EUROfusion

Multivariable feedback control of radiative loss-processes using multi-spectral imaging

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Supported by: K. Verhaegh, B. Dudson, L. van Leeuwen, G.L. Derks, J. Caballero, L. Martinelli, E. Huett

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Motivation

EUROfusion roadmap mission-2: Heat-exhaust systems

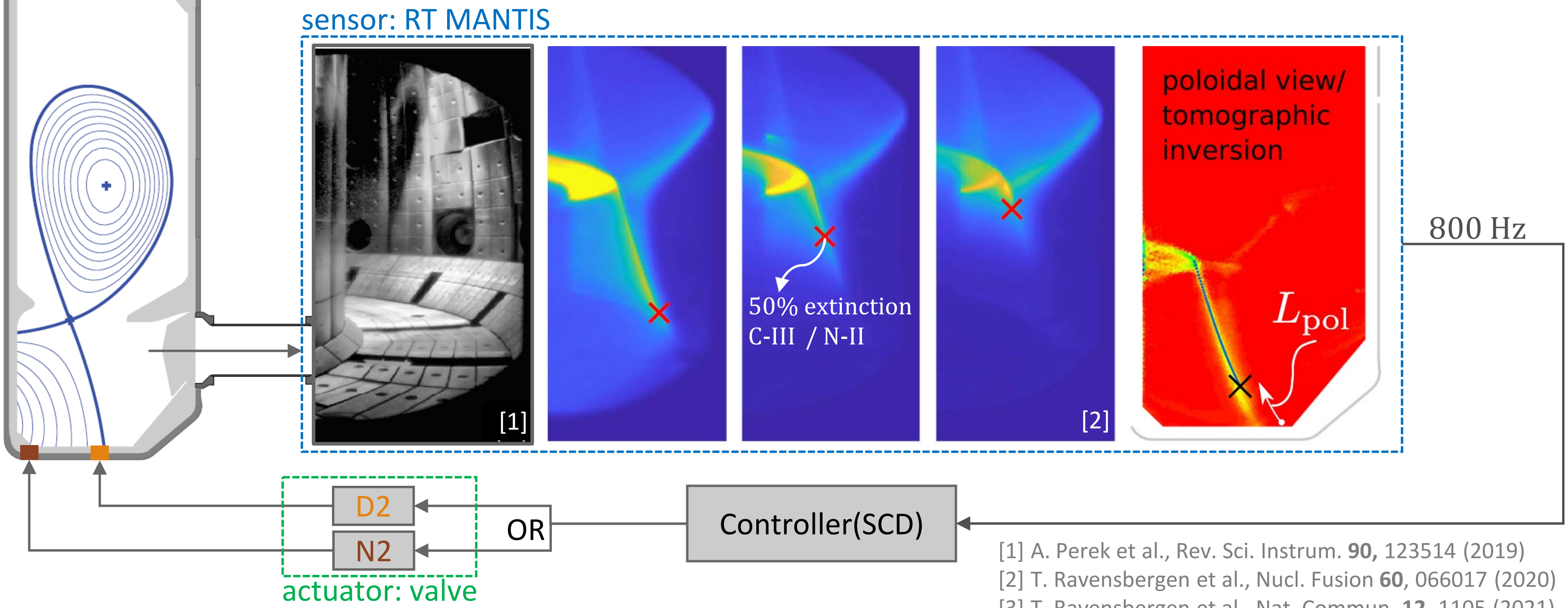
- capable of withstanding the large heat and particle fluxes of a fusion power plant;
- allow as high performance as possible from the core plasma.

Foreseen to be achieved by producing ‘detached’ divertor conditions, maintained by an active control system.

Inherently a multi-input multi-output problem (multiple performance parameters and multiple actuators).

Introduction

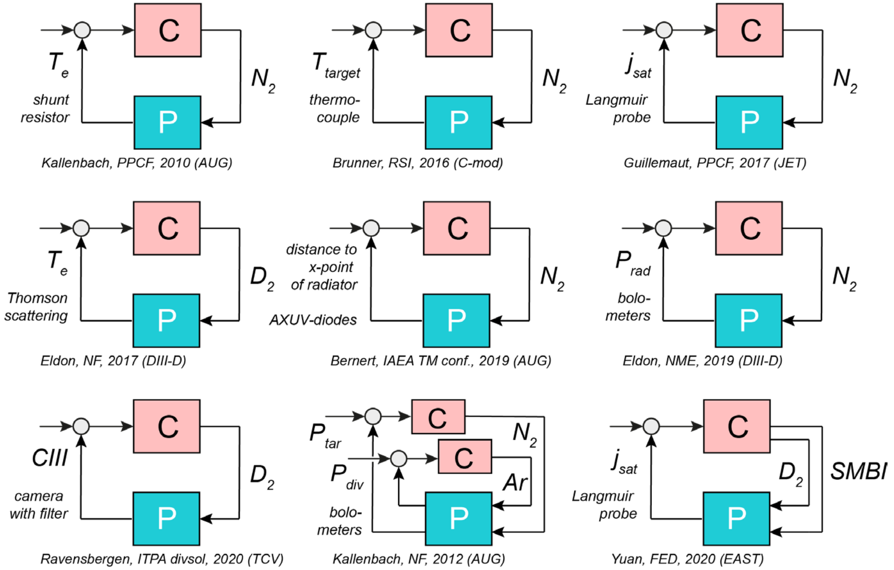
- Real-time detection of emission fronts with multi-spectral imaging (MANTIS)
- Impurity emission fronts (C-III, N-II) strongly related to local temperature
- Actuation of front position by D2 fueling or N2 seeding



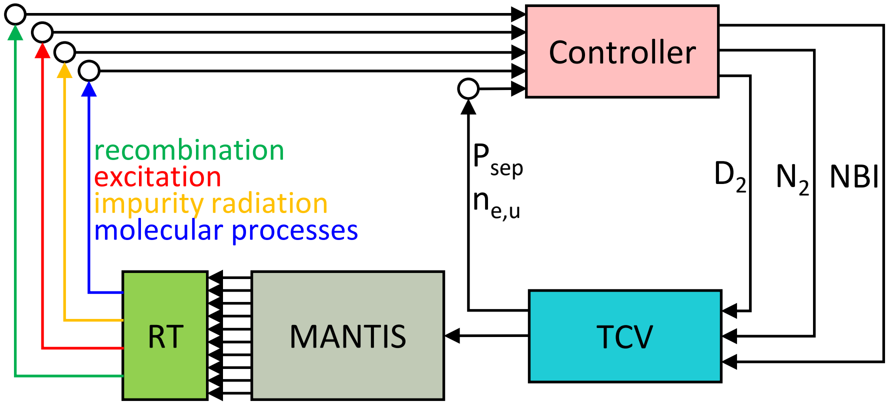
[1] A. Perek et al., Rev. Sci. Instrum. **90,** 123514 (2019)
[2] T. Ravensbergen et al., Nucl. Fusion **60**, 066017 (2020)
[3] T. Ravensbergen et al., Nat. Commun. **12,** 1105 (2021)
[4] J.T.W. Koenders et al., 47th EPS on Plasma Physics, P1.1058

