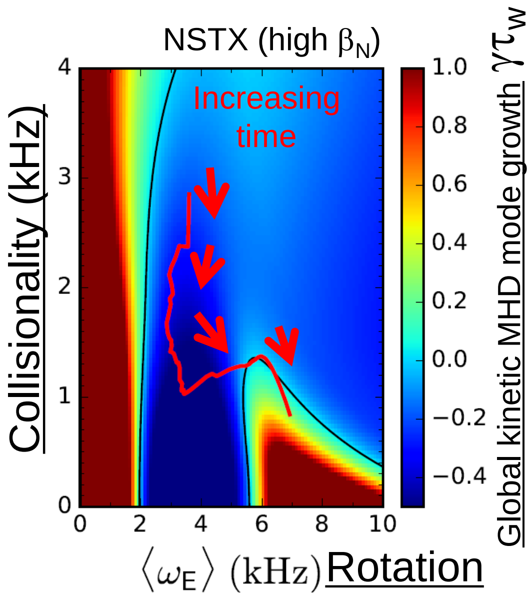
Physical event modules

- Density Limits
- Confinement
- Stability
- Tokamak dynamics
- Power/current handling
- Technical issues

Automated disruption event chain analysis



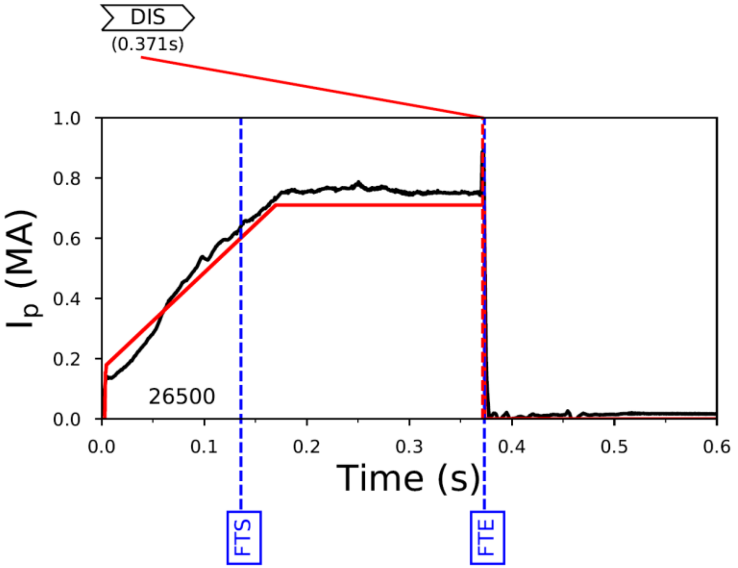
Disruption forecasting

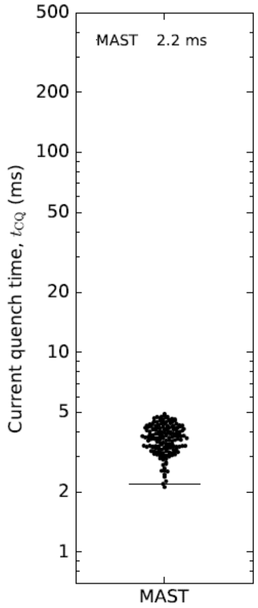


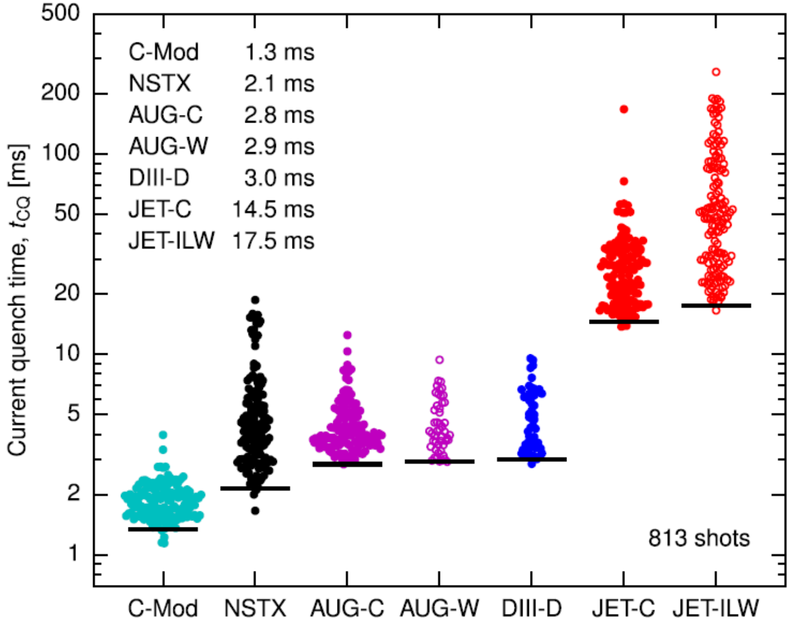
[J.W. Berkery et al., Phys. Plasmas **24** 056103 (2017)]

- ❑ DECAF analysis will test effective cues for disruption avoidance
- ❑ Includes physics based disruption forecasting models, validated against experiments
- ❑ Automated, modular code for collaborative international studies

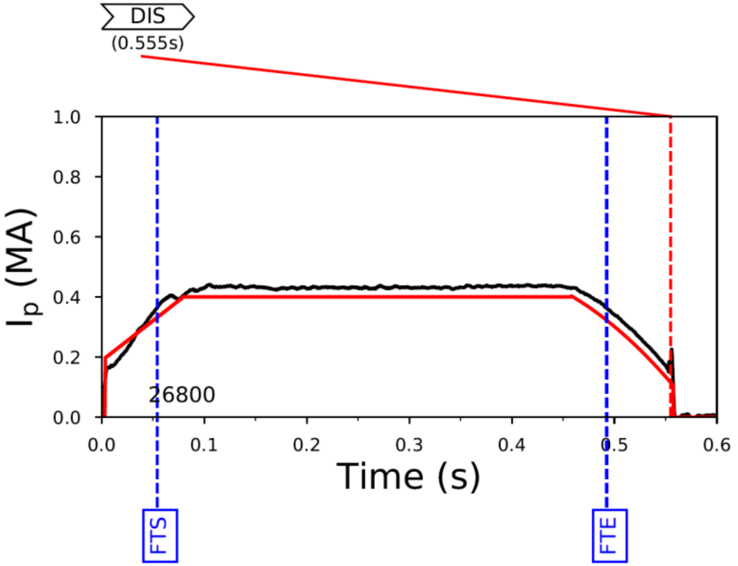
Automatic detection of disruptions in MAST database has been implemented in DECAF





