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Integrated plasma state reconstruction, off-normal event handling and control with application to TCV and ASDEX Upgrade

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[*] See author list of S. Coda et al., Nucl. Fusion **59** 112023 (2019) [**] See author list of H. Meyer, et al., Nucl. Fusion **59** (2019) 112014
[***] See author list of B. Labit et al., Nucl. Fusion **59** 086020 (2019)

Main points:

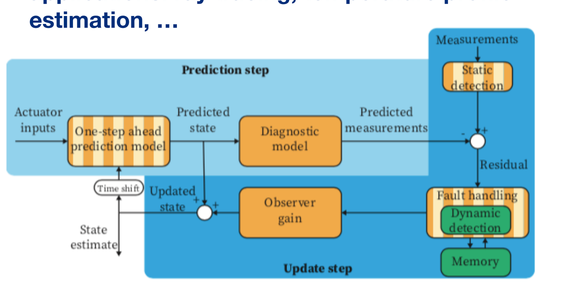
- Future devices need more advanced integrated plasma control solutions including supervision, actuator management, event handling
- Report on advances in tokamak control from collaborative work on TCV and ASDEX Upgrade within the EUROfusion MST1 work package
- Advances in real-time plasma state estimation:
  - Kinetic equilibrium reconstruction on TCV, real-time RABBIT and improved density reconstruction on ASDEX Upgrade.
- Generic control frameworks for supervisory control & off-normal event handling
  - Application to high density limit disruption avoidance on TCV and ASDEX Upgrade, use of virtual actuators on ASDEX Upgrade
- Iterative learning control tests for central T_e/T_i control on ASDEX Upgrade
- Outlook: new real-time TORBEAM version + real-time event detectors using deep learning

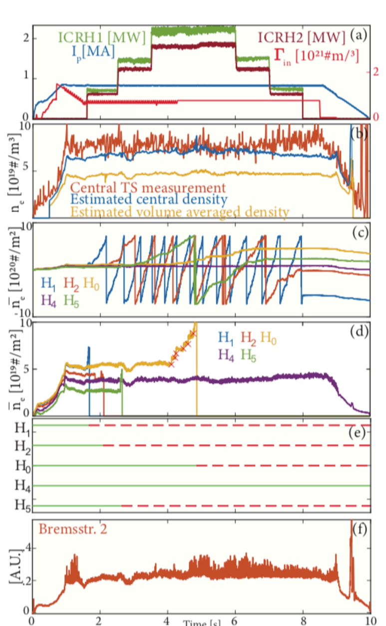
Motivation: future tokamak reactors will need to fulfil multiple control tasks with a limited set of actuators

- New control challenges:
  - Simultaneous execution of several (complex) control tasks with scarce actuators.
  - Real-time prioritisation of these tasks based on evolving plasma state/events.
  - Real-time automated assignment of scarce actuators to fulfil various tasks.
- This poster discusses new developments on TCV and ASDEX Upgrade to address key control challenges for future devices.
  - Collaborative work carried out within EUROfusion MST1 work package

Improved density profile estimation during ICRH by improved RAPDENS ionization and transport model

- RAPDENS (like RAPTOR) combines
  - Model-based predictions of the profile evolution
  - Update to these predictions using interferometer & bremsstrahlung measurements
  - Detection and rejection of faults.
- Improvements to RAPDENS on AUG
  - Density profile agrees with off-line Thomson Sc.
  - Yields routinely usable density profiles for various applications: ray tracing, temperature profile estimation, …

