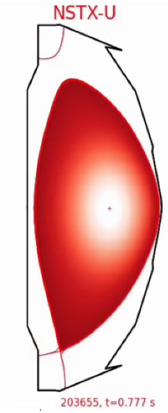
Integrated magnetic control to facilitate H-mode access in NSTX-U

A. Pajares, A. S. Welander, W. P. Wehner, K. E. Thome, N. W. Eidietis, and H. Anand

General Atomics



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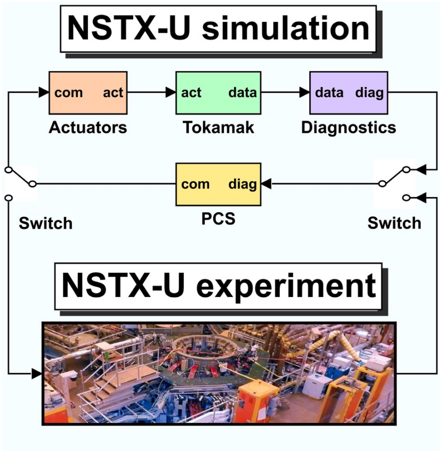
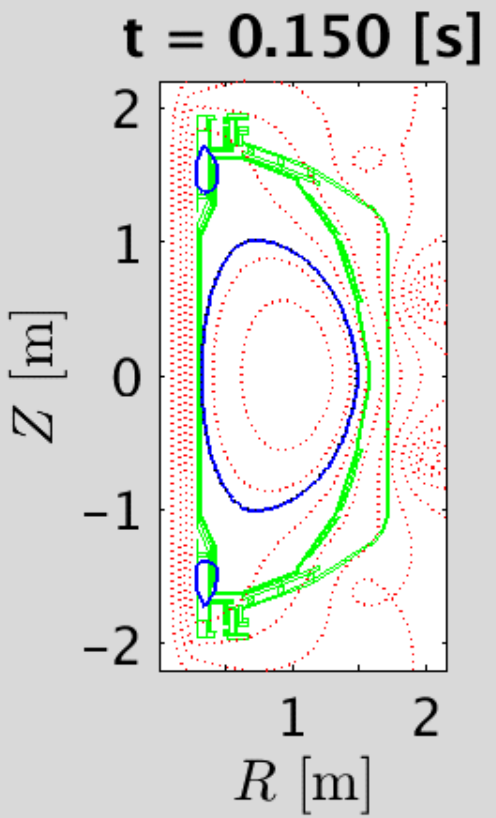
November 18, 2024





Supported by US DoE under contract DE-SC0021113

Outline

- **Introduction:** the "bobble" control issue in NSTX-U
  - Characteristics of the bobble
  - Modeling with GSEvolve
- **Analysis to find source causes for bobble:**
  - System's stability via system's poles
  - Input/output cross-coupling via singular-value decomposition
- **Control solution 1:** two-stage I_p ramp
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- **Conclusion**

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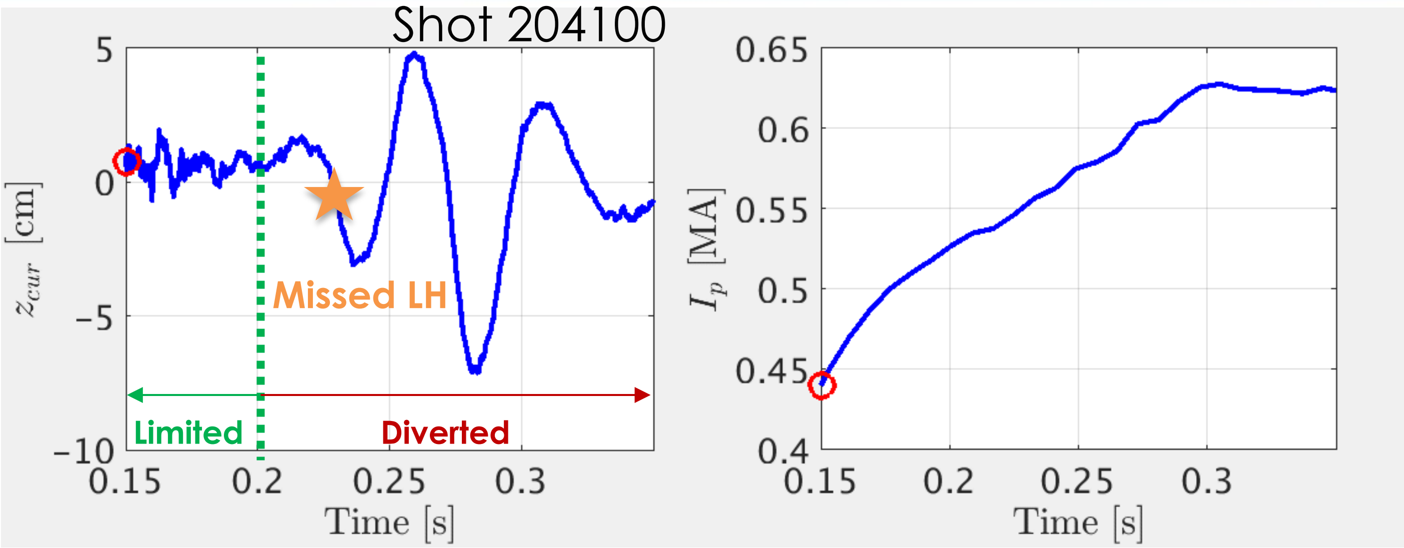

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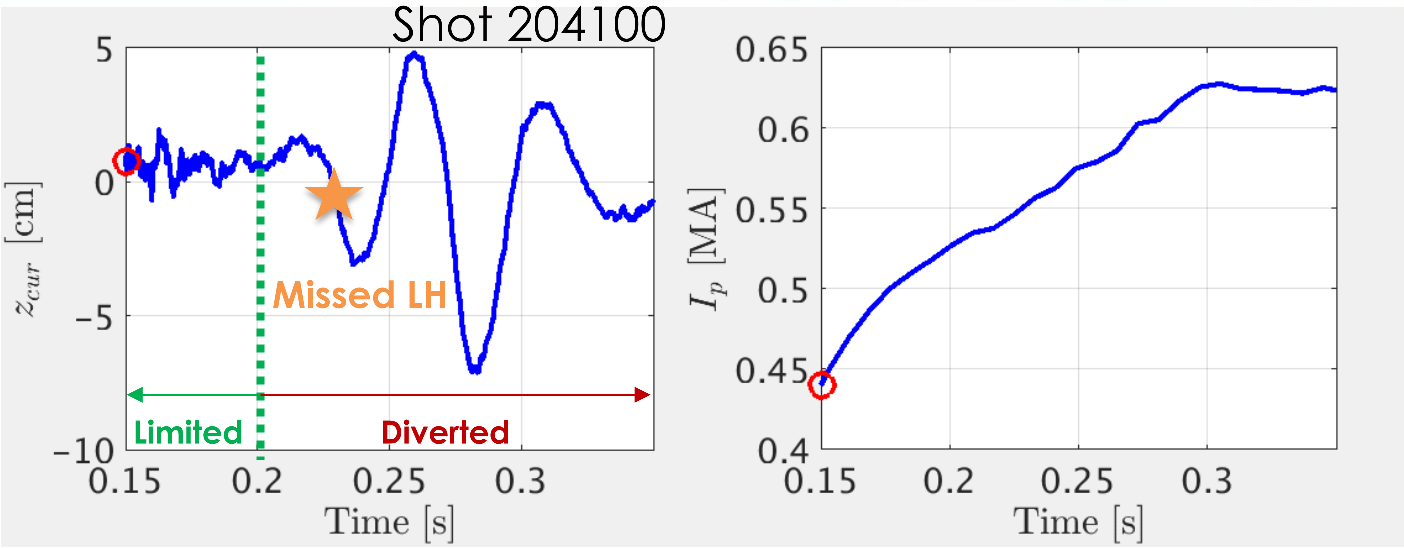

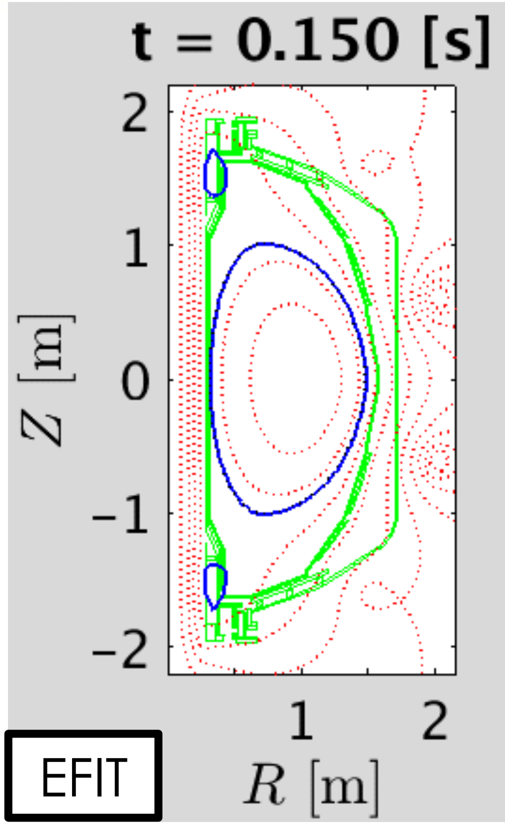

Problem = z_{cur} oscillation + shape dithering to/from USN/LSN prevented access to H-mode (low l_i, high performance)

NSTX-U

GENERAL ATOMICS

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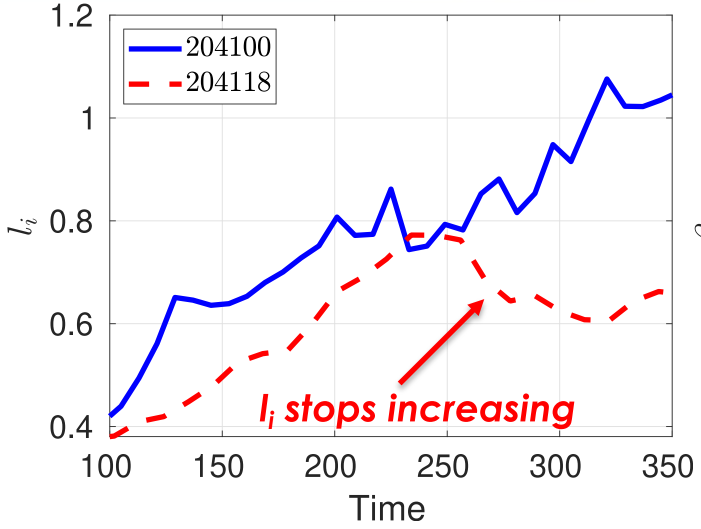

