

FIRST EXPERIMENTAL DEMONSTRATION OF USING A CRAB-CROSSING COLLISION SCHEME FOR EFFICIENT LASER-TO-ION BEAM INTERACTION*

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Abstract

Lasers are used in many applications with H⁻ beams, including laser charge exchange, laser wire scanners, and laser temporal pulse patterning. In these applications, the H⁻ beams exhibit a wide range of bunch lengths that depend on the focusing by the RF cavities, the energy spread of the beam, and space charge forces. Achieving the required laser pulse length for complete overlap with the H⁻ beam can be challenging in scenarios where available laser power is constrained. A crab-crossing scheme was proposed to achieve efficient overlap of a short laser pulse with an arbitrarily long H⁻ beam pulse. This presentation reports the first experimental demonstration of this technique, which increases the efficiency of laser-to-ion beam interaction in a laser charge exchange experiment at SNS

INTRODUCTION

Lasers have recently been used in many applications involving H⁻ beams, including laser charge exchange, laser wire scanners, and laser temporal pulse patterning [1]. Although the details differ from case to case, all these applications require efficient interaction between ions and photons. The technique described below is being developed for laser-assisted charge injection at SNS, but it can be used for other applications as well.

Charge-exchange injection is used to inject proton beams into circular accelerators. Typically, a thin foil is used to convert accelerated negative hydrogen ions into protons. Passing a high-intensity, high-power beam through the foil leads to foil heating and particle loss due to scattering. Eventually, foil performance and lifetime can become the limiting factors for further increases in injected beam power [2].

An alternative charge-exchange injection scheme, known as laser-assisted charge exchange (LACE), is being developed at the Spallation Neutron Source (SNS) [2]. The scheme uses two magnets to remove the two electrons from the ion. A laser is used to excite the second electron from the ground state to an upper level, thereby reducing the magnetic field strength required in the second magnet. The required laser power is the main limiting factor of this method. Several laser-power-reduction techniques have been proposed, and some have been tested experimentally [3,4].

To mitigate ion-bunch longitudinal expansion in the long beamline between the linac exit and the laser-ion interaction point, we previously proposed a simple crab-crossing collision scheme to improve the temporal overlap between a short laser pulse and a long ion bunch [5]. This

paper reports the first experimental demonstration of this technique and its effectiveness in increasing LACE efficiency.

BUNCH SIZE COMPRESSION

The efficiency of the laser-ion interaction scales with the laser power density $\frac{Q}{a_x a_y a_z}$, where Q is the laser pulse energy and a_i are the laser spot size in horizontal, vertical and longitudinal directions. This power density can be increased either by raising Q or by reducing the spot sizes. However, to maintain good overlap, the laser spot cannot be made smaller than the ion bunch in any dimension. In practice, the ion bunch size therefore sets the lower limit on the laser spot size and becomes the primary constraint on achievable power density.

The SNS accelerator layout is shown on Fig.1.

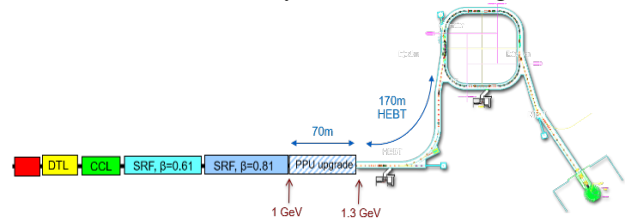


Figure 1: A layout of the SNS accelerator.

The transverse bunch size can be reduced with the quadrupole magnets in the HEBT transport line, down to the limit set by the beam emittance. In contrast, the longitudinal bunch length increases in the $\sim 240\text{m}$ drift between the end of the linear accelerator and in the interaction point due to the particle energy spread; for the nominal linac tune, this evolution is shown by the blue curve in Fig. 2. Because the SNS superconducting linac cavities are independently powered and controlled, several cavities near the end of the linac can be re-tuned to provide longitudinal focusing to the laser-ion interaction point, producing the red curve in Fig.2. However, this approach is effective only at low beam current, since space-charge forces prevent the bunch from remaining longitudinally compressed over a long distance. The bunch-length evolution for zero current and for the nominal 30mA beam current is shown in Fig. 3.

We also considered two other approaches for longitudinal bunch compression: (1) beam optics with a negative momentum compaction factor, in which lower-energy particles follow a shorter trajectory; and (2) installing dedicated RF cavities in the beam line closer to the interaction point.

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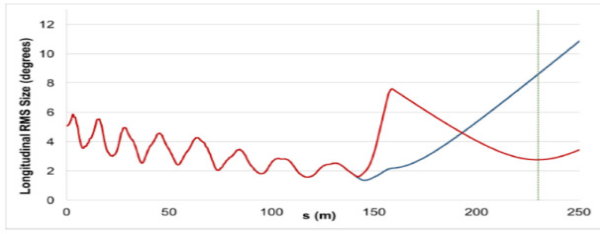


Figure 2: Evolution of the longitudinal bunch size in the SNS linac and HEBT for the nominal (blue) and the longitudinal compression (red) tunes. $1^\circ \approx 3.45\text{ps}$ @805MHz.

