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Quantifying Differences Between High-Dimensional Beam Phase Space Distributions Using f-Divergences

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Quantifying differences between high-dimensional phase space distributions is essential for analyzing beam measurements and simulations. While f-divergences such as KL or JS divergence are increasingly used for this purpose, including in machine learning applications, their values lack physical interpretability. This work establishes the first physics-grounded framework for f-divergences in accelerator beam contexts. Through systematic analysis of 4D transverse phase space distributions with elliptical symmetry, we reveal how distinct f-divergences assign region-specific weights to distribution cores, tails, and halos. We also prove rigorous correspondences between f-divergence values and conventional beam physics quantities: emittance differences and mismatch factors. These results, validated by statistical analysis of synthetic distributions, provide concrete selection guidelines for f-divergences in phase space comparisons and establish assessment standards for evaluating f-divergence values in beam physics applications.

Footnotes

Funding Agency

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Yes

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