Development and preliminary calibration of an off-normal warning system for SPARC

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3rd Technical Meeting on Plasma Disruptions and their Mitigation – 4 September 2024

Creation of a cross-institutional team for the development of SPARC's Off-Normal Warning System

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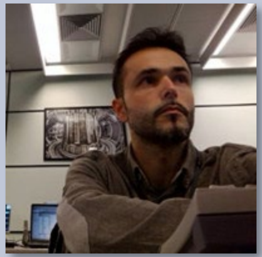


Alessandro Pau (PI)

And we welcome more collaborators!!

Overview

- **Scope of SPARC's *Off-Normal Warning* (ONW) system**

- **Progress on its development**
  - ONW system structure
  - Creation of *Off-Normal Event* (ONE)-specific warnings

Scope of SPARC's *Off-Normal Warning* (ONW) system

The ONW system will play two crucial roles in SPARC operations

- **Plasma control**
  - Integration into the Plasma Control System
  - *Identify when a disruption may be imminent and decide on a response based on the risk to the device*

- **Scenario design**
  - Integration into Pulse-Planning workflow
  - *Identify the cause(s) of plasma disruptions and identify scenarios that may be less disruptive for future campaigns*

SPARC's ONW systems need to address several ITER-relevant challenges specific to high-power devices

- **SPARC has a "Disruption Budget"**
  - *The number of disruptions (cumulative thermal loads) the tokamak is designed to withstand*

- **The budget needs to be managed early in operation**
  - This requires the ONW system to be ready provided a limited amount of data
  - This will be a stress test of ***cross-machine transferability*** for both physics and data-driven models
  - This is an opportunity to test the implementation of *adaptive training*
    - Which has been explored on JET [1,2], EAST [3], ASDEX [4]

- **There will be little (if any) room to commission the warning system at high performance**
  - The risk associated with an un-mitigated disruption may be too great

- **The ONW system needs to be tunable assuming limited performance info**
  - The performance of the system can be unclear when running in mostly closed-loop
  - However, this is also an opportunity to explore the cost-benefit analysis of running in open-loop

[1] Murari, A. *et al* Nat Commun 15, 2424 (2024)
[2] R. Rossi *et al* 2024 Nucl.Fusion 64 046017
[3] arXiv:2404.08241v2
[4] B. Cannas *et al* 2010 Nucl.Fusion 50 075004

These challenges set some priorities in development

- **Operator friendly**
  - When a warning fails, it needs to be clear why, as well as how to update it
  - The triggering of a warning should make it clear why a plasma disrupted, and suggest how to adjust the scenario for the next pulse

- **Starting development with *physics-driven* warning models**
  - Provides the *clear tuning knobs* and *interpretability* for the low-data budget available early on

- **Followed by *data-driven* warning models**
  - This is expected to provide higher accuracy and better warning-times provided enough data

- **Closed-loop and real-time *Off-Normal SIMulations* (ONSIMs) will be used to relieve the burden of needing real SPARC data**
  - SPARC data + physics knowledge can potentially fill in unexplored regions of stability-space without explicit experimentation
  - Can potentially implement data earlier with the help of ONSIMs

Progress on development

ONW system structure

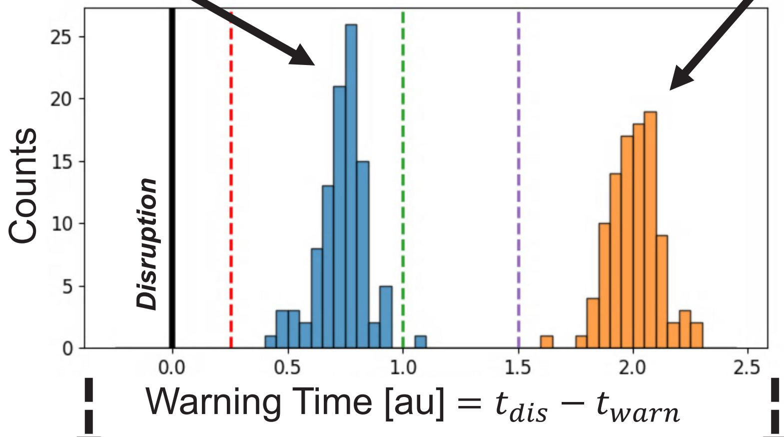
Each *Off-Normal Event* (ONE) has its own ONW module containing control-focused detectors within it

[5] J. Vega *et al* 2024 Nucl.Fusion 64 046010
[6] M Maraschek *et al* 2018 PlasmaPhys.Control.Fusion 60 014047

ONE → Control response(s) → Appropriate Detector(s) → Optimized threshold(s)

VDEs → *Disruption Mitigation System* (DMS) → $\tau_{VDE} \sim \tau_{warn} > \tau_{DMS}$ → Optimal threshold

VDEs → Avoidance → $\tau_{warn} \gg \tau_{shape}, \tau_{VDE}$ → Optimal threshold



[5, 6]

Different control responses may have different optimization metrics

- **A common set of performance metrics to all optimizations is the True Positive Rate (TPR) and False Positive Rate (FPR)**
  - TPR = Frequency that the model *correctly* identifies an event
  - FPR = Frequency that the model *falsely* identifies an event

- **A flexible optimization metric has been developed for the *Disruption Mitigation System* (DMS) warnings based on the expected cumulative disruption loads $\langle D \rangle$**

