Discussion on re-attachment times

Update on control-oriented modelling

Eurofusion

11-03-2025

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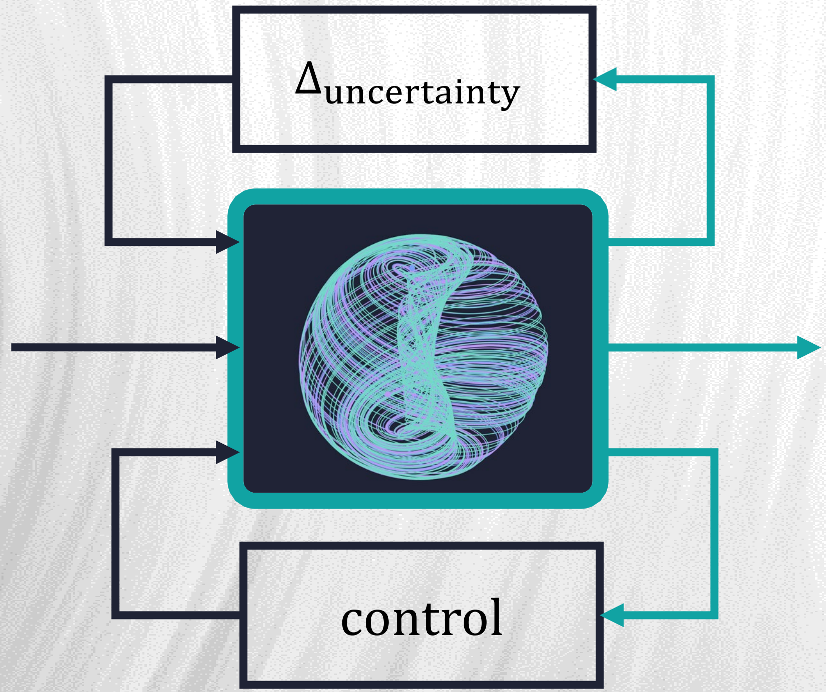
DIFFER

NWO

ENERGY SYSTEMS & CONTROL



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Summary of this presentation

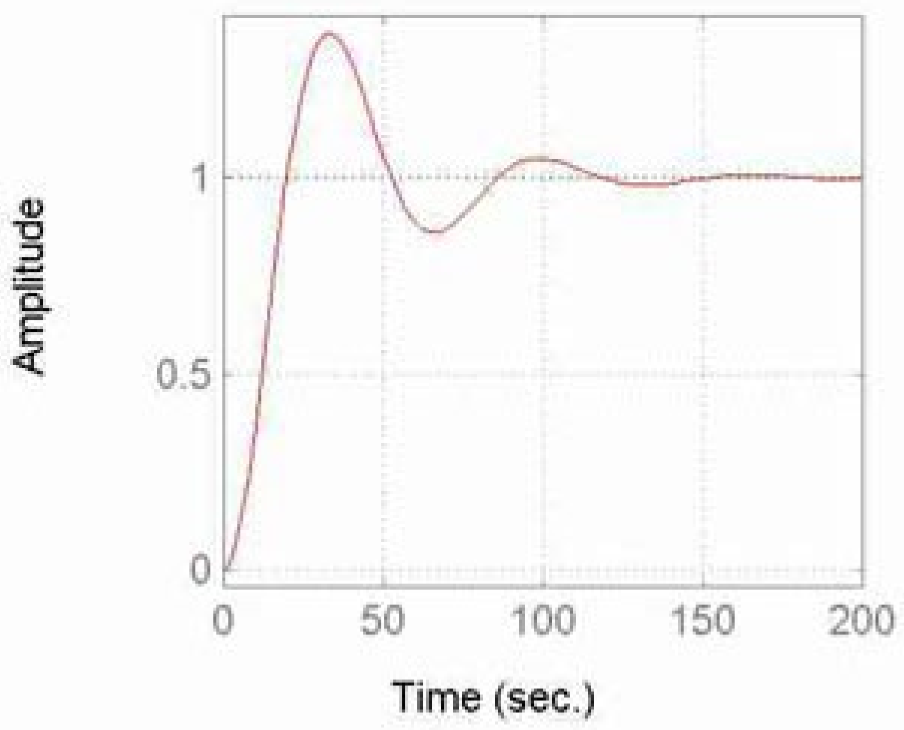
- Why time dependent excitations/perturbations are the same as frequency domain
  - Why multi-sines are generally better than step-responses!
- Proper re-attachment (times) analysis based on control oriented “digital twin”
- Necessity of proper impurity observer
  - Overseeding is consistently wasting significant amount of discharges
- Challenges for validation and working on the next steps?

System identification
time (step) vs. frequency (bode)

https://web.mit.edu/2.010/www_f00/psets/hw2_dir/tutor2_dir/tut2_c.html

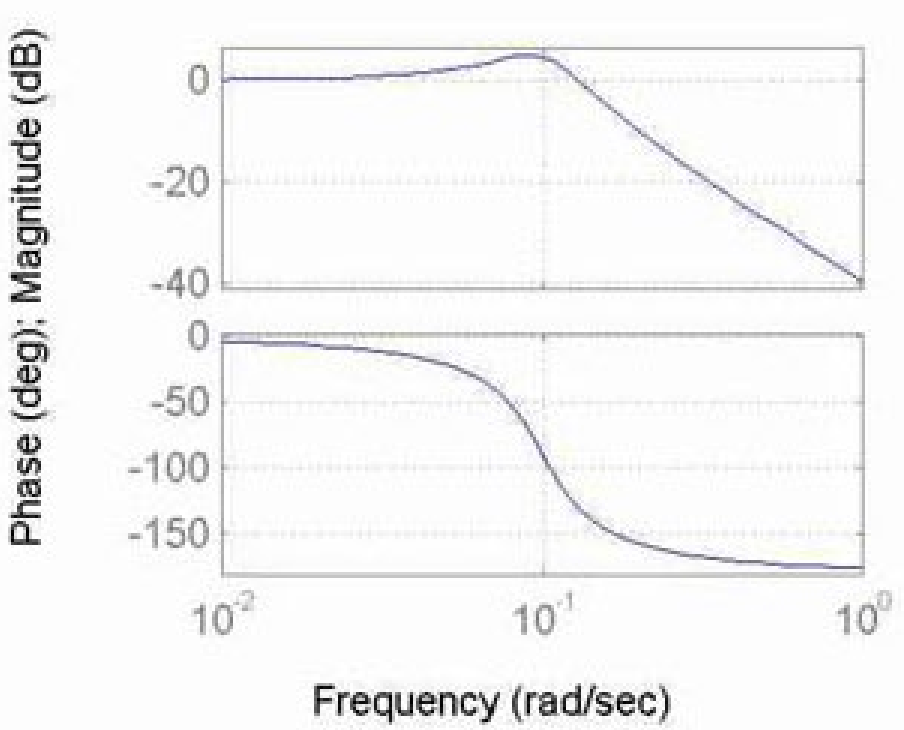
Step responses and multi-sines identify the same (but differently)

Transient Response is the same thing as "step response"



$\stackrel{def}{=}$

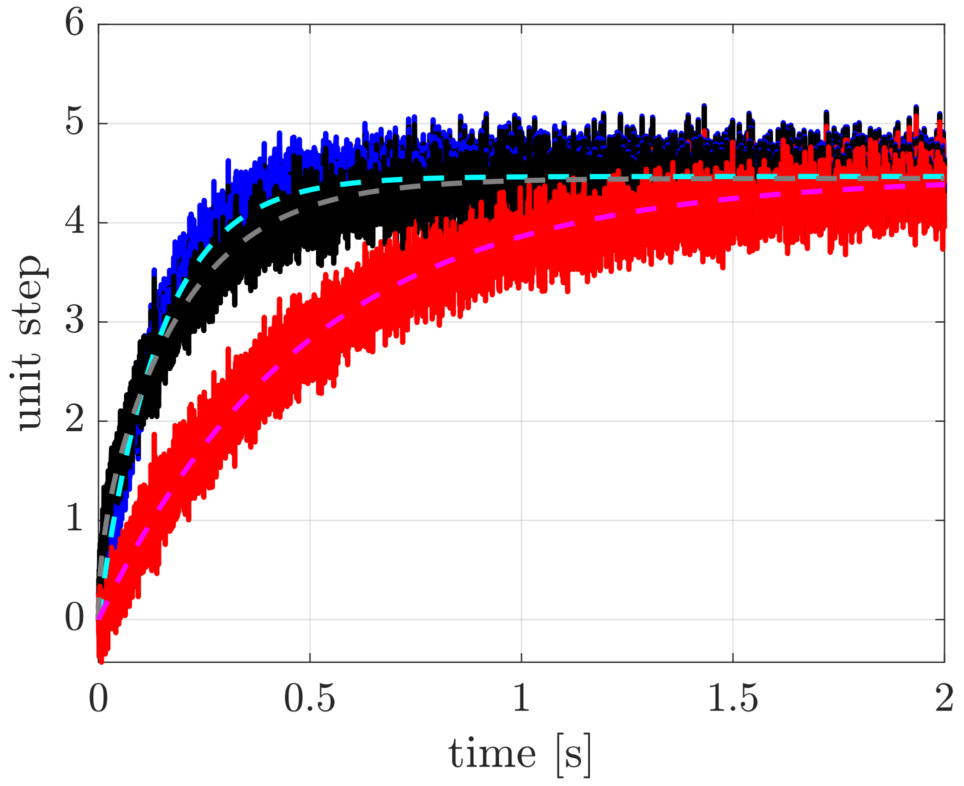
Frequency Response is typically shown using a "Bode plot"

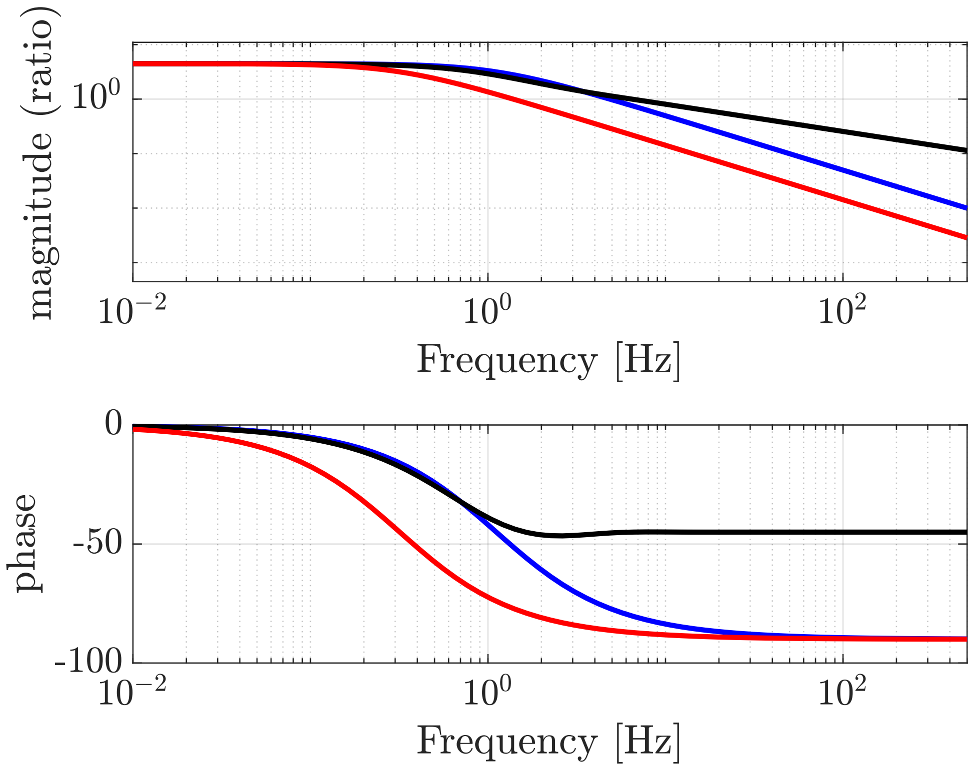


- You make an abrupt change to the INPUT and watch the response of the OUTPUT over TIME.

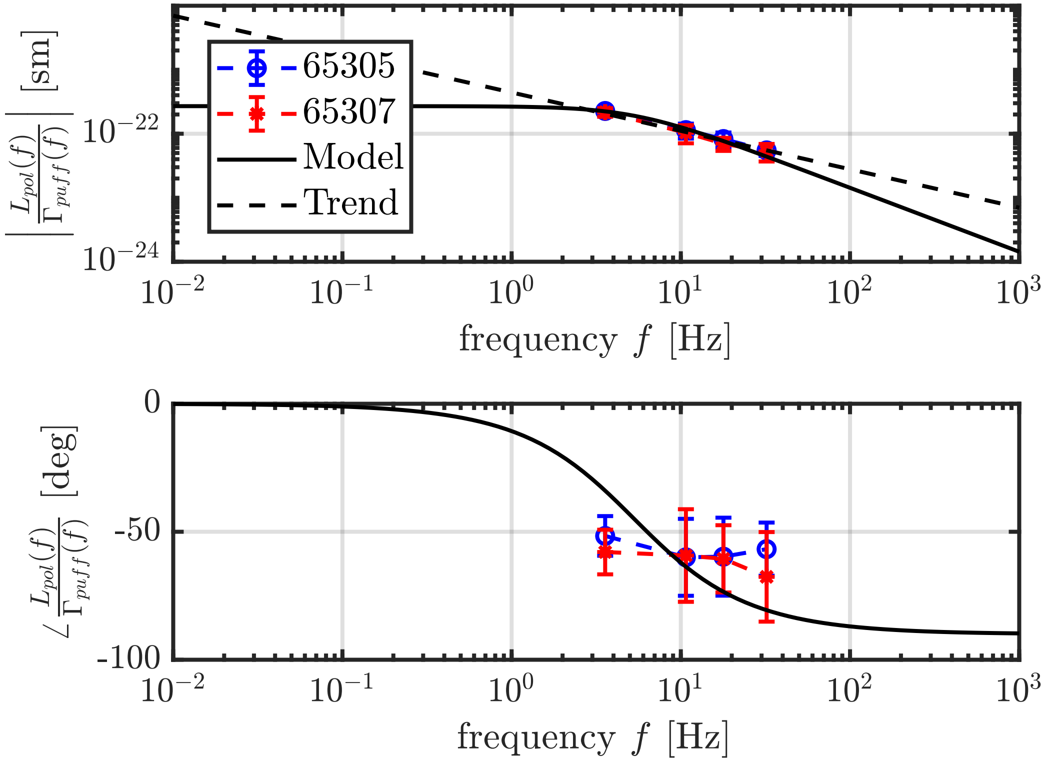
- You use a sinusoidally-varying INPUT signal at some particular frequency.
- You determine the GAIN, PHASE which is the ratio of OUTPUT/INPUT sine waves

