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SIMULATION MODELING OF FIRST-TURN LOSSES FOR THE LANSCE PROTON STORAGE RING (PSR)

J. T. Yoskowitz*, A. Alexander, E. Henestroza, E.-C. Huang, J. W. Lewellen, C. E. Taylor, H. Xu
Los Alamos National Laboratory, Los Alamos, NM, USA

Abstract

The LANSCE proton storage ring (PSR) accumulates 795 MeV protons into a short, 290 ns pulse over 625 µs, or about 1745 turns. One of the primary limitations for maximum proton pulse intensity is beam loss between the stripper foil and the first dipole magnet downstream of the foil. One of the major beam losses in this region, referred to as "first-turn losses," are due to incomplete stripping of the injected H^- beam into H^+ during the injection process. H^- that foil strip into H^0 can either pass through the first dipole magnet to the injection beam dump, or get Lorentz stripped by the magnetic field of the dipole or the defocusing quadrupole magnet between the foil and dipole. First-turn losses not only result in a lower extracted proton pulse intensity but can also result in longer maintenance periods following beam runs due to the activation of PSR components, which require "cooling down" prior to any hands-on maintenance. In this work, a detailed particle-tracking model of the PSR injection system was created using the simulation package General Particle Tracer (GPT) using three C++ custom elements created to simulate foil scattering, foil stripping, and Lorentz stripping. The simulation model will be described, and the simulation results will be presented at the conference.

INTRODUCTION

The LANSCE PSR is a 90.2 m accumulator ring that delivers intense, 290 ns proton pulses at 795 MeV to the Manuel Lujan Neutron Scattering Center and the Weapons Neutron Research (WNR) Facility for spallation neutron experiments [1]. These experiments require the proton pulses to have high intensity to optimize the signal-to-noise ratio [2,3]. Historically, the intensity of the proton pulses has been on the order of 10^{13} protons/pulse [4]. However, the maximum intensity achievable by the PSR is limited primarily by beam loss. The main sources of beam loss include first-turn losses — losses during PSR injection [5], emittance growth (i.e., beam scraping) [6,7], losses during extraction [4], and beam instabilities [8].

First-turn losses occur due to incomplete foil stripping of the injected H^- beam. If H^- strip into H^0 instead of H^+, or if the H^- miss the foil entirely, they are either transported to the injection beam dump or are Lorentz stripped by the B-field and are lost. These losses have been estimated to account for about half of the total losses in the ring and therefore are of primary concern [4]. Beam losses can cause equipment damage and the activation of beamline components, which lead to long maintenance periods following beam operations. Several upgrades to the PSR have been proposed to reduce first-turn losses, such as introducing a magnetic field to Lorentz strip H^0 immediately after the foil [9], or modifying the foil material to improve its stripping efficiency [10, 11]. However, predicting the effectiveness of these mitigation techniques requires a detailed simulation model.

In this work, particle-tracking simulations of the PSR injection system were created within the framework of the simulation package General Particle Tracer (GPT) [12]. To model foil stripping, foil scattering, and Lorentz stripping, C++ custom elements were developed and implemented in the simulations. The GPT model and the simulation results are described in the following sections.

* jty@lanl.gov

PSR INJECTION SYSTEM AND FIRST-TURN LOSSES

The injection system of the PSR is shown in Fig. 1. A 795 MeV H^- beam composed of 625 µs pulses, each of which are composed of 290 ns "minipulses," are injected into the PSR at 20 Hz. A 6.8° dipole magnet bends the H^- beam such that it joins with the recirculating H^+ beam at the foil. The H^- undergoes foil scattering and foil stripping into H^0 and H^+. When the H^-, H^0, and H^+ reach the first of two 16.2° dipole magnets there are several possibilities:

1. H^- that miss the foil are Lorentz stripped into H^0 or H^+ and are lost on the beam pipe.
2. H^0 in the ground state (n=1) or first excited state (n=2) pass straight through the two dipole magnets and are transported to a beam dump.
3. H^0 in higher excited states (n>2) can undergo Lorentz stripping within the dipole magnet into H^+. Because these H^+ are sufficiently displaced from the recirculating H^+ beam to be outside the PSR acceptance region, they are lost [13].
4. H^+ are bent towards the PSR and begin recirculation around the ring.

