WPENR, Technology and Systems, Project no.11

EUROfusion

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

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Motivation

EUROfusion roadmap mission-2: Heat-exhaust systems

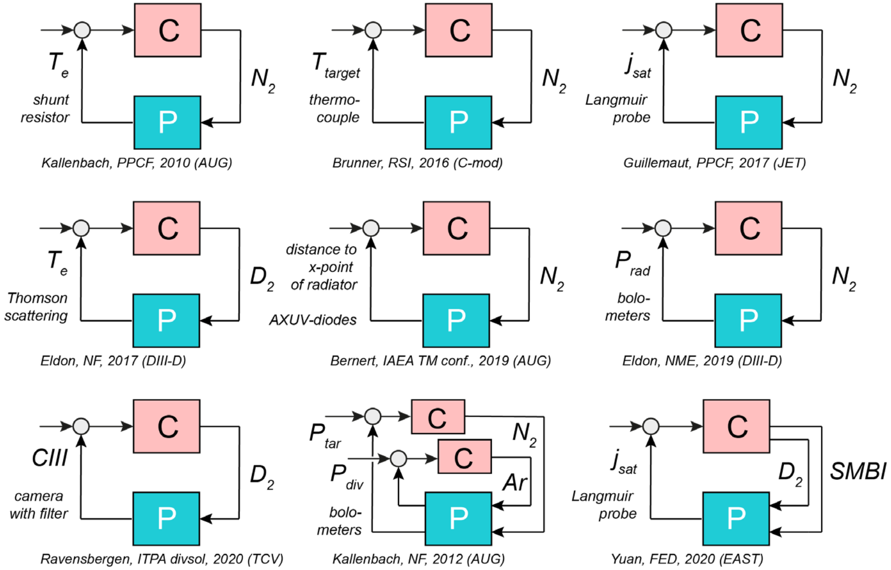
- capable of withstanding the large heat and particle fluxes of a fusion power plant;
- allow as high performance as possible from the core plasma.

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

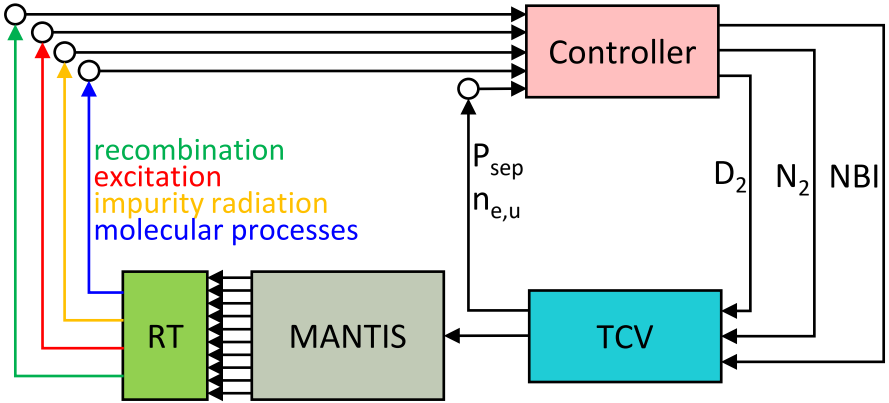
Inherently a multi-input multi-output problem (multiple performance parameters and multiple actuators).

Introduction

Single-input single-output (SISO)



Multiple-input multiple-output (MIMO)

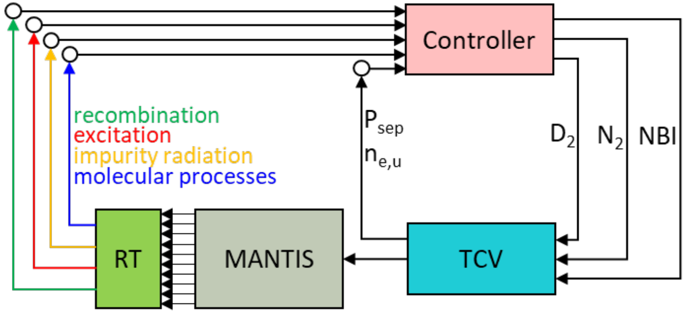


Introduction

A. Perek et al., Rev. Sci. Instrum. **90,** 123514 (2019)

TCV view of divertor

Multiple-input multiple-output (MIMO)



Other possible diagnostics for control (not RT-ready): DSS (spectroscopy), **RadCam (Soft-X, Bolometer, AXUV)**, Thomson, MANTISIIa, MANTISIIb mid/top-port views

