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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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DIFFER EPFL University of Strathclyde Glasgow TU/e

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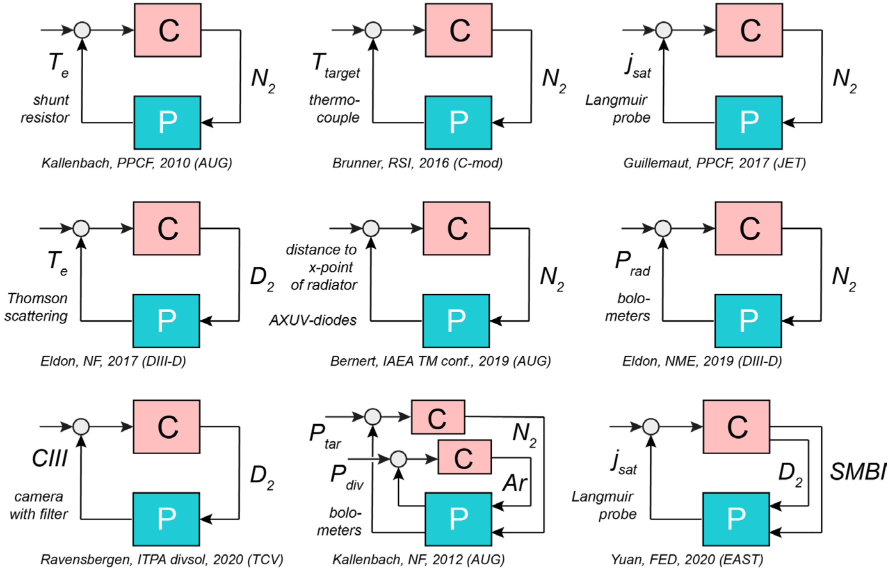
Agenda

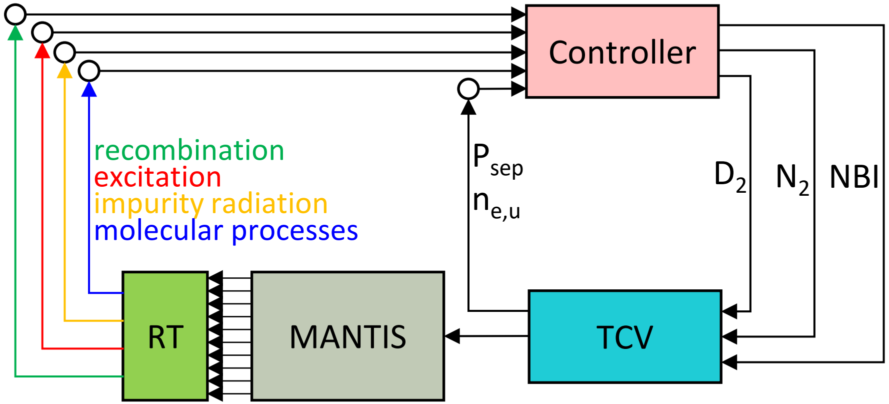
- Short overview of the ENR project
- One slide journal paper summaries
- Full MIMO feed-back control (to be done)
- Impact on next steps (three examples)
- Summary

Introduction

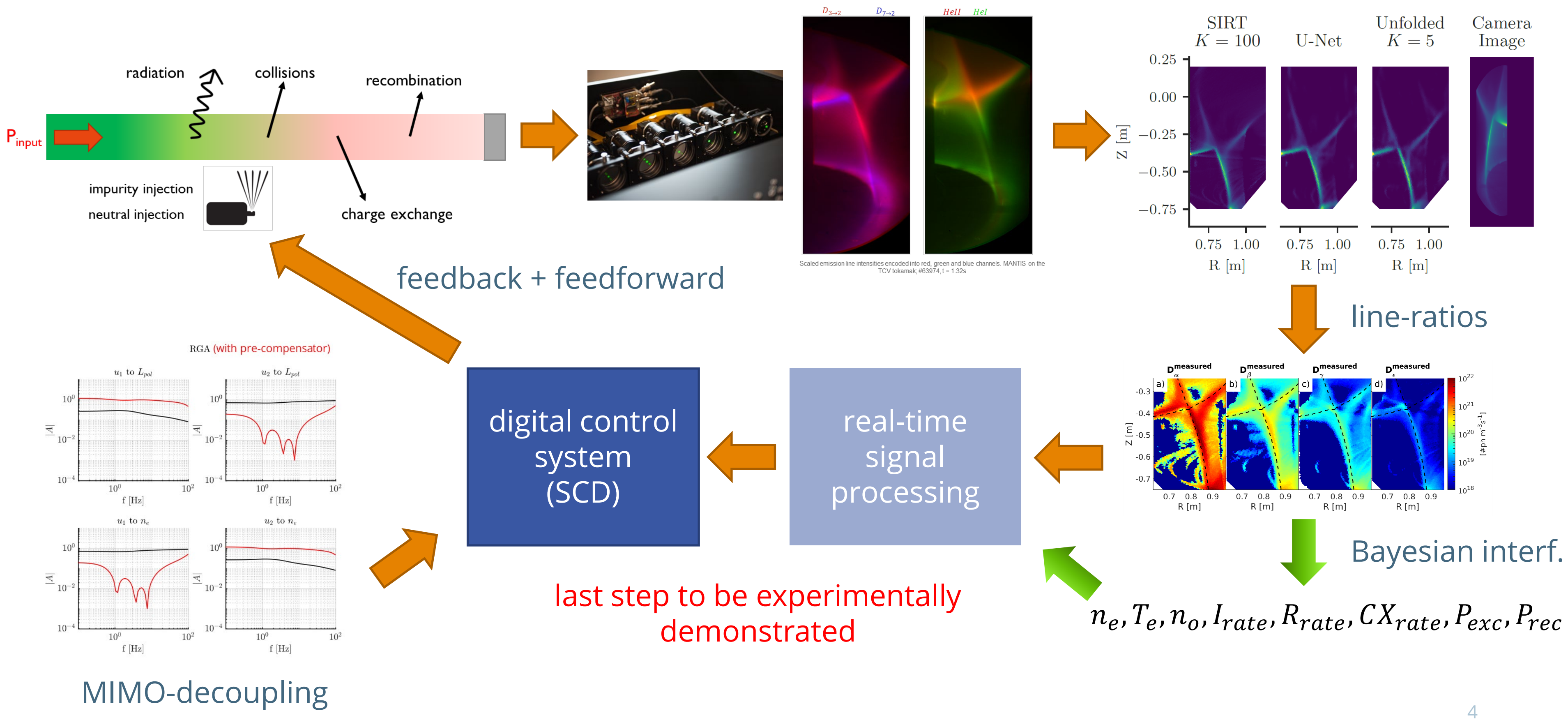
Single-input single-output (SISO)



Multiple-input multiple-output (MIMO)



Project overview (and status)



Overview of goals

- **Real-time (millisecond range) tomographic reconstruction of MANTIS images.**
  - ✓ Is achieved using a machine learning accelerated approach (2 ms)
  - ✓ GPU for implementation card is available and largely integrated
  - ✓ Demonstrated on GPU
- **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
  - ✓ Further development necessary to improve Bayesian inference and validate results, e.g., ionization: Jaime's presentation
- **Control-oriented modelling for MIMO exhaust control**
  - ✓ 1 dimensional dynamic SOL Model DIV1D was benchmarked against SOLPS-ITER in steady-state
  - ✓ 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
  - o Repeat of above with real-time inferred processes (ionization, etc.) from MANTIS camera's This was planned before end of project but not attained due to problems with implementation. *(planned December 2024)*

We are planning to demonstrate the last open point experimentally in the coming months. As everything is now working offline (26th of September 2024), we expect a quick experimental demonstration. Of course, the dissemination of the results (publications) will take longer.

Journal publications

First Author	Initials	Journals published under the ENR	Pinboard ID
Koenders	J.T.W.	Nuclear fusion	34993
Derks	G.L	Fusion Engineering and design	36329
Derks	G.L	Plasma Physics and Controller Fusion	36331
Derks	G.L	Plasma Physics and Controller Fusion	32773
Koenders	J.T.W.	Nuclear fusion	31120
Koenders	J.T.W.	Nuclear fusion	32797
Raukema	J.	Nuclear fusion	35095
Perek	A.	Nuclear fusion	29903
van Leeuwen	L.S.	Plasma Physics and Controlled Fusion (accepted)	33861

Unpublished

van Berkel	M.	Nuclear fusion (WPENR together with WPTE)	In prep.
Derks	G.L.	Nuclear fusion	In prep.
Caballero	J.	Plasma Physics and Controlled Fusion	Ready for pinboard
van Berkel/Perek	M./A.	High impact journal	Written after final experiments

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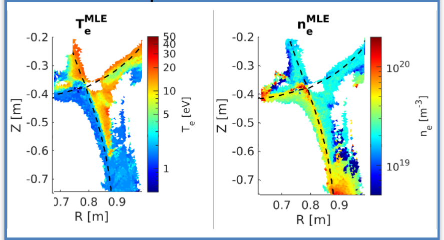
MANTIS interpretation development (WP 1 & WP 2)

A spectroscopic inference and SOLPS-ITER comparison of flux-resolved edge plasma parameters in detach. exp. on TCV, Perek et al.

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:

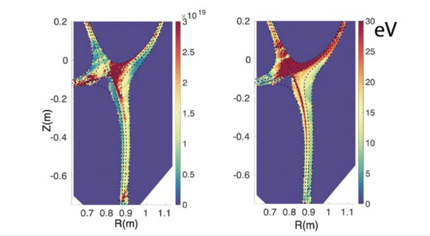
- The 2D map of the ionization and recombination rates can be inferred in the divertor leg.
- Molecular contributions to the Balmer series can significantly skew the results below 5eV and must be included in the analysis.