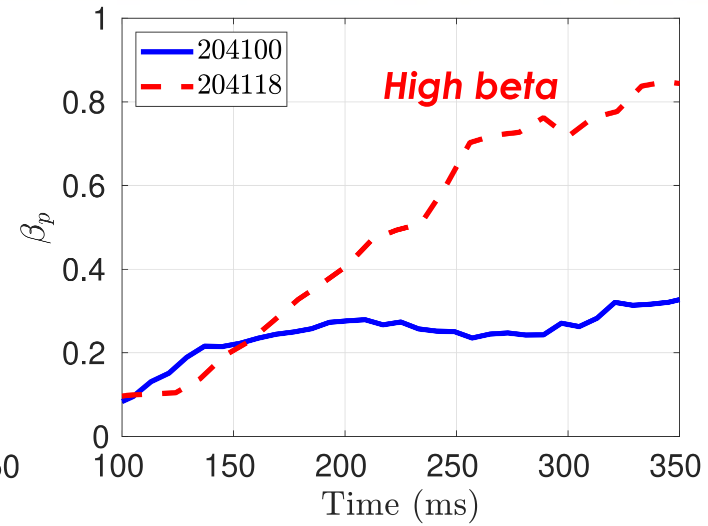

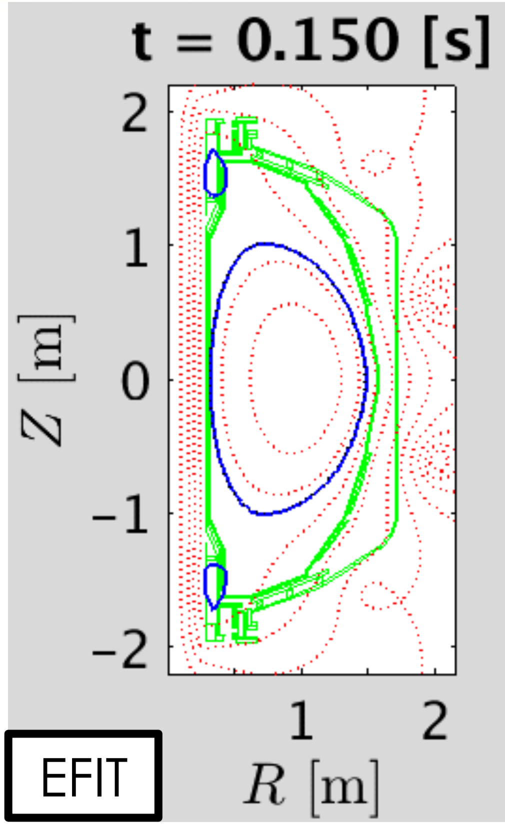

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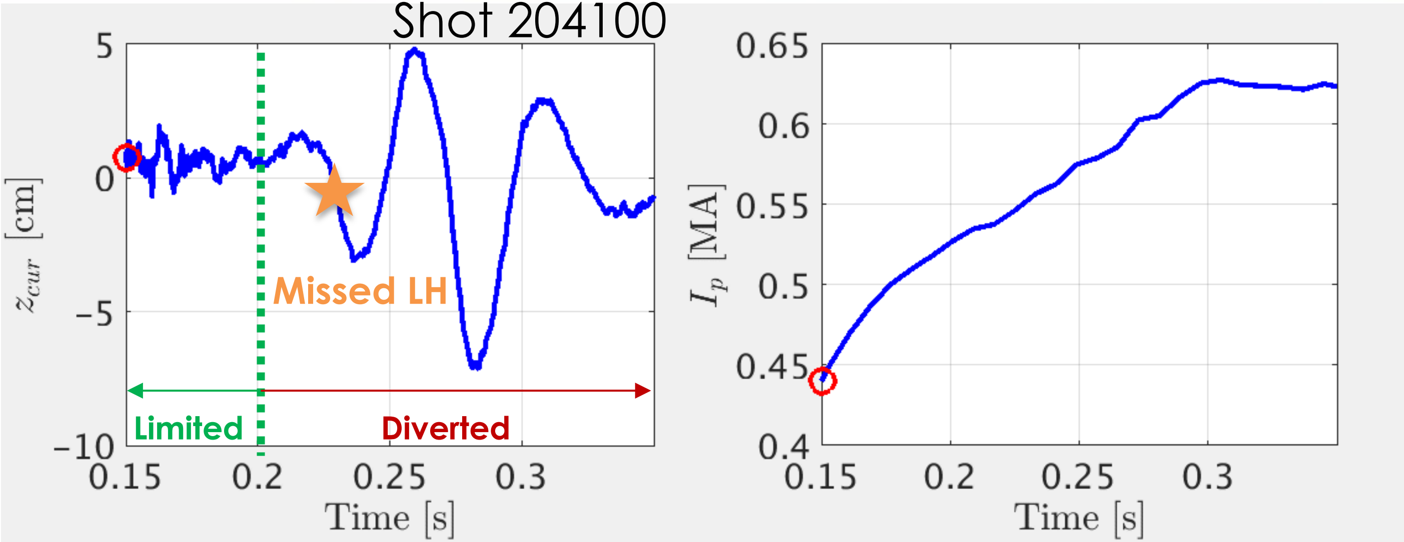

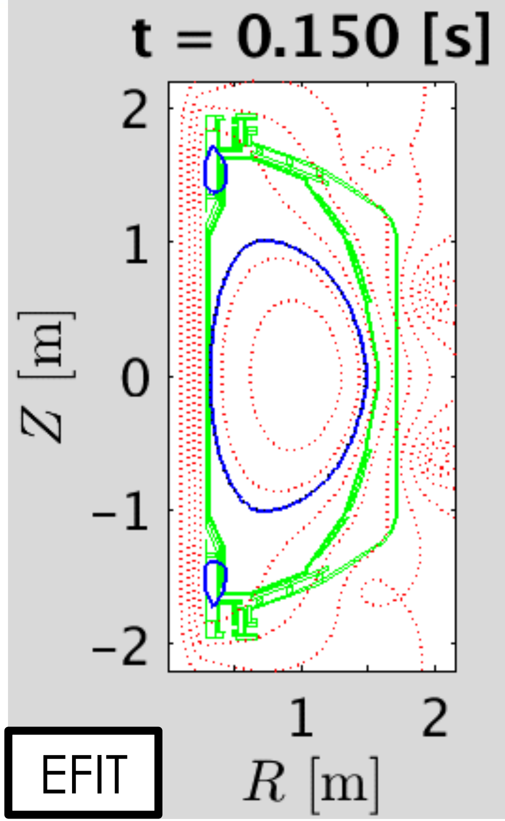

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H-mode access required stable double-null shape [1]

Lots of dedicated scenario & control development [2,3,4]

[1] D. Battaglia et al, 2018 NF 58
[2] J.E. Menard et al, 2017 NF 57
[3] M. Boyer et al, 2018 NF 58
[4] J. Wai et al, APS DPP 2022

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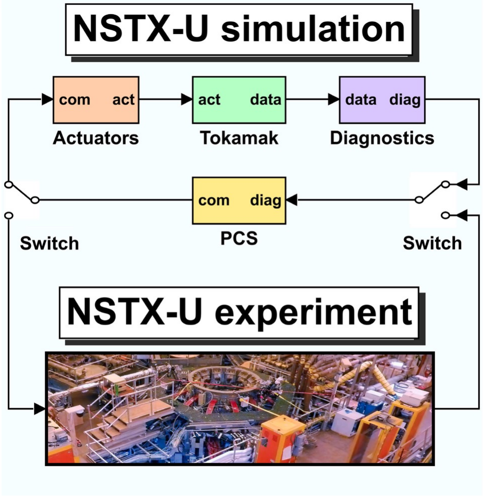
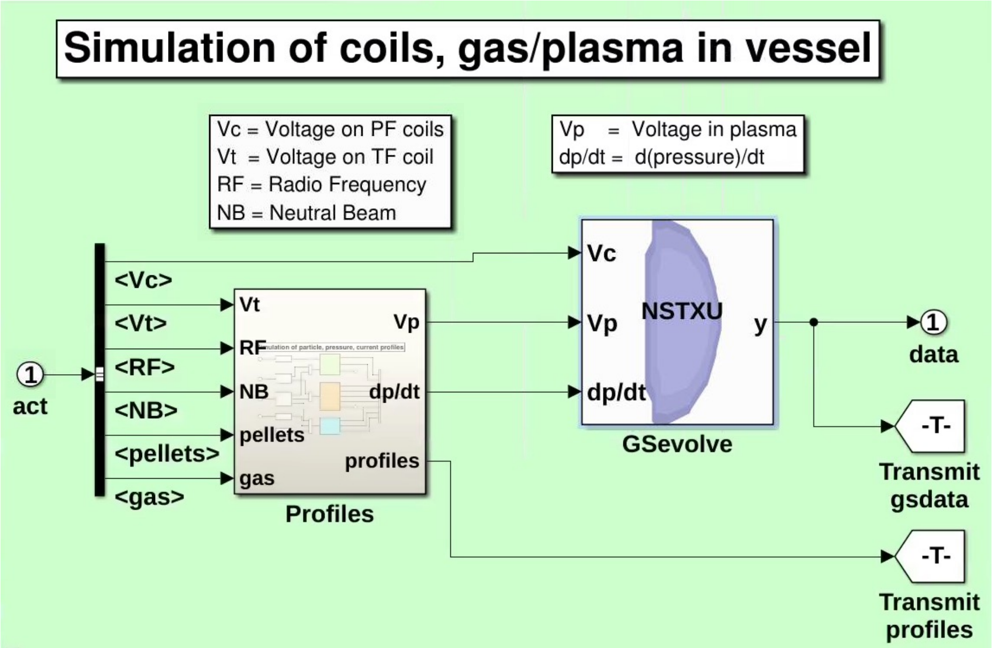
GSEvolve is a control-simulation framework that uses the NSTX-U plasma control system (PCS) and can simulate the bobble



GSEvolve **[4,5]** plasma-response model within **Tokamak** is based on Grad-Shafranov equation. **Actuators (H&CD, Power supply)** + **Diagnostics** models, plus **PCS**

Tokamak



[4] Welander et al, Fusion Eng. Des. 416 (2019)
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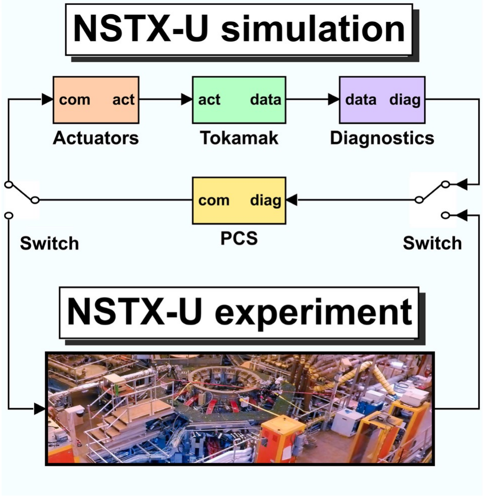

