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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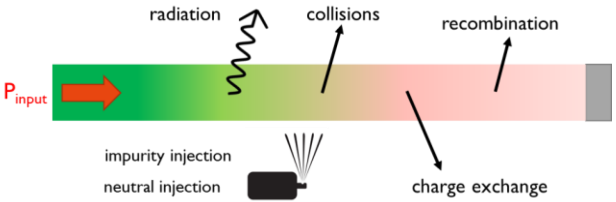
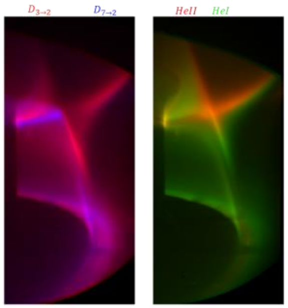
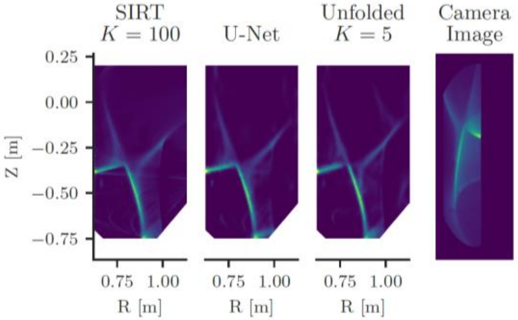
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Project overview (and status)

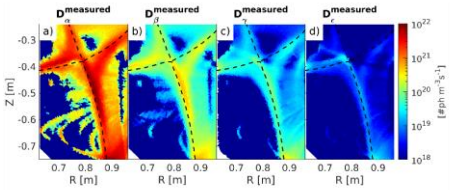




Scaled emission line intensities encoded into red, green and blue channels. MANTIS on the TCV tokamak, #63974, t = 1.32s



line-ratios



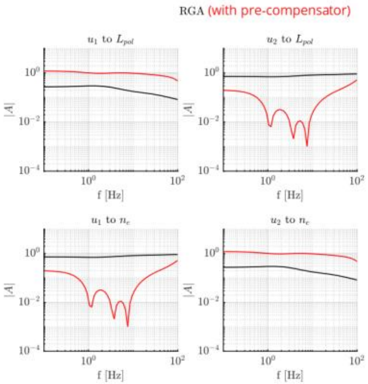
Bayesian interf.

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

real-time signal processing

digital control system (SCD)

feedback + feedforward



MIMO-decoupling

implementation finished
pipeline to be tested in the coming weeks

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Journal publications

First Author	Initials	Title of work	Journal / Conference	Pinboard ID
Koenders	J.T.W.	Systematic design of a decoupled multi-input multi-output controller: a demonstration on TCV using multi-species gas injection	Nuclear fusion	34993
Derks	G.L	Development of real-time density feedback control on MAST-U in L-mode	Fusion Engineering and design (2nd review)	36329
Derks	G.L	Multi-machine benchmark of the self-consistent 1D scrape-off layer model DIV1D from stagnation point to target with SOLPS-ITER	Plasma Physics and Controller Fusion (2nd review)	36331
Derks	G.L	Benchmark of a self-consistent dynamic 1D divertor model DIV1D using the 2D SOLPS-ITER code	Plasma Physics and Controller Fusion	32773
Koenders	J.T.W.	Systematic extraction of a control-oriented model from perturbative experiments and SOLPS-ITER for emission front control in TCV	Nuclear fusion	31120
Koenders	J.T.W.	Model-based impurity emission front control using deuterium fueling and nitrogen seeding in TCV	Nuclear fusion	32797
Perek	A.	Quantitative Balmer line analysis of multispectral imaging data to infer 2D maps of edge plasma parameters in TCV	Nuclear Fusion	29903

Hardware and software implementation for real-time analysis

Does the GPU Direct Memory Access work? ✓
- Yes, I tested it on Mantis2b PC.

