ISBN: 978-3-95450-200-4 doi:10.18429/JACoW-ICAP2018-WEPAF02

SIMULATIONS OF BEAM CHOPPING FOR POTENTIAL UPGRADES OF THE SNS LEBT CHOPPER*

B. X. Han†, V. V. Peplov, R.F. Welton, R. B. Saethre, S.N. Murray Jr., T. R. Pennisi, C.M. Stinson, M. P. Stockli, SNS, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

Abstract

The LEBT chopper is a critical element of the SNS accelerator system. In this work, the benefit of increasing the chopping voltage amplitude for the present chopping pattern is shown with beam simulations, and an ongoing hardware upgrade of the chopper pulser units is discussed. In addition, with the prospect of higher voltage capability of the new pulser design, two alternative chopping patterns which reduce the switching frequency of the chopper pulsers down to ½ or ¼ of the present chopping pattern, are also explored with beam simulations.

INTRODUCTION

The Spallation Neutron Source (SNS) accelerator system consists of a 65 keV H^- injector, a 2.5 MeV RFQ, a 1 GeV linac chain (DTL-CCL-SCL), and a proton accumulator ring. The H^- injector is made of a RF-driven, Cs enhanced H^- ion source and a two-lens electrostatic low energy beam transport (LEBT). The injector feeds the RFQ accelerator with 1 ms long H^- beam pulses at 60 Hz. Figure 1 shows a cross-section view of the SNS H^- injector.

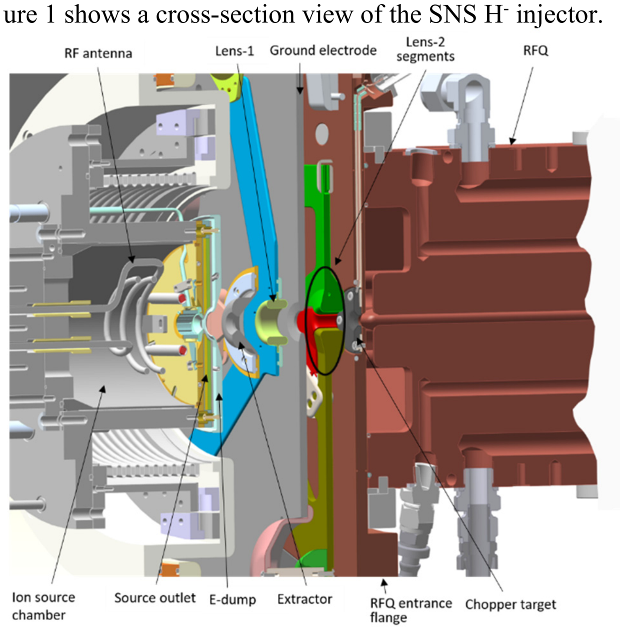

Figure 1: A cross-section view of the SNS H^- injector.

To facilitate the multi-turn beam stacking in the accumulator ring and to create gaps for clean beam extraction from the ring, the 1 ms H^- pulses are chopped ~300 ns at the ring revolution frequency (~1 MHz) in the LEBT in front of the RFQ. The second lens electrode of the LEBT is azimuthally split into four segments to allow applications of various transverse electric fields on top of the lens voltage for beam steering (misalignment correction), chopping or blanking. A donut-shape TZM plate surrounding the RFQ entrance aperture serves as chopper target as shown in Figure 1 [1, 2].

THE PRESENT CHOPPING PATTERN AND BEAM SIMULATION

The Present Chopping Pattern

The four segments of the lens-2 are driven independently by four bipolar high voltage pulsers for beam chopping. With the present chopping pattern, a pair of neighbouring two segments are driven to negative potential and the other two are driven to positive potential, i.e. the lens-2 segments are driven as two opposing pairs with opposite potentials, to generate the transverse field needed for beam chopping. The waveforms of the four pulsers are configured in a manner as shown in Figure 2 so that the beam deflection is sequentially rotated to four different directions to avoid sputtering and heat loading at a single spot on the chopper target. The lens-2 is oriented in a way that the beam deflection directions coincide with the gaps between the neighbouring vanes of the RFQ to minimize ions impacting the vanes if the beam is not completely intercepted at the chopper target during beam chopping [3].

