EUROfusion

IAEA TM on Plasma Disruptions and their Mitigation 2020

Off-normal event-detection and NTM-control for integrated disruption avoidance and scenario control

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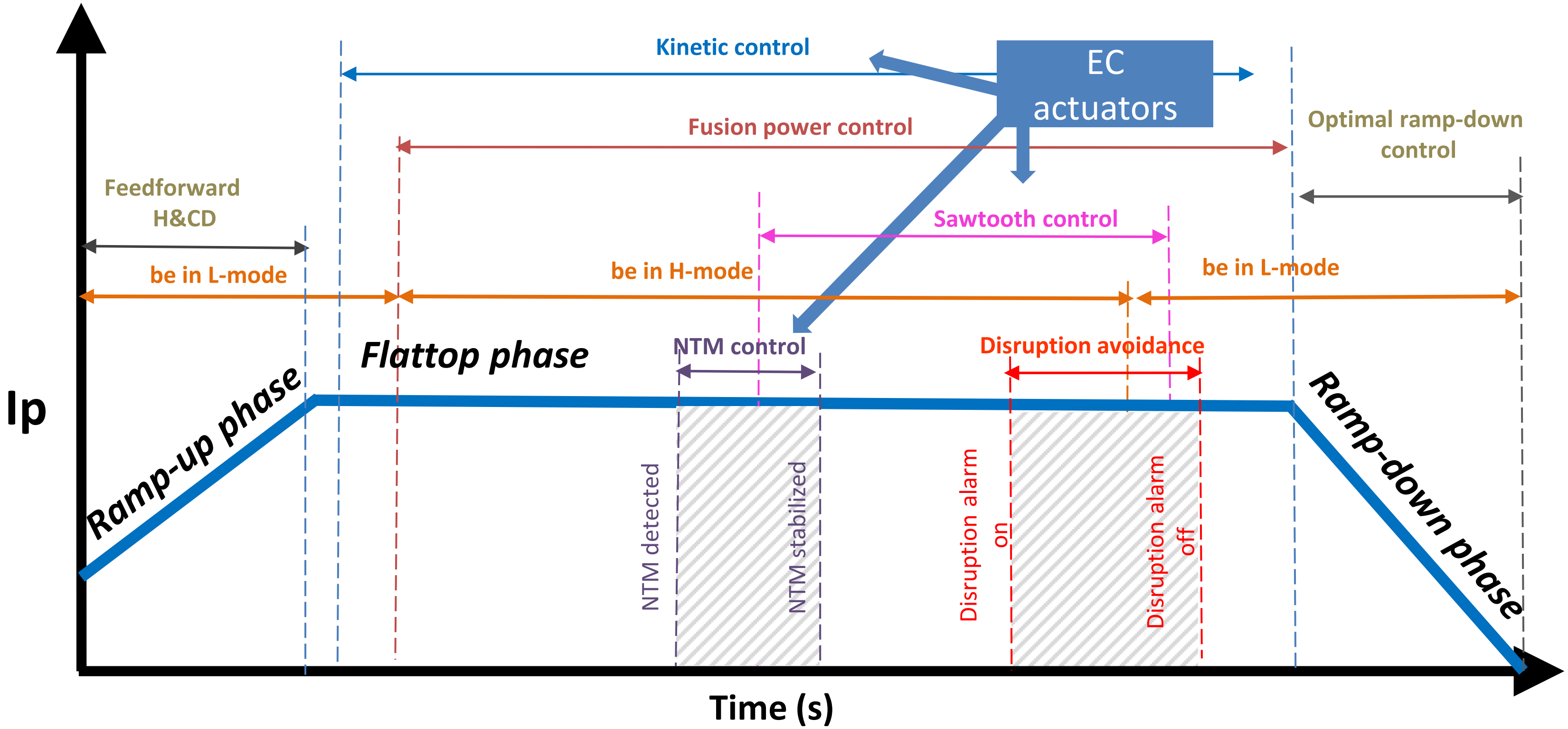
Need for real-time task prioritization



Real-time decision:
- control scenario
- multiple control tasks
- actuator sharing
- time varying priority

⇨

Solution:
controller cross-talk

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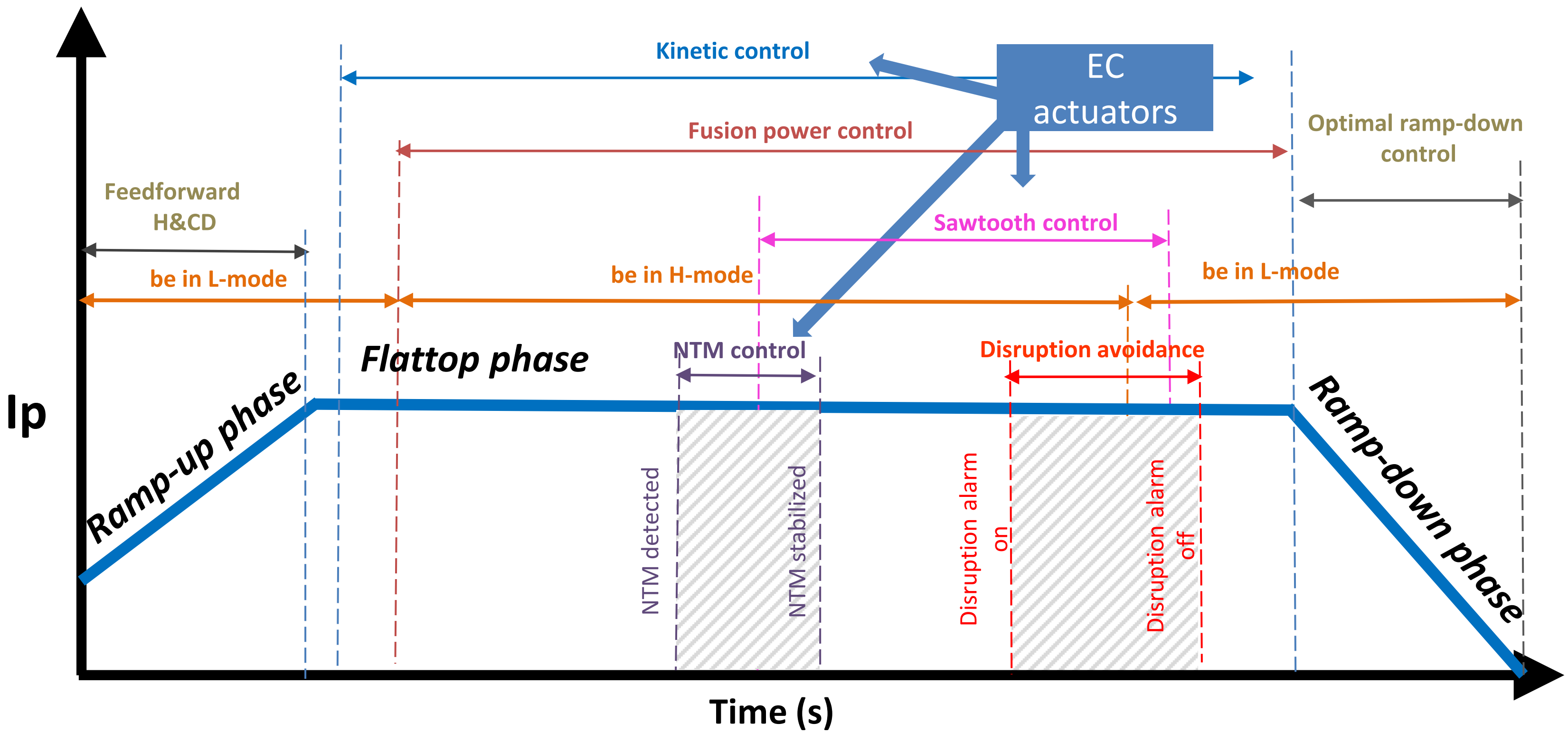
Need for real-time task prioritization



Real-time decision:

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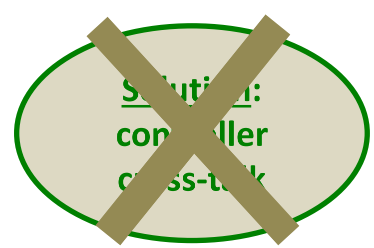

Outline

- I PART: Plasma Control System (PCS) architecture
  - Generic framework for the Plasma Control System (PCS)
  - NTM control and plasma state monitor
  - Off-normal events handling: from physics-based and data-driven detection to disruption avoidance;
- II PART: NTM real-time integrated control
  - Actuator Manager, Supervisor and RT integrated control
- III PART: RT-Capable Modified Rutherford Equation (MRE)
  - MRE tool interpretative analysis & Real-time integration
  - Real-time MRE coefficients adaption and prediction
- Summary & outlook

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1st PART

A generic framework for Plasma Control Systems (PCS):

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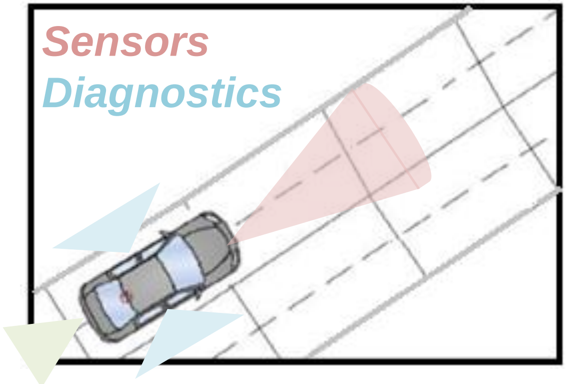
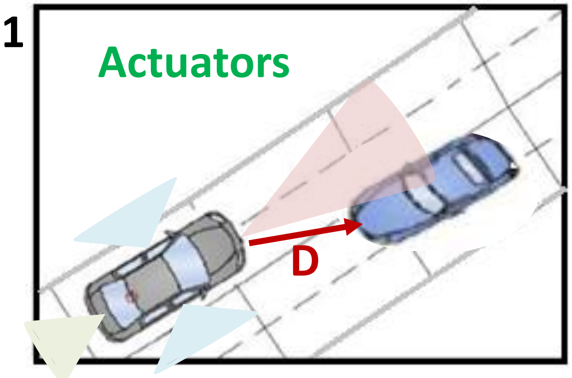
State monitoring, supervisor and actuators