Beam losses due to #1-3 comprise first-turn losses and account for about 2-3% of the injected beam.

FIRST-TURN LOSS SIMULATIONS

To explain and predict the effect of using different stripper foil parameters on first-turn losses, a simulation model of the PSR injection system was created using GPT. In each simulation, a 795 MeV H^- pulse, representing the injected H^- beam, is tracked from 0.1 m upstream of the stripper foil to 2 m past the two 16.2° dipoles, modeled using magnetic field maps, after the foil. The H^- pulse is composed of 10^4

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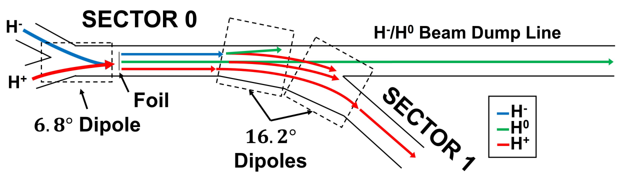

Figure 1: Schematic of the PSR injection system showing the trajectories of the injected H$^-$ and recirculating H$^+$ beams incident on the foil, and the trajectories of the H$^-$, H^0, H$^+$ after the foil.

macroparticles with a total charge of 1 nC. The coordinate system is such that the H$^-$ pulse initially travels along the z-axis with the y-axis pointing up and the x-axis pointing to the left when looking downstream from the foil. The PSR beam pipe, including the H$^-$/H^0 beam dump line, is 4 inches in diameter. Any particle that hits the beam pipe is removed from the simulation. Figure 2 shows a time-lapse plot of a GPT simulation, with relevant simulation parameters shown in Table 1.

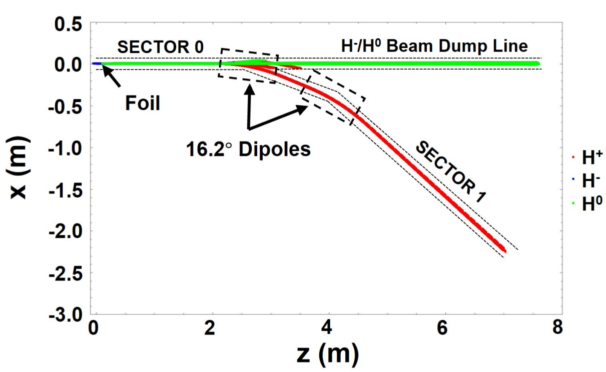

Figure 2: Time-lapse plot of a GPT simulation of the PSR injection system, showing the injected H$^-$ pulse passing through the stripper foil and the two 16.2° dipole magnets.

Table 1: GPT Simulation Parameters

Simulation Parameter	Value
Initial # H$^-$ macroparticles	10^4
Initial H$^-$ bunch charge	1 nC
16.2° dipole field strength	1.26 T

C++ custom elements were developed and implemented in the GPT simulations to model foil stripping, foil scattering, Lorentz stripping, and H^0 transition lifetimes, all of which are not built-in features of GPT. The simulation results are described in the following subsections.

Foil Stripping and Scattering

When the H$^-$ beam passes through the stripper foil, the H$^-$ can strip into H$^+$ or H^0. If we consider an H$^-$ macroparticle representing n H$^-$ ions passing through a distance d of the stripper foil, the number of stripped H$^-$ is given by:

$$N = \rho\sigma dn \tag{1}$$

where σ is the stripping cross section and ρ is the foil density, given by:

$$\rho = \frac{t}{zmN_A} \tag{2}$$

where t is the foil thickness (or "areal density"), z is the foil depth, m is the molar mass of the foil material, and N_A is the Avogadro constant. Stripping cross sections for 800 MeV H$^-$ through a carbon foil are given by M. Gulley *et al.* [14]. The C++ custom element for foil stripping/scattering uses these equations to calculate the number of H^0 and H$^+$ produced for each H$^-$ macroparticle.

