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INTERACTIONS BETWEEN THE CIRCULATING BEAM AND THE INJECTION FOIL AT THE PROTON STORAGE RING OF LANSCE*

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Abstract

At the Los Alamos Neutron Science Center (LANSCE), the Proton Storage Ring (PSR) utilizes charge-exchange injection via a carbon stripper foil to convert H⁻ ions into circulating protons. While beam loss due to partially stripped neutrals is a well-known concern, interactions between the circulating beam and the injection foil also play a significant role in limiting beam quality and foil lifetime. Simulations indicate that each stored proton typically interacts with the foil around 30 times during accumulation. These repeated encounters result in large-angle scattering, which becomes a dominant loss mechanism. To reduce the number of foil traversals, a set of bump magnets is employed to move the closed orbit away from the foil over time. In this study, we benchmark foil scattering models in PyORBIT against Monte Carlo simulations using MCNP and Geant4, evaluate different bumping schemes, quantify sensitivities to injection offsets, generate spatial distribution of beam-foil interactions on the foil, and assess the impact of different injected beam distributions. The results inform both operational optimization and future upgrade paths for foil injection systems in high-intensity proton rings.

INTRODUCTION

The Proton Storage Ring (PSR) at LANSCE accumulates protons from an 800 MeV H^- linac via charge exchange injection at a Hybrid-Boron-Carbon (HBC) stripper foil [1]. Charge-exchange injection using a thin stripper foil is a fundamental technique in high-intensity proton rings, including the PSR. During injection, H⁻ ions from the linac are stripped of their electrons, converting them to protons which are then accumulated in the PSR. However, two of the three main sources of the beam losses are related to the stripper foil: Lorentz stripping from partially stripped excited H^0 at injection and the nuclear scattering between the injection foil, while the third main source of the ring losses come from extraction [2]. In this work, we are trying to improve our simulation capability for the foil-related losses. In [3] at this conference, J. Yoskowitz will present the simulation effort to understand the partially stripped H^0 and its corresponding loss location.

In this paper, we will focus on improving our simulation capability on the interactions between the stripper foil and the circulating beam. Figure 1 shows that loss level along the PSR decreases when the foil thickness in the model decreases, showing the importance of the foil's contribution to ring losses. Note that the loss contribution at 0.083% for the stored beam with the nominal foil thickness at 450 µg/cm^2 is slightly lower than 0.11-0.17% estimated in [1]. To understand the interplay between the circulating beam and the foil, we focus on two major items: (1) the comparison of different simulation models on the nuclear scattering and (2) the number of interactions between each proton and the foil.

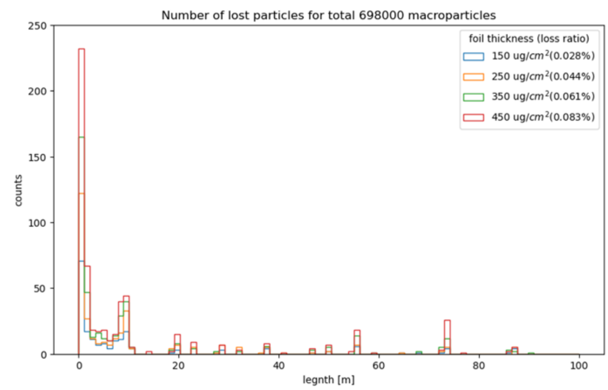

Figure 1: Simulated loss level across the PSR with different foil thickness using PyORBIT. For this simulation, the losses due to partially stripped H^0 are not considered; the simulation directly starts with a H^+ beam. Therefore, the losses centered right after the foil (at x=0) demonstrate the losses due to nuclear scattering.

NUCLEAR SCATTERING

Since the nuclear scattering effect contributes almost 50% of the losses from the earlier estimate [2], it is critical for us to benchmark the performance of the simulation code. Specifically, we'd like to compare beam dynamics codes like PyORBIT [4] and Xsuite [5] (xcoll [6], particularly for the material interaction) against high-fidelity Monte Carlo code like MCNP [7] and BDSIM [8] (based on Geant4 [9]). We used 1M random particle distribution generated by MCNP according to the injection design Twiss parameters and the nominal 800 MeV kinetic energy for protons. Each code assumes that the foil is composed of 100% carbon at a thickness 450 mg/cm2, 1000x of the nominal thickness at thickness 450 µg/cm2 for operation), while each code adopts its own definition of the carbon material, and therefore, calculate its thickness in length. The difference in calculated lengths (~mm) should be negligible for the outcome.

