SFERA-III

Solar Facilities for the European Research Area

"Model predictive control for molten salt solar tower receivers"

Rudolf Popp, Institute of Automatic Control

NETWORKING

Summer School: "Smart CSP: How Smart Tools, Devices, and Software can help improve the Design and Operation of Concentrating Solar Power Technologies" - WP1 Capacity building and training activities - Cologne, Germany, September 14th-15th 2023

THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO **823802**

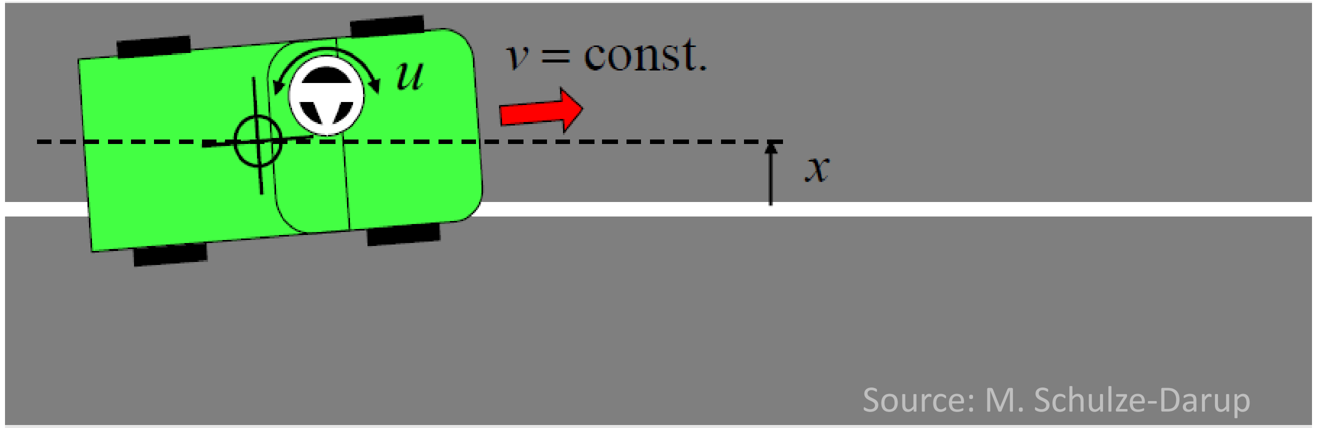
Agenda

- Introduction
  - What is Model Predictive Control (MPC): Example
  - Why applying MPC to Molten Salt Receivers
- Controlling the Molten Salt Receiver
  - Conventional Control
  - MPC Control Structure
- Setting Up the MPC
  - Model
  - Cost Function
- Results
  - Comparison of MPC with Conventional Control

Introduction

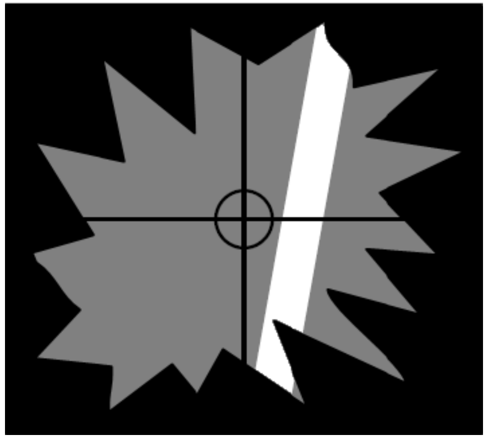
Example: Steering a vehicle

- Goal:
  - **Find and track a lane**
  - Avoid obstacles



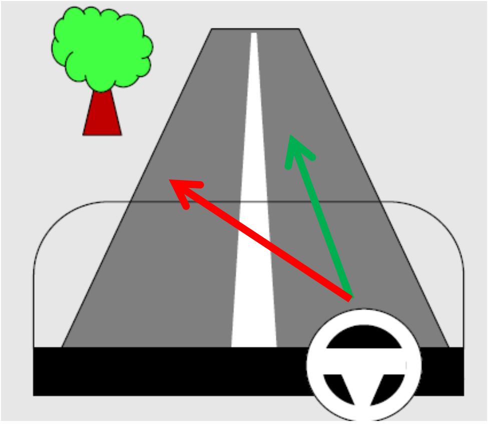
PID-Control

- The PID controller only looks at whether it is **currently** in the lane
- Purely reactive behavior