Introduction

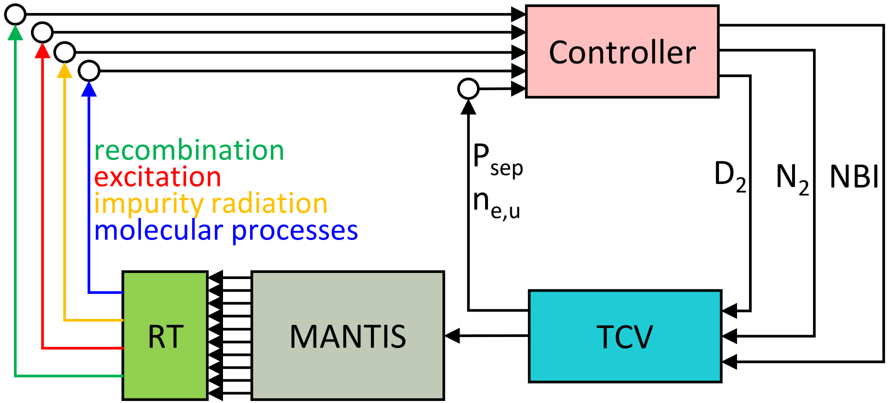
MIMO control: Interaction is key

- Actuators affect multiple outputs

Stacking SISO controllers will lead to

- other behavior than based on the individual SISO controllers
- ➢ extreme case: instability

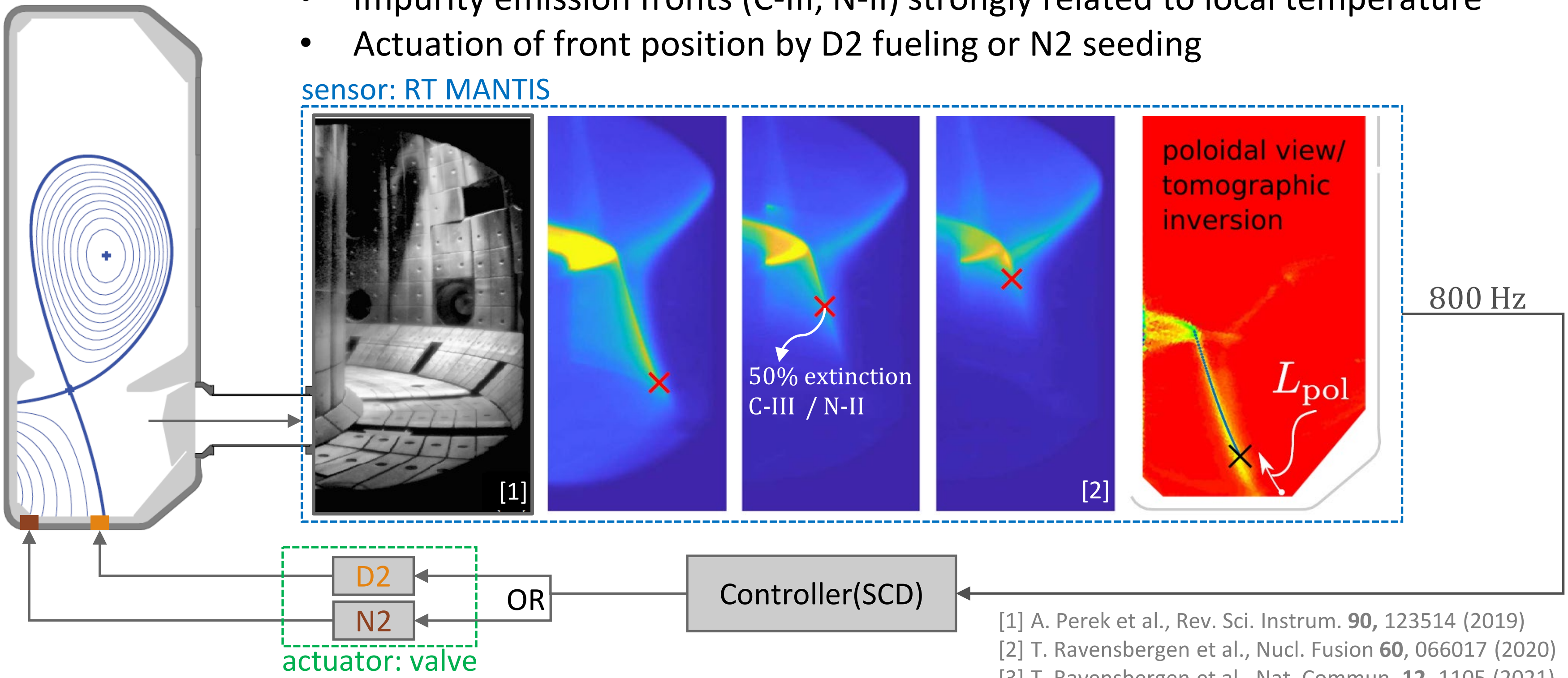
Requires interaction analysis and MIMO controller design techniques



See: Skogestad and Postlethwaite.
Multivariable Feedback Control, Analysis and Design (2007)

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

Overview

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

Delayed: main (full-time) person is missing and will start 1st 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).