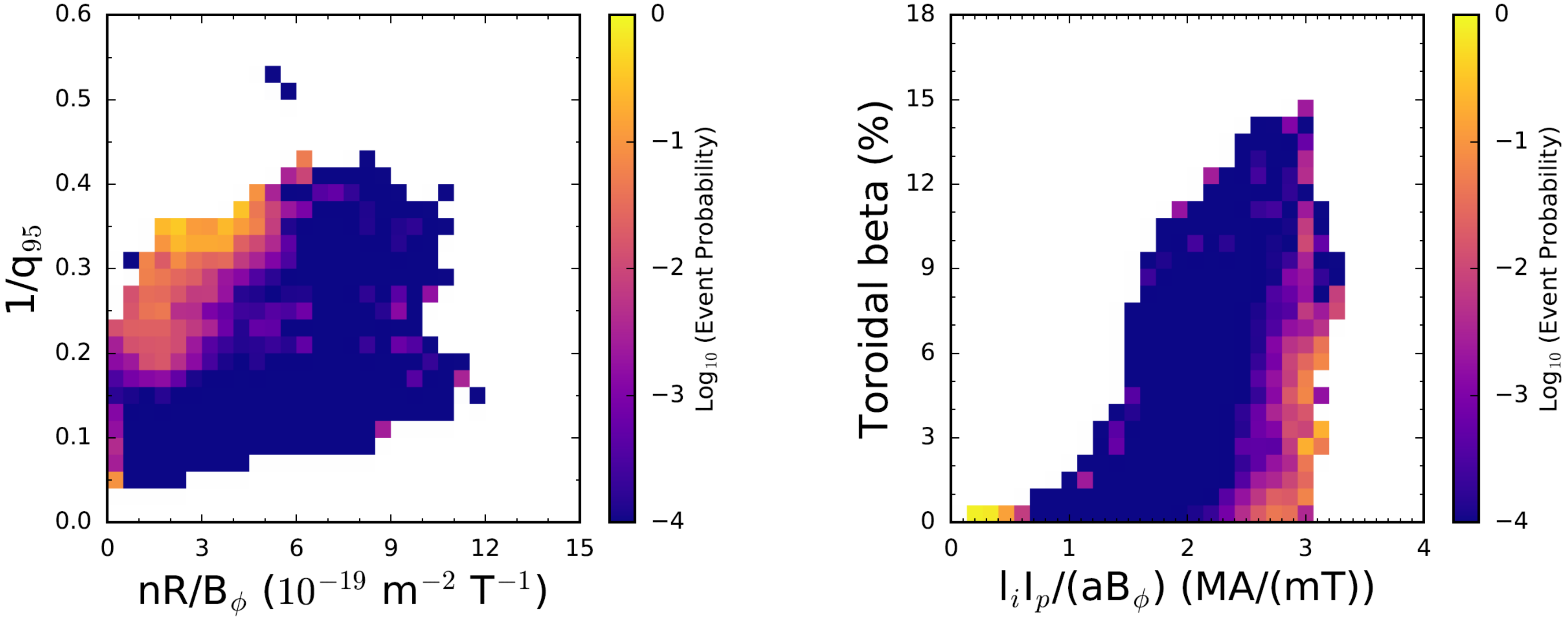


[C.E. Myers et al., Nucl. Fusion **58** 016050 (2018)]



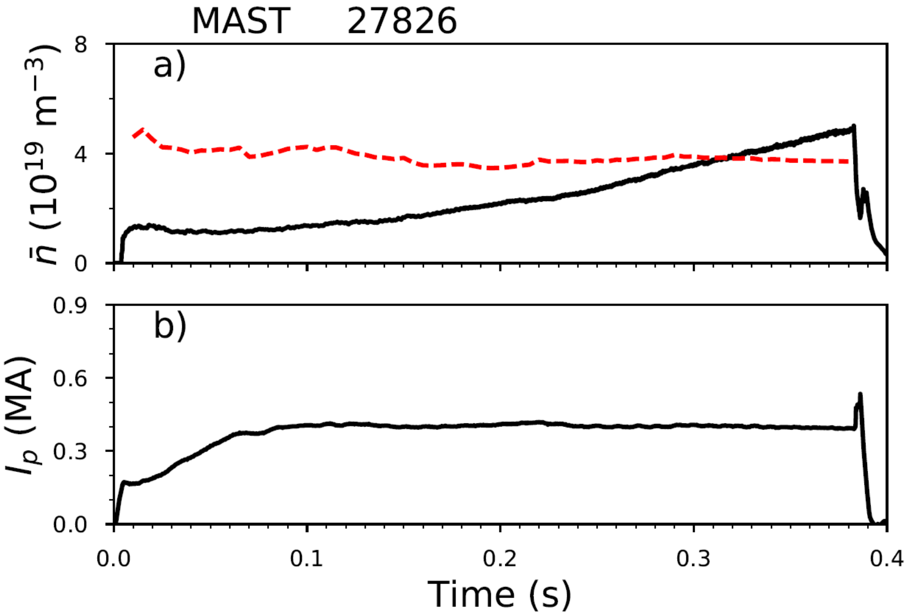
- Current quench times similar to NSTX
- Disruptions can happen in the flattop or in the rampdown
- Time of disruption consistent with previous MAST analysis

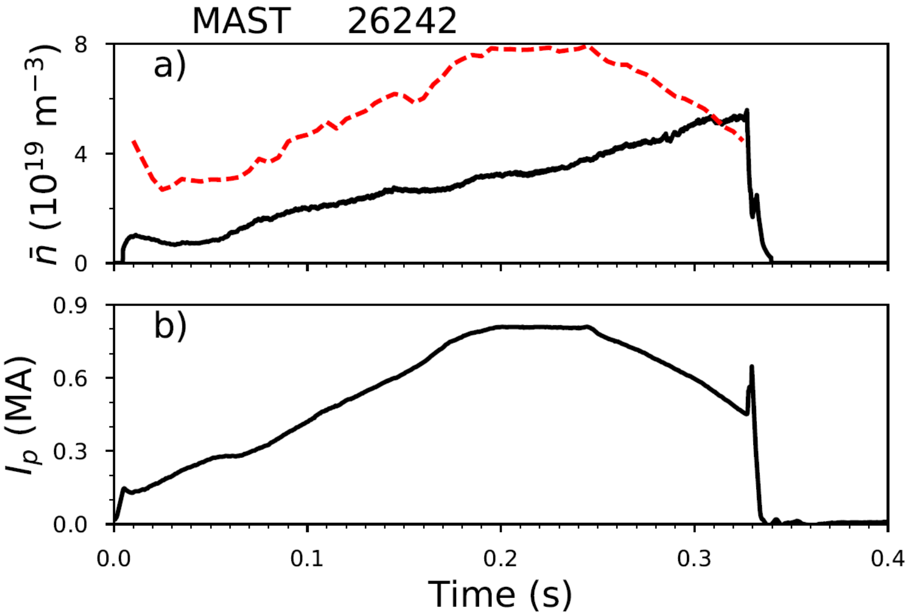
Disruptivity plots illustrate where disruptions, from all causes, are more common



- Disruptivity for 8902 MAST discharges
  - Kept only those with EFIT data from a range of 15,363 discharges (M5 - M9 campaigns: 13005-30473, May, 2005 – Sept. 2013)
- Similar results to a previous study
  - [A. Thornton, PhD thesis, (2011)]

