Abstract

A database comprised of the temporal evolution of several thousand DIII-D discharges from start-of-flattop to end-of-flattop or disruption was initially constructed in 1999 and extended thereafter. All discharges include at least 100 kW of auxiliary neutral beam heating. We report on several analysis results from this database. We use a "runs test of randomness" to show that plasma disruptions are not caused by random events. This analysis is done on the entire database and on several subsets of discharges with similar parameters. We show that disruptivity, the likelihood that a discharge in the database will disrupt, is statistically insensitive to β_n but is sensitive to low density and to q_{95} below 5. We also show that disruptivity tends to zero for plasmas which survive more than about 4 seconds after 95% of the maximum achieved β_n is reached.

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INTRODUCTION

A Disruption is the rapid (> 10 MA/s) uncontrolled loss of plasma current and energy. They can be initiated by causes external or internal to the plasma. In this poster we concentrate on internally caused disruptions. Disruptions are a major tokamak fusion energy issue due to the large amount of energy released (~ 1 GJ). A database of DIII-D shots from 1998 – 2001 is generated to study internally caused disruptions.

In this study we find:

- Disruptions are NOT statistically random events.
- The likelihood of disruption drops sharply, maybe to zero, after several seconds evolution at the working β level.

Disruptivity is usually discussed in terms of probability of disruption per shot, not per unit time. Per-shot analysis requires a determination of how (or when) to characterize the shot parameters.

- **Both per-shot and per-time disruptivity are required as pulse lengths increase.**
- **Using parameters characterized at a single time such as the time of maximum beta can give misleading results.**
- **Per-shot analysis may be useful in determining parameter regions of low disruptivity.**

An average disruptivity over many shots does NOT imply disruptions are statistically random for any given set of plasma parameters.

DIII-D has run many consecutive shots without disruption

Constructing the Database

Shots are candidates for the database if they reside in the online MDSPlus database and have MSE data available. This means they have some neutral beam heating.

- The MDSPlus database contains the standard plasma operations' automatic EFITs that typically span the discharge at 50 msec intervals.

Candidates are excluded by exhibiting:

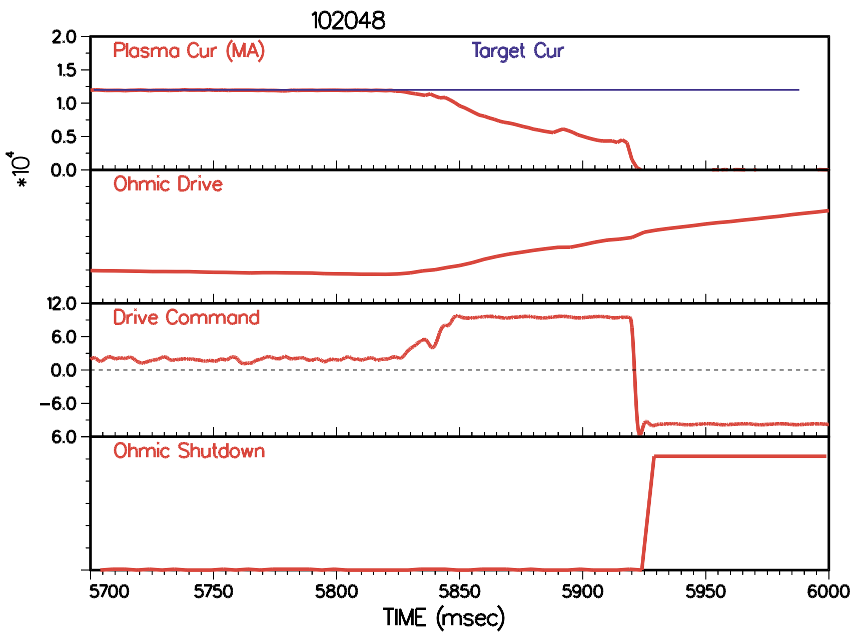
- Excessive impurity gas injection (> 10 T-l).
- Disruption in current rampup.
- Forced disruption experiments.
- Poor EFIT equilibrium analysis ($\chi^2 >$ 100)

Acceptable candidates are labeled 'terminated' if factors outside the plasma initiate loss of current – such as a loss of Ohmic drive or a shaping coil power supply. A shot has 'disrupted' if the plasma initiates the loss of current.

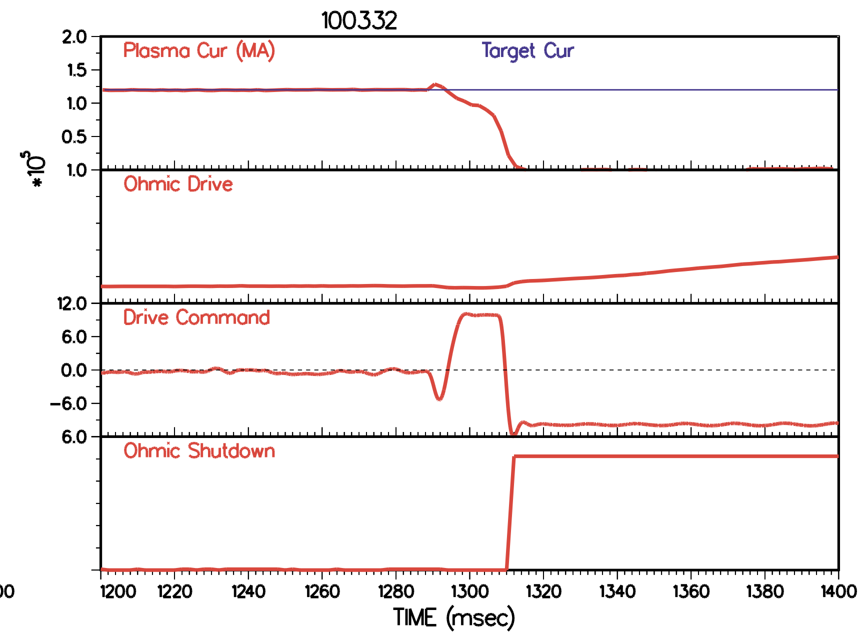
Constructing the Database (con't)

Shots are considered disruptive if they meet the criteria:

- **Plasma current falls to zero while under active plasma current feedback control.**
- **The current fall starts in programmed flattop.**



Not Disruptive



Disruptive

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About 14% of All Shots Disrupt in DIII-D

Starting with this year's shots and going back a couple of years the database presently is comprised of:

- **3856 candidate shots from 1998-2001**
- **3594 analyzed shots. Those excluded are due to:**
  - **3 "forced disruption" shots**
  - **197 high volume impurity injection shots**
  - **62 poor fit quality EFIT data shots.**
- **493 internally caused disruptions in 3594 shots**

  This is an overall per-shot disruptivity in flattop of 0.137 (13.7%). This compares with a reported 9.6% flattop disruptivity in JT-60U (ref: ITER Physics Basis)

This disruptivity is averaged over all types of shots covering many varied parameters from many kinds of experiments.

