Integrated real-time supervisory management for off-normal-event handling and feedback control of tokamak plasmas

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***Abstract*—For long-pulse tokamaks, one of the main challenges in control strategy is to simultaneously reach multiple control objectives and to robustly handle in real-time (RT) unexpected events (off-normal-events - ONEs) with a limited set of actuators. We have developed in our previous work [1] a generic architecture of the plasma control system to deal with these issues. Thanks to this generic feature, we are able to extend it with an advanced supervisor to deal with multiple ONEs and multiple control scenarios SAMONE (Supervisory control & Actuator Management with ONEs) in this work. We first standardize the evaluation of ONEs and thereby simplify significantly the supervisor decision logic, as well as facilitate the modifications and extensions of ONE states in the future. Then we present the recent developments of real-time decision-making by the supervisor to switch between different control scenarios (normal, backup, shutdown, disruption mitigation, etc.) during the discharge, based on off-normal-event states. The developed SAMONE has been implemented on the TCV tokamak, applied to disruption avoidance with density limit experiments, demonstrating the excellent capabilities of the new RT integrated strategy.**

***Index Terms*—tokamak plasma control system, supervisory control, integrated control, off-normal-event handling**

I. Introduction

THE development of an advanced tokamak plasma control system (PCS) has recently gained more attention with the requirements of a robust off-normal-event (ONE - plasma or subsystem/plant failures) handling and of an integrated control approach. These are crucial to ensure a feasible discharge both for the plasma and the plasma-facing components in long-pulse tokamaks like ITER. On the one hand, this advanced PCS will act as the first line of defense of disruption, where all the plasma energy is released in few ms, to avoid unnecessary mitigation actions. On the other hand, it must be able to reach the desired discharge performance by simultaneously fulfilling multiple control tasks (control objectives) with a minimal set of actuators and diagnostics. Our work on SAMONE (Supervisory control & Actuator Management with Off-Normal-Events) extends the entire chain of the tokamak-agnostic layer in the PCS [1] with a standardized evaluation of ONEs as well as an advanced supervisor for multiple ONEs and multiple control scenarios. It demonstrates the efficiency of the proposed approach via the first applications on TCV.

Regarding ONE handling, several work has focused on the use of a discharge manager to decide appropriate actions depending on the seriousness of the events ([2]–[6]). In this work, different ONEs categories are distinguished and several control scenarios are investigated as well. The basic idea of ONE handling is shown in [2], where a discharge management system plays the roles of both a ONE monitor to classify the events and a supervisor to select a control scenario. In [5], [6], a supervisor is proposed for exception handling by changing the control segments, which are equivalent to our control scenarios. In [3], a supervisory logic, using finite-state machines[1], is developed for event detection. In this early stage, the simple threshold test on the individual event can only trigger a soft-shutdown or a mitigation scenario. In [4], based on disruption root causes, different decentralized handlers are deployed with their pre-assigned actuators to directly tackle ONEs.

However, in these works, the supervisory decision is done by the selection of reactions as well as the corresponding actuators via the prioritization of ONEs. This leads to a direct link between ONEs and actuators. In other words, the supervisor needs to be aware of ONE nature and tokamak specific actuator systems. Here, we propose a systematic way to handle ONEs by the supervisor. Therefore, more stages are necessary to clearly classify the *danger level,* the *reaction level* for each ONE, and a *ONE-reaction to Scenario* (OS) mapping is finally used to allow the supervisor to automatically switch between different control scenarios (normal, backup or shutdown scenarios, etc.). Since the supervisor only takes care of selecting an appropriate scenario, the actions to deal with ONEs, once they are detected, are (flexibly) customized as a list of prioritized control tasks in different control scenarios. This leads to an automatic actuator resource assignment of the actuator manager and control (feedback) actions of the controllers (see Fig. 2). The modular feature of the entire framework allows a simple and generic implementation, algorithm or functionality of each component in the control system. Moreover, the proposed scheme is also generic for any tokamak, thus it can be easily tested, developed and maintained. For our previous related works, the readers can

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[1] a representation of an event-driven (reactive) system which can be in one of a finite number of states depending on its previous condition and on the present values of its inputs.

refer to [7] for the plasma state and event monitoring, and to [1] for the generic actuator management strategy to deal with multiple control tasks and actuator sharing.