MAST plasmas can cross the Greenwald limit before disrupting

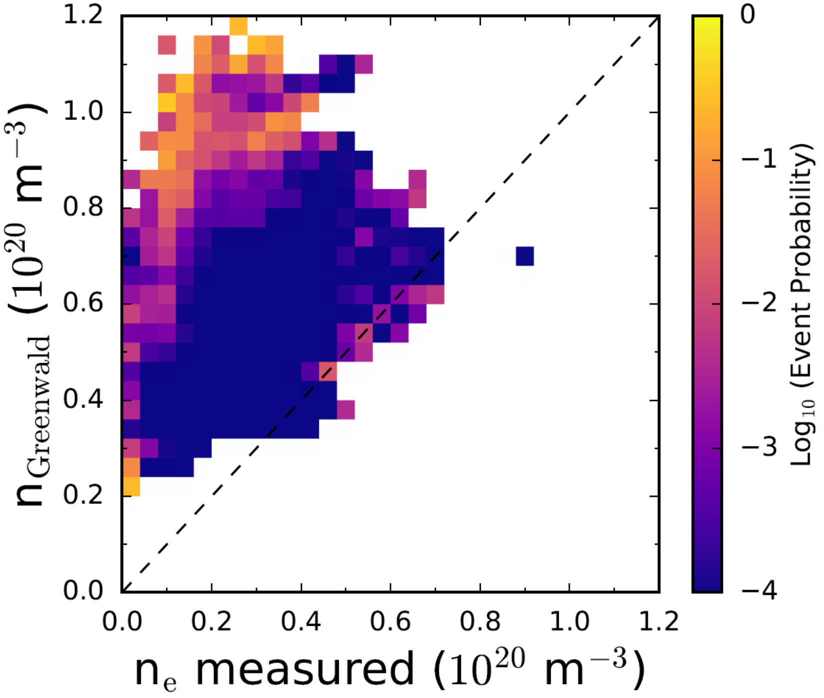




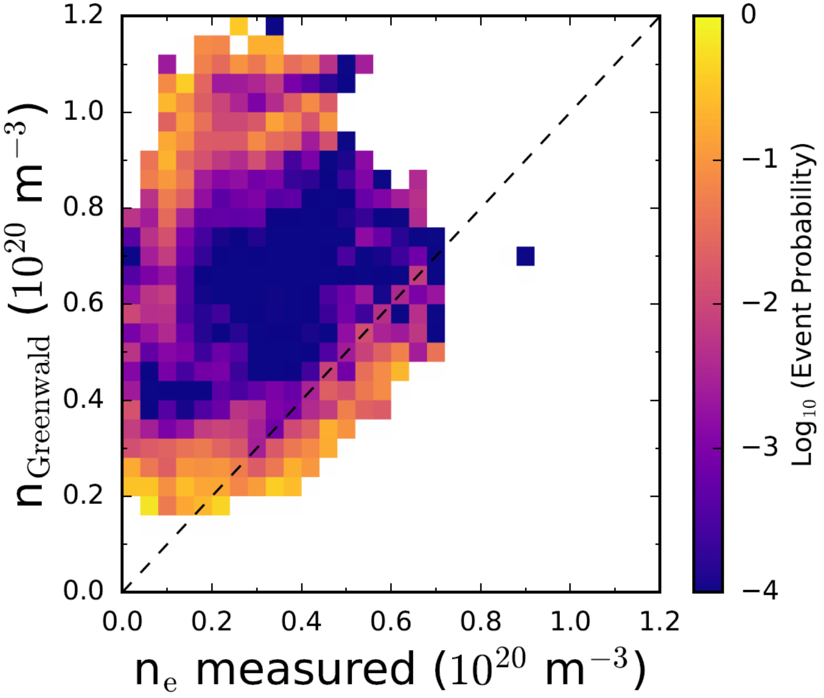
- Two ways of crossing the Greenwald limit:
  - Density rises high enough to cross the limit
  - Plasma current ramps down, bringing the limit down

Disruptivity database shows that MAST plasmas can exceed the Greenwald density limit