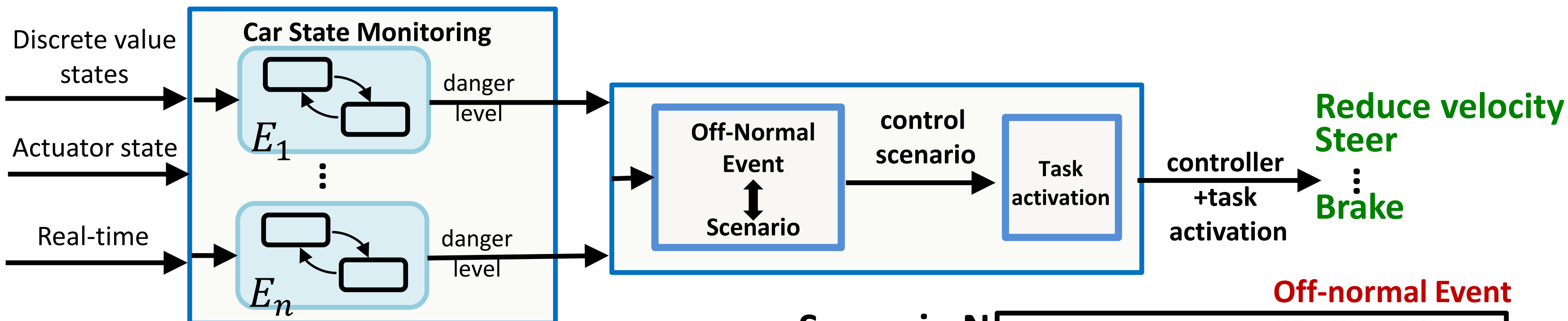


AUTONOMOUS DRIVING

Off-normal Event

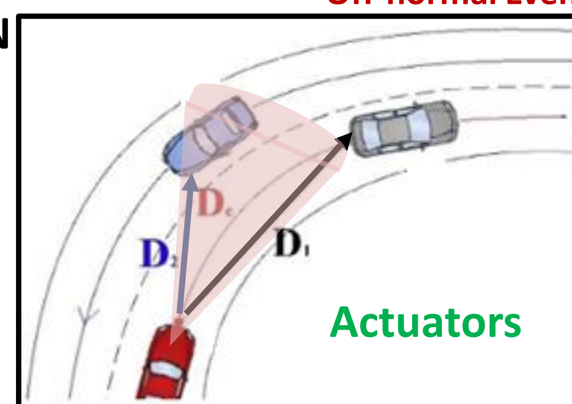
Scenario 1





Off-normal Event

Scenario N



Off-normal events detection/prediction
Definition of **"proximity measure"** and **probability of occurrence**

- **Physics-based** models
- **Data-driven** models **(ML/AI)**

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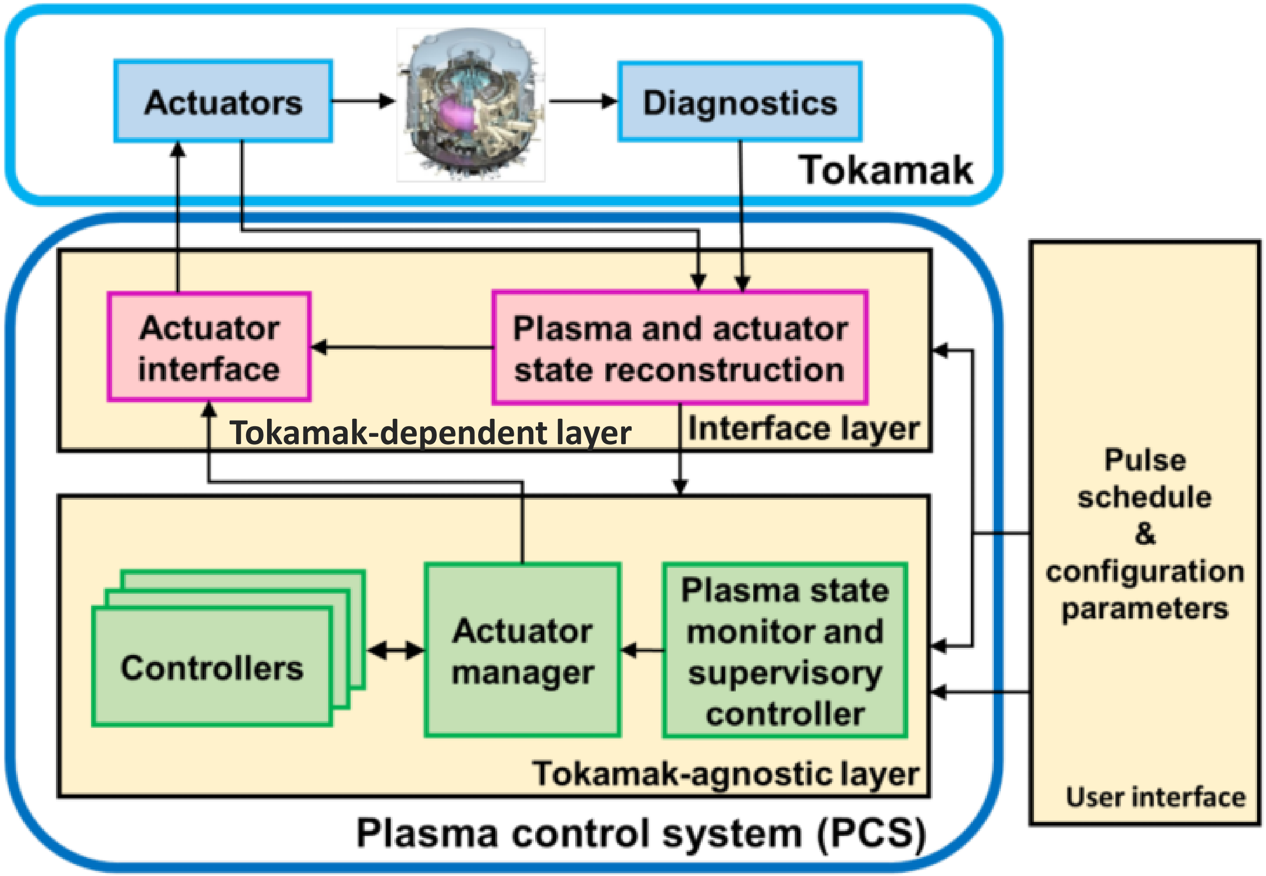
A generic framework for the PCS



Ref: T. Vu et al, FED 2019

- **Maintainability**
- **Portability**
- **Extendability**

Task-based approach:

supervisory controller and **actuator manager** prediction handle control tasks allocating actuators resources and controllers

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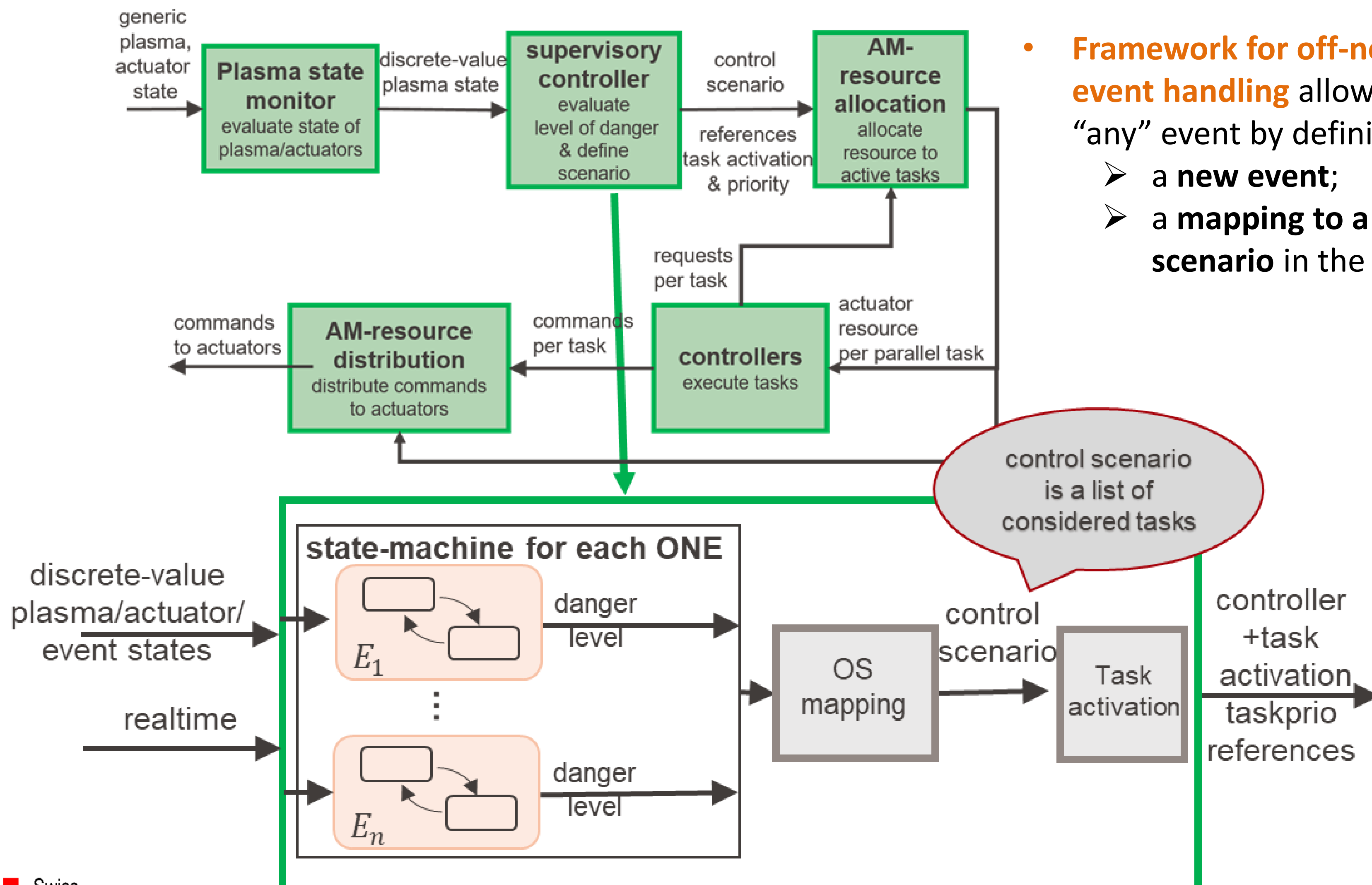
Off-normal events handling



- **Framework for off-normal event handling** allows to handle "any" event by defining:
  - a **new event**;
  - a **mapping to a control scenario** in the supervisor;

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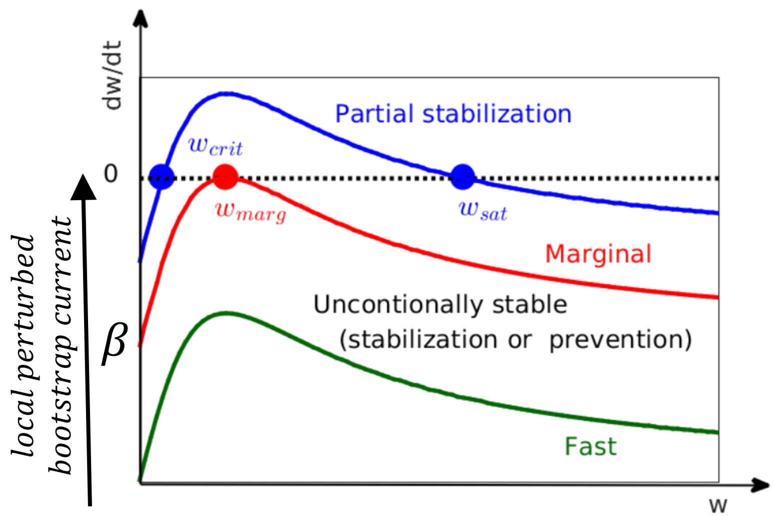
NTM control & physics-based event detection

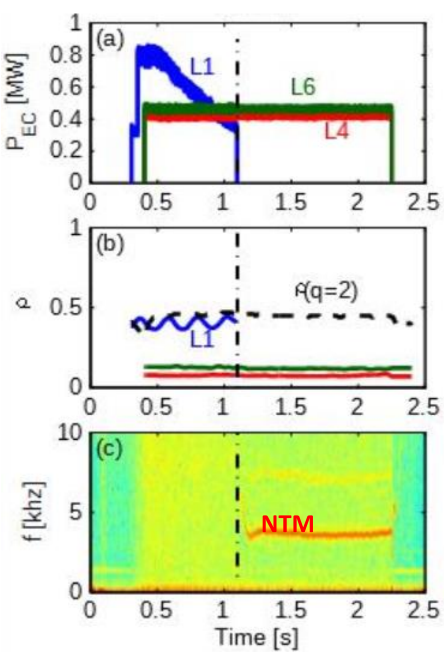


Onset of NTMs

- local flattening of the pressure profile and **confinement degradation**
- **mode locking** and potentially **disruption**;
- **metastable:** ${}^{dw}/_{dt} = f(w)$ & large enough seeding island to grow (**Sawtooth crashes**, **ELMs**, **Fishbones**, …);
- **"triggerless"** if developing from TM with $\Delta' > 0$ (depending on j and q profiles).