Using $t = 450$ µg/cm^2, $z = 4$ µm, and $\rho = 1.1$ g/cm^3 for the PSR carbon foil, the populations of H$^-$, H^0, and H$^+$ produced when 1 nC of H$^-$ passes through the foil in the GPT simulation are shown in Fig 3. Gulley et al. also gives cross sections for different H^0 energy states n – the first five are shown in Fig. 3. The angular momentum state of the H^0 determines its transition lifetime, as detailed in the next section, and is assumed to be random for a given n. This assumption is necessary because Gulley's cross-sections are specified only for the energy states.

Approximately 2.6% of the simulated H$^-$ miss the foil and remain unstripped. 98.6% of the stripped H$^-$ become H$^+$, which can be attributed to the high foil thickness. The remaining 1.4% become H^0, 98.2% of which are in the n =1 or 2 state and 1.8% are in a higher energy state. The energy state determines whether the H^0 is Lorentz stripped in the dipole magnets, as explained in the next section.

The H$^-$ beam and recirculating H$^+$ beam also undergo foil scattering. The distribution of scattering angles through the PSR foil is given by MCNP6 simulations by M. Kay *et al.* [15] and is used by the custom element to determine the scattering angle for each H$^-$ macroparticle. Figure 4 shows the distribution of scattering angles for the simulated H$^-$ macroparticles. The scattering angles of the simulated H$^-$ are likely to be small, so the effect of foil scattering is negligible for one pass through the foil. However, the recirculating H$^+$ beam hits the foil an average of 30 times (out of the 1745 turns) during accumulation, so the cumulative effect of foil scattering can lead to significant emittance growth and beam scraping [4].

H^0 Transition Lifetimes and Lorentz Stripping

An H^0 or H$^-$ can undergo Lorentz stripping within the 1.2 T dipole field. The probability of Lorentz stripping within a given simulation timestep is given by Folsom et al. [16]:

$$P = \frac{Bdn}{A_1} \exp\left(\frac{A_2}{\beta\gamma cB}\right) \tag{3}$$

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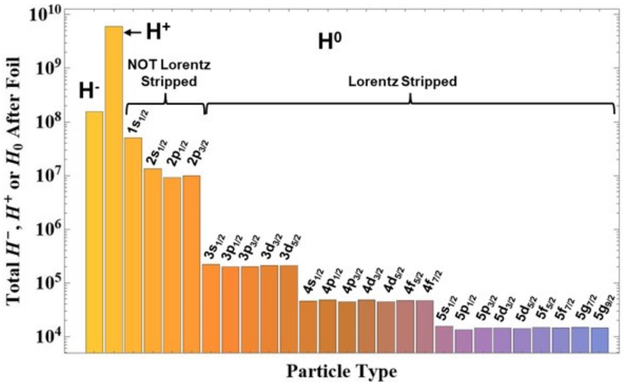

Figure 3: Populations of H^-, H^0, and H^+ due to foil stripping of 1 nC H^- incident on the PSR foil.

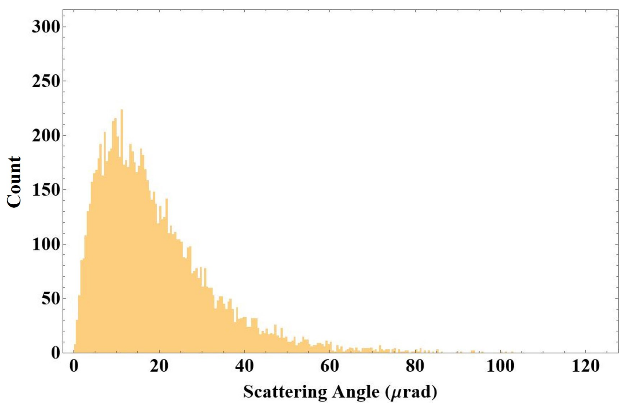

Figure 4: Distribution of scattering angles for the simulated 10^4 H^- macroparticles