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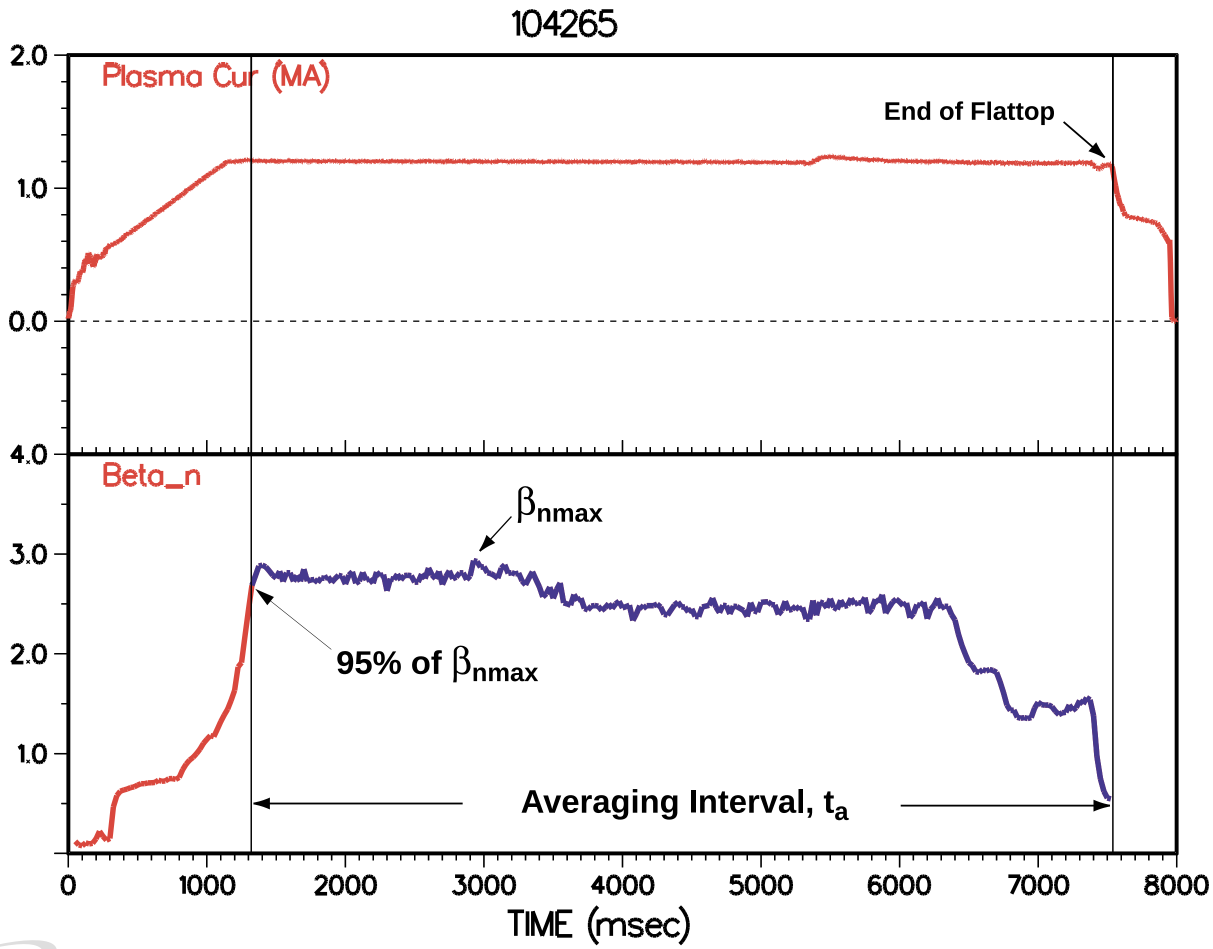
Averaging Interval for β_n

The AVERAGING INTERVAL, t_a, is defined as the time from first achieving 95% of β_{nmax} to the end of the flattop. Averaging β_n over this interval yields $<\beta_n>$.



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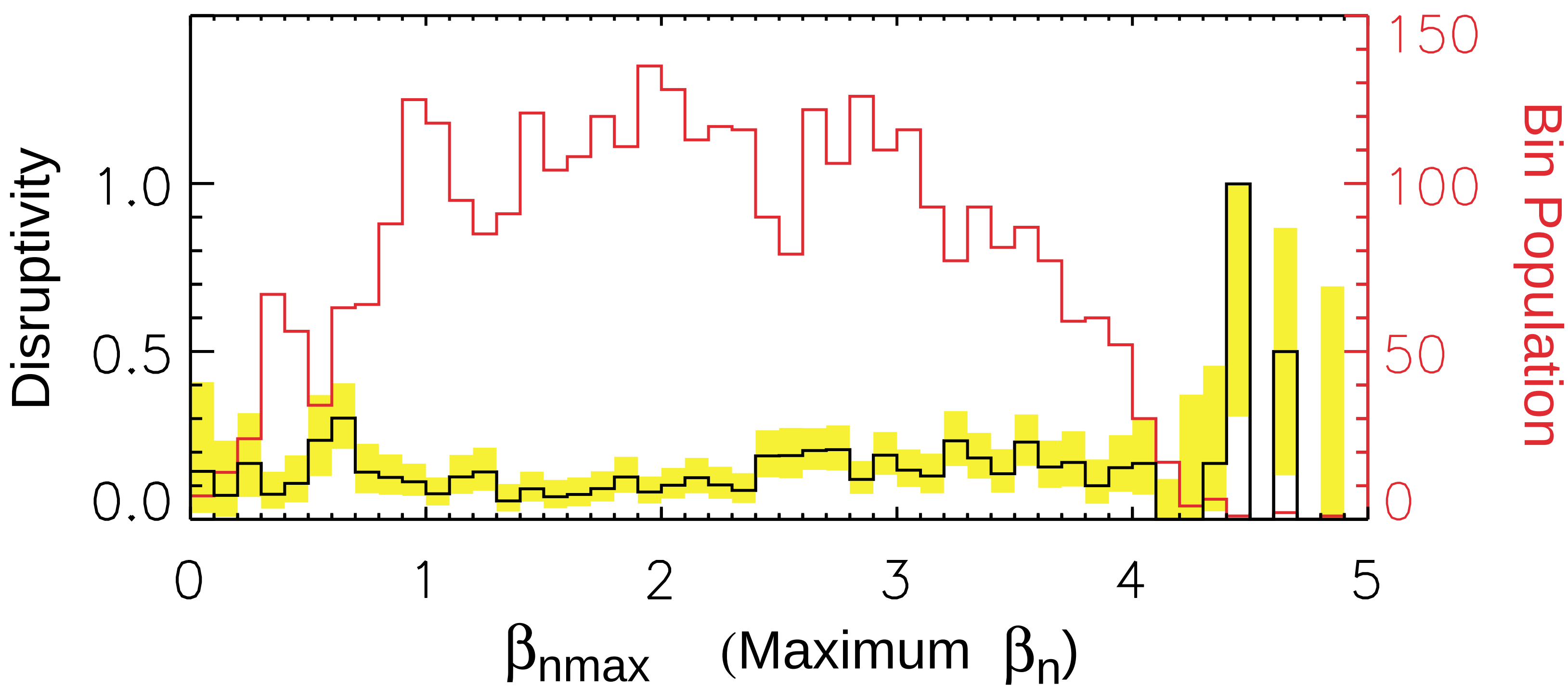
Disruptivity Appears Uncorrelated With β_{nmax}

