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Disruptivity and Density Limits in MAST and other Tokamaks

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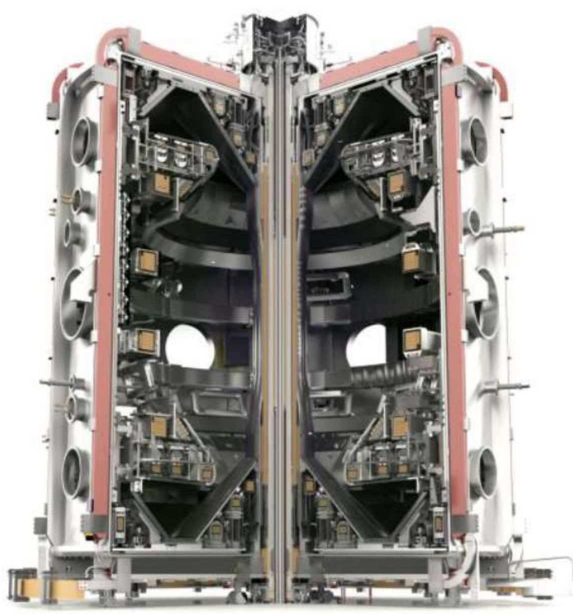


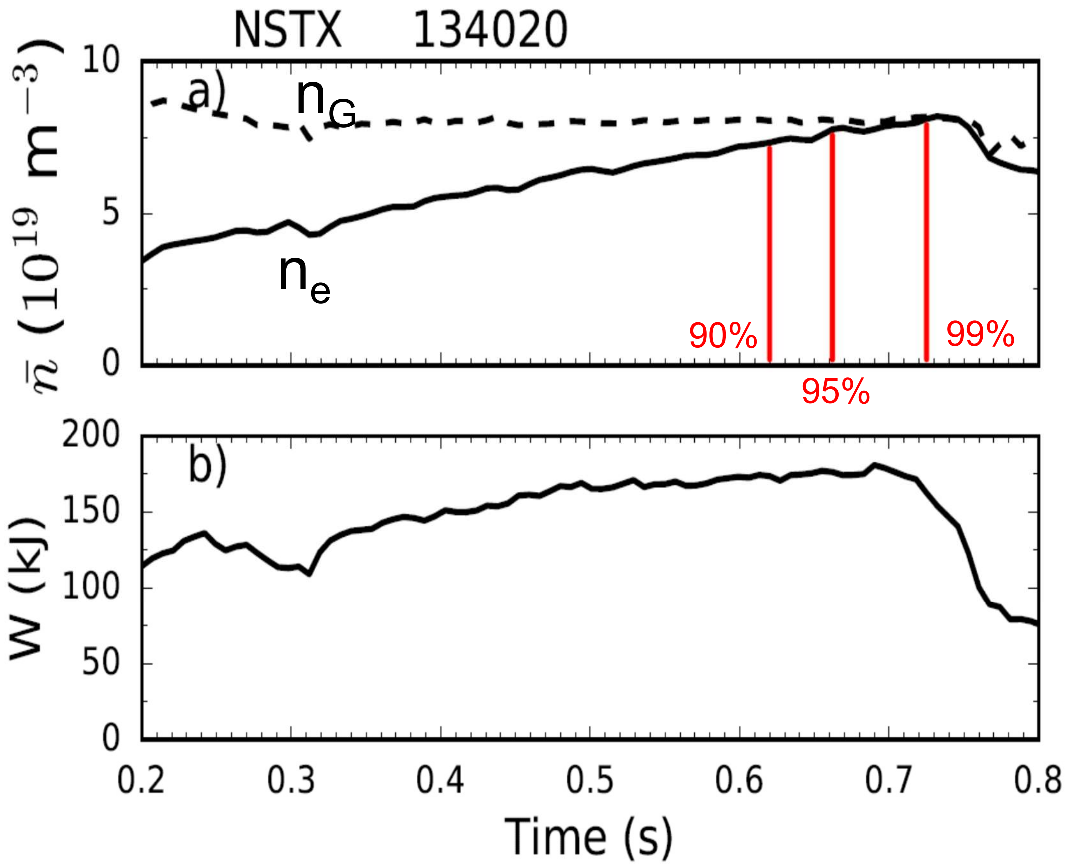
Supported by US DOE grant DE-SC0018623

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

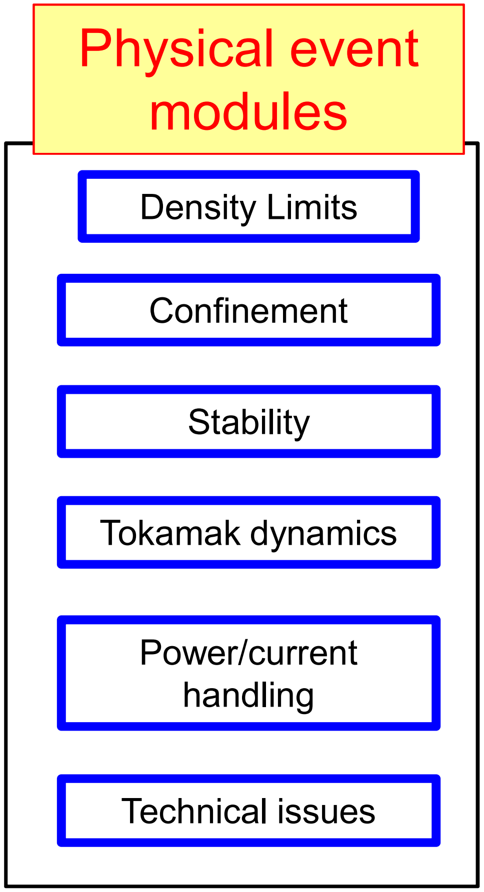
- DECAF code used to automatically detect disruptions in MAST database
  - MAST plasmas have high disruptivity above the Greenwald limit, and at low q_{95}
- Disruptivity plot (or more generally, Event Probability plots) give insight into causes of disruption
  - The large number of analyses in DECAF 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 long-known density limit is an indicator of disruptions in tokamaks

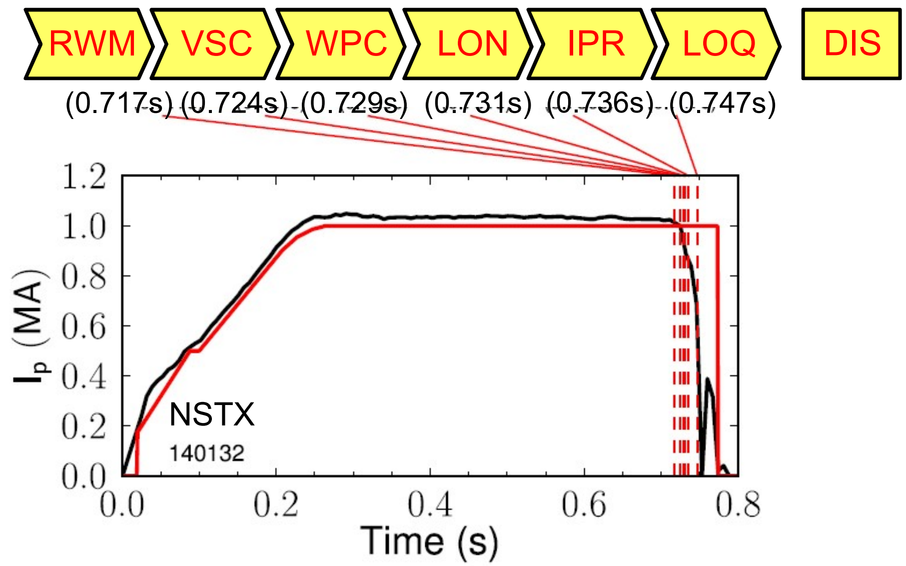
- Greenwald limit
  - n_e [10^{20}m^{-3}] < $n_G \equiv I_p$ [MA] / πa^2 [m^2]
- Comprehensive study of the physics behind the density limit is lacking
- Is there a better indicator of impending disruption that can be found?



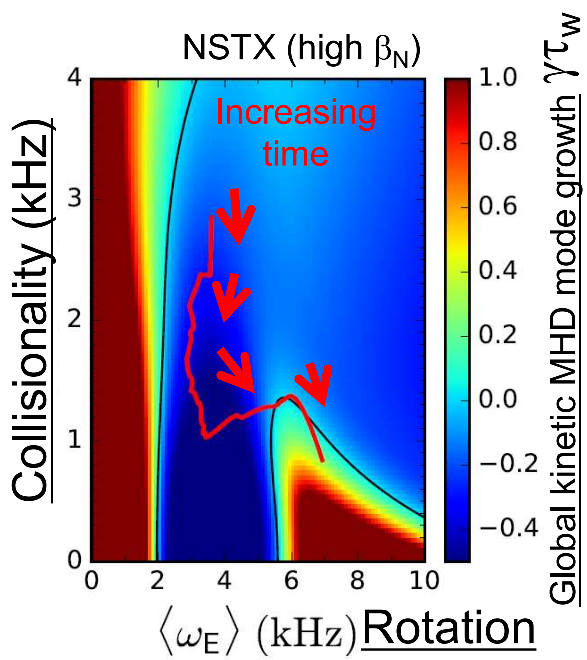
The Disruption Event Characterization And Forecasting (DECAF) code



Automated disruption event chain analysis



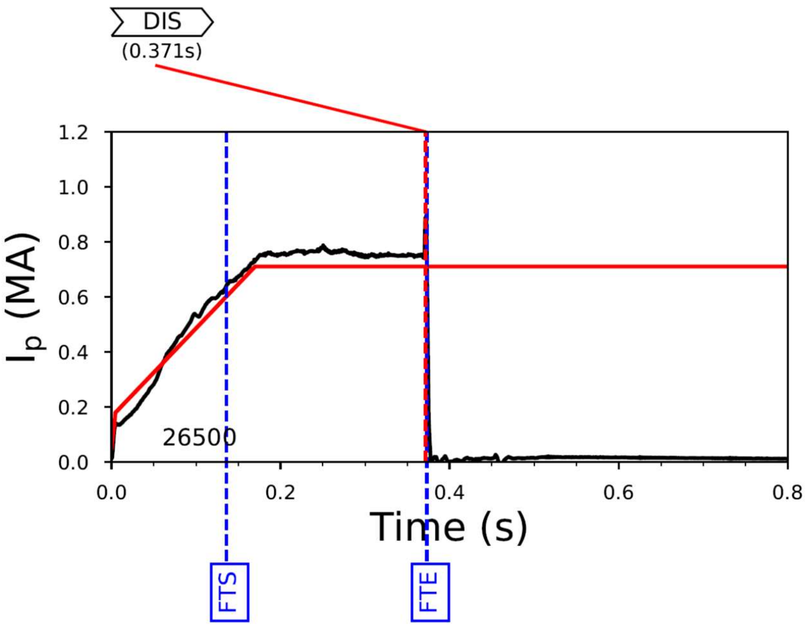
Disruption forecasting

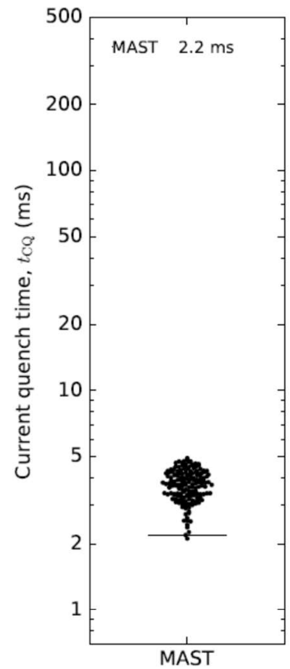


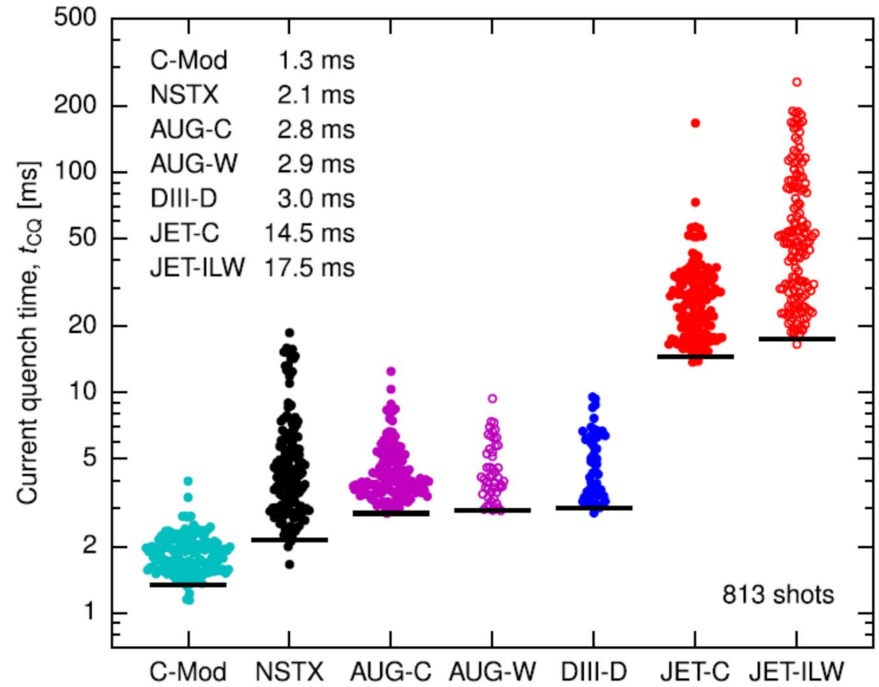
[J.W. Berkery et al., Phys. Plasmas **24** 056103 (2017)]

