High Precision Temperature Control of Normal-Conducting RF GUN for a High Duty Cycle Free-Electron Laser

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Faculty of Life Sciences

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DESY

SIMULTECH 2015

Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

Content

Content

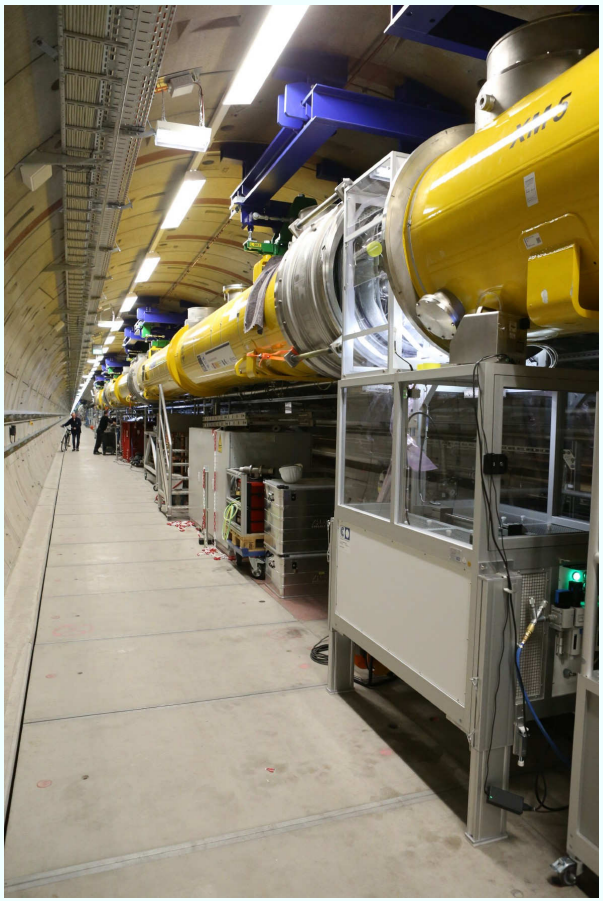
XFEL

- Joint work with Deutsches Elektronen Synchrotron (DESY)
- European X-Ray free-electron laser XFEL

Facts XFEL

- Costs: 1.15 billion Euro
- Length: 3.4 km
- 101 superconducting acceleration modules
- Femtosecond ($\sim 10^{-15}$ s) laser pulses
- Wavelength down to 0.05 nm
- Under construction

[Source: DESY]



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Motivation

- Temperature stability of the gun is the **limiting factor of the overall performance** of XFEL
- Simulation methods allow to develop model-based feedback schemes **even before XFEL is under operation**
- Test controller design in simulation
- Smaller free-electron laser FLASH with comparable structure
- Approaches tested with data from FLASH

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RF GUN

- Free electron laser: Acceleration of electrons to generate the beam
- RF GUN: Electron source
- Resonance frequency of 1.3 GHz
- Very important: Frequency stability for efficient acceleration of electrons
- Temperature variations lead to detuning
- Dissipated RF power heats up the gun
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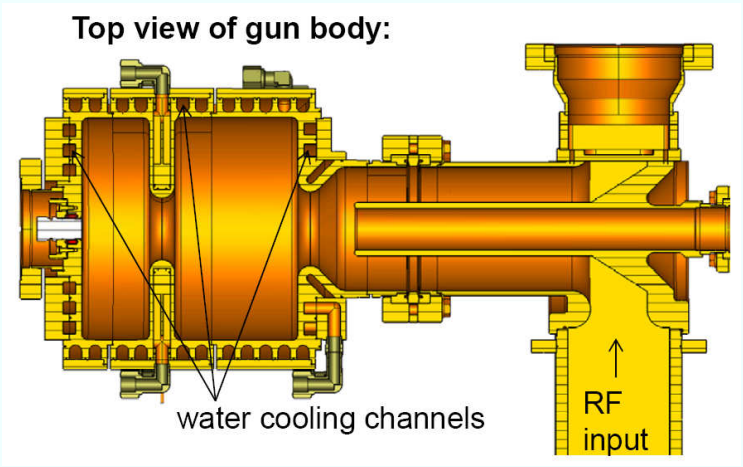

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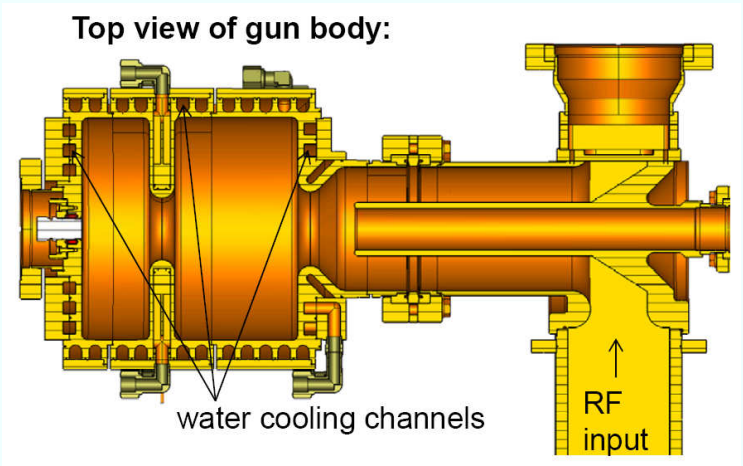

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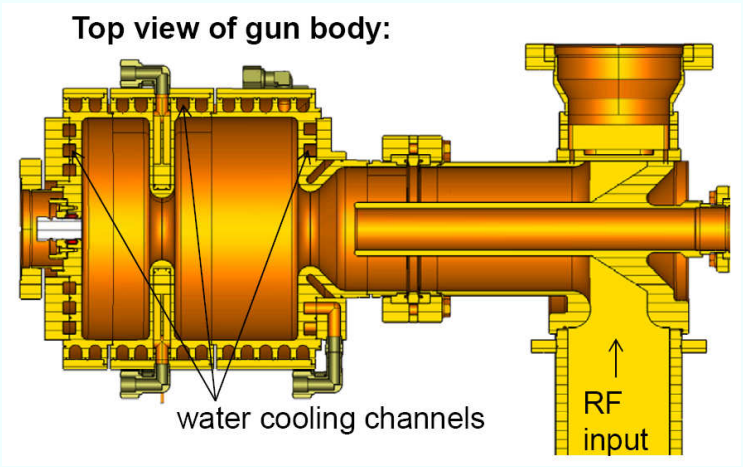

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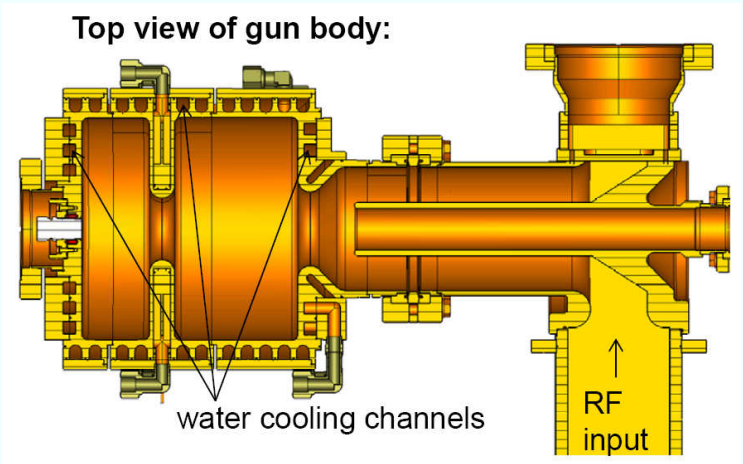

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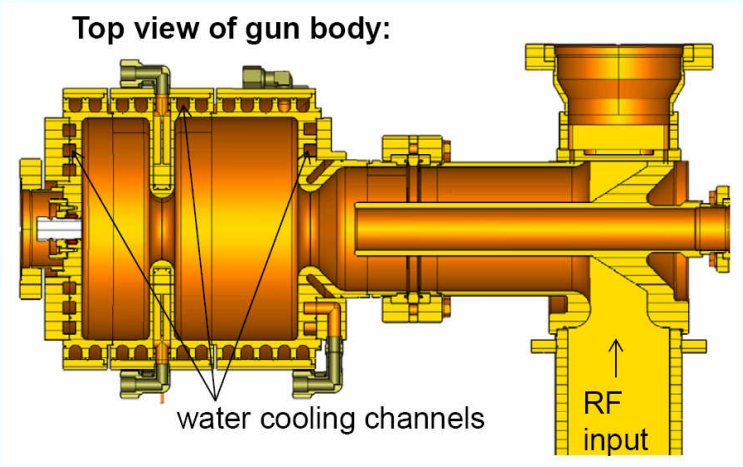

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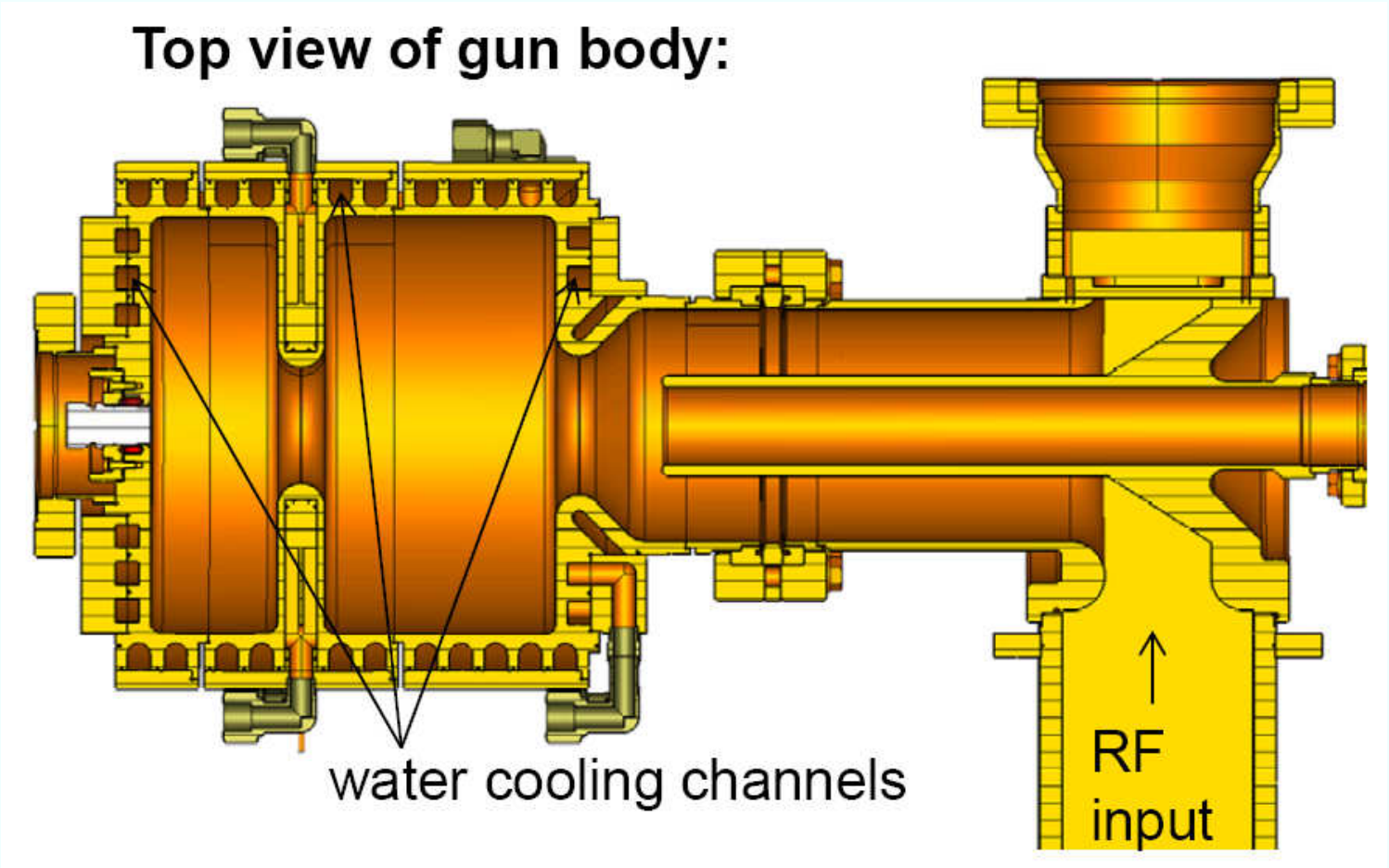

[Stephan, 2015]

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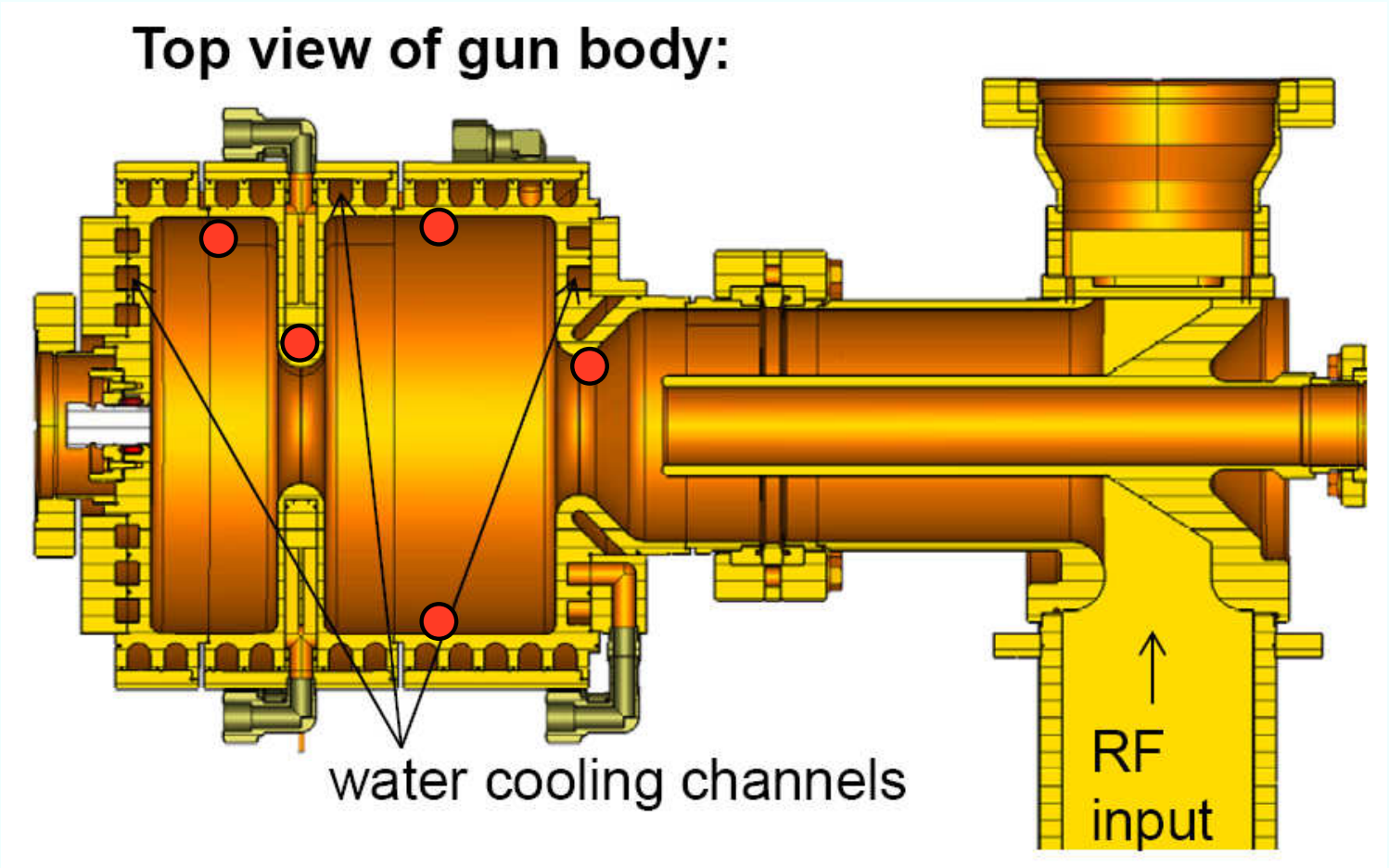

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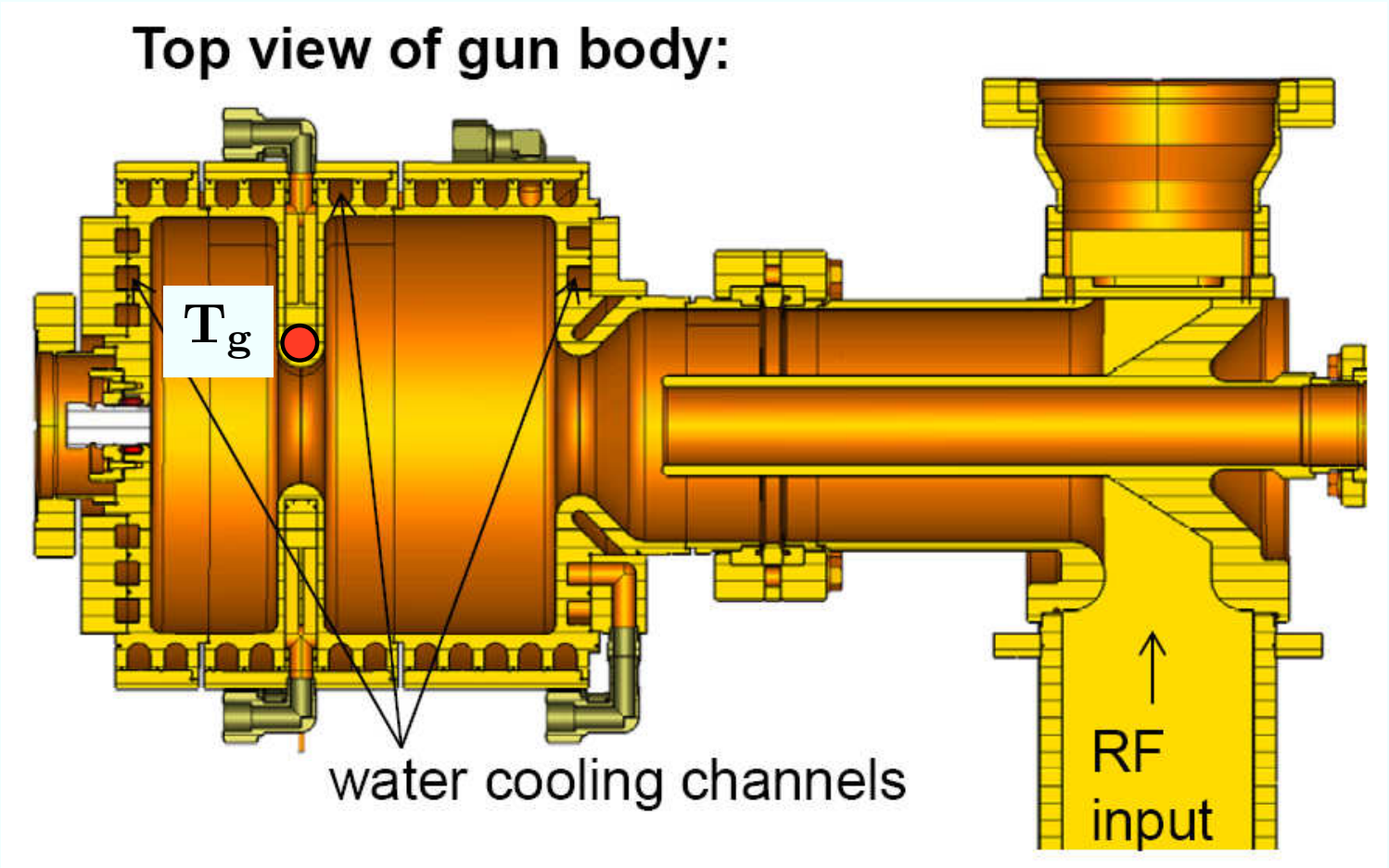