Hence, shifted focus to:

- **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.).

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.

ENR WPs overview and progess

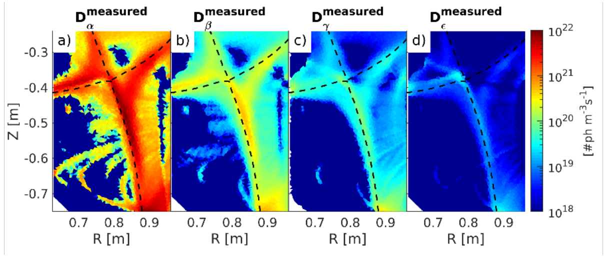
Main goal: setting up for MIMO control (P6) with different MANTIS camera’s

Progress	Project
P1	MANTIS development to determine loss-processes in 2D
P2	Detachment analysis, scenario selection, setting control requirements
P3	Conversion from off-line to real-time camera analysis (incl. machine learning)
P4	MIMO system identification
P5	Dynamic modelling for MIMO-control
P6	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 → $n_e, T_e, n_o, I_{rate}, R_{rate}, CX_{rate}, P_{exc}, P_{rec}$

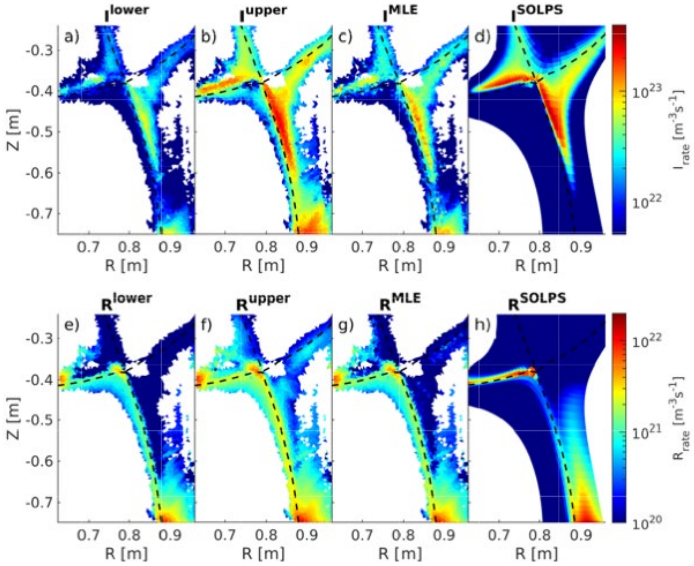
$$B_{n\to 2} = n_e^2 PEC_{n\to 2}^{rec}(n_e, T_e) + n_e n_o PEC_{n\to 2}^{exc}(n_e, T_e)$$

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

Probability that multiple measured lines are observed:

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

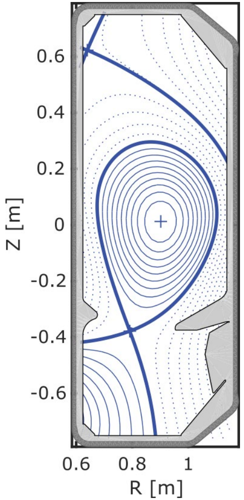
$$P(n_e, T_e, n_o) \to P(I_{rate}), P(R_{rate})$$



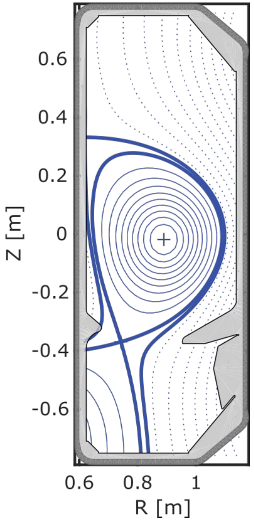
A. Perek et al. A spectroscopic inference and SOLPS-ITER comparison of flux-resolved edge plasma parameters in detachment experiments on TCV, submitted to Nuclear Fusion.

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 / higher I_{plasma}

WP2 – Scenario and control requirements

- Actuators
  - Gas fueling and/or impurity seeding with weakly (N_2) and strongly (Ne, Ar, ..) recycling species
  - Input power (NBH, possibly ECRH)

- Performance variables
  - Neutral compression (baffles)
  - Location of CIII/NII impurity emission front (inter-Elm)
  - Ionization / recombination in the divertor
  - Upstream conditions, e.g. $\langle n_e \rangle$, $P_{seperatrix}$

➢ Ideally go for robust control approach (weight functions)

WP2 – Scenario and control requirements

Simultaneous (MIMO) control upstream density and detachment

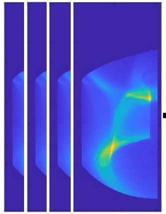
- detachment control (using MANTIS)
- upstream density control (more complicated no direct sensor)
  - using FIR in observer to determine density profile (upstream density)
  - model based synthesis of upstream density control