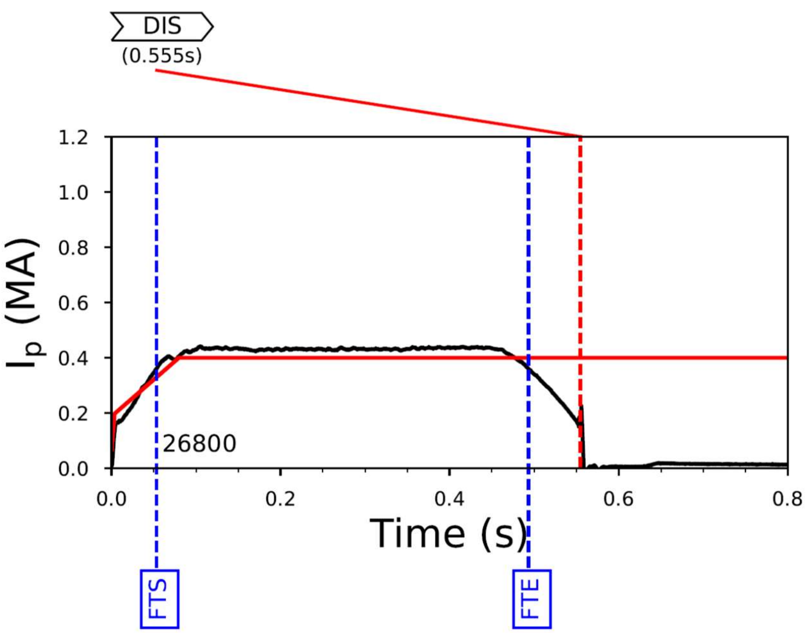
- DECAF analysis will test effective cues for disruption avoidance
- Includes physics based disruption forecasting models, validated against experiments
- Automated, modular code for collaborative international studies

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





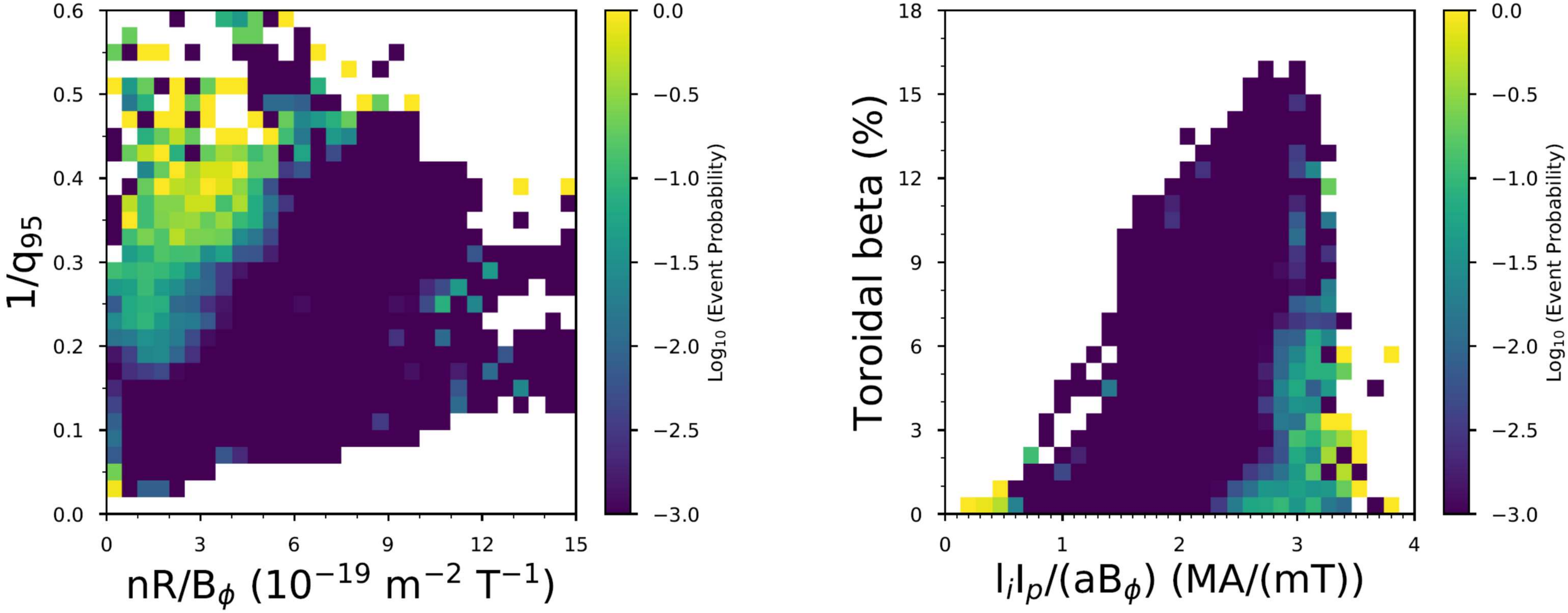




[C.E. Myers et al., Nucl. Fusion **58** 016050 (2018)]

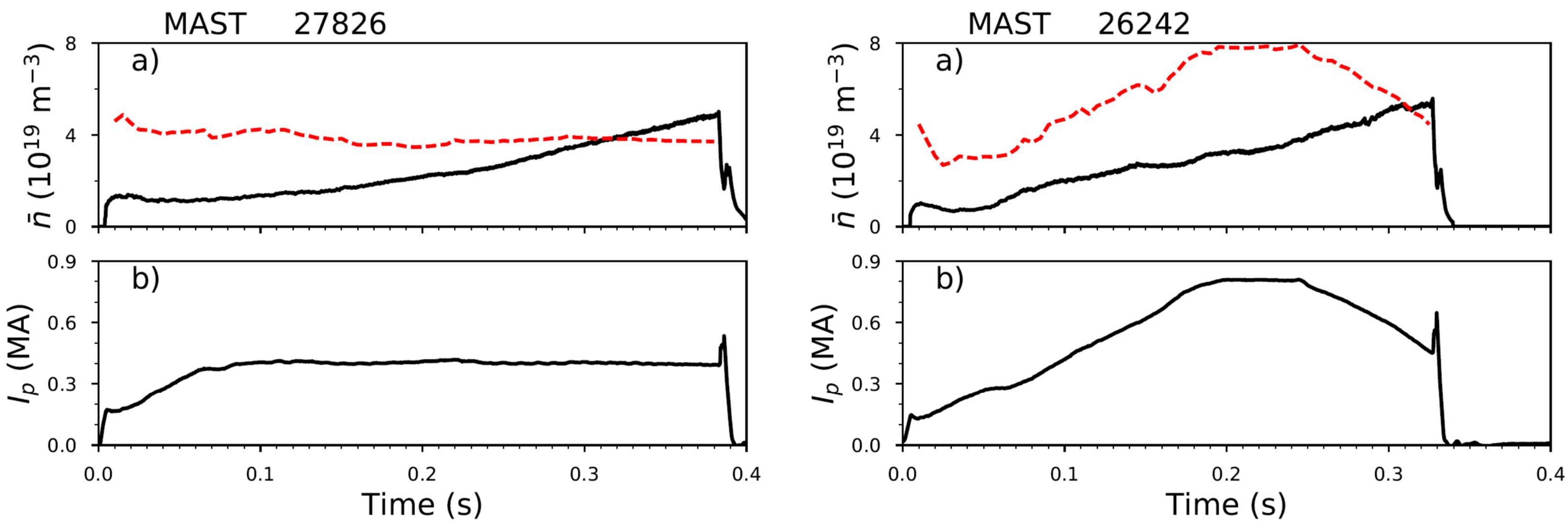
- Current quench times similar to NSTX
- Disruptions can happen in the flattop or in the rampdown
- Time of disruption consistent with previous MAST analysis

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)]

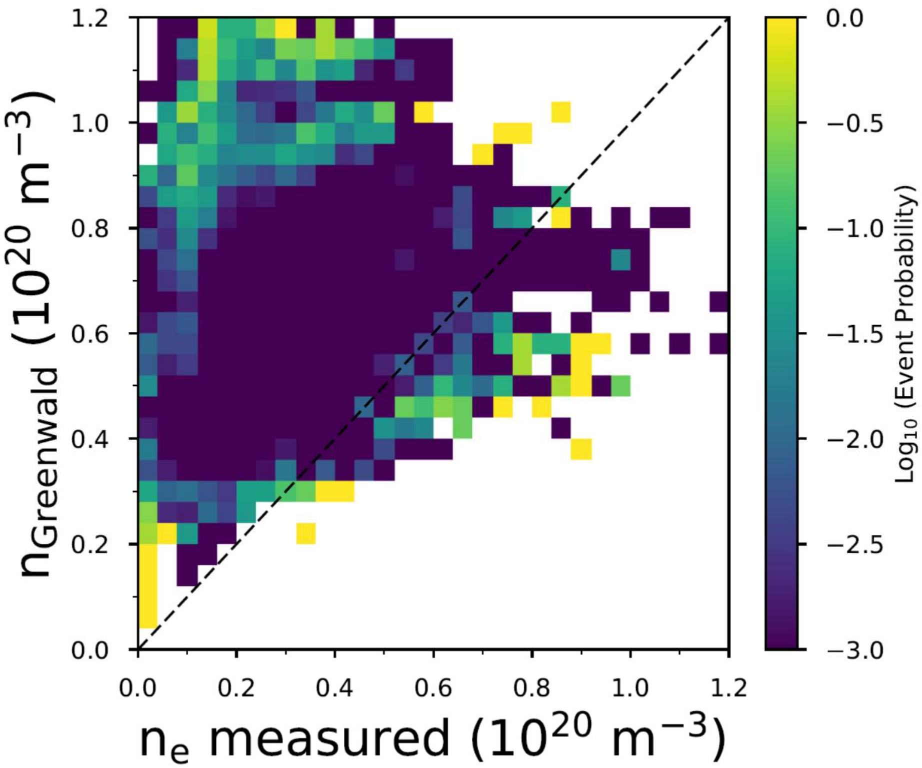
MAST plasmas can cross the Greenwald limit before disrupting



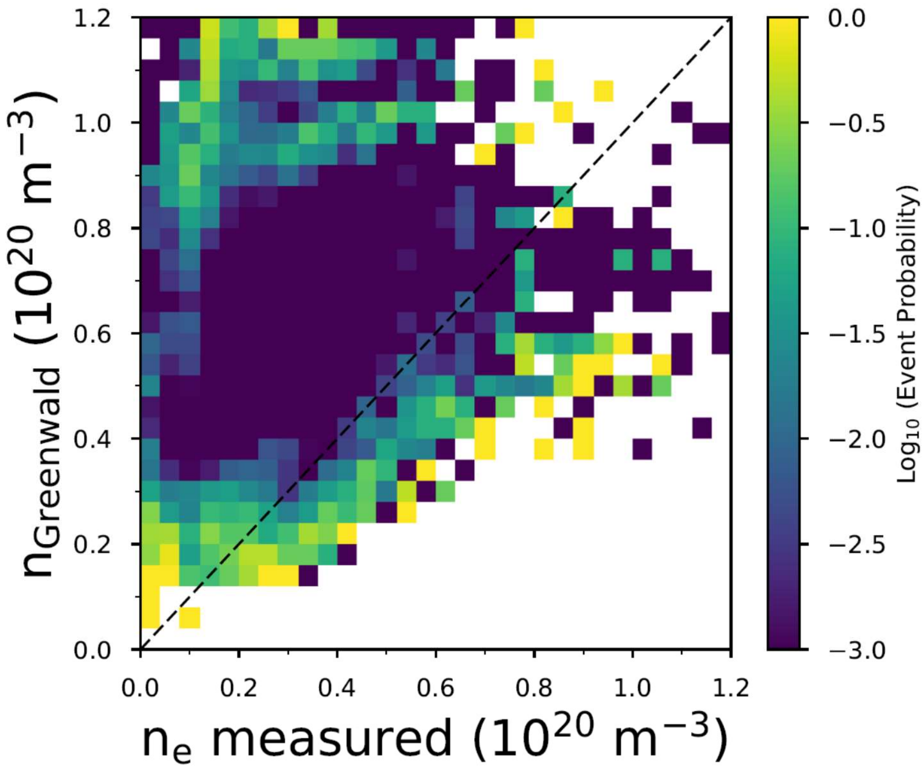
- Two ways of crossing the Greenwald limit:
  - Density rises high enough to cross the limit
  - Plasma current ramps down, bringing the limit down