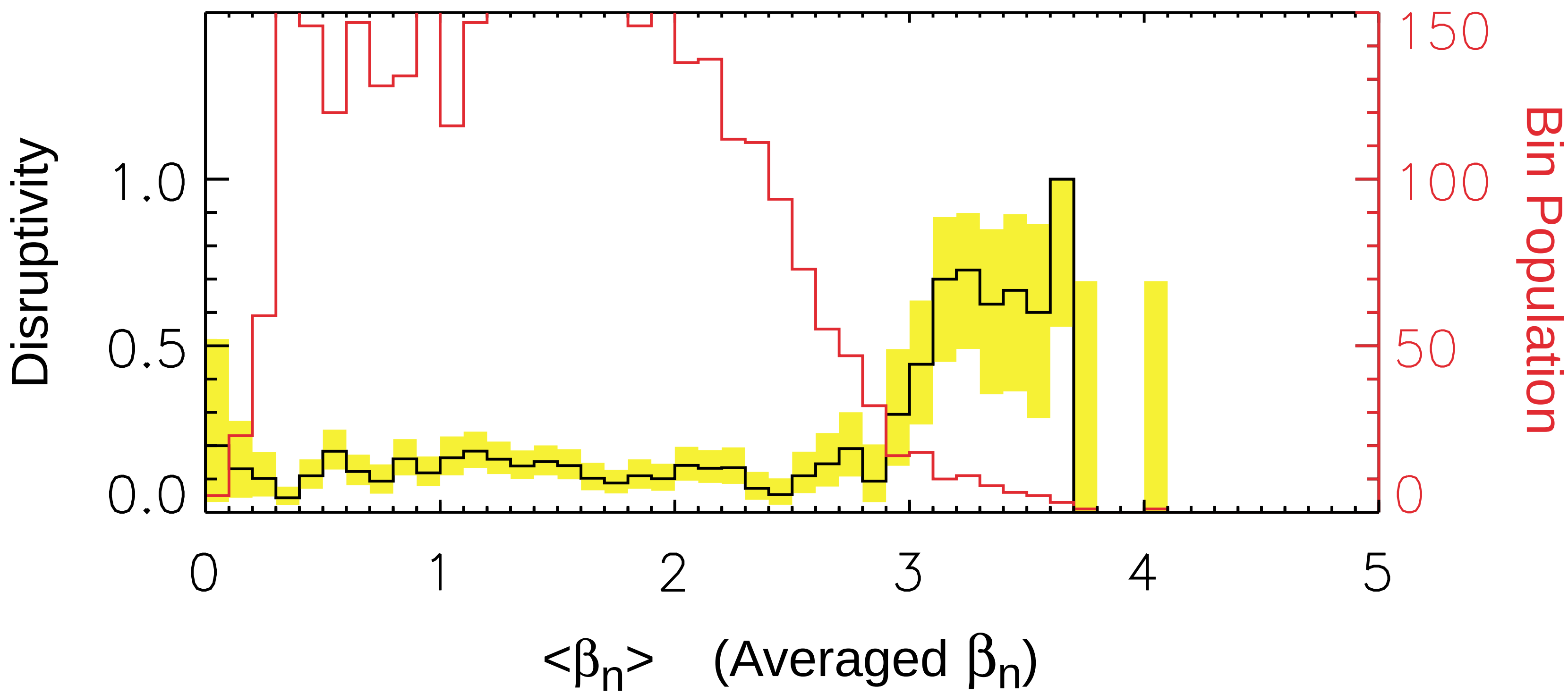
Disruptivity is the fraction of the bin population that disrupt.

The yellow shaded region is the 90% confidence limit for each bin



Disruptivity Rises Sharply at <β_n> ~ 3

This result and the β_{nmax} result together imply that if, after attaining a high β_{nmax}, the plasma then loses energy rapidly enough, either by instability or by design, it is no more likely to disrupt than any other plasma.



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Averaging β_n Illuminates Disruptivity at High β_n

Shot characterization using averaged β_n (from 95% of β_{nmax} to end-of-flattop) yields a clearer picture of the average disruptive β-limit boundary in DIII-D than using β_{nmax}.

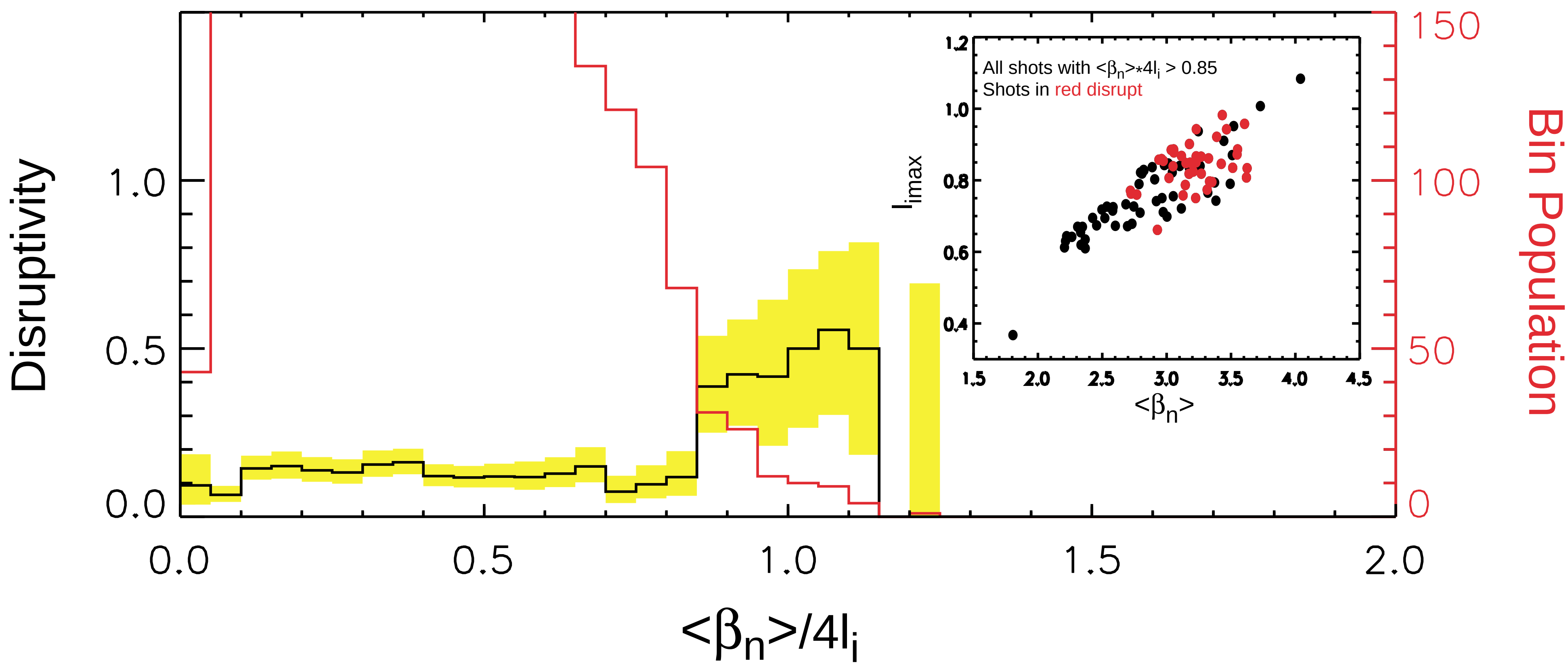
The β_{nmax} data show that simply attaining a high β_{nmax} does not increase the chances of disruption.