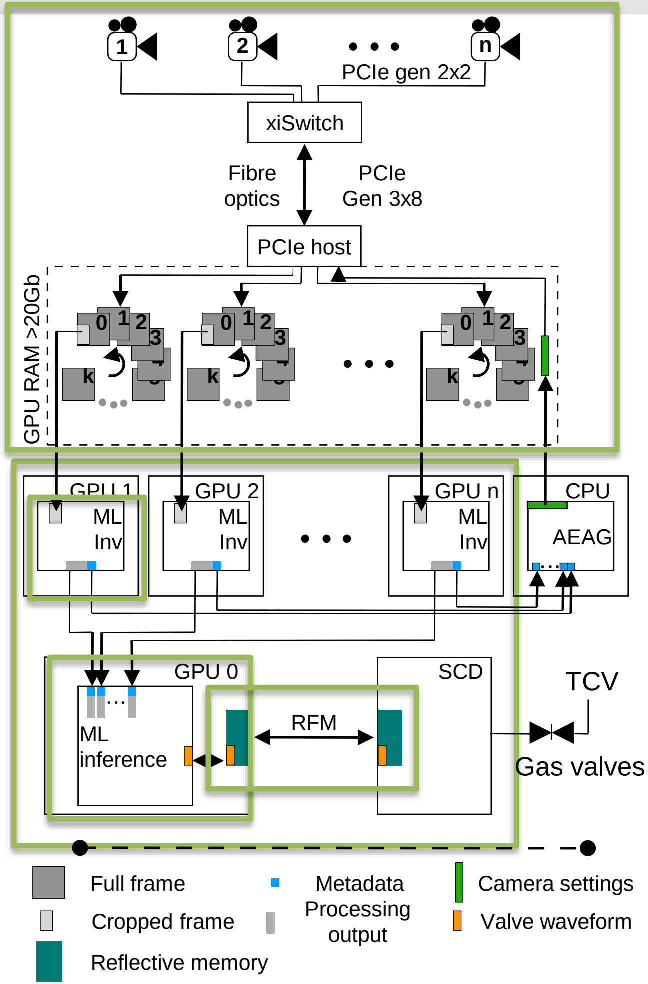
Can we perform the real-time tomographic inversion? ✓

Can we perform the real-time parameter inference? ✓

Can we setup parallel processing streams on the GPU using Multi-Instance GPU? ✓

Can we perform operations within a <1ms jitter to ensure real-time performance? ✓

There are no known obstacles to performing integration for real-time control.



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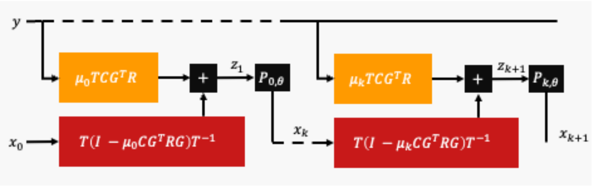
Further tests of data manipulation:
- Image copy between CPU RAM and GPU RAM (100-200us), calibration (30us), preprocessing (30us) etc. are practically negligible!

Previously reported tomographic inversion timings were faulty!
- Reported 2ms -> measured 40-60ms.
- Upon close inspection, the inverted data was up to 40% off when forward-modelled.
- A few more things came out upon close inspection…

There <u>were</u> no known obstacles to performing integration for real-time control.

Neural network: timing

Network Architecture: Unfolded



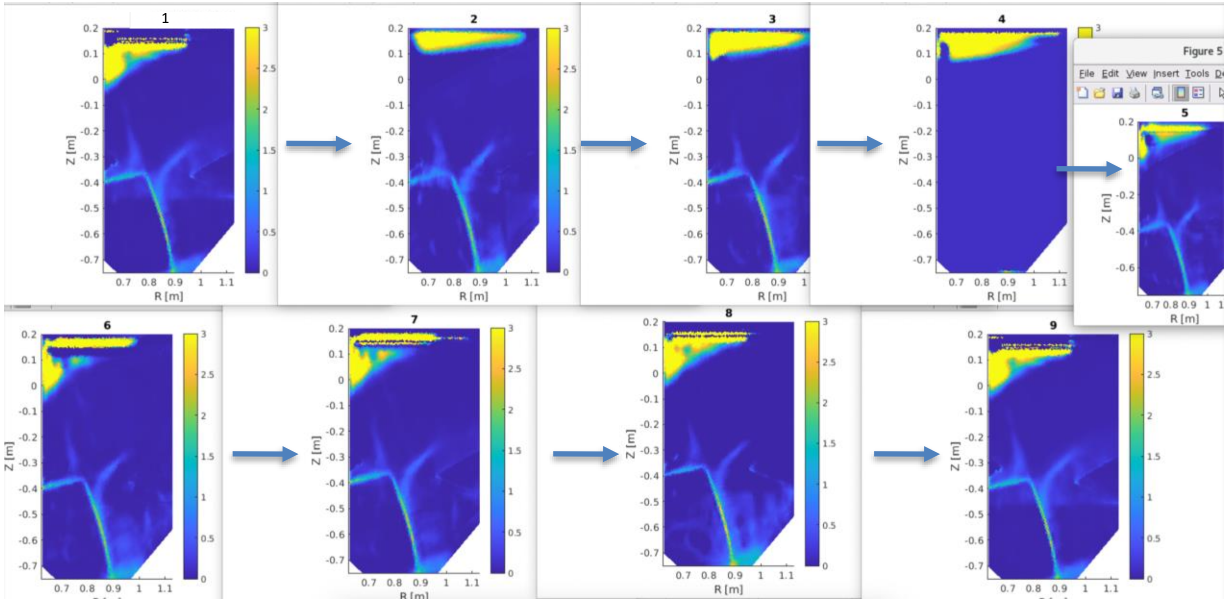
We used 3 (40ms to 60ms) or 5 unfolds.