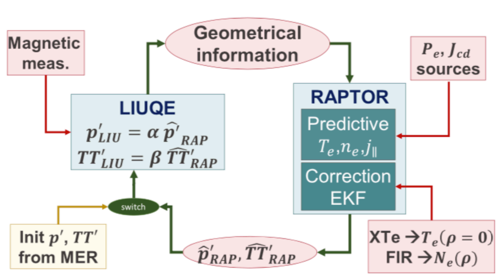




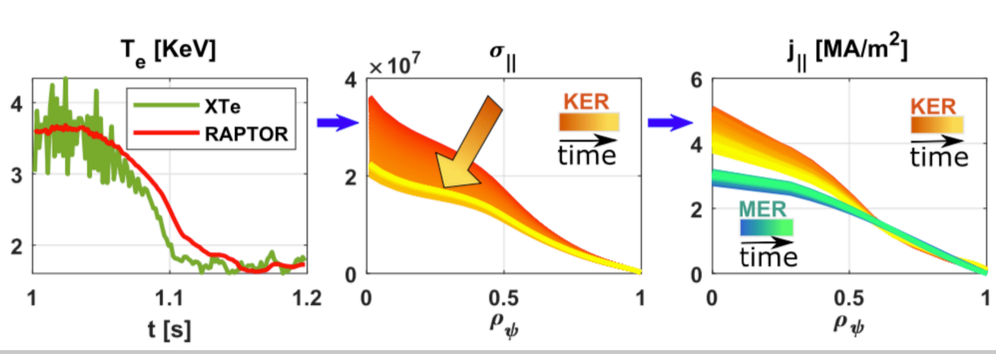
[T. Bosman, Fus. Eng. Des, accepted]

Real-time kinetic equilibrium reconstruction demonstrated on TCV for the first time

[F. Carpanese NF 2020]



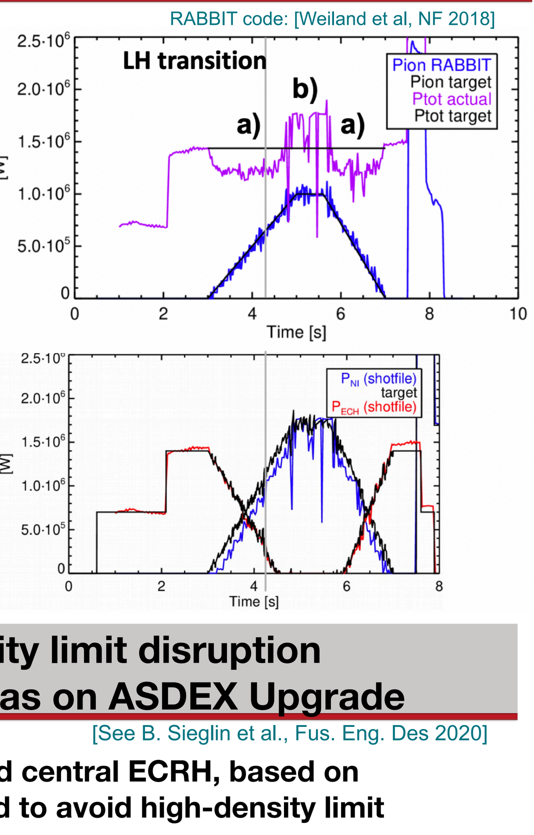
- RAPTOR computes profiles from model + measurements.
- LIUQE equilibrium reconstruction uses RAPTOR profiles as basis functions.
- 1 loop in < 2ms



Real-time feedback of NBI power deposited to ions on ASDEX Upgrade using RABBIT code

- Fast calculation of NBI deposition using RABBIT code
- Implemented in ASDEX Upgrade real-time control system DCS
- Used for feedback control
  - Ramp total power deposited to ions
  - Keep total deposited power constant (feedback of ECRH)
  - LH transition occurs at higher ion power
  - Some discrepancy w.r.t. off-line analysis explained by
    - More accurate off-line P_{NBI} estimate (now corrected)
    - Lower saturation of ECRH power at 0.

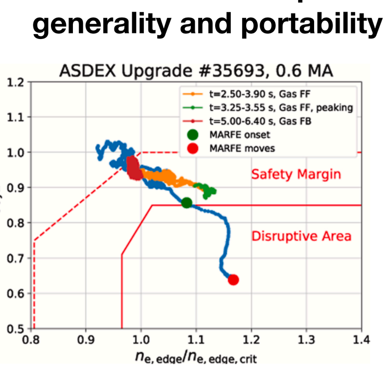
RABBIT code: [Weiland et al, NF 2018]

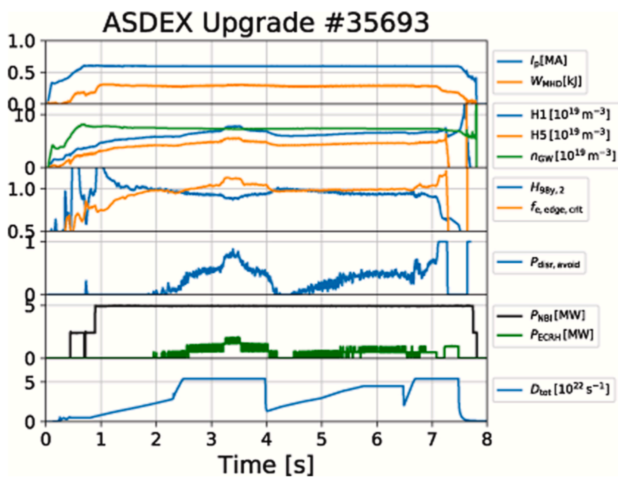


Demonstration of high-density limit disruption avoidance using heating & gas on ASDEX Upgrade

