ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC31

DYNAMICS STUDY OF LASER STRIPPING INJECTION OF H^- BEAM IN THE SNS*

F. Lin†, A. Aleksandrov, S. Cousineau, N. Evans, T. Gorlov, Y. Liu, A.R. Oguz, A. Shishlo
Oak Ridge National Laboratory, Oak Ridge, USA

Abstract

A Laser Assisted Charge Exchange (LACE) injection in the Spallation Neutron Source (SNS) is under development. By utilizing powerful lasers and magnetic fields, electrons are stripped off of the H^- beam without foils. Such a process avoids any foil-based charge exchange injection problems, such as foil degradation and beam loss, especially for future multi-megawatt power beams. The principle of LACE has been experimentally demonstrated in the SNS in a transport line. Integration of the LACE injection into the SNS accumulator ring is in progress. In this paper, we present preliminary results of optics design and beam dynamics study.

INTRODUCTION

A charge exchange injection through a thin foil is a mature technology for accumulating proton beams in storage rings. Negative ions of hydrogen (H^-) are stripped of their electrons and converted to protons. The drawback of this foil-based charge exchange process is three-fold: i) high-intensity high-power beam heats up the foil, limiting the foil lifetime, ii) charge exchange increases the phase space volume, and iii) particle scattering through the foil is the main source of beam loss. A Laser Assisted Charge Exchange (LACE) injection in the Spallation Neutron Source (SNS) is under development. This concept, involving practical powerful lasers and relatively strong magnetic fields for stripping of H^- beam without any foil $H^- \rightarrow p^+ + 2e^-$, was initially proposed by I. Yamane and V. Danilov [1-3] and demonstrated in proof-of-principle experiments at the SNS with high stripping efficiency of ~90% for short ns to µs beams in a four-step LACE scheme [4-6]. All LACE experiments in the SNS were carried out on the experimental stand in the LINAC part of the SNS for demonstration of stripping of a single pass beam only.

Therefore, along with further design optimization of the LACE scheme in the SNS [7], integration of the LACE optics and simulation of injection and accumulation of proton beams in the SNS ring have been initiated recently. In this paper, we focus on the discussion of the accelerator optics change due to the strong magnetic fields for LACE and its possible consequences for the beam dynamics in the process of proton beam accumulation during injection into the SNS ring.

Note that, if successful, the LACE injection scheme benefits future accelerators with multi-megawatt power beams; however, it is not required for the SNS proton power upgrade (PPU).

OPTICS

Design and optimization of the LACE scheme are driven by the beam parameters. Therefore, they require customized development of such a scheme for different accelerators. For the SNS accumulator ring operating with a foil-based injection in an existing accelerator facility, it is challenging to integrate a workable LACE design into a limited available space and meet the injection and accumulation requirements.

Several LACE designs have been studied for the SNS [4-7]. The one utilizing two dipole magnets to remove two electrons from the H^- ion is implemented in the optics. In this design, the weaker-bound electron in the ion is stripped when the H^- beam passes through the first dipole magnet. Laser(s), located between the two magnets, are used to excite the remaining electron from the stable ground state to an excited state. This significantly reduces the required magnetic field of the second dipole for stripping the electron when the H^0 beam passes through it. The two dipole magnets have the same field strength but opposite polarities for a net zero integral field to minimize their effects on the existing injection beam line.

Figure 1 shows one possible schematic layout of four existing chicane dipoles (green) and two new LACE dipoles (orange) in the SNS ring injection region. To keep the injection region intact, the two LACE dipoles (horizontal fields) are inserted in a relatively short space of 63 cm, between the 2nd and 3rd dipoles of the chicane. These two dipoles are identical in terms of the field strength of 1.5 T and the length of 14 cm but have opposite polarities. The dipole field of 1.5 T is selected considering a balance of a sufficiently high Lorentz stripping rate and a reasonably high magnetic field [7].

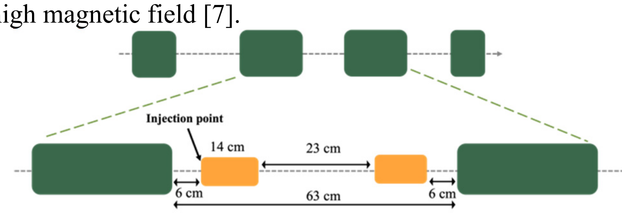

Figure 1: Schematic layout of four existing chicane dipoles (green) and two new LACE dipoles (orange) in the SNS ring injection region.