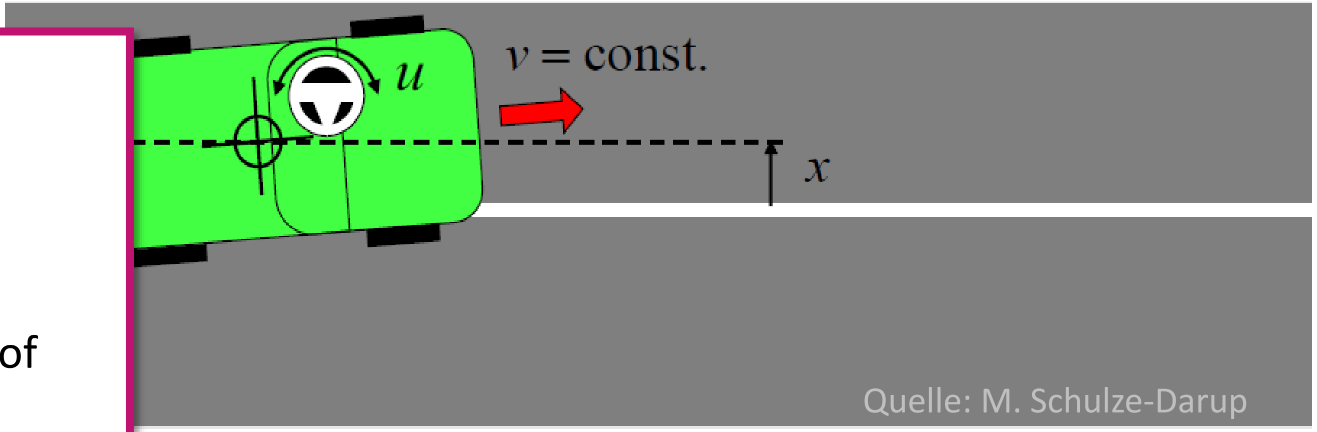


Model Predictive Control

- MPC can predict what the future deviation will be
- Predictive behavior



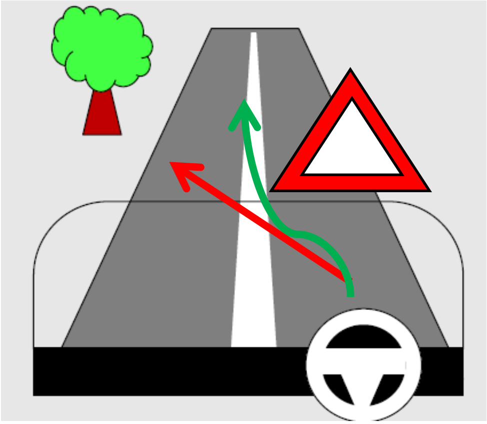
Example: Steering a vehicle



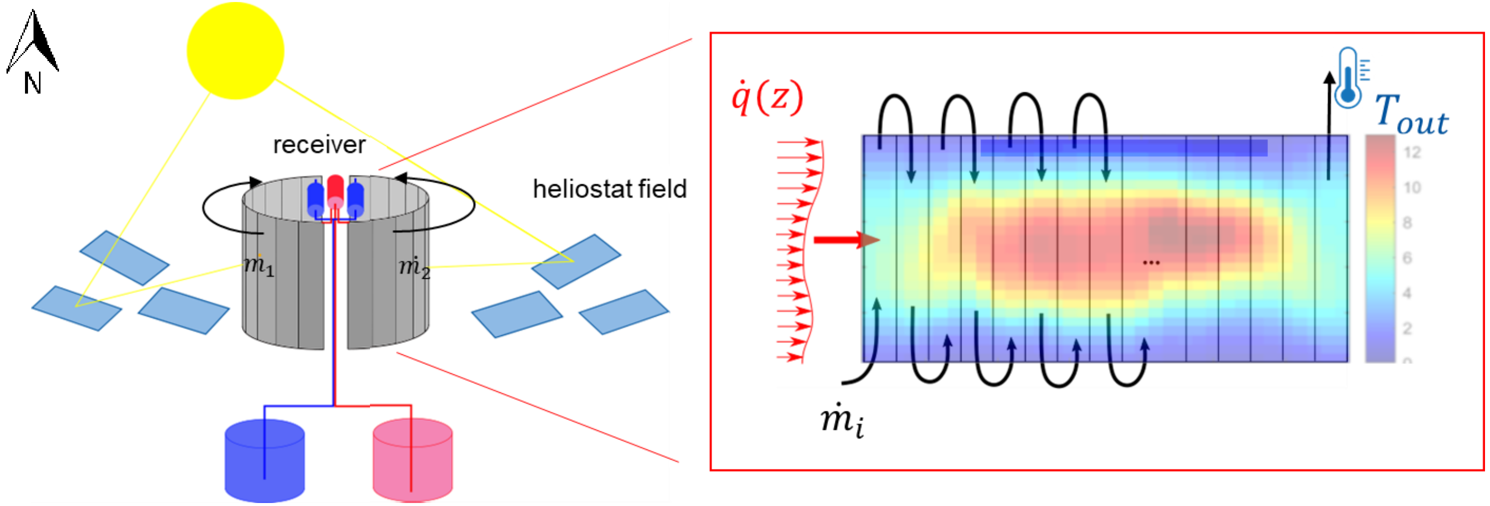
- **Prediction model:** How does the vehicle move if the steering wheel is operated?
- **Constraints:** maximum steering wheel angle (radius of curvature), stay on the road
- **Disturbances**: obstacles on the street
- **Reference value**: desired track, lane
- **Cost function**: reach the destination in minimal distance

Model Predictive Control

- MPC can predict what the future deviation will be
- Predictive behavior



Why Applying MPC to Molten Salt Receivers



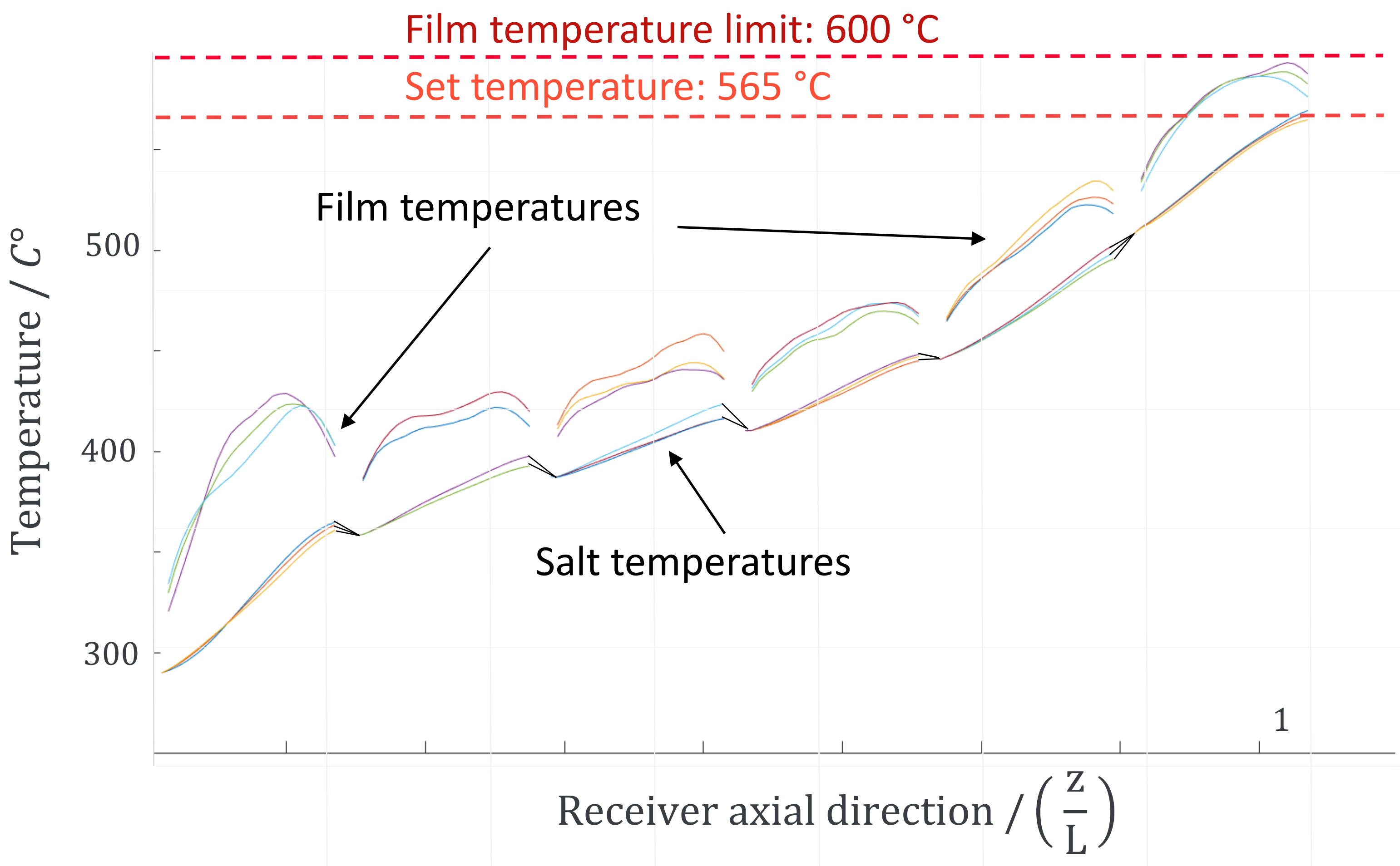
Control Task

- Control variables:
  - $T_{out,1}$, $T_{out,2}$
  - Set point temperature: 565 °C
- Input variables
  - Manipulated variable: Mass flows $\dot{m}_1$ and $\dot{m}_2$
  - Measurable disturbance: Distribution of solar flux density on the receiver $\dot{q}(z)$
- Constraints:
  - Mass flow, salt temperatures, absorbed flux density

