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ML-enhanced start-to-end simulations of plasma acceleration facilities integrated with Geant4

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Plasma acceleration is an emerging technology with transformative potential for accelerator and light source facilities, as well as applications in medical and nuclear physics. However, its broader adoption is hindered by the reliance on computationally intensive Particle-in-Cell (PIC) simulations, which require expert knowledge and multiple simulation tools.

Geant4 [1] is a widely used Monte Carlo (MC) toolkit to simulate various applications across high-energy, accelerator, nuclear, medical physics and space science. Despite its broad utility, Geant4 lacks native support for plasma acceleration modeling.

We present a novel mechanism of integration of a generic Machine Learning (ML) surrogate model [2], trained on PIC simulations, into Geant4 as a particle source. This approach enables the realistic generation and tracking of plasma-accelerated beams within complete experimental setups, effectively bridging PIC and MC methods. As a proof-of-concept, we showcase start-to-end simulations of the PALLAS laser-plasma accelerator facility [3-5], incorporating the full experimental setup within Geant4. This demonstrates the feasibility and flexibility of simulations for plasma acceleration applications within a single framework.

[1] S. Agostinelli et al., NIMA 506, 250-303 (2003).
[2] A. Sytov et al. arXiv2503.12154 (2025).
[3] G. Kane et al. arXiv2408.15845 (2024).
[4] P. Drobniak et al., PRAB 26, 091302 (2023).
[5] https://pallas.ijclab.in2p3.fr/.

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