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

MAST, flattop only

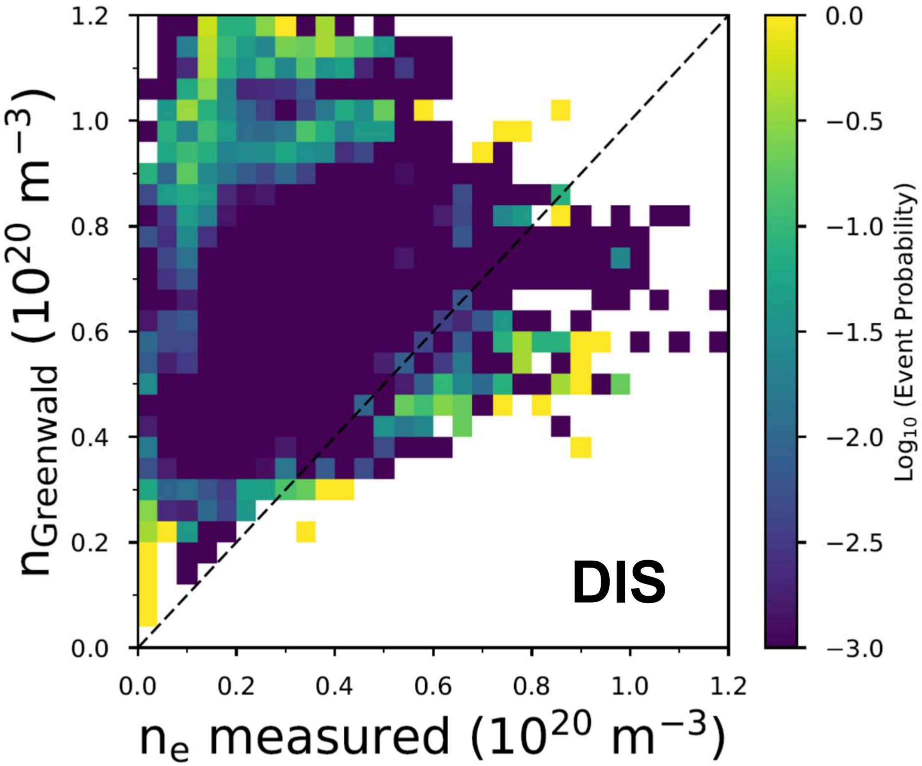


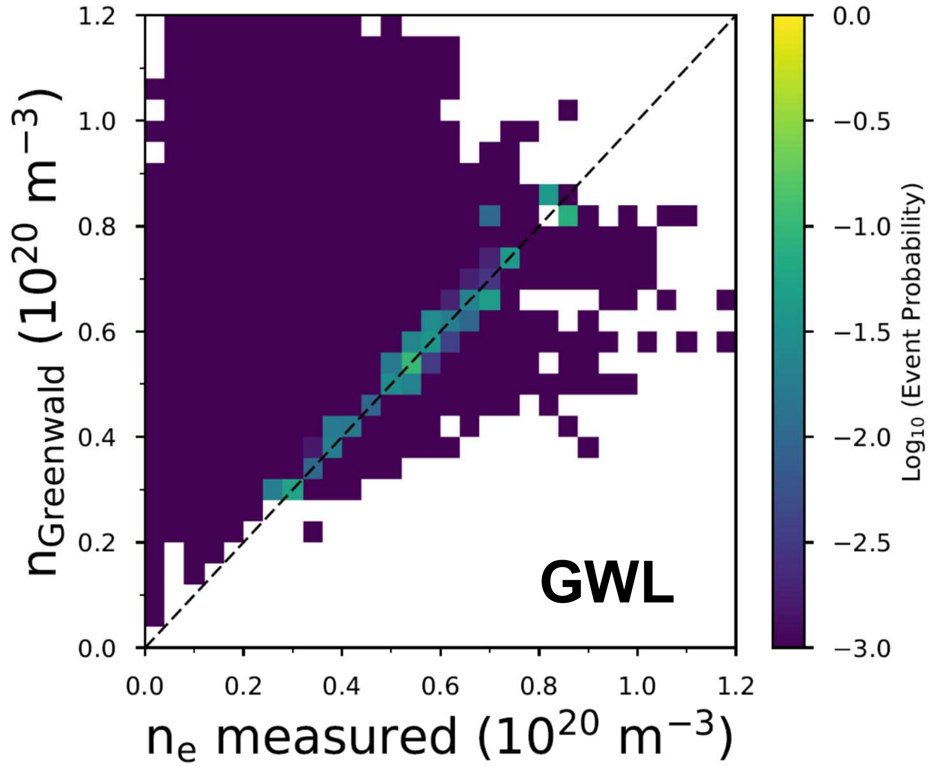
MAST, flattop and rampdown



- 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

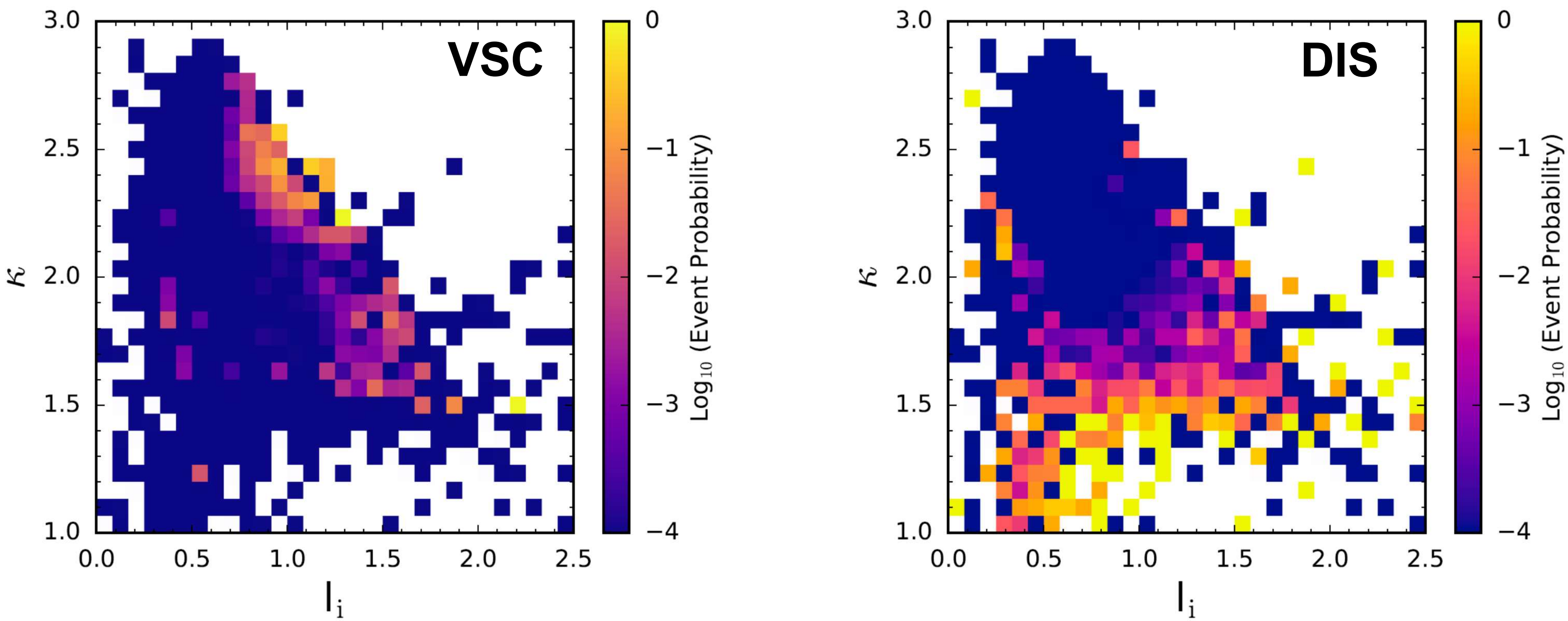
Instead of disruptivity plots, DECAF can produce more general event probability plots





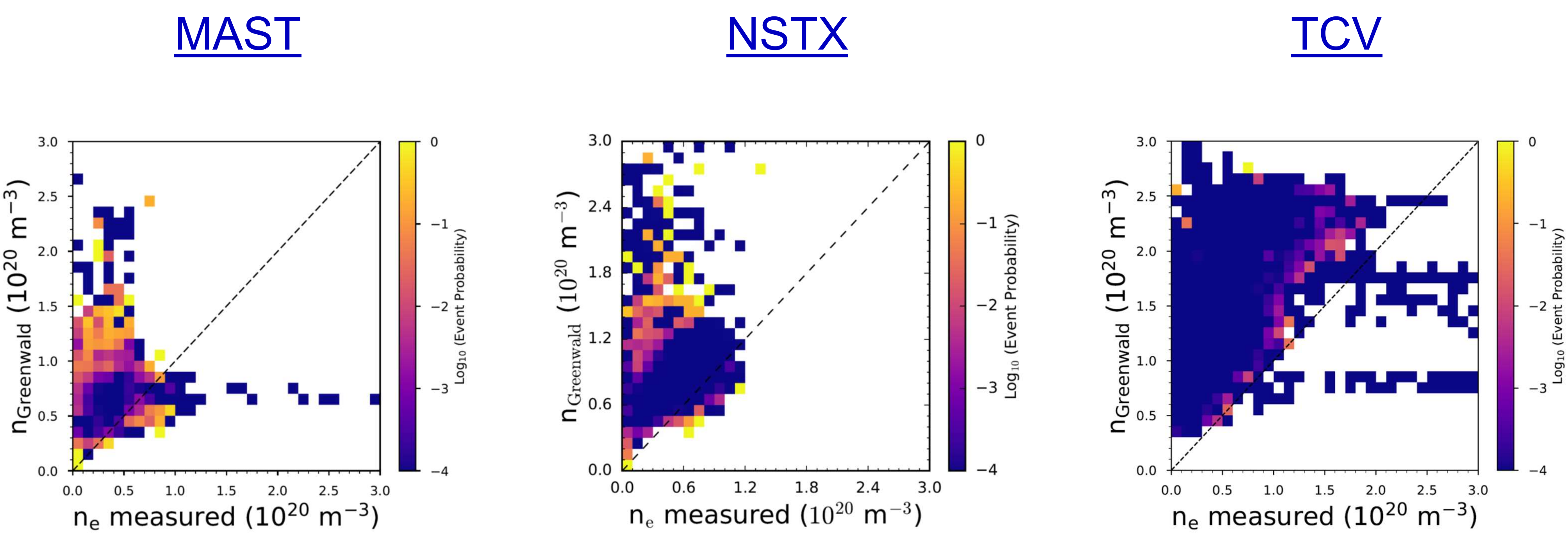
- On the left, the traditional disruptivity plot shows the probability of the DIS event in the parameter space
- But DECAF can plot the probability of <u>any</u> event
  - A trivial example shows the GWL event occurs when n_e goes above n_{GW}

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)]

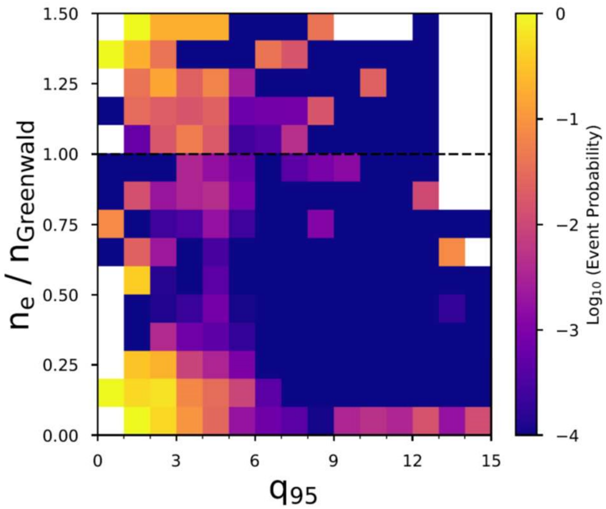
Cross-machine comparisons can give insight into density limits