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

+

He

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



Main conclusions:

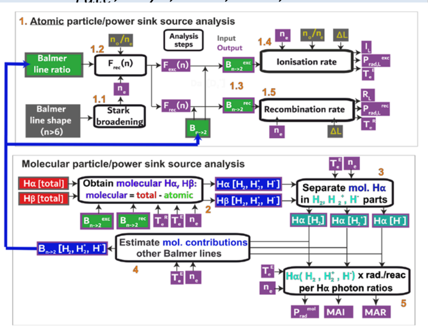
- CRM accounting for the magnetic field is needed to capture measured line ratios when validated against TS for T_e, n_e
- Below 10 eV, in a H-He working gas mixture, plasma-molecule interaction can significantly skew the analysis.

B.L Linehan et al. Validation of 2D Te and ne measurements made with Helium Imaging Spectroscopy in the Edge of a Diverted Plasma, 2023 *Nucl. Fusion* **63** 036021

+

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

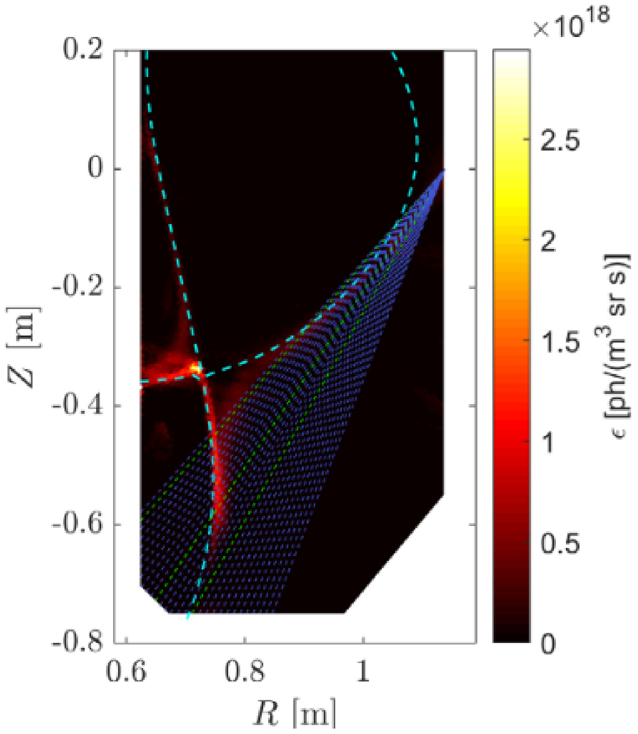
Combine the hydrogen, helium and plasma-molecule interaction analysis to complement each other and gain more complete and accurate power and particle balance in the TCV divertor.

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

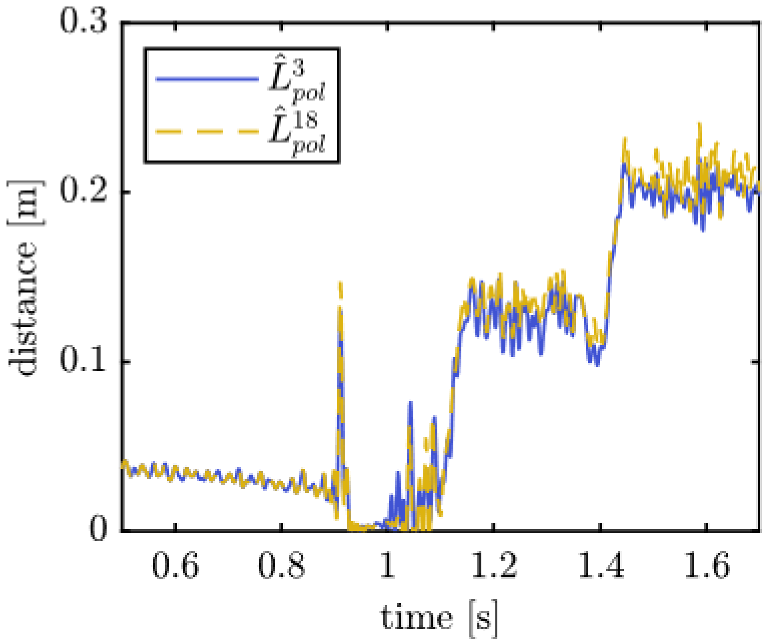
[1] L. Martinelli et al., Implementation of high-resolution spectroscopy for ion (and electron) temperature measurements of the TCV divertor plasma, *Rev. Sci. Instrum.* 93, 123505 (2022)

DIFFER EPFL

Demonstration of a sparse sensor placement technique to the limited diagnostic, Raukema et al. (with WPD&C)



CIII emissivity with lines of sight originating from the mid-plane



3-spectral line reconstruction using developed sparse sensor placement with vs. 18-spectral line reconstruction

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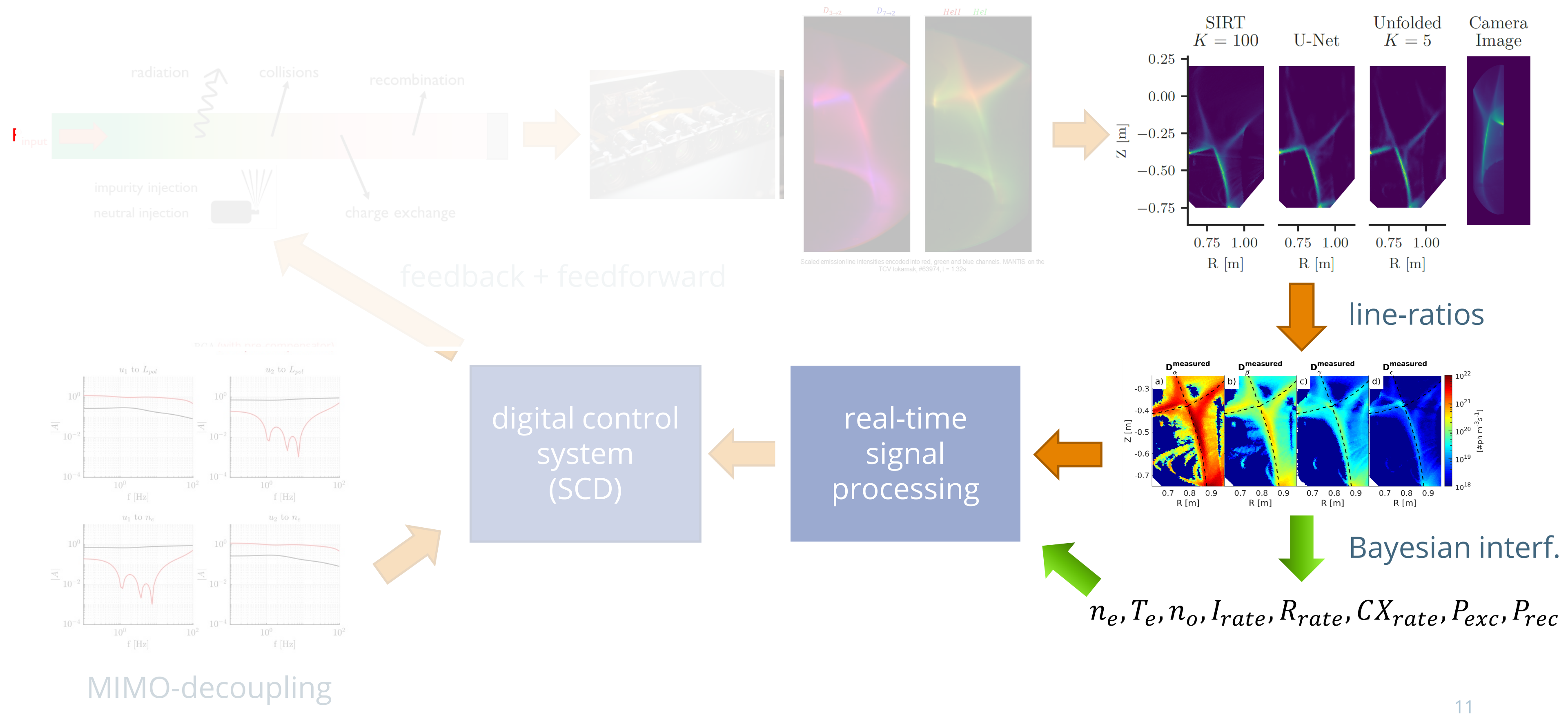
Real-time MANTIS development (WP 3)

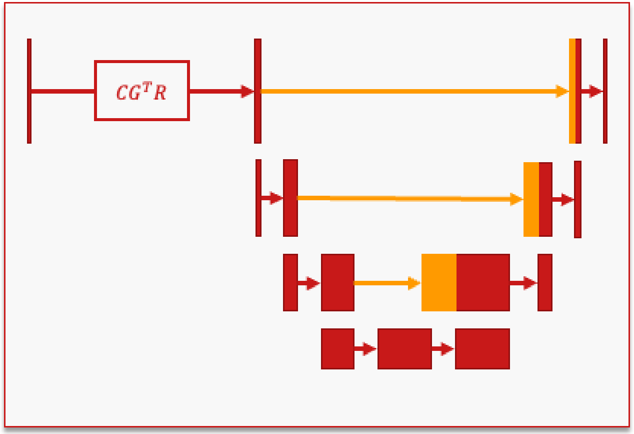
Project overview



Machine Learning Enhanced Tomographic Reconstruction for Multispectral Imaging on TCV, van Leeuwen et al.

