32nd Linear Accelerator Conference (LINAC2024),Chicago, IL, USA JACoW Publishing
ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOPB030

SIMULATION AND EXPERIMENT STUDY OF PROTON GENERATED BY RESIDUAL GAS STRIPPING IN CSNS

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Abstract

The CSNS consists of an H^- linac as injector, the interaction of the residual gas with H^- particles will strip the electrons to produce associated protons within the LEBT, which follow the H^- into the subsequent accelerating structure. In order to avoid the adverse effects of proton loss on the device, the feasibility of employing a bump for associated proton separation at the MEBT was investigated firstly using multiparticle tracking simulations. Beam experiment was carried out in the existing CSNS MEBT device, in which the transverse profile signals of the associated protons were observed. Intensity of the associated proton with and without the bump separation are compared downstream the DTL, which proves bump separation is an effective method for the removal of associated protons. The simulation and experimental results can provide scheme references for solving the associated proton problem faced in CSNS-II.

INTRODUCTION

The China Spallation Neutron Source (CSNS) leverages a high-energy proton accelerator to generate neutrons for a diverse array of scientific investigations [1]. The proton accelerator complex presently consists of an 81 MeV H^- linear accelerator and a 1.6 GeV Rapid Cycling Synchrotron (RCS), as shown in Fig. 1. The linac consists of a 50 keV H^- ion source, a low energy beam transport line (LEBT), a 3 MeV Radio Frequency Quadrupole (RFQ), a medium energy beam transport line (MEBT), an 81 MeV Alvarez-type Drift Tube Linac (DTL) [2]. The H^- linac is an injector of RCS, and the charge-exchange injection is adopted to mitigate the space-charge effects. Protons are finally extracted to the target where generates neutron.

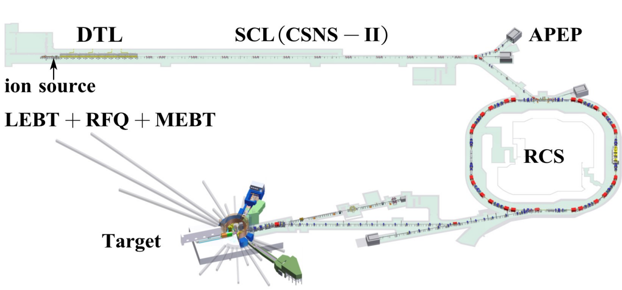

Figure 1: The layout of proton accelerator in CSNS.

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Generation of Associated Proton

H_2 gas flows from the ion source into vacuum pumps in LEBT, H_2 gas is ionized to positive ion such as H_2^+ after colliding with H^- particles to neutralize space charge force. A small fraction of H^+ and H^0 are generated by electron stripping of H^- particles with residual gas [3]. The stripping process is described by Eqs. (1a)-(1c) [4]:

$$H^- + N \rightarrow H^0 + X \tag{1a}$$

$$H^0 + N \rightarrow H^+ + X_1 \tag{1b}$$

$$H^- + N \rightarrow H^+ + X_2\ , \tag{1c}$$

where N is the remnant gas molecule, and X, X_1, X_2 are the other products.

Transportation of Associated Proton

Processes and protons have been observed in other facilities, such as SNS and LAMPF, protons will be absorbed by electrodes of quadrupoles in LEBT immediately. However, CSNS adopts solenoids focusing for LEBT to mitigate the emittance growth with the help of space-charge neutralization effect. In that case, a substantial fraction of the H^+ will reach the RFQ and gradually bunched around the RF phase shifted by 180 degrees with respect to the phase of the H^- bunch. Even worst, H^+ particles can be eventually accelerated to the same energy with H^- of 3 MeV as they have almost the same charge-to-mass ratio with opposite charge. According to the particle tracking simulation, H^+ can transport through the MEBT and captured by DTL. Finally, H^+ will be accelerated to 80 MeV, because there is no RF frequency jump within MEBT and DTL. 80 MeV H^+ is deflected to Associated Proton beam Experiment Platform (APEP) which is opposite to that of H^- [5].