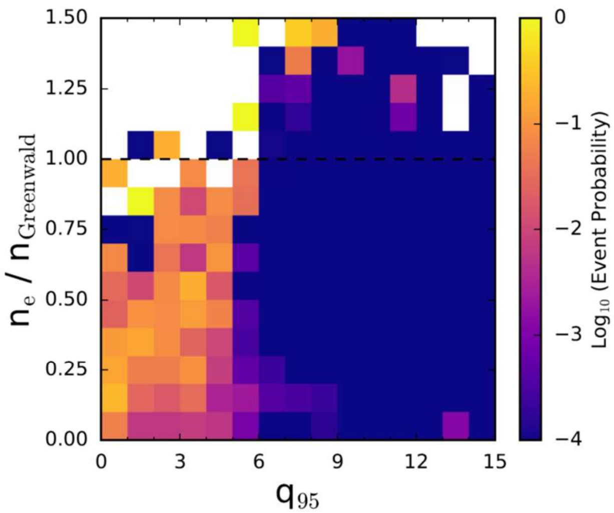
- Preliminary database data shows long-known ubiquity of density limit disruptions
  - Similarities between MAST and NSTX, as expected
  - Limited data sets so far. Work continues…

Cross-machine comparisons can give insight into density limits

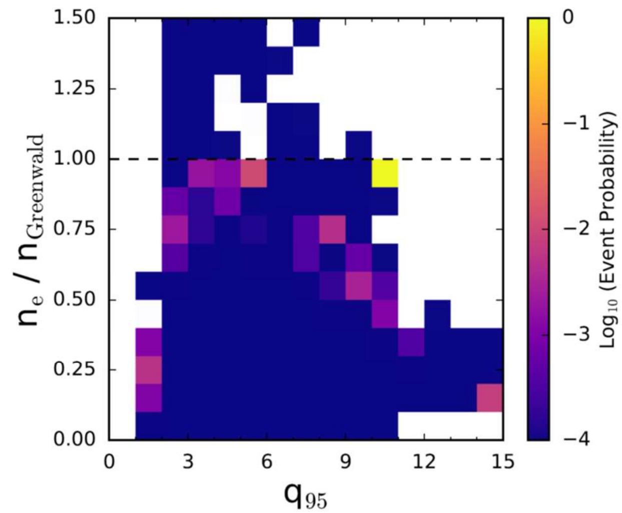
MAST



NSTX

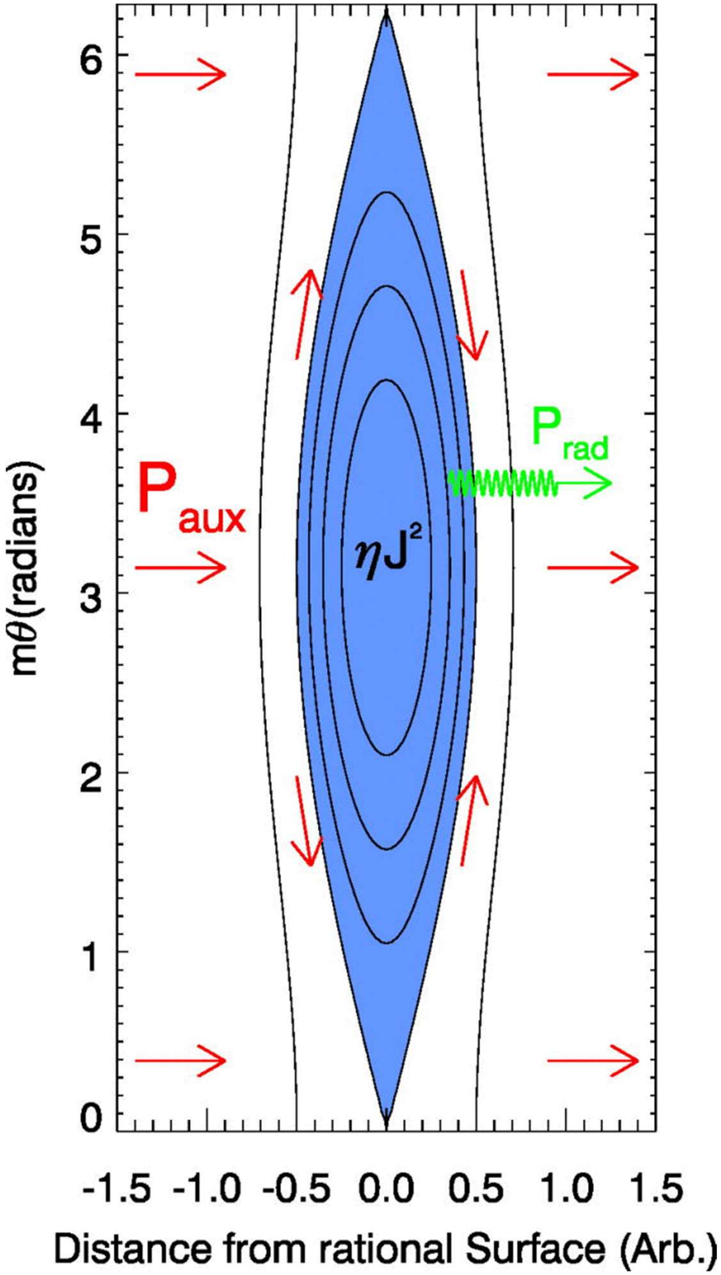


TCV



- 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 the radiated power at the island exceeds the input power (P_{loss} > P_{input}), then the island grows and can lead to disruption of the plasma

<u>Power density balance</u>

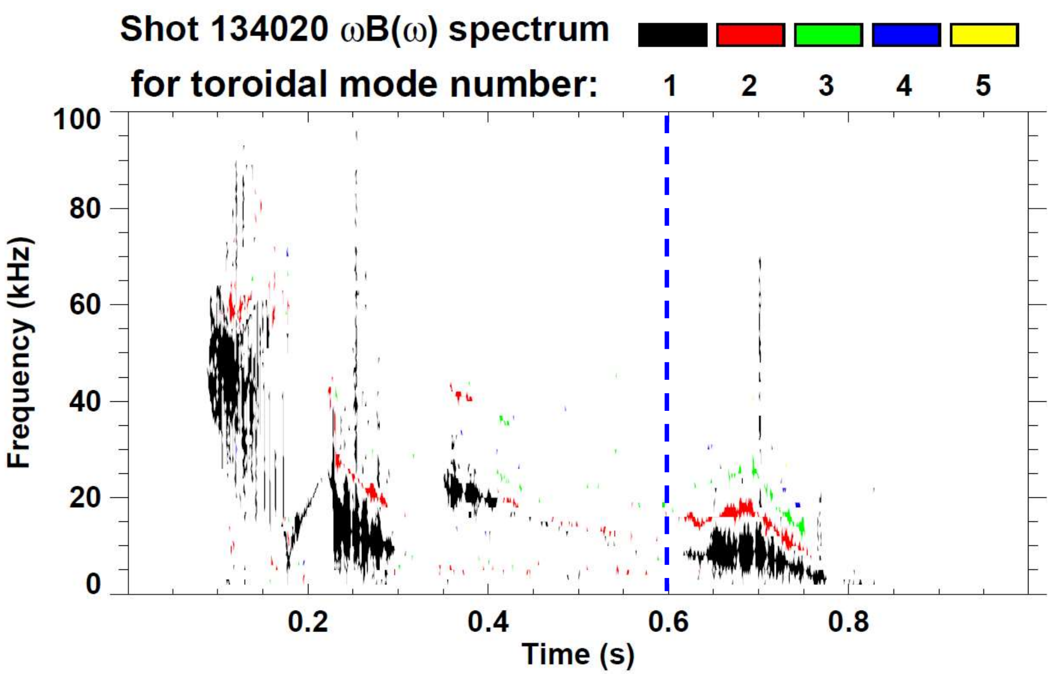
$$P_{\rm loss} < P_{\rm input}$$

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

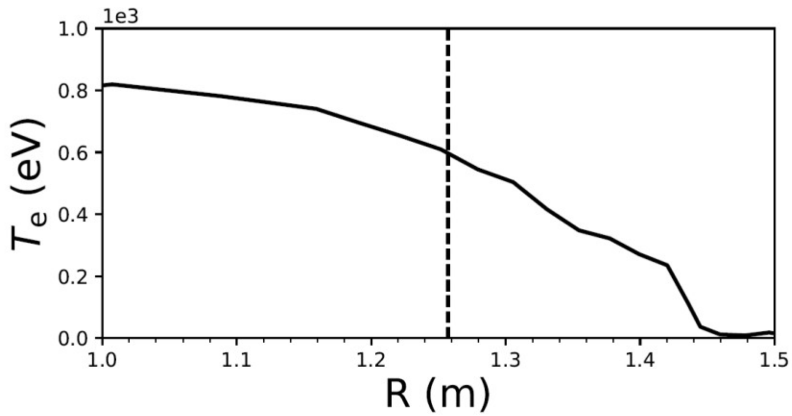
[D. Gates et al., Phys. Rev. Lett. **108** 165004 (2012)]

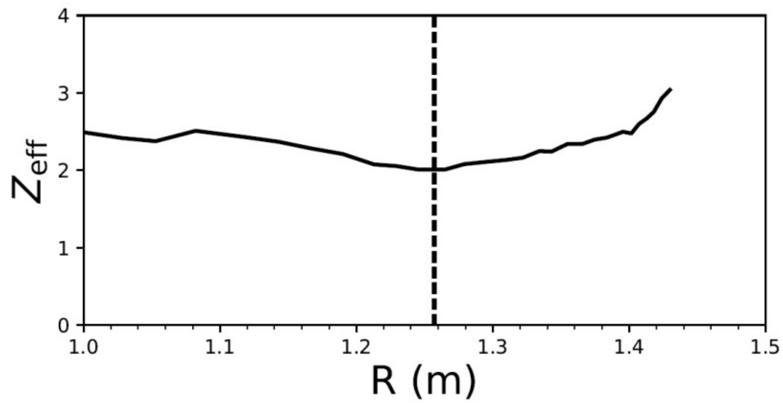
Discharges from NSTX were selected to test the theory

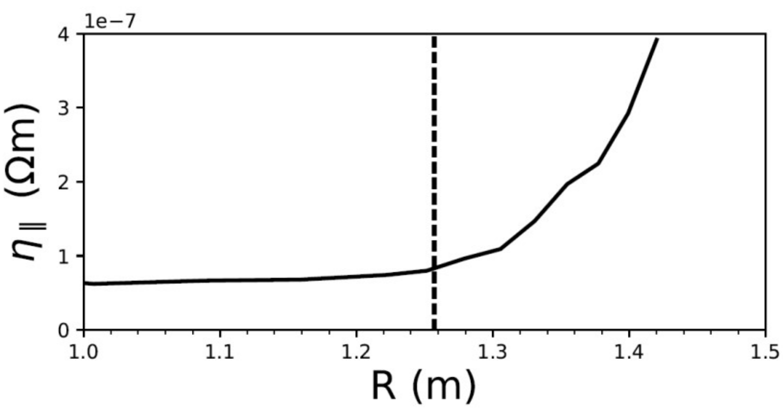
- Discharges selected with:
  - long flat-top periods of rising density
  - no MHD activity until low frequency n=1 activity appears
    - with a clean signature in the spectrogram
    - lasts less than 200 ms
    - then the discharge terminates