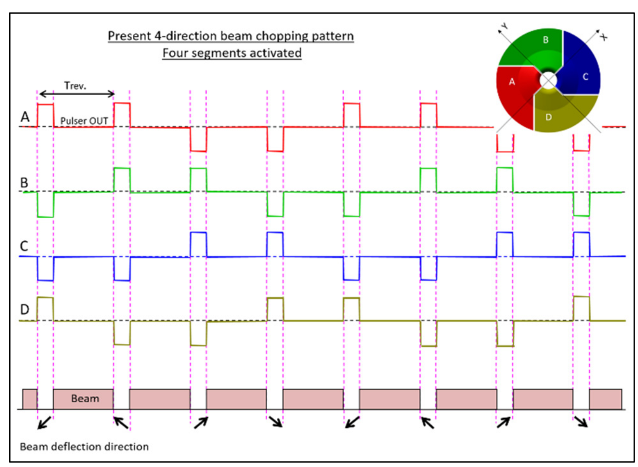

Figure 2: Bipolar chopping voltages applied sequentially on opposing pairs of the lens-2 segments.

Beam Simulations

The SIMION 8.1 code [4] was used to track the ions starting from the ion source outlet aperture to the RFQ vanes. A total of 10000 H^- ion macro-particles were launched with a total charge of 1.5×10^{-8} coulomb over 0.25 µs to simulate the space charge effect of a 60 mA

* This work was performed at Oak Ridge National Laboratory, which is managed by UT-Battelle, LLC, under contract number DE-AC05-00OR22725 for the United States Department of Energy.
† hanb@ornl.gov

ISBN: 978-3-95450-200-4 doi:10.18429/JACoW-ICAP2018-WEPAF02

beam. Typical operational voltage settings on the ion source and LEBT electrodes were used for beam transport, and different chopping voltages were superimposed on the lens-2 segments to examine the beam chopping performance. The tips of the RFQ vanes were included in the geometry, but the RFQ fields were not modeled. Shown in Figure 3 is a simulation of beam transport through the LEBT and injection into the RFQ. In Figure 4, the X-X′ phase space distribution output from the SIMION simulation is plotted at the RFQ injection reference plane along with an output from PBGUNS (a 2-D code capable of plasma emission model) [5] simulation and a real emittance measured on an injector test stand. The RFQ acceptance ellipse with 4x normalized rms emittance, $4\varepsilon_{n,rms}$ = 1.4 π mm·mrad, and α= 1.6, and β = 0.06 mm/mrad is overlaid on the phase-space plots. The SIMION output agrees reasonably well with PBGUNS output and (more importantly) with the real measurement data in terms of overall beam size and angle.

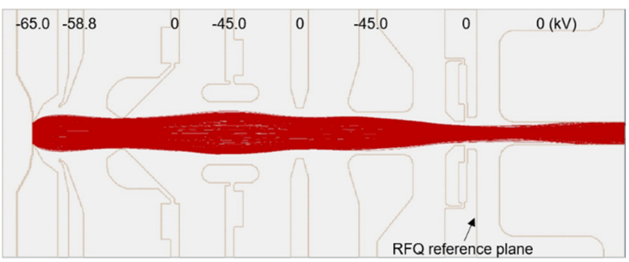

Figure 3: SIMION simulation of beam transport through the LEBT and injection into the RFQ.

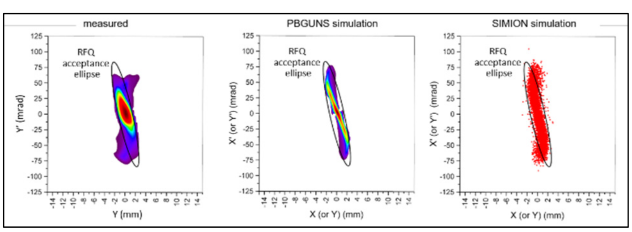

Figure 4: X-X′plots of the injected beam at the RFQ injection reference plane for a measured emittance and outputs from simulations with PBGUNS and SIMION.

Figure 5 shows a case of simulation of beam chopping. Bipolar voltages ±2.5 kV, the maximum voltage amplitude available for routine operation, were applied on opposing two pairs of the lens-2 segments representing one of the four chopping cycles illustrated in Figure 2. This figure shows a cross-section view on the plane of beam deflection and its isometric view is shown at the bottom.

