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Modelling and Analytical Stability Analysis of Feedback Controlled Reactive Sputter Processes

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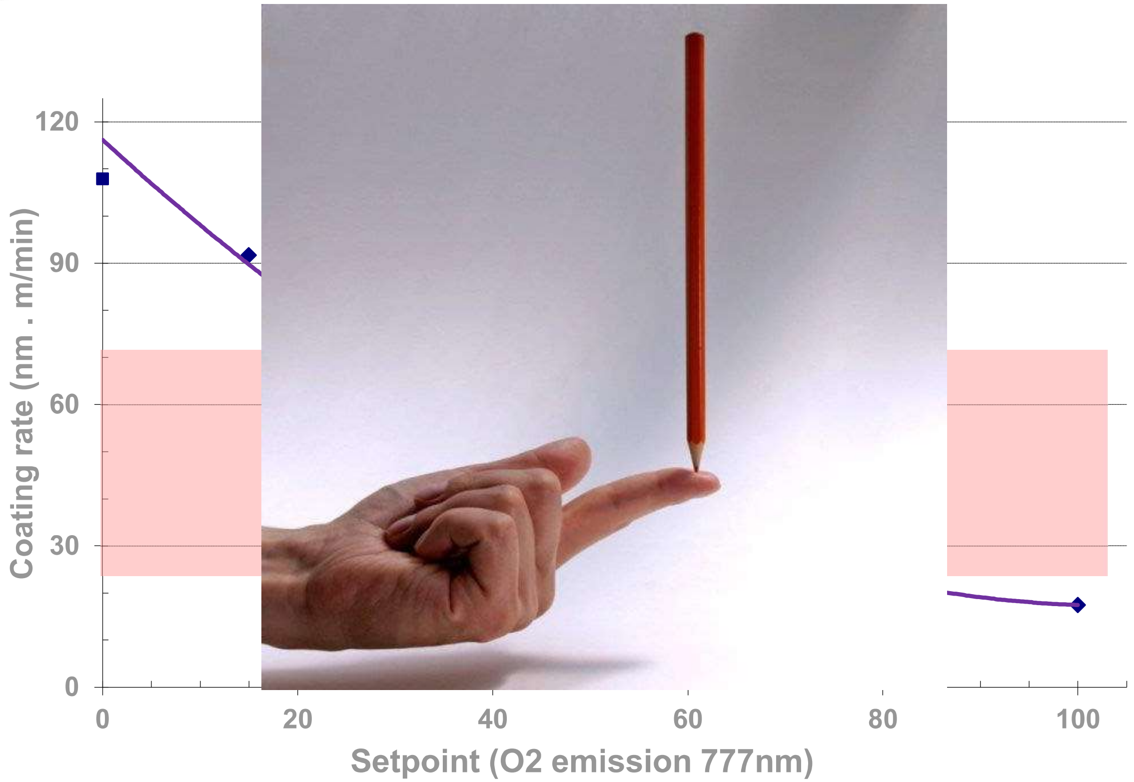
Introduction

- Why feedback controllers are used for reactive sputtering:



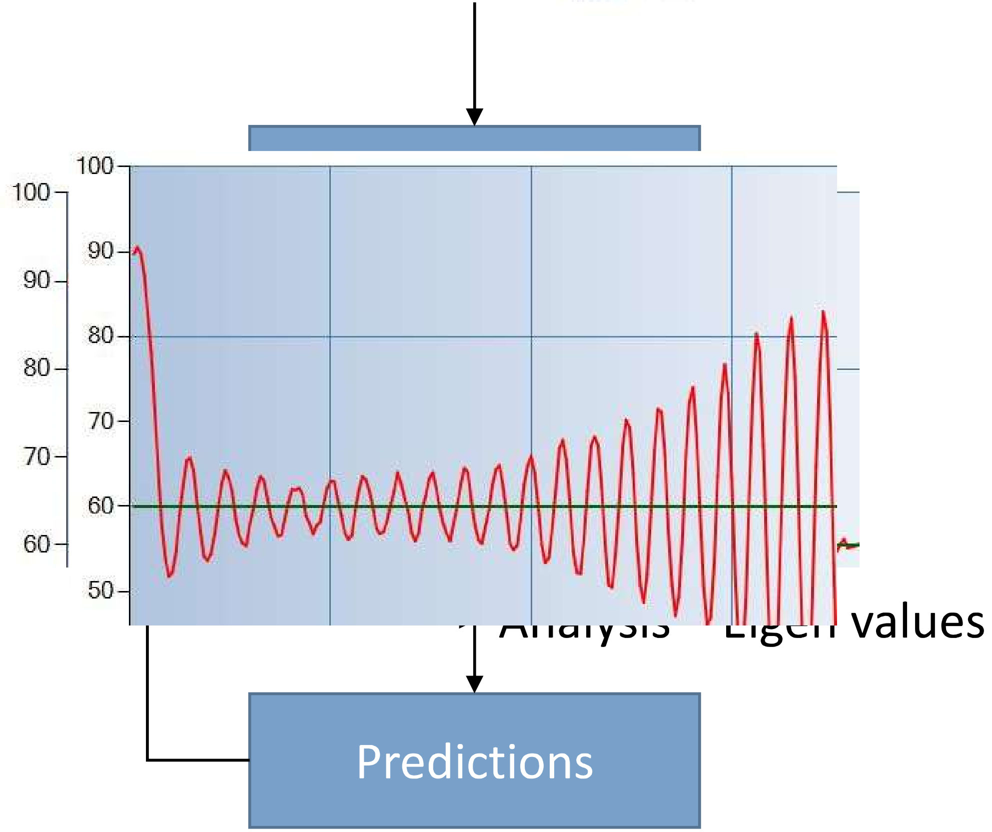
3 fold increase in rate for SiO_2

- Deposition Rate
- Stoichiometry
- Process stability –
  Short term
  Long term

How do we predict stability?

Approaches to evaluating stability

- Rule of thumb / best practice
- Simulation
- **Analytic methods?**

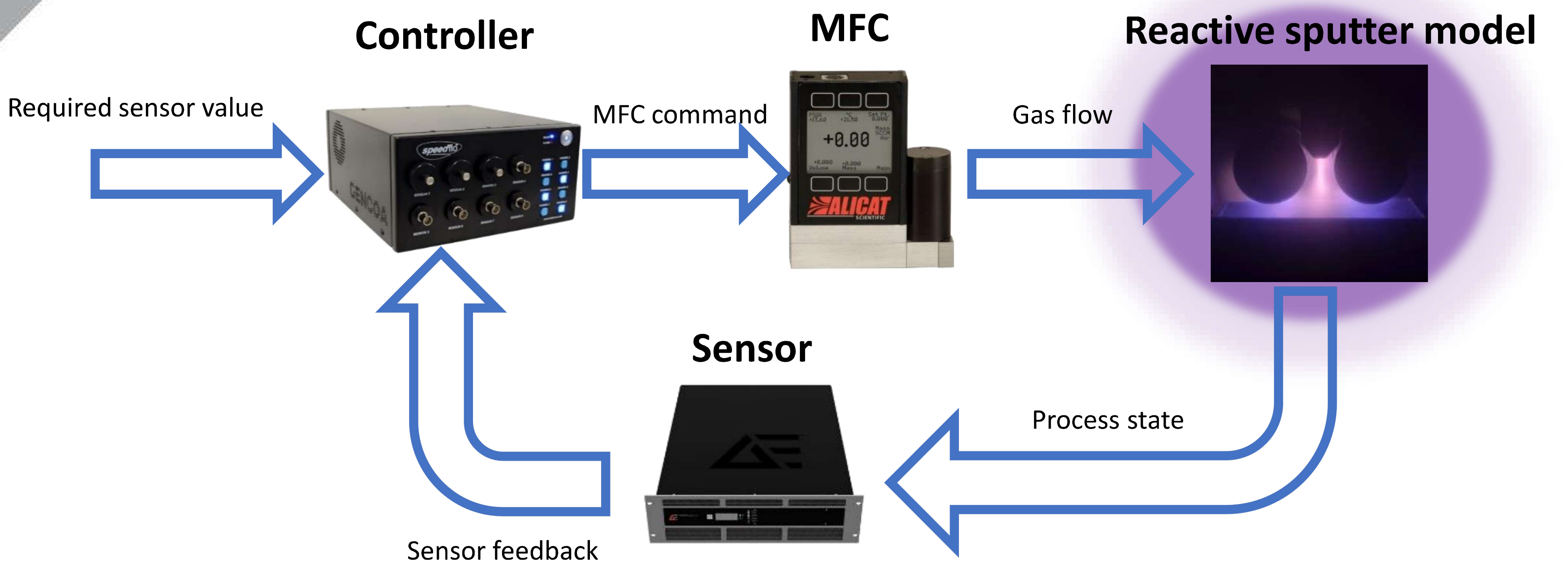


- Does not rely on **simulation**
  - Faster, more efficient
  - Deeper insight
  - Does not need interpretation – can be automated!

Modelling of the stability of reactive sputtering processes, Bartzch, Frach, Surface Coatings Technology, 2001
Controllability Analysis of Reactive Magnetron Sputtering Process, Acta Physica Polonica A, 2012

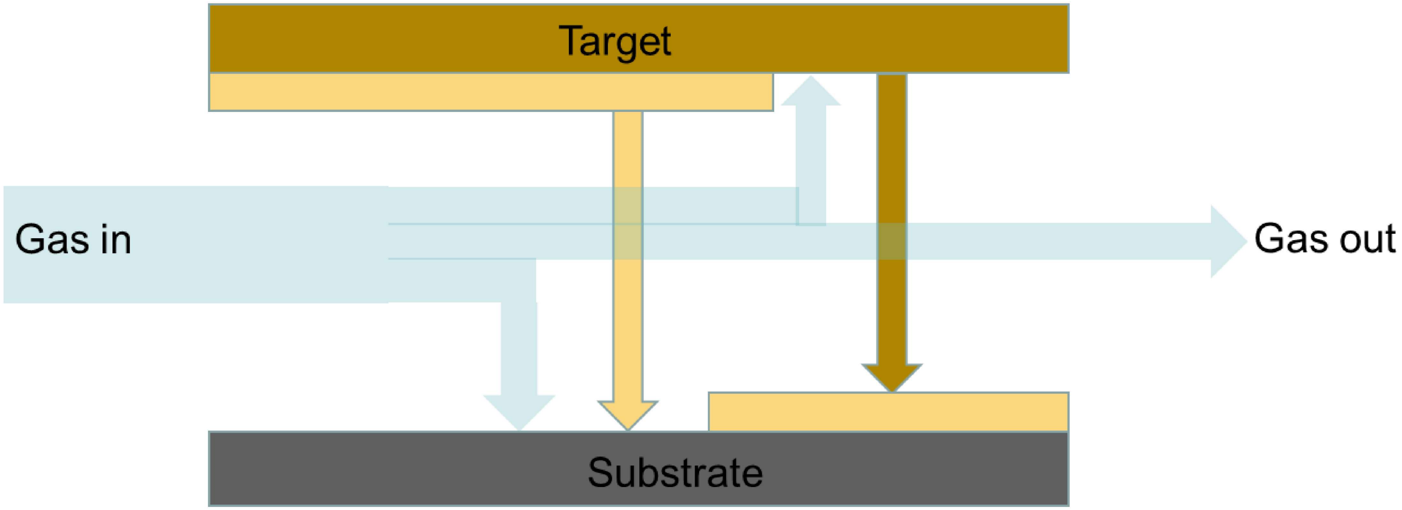
System model

Process



- A model of reactive sputtering – what kind of model?
- Low order required
- **Berg model** is ideal