How many do we need?
The target is 5ms!

↓

The results did not improve with multiple unfolds: use only one unfold (~23ms)

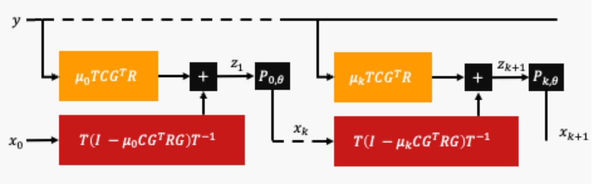
Output after each unfold of a 9-fold network:



Output of the first and last unfold were within 2%!

Solution: Neural network: timing for 1 frame

Network Architecture: Unfolded



One unfold (~23ms)

↓

Decrease the input by 2x binning and a region of interest from 1032x772px to 345x205px (~17ms)

↓

Decrease the output to 128x128 instead of 256x256 (~6ms)

↓

Compile with tensorRT:

- Full precision (5ms)
- Half precision (4.3ms)

Current network architecture:

	Name	Type	# Parameters	Output Shape
	input_1	InputLayer	0	,345,205,1
	flatten	Flatten	0	None, 70725
	batch_sparse_dense_matmul_2	BatchSparseDenseMatmul	0	None, 32768
	tf.zeros_like	TFOpLambda	0	None, 32768
	square_sirt_block__square	SquareSirtBlock_Square	1	None, 32768
	sequential	Sequential	278241	None, 256, 128, 1
	instance_normalization_16	InstanceNormalization	2	None, 256, 128, 1
	flatten_1	Flatten	0	None, 32768
	reshape_1	Reshape	0	None, 256, 128, 1
	inversion	Conv2D	10	None, 256, 128, 1

Replace the triangular grid with a square one: Full precision (3ms); half precision (2.6ms) with 256x128 output

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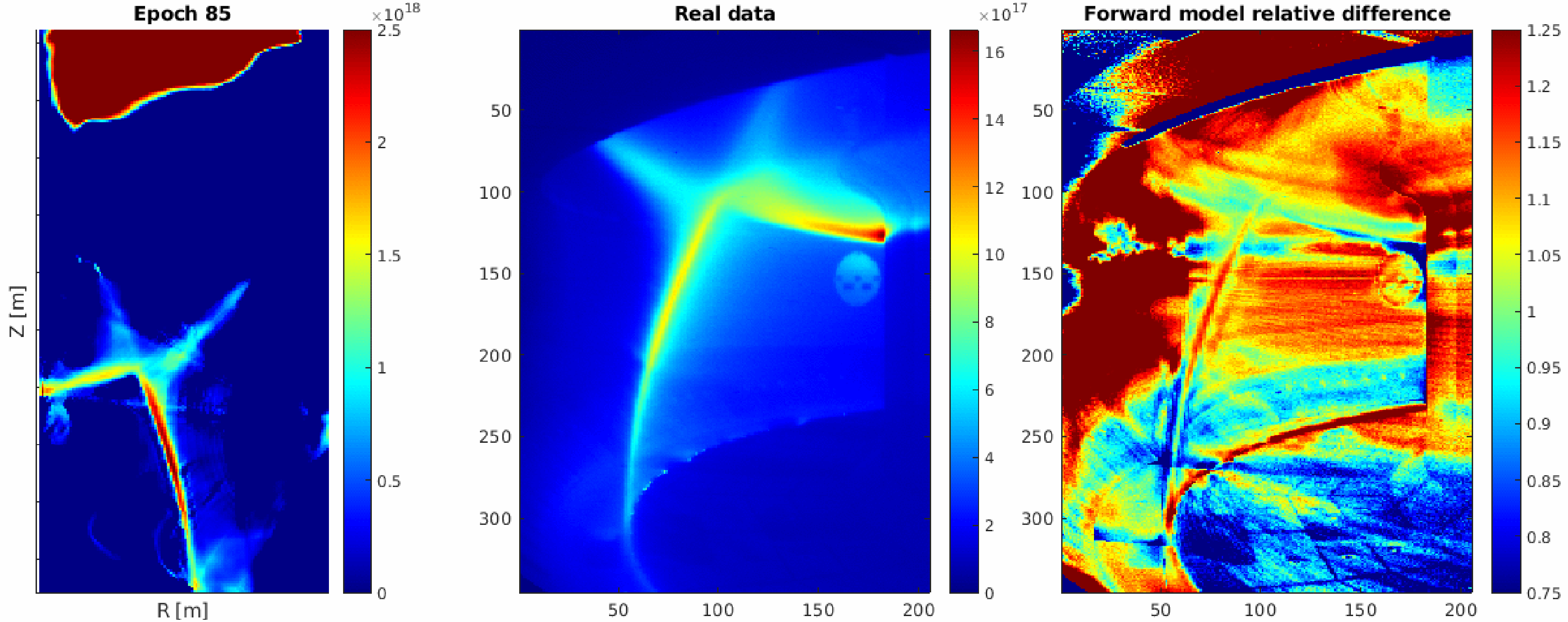
Neural network: Training