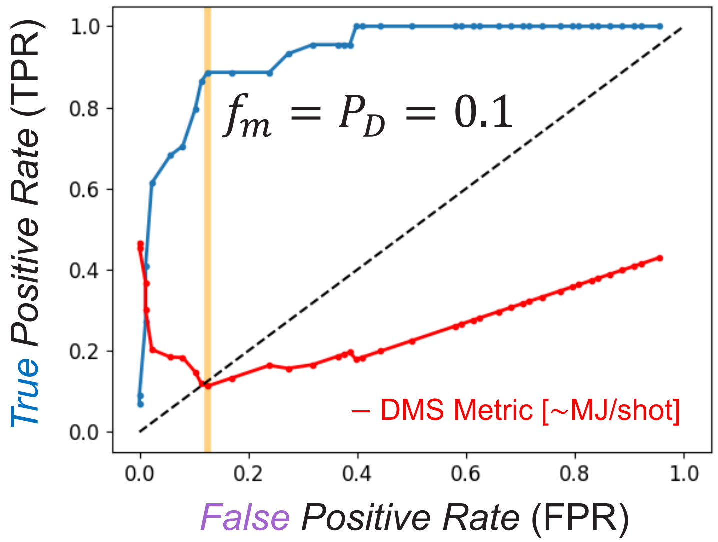
$$\text{DMS Metric} = f_m(1 - P_D)\boldsymbol{FPR} + P_D\boldsymbol{FNR} \propto \sim\langle D \rangle$$

f_m = mitigation efficiency

P_D = natural disruptivity

- Optimization looks for minimum in DMS Metric $\propto \sim\langle D \rangle$

Performance Metrics



We use an *extension* of Gerhardt's Points-Based model for establishing warning thresholds

- **The original Point-Based model [7] maps thresholds → points for each input and then sums them**
  - Contours of constant sums draw stability boundaries
  - Used with success on NSTX by both Gerhardt [7] and DECAF [8]

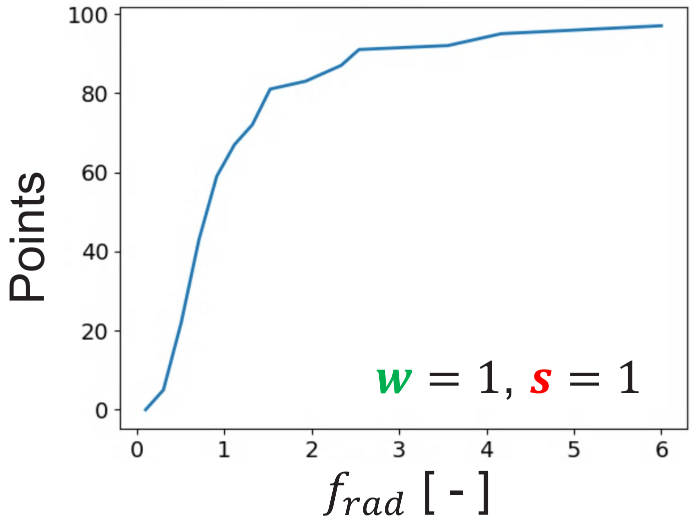
- **The *extension* to this model implemented here makes the point-assignments more continuous, and easily tunable**

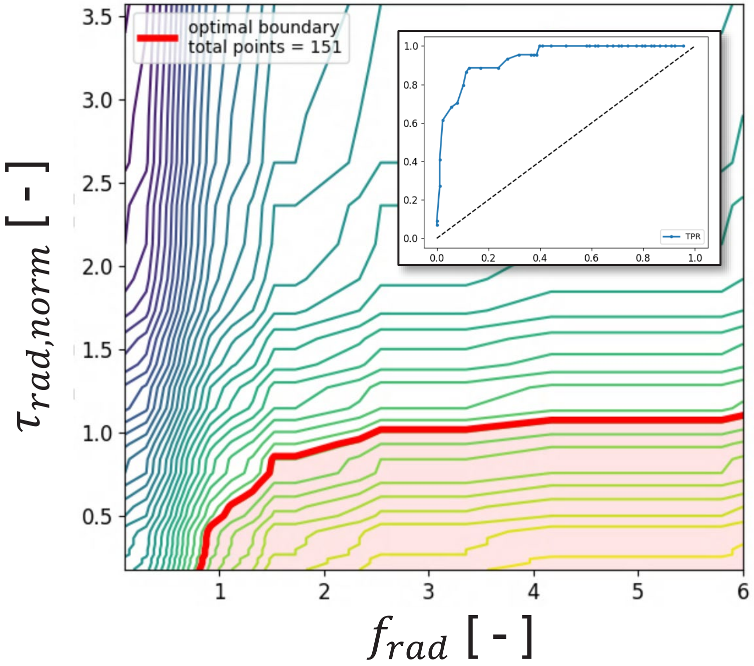
$$Points(\boldsymbol{FPR}) = \boldsymbol{w} * 100 * (1 - \boldsymbol{FPR})^{\boldsymbol{s}}$$

$$Total\ Point\ Threshold = \sum_f (Points)_f$$

- **2* primary tuning knobs**
  - Weight ($\boldsymbol{w}$), shape ($\boldsymbol{s}$): set FPR → points mapping
    - $\boldsymbol{w}$ sets the weight of each input
    - $\boldsymbol{s}$ sets the shape of the $points$ profile