Control of NTMs

- **Stabilization** of already existing NTMs;
- **Prevention/Preemption** of the occurrence of NTMs;
  - Electron cyclotron current drive and heating (**ECCD/ECH**) as effective tool for NTM control (will be used in ITER)



NTM Preemption
TCV #58256

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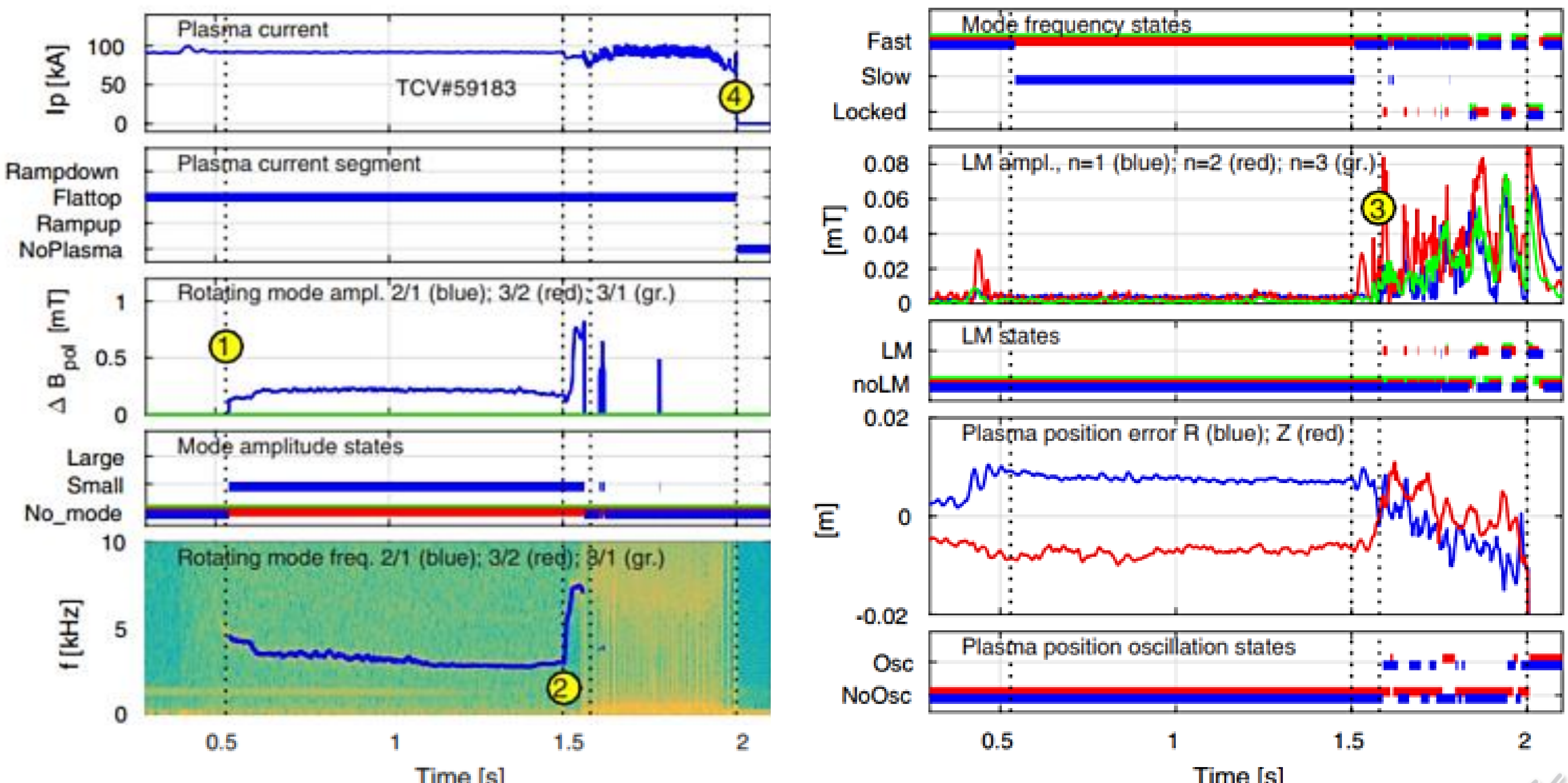
NTM control: TCV plasma state monitor

- Rotating mode analysis based on **Singular Value Decomposition** (SVD);
- Reconstruction of mode **amplitude**, **frequency**, and **acceleration**;

- **NTM** amplitude and frequency, and **Locked Mode** states & transitions represented in a **Finite State Machine** (Tokamak agnostic layer)



Ref: T. Blanken et al NF 2019

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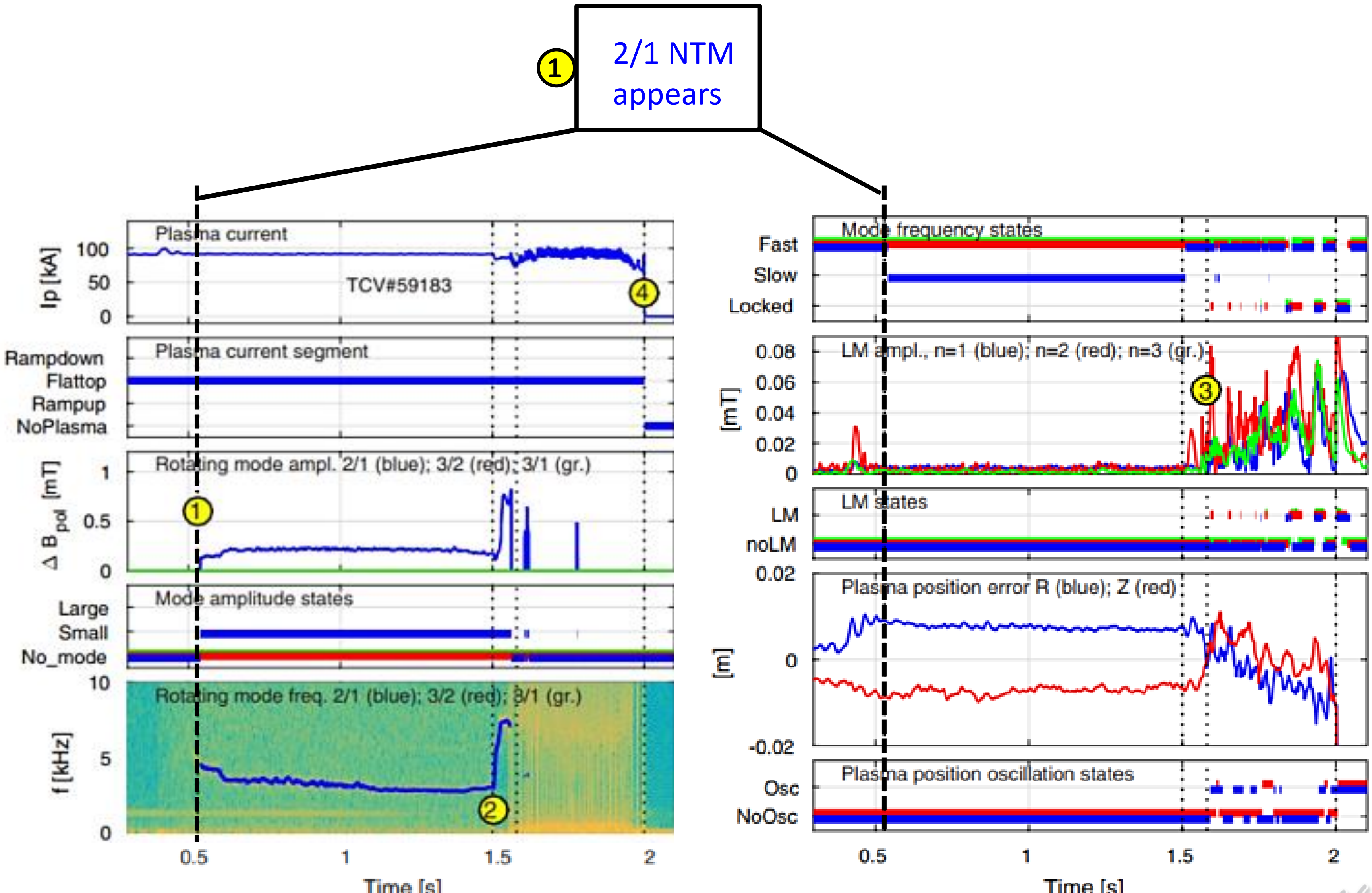
NTM control: TCV plasma state monitor