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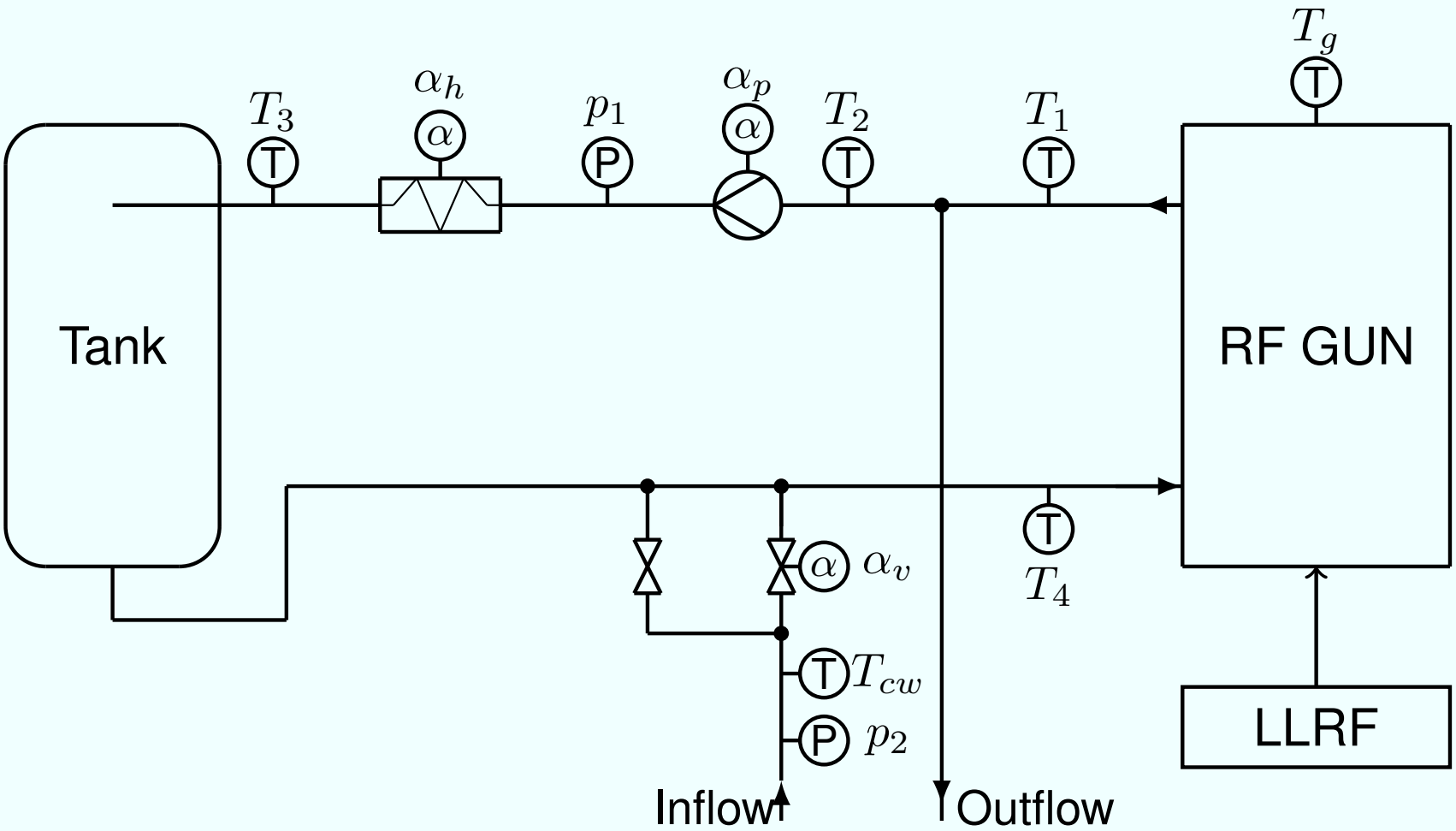
Gun with cooling circuit



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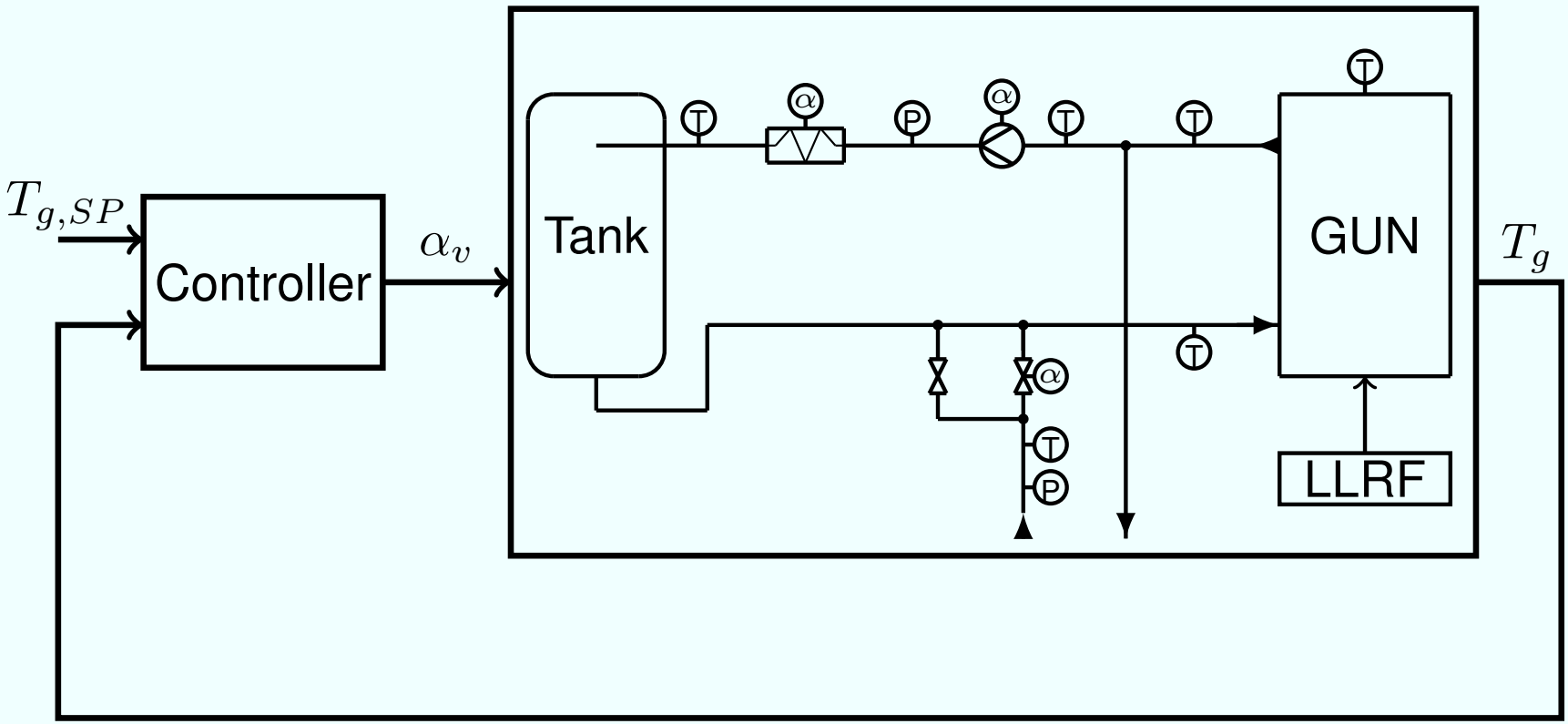


Content

Modeling Principles

- Grey-box model
- Suitable for controller design

Heat

$$Q = c\rho VT$$

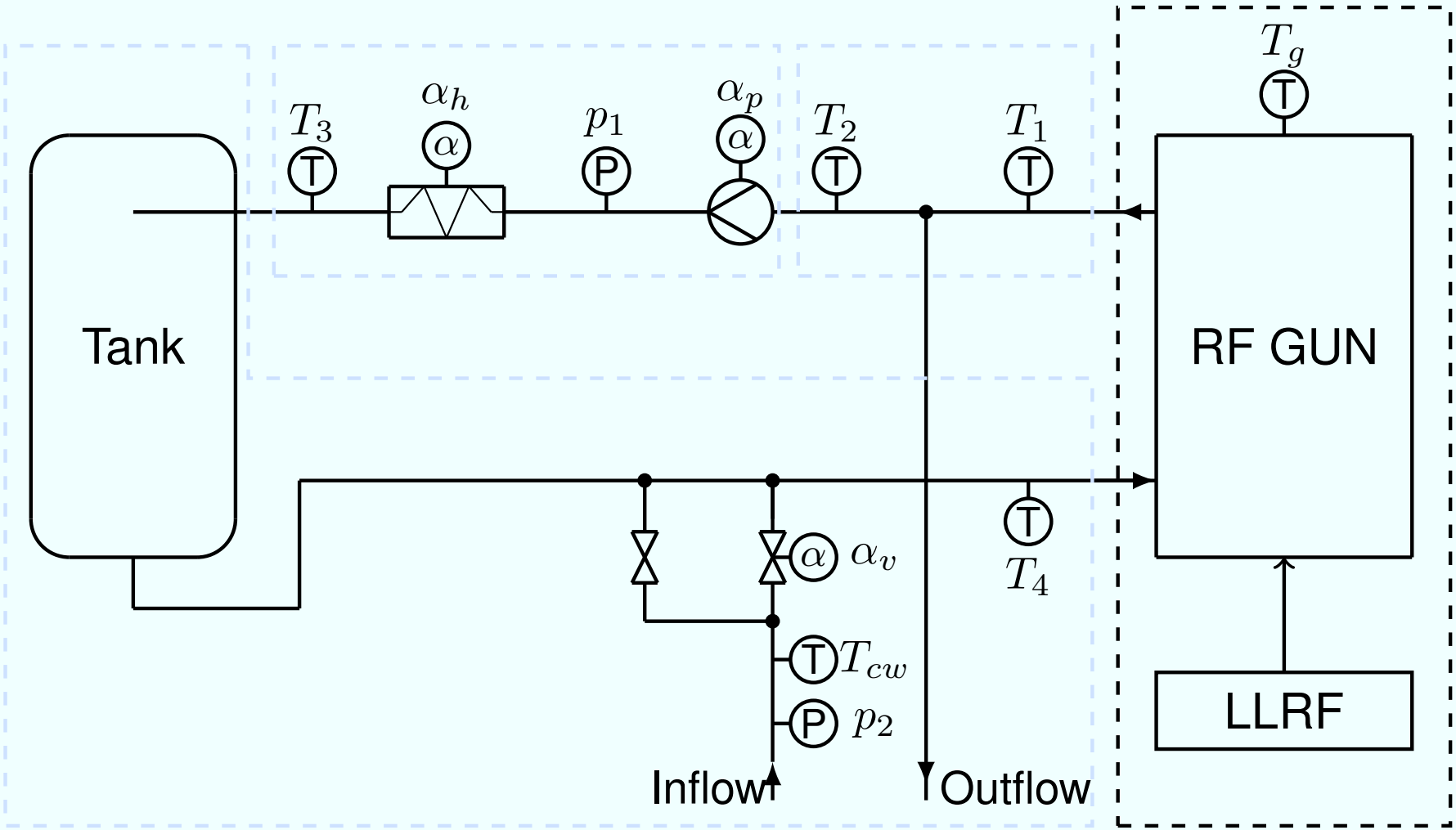
Heat flow balance

Stored power = Sum of supplied (+) and discharged (-) power

$$\dot{Q}_{stored} = \sum_i \dot{Q}_{in,i} - \sum_j \dot{Q}_{out,j}$$

Modeling Idea

- Component-wise modeling



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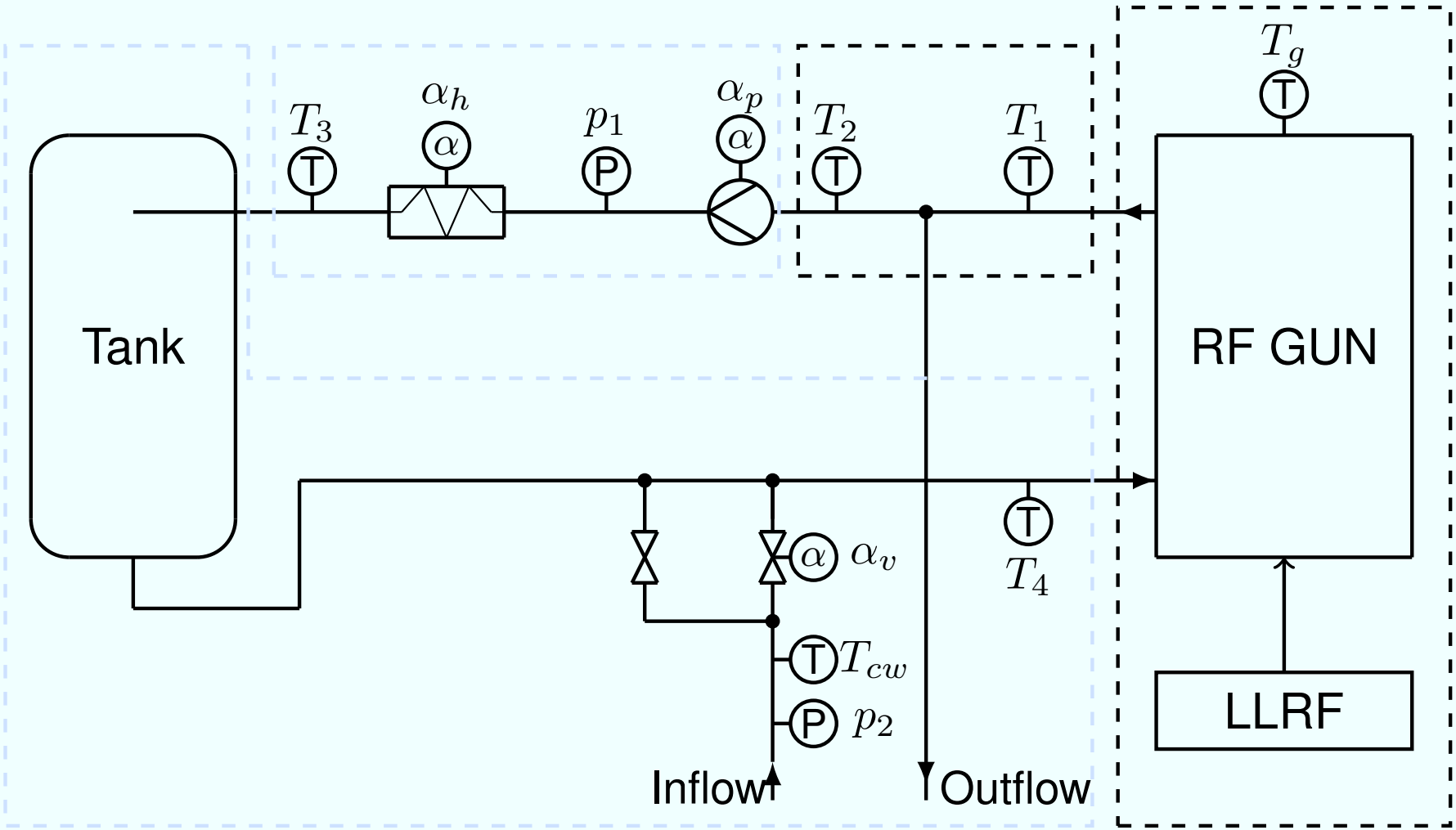

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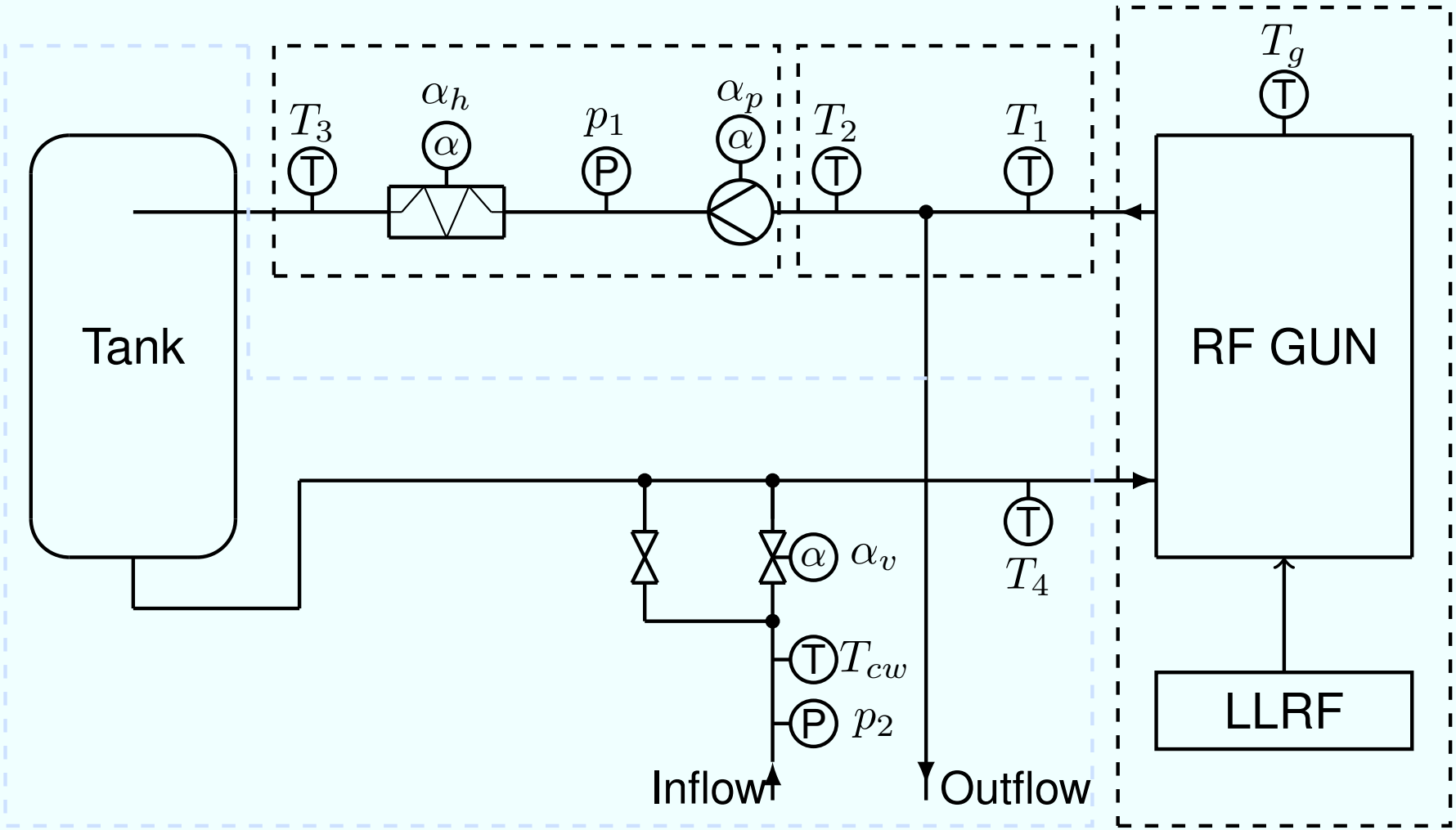