Introduction

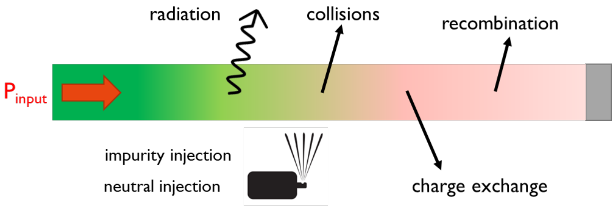
Single-input single-output (SISO)

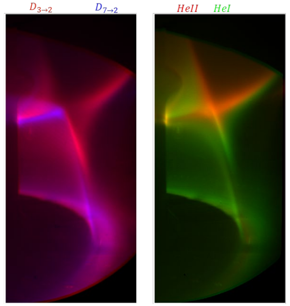


Multiple-input multiple-output (MIMO)

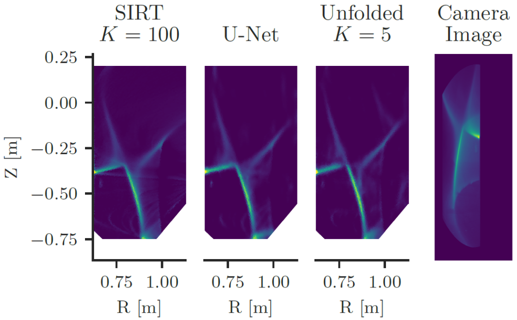


Project overview (and status)



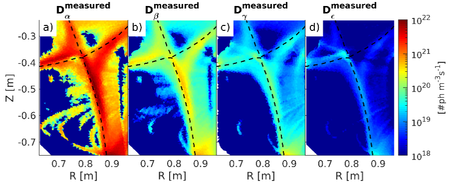


Scaled emission line intensities encoded into red, green and blue channels. MANTIS on the TCV tokamak; #63974, t = 1.32s



feedback + feedforward

line-ratios



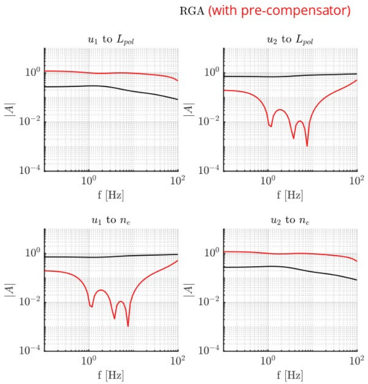
Bayesian interf.

$n_e, T_e, n_o, I_{rate}, R_{rate}, CX_{rate}, P_{exc}, P_{rec}$

digital control system (SCD)

real-time signal processing

implementation currently under development



MIMO-decoupling

Last year's conclusions

Made deliverables (from 2022):

- **Simple-MIMO identification demonstration**: Demonstrate MIMO system identification algorithms developed in this proposal for the simplified case of D2 and N2. (initial testing RT-alg.).

Intermediate conclusion:

- Strong coupling between (NII/CIII) fronts necessitates MIMO-control (multiple valves) but limits independent control

Next year:

Main (full-time) person is missing and will start 1st of march:

- **RT-image processing (based on past experiments):** Improve and make current algorithms real-time (not in the control system yet) for nitrogen and Balmer lines to determine recombination and excitation regions.
- **Qualitative RT-image processing:** Qualitative real-time algorithms for the observation of nitrogen, recombination and excitation (ionization) based on camera images only (based on ~ 5 cameras).

Ongoing process:

- **Selection of control targets:** Scenario selection and determination on control targets is performed, ongoing process.
- **Integration DCS**: Integration of algorithms into the digital control system TCV and verify real-time algorithms.

First MIMO control experiments! !BIG SUCCES!

Where do we stand now: deliverables?

Made deliverables (from last year 2021):

Main (full-time) person is missing and will start 1st of march:

- **RT-image processing (based on past experiments):** Improve and make current algorithms real-time (not in the control system yet) for nitrogen and Balmer lines to determine recombination and excitation regions.
- **Qualitative RT-image processing:** Qualitative real-time algorithms for the observation of nitrogen, recombination and excitation (ionization) based on camera images only (based on ~ 5 cameras).

Made deliverables (from 2022):

- **Simple-MIMO identification demonstration**: Demonstrate MIMO system identification algorithms developed in this proposal for the simplified case of D2 and N2. (initial testing RT-alg.).

Deliverables (from 2023) almost made:

- **Loss-process measurements in 2D: Quantitative real-time algorithms for the observation of the loss-processes (based on MANTIS + other diagnostics):** Successful first publication on off-line quantitate modelling, heavy investment in ML algorithms to speed up calculations (recombination is quantitative, ionization not yet), implementation on hardware GPU ongoing process

- **Dynamic detachment models: Control-oriented (hybrid) models useful for time-dependent detachment simulations and control development:** First publication G.L. Derks, static maps with DIV1D, dynamic models based on data also ready. Requires only integration.

Where do we stand now: milestones 2022?

