Exhaust control in alternative divertors for transient heat load management

IAEA Divertor concepts 2025 - Vienna

B. Kool[1,2], K. Verhaegh[2], P.A. Figueiredo[1,2], G.L. Derks[1,2], T.A. Wijkamp[1], N. Lonigro[3,4], V. Kachkanov[3], M. Kochan[3], C. Vincent[3], G. McArdle[3], J. Lovell[5], S.S. Henderson[3], J.L. Baker[3,4], M. van Berkel[1,2], The EUROfusion tokamak exploitation team*, and the MAST-U team†

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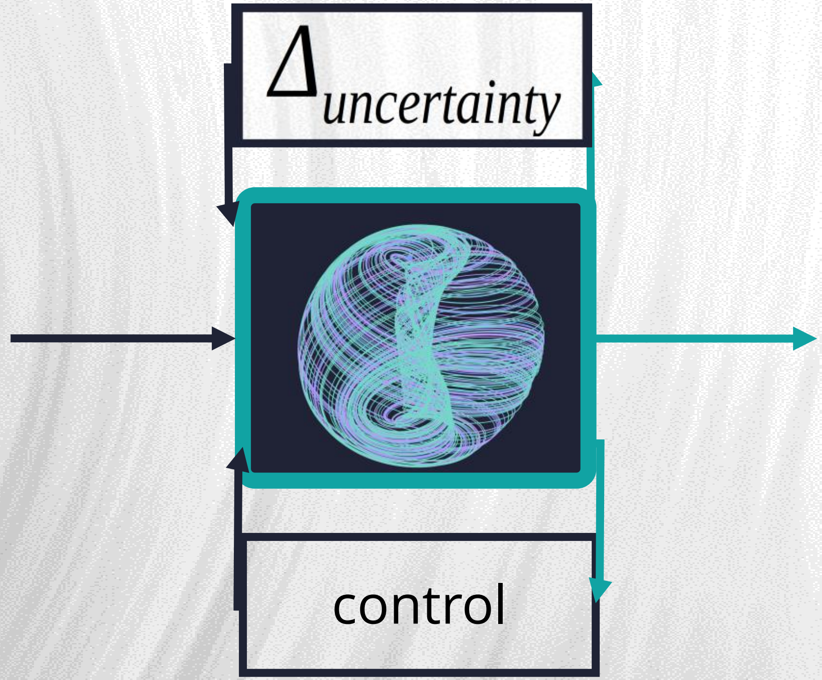
*See author list of E. Joffrin et al. Nuclear Fusion 2024, doi: 10.1088/1741-4326/ad2be4

ENERGY SYSTEMS & CONTROL



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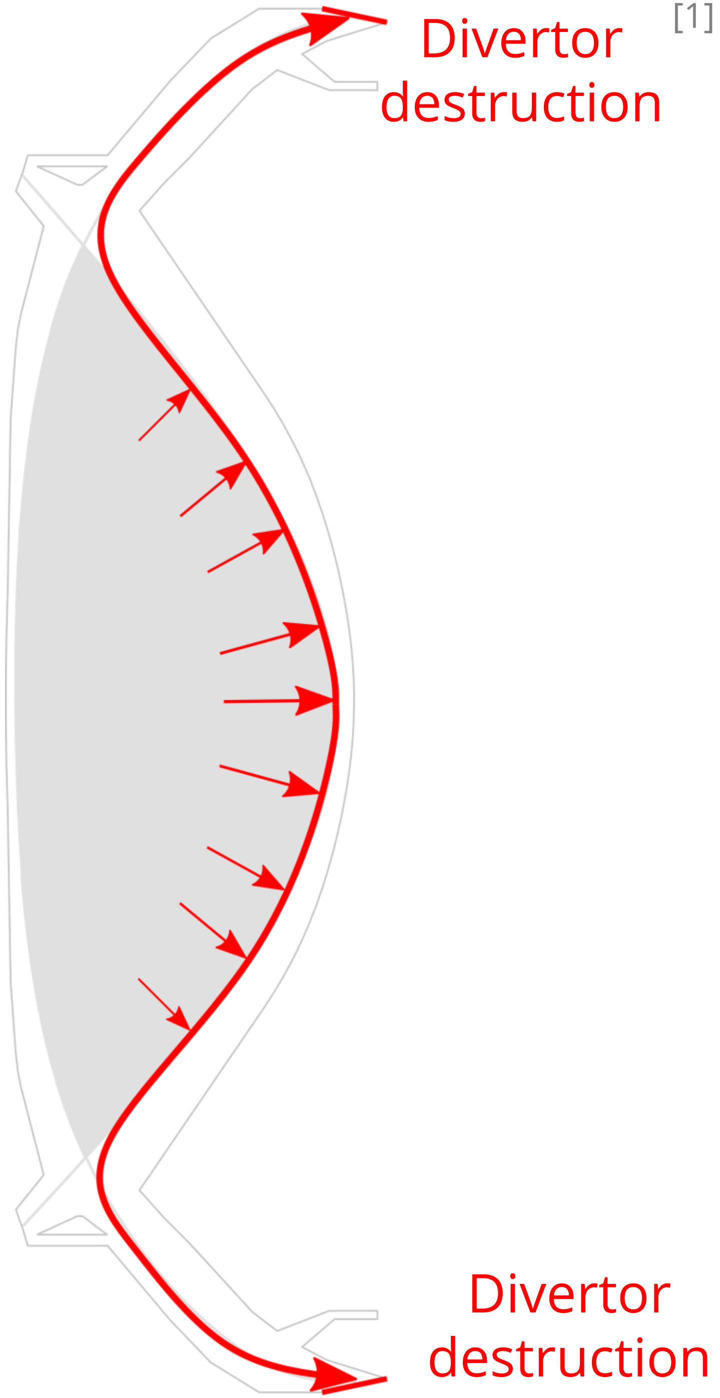
The exhaust problem

A control perspective

Exhaust problem

Heat load
- Divertor heat load greatly exceeds material limits [1]



Exhaust problem

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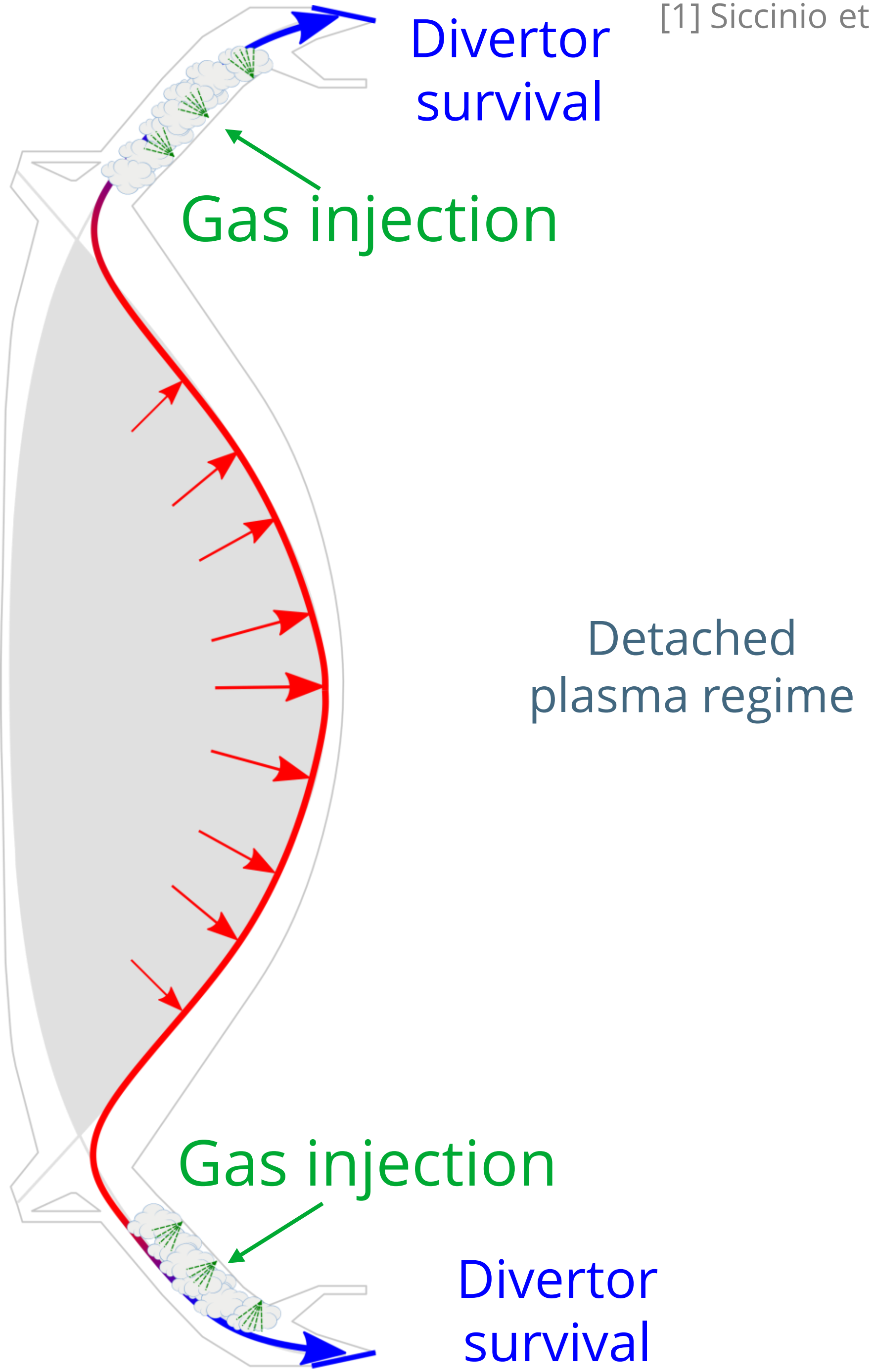
→ Injection of hydrogenic and impurity particles



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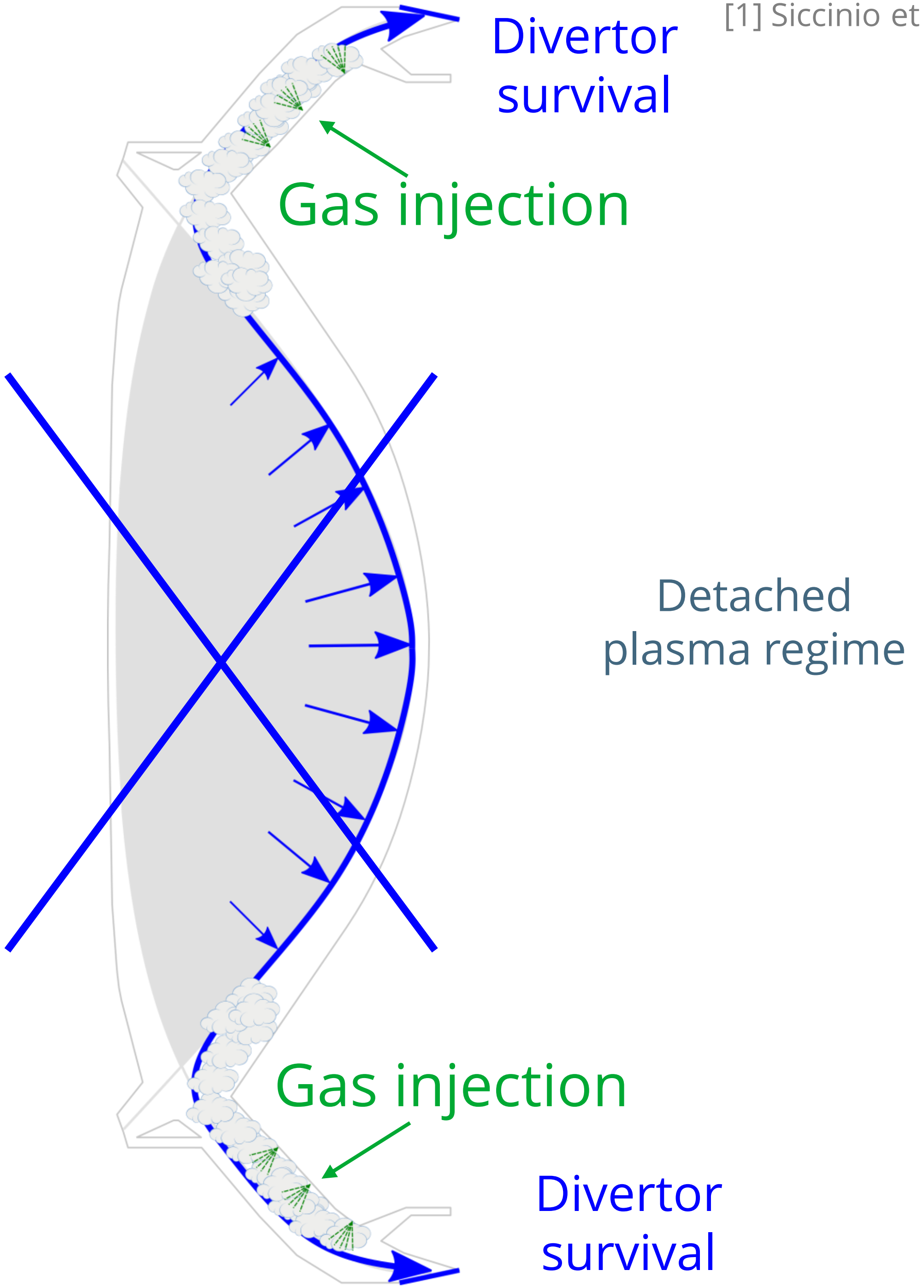
Core conditions
- Over injection promotes radiative instabilities



[1] Siccinio et al. 2022

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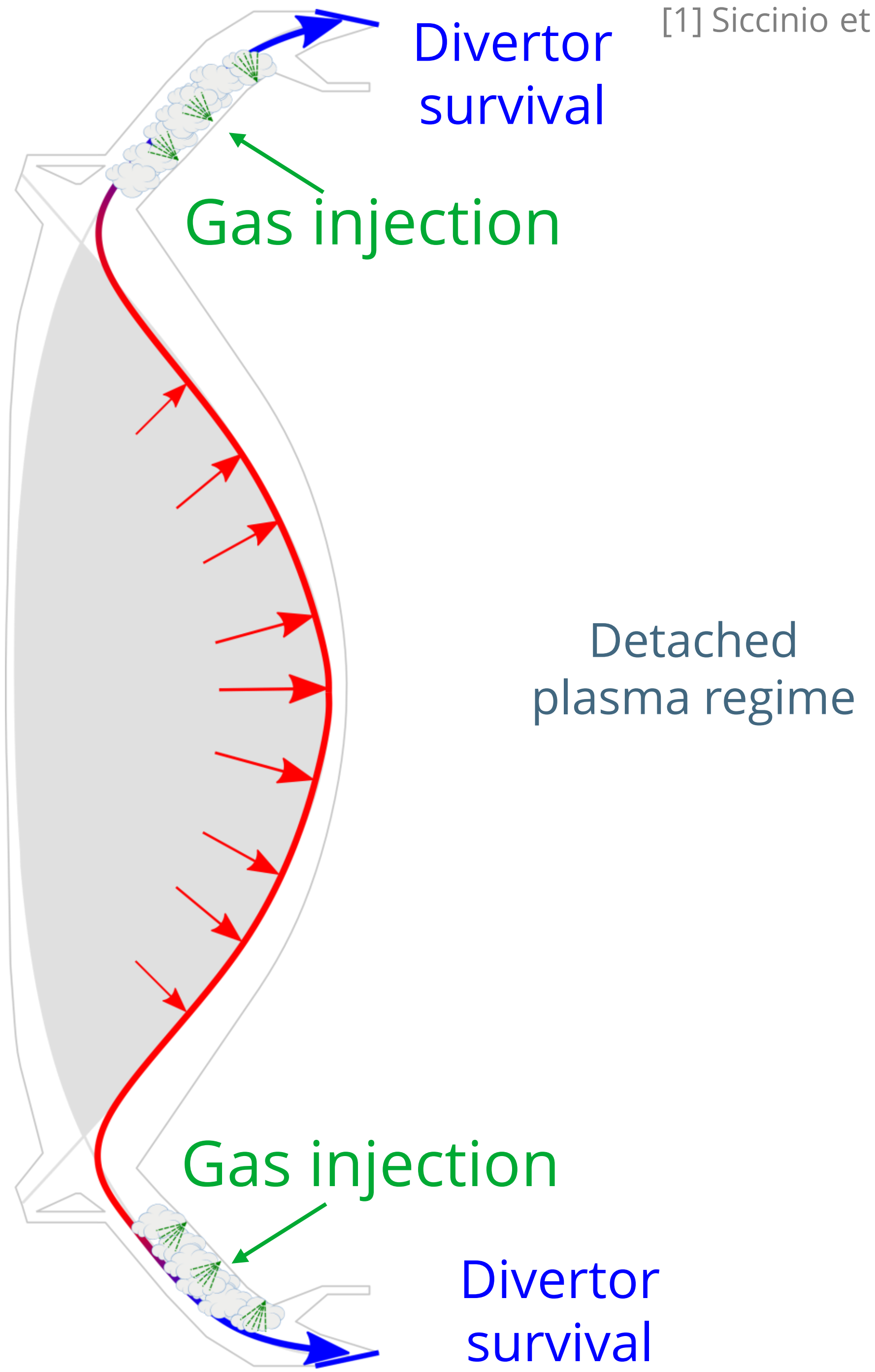
Exhaust control is a requirement!



Exhaust problem

Heat load
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Core conditions
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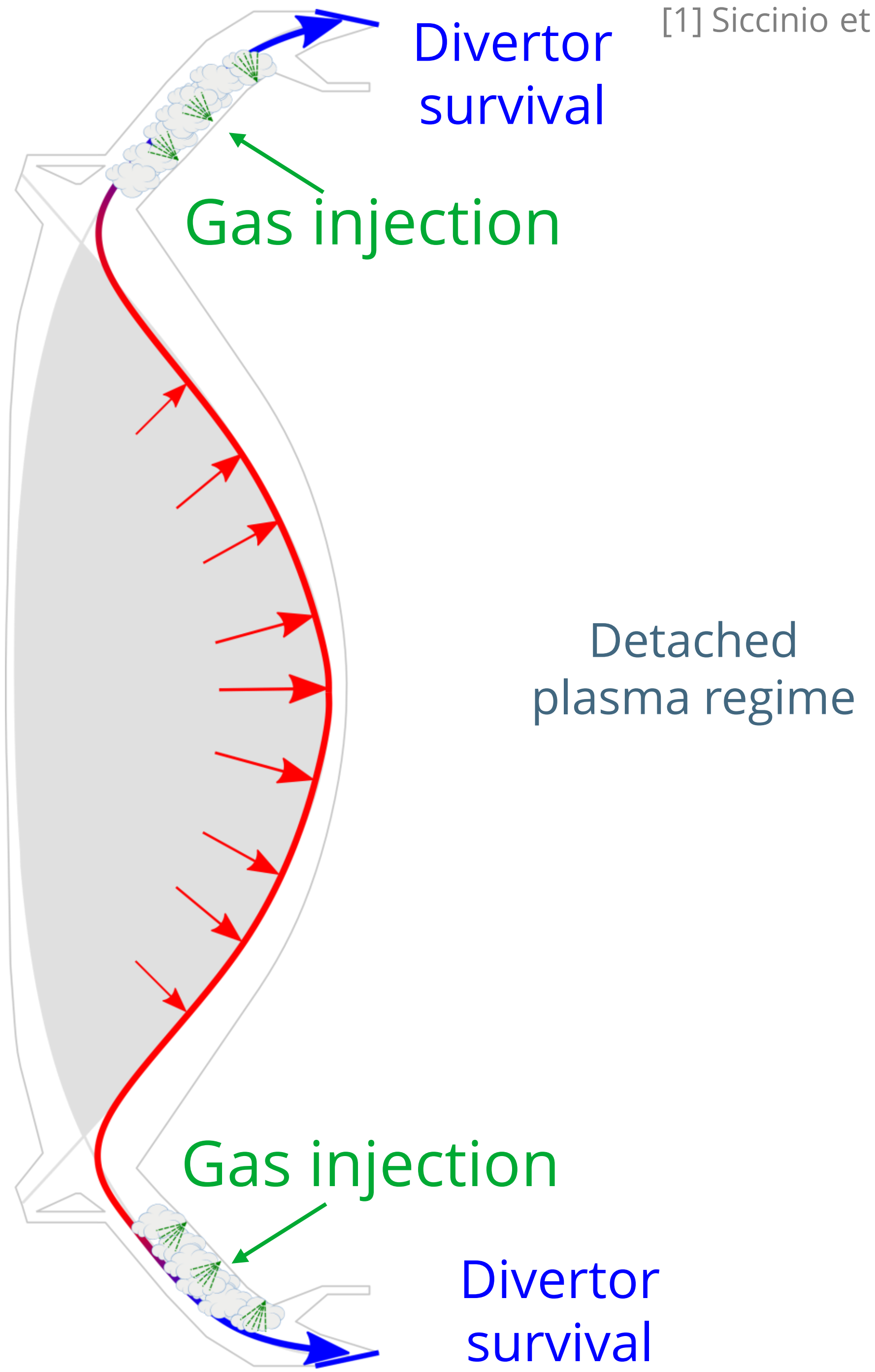
Exhaust control is a requirement!

Suppress transients from core
→ Challenging with slow gas actuators



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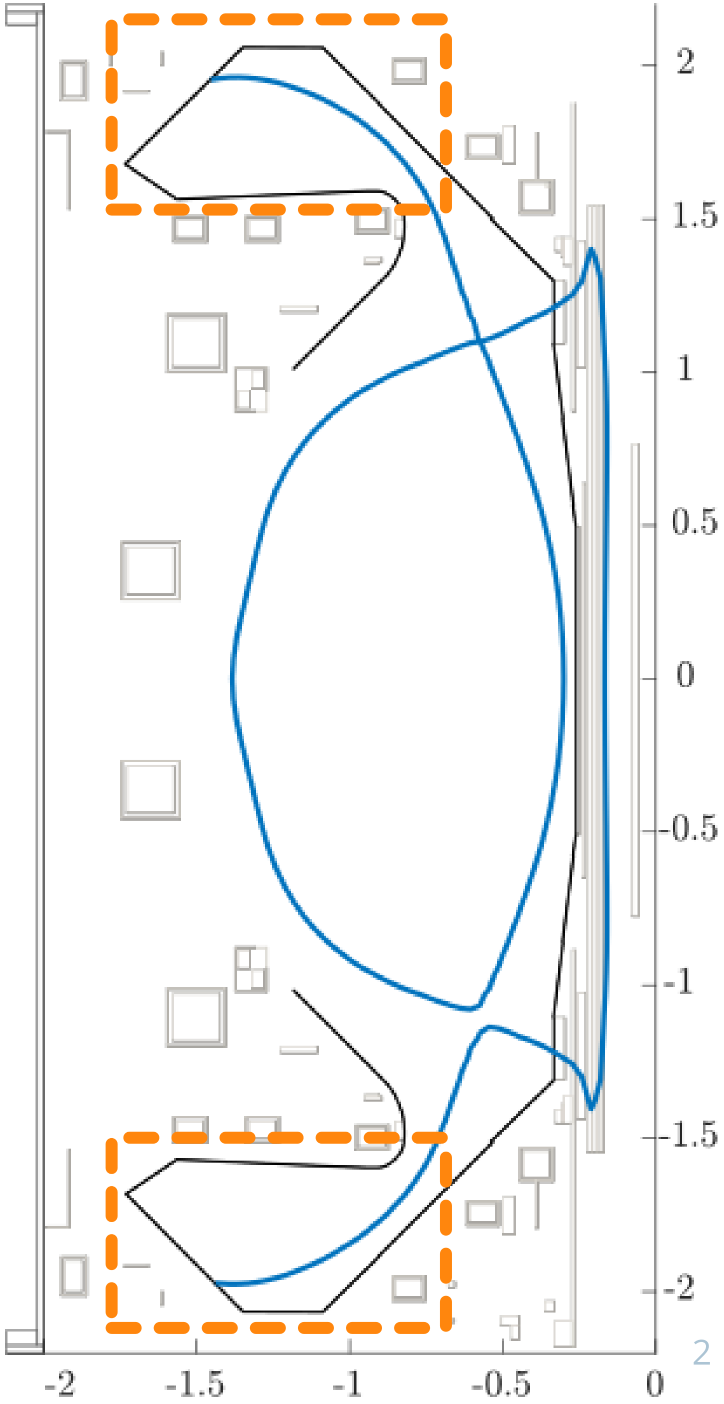
Exploring exhaust in MAST-U

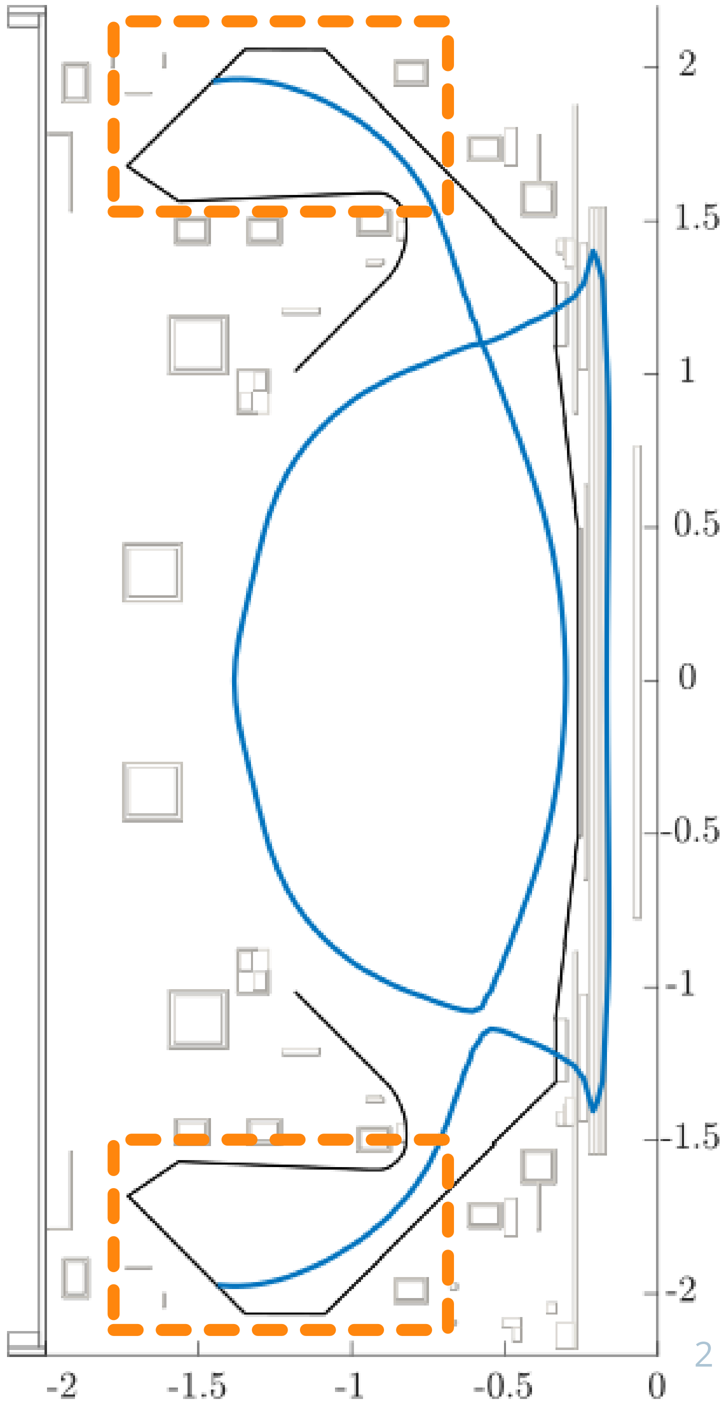
MAST-U

Exploring plasma exhaust
- Double-null configurations
  → Distribute heat load



MAST-U

Exploring plasma exhaust
- Double-null configurations
  → Distribute heat load
- Closed divertor chamber
  → Restrict flow of neutrals



MAST-U

Exploring plasma exhaust
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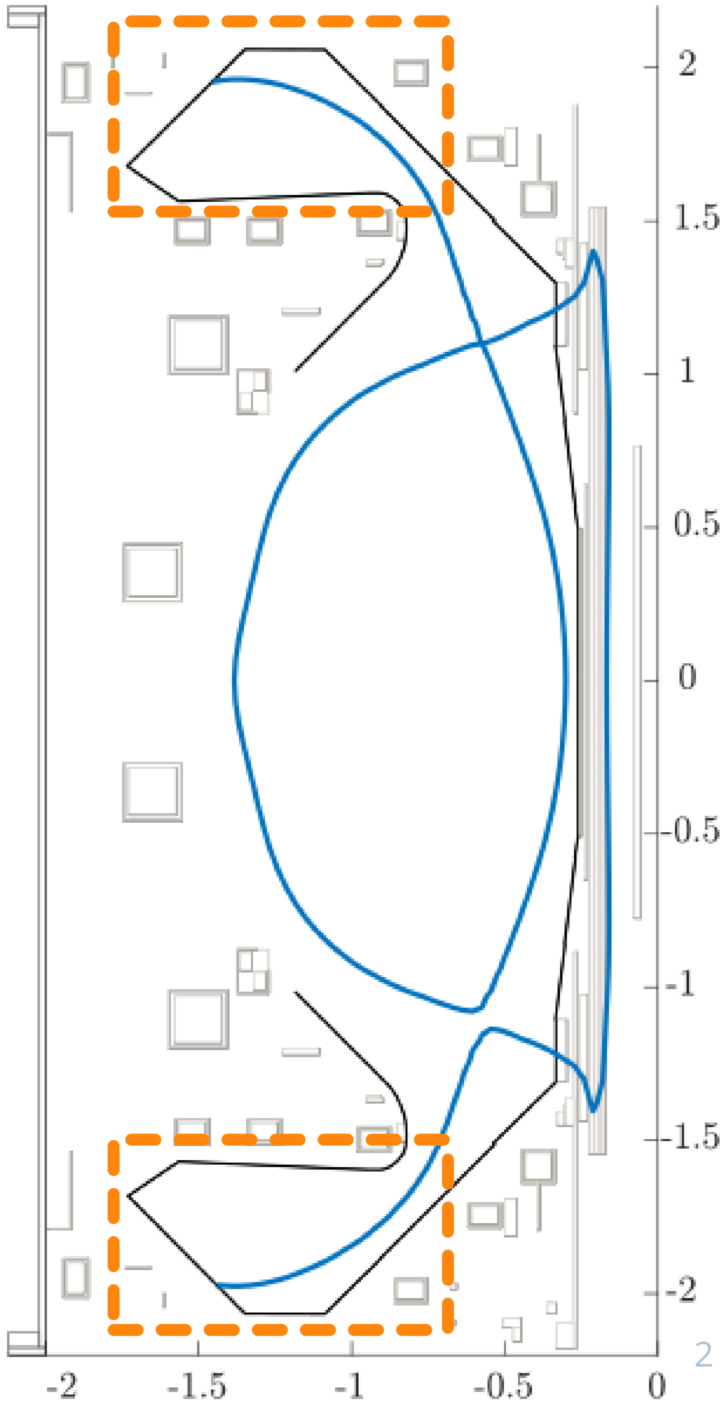
- Extreme shaping capabilities
  → Alternative Divertor Configurations