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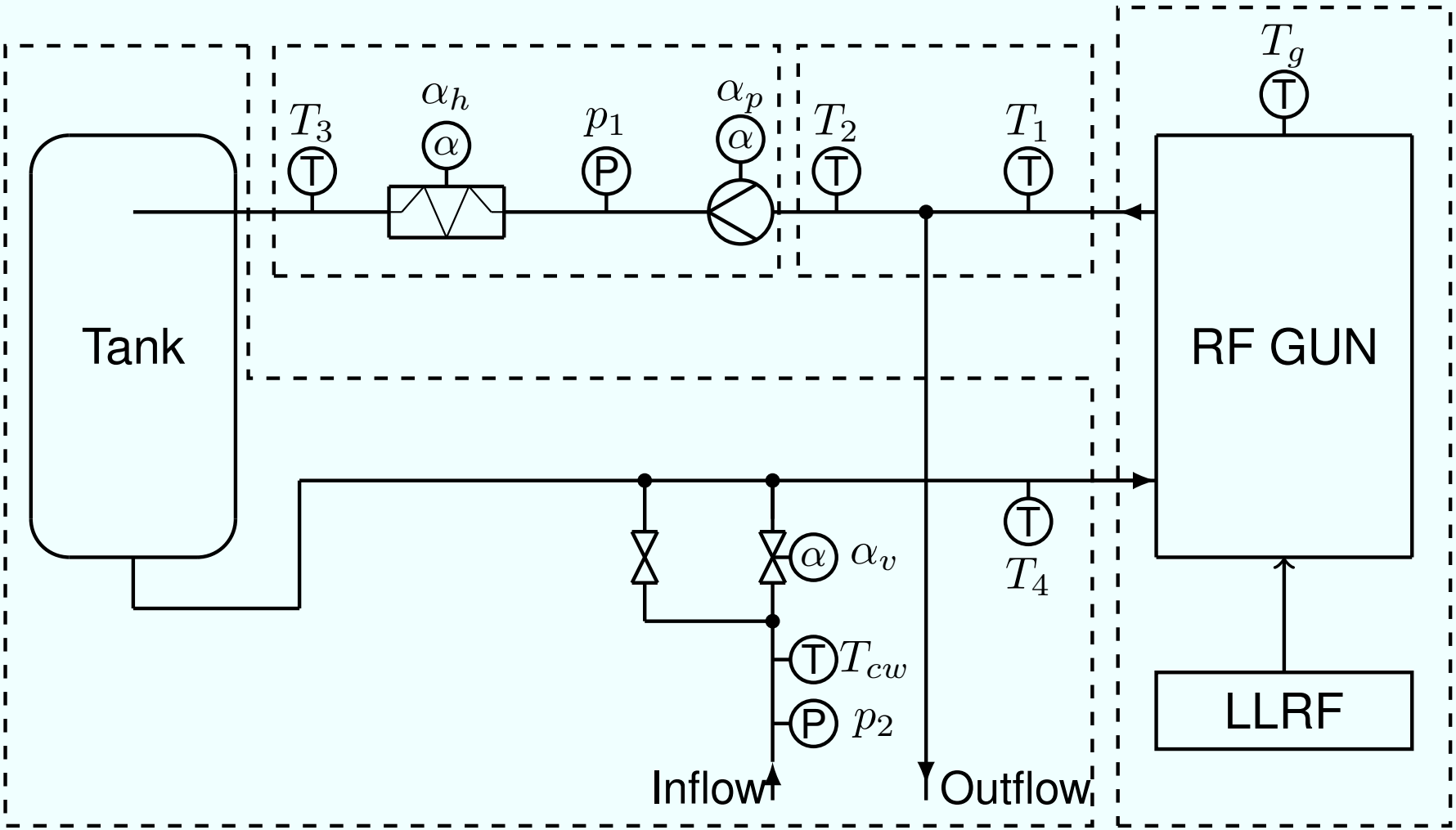
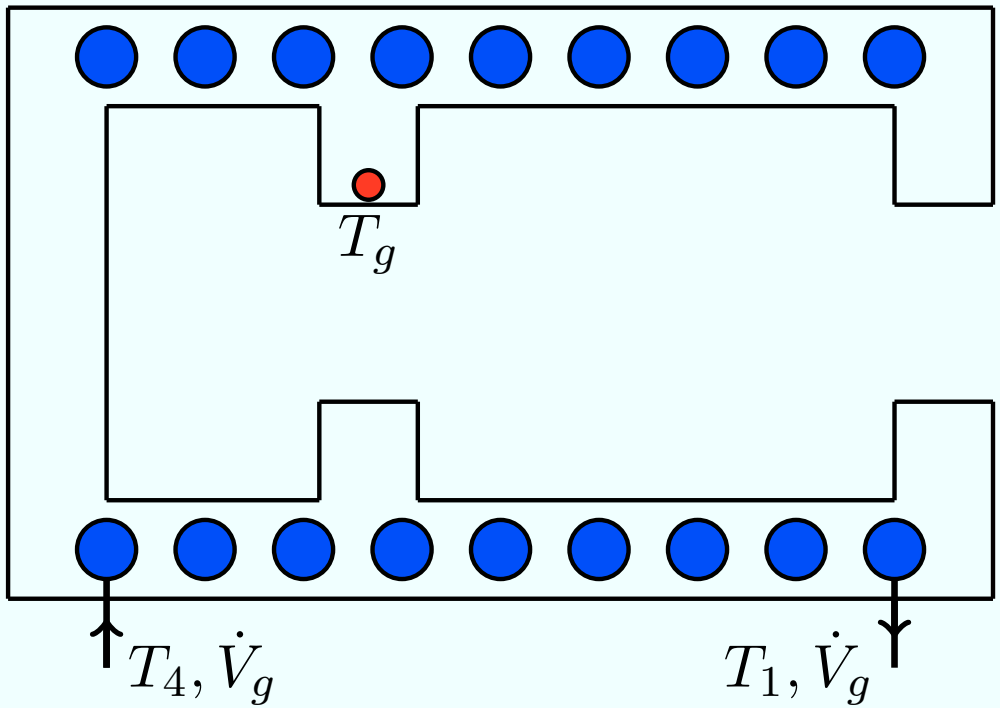


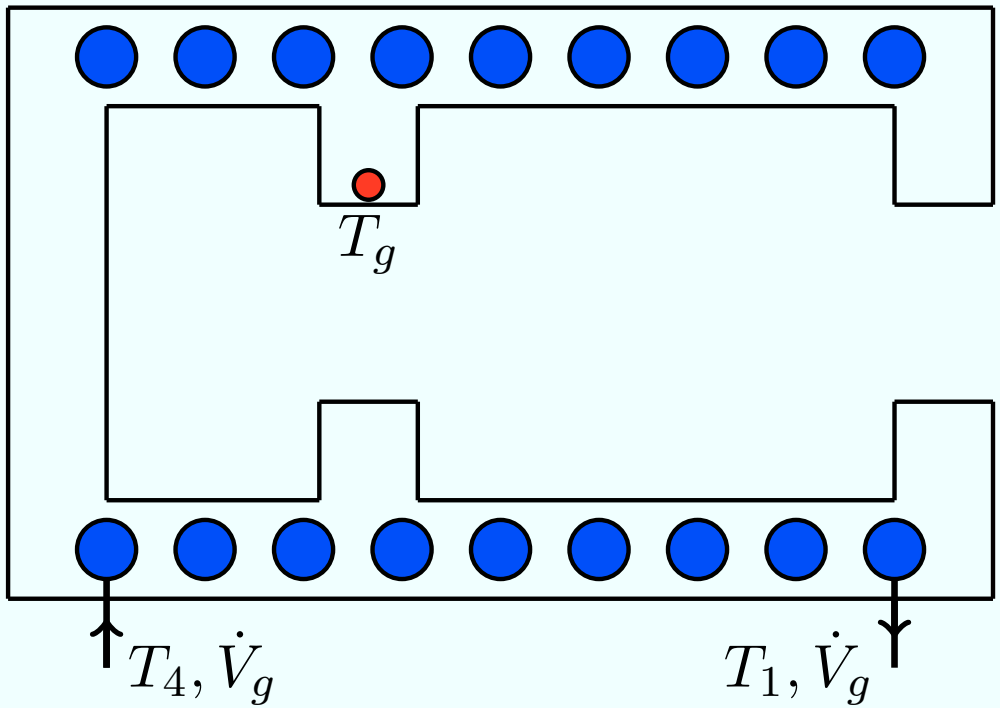
Cooling pipes



- Heat flow caused by volume flow

$$c_w \rho_w V_c \dot{T}_1 = c_w \rho_w \dot{V}_g (T_4 - T_1) - k_{ce}(T_1 - T_{env}) - k_{cg}(T_1 - T_g)$$

Cooling pipes



- Losses to the environment

$$c_w \rho_w V_c \dot{T}_1 = c_w \rho_w \dot{V}_g (T_4 - T_1) - k_{ce}(T_1 - T_{env}) - k_{cg}(T_1 - T_g)$$

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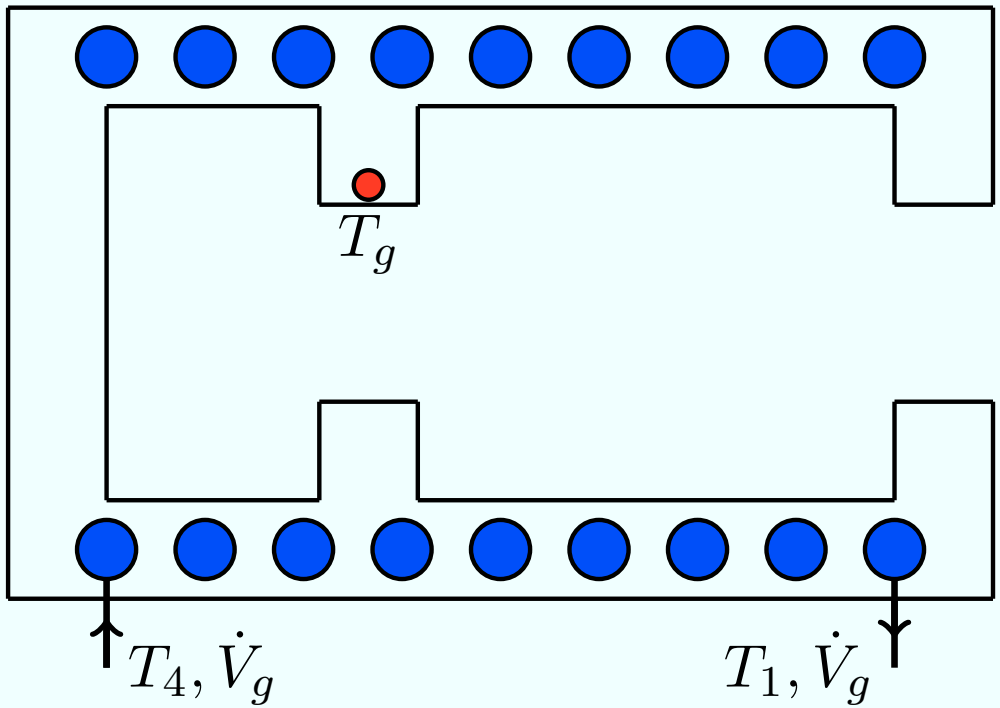
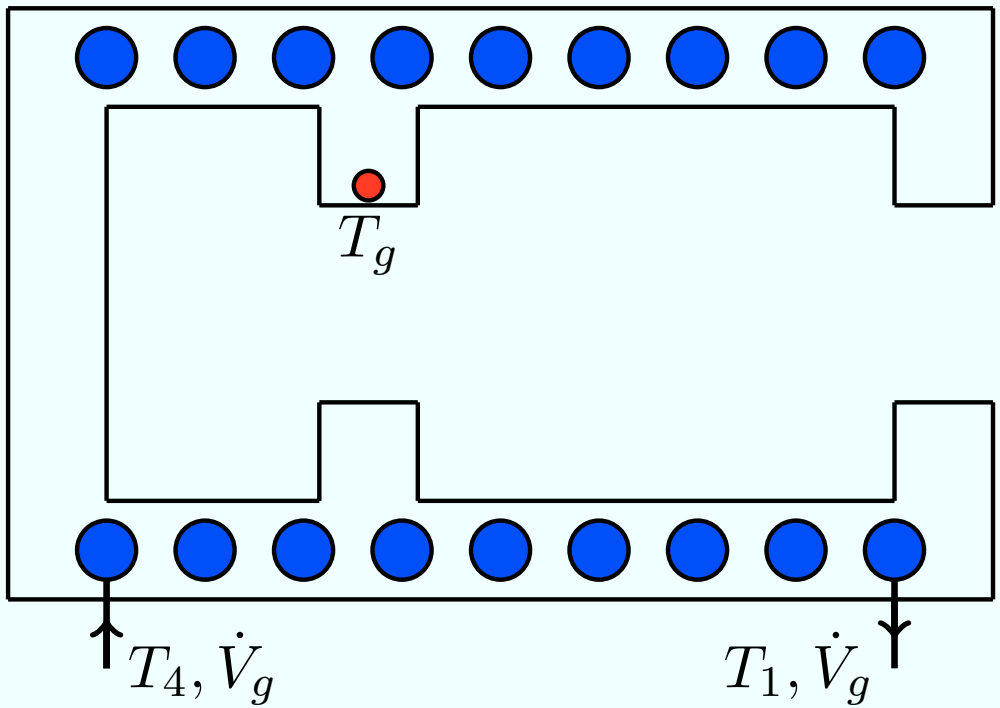


- Heat transfer with the gun body

$$c_w \rho_w V_c \dot{T}_1 = c_w \rho_w \dot{V}_g (T_4 - T_1) - k_{ce}(T_1 - T_{env}) - k_{cg}(T_1 - T_g)$$

Gun body

- Assumption: One-zone model of interior



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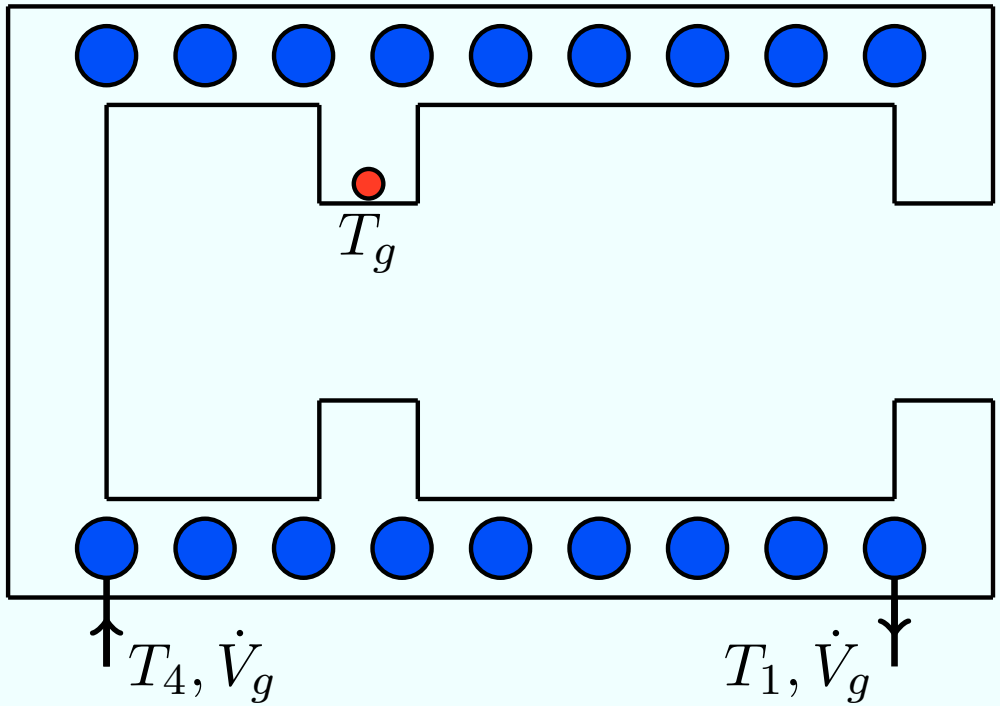

- Heat transfer with cooling pipes

$$c_c \rho_c V_g \dot{T}_g = k_{cg}(T_1 - T_g) - k_{ge}(T_g - T_{env}) + P_{diss}$$

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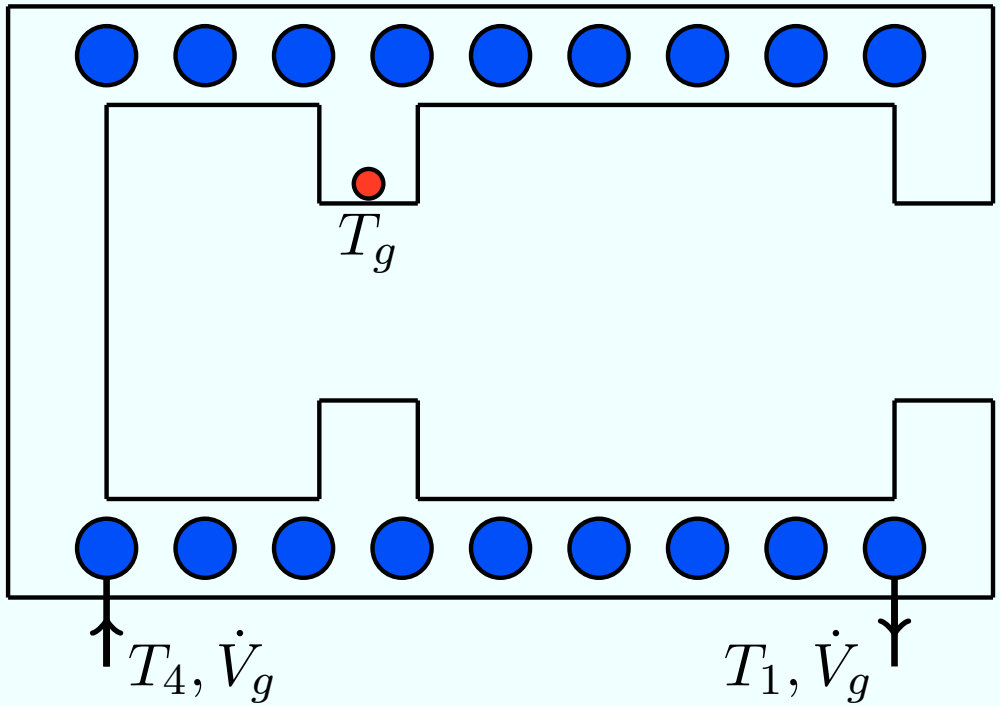

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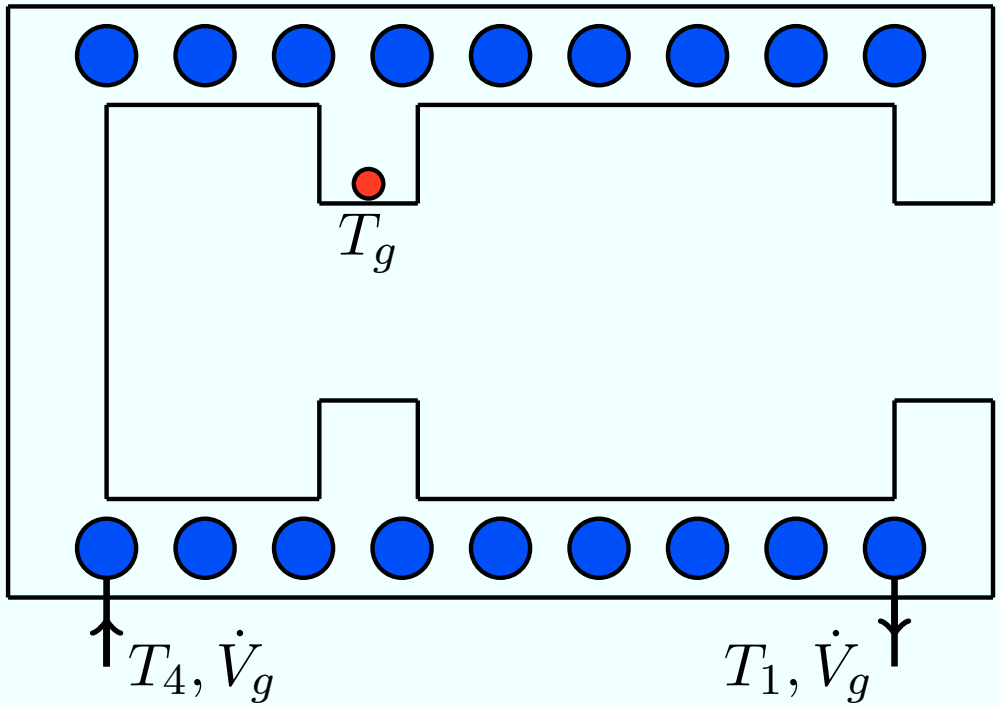

- Dissipated power P_{diss} by LLRF

$$c_c \rho_c V_g \dot{T}_g = k_{cg}(T_1 - T_g) - k_{ge}(T_g - T_{env}) + P_{diss}$$

Dissipated power

- Electric field inside the cavity accelerates electrons
- Induces surface current

$$P_{diss} = \frac{|V_{cav}|^2}{R_{sh}}$$

- RF behavior of gun modeled by LCR resonator circuit

$$V_{cav} = \hat{V}_{cav} \sin(\omega t + \psi),$$

[Schilcher, 1998]

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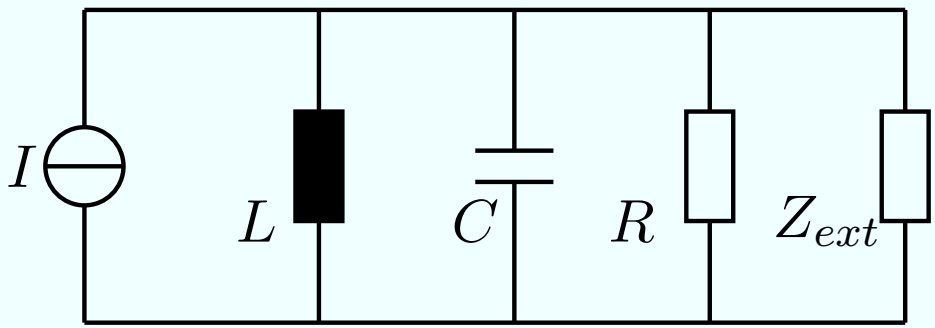