Addressing this:

- ➢ dynamics multiple valves with both core and exhaust tasks
- ➢ observer development (RAPTOR-RAPDENS) to RT-reconstruct density profile (together with RT-04 Thomas Bosman, Federico Felici)

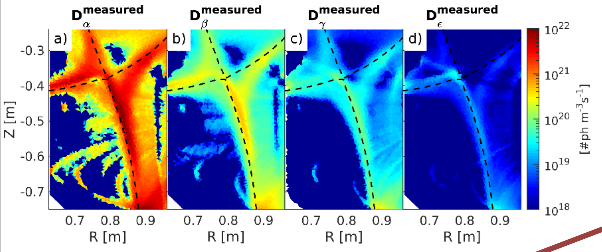
WP3 – Conversion to RT (neural networks)

Filtered camera images of the Balmer line emission



Tomographic inversion ~10s per frame per camera

Emissivity of the Balmer series



Bayesian inference using ADAS model ~5000s per frame

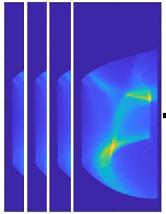
$n_e, T_e, n_o, I_{rate}, R_{rate}, CX_{rate}, P_{exc}, P_{rec}$

Those two steps combined must be speed up by at least 6 orders of magnitude for real-time use. This will be attempted using Machine Learning:

- Tomographic inversion — proposal submitted for Marconi.
- Bayesian inference — convolutional neural networks.

WP3 – Conversion to RT (neural networks)

Filtered camera images of the Balmer line emission



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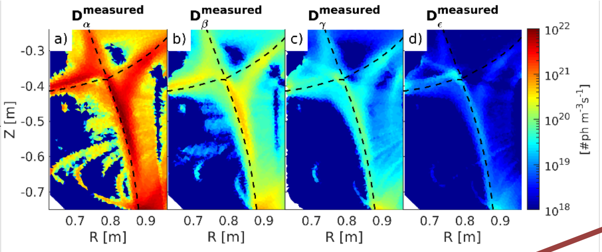


Bayesian inference using ADAS model ~5000s per frame

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

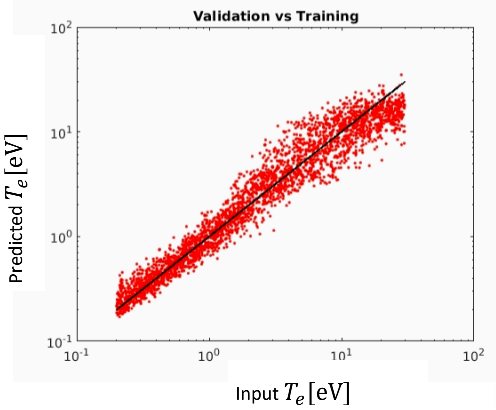
Approximation of the electron temperature using convolutional neural networks and the ADAS model

3000 samples of random combinations of plasma parameters within the ranges below were used to generate training and validation Balmer line emissivities using the ADAS model.
10% noise was added.

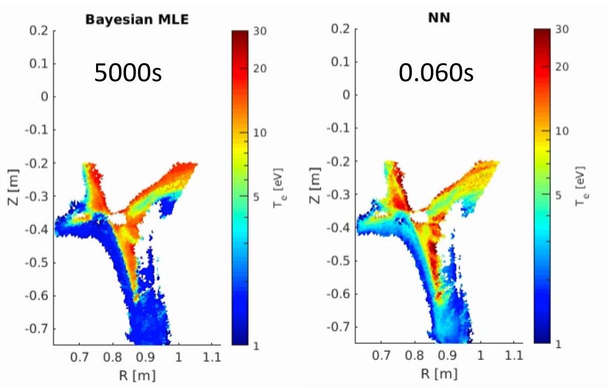
$T_e = (0.2,30)[eV]$

$n_e = (5e18,2e20)[m^{-3}]$

$n_o = (5e16,5e18)[m^{-3}]$



Application to the experimental data



WP4 – MIMO System Identification

MIMO control: system identification experiment with periodic perturbation. Design controller on resulting FRF Matrix.