- **Simple-MIMO identification demonstration:** Demonstrate MIMO system identification algorithms developed
- **Simple-MIMO control demonstration:** Demonstrate using the nitrogen and carbon filters that both fronts can be simultaneously controlled using (at least) two actuators. Test if the fronts can be separated.
  - ➢ Practical (possibly theoretical) impossible, changed control targets to line integrated density and front control (core-edge integration) successfully executed
- **MIMO-modelling for control (off-line):** Complete dynamical (black-box) models based on the MIMO-system identification and design and test several control algorithms. Procedure demonstrated successfully, awaiting integration
- **Integration DCS:** Integration of algorithms into the digital control system TCV and verify real-time algorithms (in progress)

ENR WPs overview and progess

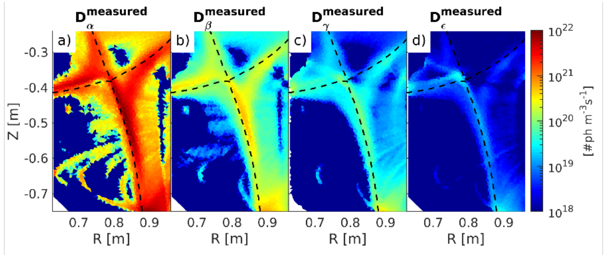
Main goal: setting up for MIMO control with different MANTIS camera's

Progress	Project
P1 (largely finished) development only in terms of P3	MANTIS development to determine loss-processes in 2D
P2 (continued evolution, especially with respect with control)	Detachment analysis, scenario selection, setting control requirements
P3 (ongoing)	Conversion from off-line to real-time camera analysis (incl. machine learning)
P4 (largely finished)	MIMO system identification
P5 (ongoing)	Dynamic modelling for MIMO-control
P6 (ongoing)	MIMO feed-back control (and integration)

WP1 – Determine loss-processes in 2D

Spectroscopic emissivity analysis

Emissivity of 4 Deuterium lines



ADAS Collisional-Radiative model

↓

Hydrogen Analysis → n_e, T_e, n_o, I_{rate}, R_{rate}, $CX_{rate}, P_{exc}, P_{rec}$

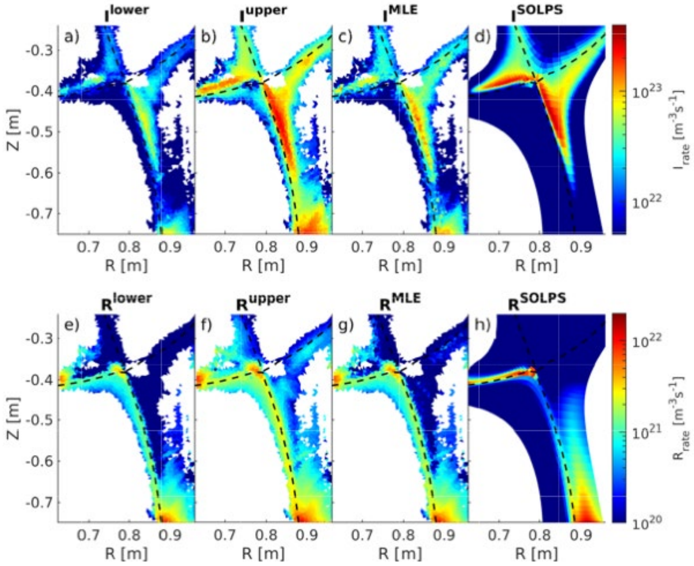
$$B_{n\to 2} = n_e^2 PEC_{n\to 2}^{rec}(n_e,T_e) + n_e n_o PEC_{n\to 2}^{exc}(n_e,T_e)$$

$$P_{n\to 2}(n_e,T_e,n_o) \propto e^{-\left(\frac{B_{n\to 2}^{model} - B_{n\to 2}^{measured}}{B_{n\to 2}^{err}}\right)^2}$$

Probability that multiple measured lines are observed:

$$P(n_e,T_e,n_o) = P_{3\to 2}P_{4\to 2}P_{5\to 2}$$

$$P(n_e,T_e,n_o) \to P(I_{rate}), P(R_{rate})$$



A. Perek et al. A spectroscopic inference and SOLPS-ITER comparison of flux-resolved edge plasma parameters in detachment experiments on TCV, Nuclear Fusion 2022

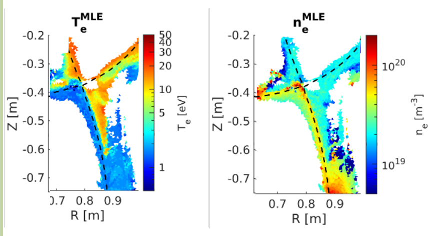
WP1: extension to further improve 2D analysis

H

Uses emissivities of 4 Balmer lines:

$D_{3\to2}, D_{4\to2}, D_{5\to2}, D_{7\to2}$

to infer maps of:



Main conclusions:

- The 2D map of the ionization and recombination rates can be inferred in the divertor leg.
- Molecular contributions to the Balmer series can significantly skew the results below 5eV and must be included in the analysis.

A. Perek et al. 2022 Nucl. Fusion **62** 096012

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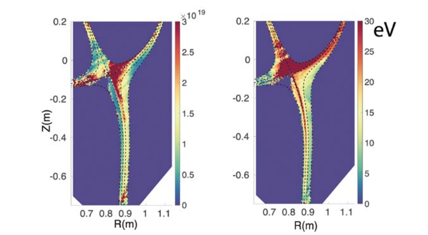
He

Uses emissivities of 3 neutral helium lines at 728nm, 667nm and 706nm to infer maps of:

T_e, n_e



Main conclusions:

- CRM accounting for the magnetic field is needed to capture measured line ratios when validated against TS for T_e, n_e
- Below 10 eV, in a H-He working gas mixture, plasma-molecule interaction can significantly skew the analysis.

B.L Linehan et al. Validation of 2D Te and ne measurements made with Helium Imaging Spectroscopy in the Edge of a Diverted Plasma, in prep for Nuclear Fusion.

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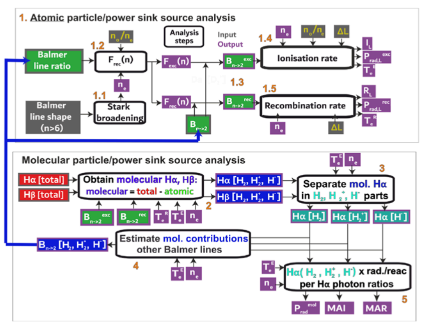
H + molecular

Balmer spectroscopy plasma–molecule interaction (BaSPMI) uses divertor spectroscopy measurements of the line emission and shape from $D_{3\to2}$, $D_{4\to2}$ and two lines from $D_{5\to2}, D_{6\to2}, D_{7\to2}$ to separate atomic and plasma-molecule contributions to infer:

$T_e, n_e, n_0, I_{rate}, R_{rate}, MAI_{rate}, MAR_{rate}, CX/I, P^{exc}, P^{rec}, P^{mol}$



Main conclusions:

- H_2 plasma chemistry involving H_2^+ and/or H^- can substantially elevate medium-n Balmer lines as well as the Ly_α emission.