Point Mapping



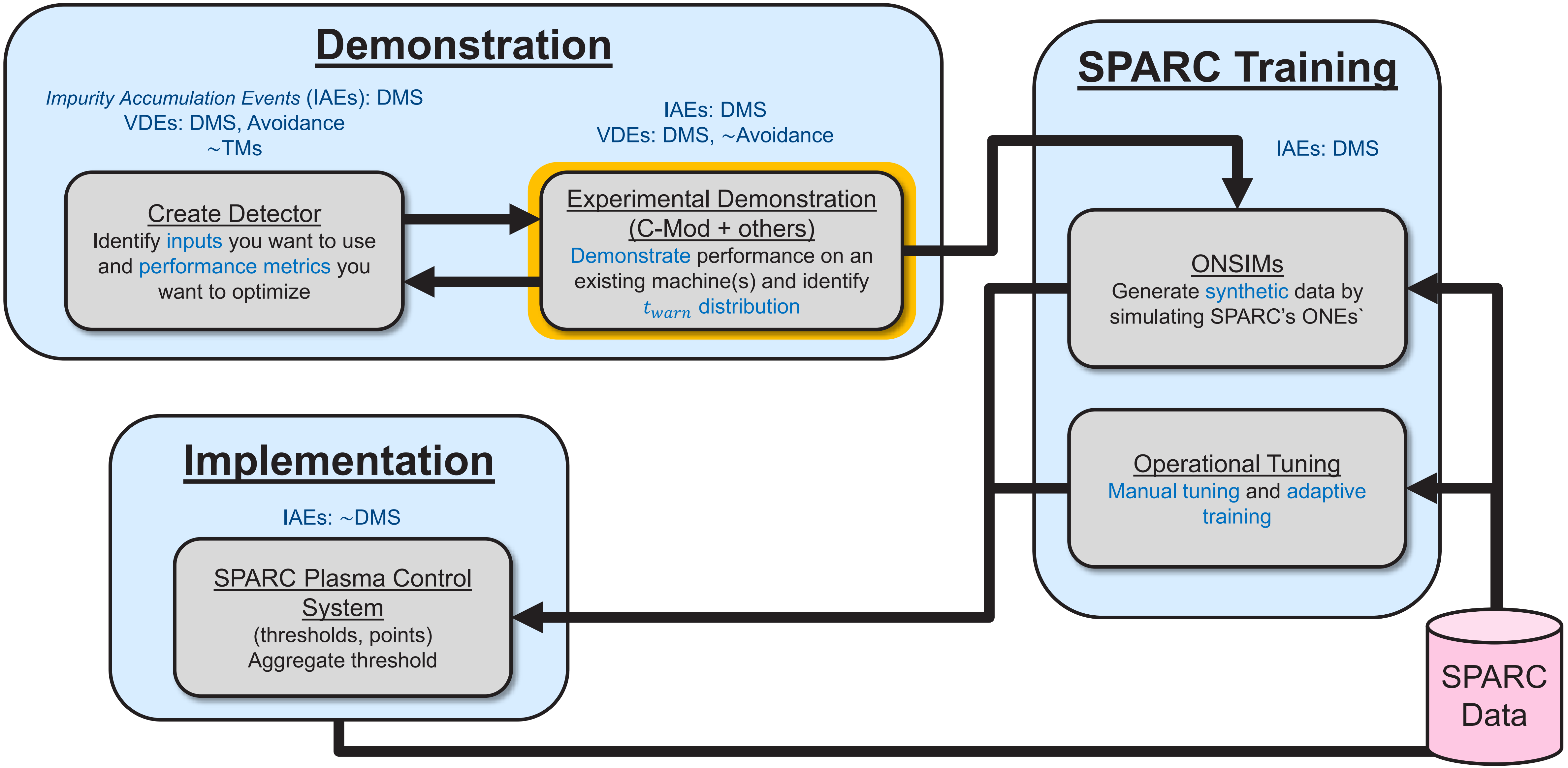


[7] S.P. Gerhardt *et al* 2013 *Nucl. Fusion* **53** 063021
[8] S.A. Sabbagh *et al* Phys. Plasmas 30, 032506 (2023)

Progress on development

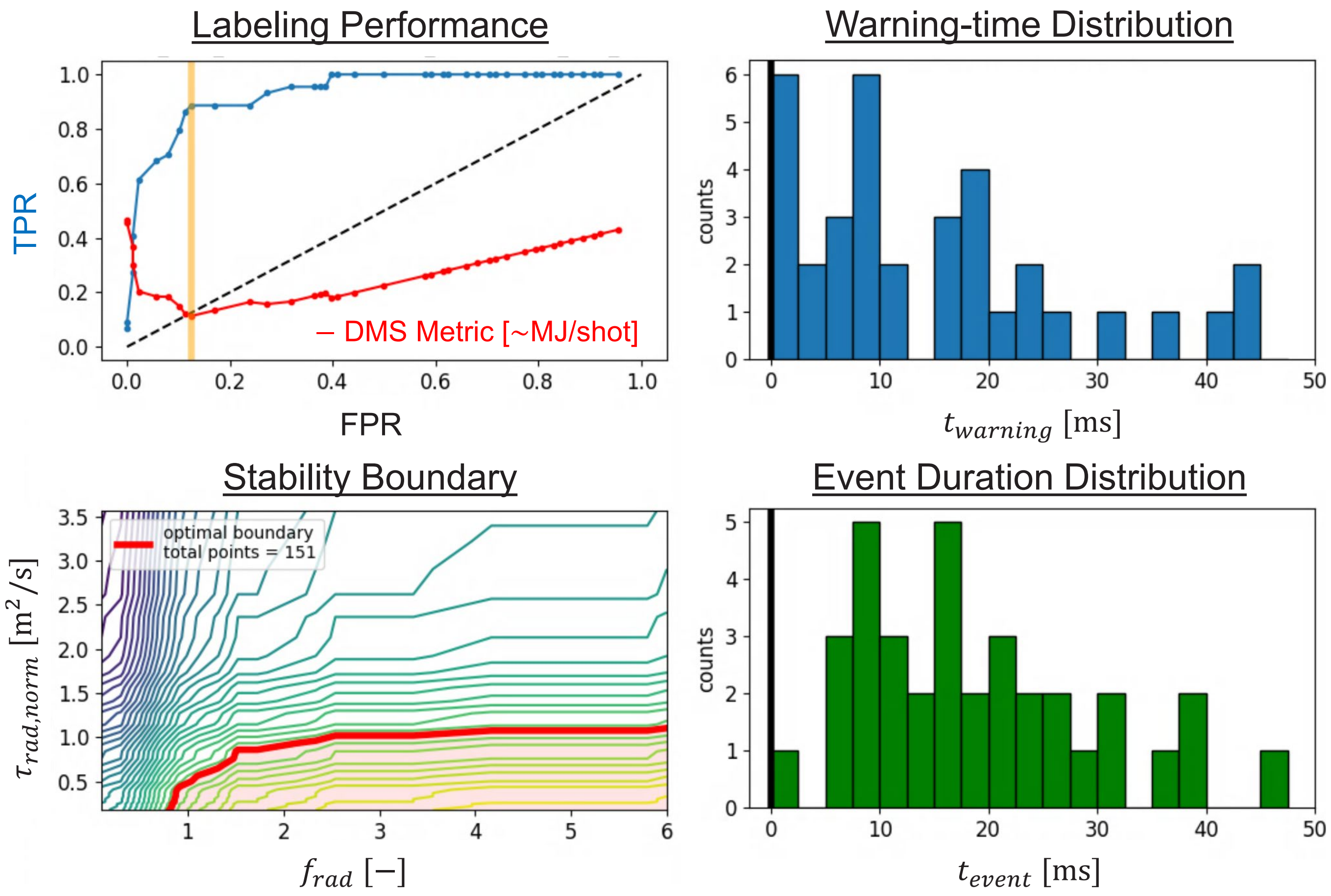
Creation of ONW modules

ONW detector development workflow



DMS detector for *Impurity Accumulation Events* (IAEs) has been demonstrated on C-Mod