Considerations for Associated Proton Removal

The ongoing upgrade of the CSNS, known as CSNS-II, aims to enhance the linac peak current to 50 mA while the energy increase to 300 MeV, facilitated by a superconducting accelerator featuring Double-Spoke Resonators (DSR) [6] and Elliptical Resonators (EllipR). Most importantly, the Elliptical Resonators operate at RF frequency of 648 MHz, which is twice of the DTL and RFQ. In that case, associated H^+ will be lost in resonators of 648 MHz. In order to avoid contamination of the superconducting resonators, the removal of associated protons generated by residual gas stripping should be considered in advance. Series of research and experiments have been conducted.

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We leverage the differential deflection of H^+ and H^- in a magnetic field, where they deflect in opposite directions, to effectively separate the two particles within the MEBT.

ASSOCIATED PROTON SEPARATION IN CSNS MEBT

The current Medium Energy Beam Transport (MEBT) system at CSNS comprises ten quadrupoles, two bunchers, and six correctors, as illustrated in Fig. 2. Seven Beam Position Monitors (BPMs) are incorporated within the quadrupoles, so as the correctors.

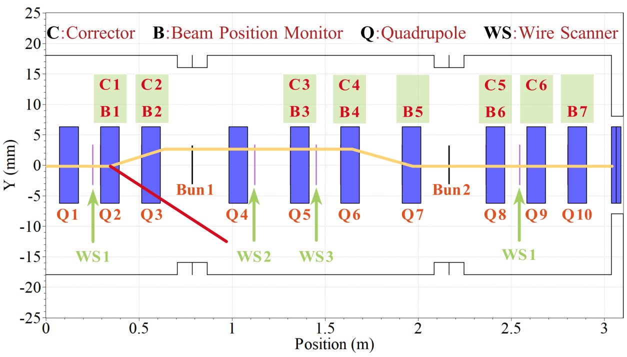

Figure 2: The layout of existing MEBT in CSNS.

Simulation Results

These components have been integrated into the multiparticle tracking simulation software, TraceWin [7]. Additionally, four Wire Scanners are utilized for transverse profile measurements. To achieve the separation of the two beams, a bump is constructed with the aid of transverse correctors. As shown by the orange trajectory in Fig. 2, the H^- are expected to separate from the H^+ (the red trajectory in the figure) by the combined action of the two correctors, C1 and C2, and the dipolar field in the quadrupole Q2 and Q3. Orbit correction using C3/C4/C5/C6 to bring H^- particles back into the DTL acceptance.

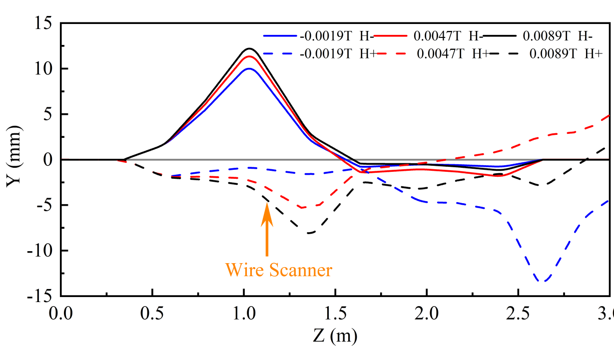

Figure 3: Simulation results of bunch centers with H^- and H^+ particles within MEBT.

The evolution of the bunch center of H^- and H^+ particles within the MEBT with different bump is shown in Fig. 3, in which the magnetic field of C1 is fixed at 0.02 T, while C2 is set to -0.0019 T, 0.0047 T, and 0.0089 T, corresponding to three sets of bunch center trajectory. It can be seen that through orbit correction, H^- particles at different bump all return to the beam axis, and transport in DTL without loss. As there is currently no beam absorber, the H^+ will deviate from the injection orbit of the DTL and be lost inside.

The simulation results of the bunch Y-direction profile at different heights of the orbit at the WS2 location have been analyzed and are shown in Fig. 4.