Step responses more difficult to distinguish than FRF

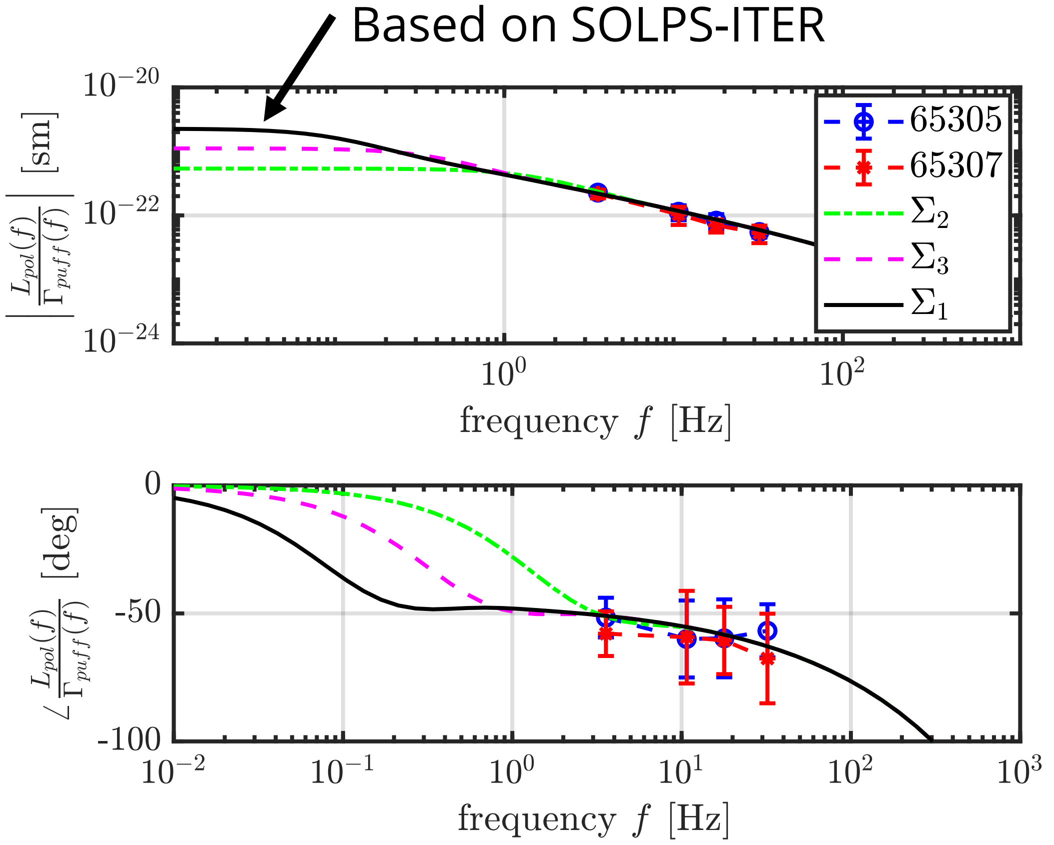




Two simple dynamic models: fitted to data



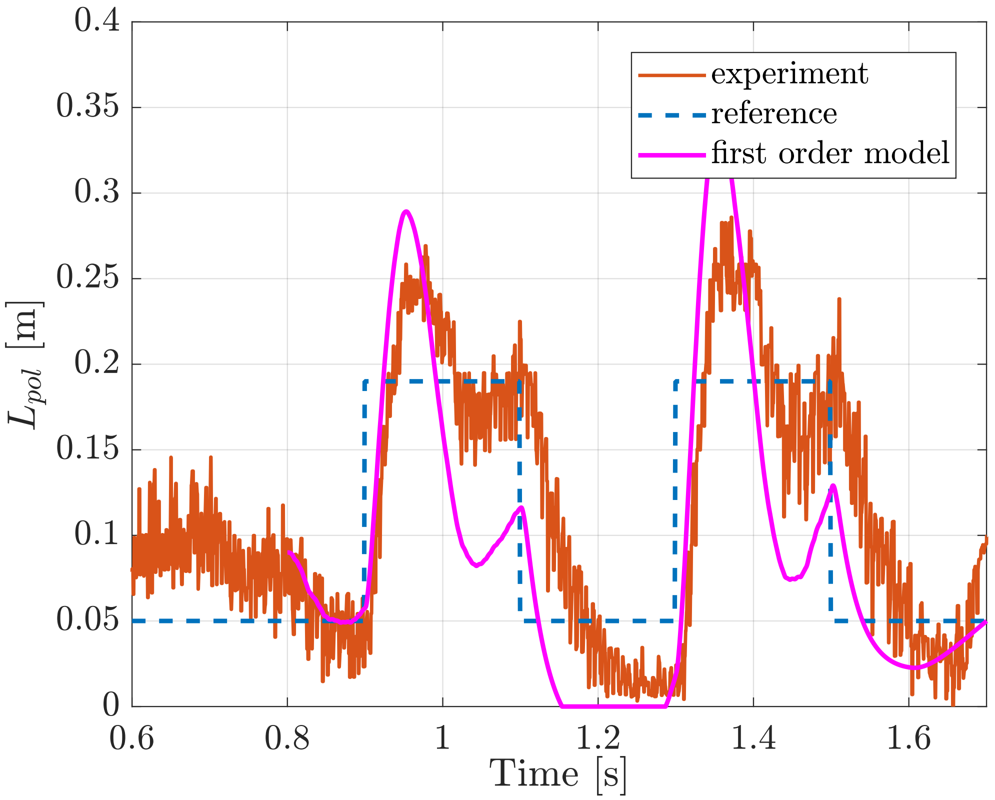
first order model (inventory)



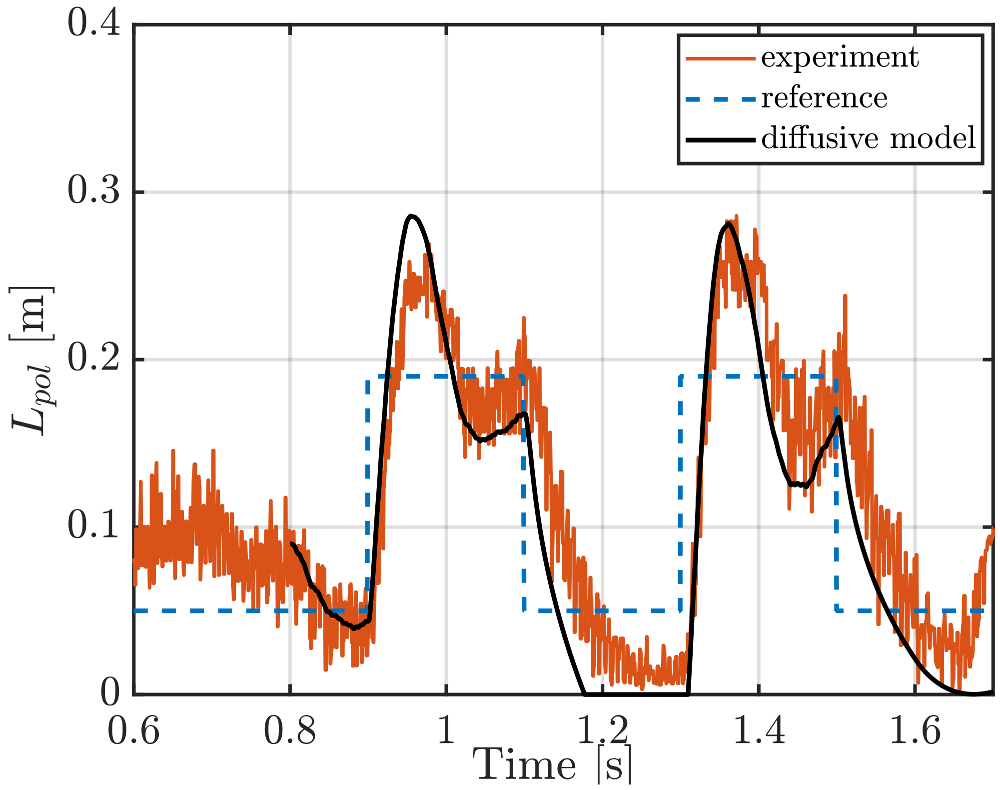
diffusive

[2]Based on J. Koenders et al., Nucl. Fusion 62, 066025, 2022

Improvement of dynamical models



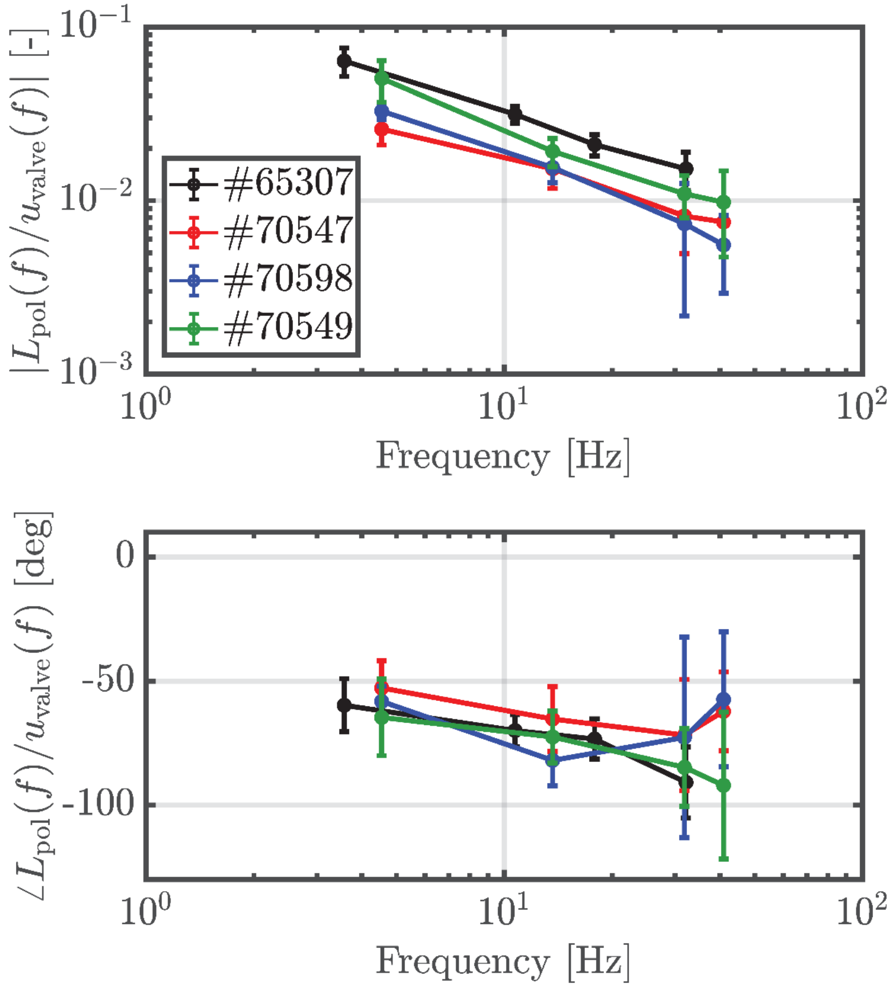
first order model (inventory)



fractional (transport)

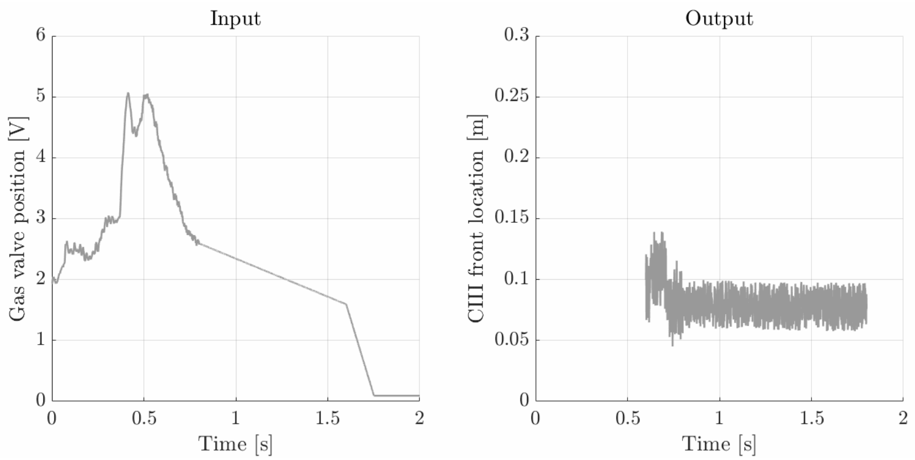
Non-linearity analysis (closed-loop system identification)

L_{pol} = 0.09 m, L_{pol} = 0.17 m
L_{pol} = 0.23 m, L_{pol} ≈ 0.12 m (ol)



- Dynamics insensitive to C-III front position
- Single/linear controller sufficient within one scenario
- Same conclusion for elmy H-mode #65309, #70686, #70688, #70689
- Similar for nitrogen seeding experiments, but faster phase decay over frequency
- Weak dynamic dependence over different scenario's