Berg reactive sputter model



Three states

θ_t	**Target compound coverage**
θ_s	**Substrate compound coverage**
p	**Reactive gas partial pressure**

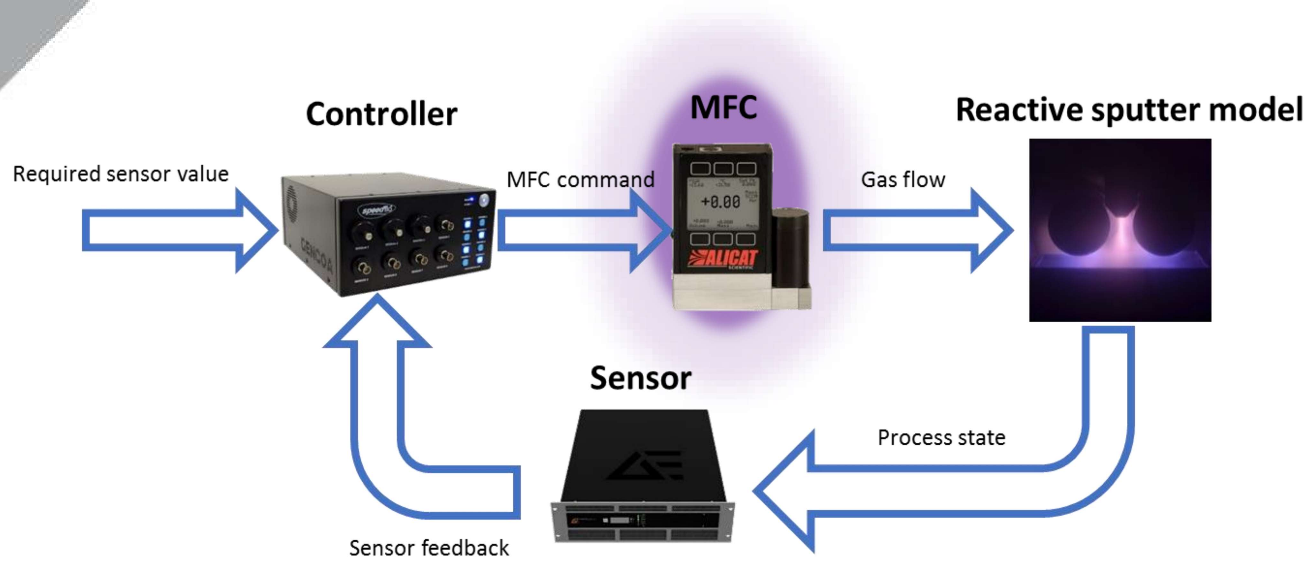
$$\dot{p}(t) = \frac{k_B T_c}{V_c}\left(q_{in}(t) - K_p p(t) - p(t)\overline{F}r\alpha_t A_t\left(1-\theta_t(t)\right) - p(t)\overline{F}r\alpha_s A_s\left(1-\theta_s(t)\right)\right)$$

$$\dot{\theta}_t(t) = \frac{1}{\rho A_t}\left(p(t)\overline{F}r\alpha_t A_t a_t\left(1-\theta_t(t)\right) - \frac{J}{e}Y_c A_t \theta_t(t)\right)$$

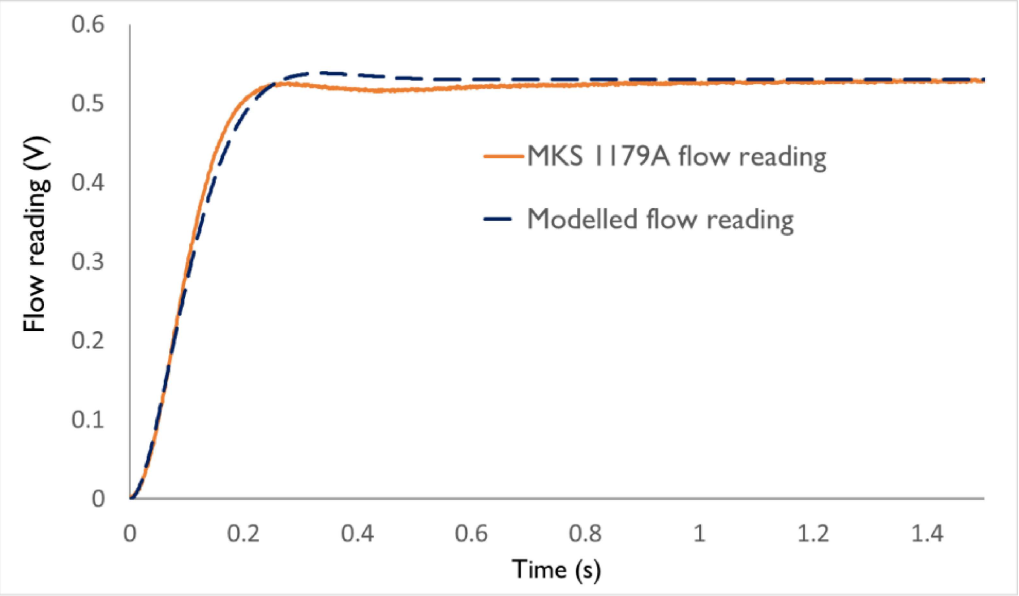
$$\dot{\theta}_s(t) = \frac{1}{\rho A_s}\left(p(t)\overline{F}r\alpha_s A_s a_s\left(1-\theta_t(t)\right) + \frac{J}{e}Y_c A_t \theta_t(t) - \frac{J}{e}Y_m A_t \theta_s(t)\left(1-\theta_t(t)\right)\right)$$

Dynamic behaviour of the reactive sputtering process, Kubart et al, thin solid films, 2006