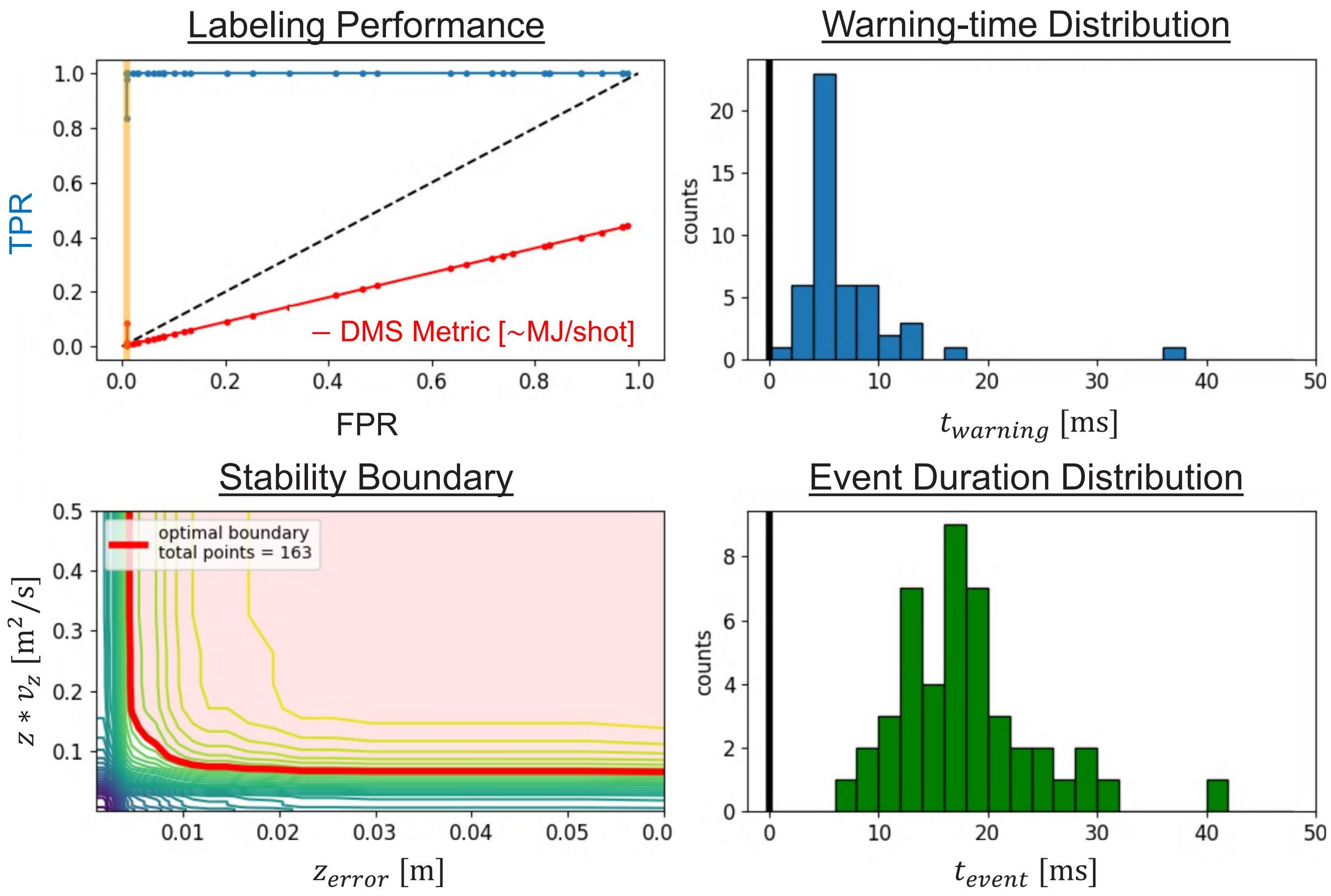
- **Success with f_{rad} and $\tau_{rad,norm}$ [9] as IAE DMS observers**
  - Radiative cooling timescale
    - $\tau_{rad} = W_{th}/P_{rad}$
  - $\tau_{rad,norm} = \tau_{rad}/\langle\tau_E\rangle$
  - FPR,TPR $\sim (12\%, 85\%)$
- **Warning-time distribution is limited by distribution of radiated collapse durations on Alcator C-Mod**
  - $\sigma_{\tau_{Event}} \sim \langle\tau_{Event}\rangle$
- **But $\langle\tau_{IAE}\rangle$ should scale well to SPARC for longer τ_{rad}'s**