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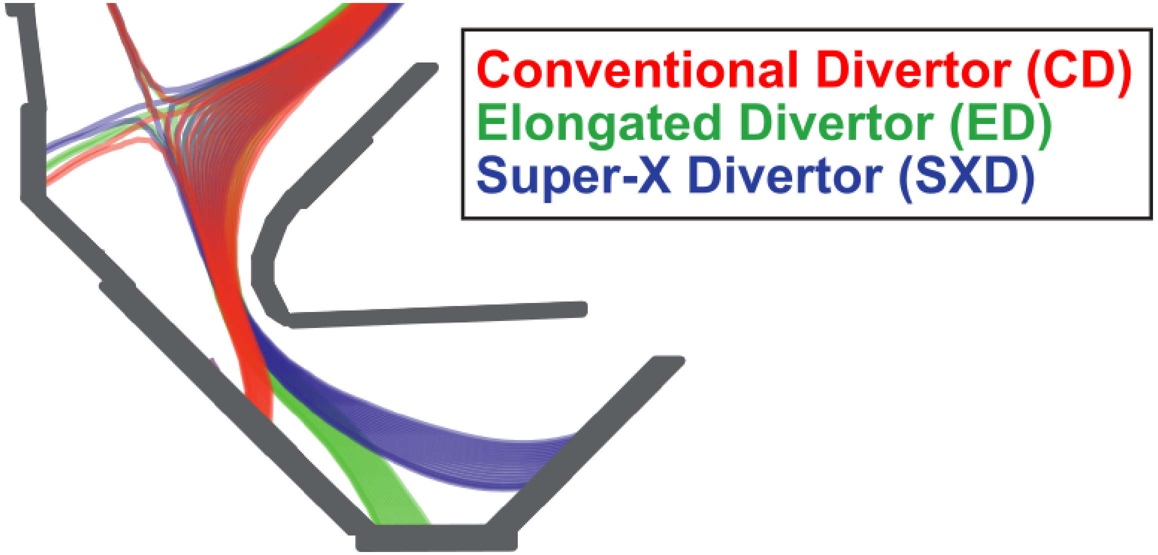
Alternative Divertor Configurations (ADCs)
Strong plasma shaping to improve performance [1]
→ ~20x decreased heat load (Super-X)
→ Much improved detachment access

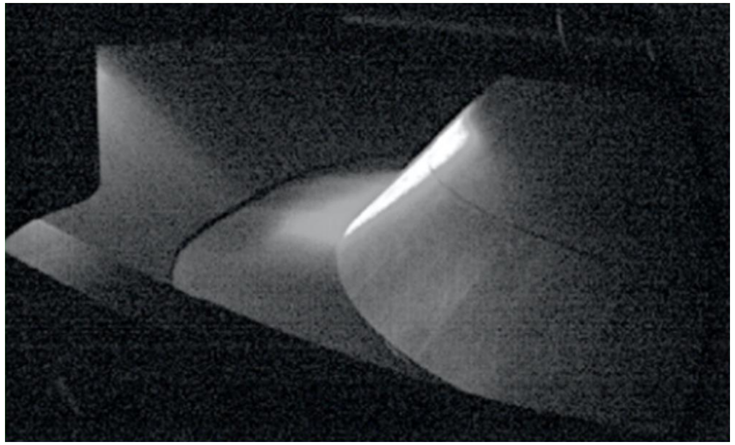


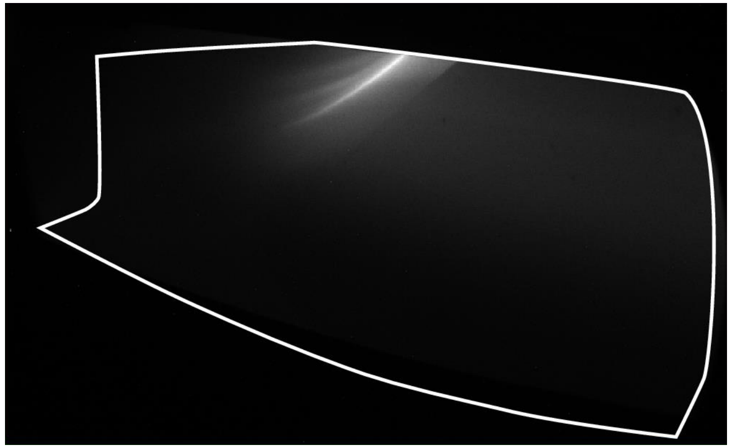
[1] K. Verhaegh et al. 2025

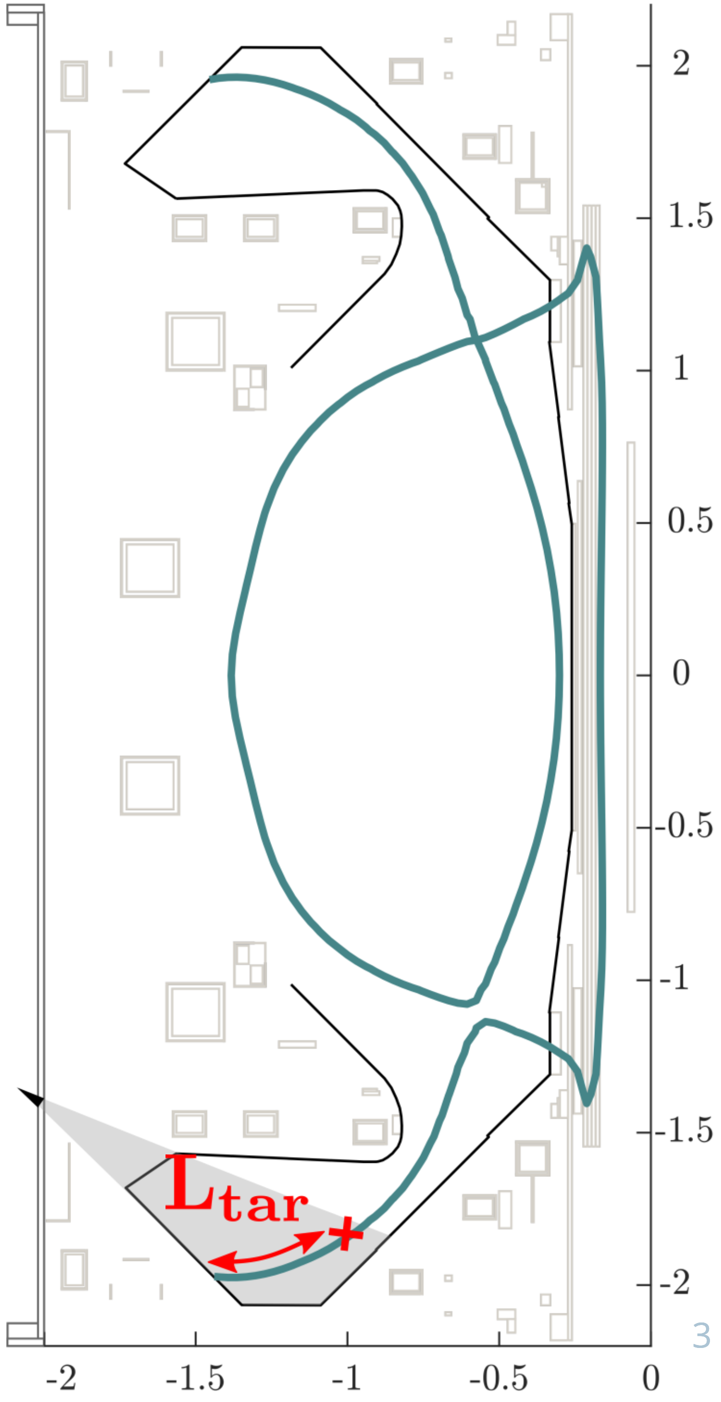
Exhaust control in ADCs

Exhaust sensor

Diagnostic
MWI filtered camera system [1,2]
Fulcher band emission front position
→ Proxy for ionisation region [3]
→ Real-time tracking, 400 Hz [4]







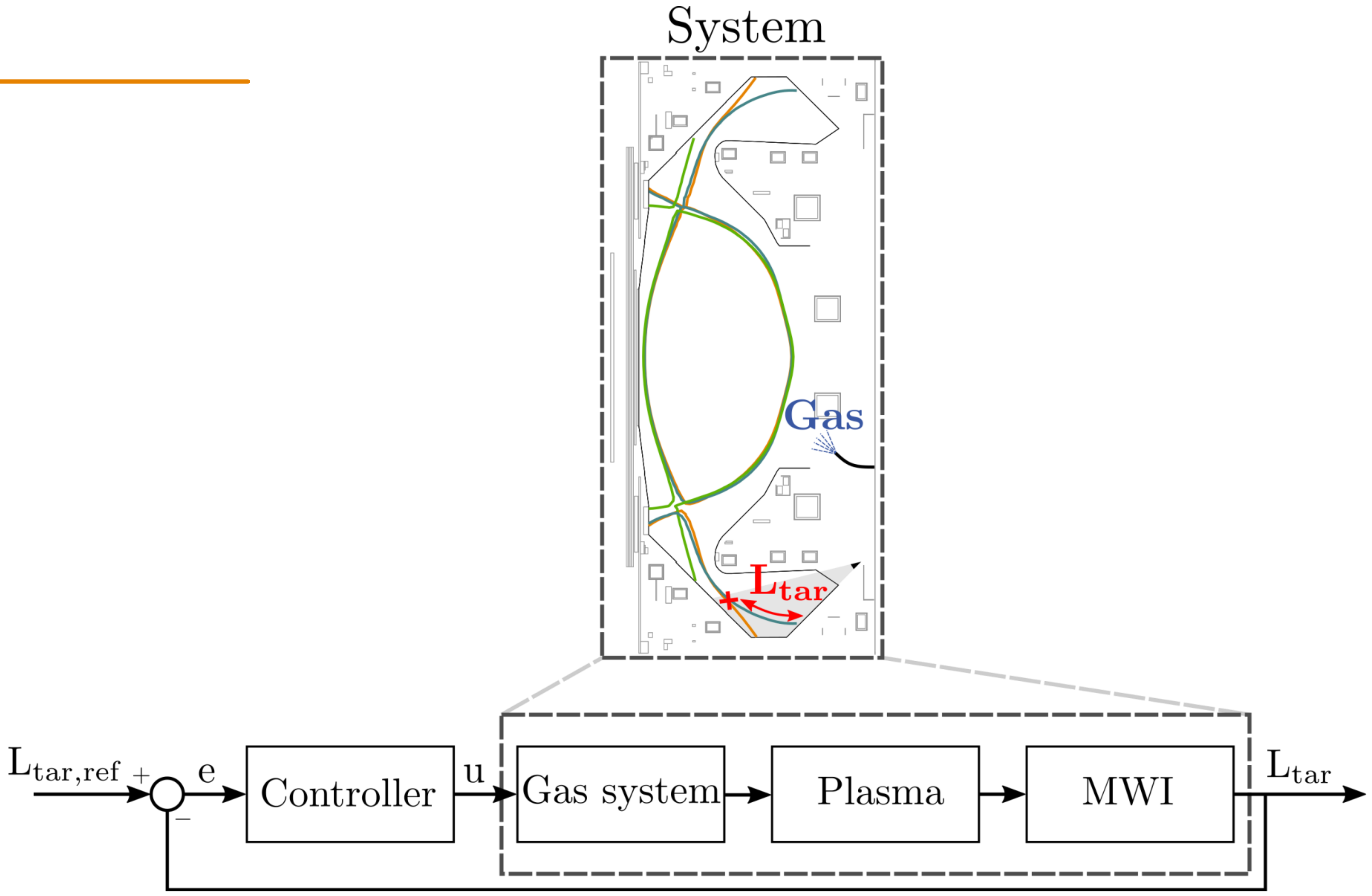
[1] X. Feng et al. 2021
[2] A. Perek et al. 2019
[3] K. Verhaegh et al. 2023
[4] T. Ravensbergen et al. 2020

The control loop

Goal:
Control front position

Input:
D_2 valve midplane

Ouput:
Fulcher band front position



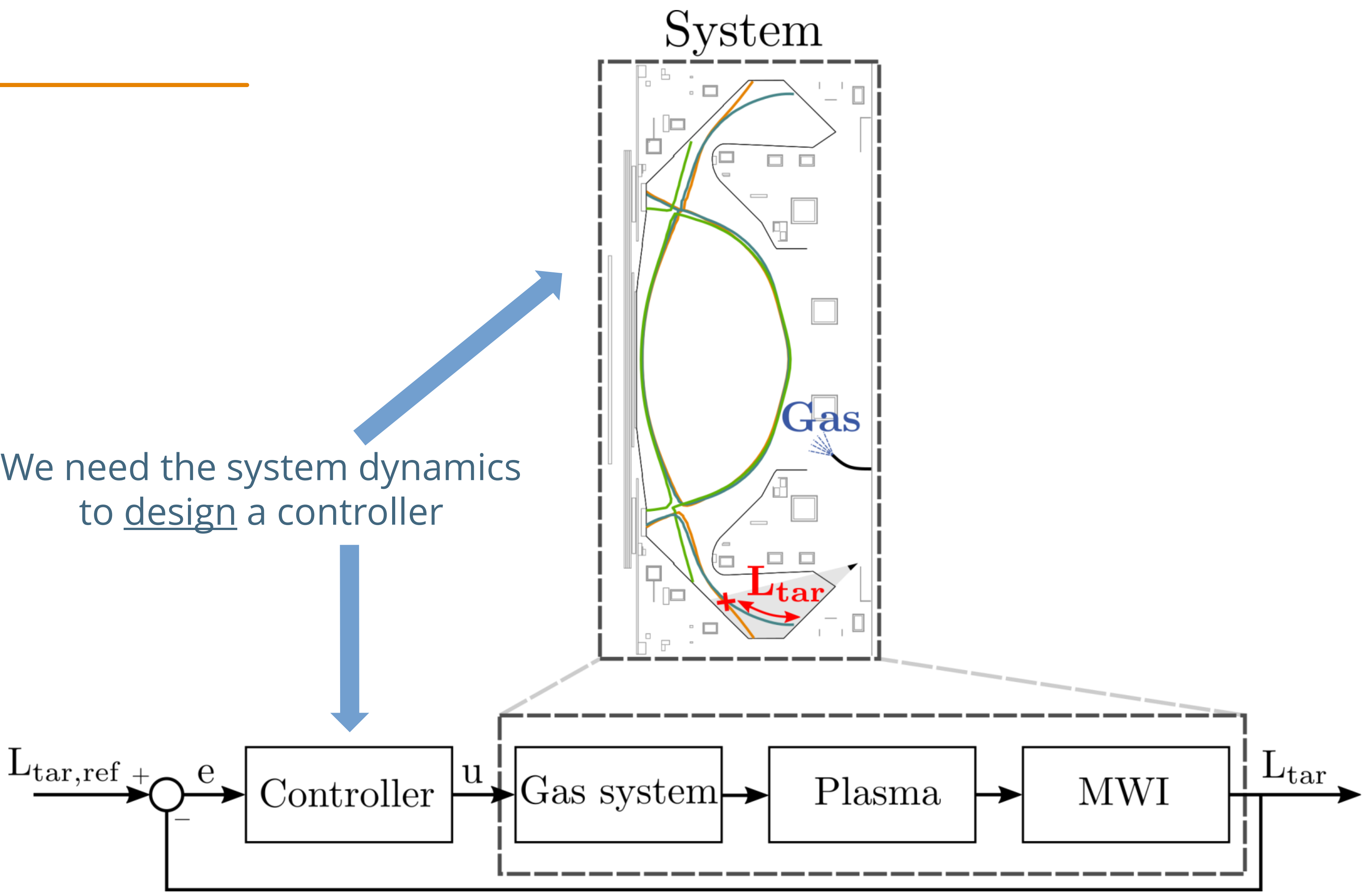
The control loop

Goal:
Control front position

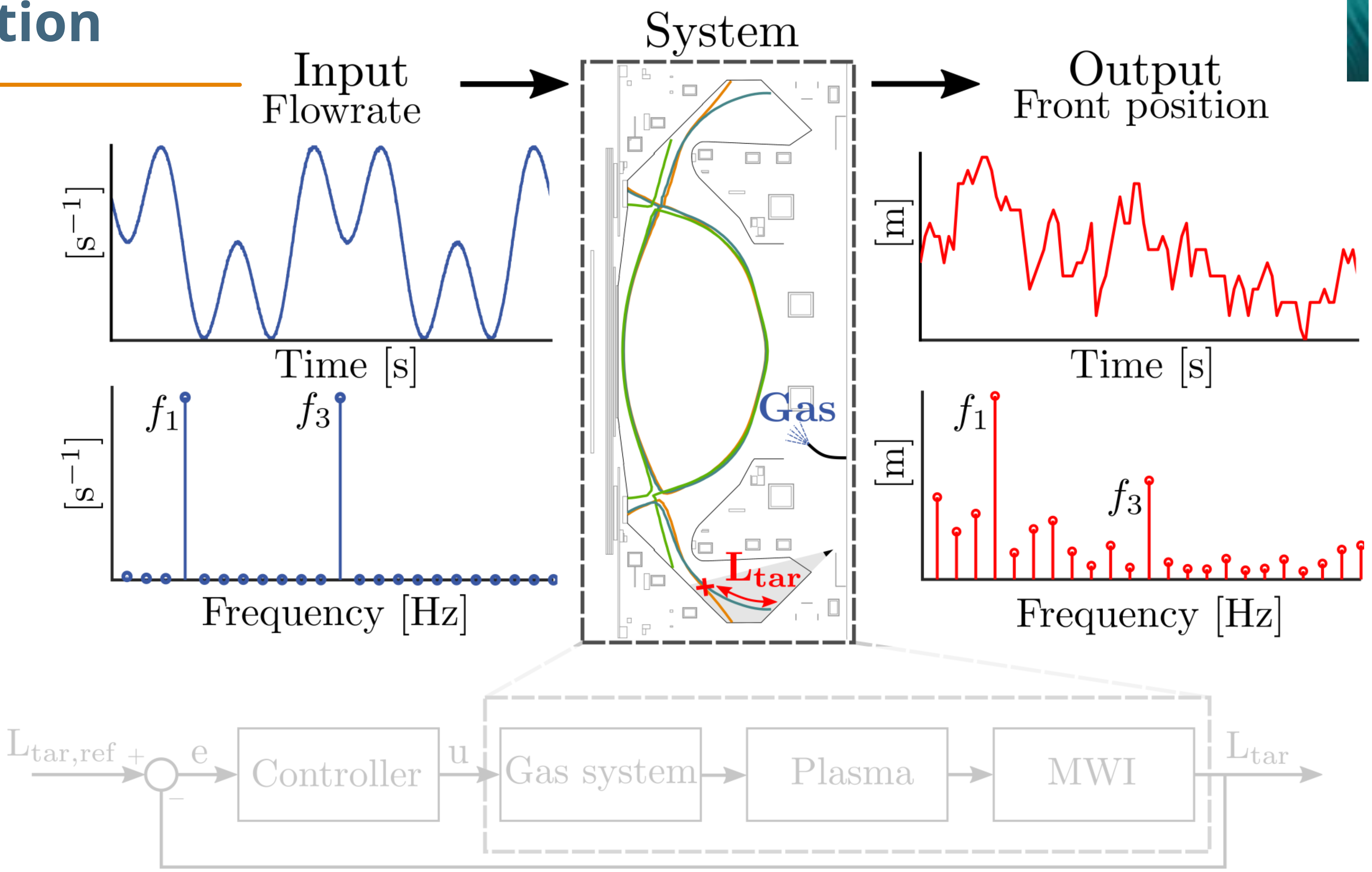
Input:
D_2 valve midplane

Ouput:
Fulcher band front position

We need the system dynamics
to <u>design</u> a controller

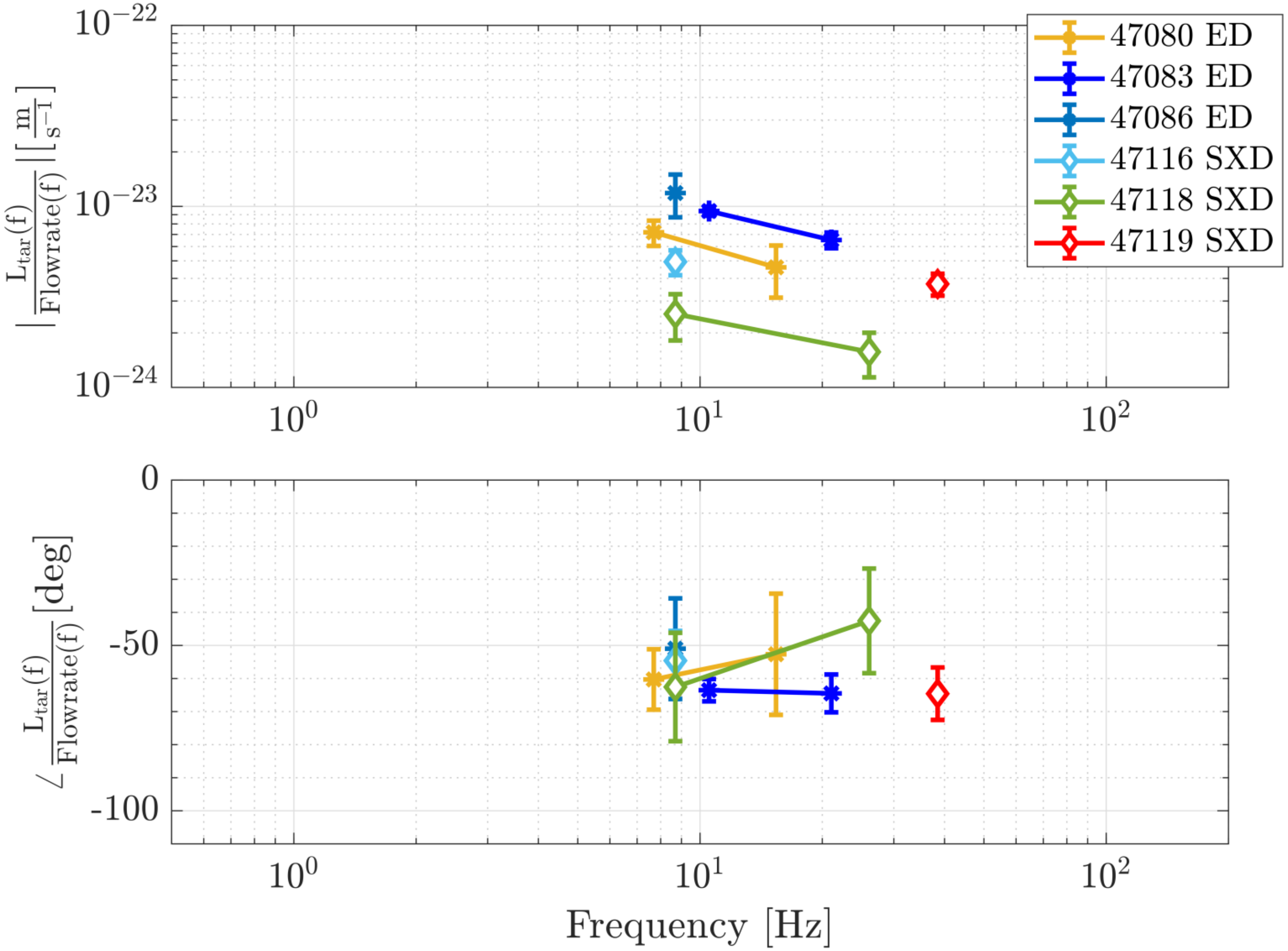


System Identification



System Response

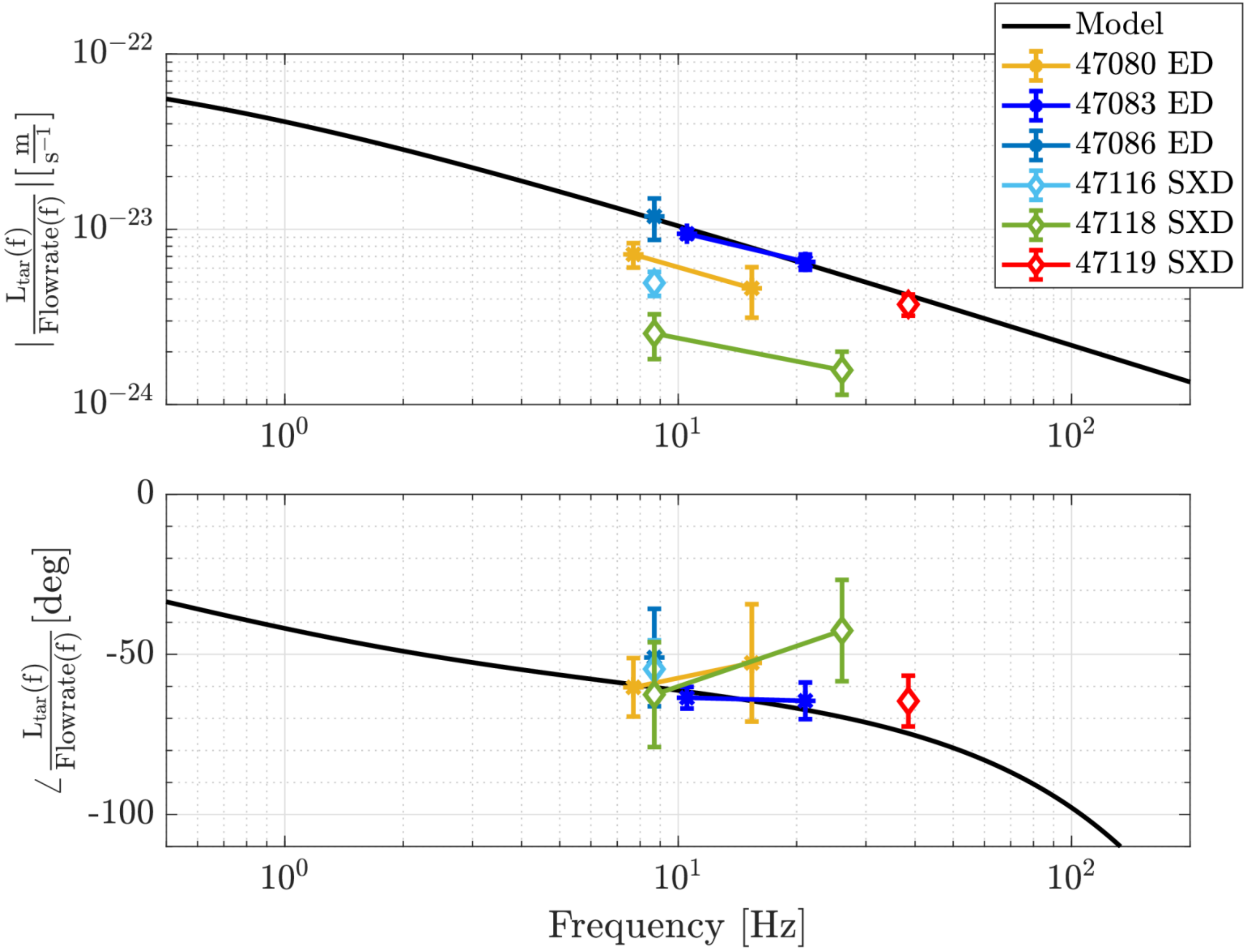
Frequency Response Function (FRF)
Output over input
→ Description of linear dynamics



System Response

Frequency Response Function (FRF)
Output over input
→ Description of linear dynamics

Model
Fit of simple model
→ Reproduce dynamics



System Response

Frequency Response Function (FRF)
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Fit of simple model
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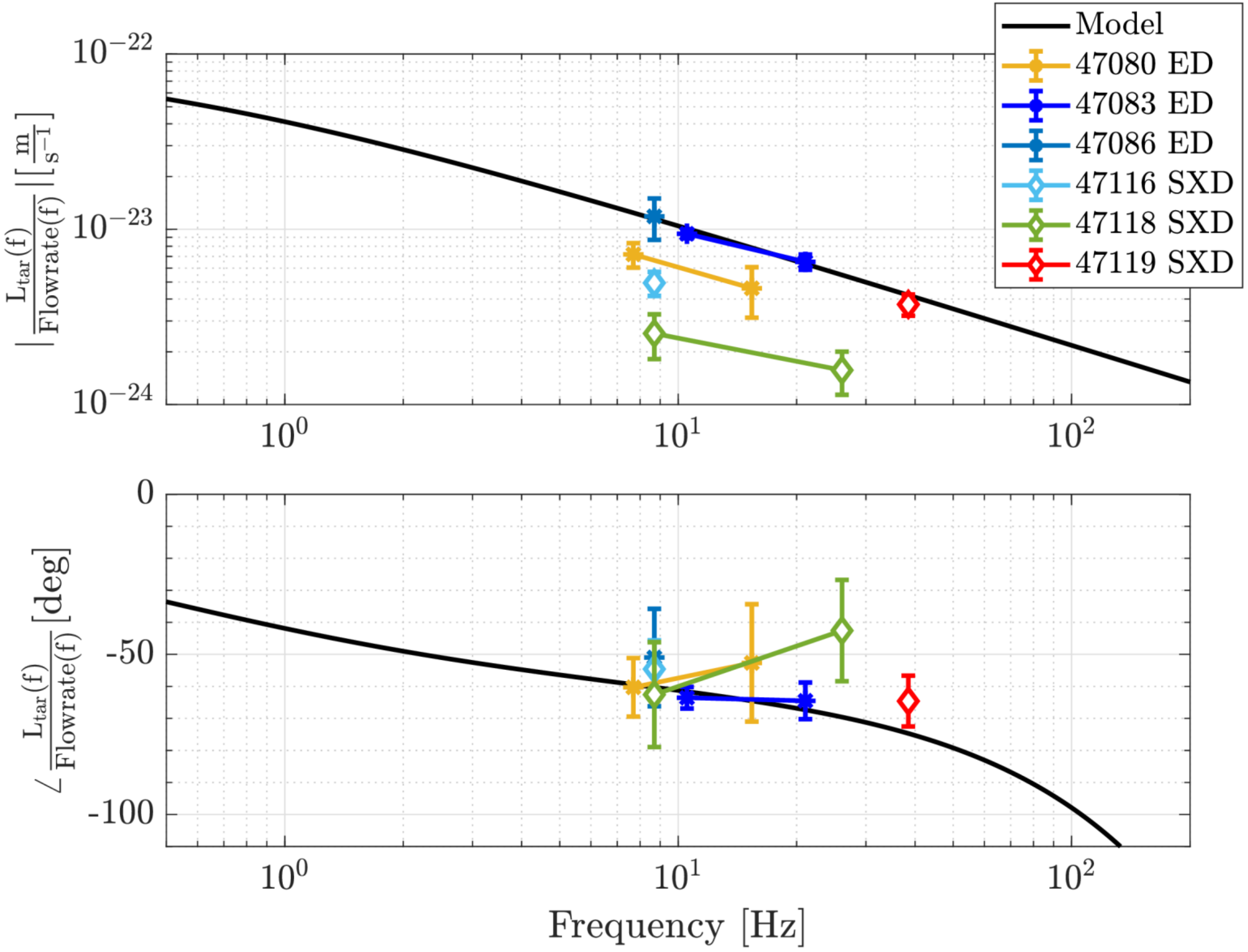
Control design
Proportional-Integral controller
→ Control front position