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







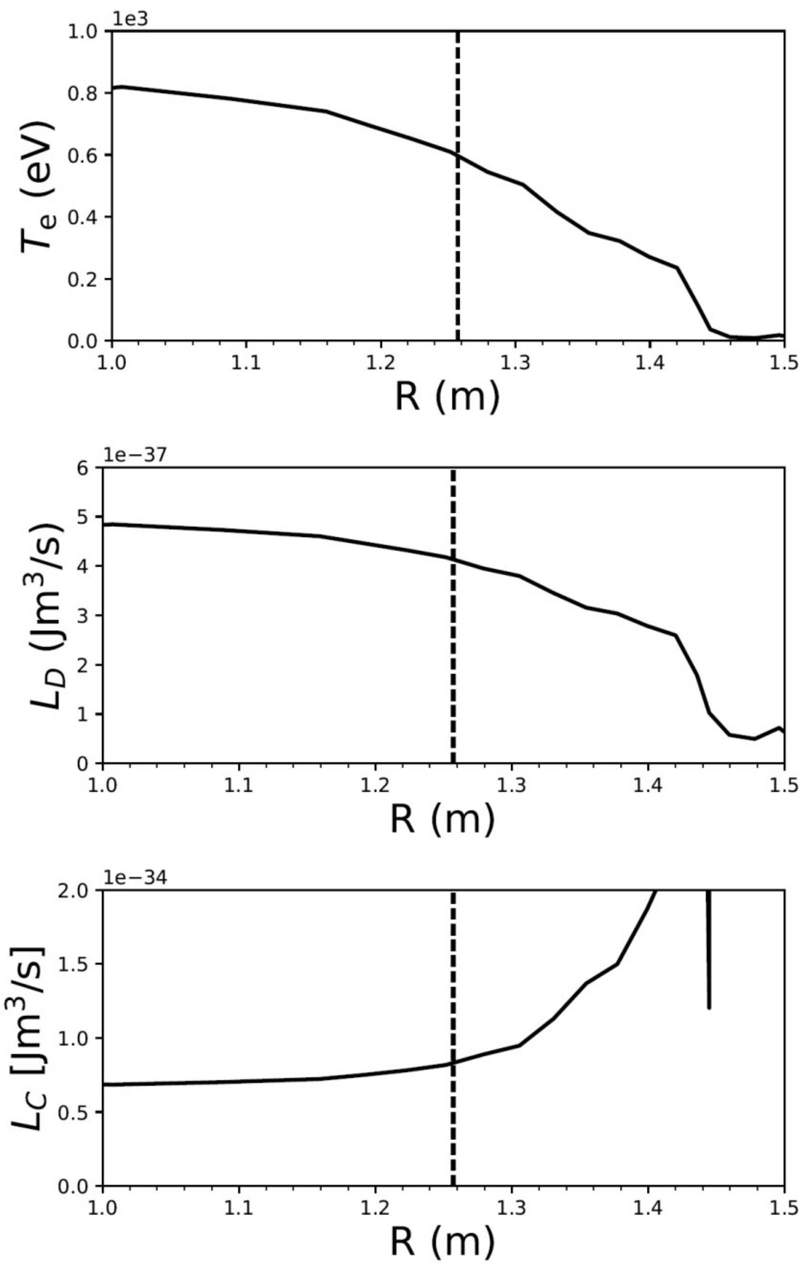
$$n_e n_{\mathrm{D}} L_{\mathrm{D}}(T_e) + \sum_Z n_e n_Z L_Z(T_e) < \eta j^2$$

- 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



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

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

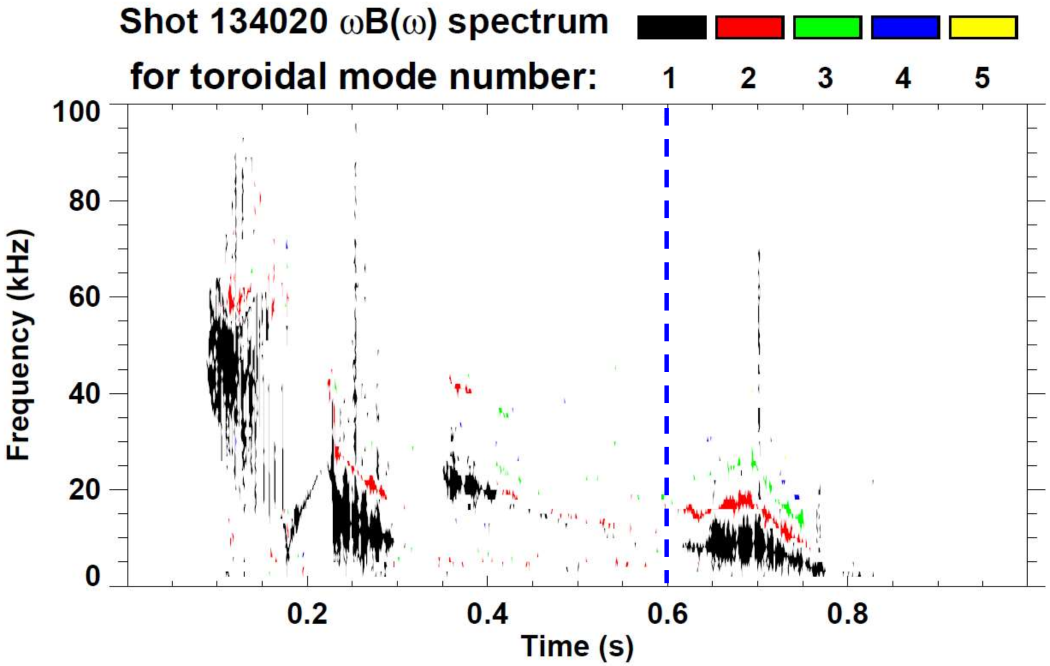
$$L_D = 5.35 \times 10^{-37} T_e^{1/2}\ (\mathrm{keV})\ W \cdot \mathrm{m}^3$$

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

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

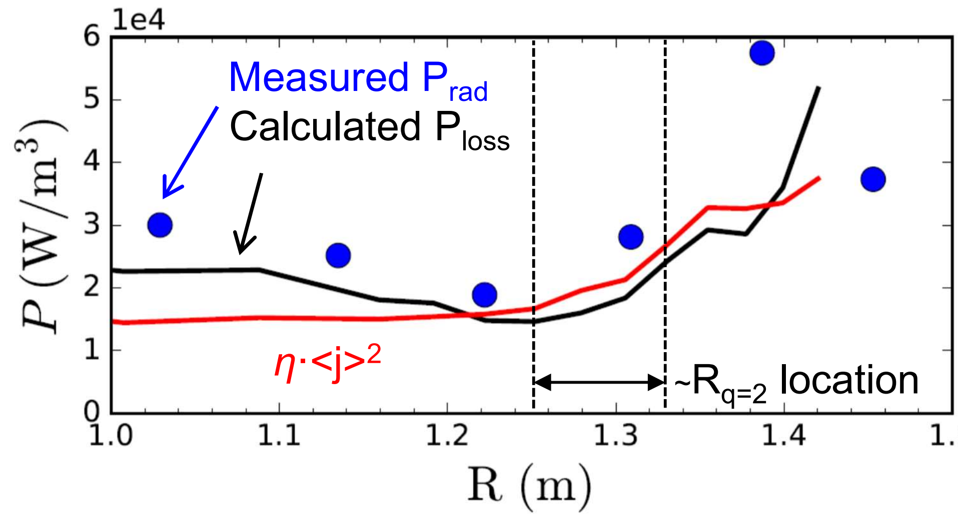
[D.E. Post et al., At. Data Nucl. Data Tables **20** 397–439 (1977)]

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



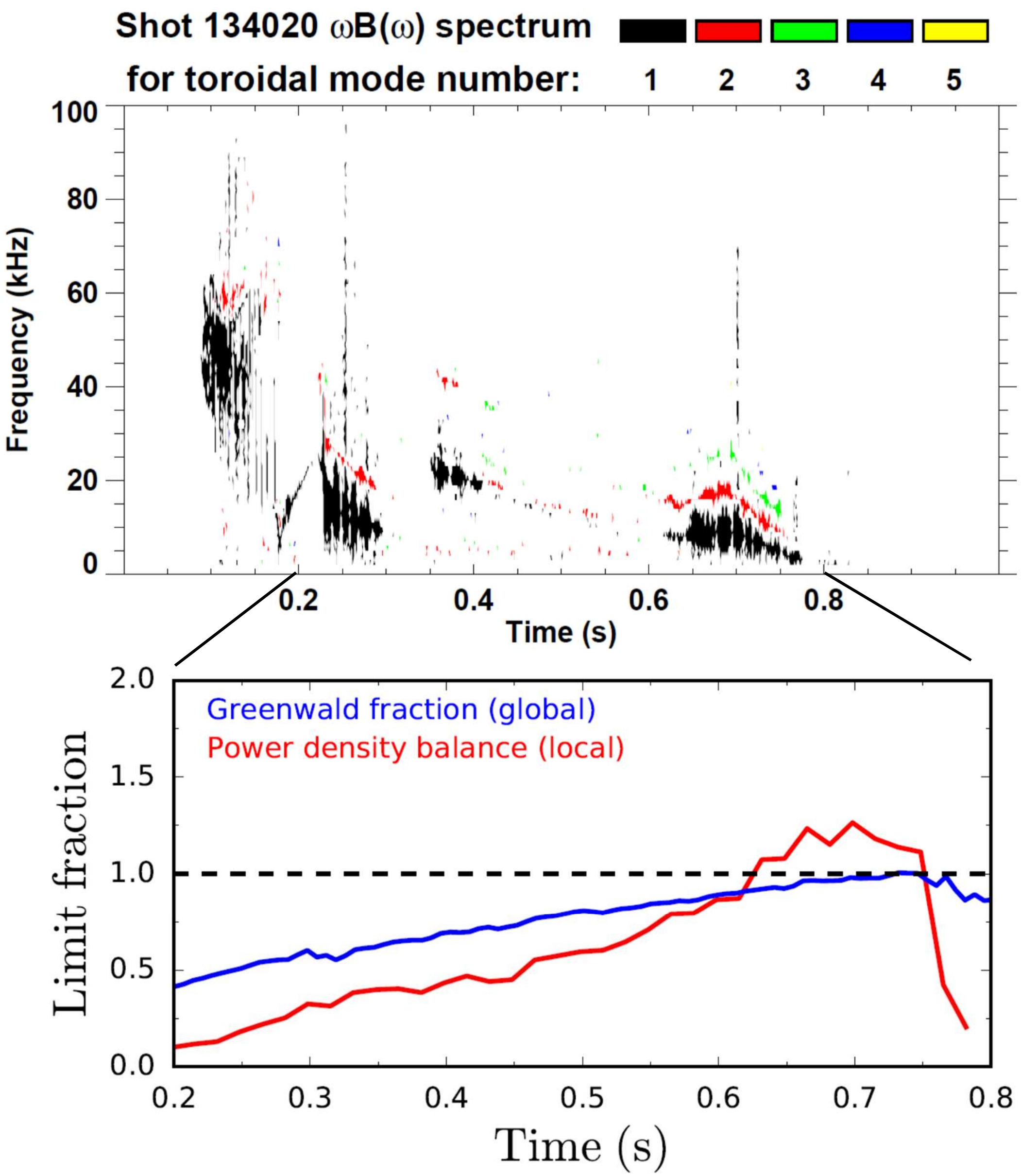
Power density balance

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



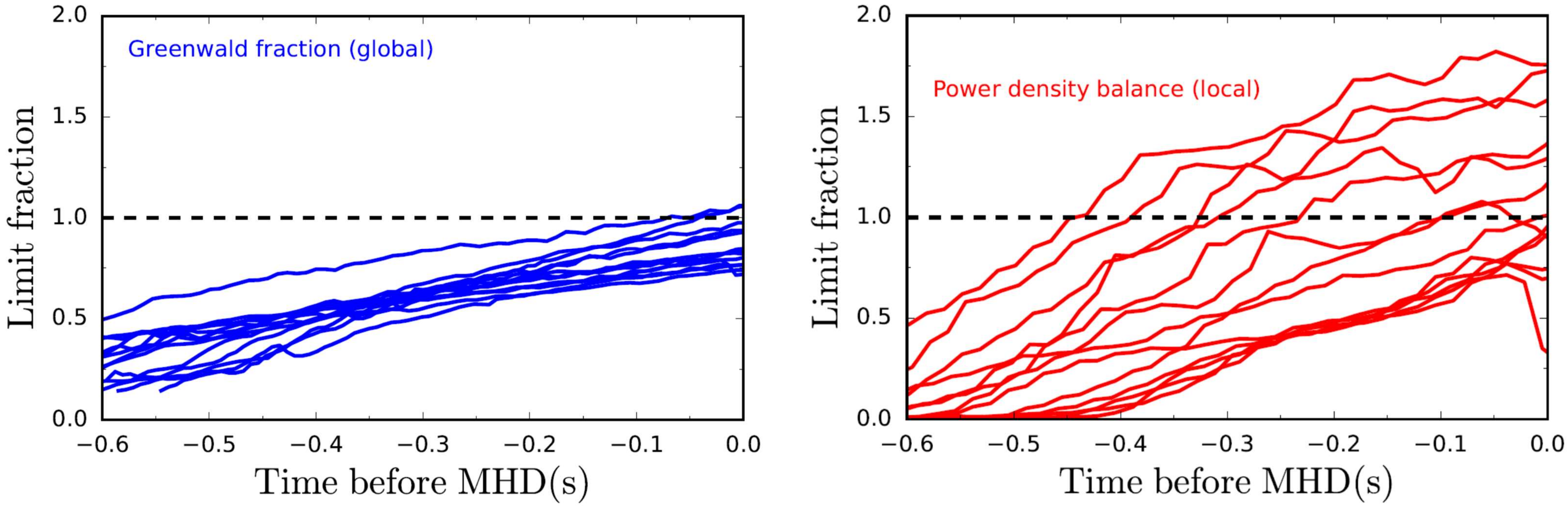
- Power balance at q=2 location is just at the limit before MHD activity onset
  - P_{input} calculated using total current density
  - P_{loss} slightly below measured P_{rad}