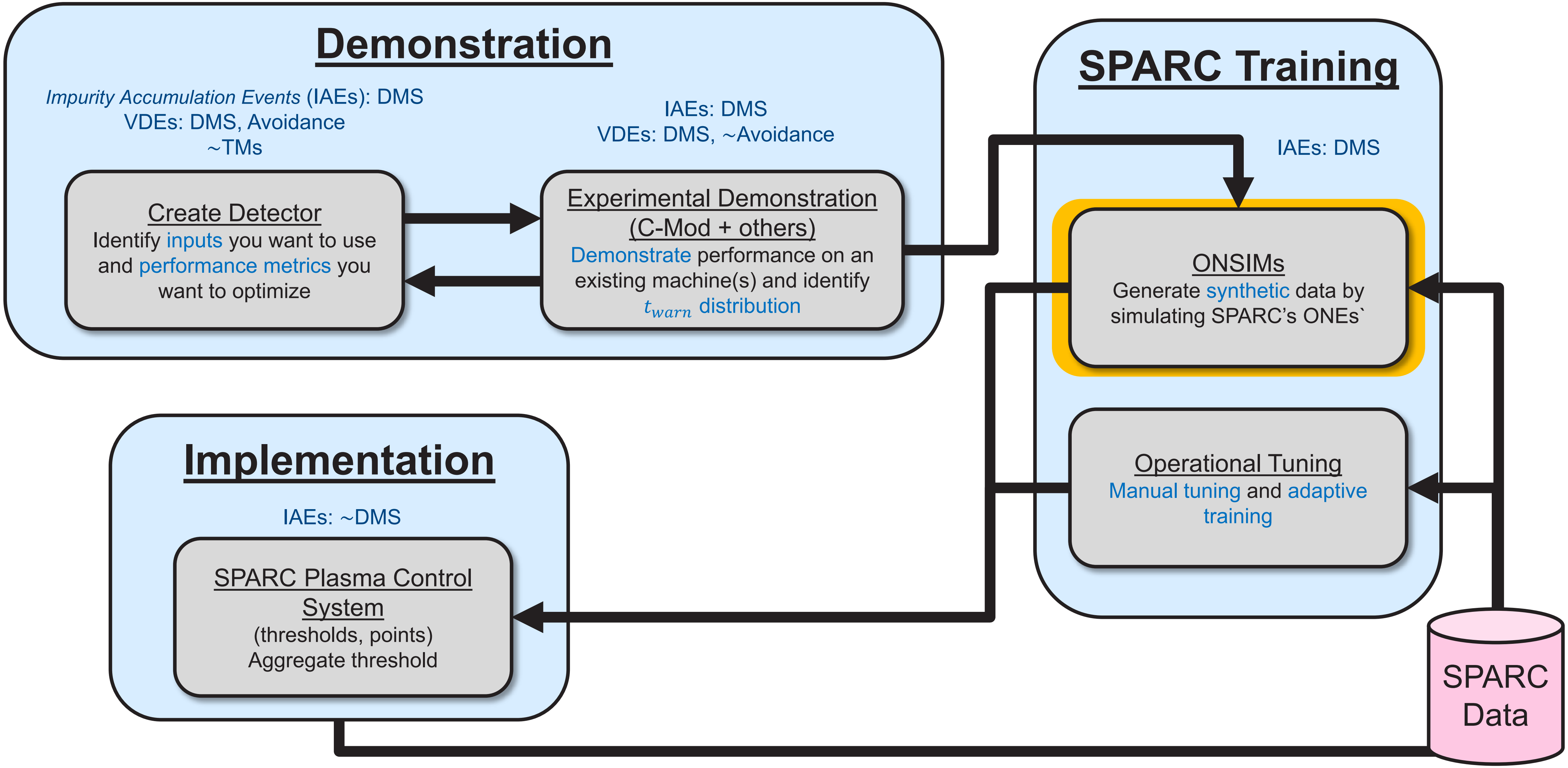
[9] R. Rossi *et al* 2024 *Nucl. Fusion* **64** 046017

DMS detector for VDEs has been demonstrated on C-Mod

- **Success with z_{error} and $z * v_z$ as VDE DMS observers**
  - FPR,TPR $\sim (1\%, 100\%)$
- **Better localized warning-time distribution**
  - But still limited by short event durations
  - Which should scale optimistically to SPARC as well for lower γ_{VDE}'s



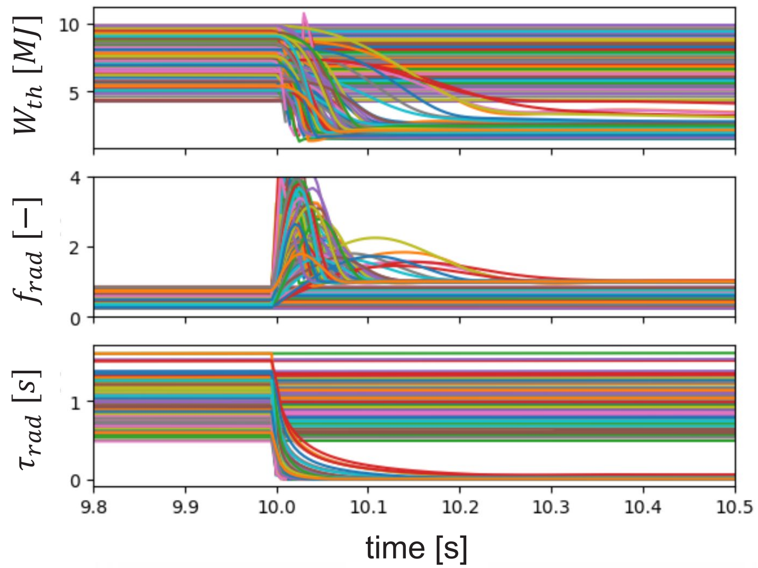
ONW detector development workflow

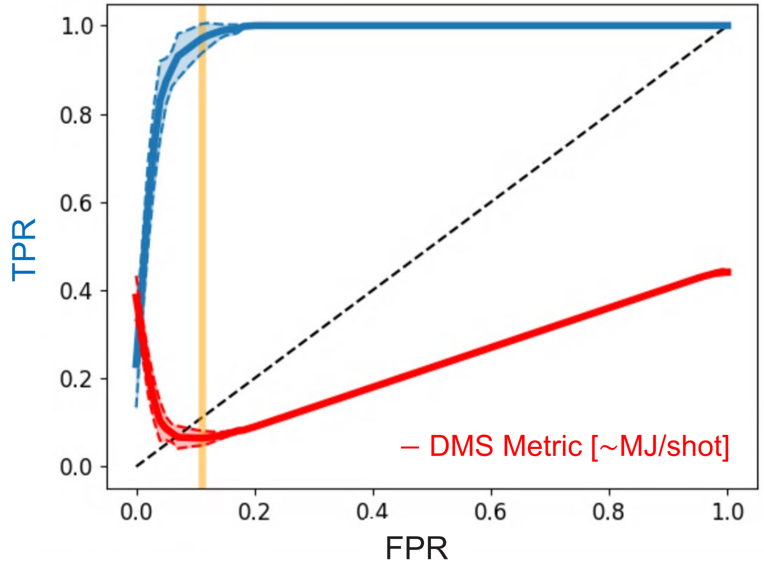


DMS detector for IAEs has been tested in simulated SPARC-like environment

- **We have introduced IAEs and generated a database of stable and disruptive shots**
- **A DMS detector has been trained/tested on this database**
- **The performance is reasonable, but the physics fidelity needs to be improved to get more appropriate thresholds**