[See B. Sieglin et al., Fus. Eng. Des 2020]

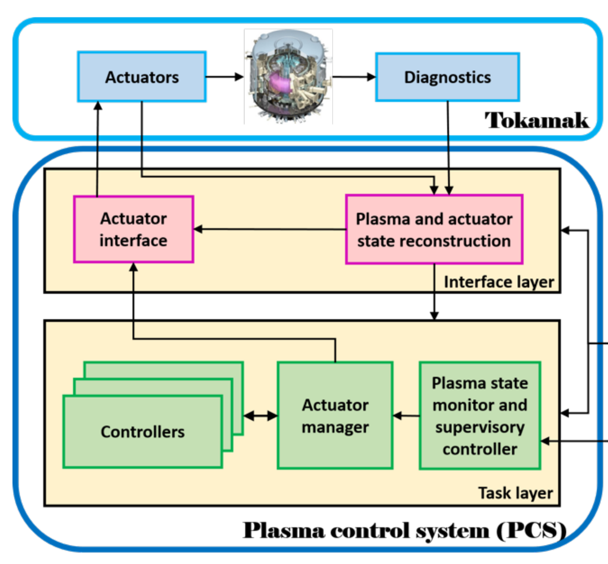
- Feedback control of gas fueling and central ECRH, based on distance from Disruptive Area, used to avoid high-density limit disruption.
- Starting point for TCV implementation of similar control scheme to prove generality and portability

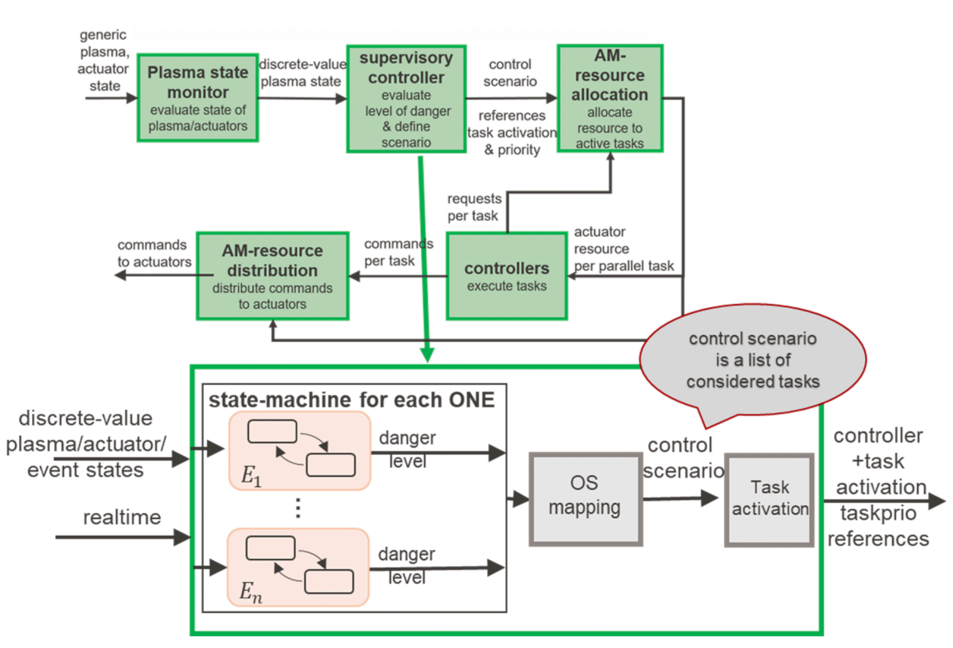




Architecture of task-based PCS: separation between specific interface layer and generic task layer

For more details:
[T. Blanken Nucl. Fus 2019]
[T. Vu Fus. Eng. Des 2019]
[T. Vu IEEE TNS, accepted]





Example of application for TCV High Density Limit disruption avoidance experiments

- Define Off Normal Events (ONE) and program danger levels per events based on thresholds

TABLE 1. Table of danger levels conditions programmed for TCV HDL avoidance experiments

ONE \ Danger level	no	low	mid	high
Disruption limit (D)	d≥0.15	d<0.15	d<0	d<0 for Δt>0.5s
Actuator limit (A)	<50% energy used	>50% energy used	-	>95% energy used

- Define mapping between ONE danger level and reaction level (0-4)

TABLE 2. Mapping between danger levels for each off-normal event (ONE) and desired reaction level. Levels 2 (backup scenario) and 4 (DMS triggering) are also available but not used in this example.