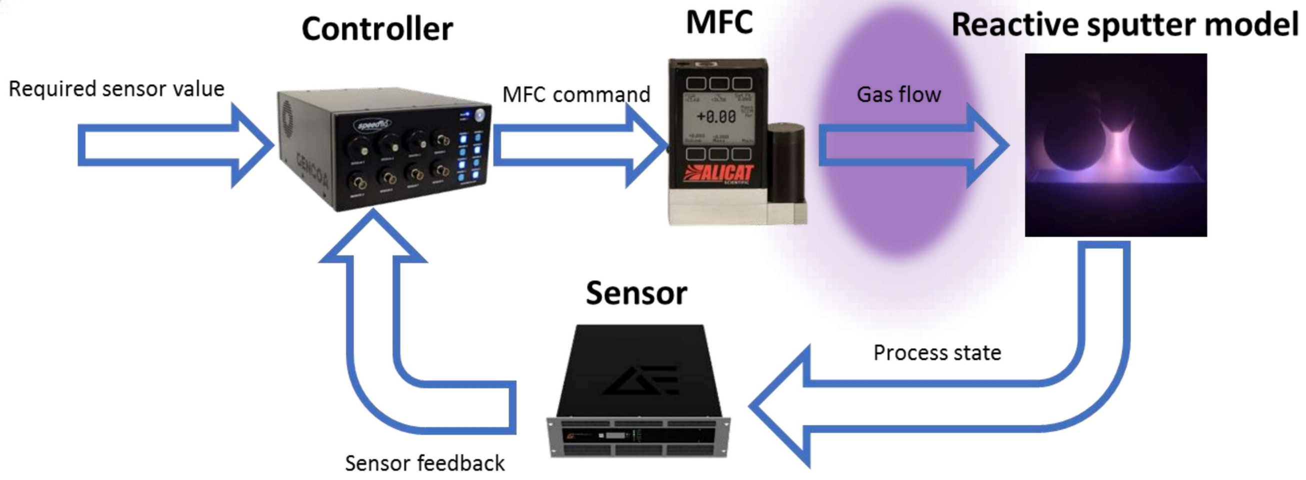
MFC model



$$\ddot{q}_a(t) = -2\omega_a v_a \dot{q}_a(t) + {\omega_a}^2 (u_c(t) - q_a(t))$$



Gas delivery



Controller

MFC

Reactive sputter model

Sensor

Required sensor value

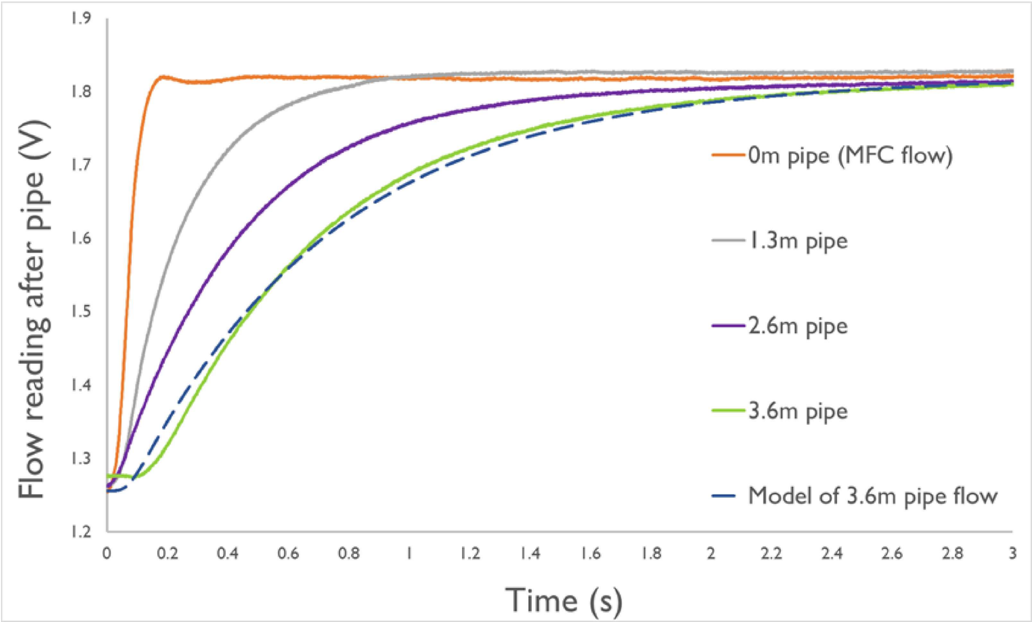
MFC command

Gas flow

Process state

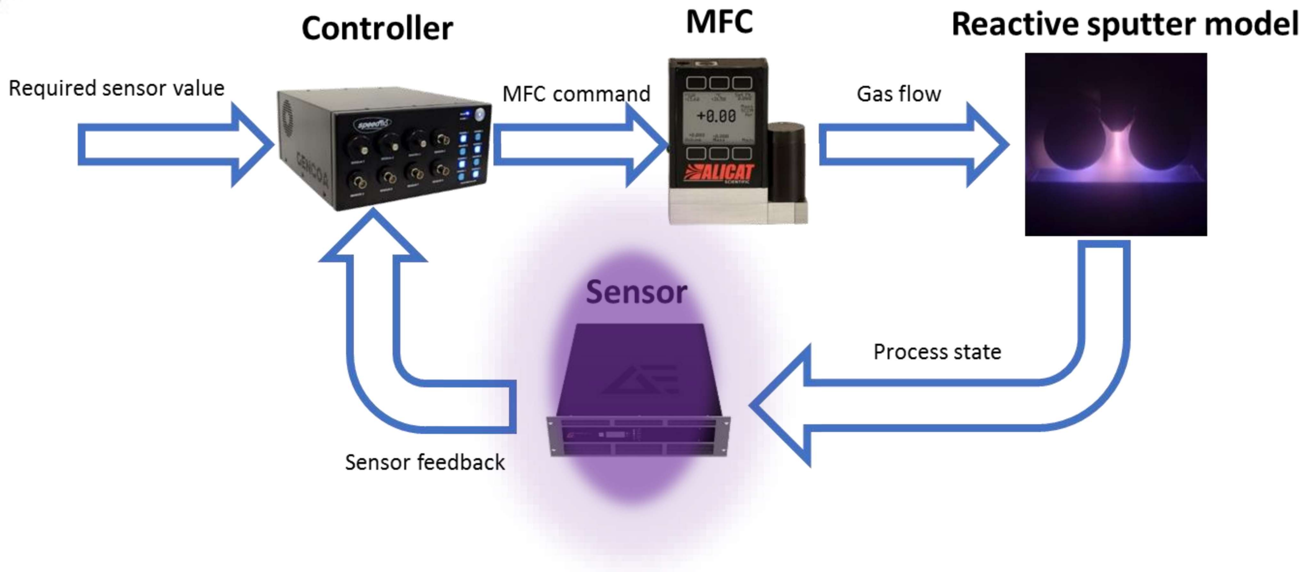
Sensor feedback

- Transport of gas from the MFC to the magnetron surface



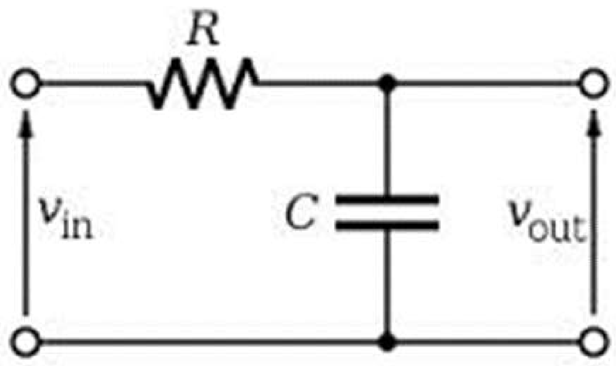
$$\dot{q}_p = \frac{1}{\tau_p}(q_a - q_p)$$

Target Voltage Sensor



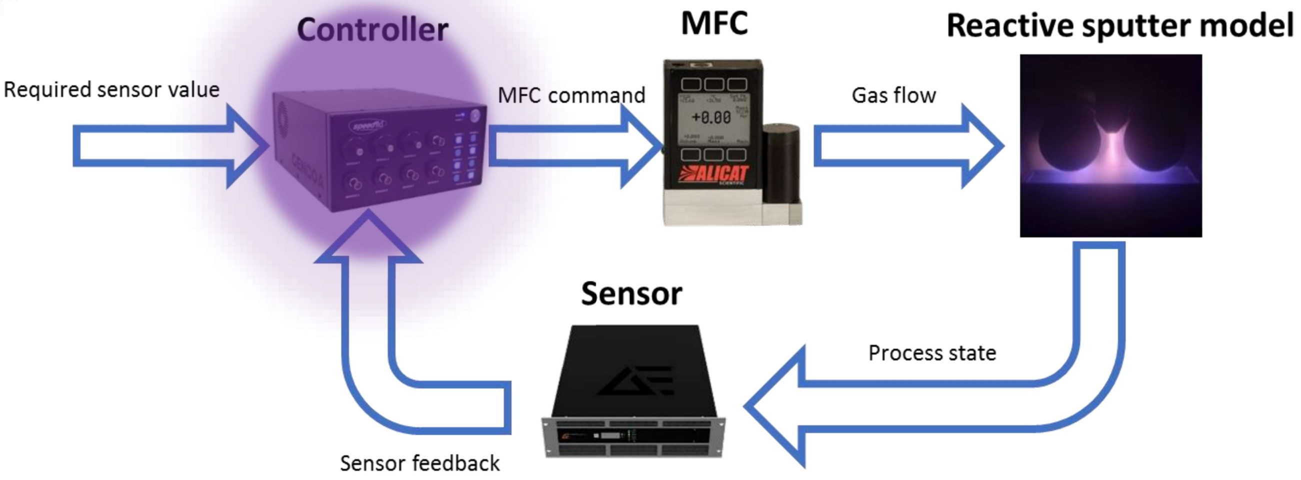
- Target voltage feedback

- Filtering is present in the power supply and controller

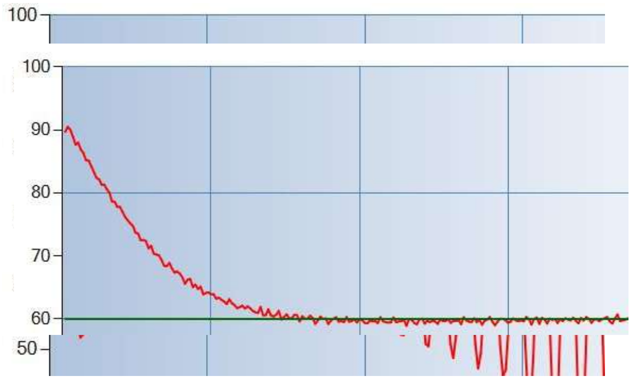


$$\dot{V} = \frac{1}{\tau_s}(\theta_t - V)$$

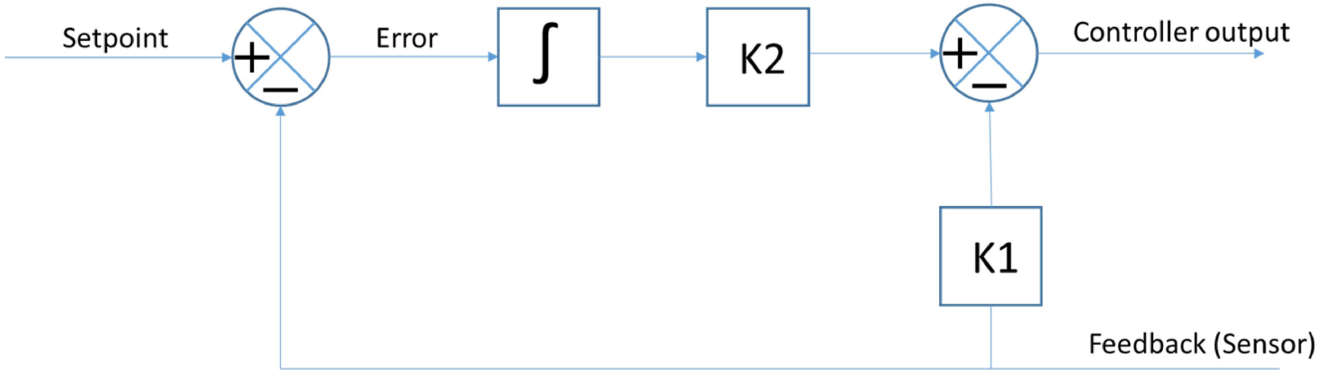
Controller



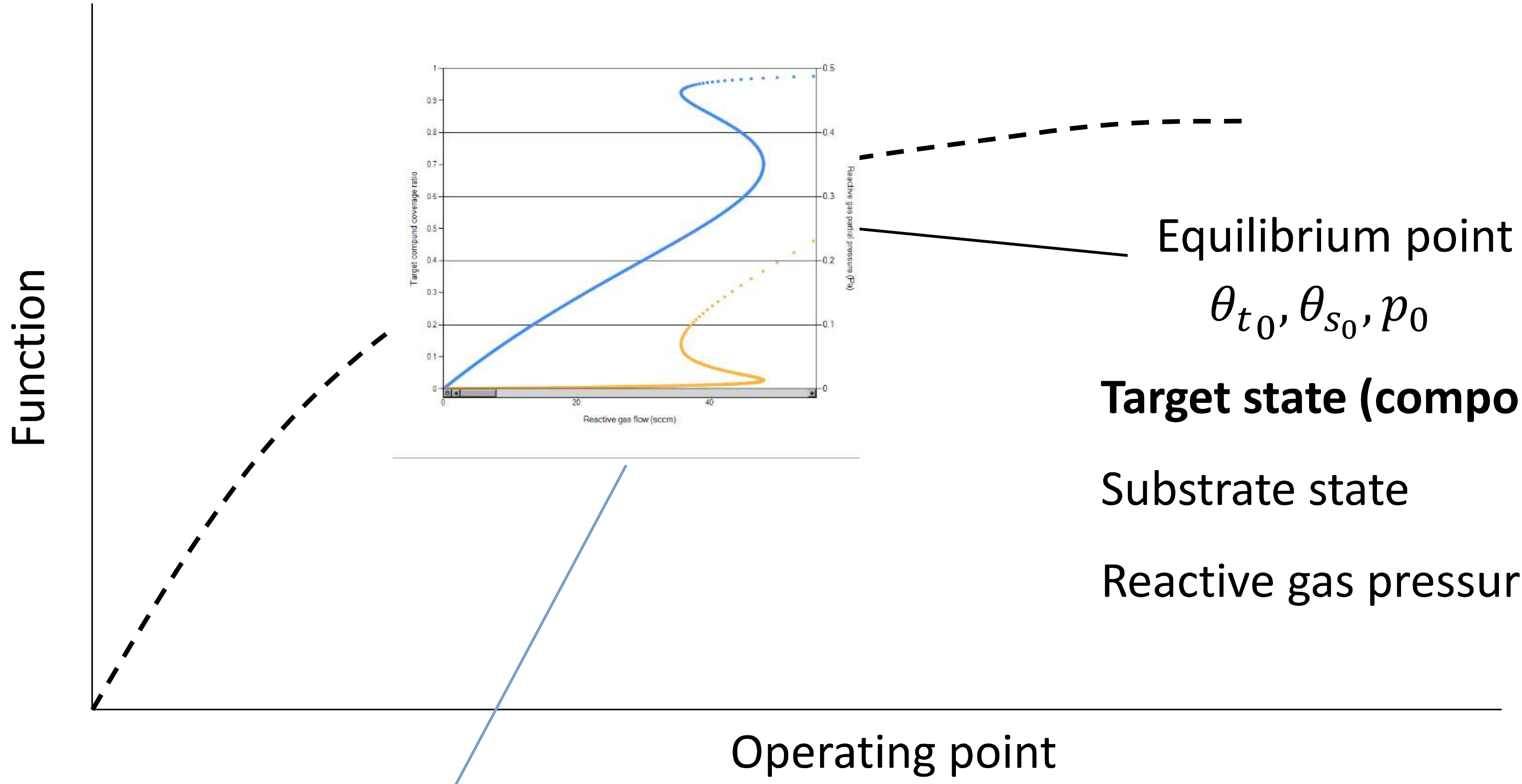
$$u_c(t) = K2z(t) - K1w(t)$$
$$\dot{z}(t) = w_s - w$$