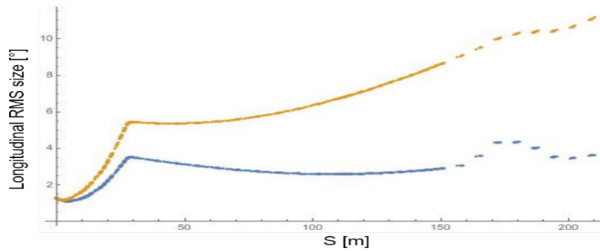


Figure 3: Evolution of the bunch size from the linac exit to the interaction point with bunch compression tune for zero beam current (blue) and 30mA (gold).

For the first option, we were unable to identify a viable solution within the constraints of the existing beamline magnets. The second option would require adding multiple RF cavities and the associated infrastructure to provide a total energy gain of $\sim 15\text{MeV}$, which is cost prohibitive.

Instead, we propose configuring the interaction-region optics to achieve efficient overlap between a short laser pulse and an ion bunch of nominal length, eliminating the need for longitudinal bunch focusing

CRAB-CROSSING COLLISION SCHEME

The bunch length increases in the long drift because of the energy spread: higher-energy particles travel faster and reach the interaction region earlier than lower-energy particles, as illustrated in Fig. 4

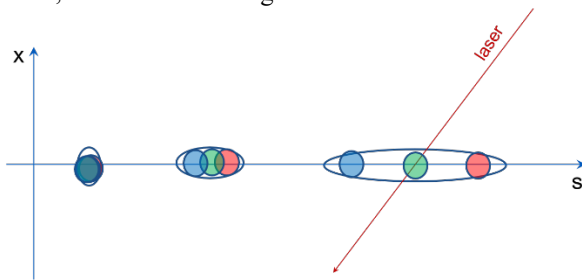


Figure 4: Illustration of longitudinal bunch expansion in a long drift due to energy spread, with the low energy particles shown in blue, the nominal energy in green, and the high energy in red.

With nonzero dispersion at the laser-ion interaction point, the bunch develops an energy-position correlation in the horizontal plane (“rotates” in $x-s$ projection): higher-energy particles are displaced to the left of the reference

trajectory, while lower-energy particles are displaced to the right, as illustrated in Fig. 5.

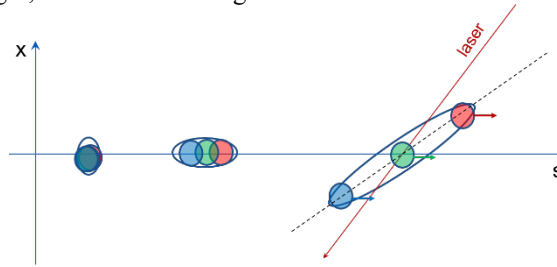


Figure 5: Illustration of bunch rotation with non-zero dispersion function at the interaction point. The color scheme is the same as in Fig.4.

With a suitable rotation angle of the dispersed bunch, a short laser pulse can interact with the entire ion bunch—though different ions interact at different times—so full temporal overlap at any single instant is not required. The kinematics of this process are shown schematically in Fig.6.

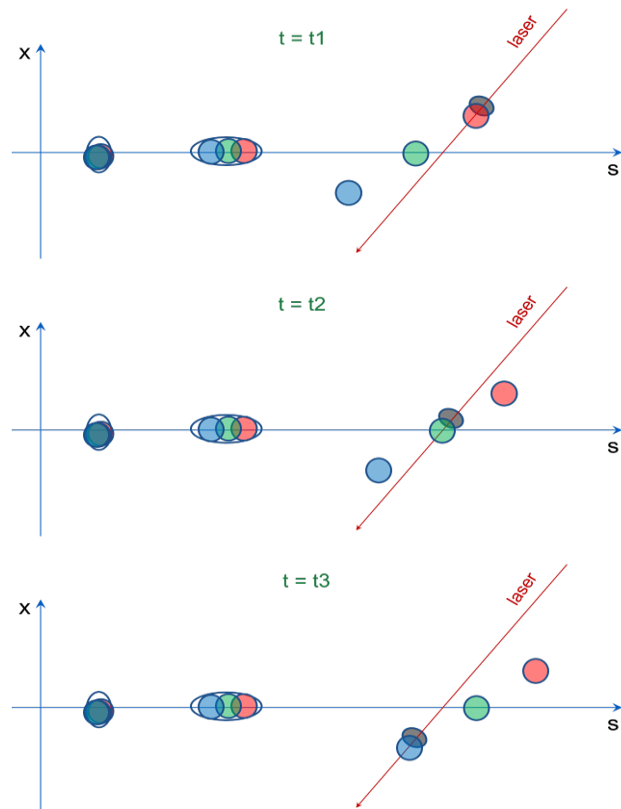


Figure 6: Illustration of crab-crossing collision kinematics. The color scheme is the same as in Fig.4.