Why we use multisines instead of step responses

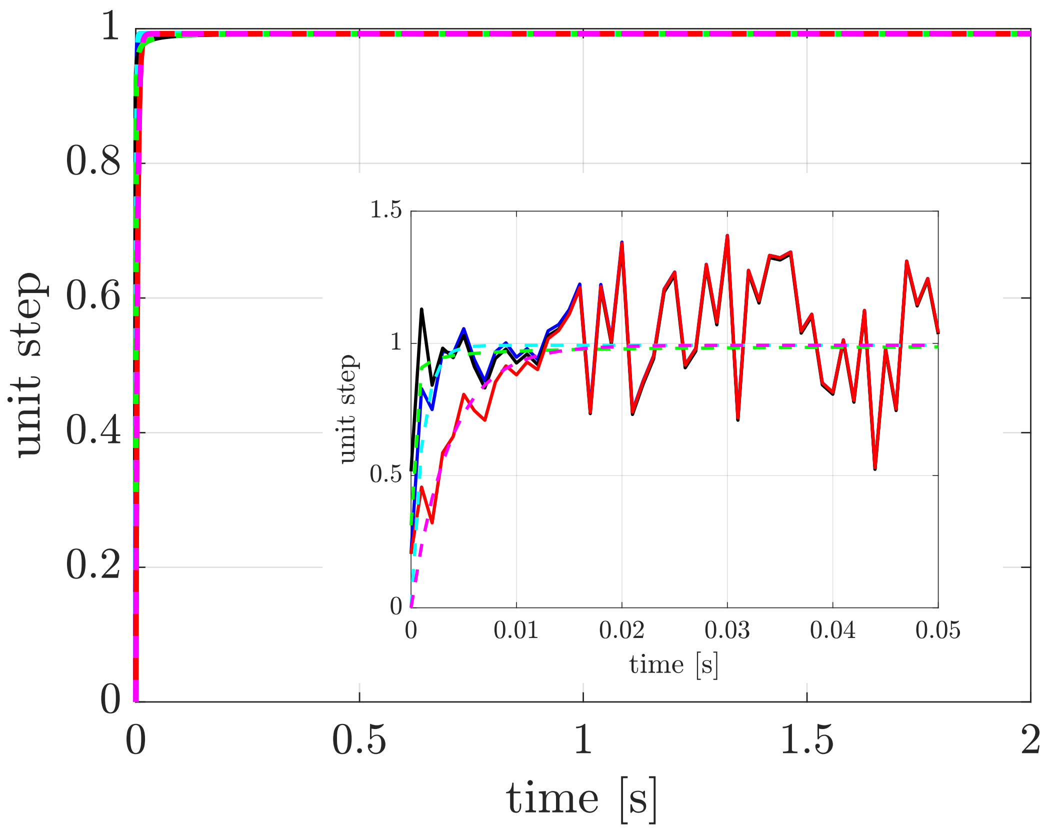


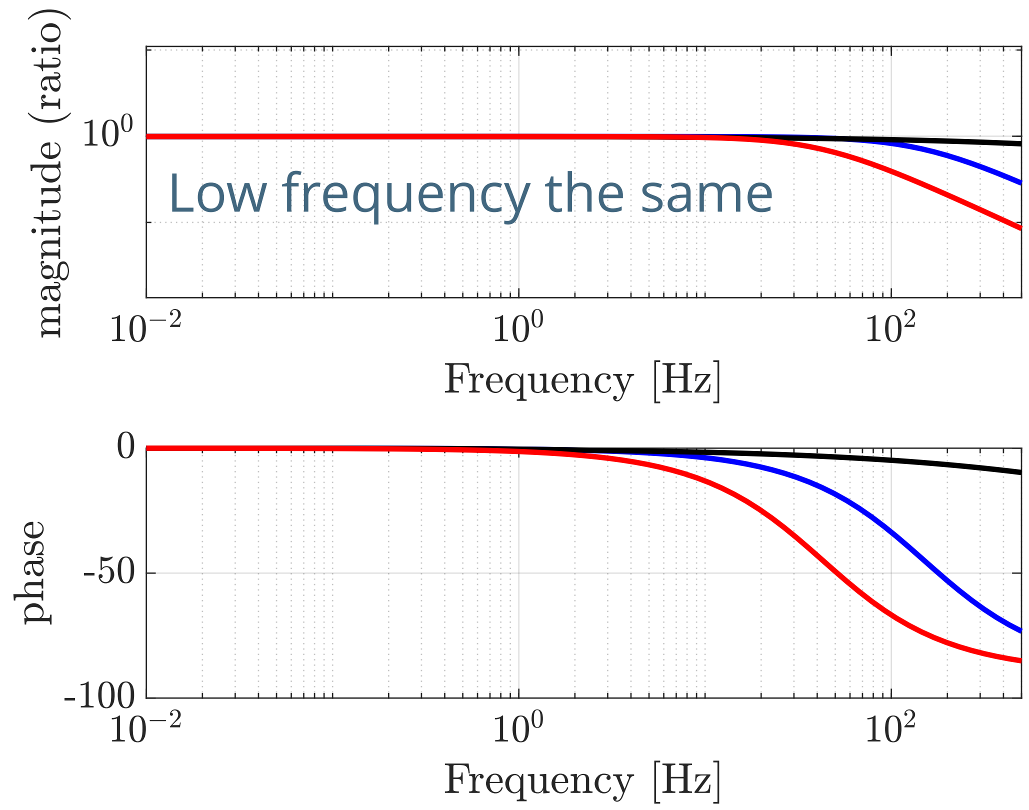
- No model free interpretation of step responses
- Exhaust is not described by a time-constant but an intermix of time-scales (follows from FRFs)
- No method to distinguish between linear and non-linear response
- Questionable convergence to equilibrium: a necessity for step responses (step down, e.g. gas cut)

Advantages multi-sines (incomplete list)

- Non-linearity tested and described over operating points
- High SNR due to averaging over periods
- Drifts/trends can be removed response does not need to go from equilibrium to equilibrium
- Model free (not fitting methods)

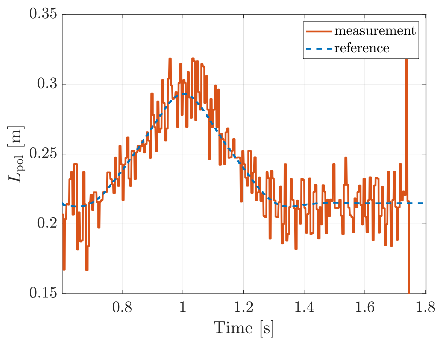
Closed-loop tracking control (low frequency irrelevant)



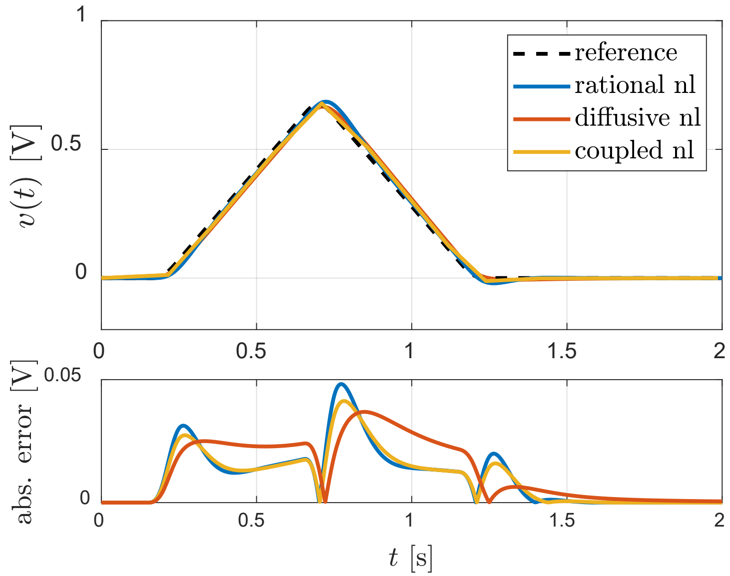


Slow dynamics (first order approximations) suppressed by control and no longer visible/relevant in controlled scenarios

Closed-loop: Controller stability and performance is determined by the "high frequency" dynamics

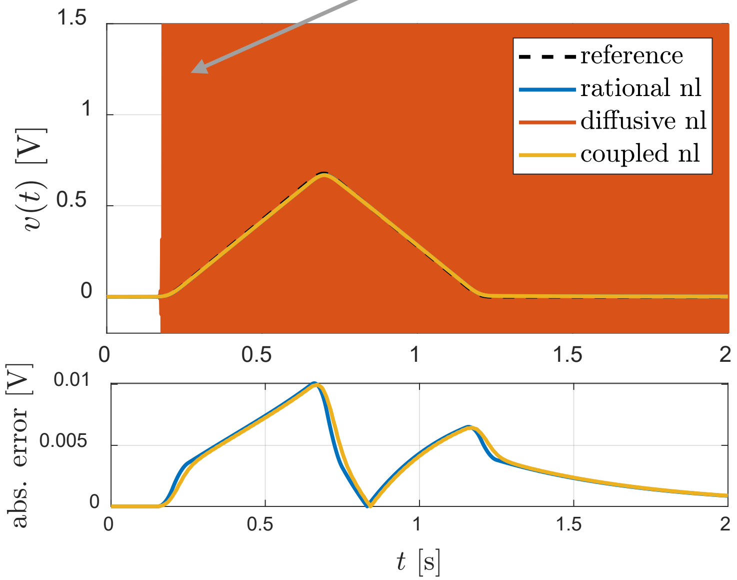


oscillation



improve control

increase gain
P x 10

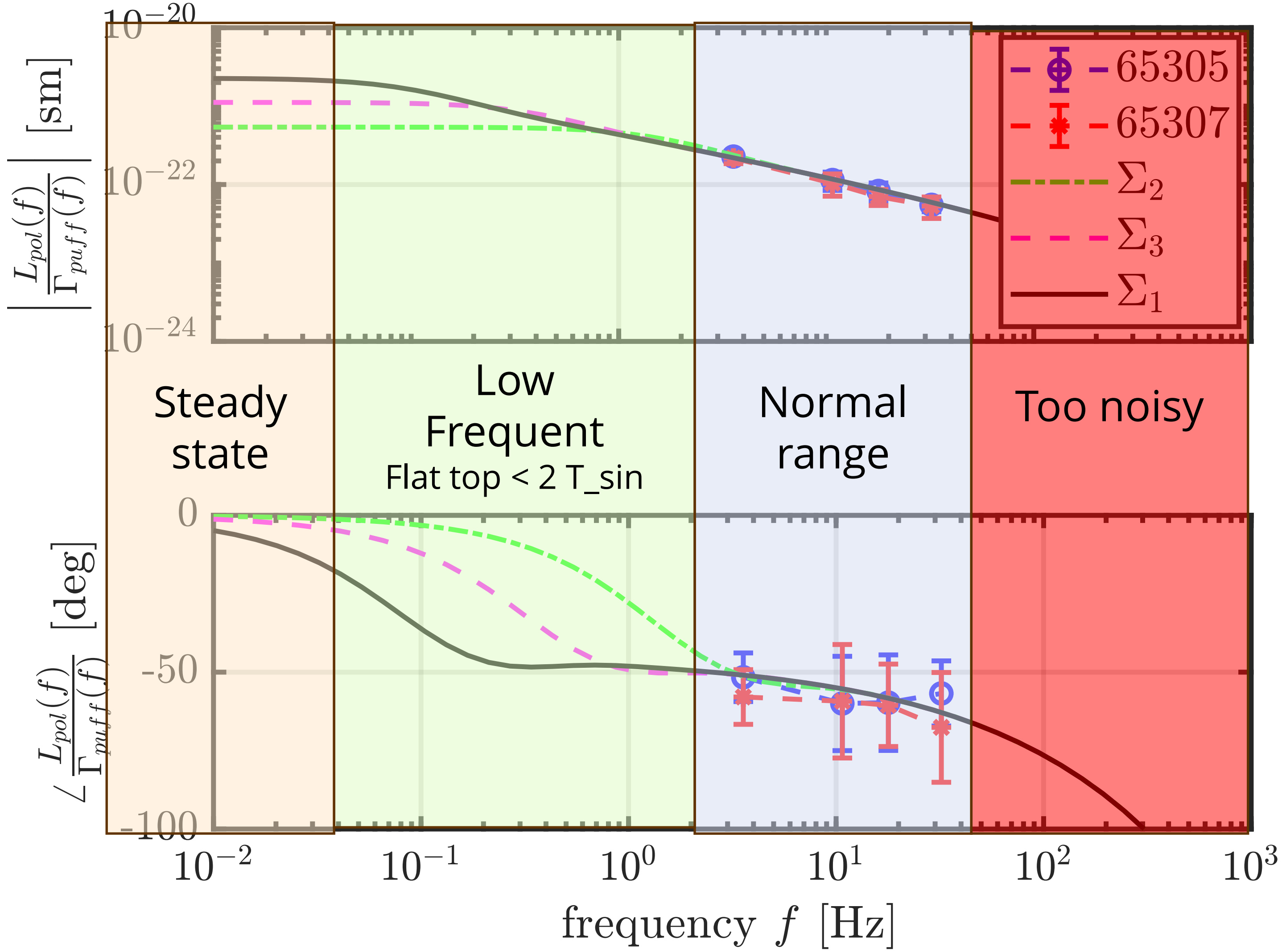


Low-performance (PI) controller

High-performance (PI) controller

- Disturbance rejection low-frequency can matter
- Extrapolation multiple timescales need to be distinguished as they are generally associated with different plasma processes