The $\langle\beta_n\rangle$ data show that a high $\langle\beta_n\rangle$ does increase disruptivity. But almost all of the $\langle\beta_n\rangle \geq 3$ shots that disrupt do so within 300 milliseconds of reaching β_{nmax}.

Together these results suggest that in DIII-D, reaching a high β_{nmax} usually just leads to a rapid loss of energy and a lower $\langle\beta_n\rangle$, but not a disruption. When a disruption does occur it is almost always ‘prompt’, so $\langle\beta_n\rangle$ remains high. These disruptions are causally linked to high $\langle\beta_n\rangle$. The reason they stand out in the $\langle\beta_n\rangle$ plot is the difficulty in sustaining high $\langle\beta_n\rangle$ plasmas; instabilities usually lead to lower $\langle\beta_n\rangle$. They exist but we’re just learning how to reliably make them.

$<\beta_n>_*4\,l_i$ results are similar to $<\beta_n>$ results

It appears that $<\beta_n>$, not $<\beta_n>_*4l_i$, is the relevant disruptivity parameter



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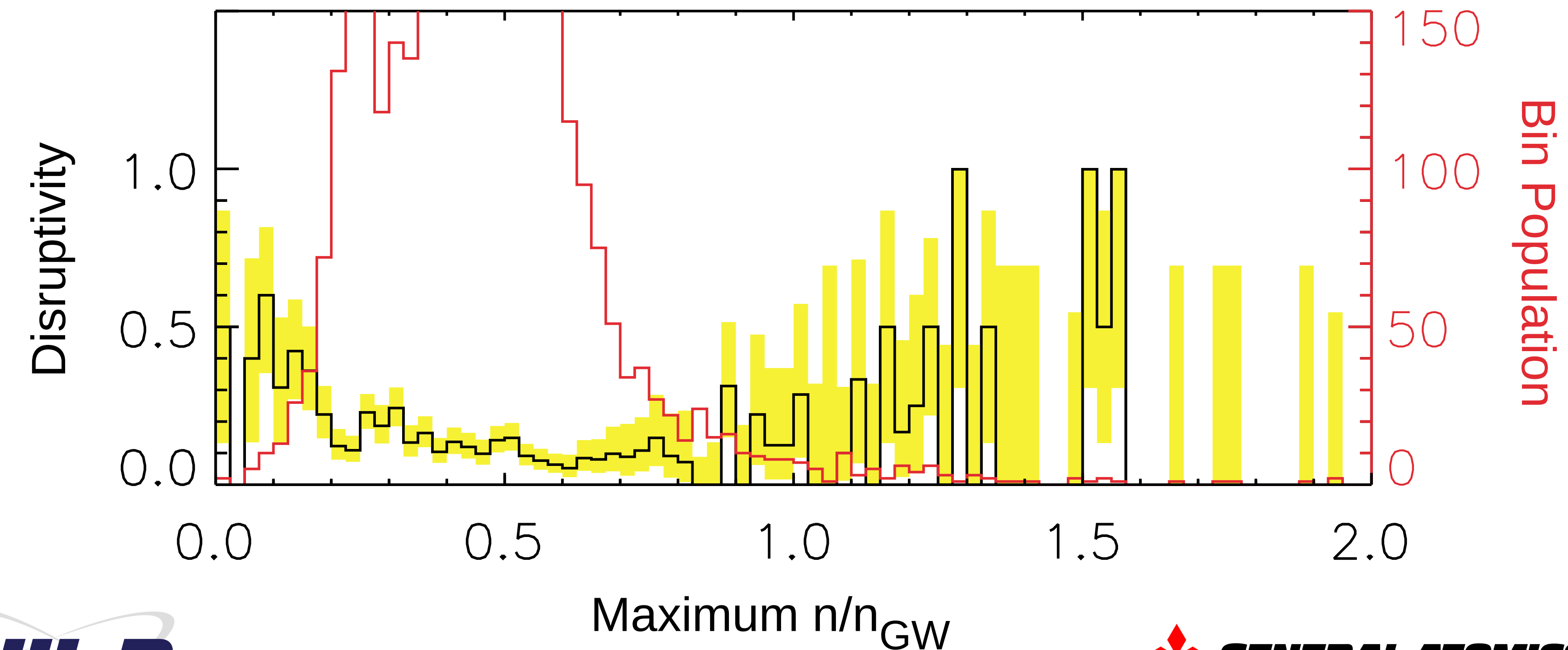
Disruptivity Has a Broad Minimum at $n/n_{GW} \sim 0.6$

Here we use the maximum attained n/n_{GW} as the measure. n/n_{GW} is the ratio of the density to the Greenwald density; $n_{GW} \propto I/\pi a^2$. Disruptivity rises sharply below $n/n_{GW} \sim 0.2$. This is due to the increased sensitivity to locked modes at low density. There is an apparent rise in disruptivity as n/n_{GW} increases past 1.0, but no sharp boundary is seen, and this may not be real. Overall disruptivity for $n/n_{GW} > 1.0$ is only 0.17, about the same as for $n/n_{GW} = 0.5$



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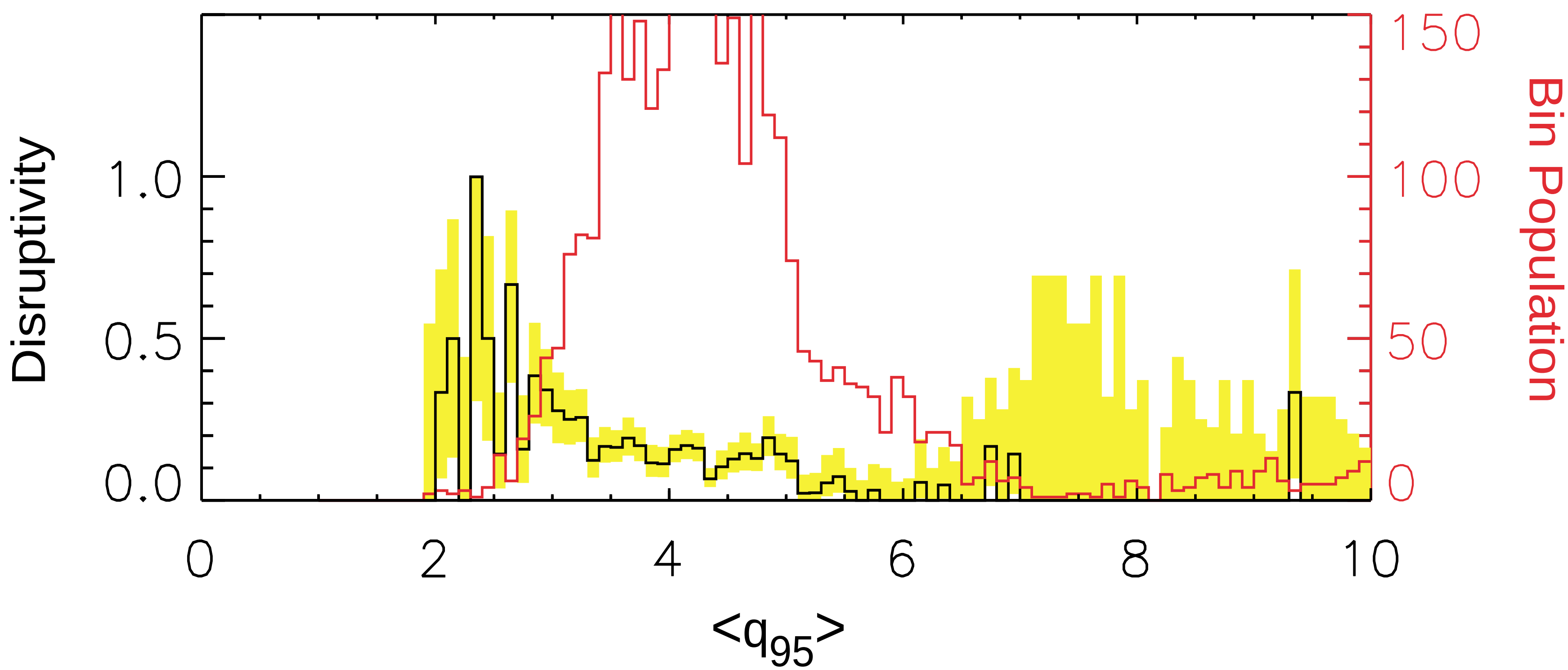
Disruptivity Drops at $\langle q_{95} \rangle$ ~ 5.0