The next section gives an overview of the generic PCS architecture developed in [1]. Sec. III zooms in the supervisor in the PCS, with the details of several evaluation levels of ONE and of decision-making, as well as a concrete example for clarification. The developed PCS is implemented on TCV and the first results of disruption avoidance experiments are discussed in Sec. IV. Finally Sec. V concludes the work and gives some prospects for future works.

II. Generic plasma control system

The generic PCS presented in [1] is revisited hereafter with the main principles shown in Fig. 1. This PCS is clearly separated into two layers: the tokamak-dependent layer and the tokamak-agnostic layer. The tokamak-dependent layer includes various real-time (RT) state reconstruction codes for plasma and actuator states [7]. This layer thus converts specific plant signals to generic continuous-value states of the plasma and actuators which are used by the tokamak-agnostic layer and vice-versa. For example, on TCV, the RT kinetic plasma equilibrium reconstruction can provide realistic pressure and current density profiles [8]; and the RT measures, combined with models, of heating sources provide the states of EC and NBI actuators ([9], [10]). Since the inputs to these models are tokamak dependent, they are in the tokamak-dependent layer. The SAMONE tokamak-agnostic layer specifically deals with the ONEs and the execution of control tasks according to the pulse-schedule. Note that *tokamak-agnostic* is used in the sense that the functionality, algorithm and implementation of each component are independent of the tokamak subsystems (diagnostics and actuators), even the inputs and outputs are tokamak-agnostic and therefore well standardized. However the parameterization and specific usage (e.g. control tunable parameters such as controller gains, thresholds, feedforward and control references, etc. can be adapted for each discharge and each tokamak) are specified by the user via the pulse schedule (user interface). Thus the tokamak-agnostic layer can be directly transferable to different devices, independently developed and maintained; while the tokamak-dependent layer, also transferable, should be adapted (inputs/outputs) for each tokamak.

The task-based approach [1] is used in the tokamak-agnostic layer. In this approach, all decisions are made based on control tasks and not on controllers. Generic controllers themselves cannot choose actuators for their own interests. The controllers, on the one hand, request actuator resources (or virtual actuators [11]) to perform their tasks, and on the other hand receive assigned generic actuator resources per task to try to fulfill their jobs. As a result, this scheme can avoid controller cross-talk which is the main issue in integrated control ([1], [11], [12]). It also allows us to design controllers in a more generic way, focusing on the physics properties of a given scenario. Moreover, the task-based approach greatly facilitates the interaction between the operators and the plasma control system software, since they only need to specify the control tasks from physics goals (or pulse schedule), which are generic and similar among different tokamaks, regardless of the details of the relevant controllers and actuators.

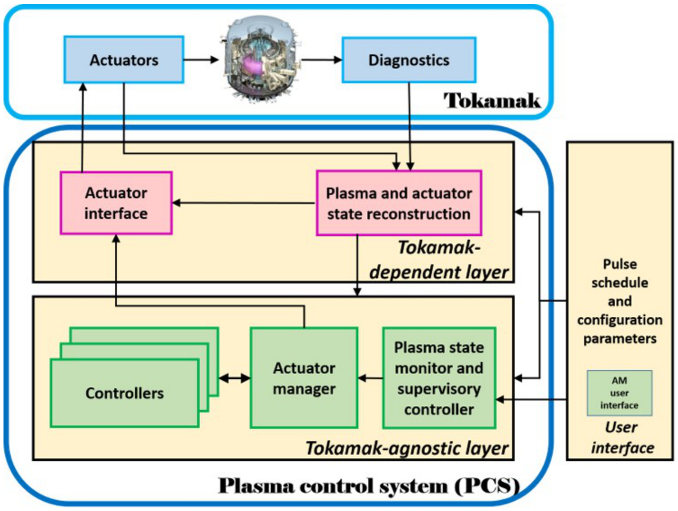

Actuators
Diagnostics
Tokamak
Actuator interface
Plasma and actuator state reconstruction
Tokamak-dependent layer
Pulse schedule and configuration parameters
Controllers
Actuator manager
Plasma state monitor and supervisory controller
AM user interface
User interface
Tokamak-agnostic layer
Plasma control system (PCS)

Fig. 1. General PCS with two separated layers: tokamak-dependent and tokamak-agnostic layers

A *control scenario* as pre-defined by the physicists or the operators becomes a list of prioritized control tasks [1], which will ensure the plasma evolution is as close to the target scenario as possible. The pulse schedule is the interface between the control scenario and a given list of tasks. Note also that the pulse-schedule and the tunable parameters for the components in the PCS, which are tokamak specific, are supplied via a user interface (Fig. 1).