Ref: T. Blanken et al NF 2019

NTM control: TCV plasma state monitor

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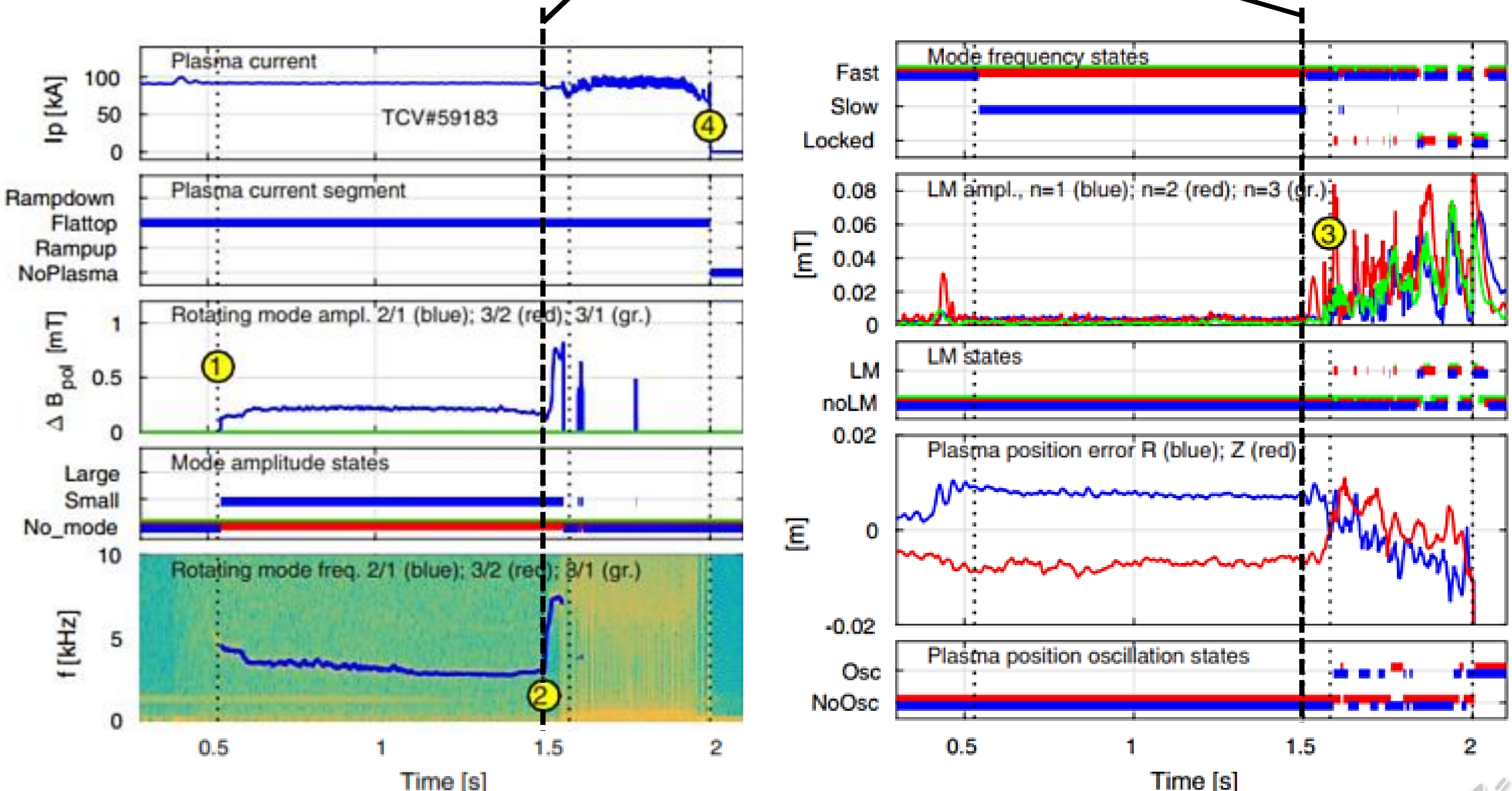
Deliberate *Ne* injection
Mode accelerates up to 7-8kHz



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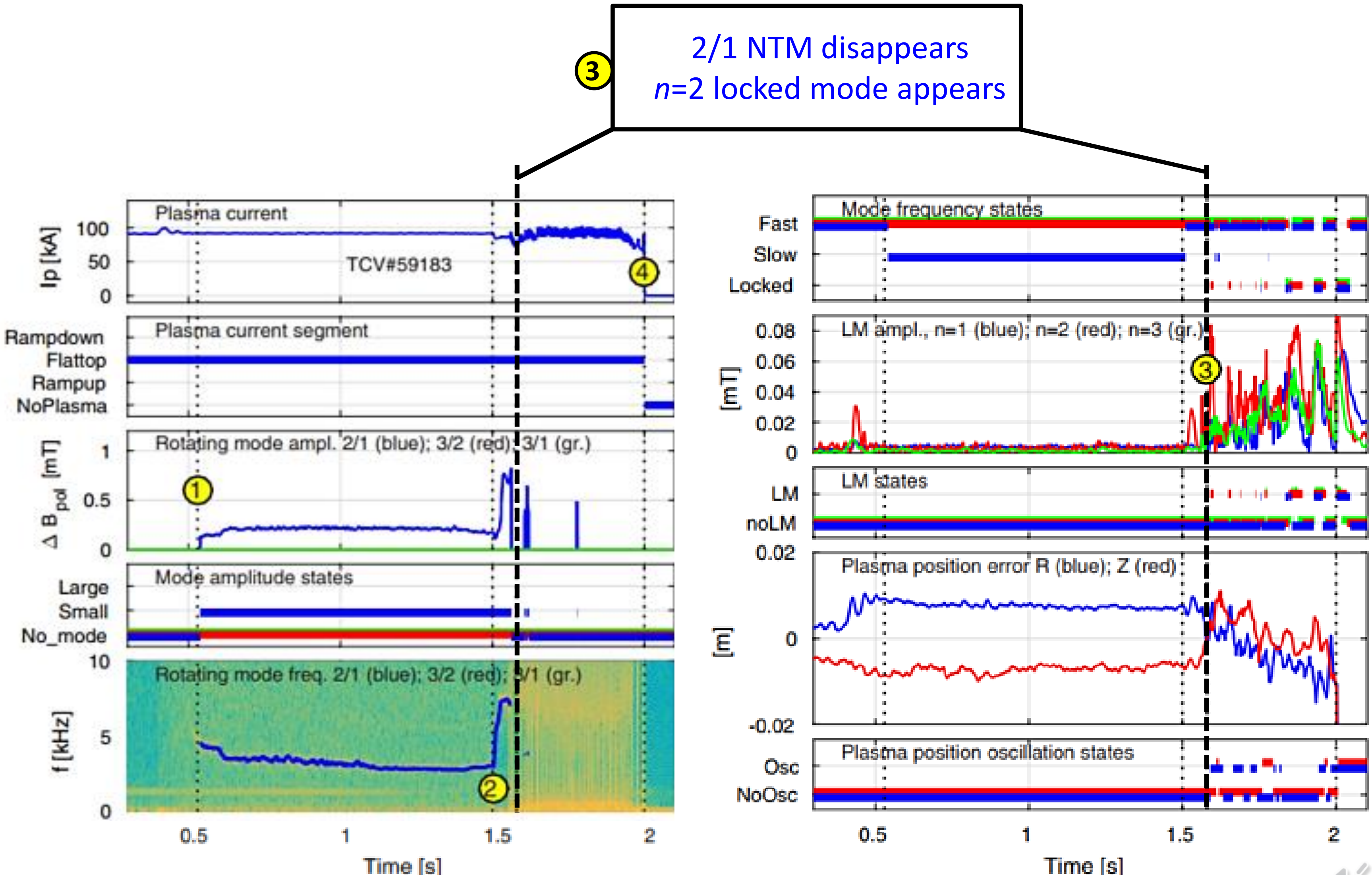
NTM control: TCV plasma state monitor



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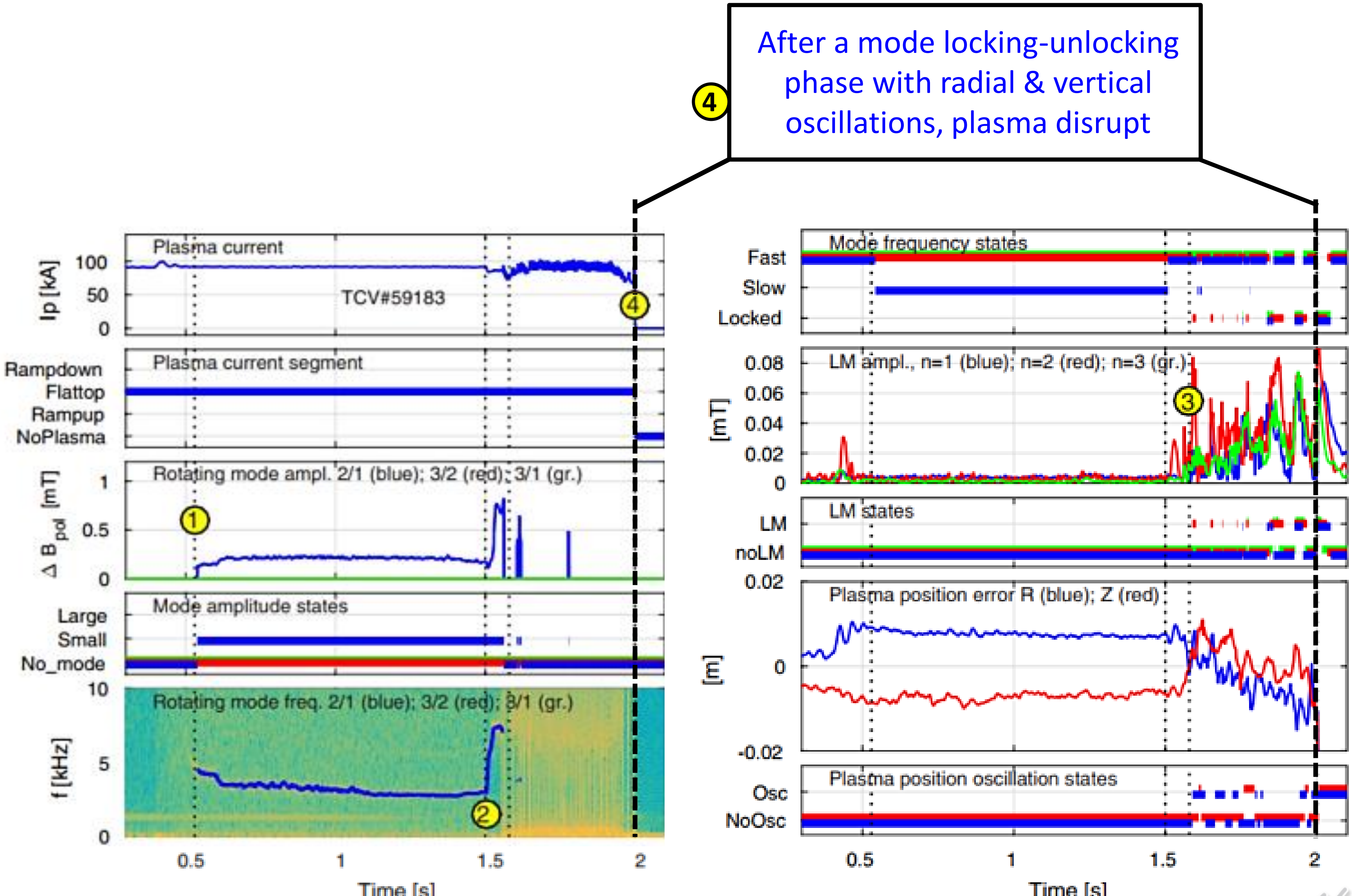
NTM control: TCV plasma state monitor



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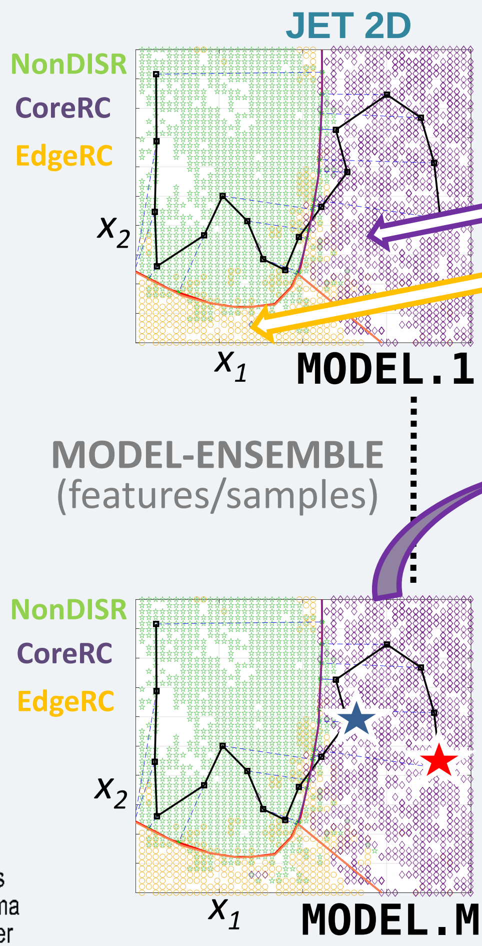
Data-driven/Machine Learning-based off-normal event detection
Generative Topographic Mapping (GTM)