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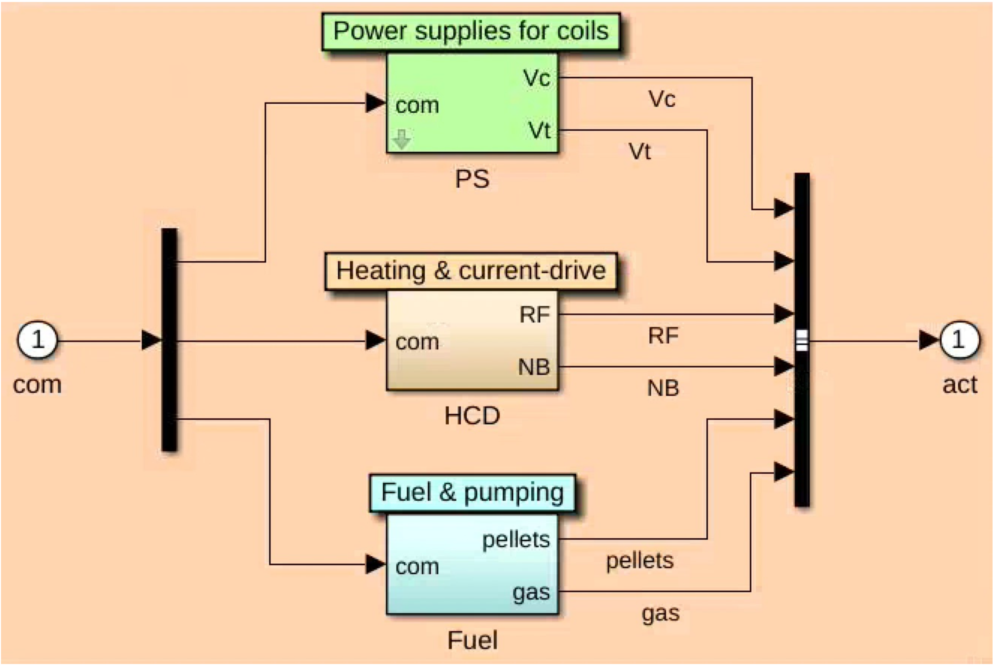
Actuators



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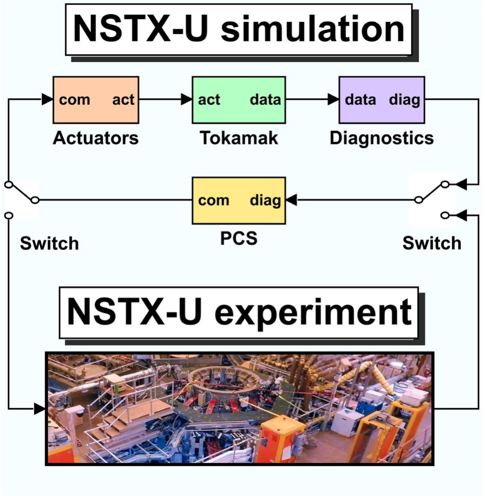

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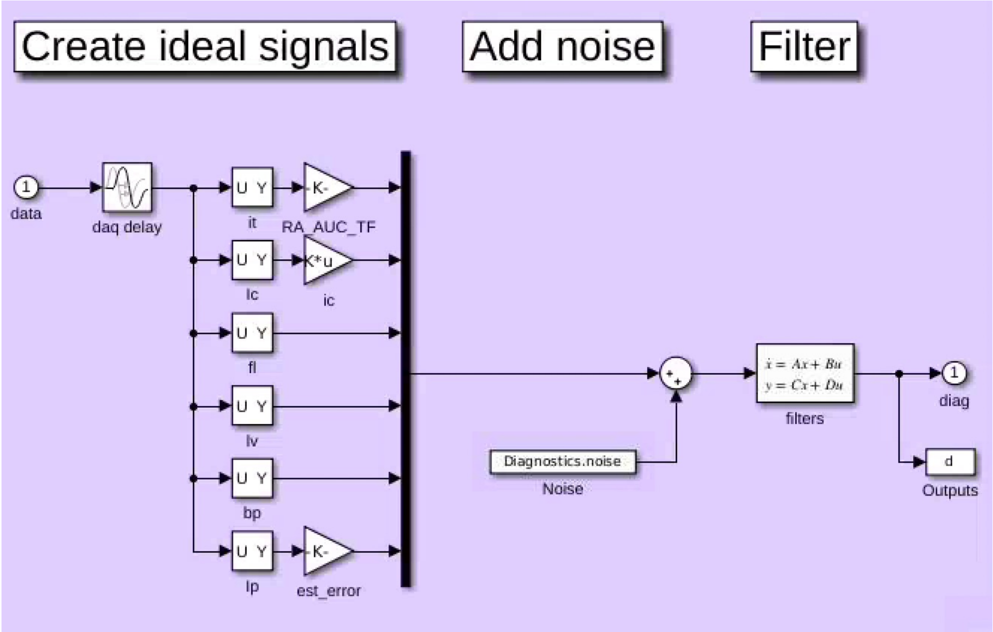
Diagnostics



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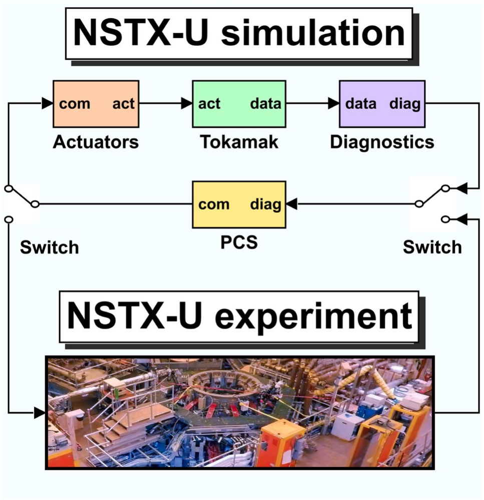

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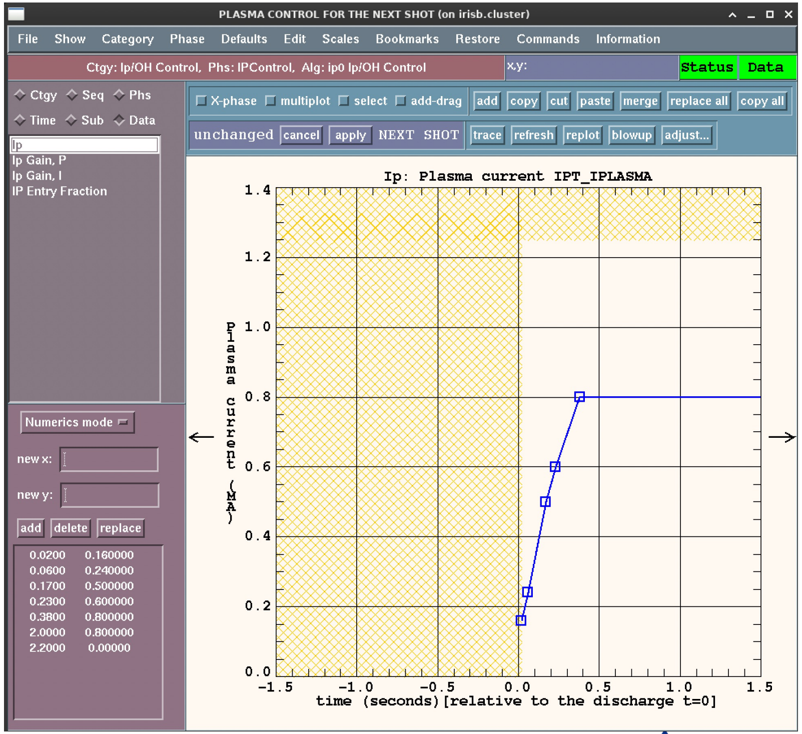
Plasma control system (PCS)



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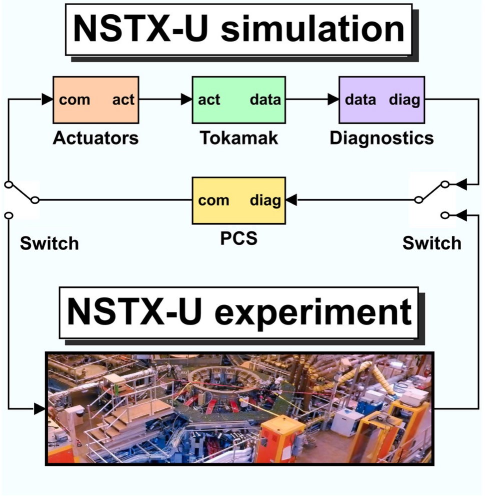
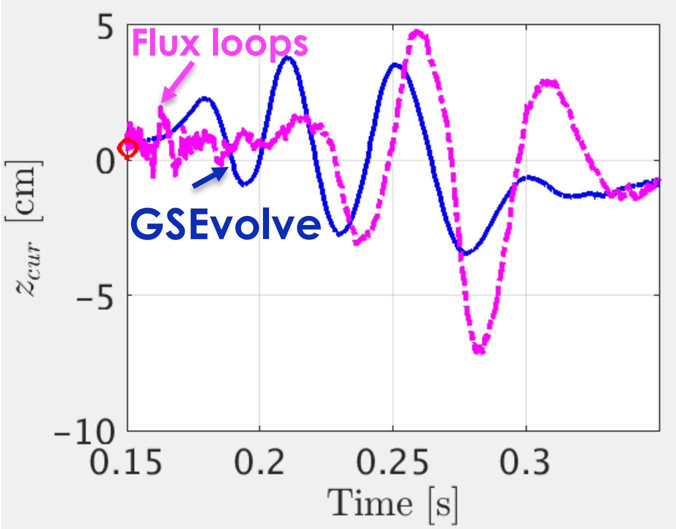
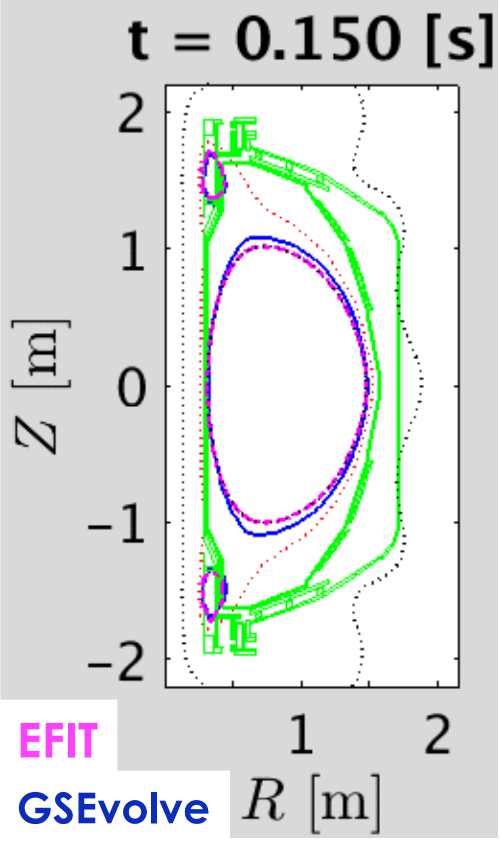


Main "bobble" dynamical features reproduced (no shot-specific tuning):

- Vertical oscillation frequency
- Shape dithering
- Oscillation starts after diverting and ends in flattop (w/ small lag)





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GSEvolve provides a simulation testbed to analyze this NSTX-U magnetic-control problem and explore control solutions