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



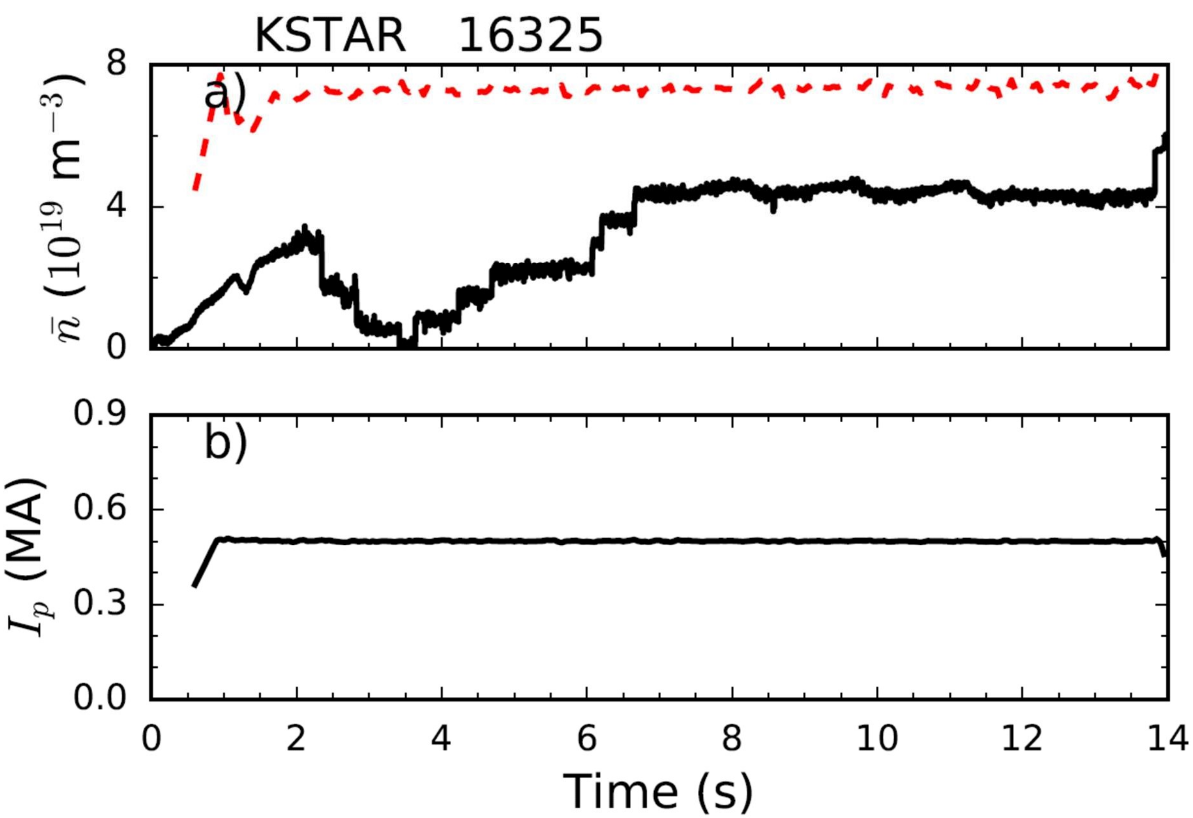
- Greenwald limit within about 30% at time of disruption
  - Consistent with previous studies
  - May be sufficient when combined with other DECAF analysis
- Initial implementation of power balance model follows GW trend
  - Presently determining if different input parameter assumptions can reduce variation

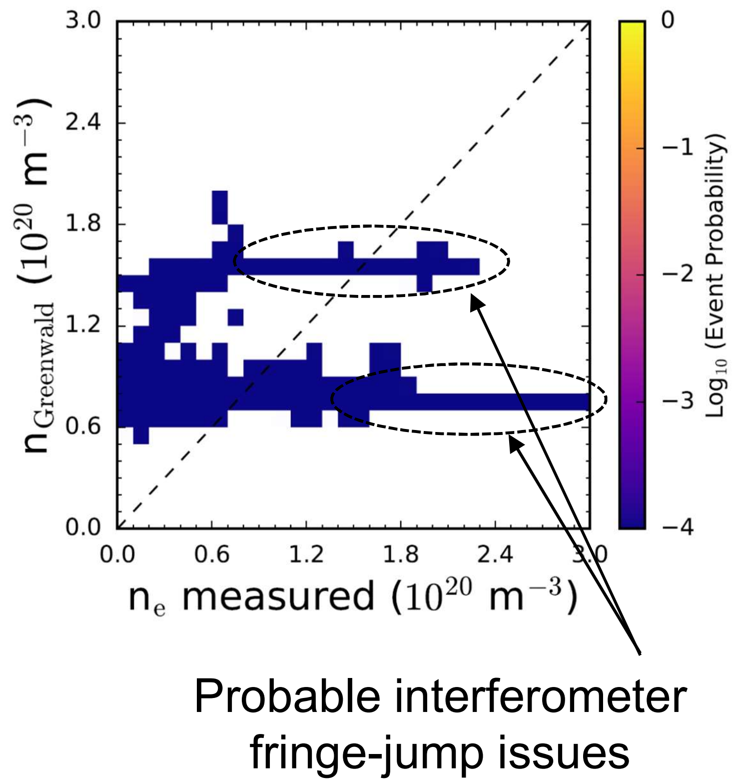
Conclusions

- 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
- Evaluation of the local island power balance limit has begun in DECAF
  - Shows some potential promise as a disruption warning

backup

DECAF disruption analysis of KSTAR plasma has begun

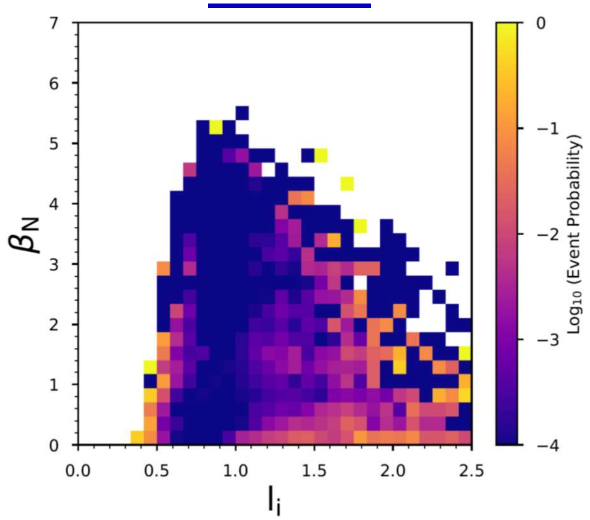




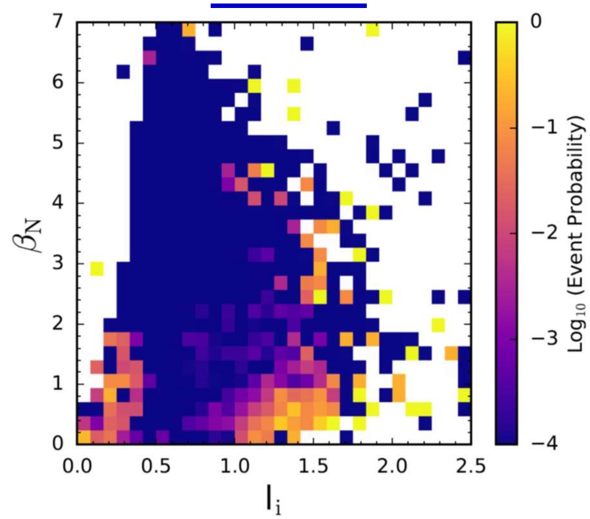
- Because of the long pulse lengths, disruptivity in KSTAR will be much lower than other machines
- First analysis of 70 discharges (in shot range 16300-16399) found zero disruptions

Cross-machine comparison of disruptivity vs. β_N and l_i

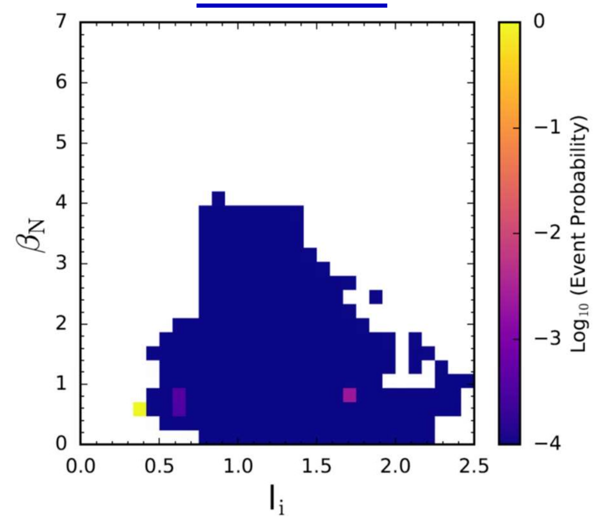
MAST



NSTX



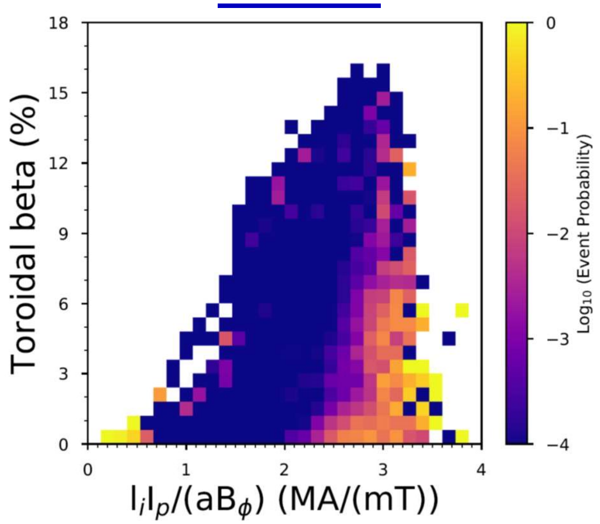
KSTAR



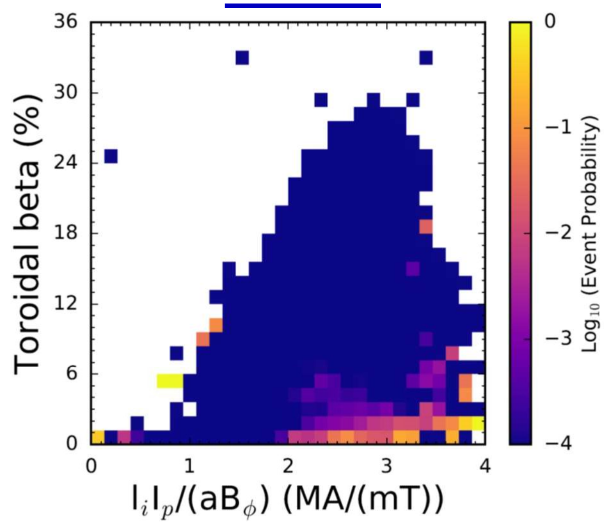
- 8902 MAST discharges
  - Kept only those with EFIT data from a range of 15,363 discharges (M5 - M9 campaigns: 13005-30473, May, 2005 – Sept. 2013)
- 4706 NSTX discharges
  - Those with EFIT data from a range of 10,000 discharges (130000-140000)
- 750 KSTAR discharges (8 (!) disruptions)
  - Those with EFIT data from a range of 1,000 discharges (16000-17000)