Challenges

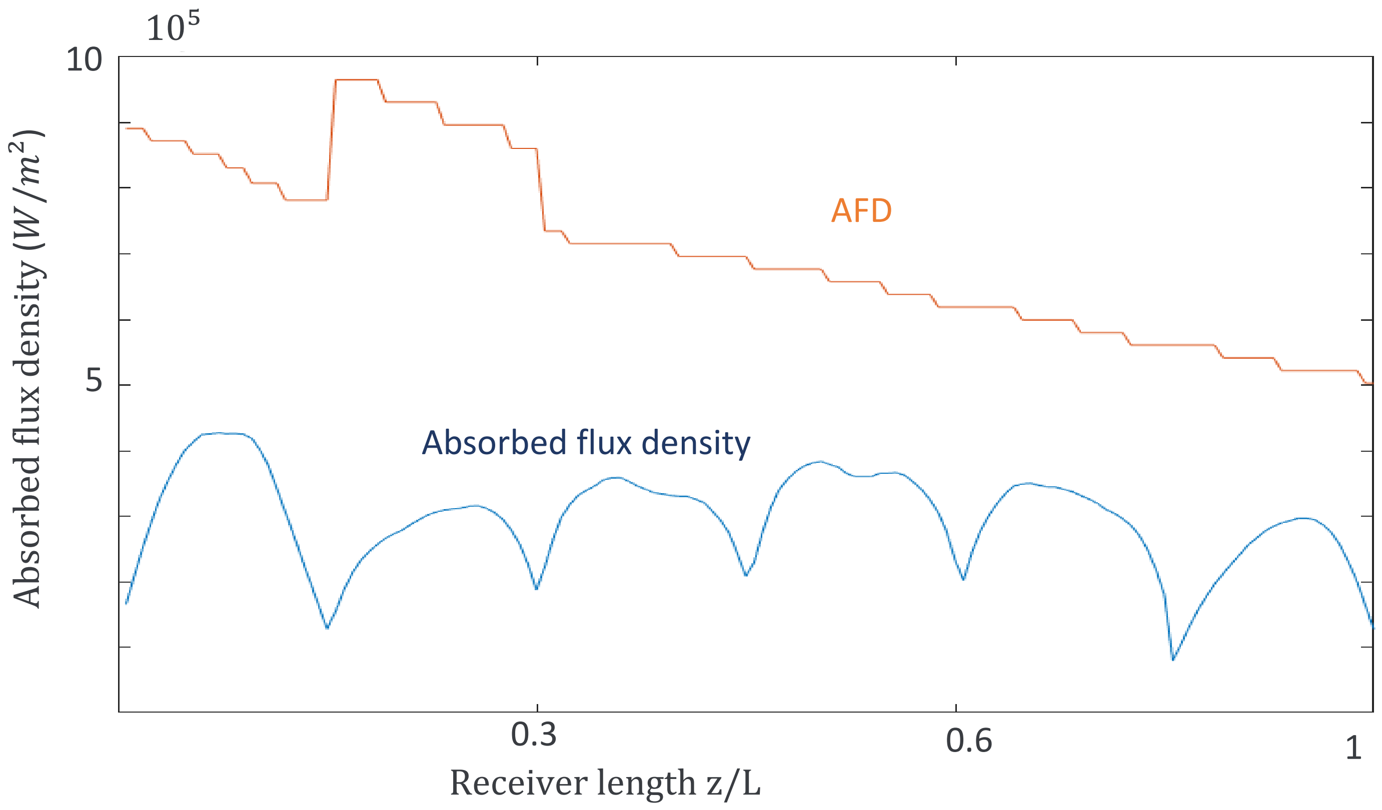
- Slow dynamics
  - Settling time ~ 150 s - 500 s
- Constraints
  - Qualities, to be restricted, not measurable
  - Limits can be exceeded dynamically at different locations.

Why Applying MPC to Molten Salt Receivers



Temperature limits	Salt	Film
transient (max. 5 min)	602 °C	616 °C
steady	580 °C	600 °C

- Constraining salt temperatures and film temperatures to prevent degradation

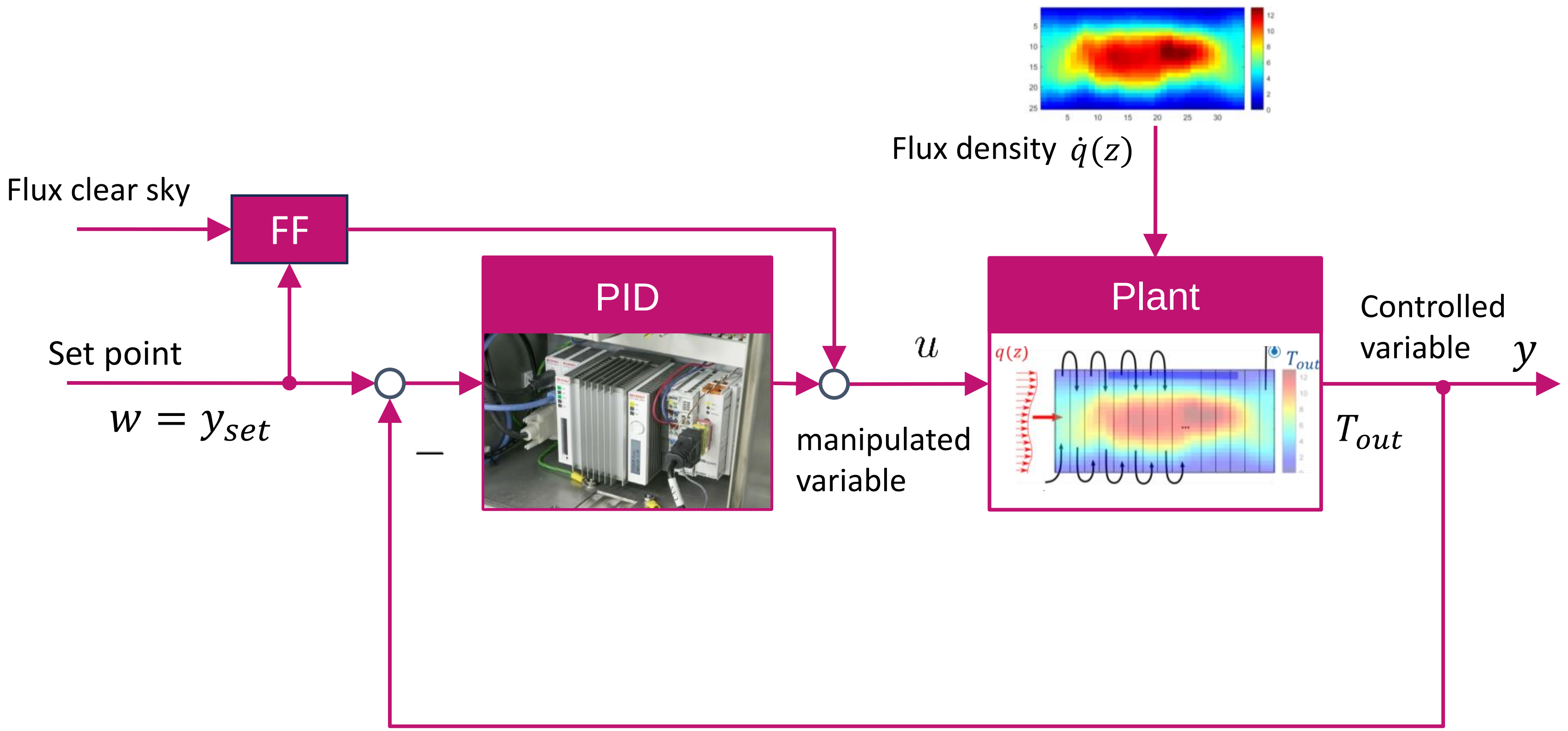


Temperature limits	Salt	Film
transient (max. 5 min)	602 °C	616 °C
steady	580 °C	600 °C