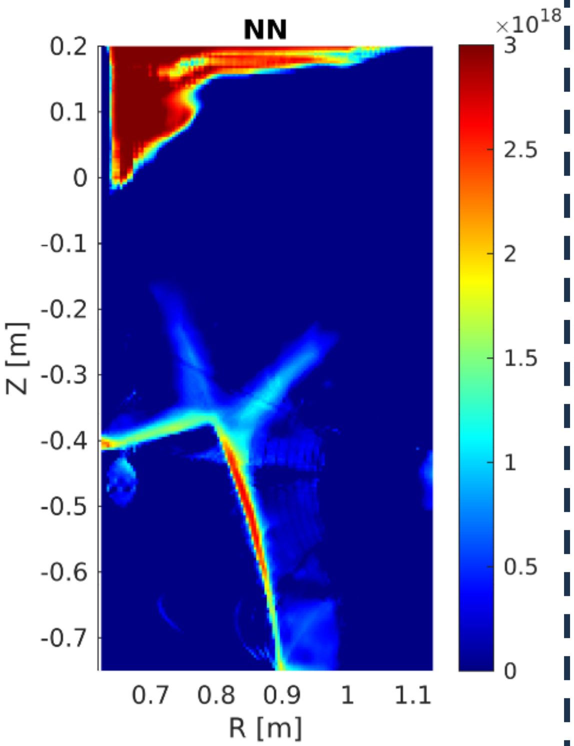
>1200Hz vs 5 Hz on a GPU

U - Net

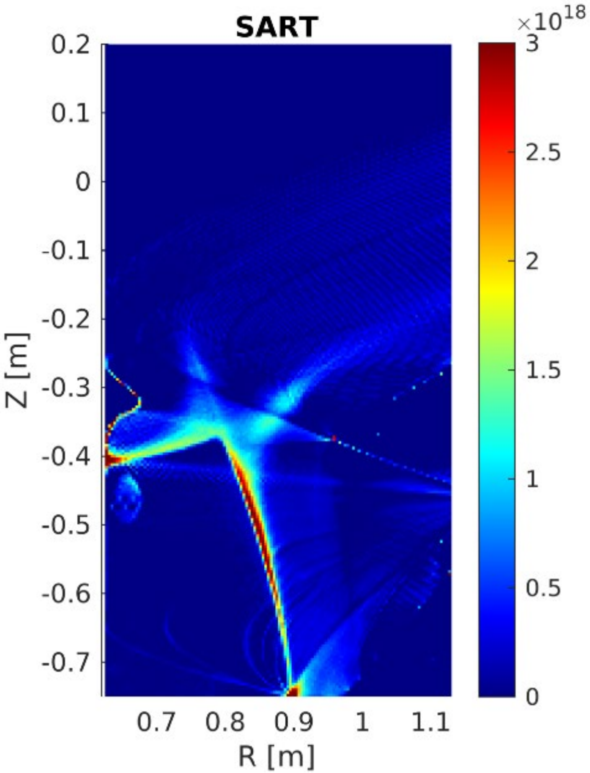


Uses convolutional layers to encode images to a latent space and decode them to a poloidal emissivity profile

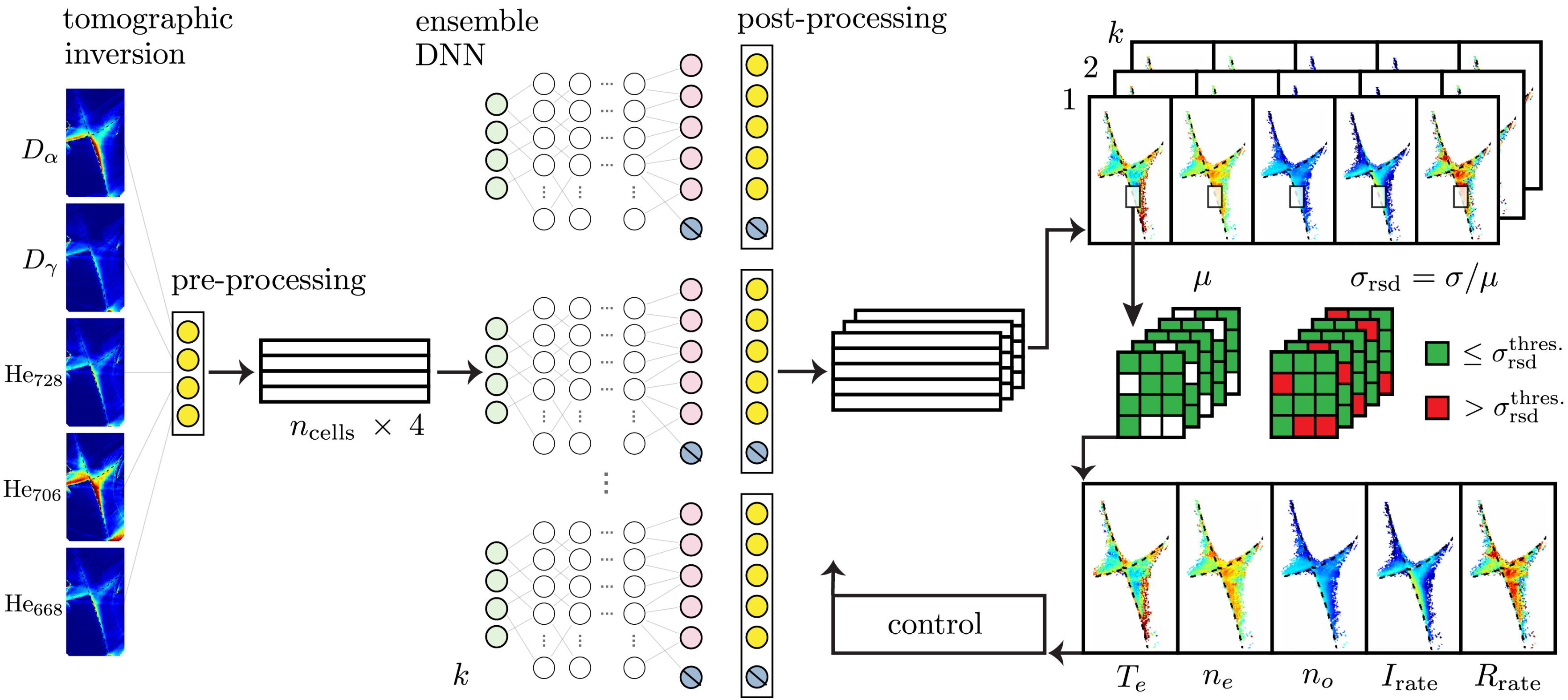
ML algorithm



Classic



ms inference of 2D edge plasma parameters for accelerated data analysis and rt power exhaust control, Caballero et al.



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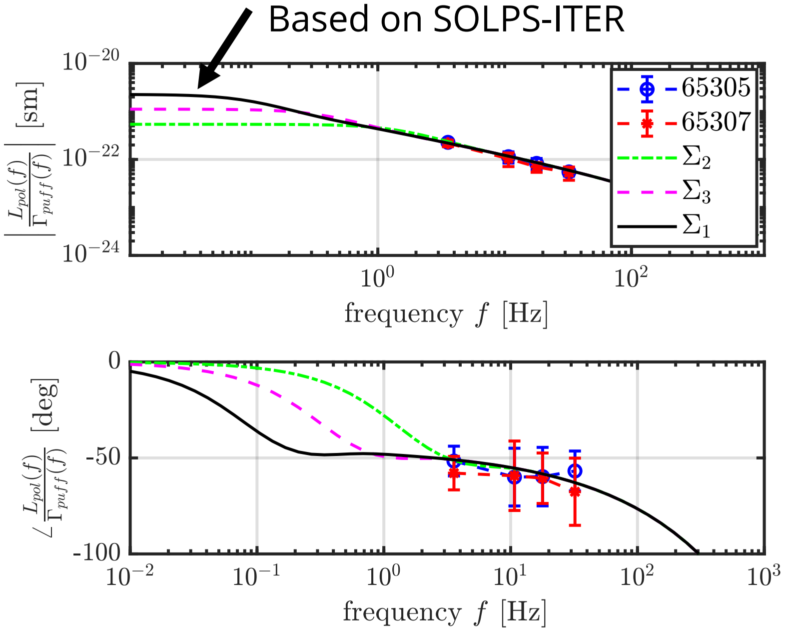
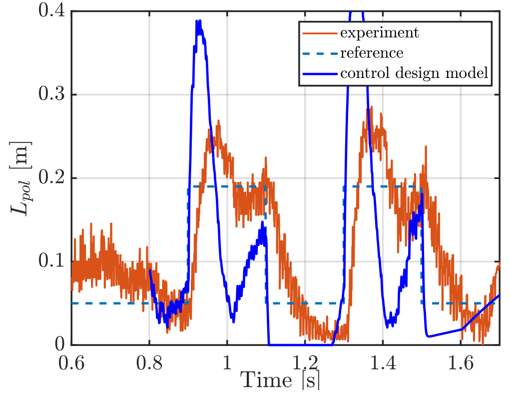
MIMO system identification & dynamic modelling (WP 4 & WP 5)

Systematic extraction of a control-oriented model from pert. experiments and SOLPS-ITER for front control in TCV, Koenders et al.