Cross-machine comparison of disruptivity

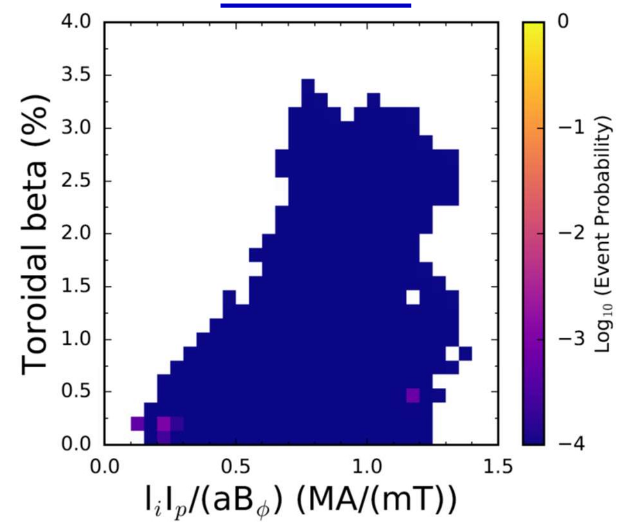
MAST



NSTX



KSTAR



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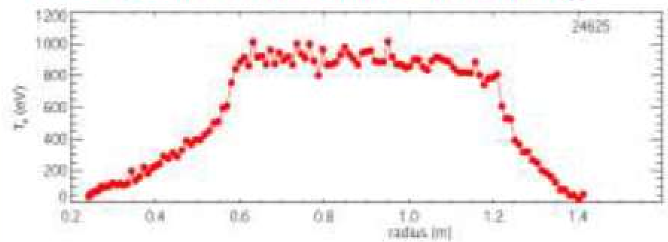
MAST-U has world class diagnostics for high quality kinetic reconstructions required for stability analysis

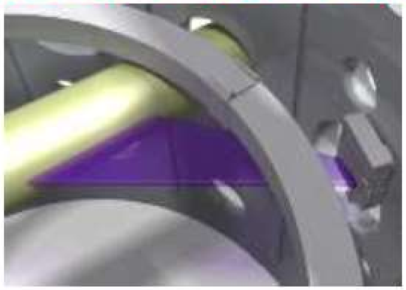
- MAST-U has world class diagnostics for kinetic reconstructions
  - Comprehensive set of magnetics
  - High resolution Thomson scattering measurements of electron temperature and density
  - Charge exchange recombination spectroscopy measurements of ion temperature, toroidal velocity, and impurity density
  - Magnetic field pitch angle measurements from motional Stark effect diagnostic for q profile reconstruction
- Energetic particle pressure profiles to be obtained from TRANSP analysis

Core & edge diagnostics

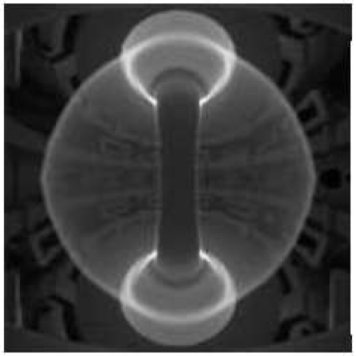
130 pt Thomson scattering



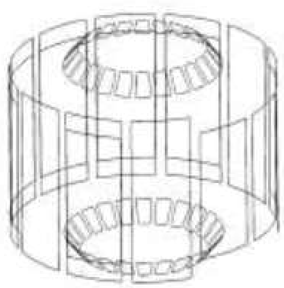
Charge-exchange, MSE, BES



Visible imaging



Magnetics

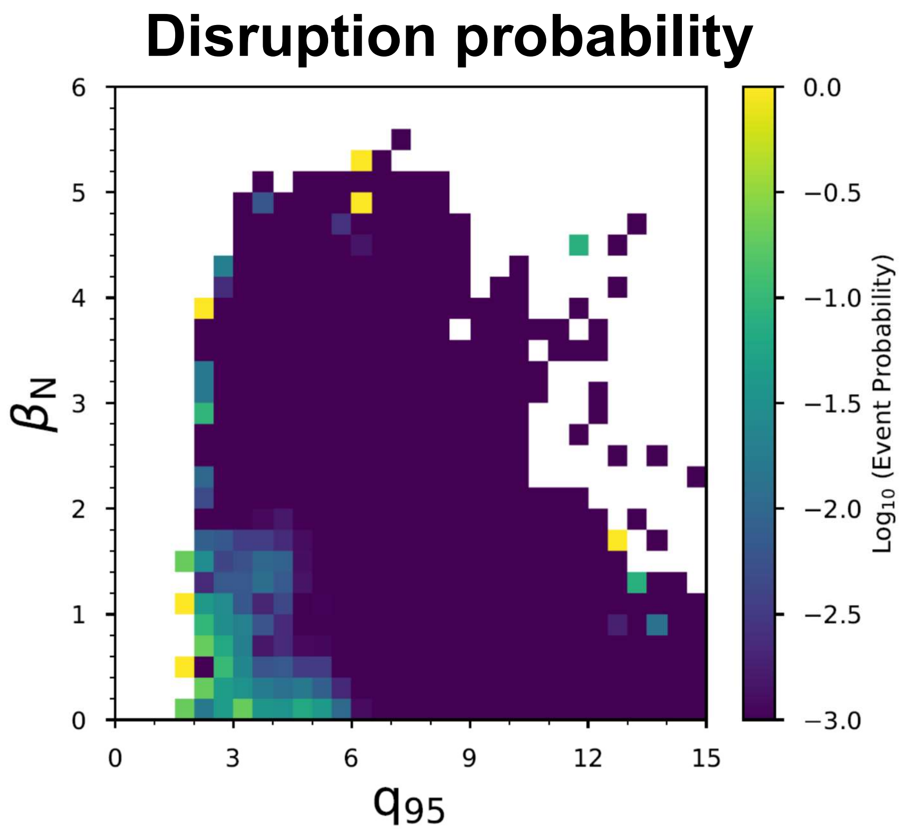


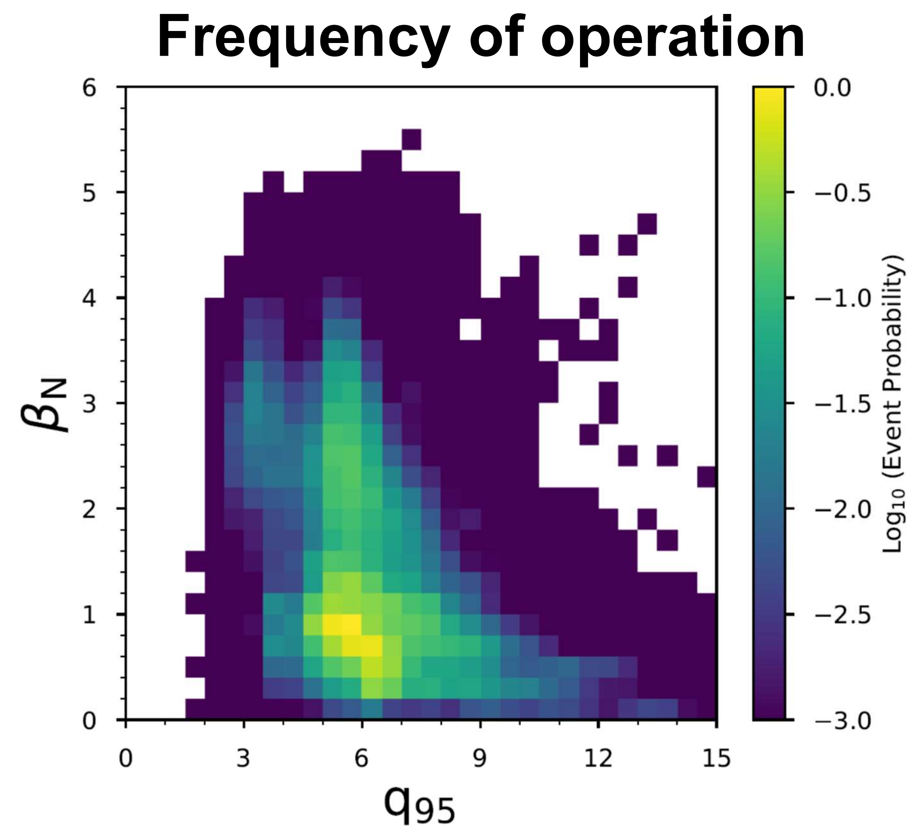
(J. Harrison, APS (2017))

MAST-U has world class diagnostics for high quality kinetic reconstructions required for stability analysis

- MAST-U has world class diagnostics for kinetic reconstructions
  - Comprehensive set of magnetics
  - High resolution Thomson scattering measurements of electron temperature and density
  - Charge exchange recombination spectroscopy measurements of ion temperature, toroidal velocity, and impurity density
  - Magnetic field pitch angle measurements from motional Stark effect diagnostic for q profile reconstruction
- Kinetic reconstructions are necessary for stability analysis
  - Sufficient for disruptivity plots
  - Required for advanced density limit analysis; profile for pressure peaking
  - Needed for kinetic resistive wall mode (RWM) stability calculations; rotation can also affect long-lived mode (LLM)
  - Locked modes and LLM stability analysis need accurate q profile
- Energetic particle pressure profiles to be obtained from TRANSP analysis → EPs can also affect RWM, LLM, and fishbone stability

The range of high disruptivity does not generally overlap with the range of highest frequency of operation





Plot shows normalized number of time points in the database spent in each square of parameter space (here the maximum, 1 (Log10 = 0) is equal to 3850)

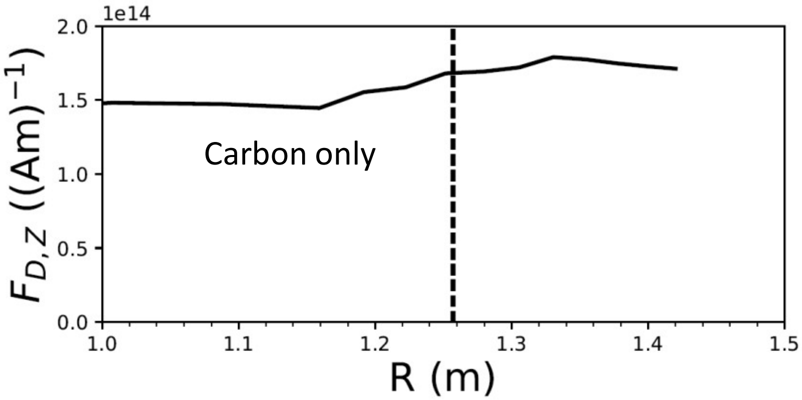
DECAF calculation of local density limit tested for NSTX discharge 134020 @ 0.60 s

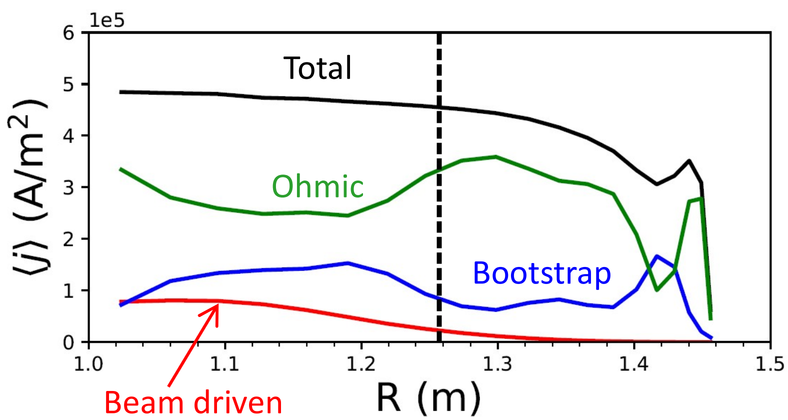
Two equivilent criteria for radiation-driven thermo-resistive island growth

