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LASER ASSISTED CHARGE EXCHANGE INJECTION AT THE SPALLATION NEUTRON SOURCE*

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Abstract

Laser Assisted Charge Exchange (LACE) technology is being developed to replace foil-based charge exchange injection in high power H^- accelerators. Replacing the foil with field-stripping has the potential to significantly reduce injection losses, making LACE a promising solution for future high-intensity multi-megawatt power H^- beams. While the LACE technique has been successfully demonstrated, it has not yet been implemented in a configuration suitable for beam injection into a ring. This paper will present recent progress on evaluation of High Energy Beam Transport (HEBT) optics for providing required beam for LACE, design of LACE for the Spallation Neutron Source (SNS) ring injection and simulation of LACE-produced circulating beam in the SNS ring to explore the beam dynamics.

INTRODUCTION

A Laser Assisted Charge Exchange (LACE) injection [1-3] has been under development in the SNS in the past two decades. In this concept, negative ions of hydrogen H^- are stripped of their electrons, $H^- \rightarrow p^+ + 2e^-$, through relatively strong magnetic fields and powerful lasers. A three-step LACE scheme is as shown in Fig. 1. H^- beam is stripped of one electron due to its small binding energy, $H^- \rightarrow H^0 + e^-$, through the first magnet. A laser with an exact wavelength is utilized to excite the remaining electron from the ground state to an excited state, $H^0 \rightarrow H^{0*}$. Then H^{0*} is stripped of the second electron when it passes through the second magnet. Early proof-of-principle experiments have been carried out on the experimental stand in the SNS LINAC and demonstrated high stripping efficiency of ~90% for a single pass beam with a duration of ns to us [4-6].

With the recent successful commission of Proton Power Upgrade (PPU) in the SNS, the H^- beam energy has been upgraded from 1 GeV to 1.3 GeV. This energy upgrade offers new opportunities to optimize the configurations of laser and beam, and their parameters achieve high stripping efficiency with reduced laser power requirements. A new experimental vessel has been fabricated and installed in the HEBT line in the SNS for testing three choices of laser light, UV, green-green and green-IR. Preparation for the ongoing LACE experiments have been discussed in [7].

Along with the ongoing experimental optimization of laser and beam parameters for LACE, progress has also been made in several related areas: evaluating the capability of HEBT to deliver the desired beam parameters for LACE, designing the LACE injection system for the SNS ring, and performing simulations of LACE-produced beam in the SNS to study its dynamics. This paper presents our recent results in each of these areas.

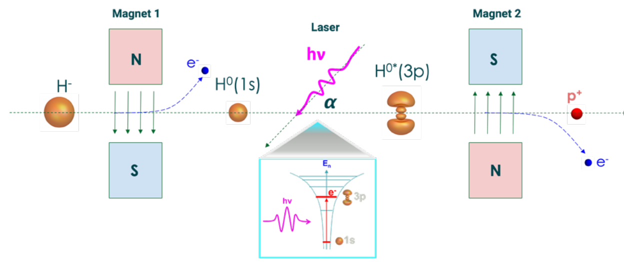

Figure 1: Scheme of a three-step LACE concept.

LACE INJECTION DESIGN

The SNS ring injection region is designed to accommodates foil charge exchange injection and consists of four chicane dipole magnets along with four sets of horizontal and vertical kicker magnets for a turn-by-turn painting injection. The injection region layout after the SNS Proton Power Upgrade (PPU) is shown in Fig. 2, with only about 63 cm available space for a LACE injection scheme. Figure 3 shows a schematic drawing of the injection region, where the foil has been replaced by the LACE system. The following sections provide a detailed description of recent progress in integrating the LACE system into the SNS ring injection region.

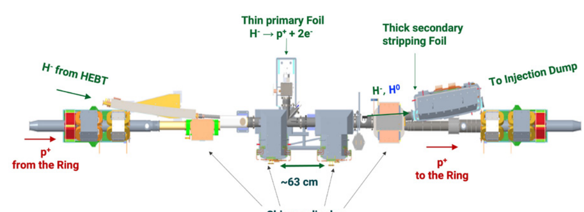

Figure 2: Layout of the SNS injection region after the PPU project.

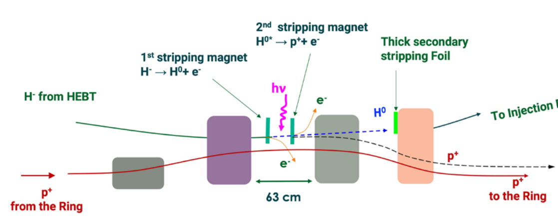

Figure 3: Schematic drawing of the SNS injection region with a LACE system.