The new injection region with the LACE dipoles is integrated into the SNS accumulator ring. Figure 2 shows the ring optics, i.e. the Twiss functions and dispersions, under three different conditions: i) proton beam energy of 1 GeV, ii) proton beam energy of 1.3 GeV, and iii) proton beam energy of 1.3 GeV with the LACE dipoles. There is no

* Work supported by UT-Battelle, LLC, under contract DE-AC05-00OR22725.
† Email: linf@ornl.gov

15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC31

difference in the optics for conditions i) and ii) because the magnetic fields ramp up with the beam energy. There are no significant changes on the Twiss functions and horizontal dispersion for the condition iii), compared to conditions i) and ii), due to a net zero integral field of the two LACE dipoles. However, there is a residual vertical dispersion with an amplitude of about 1 cm around the accumulator ring resulting in changes of the betatron tunes shown in Fig. 3.

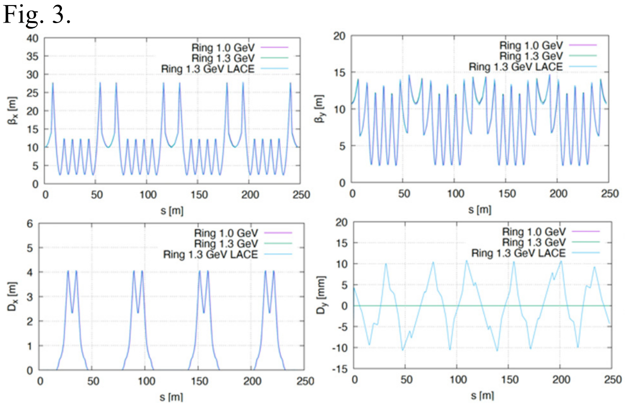

Figure 2: SNS accumulator ring optics under three different conditions: i) proton beam energy of 1 GeV, ii) proton beam energy oft 1.3 GeV, and iii) proton beam energy of 1.3 GeV with the LACE dipoles.

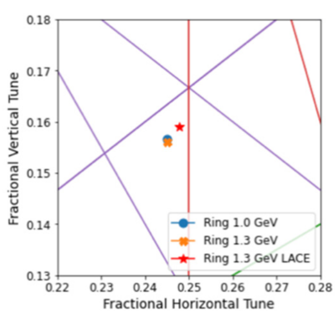

Figure 3: SNS accumulator ring betatron tunes in the resonance diagram for the three different optics conditions listed in Fig. 2.

SIMULATION

Particle tracking simulations are carried out for the SNS accumulator ring with the LACE optics integrated, i.e., condition iii) in Fig. 2. The injection straight is composed of four horizontal chicane dipole magnets (green in Fig. 1), eight injection kicker magnets and the usual quadrupole and corrector magnets. The chicane magnets are on all the time while the kicker magnets ramp down during the injection and accumulation process. In the foil-based SNS operation mode, the H^- beam from the linac merges with the circulating proton beam inside the second chicane magnet. In the proposed LACE scheme for injection into the SNS, the foil is no longer needed and the H^- beam merges with the circulating proton beam after the second chicane magnet. The circulating proton beam sees the two LACE magnets during the entire accumulation process. Though the integral field of the two LACE magnets is zero, it causes a shift in the betatron tunes to the vicinity of strong resonances shown in Fig. 3 and creates non-zero vertical dispersion. In addition to these changes in the optics, the kicker magnets move the circulating beam orbits continuously. Simulation is required to verify the stability of circulating particles during injection.

Tracking simulations take into account two aspects impacting the initial particle phase-space distributions: increase in the vertical emittance due to interaction of the laser and beam, and longitudinal bunch expansion introduced for efficient temporal overlap of a short laser pulse with the ion bunch through a crab-crossing collision scheme [8]. Figure 4 shows the initial particle distributions for 1) originally defined vertical emittance and longitudinal bunch length, 2) vertical emittance increased by a factor of 2 and bunch expanded and rotated through non-zero horizontal dispersion of 4.5 m, and 3) vertical emittance increased by a factor of 2 and bunch expanded and rotated through non-zero horizontal dispersion of 4.5 m and non-zero dispersion slope of 2. The dispersion and its slope create particles' correlation between the longitudinal and horizontal motions, resulting in rotation of the proton bunches in the (z,x) plane as illustrated in Fig. 4 and crab-crossing of the laser pulse and ion bunch.