Simulated Database





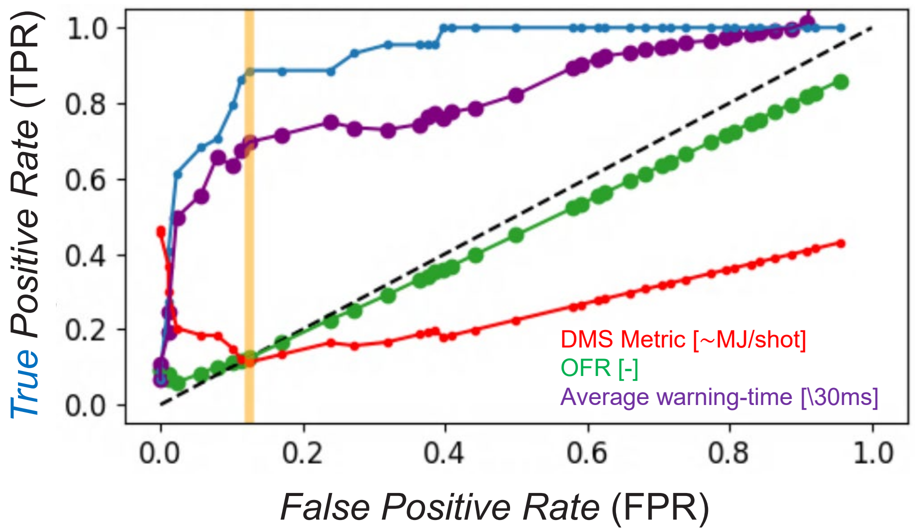
Summary

- **The structure for SPARC's ONW system has been mostly established**
  - Control-response structure for ONW modules
  - Detectors are designed to meet specific warning-time distributions
  - A tunable extension of the Points-Based model is used for triggering warnings
- **ONW modules for IAEs, VDEs, and TMs are currently in development**
  - DMS detectors for IAEs and VDEs are working well on C-Mod, and scale optimistically to SPARC
  - An IAE warning module has been tested on preliminary simulations of a SPARC-like environment
  - An Avoidance detector for VDEs is also in the works → *See talk after this one*
- **Coming soon**
  - Collaboration with EPFL to integrate ONW development with DEFUSE, and benchmark these physics-driven models against existing scalings and data-driven models
  - Planning to test ONW system during ramp-up and ramp-down

Extra slides

Other optimization metrics considered

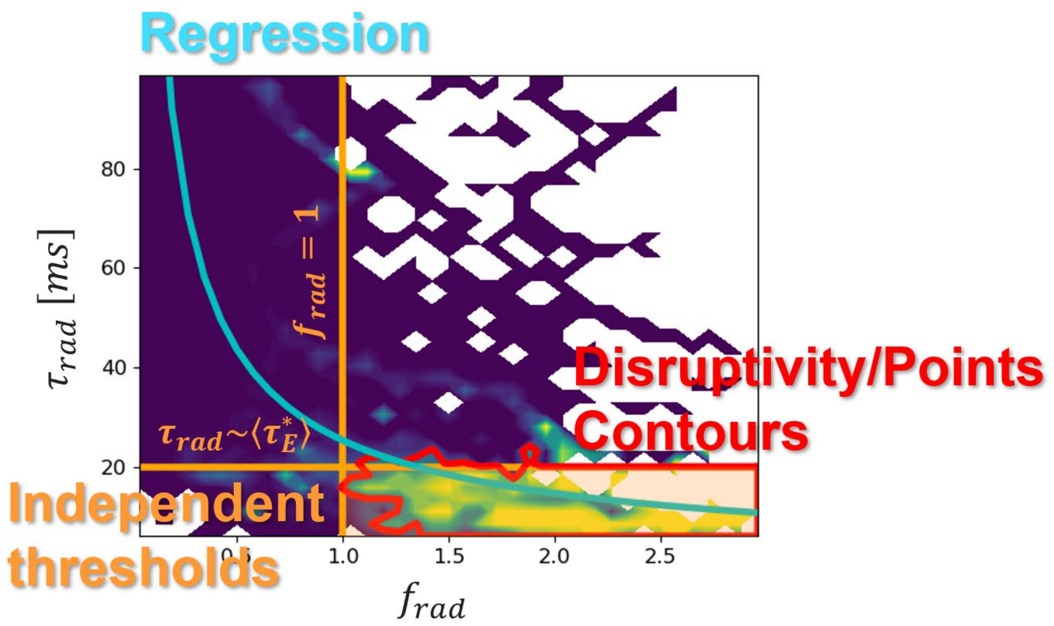
- Expected cumulative loads per shot
  - $\langle D\rangle = P_D\langle D_{um}\rangle\{1 + P_D^{-1} f_m \boldsymbol{FPR} - (1 - f_m)\boldsymbol{TPR}\}$
    - $\langle D_{um}\rangle$ = average un-mitigated disruption load [J or N /shot]
  - Expected cumulative loads over lifetime
    - $\langle D\rangle$ x number of shots