The main function of each component in the tokamak-agnostic layer is summarized as follows:

- a plasma and actuator event monitor [7] categorizes the state representation of the plasma, the events and the actuators
- a supervisor evaluates the occurrence of ONEs and decides the appropriate control scenario (list of control tasks), then activates and prioritizes relevant tasks
- an actuator manager defines the best actuator resource allocation to active tasks by solving an optimization problem based on the available actuator resources, the task priority and the resource requests from controllers; and later distributes commands to corresponding actuators [1]
- controllers execute control laws to fulfill their tasks with assigned resources and also ask for new actuator resources for the next time step [1]

The modular and interface-standardized features of the tokamak-agnostic layer allow us to reduce implementation errors, as well as improve maintenance and development capabilities. For more details about the tokamak-agnostic layer and the interfaces of each component in this layer and how cross-talk is avoided with tasks priorities, the reader can refer to our previous work [1] and the references therein.

III. Supervisor decision

We will focus on a strategy of supervisor decision to deal with ONEs (e.g. magneto-hydrodynamic instabilities such as Neoclassical Tearing Mode (NTM), locked mode; or the events when the plasma/actuator states approach the physical/technical limits, such as density limit, actuator amplitude limit, actuator energy limit, etc.) which can lead to plasma disruption or plasma performance deterioration. Here the centralized supervisor plays the main role to decide the action for ONE handling. Associated with the centralized actuator resource allocator, this supervisory level can ensure a non-conflicting and flexible use of available actuators. A series of control scenarios are prepared in the pulse schedule corresponding to various actions to be selected in real-time by the supervisor.

Fig. 2 presents the relevant modules of the tokamak-agnostic layer, as well as a zoom of the supervisor which determines the control scenario output, based on the discrete-value plasma state and actuator state inputs. For each ONE, first the *danger level* and the *ONE-reaction level* are determined. Then a ONE to Scenario (OS) mapping is used to decide the appropriate control scenario based on a given set of ONEs and the associated *ONE-reaction levels*.

Two finite-state-machines are used to classify the danger level and reaction level of each ONE (Fig. 2). It is important to notice that the thresholds for the transitions from one state to another in the finite-state-machines are customized in the user interface as tunable parameters, which can be modified from shot to shot. Two lists of states of these finite-state-machines are also shown in TABLE I.

TABLE I
State lists of the danger level (a), and of the ONE-reaction level (b)

a.

danger level
no
low
medium
high
extreme

b.

ONE reaction level
no action (0)
recovery (1)
backup (2)
soft shutdown (3)
mitigation (4)

The number of danger levels and reaction levels are independent and only coincidental the same here.

A. Danger level

Five (states) levels of danger are defined in TABLE I.a. The classification of a ONE danger level is based either on one generic state (amplitude state, position state, etc) or on the combination of various generic states from the plasma event monitor. On the other hand, in order to avoid ambiguity while several ONEs simultaneously appear and their combination can significantly change the situation, a virtual ONE using their combination should be created as a new independent event. For example, a locked mode in *low* danger level will really become significant if there is also an observed increase in radiated power. In this case, an additional combined event is defined separately from the lock mode and the radiated power events. This is important and significantly simplifies the supervisor level by avoiding an additional decision level related to "what should I do if I have this ONE_1 and that ONE_2". This is moved to the definition of ONEs and their reactions.