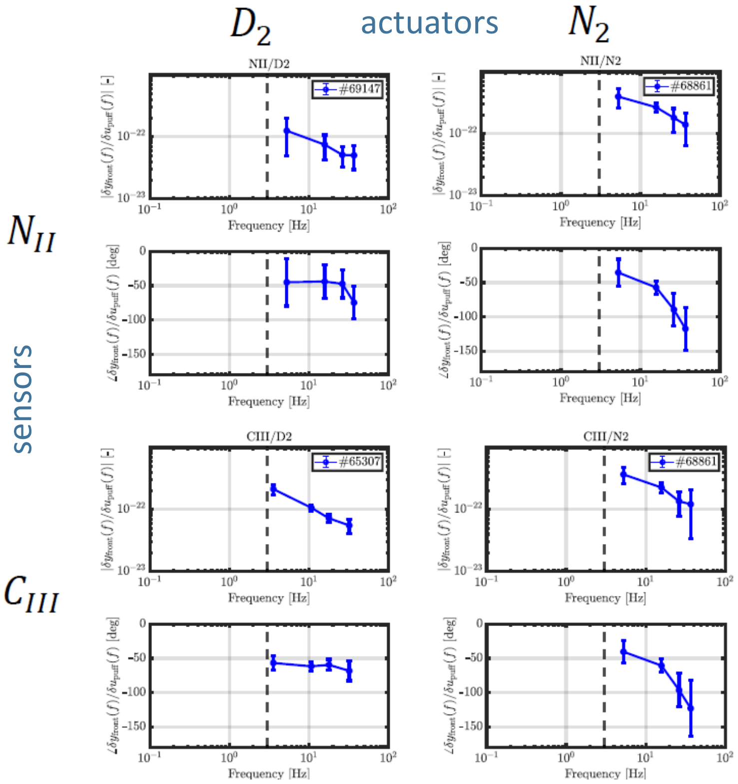
Filling the matrix with SISO identification:

- Requires (at least) 1 experiment per actuator

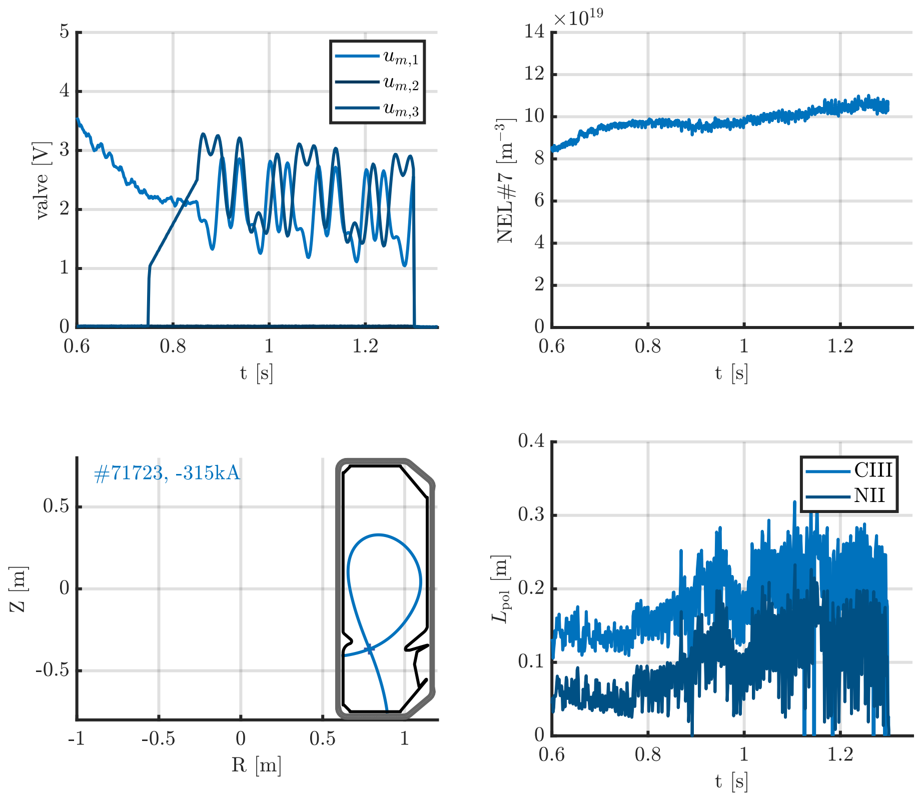
Filling the matrix with tailored MIMO identification:

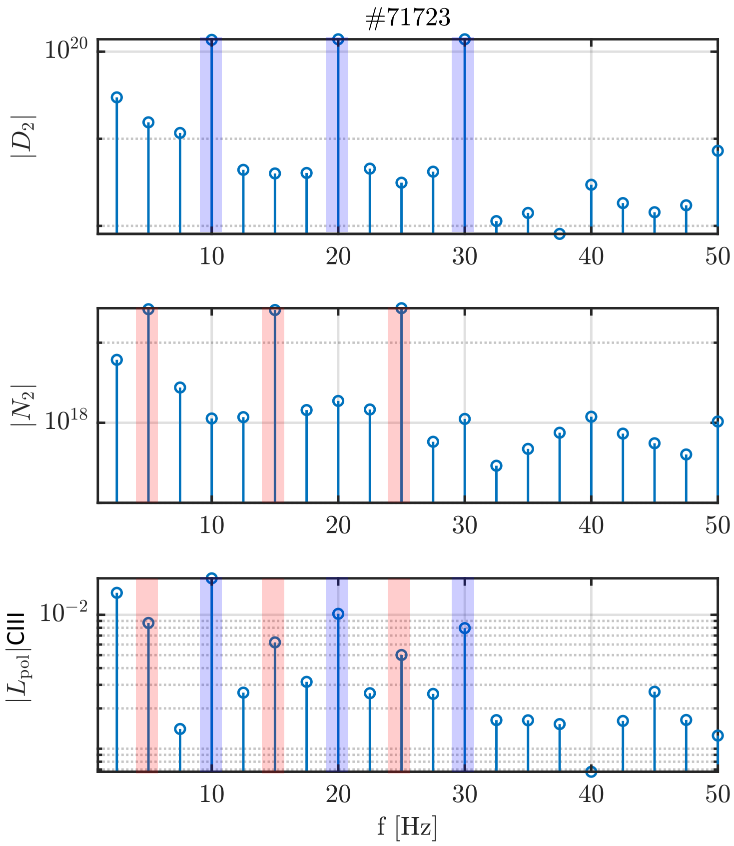
- Requires only 1 experiment in total
  - Note, trade-off in quality is present

Multiple-input multiple-output (MIMO)



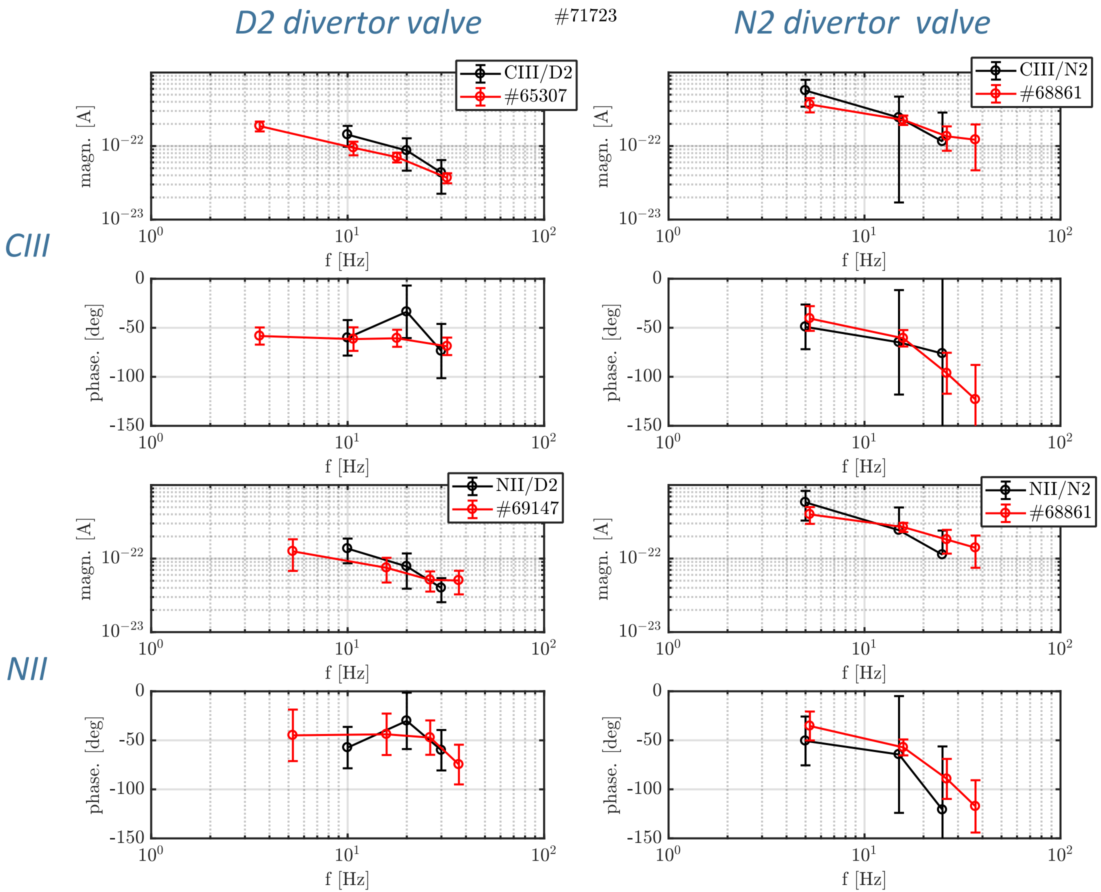
WP4 – MIMO System Identification





WP4 – MIMO System Identification

- First results of MIMO system identification experiments
- 2x3 5 Hz zippered multisine
- ML in agreement with previous SISO results (red), but trade-off of single experiment means larger uncertainties
- Next step: continue analysis of interaction and actuator / sensor directions + start investigation of MIMO controller design