To evaluate beam chopper performance in simulations, first of all, we examine the primary goal of beam chopping, i.e. deflecting the beam out of the RFQ acceptance either in real space or in position-angle phase space; meanwhile we also check the beam spot profile on the chopper target and the behavior of the fraction of the beam that enters the RFQ cavity if the beam was not fully intercepted at the chopper target. Figure 6 shows the deflected beam (in red dots) at three longitudinal locations, 1) at the front face of the chopper target, plotted vs. the RFQ entrance aperture and the injected beam (green dots) in real space, 2) at the RFQ reference plane, plotted vs. the RFQ acceptance ellipse and injected beam in X-X′ phase space (X axis is aligned with the beam deflection direction), and 3) at the tips of the RFQ vanes. Simulations were conducted for higher voltage amplitudes with ±3.0 kV and ±3.5 kV in addition to the case of ±2.5 kV, and the results are shown in Figure 6.

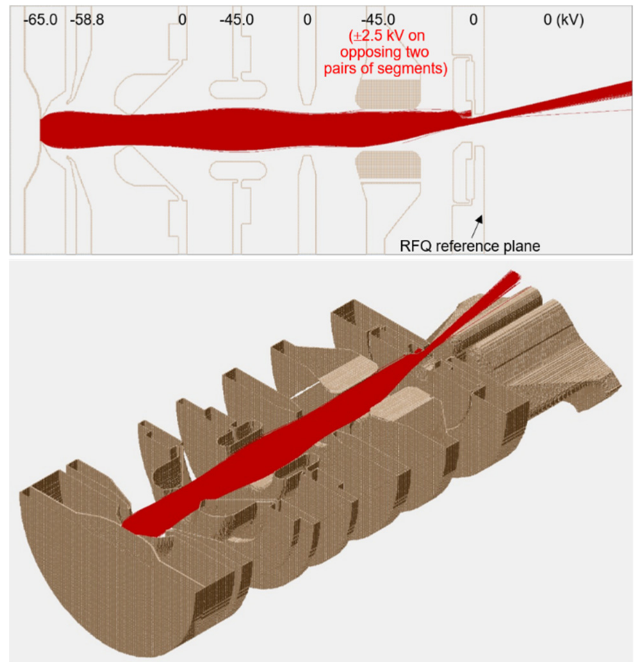

Figure 5: SIMION simulation of beam chopping with ±2.5 kV on the opposing two pairs of the lens-2 segments.

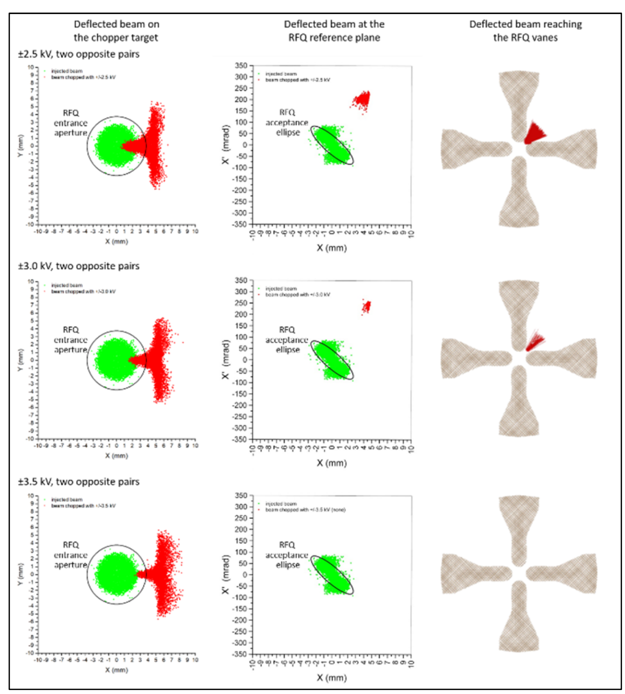

Figure 6: Simulation outputs for chopping with ±2.5, ±3.0, and ±3.5 kV on opposing pairs of lens-2 segments.

ISBN: 978-3-95450-200-4 doi:10.18429/JACoW-ICAP2018-WEPAF02

It can be seen from Figure 6 that chopping with ±2.5 kV deflects the beam adequately out of the RFQ acceptance ellipse. In practice, post-RFQ beam current waveforms show clean gaps created with ±2.5 kV chopping, as shown in Figure 7.