ONE \ Danger level	no	low	mid	high
Disruption limit (D)	0	0	1	1
Actuator limit (A)	0	0	0	3

- Map all combinations of reaction levels to desired control scenario

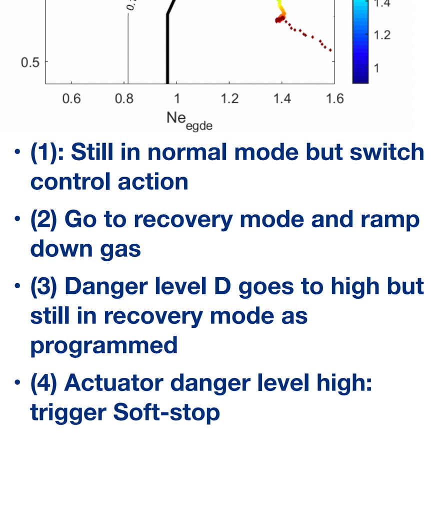
TABLE 3. Lookup table (OS mapping) that maps all possible combinations of reactions for each ONE to control scenarios. Note that reaction levels 2 and 4 were not used in this experiment.

D reaction level	A reaction level	Control Scenario
0	0 or 1	normal
1	0 or 1	recovery
0 or 1	3	soft-stop

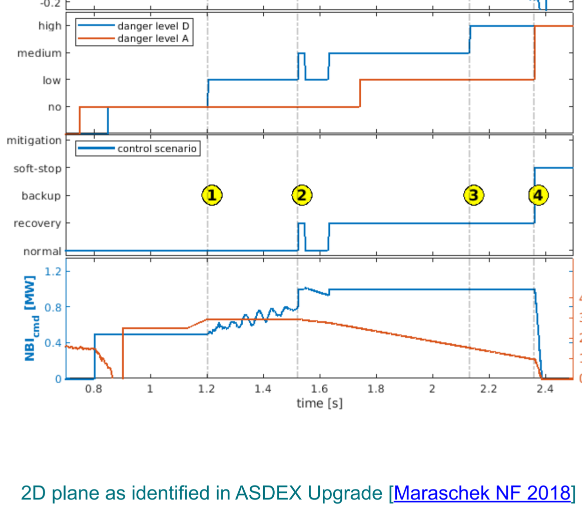
- Define control tasks for each control scenario

TABLE 4. Control tasks defined for each Control Scenario

Control scenario	Additional conditions	Gas control task	Heating control task
Normal	d>=0.15	Feedforward	Feedforward
	d<0.15	Freeze	Increase proportionally to $-d$
Recovery		Decrease	Maximum
Soft-stop		Fast ramp-down	Fast ramp-down

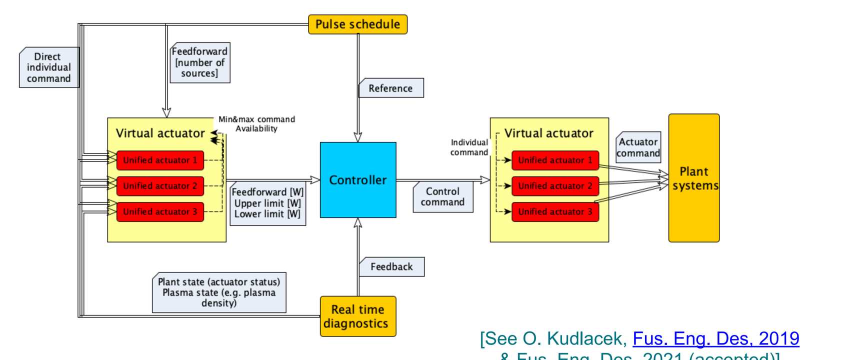


- (1): Still in normal mode but switch control action
- (2) Go to recovery mode and ramp down gas
- (3) Danger level D goes to high but still in recovery mode as programmed
- (4) Actuator danger level high: trigger Soft-stop