A one dimensional code to model divertor plasma dynamics from X-point to divertor target

Basic equations [1,2,3]

- particle balance

$$\frac{\partial n}{\partial t} = -\frac{\partial}{\partial x}\Gamma_n + S_n, \quad \Gamma_n = n v_\parallel$$

- momentum balance

$$\frac{\partial n m v_\parallel}{\partial t} = -\frac{\partial}{\partial x}\left(n m v_\parallel^2 + p\right) + S_{\mathrm{mom}},$$

- energy balance

$$\frac{\partial 3neT}{\partial t} = -\frac{\partial}{\partial x} q_\parallel + v\frac{\partial}{\partial x}p + Q,$$

$$q_\parallel = 5neTv_\parallel - \kappa_\parallel \frac{\partial}{\partial x}T,$$

- neutral particle balance

$$\frac{\partial n_n}{\partial t} = \frac{\partial}{\partial x}D\frac{\partial}{\partial x}n_n - S_n,$$

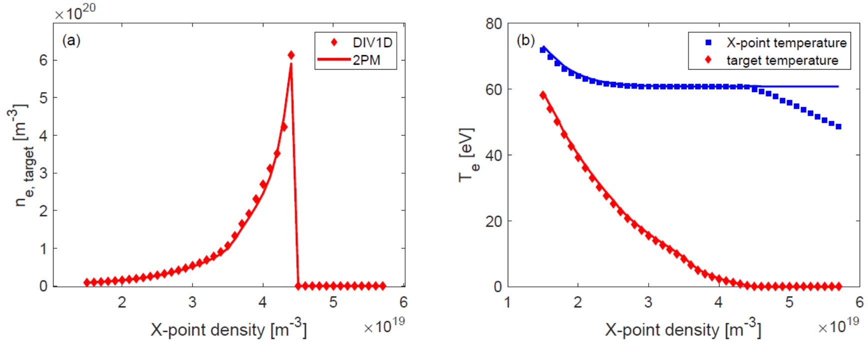
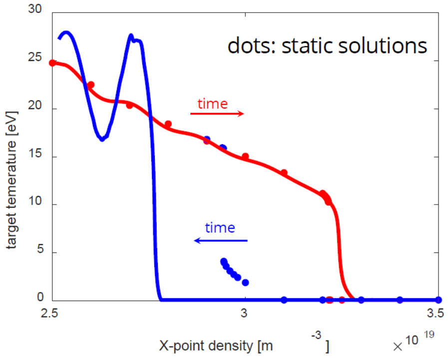


Figure 1: Results of an X-point density scan with a 1% Carbon impurity fraction. (a) Target density (diamonds) as a function of X-point density. (b) X-point (squares) and target (diamonds) temperatures. Corresponding results of the two-point model are shown as full lines.

Bifurcation in dynamic simulations of X-point density ramp-up and ramp-down

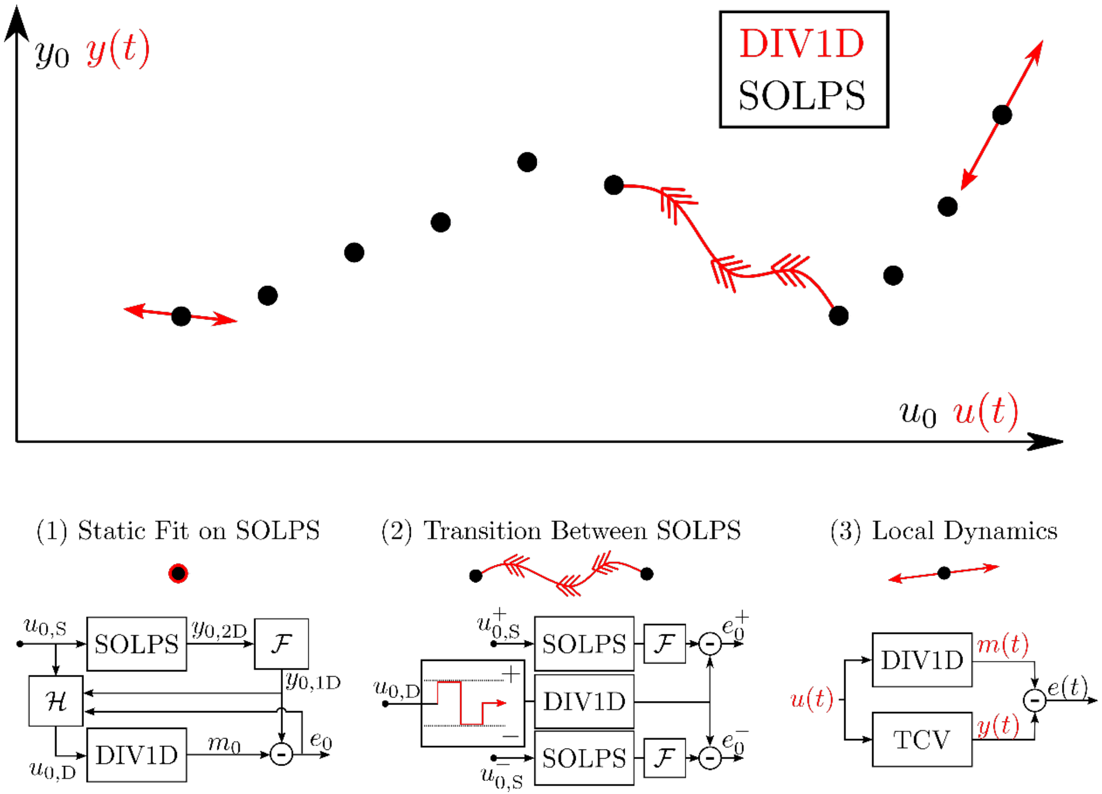
- 5% Carbon
- 10 ms density ramp @ $\pm 10^{21}$ m^{-3}