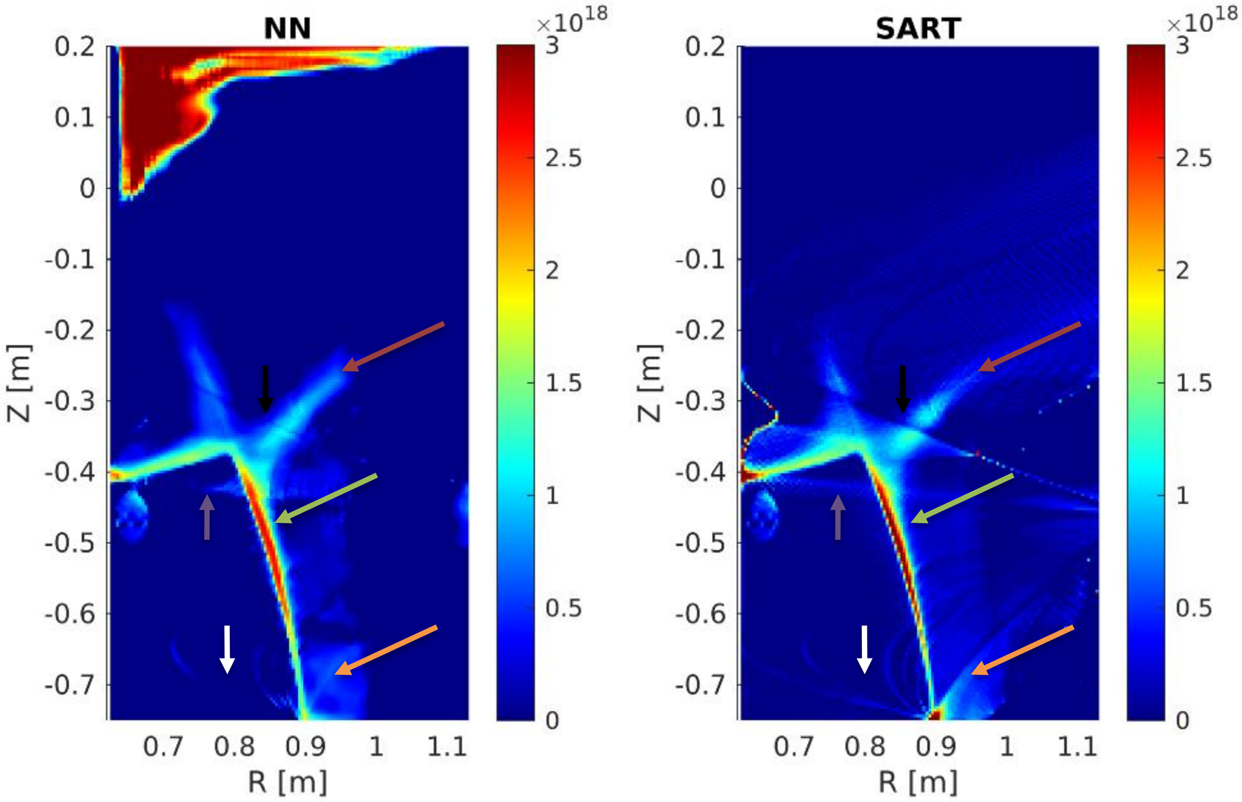
Predicted poloidal plane ← Image

Inversion loss ↕ → ↕ Forward modelling loss

Poloidal plane — Predicted Image



Neural network: Comparison to SART



Differences:

- Gradients
- Reconstruction limits
- Artefacts
- >1200Hz vs 5 Hz on a GPU

Next questions:

- Can it be taught that the data can be translated?
- What needs to be changed/added for the gradients to be recovered?