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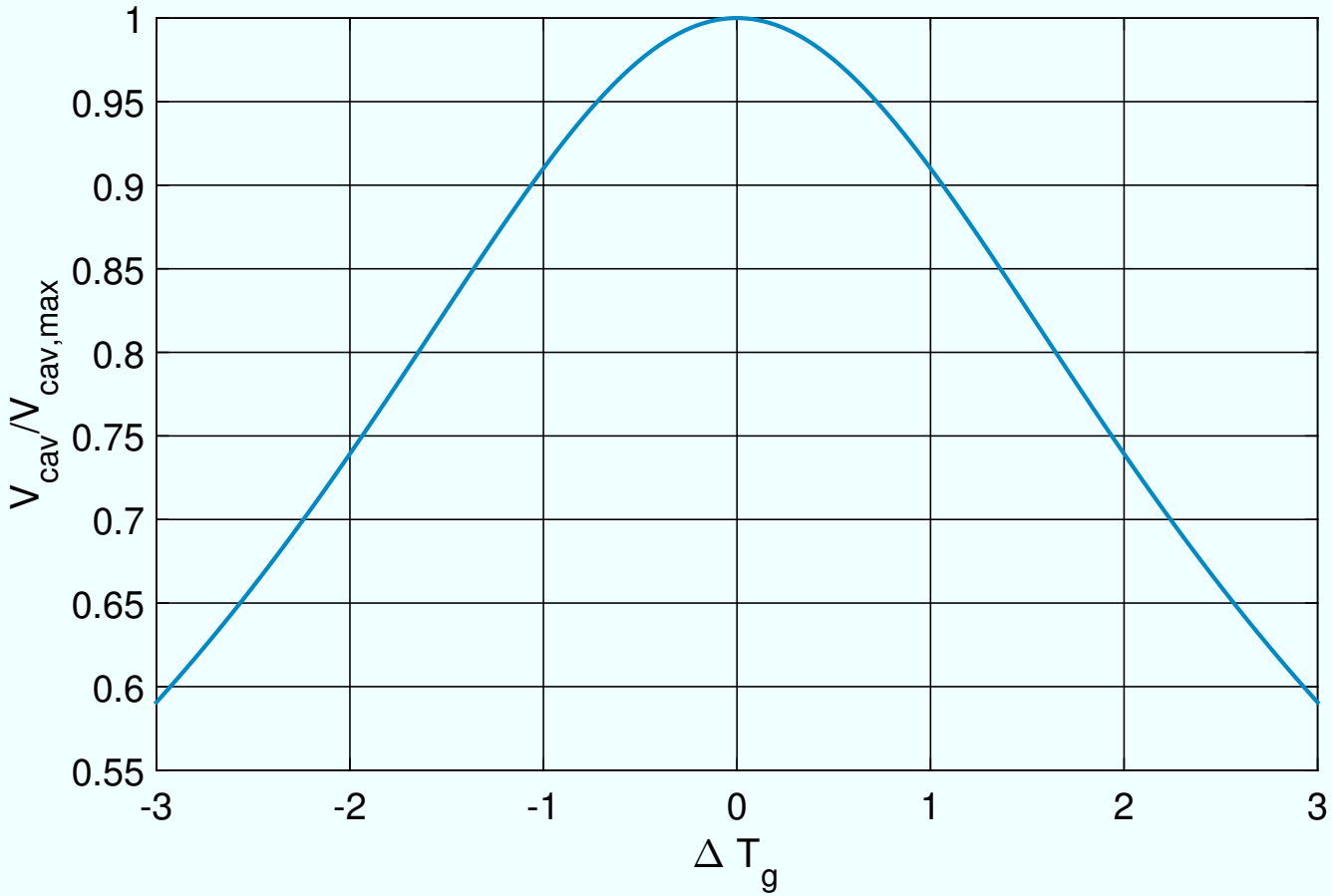
Dissipated power

$$V_{cav} \sim \sqrt{\frac{P_{for}}{1 + \alpha^2 \left(T_g - T_{g,SP}\right)^2}} \rightarrow P_{diss} = \frac{|V_{cav}|^2}{R_{sh}}$$



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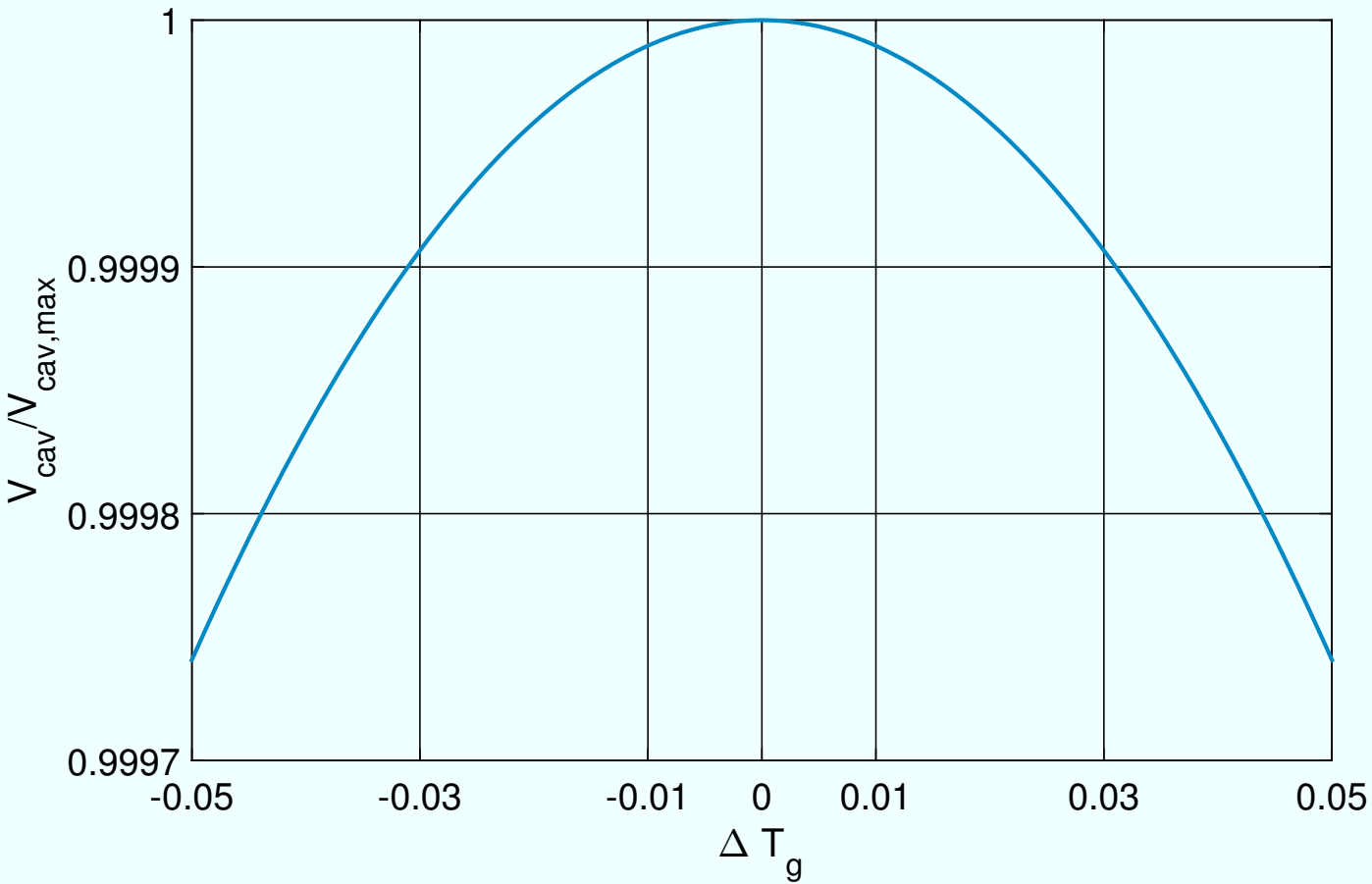

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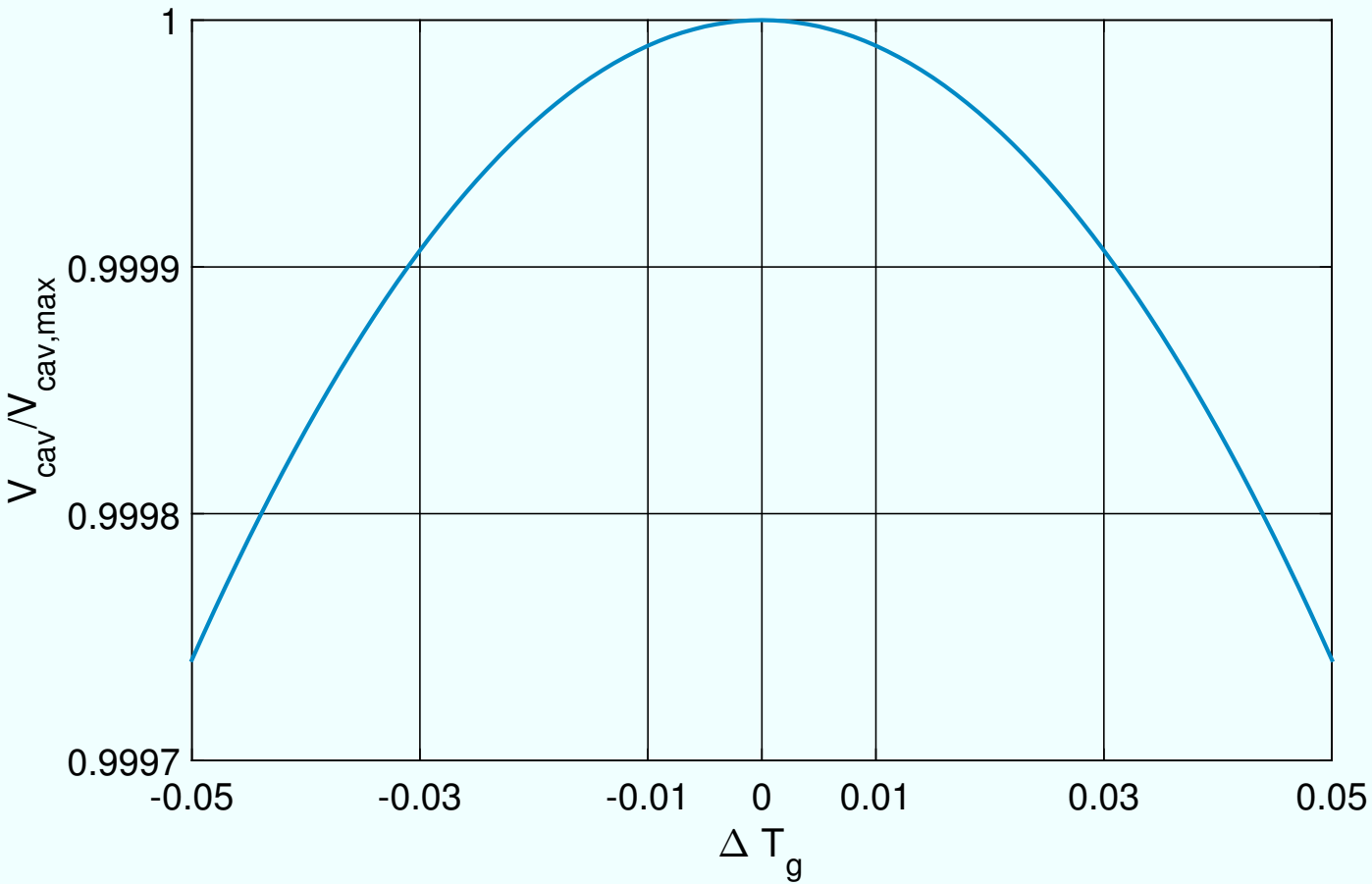
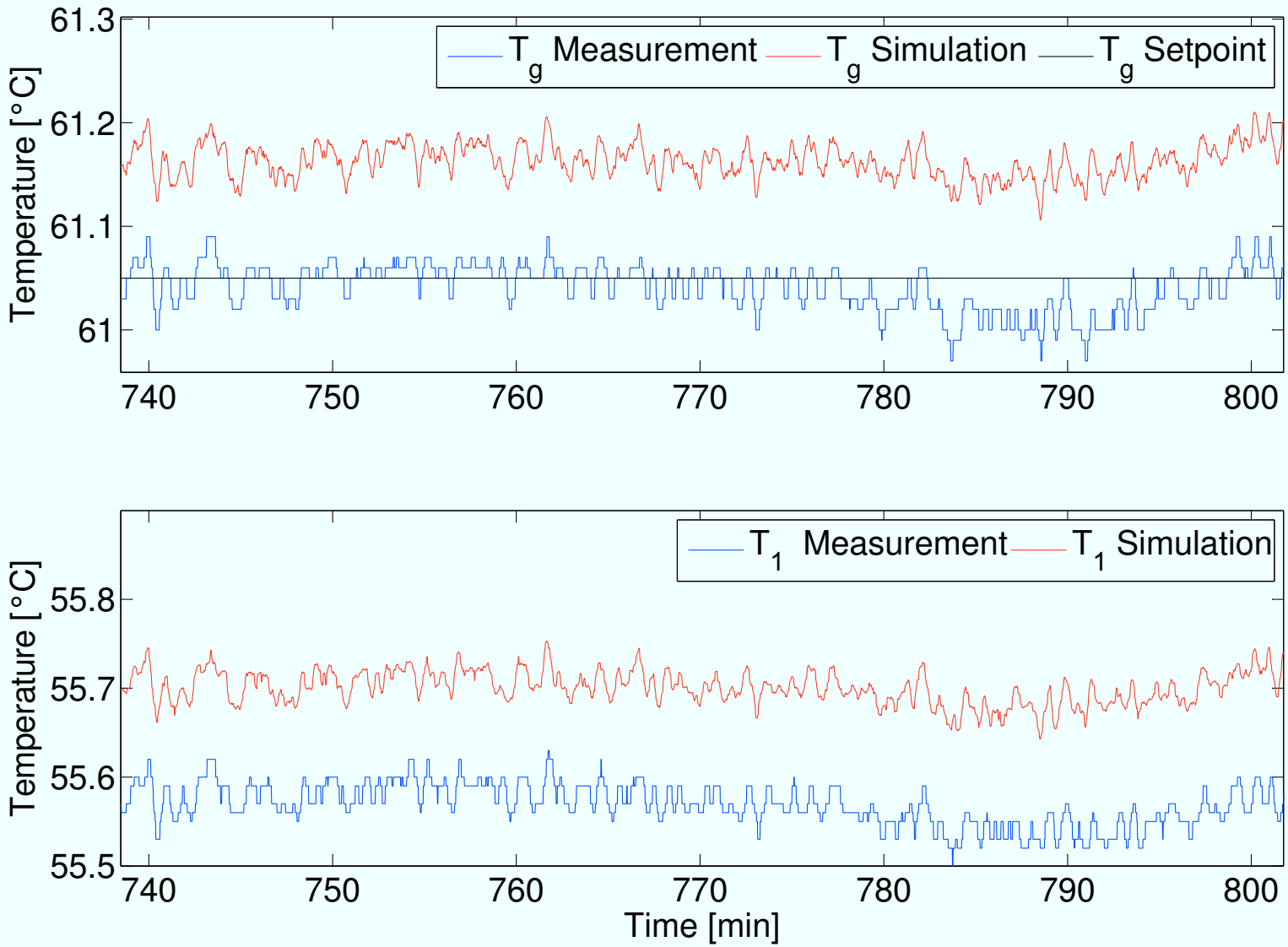
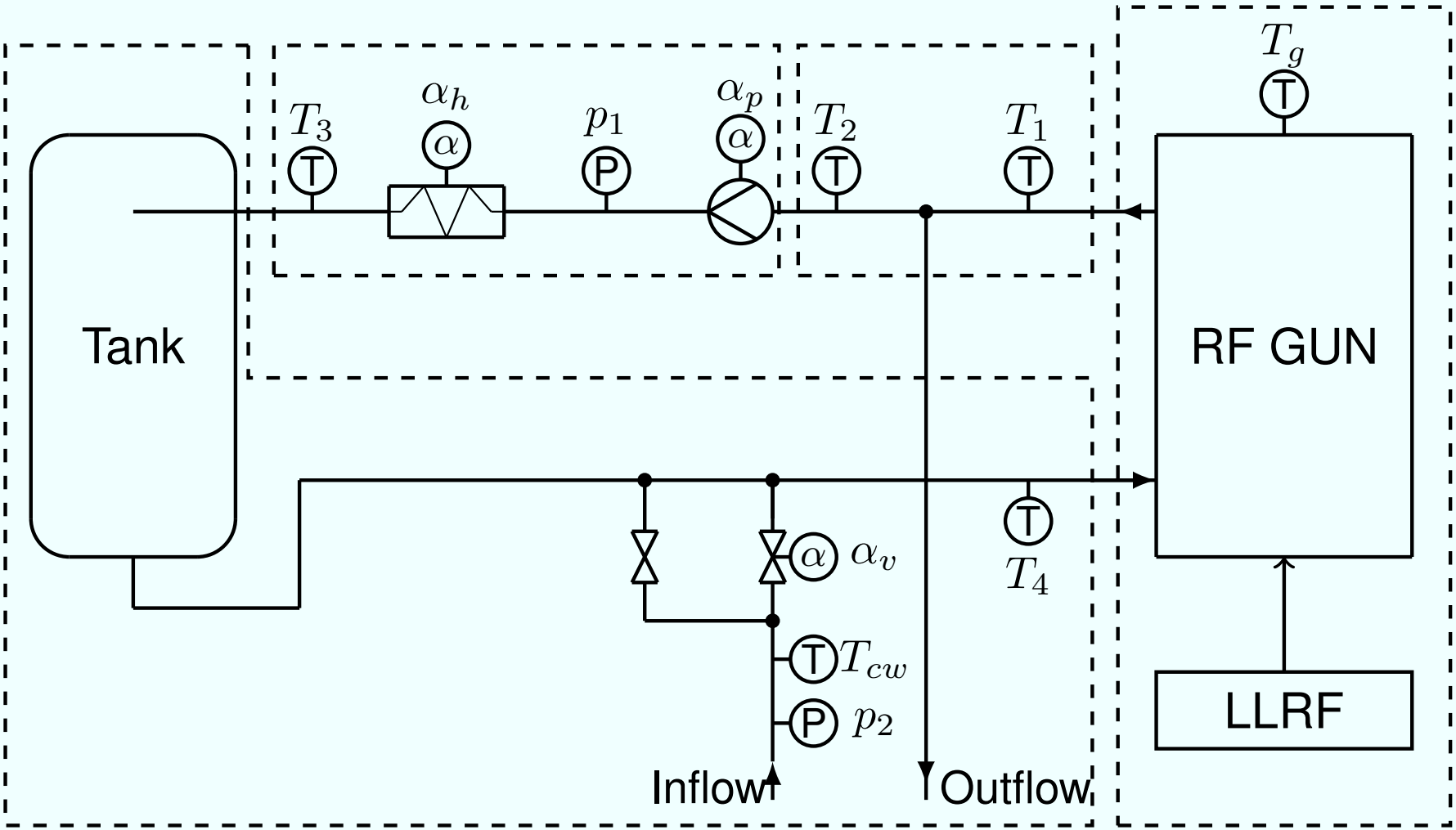


Validation: Gun body



Overall model



Overall model

- Nonlinear multiple input multiple output (MIMO) model
- State space representation

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}),$$
$$\mathbf{y} = \mathbf{g}(\mathbf{x}, \mathbf{u})$$

- 5 states $\mathbf{x} = \begin{bmatrix} T_g & T_1 & T_x & T_3 & \tilde{\alpha}_v \end{bmatrix}^T$
- 6 inputs $\mathbf{u} = \begin{bmatrix} T_{g,SP} & P_{for} & \alpha_h & \alpha_v & T_{cw} & \alpha_p \end{bmatrix}^T$
- 20 parameters
- $\rightarrow$ Implemented in MATLAB/Simulink

