A CRAB-CROSSING SCHEME FOR LASER-ION BEAM APPLICATIONS*

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Abstract

Lasers have recently been used in many applications to H- beams, including laser charge exchange, laser wire scanners, and laser temporal pulse patterning [1]. The H-beam in these applications has a wide variation of micro pulse length dependent on the focusing of the RF cavities, the energy spread of the beam, and the space charge forces. Achieving the required laser pulse length for complete overlap with the H- beam can be challenging in some scenarios when available laser power is constrained. The scheme proposed here utilizes a crab-crossing concept between the laser and the ion beam to achieve overlap of a short laser pulse with an arbitrarily long H- beam pulse. An experiment to test the hypothesis in the context of H-charge exchange is described.

INTRODUCTION

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

The charge exchange injection is the technology of choice for injecting beam of protons in circular accelerators. Typically, a thin foil is used to convert accelerated negative ions of hydrogen to protons. Passing a high intensity high power beam through the foil leads to foil heating and particle loss through scattering. Eventually, the foil performance and lifetime can be the limiting factor for further increase of the injected beam power [2].

An alternative charge exchange injection scheme, so called laser-assited charge exchange, or in short laser stripping, is being developed at the Spallatoin Neturon Source (SNS) [2]. The scheme uses two magnets to remove two electrons from the ion. A laser is used to excite the second electron from the ground state to one of upper levels in order to reduce the required magnetic field strength of the second magnet. The required laser power is the main limiting factor of the method. A number of laser power reducing techniques have been proposed and some tested experimentally [3,4]. With all the advances in laser stripping development, practical implementation seems feasible for the SNS accumulator ring after the upcoming linac energy upgrade to 1.3GeV [5].

One of the reamining problems to be resolved is mitigation of the ion bunch longitudinal expansion in the long beam line between the linac exit and the laser-ion interaction point. In this paper we propose a simple method of providing efficient temporal overlapping of short laser pulse with long ion bunch using a crab-crossing collision scheme.

BUNCH SIZE COMPRESSION

The efficiency of the laser-ion beam interaction is proportional to 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 dimensions. The power density can be increased by increasing the pulse energy or by reducing the spot sizes. The laser spot size cannot be smaller than the ion bunch size to ensure good overlap for efficient interaction. In practice, the ion bunch size is the limiting factor. The SNS accelerator layout is shown in Fig.1.

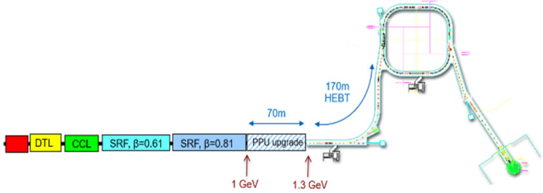

Figure 1: A layout of the SNS accelerator.

The transverse bunch size can be compressed to the limit determined by the ion bunch emittance using the quadrupole magnets in the transport line. A vertical RMS size of 100um was achieved during the laser stripping demonstration experiment [4].

Unfortunately, there are no longitudinally focusing elements between the linac exit and the interaction point. The energy spread of the particles causes the longitudinal bunch size to increase in the ~240m long drift. The longitudinal bunch size evolution for the nominal linac tune is shown by the blue line in Fig.2. The SNS superconducting linac has independently powered and controlled RF cavities. Several RF cavities in the end of the linac can be tuned to focus the bunch longitudinally at the interaction point, as shown in Fig.2 by the red line.

This solution works only for low beam current because the space charge effect does not allow the bunch to remain compressed over a long distance. The bunch size profile evolutions for the zero-beam current and the nominal beam

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current of 30mA are shown in Fig.3. Because of this, the most recent laser stripping demonstration experiment was conducted with a low beam current of 0.6mA [4].

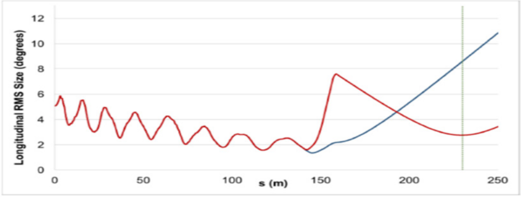

Figure 2: Evolution of the longitudinal bunch size in the SNS linac and HEBT for the nominal (blue) and the longitudinal compression (red) tunes. $1^{\circ} \approx 3.45ps\ @805MHz$.