where B is the experienced magnetic field strength, d is the distance traveled in this timestep, n is the number of particles the H^0 or H^- macroparticle represents, c is the speed of light, and A_1 & A_2 are empirical constants given by Jason et al. [17]. H^- can strip to H^0 within the dipole field due to the small binding energy of the electron. H^0, on the other hand, can strip to H^+ within the dipole only if the electron energy state is $n = 3$ or higher [18]. The H^0 electron may transition to a lower energy state during transport to the dipole magnet depending on its energy state. The transition probability within a given simulation timestep is given by:

$$P = 1 - \exp\left(\frac{\Delta t}{\tau}\right) \tag{4}$$

where Δt is the timestep length and τ is the transition lifetime. Transition lifetimes for the first 5 energy states are given by NIST [19] and are also dependent on the angular momentum state.

Two GPT custom elements were developed and implemented to simulate H^0 transitions and Lorentz stripping. Figure 5 shows the populations of H^-, H^0, and H^+ throughout the GPT simulation. H^0 in the $n > 2$ state have relatively long lifetimes and thus are likely to Lorentz strip within the first few centimeters of the dipole magnet. On the other hand, H^0 in the $n \leq 2$ state have short transition lifetimes, but do not Lorentz strip within the dipole magnet.

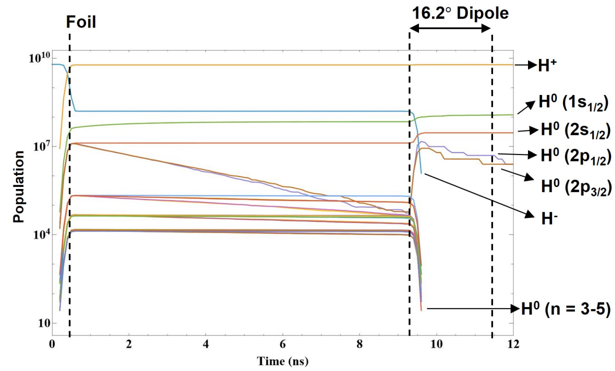

Figure 5: Plots of H^-, H^0, and H^+ populations throughout the GPT simulation.

First-Turn Losses

Figure 6 shows a zoomed-in time-lapse plot of the GPT simulation and shows three sources of uncontrolled beam loss: H^- stripping to H^0, H^- stripping to H^+, and H^0 stripping to H^+, each of which is lost on the beam pipe. H^0 in the $n = 1$ or 2 state passes through the dipole magnet and reaches the H^0 beam dump, and thus is controlled beam loss.

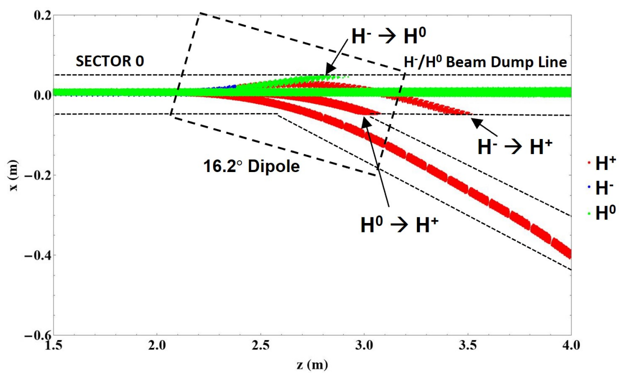

Figure 6: Time-lapse plot of the GPT simulation (shown in Fig. 2), zoomed-in to show the locations of first-turn losses within the first dipole magnet.

CONCLUSIONS AND FUTURE WORK

The GPT simulation model of first-turn losses within the PSR injection system using three C++ custom elements has been successfully developed. The simulation results showing the locations of first-turn losses within the first dipole magnet. There is ongoing work to improve the model so that it can be used to study the effect of different stripper foil parameters (i.e., foil materials, thicknesses, etc.) and injection offsets on first-turn losses.

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