Not all ranges are easy to measure



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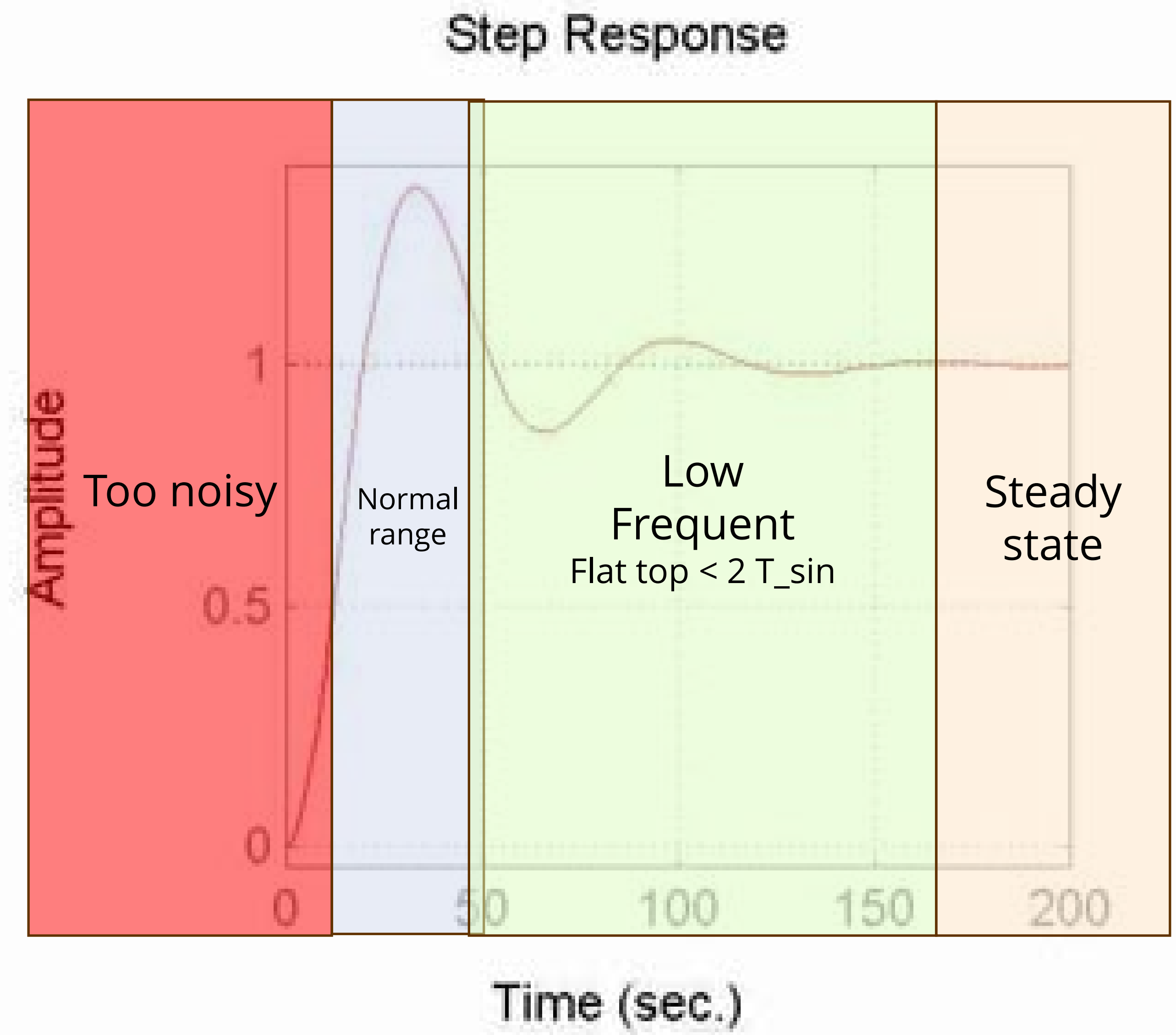
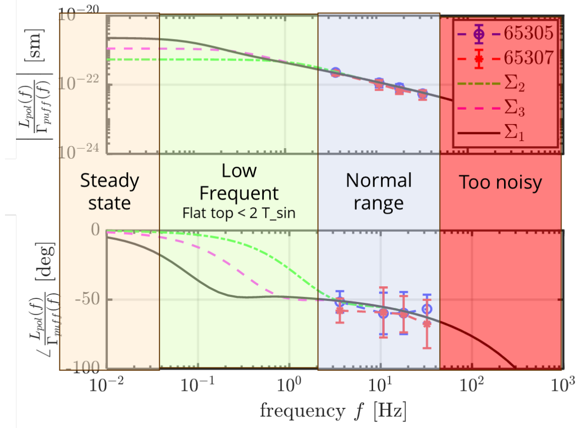
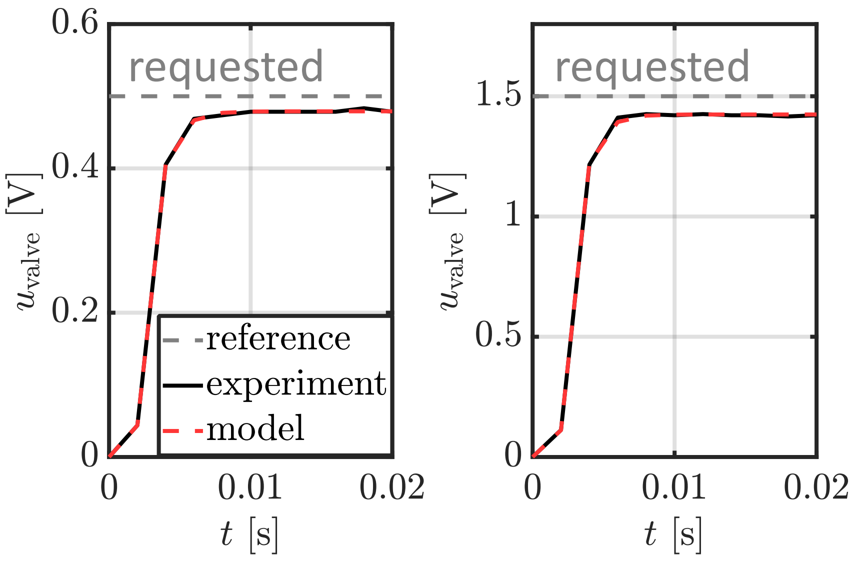




Integration into a transport model

Systematic controller design

- First-order + dead time model



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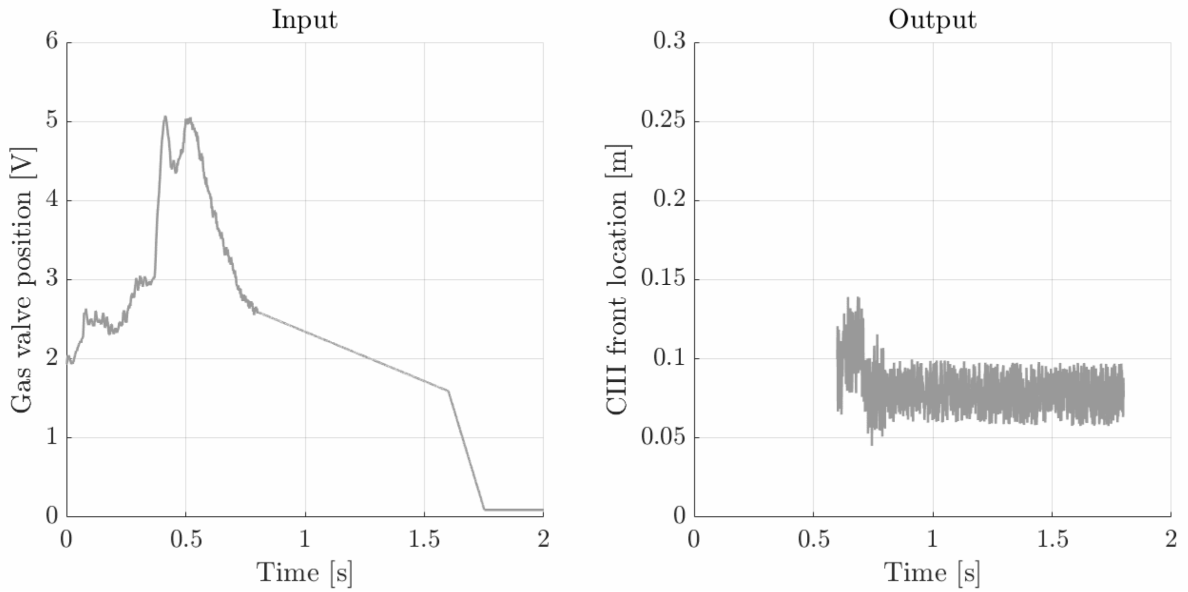
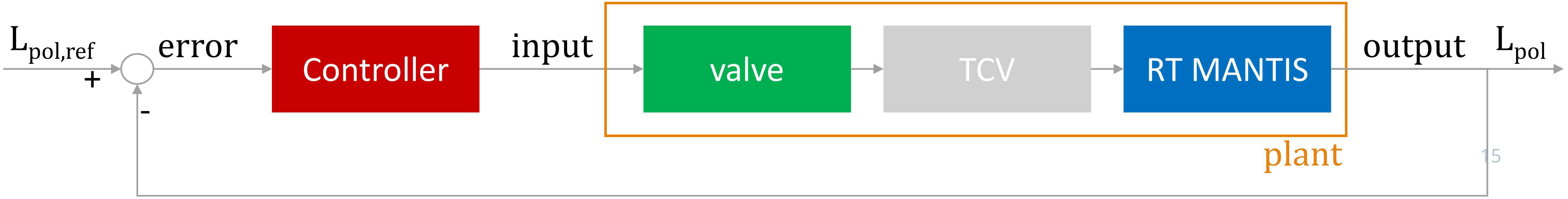
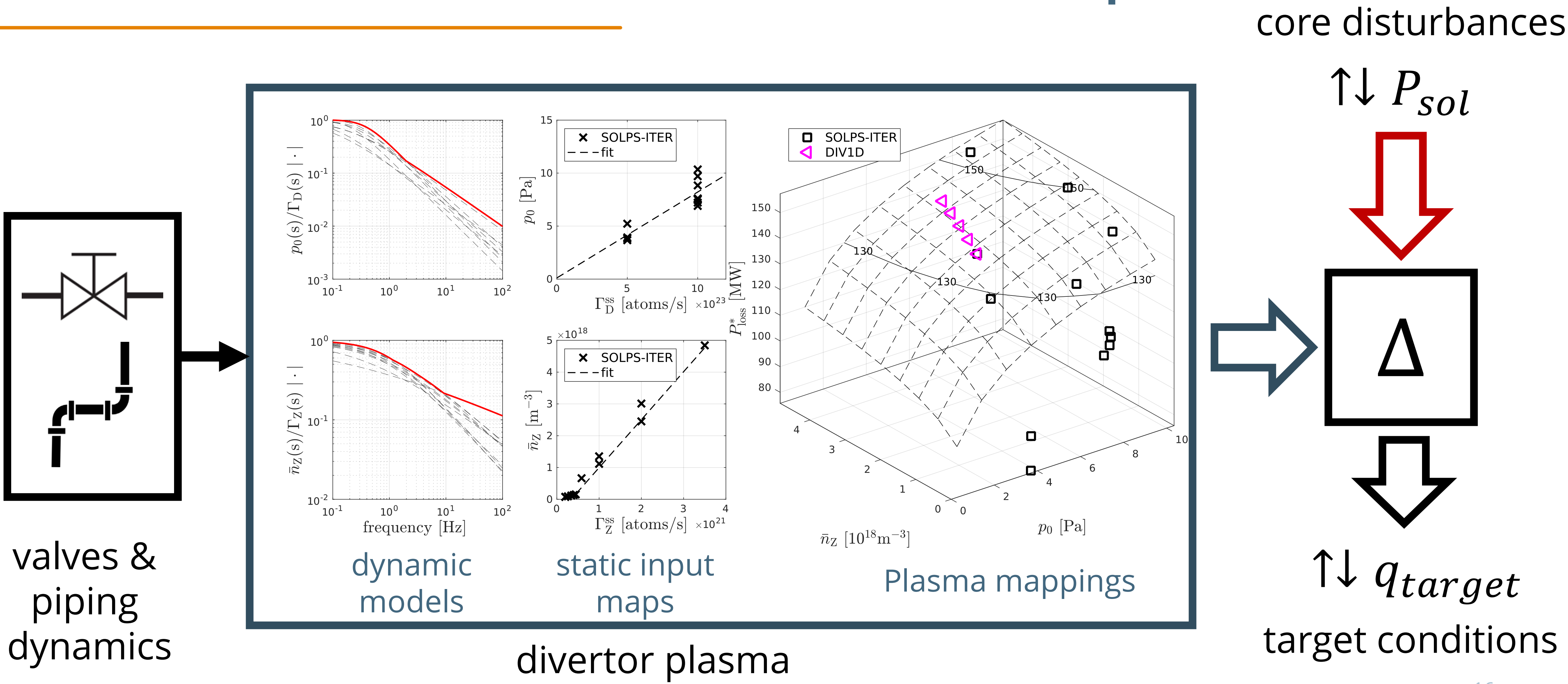
- FRF data from system identification



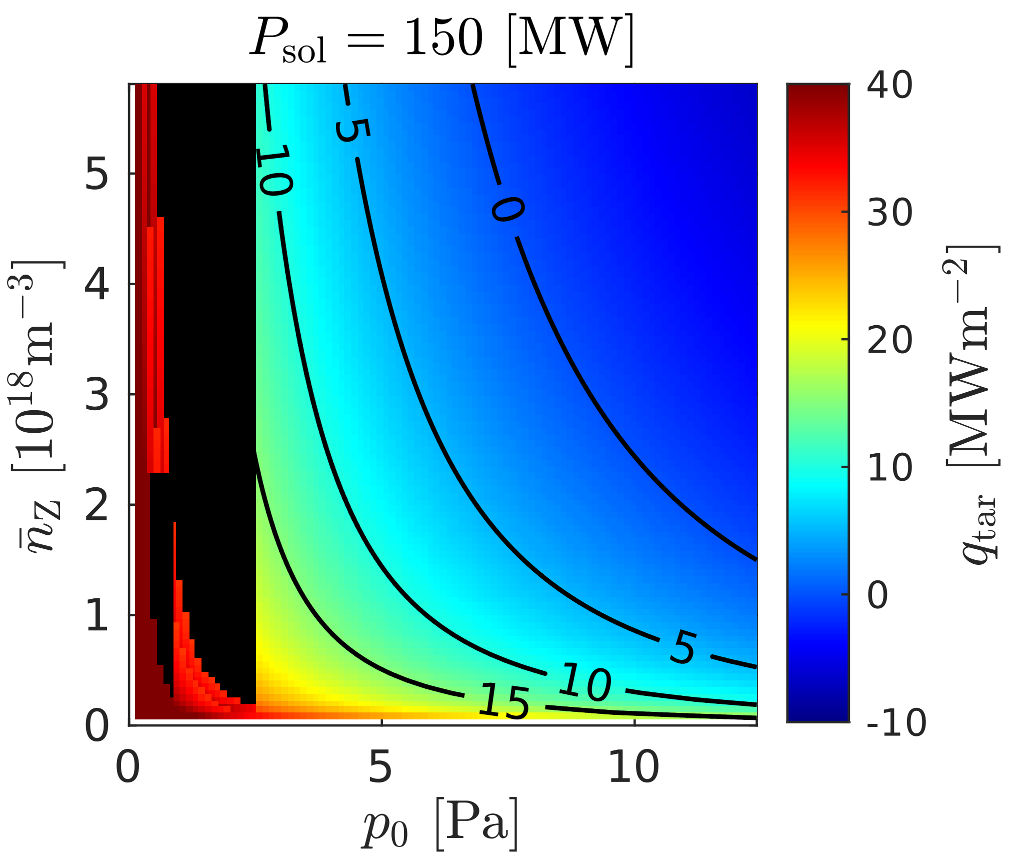


Framework: ITPA DivSOL 2023 / Mosaic workshop 2023

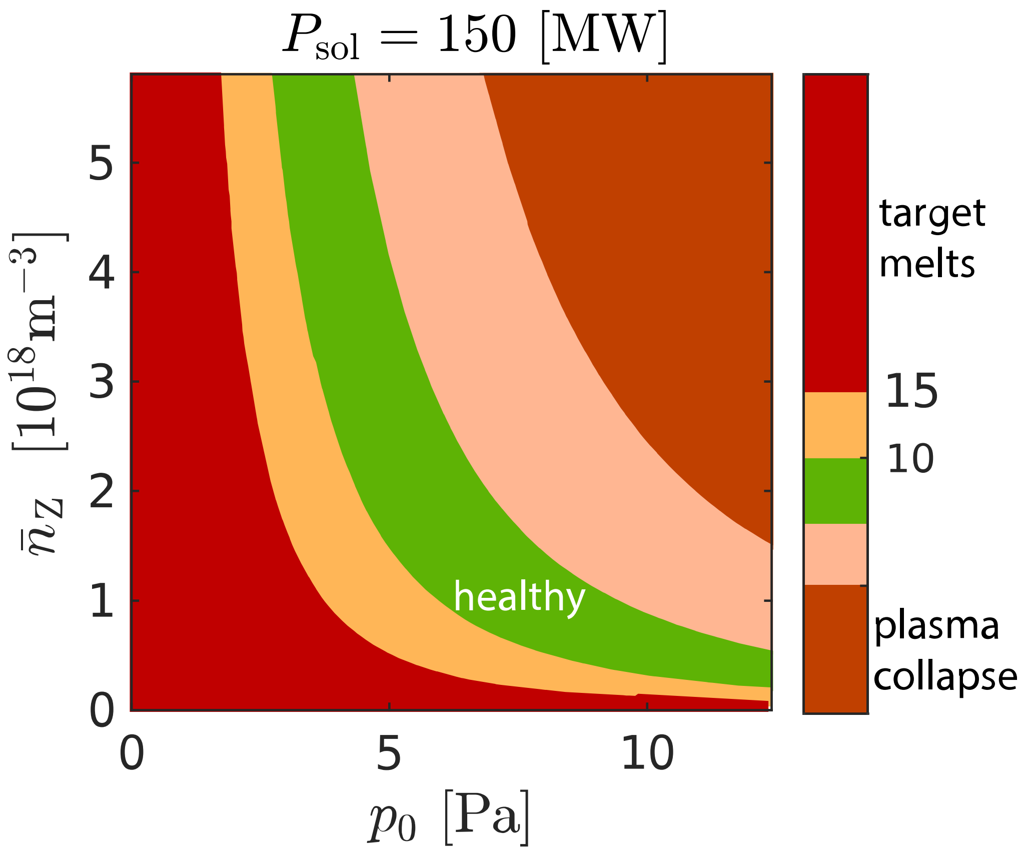


Van Berkel et al. First systematic multi-machine analysis of the exhaust dynamics in tokamaks, to be submitted to nuclear fusion, 2025, pinboard: 39970