MAST, flattop only

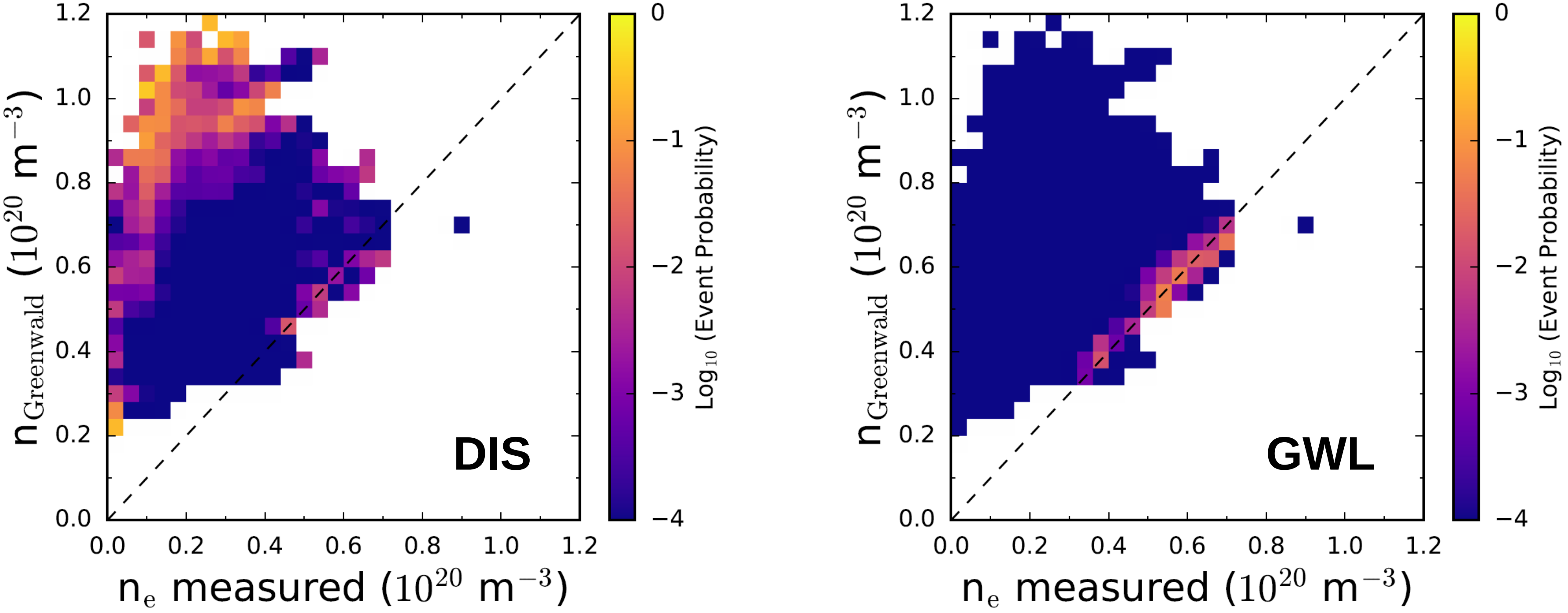


MAST, flattop and rampdown



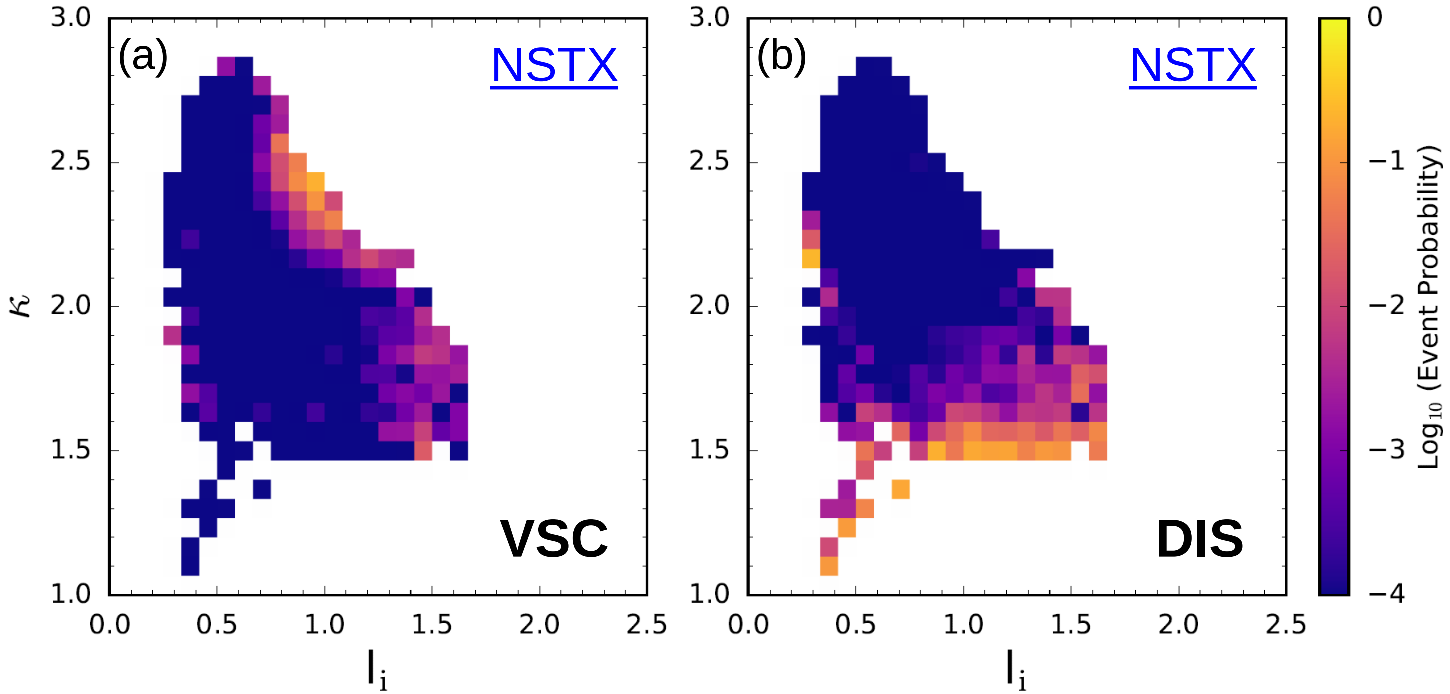
- Previously shown for MAST [A. Thornton, PhD thesis, (2011)]
- When rampdowns are included more disruptions over the Greenwald limit appear, especially at lower density
  - Left, disruptivity in the flattop only; Right, flattop and rampdown

Instead of disruptivity plots, DECAF can produce more general event probability plots



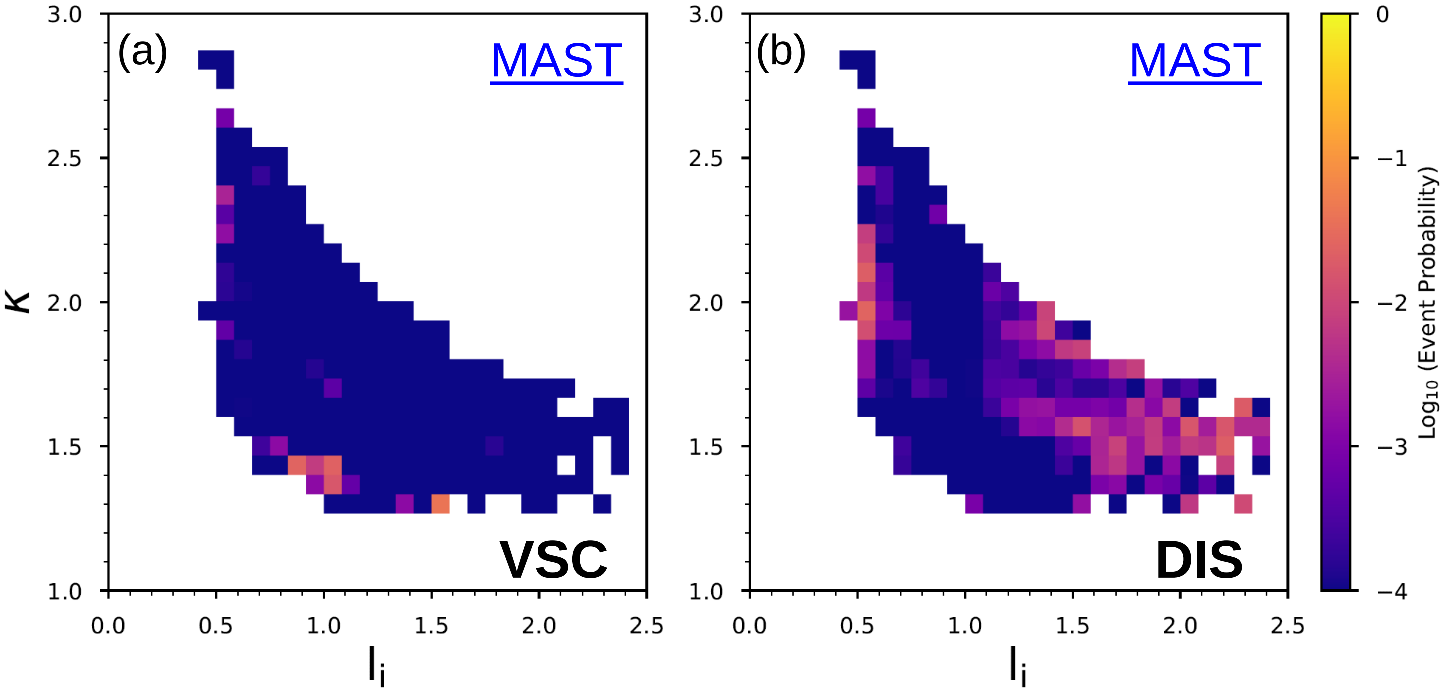
- On the left, the traditional disruptivity plot shows the probability of the DIS event in the parameter space
- But DECAF can plot the probability of <u>any</u> event
  - A trivial example shows the GWL event occurs when n_e goes above n_{GW}

Insight can be gained by illustrating where in parameter space DECAF events happen (other than DIS)