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HEBT Capability

The HEBT line delivers the H⁻ beam at energies up to 1.3 GeV from the LINAC to the SNS ring. There are three optics sections in the HEBT in the SNS production operation: Linac-Achromat Matching Section for matching the optics from the LINAC to the transport line, Achromat Section for momentum selection, and Achromat-Ring Matching Section for matching the beam to the ring injection. IN addition, the HEBT line includes a collimator system for halo cleanup and provide a beam dump for the LINAC. A schematic layout of HEBT line is shown in Fig. 4.

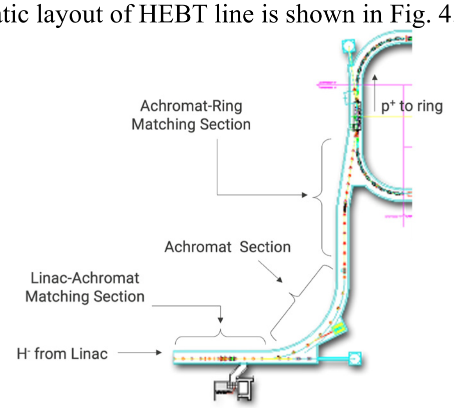

Figure 4: A schematic layout the HEBT line.

To enhance LACE stripping efficiency and reduce the required laser power**,** several considerations have been applied to optimize the H⁻ beam parameters at the laser–beam interaction point (IP): i) small vertical beam size σ_y and energy spread δ to increase the laser power density, ii) finite horizontal dispersion D_x to create a crab-crossing collision of laser and beam [8], iii) finite derivative of horizontal dispersion D_x' to eliminate the Doppler broadening of linewidth [2]. As the first step of designing the LACE injection system for the ring, the HEBT optics needs modification to achieve the required optics and beam parameters at the IP, listed in Table 1. These parameters serve as a baseline and will be further optimized based on results from ongoing experiments.

Table 1: Required Optics and Beam Parameters at the Laser and Beam Interaction Point

	Unit	
$\beta_{x,y}$	m	1.67, 0.42
D_x	m	7.03
D_x'		-2.34
$\epsilon_{x,y}$	um	0.6, 0.4
$\sigma_{x,y}$	mm	3.35, 0.4
ϵ_z	um	1.5
δ	10^{-4}	5
σ_z	mm	3

Two hardware limitations must be considered in the optimization of the HEBT optics: 1) the magnetic pole tip field must remain below 0.2 T to avoid potential stripping of electrons, 2) the existing magnet apertures, particularly the small aperture near the injection septum, constrain the maximum allowable beam size.

Figure 5 shows one possible solution for the optimized optics. In this configuration, a large horizontal dispersion D_x of up to ~40 m and a vertical beta function β_y of up to ~400 m are excited. These features are introduced to achieve large D_x, D_x' , and a small β_y at the interaction point (IP). However, this results in large beam sizes at certain locations along the HEBT beamline.

As illustrated in Fig. 6, the resulting beam envelopes approach the aperture limits near the injection septum, posing a risk of beam loss or hardware interference. There are two possible solutions to address this aperture limitation: 1) scrape the beam using the existing collimation system to limit the beam halo and reduce the transverse beam size before it reaches the critical aperture region, 2) replace the injection septum with a larger-aperture design to accommodate the full beam envelope and avoid beam losses in this region.

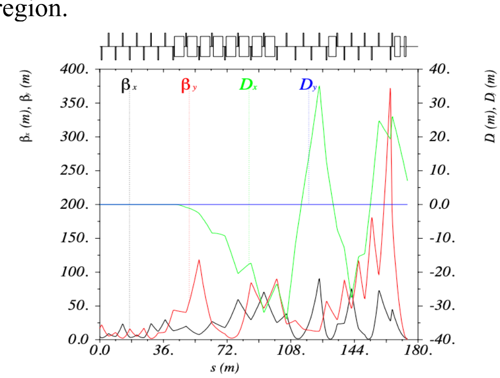

Figure 5: One optimized HEBT optics for LACE injection to the SNS ring.

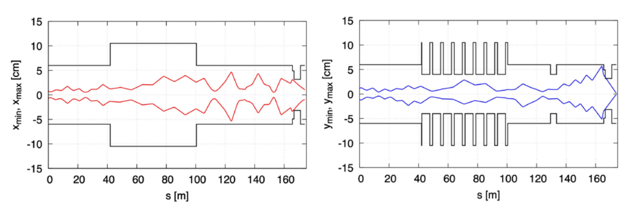

Figure 6: H⁻ beam envelopes (horizontal in red and vertical in blue) with the magnet apertures in the HEBT for LACE.

Preliminary LACE Magnet Design

In its rest frame, an H⁻ beam experiences an electric field when it travels through a transverse magnetic field in the laboratory frame, as a result of the Lorentz transformation. At relatively high energies, typically above 800 MeV, magnetic fields in the range of several kilogauss (up to about 1 T) can be sufficient to strip off the weakly bound electron from the H⁻ ion. Figure 7 shows the stripping rate curves along the beam propagation direction for a 1 GeV H⁻ beam**,** under three different cases of linearly increasing magnetic fields. As observed, the maximum stripping rate occurs at a magnetic field of 1 T, regardless of the field gradient.