Framework: ITPA DivSOL 2023 / Mosaic workshop 2023 (cont'd)

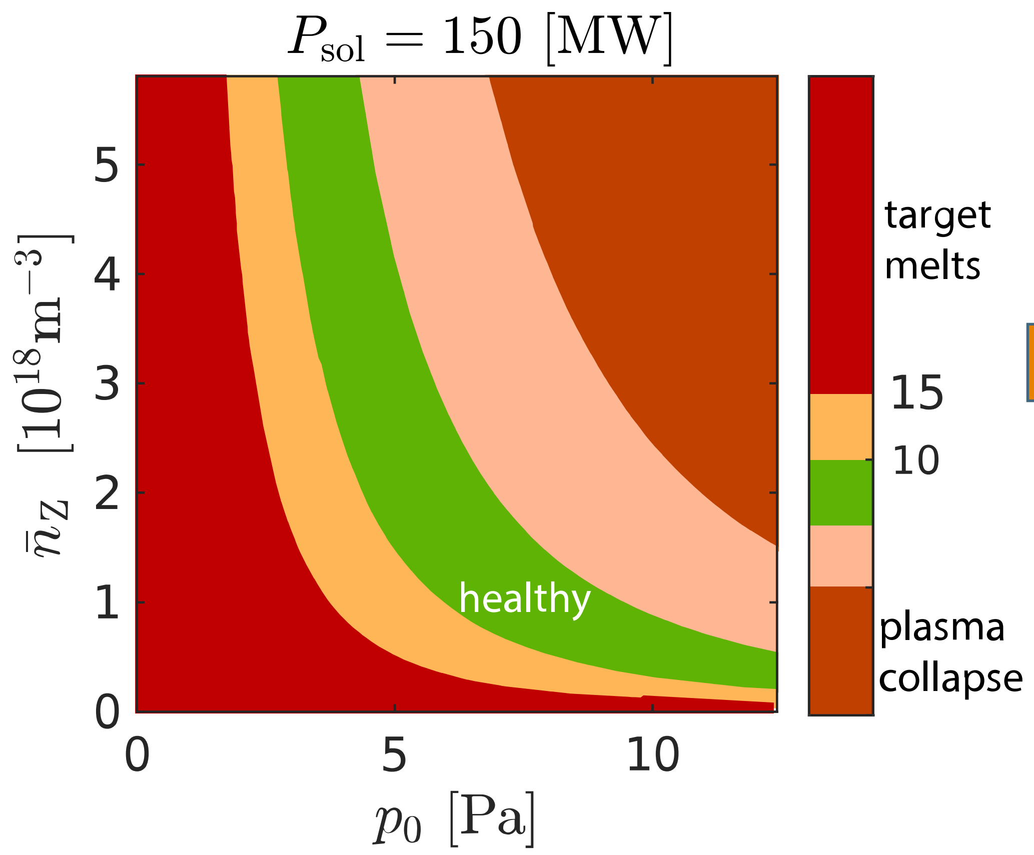


state map (simplified)

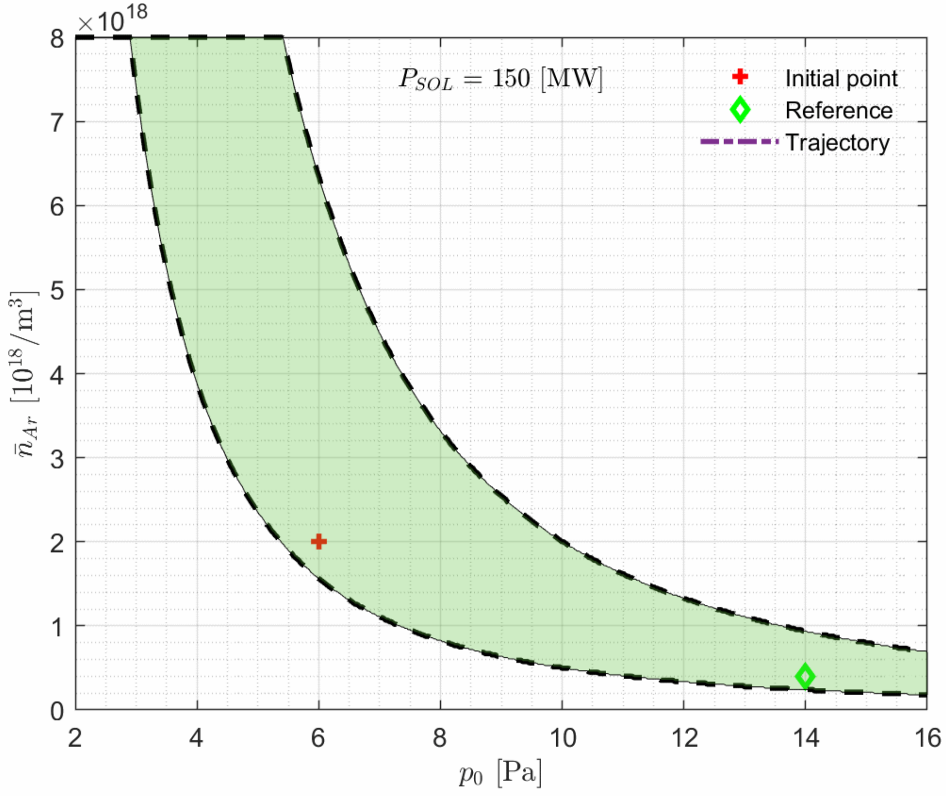


constrained map (simplified)

Framework: ITPA DivSOL 2023 / Mosaic workshop 2023 (cont'd)



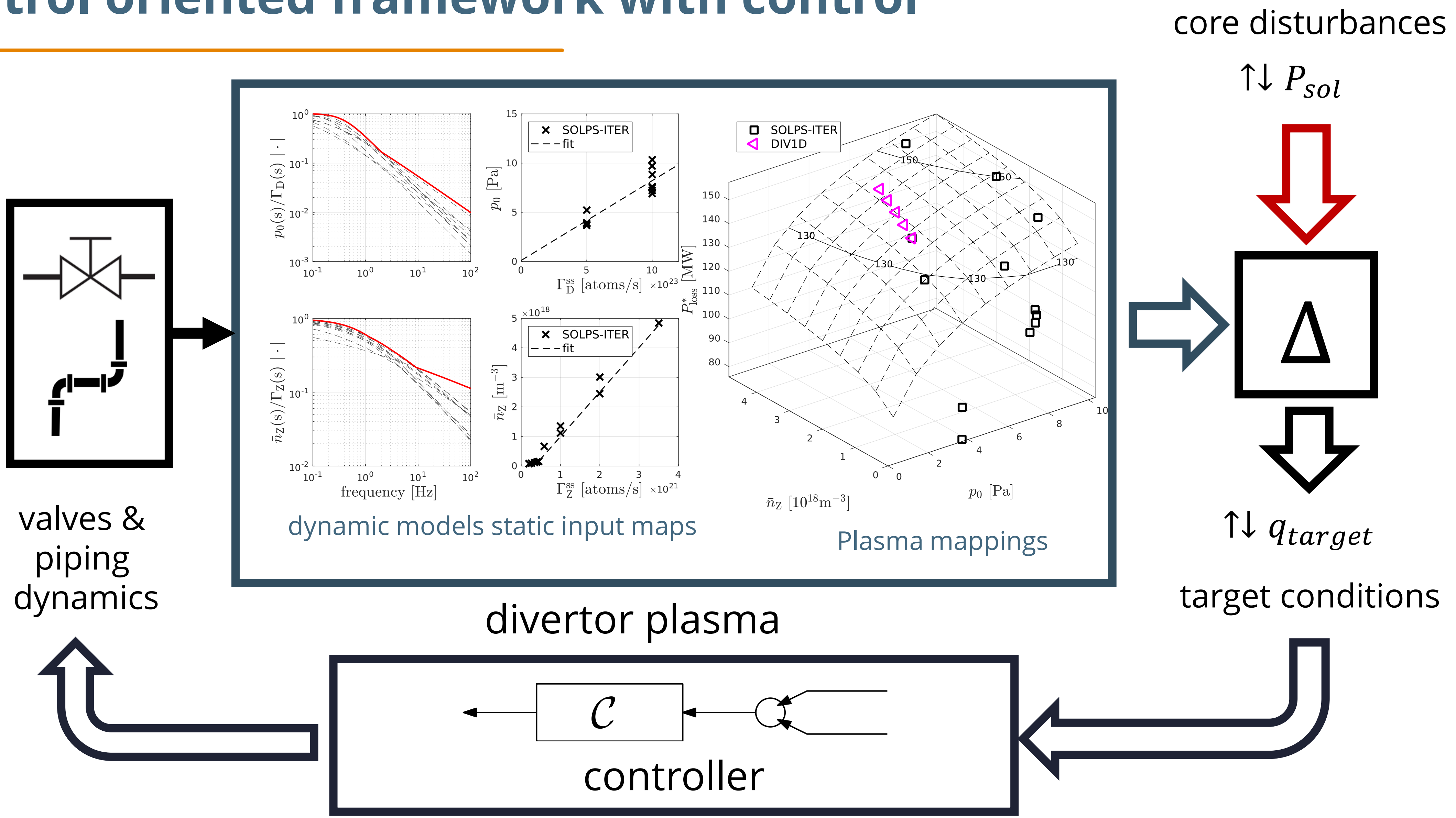
constrained map (simplified)



model predictive control (simplified)
(dynamics included)

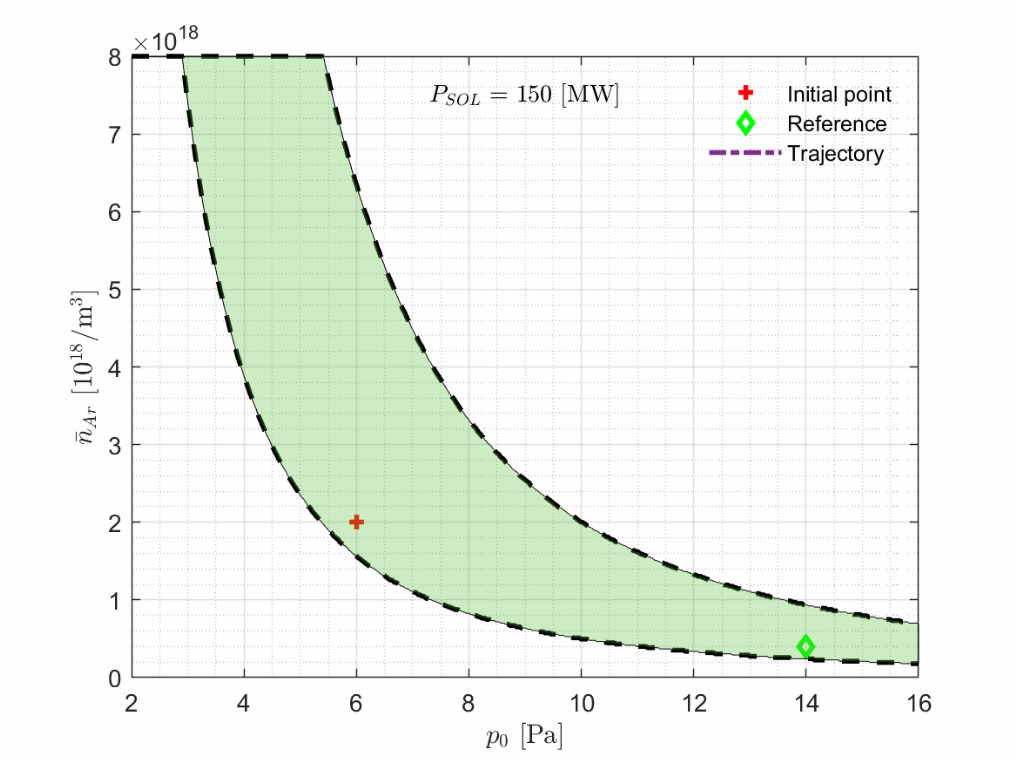
Re-attachment times

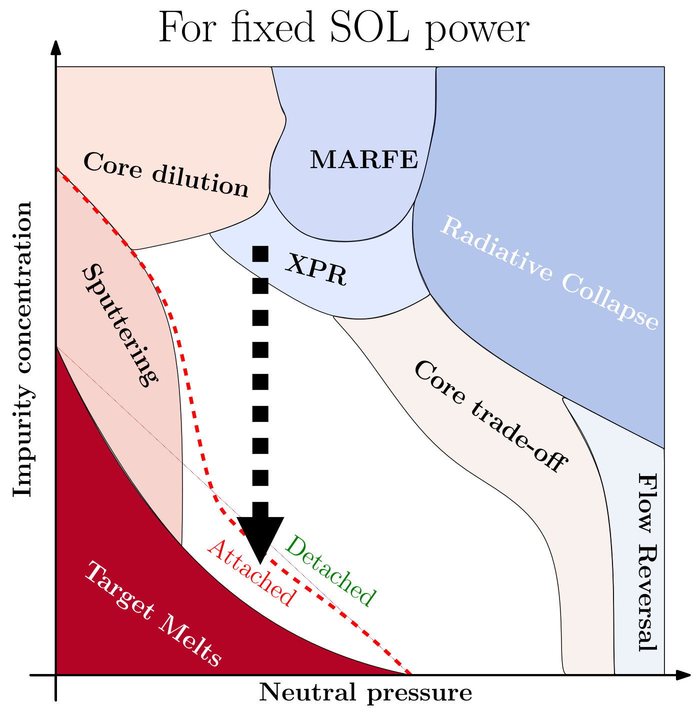
Control oriented framework with control



Case study: time to re-attachment

- Re-attachment time-scale do not exist but there is a time to re-attachment:





Failing impurity valve

Case study: time to re-attachment

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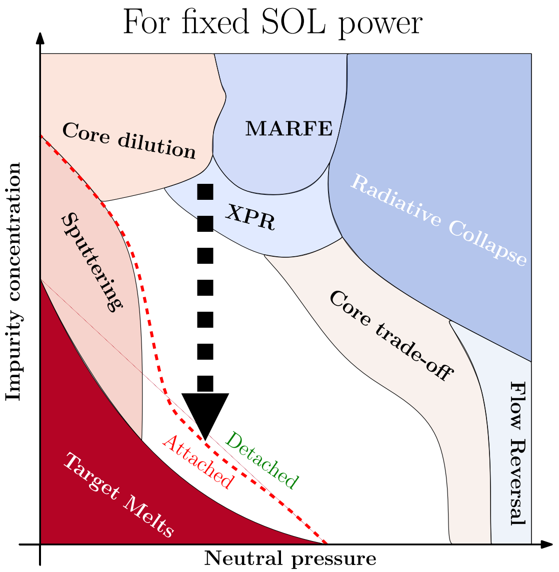
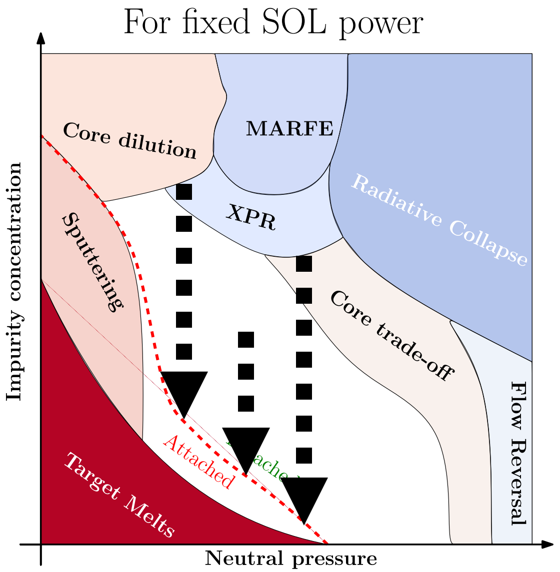
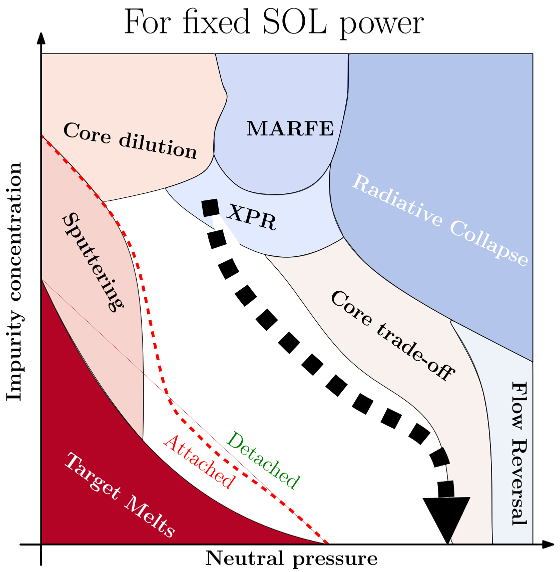


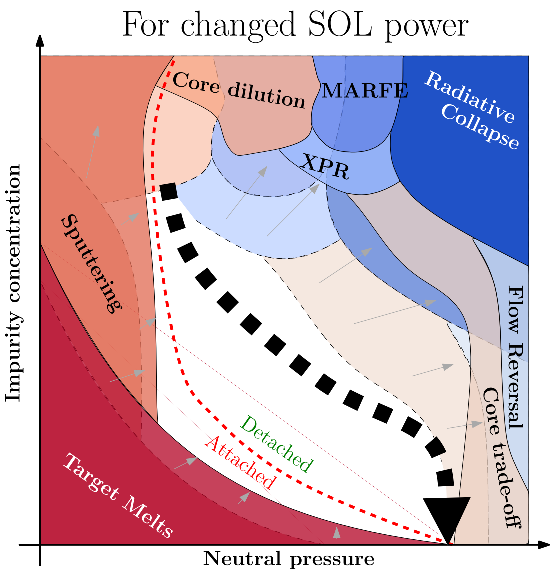
Failing impurity valve



Failing impurity valve (different initial conditions)

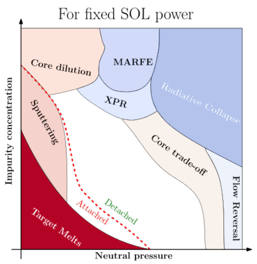


Failing impurity valve + control

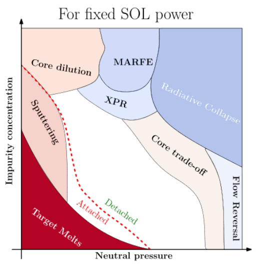


Failing impurity valve + varying (increased) Psol

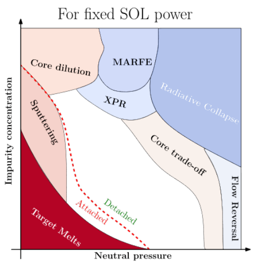
Time to re-attachment



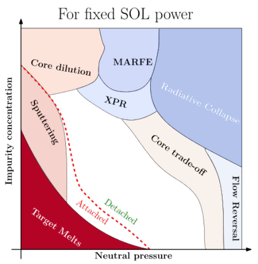
Failing impurity valve



Failing impurity valve (different initial conditions)



Failing impurity valve + control



Failing impurity valve + varying Psol

- Re-attachment time-scale does not exist but there is a time to re-attachment which depends on various factors:

➢ plasma dynamics which is generally not one time-scale (but mixed time-scales), e.g., transport
  - ➢ an approximation of a time-constant exists but it is generally incomplete, especially for advanced control

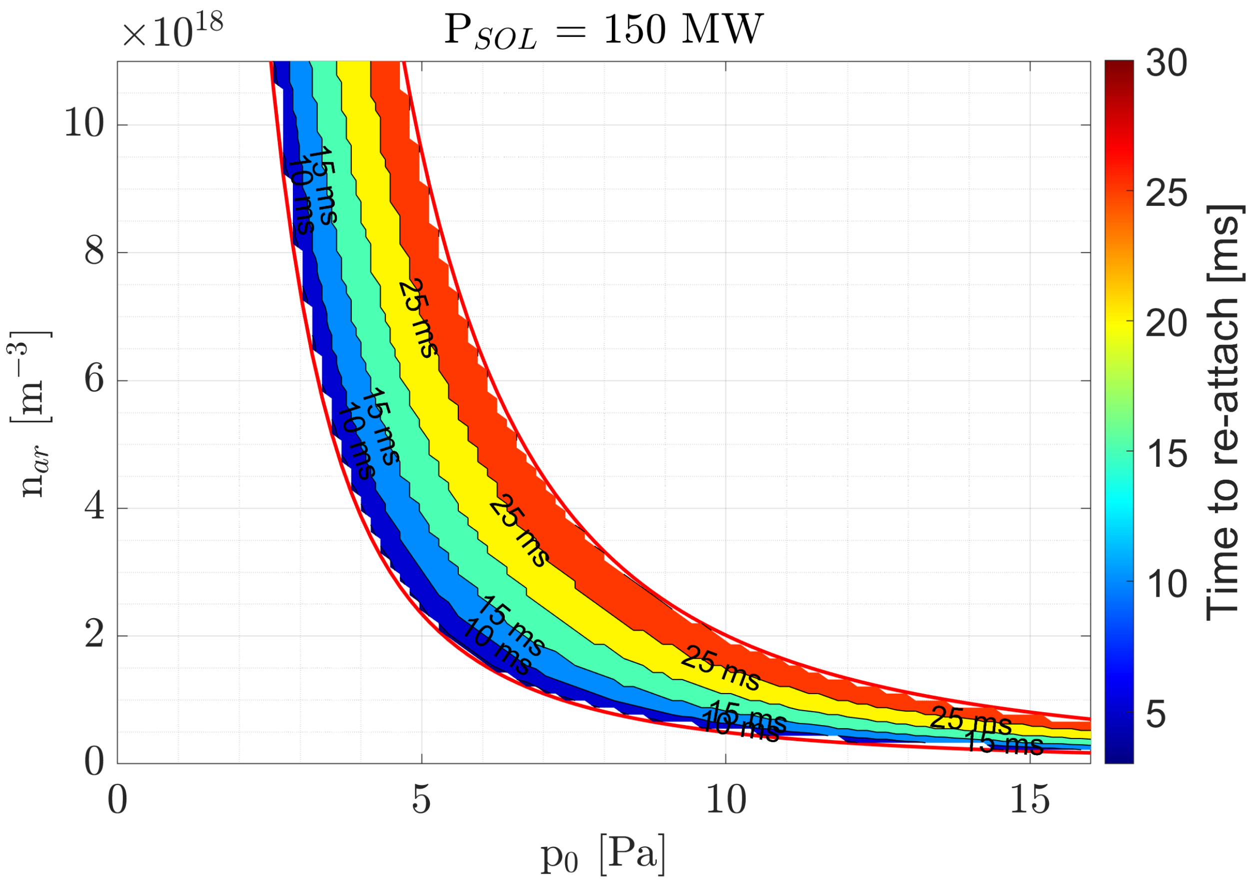
➢ valve + pipe have dynamics and can be well modelled by time-scales (first order system)
  - ➢ dominates generally the time-scale to re-attachment because its phase “delay” >> phase “delay” of the plasma

➢ initial condition (from where are we coming) and type of disturbance is critical to determine time to re-attachment

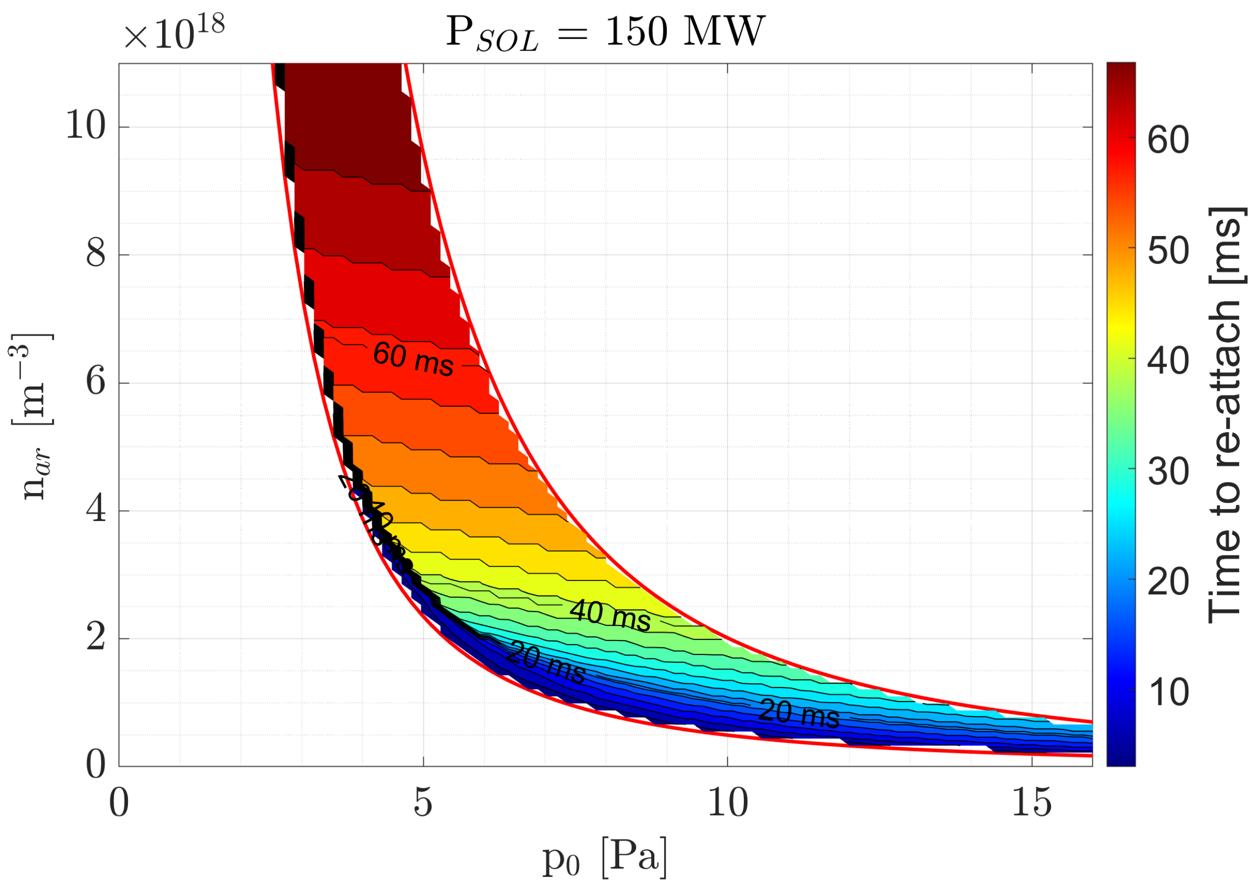
➢ (model-predictive) control is there to counter-act re-attachment and increases the time to re-attachment significantly (if done correctly)

Hence, a complete model of all these components (digital twin) necessary to assess re-attachment times and scenarios

What control can do when the impurity valve fails?