PDF control algorithm



Stability analysis method



Equilibrium point

$\theta_{t_0}, \theta_{s_0}, p_0$

Target state (compound coverage)

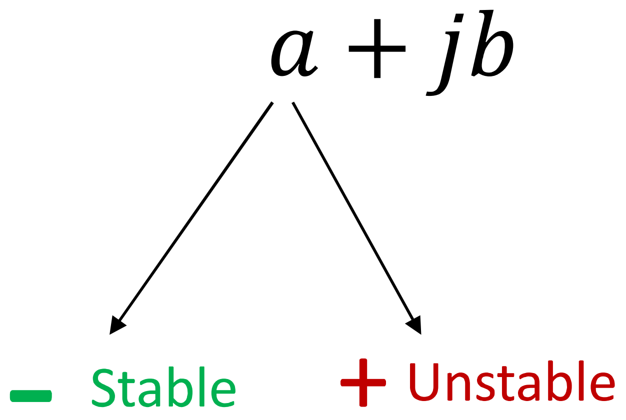
Substrate state

Reactive gas pressure

Calculate Eigen values

Stability analysis method

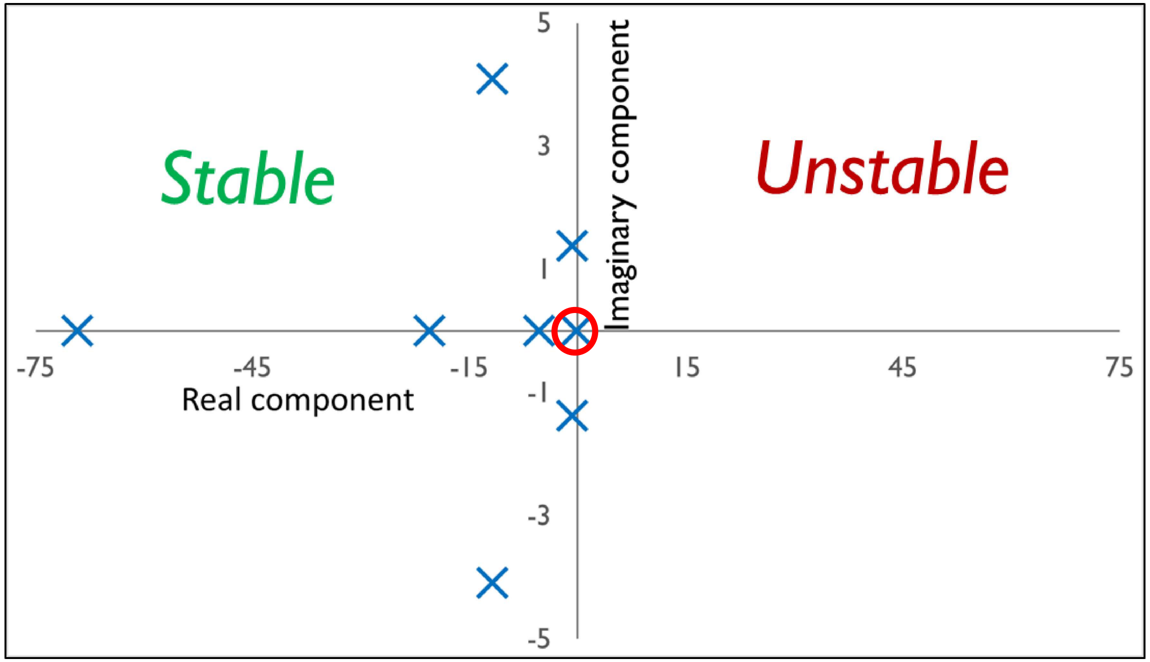
Eigen values



$$a + jb$$

– Stable

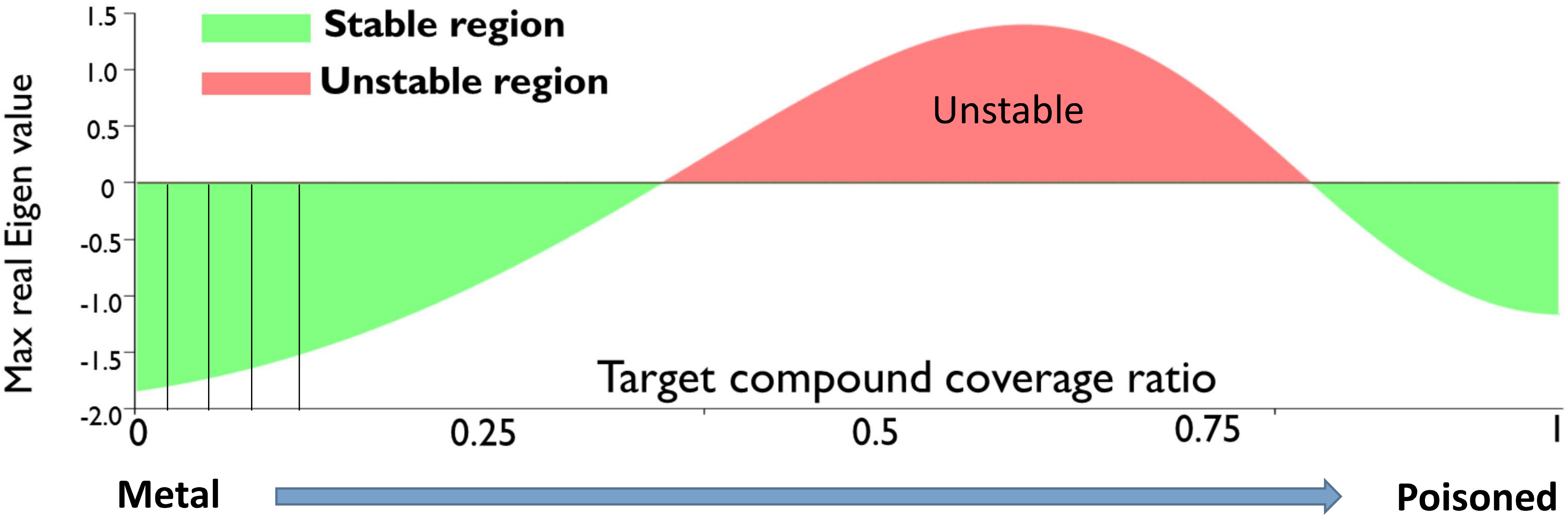
+ Unstable



A single number that represents stability of the whole system!