However, a rapid increase in magnetic field along the beam path is preferred, as it offers three key advantages. First, it shortens the time required to reach the maximum stripping rate, which results in a smaller energy spread—a condition favourable for subsequent resonant excitation.

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Second, it minimizes emittance growth of the generated protons by reducing the spatial spread caused by varying stripping rates along the beamline. Third, it helps limit the extent of fringe fields, thereby minimizing magnetic field leakage into adjacent magnets in the injection region, which is critical for maintaining field quality and injected beam stability.

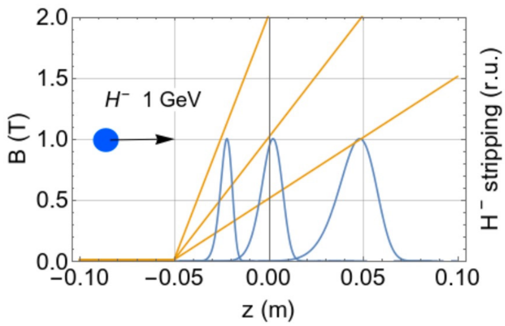

Figure 7: Magnetic field and its corresponding stripping rate along the 1 GeV H- beam propagation direction.

Recently, the design of the LACE stripping magnet has been initiated, taking into account two key considerations: the requirement for a high magnetic field gradient and the limited space available in the injection region. These constraints pose significant engineering challenges for the magnet configuration and mechanical integration.

Figure 8 shows a preliminary magnet design that contains 170 permanent magnets and two vertical poles. Both poles are parallelepiped-shape with tetrahedral pyramid pole tips that ensure the required magnetic field about 1 T at the LACE injection point. The magnet is positioned outside the main beamline, and its geometry is shaped to fit within the aperture constraints of the adjacent chicane magnet. In the LACE injection scheme, two such magnets are needed to strip both electrons from the H^- ion.

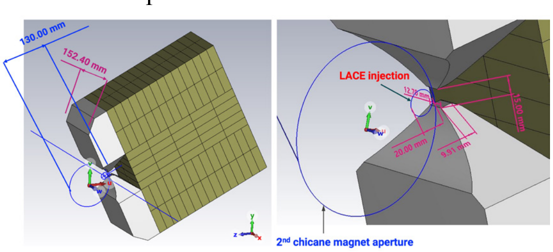

Figure 8: Preliminary design of a customized permanent stripping magnet for the LACE. The left plot shows the overall geometry; the right plot provides a detailed view of injection area.

Figure 9 illustrates the magnetic field distribution from the two LACE stripping magnets. The left plot shows all magnetic fields along the beam line in the transverse plane, including the LACE aperture (small red circle) and the nearby second chicane magnet aperture (large blue circle). The right plot presents the magnetic fields along the beamline at several locations within the LACE aperture.

To achieve the required 1 T magnetic field at the center of the LACE aperture (C), a higher field (>1 T) is observed at adjacent locations (D, E, F) near the poles of the stripping magnet, due to the magnet's geometry. The resulting field distribution is highly nonlinear, posing challenges for beam dynamics in the injection and accumulation of the ring. Design optimization is currently underway to reduce both the magnet size and fringe fields while maintaining the desired stripping performance.

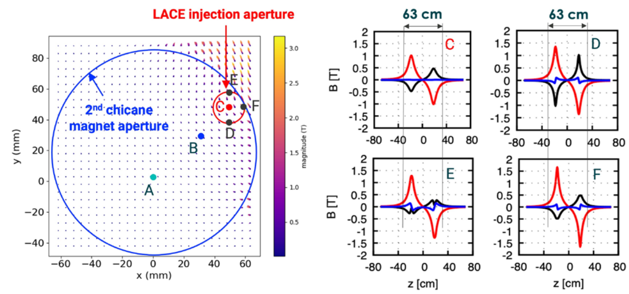

Figure 9: Magnetic field distributions of the two LACE stripping magnets. Left: Magnetic fields plotted in transverse plane (A: designed orbit; B: closed orbit; C: center of LACE aperture). Right: Magnetic field profiles along the beamline at several positions within the LACE injection aperture. 63cm is the current available space in the SNS injection region for LACE scheme.

Beam Dynamics of LACE-produced Proton Beam in the SNS Ring

Progress has been made in exploring the beam dynamics of stripped particles in the SNS ring with a LACE injection system. Simulations have been performed using the code *PyORBIT* [9], incorporating the strongly non-linear magnetic fields shown in Fig. 9.

