Performance analysis of the centroid method predictor in the JET RT network

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- Introduction to PETRA
- Comparison of Centroid method with several other protection systems on board PETRA
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Centroid method

- Data-driven models from machine learning methods can be difficult to interpret due to
  - Feature vectors belonging to multi-dimensional spaces
  - Predictions based on black boxes: no physics interpretation
  - Complex equations of the separating hyperplanes

- Centroid method highlights
  - Based on a single signal (ML or ML/Ip)
  - Makes use of the difference between consecutive samples
  - The separation frontier is linear
  - Easy physics interpretation

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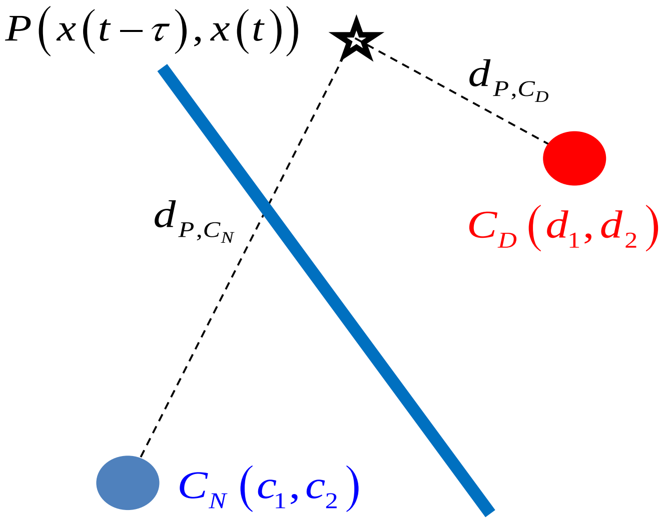
Centroid method: rationale



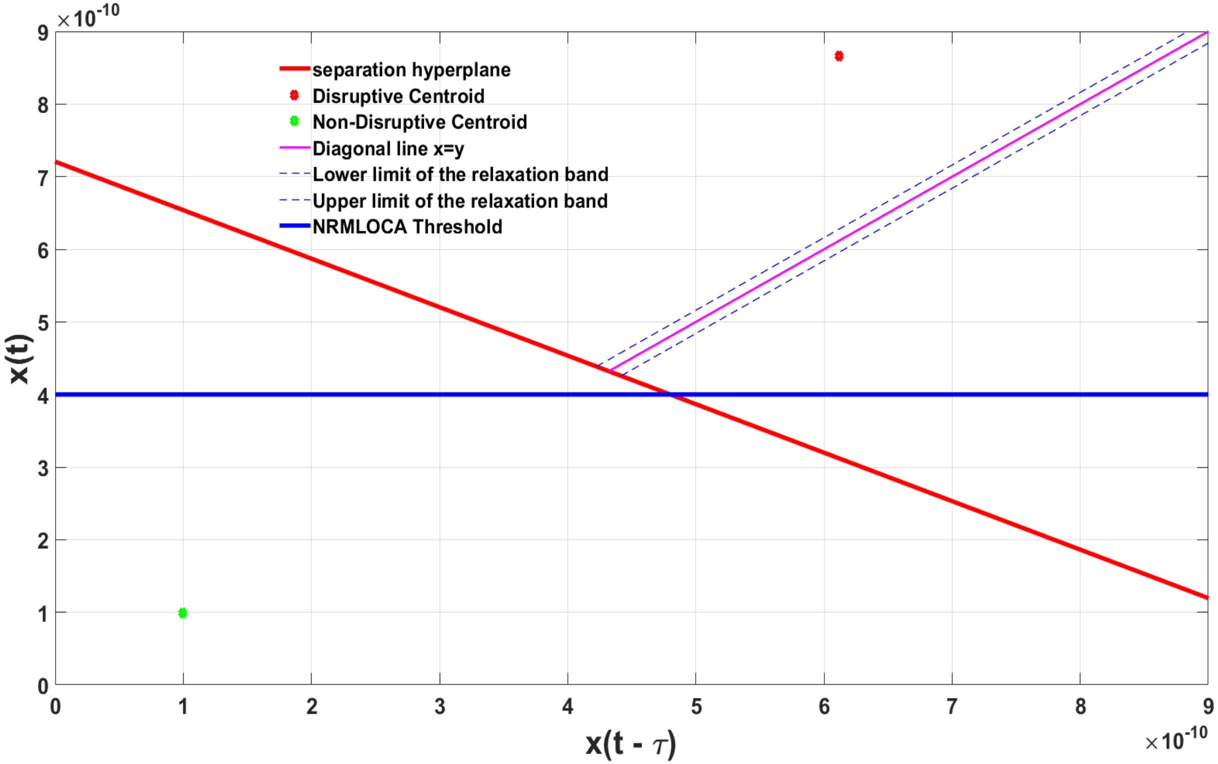
disruptive behaviour : $d_{P,C_D} < d_{P,C_N}$

