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Digital twin framework for PIP-II linac: AI-driven multi-scale modeling from ion source to 800 MeV

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The PIP-II superconducting linac at Fermilab is designed to deliver multi-megawatt proton beams for neutrino physics and other high-intensity applications. To expedite commissioning and enhance operational reliability, we have developed an EPICS-based data flow framework that seamlessly integrates digital twins (DT) with physical twins (PT). These digital twins comprise high-fidelity beam dynamics models or data-driven surrogate models connected to their physical counterparts through real-time diagnostics and advanced machine-learning algorithms.

Central to this framework is Linac_Gen, an accelerated simulation tool that incorporates convolutional neural networks, random forests, and genetic algorithms to provide up to a tenfold speedup in optimizing the accelerator geometry model. An EPICS translator layer ensures interoperability by efficiently mapping lattice parameters across diverse simulation platforms.

Our EPICS-based framework supports multiple operational modes—monitoring, passive learning, closed-loop control, and online learning—covering the entire machine lifecycle. By leveraging HPC resources and multi-objective optimization techniques, the digital twin enables adaptive trajectory correction, real-time fault detection, and predictive modeling of beam stability. This comprehensive approach paves the way for robust, high-intensity operation and data-driven accelerator R&D at Fermilab.

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Footnotes

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