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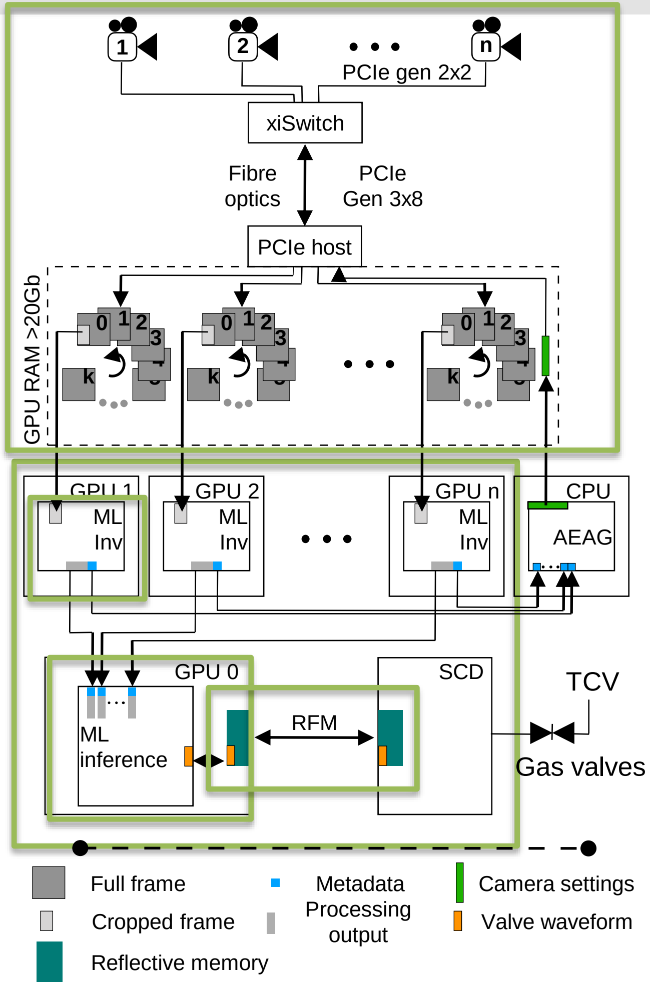

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Exhaust control schematic

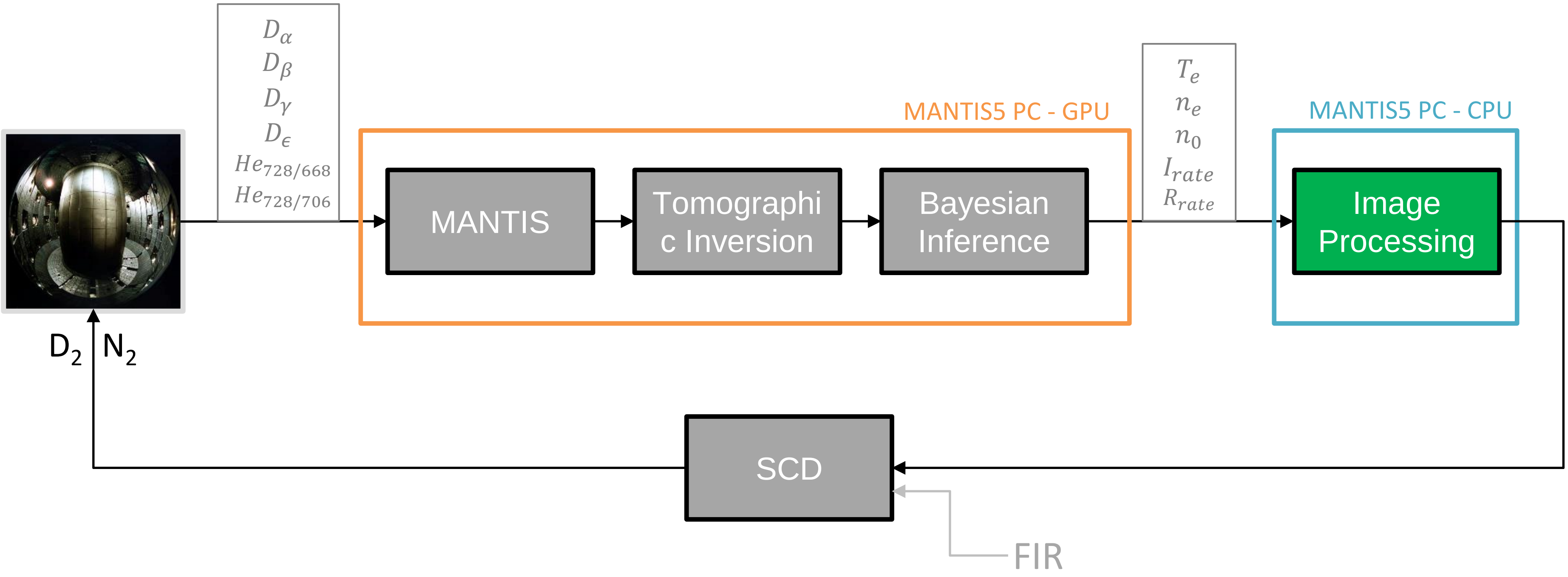
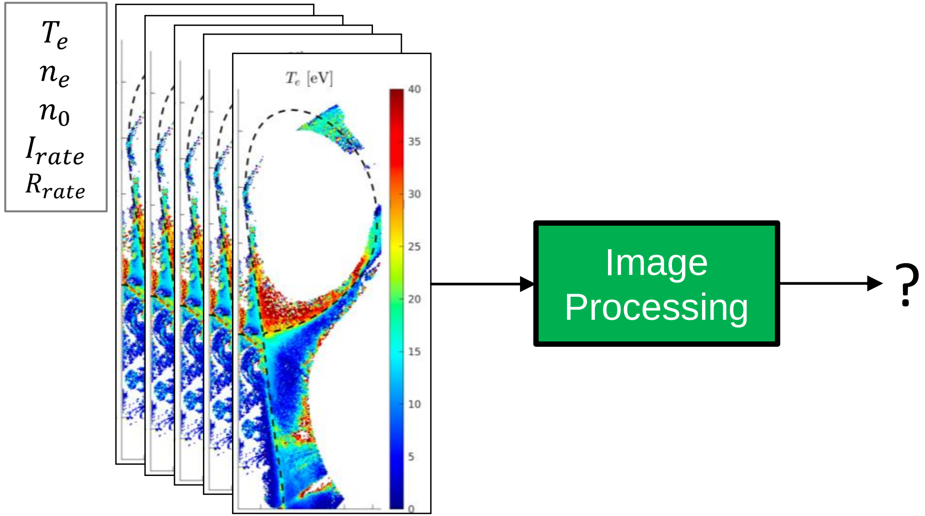