$$\sqrt{\sum_{i=1}^{2}\left(x_i - d_i\right)^2} < \sqrt{\sum_{i=1}^{2}\left(x_i - c_i\right)^2}$$

$$x(t) = -\frac{d_1 - c_1}{d_2 - c_2} x(t-\tau) + \frac{d_1^2 + d_2^2 - c_1^2 - c_2^2}{2\left(d_2 - c_2\right)}$$

Linear frontier

Physics interpretation



- $x(t) = ML(t)/Ip(t)$
  - Signal increases when
    - The rotation of an MHD mode slows down and can be locked
    - The MHD mode amplitude grows
  - Signal decreases when
    - The MHD mode amplitude drops
    - The MHD mode unlocks and the rotation speeds up

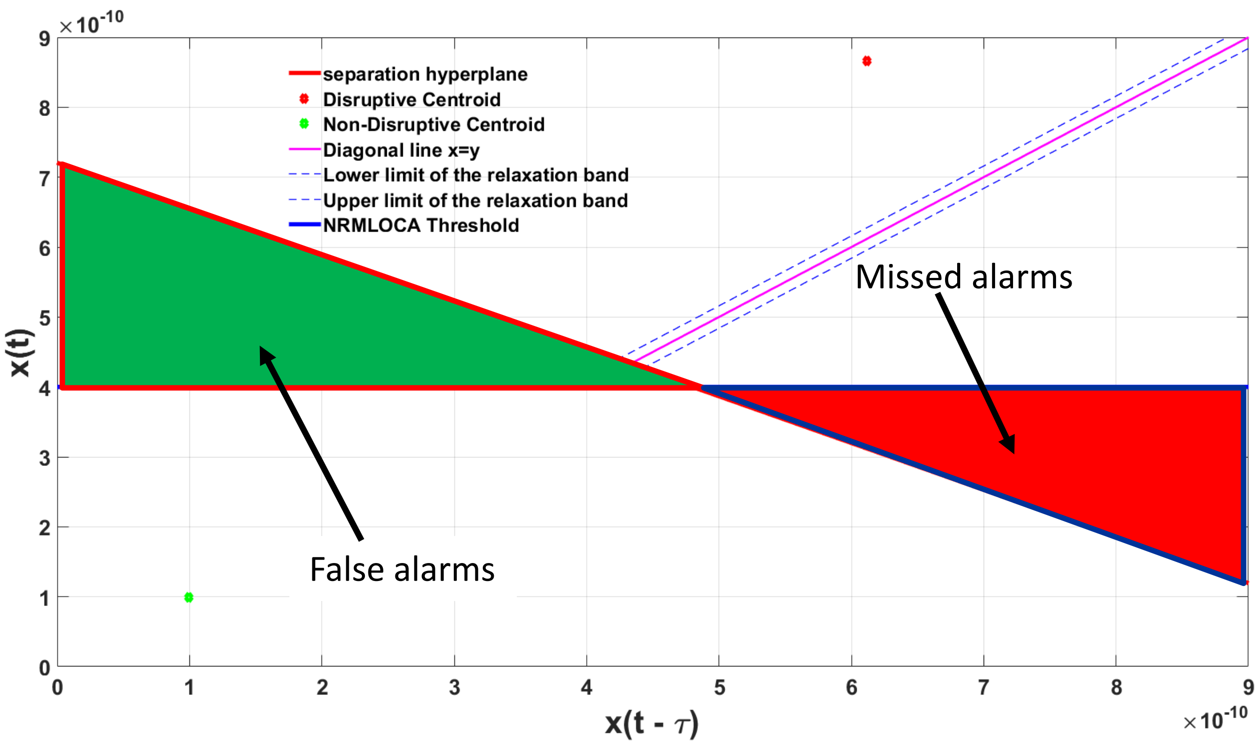
- $\Delta(x(t)) = x(t) – x(t – t)$
  - Large jumps means strong variations either in the MHD mode rotation or in the MHD mode amplitude
    - Large jumps in the non-disruptive zone do not mean incoming disruptions
  - Small jumps means soft variations
    - Small jumps in the disruptive zone within a narrow band determine a non-disruptive behaviour

