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Bayesian optimization for plasma wakefield acceleration

Artificial intelligence (AI) has become a cornerstone in addressing complex optimization challenges across scientific domains. Among AI techniques, Bayesian optimization (BO) has proven particularly effective for navigating high-dimensional and computationally expensive parameter spaces. In plasma-based accelerators, BO offers a powerful framework for overcoming the inherent non-linear dynamics and multi-scale nature of these systems. By leveraging probabilistic models such as Gaussian processes, BO enables efficient exploration and optimization of laser and plasma parameters, facilitating advancements in beam quality and accelerator stability.

This contribution provides a comprehensive review of BO in the context of plasma-based accelerators, emphasizing its applications, methodologies, and recent developments. Plasma accelerators rely on intricate interactions between laser pulses (or charged particle beams) and plasma media, requiring precise control over parameters such as plasma density profile, laser (beam) energy and dynamics. Traditional optimization methods often fail due to strong parameter coupling and experimental (or numerical) uncertainties. BO addresses these limitations by constructing surrogate models of the parameter space and iteratively refining them based on sparse data, enabling autonomous tuning of accelerator outputs.

Recent studies have demonstrated BO's ability to optimize electron beam properties to achieve small energy spreads, improve stability across experimental runs, and reduce computational costs through multi-fidelity approaches. Multi-objective BO further expands its capabilities by simultaneously optimizing competing objectives while dynamically adjusting simulation fidelity. Notably, EuPRAXIA project can benefit of BO techniques for beam-driven plasma acceleration schemes. This integration aims to enhance the performance and stability of these accelerators, which are crucial for delivering high-quality electron beams for applications. This contribution highlights the transformative role of Bayesian optimization in plasma accelerator research and its potential to advance cutting-edge technologies and applications in EuPRAXIA.

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