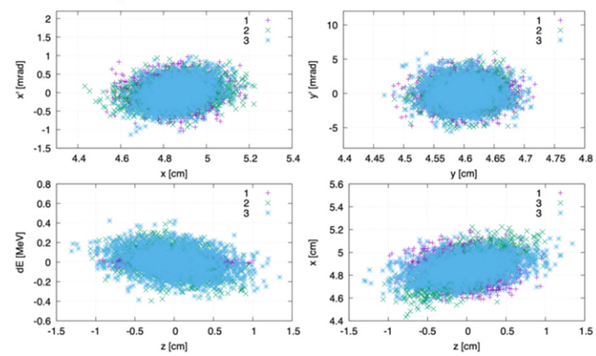

Figure 4: Initial particle phase-space distributions (x,x'), (y,y'), (z,dE) and (z,x) for 1) originally defined vertical emittance and longitudinal bunch length, 2) vertical emittance increased by a factor of 2 and bunch expanded and rotated through non-zero horizontal dispersion of 4.5 m, and 3) vertical emittance increased by a factor of 2 and bunch expanded and rotated through non-zero horizontal dispersion of 4.5 m and non-zero dispersion slope of 2.

The SNS accumulator ring adopts a correlated painting scheme for injection and accumulation of protons to minimize foil hits reducing the beam loss and to provide a more uniform distribution on the target. Our LACE simulation models the same scheme (except for exclusion of the foil) by initially placing the circulating beam's closed orbit right at the injection point and then pulling the closed orbit away with a square-root time dependence.

Figure 5 show the protons' transverse phase-space distributions after accumulation of 30 turns with initial conditions 2) and 3) of Fig. 4. The fractional tunes of 0.25 and 0.15 lead to the fourth- and sixth-fold symmetries in the horizontal and vertical plane distributions, respectively. Figures 6 and 7 show the transverse phase space distributions and their histograms after accumulation of 1000 turns, with initial conditions 2) and 3) of Fig. 4,

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC31

respectively. Note that all simulations are carried out without considering the space charge effect to allow us to explore any potential single particle dynamics issues without nonlinear collective effects.

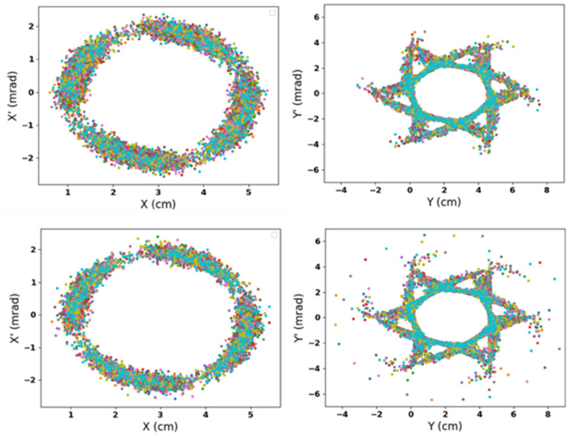

Figure 5: Proton transverse phase-space distributions after accumulation of 30 turns. The plots on the top are for condition 2) of Fig. 4, and the plots on the bottom are for condition 3) of Fig. 4.

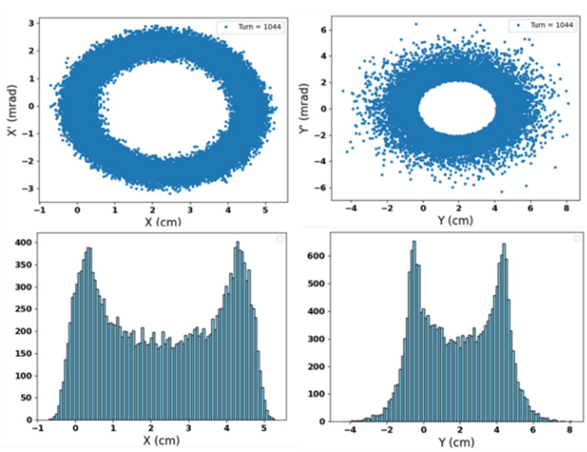

Figure 6: Proton transverse phase-space distributions after accumulation of 1000 turns with initial condition 2) of Fig. 4.