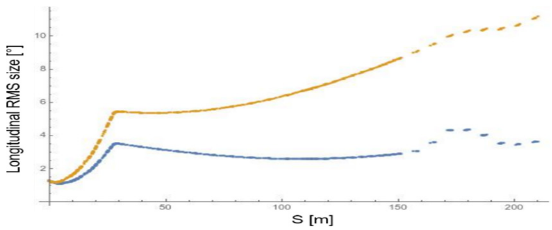

Figure 3: Evolution of the bunch size from the linac exit to the interaction point with bunch compression tune for zero beam current (blue) and 30mA (gold).

Other methods of longitudinal bunch compression we considered were: 1) beam optics with negative momentum compaction factor (trajectory length is shorter for lower energy particles); and 2) dedicated RF cavities in the beam line closer to the interaction point. We have not been able to find a solution within the constraints of the existing beam line magnets for the first option. The second option requires adding several RF cavities with the associated infrastructure to provide a total energy gain of about 15MeV, which is cost prohibitive to incorporate to the existing real estate.

Alternatively, we propose a technique of arranging interaction region beam optics in such a way that efficient overlapping between a short laser pulse and the nominal length ion bunch is provided without the need for longitudinal bunch focusing.

CRAB-CROSSING COLLISION SCHEME

The bunch expansion in the long drift is caused by the energy spread in the bunch: particles with higher energy move faster and arrive to the interaction region earlier than particles with lower energy as illustrated in Fig. 4.

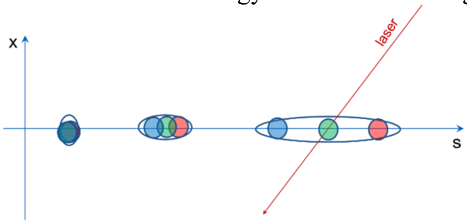

Figure 4: Illustration of longitudinal bunch expansion in a long drift due to ions energy spread, with the low energy particles shown by the blue, the nominal energy by the green, and the high energy by the red circles correspondingly.

The transport line has dipole magnets to bend the beam over a 90° bend. Particles with different energies have different trajectories inside the bend area in accordance with the dispersion function of the beam line. The nominal beam line optics is designed to provide zero dispersion function from the bend exit to the injection point. The beam line magnets have enough tuning range to change the dispersion function and its derivative after the bend exit. If there is non-zero dispersion function at the interaction point, the bunch rotates in the horizontal plane as shown in Fig. 5: the higher energy particles are shifted to the left of the central trajectory, the lower energy particles are shifted to the right.

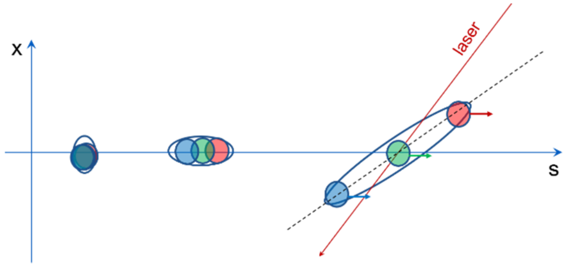

Figure 5: Illustration of bunch rotation with non-zero dispersion function at the interaction point. The color scheme is the same as in Fig.4.

With proper angle of the bunch rotation, a short laser pulse will interact with all ions, though at different time, without need for full overlap at any given moment. Kinematics of the process are shown schematically in Fig. 6.