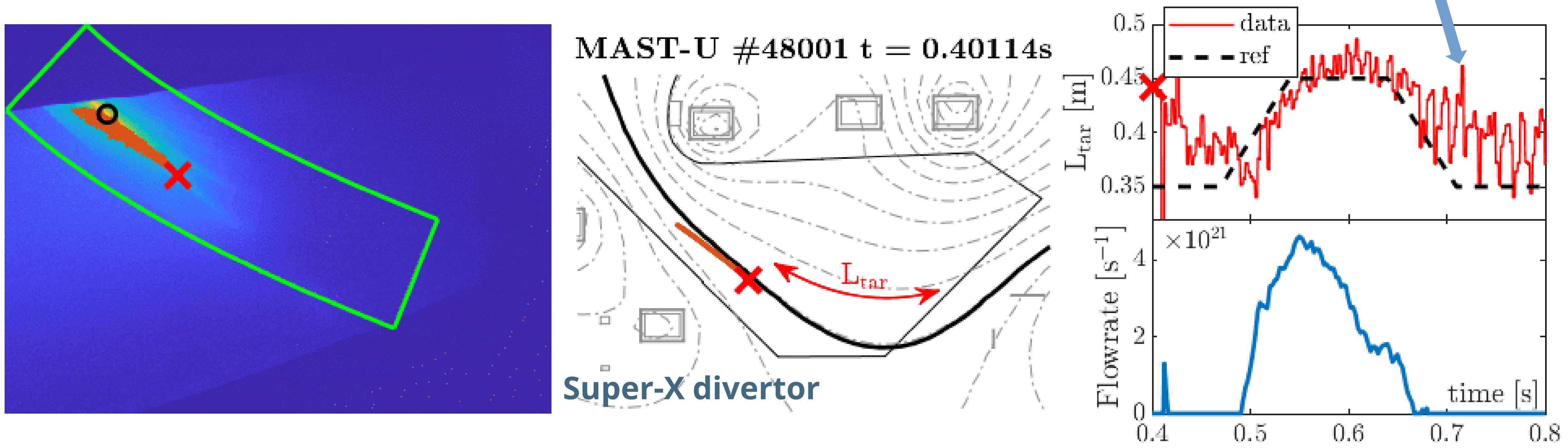
B. Kool, et al. *Nat Energy* (2025). https://doi.org/10.1038/s41560-025-01824-7

First ADC Exhaust control

Difficult to move the front down

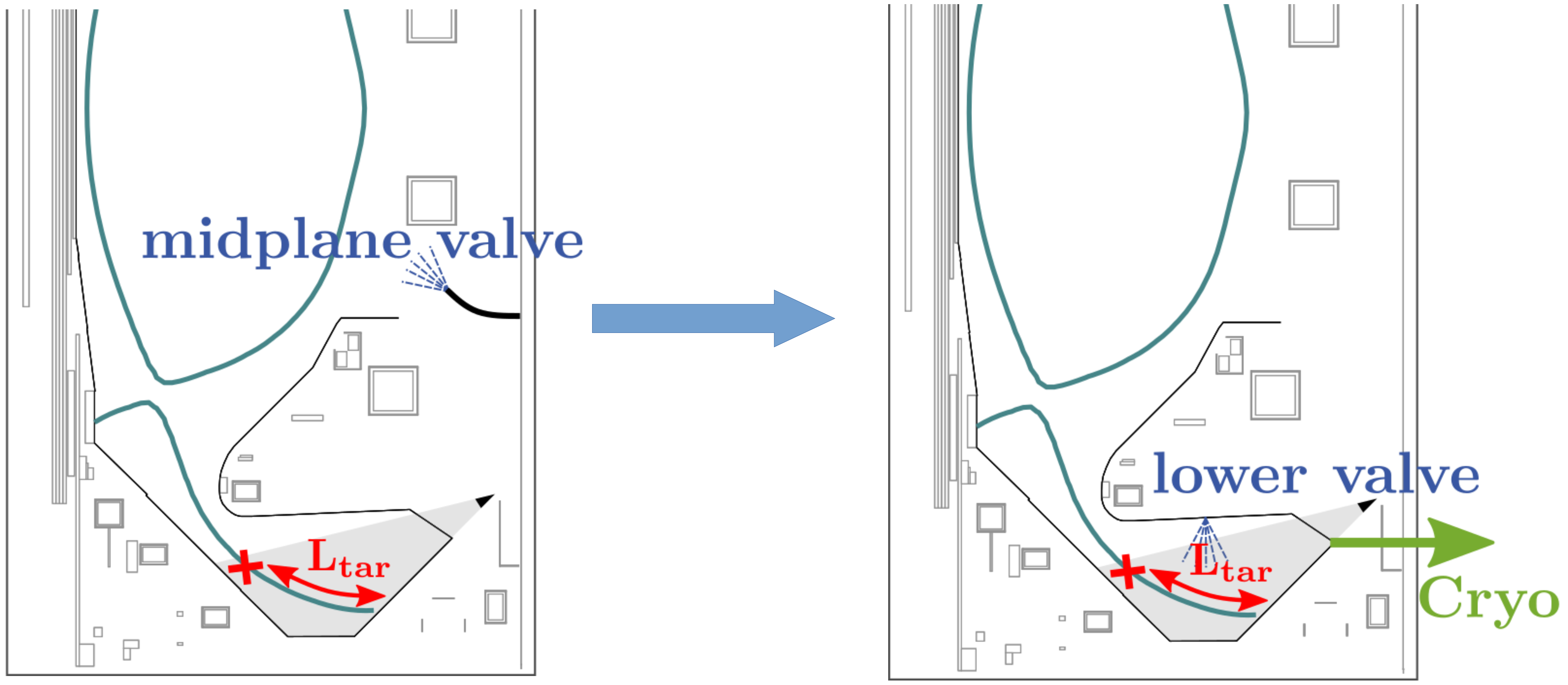
Success in both Elongated and Super-X configuration!

→ **Demonstrated that alternative divertors can be controlled**



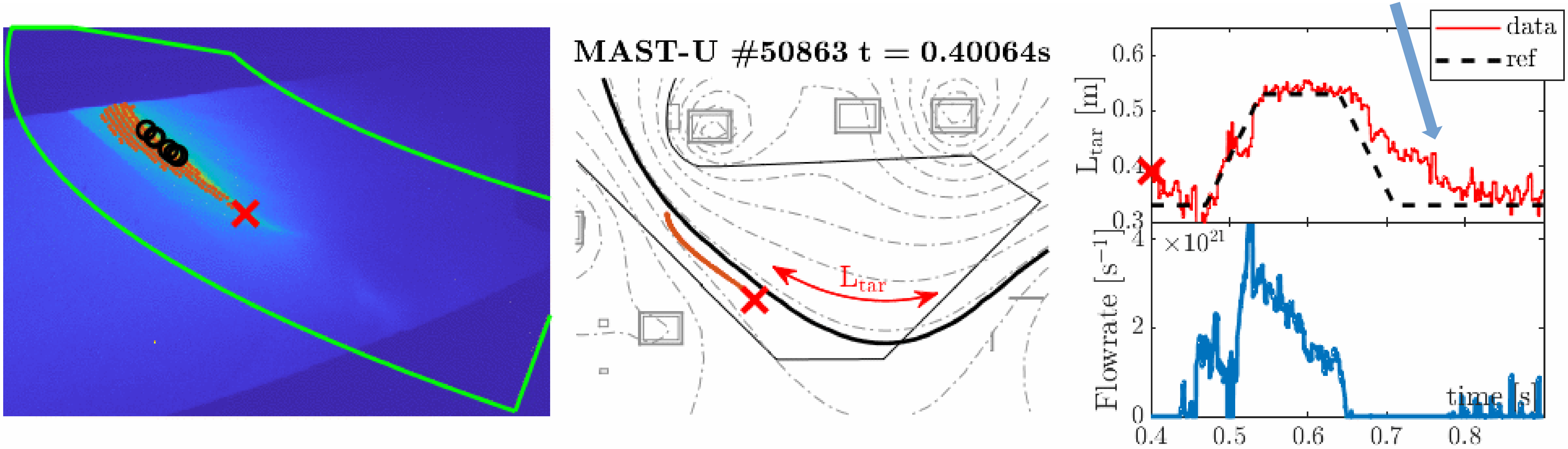
The importance of pumping

Divertor valve + cryopumping

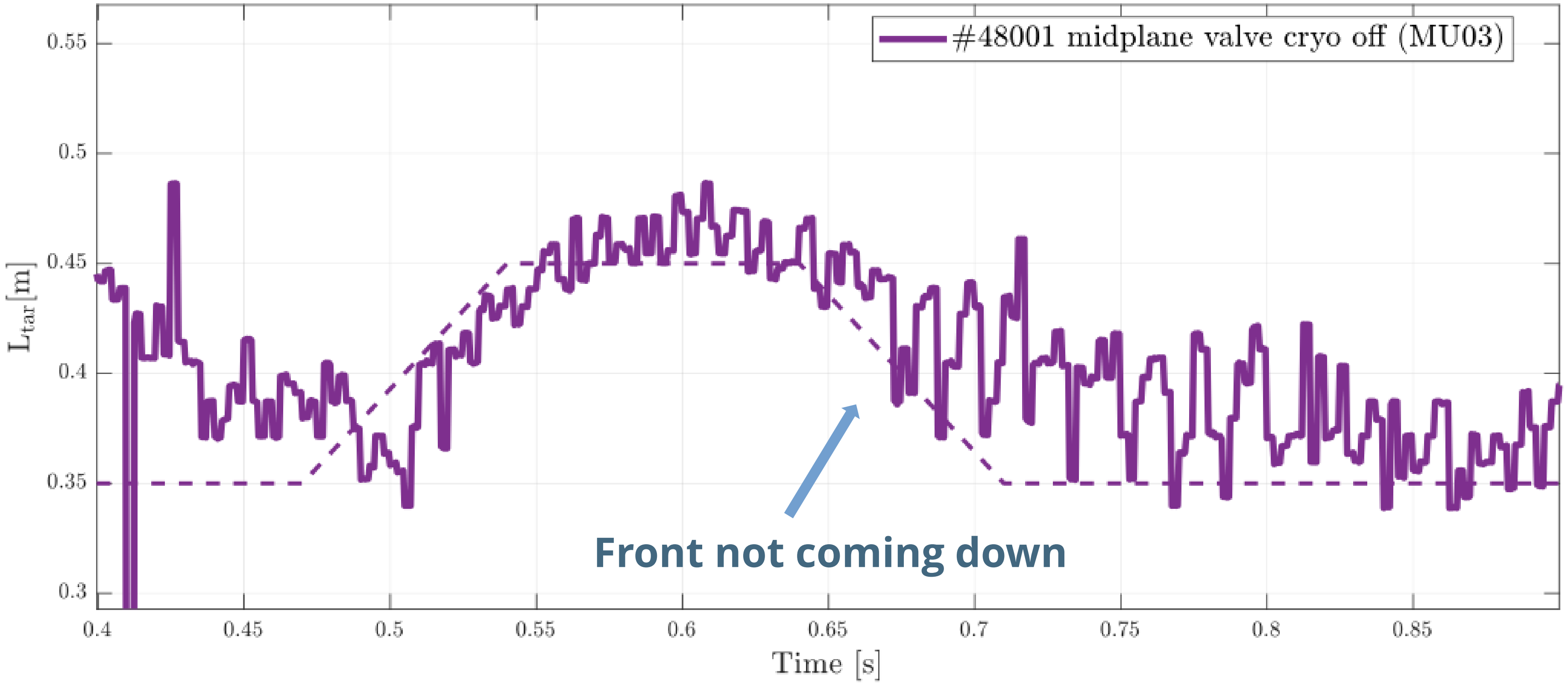


Divertor valve + cryopumping

Front coming back down!



Comparison to mid plane valve without Cryo



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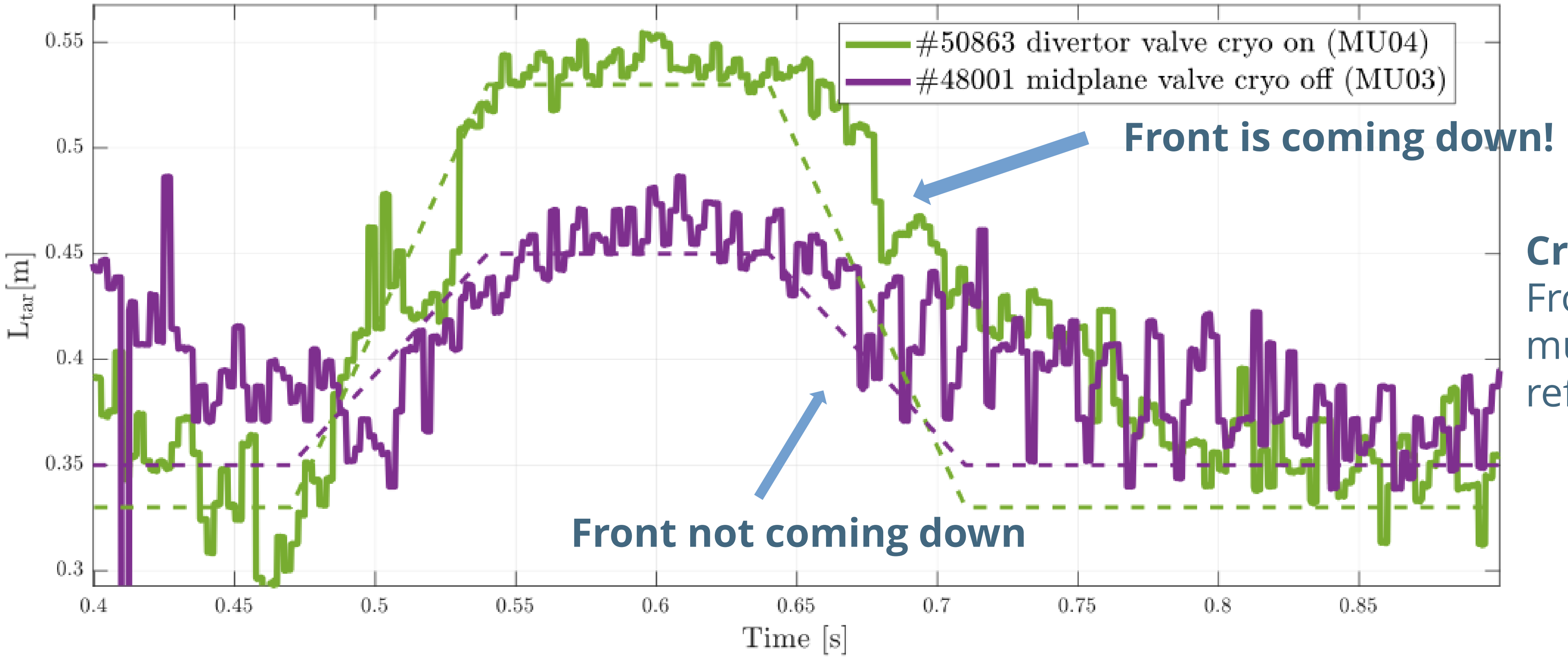
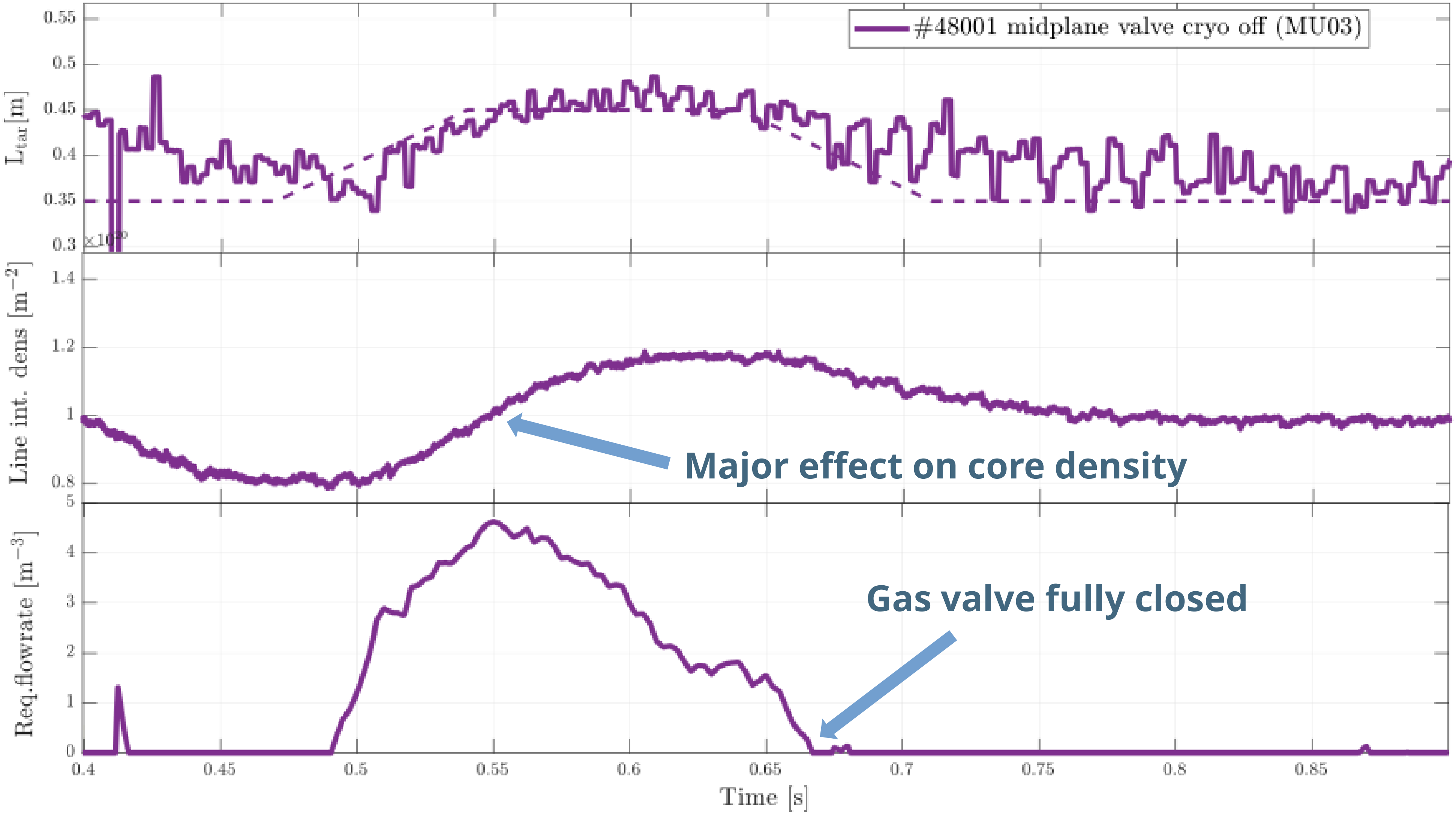


Cryo + divertor valve
Front moving down despite much more challenging reference!

Comparison to mid plane valve without Cryo



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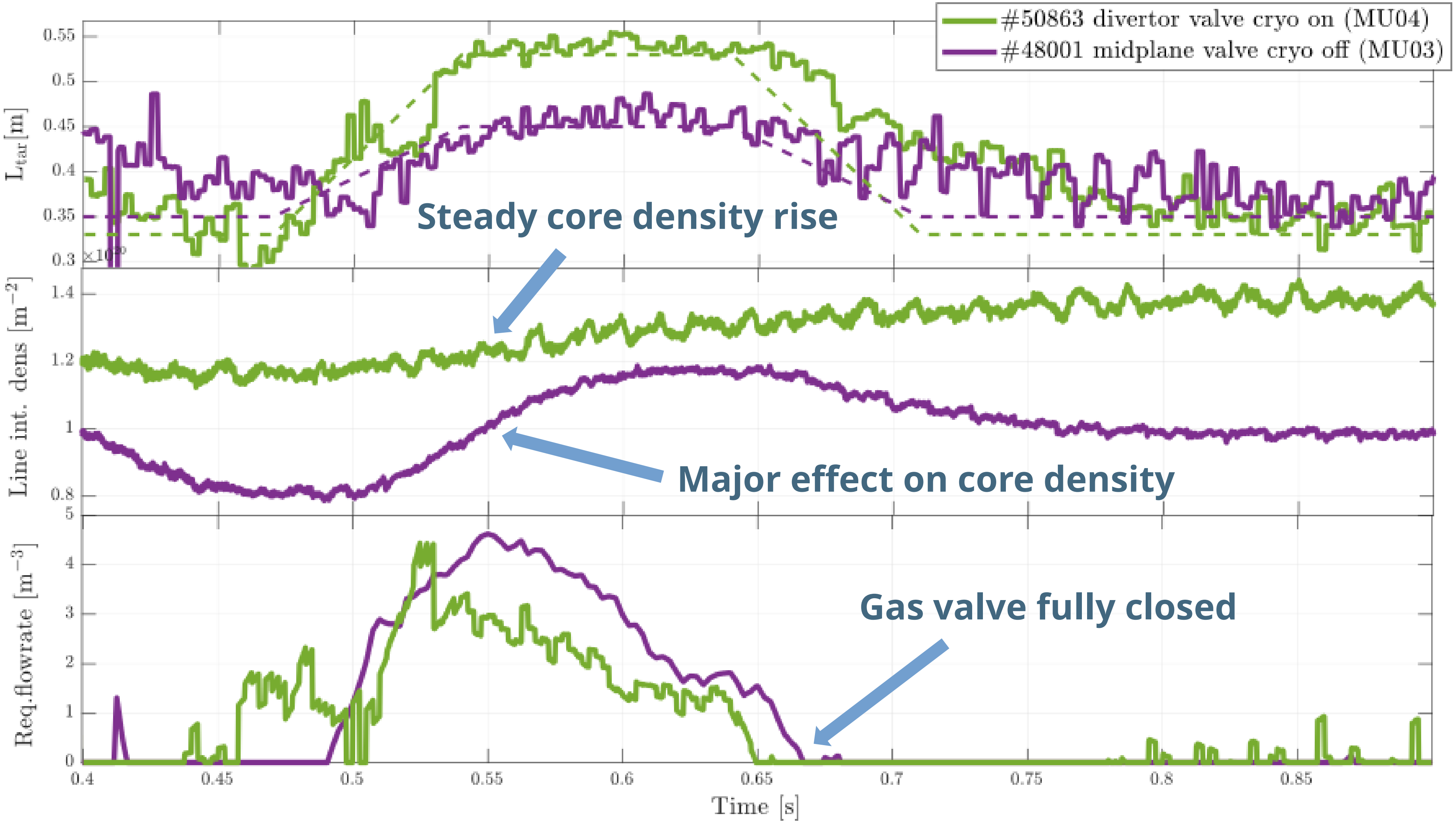

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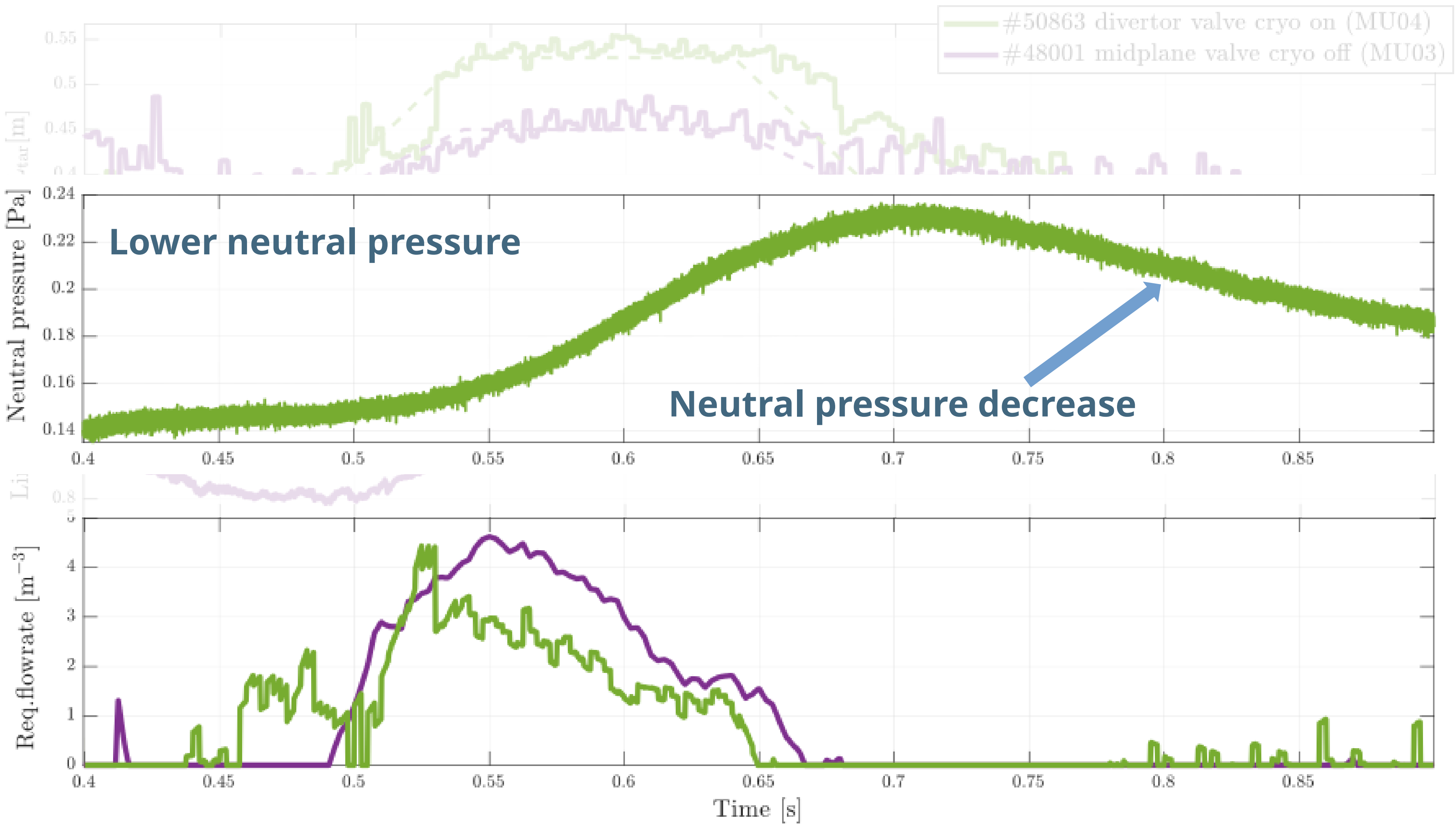
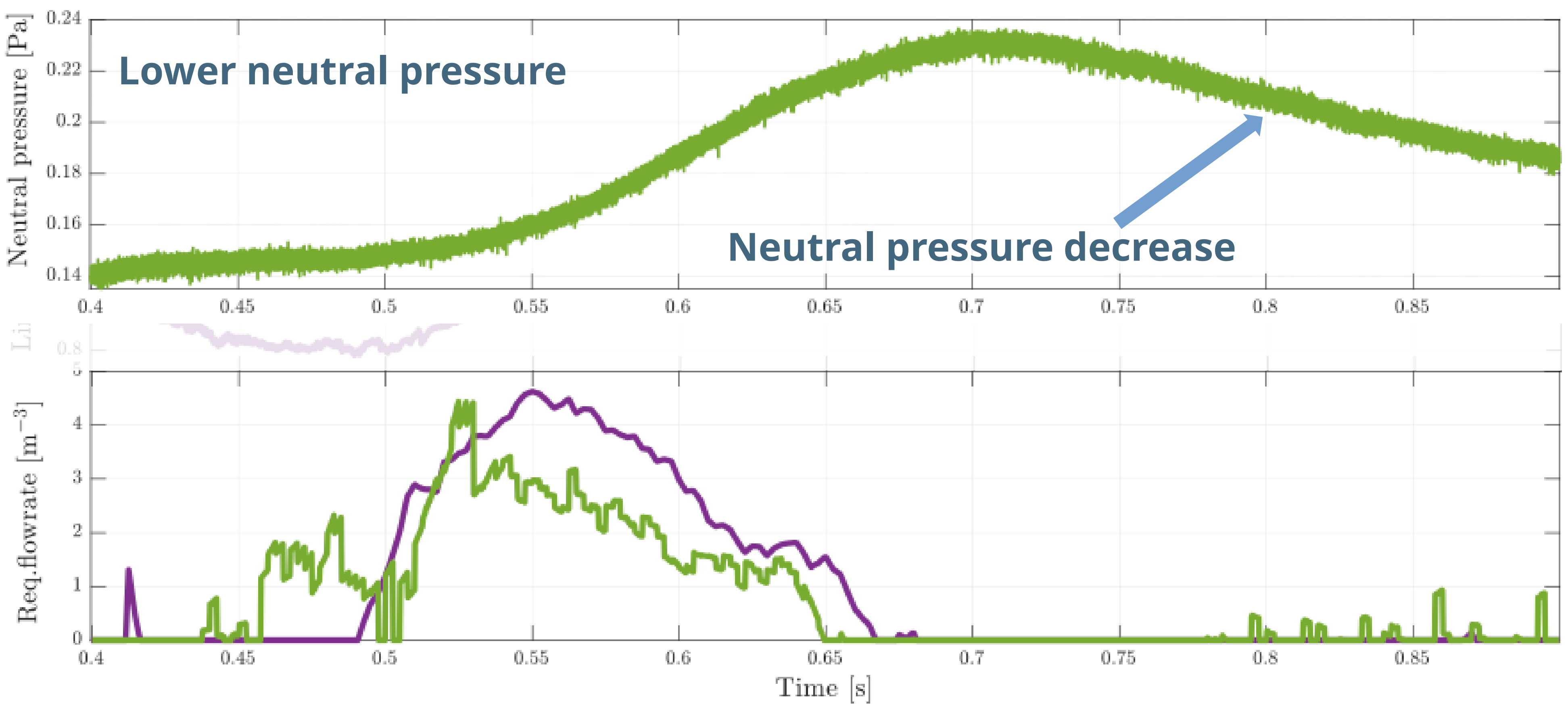