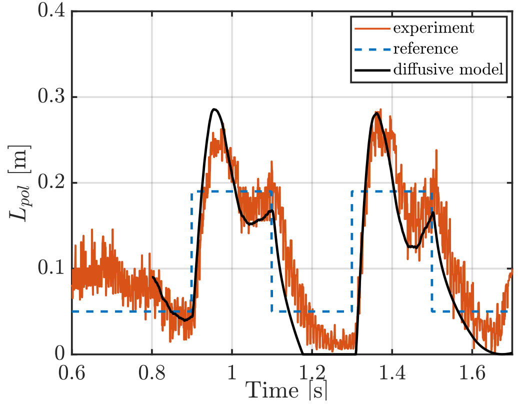


fractional (transport)

model used for controller



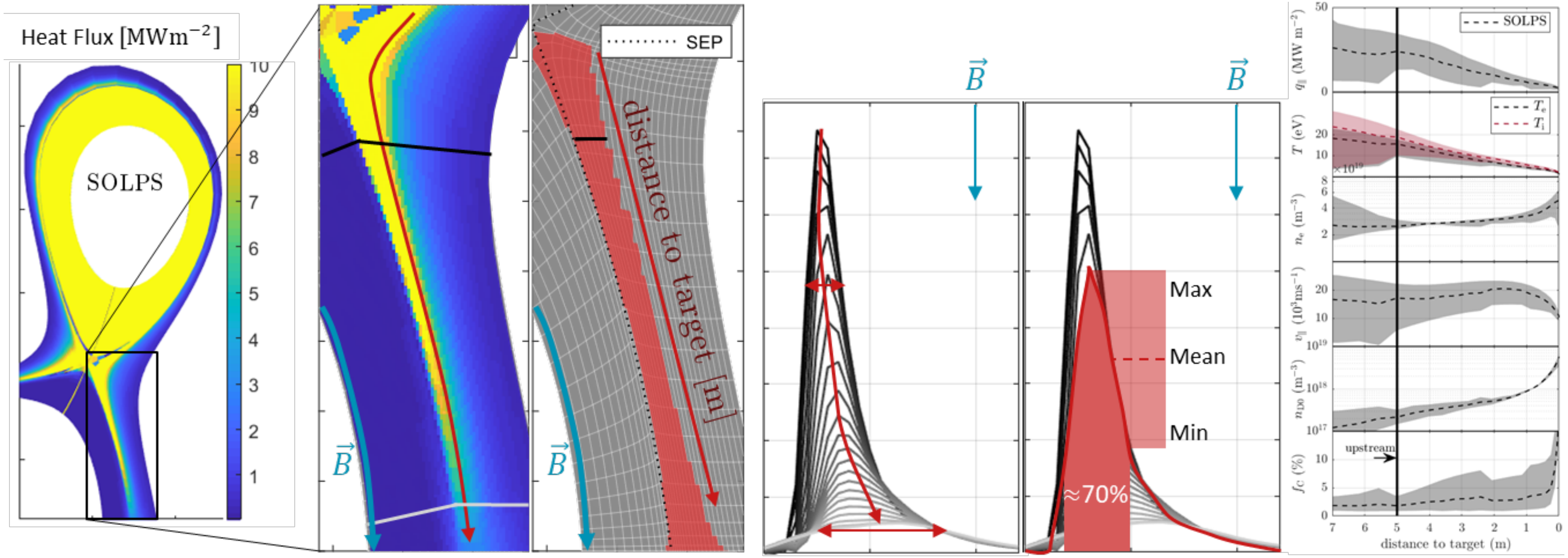
diffusive (transport) simulation model



Benchmark of a self-consistent dynamic 1D divertor model DIV1D using the 2D SOLPS-ITER code, Derks et al.

Mapping SOLPS-ITER to 1D and benchmark with DIV1D

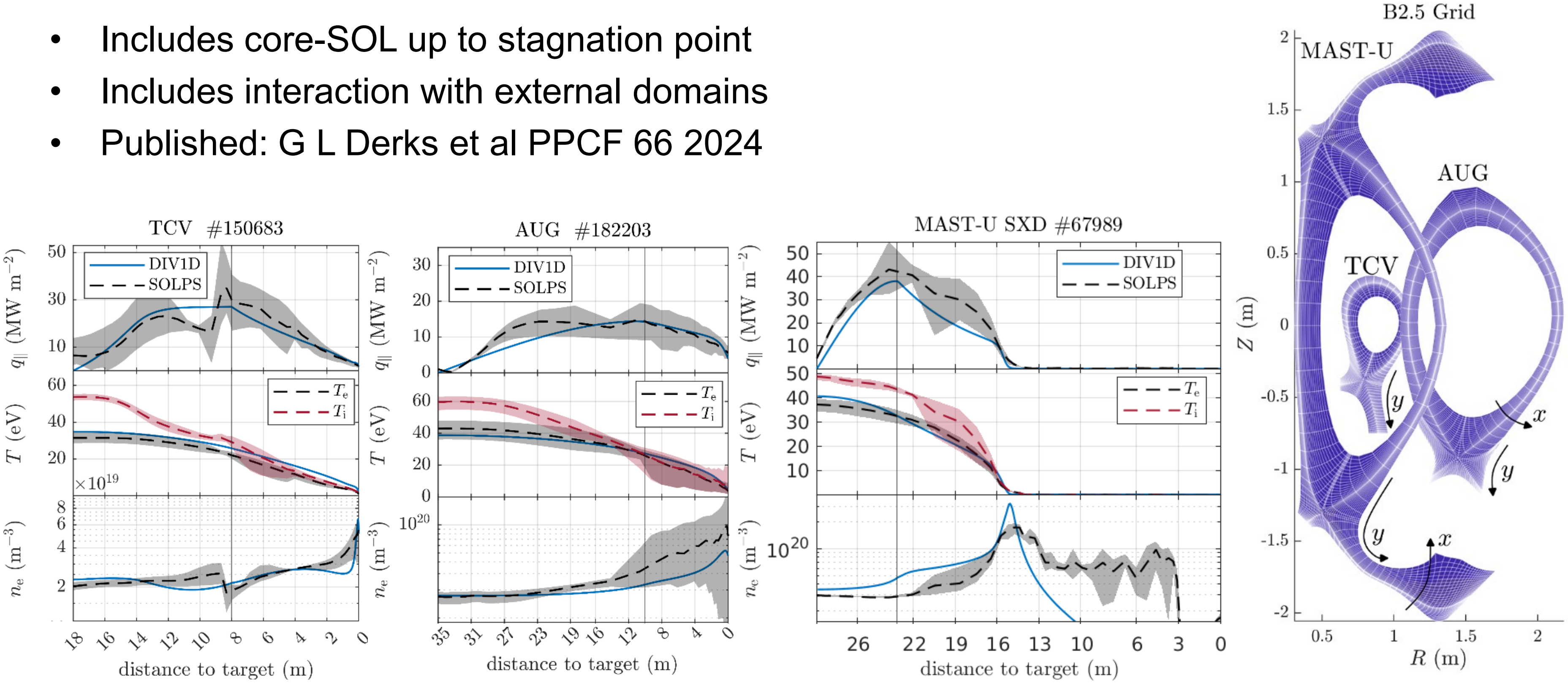
- Mapping accounts for cross-field transport and gives main heat flux channel
- DIV1D can be used to simulate SOL below X-point on TCV
- Published: G L Derks et al PPCF 64 2022



Multi-machine benchmark of the self-consistent 1D SOL model DIV1D from stagnation point to target with SOLPS-ITER, Derks et al.

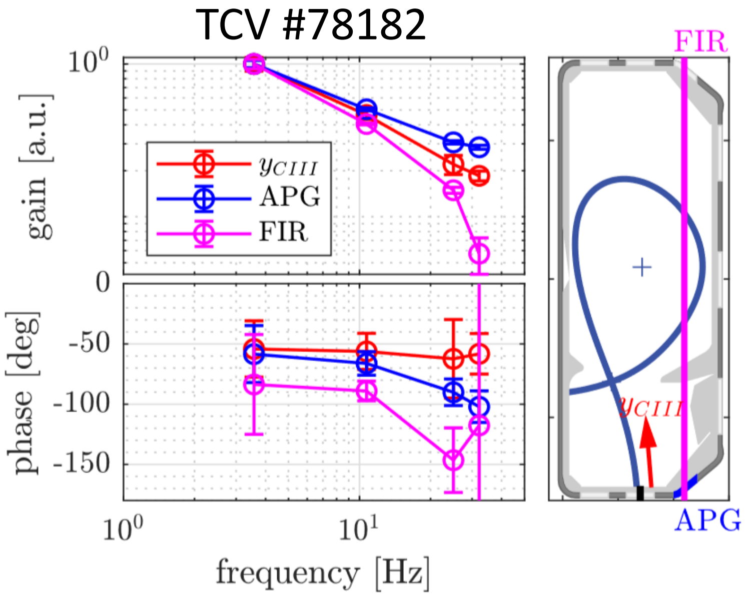
Benchmark with SOLPS-ITER for TCV, AUG and MAST-U

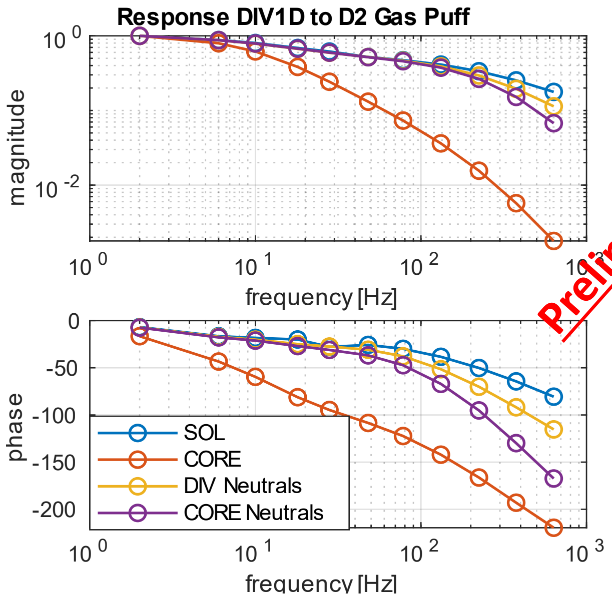
- Includes core-SOL up to stagnation point
- Includes interaction with external domains
- Published: G L Derks et al PPCF 66 2024