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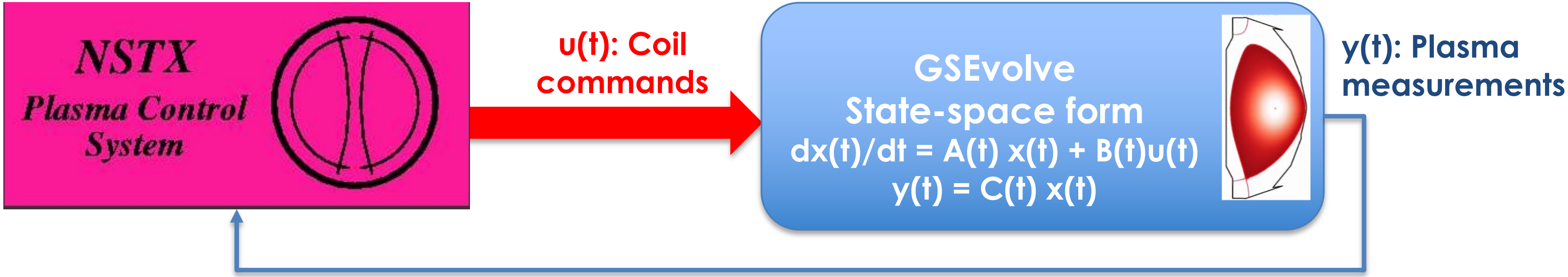
System stability w/ and without NSTX-U PCS feedback is analyzed with GSEvolve time-variant model and linear PCS algorithms



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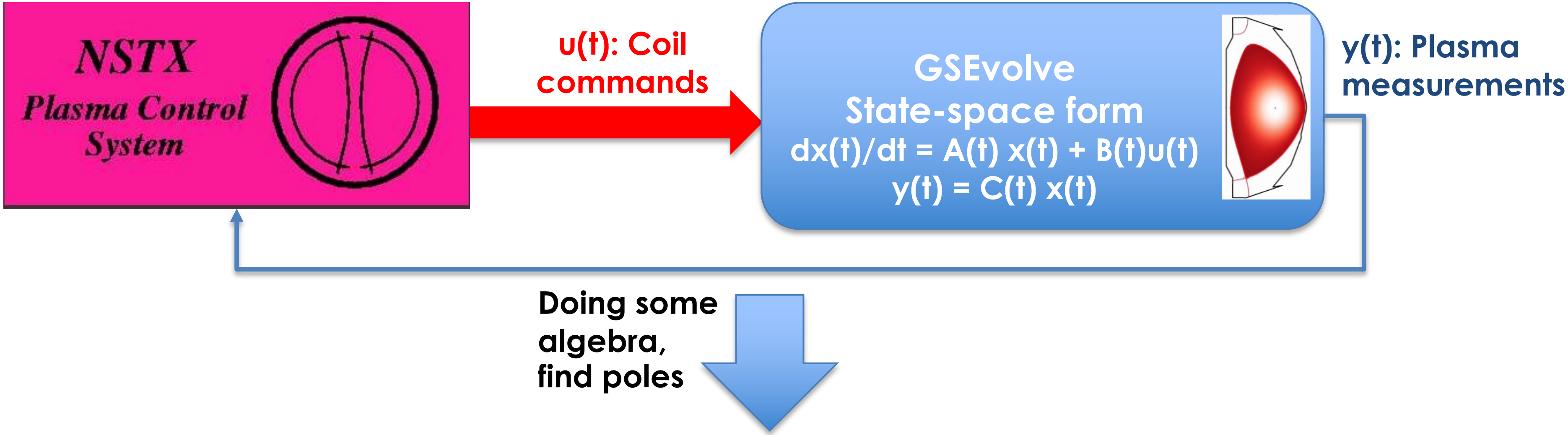

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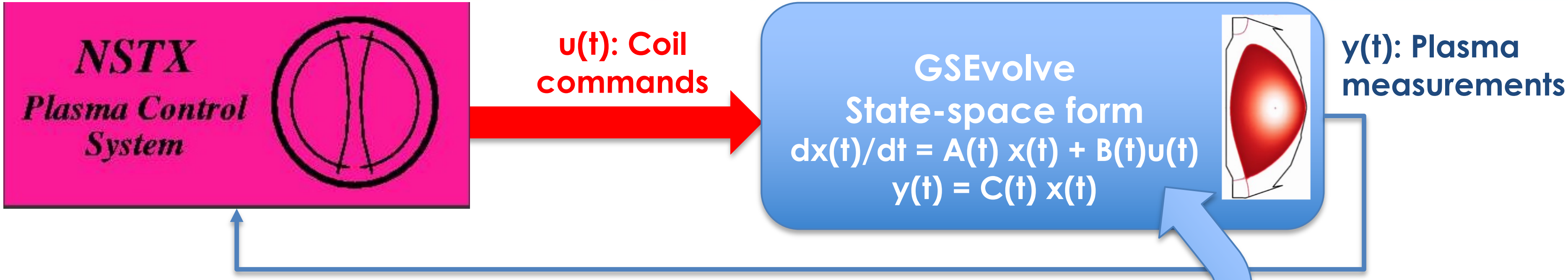
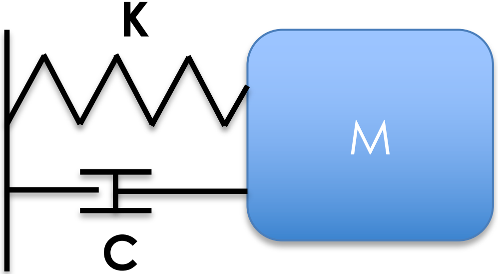


Doing some algebra, find poles

$$M\frac{d^2x}{dt^2} + C\frac{dx}{dt} + Kx = 0$$

$$Mr^2 + Cr + K = 0$$

Example:



Poles $r = -\frac{C}{2M} \pm \frac{\sqrt{C^2-4MK}}{2M}$

C>0, M>0 → poles < 0 → stable

C<0 → poles > 0 → unstable

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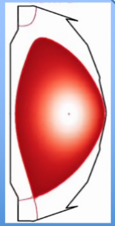
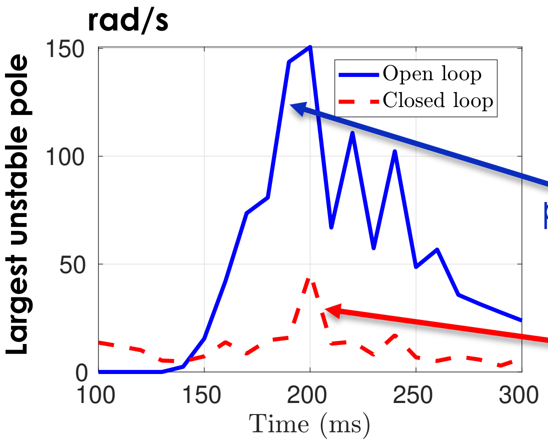
u(t): Coil commands

GSEvolve
State-space form
$$dx(t)/dt = A(t)\,x(t) + B(t)u(t)$$
$$y(t) = C(t)\,x(t)$$



y(t): Plasma measurements

Doing some algebra, find poles



Open-loop instability peaks at time of diverting

Feedback reduces instability, but does not eliminate it
System is unstable

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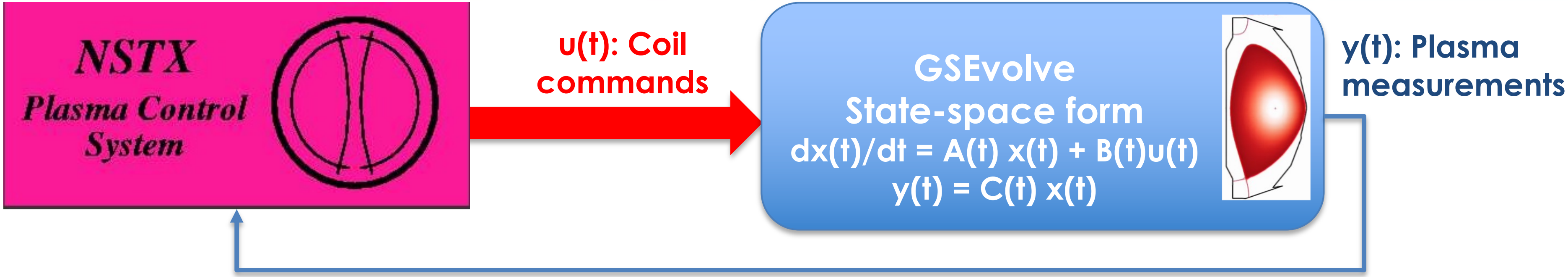

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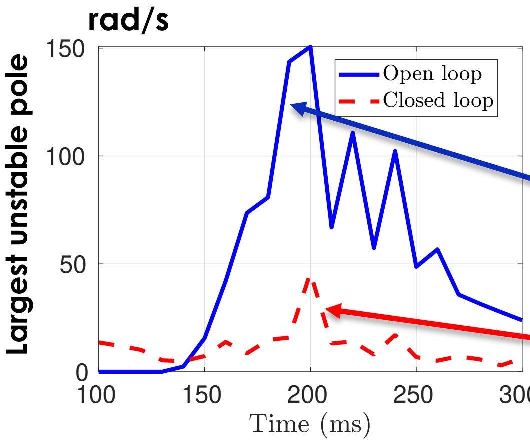

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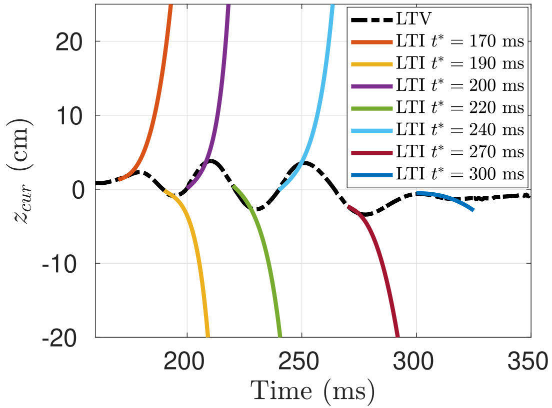
In colors: time-invariant simulations



Bobble is a composition of plasma vertical displacements that switch directions as plasma shape changes

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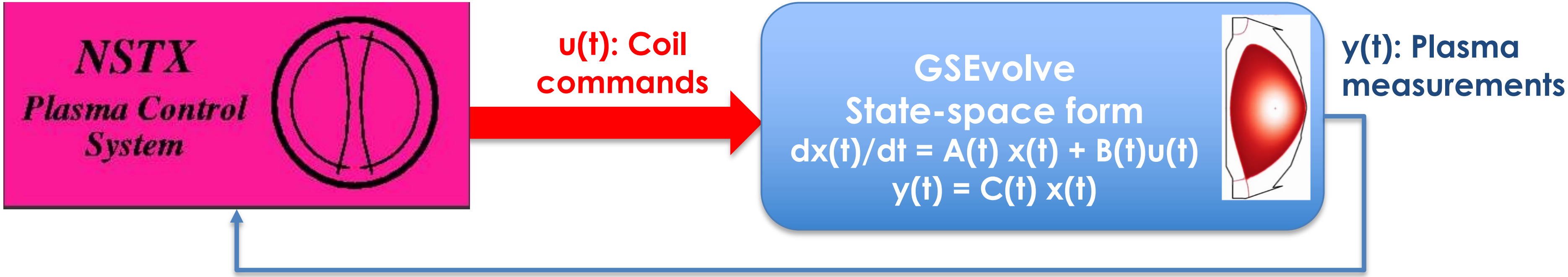

