Feedback Optimization on the EuXFEL Electron Dump Beamline

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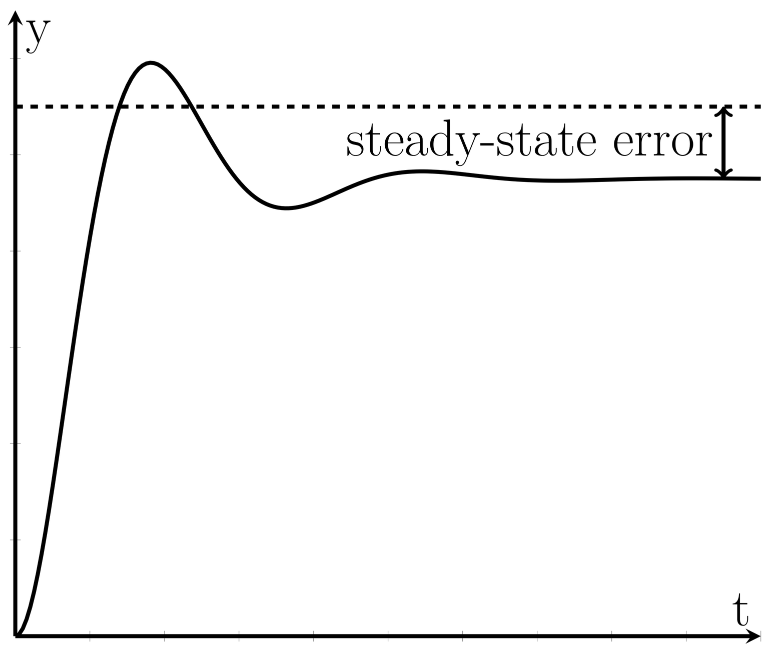
Steady-State Control of Dynamic Systems

- Nonlinear dynamic system

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

- Steady-state map

$$0 \overset{!}{=} f(\bar{x}, \bar{u})$$
$$\bar{x} = \hat{h}(\bar{u})$$
$$h(u) := g(\hat{h}(u))$$



Optimization Problem

- Cost function $\Phi(u, y)$
- Constraint sets $\mathcal{U}$, $\mathcal{Y}$

$$\begin{aligned} \min_{u,y} \quad & \Phi(u, y) \\ \text{subject to} \quad & y = h(u) \\ & u \in \mathcal{U} \\ & y \in \mathcal{Y} \end{aligned}$$

- Find optimal steady-state pair u, y

Obtaining Gradient Information

1) Rely on model knowledge
2) Approximation by sampling & heuristics
3) Recursive estimation

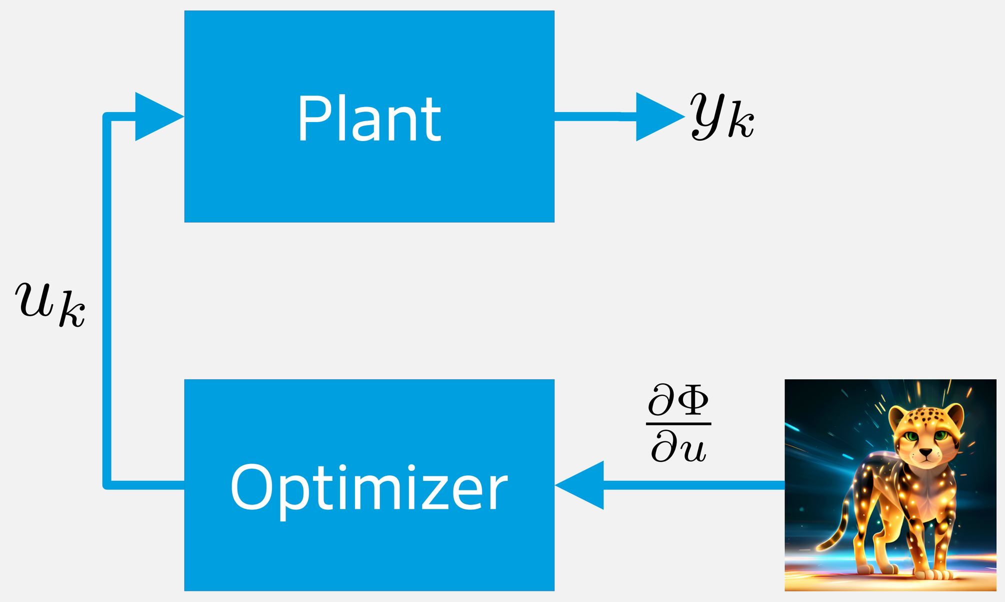
Chosen here: Recursive least-squares [Picallo et al.]