B. Off-normal-event (ONE)-reaction level

The *danger level* is then used to define the *ONE-reaction-level* whose states are listed in TABLE I.b and are enumerated from 0 to 4, corresponding to the five basic types of control scenarios that we consider at this stage (see III-C). Examples of finite-state-machines for ONE-reaction are shown in Fig. 3.a and 4.a. It is worth noting that some states are irreversible, for instance, state level 3 and 4. These states correspond to irreversible actions such as *soft-shutdown* or *mitigation.* It is important to note that, depending on the customized danger thresholds per ONE, it is possible that an ONE can never get to some danger levels. However we still need to define fine corresponding ONE-reactions (see example in Sec. III-D). Also the mapping between the *danger levels* and the *ONE-reaction levels* is specific for each ONE, thus they are not always 1-1 corresponding (see e.g. Fig. 3.a, the difference between NTM_{21} and NTM_{43} events).

C. ONE-reaction to scenario (OS) mapping

To select the control scenario to be executed in the current time-step, an OS mapping (Fig. 3.b) based on the combination of the *ONE-reaction levels* of all active ONEs is thus necessary. A finite number of control scenarios is derived from the given pulse-schedule. We define five basic types of control scenarios: *normal, recovery, backup, soft-shutdown,* and *disruption-mitigation.* Several control scenarios of the same type can be defined. For example, we often have one *normal,* which is the desired/original/basic scenario, one *soft-shutdown,* and one *disruption-mitigation*, but several *recovery* and several *backup* scenarios depending on the considered ONEs and the control actions on them. For instance, with two ONEs, three *recovery* scenarios can be considered and a pre-defined OS-mapping is compulsory as in TABLE II. Otherwise, in the simple case where there is only one basic scenario per type, the default OS-mapping, where the highest ONE-reaction level directly corresponds to the effective scenario, e.g. TABLE IV.b, is used. It is important to emphasize that any relevant combination of ONEs are included in the list of ONEs, therefore the OS-mapping defines the relevant scenario considering all relevant ONEs and any combinations through a well-defined (long) table.

Finally, a list of control tasks is determined by the user for each control scenario in order to achieve the desired control action, as shown in the example in TABLE III.

Once the appropriate control scenario is selected based on the actual plasma situation, the relevant control tasks will be activated, and the corresponding references are taken into account according to the user setting for each control scenario before the discharge. The actuator manager and the controllers

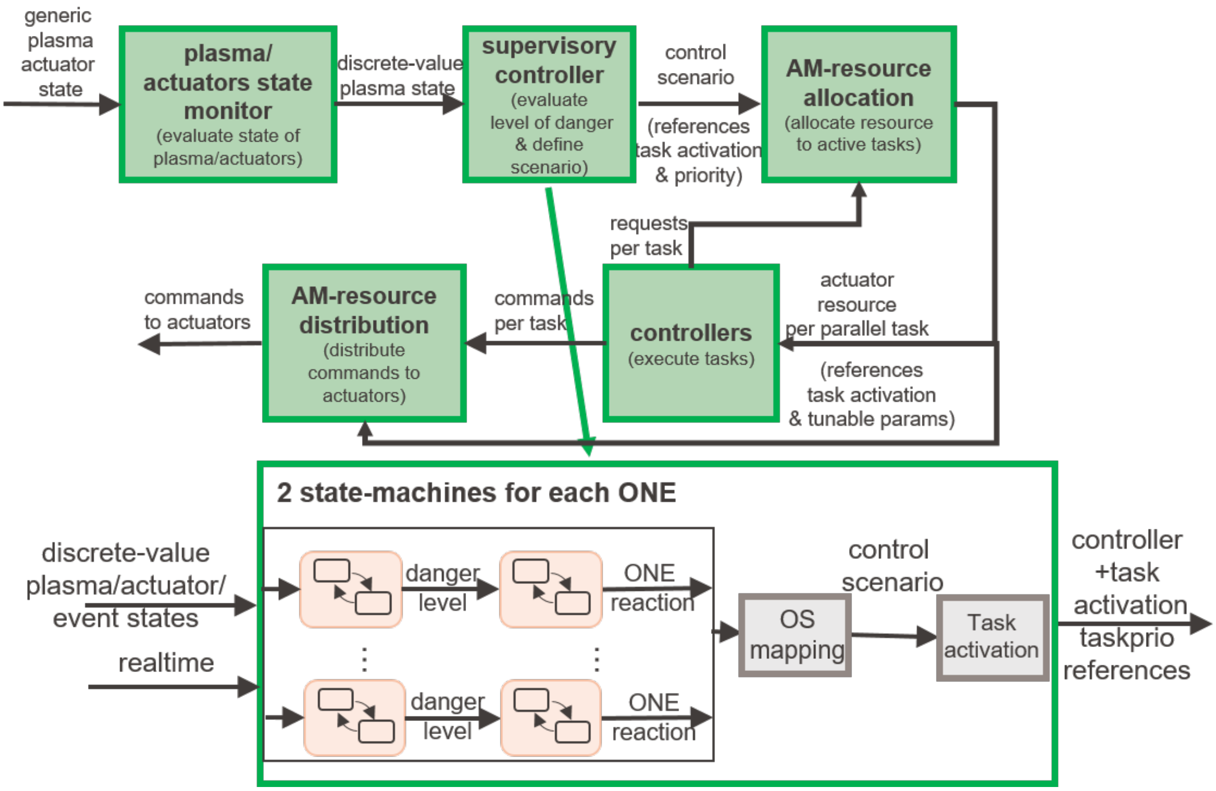
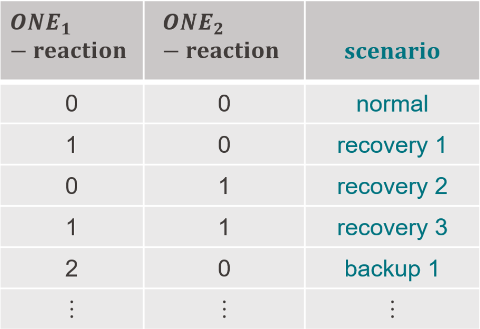