Disruptivity drops rapidly as $\langle q_{95} \rangle$ rises past 5, and appears to rise as $\langle q_{95} \rangle$ decreases below ~ 3. Statistics are poor for $\langle q_{95} \rangle$ below 3. The drop at $\langle q_{95} \rangle$ ~ 5 is not seen on other machines [ref: ITER Physics Basis]. $\langle q_{95} \rangle$ is averaged over same interval as $\langle \beta_n \rangle$.

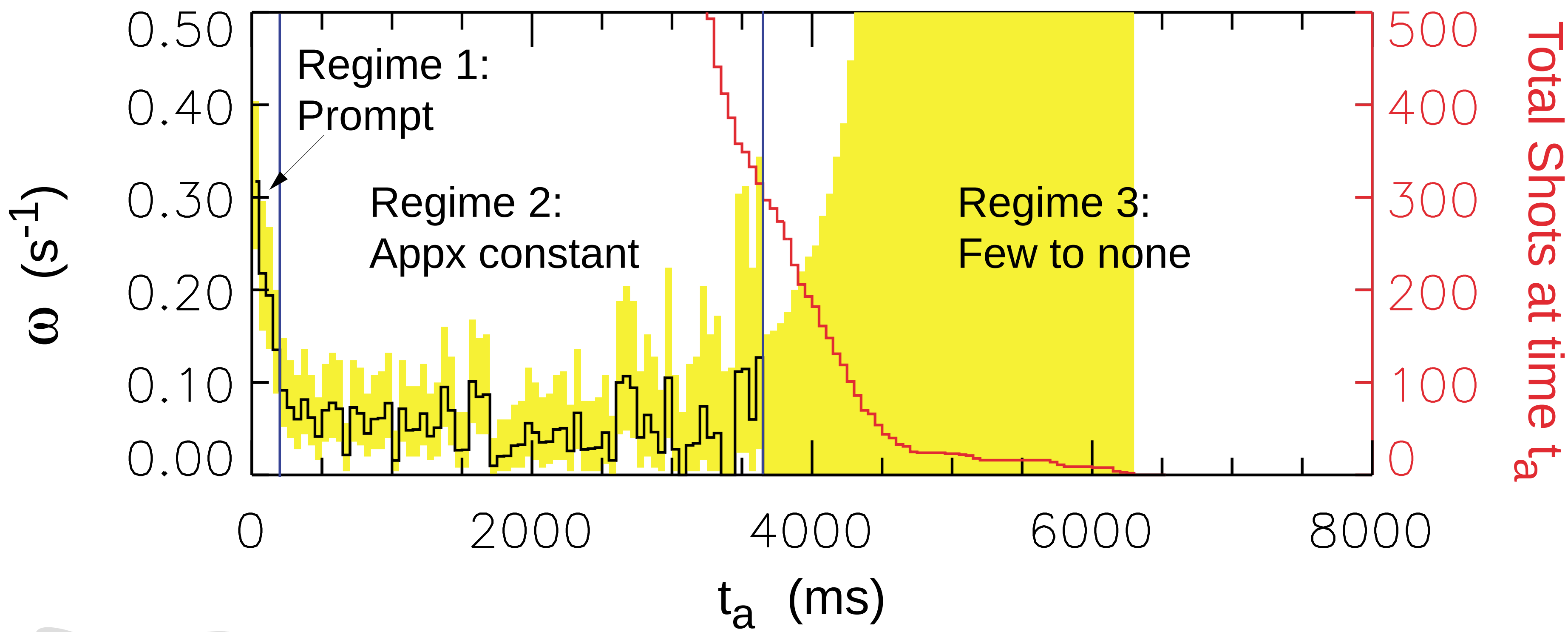


Per-time Disruptivity is Very Useful

Disruptivity measured on a per-second basis becomes more useful and meaningful as pulse lengths grow. We use the 'average elapsed time', t_a, of the $<\beta_n>$ characterization as the measure of pulse length, and calculate the percentage of shots that disrupt within 50 ms of reaching time t_a. Most shots leave this window by surviving into the next 50 ms time window, or by simple termination, but some disrupt. The fraction that disrupt, p, is related to the per-second disruption frequency, ω, by $p = \omega \Delta t_a$, where Δt_a = 50 ms.

Disruptivity/sec Drops to Zero as Shot Evolves

There appear to be three distinct disruptivity/sec (ω) regimes as shots evolve. In the first, 'prompt' regime there is a large increase in ω. In the second regime ω is to good approximation a constant. In the third regime, ω drops to one tenth or less of the constant ω of the second regime.