- Idea: First-order Taylor expansion

$$y_{k+1} = h(u_{k+1}) \approx y_k + \frac{\partial h}{\partial u}(u_k)[u_{k+1} - u_k]$$

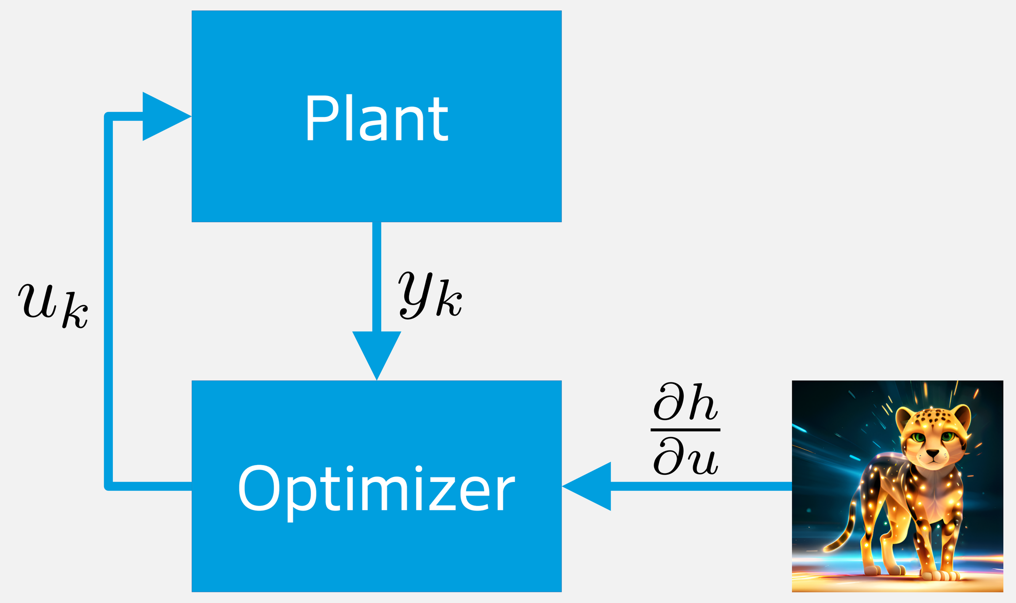
- Reformulate as linear dynamic system
- Estimation using Kalman filter

„Feedforward“ Optimization



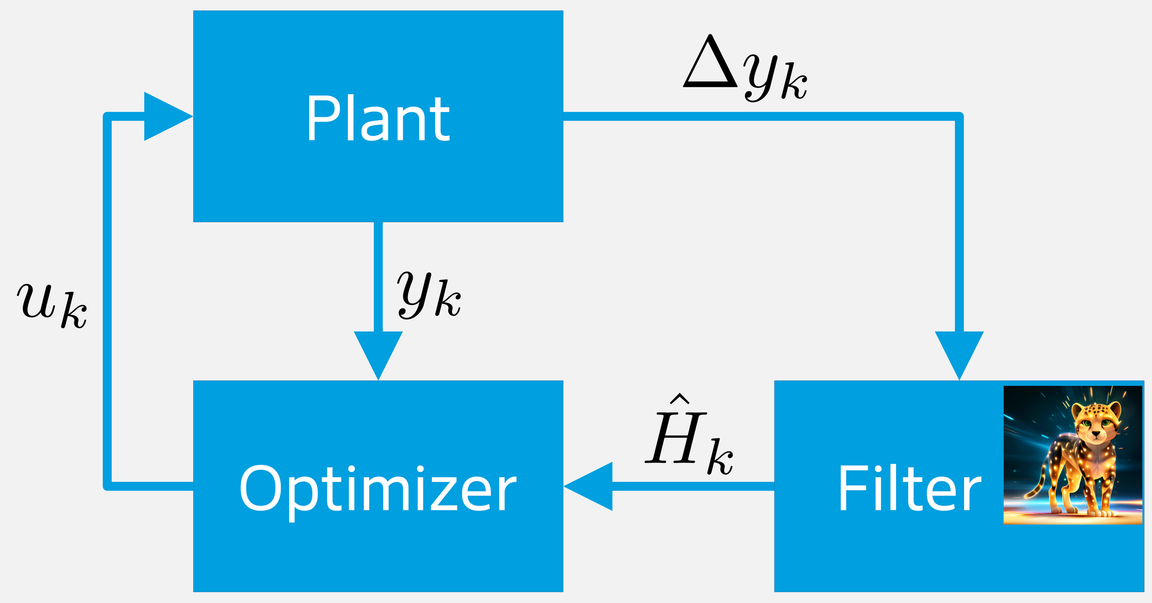
$$u_{k+1} = u_k - \alpha_k \frac{\partial \Phi(\cdot, h(\cdot))}{\partial u}(u_k)$$