No pressure data available during midplane valve feedback control

Comparison to mid plane valve without Cryo

→ Adequate pumping is **vital** for exhaust control

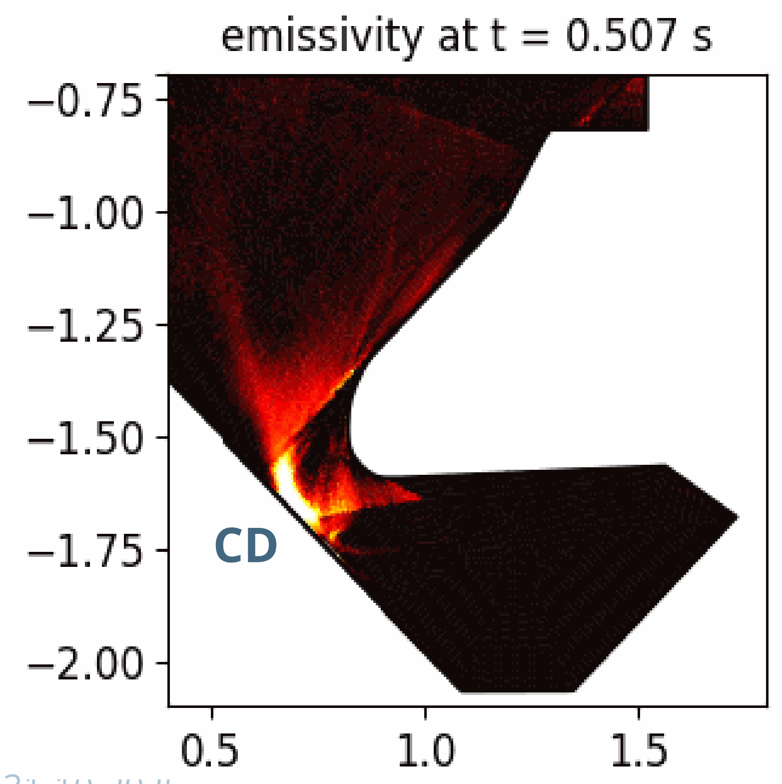


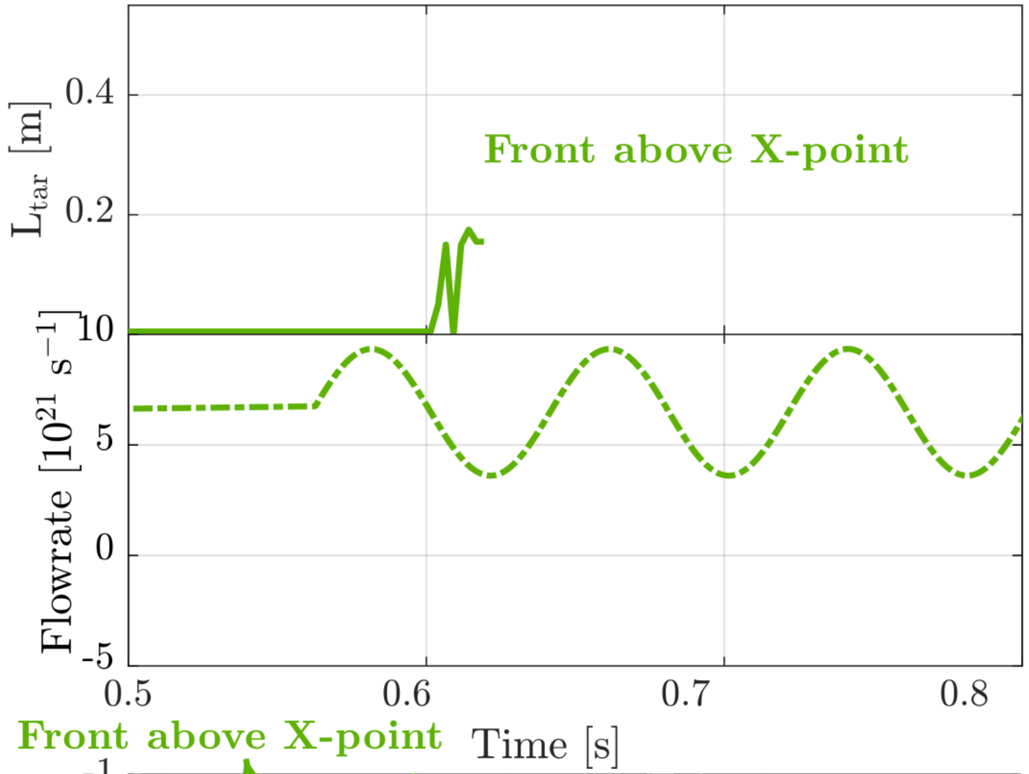
No pressure data available during midplane valve feedback control

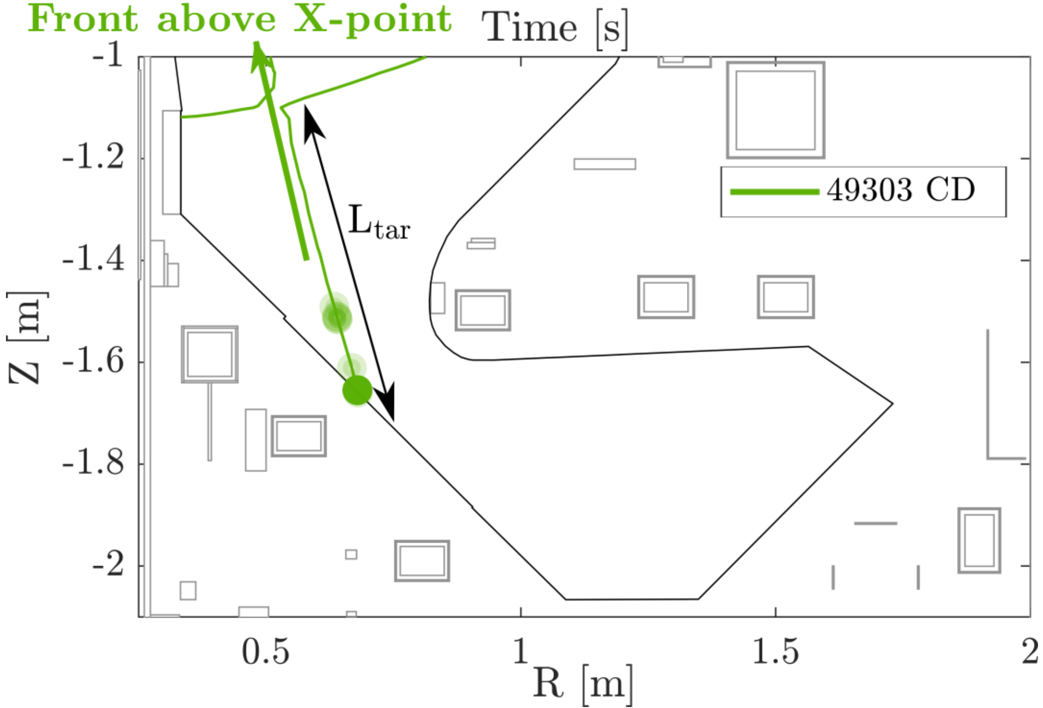
ADC advantage:
→ *Passive absorption*

System Response

Results:
Similar perturbation of midplane of gas valve:
- CD: large perturbation – outside operating range





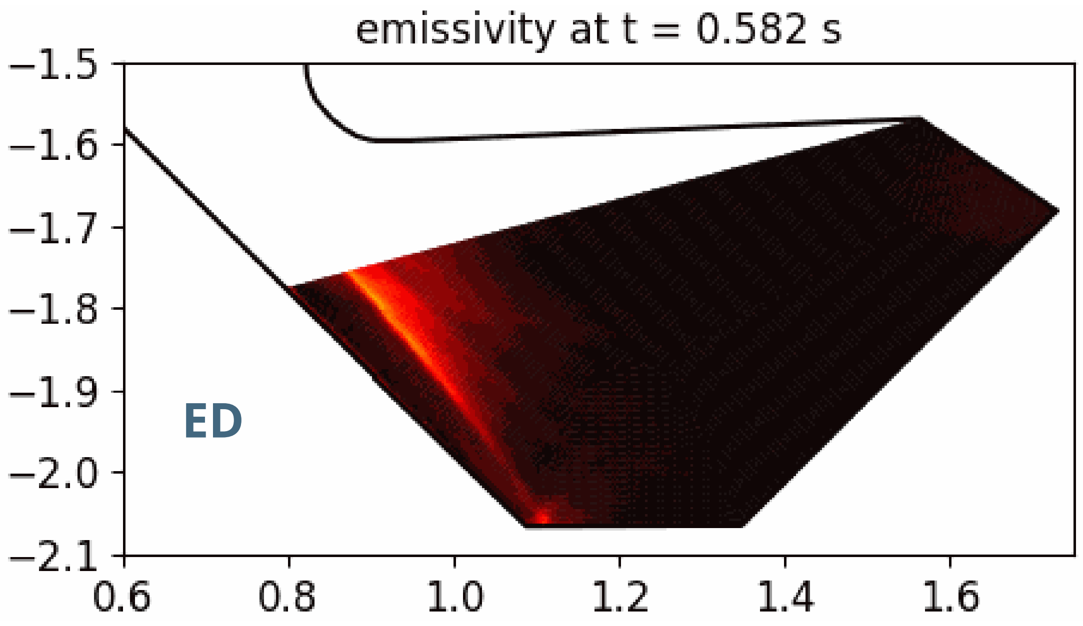


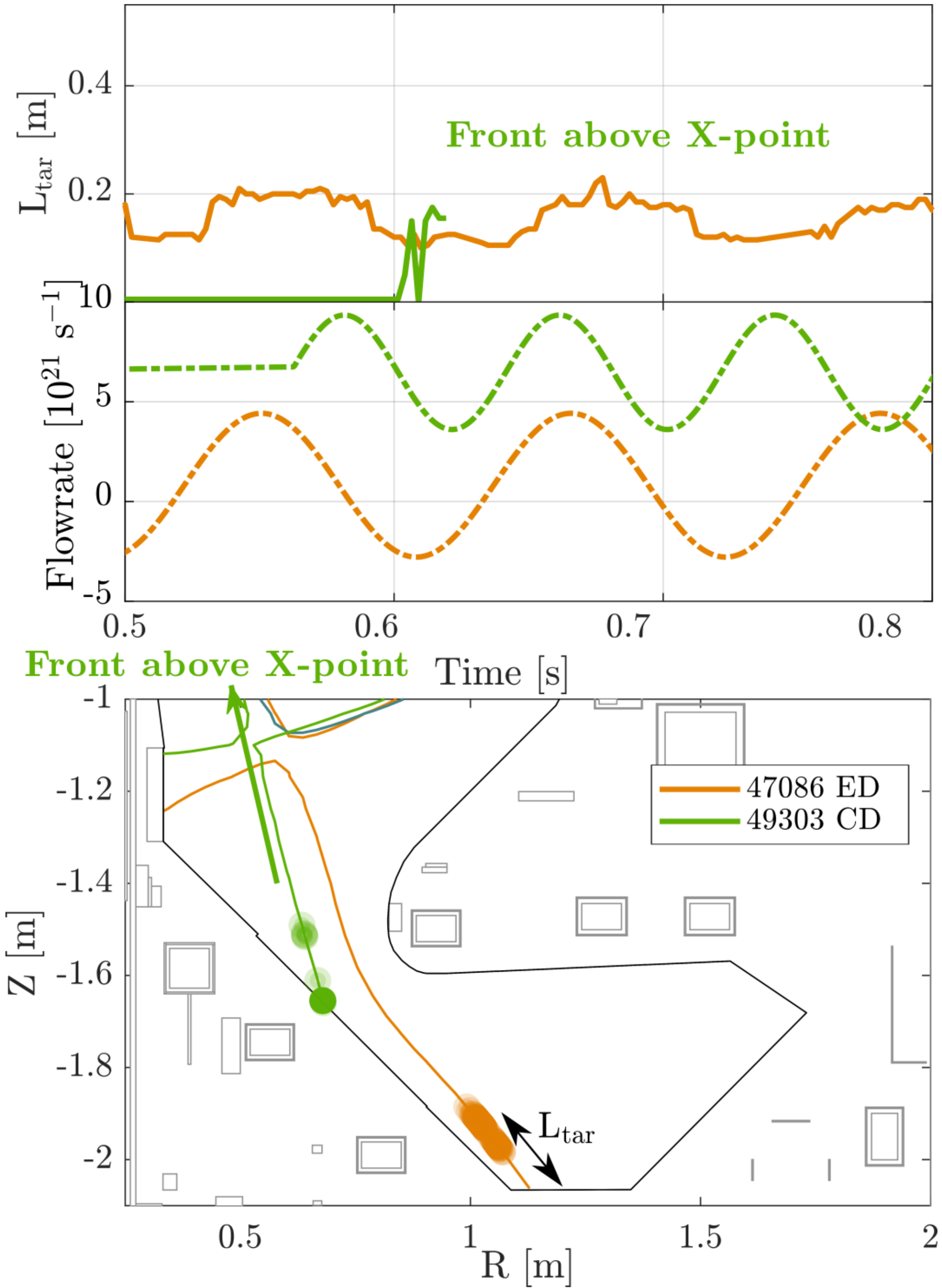
System Response

Results:

Similar perturbation of midplane of gas valve:

- CD: large perturbation – outside operating range
- ED: small perturbation





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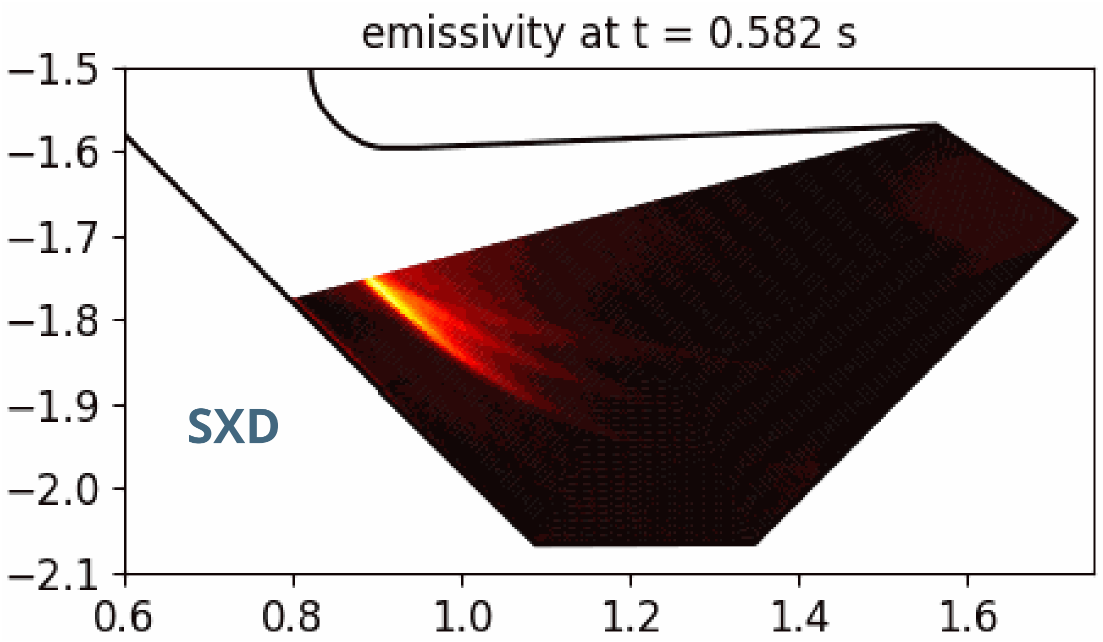

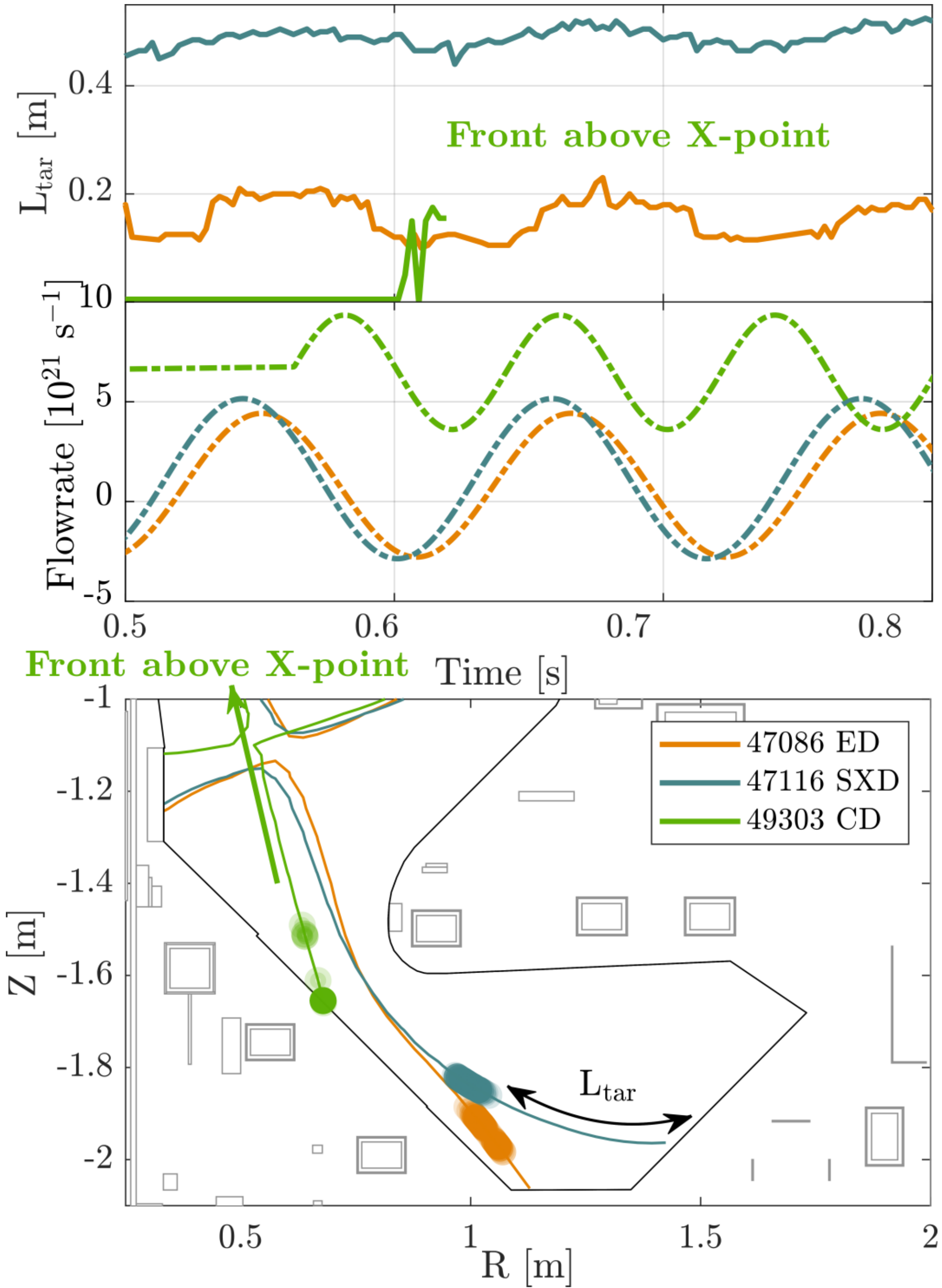

System Response

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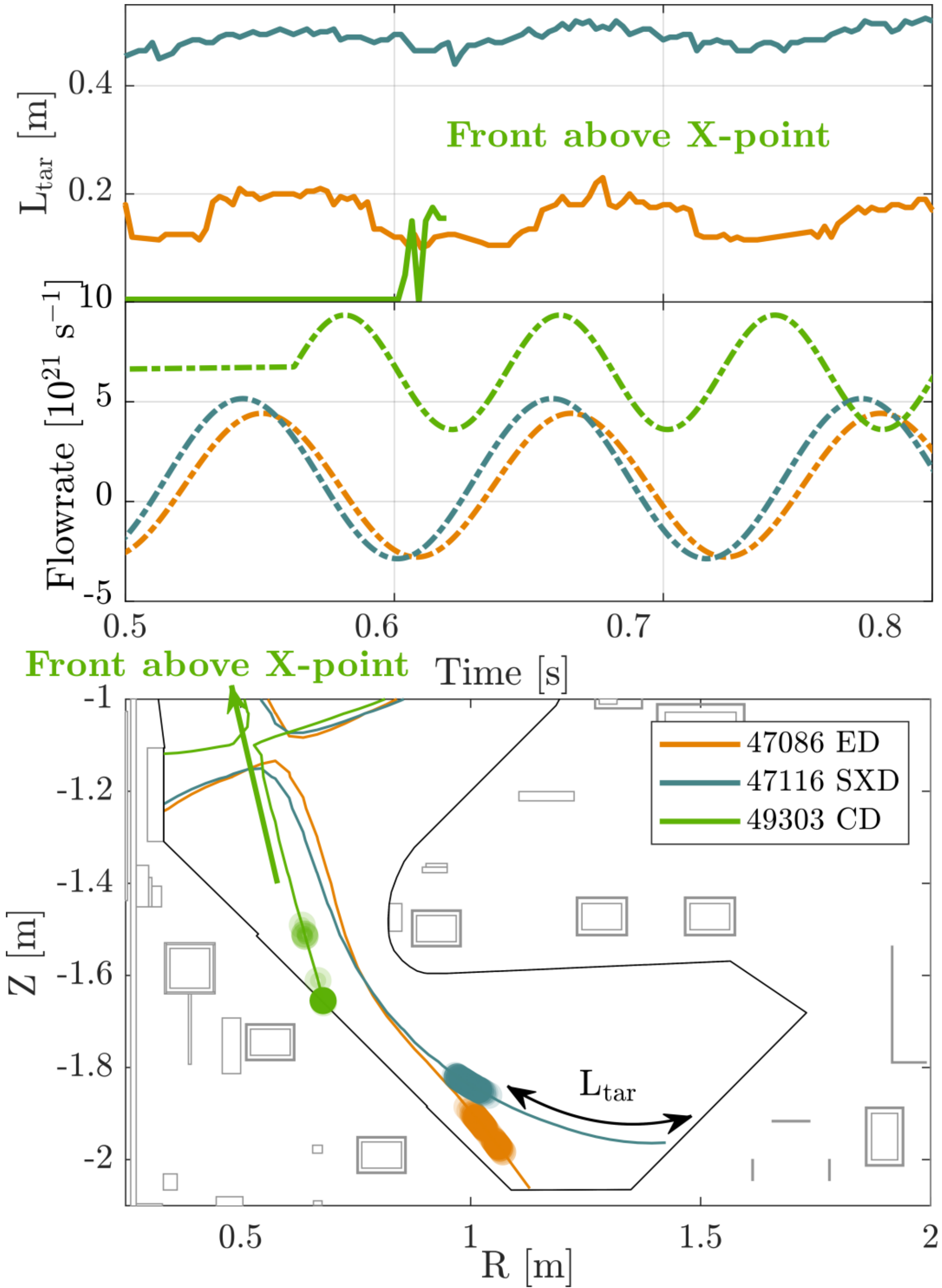
→ **Alternative divertors absorb transients better**

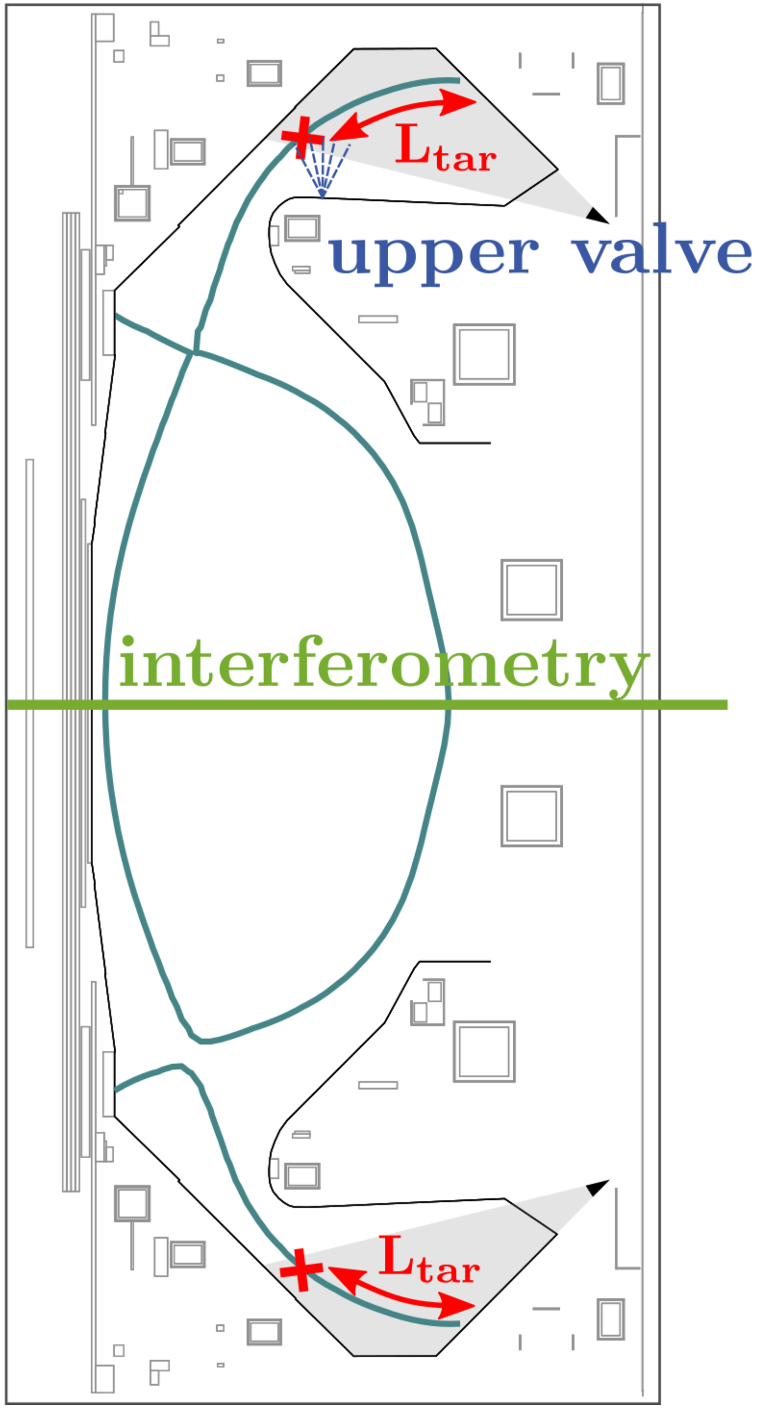


ADC advantage:
→ *Divertor decoupling*

Divertor decoupling

Employing the new upper imaging system
(N. Lonigro, V. Kachkanov)

D_2 perturbation in upper divertor:



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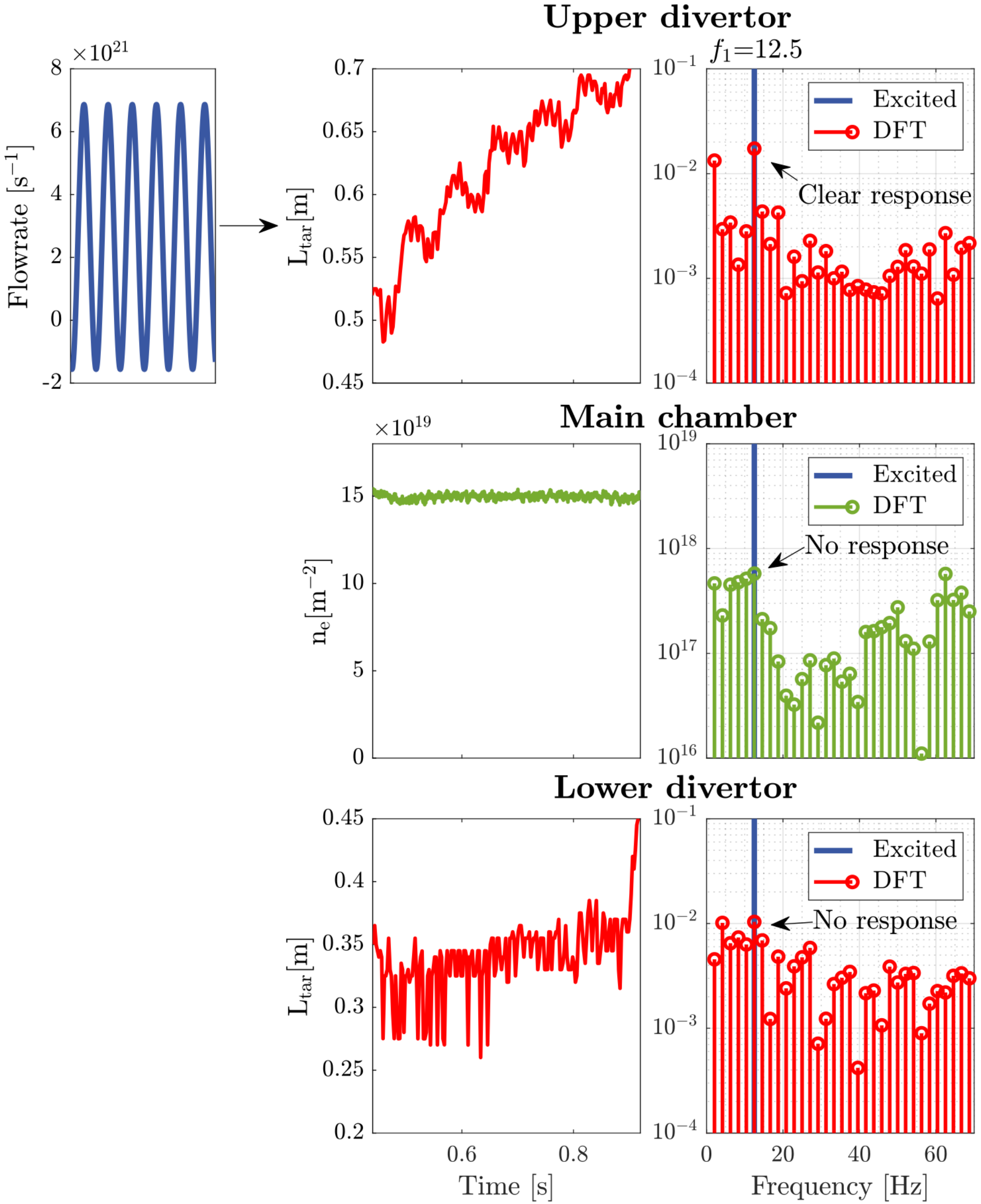