K. Verhaegh et al. Plasma Phys. Control. Fusion 63 (2021) 035018

→

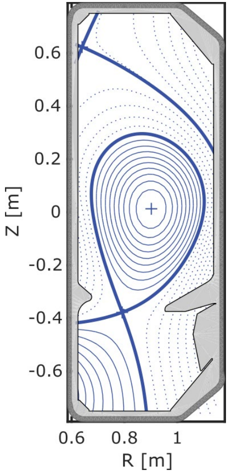
Next steps

Combine the hydrogen, helium and plasma-molecule interaction analysis to complement each other and gain more complete and accurate power and particle balance in the TCV divertor.

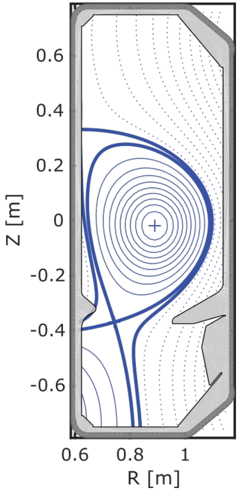
Synergy with WPTE RT05; data package already acquired for 2D emissivities of:
deuterium: $D_{3\to2}, D_{4\to2}, D_{5\to2}, D_{7\to2}$
helium: 728nm, 667nm and 706nm molecular Fulcher band: 600∓5nm. Divertor LOS spectroscopy with high resolution for line-shape analysis [1]:
$D_{3\to2}, D_{4\to2}, D_{5\to2}, D_{7\to2}$, CII and CIII and HeII.
Medium resolution:
$D_{6\to2}$ and Fulcher band in three ranges
[1] L. Martinelli et al., Implementation of high-resolution spectroscopy for ion (and electron) temperature measurements of the TCV divertor plasma submitted to Rev. Sci. Instrum. (EUROfusion pinboard)

WP2 – Scenario and control requirements

- L-mode
  - PEX 250kA
  - PEX 320 kA



- H-mode
  - Small-Elms, 1MW NBH (+ ECRH later)
  - Elmy 170kA, 1.3MW NBH (+ ECRH later)
  - Elmy 170kA, 1.3MW NBH (+ ECRH later)



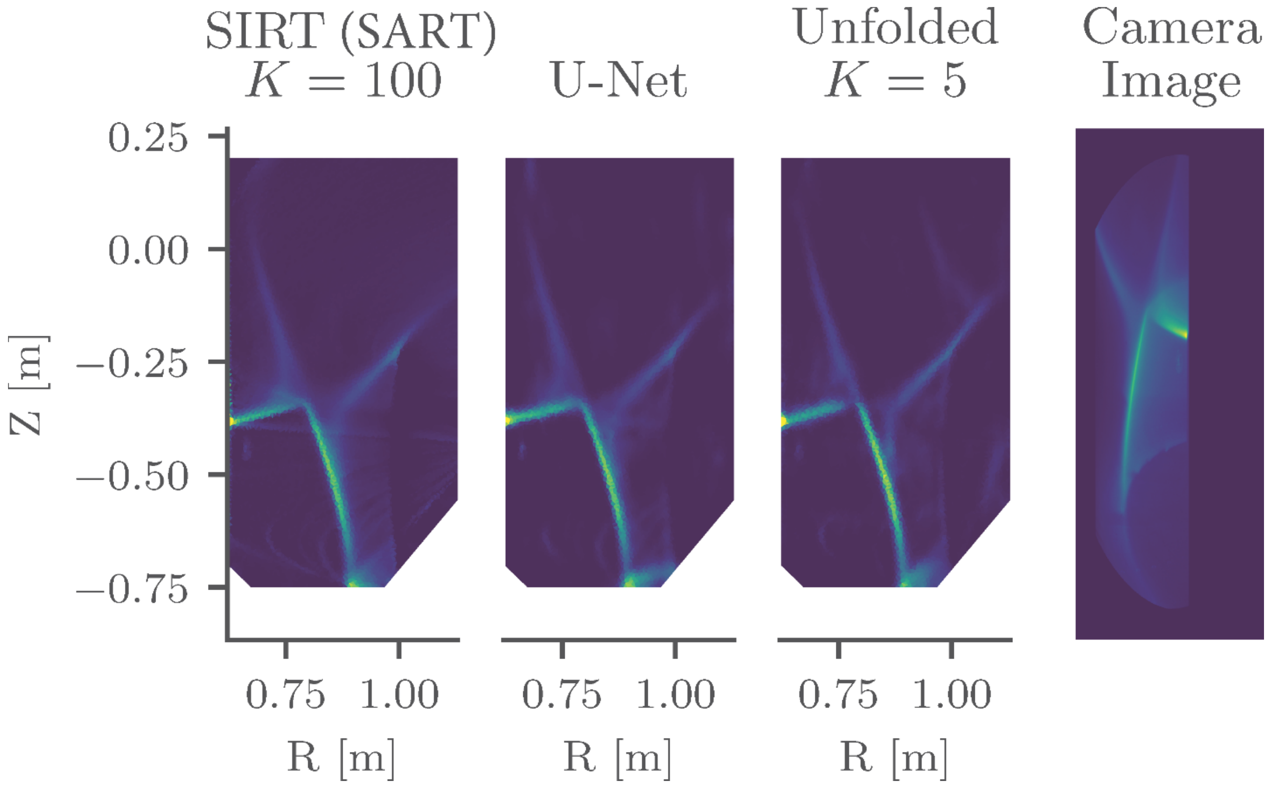
- Possible extension to more complex shapes double null (WPTE RT-04)

WP3 (key WP this phase)

Goal: going from off-line (multi-camera) MANTIS to within the loop (real-time and integrated into the control system)

- Speed up tomographic inversions with machine learning (ML)
- Speed up Bayesian analysis with machine learning (ML)
- Speed up at integration through dedicated GPU hardware in the loop

WP3: Offline to real-time analysis conversion: Machine Learning Tomographic Inversion - real data



L. van Leeuwen et al., Machine learning accelerated tomographic reconstruction for multispectral imaging on TCV, in prep. Nuclear Fusion

WP3: Offline to real-time analysis conversion

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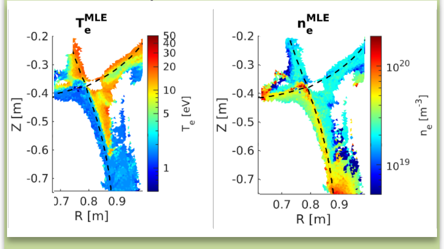