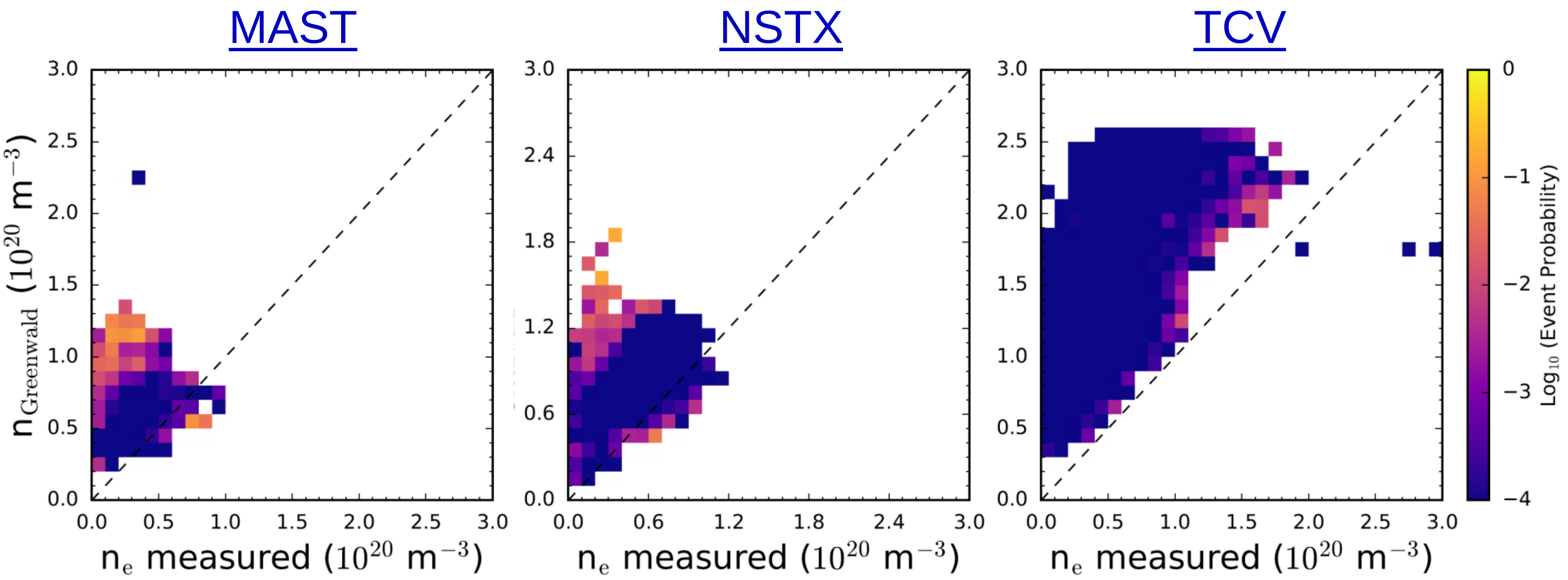
- Vertical stability in NSTX shows a strong dependence on elongation and internal inductance
  - Similar to result from [Boyer, APS, (2017)]
- After loss of vertical control is detected, plasmas tend to shrink (lower kappa) and l_i can increase before the disruption

Less VSC events occur in the MAST database



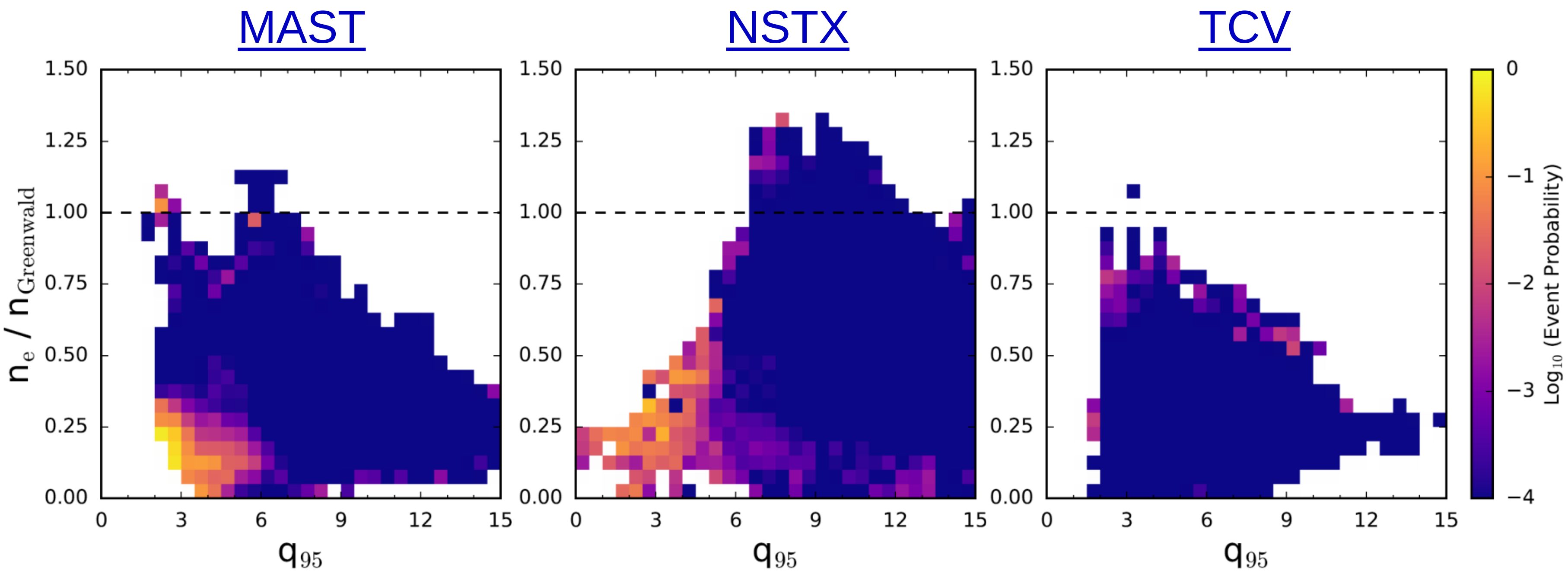
- More robust vertical control than NSTX?
  - MAST had (and MAST-U will have) close fitting internal coils that were used for active vertical control

Cross-machine comparisons can give insight into density limits



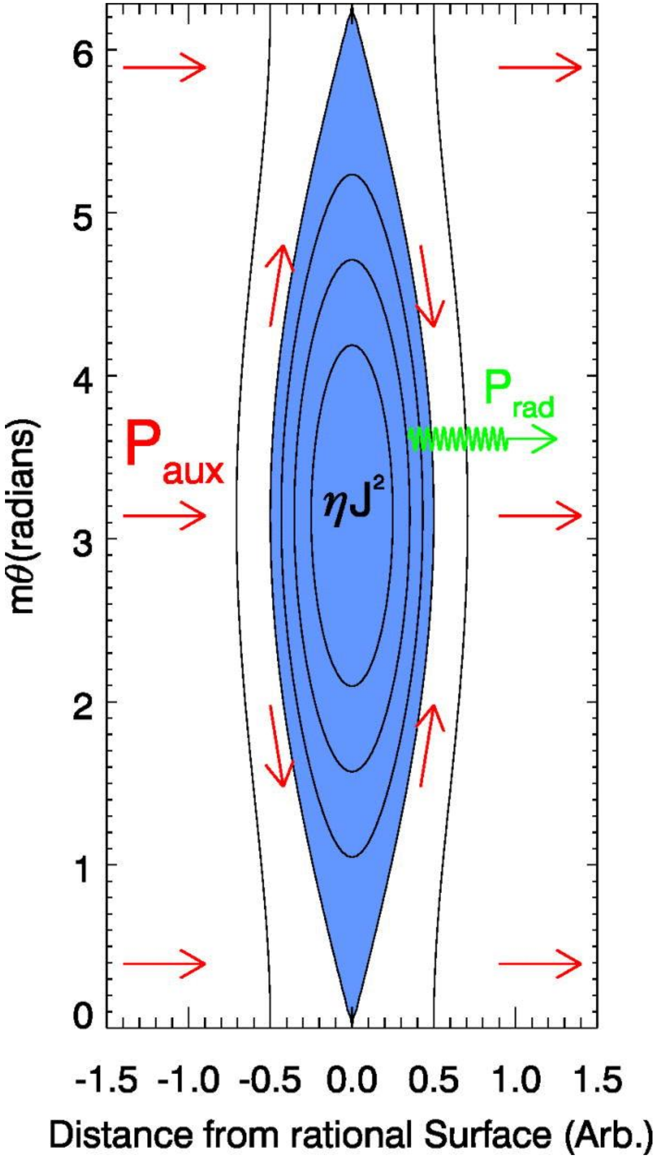
- Preliminary database data shows long-known ubiquity of density limit disruptions
  - Similarities between MAST and NSTX, as expected
  - Limited data sets so far. Work continues…