Details

Separation frontier:

$$x(t) = -0.6680 \cdot x(t - \tau) + 7.2068e - 10$$

Width of the band: $1.1667e - 11$

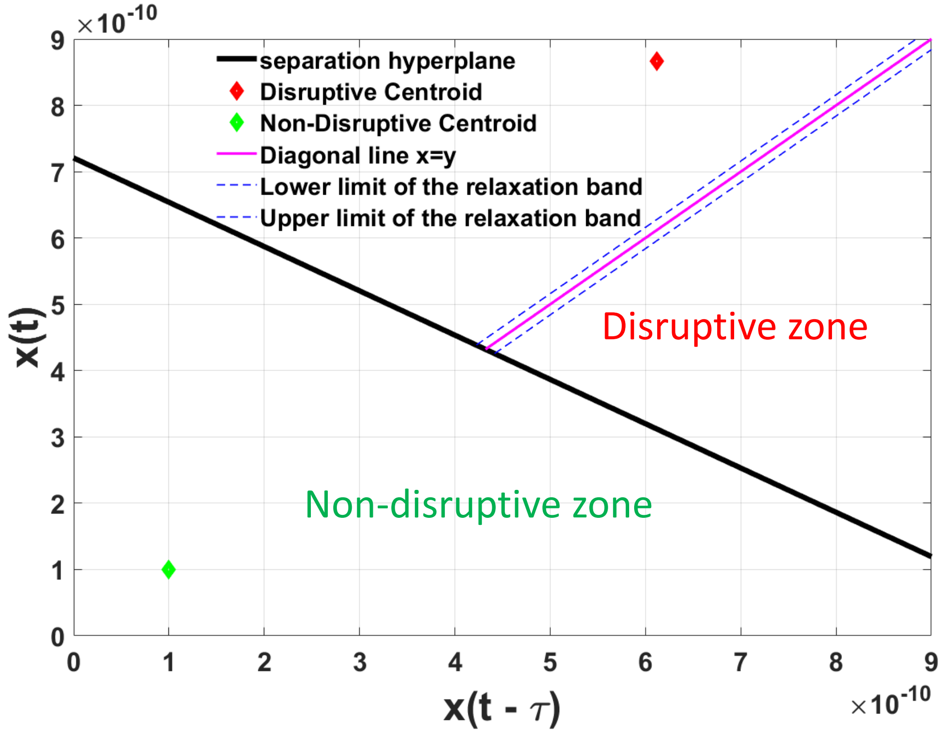


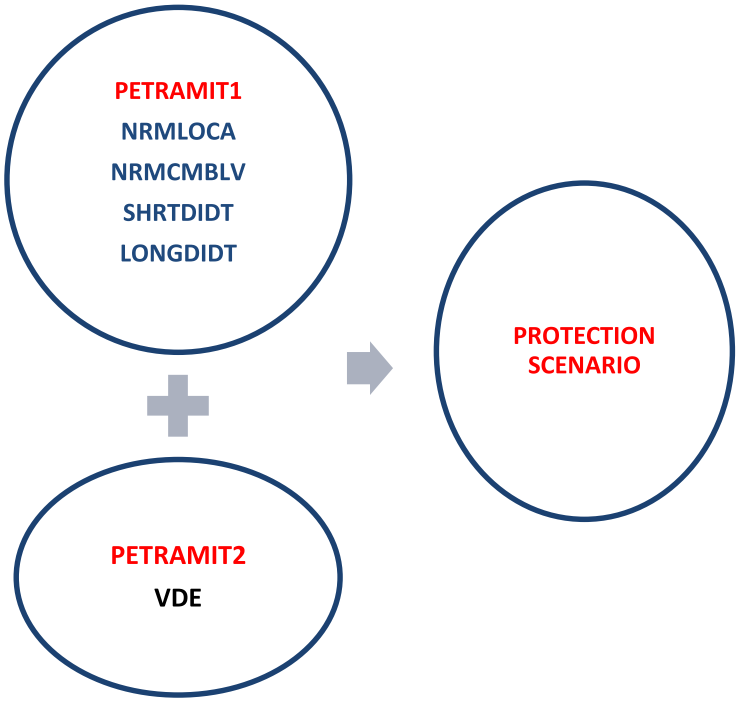
- Δ(x(t)) analysis adds extra resolution in the sense that a simple threshold to recognize a disruptive behaviour is not optimal

- The interception of the separation frontier defines a critical value above which the plasma is in a disruptive state regardless the amplitude of the previous sample

- Below the critical value, the disruptive behaviour depends on the previous amplitude

PETRA - Plasma Event TRiggering for Alarms





- Following are the conditions for triggering alarms for each system
  - NRMLOCA: Locked mode amplitude normalized to plasma current amplitude > 400 pT/A for 20 ms
  - NRMCMBLV: Restraint ring loop voltage product normalized to plasma current squared > 50 pV^2/A^2
  - SHRTDIDT: Plasma current numerical derivative over 2 ms > 50 MA/s for 10 ms
  - LONGDIDT: Plasma current numerical derivative over 16 ms > 7 MA/s for 10 ms
  - VDE: From 40.05 s onwards, plasma vertical centroid numerical derivative (over 16 ms) > 10 m/s if an Ip derivative or restraint ring loop voltage type disruption has not been detected in the last 50 ms

C. Stuart et al. Fusion Engineering and Design 168 (2021) 112412 (5 pp)

Alarm Rates: A comparison