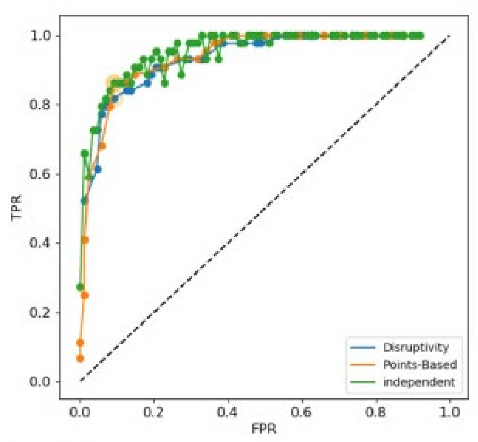
- Other* relevant metrics
  - (FPR,TPR) - *generic model* performance
  - $\langle t_{warn}\rangle$ - *controllability* performance
  - ONW Failure Rate (OFR) - *operation-time* performance
  - Average disruptive load $\langle D\rangle$ - *machine safety* performance

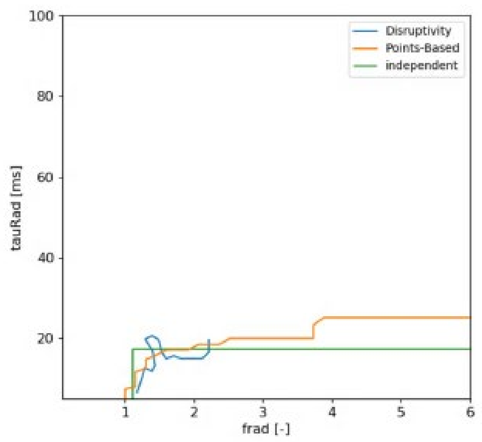
Other physics-driven models considered

- Several simple and interpretable models were investigated
  - Independent thresholds
  - Disruptivity
  - Regression
  - **(Gerhardt's) Points-Based model**

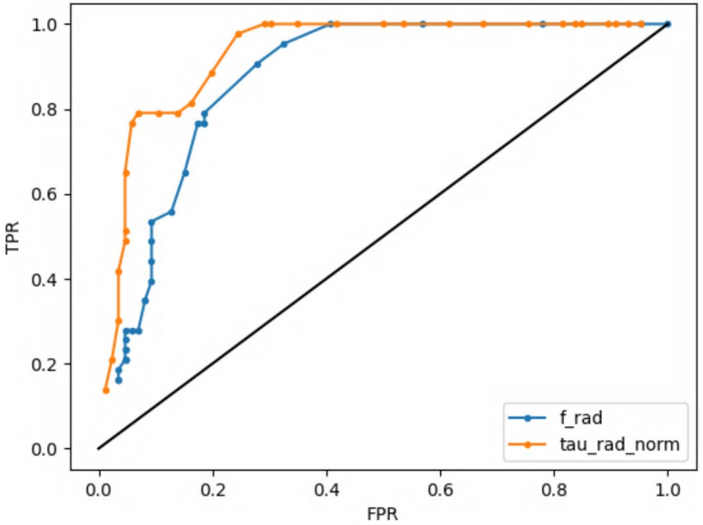


- Why the Points-Based model?
  - It has similar performance and interpretability to Disruptivity, but scales better at larger dimensionality and is much more flexible to tuning

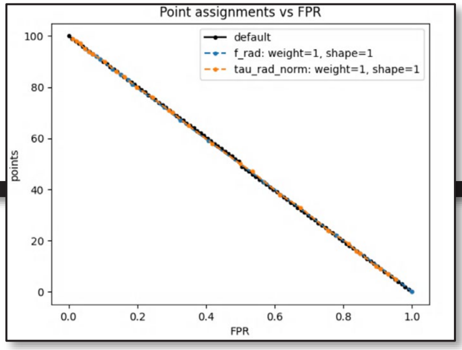




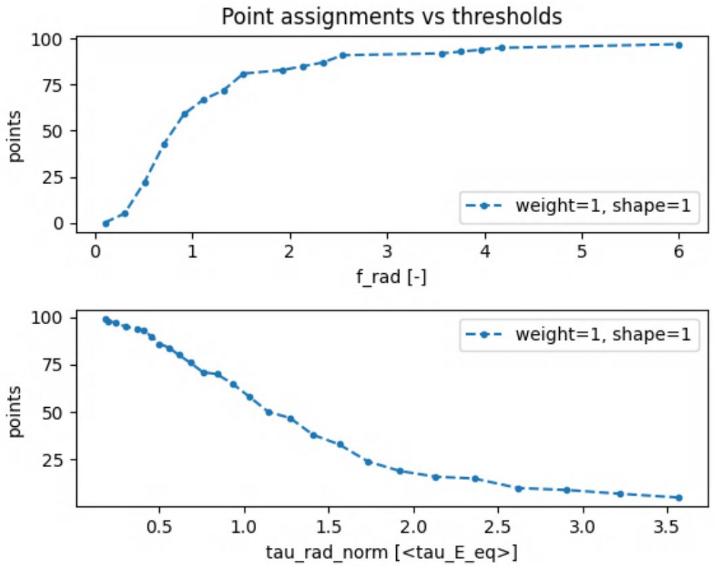
More detailed Points-model explanation



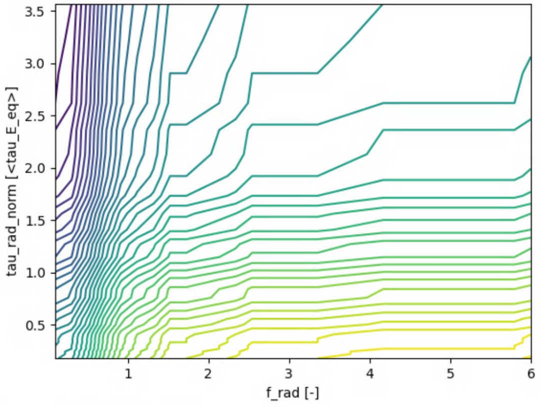
Identify relevant thresholds for each input based on their associated FPR
(*Updated by re-training*)



Reward lower FPRs with more points
Set by $P(\boldsymbol{FPR}) = \boldsymbol{w} * 100(1 - \boldsymbol{FPR})^{\boldsymbol{s}}$
(*Updated by tuning*)