E. Westerhof et al., 47th EPS Conference on Plasma Physics, P5.1015

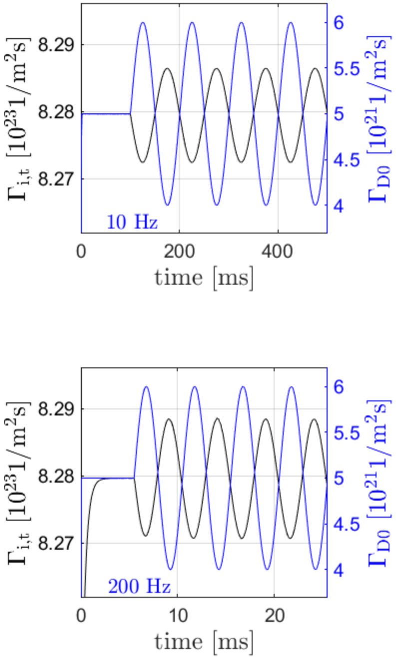
WP5 – Dynamic modelling for control

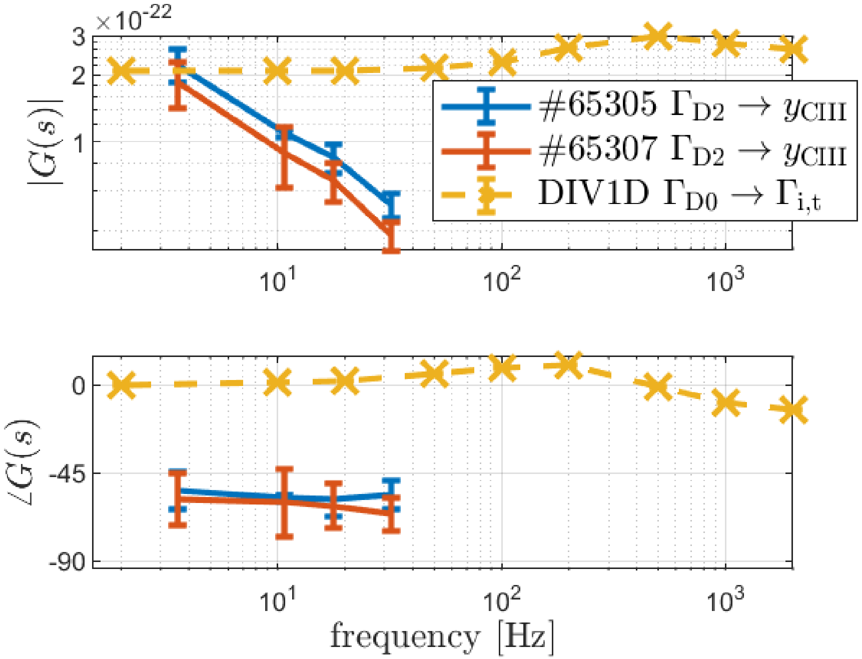
- Complementing SOLPS with DIV1D:
  - (1) Fit on SOLPS
  - (2) Transition between points
  - (3) Describe Measured Dynamics
- Requires Methods
  - F: mapping 2D to 1D
  - H: DIV1D input policy
- State of Validation DIV1D
  - (1) Reasonable agreement
  - (2) Sensitive in density ramp (WIP)
  - (3) Dynamics are too fast for control
- Outlook
  - DIV1D→ semi-heuristic transfer function models



WP5 – Dynamic modelling for control

(3) Local Dynamics





Conclusions

Made deliverables:

- **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:

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- **Integration DCS**: Integration of algorithms into the digital control system TCV and verify real-time algorithms.

First MIMO control experiments!

DIFFER

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