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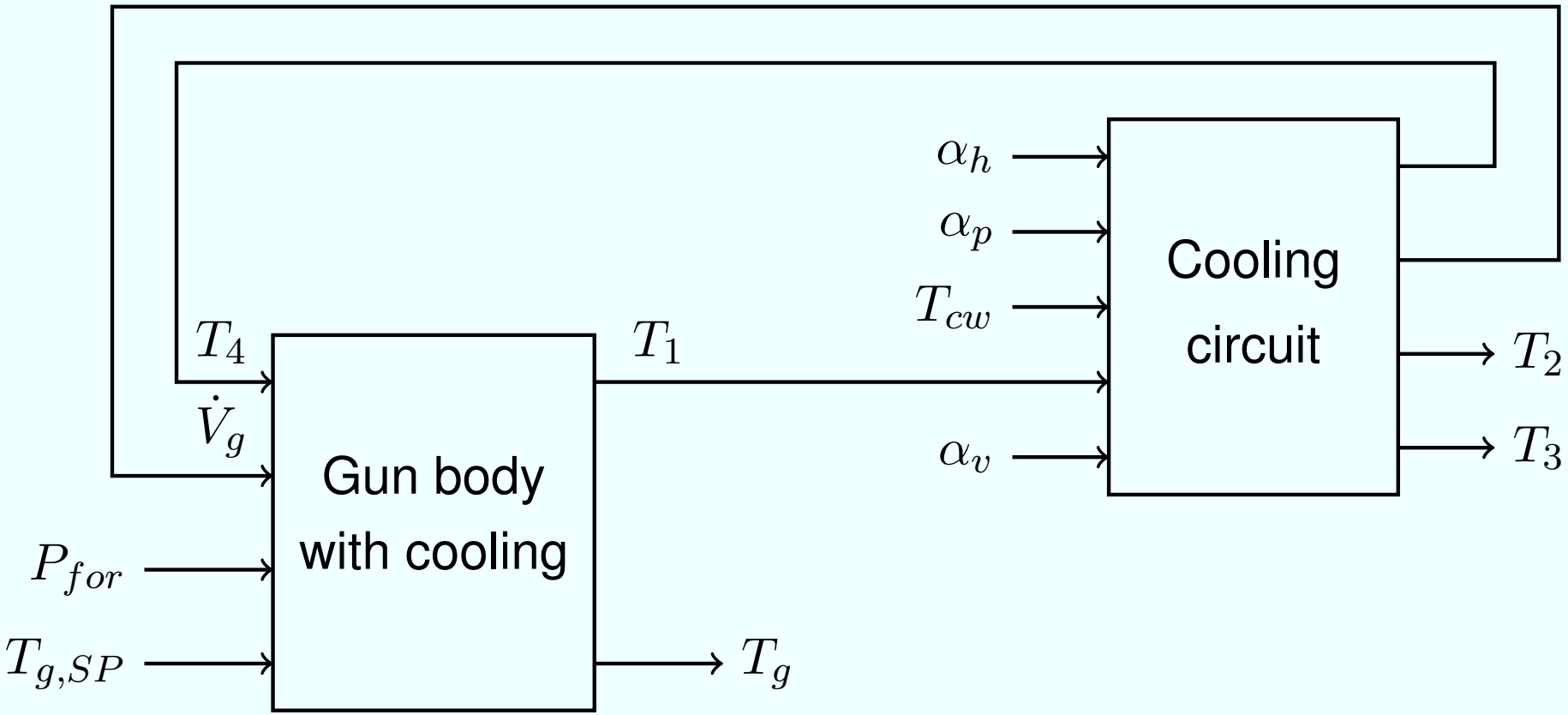

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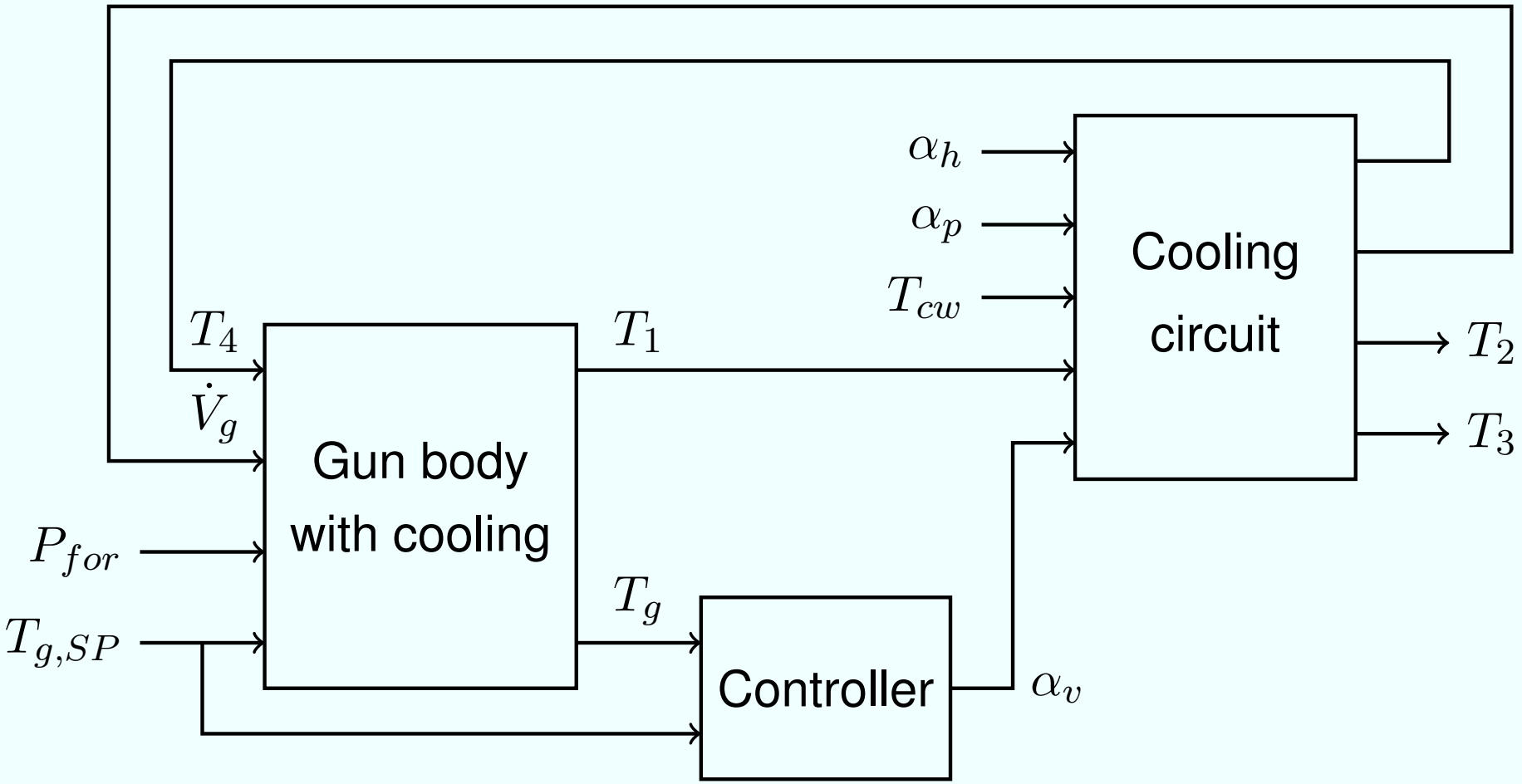

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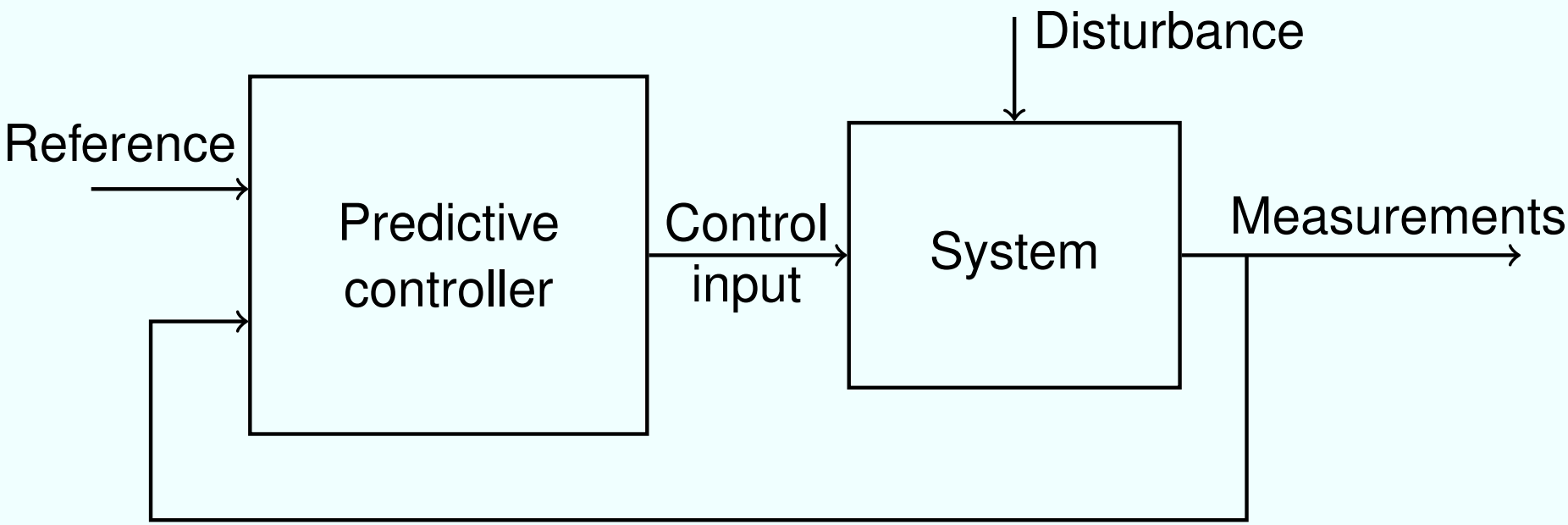
Control Problem

- Model predictive controller (MPC)
- Design and test in simulation



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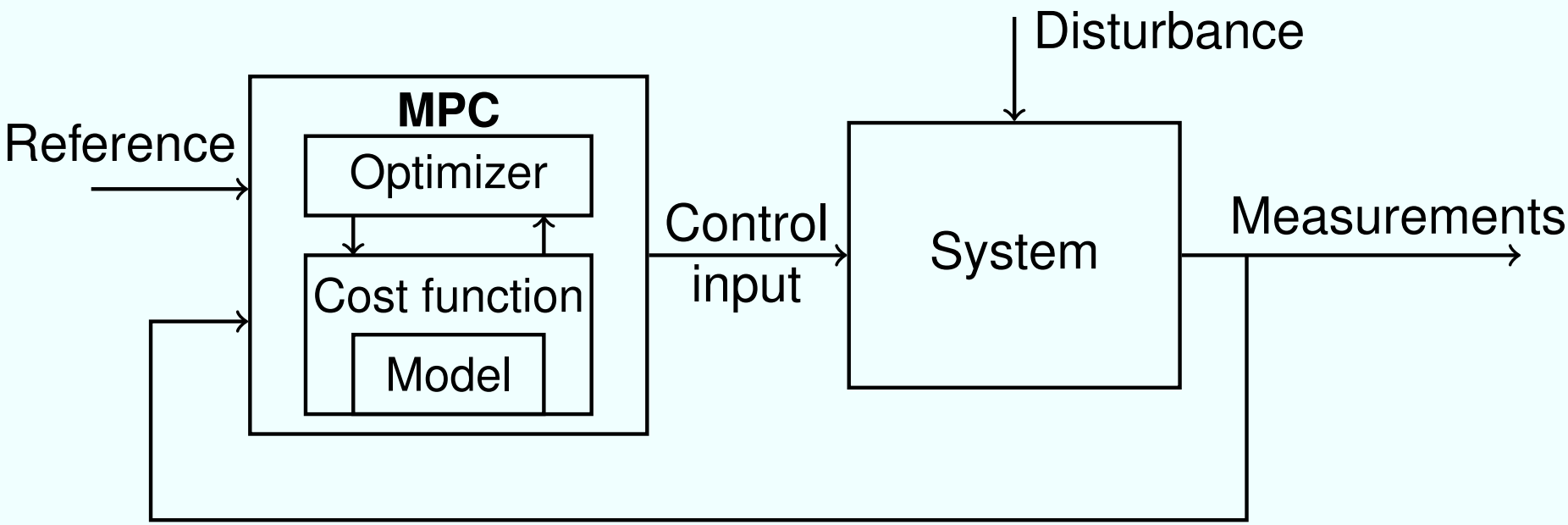

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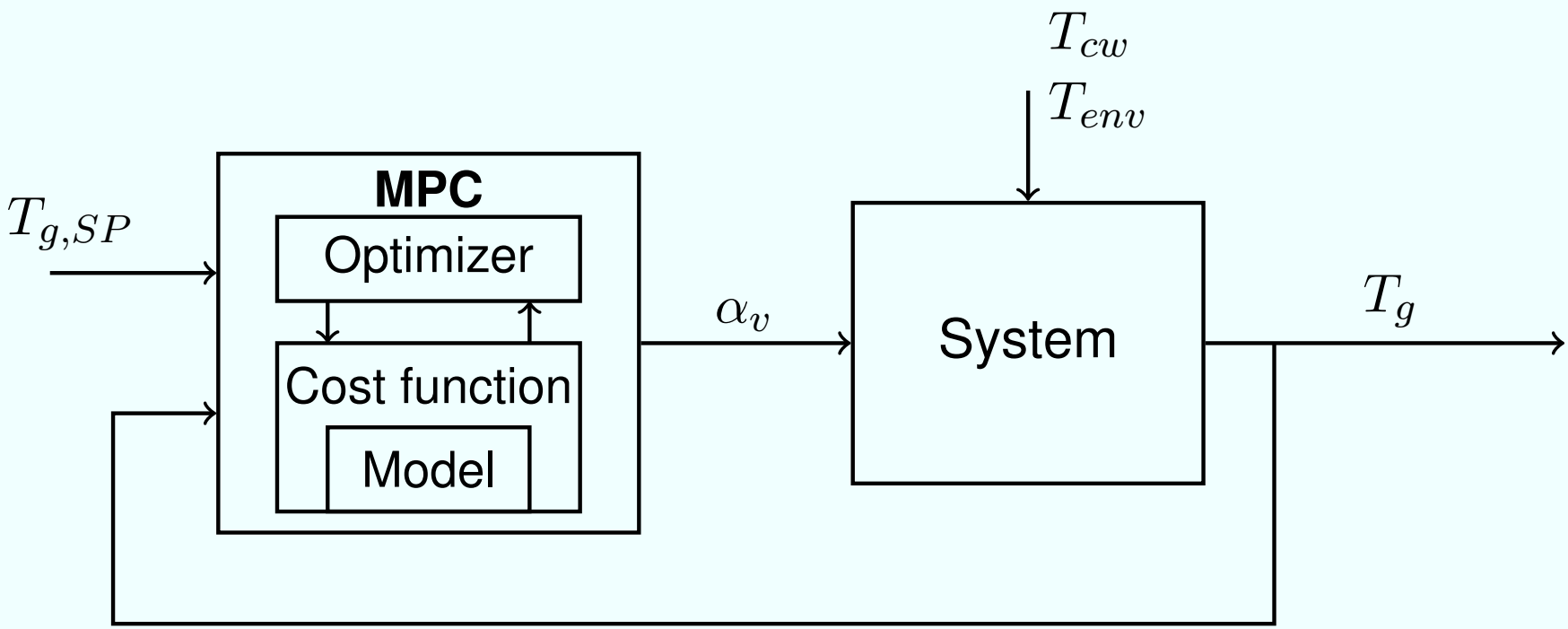
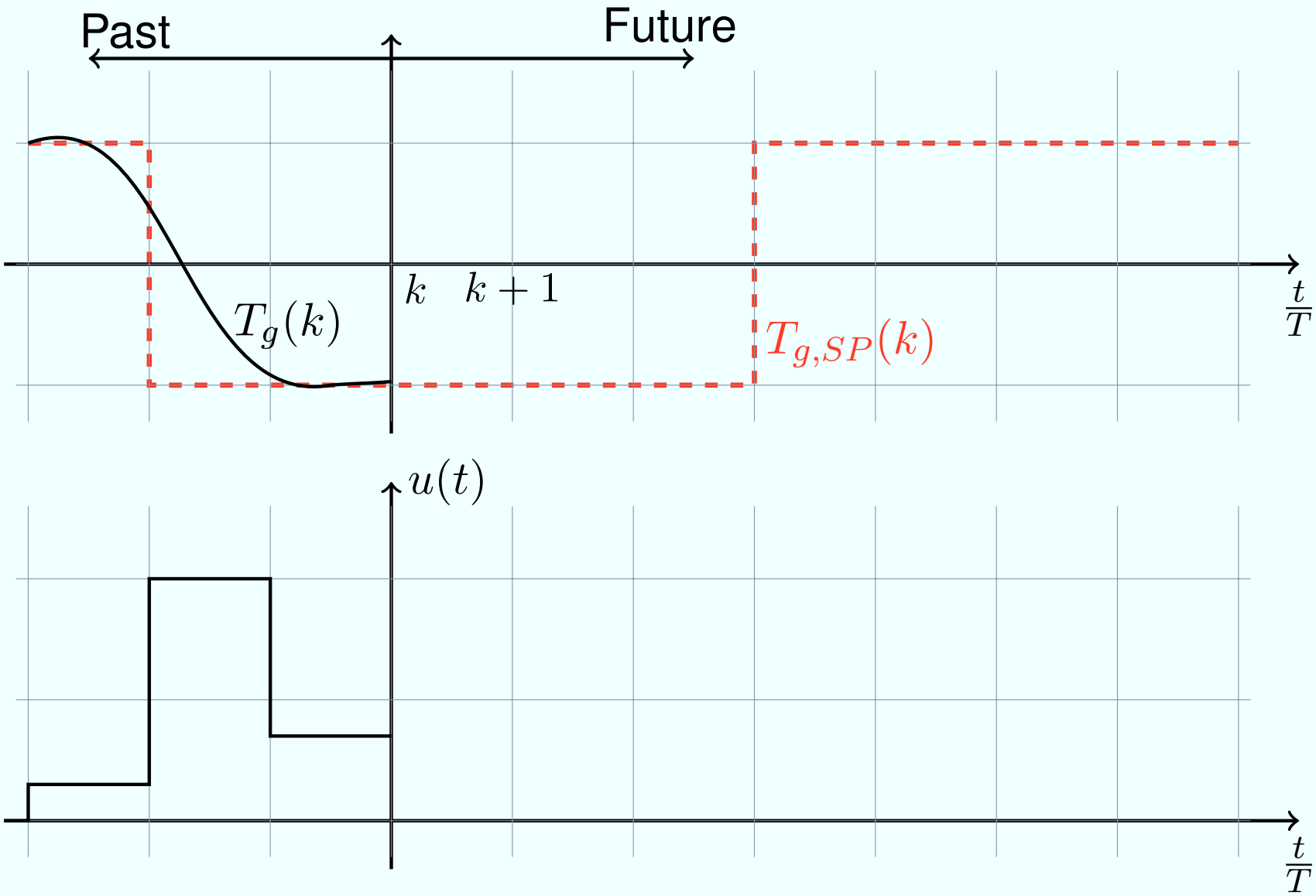


Predictive Control Theory



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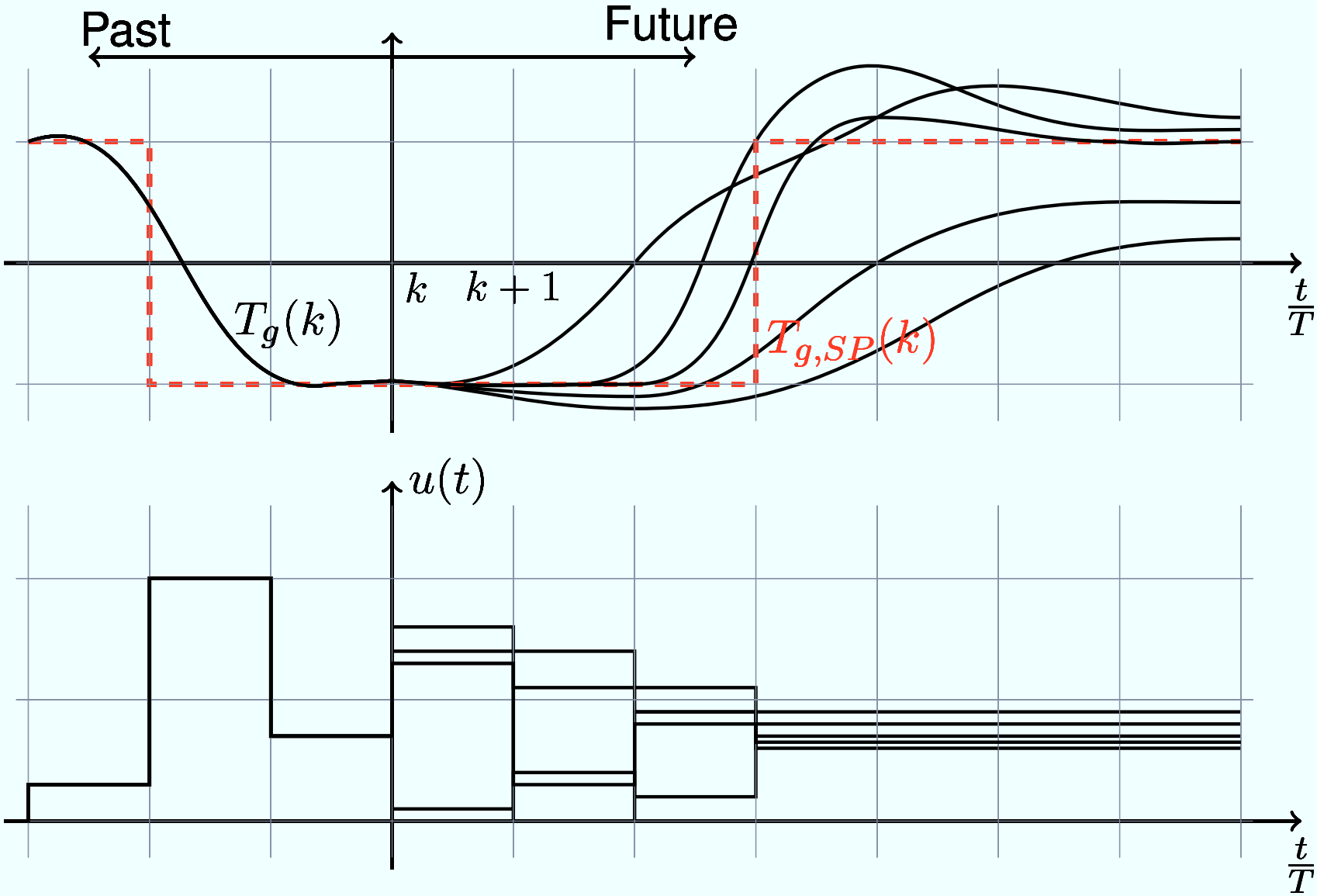