- Avoid mechanical stress due to high temperature gradients
- Allowable flux density (AFD): $f(T_{fl}, \dot{m})$ [Vant-Hull 2002]
- Challenge: Estimate both the AFD as a limit and the absorbed flux density correctly with the internal model

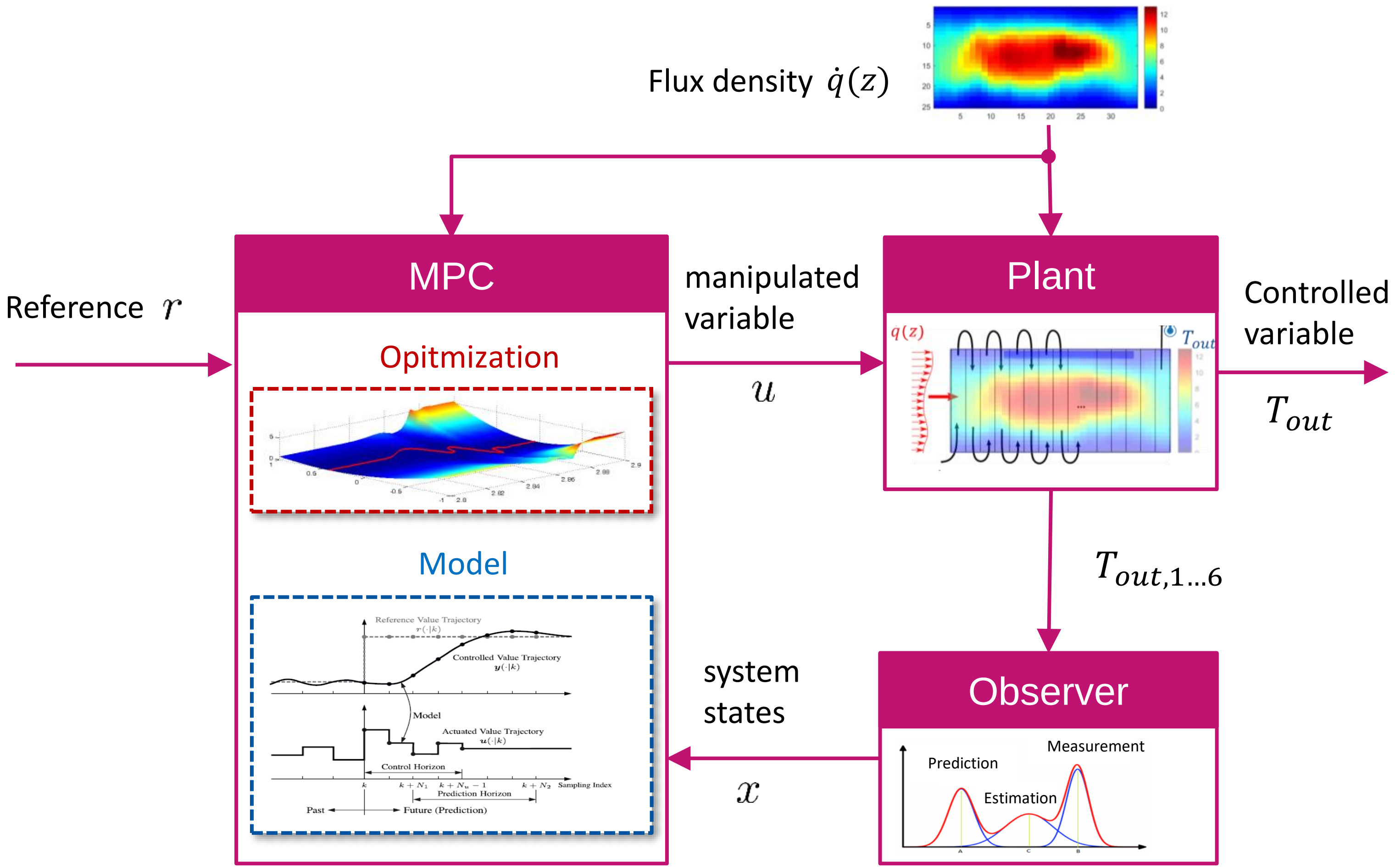
Controlling the Molten Salt Receiver

- **Conventional Control:** PID + Feed Forward control
  - FF: Designed to keep set point temperature at clear sky condition
- Strategy to avoid **violations of temperature limits**
  - Cloud Standby (CSP) if $T_{rec,out} < 510\,°C$ Feedback control is deactivated
  - If salt temperature limits are violated, some heliostats are defocused



Controlling the Molten Salt Receiver
MPC Control Structure

- **Model**: Prediction of system behaviour
- **Observer**: Calculate the full system state as starting point for the prediction
- **Optimization** of the control variable considering prediction and constraints



<u>Continuous state space model</u>

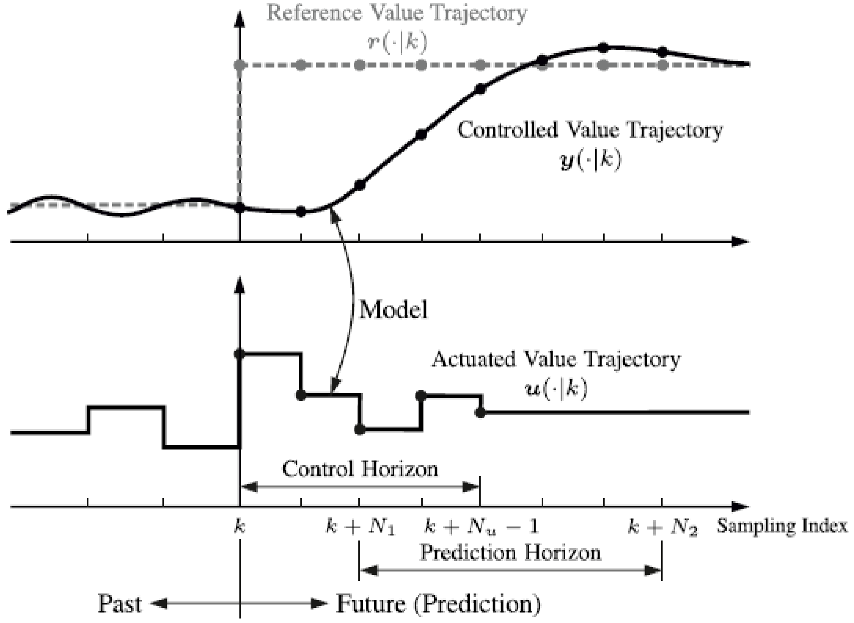
$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}\left(\boldsymbol{x}(t), \cdot\, \boldsymbol{u}(t), \boldsymbol{q}(t)\right)$$

$$\boldsymbol{y}(t) = \boldsymbol{g}(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{q}(t))$$

<u>Discretize equations in time, by integrating the differential equation</u>

$$\boldsymbol{x}(k+1) = \boldsymbol{F}(\boldsymbol{x}(k), \cdot\, \boldsymbol{u}(k), \boldsymbol{q}(k))$$

$$\boldsymbol{y}(k) = \boldsymbol{g}(\boldsymbol{x}(k), \boldsymbol{u}(k), \boldsymbol{q}(k))$$