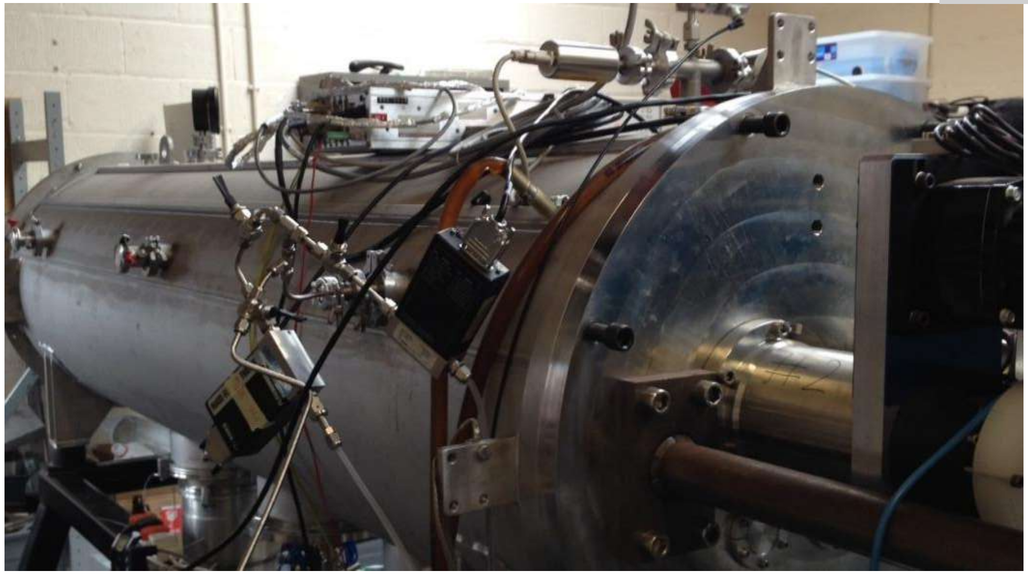
Stability analysis method

A simple representation of stability



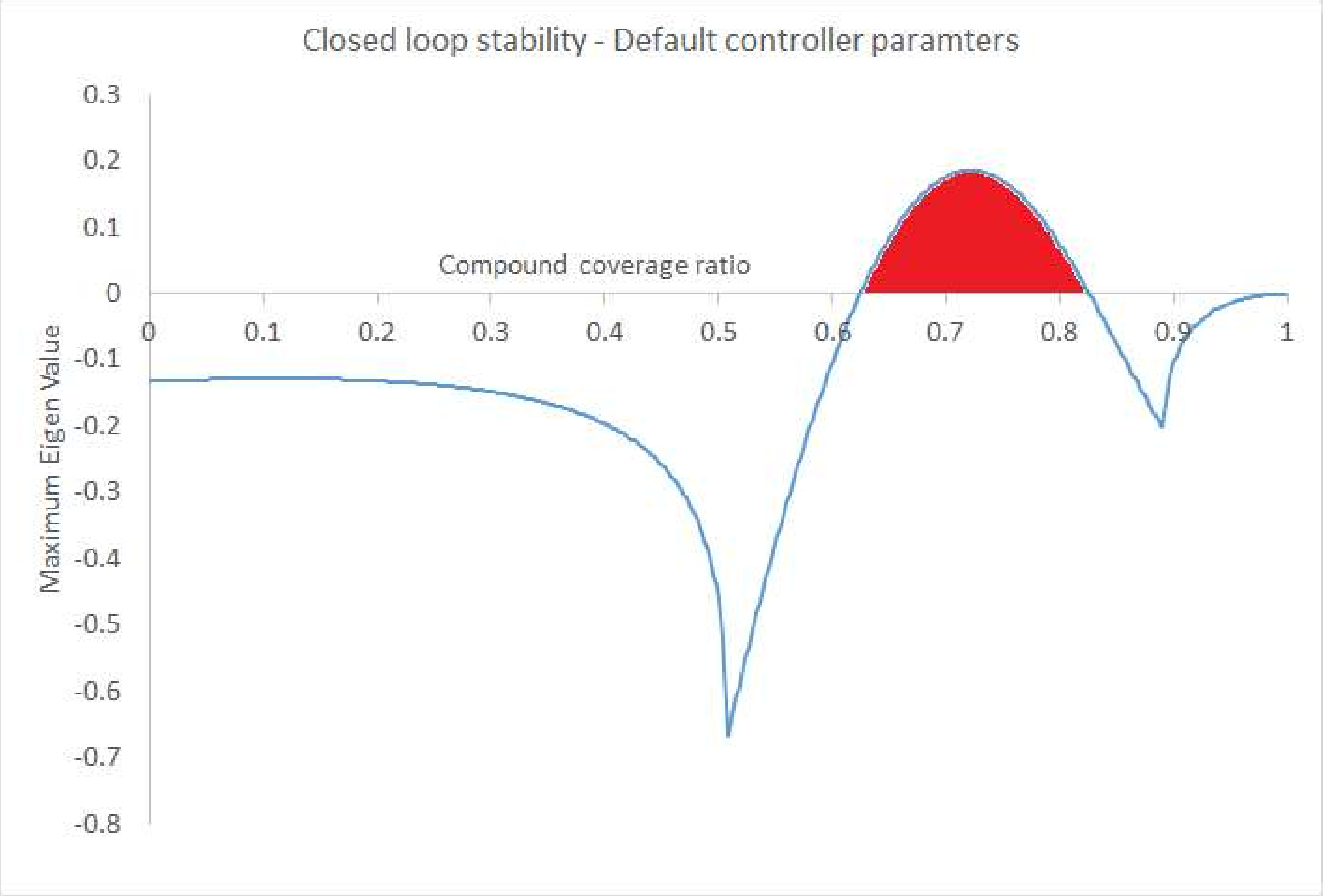
Experimental validation

- Dual rotatable cathodes – 4kW
- Al targets, O2 reactive gas
- Target voltage sensors
- Speedflo PDF controller



Experimental validation

Closed loop with default controller parameters



Experimental validation

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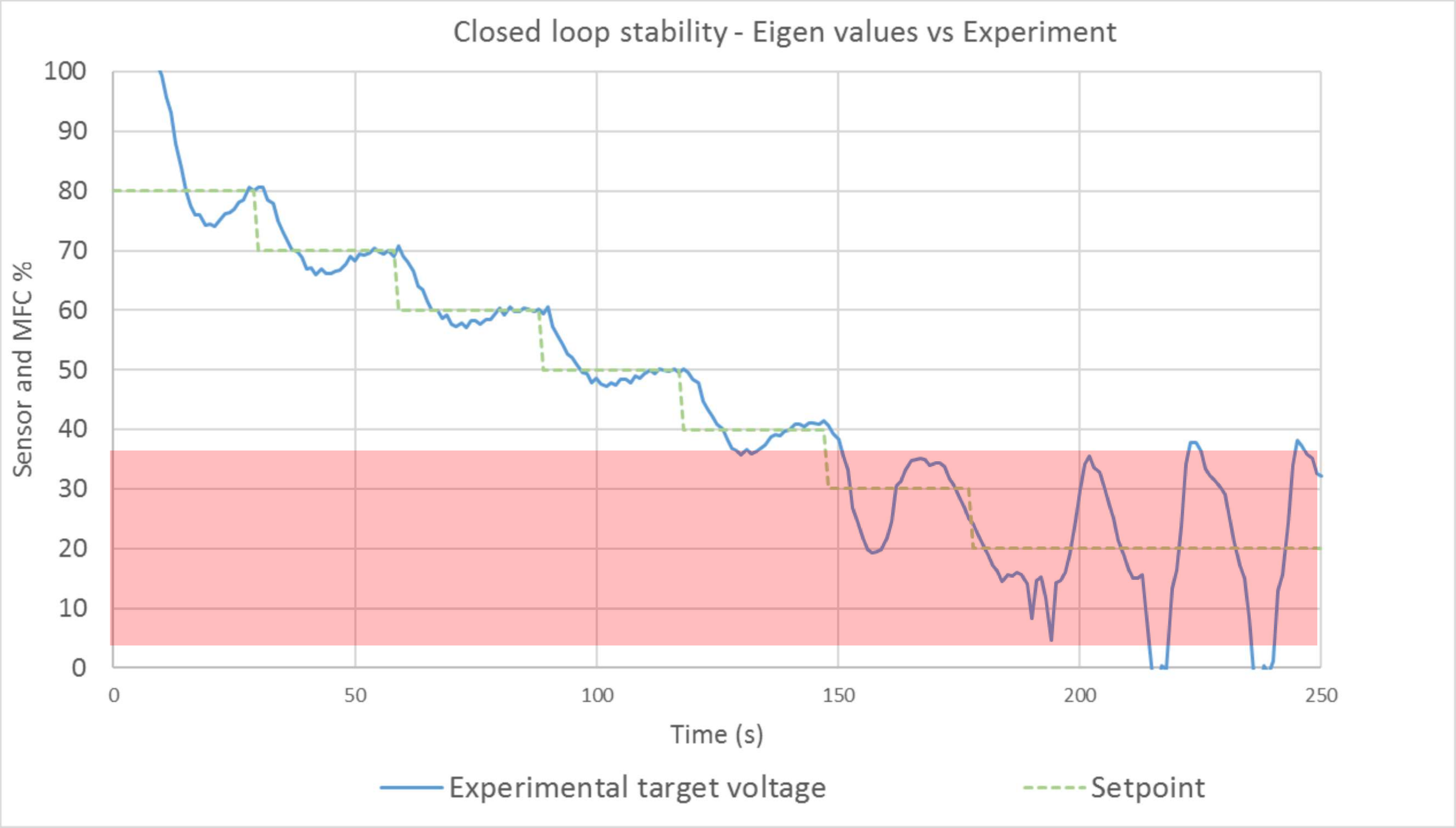
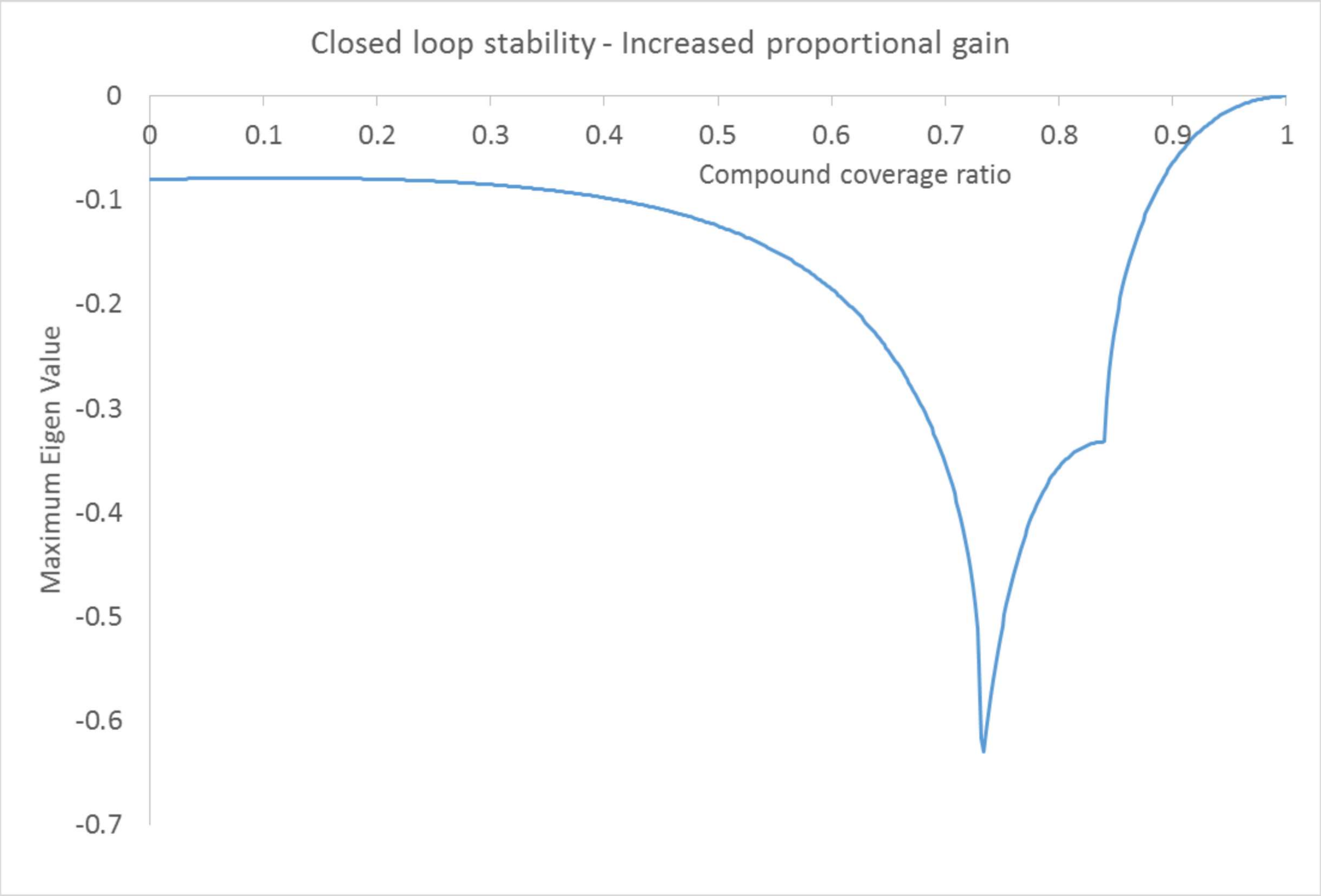