Power density balance

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

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





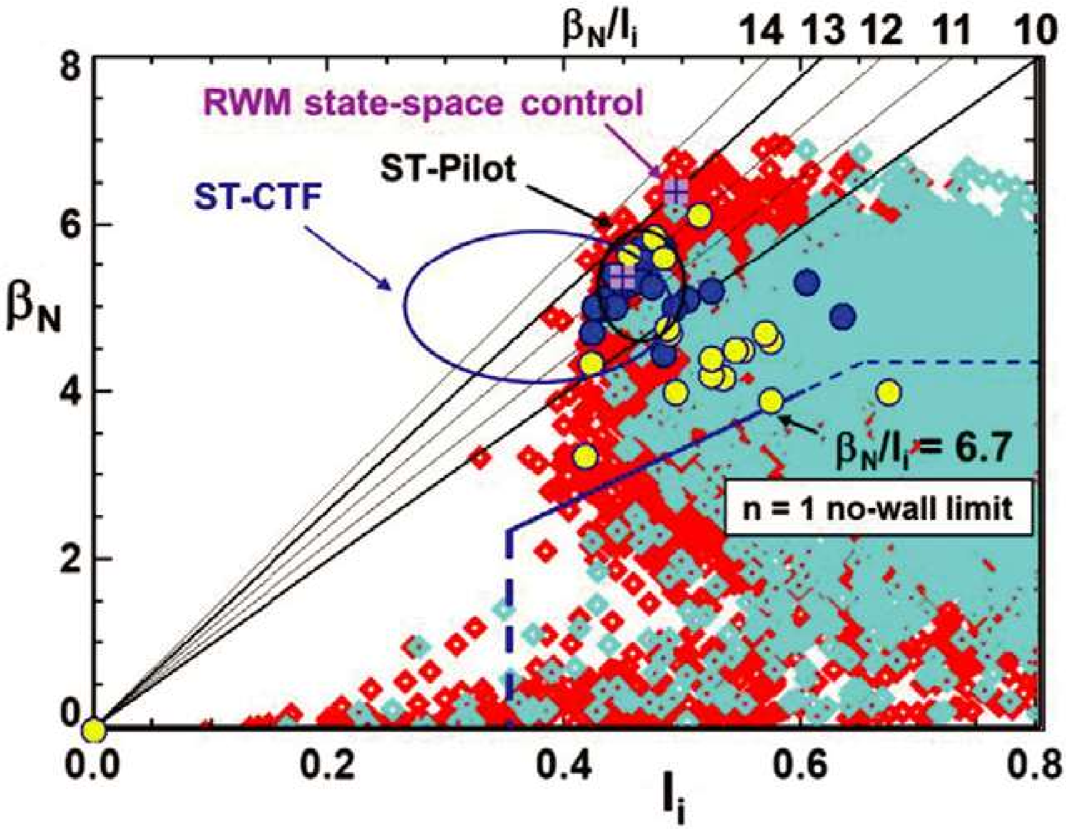
Density limit

$$n_e < \mathcal{F}_{\mathrm{D,Z}} \cdot j$$

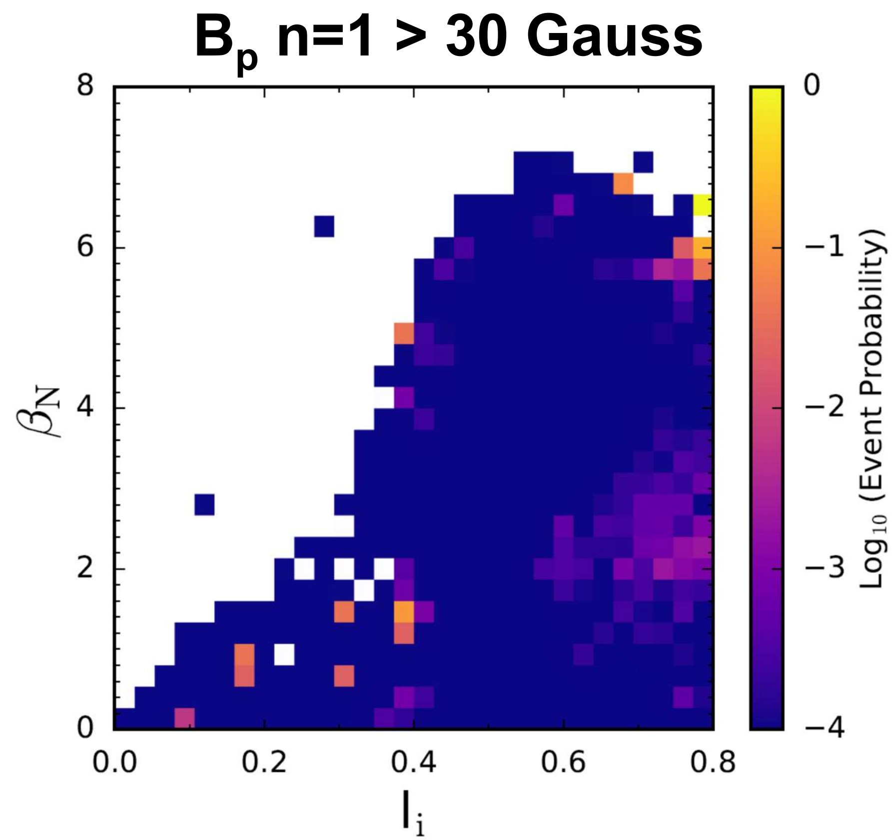
$$\mathcal{F}_{\mathrm{D,Z}} = \sqrt{\frac{\eta}{\frac{n_{\mathrm{D}}}{n_e} L_{\mathrm{D}} + \sum_Z \frac{n_Z}{n_e} L_Z}}$$

- $F_{D,Z}$ term
  - Calculated using η, n_D/n_e, n_C/n_e, L_D, L_C
  - Could be updated with other impurities
  - Could be calculated with measured P_{rad}
- Ohmic current density profile
  - Calculated with TRANSP
  - Uses flux surface average

Insight can be gained by illustrating where in parameter space DECAF events happen

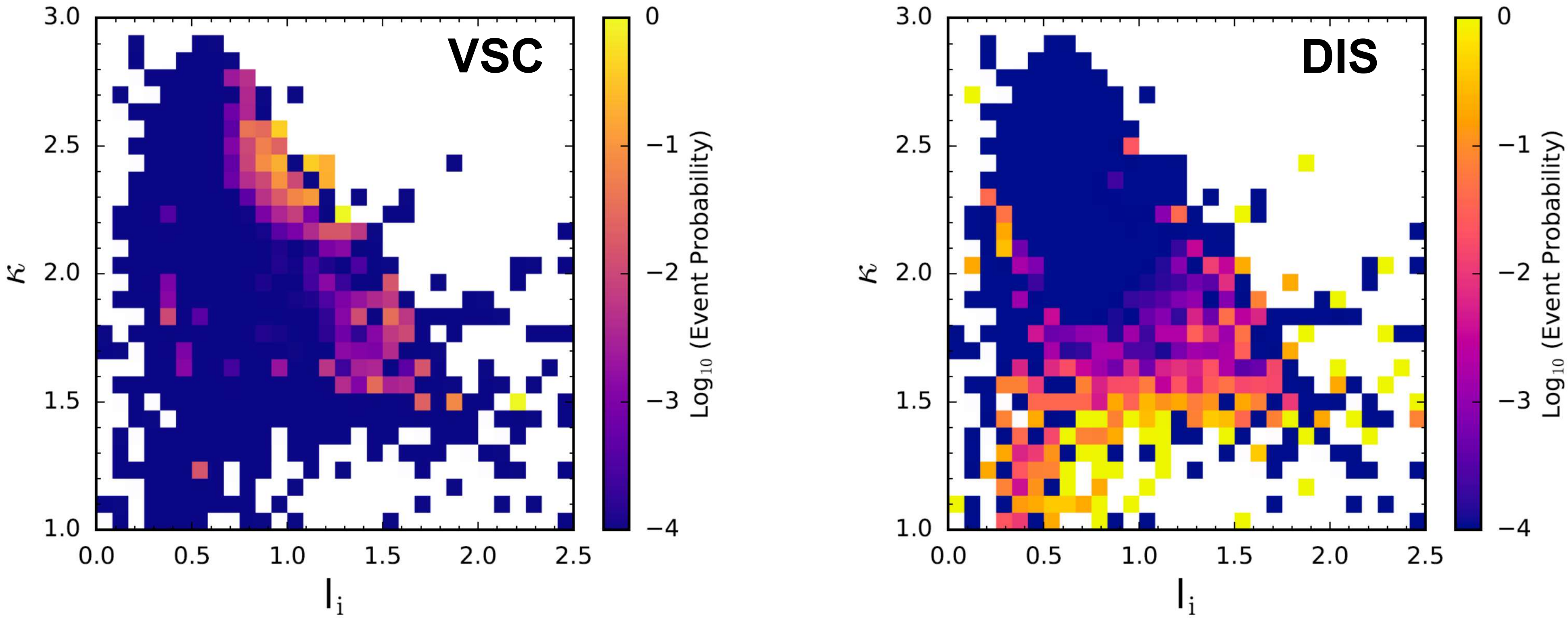


[S. Sabbagh et al., Nucl. Fusion 53, 104007 (2013)]



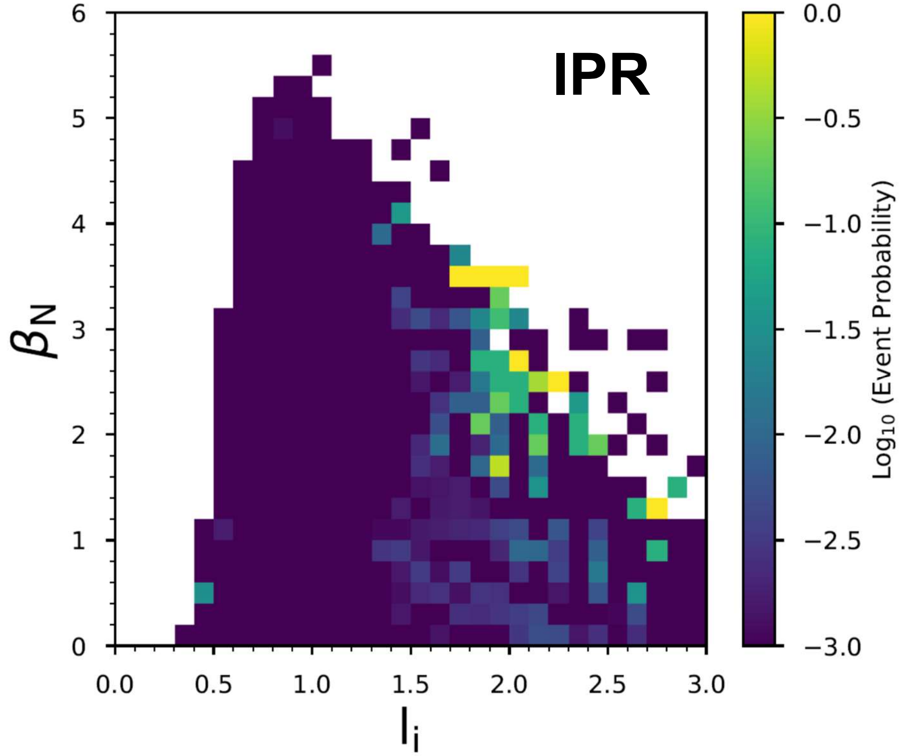
- NSTX plasmas were not the least stable at highest β_N/l_i
  - RWM magnetic sensor also does not tend to cross a threshold in high β_N/l_i space

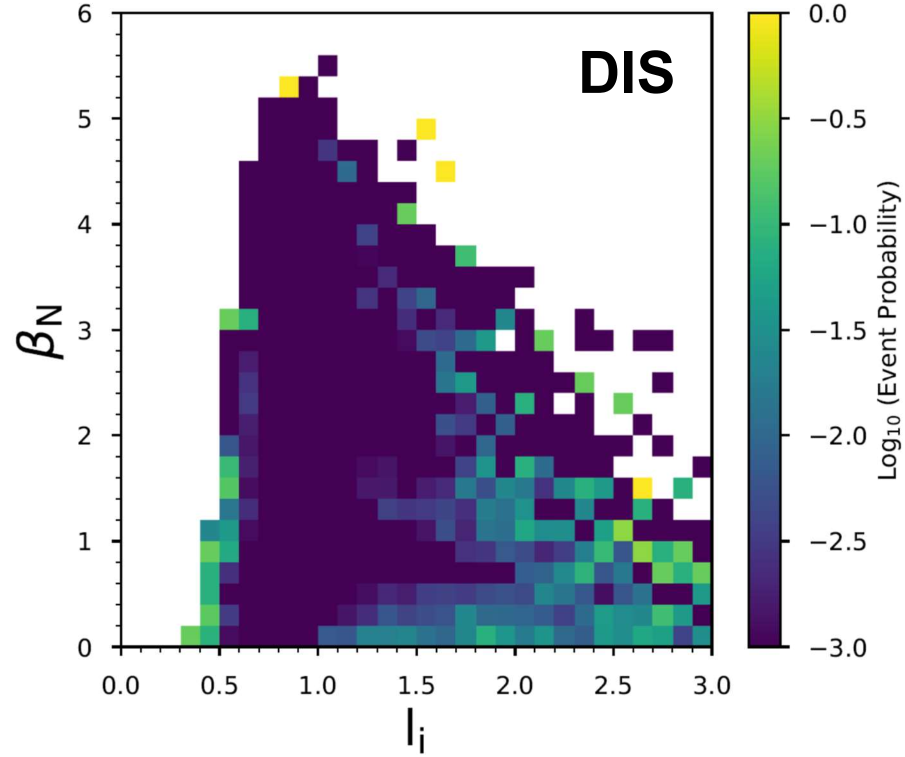
Insight can be gained by illustrating where in parameter space DECAF events happen (other than DIS)



- Vertical stability in NSTX shows a strong dependence on elongation and internal inductance
  - Similar to result from [Boyer, APS (2017)]

Instead of disruptivity plots, DECAF can produce more general event probability plots (2)





- Insight can be gained by comparing where events happen
  - IPR (plasma current not meeting request) generally happens at higher beta
  - DIS often happens during beta collapse, or rampdown