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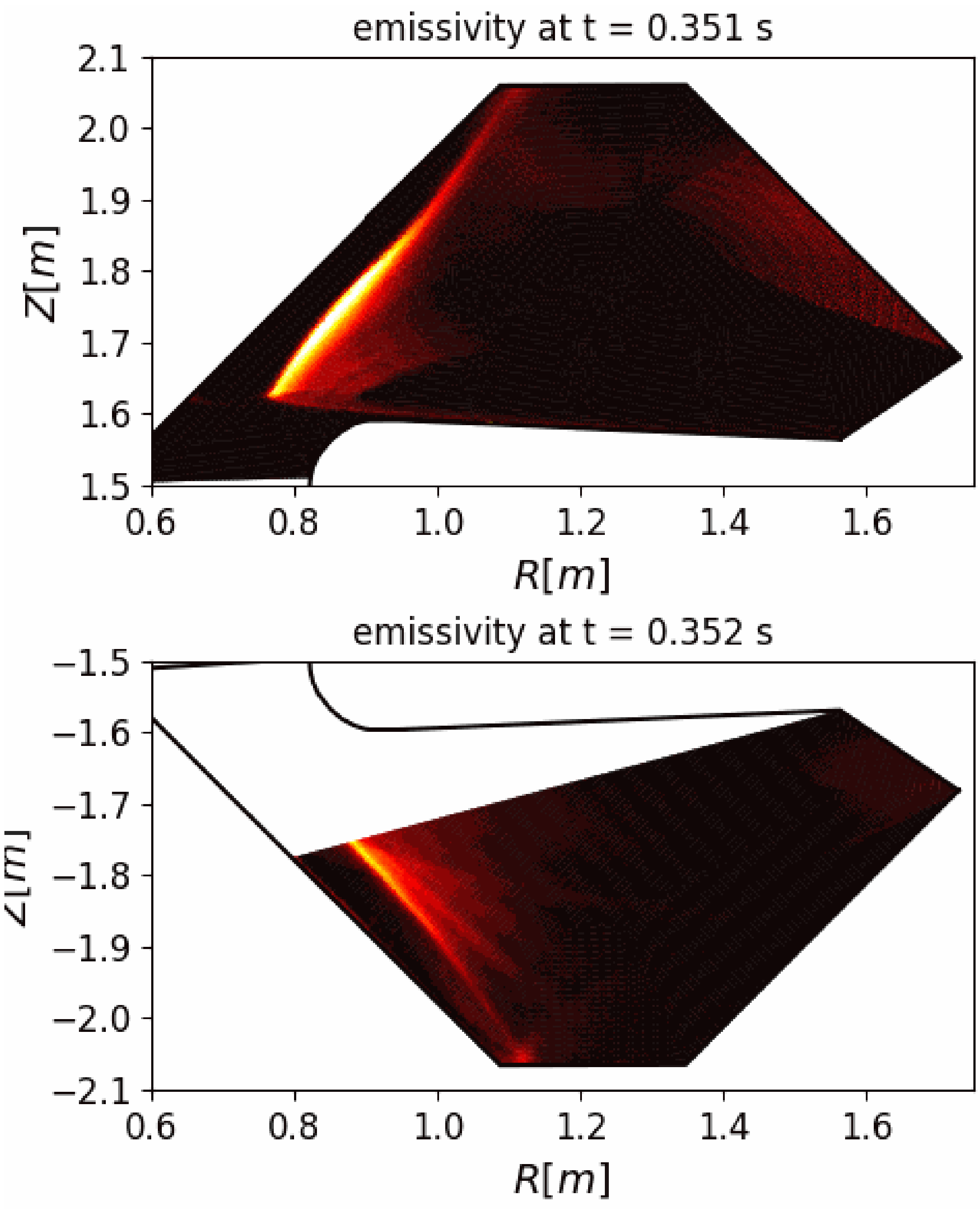

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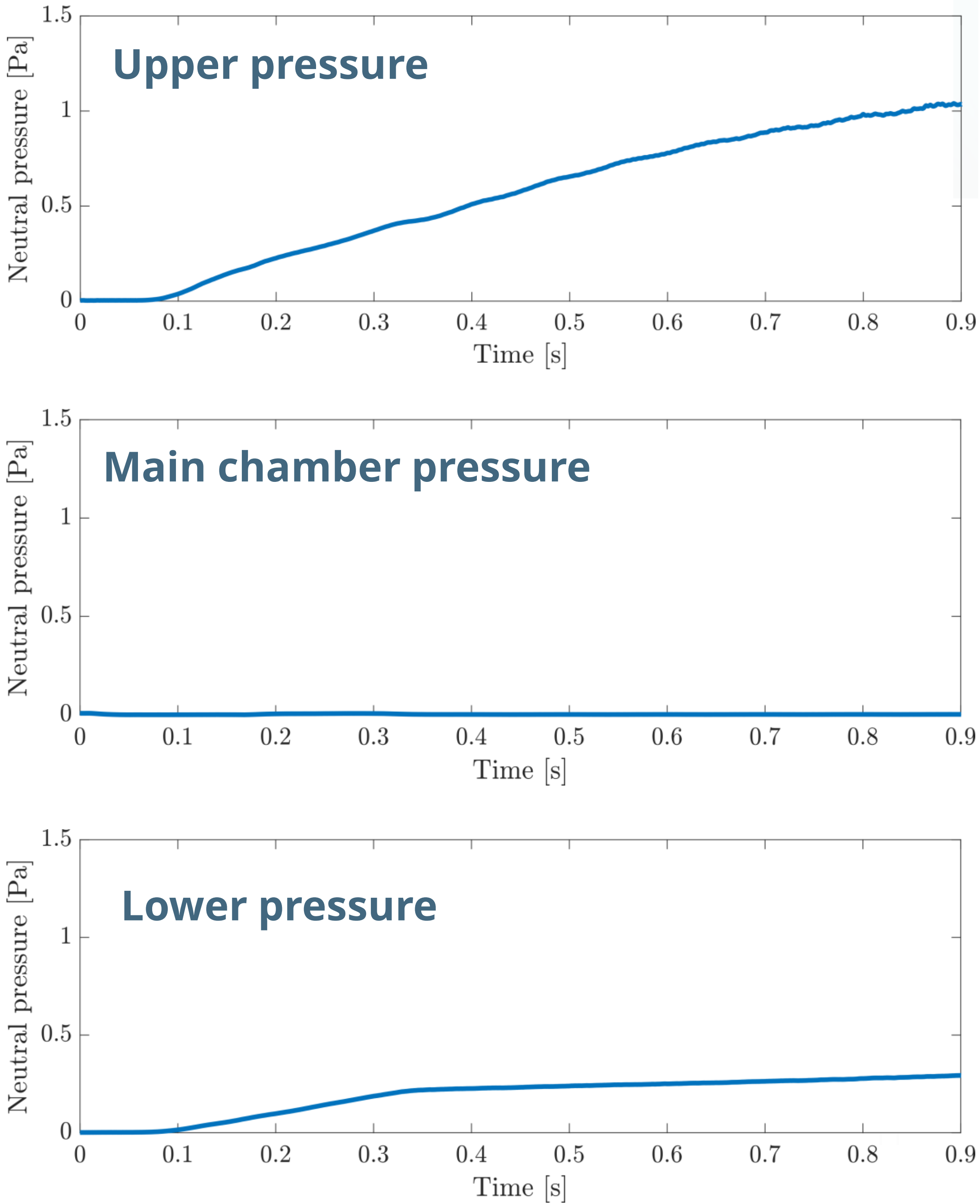

[1] O. Février et al 2021 Nucl. Fusion **61** 116064

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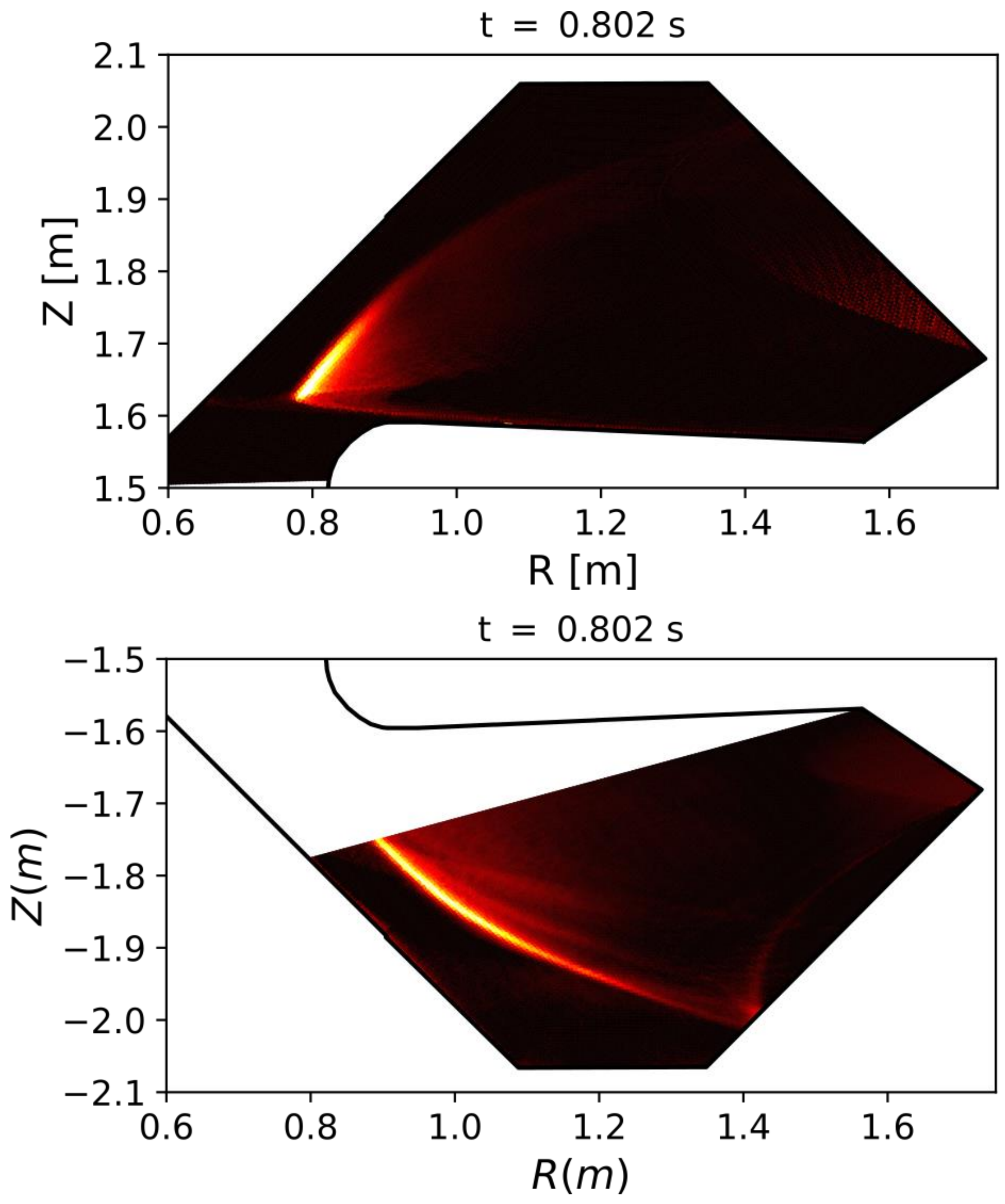
Instability due to controller interaction ruled out
→ Combined control possible



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Preliminary: Decoupling for holds for N_2

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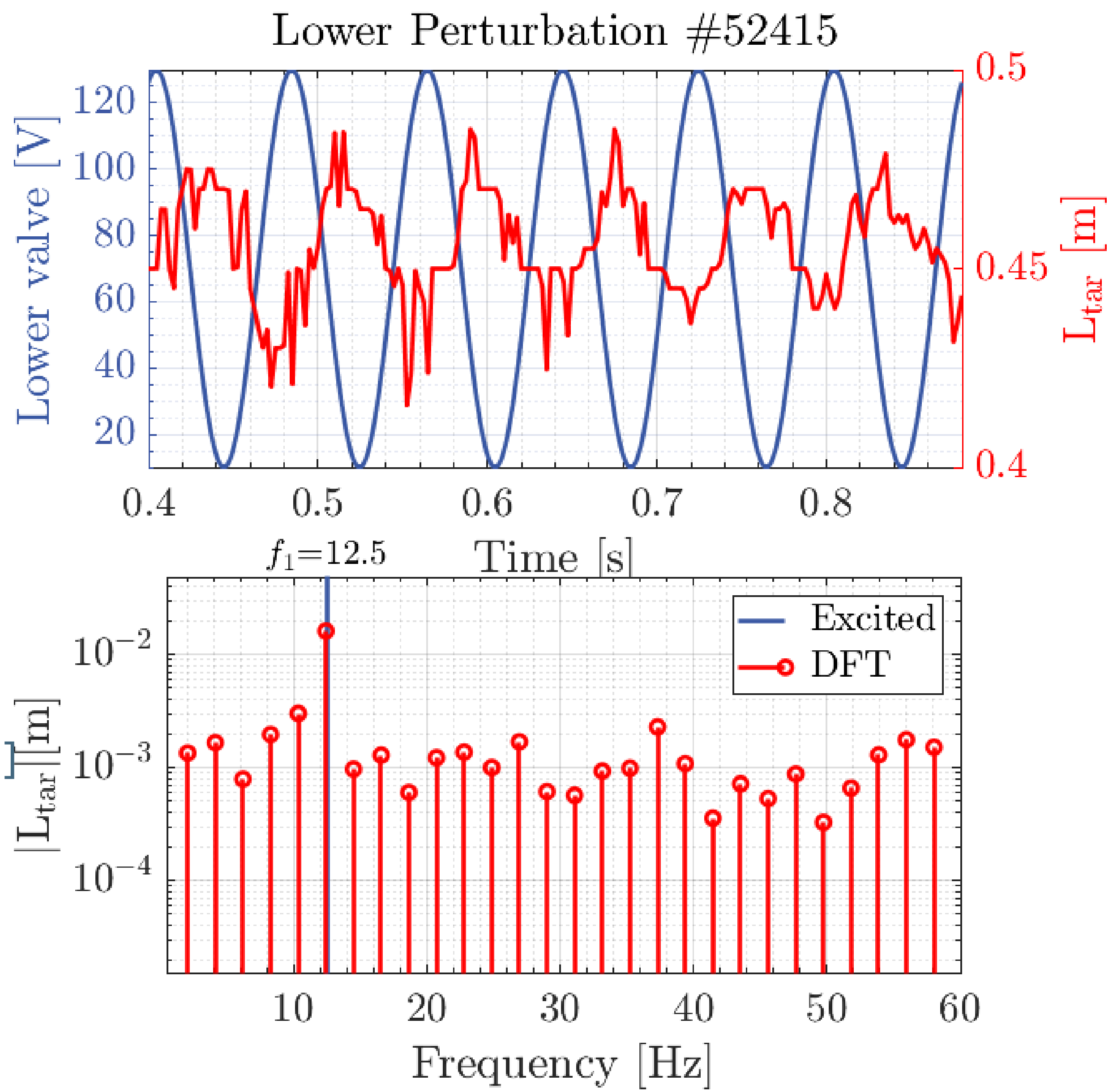

Dalpha front position

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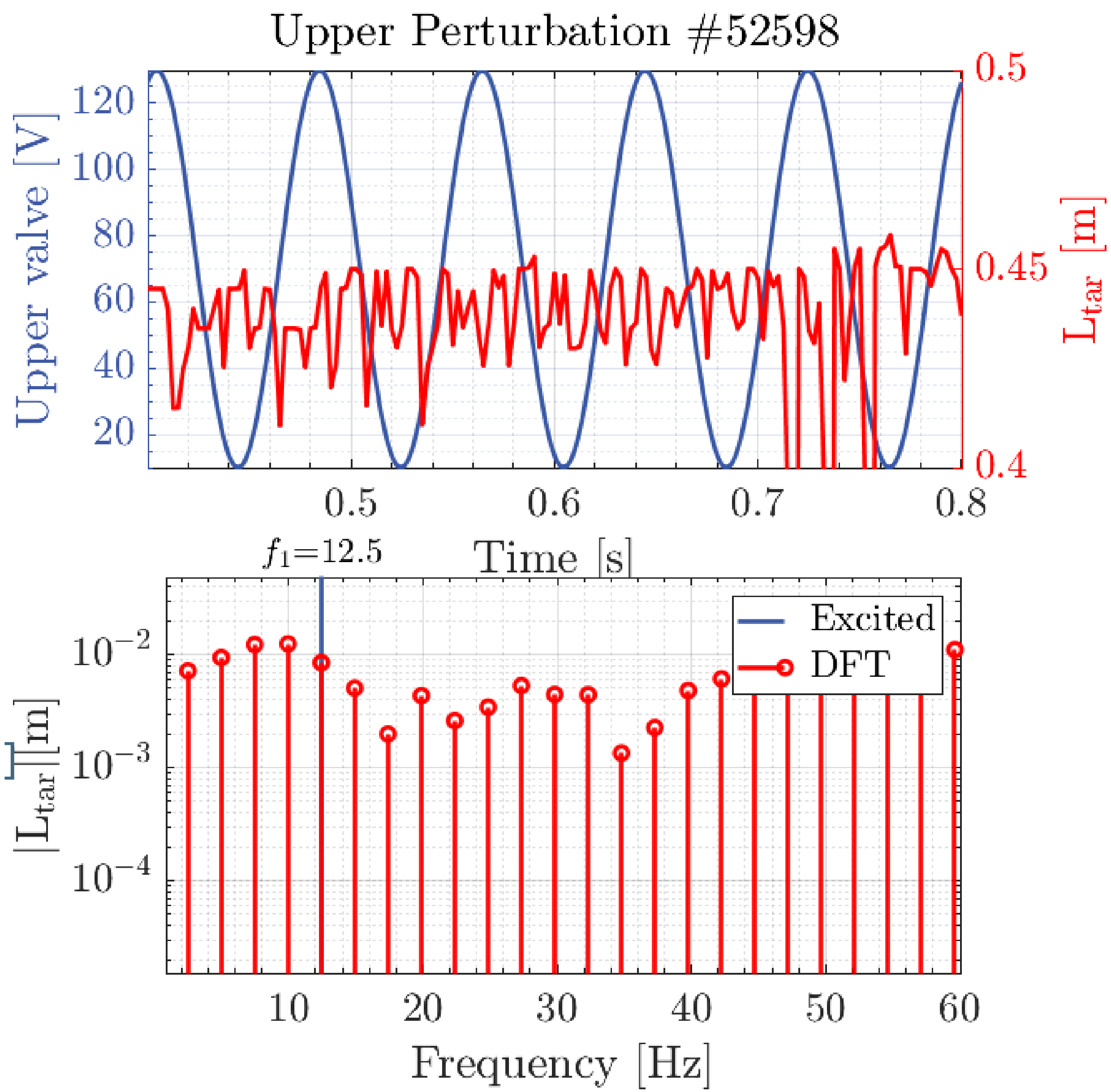


Dalpha front position

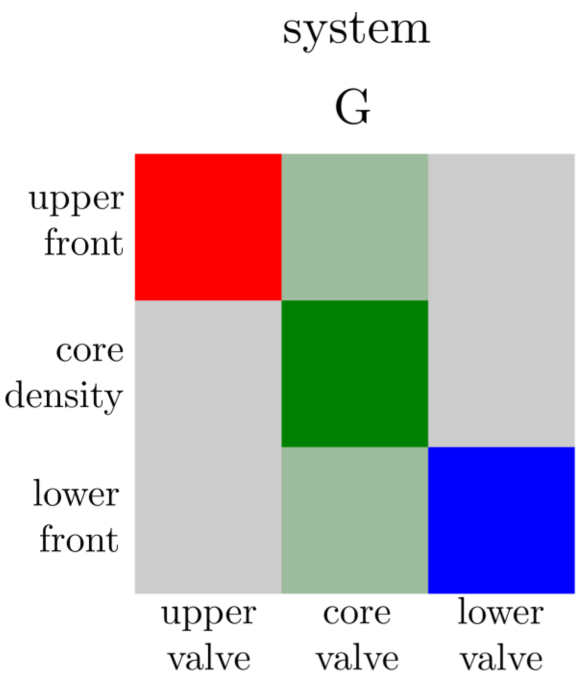
[1] O. Février et al 2021 Nucl. Fusion **61** 116064

Combined control

Combined control

Multiple-Input Multiple-Output (MIMO) → Improve on the natural decoupling

Transfer function matrix G
Only one-way interaction
→ Core affects divertor
not vice-versa



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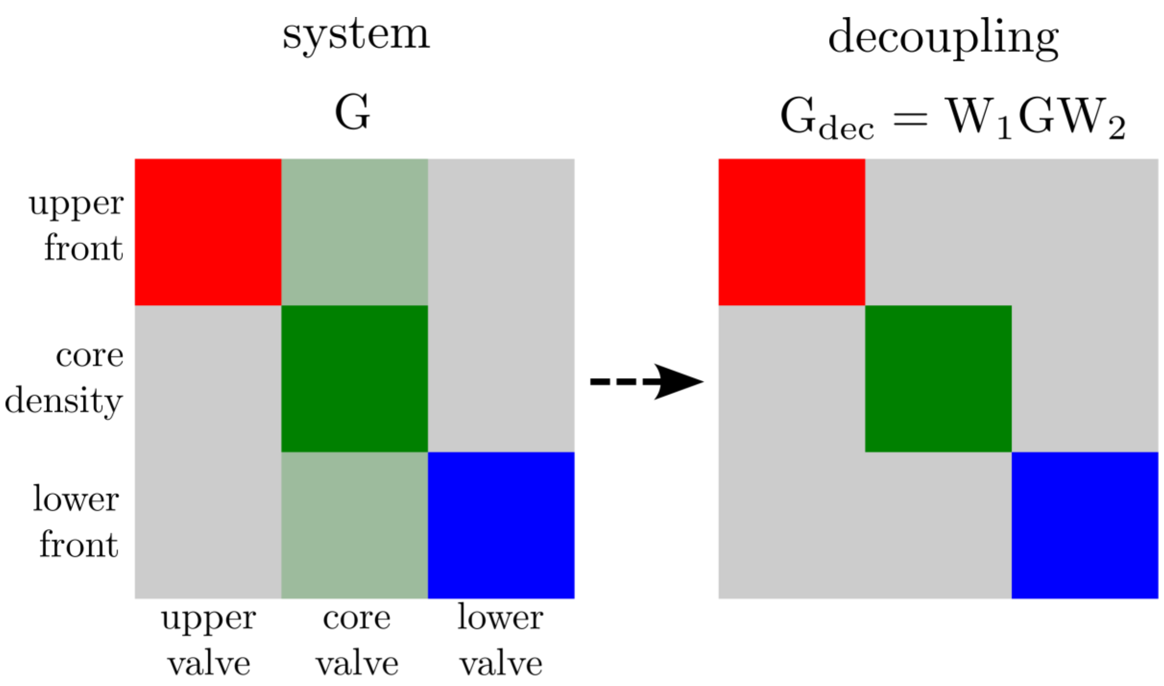
Decoupling
Diagonalization of G
→ W_1 and W_2 from SVD



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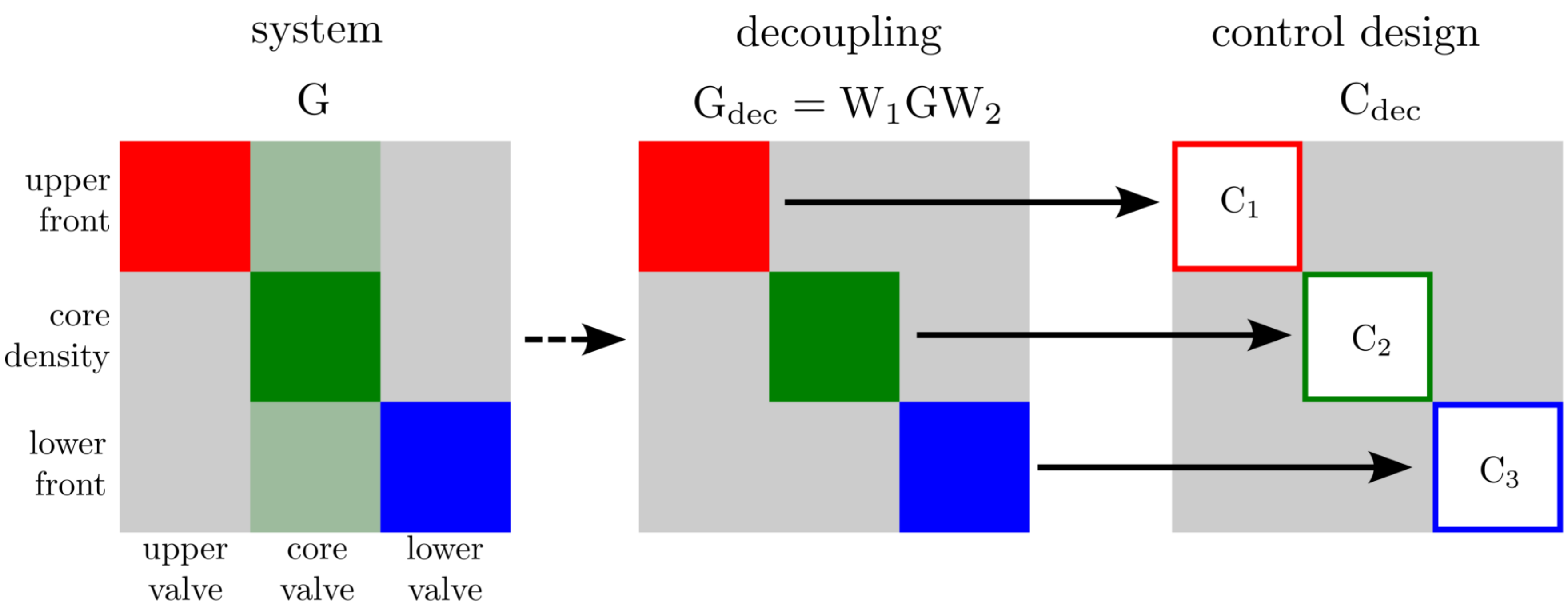
Control design
Design three PID controllers



Similair application on TCV:
Koenders et al 2023 *Nucl.Fusion* **63** 106007

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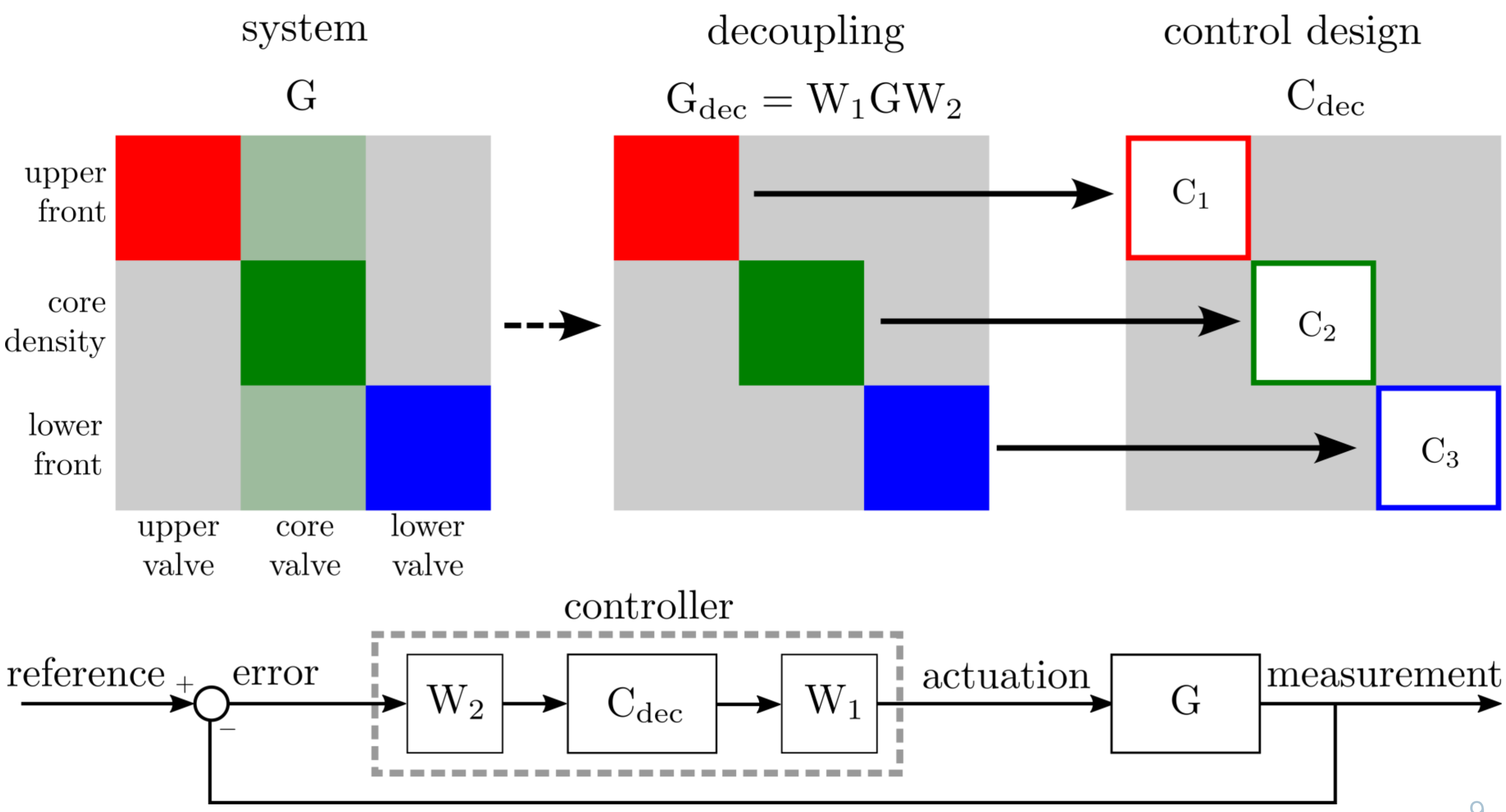
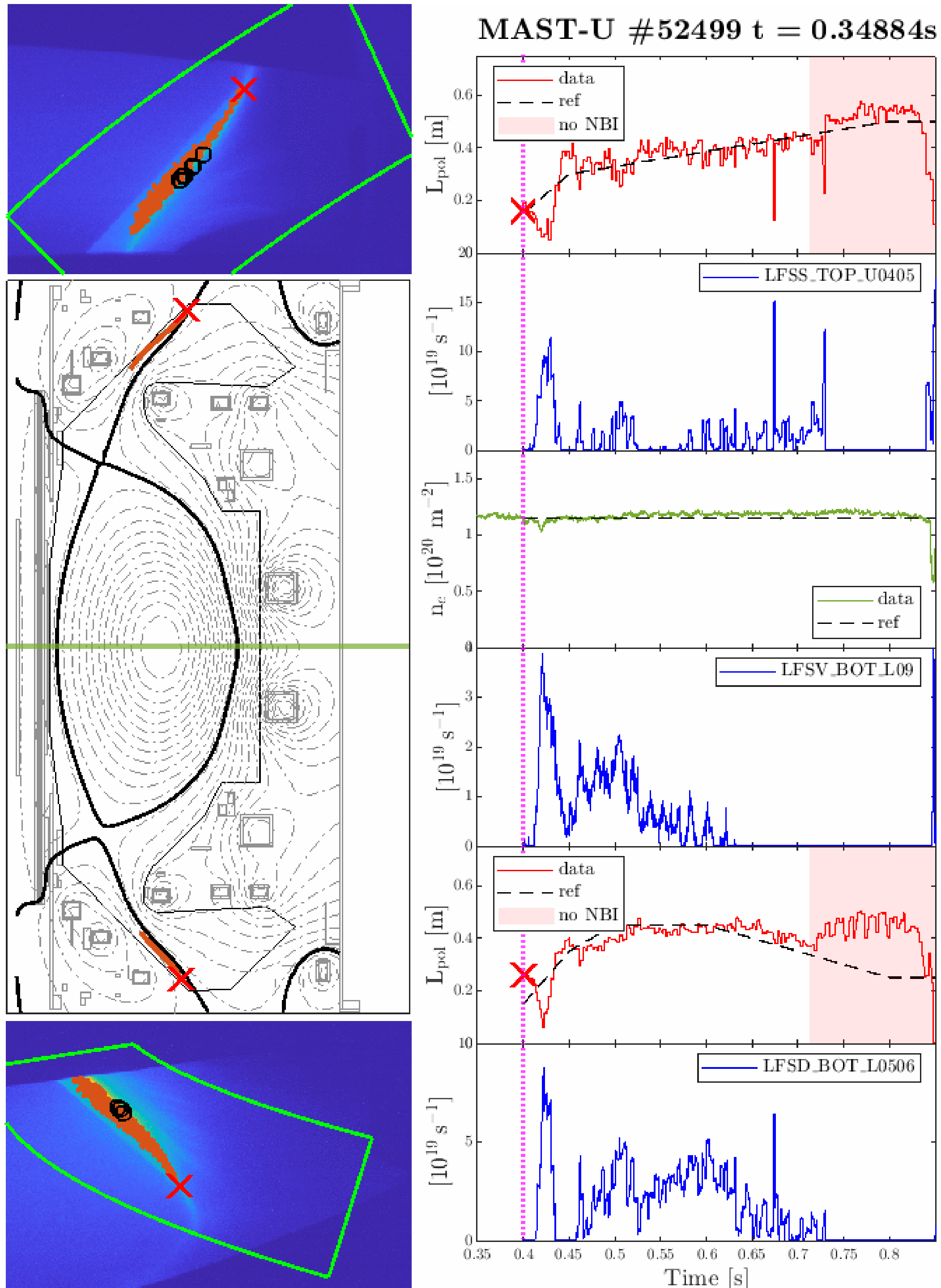