<u>Predict the future system behavior</u>

$for\ i := 0\ to\ N_u$

$$\boldsymbol{x}\,(k+1) = \boldsymbol{f}(\boldsymbol{x}(k), \cdot\, \boldsymbol{u}(k), \boldsymbol{q}(k))$$
$$\boldsymbol{y}\,(k+1) = \boldsymbol{g}(\boldsymbol{x}(k), u(k))$$

$$J = \|\Delta \boldsymbol{u}(\cdot\,|k)\|_{\boldsymbol{R}}^2$$
$$\boldsymbol{u}_{lb} \leq \boldsymbol{u}(k) \leq \boldsymbol{u}_{ub}$$

end

$for\ i := N_1\ to\ N_2$

$$\boldsymbol{x}\,(k+1) = \boldsymbol{f}(\boldsymbol{x}(k), \cdot\, \boldsymbol{u}(k), \boldsymbol{q}(k))$$
$$\boldsymbol{y}\,(k+1) = \boldsymbol{g}(\boldsymbol{x}(k), u(k))$$

$$J = \|\boldsymbol{y}(\cdot\,|k) - \boldsymbol{r}(\cdot\,|k)\|_{\boldsymbol{Q}}^2$$
$$\boldsymbol{B}_{\text{lb}} \leq \boldsymbol{h}\big(\boldsymbol{x}(k), \boldsymbol{u}(k), \boldsymbol{q}(k)\big) \leq \boldsymbol{B}_{\text{ub}}$$

end

→

$$\min_{\boldsymbol{u}} J$$

subject to:

$$\boldsymbol{h}(\boldsymbol{x}) \leq \boldsymbol{B}_{\text{Limits}}$$

Setting Up the MPC

Differential equation from energy balance

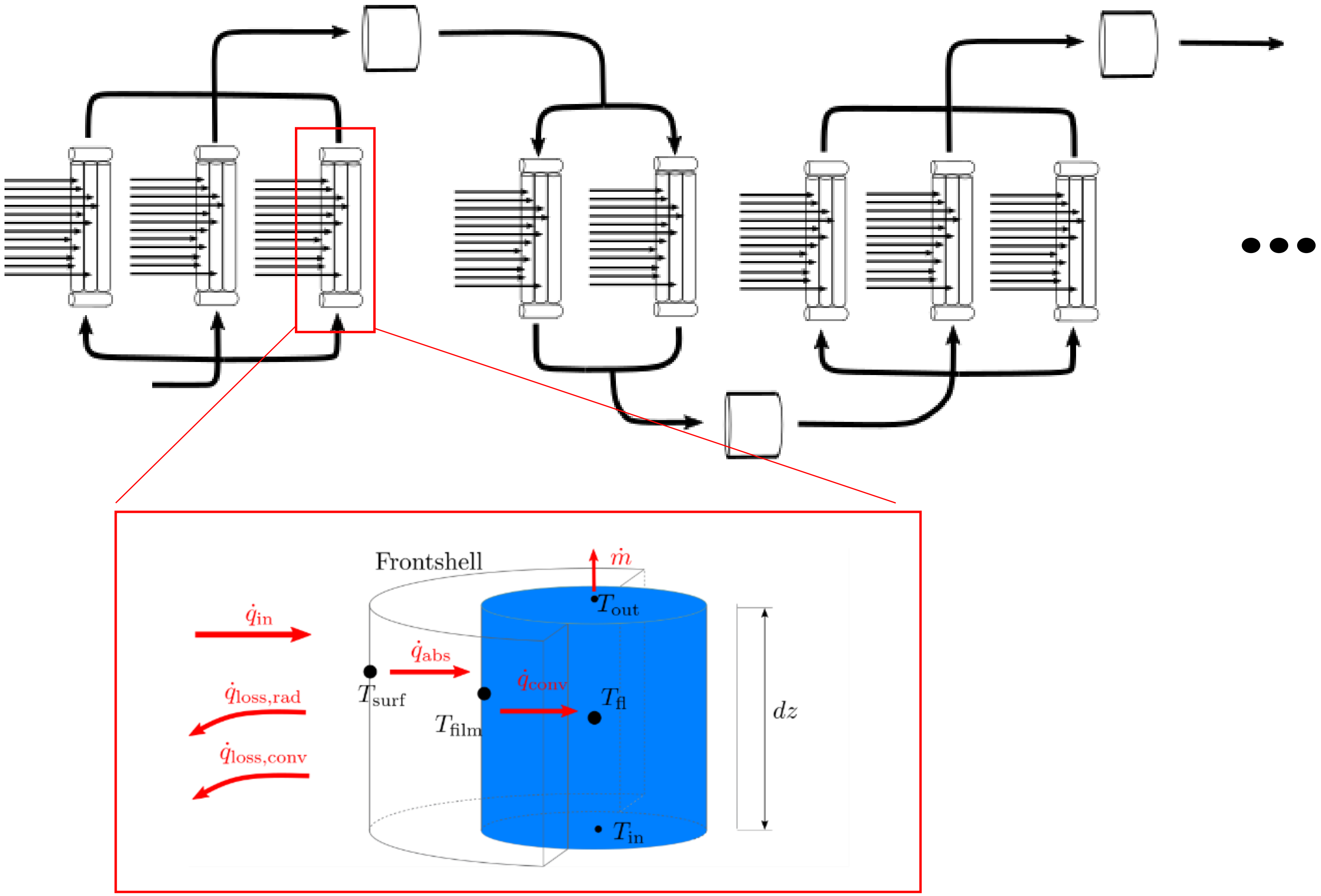
(1) $\dot{q}_{in} - \dot{q}_{loss,rad} - \dot{q}_{loss,conv} - \dot{q}_{abs} = 0$

(2) $\rho_T V_T c_T \frac{dT_{film}}{dt} = \dot{q}_{abs} - \dot{q}_{conv}$

(3) $\rho_{fl} V_{fl} c_{fl} \frac{dT_{fl}}{dt} = \dot{q}_{conv} - c_{fl} \frac{\dot{m}}{n_p n_t} \frac{(T_{out} - T_{in})}{L}$

$$\Rightarrow \dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, u, \dot{\boldsymbol{q}})$$

$$x = \begin{bmatrix} T_{fl,1} \\ T_{film,1} \\ T_{mani,1} \\ \vdots \\ T_{fl,6} \\ T_{film,6} \\ T_{mani,6} \end{bmatrix}$$



Differential equations from energy balance

(1) $\dot{q}_{in} - \dot{q}_{loss,rad} - \dot{q}_{loss,conv} - \dot{q}_{abs} = 0$

(2) $\rho_T V_T c_T \frac{dT_{film}}{dt} = \dot{q}_{abs} - \dot{q}_{conv}$

(3) $\rho_{fl} V_{fl} c_{fl} \frac{dT_{fl}}{dt} = \dot{q}_{conv} - c_{fl} \frac{\dot{m}}{n_p n_t} \frac{(T_{out} - T_{in})}{L}$

$$x = \begin{bmatrix} T_{fl,1} \\ T_{film,1} \\ T_{mani} \\ \vdots \\ T_{fl,6} \\ T_{film,6} \\ T_{mani,6} \end{bmatrix}$$

$\Rightarrow \dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, u, \dot{\boldsymbol{q}})$