CONCLUSION

Two 1.5 T LACE magnets, with a net zero integral field, are incorporated into the SNS accumulator ring injection region. This mainly results in a vertical dispersion with an amplitude of 1 cm, without too much effect on the Twiss functions and horizontal dispersion. It also shifts the horizontal betatron tune close to the fourth-order resonance. Simulations were carried out in this LACE-integrated lattice. The initial particle distribution considers the increase in the vertical emittance due to interaction of the laser with the beam and the longitudinal bunch expansion required for efficient temporal overlap of a short laser pulse with the ion bunch through a crab-crossing collision scheme. No particle loss is observed in the simulations in the process of proton beam accumulation during injection into the SNS ring.

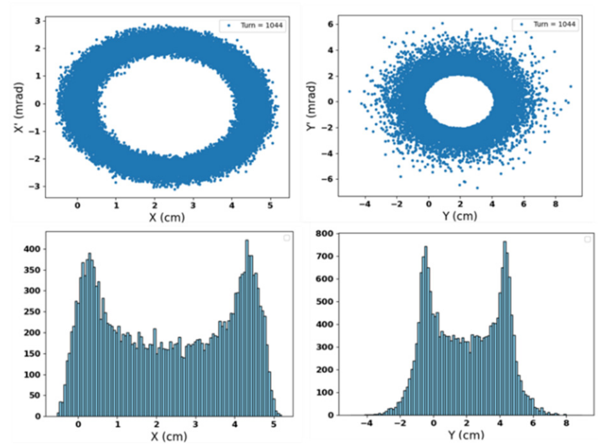

Figure 7: Proton transverse phase-space distributions after accumulation of 1000 turns with initial condition 3) of Fig. 4.

REFERENCES

[1] I. Yamane, "H−charge-exchange injection without hazardous stripping foils," *Phys. Rev. Spec. Top. Accel Beams*, vol. 1, no. 5, p. 053501, Sep. 1998. doi:10.1103/physrevstab.1.053501

[2] V. Danilov *et al.*, "Three-stepH−charge exchange injection with a narrow-band laser," *Phys. Rev. Spec. Top. Accel Beams*, vol. 6, no. 5, p. 053501, May 2003. doi:10.1103/physrevstab.6.053501

[3] V. Danilov *et al.*, "Proof-of-principle demonstration of high efficiency laser-assistedH−beam conversion to protons," *Phys. Rev. Spec. Top. Accel Beams*, vol. 10, no. 5, p. 053501, May 2007. doi:10.1103/physrevstab.10.053501

[4] S. Cousineau *et al.*, "First Demonstration of Laser-Assisted Charge Exchange for Microsecond Duration H− Beams," *Phys. Rev. Lett.*, vol. 118, no. 7, p. 074801, Feb. 2017. doi:10.1103/physrevlett.118.074801

[5] T. Gorlov, A. Aleksandrov, S. Cousineau, Y. Liu, A. Rakhman, and A. Shishlo, "Sequential excitation scheme for laser stripping for a H− beam," *Phys. Rev. Accel. Beams*, vol. 22, no. 12, p. 121601, Dec. 2019. doi:10.1103/physrevaccelbeams.22.121601

[6] A. Aleksandrov *et al.*, "Experimental demonstration of sequential excitation scheme for H− laser assisted charge exchange," *Phys. Rev. Accel. Beams*, vol. 26, no. 4, p. 043501, Apr. 2023. doi:10.1103/physrevaccelbeams.26.043501

[7] T. Gorlov, A. Aleksandrov, F. Lin, N. Evans, and S. Cousineau, "Study of stripping magnets for LACE at the SNS", presented at the IPAC'24, Nashville, TN, USA, May 2024, paper THPR44, this conference.

[8] A. V. Aleksandrov, S. M. Cousineau, T. V. Gorlov, Y. Liu, A. Rakhman, and A. P. Shishlo, "A Crab-Crossing Scheme for Laser-Ion Beam Applications", in *Proc. NAPAC'19*, Lansing, MI, USA, Sep. 2019, pp. 639-641. doi:10.18429/JACoW-NAPAC2019-WEYBB5