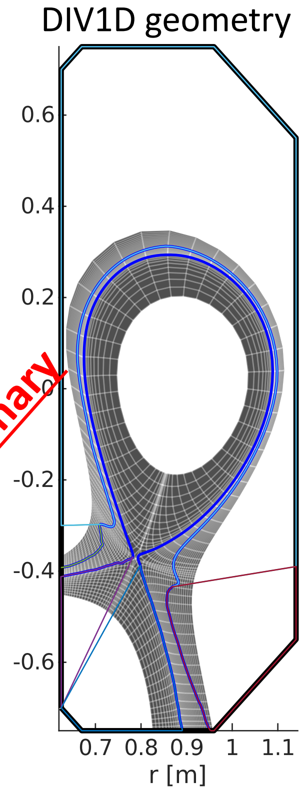


Towards validation with system-identification experiments

- Added dynamics of neutral and core reservoirs
- Simulate from inner to outer target
- Compare dynamics in response to molecule injection

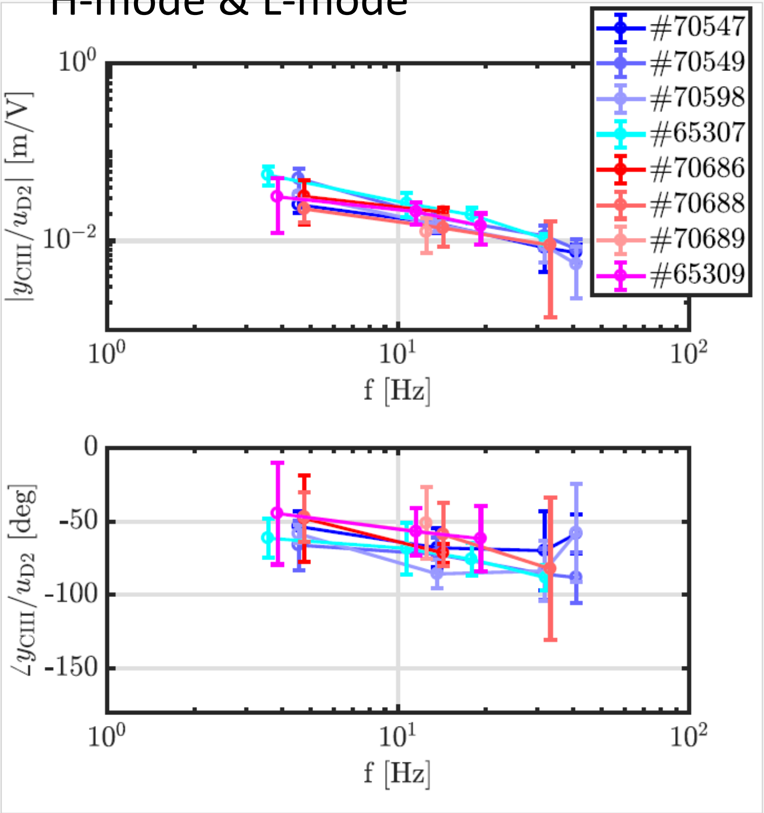




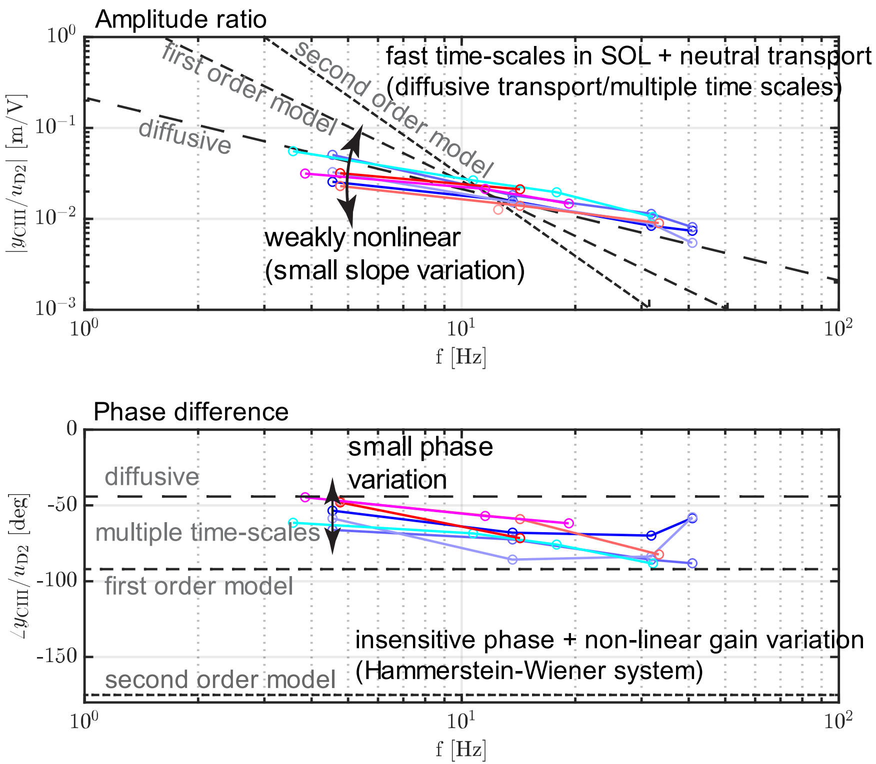


First systematic multi-machine analysis of the exhaust dynamics in tokamaks, van Berkel et al. (with WPTE & WPDES)

All TCV discharges in the WPTE and ENR H-mode & L-mode

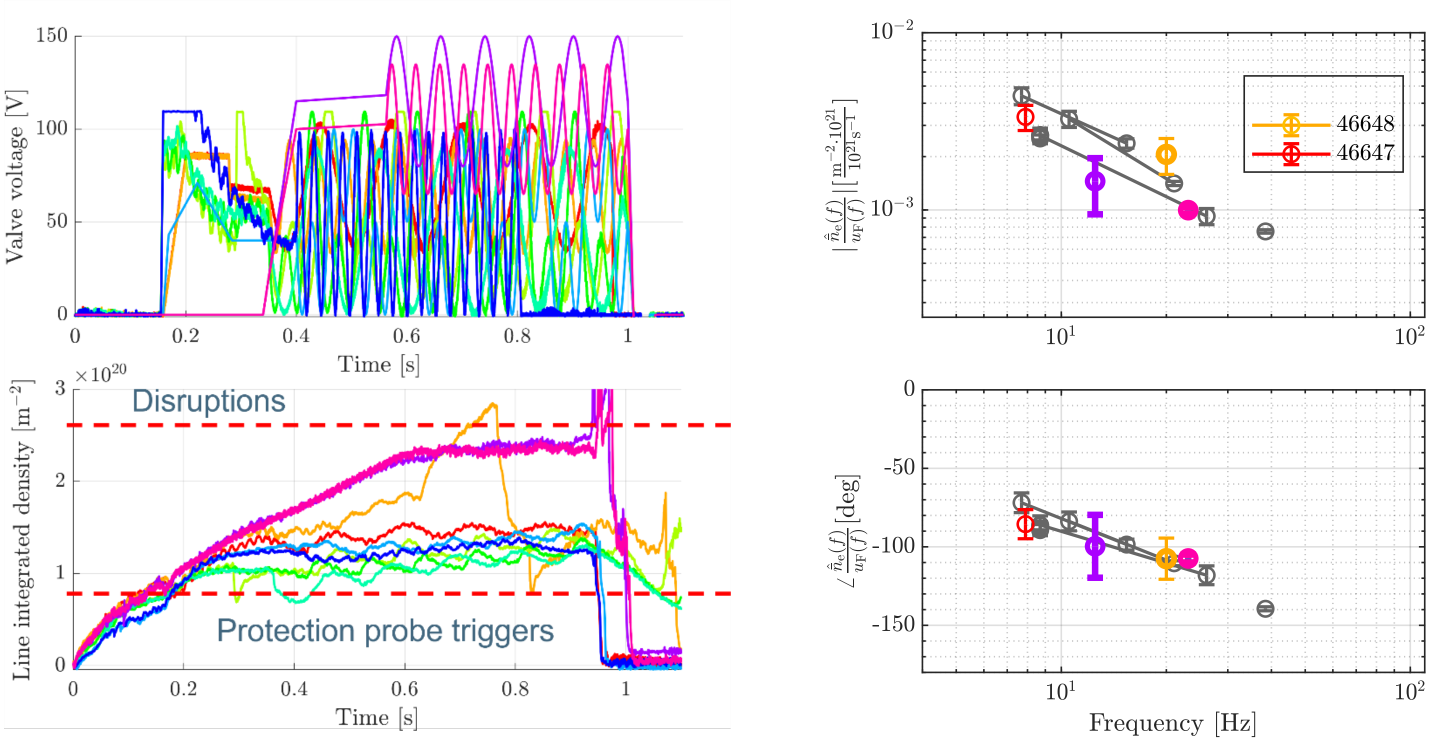


Multiple-machines show very similar behavior



Development of real-time density feedback control on MAST-U in L-mode, Derks et al. (by-catch exhaust experiments on MAST-U)