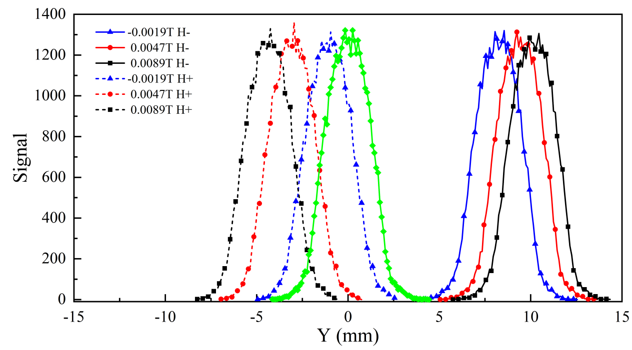

Figure 4: Simulation results of bunch profile at WS2 with different orbit.

Experiment Results

The simulation results demonstrate that the separation of accompanying protons can be achieved by bump trajectory. Subsequently, relevant beam experiments have been conducted on the existing MEBT.

Similar to the simulation, experiments were conducted with three sets of different heights of bump. C1 and C2 were set to the same values as in the simulation, while other correctors were adjusted based on the orbit correction to ensure the beam transmission in MEBT. The Y-direction profiles of the bunch at different bump heights were measured using WS2, as shown in Fig. 5. The image of the signal of the H^+ is locally amplified in the figure. Since the H^- and H^+ particles have opposite charges, the two particles generate signals of opposite polarity on the wires.

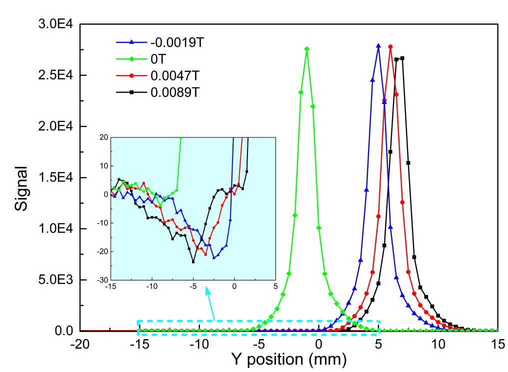

Figure 5: Profiles at WS2 with different bump in the experiments.

For comparison, the experimental and simulation results were compared, as shown in Fig. 6. The voltage signal on the left is produced by H^+, which has been amplified by a

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factor of 1000 as well as polarity reversed. The signal on the right is produced by H^-. Consistent with the simulation results, a distinct separation of the H^- and H^+ bunch in the Y-direction is observed with the implementation of bump. Furthermore, it is evident that the profiles of the two bunch exhibit movement influenced by various bump, aligning closely with the simulation results.

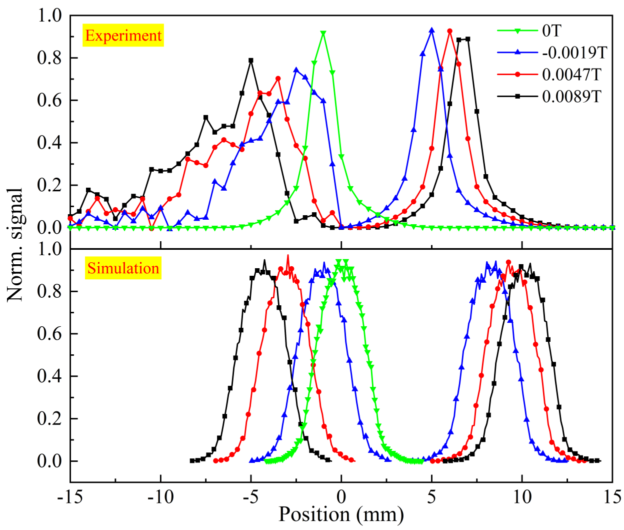

Figure 6: Comparison of profiles at WS2 with different bump between experiments and simulations.