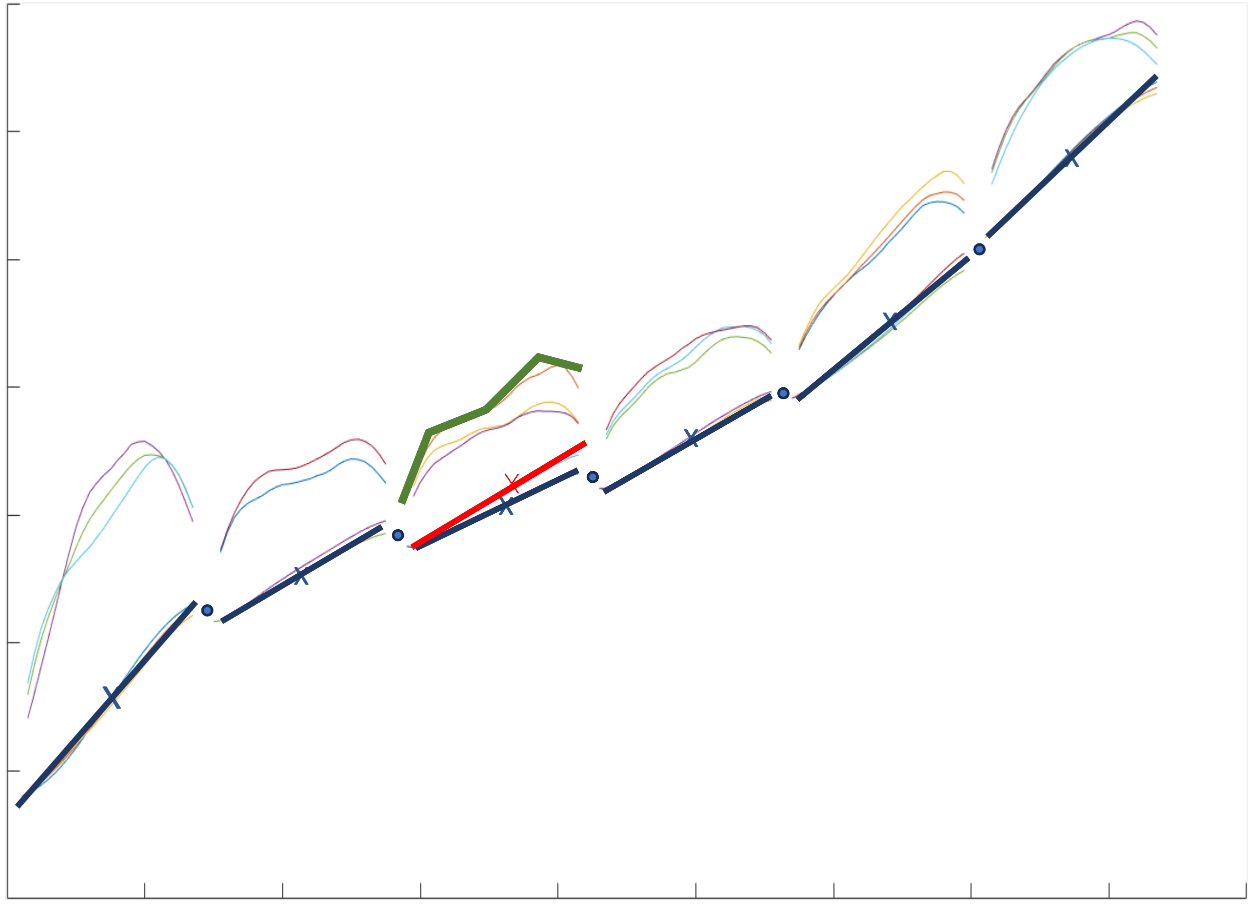
+

Static nonlinear equations

$$\boldsymbol{T}_{fl,max} = \frac{\partial f}{\partial x}^{-1} \frac{\partial f}{\partial \dot{q}} (\dot{\boldsymbol{q}}_{max} - \dot{\boldsymbol{q}}_{mean}) + \boldsymbol{T}_{fl,mean}$$

$$\boldsymbol{T}_{film}(\boldsymbol{z}) = \boldsymbol{g}_1(\boldsymbol{q}_{in}(\boldsymbol{z}), \boldsymbol{T}_{fl\_max}(\boldsymbol{z}), \dot{\boldsymbol{m}})$$

$$\dot{\boldsymbol{q}}_{abs}(z) = \boldsymbol{g}_2(\boldsymbol{q}_{in}(z), \boldsymbol{T}_{fl\_max}(z), \dot{m})$$



Cost function

$$\min_{\substack{u_0 \ldots u_{N_u} \\ s_0 \ldots s_{N_2}}} J = \sum_{k=0}^{N_2} \| r_k - T_{out} \|_{Q_y}^2 + \| \boldsymbol{s}_k(\cdot|k) \|_{Q_f}^2 + \| \boldsymbol{s}_k(\cdot|k) \|_{Q_1} + \sum_{k=0}^{N_u} \| \Delta u(\cdot|k) \|_R^2$$

- Sample time in prediction $T_s = 5\,Sek$
- Prediction horizon $N_2 = 36$
  $\triangleq 36 \cdot 5\,Sek = 3\,Min$
- Control Horizon N_u=10
- Calculation time: 1.5 sec

$$s.t. \qquad \boldsymbol{x}(k+1) = \boldsymbol{F}(\boldsymbol{x}(k), \dot{\boldsymbol{q}}(z,k), u(k)),$$

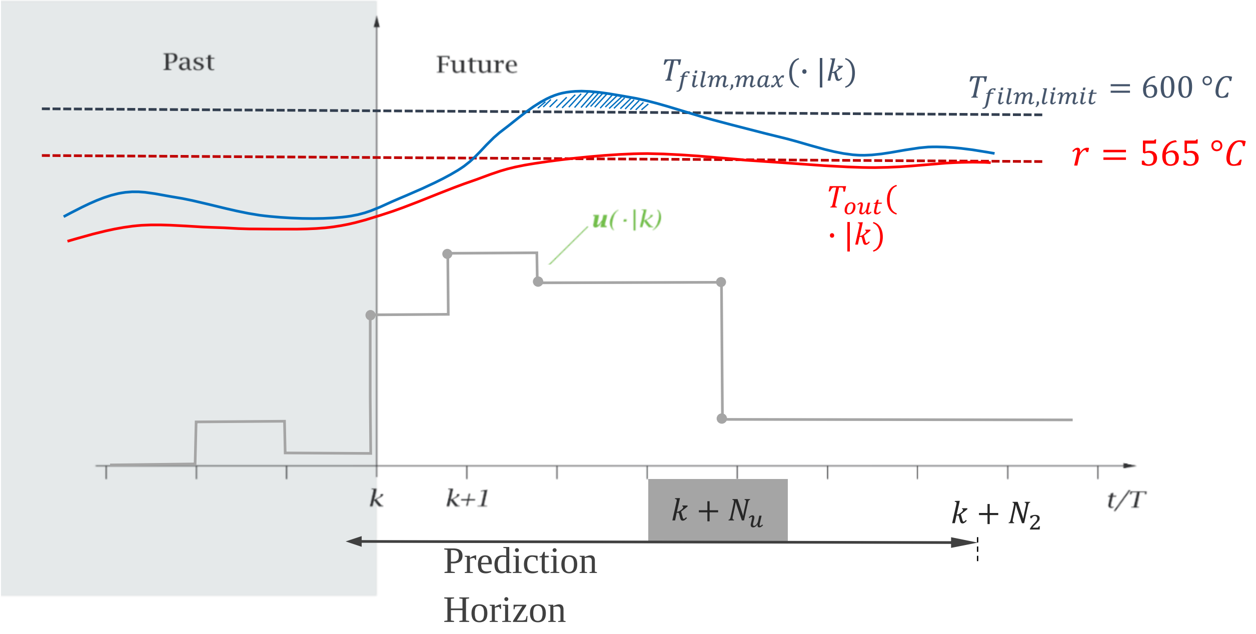
$$-0{,}2\, u_{max} \leq \Delta u \leq 0{,}2\, u_{max}$$