Measured dynamics linear and time-invariant over large variations of frequency and density in L-mode



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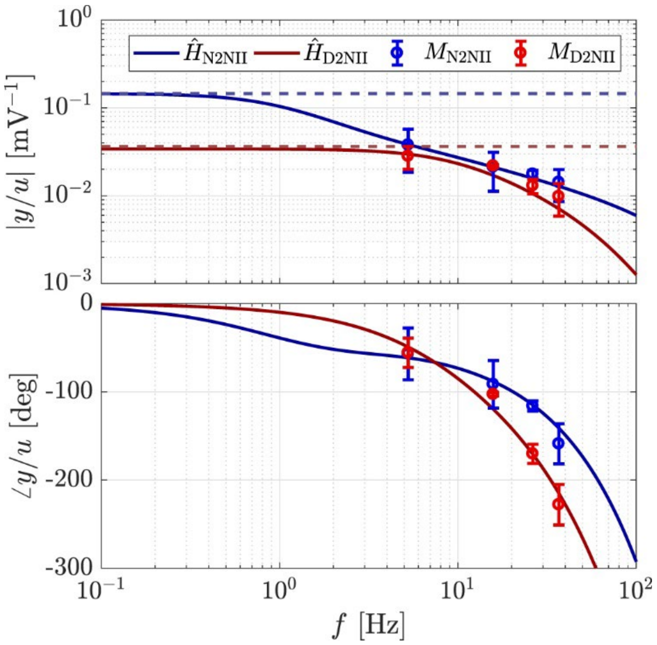
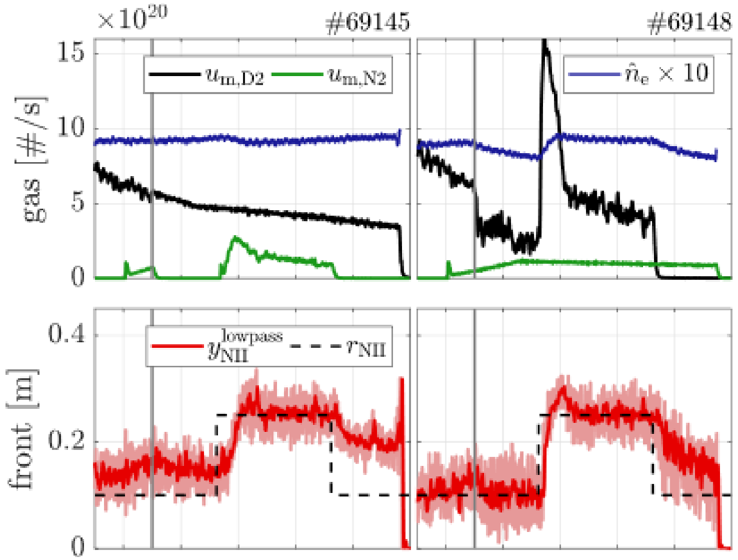
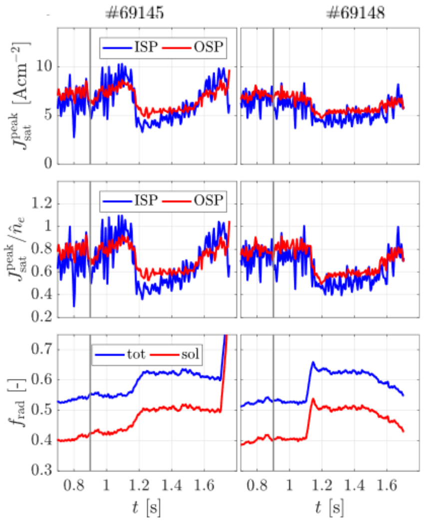
MIMO feed-back control (and integration) (WP 6)

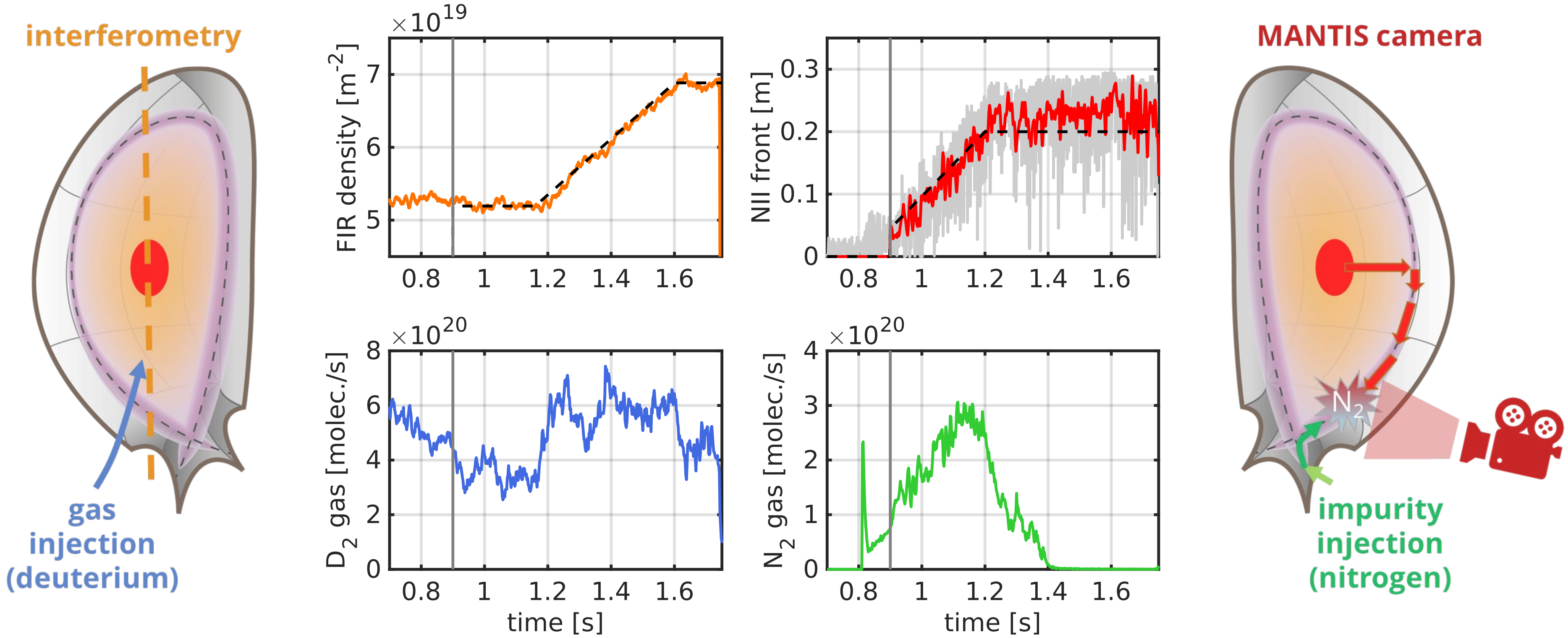
Model-based impurity emission front control using deuterium fueling and nitrogen seeding in TCV, Koenders et al.







Systematic design of a decoupled MIMO controller: a demonstration on TCV using multi-species gas injection, Koenders et al.



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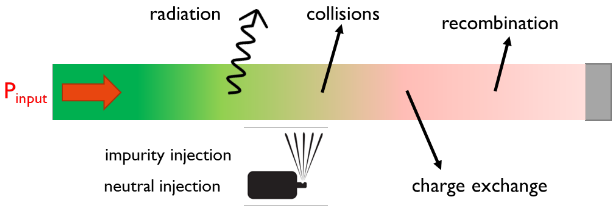
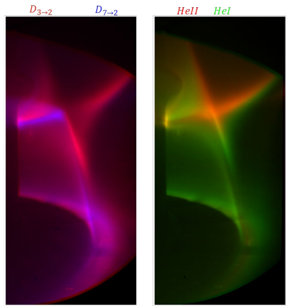
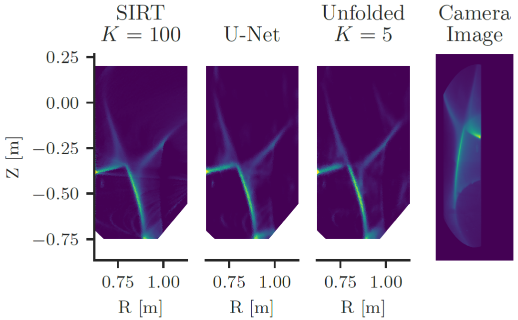
Full MIMO feed-back control (WP6) to be done

Project overview (and status)



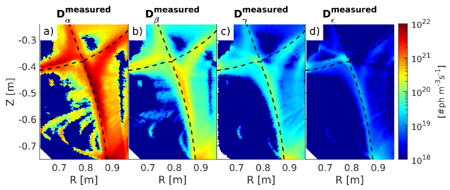


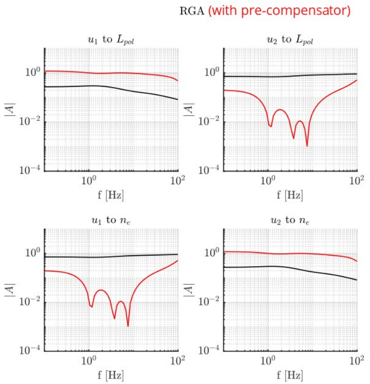
Scaled emission line intensities encoded into red, green and blue channels. MANTIS on the TCV tokamak; #63974, t = 1.32s



feedback + feedforward

line-ratios





digital control system (SCD)

real-time signal processing

Bayesian interf.