Cross-machine comparisons can give insight into density limits



- Possible q_{95} dependence in density limit
  - Identified in previous TCV work [N. Kirneva, PPCF **57** 025002 (2015)]
  - Could be related to the position of the q=2 magnetic island (local power balance theory), but this remains to be seen

Recently a density limit theory has been developed based on power balance in an island



- Local island power balance limit
  - Power balance in an island between input Ohmic heating and radiated power loss results in maximum local density that scales with local current density
  - If the radiated power at the island exceeds the input power ($P_{loss} > P_{input}$), then the island grows and can lead to disruption

Power density balance

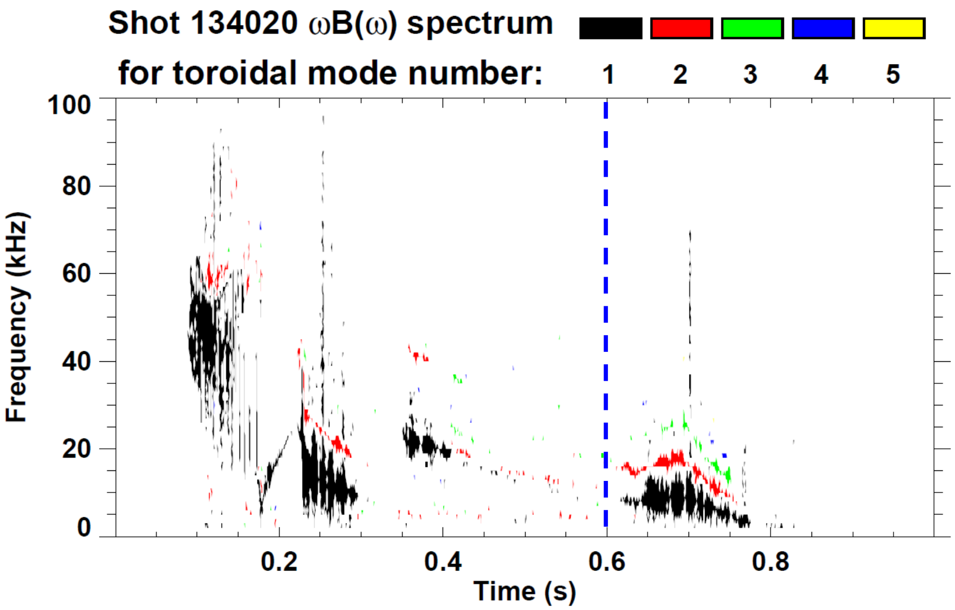
$$P_{\text{loss}} < P_{\text{input}}$$

$$n_e n_{\text{D}} L_{\text{D}}(T_e) + \sum_Z n_e n_Z L_Z(T_e) < \eta j^2$$

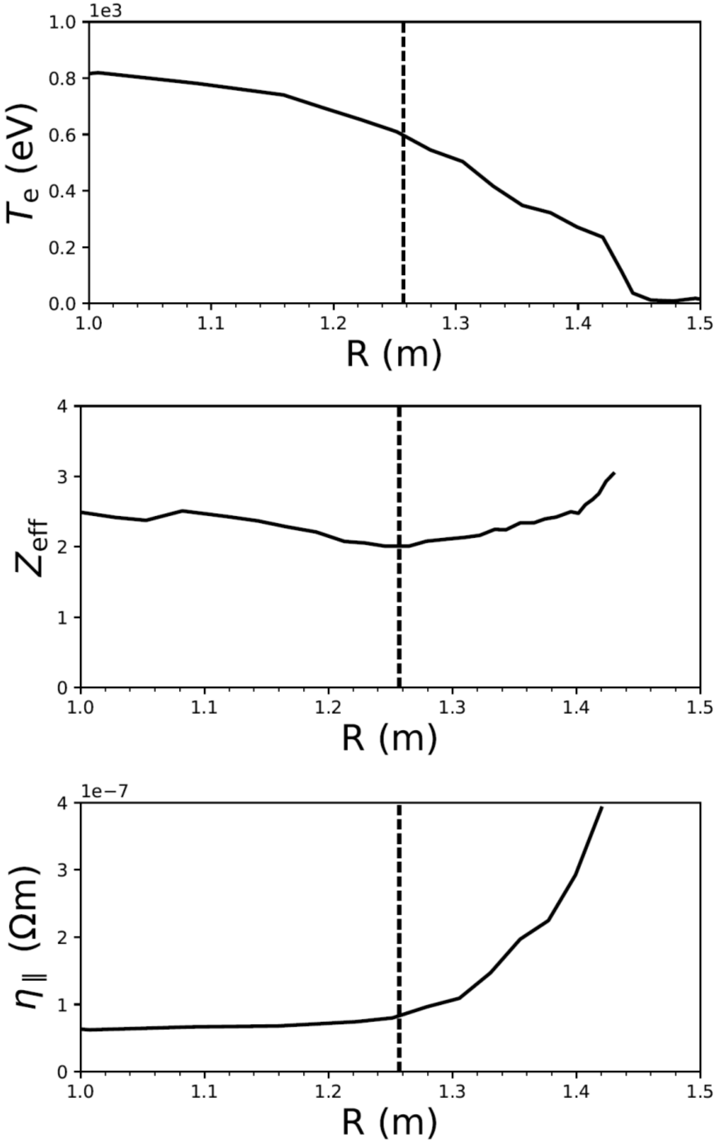
[D. Gates et al., Phys. Rev. Lett. **108** 165004 (2012)]

Discharges from NSTX were selected to test the theory

- Discharges selected with:
  - long flat-top periods of rising density
  - no MHD activity until low frequency n=1 activity appears
    - with a clean signature in the spectrogram
    - lasts less than 200 ms
    - then the discharge terminates



DECAF calculation of local density limit tested for NSTX discharge 134020 @ 0.60 s



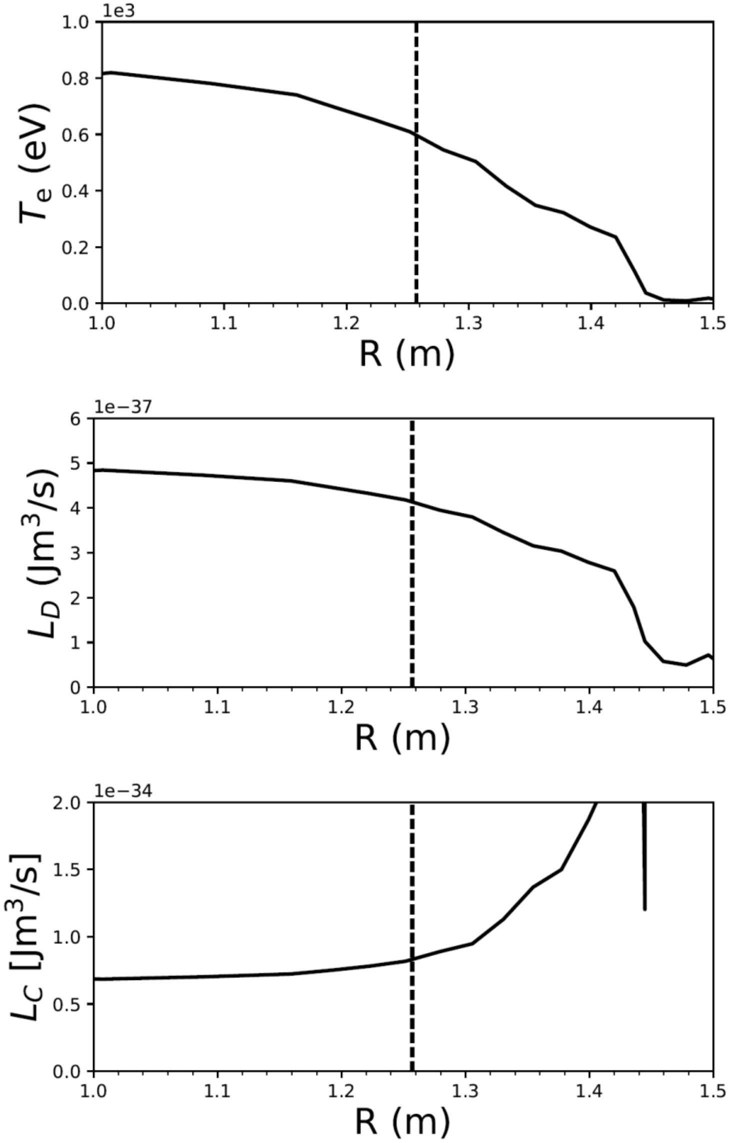
$$n_e n_{\mathrm{D}} L_{\mathrm{D}}(T_e) + \sum_Z n_e n_Z L_Z(T_e) < \eta j^2$$