Combined control

Combined control demonstrated!
-Core density
-Upper front position
-Lower front position

Three D2 valves:
-Main chamber
-Upper divertor
-Lower divertor

→ NBI drops out at 700ms



Conclusions

→ Exhaust control in ADCs demonstrated
→ Pumping is vital for exhaust control

ADC advantages:
1) Passive transient absorption
→ *Handle fast transients despite slow actuators*
1) Divertor decoupling
→ *Demonstrated combined control*

Next campaign:
- Repeat control demonstration with full beam duration
- Demonstrate asymmetric transient suppression
- Explore combined control for impurities
- Explore inner-outer divertor coupling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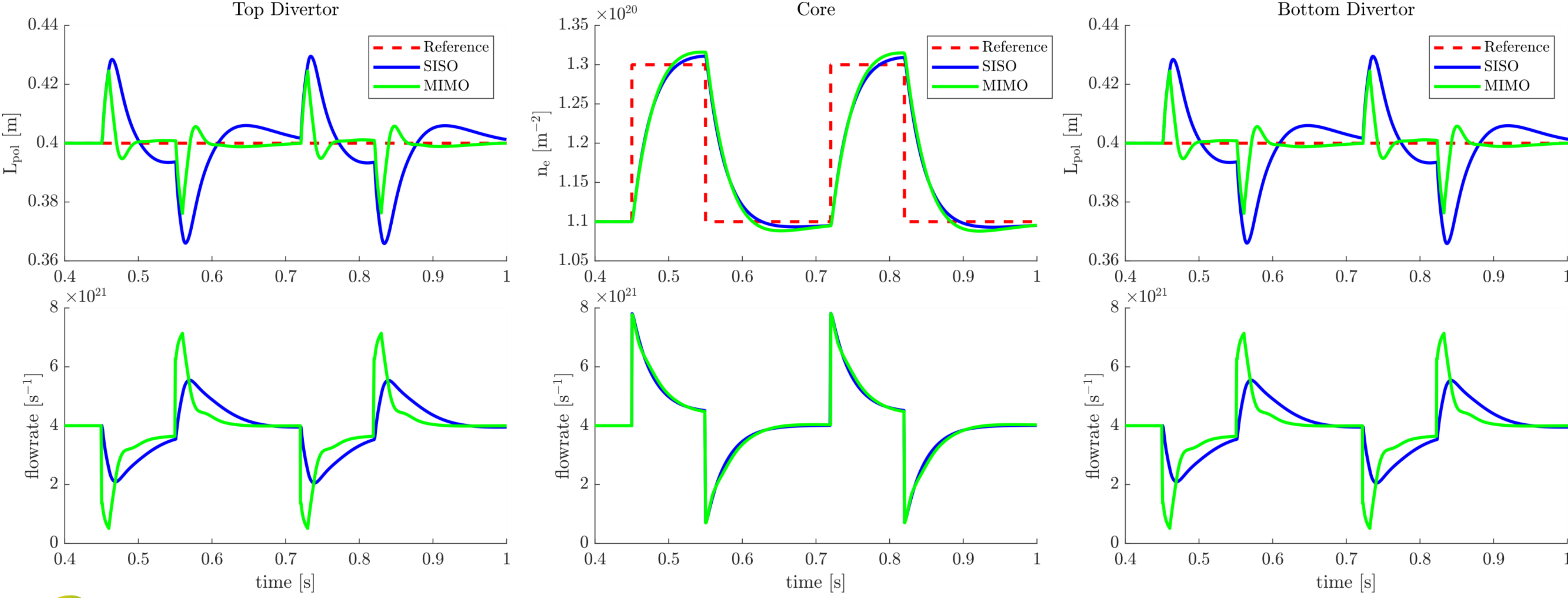
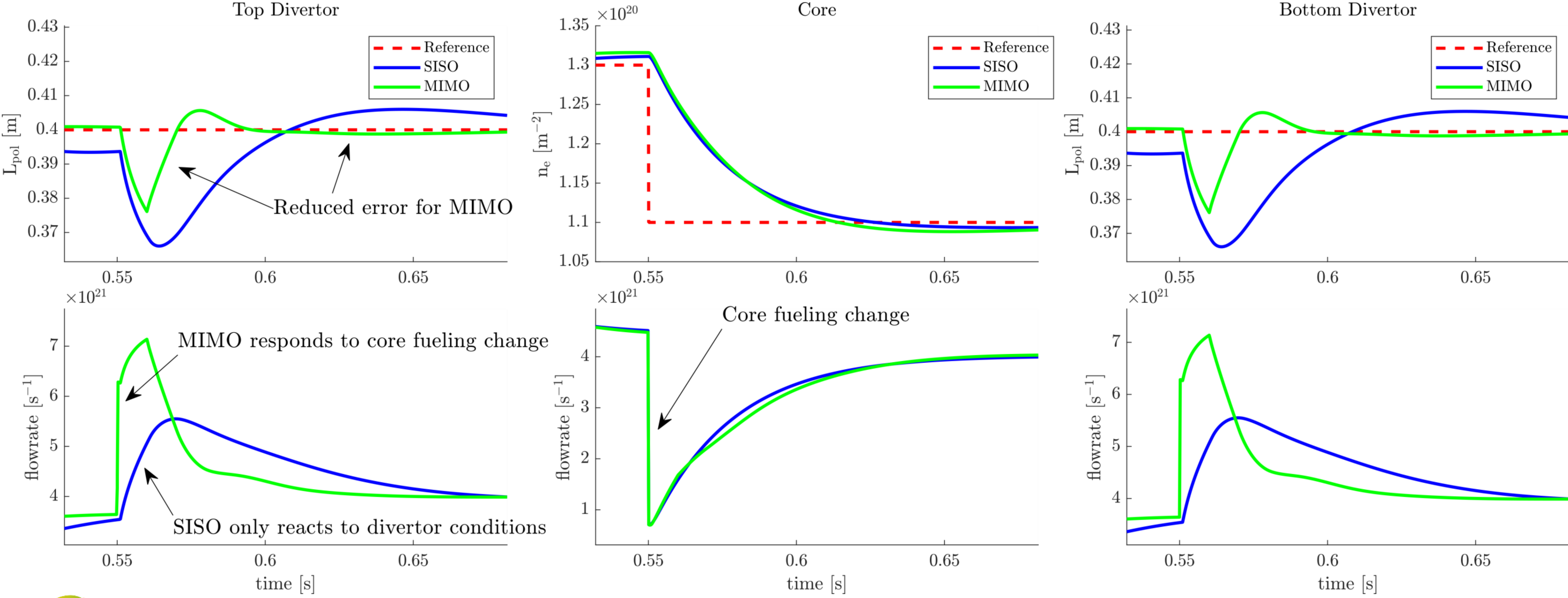
Benefit of MIMO control over separate SISO loops

Why MIMO and not separate SISO loops? → To improve performance



Simulation of controller performance

Why MIMO and not separate SISO loops? → To improve performance

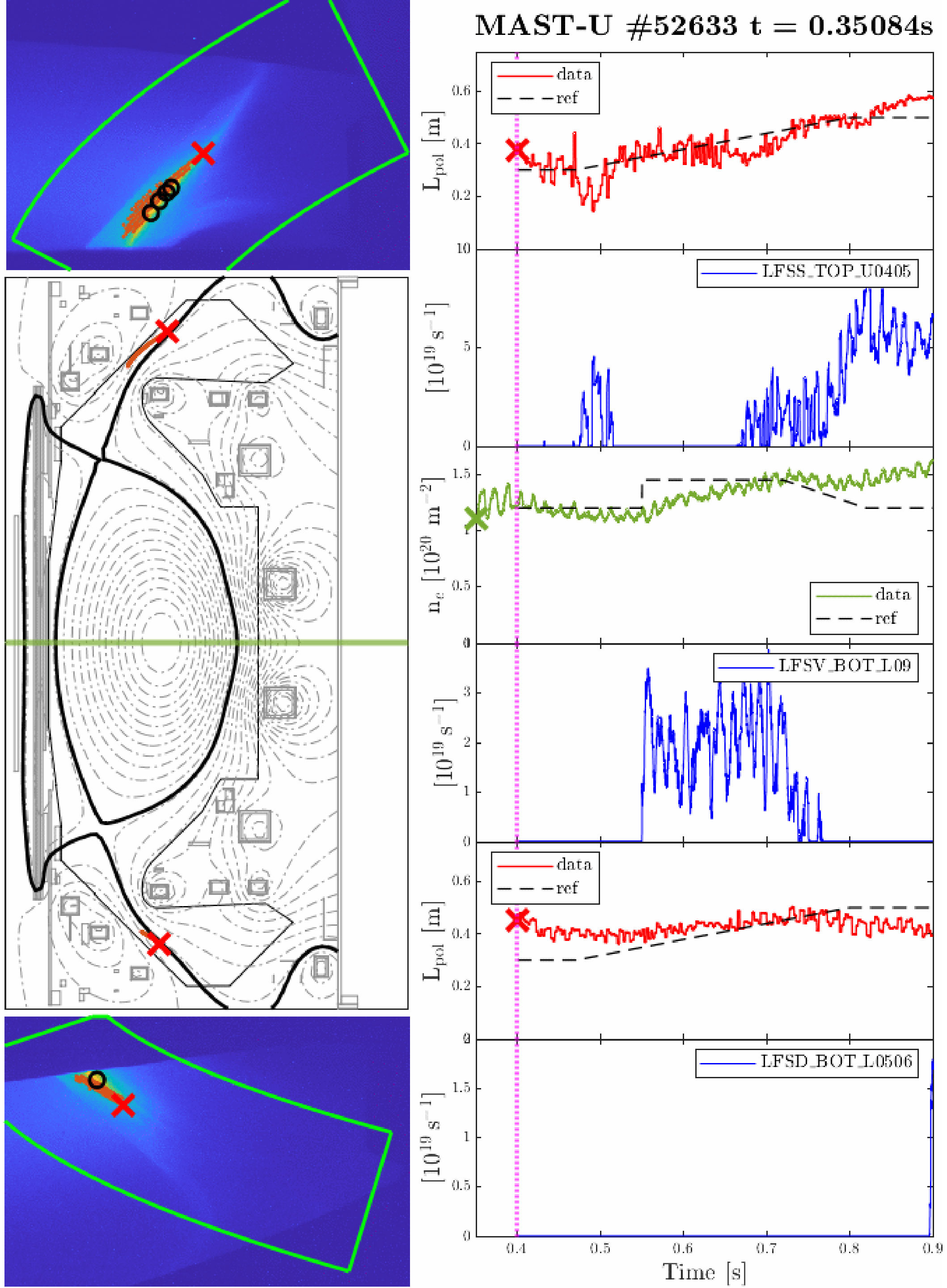


Simulation of controller performance

MIMO control experiments

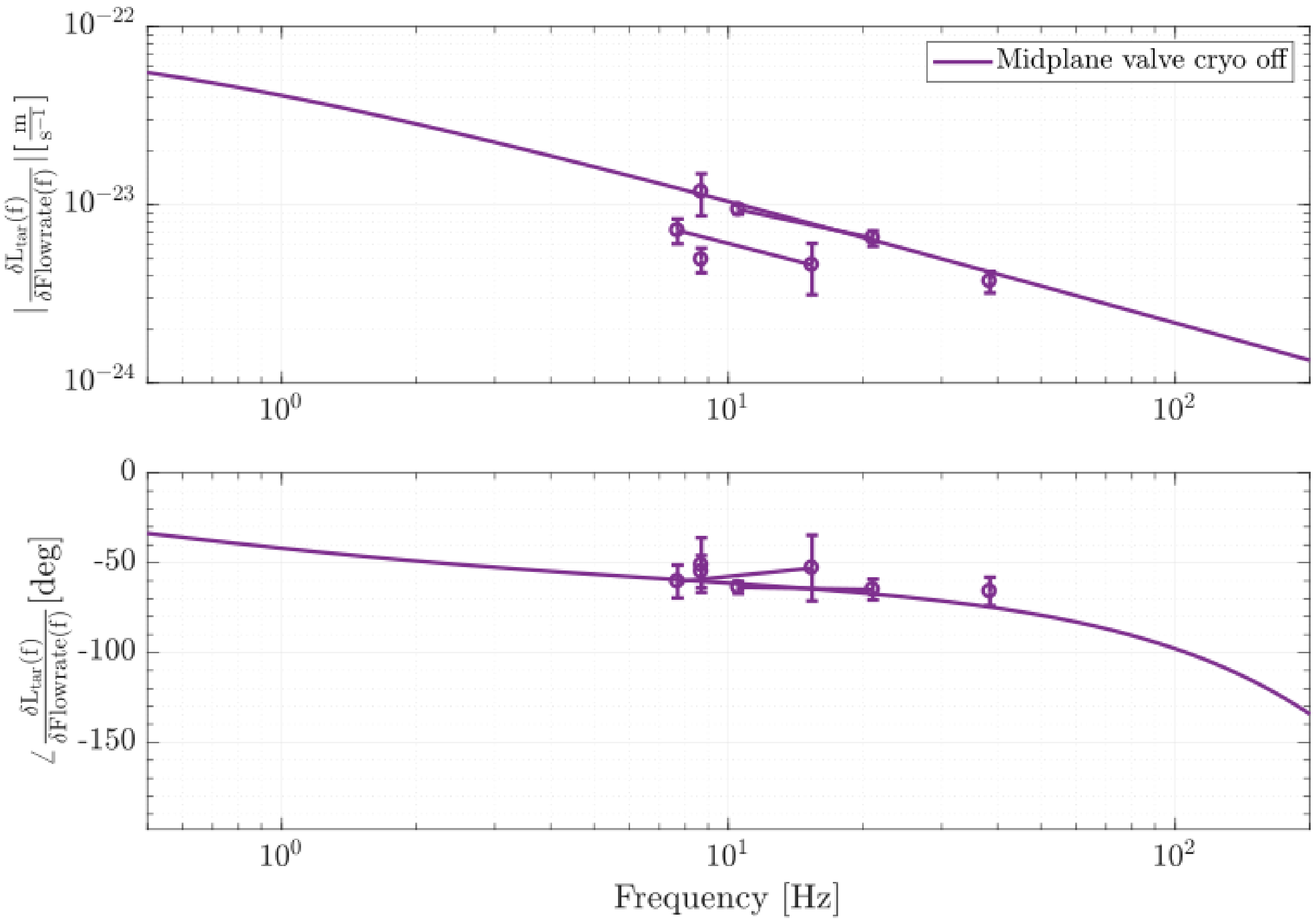
Combined control attempt

Divertor fronts too high compared to reference through impurity retention from previous experiments

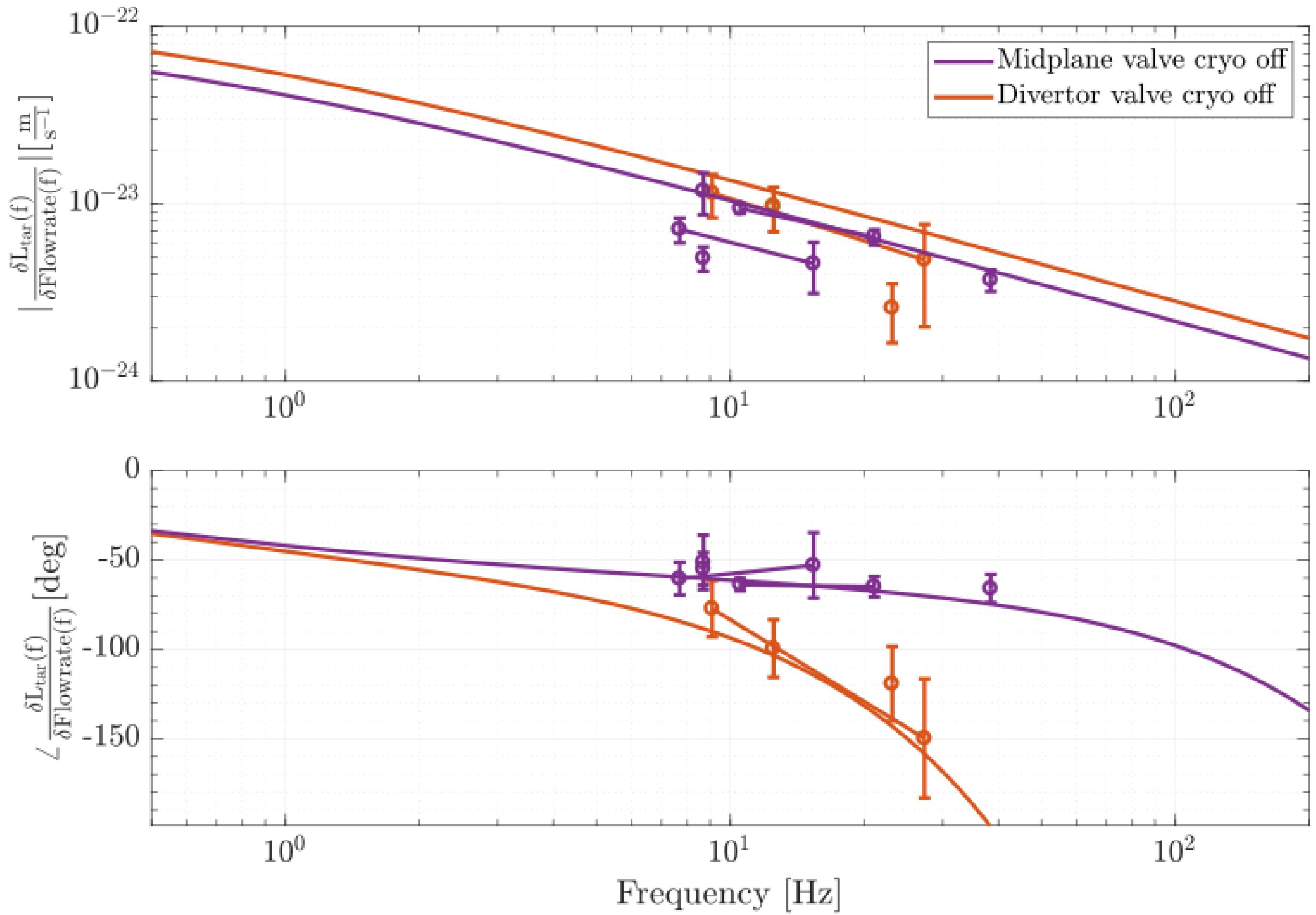


Pumping + valve effect on dynamics

System identification

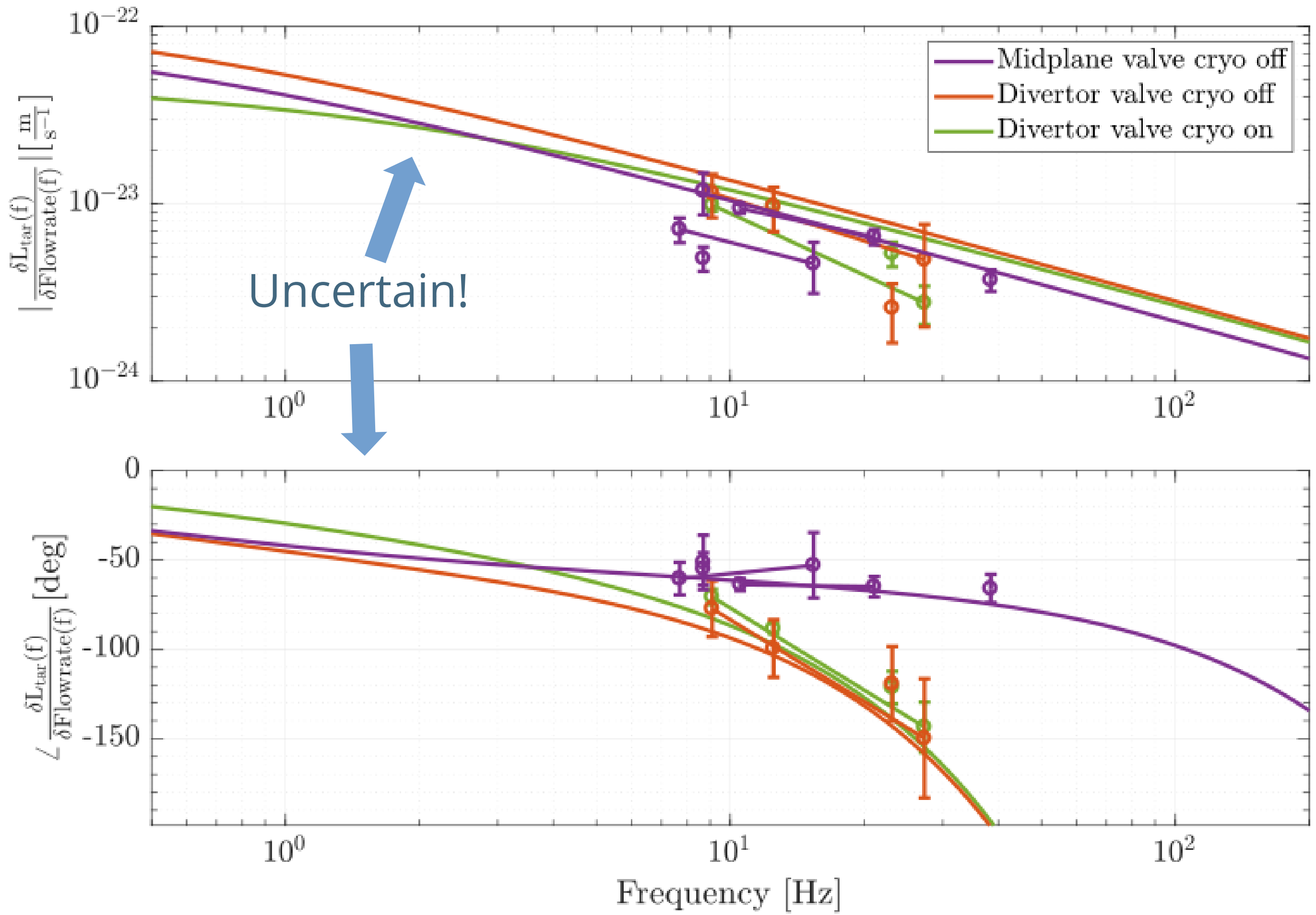


System identification



Midplane vs divertorvalve
Much larger phase lag for divertor (8 ms)
→ Longer pipes 0.6 m vs 1.5 m

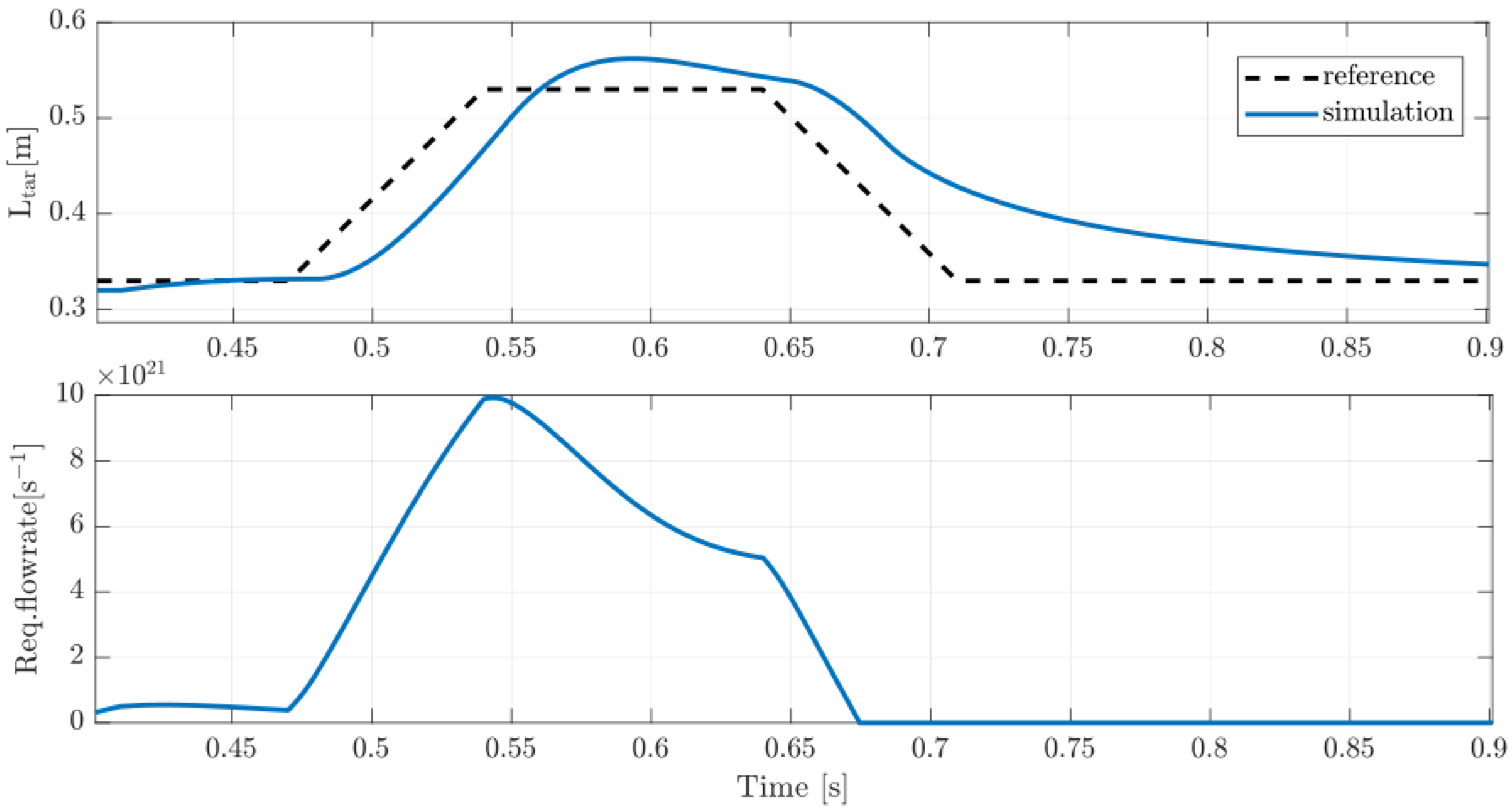
System identification



Midplane vs divertorvalve
Much larger phase lag for divertor (8 ms)
→ Longer pipes 0.6 m vs 1.5 m

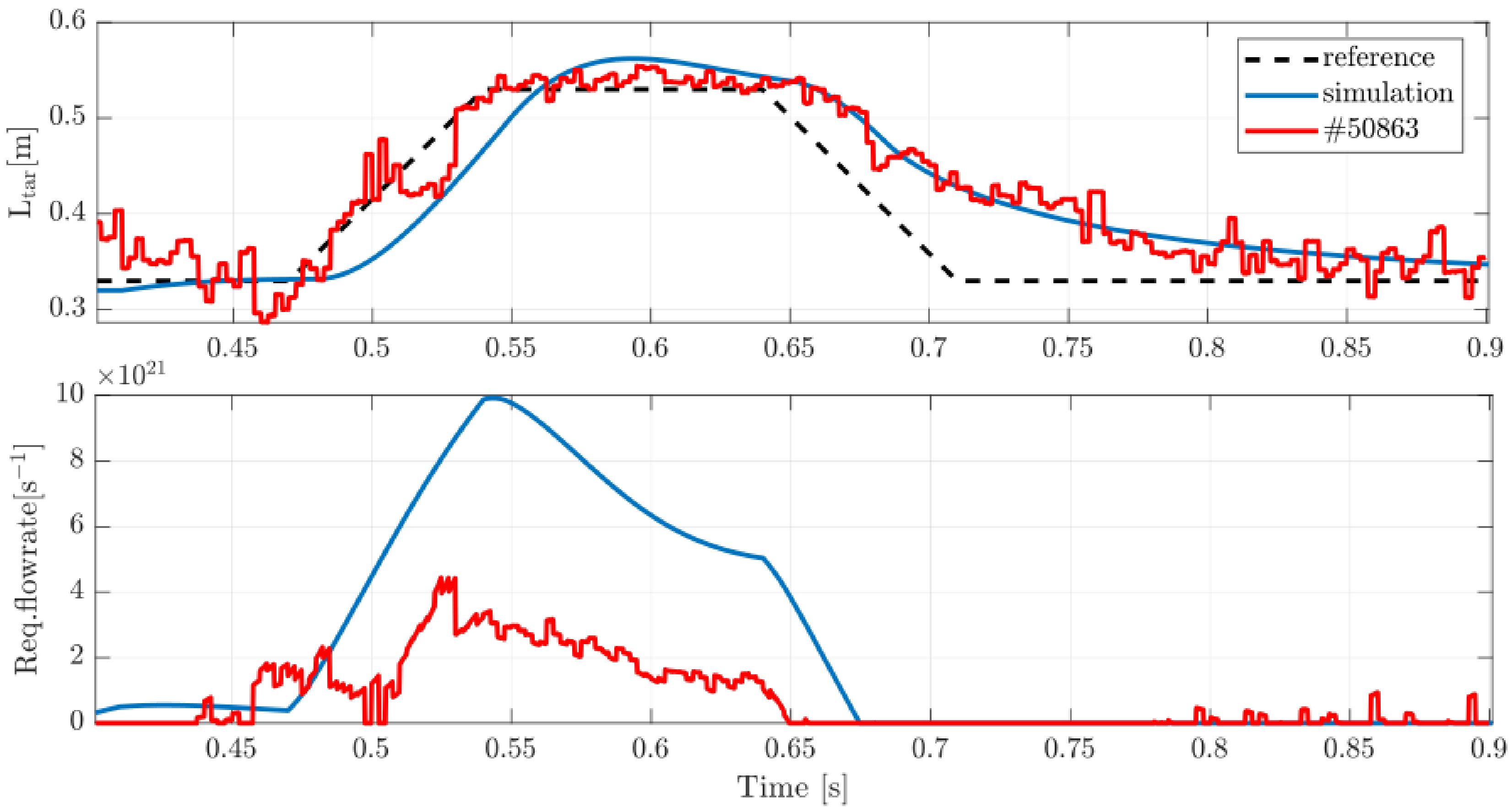
Without Cryo vs with Cryo
No real difference in measured range
→ Mainly in lower frequencies