Figure 2 and Table 1 show the comparison between the codes for x', y' and energy loss, while x and y are virtually the same so we will ignore them. Our analysis reveals that the Monte Carlo codes demonstrate consistent results between coordinates. The energy loss modeling shows

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interesting variations, with MCNP exhibiting discrete energy loss patterns while BDSIM produces a continuous spectrum. For small-angle scattering (<5 mrad), PyORBIT tends to overestimate the broadening effect while Xsuite underestimates it. In the large-angle regime (5 mrad to 50 mrad), PyORBIT results align well with the Monte Carlo codes, but Xsuite displays a notable discontinuity. For very large angle scattering (exceeding 200 mrad, which typically results in immediate particle loss), PyORBIT may slightly underestimate the effect while Xsuite overestimates it.

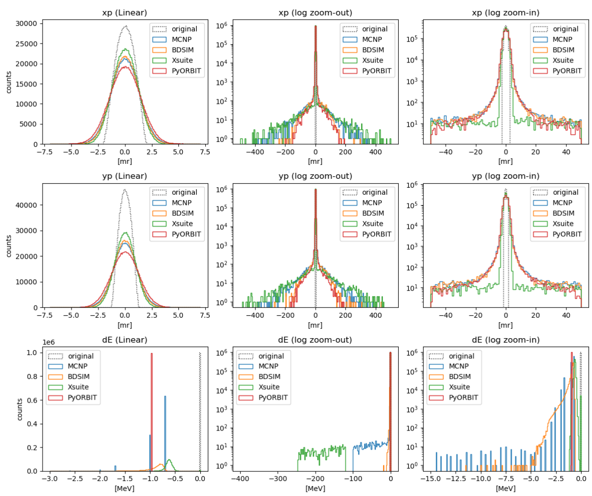

Figure 2: Comparison of MCNP, BDSIM, PyORBIT, and Xsuite for their foil scattering effects in x' (top row), y'(middle row), and energy difference (bottom row). Each column is a different zoom scale. The foil is assumed to be 100% carbon with a thickness at 450 mg/cm^2, 1000x of the nominal foil thickness.

Table 1: Statistical Analysis of the Scattering Effects

	Initial	Py-ORBIT	MCNP	BDSim	XSUITE
Loss [%]	-	0.345	0.515	0.579	0
E loss [MeV]	-	-0.967	-0.883	-0.934	-0.693
xstd [mm]	1.176	1.176	1.176	1.176	1.176
x'std [mrad]	0.83	2.587	4.804	3.123	2.587
ystd [mm]	1.772	1.772	1.772	1.772	1.772
y'std [mrad]	0.532	2.462	4.634	3.079	6.082

Regarding energy differences, which are particularly crucial since particles with significantly reduced energy are immediately lost, we observe that even the Monte Carlo codes themselves show inconsistencies. BDSIM produces a continuous energy loss spectrum while MCNP generates discrete energy loss values. The average energy loss is also off by ~0.1 MeV between them. PyORBIT simplifies this further by calculating only a single energy loss value, whereas Xsuite produces distinct "islands" of energy losses.

BUMP SCHEME

PSR is currently utilizing a vertical bump scheme to lower the number of foil traversals per proton (NHit) during accumulation. The beam is injected on a bottom corner of the foil while the closed orbit starts around 16 mm above pipe center and is linearly lowered to the center of the beam pipe over the whole accumulation period, as shown in Fig. 3.

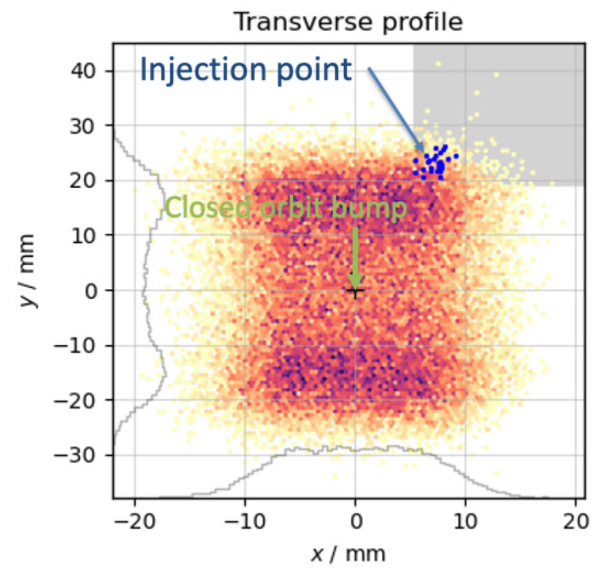

Figure 3: Vertical bumps at PSR to lower NHit.

To assess alternative mitigation strategies, simulations examined three orbit bumping schemes: linear (the current one), square-root, and a static (no bump) configuration. Figure 4 shows that, in the absence of bumping, NHit increases linearly with accumulated charge, as the circulating beam repeatedly intersects the foil at a constant location. The higher NHit increases the overall nuclear scattering caused by the foil, causing higher losses from the stored beam. Furthermore, higher NHit accelerates thermal stress and material fatigue, ultimately shortening foil lifetime.