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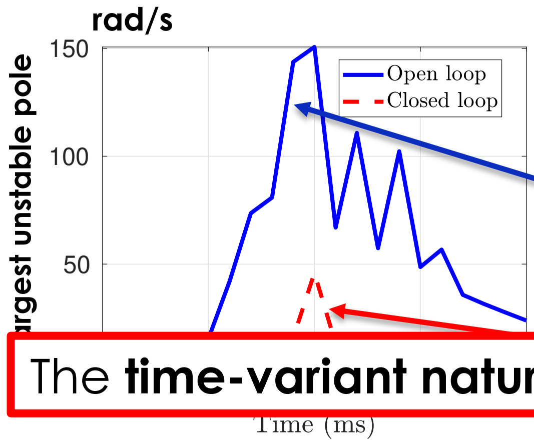

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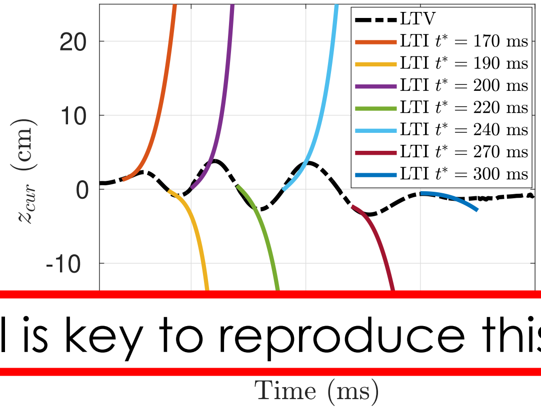

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The **time-variant nature of GSEvolve's** model is key to reproduce this dynamics

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Singular value decomposition (SVD) is a traditional linear algebra technique that informs about input/output (I/O) cross-coupling

GSEvolve model in transfer-function form:

$$\mathbf{y}(t) = G(t)\,\mathbf{u}(t)$$

Outputs: Plasma measurements

Inputs: Coil commands

G is a tensor (matrix) relating inputs and outputs

SVD: G = U Σ V^T

NSTX-U

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Σ: Diagonal matrix with singular values σ_i of the system
When $\sigma_i > 1$ → amplification from singular input to output direction

U: Matrix whose columns are the output singular directions

V: Matrix whose columns are the input singular directions

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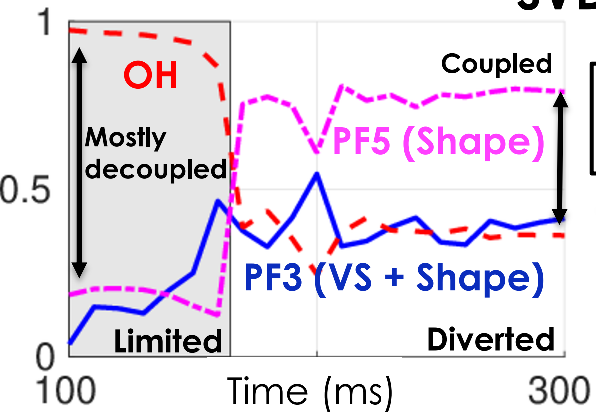
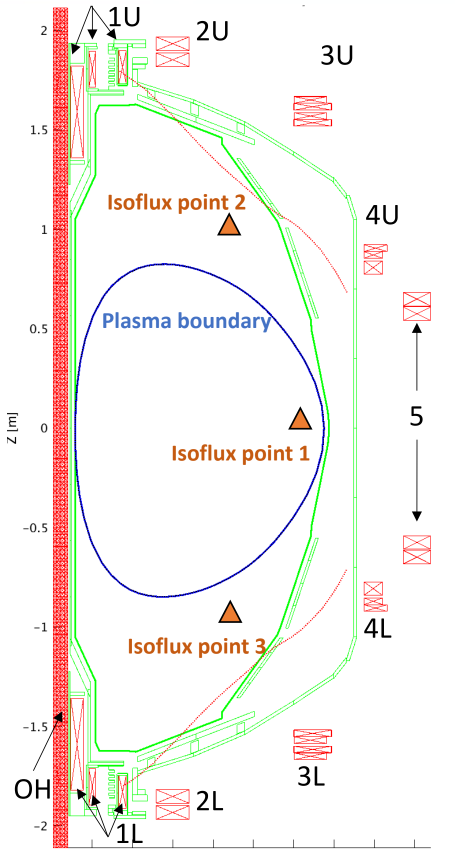
Input: Components of 1^{st} column in V





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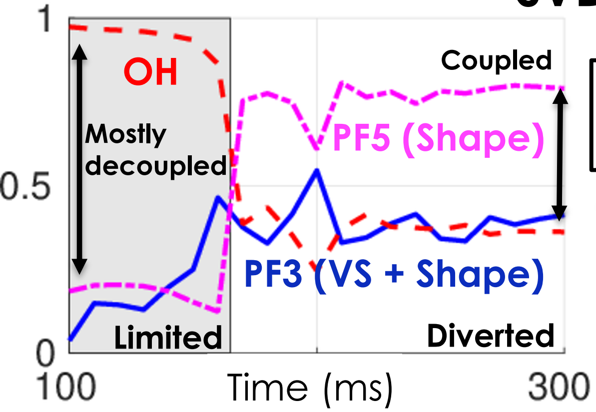
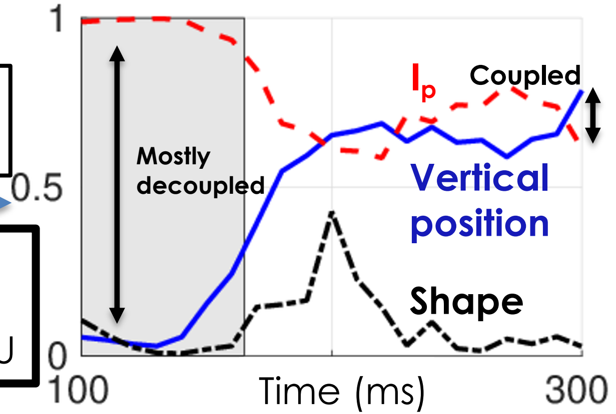


Singular directions for largest singular value in Σ: $\sigma_1 > 1$

Input: Components of 1st column in V	**Output:** Components of 1st column in U



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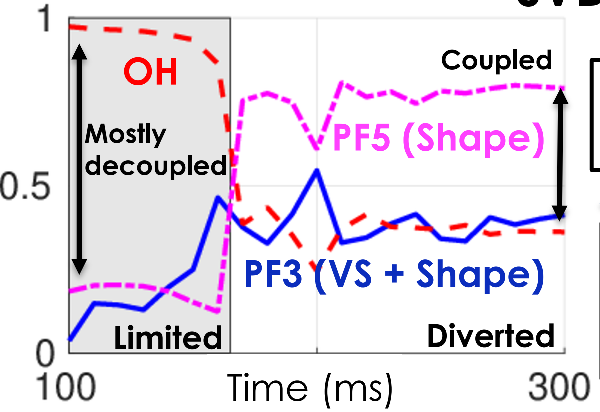

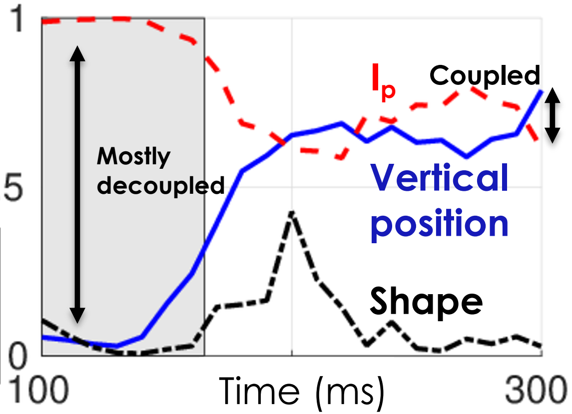

NSTX-U PCS uses "decoupled" loops, but they are not decoupled when diverted

- **OH** coil specifically used to control I_p but also strongly affects z_{cur}
- **PF5** used to control **shape** but also strongly affects I_p and z_{cur}
- **PF3** used for VS (z_{cur}) and **shape** but affect I_p

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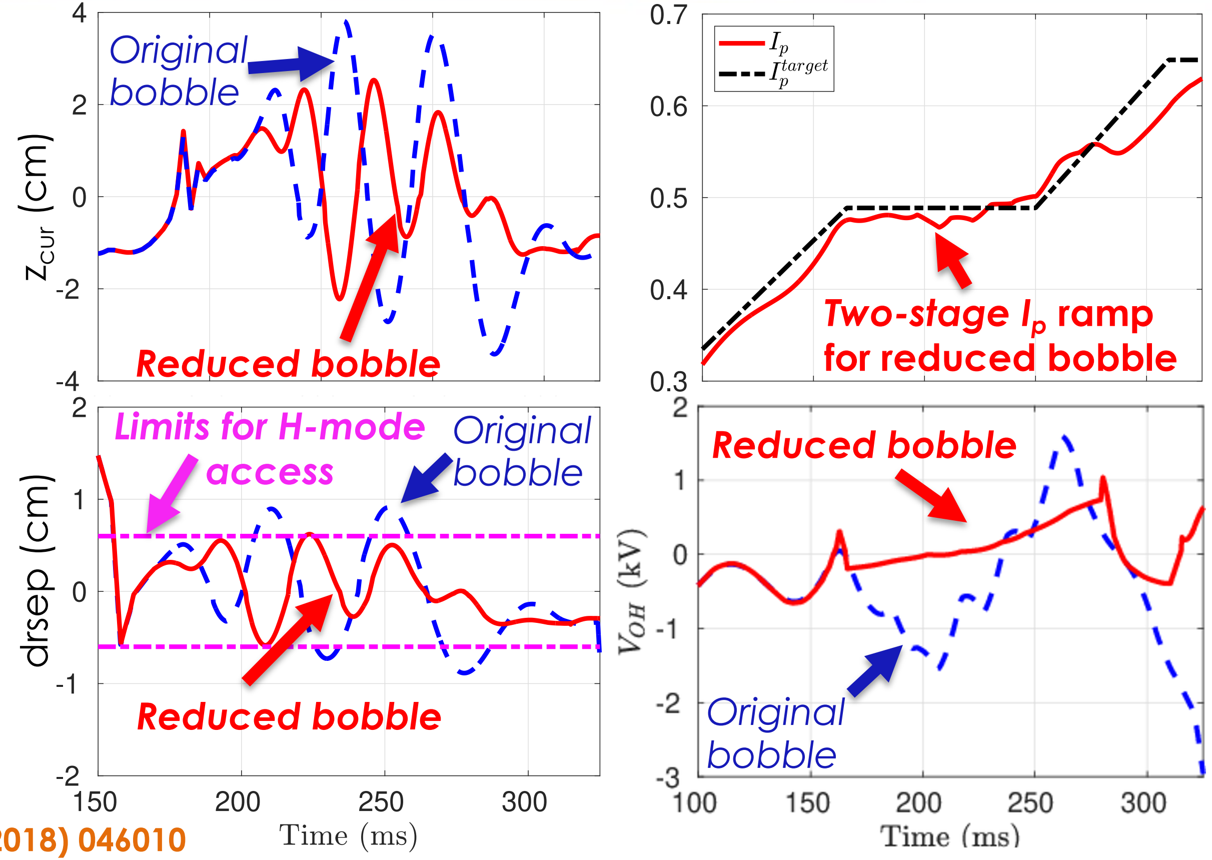
Control solution 1: use a 2-stage I_p ramp to ease I_p control, reducing OH coil oscillation and its negative interaction with z_{cur}