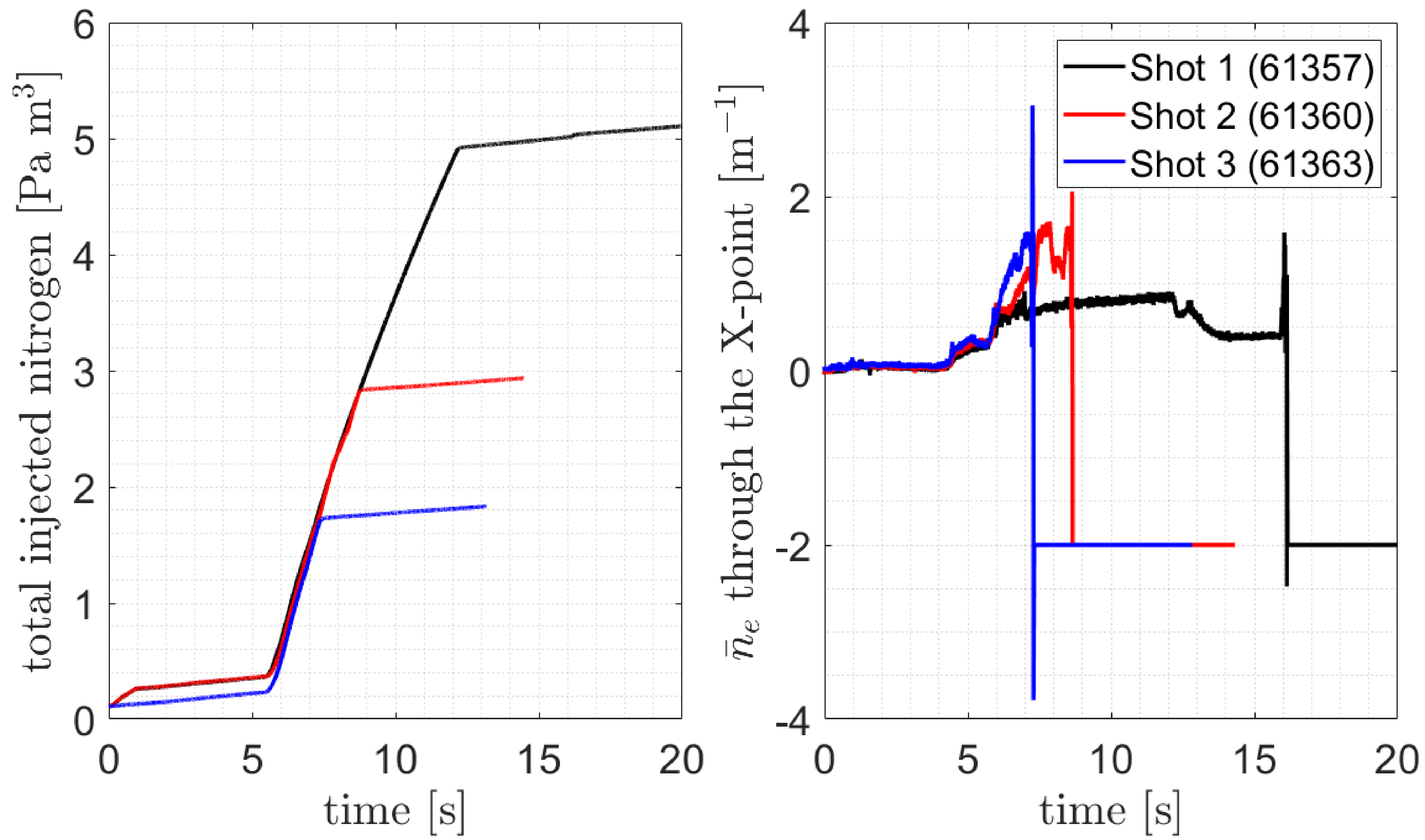
Without control



With MPC control

Impurities vary from discharge to discharge

Challenge of highly radiative regimes: discharge history critical



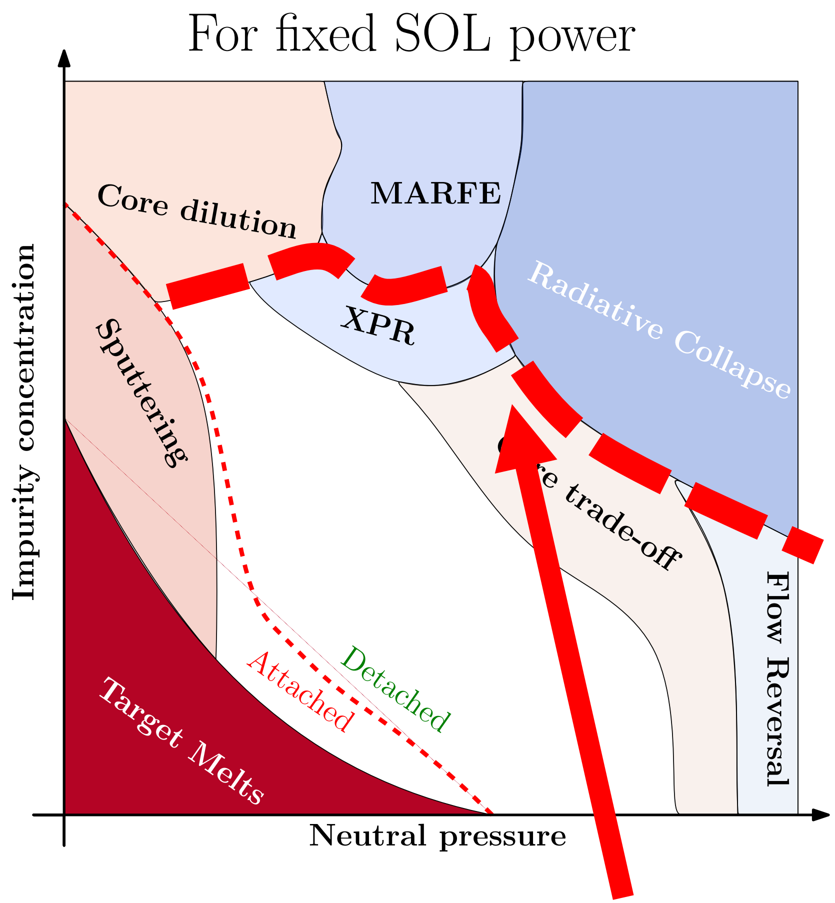
Steps necessary to consistently develop highly radiative regimes

- Scenario development is predominantly a trial & error method
  - Due to varying initial concentrations of impurities, this method leads to continuous disruptions (overseeding)
  - Bad flow control (calibrations) or its absence contributes further

- Absolute observers are necessary and to be integrated in scenario development such that the levels can be observed correctly and controlled to quantitative values

- Consequently, scenario development is done on the correct levels of impurities, also can embedded in which requested impurity levels are requested instead of "tried"

I believe this might reduce 100(s) of discharges per campaign over the machines

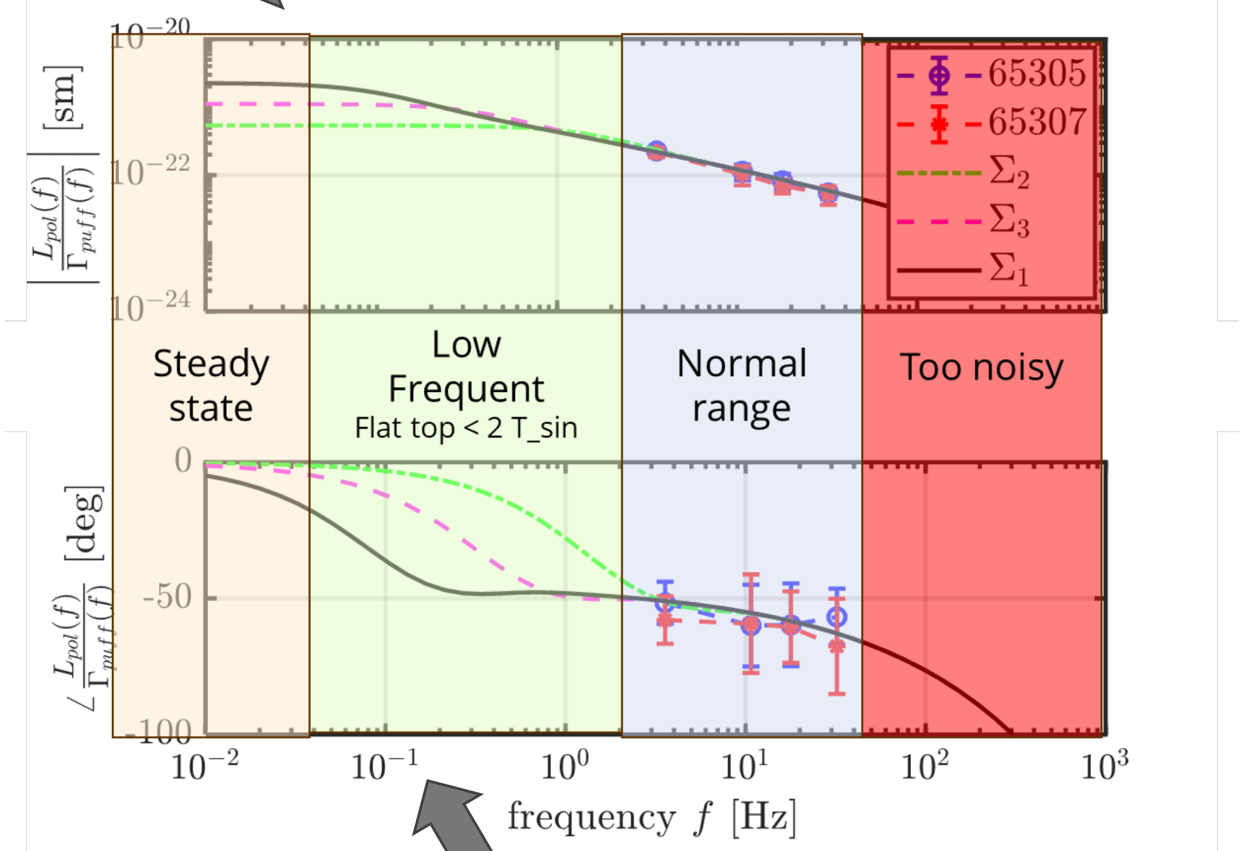


Assess (real) radiative limit not relative to injection

What needs to be done?

Steps necessary for "digital twin"

Evaluate if quasi steady-state is valid



Find first dynamic transition(s) so-called poles

Complete dynamic relationship between actuators, disturbances and processes (frequency response functions over OP)

	Modulations for the exhaust						
Machines	DT	DD	N_2	Ar	Ne	ECH	NBI
JET	✓	✓	✔	✓	✓	✗	✔
AUG	✗		✔	✓	✗	?	?
TCV	✗	✔	✔	✗	✗	✓	✓
DIII-D	✗	✔	✔	✗	✗	?	?
MAST-U	✗	✔	✗	✗	✗	✗	✗
WEST	✗	✗	✗	✗	✗	✗	✗

Table 1. ✓ one operating point, ✔ multiple operating points, ✗ not available

Extrapolation and interpolation for control "digital twin"

Questions

What kind of fault scenarios do we expect to lead to reattachment?

- actuator failures
- observer failures
- disturbances (increasing the power, reduce radiation/momentum losses)

I am more worried to overseed in highly radiative regimes

What is a realistic assumption for the conditions at reattachement (Stuart spoke mostly about the timescales, but do we expect the heat to come down at lambda_Eich or the QCE width, or somewhere in between)?

- this can be analyzed using variational analysis

Are there emergency actions other than sweeping that we could think off (like firing an impurity doped pellet into the divertor plasma)?

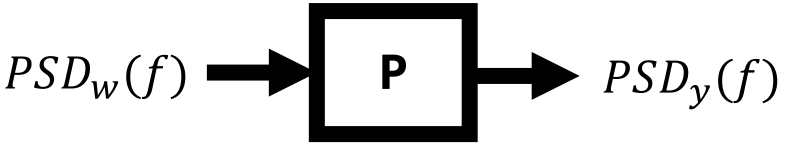
- (doped) pellets
- shorter gas-line
- more pumping capacity (over dimensioning the system)

Core disturbances: dynamic error budgeting

$$PSD_x(f) = 2 \lim_{T\to\infty} \frac{1}{T} |\hat{x}(f)|^2,$$

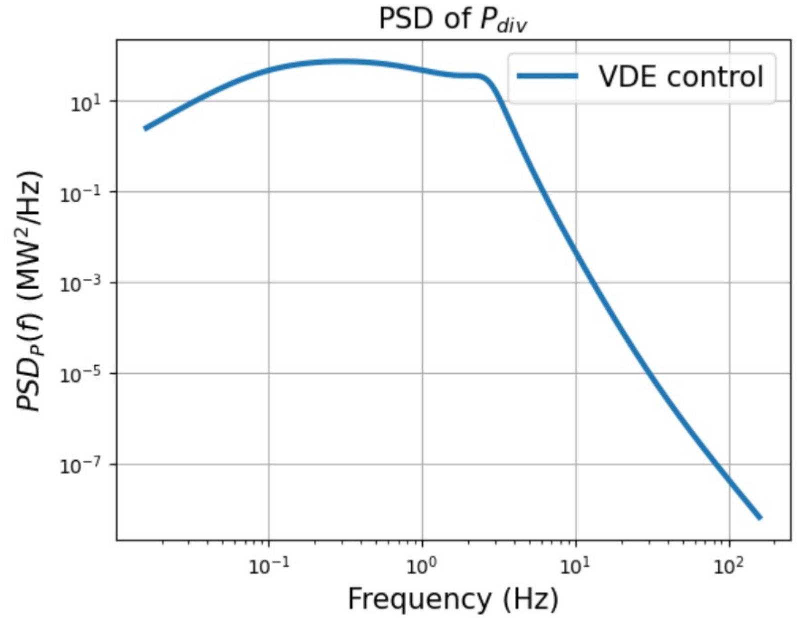
Motivation:

During operation, different disturbances will act on the divertor. Understanding their impact is crucial for control.



Procedure:

- Characterize input disturbances in terms of PSD.