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Three Distinct Disruption Frequency Regimes

1) t_a < 200 ms: Prompt disruptions

About one third of all disruptions are prompt. Promptness suggests these disruptions are directly caused by β. About one third of these have $<\beta_n> \geq 3.0$

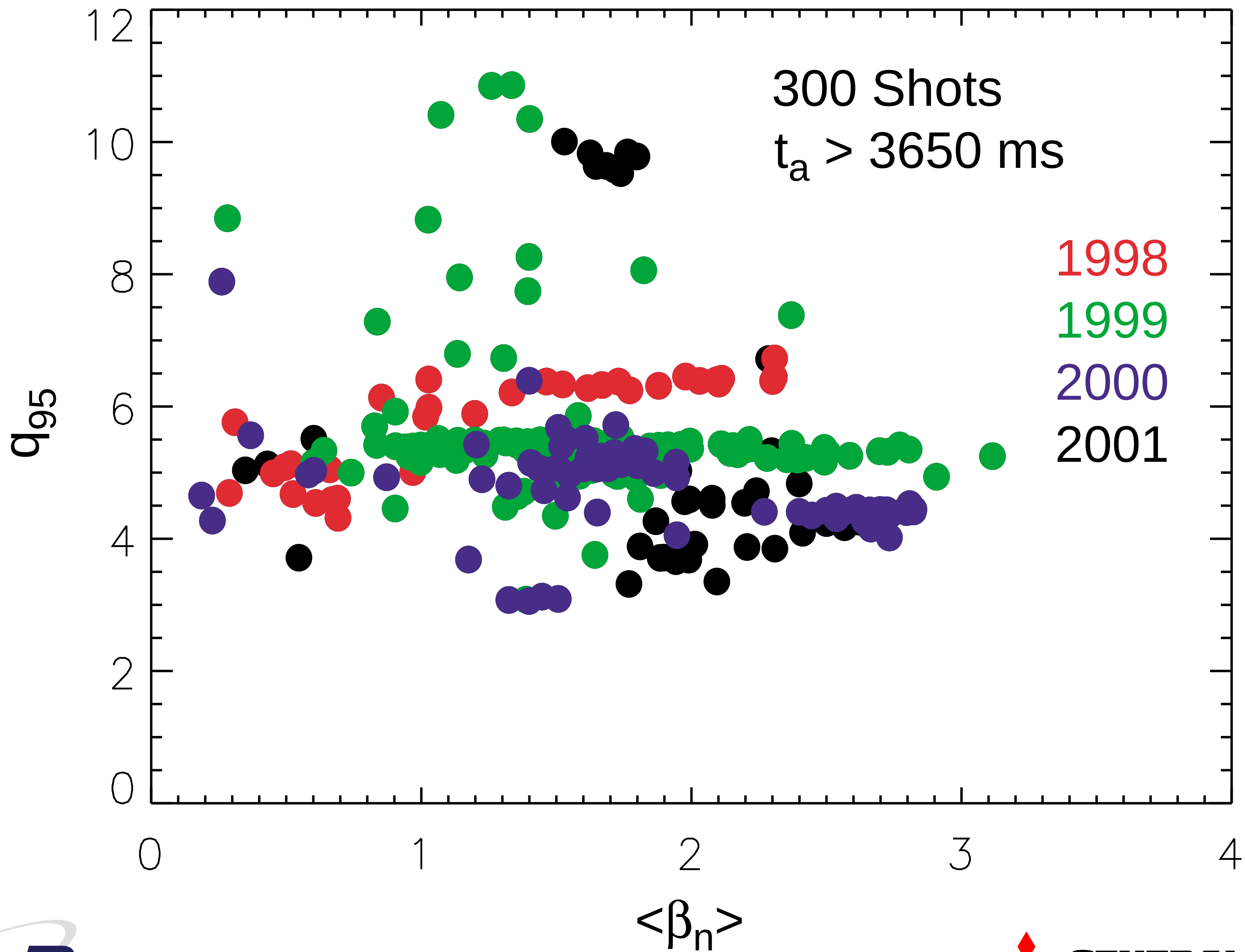
2) 200 < t_a < 3700: $\omega \approx 0.08\ s^{-1}$ everywhere

About two thirds of all disruptions occur in this regime. They appear not to be directly correlated with β_{nmax} or $<\beta_n>$.

3) t_a > 3700 ms: ω drops at least 10x, maybe to zero

About 300 shots populate this regime. If the constant ω of the middle regime held here there should be about 10 disruptions. Then the odds of no disruptions occurring is less than 1 in 50,000. This regime appears real. The time scale of several seconds is suggestive of the global current relaxation time in DIII-D. It may be that $<\beta_n>$ could be slowly raised in this regime to levels not attainable in the other two regimes.