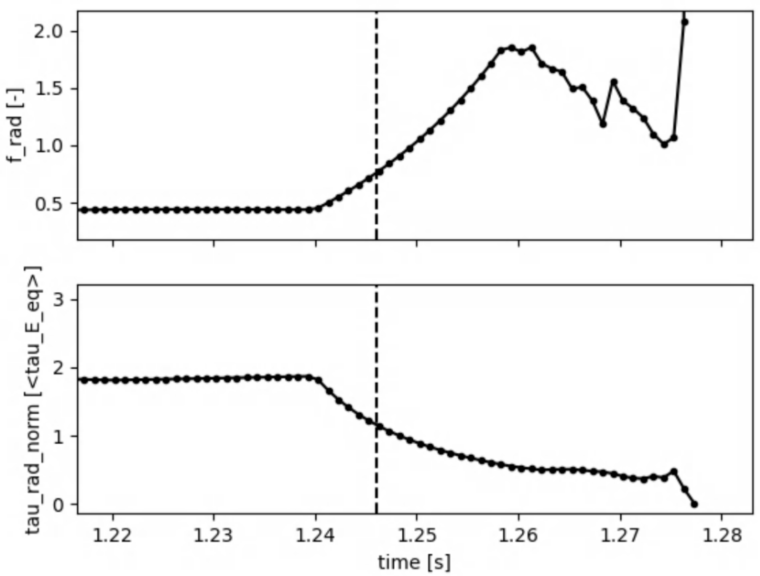
Map thresholds → points



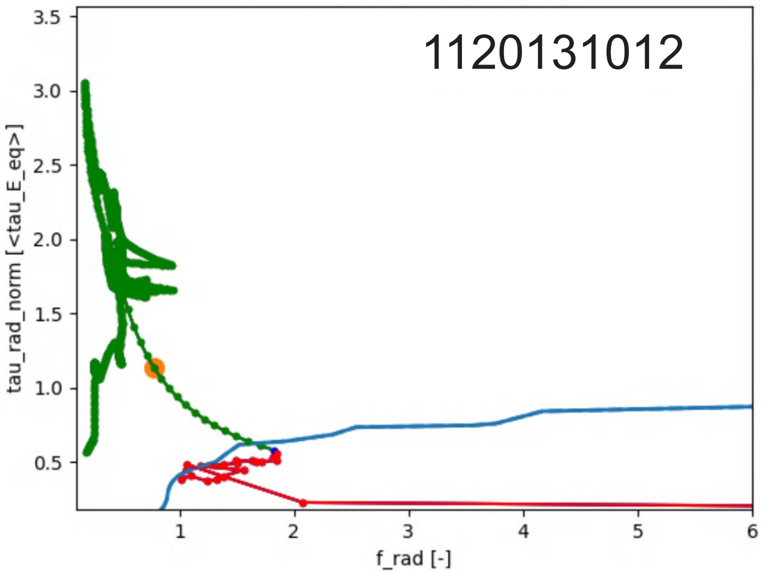
Generate contours of constant $\sum P$
(*Updated by optimizing relevant metric*)

Example ONW module output (IAE DMS detector on C-Mod)

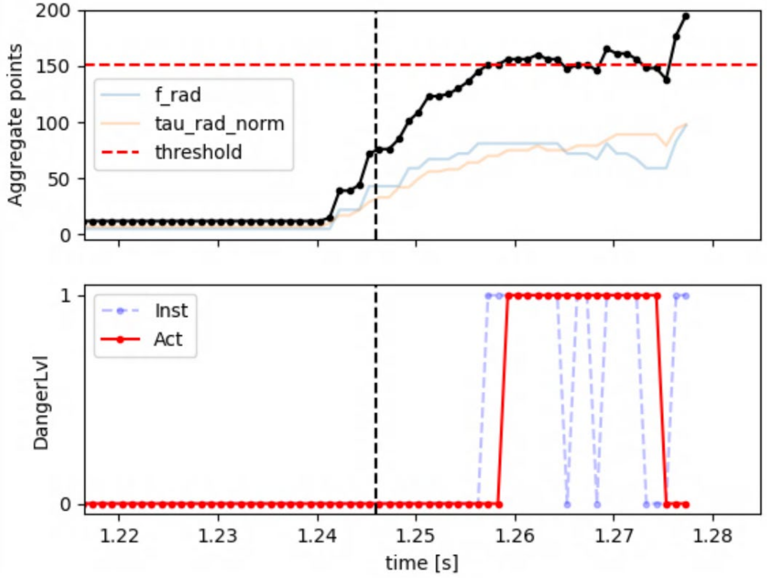
Traces of physics inputs



Trajectory in stability-space



Warnings



List of ONEs to be addressed for SPARC

- **List based on deVries 2011**

- **Priority**
  - 1) Likely to come up in nominal operation
    - 1-H) … nominal *H-mod* operation
  - 2) Unlikely to come up in nominal operation

- **IAEs**
  - SPARC scenarios are expected to operate at higher f_{rad}
  - Sensitivity to impurity seeding issues

- **VDEs**
  - High-ish elongation ($\kappa_{area} \sim 1.7$)

- **LMs**
  - Generic disruption precursor

Event	Abbr.	Priority
Impurity Accumulation Events	**IAE**	**1**
Vertical Displacement Event	**VDE**	**1**
Locked Modes	**LMs**	**1**
Rotating Tearing Modes	RMs	1
Error Field Locked Modes	EFLMs	1
Sawtooth Crashes	ST	1
Inboard/Outboard Shift		1
Detachment		1
Edge Localized Modes	ELMs	1-H
HL back-transition		1-H
Density Limit	DL	2
Internal Transport Barrier collapse	ITB	2
Low safety factor	LOQ	2
Flux consumption		2

POPSIM + ONSIMs

- **POPSIM = time-dependent POPCON**
  - *POPSIM is a control-oriented tokamak plasma simulation toolbox built in the machine-learning framework JAX*
  - Currently being developed at MIT in collaboration with CFS

- ***Off-Normal Events SIMulations* (ONSIMs) are being added to POPSIM**
  - Physics fidelity is being improved to meet ONSIM needs