- A combined dataset of 78 disruptive discharges and 346 non-disruptive discharges from C38 campaign of JET, focusing only on Baseline (BS) and Hybrid scenario (HS) experiments (53 BS + 25 HS).

Detector	Success Rate (%)	Success Rate with positive $T_{warning}$ (%)	Success Rate with negative $T_{warning}$ (%)	Avg $T_{warning}$ (ms)	σ $T_{warning}$ (ms)	Missed Rate (%)
CM	96.16	84.62	11.54	117	204	3.4
NRMLOCA	100	69.23	30.77	38	210	0
NRMCMBLV	100	61.54	38.46	546	1635	0
SHRTDIDT	97.5	52.5	45.00	-5	55	2.5
LONGDIDT	100	43.59	56.41	-16	77	0

- The discussion of false alarms can be misleading due to the fact that the moment an alarm is raised by any of these systems, protective action is immediatly taken as per of the JET operational protocols.

$T_{warning}$ comparison - I

AVERAGE for BS	CM	NRMLOCA	NRMCMBLV	SHRTDIDT	LONGDIDT
Positive $T_{warning}$ (ms)	33	18	4	0	0
Negative $T_{warning}$ (ms)	-31	-55	-17	-17	-18

AVERAGE for HS	CM	NRMLOCA	NRMCMBLV	SHRTDIDT	LONGDIDT
Positive $T_{warning}$ (ms)	21	16	4818	0	18
Negative $T_{warning}$ (ms)	-65	-182	-98	-89	-98

- Apart from being the predictor with least number of negative $T_{warning}$ detections, the CM predictor has the smallest average value for the same – a demonstration of efficiency of detections.
- Numbers from NRMCMBLV are skewed due to several premature detections as shown in upcoming slides.