The SNS accumulator ring employs a correlated painting scheme for injection and accumulation of protons, aiming to minimize foil-induced beam loss and achieve a uniform distribution on the target. A total of eight injection kicker magnets, four in the horizontal plane and four in the vertical plane, are optimized to position the initial circulating beam's closed orbits at the injection point and then steer them away following a square-root time dependence.

Though the optimum conditions are disrupted when the two LACE stripping magnets are introduced, the kicker magnets have the flexibility to be reoptimized for the close orbits. Figure 10 plots the closed orbits under three conditions: without LACE magnets, with LACE magnets before the orbit correction, and with LACE magnets after the orbit correction.

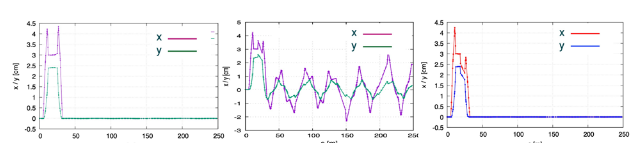

Figure 10: The SNS close orbits (left) without LACE magnets, (middle) with LACE magnets before correcting the orbits, (right) with LACE magnets after correcting the orbits.

While the kicker magnets can effectively compensate for the steering effects from the stripping magnets on a particular orbit, the strong non-linear magnetic fields present a

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significant challenge in correcting the orbits of individual particles within a bunch. This issue is especially pronounced in the LACE scheme, where the beam has a relatively large transverse size, making orbit correction more complex and less uniform across the beam profile. Figure 11 shows the transverse beam distributions obtained from the optimized HEBT optics for the LACE injection. Particles in the same bunch experience significant different magnetic fields in a range of 1-2 T at the ring injection region.

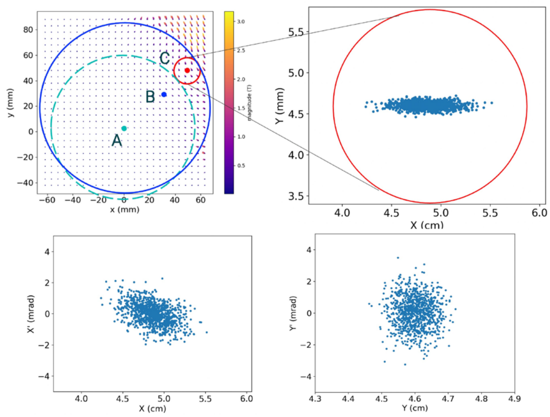

Figure 11: Beam distributions from the optimized HEBT optics for the LACE injection to the SNS ring.

Due to the complexity of orbit correction during the turn-by-turn painting injection and accumulation of proton beams in the SNS ring, simulations have been performed focusing on the circulating beam dynamics to identify potential issues in beam transport. The simulations incorporate the existing SNS ring apertures but currently do not include space charge effects. About 80% of the particles are lost after 500 turns, and Fig. 12 shows the distribution of particle losses along the SNS ring. Several beam loss mechanisms have been identified, including:

- Orbit shifts away from the magnet centers (notably at locations A and E in the injection region)
- Small magnet apertures at locations B, C, and D
- Non-optimized tunes
- Strong resonance-driving terms caused by the large non-linear magnetic fields

Future studies will focus on addressing these issues to improve beam transmission and stability.

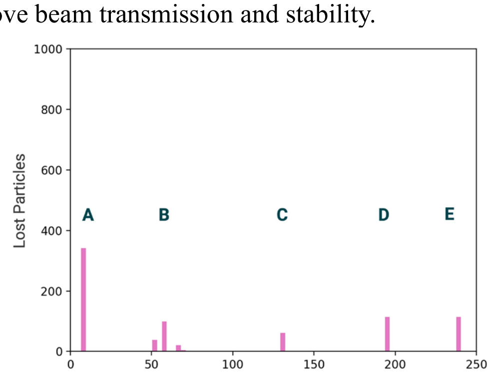

Figure 12: The distribution of particle losses along the SNS ring.

CONCLUSION

Recent progress on the integration of laser-assisted charge exchange (LACE) in the SNS injection region has been made in several key areas. First, the HEBT optics has been optimized to deliver the required H⁻ beam parameters for LACE. This optimization accounts for existing hardware limitations and demonstrates that the HEBT can provide efficient transport of the H⁻ beam to the injection point. Second, a preliminary design of the stripping magnet has been completed. The design meets the requirement for a high field gradient and achieves an optimal 1 T magnetic field necessary for maximum stripping efficiency. Third, beam tracking simulations have been performed using the LACE-generated proton beam in the SNS ring to investigate potential beam dynamics issues. The presence of strong non-linear magnetic fields from the stripping magnets leads to several beam loss mechanisms, which have been identified. Future studies will focus on addressing these challenges to further improve beam transmission and overall stability in the LACE injection scheme.

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