$$0{,}2\, u_{max} \leq u \leq 1{,}1\, u_{max}$$

$$\boldsymbol{s}_k = \begin{bmatrix} s_{film} \\ s_{afd} \end{bmatrix} \qquad \boldsymbol{T}_{film} - \boldsymbol{s}_{film} \leq \boldsymbol{T}_{film,limit}$$

$$\dot{\boldsymbol{q}}_{abs} - \boldsymbol{s}_{afd} \leq \boldsymbol{afd}$$

$$\boldsymbol{s}_k \geq 0$$

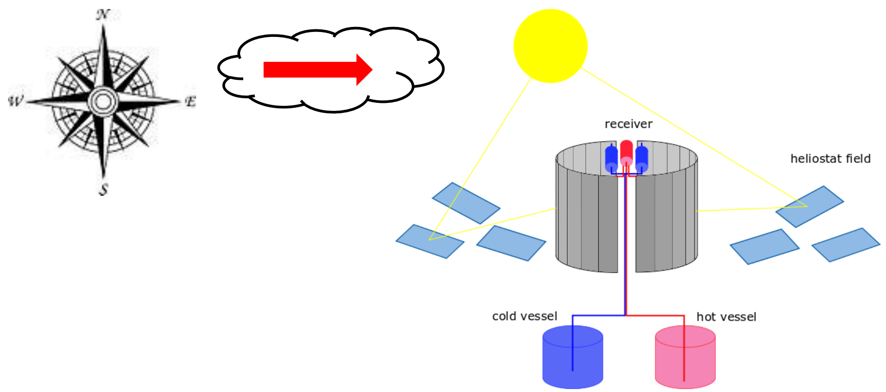


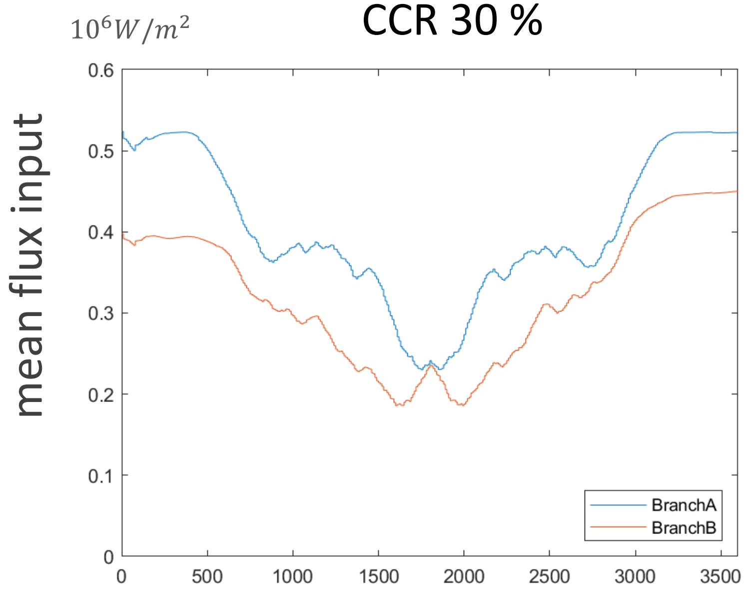
Results

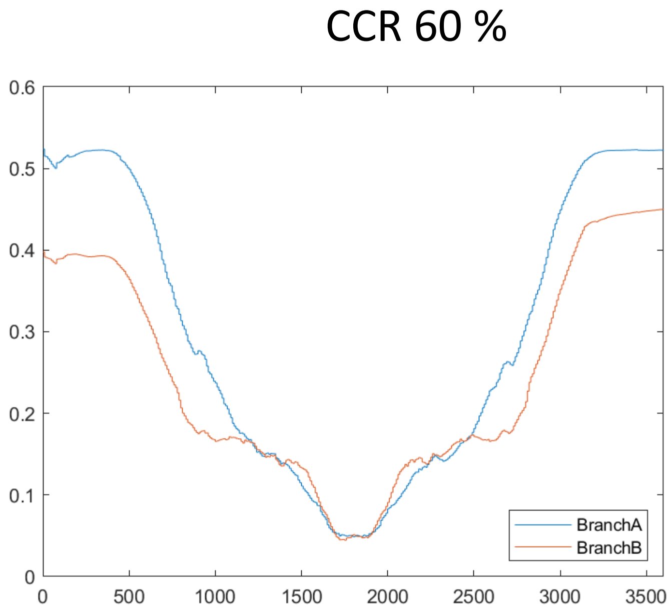
Results
Validation of the MPC with test scenarios

32 test scenarios defined
- Cloud passage within 1 hour
- 2 branches seperatly
- Wind speed inversion after 30 min

Cloud Coverage Rate (CCR)
- 30 %
- 60 %





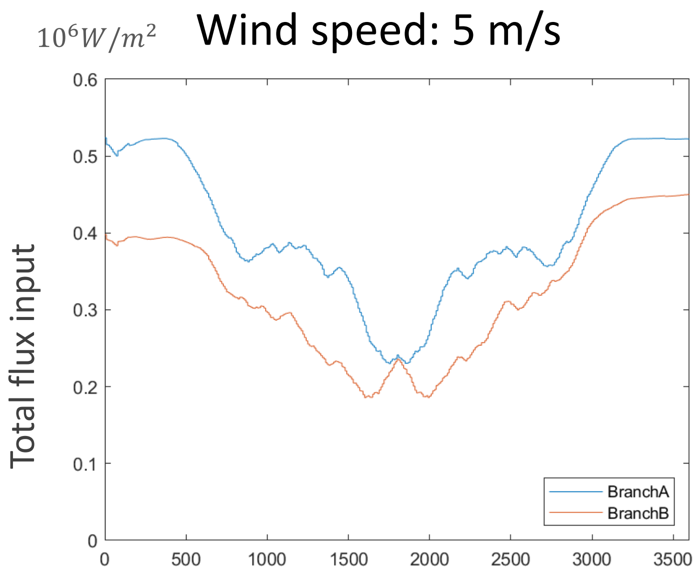


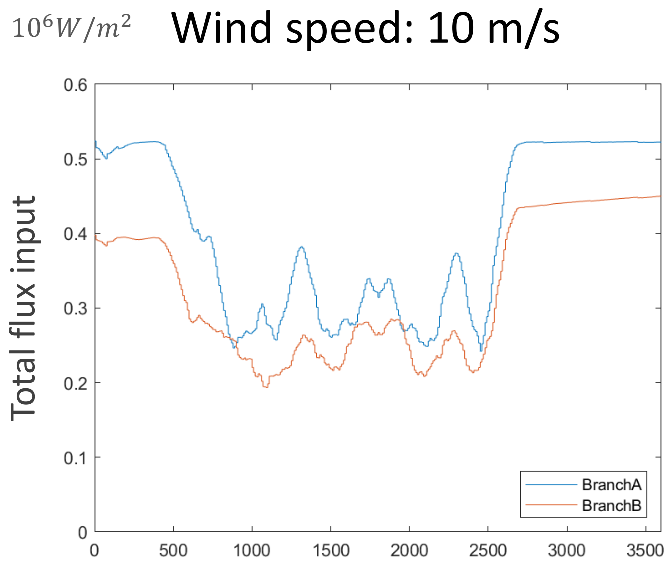
32 Scenarios defined
- Cloud passage within 1 hour
- 2 branches considered
- Wind speed inversion after 30 min