The simulated shot with the 2-stage I_p ramp has a **reduced bobble** versus the **original bobble** simulation

Reduced bobble has drsep within the *limits found in* ***[1]*** for H-mode access, and a **much smaller oscillation in the OH coil voltage (V_{OH})**



[1] D. Battaglia et al, Nuclear Fusion 58 (4) (2018) 046010

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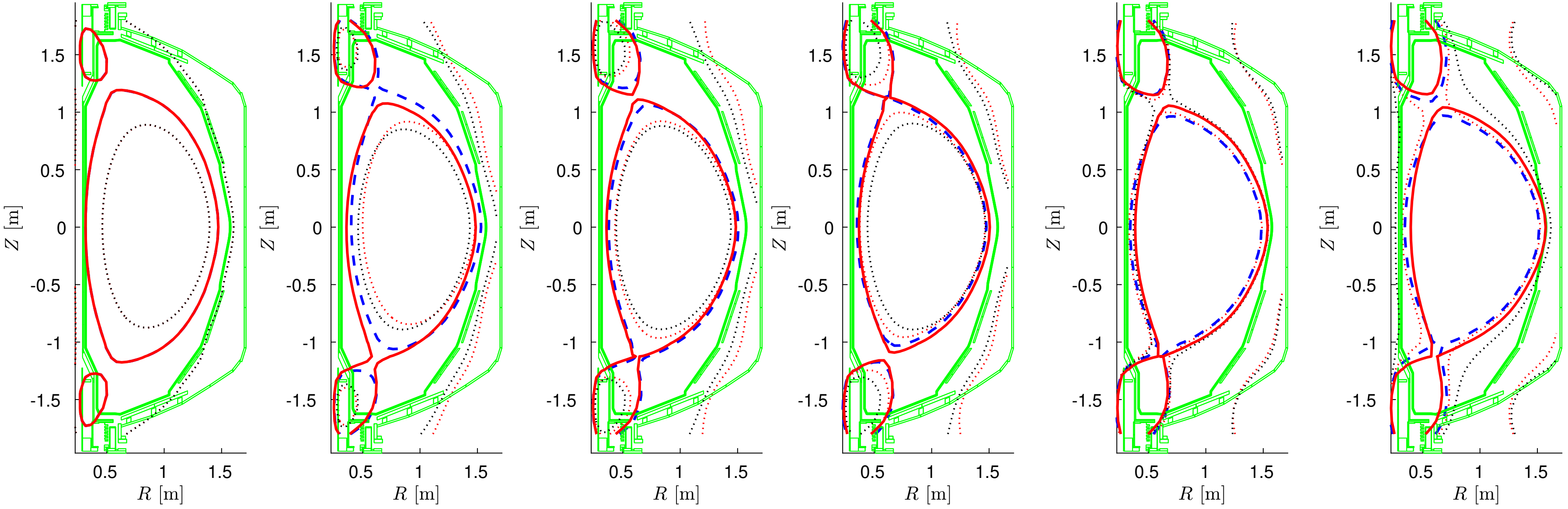
Original bobble

Reduced bobble: more stable shape, more elongated and closer to DN, but still bobbles



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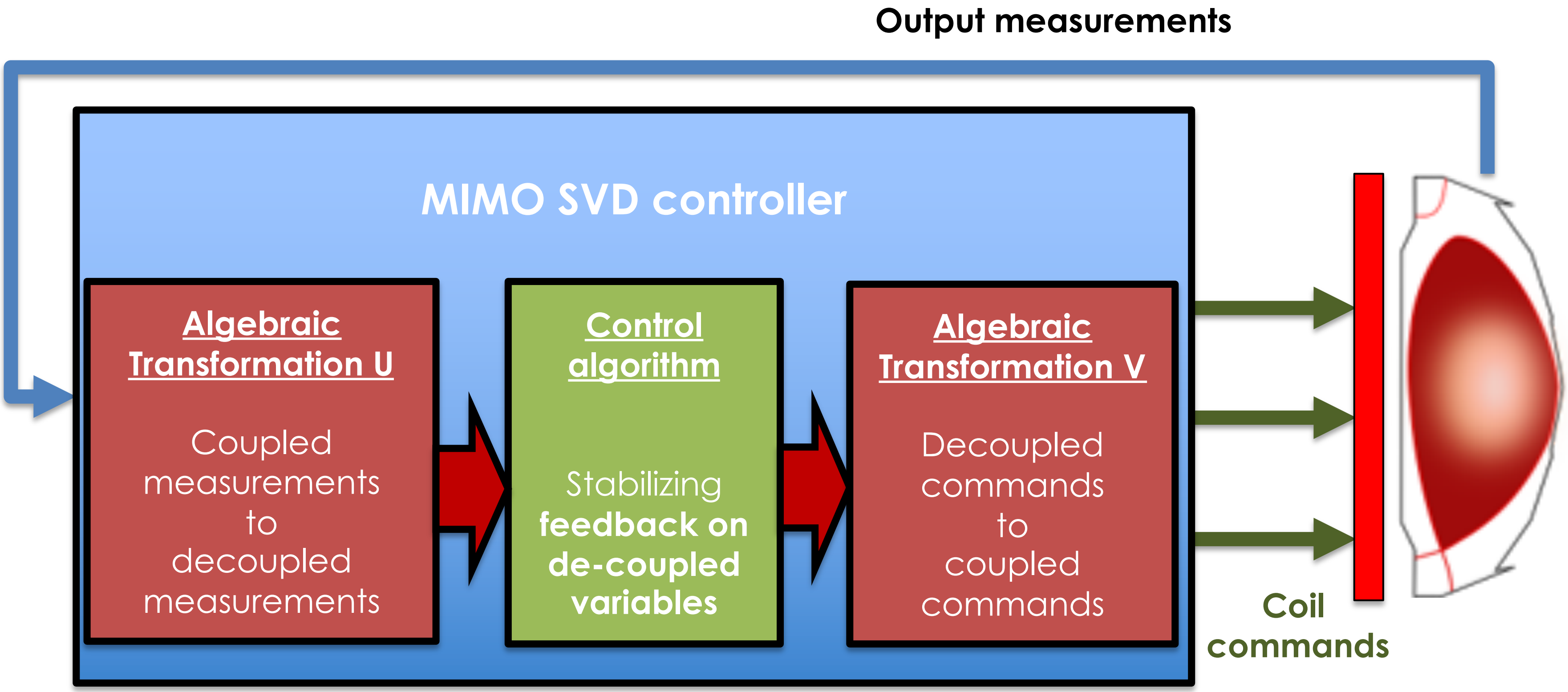
  - Input/output cross-coupling via singular-value decomposition
- **Control solution 1:** two-stage I_p ramp
- **Control solution 2:** multi-input multi-output decoupling controller
- **Conclusion**

Solution 2: use Multi-Input Multi-Output (MIMO) controller based on SVD to decouple input/output interactions



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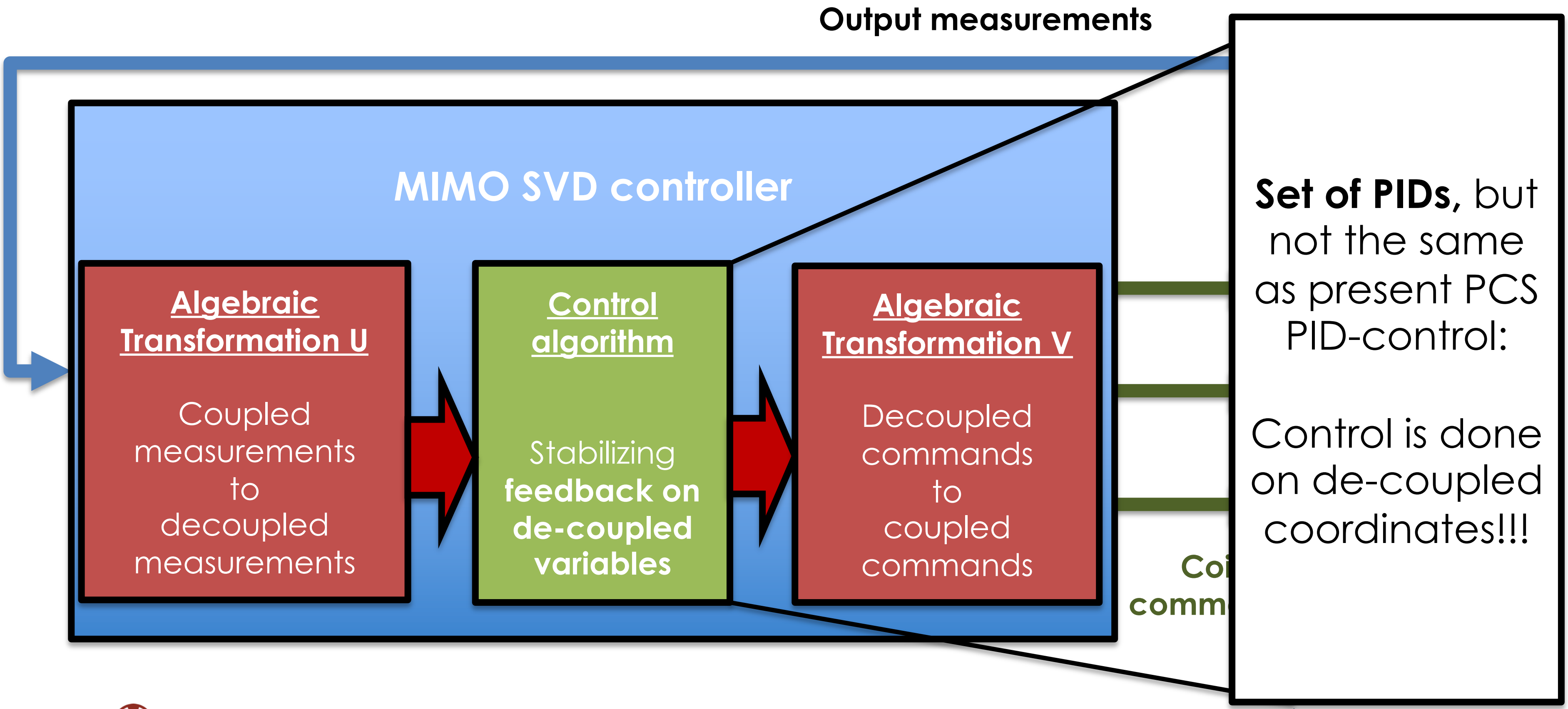
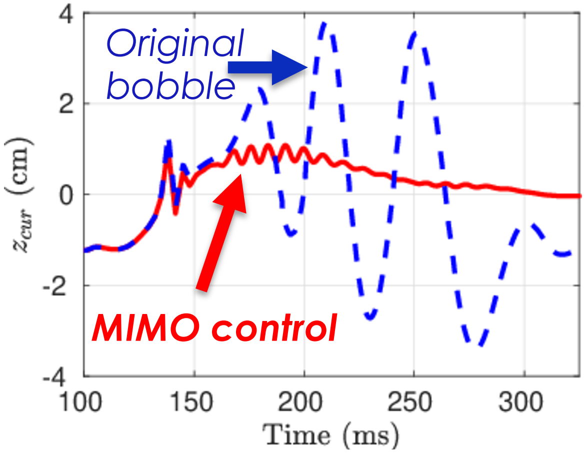
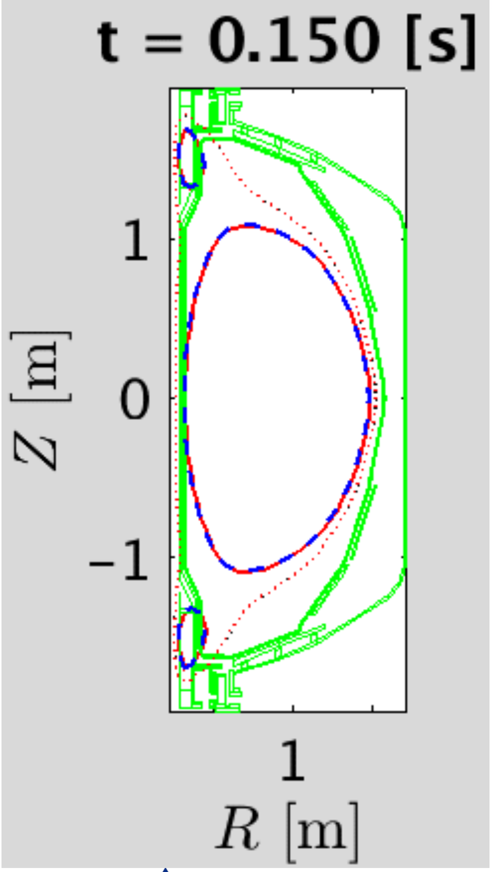