generic plasma actuator state
plasma/ actuators state monitor (evaluate state of plasma/actuators)
discrete-value plasma state
supervisory controller (evaluate level of danger & define scenario)
control scenario
(references task activation & priority)
AM-resource allocation (allocate resource to active tasks)
requests per task
actuator resource per parallel task
(references task activation & tunable params)
controllers (execute tasks)
commands per task
AM-resource distribution (distribute commands to actuators)
commands to actuators
2 state-machines for each ONE
discrete-value plasma/actuator/ event states
realtime
danger level
ONE reaction
danger level
ONE reaction
control scenario
OS mapping
Task activation
controller +task activation taskprio references

Fig. 2. Tokamak-agnostic layer and zoom in on the supervisor

TABLE II
Customized OS-mapping for 2 ONEs



ONE_1 – reaction	ONE_2 – reaction	scenario
0	0	normal
1	0	recovery 1
0	1	recovery 2
1	1	recovery 3
2	0	backup 1
⋮	⋮	⋮

perform their normal functionality without any judgment on the ONEs.

D. Example

In this subsection, two NTM events: NTM_{21} and NTM_{43} are considered to be simultaneously detected. Their *danger states* are determined based on the discrete-value states of their amplitudes from the plasma event monitor. Due to the different danger potential of the considered events, their state-machines for the ONE-reaction *level* are not the same. For instance, the NTM_{43} is not very dangerous, it only leads to a reduction of neutron productions, thus the *reaction* is either *no-action* (0) or *recovery* (1). On the other hand, the NTM_{21} requires all actions up to *mitigation* (4), since a $2/1$ mode can trigger disruptions. Depending on the reaction level associated with these ONEs as well as the pre-defined OS mapping, the control scenarios are different for the two situations as shown in Fig. 3 and 4: *backup1* and *mitigation* respectively.

In TABLE III, some relevant tasks are listed associated with each control scenario in this example. A control scenario will be chosen by the supervisor for each instant, thus the considered tasks in this scenario will be activated based on the task activation conditions (time intervals, event triggers, etc.). Regarding the first situation where the *backup1* scenario is selected, three tasks NTM_{21} *stabilization,* β *control* and *heating feedforward* can be simultaneously activated. The actuator manager determines the best actuator resource allocation per task based on the actuator states as well as the requests for actuator resources per task from the controllers. Three corresponding controllers: *NTM controller, performance controller* and *feedforward controller* are used to carry out the three considered tasks, respectively. The controllers execute their control laws and do their best to fulfill their given tasks with the assigned resources. Here, the *NTM controller* commands to move the EC beam deposition to the target (NTM position), and uses all EC power that it receives at the target. The *performance controller* in this case is a PID controller which asks to modify the heating power according to the gap between the RT estimated β (corresponding to the total thermal energy) and its reference. The *feedforward controller* reproduces a heating power command which is configured by the user before the discharge. All the commands from the controllers are combined and then sent to the tokamak-dependent layer, where they are converted into the specific actuator commands, e.g. heating power into voltage, radial deposition location of EC power into launcher angles, etc.