Main conclusions:
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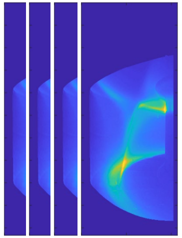
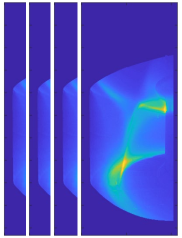
[1] A. Perek et al. 2022 Nucl. Fusion **62** 096012

Plasma emission



~5 CPUs per frame → Tomographic inversions → ~4000 CPUs per time step → Bayesian Plasma parameter inference [1] → I_{rate}, R_{rate}

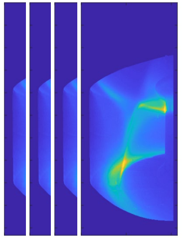
Plasma emission



Machine learning for tomographic inversions (~0.002 CPUs per frame) → Machine learning for plasma parameter inference (~0.03 CPUs per time step) → I_{rate}, R_{rate}

WP3: Offline to real-time analysis conversion

Plasma emission



~5 CPUs per frame

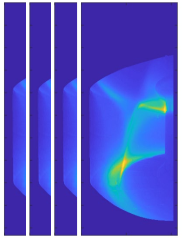
Tomographic inversions

~4000 CPUs per time step

Bayesian Plasma parameter inference [1]

I_{rate}, R_{rate}

Plasma emission



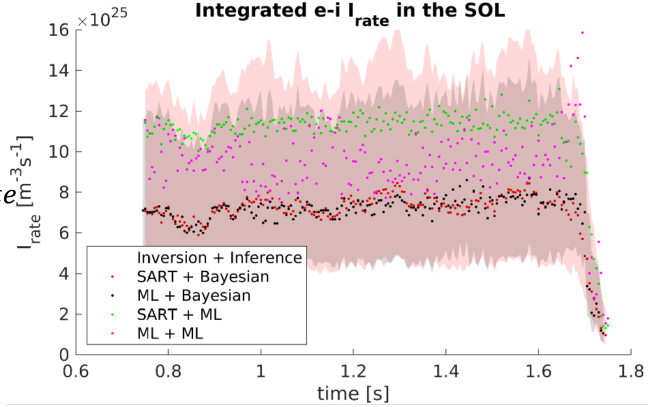
Machine learning for tomographic inversions

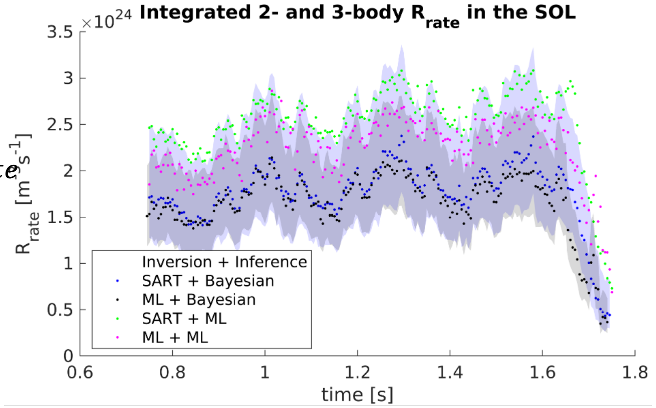
Machine learning for plasma parameter inference

I_{rate}, R_{rate}

~0.002 CPUs per frame

~0.03 CPUs per time step



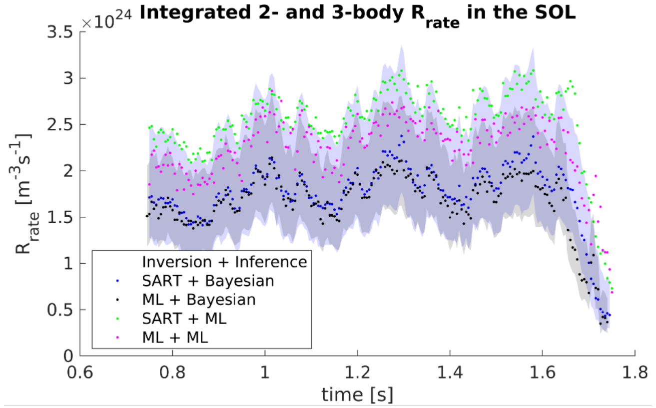


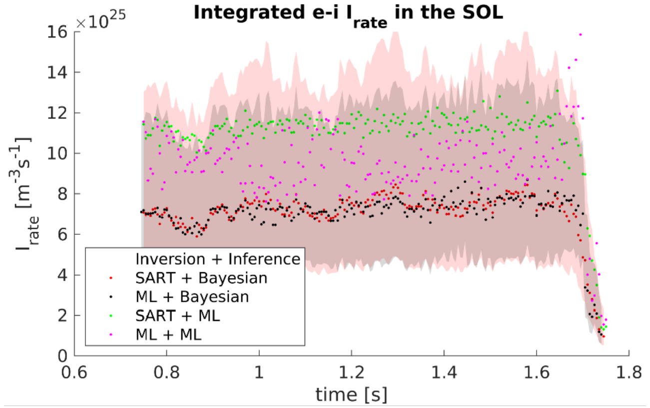
WP3: first results dynamic validation approach

recombination

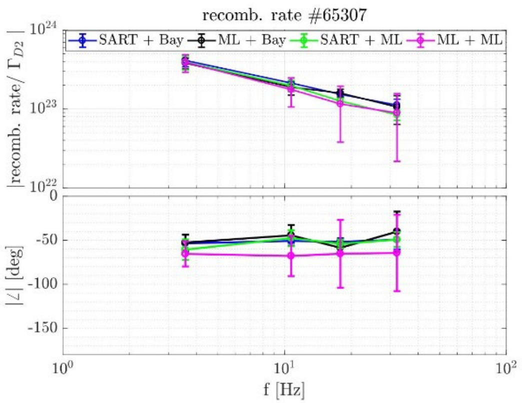
ionization

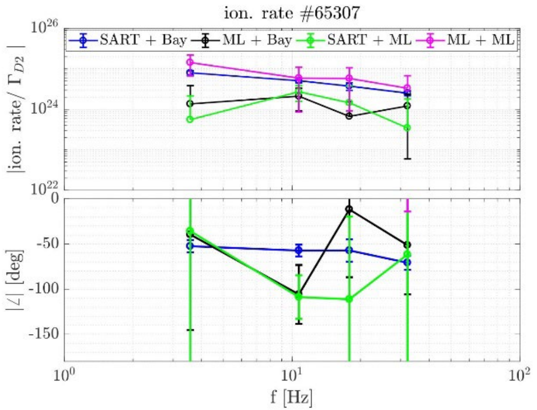
time domain





frequency domain (control)