Solution 2: use Multi-Input Multi-Output (MIMO) controller based on SVD to decouple input/output interactions

The simulated shot with the **MIMO control** does not experience the vertical oscillation found in the **original bobble** simulation





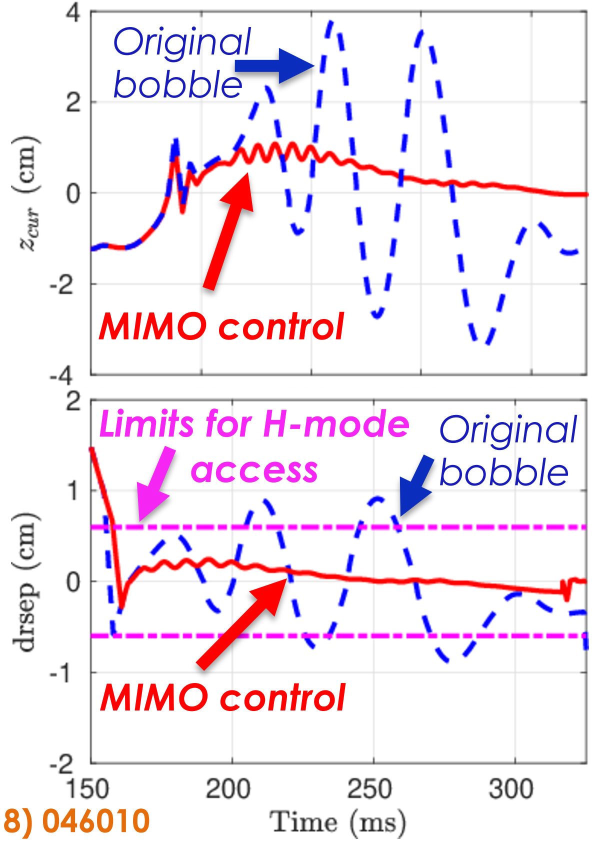
NSTX-U

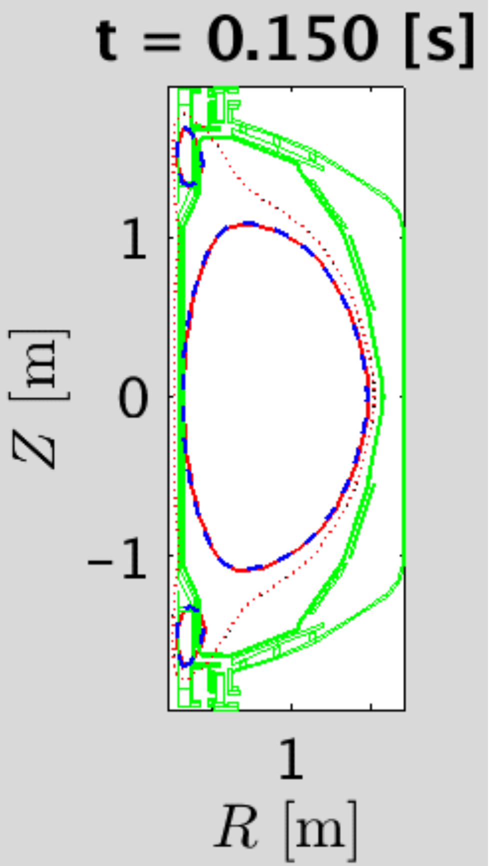
GENERAL ATOMICS

Solution 2: use Multi-Input Multi-Output (MIMO) controller based on SVD to decouple input/output interactions

The simulated shot with the **MIMO control** does not experience the vertical oscillation found in the **original bobble** simulation

MIMO control keeps drsep within ***limits [1]*** for H-mode access and **the double-null shape is well controlled**





[1] D. Battaglia et al, Nuclear Fusion 58 (4) (2018) 046010

GSEvolve provides a simulation testbed to analyze this NSTX-U magnetic-control problem and explore control solutions

- **Introduction:** the "bobble" control issue in NSTX-U
  - Characteristics of the bobble
  - Modeling with GSEvolve
- **Analysis to find source causes for bobble:**
  - System's stability via system's poles
  - Input/output cross-coupling via singular-value decomposition
- **Control solution 1:** two-stage I_p ramp
- **Control solution 2:** multi-input multi-output decoupling controller
- **Conclusion**

Conclusion (1/2)

- Phenomena as complex as the NSTX-U “bobble” can be simulated thanks to **GSEvolve’s time-variant model**
  - No shot-specific tuning carried out
  - More “traditional” time-invariant models cannot reproduce this effect
  - Only main dynamical features reproduced, but further refinement possible by looking more deeply into uncertain model parameters

- **GSEvolve** represents a valuable **tool for control development** not only for this specific “bobble” problem, but for any **general problems / scenarios**
  - Simulation tests with real device’s PCS can help tune / troubleshoot PCS design and controllers implemented (cheaper than real discharges)

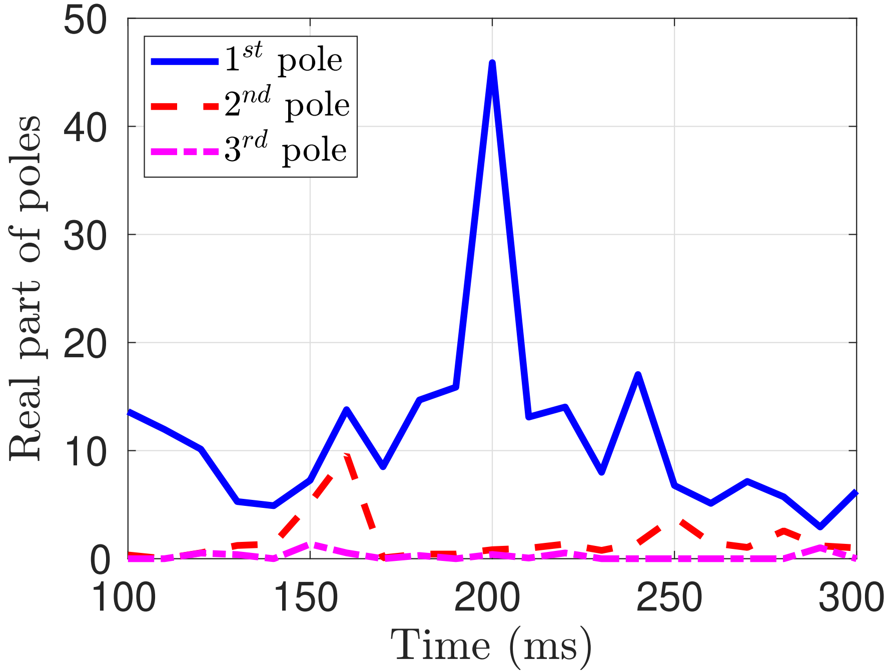
Conclusion (2/2)

- **Stability analysis and SVD** allow for **understanding the bobble origin** (source: system instability + input-output interactions) **and finding solutions to it**
  - Modifications of the I_p ramp-up trajectory may reduce bobble, but other constraints must be considered (e.g. MHD instabilities, transport…)
  - MIMO decoupling control designed to minimize loop interactions has potential to fully eliminate the bobble, needs extension to full discharge
  - FED publication will be submitted very soon
- Future work may involve:
  - **Implementation of the above control solutions (MIMO) in NSTX-U PCS**
  - **Additional solutions** (e.g. feedforward voltages, gain scheduling…)
  - Robustness studies of the control strategies proposed

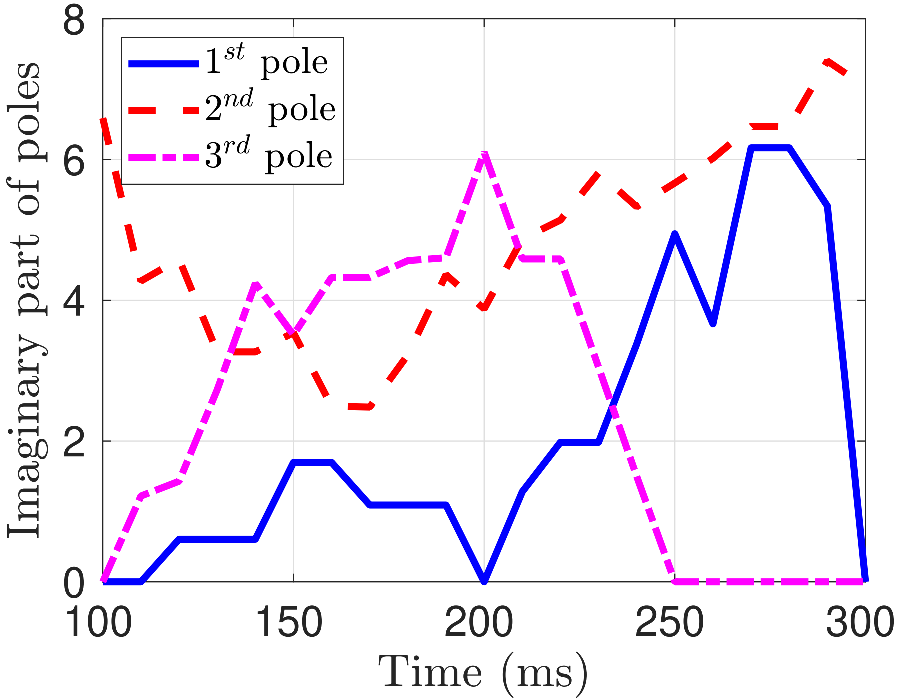
Thank you for your attention!

Questions??