Regime 3 Shots Span $\langle\beta_n\rangle$, q_{95} And All Campaigns



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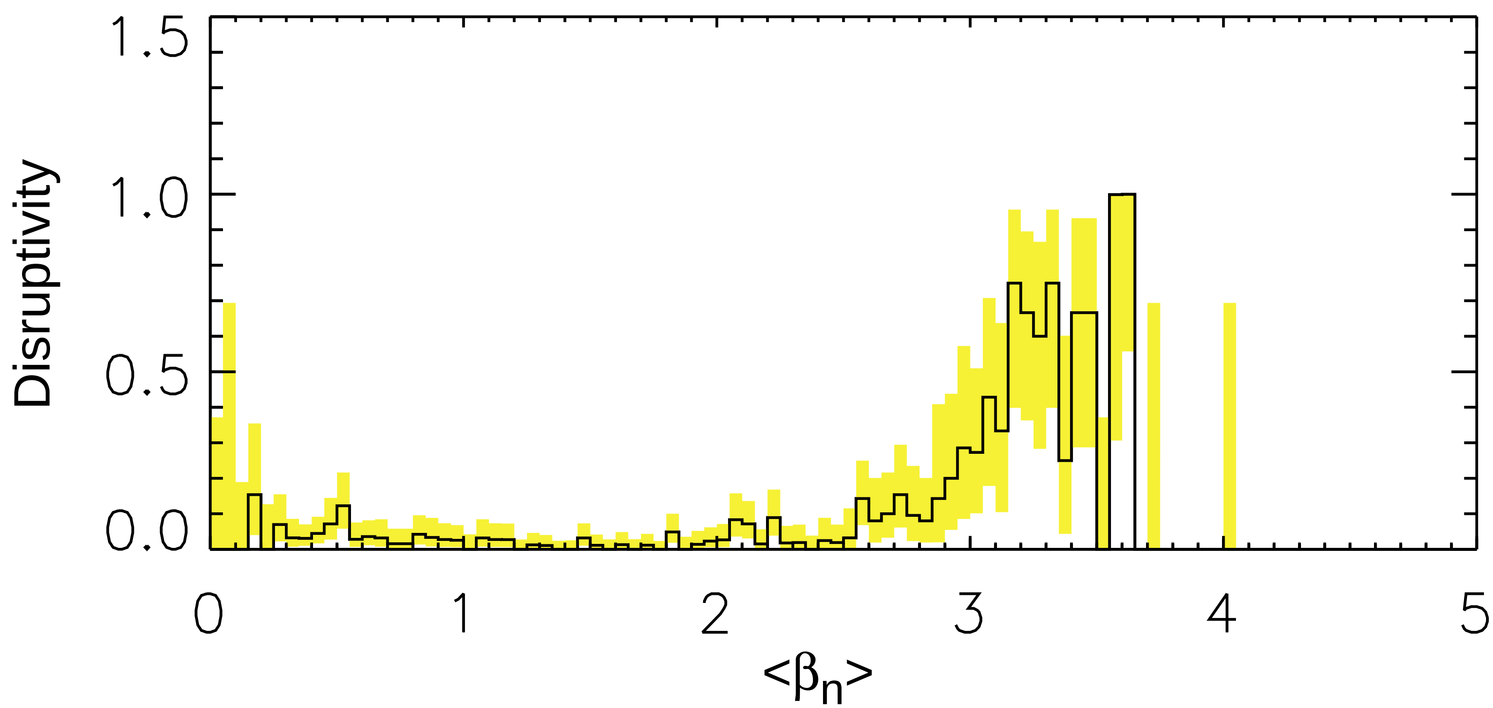
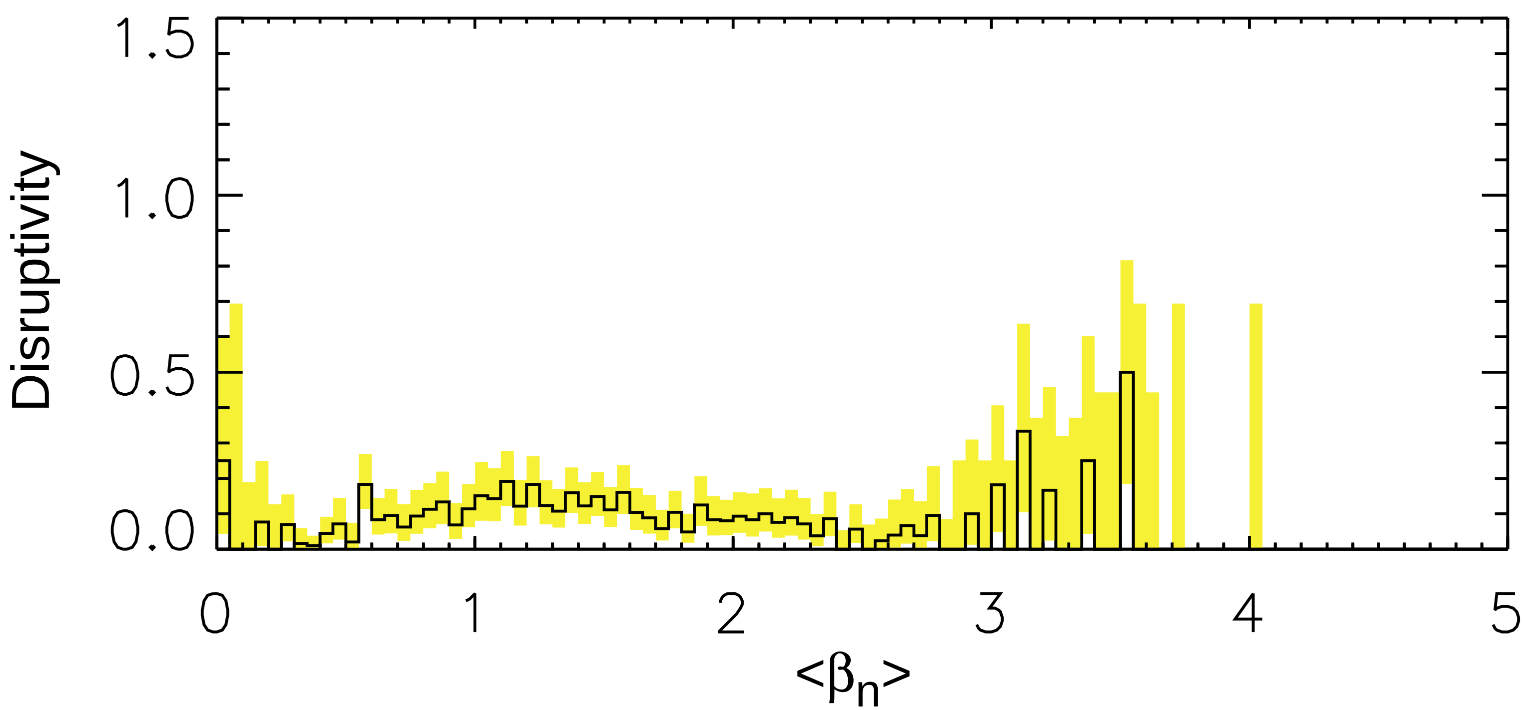
Most High $\langle\beta_n\rangle$ Disruptions are Prompt

Disruptivity for all shots where $0 < t_a \leq 200$ ms



Non-Prompt Disruptions Don't Correlate Well With β_n

Disruptivity for all shots where 200 ms < t_a



Average Disruptivity Does NOT Imply Randomness

One criticism of the tokamak fusion concept is that tokamak plasmas are irreducibly plagued by statistically random disruptions. Two significant results from this database suggest otherwise. One result is the rapid decrease in disruptivity per second, possibly to zero, as the plasma evolves past a few seconds. The other is the statistically significant null result from a Runs Test of Randomness analysis of the entire database. The Runs Test compares observed frequencies of runs of various lengths with the expected frequencies from a probabilistic model of disruptivity. The underlying probability used is the observed overall 13.7% disruptivity, though the result is not materially changed when using other values. The observed frequencies of runs is exponentially unlikely to be generated by a simple random disruptivity, but an admixture of random disruptivity at the 0.1% level cannot be ruled out.

The Runs Test of Randomness

A standard statistical test of whether a given outcome's probability is random in a sequence of trials is the "Runs Test of Randomness". A "run" is a sequence of identical outcomes, and is characterized by its length *l*, i.e. the number of times the same outcome occurred in sequence terminated by a different outcome. A theoretical distribution of runs is calculated assuming a random outcome with probability *p*. The chi-squared goodness-of-fit test is used to compare an observed distribution of runs with the theoretical runs distribution assuming *p*. The result gives a probability that the observed set was drawn from the random outcome distribution. For all analyzed shots, the probability of disruption *p*=13.7%. The probability of a run length of L shots, P(L), is given by

$$P(L) = (1-p)p[(1-p)^{L-1} + p^{L-1}].$$

The chi-squared goodness-of-fit test applied to the observed runs indicates that assuming disruptions are random, the probability of drawing the observed data is less than 1 in 10^7. However, a random component at the 0.1% level or less is not ruled out by the data.