Model-Based Feedback Optimization



$$u_{k+1} = u_k - \alpha_k \left(\frac{\partial \Phi}{\partial u}(u_k, y_k) + \frac{\partial \Phi}{\partial y}(u_k, y_k) \frac{\partial h}{\partial u}(u_k) \right)$$

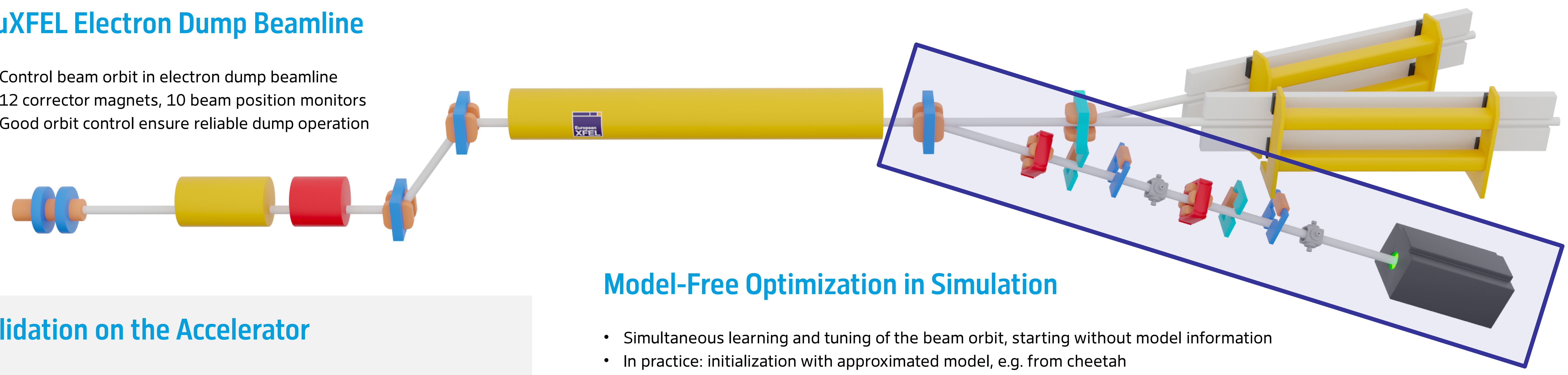
Learning-Based Feedback Optimization



$$u_{k+1} = u_k - \alpha_k \left(\frac{\partial \Phi}{\partial u}(u_k, y_k) + \frac{\partial \Phi}{\partial y}(u_k, y_k) \hat{H}_k \right) + \nu_k$$