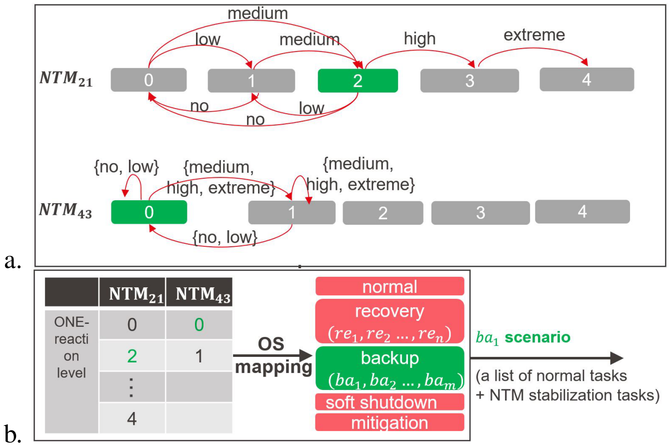


Fig. 3. a. state machine for ONE-reaction evaluation: numbers $0-4$ are the ONE-reaction levels, red arrows are the transition condition between states based on the danger level (*no, low, medium, high,* or *extreme*).
b. OS mapping for the example with two NTM events in situation 1: event NTM_{21} is at *medium* danger level, thus it needs a *backup* reaction (reaction level 2); while no reaction needed for NTM_{43} (danger level can be either *no* or *low,* thus the reaction is at level 0). Using the pre-defined OS mapping, the selected control scenario is ba_1 (list of control tasks in TABLE III).

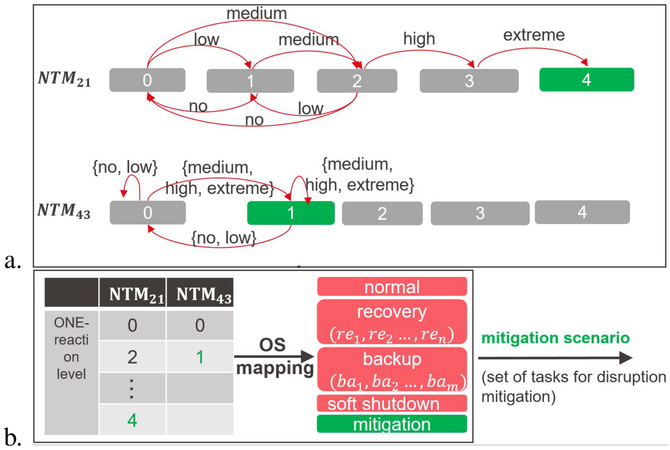


Fig. 4. Example with two NTM events in situation 2: event NTM_{21} is at *extreme* danger level, thus it needs *mitigation* (reaction level 4); while NTM_{43} also at high danger level (either *medium, high* or *extreme)* just needs a *recovery* (reaction level 1). Using the pre-defined OS mapping, the selected control scenario is *mitigation* (list of control tasks TABLE III).

IV. Experimental Result

The proposed PCS with SAMONE has been implemented in MATLAB/ Simulink, from which C code was generated and included in the TCV digital real-time control system ([13], [14]). An application for disruption avoidance experiments is presented in Fig. 6, where the discharge is pushed towards the H-mode density limit disruption by a gas-flux ramp. The main purpose of disruption avoidance experiments is to avoid the abrupt loss of energy confinement, or even to recover the plasma to the previous stable states. However, in this experiment, we aim to control the plasma to slowly approach the density limit for detailed physics studies. Several new modules have been implemented in the TCV PCS to determine in RT: the factor H_{98y2} characterizing the energy confinement time, and the normalized edge density $ne_{edge\,norm}$ [15], [16]; together, we derive the distance $d_{ne\,edge}$ between the system states $(H_{98y2}, ne_{edge\,norm})$ and the empirical disruption limit (see Fig. 5). This distance is the key factor used by the supervisory layer to determine an appropriate control scenario. In this example, two ONEs are considered: $d_{ne\,edge}$ and $actuator_{lim}$ for the NBI energy limit. The supervisor evaluates the dangers from these ONEs to switch between different scenarios: *normal, recovery*, and *soft-shutdown*, in which three sets of relevant control tasks are configured beforehand.

