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Causal GP-MPC: Where Structure, Safety, and Online Learning Meet for Robust Accelerator Control

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Robust accelerator control increasingly relies on data-driven optimisation, yet balancing adaptability with safety remains challenging. Simulation-driven, physics-informed reinforcement learning (RL) relies on soft constraints without formal safety guarantees, and classical response-matrix inversion (RMI) becomes suboptimal under noise
and hard actuator limits. Using the AWAKE electron beam-steering task at CERN as a high-fidelity benchmark, we formulate beam steering as a stochastic control problem in a linear Markov decision process (MDP) with continuous state/action spaces and realistic constraints, and compare RMI, the nominally optimal linear controller-Kalman Quadratic Programming (KalmanQP), Gaussian-process MPC (GP-MPC), and RL.

Our main contribution is a causal GP-MPC scheme that embeds the beamline's causal layout directly into the GP prior and kernel. This structural inductive bias reduces model complexity, improves conditioning, and enables accurate multi-step prediction from limited data. In simulations on the measured response matrix, RMI and KalmanQP perform well in benign conditions, but their nominal optimality is brittle performance degrades sharply under noise. PPO learns robust policies yet is data inefficient. Structured GP-MPC bridges these extremes, leveraging the RMI-based physical prior for high sample efficiency and a learned residual to surpass the robustness of standard controllers. Taken together, the results indicate that causally structured learning offers a promising route to data-efficient, interpretable, and deployable control strategies for complex accelerator systems.

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