Model Training

Generative
Topographic
Mapping



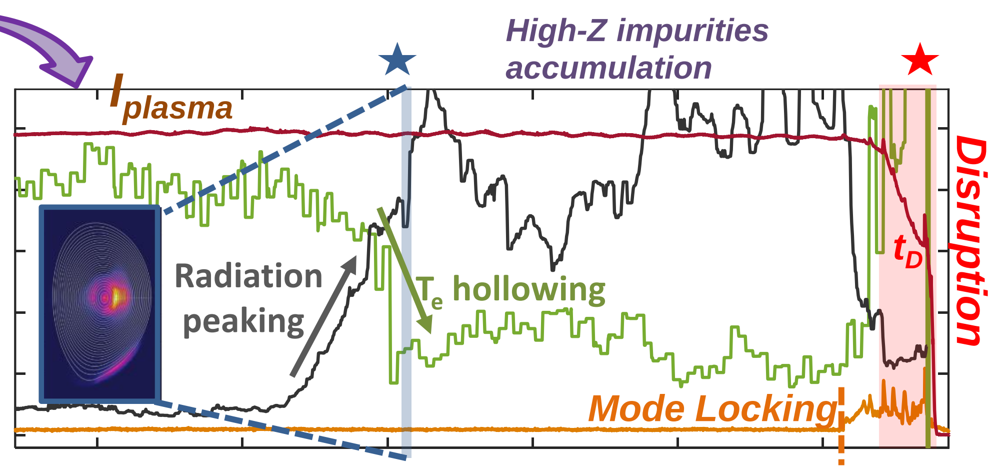
<u>Generative Topographic Mapping</u> (unsupervised learning)

- **Generative model** (<u>probabilistic framework</u>)
- Projection of a manifold embedded in **high-dimensional data space** in a reduced **latent space** (preservation of **manifold topology**)

Core Radiative Collapses (high-Z impurities accumulation)

Edge Radiative Collapses (edge cooling, MARFEs, etc.)

Disruptive regions



Goal: recognize patterns characterizing disruption event chains!

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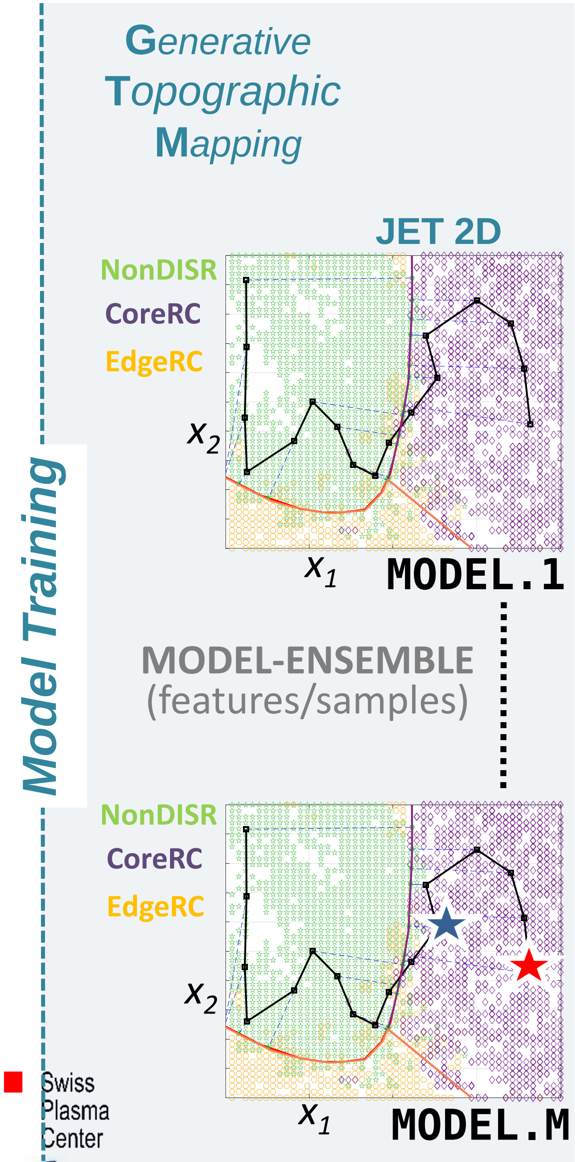
Ref: A. Pau et al NF 2019

Data-driven/Machine Learning-based off-normal event detection
Generative Topographic Mapping (GTM)



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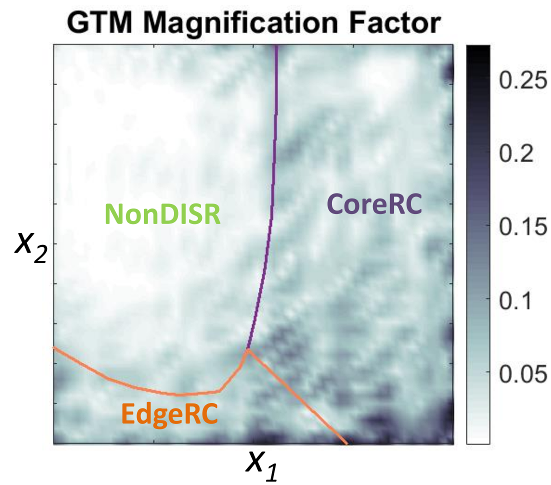
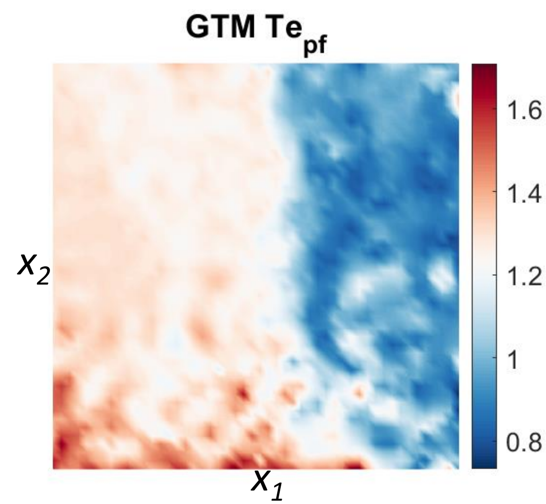
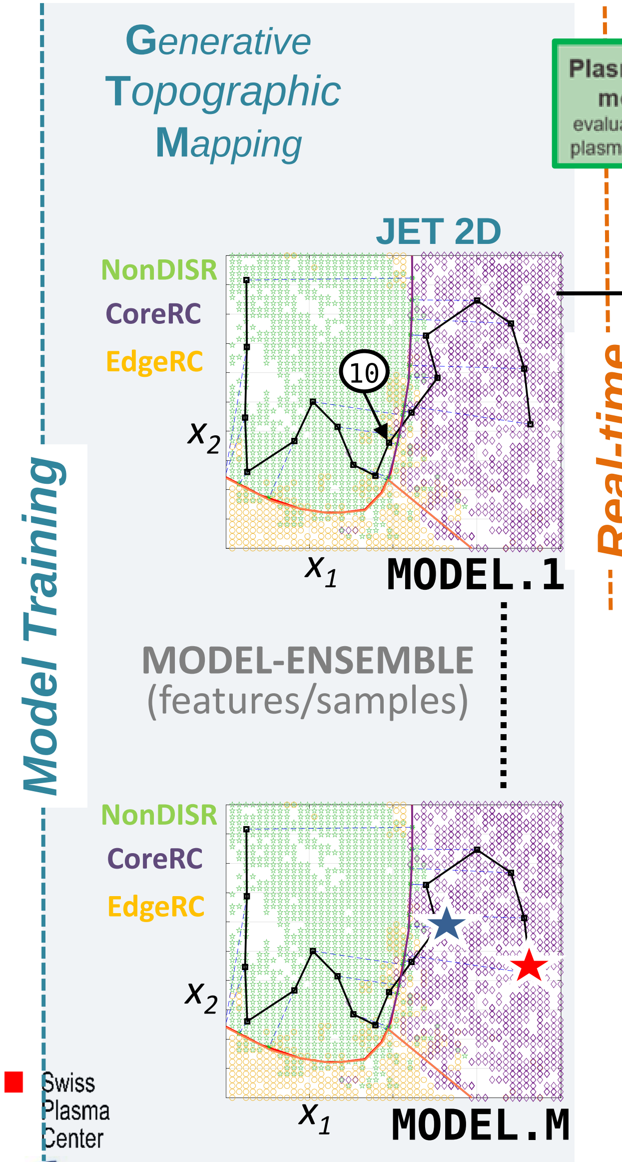


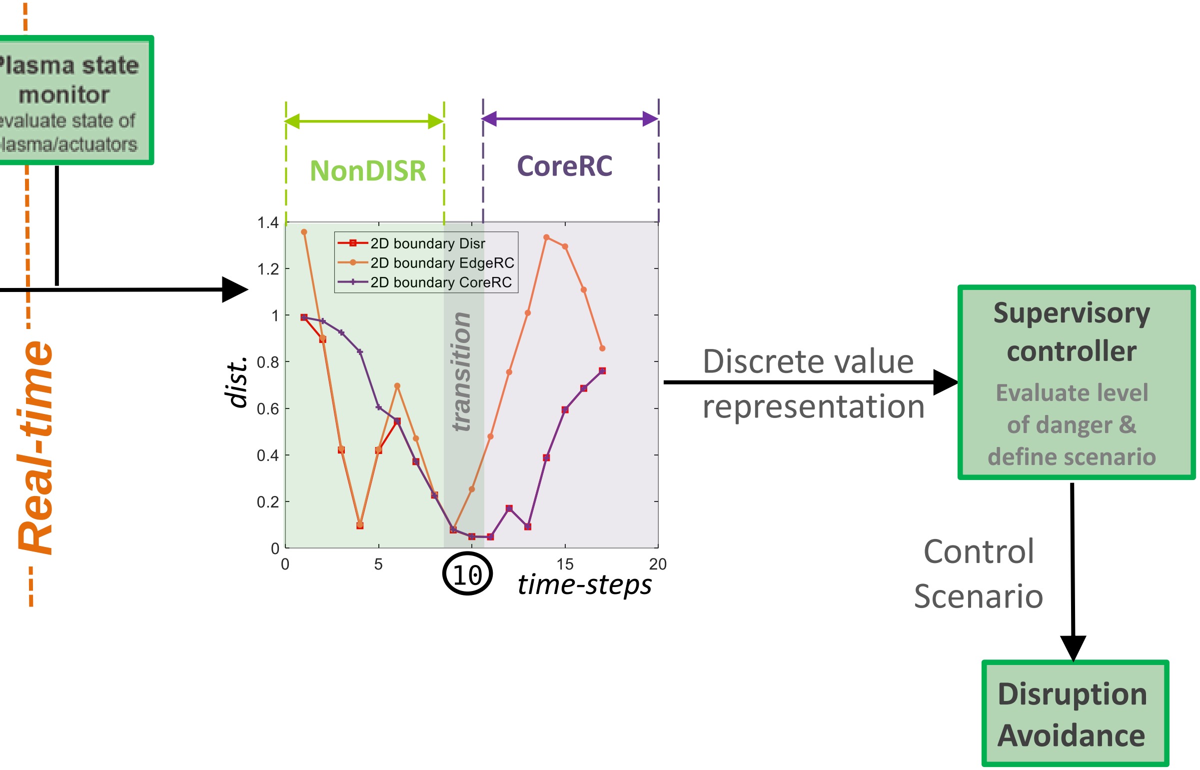
- Local "**compression**" or "**stretching**" of the manifold fitted to the data;
- **Boundaries** separating "clusters".