Image processing (extracting control parameters)



For now, focus on

- Emission front (e.g. HeII)
- Total ionization rate
- Ionization front
- Total recombination rate
- Recombination front
- MARFE detection
- 2-point temperature gradient
- 2-point density gradient
- 2-point model; f_{mom} f_{cool}
- ……

Image processing (extracting control parameters)

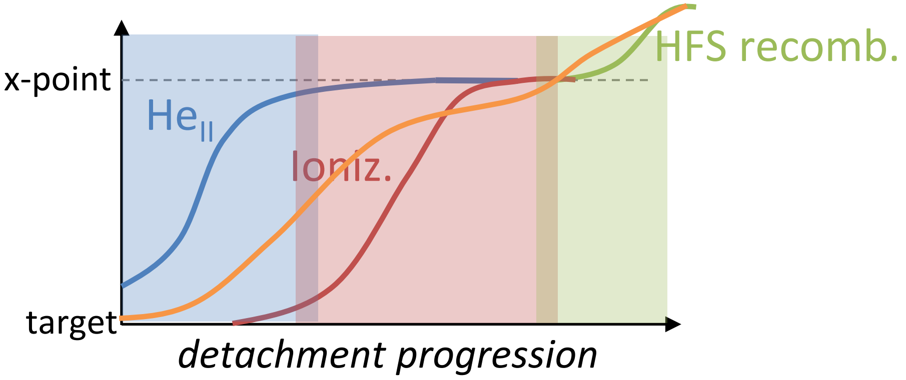
Control parameters

- HeII front
- Ionization front
- MARFE detection

} C_{exh}

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

Density ramp cartoon



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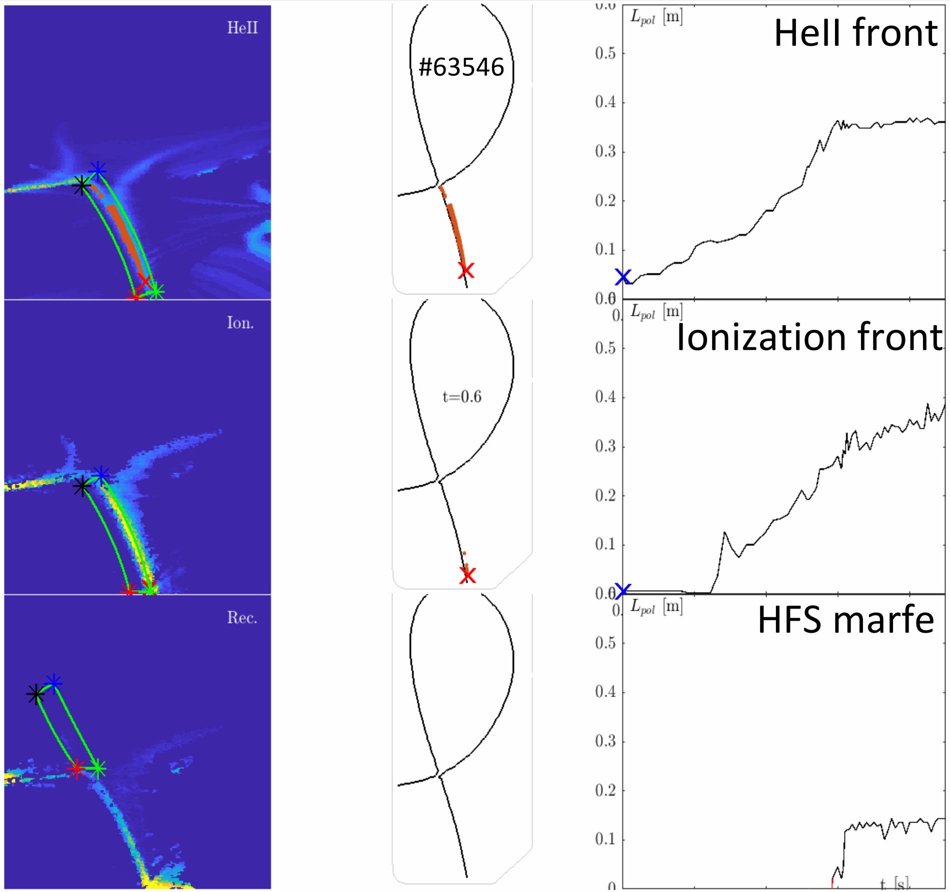
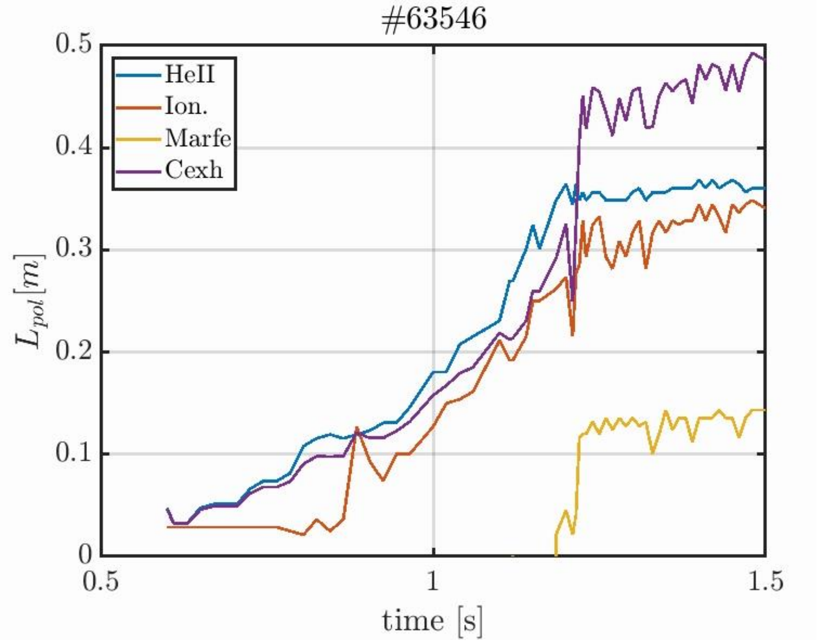
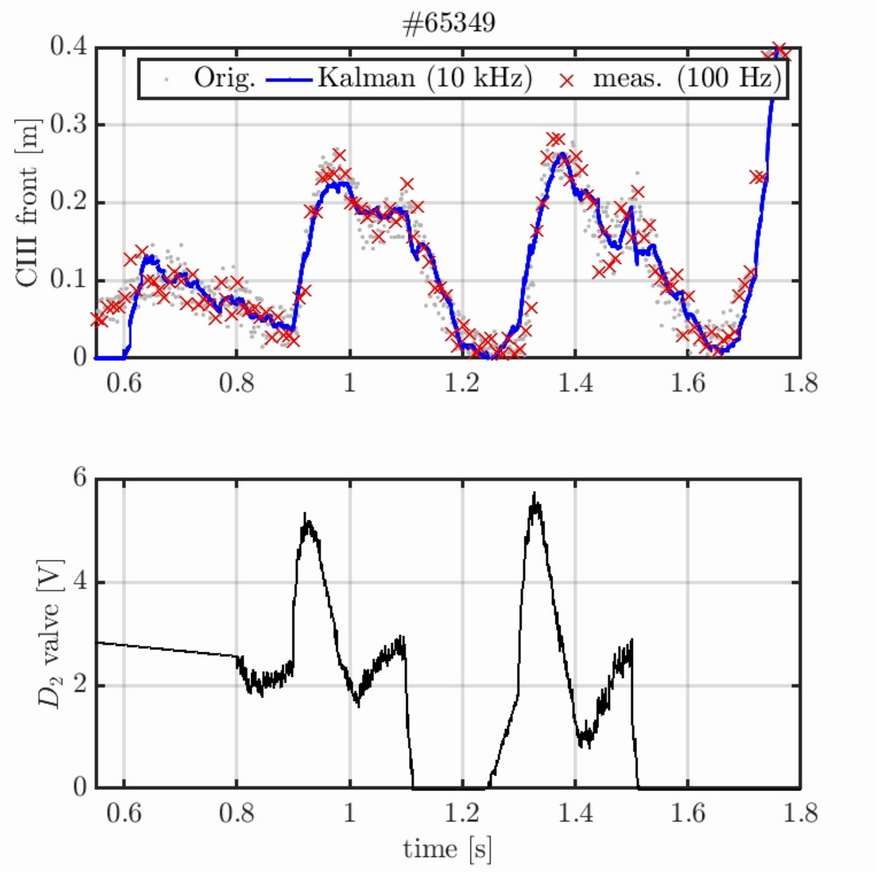