Linear approximation

- Use of linear model inside the controller
- Linearization around operating point $(\overline{\mathbf{x}}, \overline{\mathbf{u}})$
- Linear SISO model with $u = \alpha_v$ and $y = T_g$

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{B}u,$$
$$y = \mathbf{C}\mathbf{x} + \mathbf{D}u$$

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$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{B}u,$$
$$y = \mathbf{C}\mathbf{x} + \mathbf{D}u$$

Cost function

- Cost function

$$J(k) = \sum_{i=1}^{H_p} \|T_g(k+i) - T_{g,SP}(k+i)\|^2_{\mathbf{Q}(i)} + \sum_{i=1}^{H_u} \|\Delta\alpha_v(k+i)\|^2_{\mathbf{R}(i)}$$

- Minimization in every time instant

$$\min_{\alpha_v(k+i),\ i=1,\ldots,H_u} J(k)$$

$$\text{subject to} \quad 0 \leq \alpha_v(k+i) \leq 1$$

- Very efficient computation by standard QP solvers
- Moving horizon: First element of input sequence is used as input to the plant

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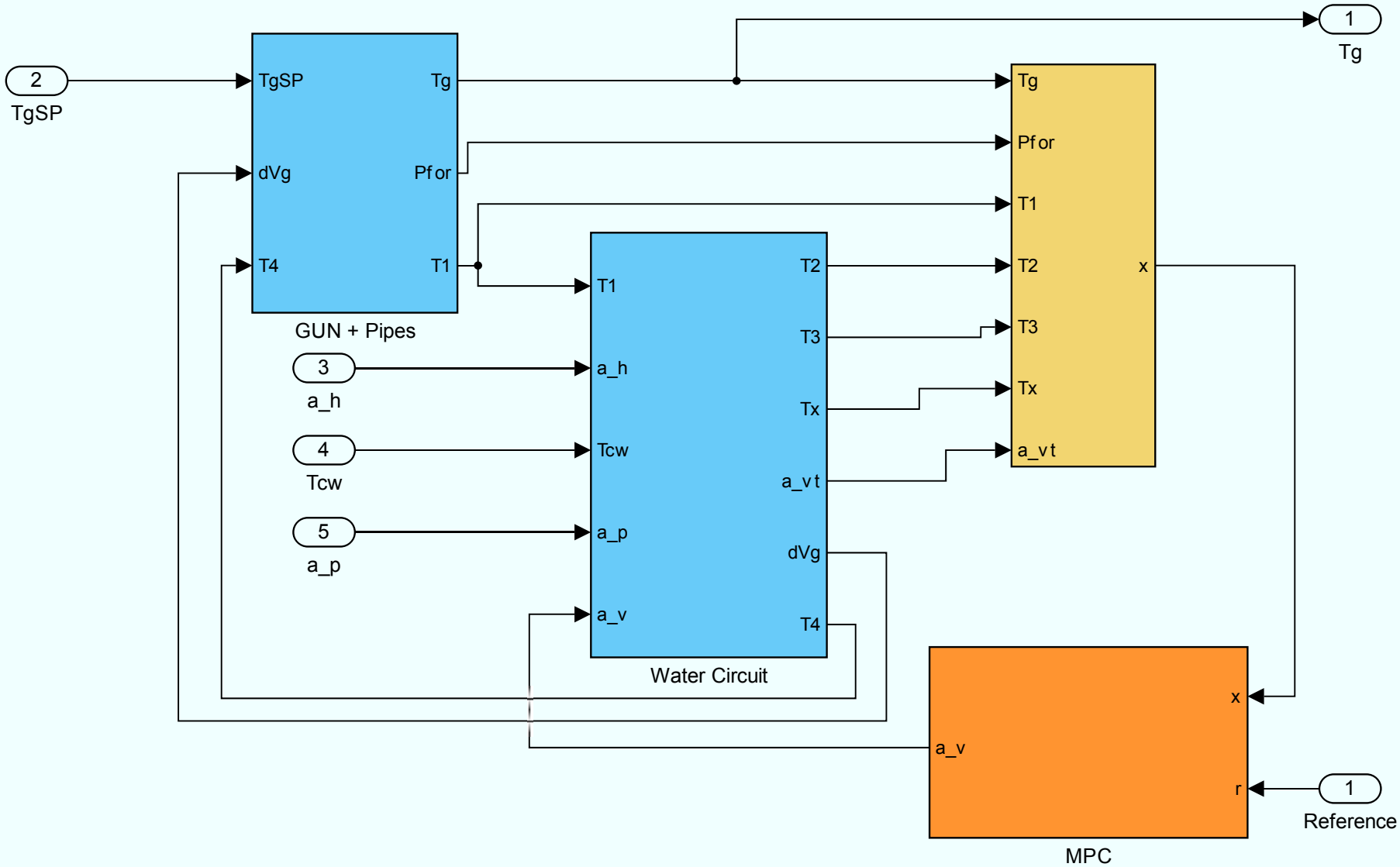
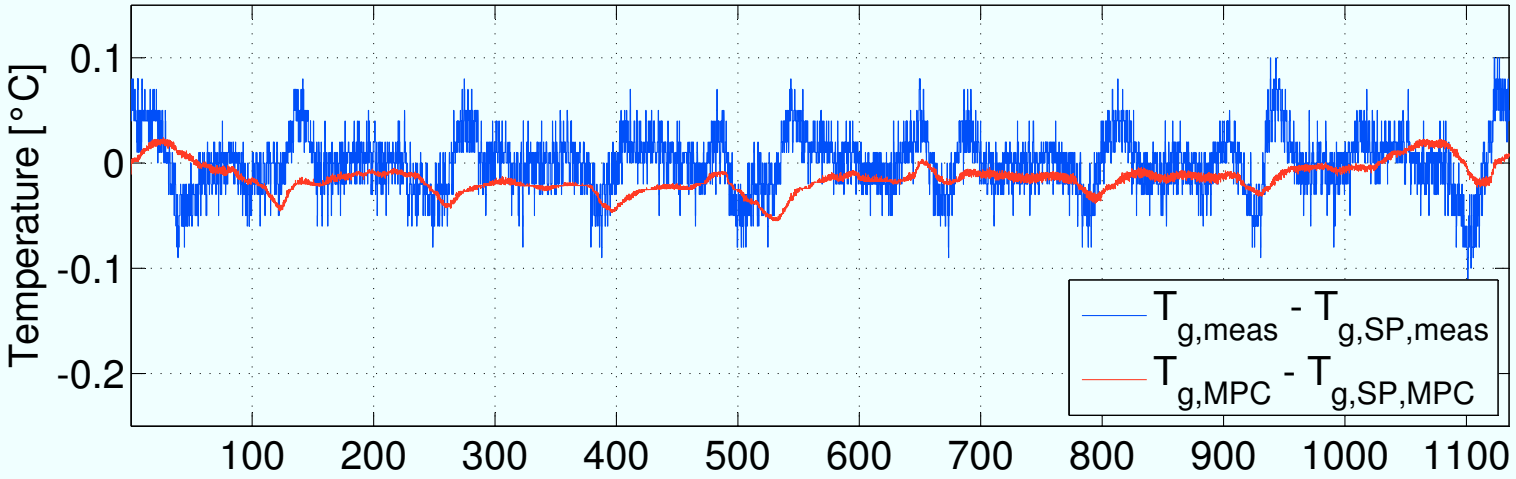
MATLAB/Simulink Implementation

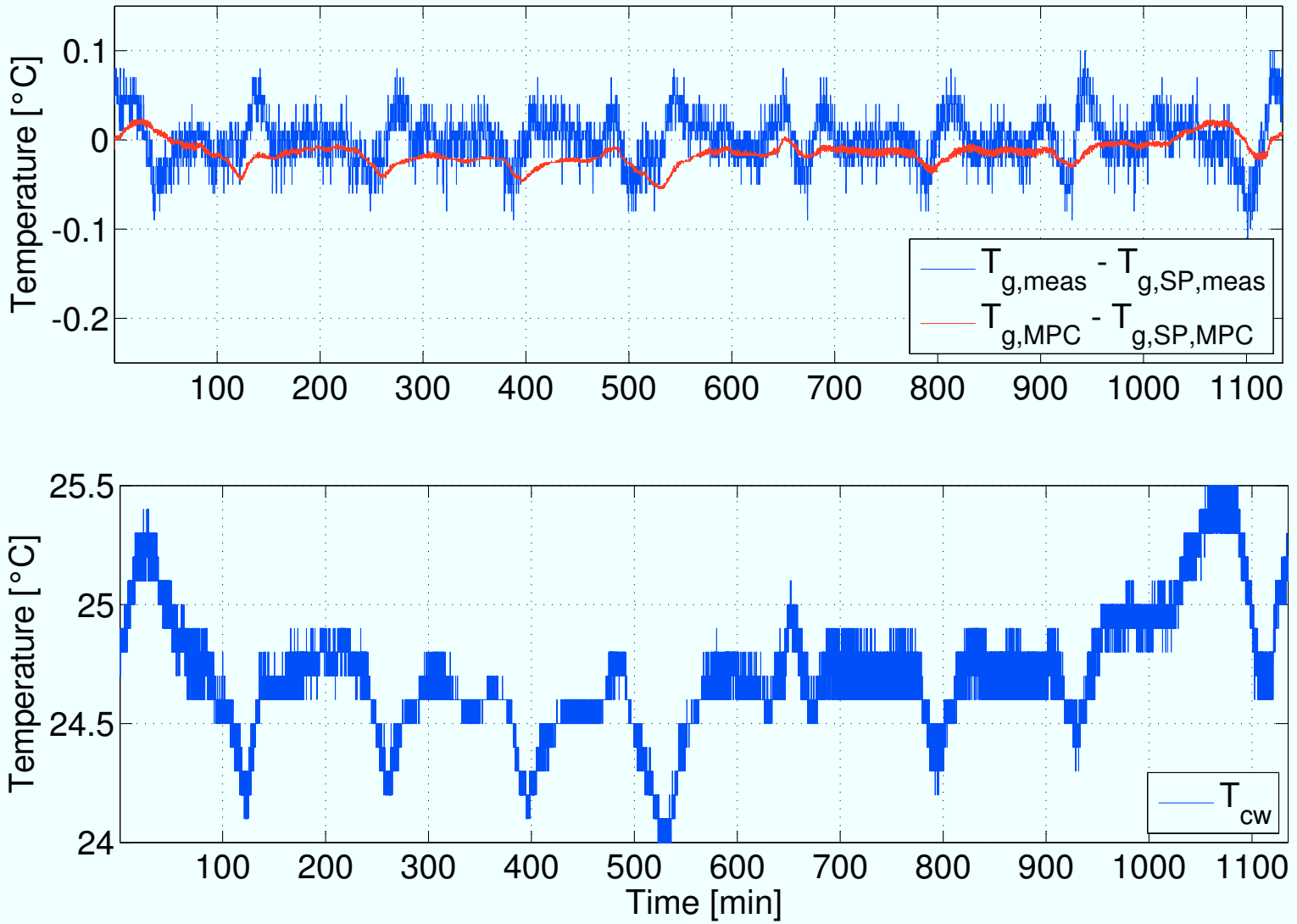


Closed Loop Simulation



- Simulation test: Improvements in stability possible
- Still improvements with same model achievable

Closed Loop Simulation



Content

Conclusion

- MIMO model of thermal behavior of RF GUN
- Considering cooling circuit and LLRF influence
- Adjustable to European XFEL
- Only few measurement information
- Promising results with model predictive controller design
- Testable at FLASH
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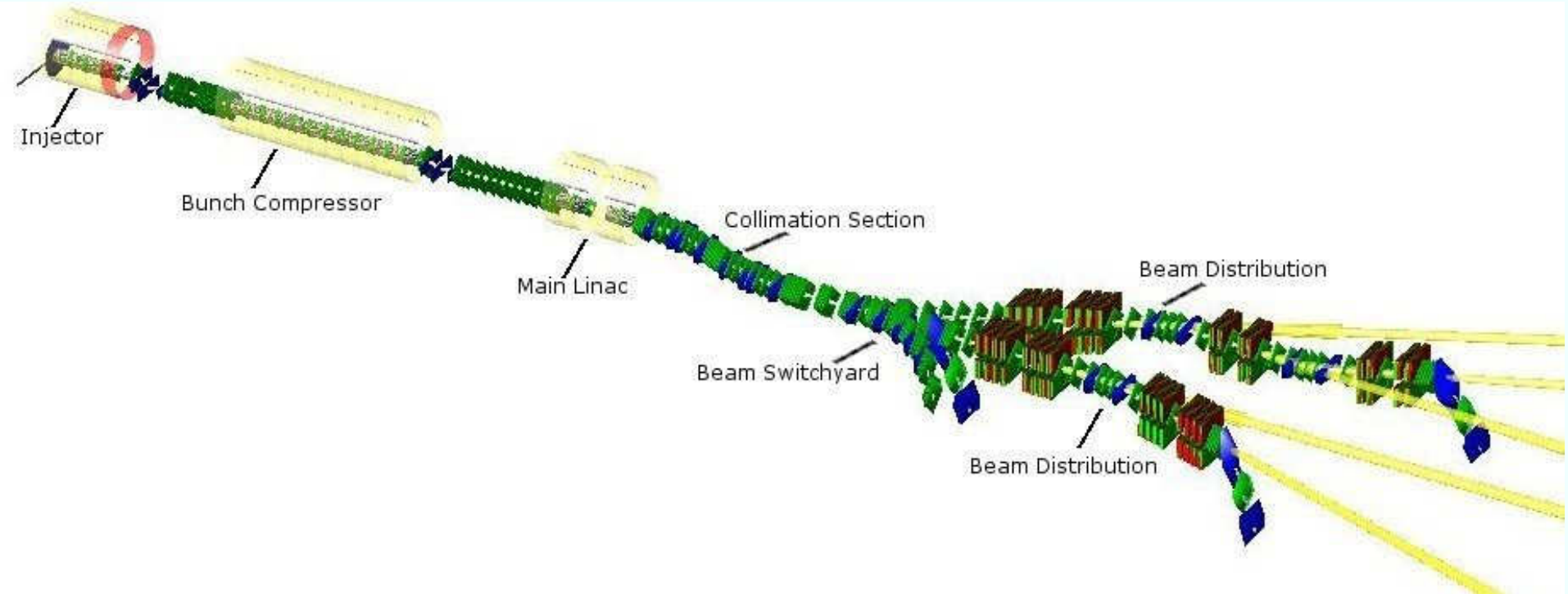
Thank you for your attention!
Je vous remercie de votre attention!
Vielen Dank für Ihre Aufmerksamkeit!
Muchas gracias por su atención!
Grazie per avermi ascoltato.
Muito obrigado pela vossa atenção.

Beam Line



[Source: DESY]