- Relative **component distribution** of T_e peaking factor in the latent space

Data-driven/Machine Learning-based off-normal event detection
Generative Topographic Mapping (GTM)





Proximities measures wrt disruptive boundaries
(RT plasma trajectory)

→ **Danger levels** to switch to specific control scenario
(e.g. **Disruption avoidance**)

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Ref: A. Pau et al NF 2019

2nd PART

Neoclassical Tearing Modes (NTM) & RT Integrated Control

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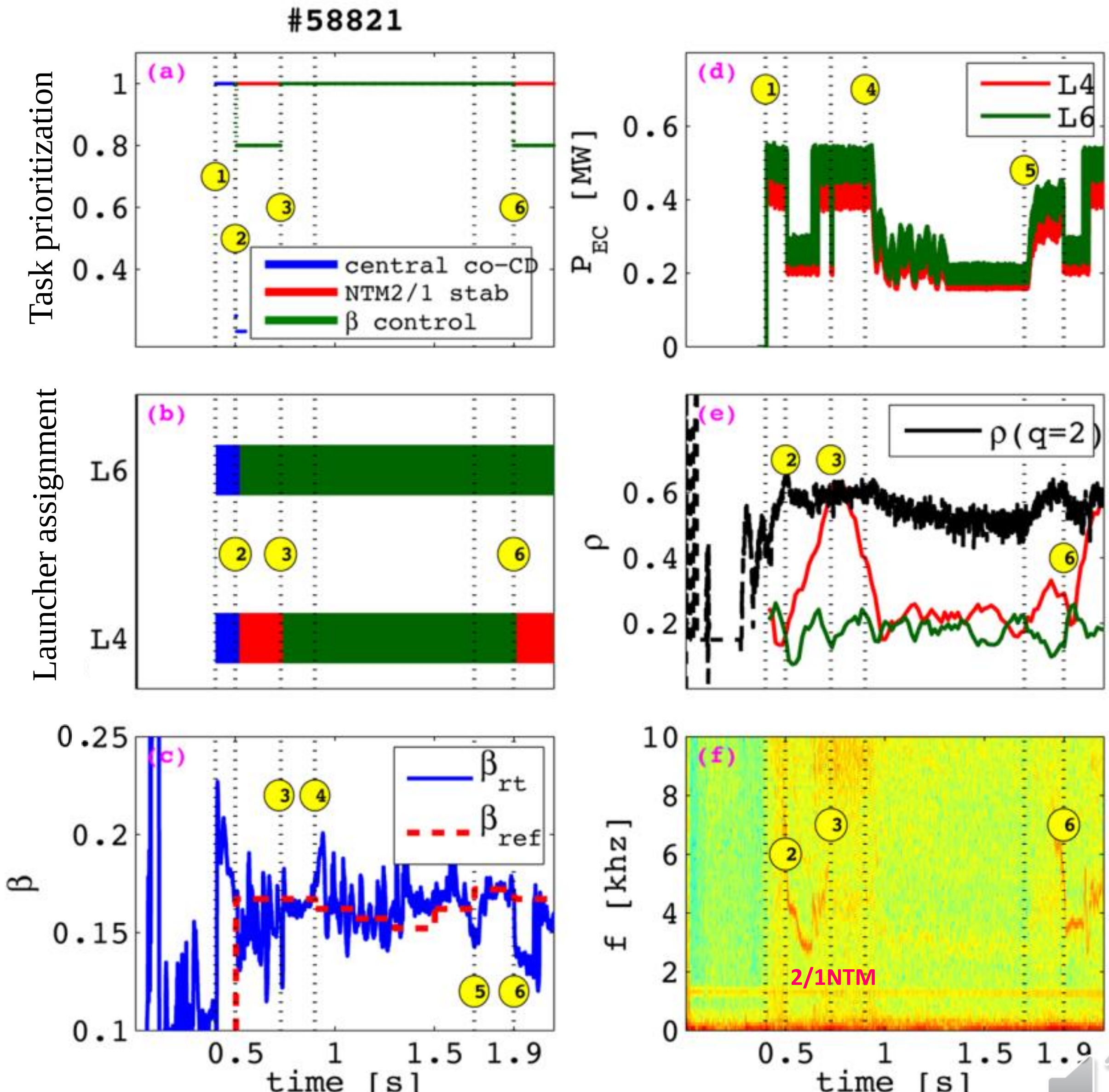
Real-time NTM and β integrated control

Task-based approach

- a **Supervisor** decide in **real-time** which tasks should be activated (**prioritization**);
- an **Actuator Manager** assign available actuators to each activated task;

3 tasks	Activation
Central co-CD	[0.4 0.55] s
2/1 NTM stabilization	[0.5 2.5] s + NTM onset
β control	[0.5 2.5] s

2 actuators	
EC launcher *L4*	co-CD (0.5MW)
EC launcher *L6*	co-CD (0.5MW)



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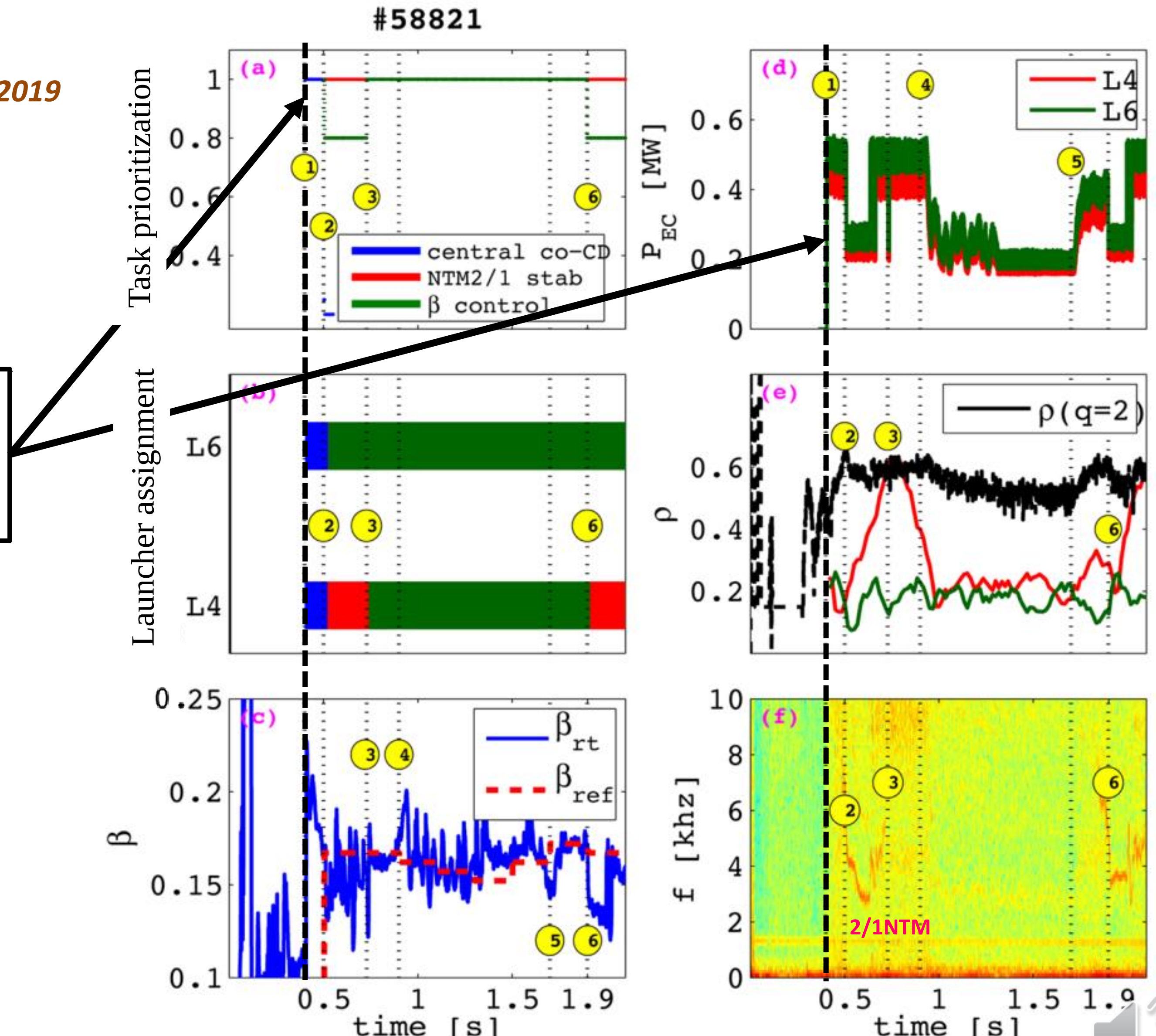
Real-time NTM and β integrated control