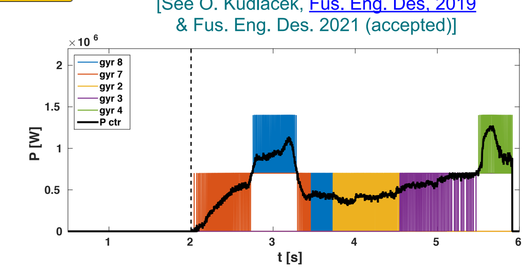
2D plane as identified in ASDEX Upgrade [Maraschek NF 2018]

Use of virtual actuators on ASDEX Upgrade



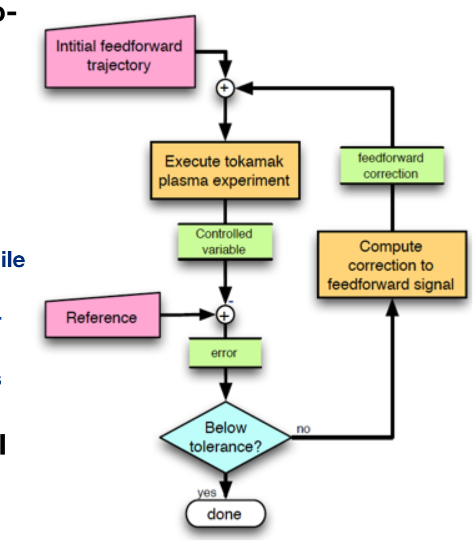
[See O. Kudlacek, Fus. Eng. Des. 2019 & Fus. Eng. Des. 2021 (accepted)]

- Use multiple EC gyrotrons in for same control task
- Substitute for tripped gyrotrons with another one
- Example time trace required for beta control:



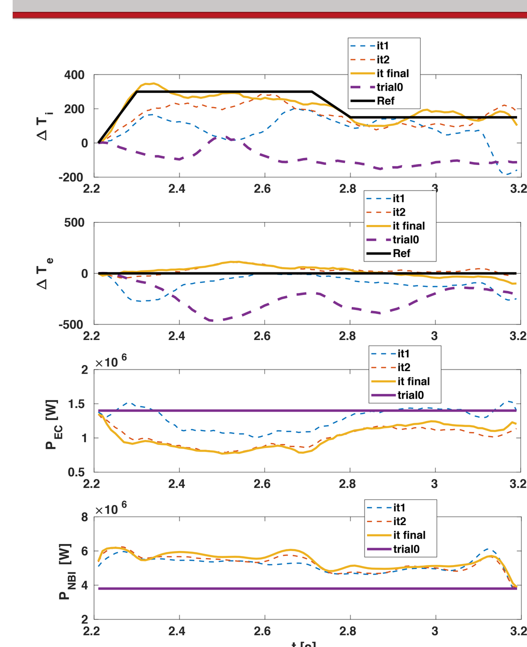
Iterative 'learning' control - shot to shot optimization of actuator trajectories

- Iterative learning control: fast shot-to-shot scenario optimization, proof of principle at AUG
  - Iterative improvement of feedforward trajectories based on error in previous trial
  - High interest from ITER
- Correction computation:
  - New input to reduce error in next iteration while not making too large steps
    - Linearized response of control variable to actuator action computed by RAPTOR
  - For error computation, IDA and IDI analysis is run between the shots
- 2 optimization experiments using NBI and central ECRH as actuators :
  - Central Ti optimization at constant T_e
  - central Te/Ti optimization at constant W_{MHD}



More ILC applications for fusion: [F. Felici, CDC conference Osaka, Japan 2015]

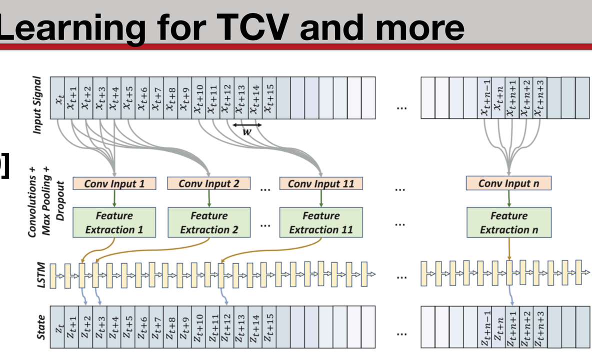
Application to T_i, T_e control on ASDEX Upgrade