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

last step to be experimentally demonstrated

MIMO-decoupling

From full front control to MIMO-control

Image processing (extracting control parameters):

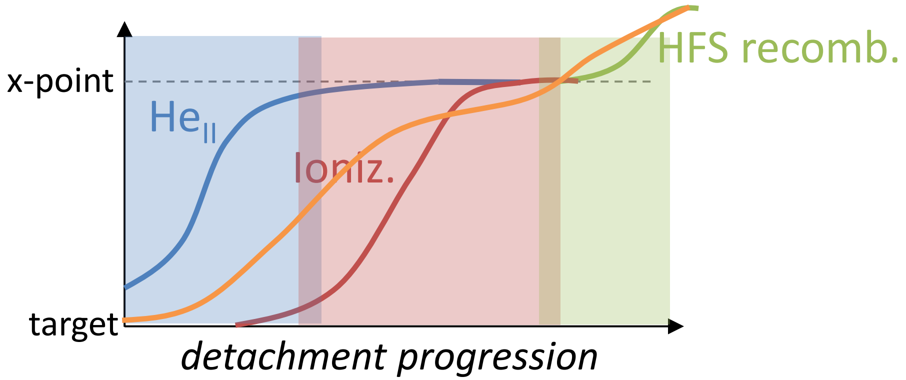
Control parameters

- HeII front
- Ionization front
- MARFE detection

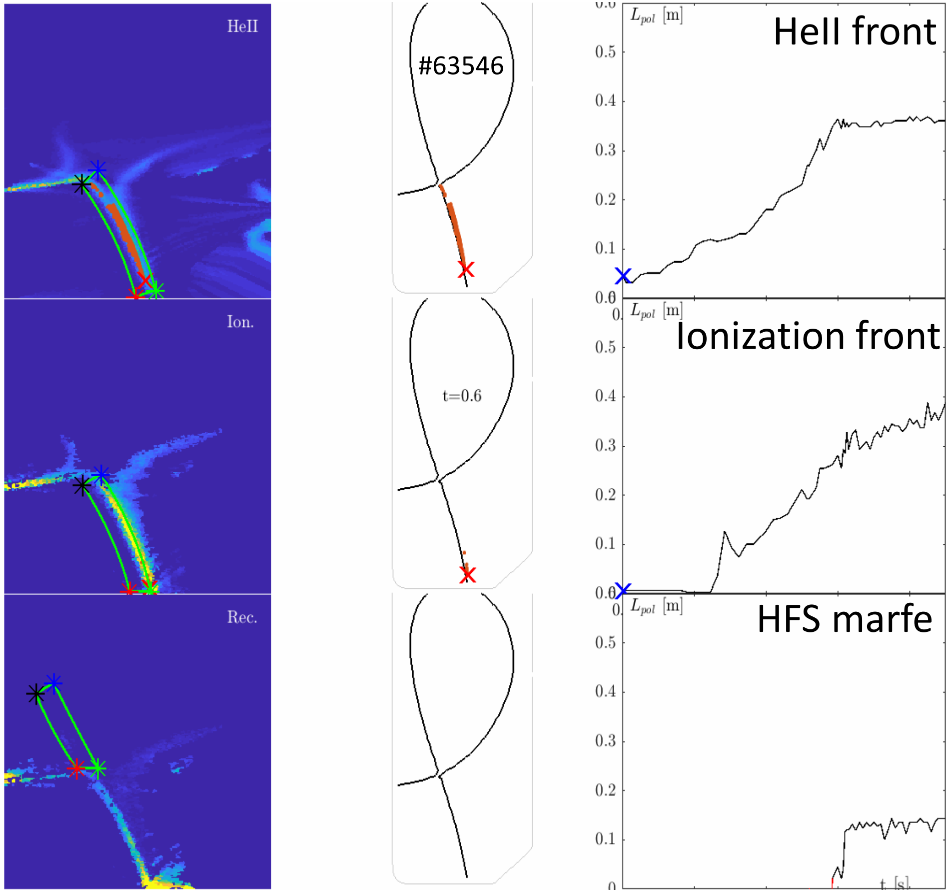
} C_{exh}

➢ not expected to be decoupled
➢ complement each other in the operating space.

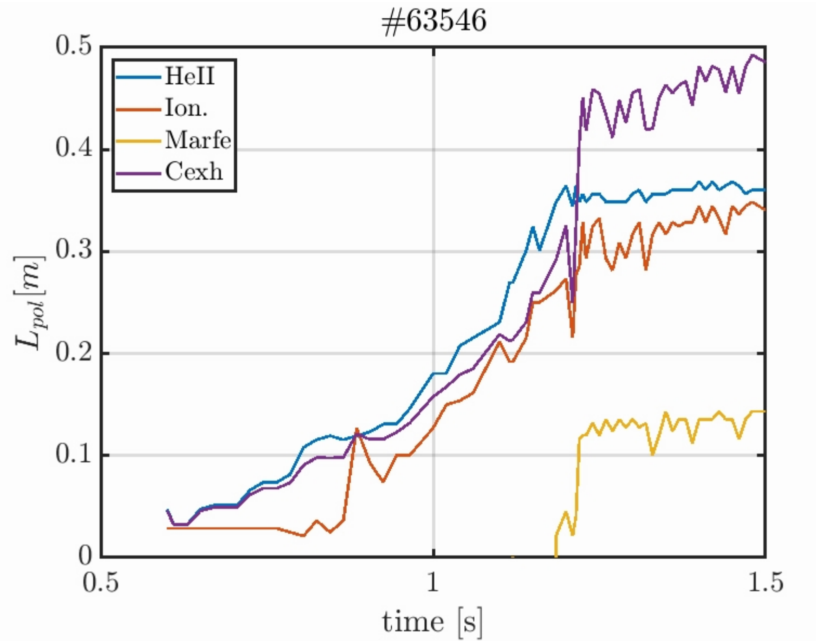
Density ramp cartoon



From full front control to MIMO-control



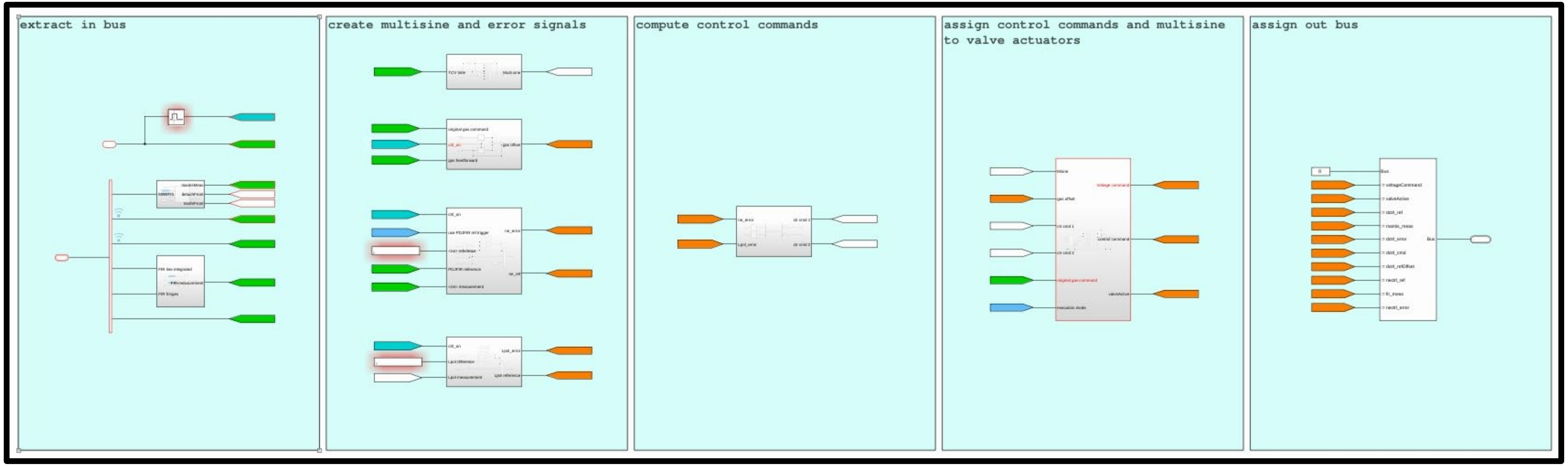
Weighted average trough logistic function +marfe



Full MIMO control: SCD general structure

Present functionality (*inter-shot changeable configuration*)

- Use any one of 10 possible control signals from MANTIS5
  - Take weighted average of multiple front measures (tunable)
  - Trigger on MARFE threshold, or add to control signal
- Use FIR line-integrated density measurement
- Multi-sine perturbations on valve 1, 2 and 3 (open- and closed-loop)
- MIMO (2x2) and SISO control