Feedback control prediction



Transfer function model
→ Offline controller design

Feedback control prediction

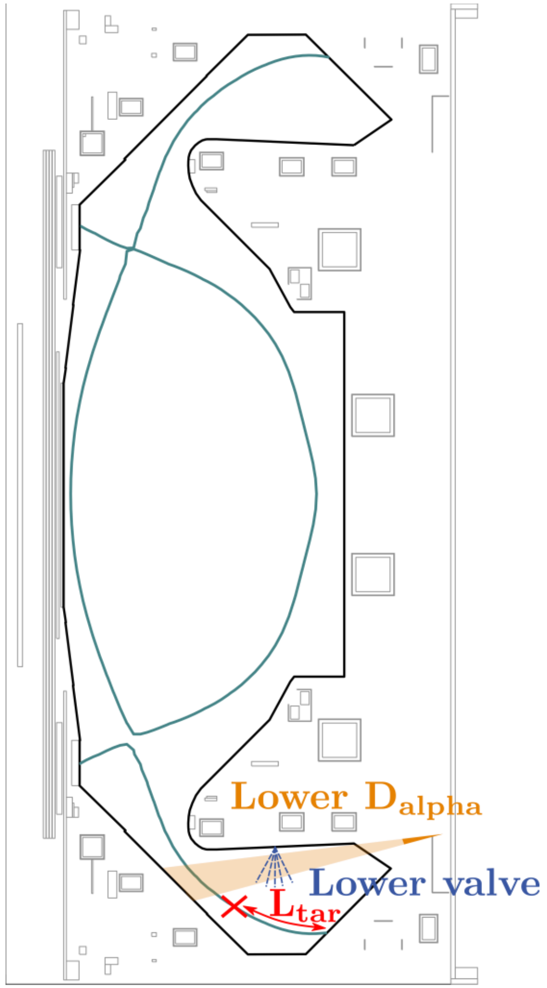


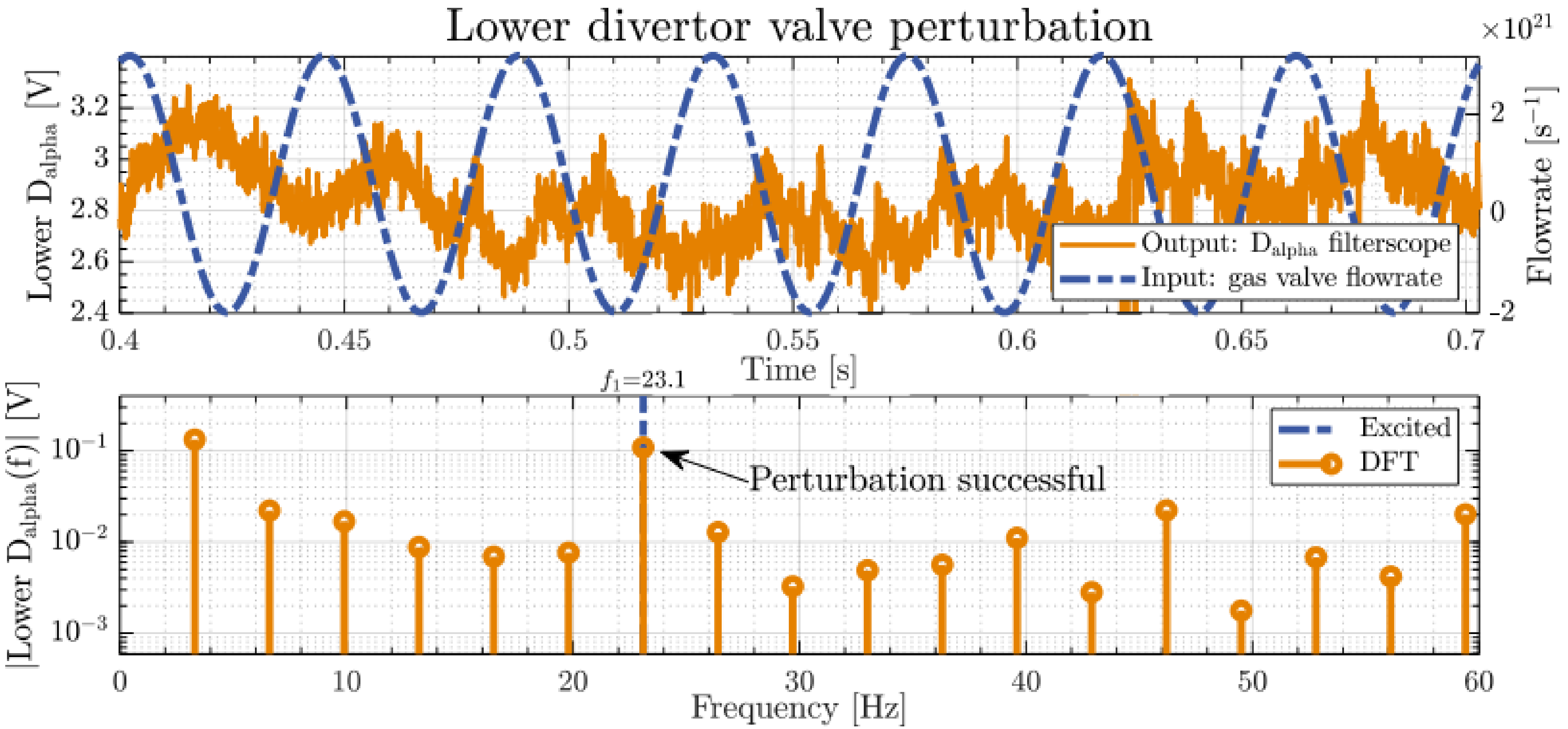
Transfer function model
→ Offline controller design

Good match with experiments

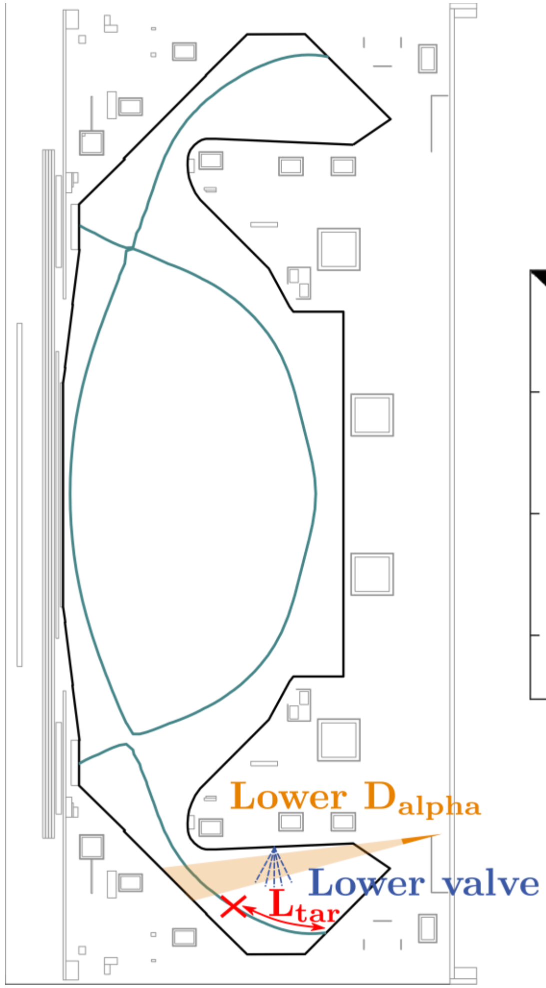
Divertor decoupling
Results from previous campaign (MU03)

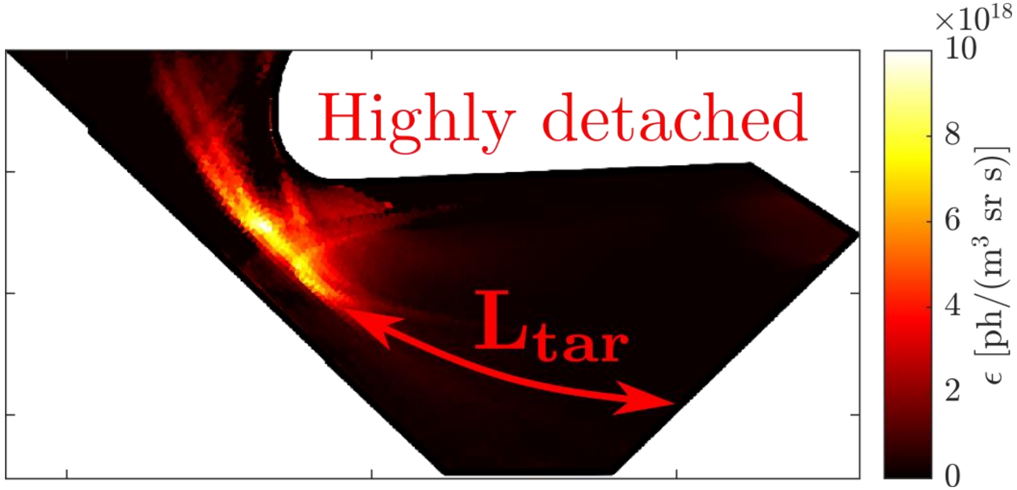
Lower perturbation

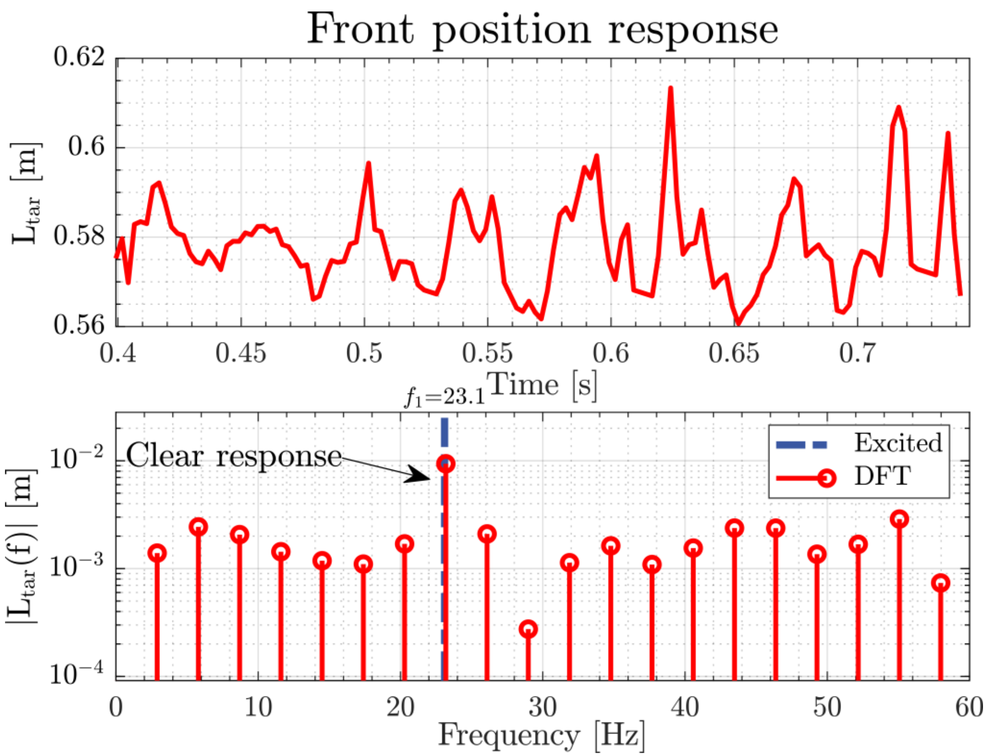




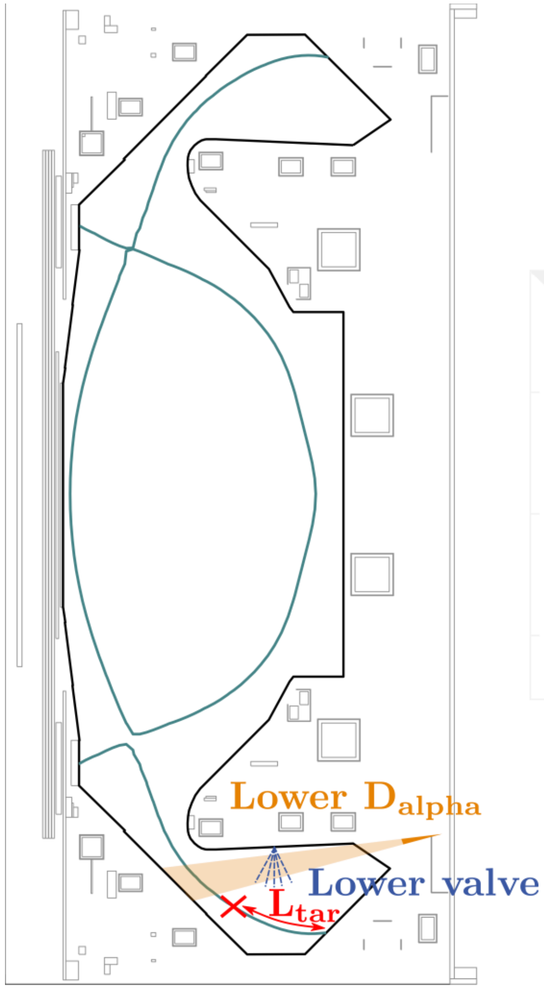
Lower perturbation

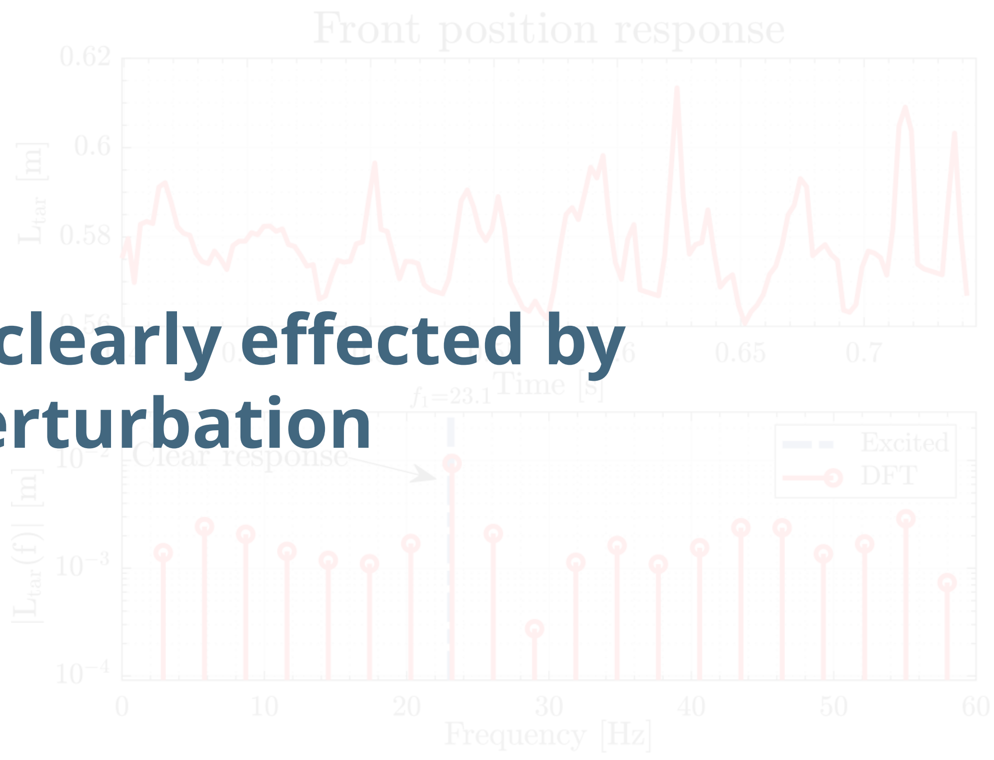






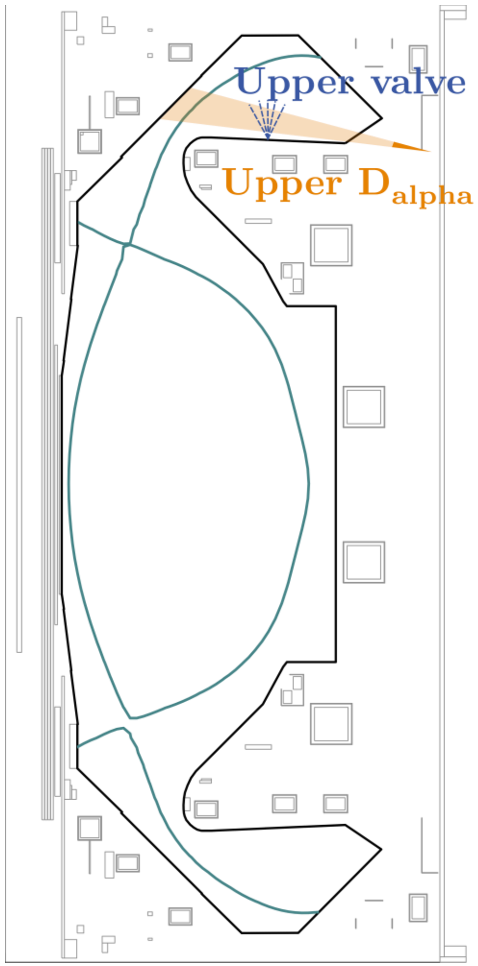
Lower perturbation

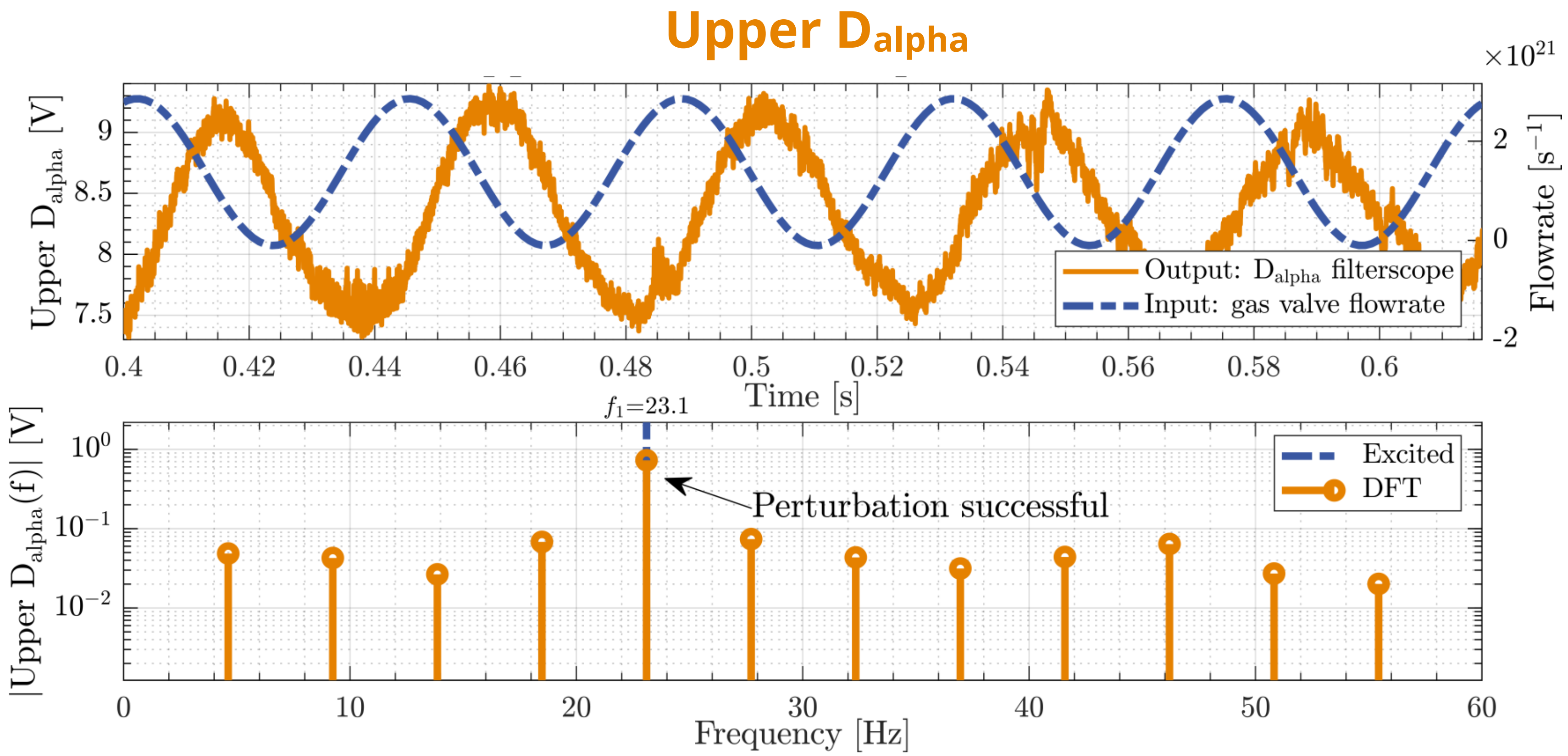




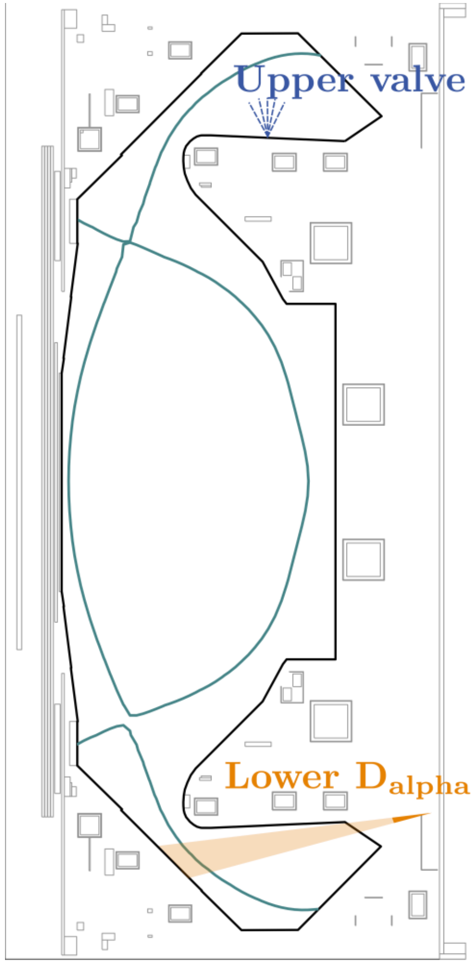
Lower divertor clearly effected by lower perturbation