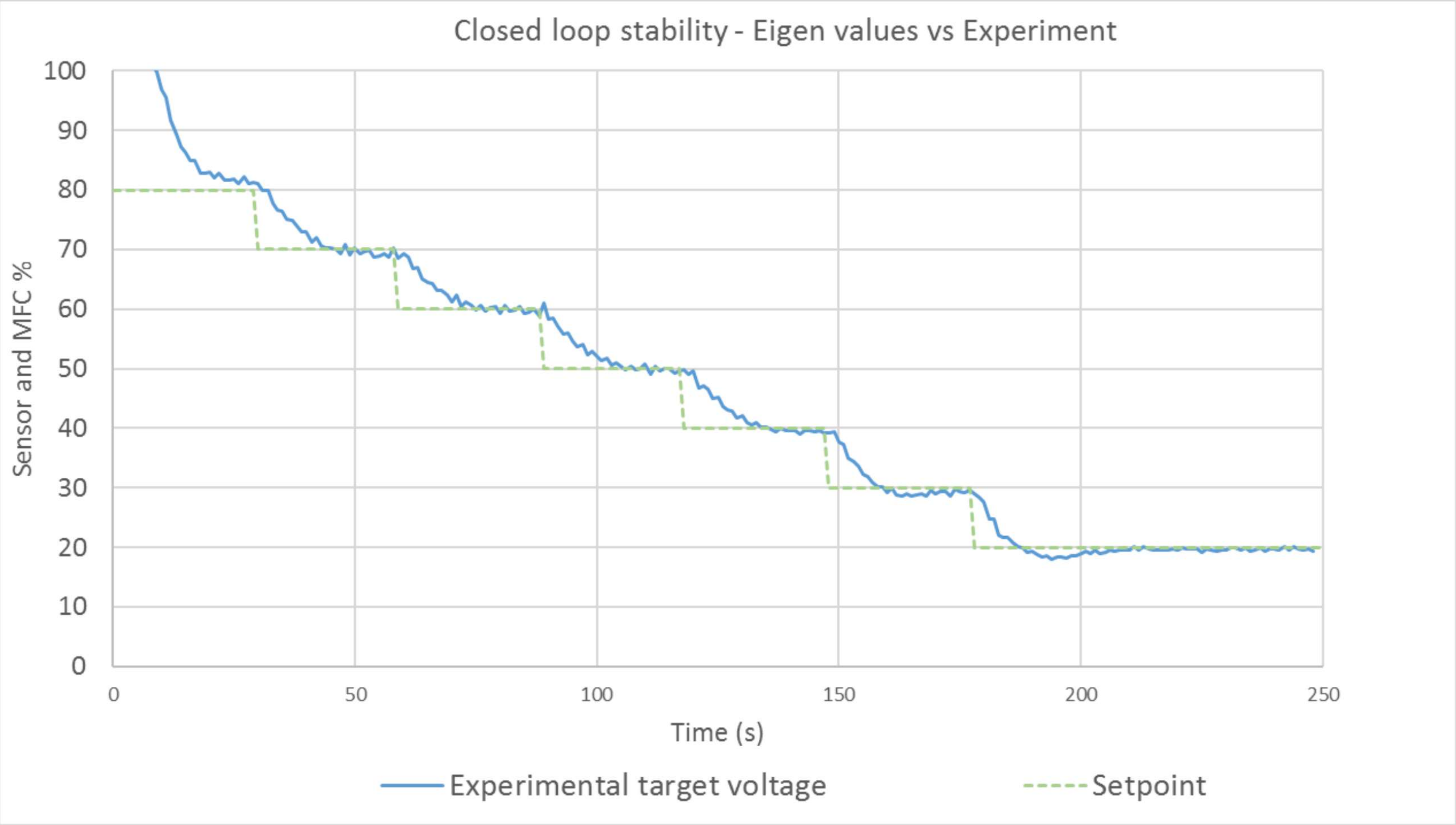
Experimental validation

Closed loop with K1 increased to 3



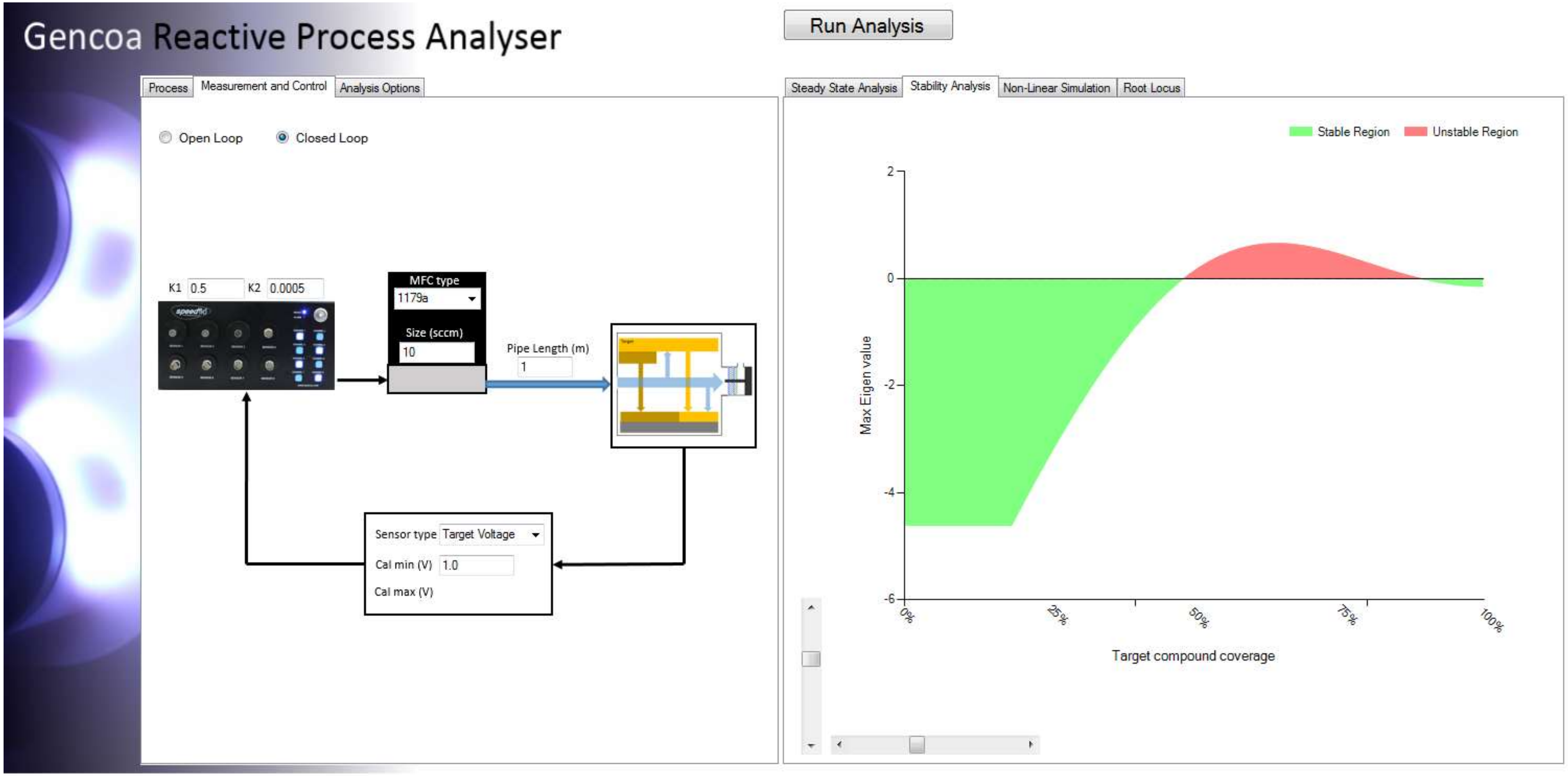
Experimental validation

Closed loop with K1 increased to 3



Case study

Software interface – automate analysis



Gencoa Reactive Process Analyser

○ Open Loop ● Closed Loop

K1 0.5 K2 0.0005

MFC type 1179a

Size (sccm) 10

Pipe Length (m) 1

Sensor type Target Voltage

Cal min (V) 1.0

Cal max (V)

Case study

Stability on a retro-fit reactive sputter tool

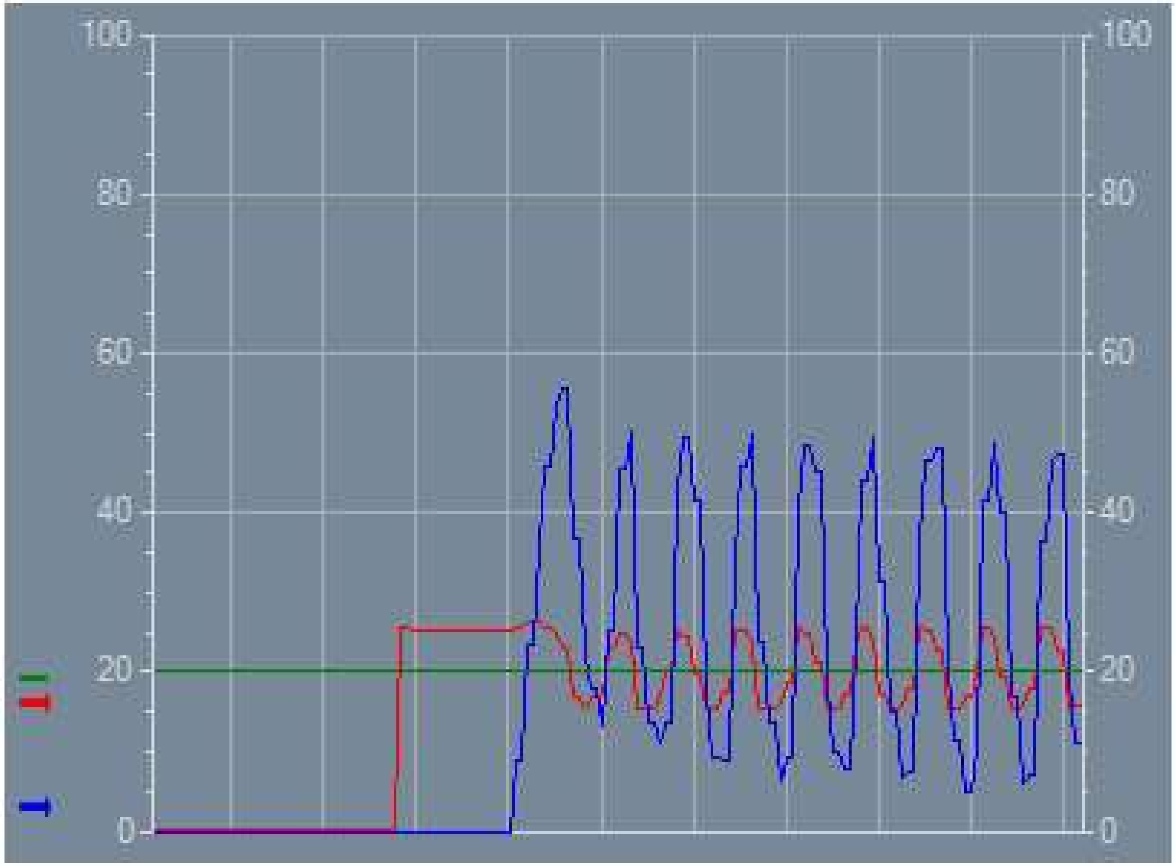
- AlOx reactive sputter deposition tool
- Planar cathodes 610mm x 130mm
- DC pulsed power, 5kW