ASSOCIATED PROTON REMOVAL EXPERIMENTS IN CSNS

The experiment was further carried out by re-injecting the orbit-corrected H^-, separated in the MEBT experiment, into the DTL for acceleration to 80 MeV, and recording the transmission along the linac. The H^+ current was recorded in the APEP terminal. The H^+, not subject to orbit correction, experience losses within the MEBT and upon injection into the DTL, leading to a decrease in current towards the APEP terminals. The experiment was set up with different heights of bump, as shown in Table 1 and Fig. 7 to verify its effect on the removal of H^+. The No. 1 set of corrector serves as the experimental control group with no bump.

Table 1: Corrector Magnetic Field in Experiments

No.	C1	C2	C3	C4	C5	C6
1	0	0	0	0	0	0
2	187	-219.4	32.3	69.8	43.5	-41.8
3	142.6	-181.2	32.3	69.8	43.5	-41.8
4	69.7	-76.3	32.3	56.8	43.5	-32.2
5	38	-50.9	32.3	56.8	43.5	-32.2

Unit: Gs

The results of the experiment are shown in Fig. 8. As the bump orbit is raised, the current of H^+ decreases, reaching 0 µA at No. 4. Throughout this progression, there is a decline in the transmission of MEBT for H^-, while the transmission in other sections remain above 99.5%. Further elevation of the bump results in the MEBT transmission dropping to 97%, signifying transverse loss of H^- towards the vacuum pipe. The experiment demonstrates that under the effect of bump at an appropriate height, H^+ is separated and unable to transport normally, whereas, after orbit correction, H^- can be accelerated and transport normally.

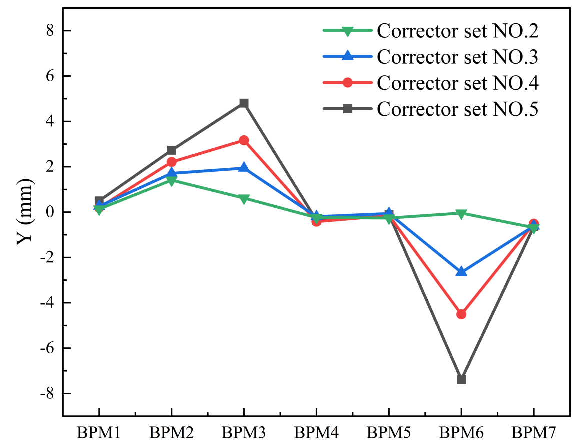

Figure 7: BPM signal in MEBT with different sets of correctors.

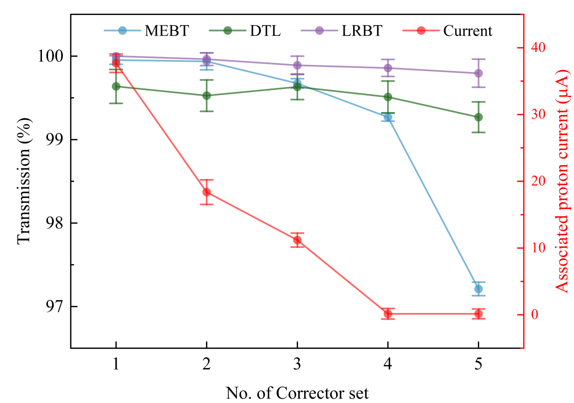

Figure 8: Transmission of H^- along the linac and current of H^+ in APEP with different bumps.

SUMMARY

The feasibility of utilizing a bump in MEBT of CSNS to separate associated H^+ generated by residual gas collisions was initially confirmed through multiparticle tracking simulations. Subsequently, beam experiments were conducted, the transverse profiles at various bump heights were measured using Wire Scanners. The movement of bunch positions for H^+ and H^- under different bump settings aligned with the simulation results. Additional beam experiments focused on the removal of associated H^+ were carried out. By employing the APEP terminal, it was validated that the bump can ensure the unaffected transport of H^- while effectively separating and removing the H^+. These findings serve as a valuable reference for the removal of associated H^+ in CSNS-II.

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