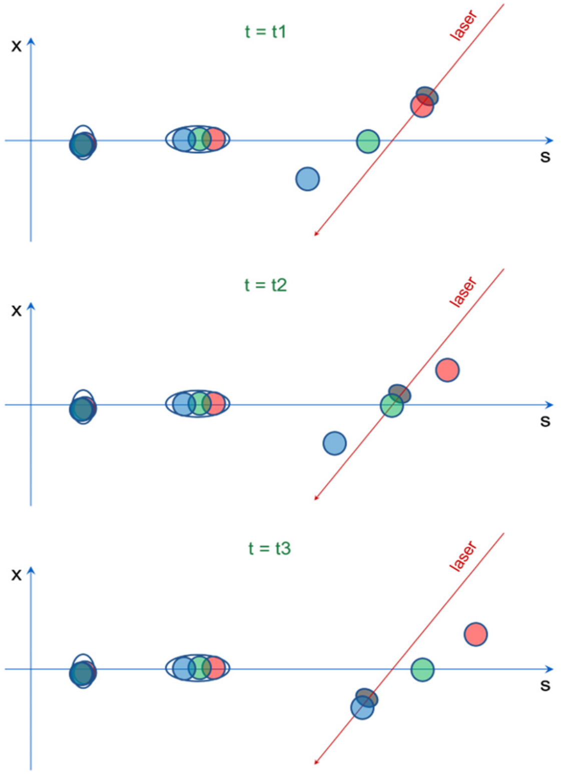

Figure 6: Illustration of crab-crossing collision kinematics. The color scheme is the same as in Fig. 4.

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.

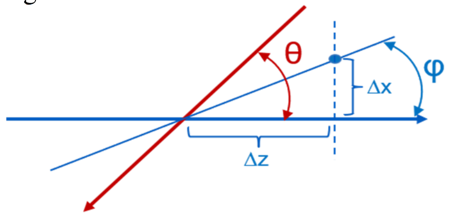

Figure 7: Geometry of the crab-crossing collision. φ is the bunch rotation angle, θ is the angle between the laser and ion beam.

The angle of the ion bunch rotation is chosen to ensure synchronous motion of the laser pulse and the ion bunch. It is easy to derive the synchronicity condition using the geometry shown in Fig.7:

$$\tan\varphi = \frac{\sin\theta}{\beta+\cos\theta} \qquad (1)$$

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

The dispersion function required to achieve that bunch rotation is

$$D = \frac{\Delta z}{\Delta w/w}\,\frac{\sin\theta}{\beta+\cos\theta} \approx \frac{L}{\gamma(\gamma+1)}\,\frac{\sin\theta}{\beta+\cos\theta}, \qquad (2)$$

where dw/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.

For the case of SNS with the linac upgraded to 1.3GeV and using laser with 532 nm wavelength as proposed in [3], the required dispersion function is ~4.6m. This value is close to the design dispersion function in the SNS HEBT (~6.8m) and the SNS Accumulator Ring (4.0m). It is certainly achievable with the existing beam line hardware.

EXPERIMENTAL VERIFICATION OF CRAB-CROSSING SCHEME

To verify efficiency of the crab-crossing collision scheme, we intend to repeat the last laser stripping experiment at SNS with 1GeV beam. No longitudinal focusing will be applied at the end of the linac but the appropriate dispersion function will be created at the interaction point. The required dispersion function for the 1 GeV experiment parameters of ~9.5 m is rather high but achievable with the existing HEBT magnets. Figure 8 shows a beam optics design with the required dispersion function. The maximum beam size in the HEBT bend is rather large for this solution, as shown in Fig. 9, therefore some beam loss is possible. The goal of the experiment is to achieve the stripping efficiency as high as in the previous experiment (>90%) with the nominal beam current of 30mA or maybe slightly lower if some beam will be scraped in the highest dispersion region.

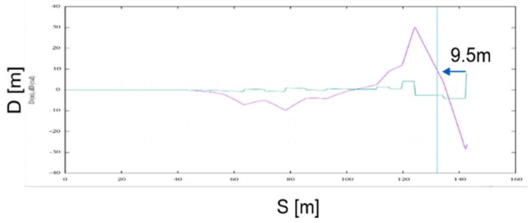

Figure 8: A solution for the dispersion function in the SNS HEBT required for crab-crossing collision at the laser stripping experiment interaction point.

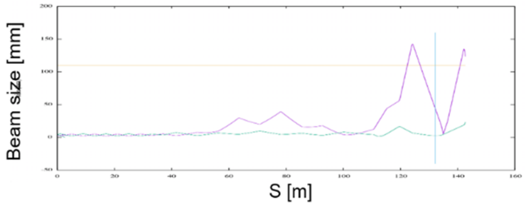

Figure 9: The horizontal (magenta), vertical (blue) beam sizes (4 times RMS) and the beam pipe aperture (gold) for 1GeV crab-crossing experiment.

CONCLUSION

A novel scheme of laser-ion beam interaction using crab-crossing collision geometry is proposed to mitigate the ion beam current limitation due to longitudinal size expansion in a long beam line. The scheme implementation requires creating non-zero dispersion function at the interaction point but no special hardware. An experimental verification of the scheme is in preparation at SNS.

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