Dissipated power

- Temperature dependent cavity voltage

$$V_{cav} = \hat{V}_{cav} \sin(\omega t + \psi),$$

- Detuning angle ψ influences amplitude

$$\hat{V}_{cav} \approx \frac{\sqrt{R_L P_{for}}}{\sqrt{1 + \tan(\psi)^2}}$$

- Detuning caused by gun temperature deviations

$$\tan(\psi) = \alpha \Delta T_g = \alpha (T_g - T_{g,SP})$$

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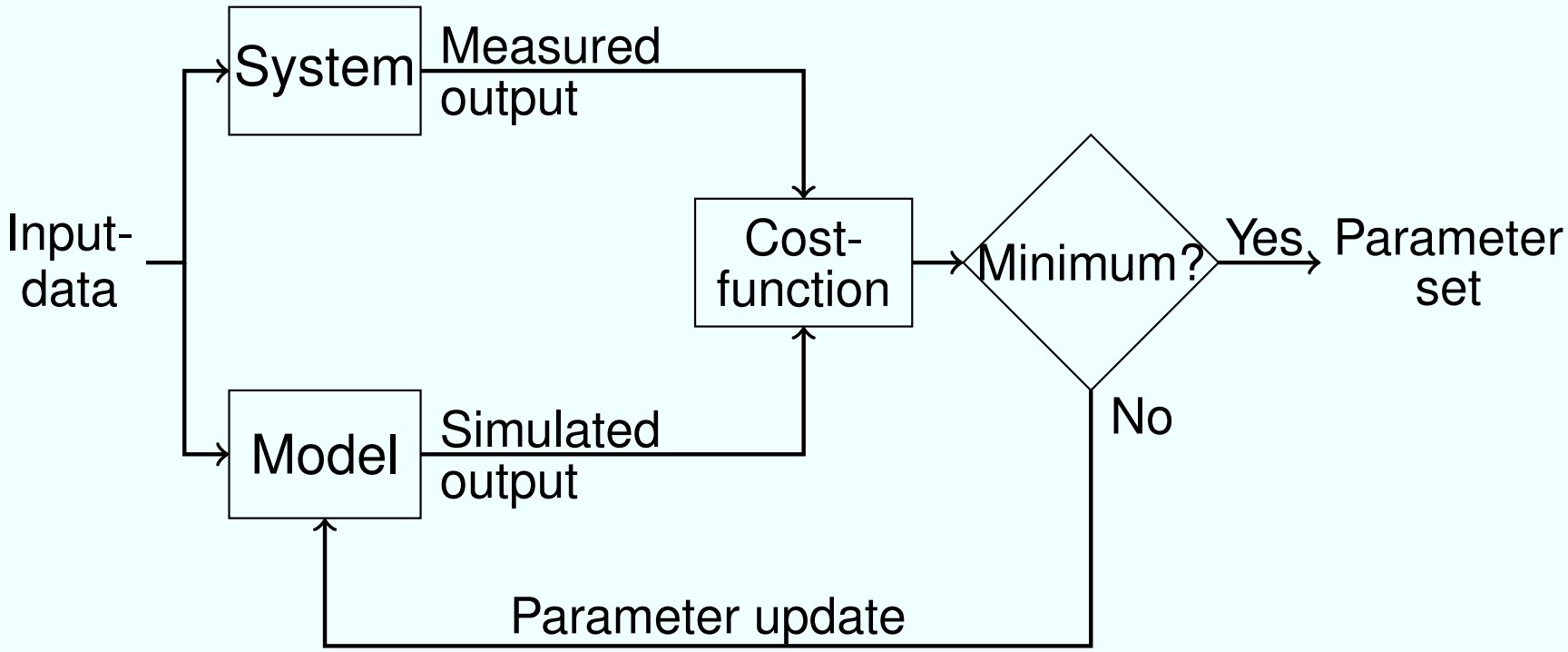
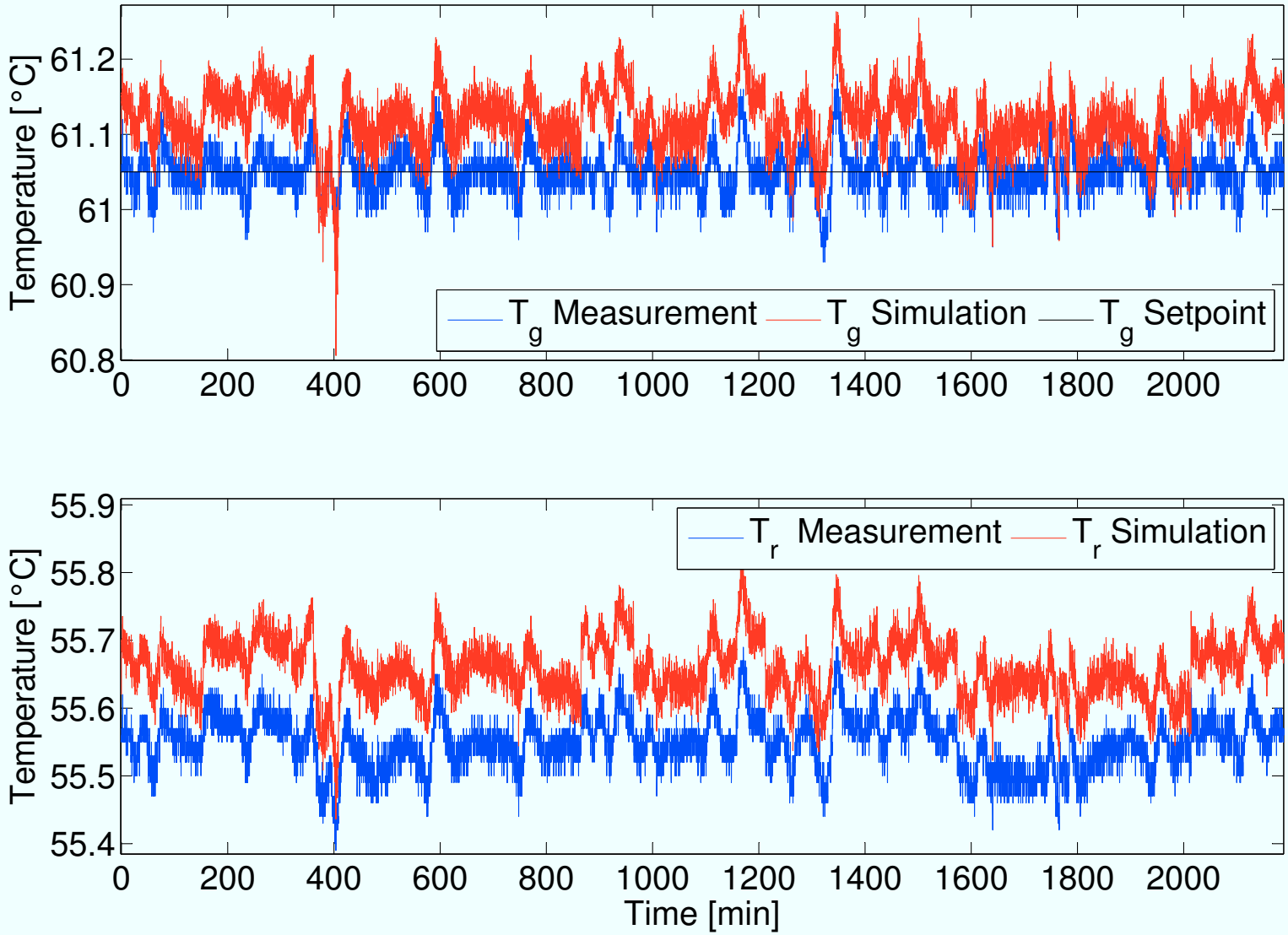
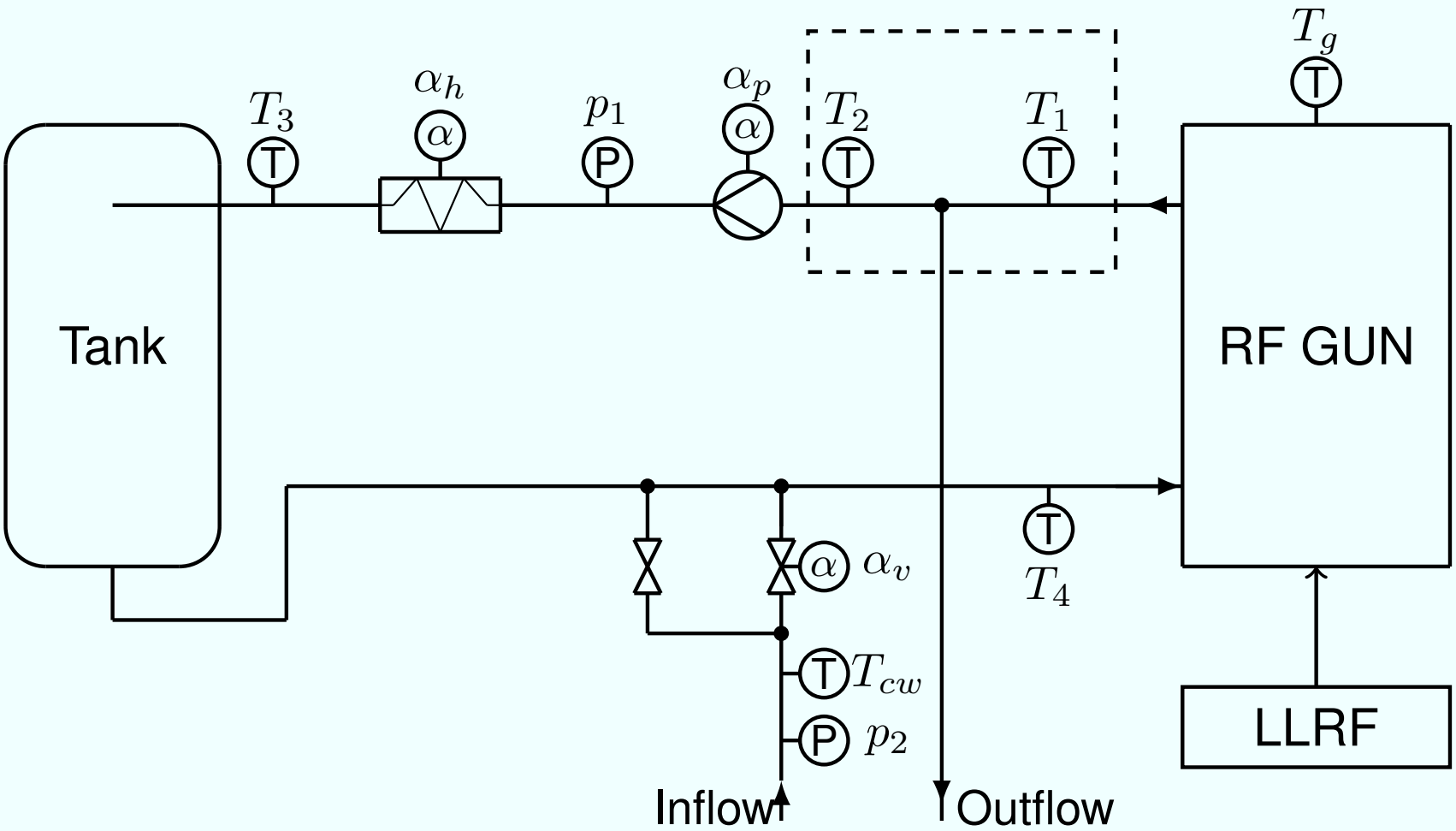
Parameter Estimation



Estimation: Gun body



Cooling circuit



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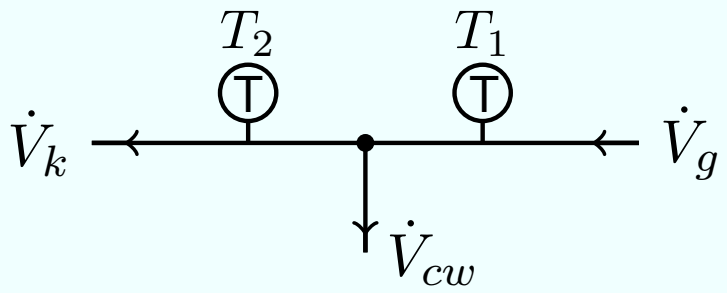


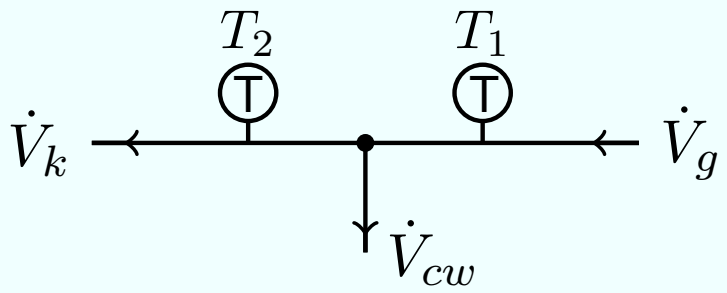
- Water outlet from gun with flow $\dot{V}_g$ and temperature T_1
- Flow $\dot{V}_{cw}$ back to cold water reservoir

$$\dot{V}_k = \dot{V}_g - \dot{V}_{cw}$$

- No temperature loss

$$T_2(t) = T_1(t - T_{d,12})$$

Cooling Circuit



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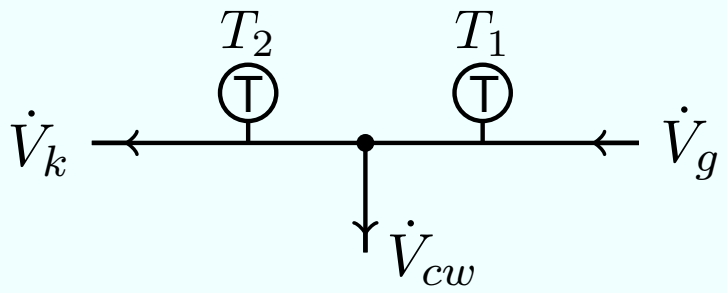

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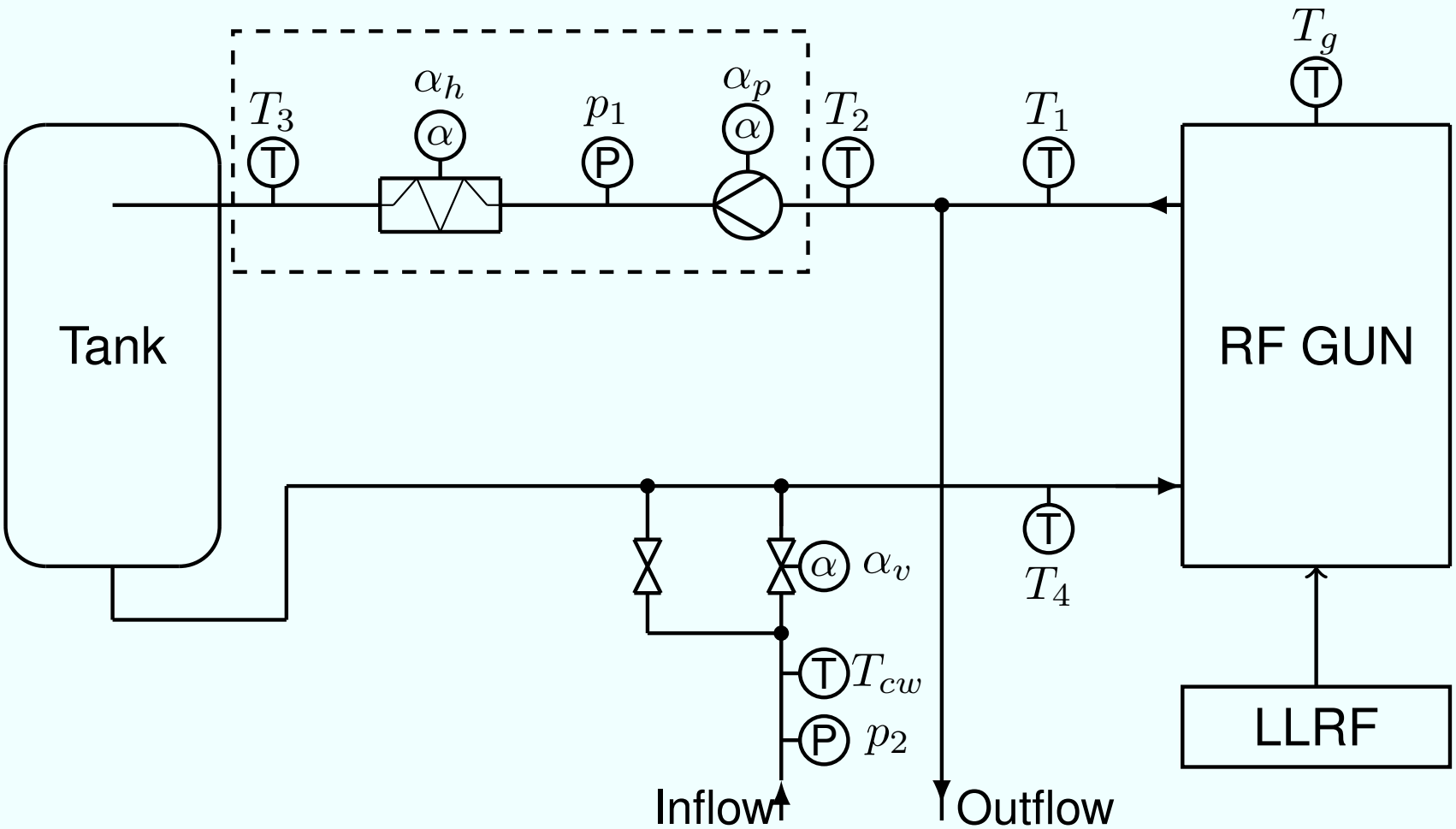

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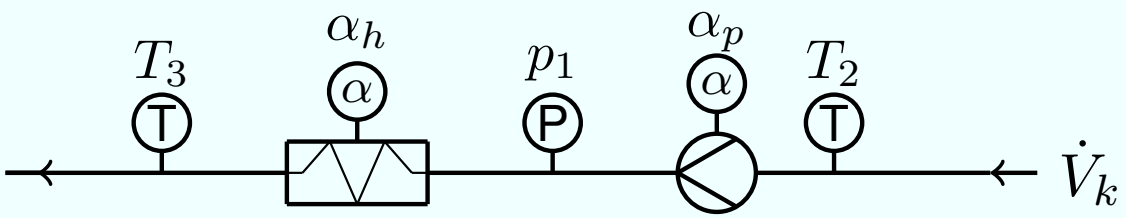


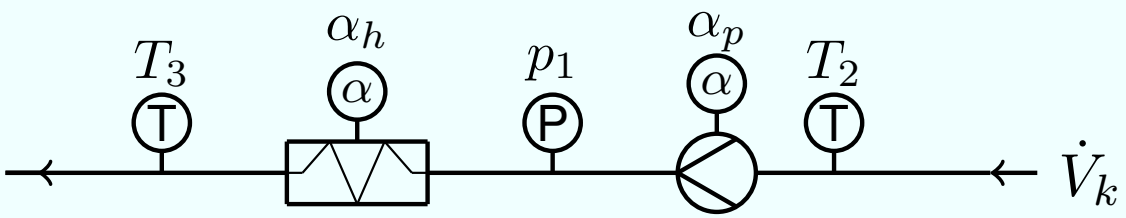
- Pump sets up flow $\dot{V}_k$ controlled by $\alpha_p \in [0, 1]$

$$\dot{V}_k = \alpha_p \dot{V}_{k,max}$$

- No flow measurements available
- Heater with maximal power $\dot{Q}_{h,max}$ and input $\alpha_v \in [0, 1]$

$$c_w \rho_w V_h \dot{T}_3(t) = c_w \rho_w \dot{V}_k \left((T_3(t) - T_2(t - T_{d,32})) + \alpha_h \dot{Q}_{h,max}(t) \right.$$

Cooling circuit



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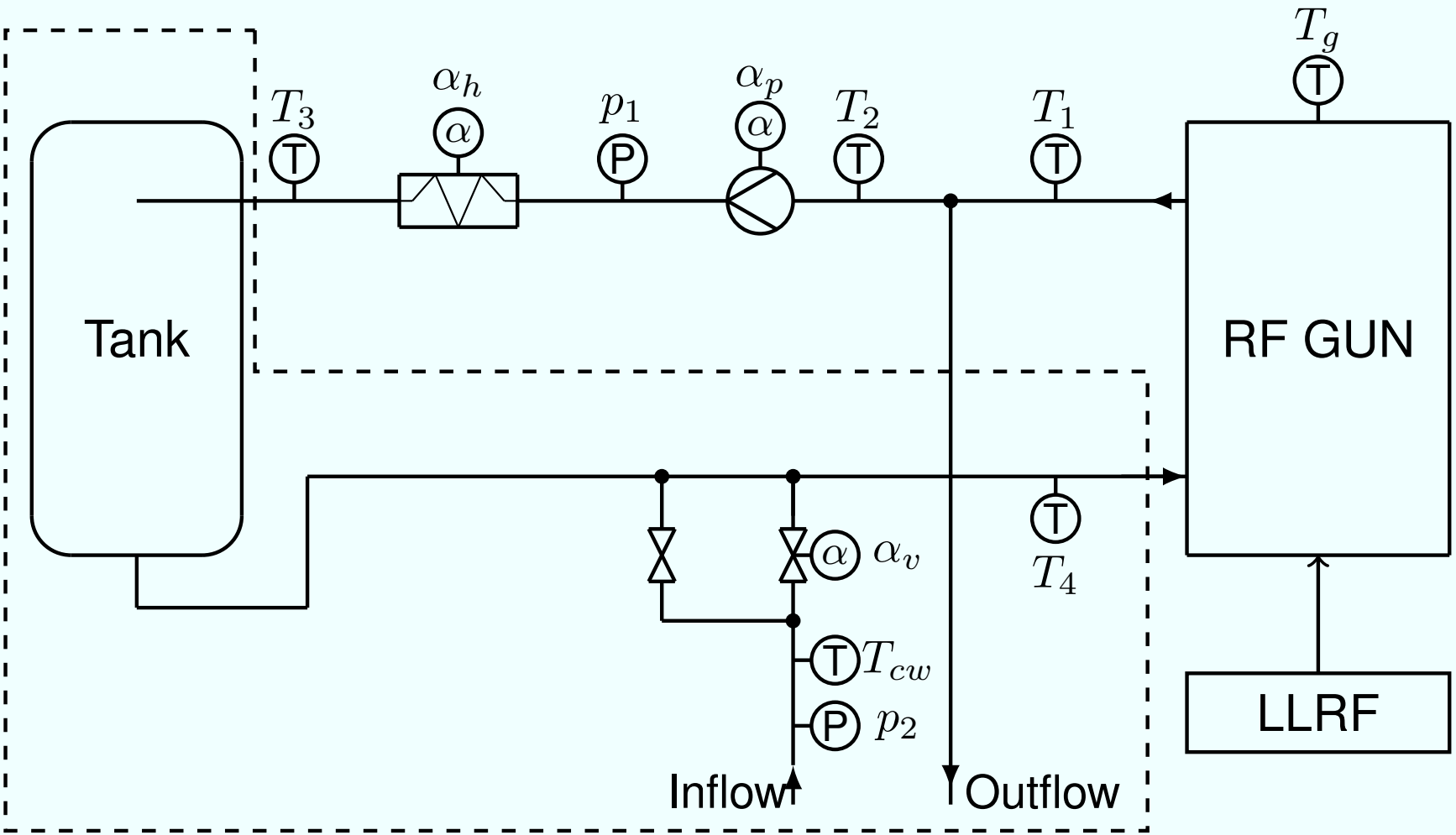
Cooling circuit

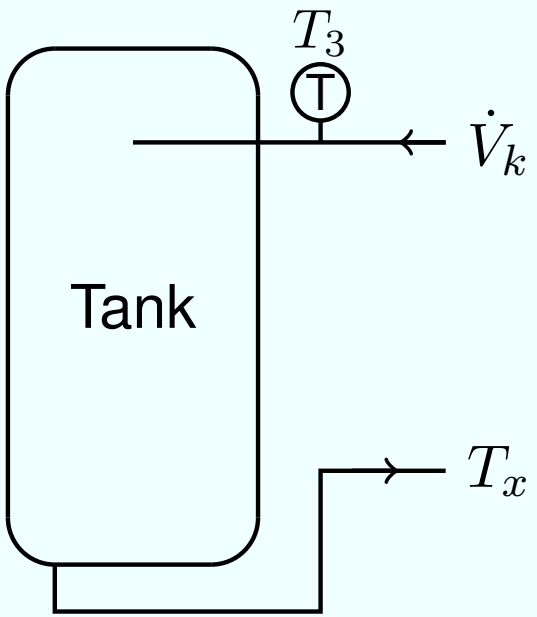


Cooling Circuit

- Tank to damp temperature fluctuations
- Output temperature T_x unknown

$$c_w \rho_w V_t \dot{T}_x = c_w \rho_w \dot{V}_k T_3 - c_w \rho_w \dot{V}_k T_x$$

$$\Leftrightarrow \dot{T}_x = \frac{\dot{V}_k}{V_t} (T_3 - T_x)$$



Cooling Circuit

- Estimation of $\dot{V}_{cw}$ by valve position

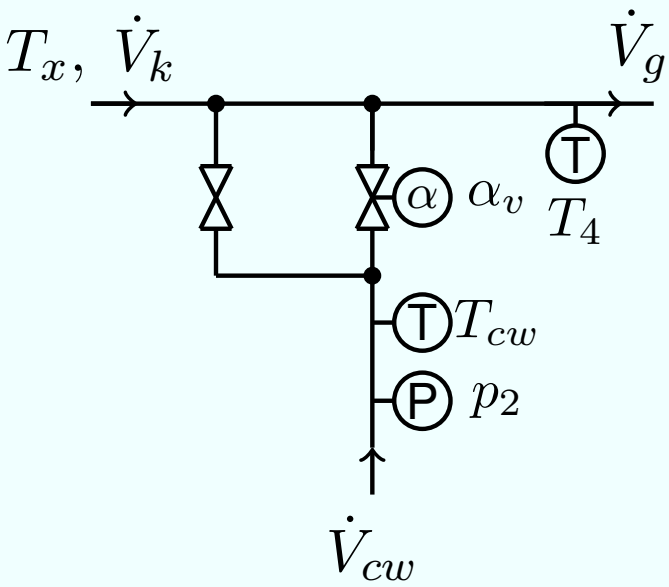
$$\dot{V}_{cw} = \tilde{\alpha}_v \dot{V}_{cw,max}$$