- ❑ Electron temperature profile
  - ❑ Measured by Thomson scattering
- ❑ Z_{eff} profile
  - ❑ Measured by charge exchange recombination spectroscopy
  - ❑ Assumes only carbon impurity
- ❑ Parallel Spitzer resistivity
  - ❑ Calculated using T_e and Z_{eff}

$$\eta = \frac{\sqrt{2m_e} Z_{\mathrm{eff}} e^2 \ln\Lambda}{12\pi^{3/2}\epsilon_0^2 T_e^{3/2}} \times \frac{1 + 1.198 Z_{\mathrm{eff}} + 0.222 Z_{\mathrm{eff}}^2}{1 + 2.966 Z_{\mathrm{eff}} + 0.753 Z_{\mathrm{eff}}^2}$$

[Q. Teng et al., Nucl. Fusion **56** 106001 (2016)]

DECAF calculation of local density limit tested for NSTX discharge 134020 @ 0.60 s



$$n_e n_{\mathrm{D}} L_{\mathrm{D}}(T_e) + \sum_{Z} n_e n_Z L_Z(T_e) < \eta j^2$$

- Electron temperature profile
  - Measured by Thomson scattering
- Cooling rate of deuterium
  - Calculated using T_e

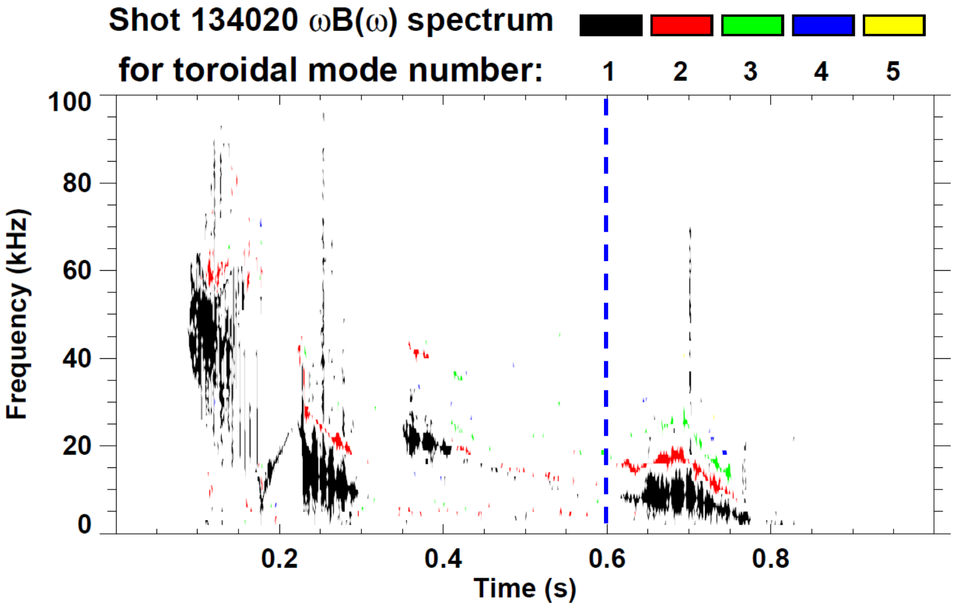
$$L_{\mathrm{D}} = 5.35 \times 10^{-37} T_e^{1/2}\ (\mathrm{keV})\ W \cdot \mathrm{m}^3$$

[Q. Teng et al., Nucl. Fusion **56** 106001 (2016)]

- Cooling rate of carbon
  - Calculated using T_e with formula from:

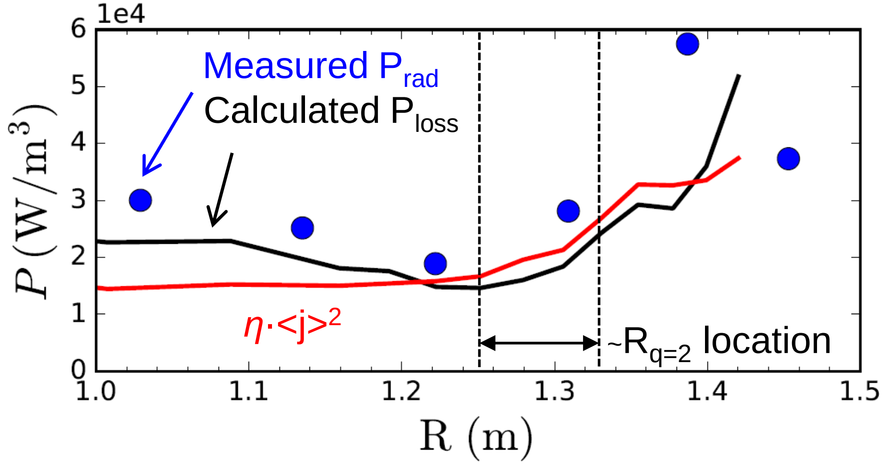
[D.E. Post et al., At. Data Nucl. Data Tables **20** 397–439 (1977)]

DECAF calculation of local density limit tested for NSTX discharge 134020 @ 0.60 s