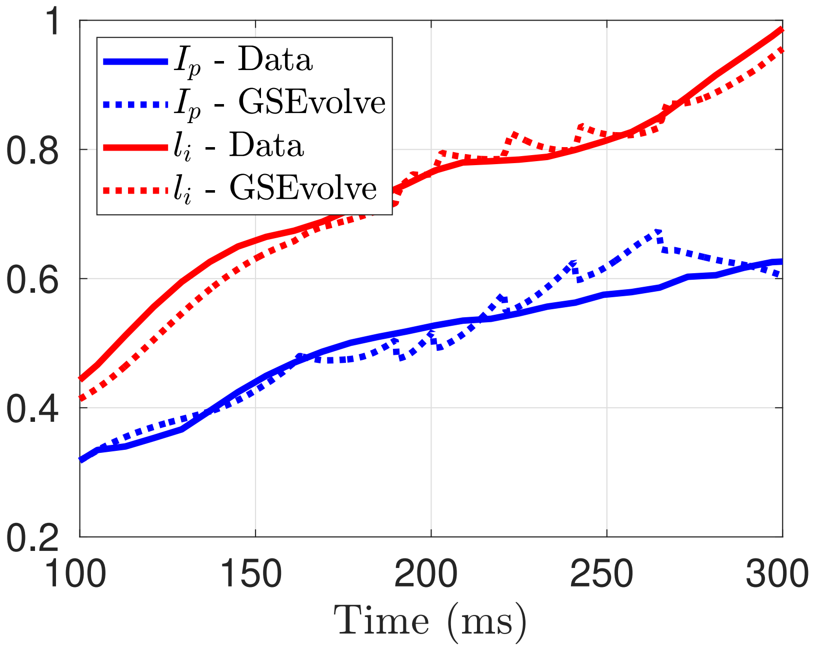
Extra slides



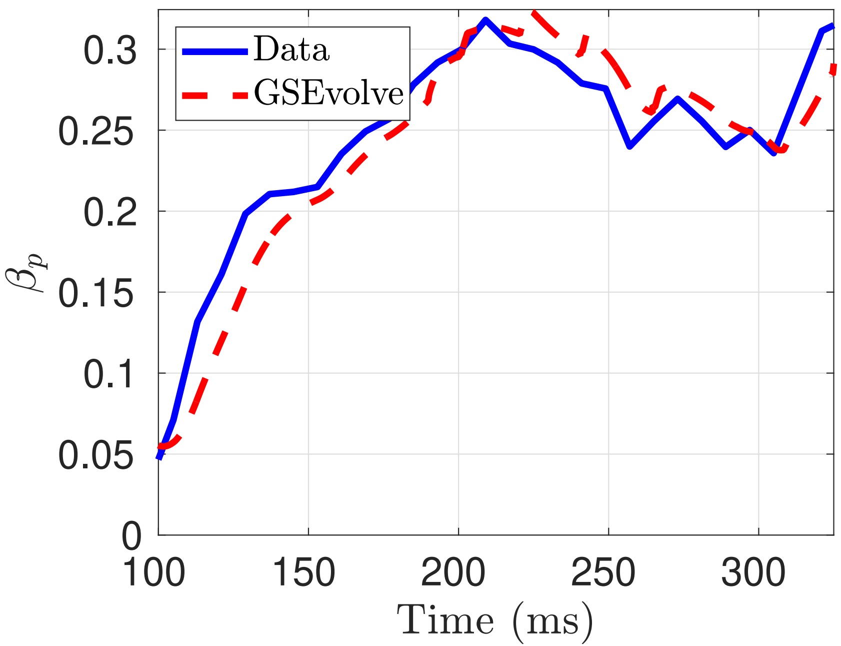
Real part of poles
Time (ms)
1^{st} pole
2^{nd} pole
3^{rd} pole
0
10
20
30
40
50
100
150
200
250
300



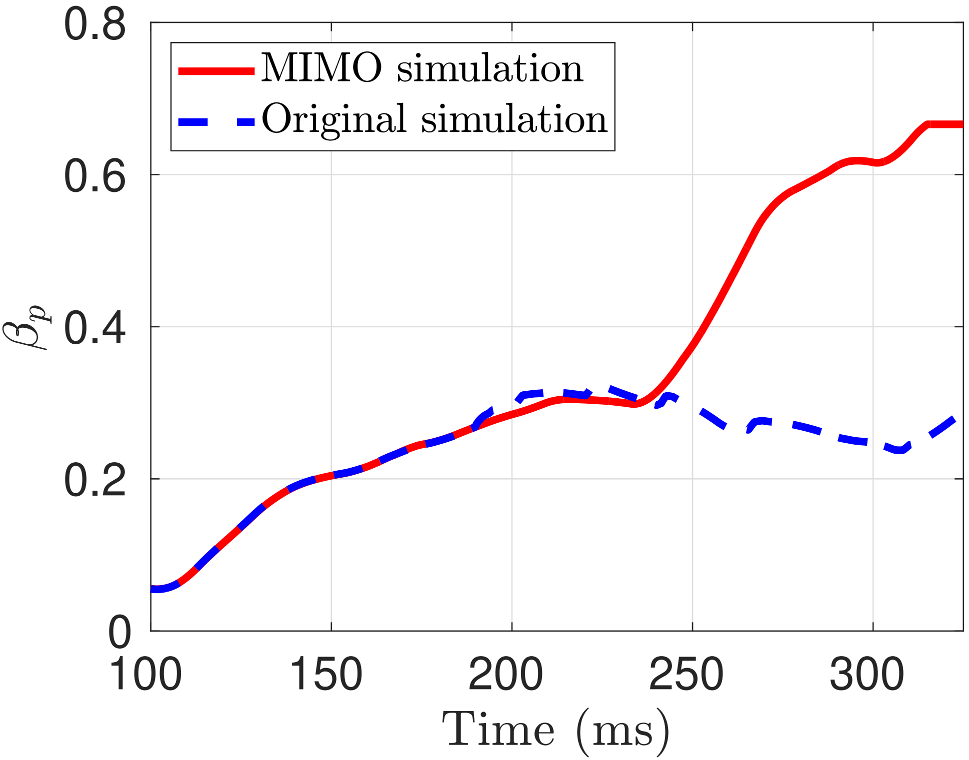
Imaginary part of poles
Time (ms)
1^{st} pole
2^{nd} pole
3^{rd} pole
0
2
4
6
8
100
150
200
250
300



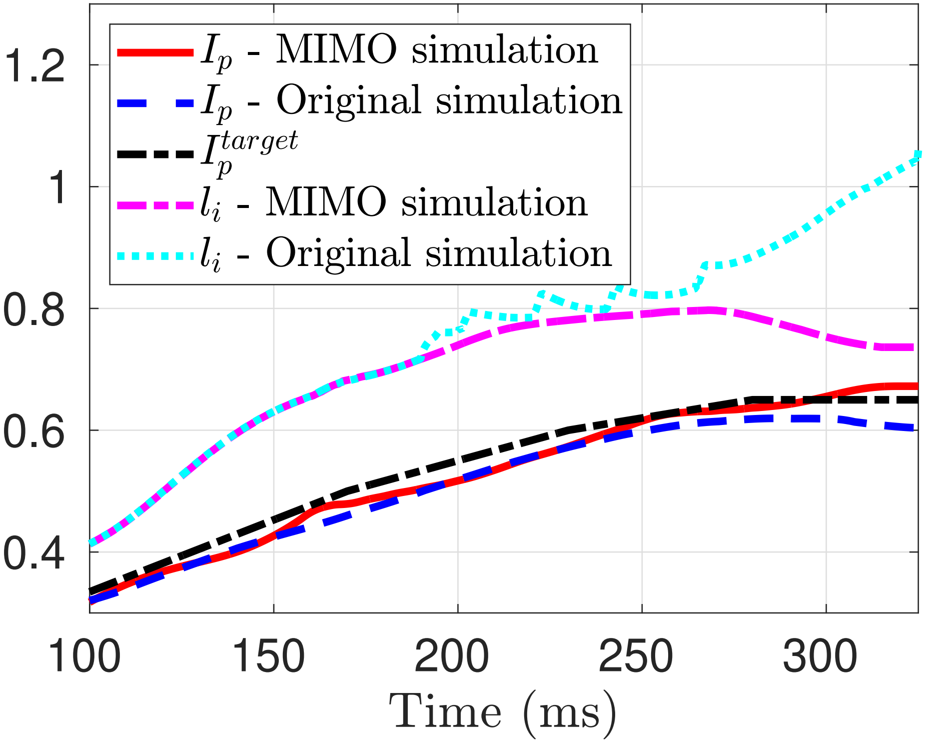
I_p - Data
I_p - GSEvolve
l_i - Data
l_i - GSEvolve
1
0.8
0.6
0.4
0.2
100
150
200
250
300
Time (ms)



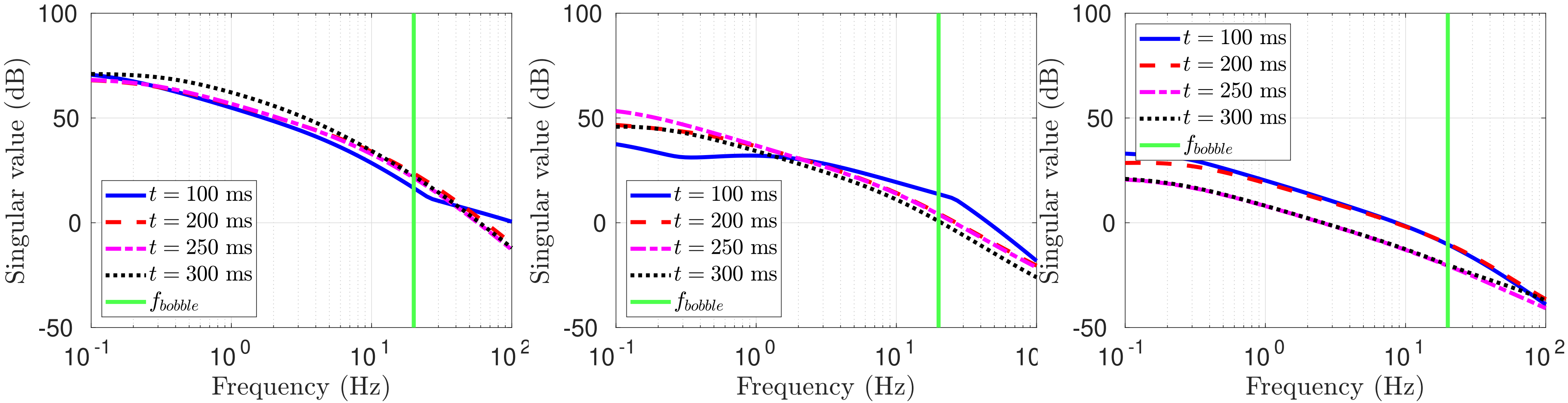
Data
GSEvolve
β_p
0.3
0.25
0.2
0.15
0.1
0.05
0
100
150
200
250
300
Time (ms)



0.8
0.6
0.4
0.2
0
β_p
MIMO simulation
Original simulation
100
150
200
250
300
Time (ms)



1.2
1
0.8
0.6
0.4
I_p - MIMO simulation
I_p - Original simulation
I_p^{target}
l_i - MIMO simulation
l_i - Original simulation
100
150
200
250
300
Time (ms)


100
50
0
-50
Singular value (dB)
10^{-1}
10^{0}
10^{1}
10^{2}
Frequency (Hz)
t = 100 ms
t = 200 ms
t = 250 ms
t = 300 ms
f_{bobble}