- Valve dynamics

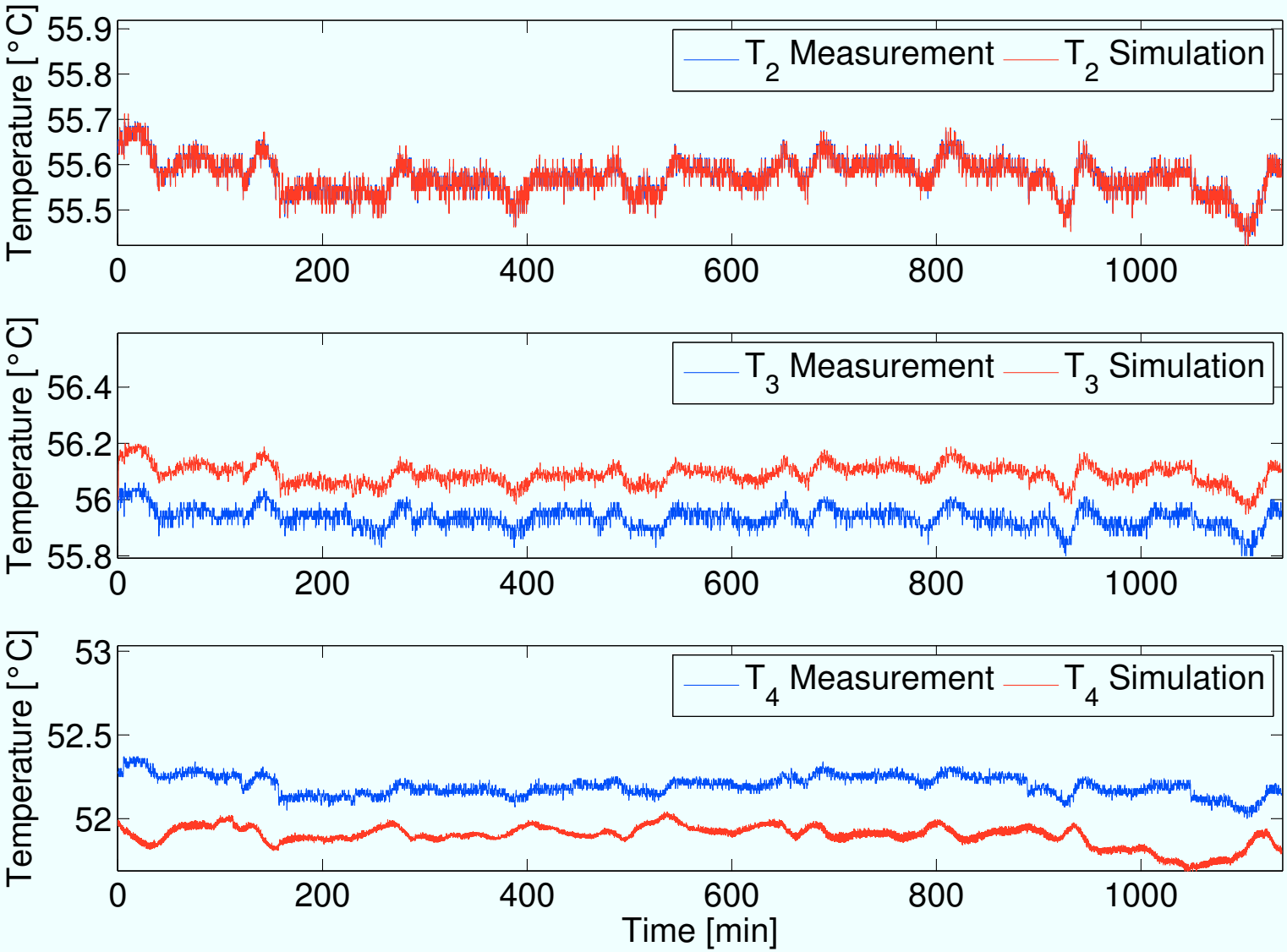
$$\tilde{\alpha}_v(s) = \frac{1}{T_v s + 1} \alpha_v(s).$$

- Gun supplied by mixed flow

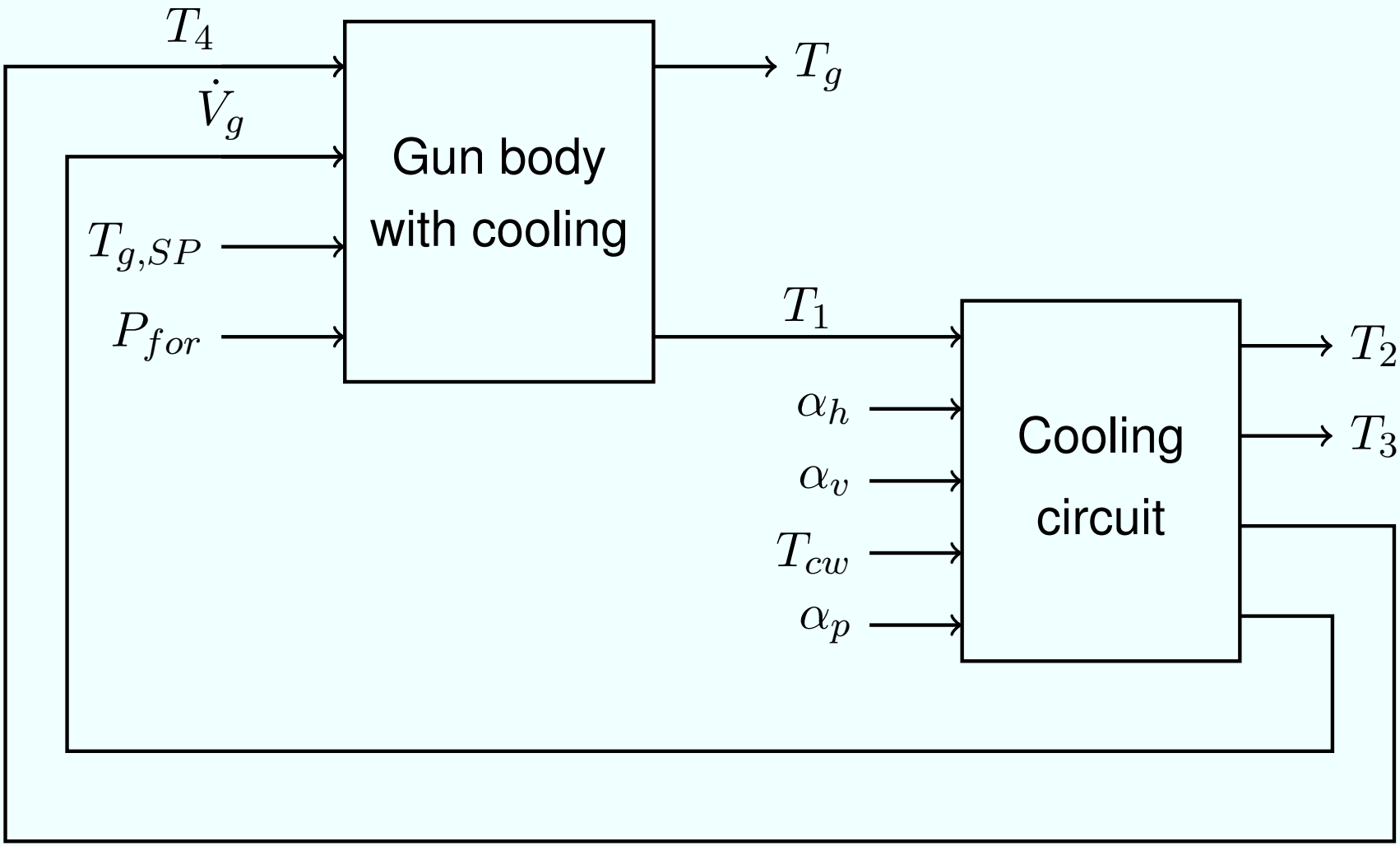
$$\dot{V}_g = \dot{V}_k + \dot{V}_{cw},$$
$$T_4 = \frac{\dot{V}_k T_x + \dot{V}_{cw} T_{cw}}{\dot{V}_k + \dot{V}_{cw}}$$



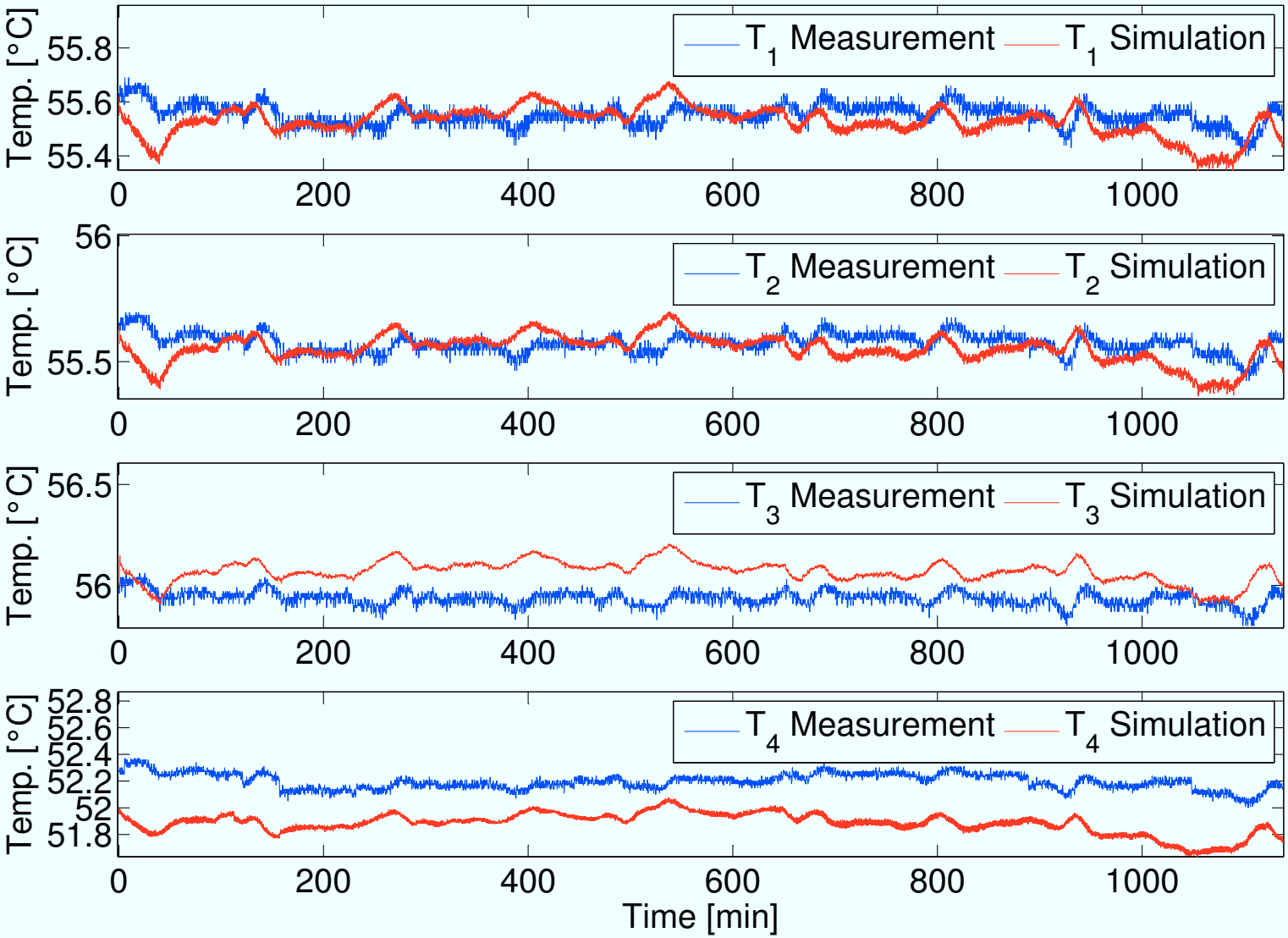
Validation: Cooling Circuit



Overall model



Estimation: Overall model



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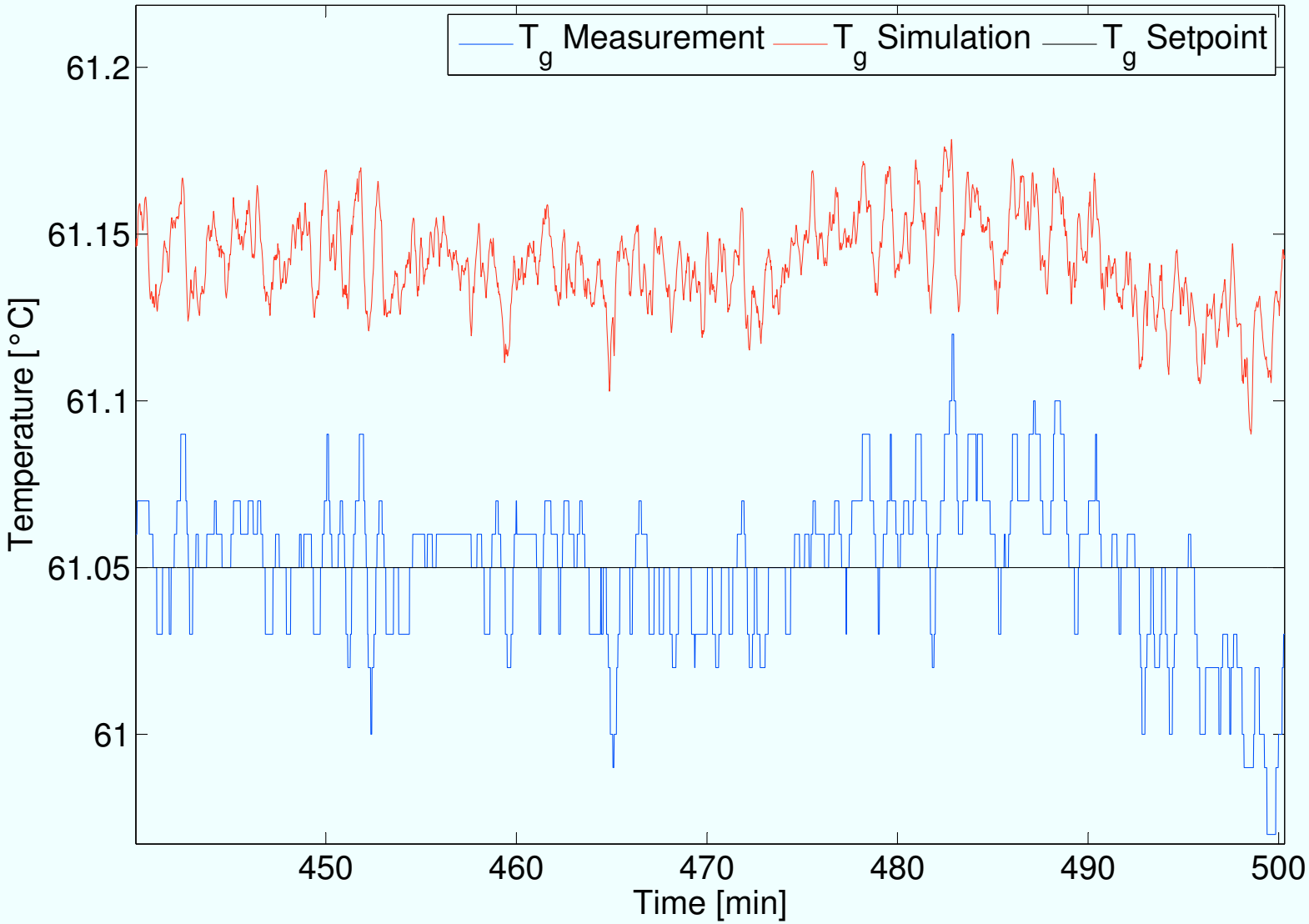
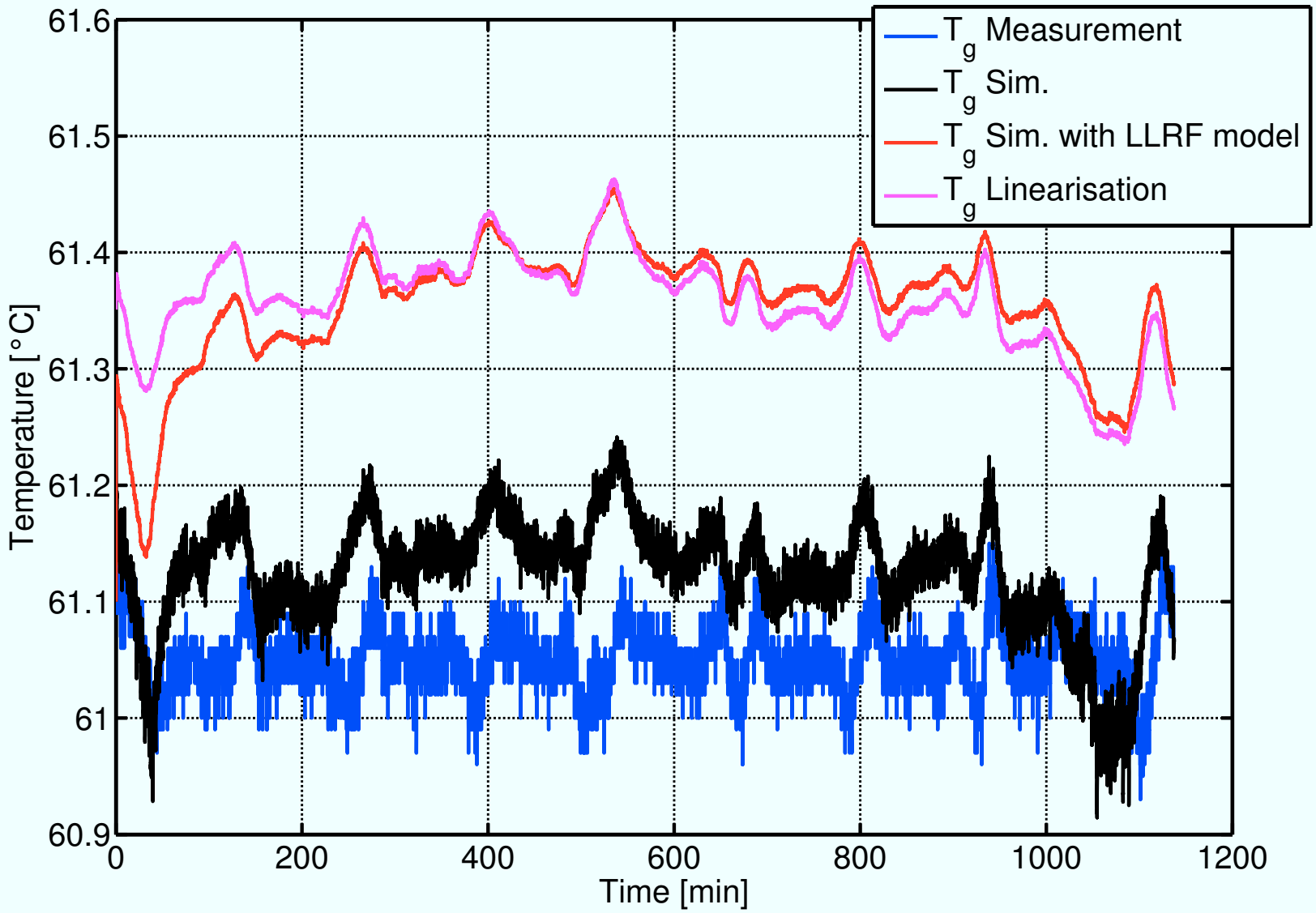


Linear approximation



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