Case study

Stability on a retro-fit reactive sputter tool

- Customer was unable to stabilise the process at the desired setpoint
- Automated and manual tuning was ineffective

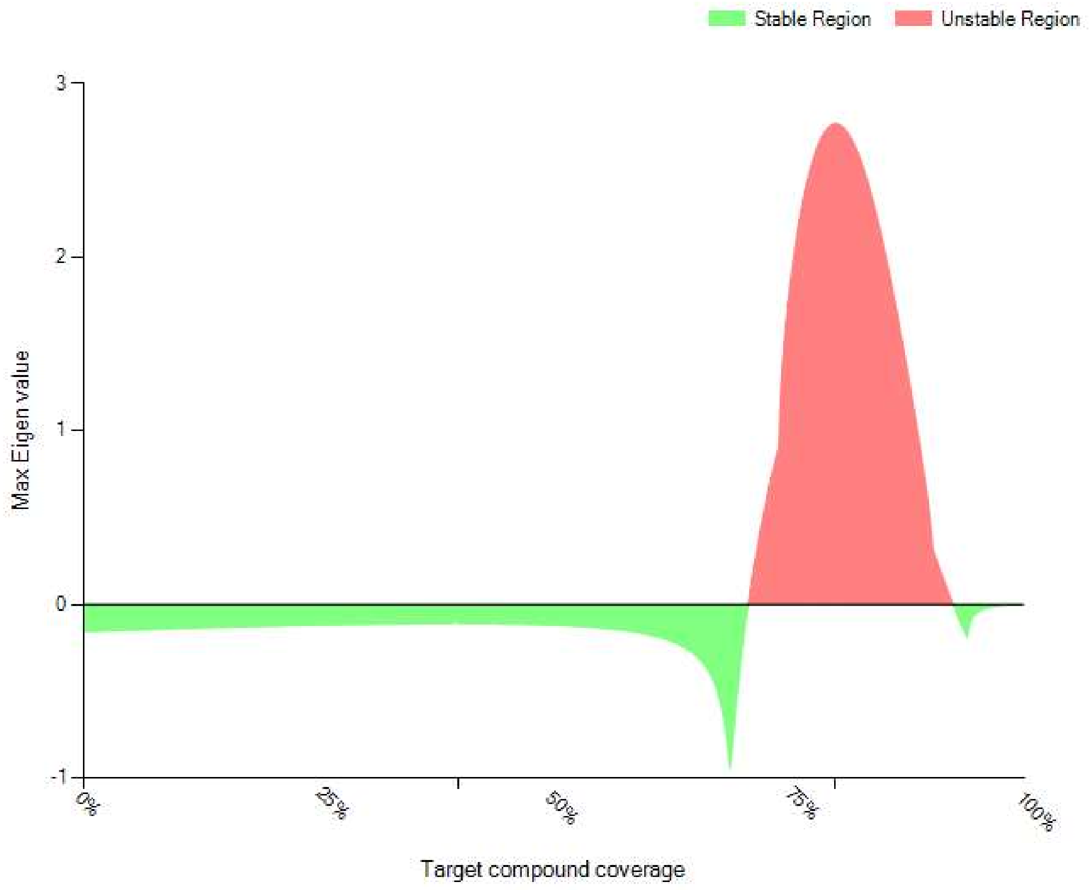
80% compound coverage ratio



Case study

Stability on a retro-fit reactive sputter tool

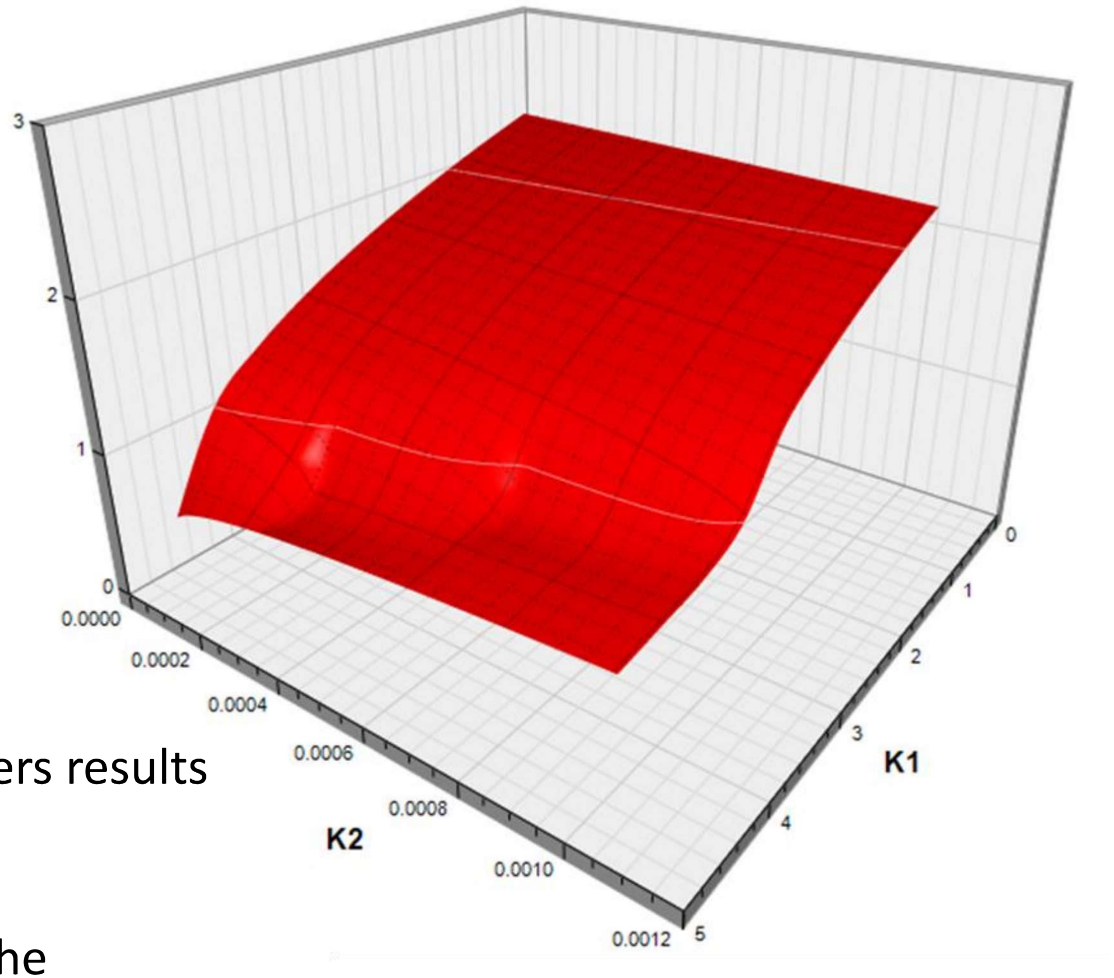
- Model predicts unstable process control with default tuning parameters
- Is there a combination of tuning parameters that will stabilize the process?



Case study

Stability on a retro-fit reactive sputter tool

Add a 3rd dimension!

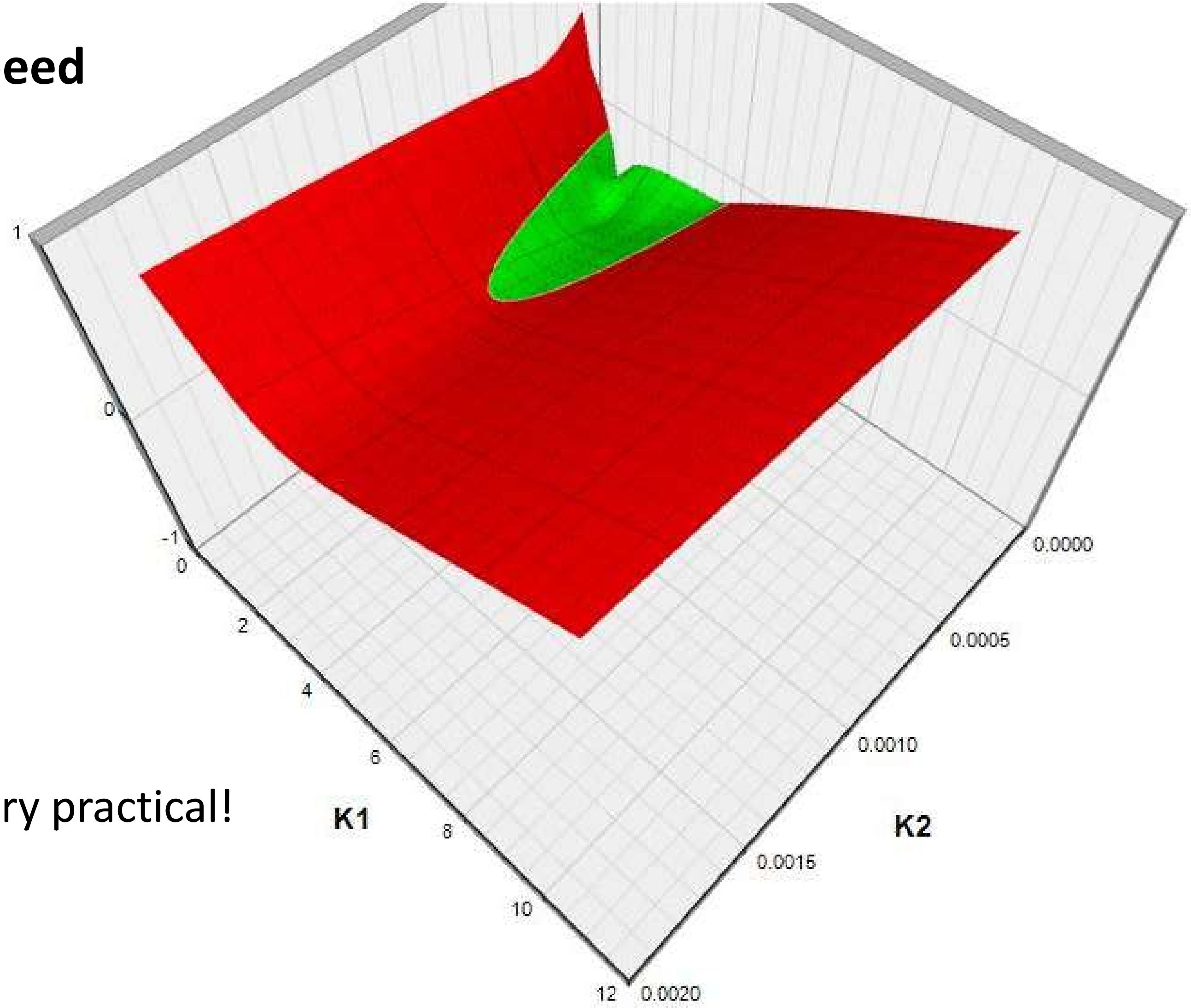


- No combination of tuning parameters results in a stable solution
- Cant solve this problem by tuning the controller