Ref: T. Vu et al, FED 2019

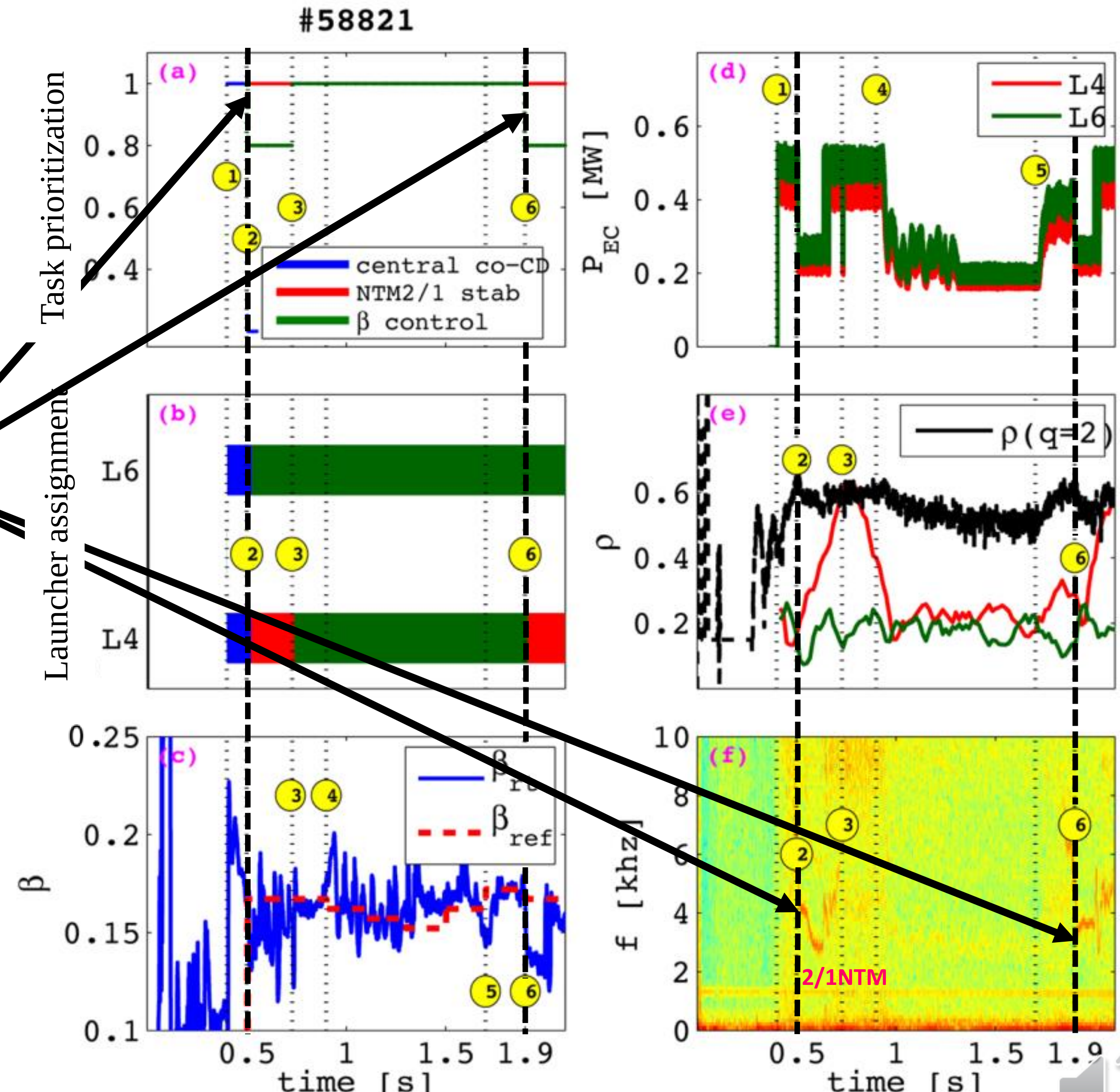
1 central **co-CD** is the only active task

Assign **L4** and **L6**



Real-time NTM and β integrated control

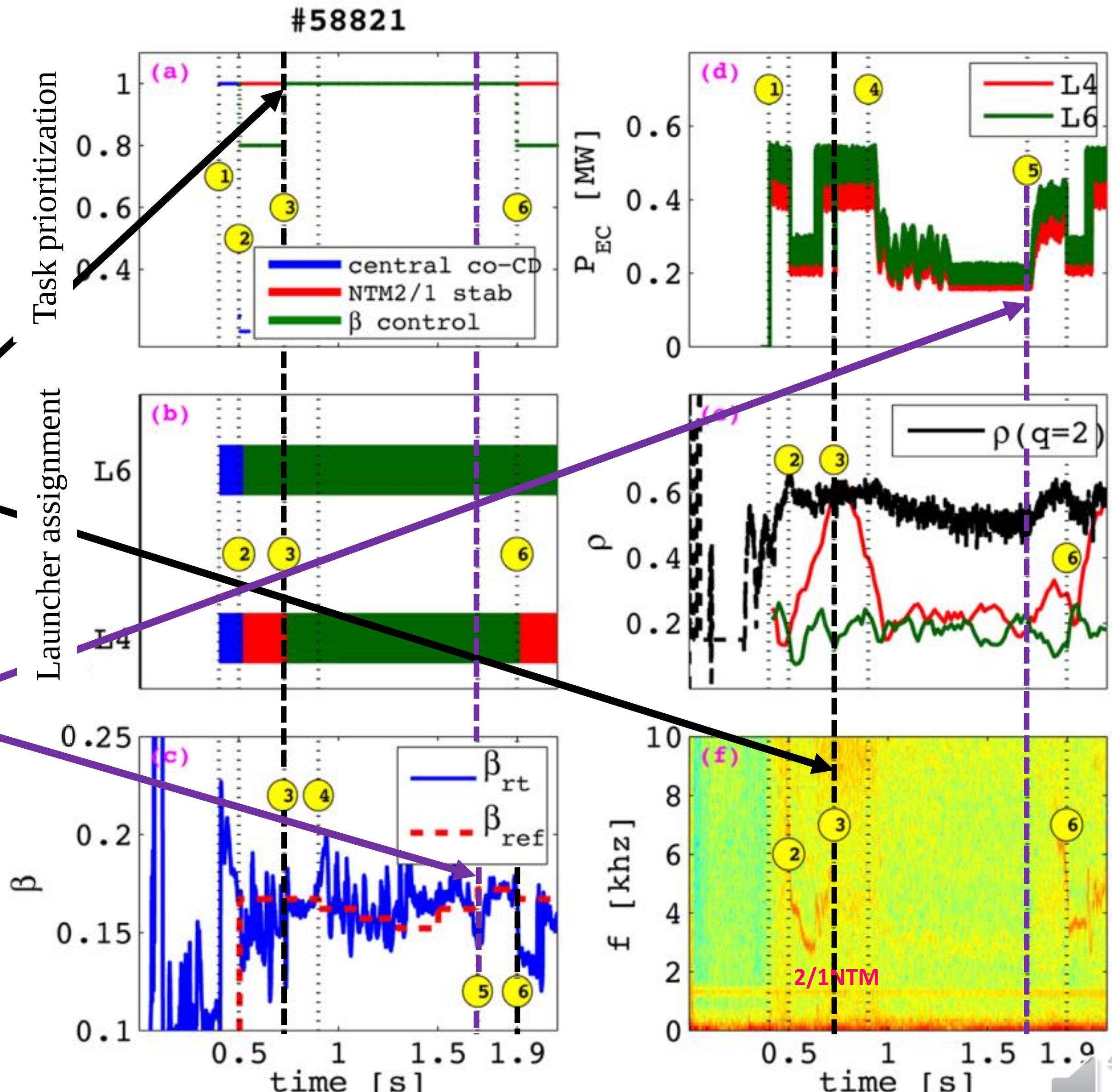
(2) (6)
2/1 NTM detection (stabilization highest priority) -> assign **L4** & **β ctrl** -> assign **L6**



Real-time NTM and β integrated control

3 **2/1 NTM** stabilized -> assign both **L4** & **L6** to **β ctrl**

5 β_{ref} is increased, plasma β_{rt} recovers & triggers a 2&1 NTM



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3rd PART

RT-capable Modified Rutherford Equation (MRE)

A powerful tool: a RT-capable Modified Rutherford Equation (MRE) module

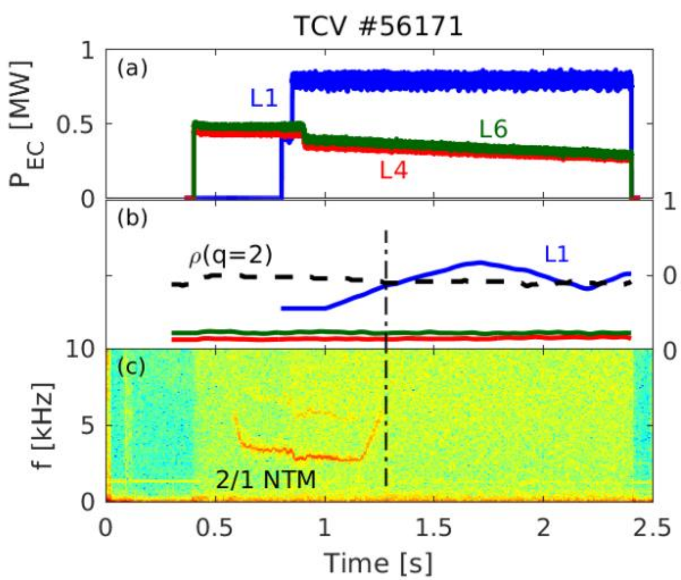
$$\frac{\tau_R}{\overline{\rho}_{mn}}\frac{dw}{dt} = \overline{\rho}_{mn}\Delta' + \underline{a_2}\,\overline{\rho}_{mn}\Delta'_{BS} + \underline{a_3}\,\overline{\rho}_{mn}\Delta'_{GGJ} + \underline{a_4}\,\overline{\rho}_{mn}\Delta'_{CD} + \underline{a_5}\,\overline{\rho}_{mn}\Delta'_{H}$$

Stability index

Perturbed bootstrap current

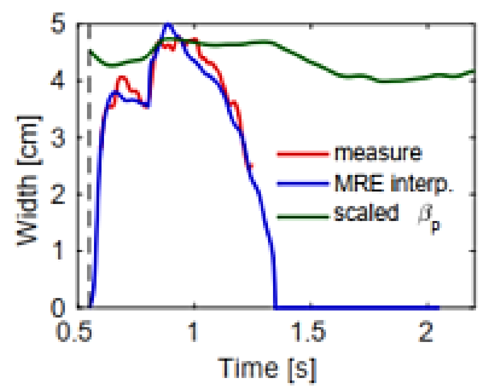
Favorable curvature

Effects of ECCD/ECRH at *q=m/n*



MRE

- Widely used in offline **interpretative simulations** of **NTM island width** (***w***) evolution (constant *coefficients*).



- **Full stabilization** with **800kW** of **co-ECCD** (Launcher **L1**)

- q & j_{BS} profiles from **Raptor**
- I_{CD} & ρ_{dep} from **TORAY**
- $a_2 = 1.3$; $a_3 = 1$; $a_4 = 0.65$; $a_5 = 0.9$.