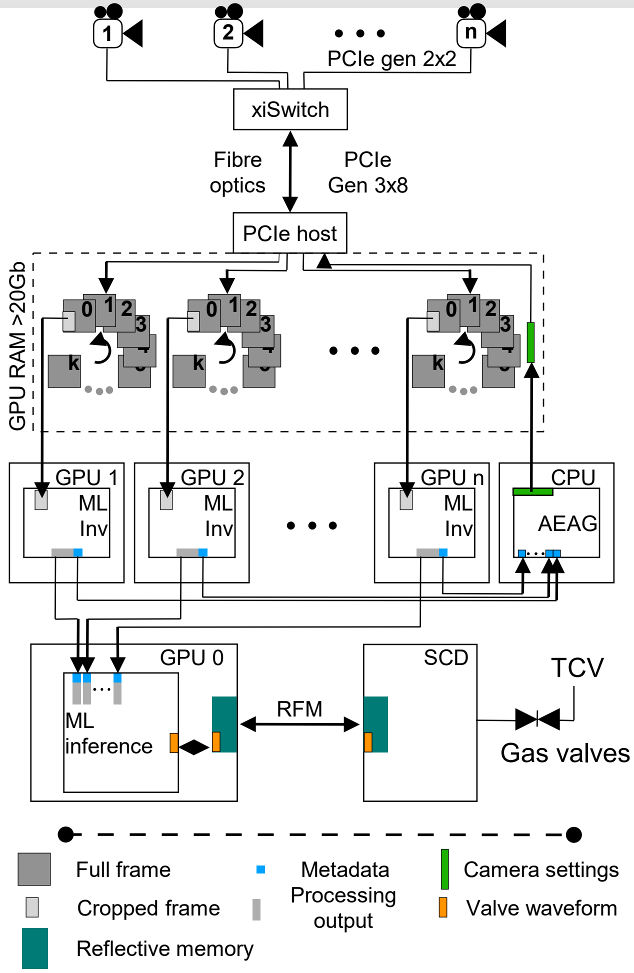


WP3: Hardware and software implementation for real-time integration

Strategy:
- Move our current CPU processing into a GPU for performance in ML applications.
- Move from our in-house developed C/C++ code to the F4E MARTe2 framework for maintainability and compatibility with other fusion experiments.
- Incorporate Nvidia Triton Inference Server to divide a single physical GPU into n parallel virtual GPUs.

GPU requirements:
- Supports remote direct memory access (RDMA) for the cameras to stream directly to the GPU
- At least 1Gb of GPU RAM for 1s of frames per camera, at least 20Gb total.
- Sufficiently powerful to deliver required performance under the Nvidia Triton Inference Server

Next steps:
- We are working with the Nvidia Science Team to test our networks on their servers and determine the most suitable GPU for our applications. Currently deciding between Nvidia V100 and A100 models (up to 15k€)
- Implementation and testing with MANTIS cameras.
- Aiming for the first experiments by the end of 2022 or the second half of 2023 (subject to TCV schedule)



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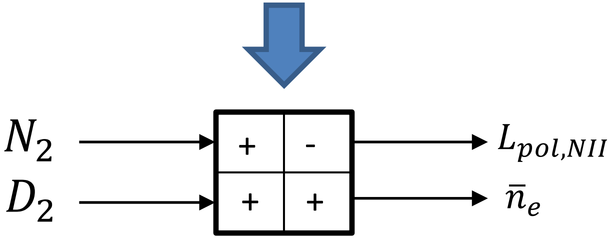
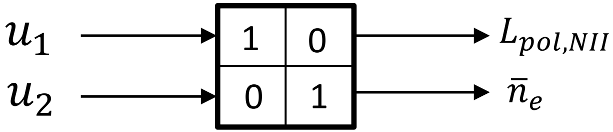
WP4&6: MIMO identification/control approach

system identification (WP4)



$$u_1 = a_1\, N_2 + b_1\, D_2$$
$$u_2 = a_2\, N_2 + b_2\, D_2$$



Decoupling based on system identification measurements

WP4&6: MIMO control design and integration

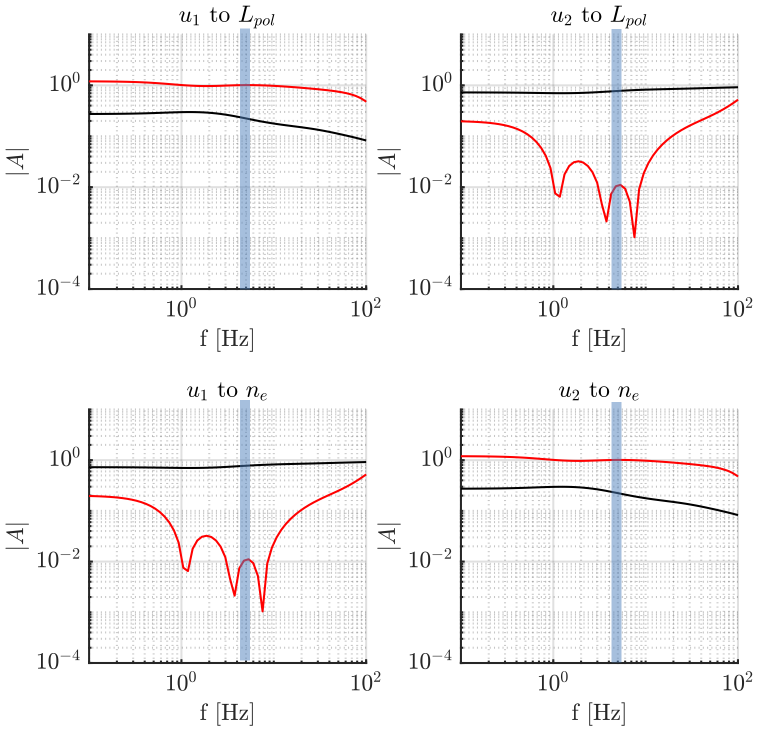
Choose decoupling frequency, and take real approximation inverse $G(f)^{-1}$ of complex response $G(f)$. Then $G(f)*G(f)^{-1} \sim 1$. We choose f = 5 Hz

- With pre-compensator (virtual inputs), two PI controllers were designed on individual loops with 5 Hz bandwidth (conservative).
- Stability of the controller is tested for interaction using the generalized Nyquist criterion.