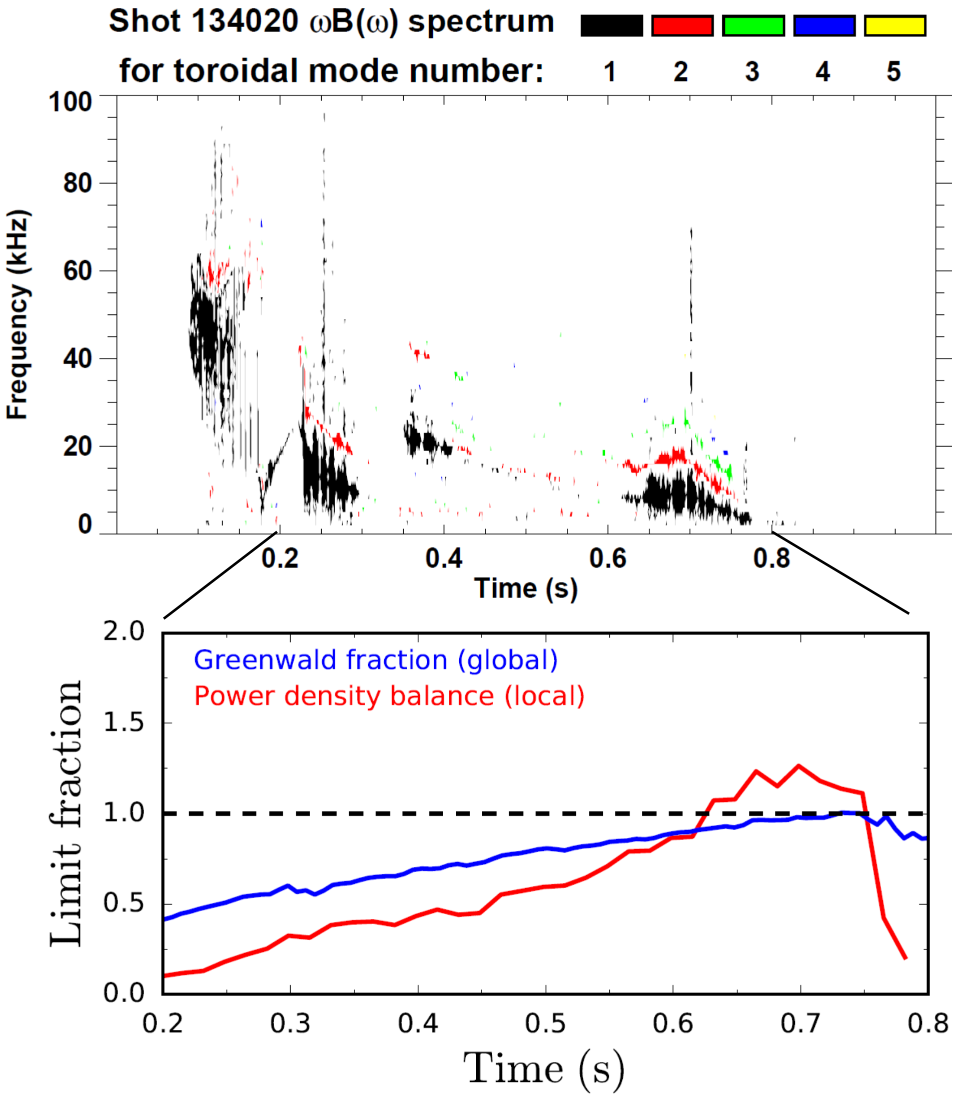
Power density balance

$$P_{\mathrm{loss}} < P_{\mathrm{input}}$$



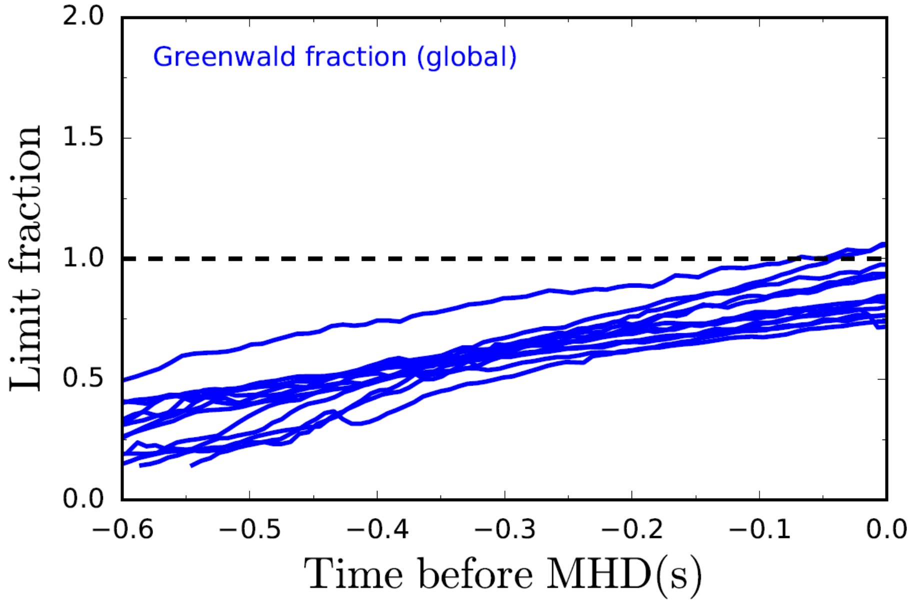
- Power balance at q=2 location is just at the limit before MHD activity onset
  - P_{input} calculated using total current density
  - P_{loss} slightly below measured P_{rad}

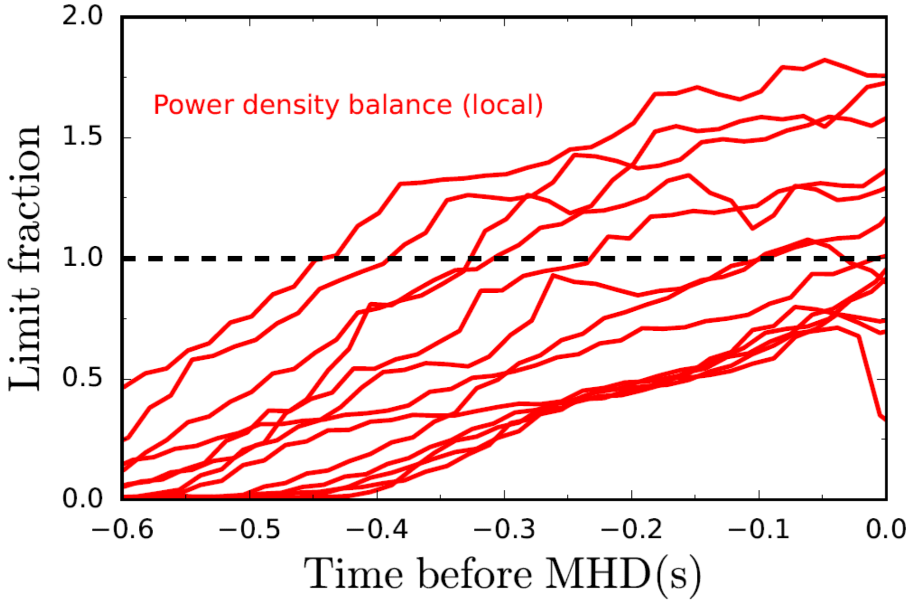
Both global and local density limits rise with density towards/crossing limit at MHD onset in our test case



- Greenwald limit
  - Approaches one at end of shot
- Power density balance
  - Hints at possible utility for early warning (of MHD activity before the disruption)
  - Evaluated at r = one-half the minor radius (rather than at r of q=2) because EFIT determination of q=2 radius is sporadic in time
  - 50 ms running average on the calculated powers

Both Greenwald fraction and local power balance models are being evaluated for disruption forecasting





- Greenwald limit within about 30% at time of disruption
  - Consistent with previous studies
  - May be sufficient when combined with other DECAF analysis
- Initial implementation of power balance model follows GW trend
  - Presently determining if different input parameter assumptions can reduce variation

Conclusions

- DECAF code used to automatically detect disruptions in MAST database
- DECAF has generated disruptivity plots from multiple tokamaks
  - MAST plasmas have high disruptivity above the Greenwald limit, and at low q_{95}
- The large number of analyses in DECAF combined with large databases from multiple machines will make event probability plots an extremely powerful tool
  - Vertical stability dependence on κ and l_i in NSTX, but not in MAST
- Evaluation of the local island power balance limit has begun in DECAF
  - Shows some potential promise as a disruption warning