Core disturbances (example STEP tokamak):

Continuous	Discrete
- Fusion Power Fluctuations	- Unexpected H-L transitions
	- ECCH mode control
- RWM control	- (Large) Pellets
- VDE control	- W-flakes

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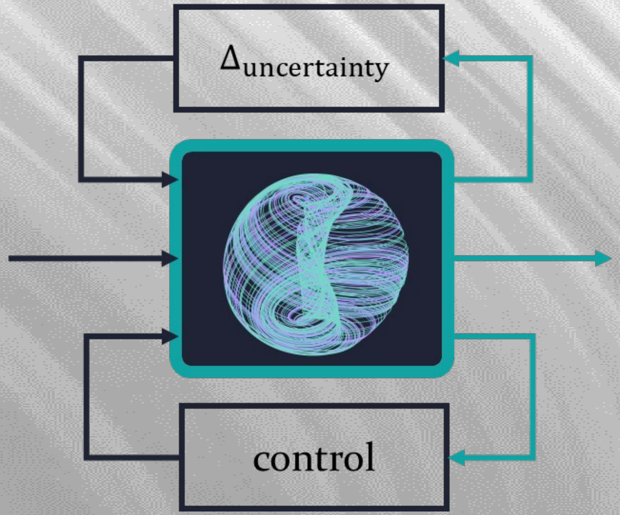
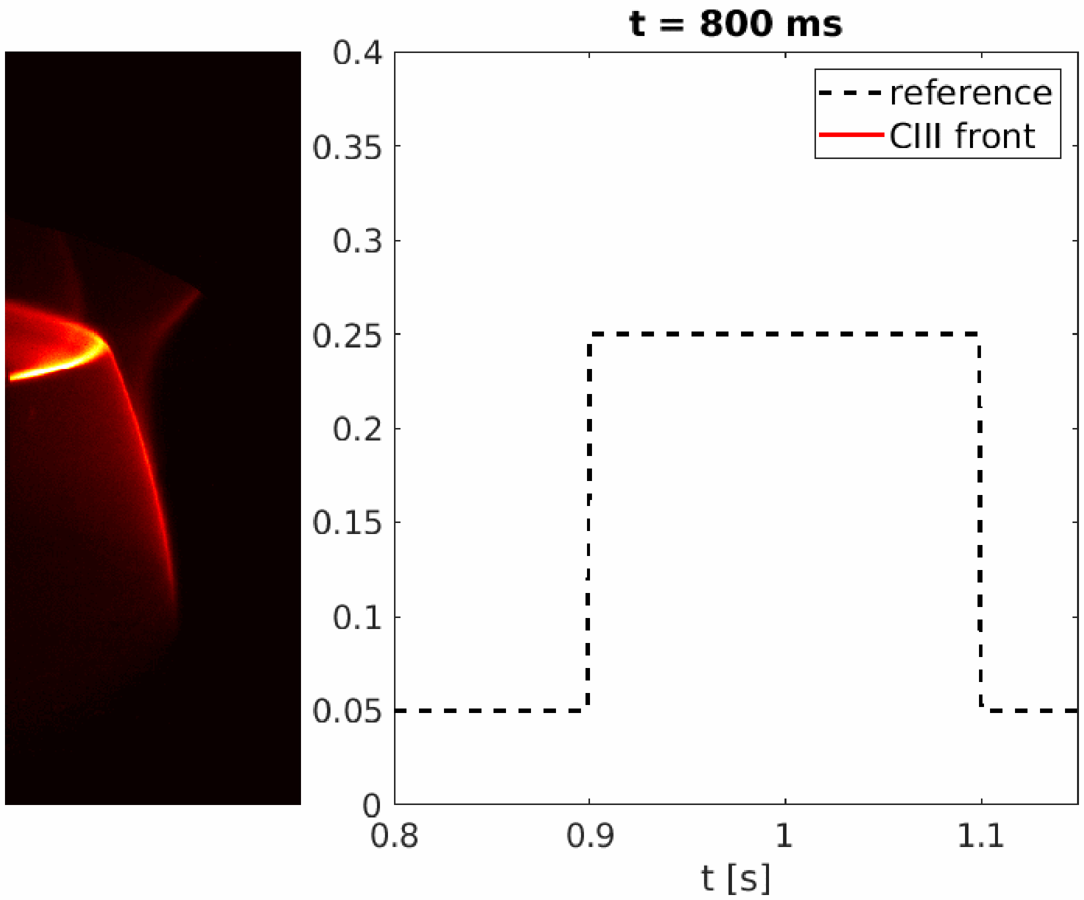


DIFFER

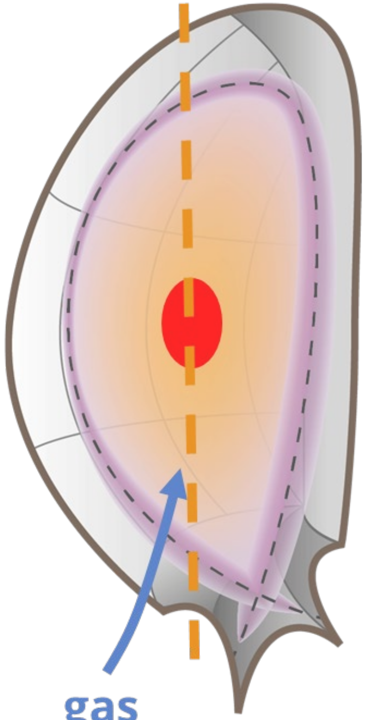
Why it is important to know limits of the operational space?

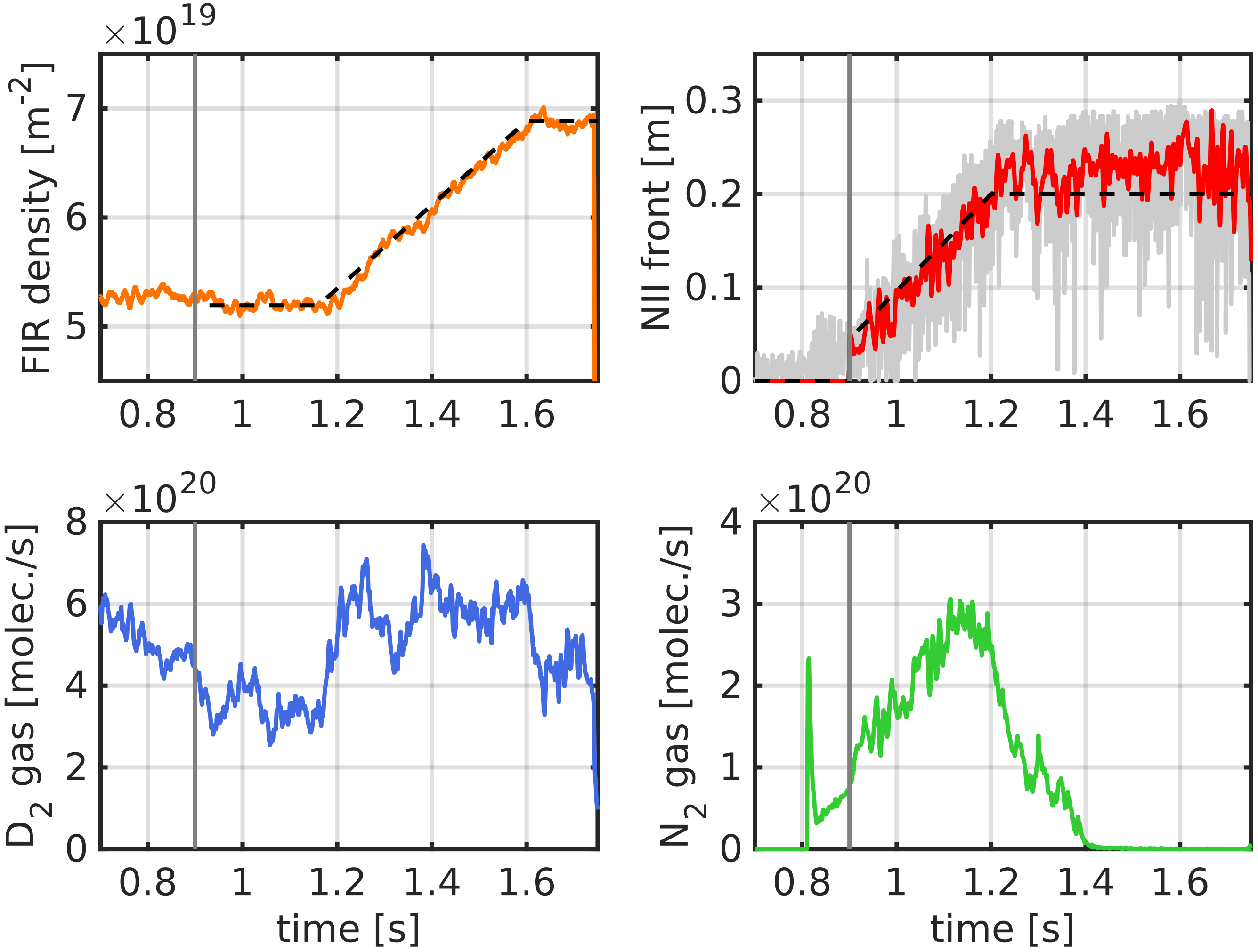


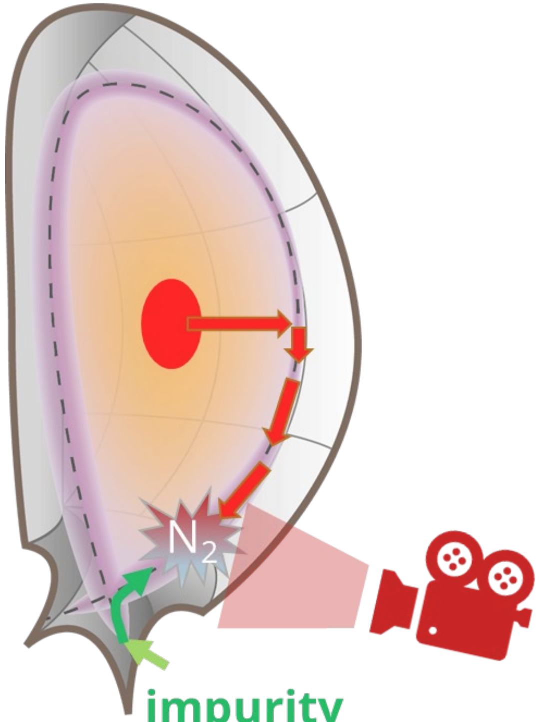
Build a model to describe all these aspects and avoid
(unobserved states leading) to machine failure

EPFL

Joint core and exhaust control (multiple-input multiple-output)







EPFL

Koenders et al., Nucl. Fusion 2023

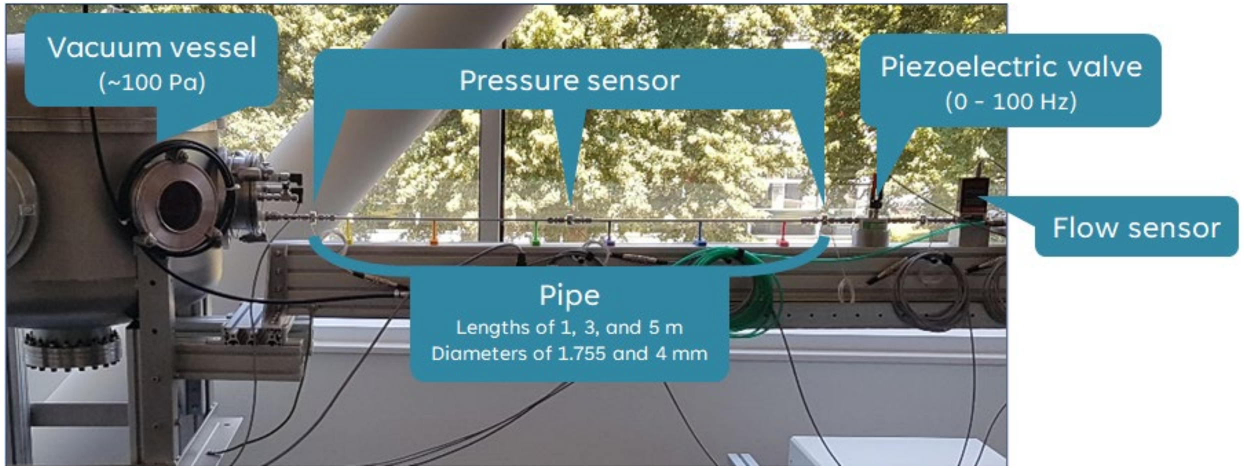
Piping dynamics

Test, validate, and develop (data-driven) dynamic models on experimental gas setup

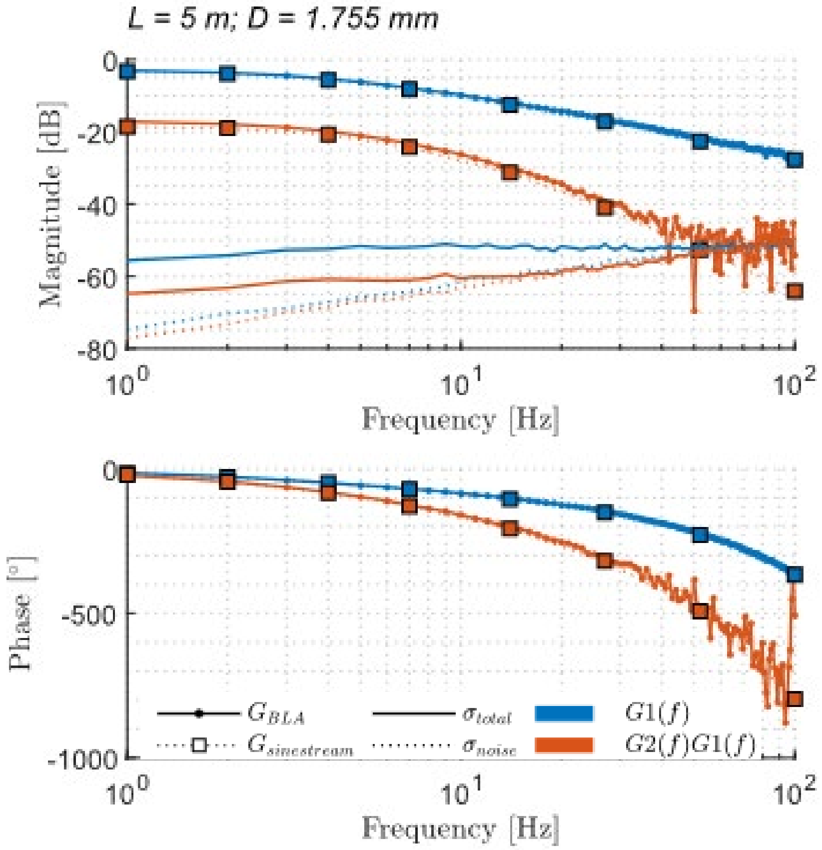
- Pipe length introduces delayed response and **amplitude attenuation** between requested and actual gas injection.

- Validated low & high fidelity model

➢ Long delays limit the ability to supress fast transients



Gas flow test setup at DIFFER



Supported by: S. Laarhoven, R. van Hoof, A. Waldus, and J. Manders