Case study

Stability on a retro-fit reactive sputter tool

3x increase in pumping speed

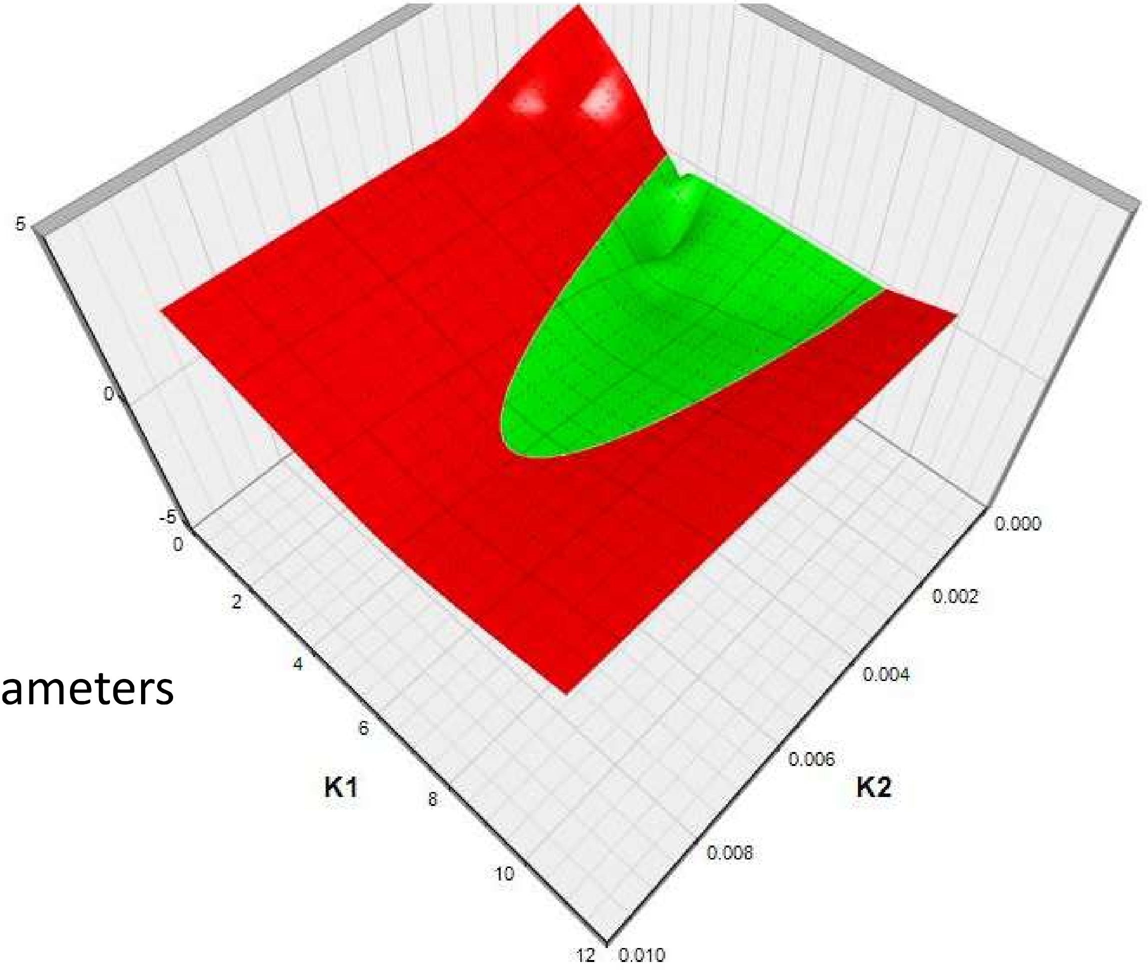


- Stable solution is now possible
- Installing 2 more pumps is not very practical!

Case study

Stability on a retro-fit reactive sputter tool

Reduction in gas distribution pipe from 2m to 50cm

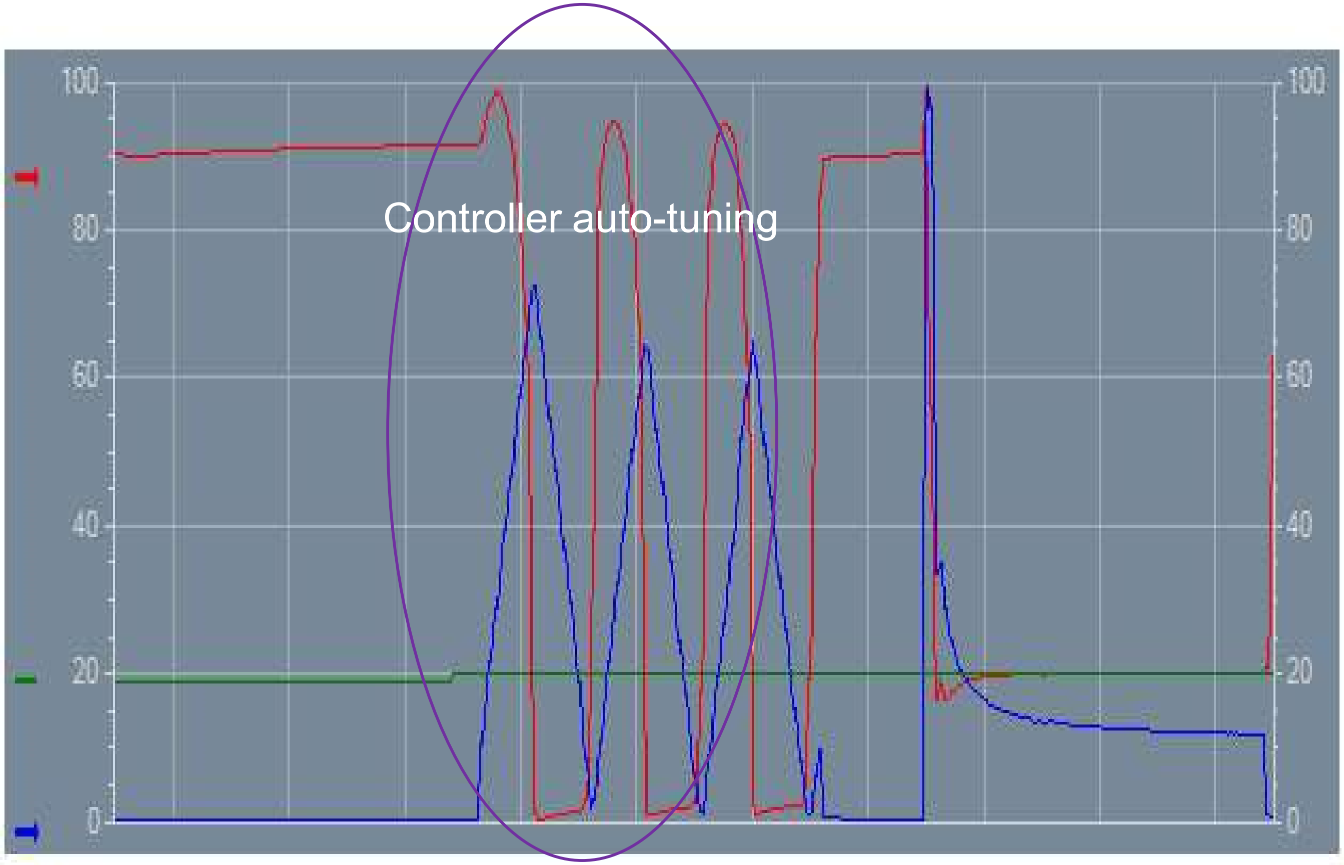


- Large range of stable controller parameters

Case study

Stability on a retro-fit reactive sputter tool

- Gas pipe distribution modified so that MFC is on the chamber wall
- The process is now stabilizable at the required setpoint



Case study

Stability on a retro-fit reactive sputter tool

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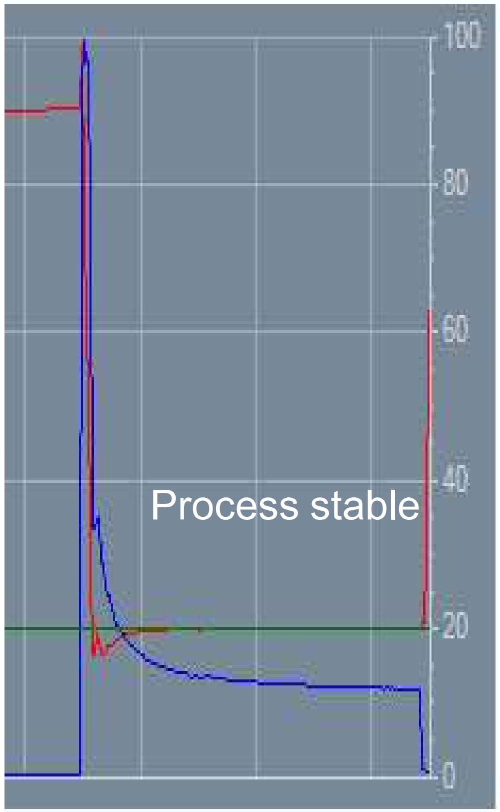

Conclusions

Summary

- A simple tool for investigating and **predicting** the stability of a reactive sputter process
- Can be used at the system design stage or for troubleshooting problems
- Does not replace experimental (or automated) tuning of the controller

Future possibilities:

- Latest models
- Co-sputtering, dual reactive gases
- Multiple process zones and gas injection points – stability of interactions
- Software environment

Journal of Physics D: Applied Physics
A time-dependent model for reactive sputter deposition
K Strijckmans and D Depla
Published 8 May 2014

Thank you for your attention!

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