$T_{warning}$ comparison - II

Baseline scenario

CM	108	0	
Detector	**Avg $T_{warning}$ (ms)**	**$(Avg\ T_{warning})_{CM}$ – $(Avg\ T_{warning})_{DETECTOR}$ (ms)**	**Disruptions detected in advance (%)**
NRMLOCA	80	28	83,87
NRMCMBLV	-3	111	87,1
SHRTDIDT	-7	115	90,3
LONGDIDT	-7	115	93,55

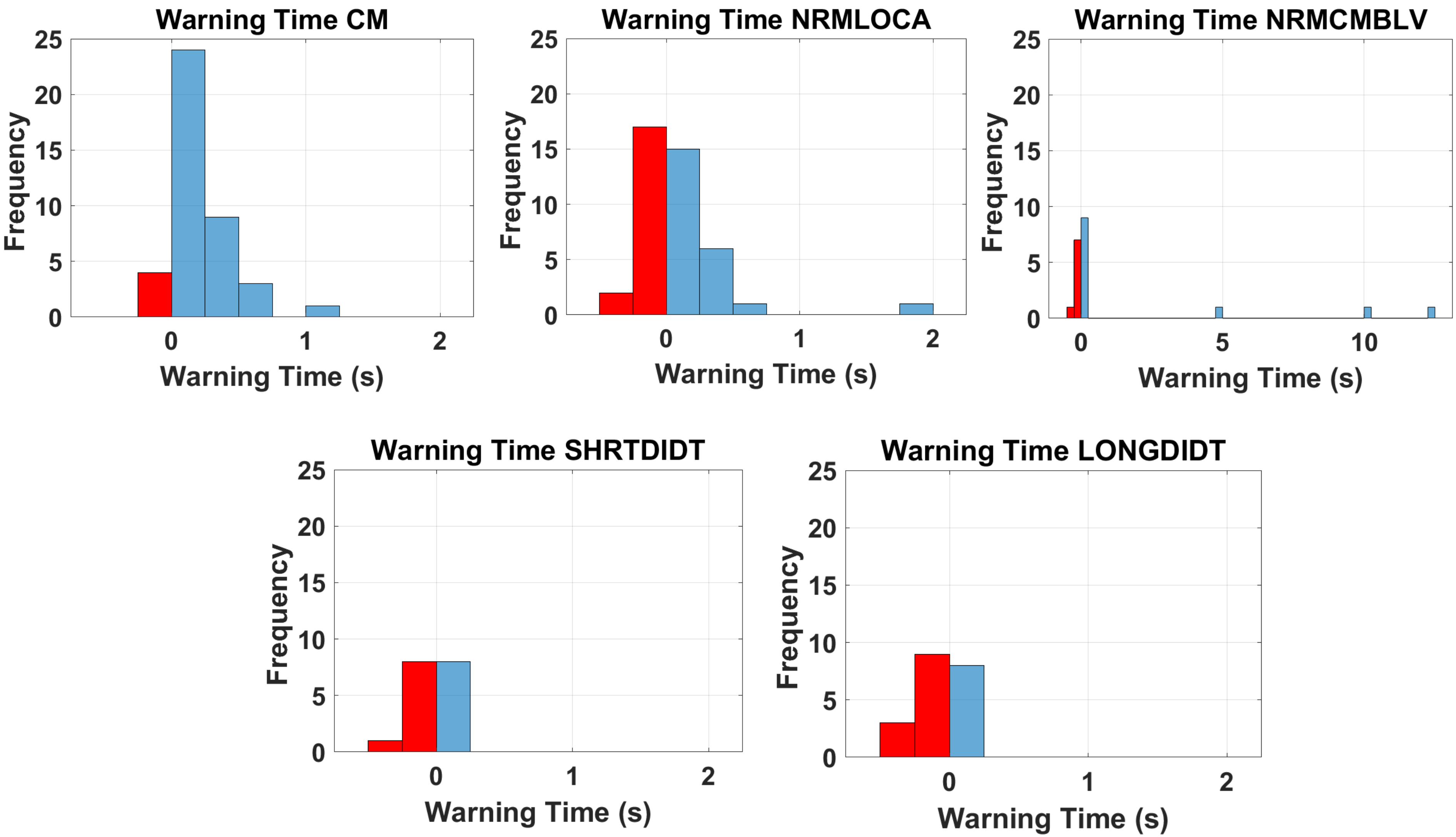
- A comparison has been made between several predictors at the time of 1st alarm of an upcoming event (T_{SIGNAL}). We always compare other signals with the one of CM Predictor (T_{CM}).