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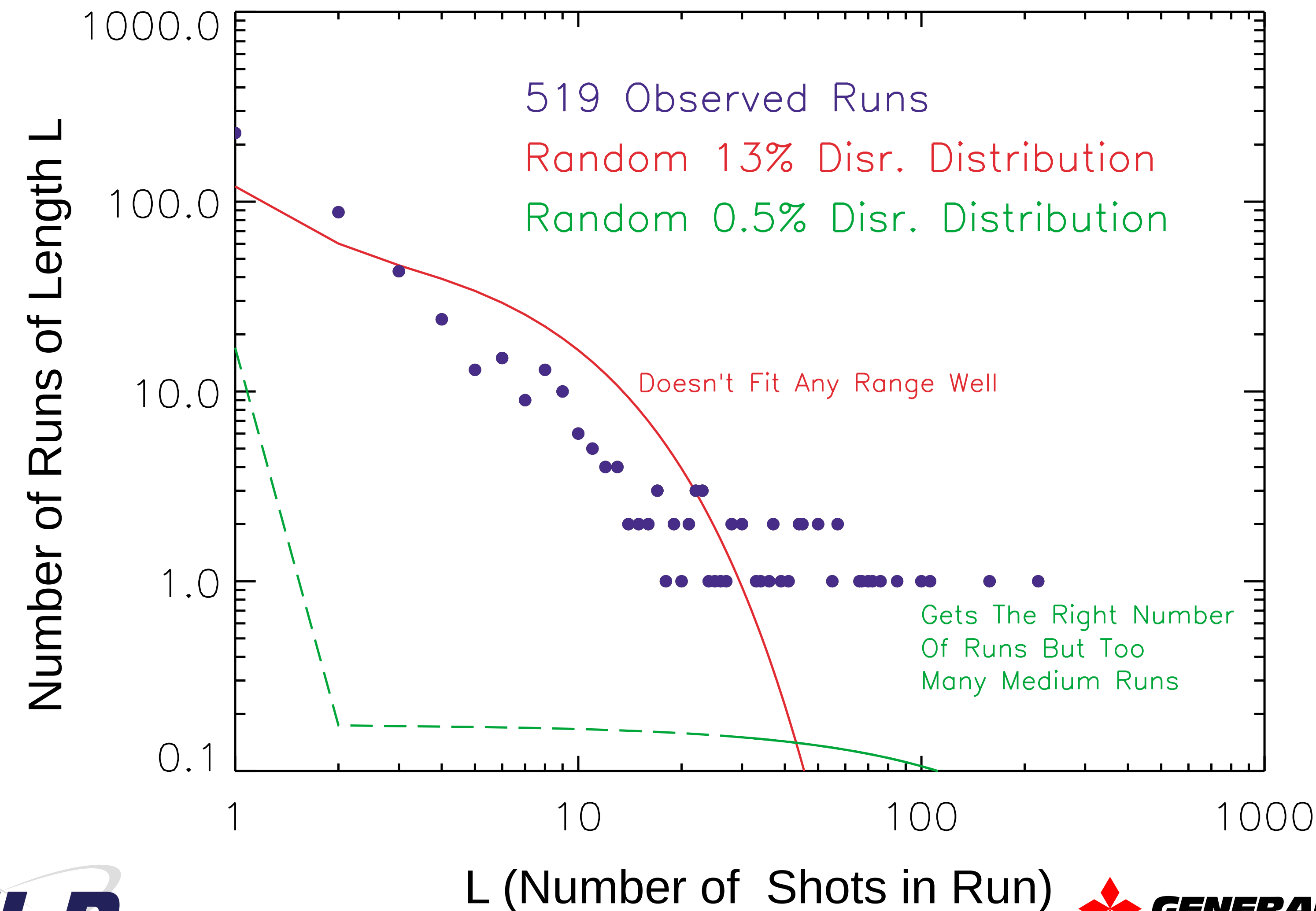
The Observed Run Distribution Cannot Be Random

Even a 0.5% admixture of random disruptivity cannot be supported by the observed distribution of runs.



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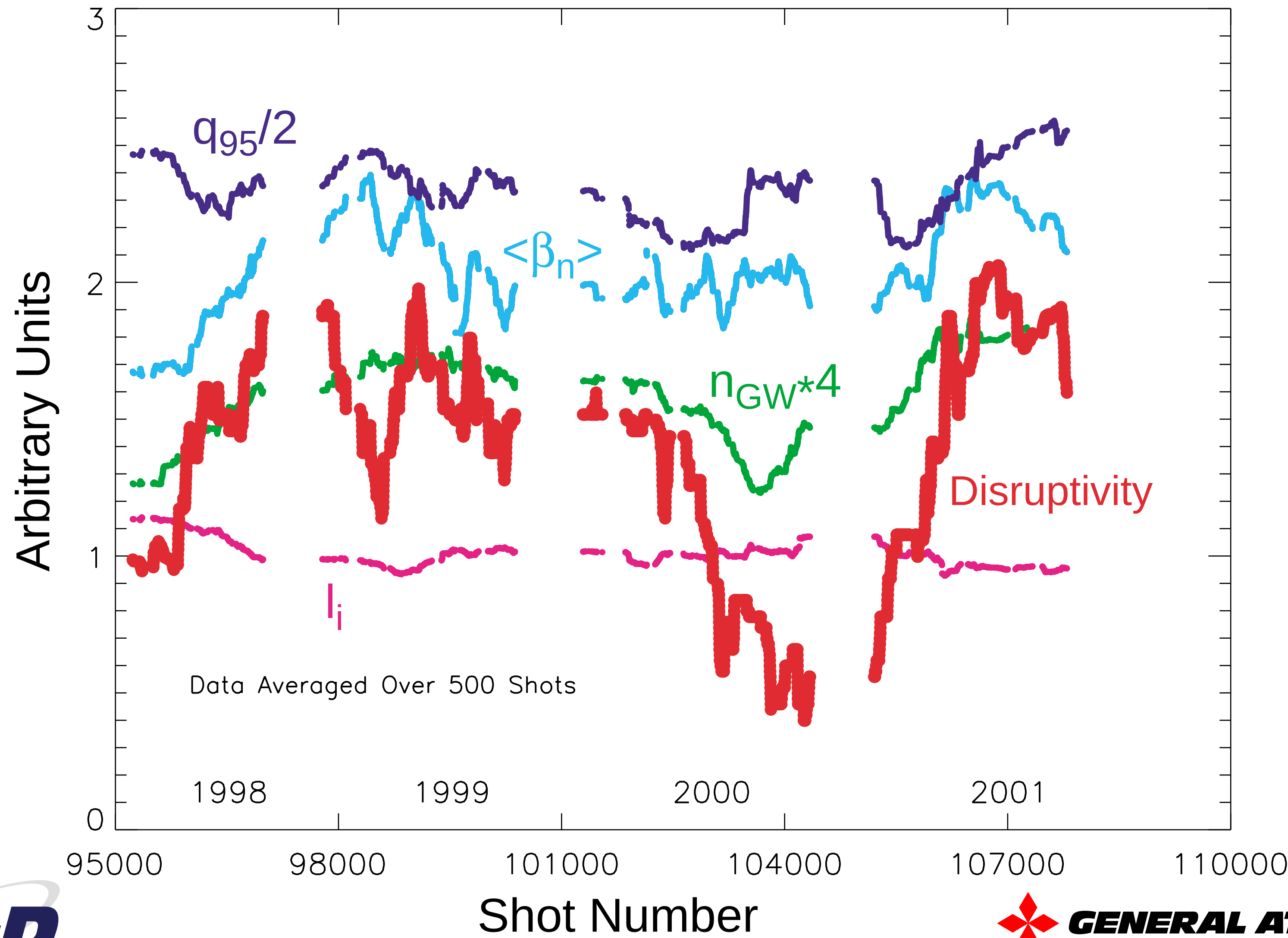
Average Disruptivity Doesn't Correlate With $<\beta_n>$, l_i or q_{95}

There is possibly a weak correlation with density. The return to relatively high disruptivity in 2001 may instead be due to a major turbopump failure at the start of the 2001 campaign.



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SUMMARY AND CONCLUSIONS

Per-shot disruptivity in DIII-D is predominantly non-random, though the data doesn't exclude a random component at the 0.1% level.

The data is consistent with a per-time disruptivity that trends to zero after several seconds of plasma evolution past reaching maximum beta. The evolution time scale is consistent with global resistive current relaxation.

Broadly speaking, except at the extremes disruptivity is not well correlated with β_n, l_i, q_{95} and only weakly with density. This suggests some functions combining these variables and/or profile specific variables will be required for better correlation.