Snowmass 2021 - Letter of Interest
Loss prediction through modeling of high dynamic range beam distributions

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Beam halo leading to uncontrolled beam loss is an obstacle for future advances in high-intensity accelerators. High-intensity hadron beams form the backbone of many programs of study, from nuclear and neutrino physics to neutrons for materials, driving science at facilities such as the ESS, SNS, J-PARC, ISIS and FNAL. Further increase in intensity to meet scientific needs is expected, in line with the historical increase in hadron accelerator power leading to the current 1 MW state-of-the-art regime [1]. Projects currently under construction are slated for the 3-5 MW range [2, 3], and applications such as accelerator driven systems presuppose the next order-of-magnitude leap to 10 MW [4].

Given current capabilities for loss control, an order-of-magnitude increase in hadron beam power will result in an accelerator that is un-serviceable. To enable routine maintenance, losses should remain below 1 Watt/meter or roughly 1 part-per-million in a 10 MW beam [4]. One mechanism driving beam loss is beam halo. In the context of beam loss, halo can be defined as the outer portion of the beam distribution with density between $10^{-4} - 10^{-6}$ of the core peak intensity. Mitigation or prevention of this loss requires predictive modeling of this extremely low-level population.

Particles are understood to be driven into the high-amplitude halo region via interactions with the beam space charge self-field. However, models such as the widely-recognized particle-core interaction [5, 6, 7, 8] are not intended to provide the required high-precision predictions. Methods like particle-in-cell are more relevant, but to date there have been no accurate predictions of the halo distribution much less translation into beam loss in an accelerator [9, 10, 11]. Even more, the beam instrumentation required to properly measure and characterize beam halo is not yet available.

Predictive capability for low-level beam loss is of interest to the accelerator community. These aims are aligned with the grand challenges identified in the 2020 summary report of the Accelerator Physics and Beams (ABP) working groups report to the HEP General Accelerator RD (GARD) program [12], specifically:

- Grand challenge #1 (beam intensity): How do we increase beam intensities by orders of magnitude?
- Grand challenge #3 (beam control): How do we measure and control the beam distribution down to the level of individual particles?

Over the past decade, advances in computing power have enabled one part-per-million resolution. The remaining hurdles of both simulation accuracy and diagnostic capability lie firmly in the domain of accelerator physics. Previous studies have concluded that a likely source of inaccuracy is incomplete description of initial beam distributions [10, 11], either through shortcomings of end-to-end modeling or limited diagnostics for measurement-based distributions. Priorities for research include:

1. high dynamic range phase space diagnostics to fully characterize halo
2. efficient methods for high-dimensional characterization of beam distributions
3. frameworks for generating fully-coupled bunches from distribution measurements

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4. investigation of alternative explanations such as "missing physics" in self-consistent simulations

Items 2 and 3 in particular may benefit from recent advances and community interest in AI/ML algorithms.

The resources needed to tackle this problem are primarily people and R&D time. This work requires extensive beam time and state-of-the-art diagnostics development, and therefore is best suited for test facilities. Such facilities exist, or may be retrofitted with modest investment. Front end test stands, such as the SNS Beam Test Facility [13, 14], provide opportunities to study irreversible halo formation in the low- and medium- energy range, with the dual purpose of allowing for concurrent development of halo diagnostics. The SNS BTF is outfitted for complete characterization of the 6D phase space [13] and cutting-edge high dynamic range measurement [15].

At this point in time, the most needed resource is funding for test stand efforts in diagnostics development and benchmarking. Although test stands often support the mission of larger facilities and may receive some facility support, dedicated funding enables additional resources, including:

1. collaboration, particularly with users of various PIC codes for broader benchmarking effort
2. dedicated research personnel, including post-doc appointments
3. computing resources
4. access to expertise in ML/AI algorithms

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