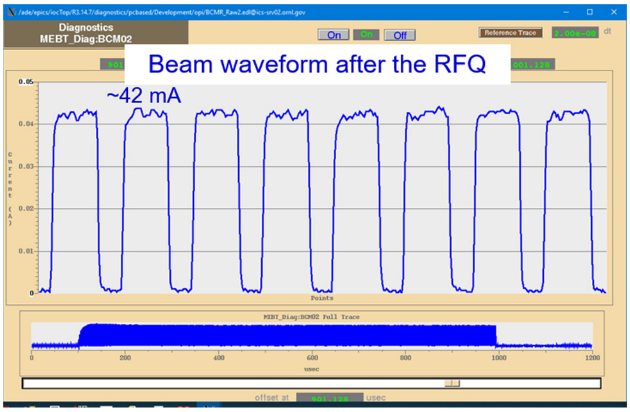

Figure 7: Chopped post-RFQ beam waveform.

However, the simulation indicates that a fraction of the beam is able to reach and impact on the RFQ vane tips. Erosion damage has been observed on the vane tips of the old RFQ which was replaced with a new one after ~16 years operation. While this is not the only scenario of ions impacting on the vane tips (others include blanking a short beam at the start and end of the 1ms pulses, and inadequate deflection of ions during the unavoidable rise and fall time of chopper pulsers [6]), it is important to mitigate the effect as much as possible. Increasing the chopping voltage amplitude is desired to reduce the amount of beam entering the cavity and reaching the vane tips during chopping. The simulation suggests, chopping with ±3.0 kV further separates the deflected beam from the RFQ acceptance ellipse and seems to also clear the beam from RFQ vanes. Increasing the voltage to ±3.5 kV appears to completely deflect the beam out of the RFQ entrance aperture and eliminate beam entering into the RFQ cavity during chopping.

THE CHOPPER PULSER HARDWARE UPGRADE EFFORT

The existing high voltage pulsers of the SNS LEBT chopper have become obsolete in terms of spare parts. Furthermore, they are functionally limited to maximum voltages of about ±2.5 kV due to arcing and power dissipation issues. A new bipolar pulser has been designed, and a prototype has been built and tested on a test-bench. The pulser uses fast push-pull transistor BEHLKE switch modules. A schematic of the new pulser unit is shown in Figure 8. According to test-bench results, the new pulser is capable of driving ±3.5 kV and up to ±5.0 kV is expected with further development. The new pulser unit also features reduced rise/fall time, improved timing stability, minimized power losses and better cooling [7].

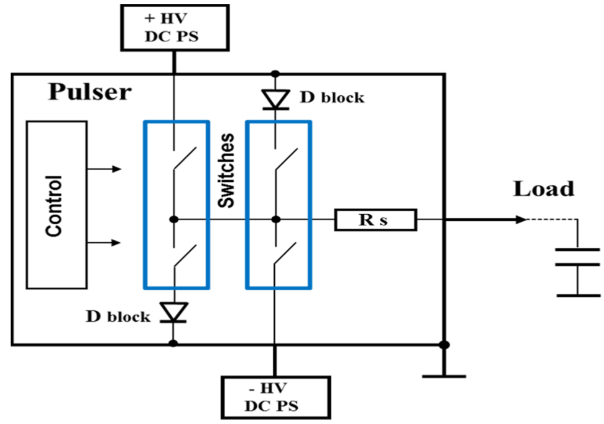

Figure 8: A schematic of the new design pulser unit.

EXPLORING POSSIBLE ALTERNATIVE CHOPPING PATTERNS

Proposed New Chopping Patterns

With the prospect of increased high voltage capability of the chopper pulser hardware, there are possibilities of alternative new chopping patterns. These involve activation of only two or even just one segment of the lens-2 at a time during beam chopping, and thus reducing the switching frequency of each of the four pulsers down to ½ or ¼ of the present chopping pattern. With reduced switching frequencies, the switches have more time to recover from charging and discharging cycles. The average currents flowing through the switches are also reduced. Less stress and less heat dissipation are desirable for operational reliability of fast HV switches.

Figures 9 and 10 are voltage waveforms of the four individual segments of lens-2 for the two alternative chopping patterns being considered. To deflect the beam in the directions of gaps between the RFQ vanes in the same way as the present chopping pattern, the lens-2 needs to be rotated azimuthally by 45°. The chopping pattern of Figure 9 was proposed in [6] with preliminary beam simulation results.