$$\Delta T = T_{SIGNAL} - T_{CM}$$

Hybrid scenario

CM	126	0	
Detector	**Avg $T_{warning}$ (ms)**	**$(Avg\ T_{warning})_{CM}$ – $(Avg\ T_{warning})_{DETECTOR}$ (ms)**	**Disruptions detected in advance (%)**
NRMLOCA	-4	130	80
NRMCMBLV	1095	-969	70
SHRTDIDT	-3	129	80
LONGDIDT	-25	151	80

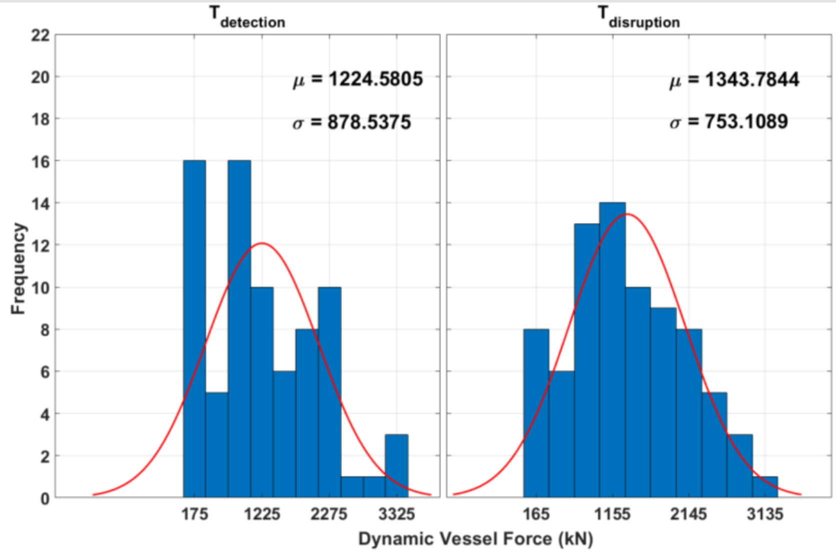
$T_{warning}$ comparison - III



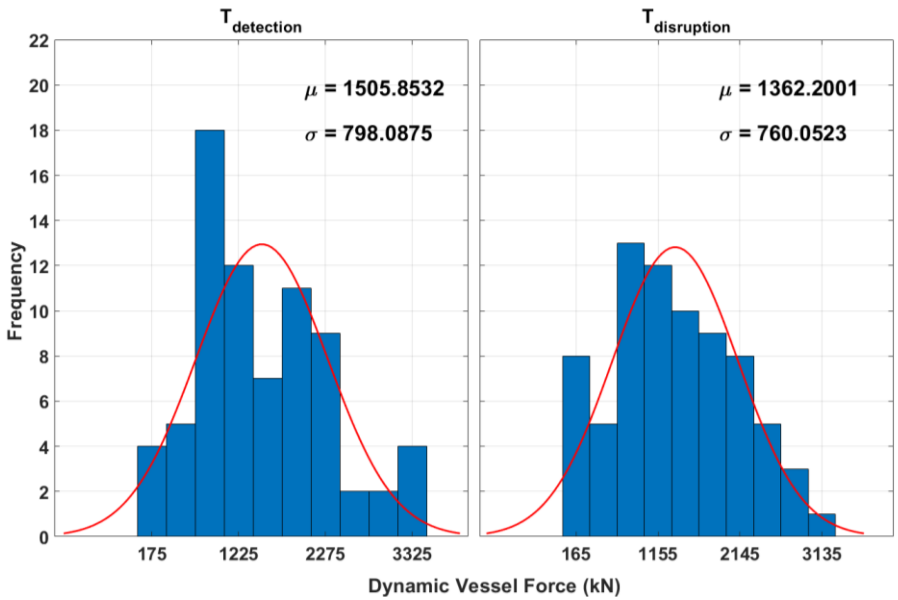
Vessel Forces

- Disruptive termination of plasmas often lead to large amounts of vessel forces, which can be very detrimental to the lifetime of the vacuum vessel.
- Hence, one factor used to determine the severity of disruptions is the Vessel Force. It was **interesting to see the patterns of vessel forces at the time of 1st alarms raised by the various predictors**.
- JET has operational protocols to ensure that the number of disruptions with large vessel force swing are minimized.
- Predicted vessel force (F_P) provides a forecast of vessel forces that will be produced without mitigation.
- F_P is obtained using a scaling law and has a strong dependence on the plasma current.