$$G(5\ Hz)^{-1} = \begin{bmatrix} 1 & 0.73 \\ 3.85 & -1 \end{bmatrix}$$

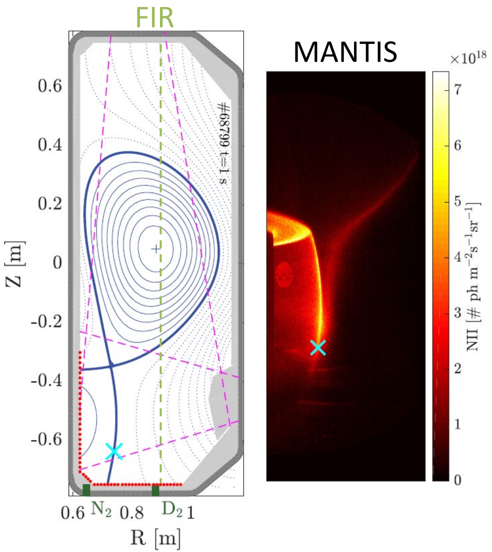
$$\begin{matrix} u_1 \\ u_2 \end{matrix} = \begin{matrix} D_2 + 3.85\ N_2 \\ 0.73 D_2 - N_2 \end{matrix}$$

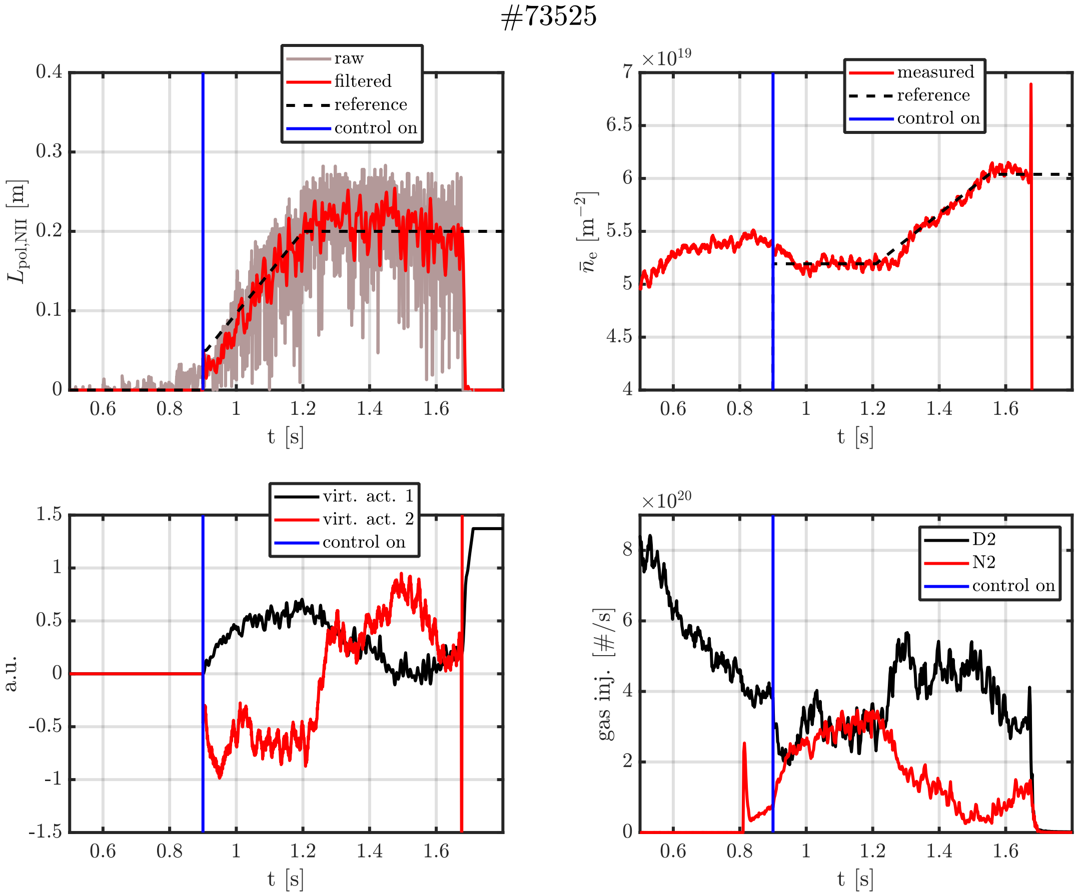
RGA (with pre-compensator)



WP6: First ever MIMO control for exhaust

- 340kA L-mode scenario
- Controller capable of following both NII front and n_e references.





Control oriented modeling with DIV1D

EUROfusion roadmap mission-2: Heat-exhaust systems

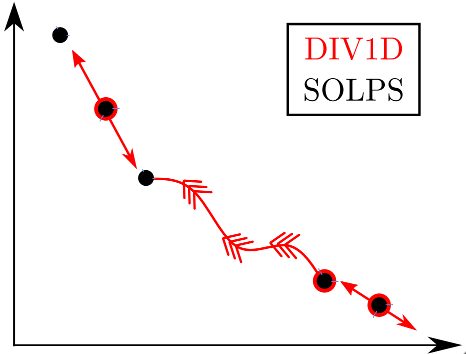
- Requires dynamic to develop and test controllers