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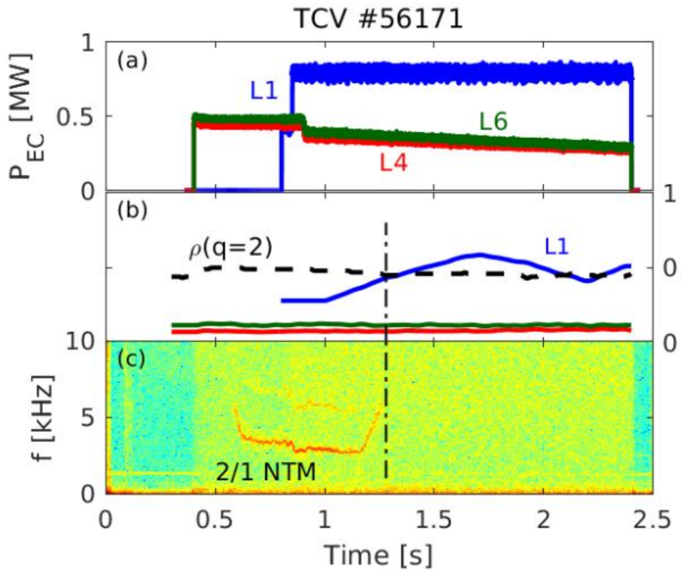
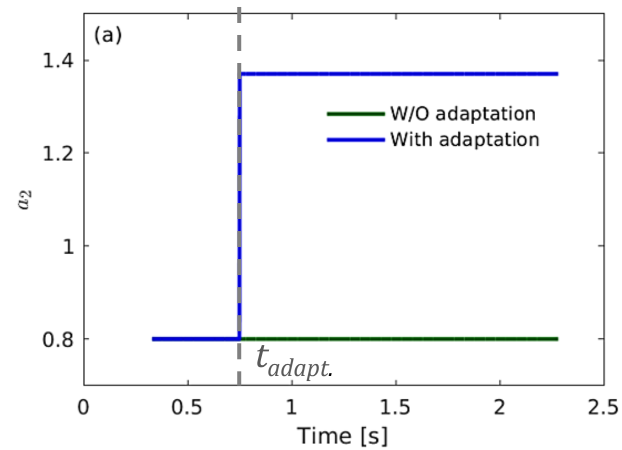
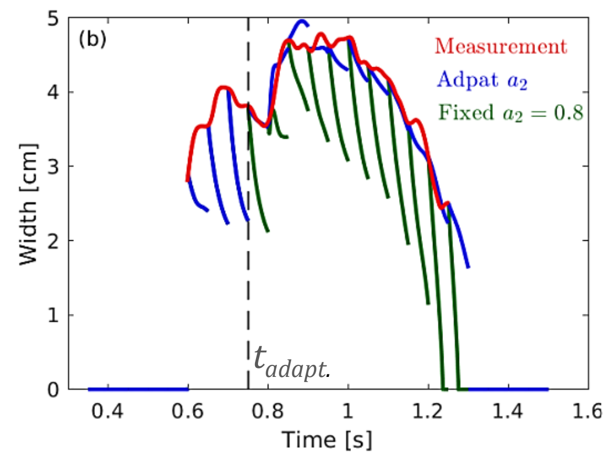
Ref: M. Kong et al, NF 2019

How to determine "free" coefficients of MRE in Real-Time





"Adapt a_2" case predicts very well *rt-w(t)*



Real-time adaption of MRE coefficients

- **coefficient adaptation** based on **tracing** of ***w(t)*** evolution;
- At each time t_N the simulation of ***w(t)*** in $[t_N - t_M, t_N]$ is compared with **RT measurements** (t_M is of the order of the resistive time scale ~50ms)

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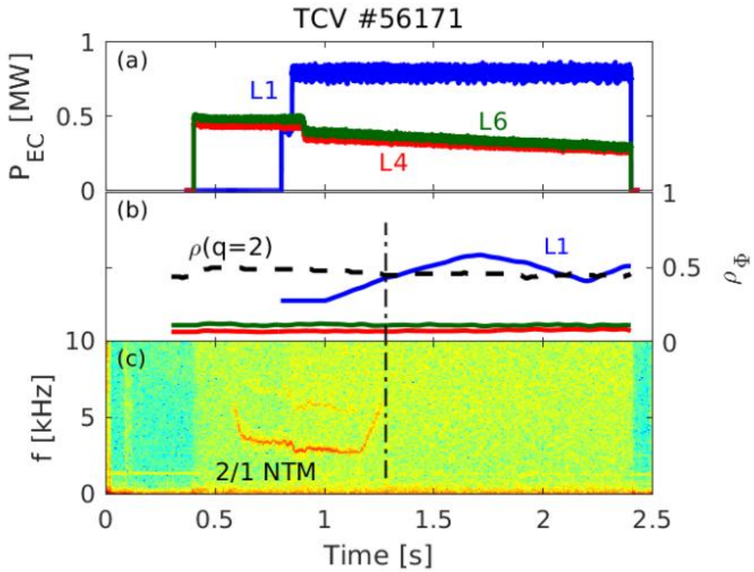
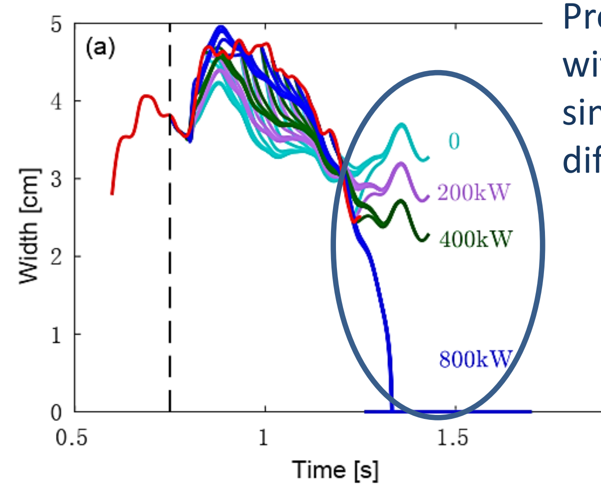
Prediction of NTM island width evolution

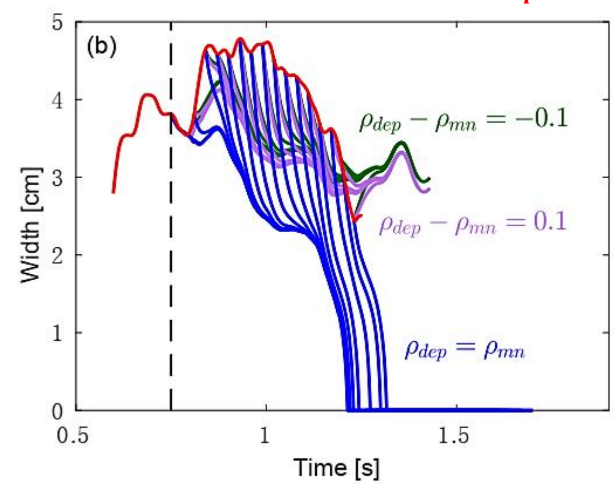


Prediction with varying P_{EC}



Predicts 800kW with parallel simulations using different powers

Prediction with varying ρ_{dep}



Prediction of the island width evolution

- At each time t_N prediction of ***w(t)*** in $[t_N , t_N + t_M]$ simulating different P_{EC} and different ρ_{dep}

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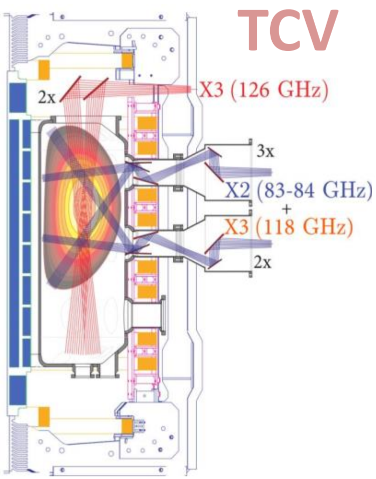
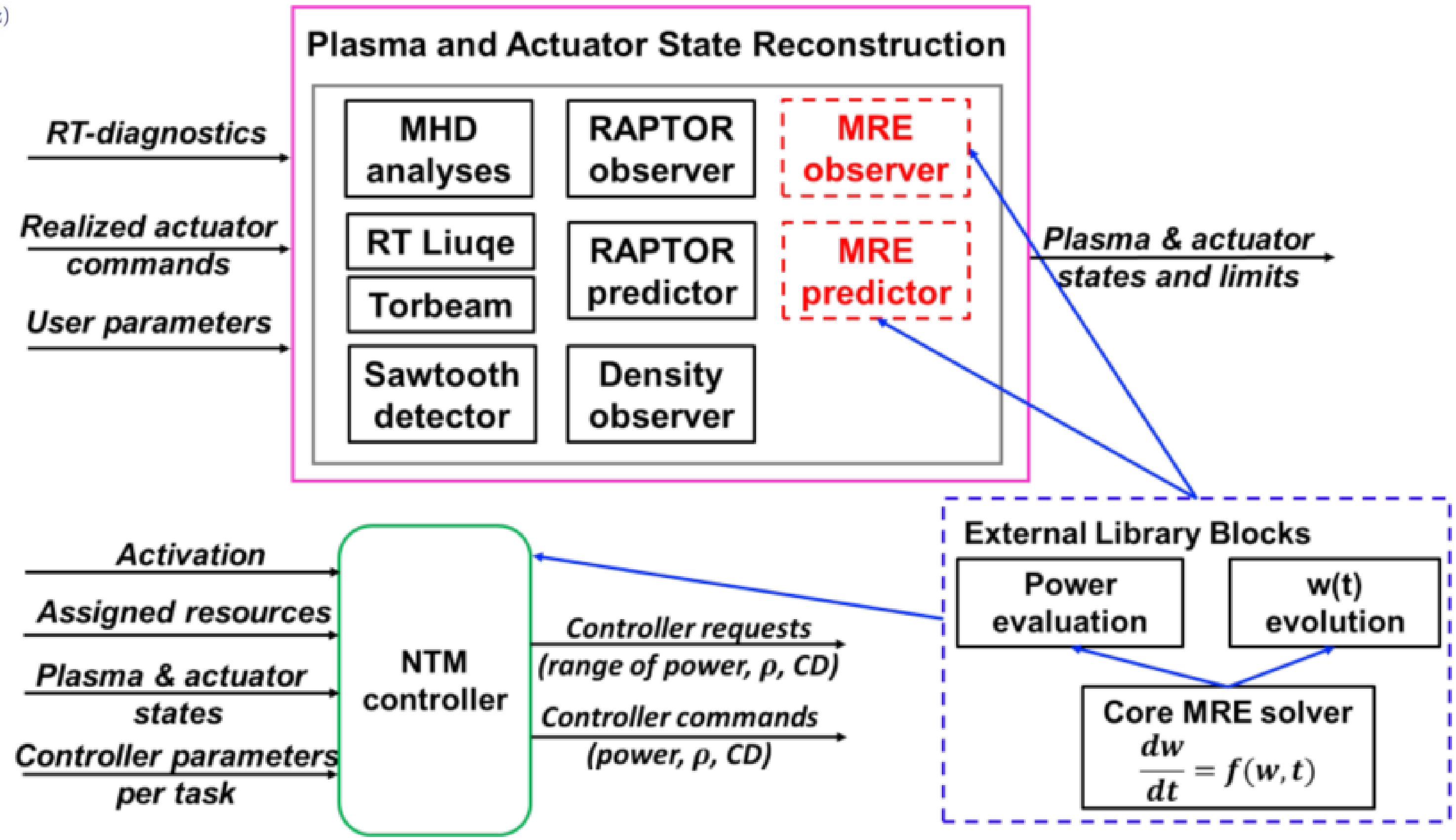
MRE RT module integration in TCV PCS



Ref: M. Kong PhD Thesis, EPFL 2020



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Summary and outlook

- **Generic framework** of **PCS** allows easy integration of new algorithms/task, as well as off-normal events detection for disruption avoidance ;
- Physics-based and data-driven **off-normal events detection** need to enable specific control actions to avoid disruptions;
  - proximity measures wrt **disruptive boundaries** & disruption **probability**;
  - the detection of specific events needs to mapped to specific control scenarios (disruption avoidance, fast termination, mitigation, etc.);
  - our approach avoids cross-talk and conflicts;
- **NTM integrated control** is an important “piece” both for performance and **disruption avoidance**;
- **MRE** is a powerful tool for **RT prediction** for level and deposition (localization) of the power needed to prevent/stabilize NTMs;
  - demonstrates potential of integration of **physics-based tools**.
    (see M. Marasheck talk in this meeting for H-mode density limits)