Weighted average trough logistic function +marfe



SCD: model-based 'upsampling'

- Example: controlled discharge of CIII front position with D2 gas
- Prediction allows controller to 'see' result of its actions before waiting for the next measurements
- Prevents strong overshoot due to integral wind-up in low-sampling rate or high-delay cases



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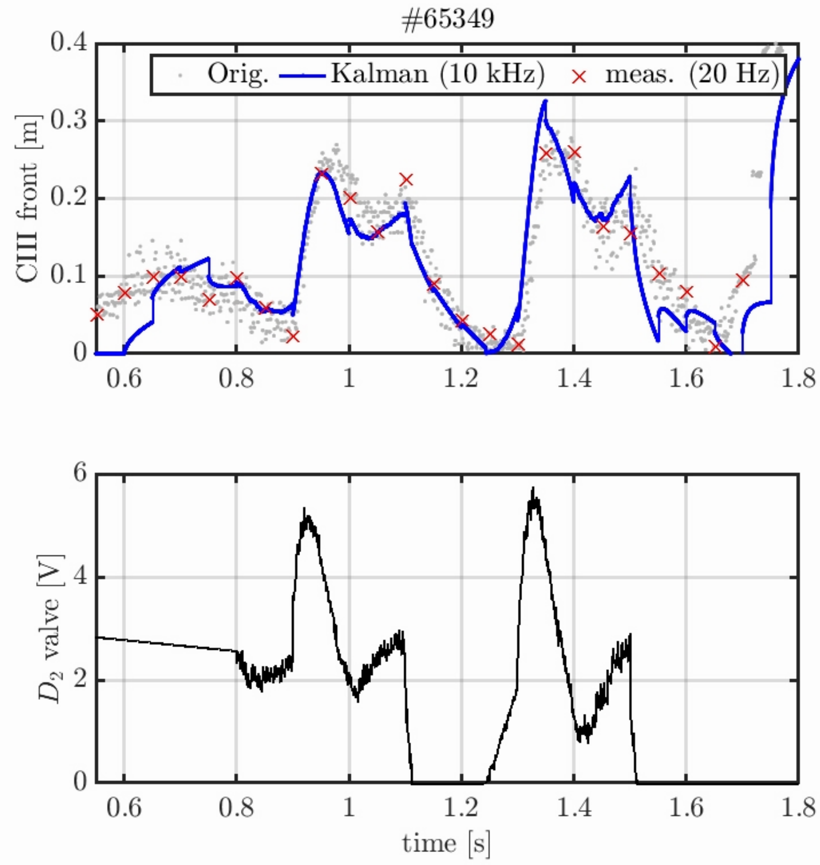

Focus experimental demonstration last half year

1. Establish/choose an L-mode PEX shape density ramp scenario
   - Check control variables through detachment progression

2. Deploy system-identification measurements around expected control bandwidth of 5-7 Hz.

3. Design and test Ionization front controller with ML in the loop
   - Deploy Kalman filter if needed

4. Design and test combined HeII, Ionisation, MARFE controller
   - Deploy Kalman filter if needed

5. Demonstrate multivariable control, including FIR measurement