In contrast, both the linear and square-root bump profiles gradually displace the closed orbit during accumulation. These dynamic schemes reduce the average NHit per particle to around 30–31 across 1745 turns, thereby mitigating concentrated heating effects and prolonging foil usability. The square-root scheme provides the greatest benefit in these early turns, since it bumps the closed-orbit down faster than the linear method in early turns. Though its relative advantage decreases as injection progresses. These findings underscore the importance of carefully optimized bumping strategies. Furthermore, Fig. 5 shows the spatial distribution of beam-foil interactions over the whole accumulation period. This data provides critical input for thermodynamic modeling to extend foil lifetime.

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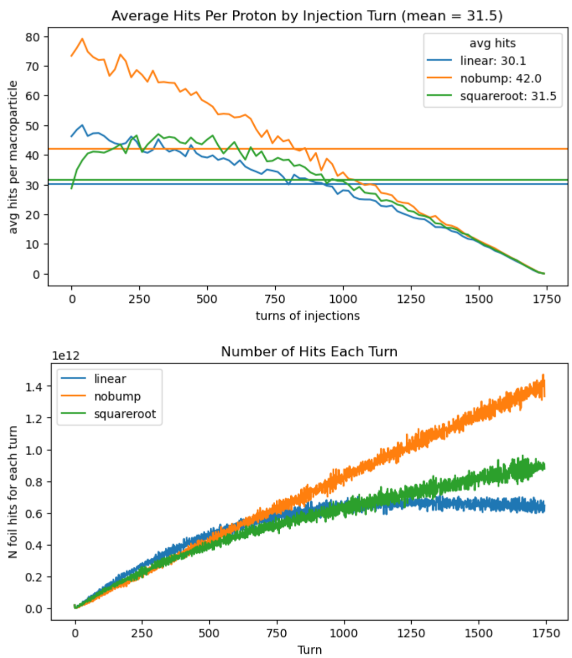

Figure 4: Average NHit by the particle's turn of injection (top) and number of hits on the foil at each turn.

CONCLUSION AND FUTURE

This study was conducted to model and match the current operational status of the PSR and to explore potential upgrade paths. Our focus is on addressing two primary sources of beam loss in the ring—both linked to the injection foil: (1) partially stripped excited H^0 atoms during injection (covered in a separate contribution at this conference [3]), and (2) emittance growth due to nuclear scattering between the foil and the circulating beam (addressed in this work).

A comparative study of beam dynamics codes (PyORBIT, Xsuite) and high-fidelity Monte Carlo simulations (MCNP, BDSIM) revealed notable differences in their treatment of angular scattering and energy loss mechanisms. While the codes agree reasonably well under specific conditions, observed discrepancies emphasize the importance of careful code selection and could potentially determine the simulation uncertainties.

We also investigated orbit bumping strategies, including an alternative square-root bump profile in place of the conventional linear scheme. Although the linear bump slightly outperforms the square-root profile overall, the square-root function shows particular promise in reducing beam-foil interactions during the early turns of accumulation.

Looking ahead, we plan to carry out detailed thermomechanical modeling using the spatial hit distribution data to predict temperature gradients and stress patterns in the carbon foil. Additionally, we aim to develop a virtual diagnostic tool to estimate NHit in real time for the central control room, based on beam measurements and simulations. These efforts are expected to contribute to extending foil lifetime, reducing beam losses, and ultimately improving the operational efficiency and reliability of the PSR injection system.

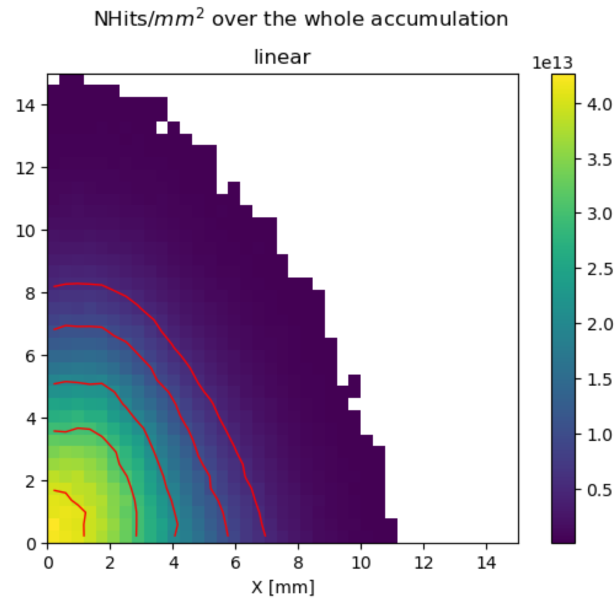

Figure 5: The map of the interaction area density on the foil over the whole accumulation period.

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