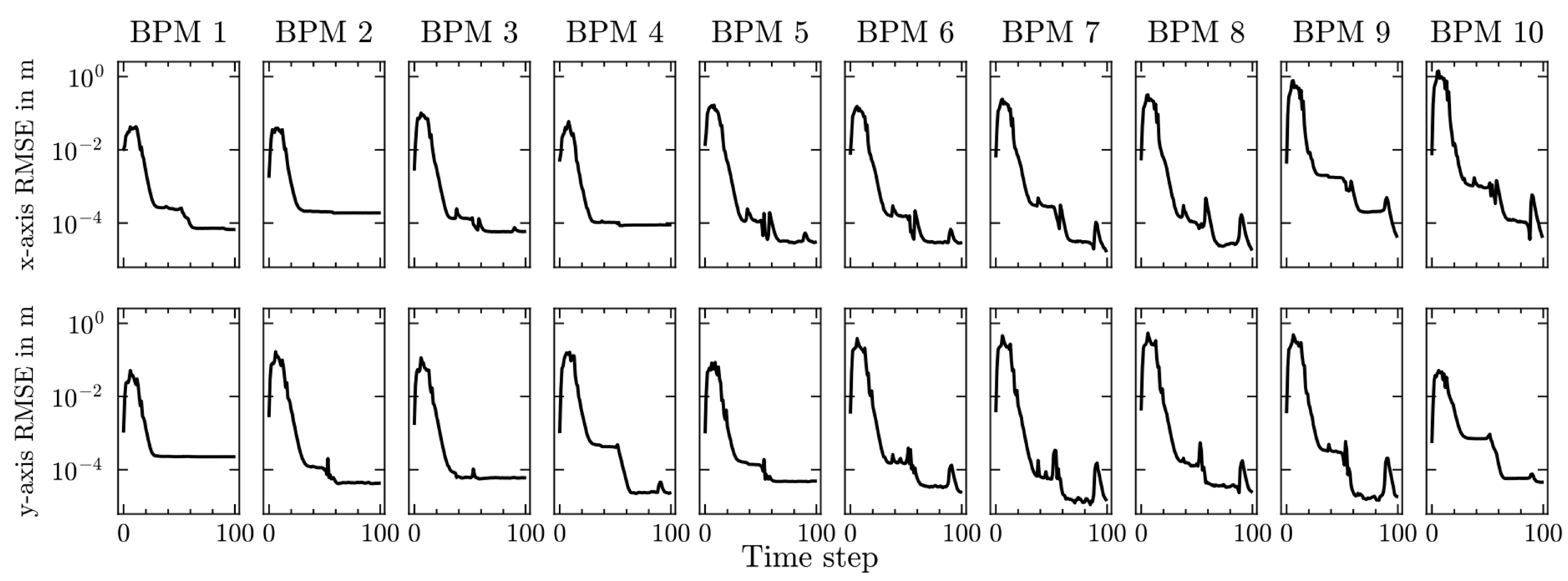
EuXFEL Electron Dump Beamline

- Control beam orbit in electron dump beamline
- 12 corrector magnets, 10 beam position monitors
- Good orbit control ensure reliable dump operation



Model-Free Optimization in Simulation

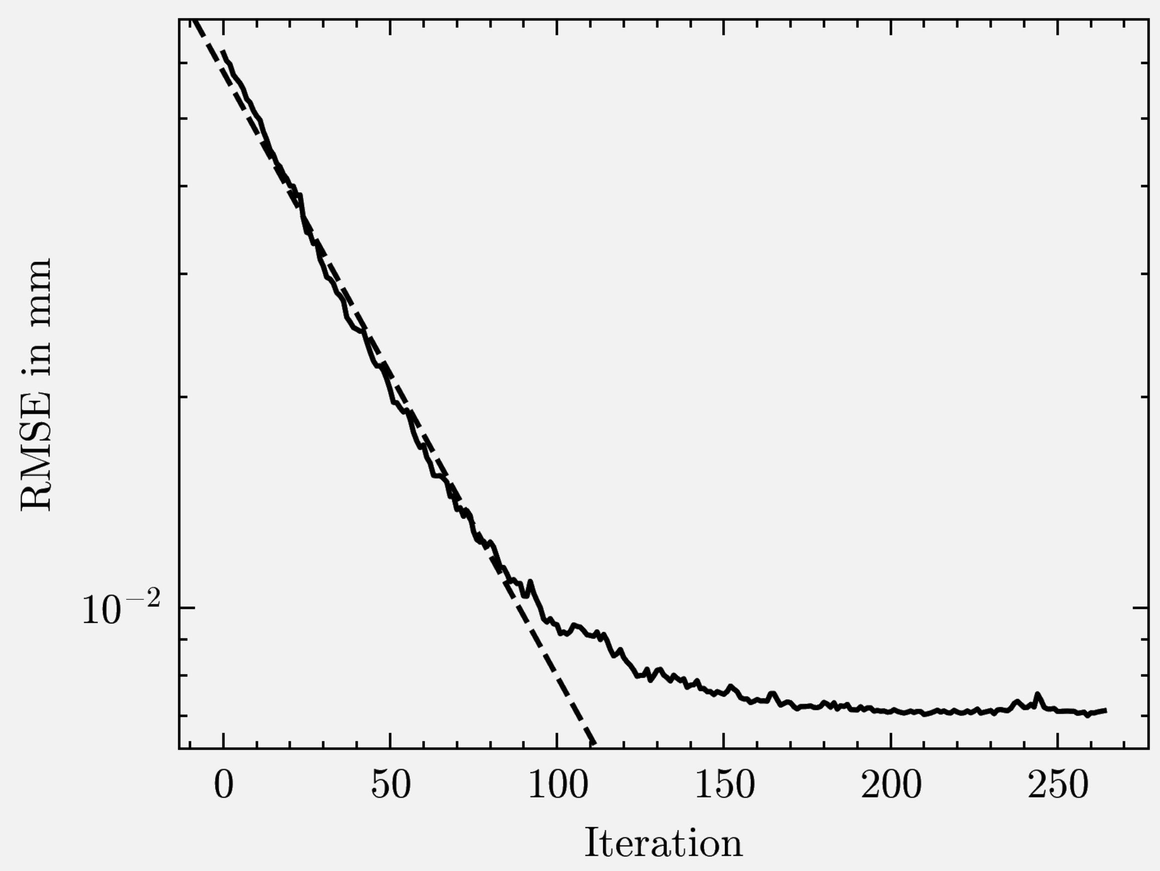
- Simultaneous learning and tuning of the beam orbit, starting without model information
- In practice: initialization with approximated model, e.g. from cheetah



Validation on the Accelerator

- Only model-based feedback tested - Algorithm is sufficiently robust
- Single bunch operation tested, 1 Hz update rate of the algorithm

- Reliably converged for different initial conditions
- Magnet current limits respected
- Convergence rate ≈0.02, deliberately slowed down



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