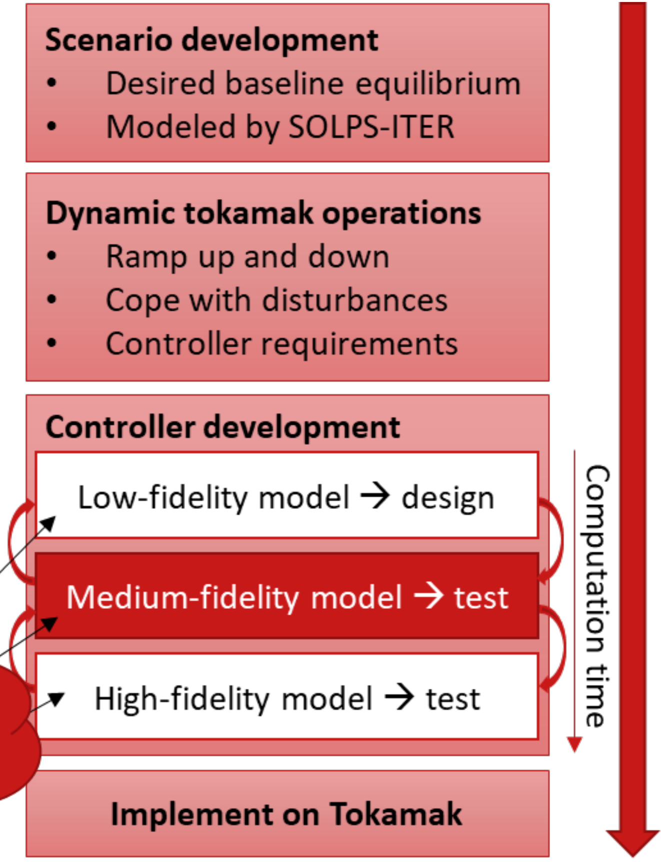
Envisioned role for DIV1D

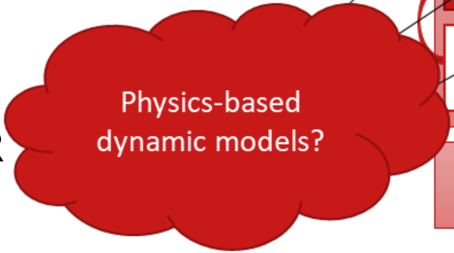
- Match SOLPS-ITER equilibria
- Transition between equilibria
- Describe local dynamics

Overview

- DIV1D & SOLPS-ITER
- Mapping SOLPS-ITER to 1D
- Benchmark DIV1D on SOLPS-ITER

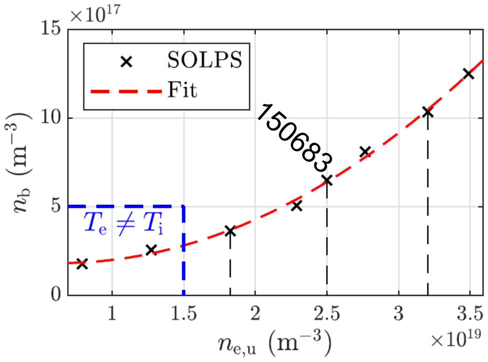




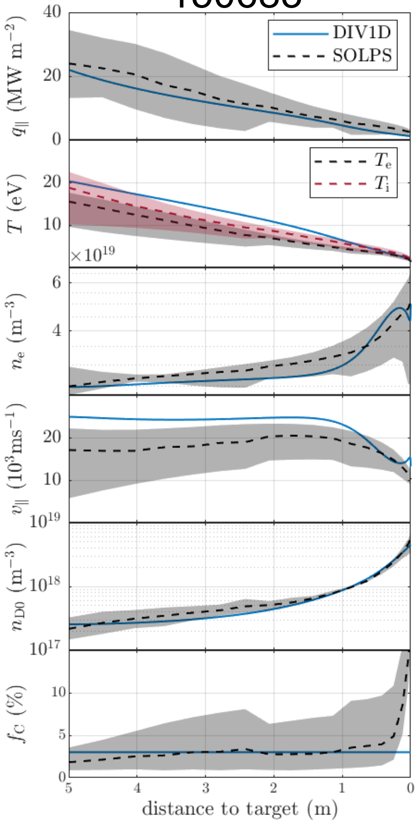


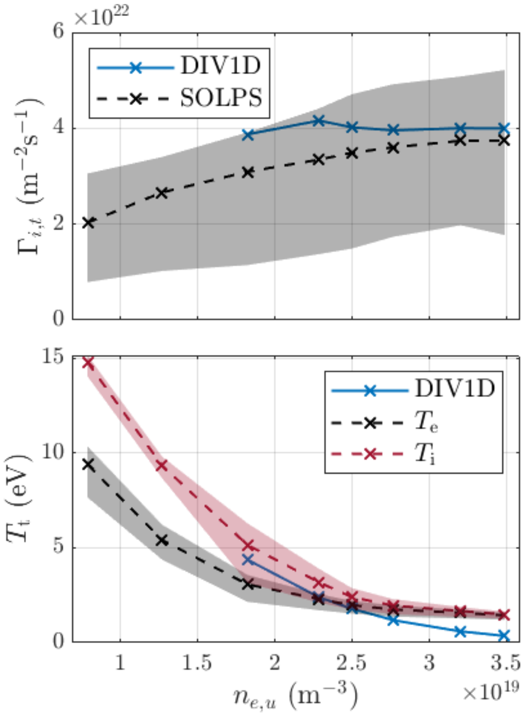
WP5: benchmark DIV1D on SOLPS-ITER

Methodology
- Extract DIV1D settings from 1D SOLPS-ITER
- Scan upstream and background density



Result (on the right)
- DIV1D reasonably fits SOLPS-ITER across a range of simulations





G.L. Derks et al. (in review), PPCF 2022

DIFFER EPFL

Overview complete project

Main objective: MIMO control of the divertor state using multiple MANTIS camera's

Sub-objectives

- **Real-time (millisecond range) tomographic reconstruction of MANTIS images.**
  - ✓ Is achieved using a machine learning accelerated approach (2 ms)
  - ❑ Awaiting a new GPU for implementation (<2 ms)
  - ❑ Aim for an experimental demonstration before 2023.
- **Real-time inference of recombination, ionization and impurity radiation power losses**
  - ✓ Basic version for inference of ionization, recombination, and divertor $T_{electron,} n_{electron,} n_0$ from filtered camera images [1]
  - ❑ Further development necessary to improve Bayesian inference and validate results, e.g., ionization
  - ❑ Aim for an experimental demonstration before 2023
- **Control-oriented modelling for MIMO exhaust control**
  - ✓ 1 dimensional dynamic SOL Model DIV1D was benchmarked against SOLPS-ITER in steady-state [2]
  - ❑ Ongoing benchmark against dynamic experiments
- **MIMO system identification + feedback control (and integration in SCD)**
  - ✓ MIMO sys.id. and control of line-averaged electron density and NII emission front position [3]
  - ❑ Repeat of above with real-time inferred processes (ionization, etc.) from MANTIS camera's

[1] A. Perek et al., Nucl. Fusion 62, 096012 (2022)
[2] G.L. Derks et al., PPCF (2022) (in review, see EUROfusion pinboard)
[3] J.T.W. Koenders et al., 48th EPS conference on plasma physics (2022), P4b.122 -> journal publication in preparation
[4] L. van Leeuwen et al., Machine learning accelerated tomographic reconstruction for multispectral imaging on TCV, in prep for Nuclear Fusion

Extension of the project

Would extension of the project beyond the currently accepted date benefit EUROfusion programme?

- *MIMO control results (shown here), already impact future control on several WPTE devices that want to follow same approach (and beyond)*
- *Expectation to go closer to reactor relevant (ITER/DEMO) control design in the coming year(s), which will impact EUROfusion work packages*
- *1 year and 3 months in, way too early*