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Detailed Phase Space Reconstruction from a Limited Number of Beam Measurements Using Neural Networks and Differentiable Simulations

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Characterizing the phase space distribution of particle beams is essential in the study of accelerator systems. As the accelerator community keeps pushing the brightness frontier, resolving fine details in the 6D beam phase space density has become important in the optimization and control of next-generation beamlines. However, conventional reconstruction-based techniques either use simplifying assumptions, reducing the level of detail, or require specialized diagnostics to infer high dimensional (>2D) beam properties. In this work, we introduce a general-purpose algorithm that combines neural networks with differentiable particle tracking to reconstruct high-dimensional phase space distributions without using specialized beam diagnostics or beam manipulations. We demonstrate that our algorithm reconstructs detailed 4D phase space distributions with corresponding confidence intervals in both simulation and experiment using a single focusing quadrupole and a limited number of measurements on a diagnostic screen. This technique allows for the simultaneous measurement of multiple correlated phase spaces, enabling simplified 6D phase space reconstruction diagnostics in the future.

Primary authors: ROUSSEL, Ryan (SLAC National Accelerator Laboratory); EDELEN, Auralee (SLAC National Accelerator Laboratory); MAYES, Christopher (SLAC National Accelerator Laboratory); RATNER, Daniel (SLAC National Accelerator Laboratory); GONZALEZ-AGUILERA, Juan Pablo (University of Chicago); KIM, Seongyeol (Argonne National Laboratory); Dr WISNIEWSKI, Eric (Argonne National Laboratory); POWER, John (Argonne National Laboratory)

Presenter: GONZALEZ-AGUILERA, Juan Pablo (University of Chicago)

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