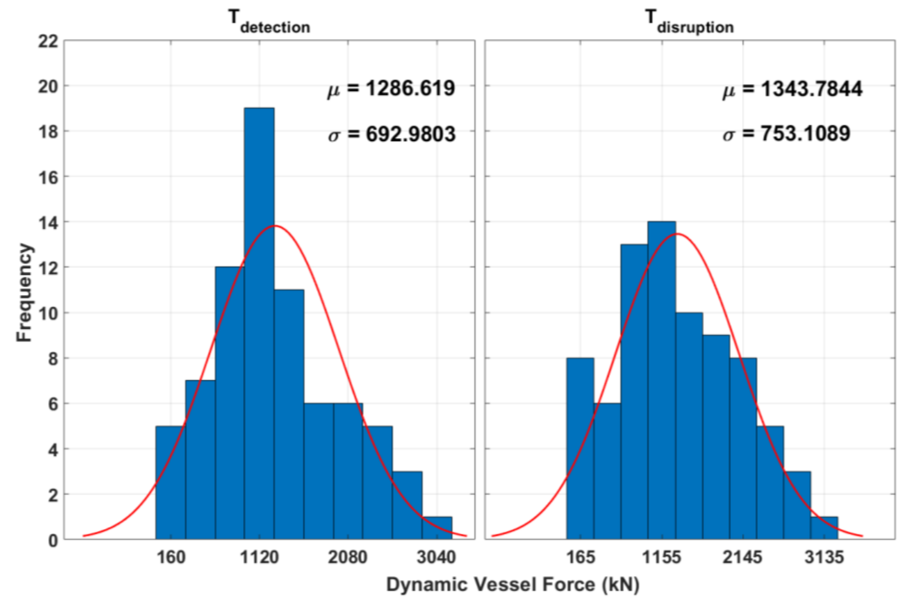
Comparison of F_P :CM vs other systems



NRMLOCA

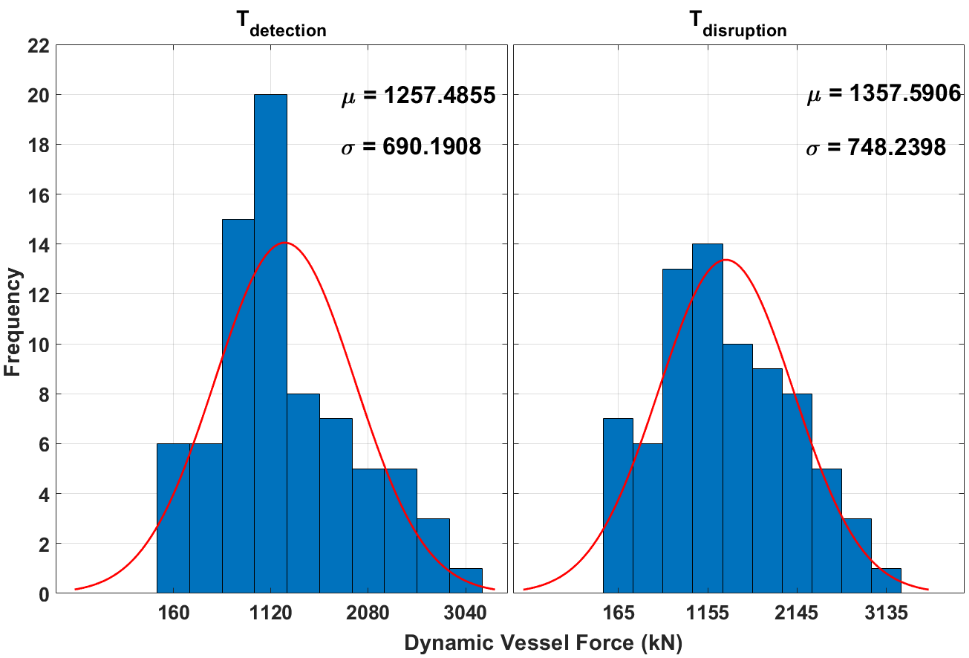


CM



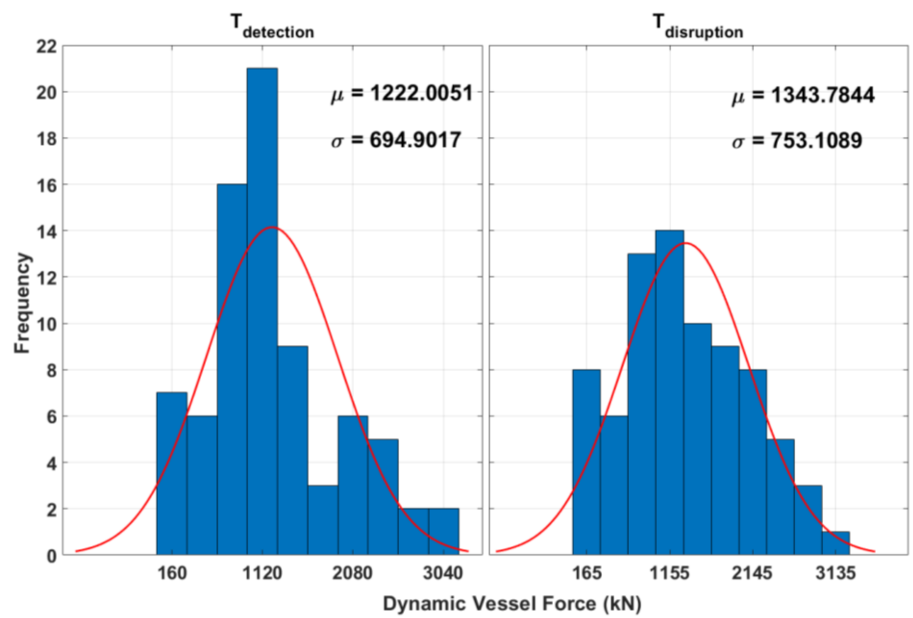
NRMCMBLV

Comparison of F_P :CM vs other systems



SHRTDIDT

LONGDIDT



CM predictor detections are faster and at higher values of F_P , providing more time and reason for mitigation action.

Summary and Conclusion

- The advantage in detection time is a reflection of the fact that the CM predictor is not reliant on a single threshold value nor does it rely on fulfilment of a given condition for a certain amount of time.
- The CM predictor predicts disruptions 79 ms in advance on average before NRMLOCA, its nearest competitor. Rest of the detectors are outperformed comprehensively.
- The comparison of F_P at $T_{detection}$ provides sufficient evidence that the CM predictor predicts an approaching disruption when the vessel forces are high, hence avoiding possible error of discarding the alarms in case of hard threshold values of F_P for reaction.