Cloud coverage (CCR)
- 30 %
- 60 %

Day time
- 9 am
- 12 pm

Wind speed and direction
- 5 m/s, 10 m/s
- N, S, W, E



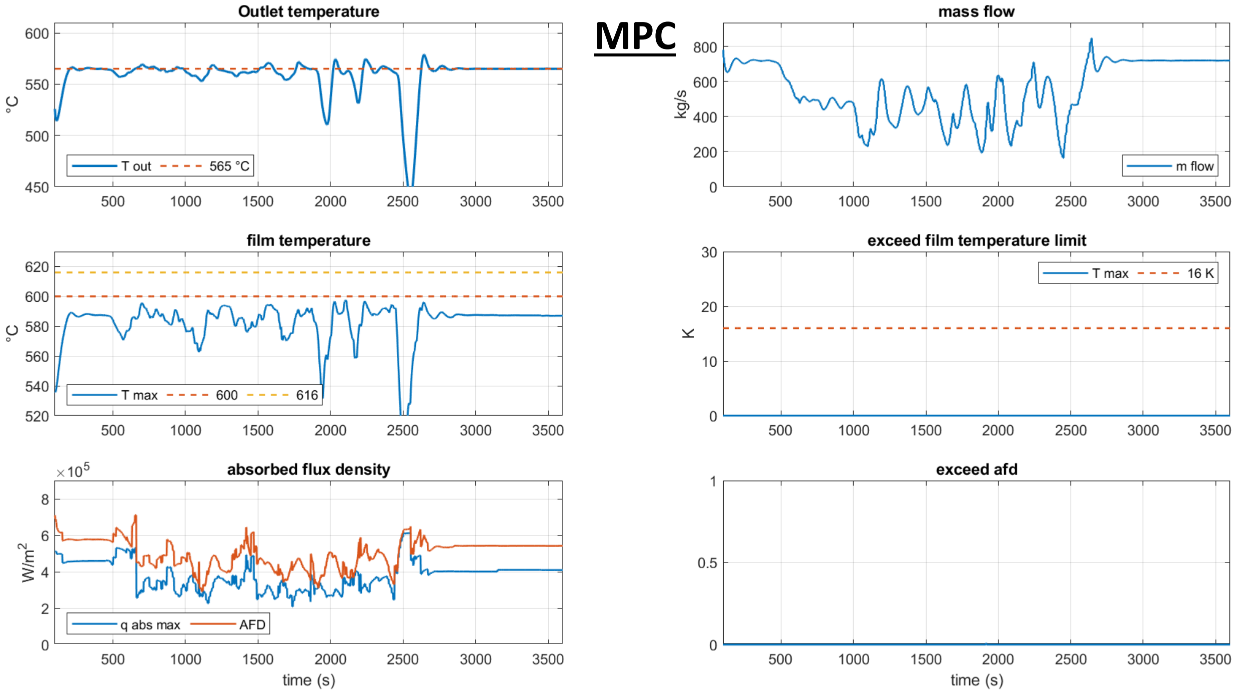


Higher wind speeds lead to a more transient flux input
- ➢ Greater challenge for the controller

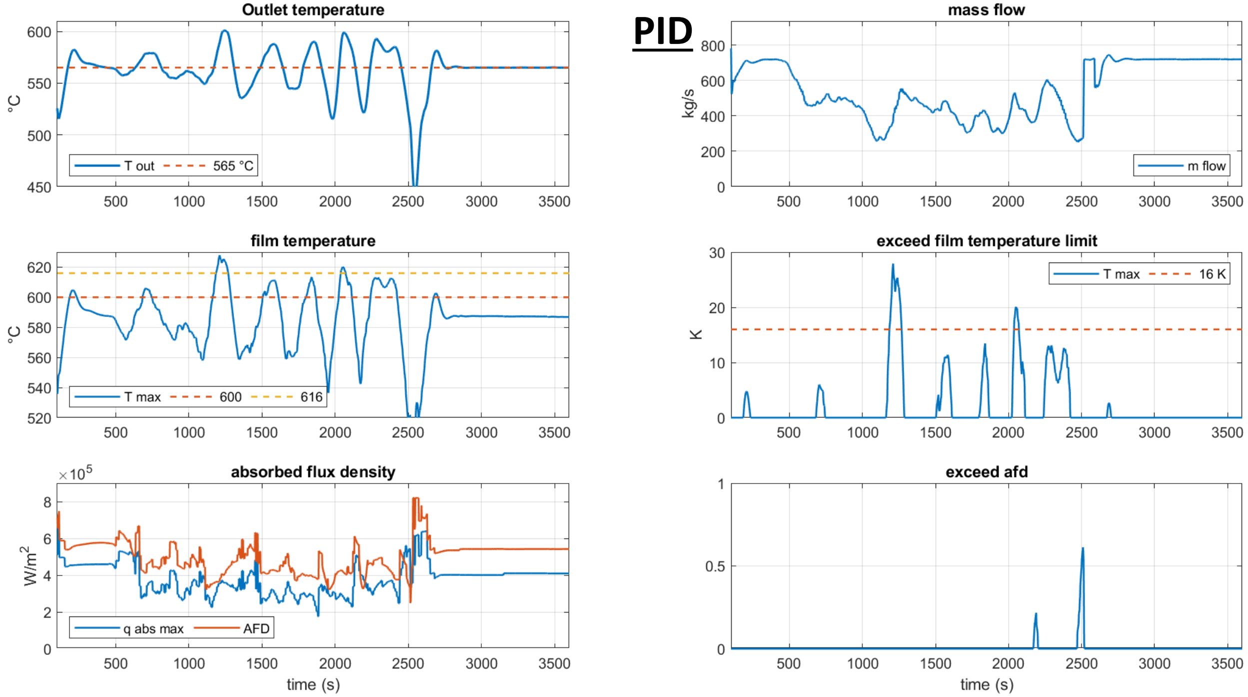
Results

Test case: CCR 30 %, Vel_N = - 10 m/s

MPC



PID



MPC

Outlet temperature:

- Control deviation (RMSE) = 20.1 K

Film temperature

- Max. value 597 °C
- No limit violation

Absorbed flux density:

- No AFD violation

PID

Outlet temperature:

- Control deviation (RMSE) = 22.7 K

Film temperature

- Max. value 627 °C
- Several and critical limit violations

Absorbed flux density:

- 60 % violation of AFD

Results
Evaluation on 24 validation cases

	MPC	PID
Thermal efficiency	85,97 %	85,96 %
Mean control deviation (rmse)	15,3 K	27,4 K
violations of film temperature limits		
Average of max violations	0,32 K	41 K
Cases: > 16 K (critical violation)	0 %	88 %
0 - 16 K	21 %	12 %
No violation	79 %	0 %
violations of AFD		
Average of max violations	1,5 %	28 %
Cases : > 5 %	0 %	79 %
0 – 3 %	42 %	0 %
No violation	58 %	21 %

Conclusion

- The Model Predictive Control can provide a safe operation without the necessity to defocus heliostats

- The conventional control approach does not explicitly comply with the operation constraints and provides poor safety performance. It needs further heuristics that are difficult to adjust to work properly.
- The tracking behavior of the outlet temperature is worse than with MPC.

Thank you for your attention!