It is important to note that all ions in the bunch move in the same direction along the central trajectory, maintaining the correct angle with the laser pulse direction.-The scheme is dubbed “crab-crossing” because the bunch tail-to-head direction is different from the ion motion direction, resembling a crab’s side-wise walk.

The ion-bunch rotation angle is selected so that the laser pulse and the ions remain synchronous as they traverse the interaction region.

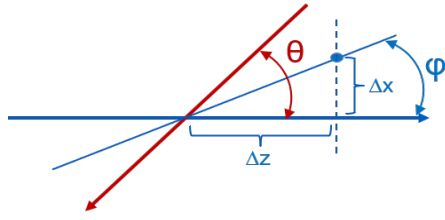


Figure 7: Geometry of the crab-crossing collision. ϕ is the bunch rotation angle, and θ is the angle between the laser and ion beam.

It is easy to derive synchronicity using the geometry shown in Fig.7:

$$\tan \phi = \frac{\sin \theta}{\beta + \cos \theta},$$

where ϕ is the bunch rotation angle, θ is the angle between the laser and ion beam, and β is the ions velocity to speed of light ratio.

The dispersion function required to achieve that bunch rotation is

$$D = \frac{\Delta z}{\Delta w/w} \frac{\sin \theta}{\beta + \cos \theta} \approx \frac{L}{\gamma(\gamma+1)} \frac{\sin \theta}{\beta + \cos \theta},$$

where $\Delta w/w$ is the ions energy spread, γ is the ions relativistic factor, and L is length of the drift from the linac exit to the interaction point. An approximation of bunch expansion in a drift is assumed in the last part of the formula.

EXPERIMENTAL VERIFICATION OF CRAB-CROSSING SCHEME

To verify the effectiveness of the crab-crossing collision scheme, we performed an experiment at SNS using a dedicated experimental station built at the SNS 1.3 GeV High Energy Beam Transport (HEBT) beam line. This station includes a high-power mode-locked UV laser, a laser beam transport line with the final optics and a pointing stabilization system, a vacuum vessel with the stripping magnets, and beam diagnostics. A detailed description of the experimental set up is given in [4]. The ion- and laser-beam parameters are listed in Tables 1 and 2. Figure 8 shows the beam-optics design with the required dispersion function. The goal of the experiment was to strip both electrons from H- using the LACE scheme with and without crab crossing to understand the relative efficiency improvement due to improved laser-ion beam overlap. Achieving the maximum absolute stripping efficiency requires optimizing several more parameters: bunch energy spread, dispersion derivative and the laser beam divergence, which will be done in subsequent LACE technique development experiments.

A histogram of stripping efficiency for a collision with and without crab-crossing is shown in Fig. 9. The relatively wide spread of the histograms is due to the laser beam jitter at the interaction point after propagating through 60m long free space transport line.

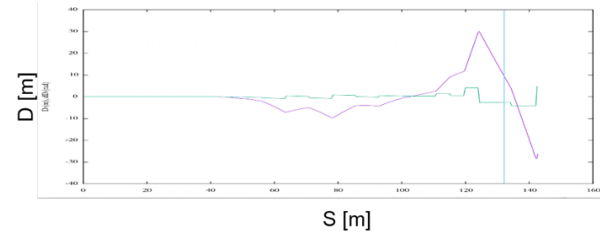


Figure 8: A solution for the dispersion function in the SNS HEBT required for crab-crossing collision at the laser stripping experiment interaction point.

Table 1: Laser Beam Parameters at I.P.

Measurement	Value
Pulse duration	1us
σ_t	~15ps
σ_y	.6 mm
Peak power	1.3MW
Wavelength	355nm
Collision angle	37.5°
RF frequency	402.5MHz

Table 2: Ion Beam Parameters at I.P.

Measurement	Value
Pulse duration	600ns
σ_t	50ps
σ_y	.3mm
Peak current	30mA
Kinetic energy	980MeV
RF frequency	402.5MHz

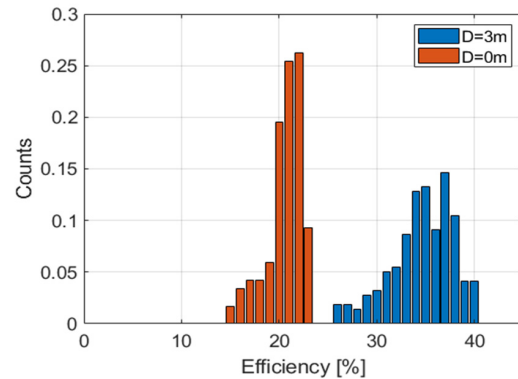


Figure 9 A histogram of stripping efficiency for a collision with and without crab-crossing.

CONCLUSION

A novel laser-ion interaction scheme using a crab-crossing collision geometry was experimentally tested to mitigate ion-beam current limitations caused by longitudinal bunch-length expansion in a long transport line. The tests demonstrated a significant increase in stripping efficiency. To fully utilize the crab-crossing advantage for the LACE efficiency increase, more development is needed to simultaneously optimize other relevant parameters: the bunch energy spread, dispersion derivative and the laser beam divergence. This work is ongoing.

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