TABLE III
NTM event: example of tasks for each defined control scenario

control scenario	list of control tasks
normal	normal tasks (e.g. β control / Pheat feedforward)
recovery 1	$\boldsymbol{NTM_{21}}$ stabilization + normal tasks
recovery 2	$\boldsymbol{NTM_{43}}$ stabilization + normal tasks
recovery 3	$\boldsymbol{NTM_{21}}$ + $\boldsymbol{NTM_{43}}$ stabilization + normal tasks
	…
backup 1	β control / Pheat feedforward with new references + $\boldsymbol{NTM_{21}}$ stabilization
	…
soft-shutdown	set of tasks for controlled ramp-down
mitigation	set of tasks for disruption mitigation

Note that β reference, feedforward reference, etc. are tunable parameters which are given from the user interface

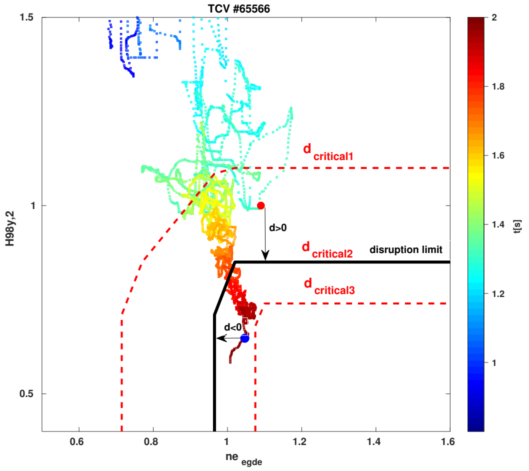


Fig. 5. Time-evolution of the edge density limit $d_{ne\,edge}$ on the state plane $(H_{98y2}, ne_{edge\,norm})$ (colored dots), the empirical disruption limit (black line), and different user-defined critical thresholds (red-dash lines)

In Fig. 6, second panel, the danger level of the $d_{ne.edge}$ is *low* from ① when the distance is below the first critical threshold $d_{critical1}$, and is *medium* from ② when the distance is below the second threshold $d_{critical2}$; while the $actuator_{lim}$ danger is *high* when the NBI energy reaches the threshold 95% of the total energy of $1.3MJ$ (which is not the case in this experiment) and is *no* otherwise. Here, the customized ONE-reaction levels based on the danger level of each ONE are specified in TABLE IV.

TABLE IV
Reaction levels corresponding to each danger level of each ONE (a) and the default OS mapping based on the maximum value of ONE-reactions (b)

a.

ONEs danger level	d_{nelim}	$actuator_{lim}$
no	0	0
low	0	0
medium	1	0
high	1	3
extreme	3	3

b.