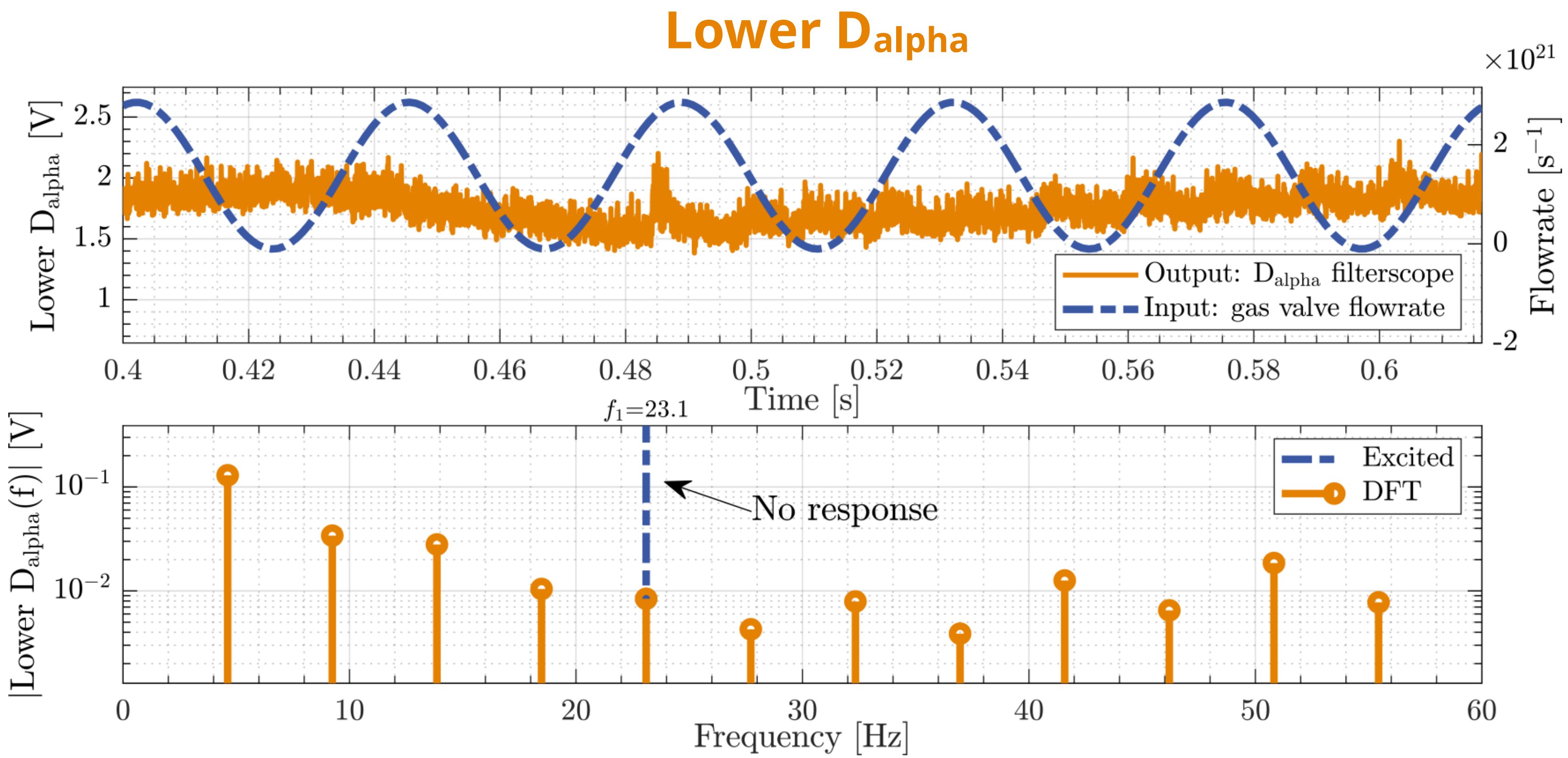
Upper perturbation



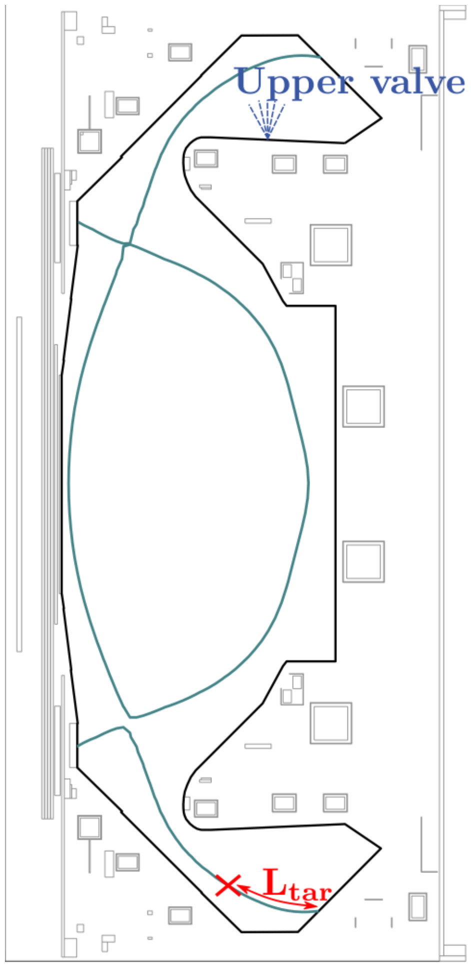


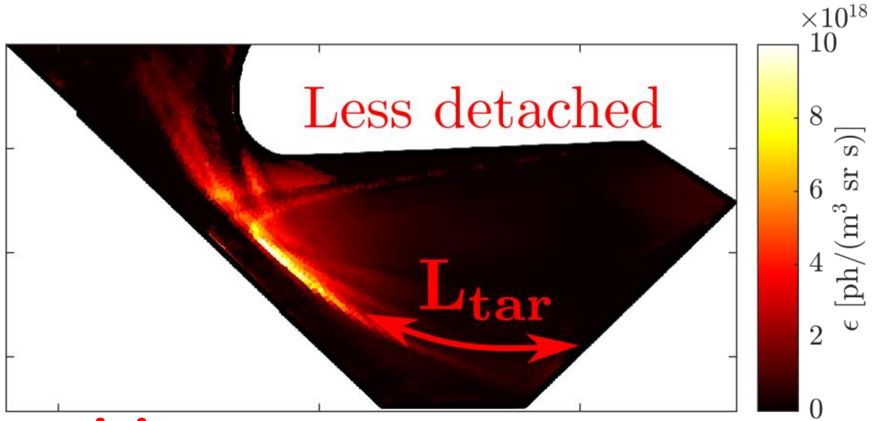
Upper perturbation



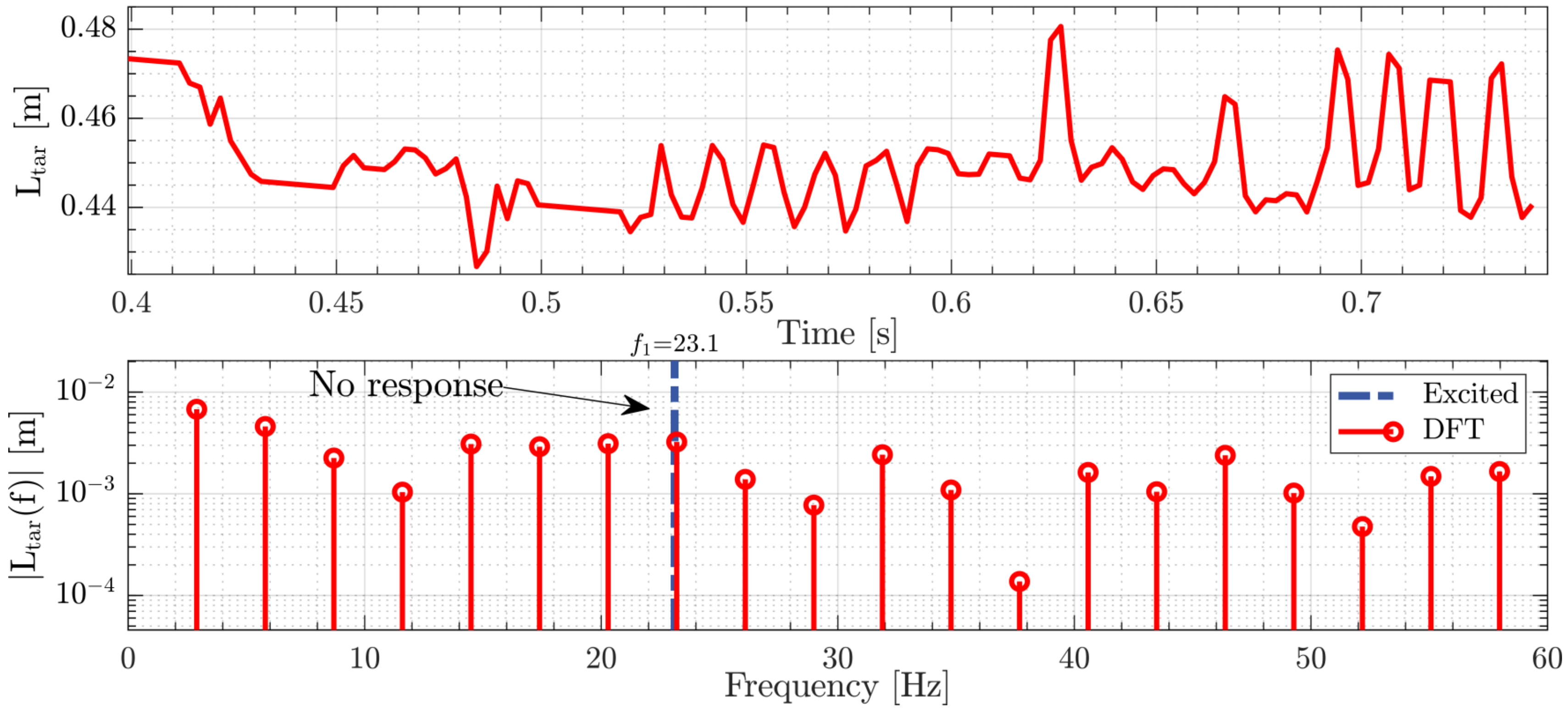


Upper perturbation

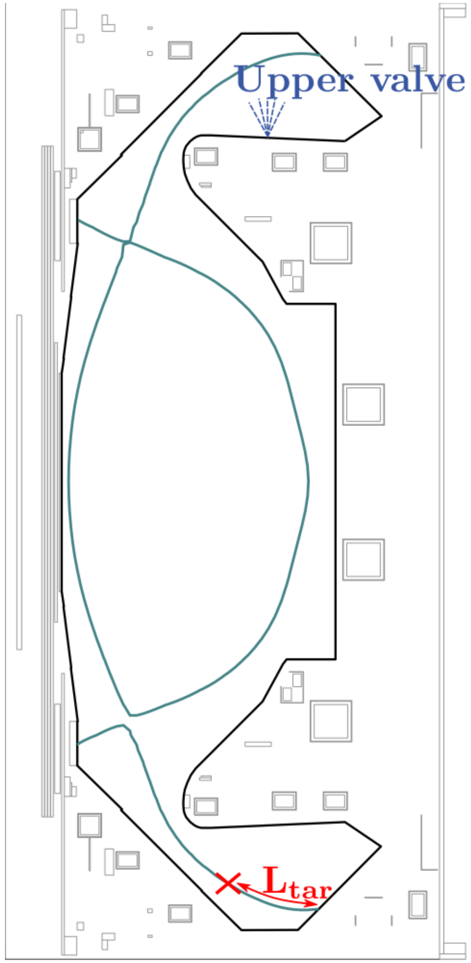




Lower front position



Upper perturbation



Lower divertor is not effected by upper perturbation!

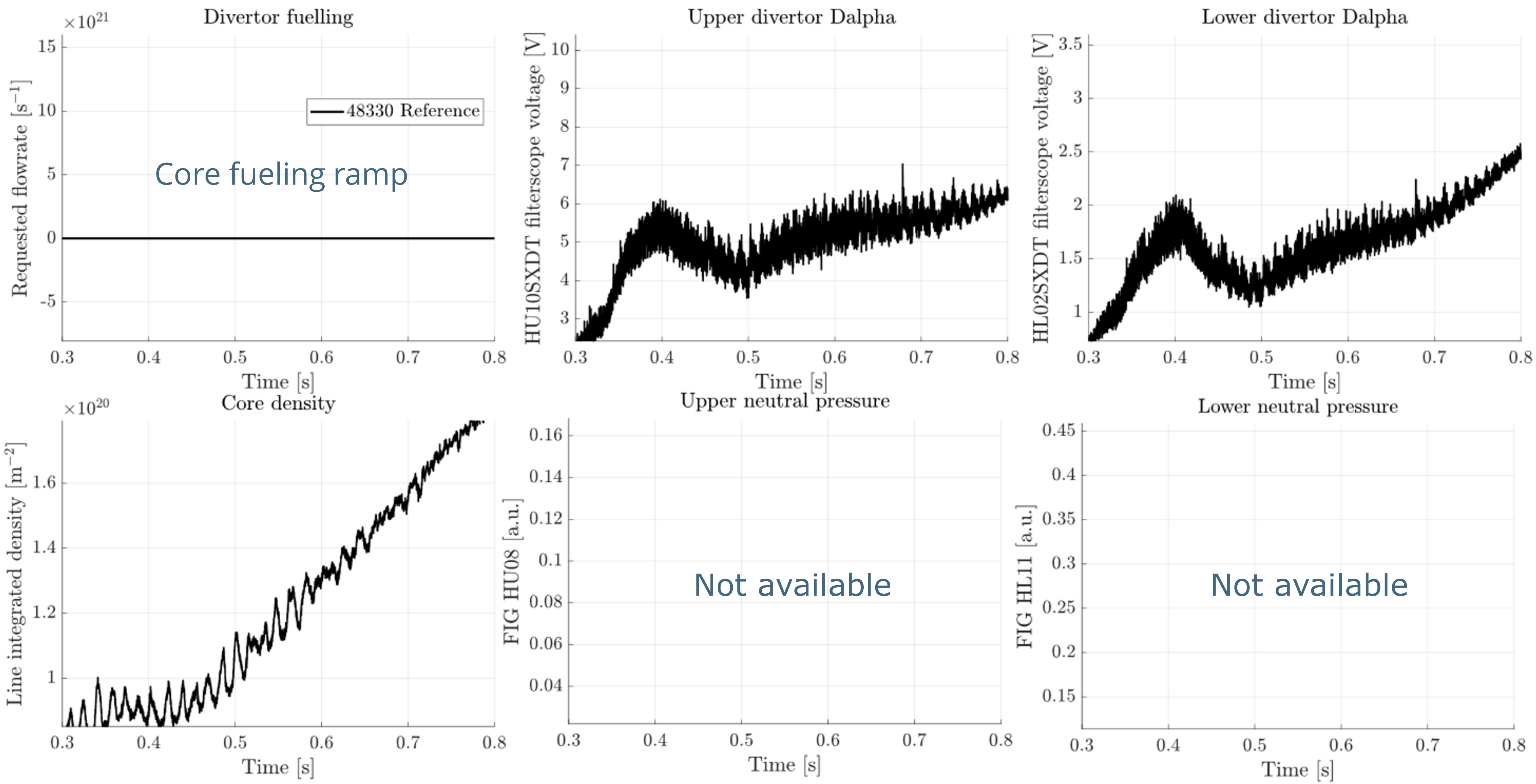
Contrary open divertor results from TCV [1]

[1] O. Février et al 2021 Nucl. Fusion **61** 116064

Divertor interaction overview

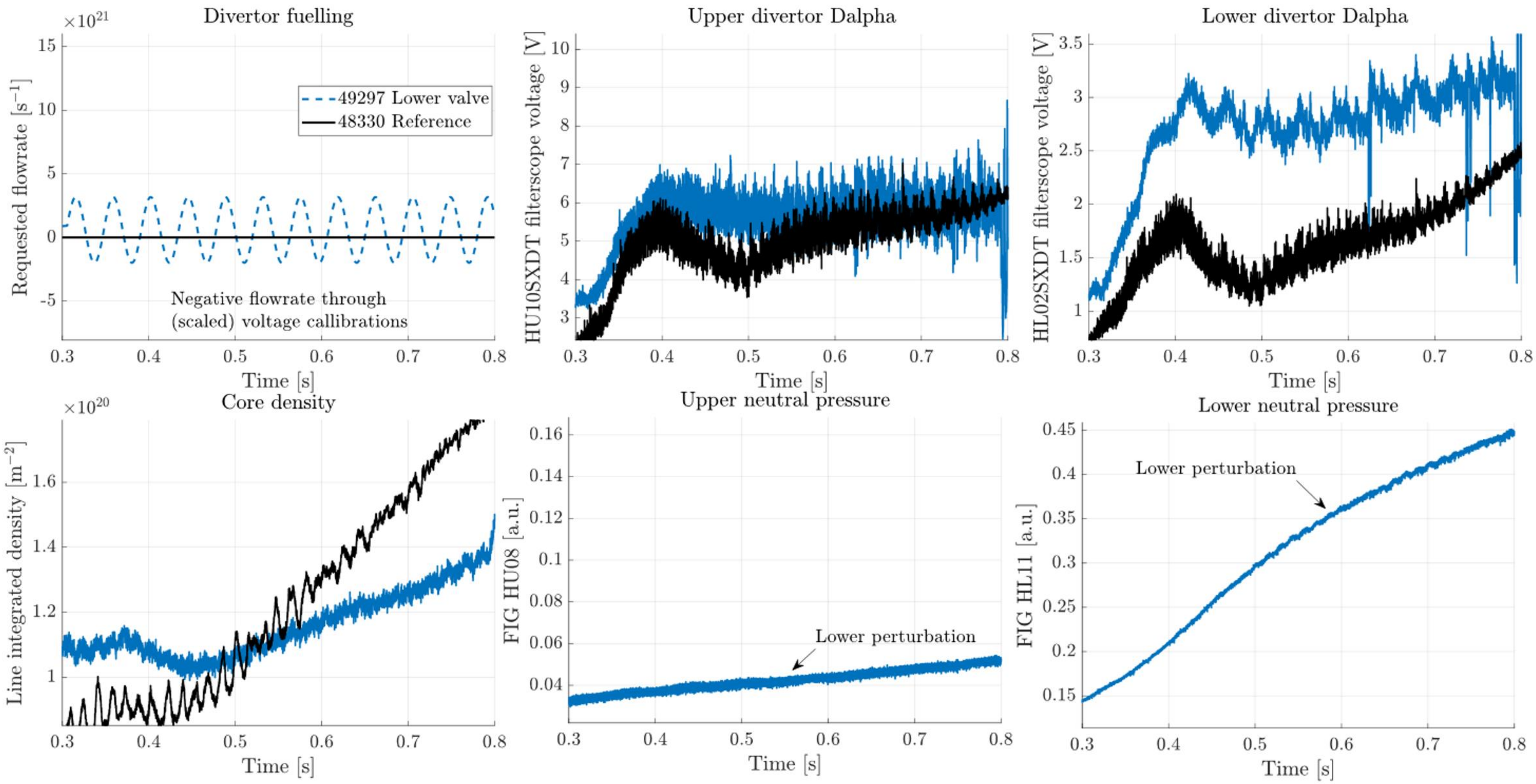
Interaction overview

Divertor valves:
Upper LFSD_TOP_U0102
Lower LFDS_BOT_L0506



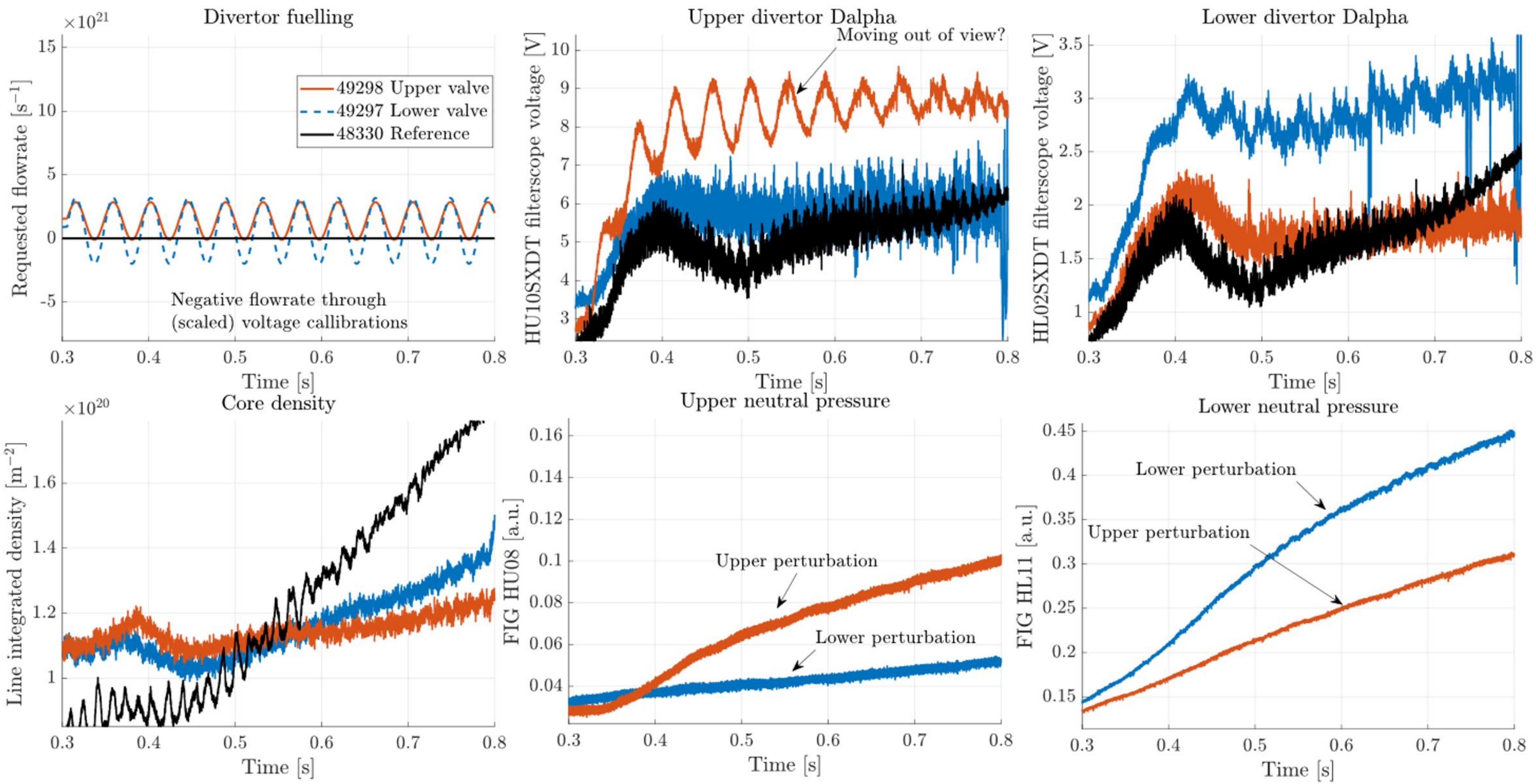
Interaction overview

Divertor valves:
Upper LFSD_TOP_U0102
Lower LFDS_BOT_L0506



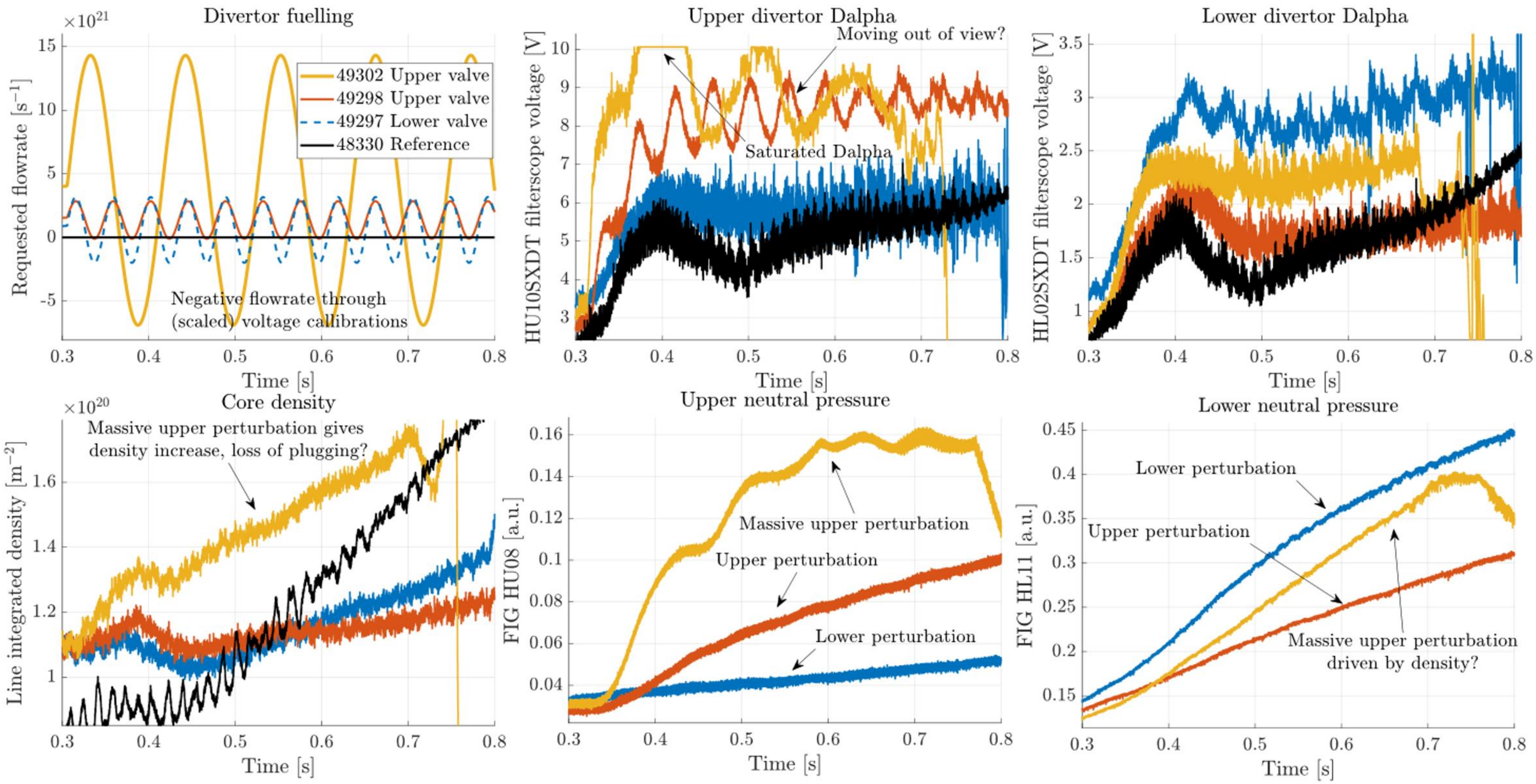
Interaction overview

Divertor valves:
Upper LFSD_TOP_U0102
Lower LFDS_BOT_L0506



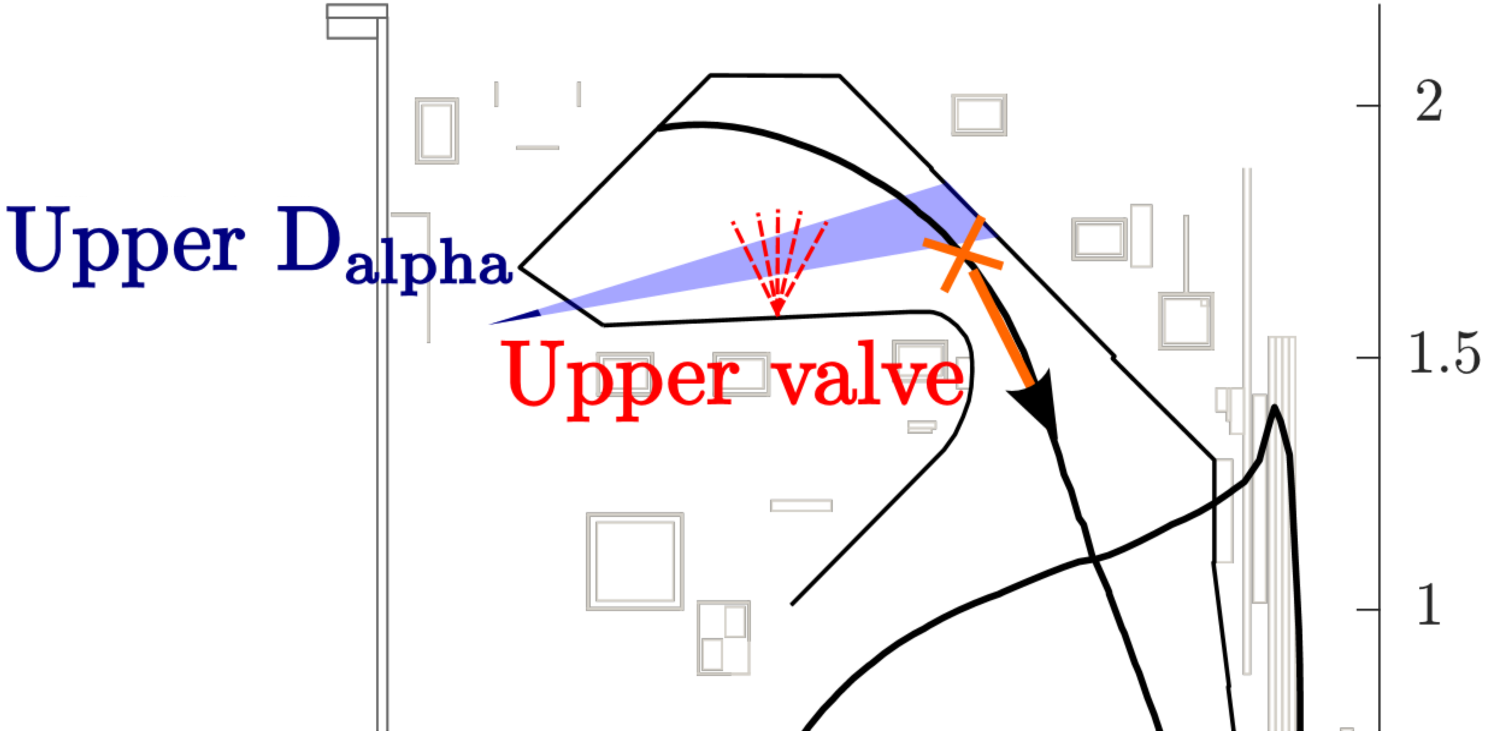
Interaction overview

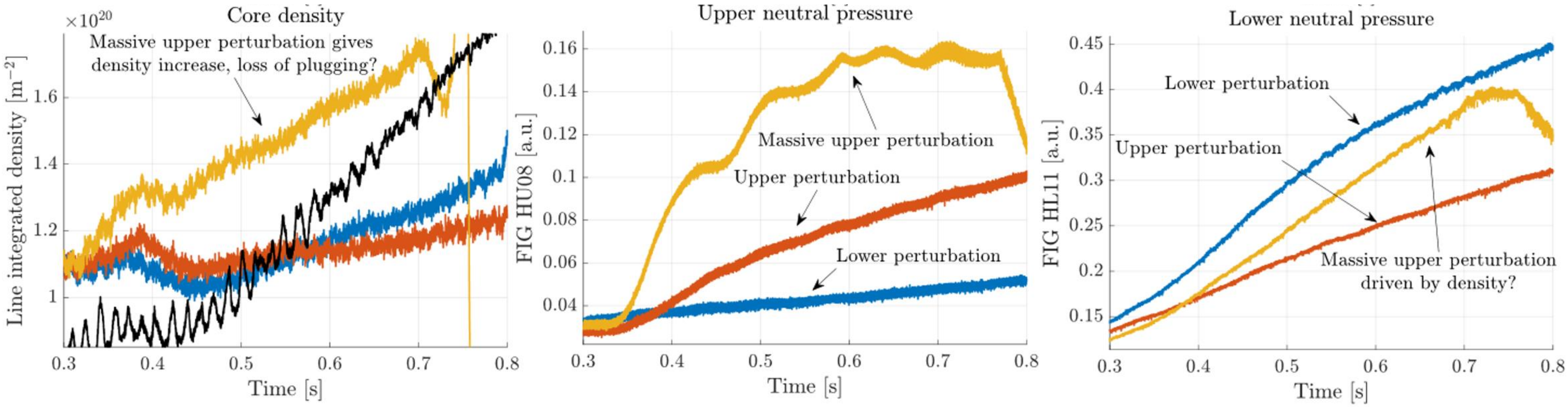
Divertor valves:
Upper LFSD_TOP_U0102
Lower LFDS_BOT_L0506



Interaction overview

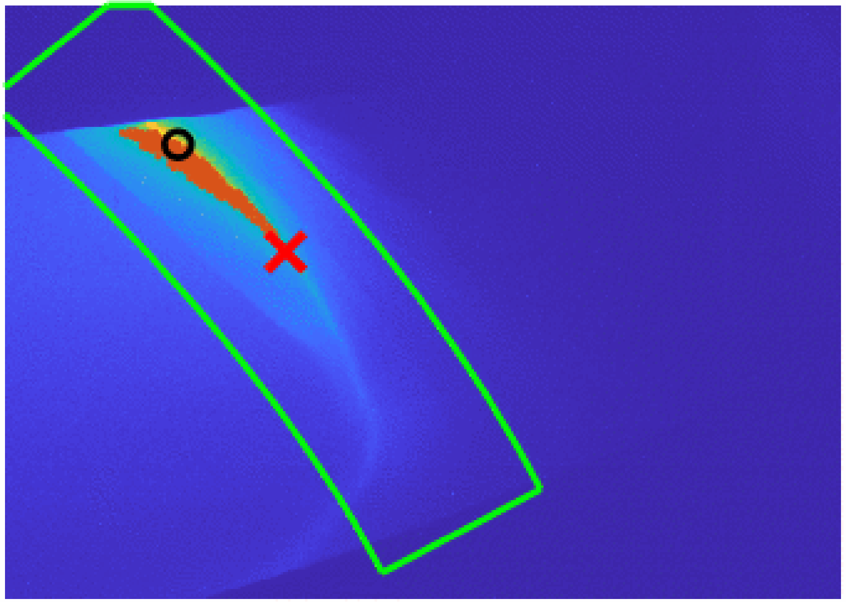
Loss of plasma plugging
→ Leakage into main chamber
→ Core density increase

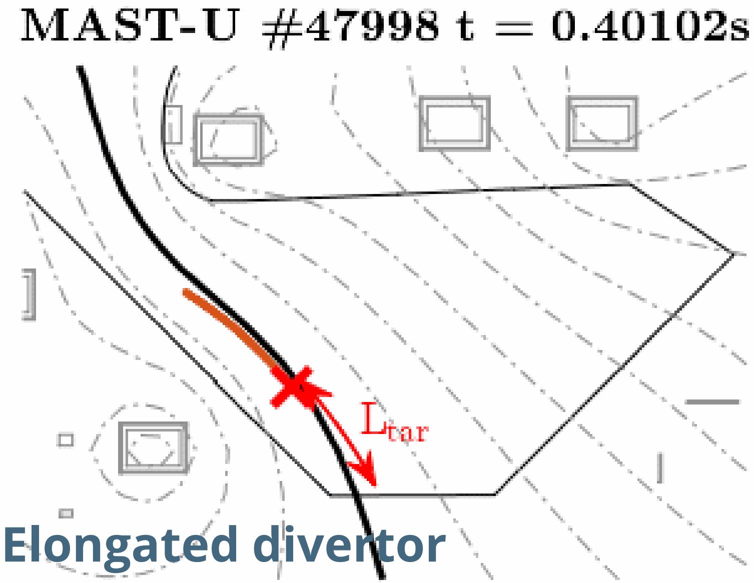


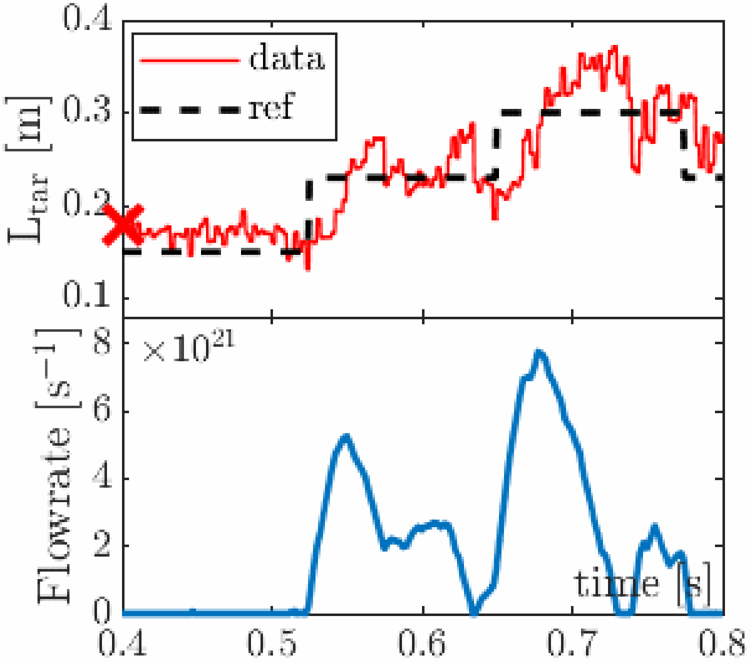


Elongated divertor exhaust control

Feedback control







Bolometry in conventional divertor

IRVB Bolometry during MARFE-like conventional divertor response

Provided by Fabio Federici