SCDalgo_detachment simulink model

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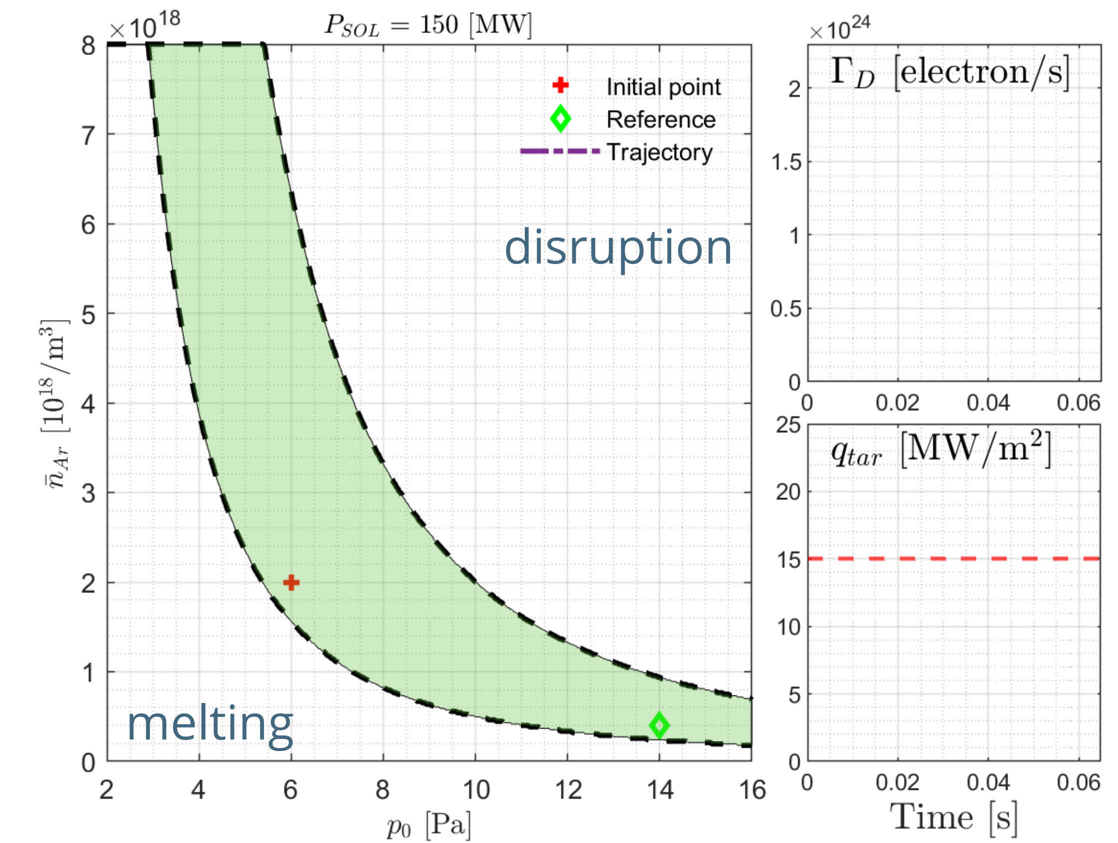
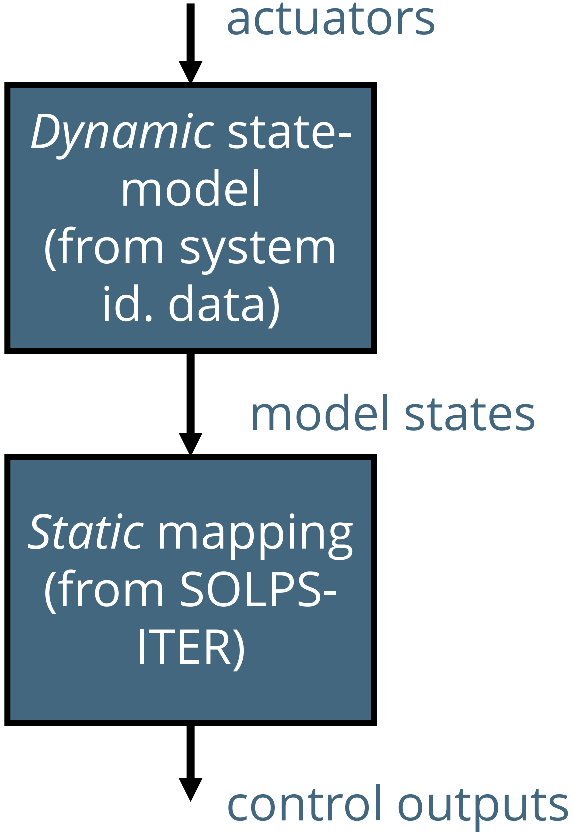
Impact on next steps (three examples)

ENR's impact on divertor modelling for model predictive control, DEMO example



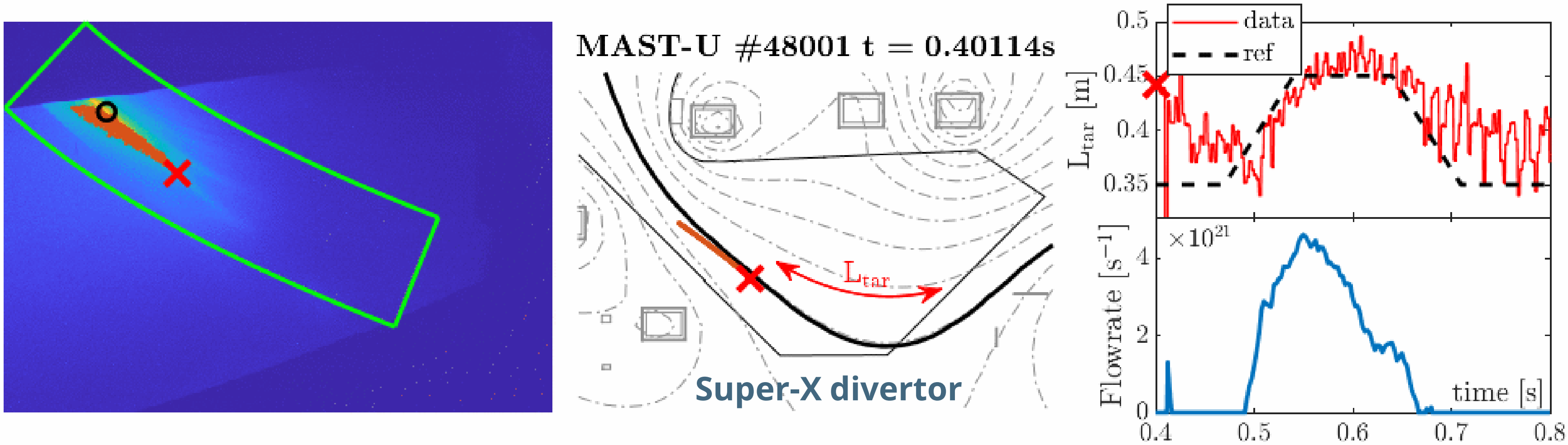


Successful feedback control of advanced divertor configurations in MAST-U

Next to successful control of exhaust in standard divertor configurations [1,2] on MAST-U recently also the control in the Elongated and Super-X configuration is demonstrated [3]!

Initial results show ADCs have desirable properties in terms of:

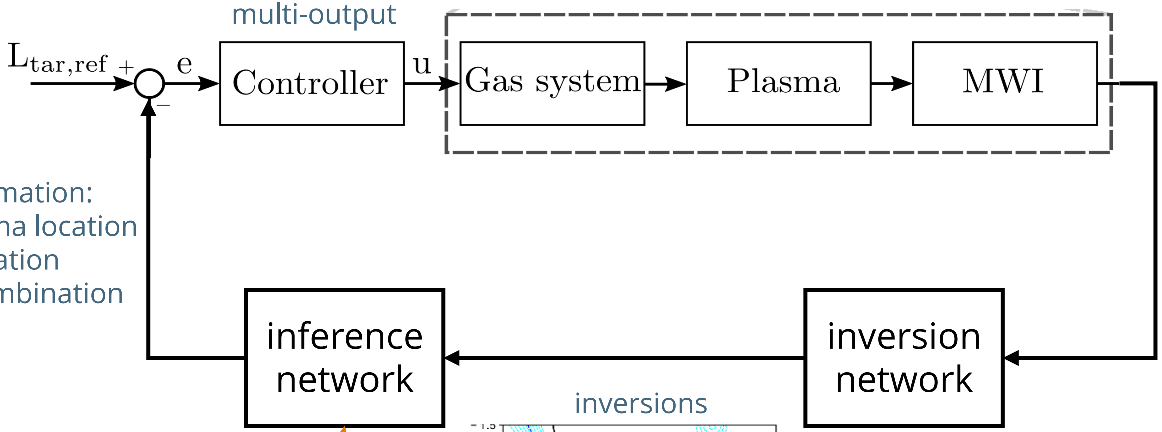
control sensitivity to actuators and absorption of transients



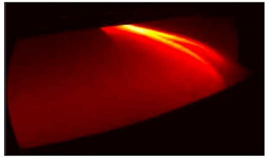
[1] T. Ravensbergen et al. Nat. Comm. 2020
[2] J.T.W. Koenders et al. Nucl. Fusion 2023
[3] B. Kool et al. submitted to Nat. Energy 2024

Next step (2025): implementation on MAST-U (support by UKAEA)

multi-input
multi-output



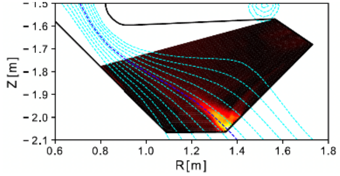
camera images



2D information:

- plasma location
- ionization
- recombination

inversions



physics

Summary

ENR results

- 9 journal publications published
- 4 journal publications in preparation/planned
- In simulation entire pipeline demonstrated
- Full experimental demonstration planned December 2024
- Significant *by-catch* results, e.g., MAST-U

ENR impact

- Huge steps made in dynamic quantification and understanding of the exhaust
- Modeling inspiration for next step: model-predictive control with full state-observer
- Porting to MAST-U in progress, e.g., MIMO control of n_e & upper & lower divertor
- Success of MANTIS system leads to roll-out at W7X, AUG, MAST-U (second system), MAGNUM-PSI