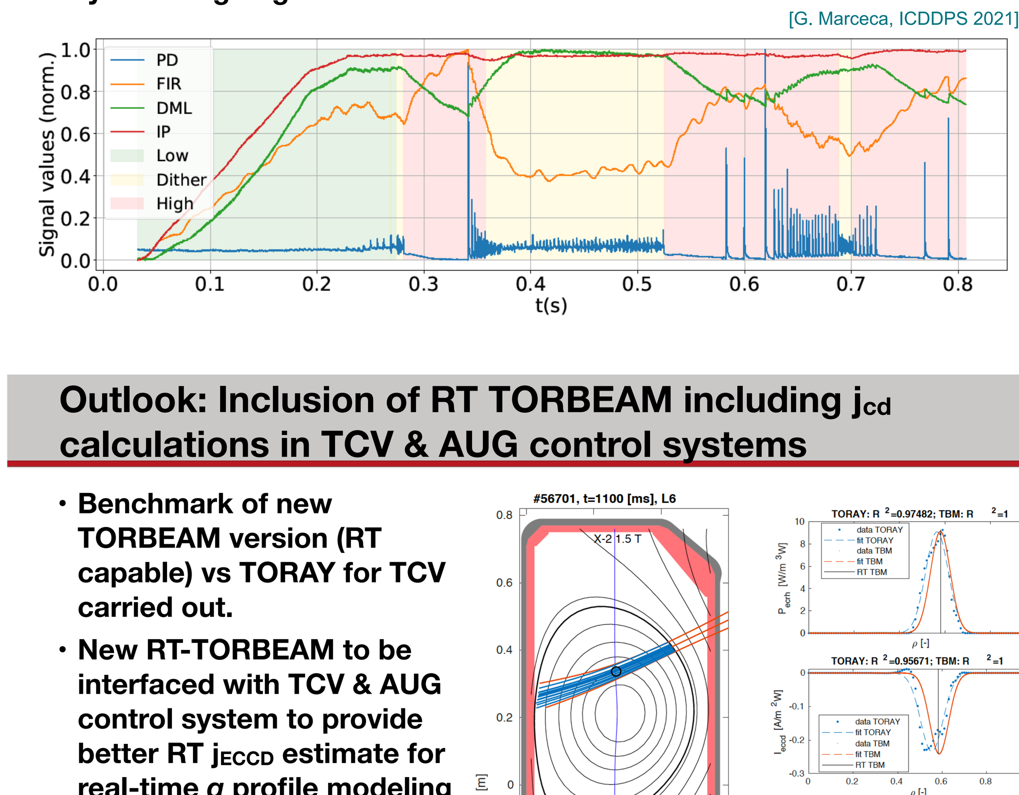
- Goal: increase central T_i at constant T_e with respect to the starting point
  - Good convergence after 3 iterations
  - Increase in NBI heating, decrease in ECRH

Outlook: Real-time plasma confinement state detector using Deep Learning for TCV and more

- Combines convolutional layers (CNN) + LSTM
- Based on [Matos, NF 2020]
- Reduced number of parameters for real-time implementation.
- Tests in TCV control system ongoing

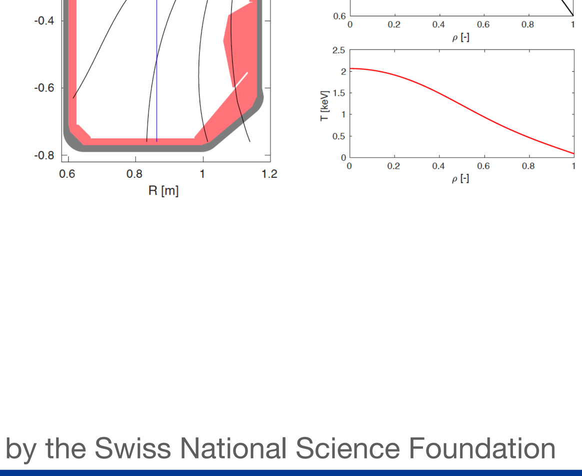


[G. Marceca, ICDDPS 2021]



Outlook: Inclusion of RT TORBEAM including j_{cd} calculations in TCV & AUG control systems

- Benchmark of new TORBEAM version (RT capable) vs TORAY for TCV carried out.
- New RT-TORBEAM to be interfaced with TCV & AUG control system to provide better RT j_{ECCD} estimate for real-time q profile modeling



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EPFL Swiss Plasma Center | ASDEX Upgrade IPP Max-Planck-Institut für Plasmaphysik | ISTP Consiglio Nazionale delle Ricerche | TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

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