$max_{ONE\ reaction}$	scenario
0	normal
1	recovery
3	soft-shutdown

The control scenario (third panel) is based on the combination of the reaction levels of the two ONEs, which is *recovery* if the highest danger level reaches *medium* from ②, otherwise it remains *normal*. According to the chosen scenario, different control tasks are activated and prioritized (fourth panel). In *normal* scenario, the feedforward task $FF_{power.nor}$ asks for a constant heating power of $0.65MW$ and the $FF_{gas.nor}$ commands a fast gas-flux ramp. The disruption-avoidance task $DA_{power.nor}$ modifies the power according to the distance $d_{ne.edge}$ only when it is below the $d_{critical1}$, and the $DA_{gas.nor}$ reduces the gas-flux ramp. In *recovery* scenario, the $FF_{power.rec}$ is the same as the $FF_{power.nor}$, while the $DA_{power.rec}$ asks for the maximum power and the $DA_{gas.rec}$ keeps the gas flux constant. Consequently, on the one hand, the NBI power (last panel) is composed of a constant power $0.65MW$ ($FF_{power.nor}$) and an extra power ($DA_{power.nor}$) increasing proportionally up to the maximum heating power $1.3MW$. On the other hand, the gas flux is first increasing fast ($FF_{gas.nor}$), then slowly ($DA_{gas.nor}$) at ①, and finally is frozen ($DA_{gas.rec}$) at ②. It is important to note that the threshold $d_{critical2}$ identical to the disruption limit, which is associated with the *medium* danger instead of a higher danger level, is a particular choice in this test. This allows us to continue a slow and well-controlled approach to the density limit for detailed physics studies. A *soft-shutdown* scenario is also set up with two feedforward tasks to cut off both the NBI power and the gas flux in a controlled manner when the distance $d_{ne.edge}$ goes below the $d_{critical3}$. However, this threshold is not well-determined at this stage and the discharge disrupted at ③ [4] before that situation happens. Since the thresholds are empirically defined, we need to collect more data from the experiments. Therefore, in this experiment, it is intentionally chosen quite far from the disruptive limit in order to reach disruption to contribute to the physics programme. We also aim to find better critical thresholds using machine learning techniques in our upcoming work.

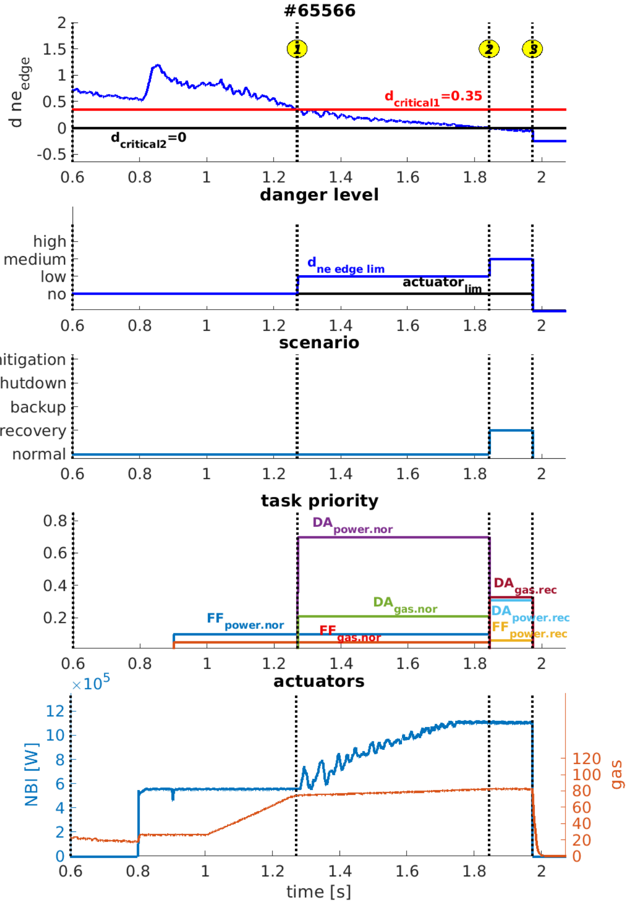


Fig. 6. Experimental result of TCV discharge #65566: At ①, $d_{ne.edge}$ violates the first critical distance $d_{critical1}$, which activates DA tasks in the scenario *normal*. At ②, $d_{ne.edge}$ goes below the second critical distance $d_{critical2}$; the supervisor switches the scenario to *recovery* and activates the corresponding tasks. At ③ the plasma finally disrupts.

V. Conclusion

This work presents a supervisory strategy to deal with off-normal-events. Each ONE is evaluated for its danger level and the necessary reaction, then a global decision is made to define an appropriate control scenario. The presented control architecture has been successfully implemented and tested on the TCV tokamak in the context of density limit disruption avoidance experiments; employing the exposed control scenario switching methodology. It has been fruitfully capable of smoothly reaching density limits in various plasma discharges.

This architecture will be used for different integrated control objectives such as simultaneous controls of L-H mode, NTM, β, and $q-$profile, etc. in the upcoming experiments.

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