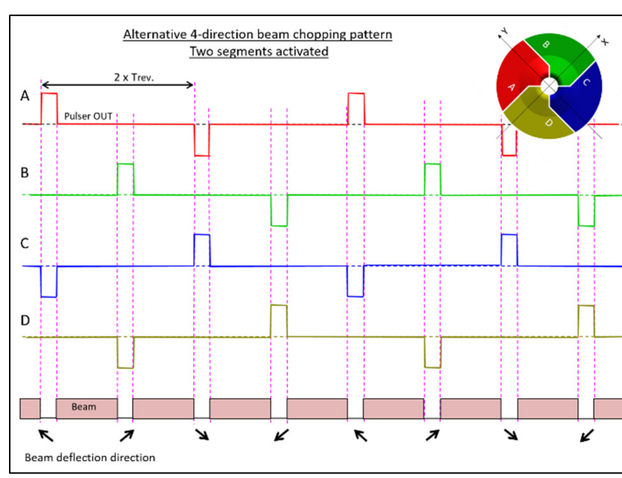

Figure 9: Bipolar chopping voltages applied sequentially on opposing segments of lens-2.

ISBN: 978-3-95450-200-4 doi:10.18429/JACoW-ICAP2018-WEPAF02

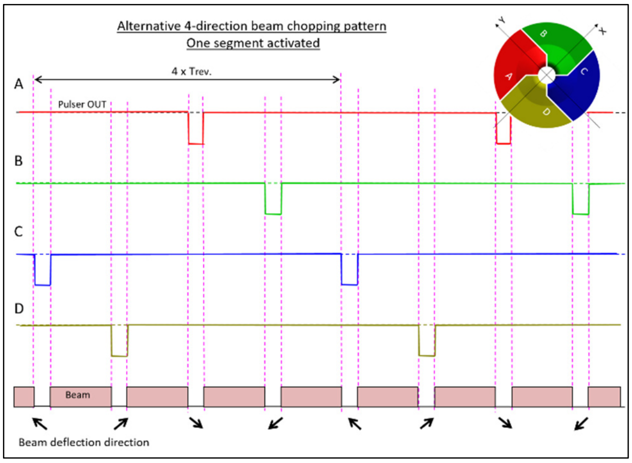

Figure 10: A negative chopping voltage applied sequentially on segments of lens-2.

Simulations of Beam Chopping

Simulations were conducted for the proposed new chopping patterns with different voltage amplitudes for the opposing two segments starting from ±2.5 kV up to ±5.0 kV and -8.0 kV for the single segment case. Figure 11 shows visualization of beam deflection for the ±2.5 kV case, as in Figure 5. Figure 12 summarizes the outputs of all simulation runs for the new chopping patterns in the same way as in Figure 6.

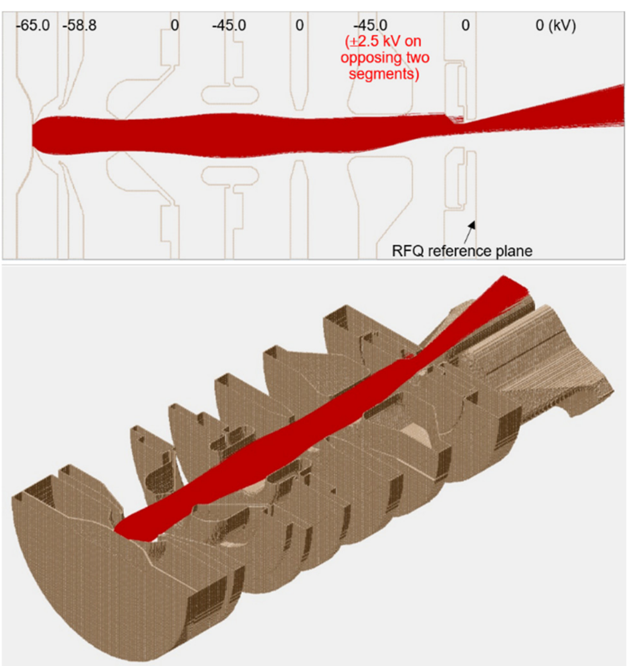

Figure 11: SIMION simulation of beam chopping with ±2.5 kV on the opposing two segments of lens-2.

The simulation output suggests that the proposed new chopping patterns require higher voltage, such as ±4.0 kV (-8.0 kV for single segment case) or more to achieve separation of the beam from the RFQ acceptance ellipse with reasonable margin. Clearing the RFQ vane tips from impacting ions would require even higher voltage - beyond the capability of the chopper pulsers under development. For the single segment chopping case, it is a serious challenge at this point to achieve the required voltage amplitude even with the new chopper pulsers.

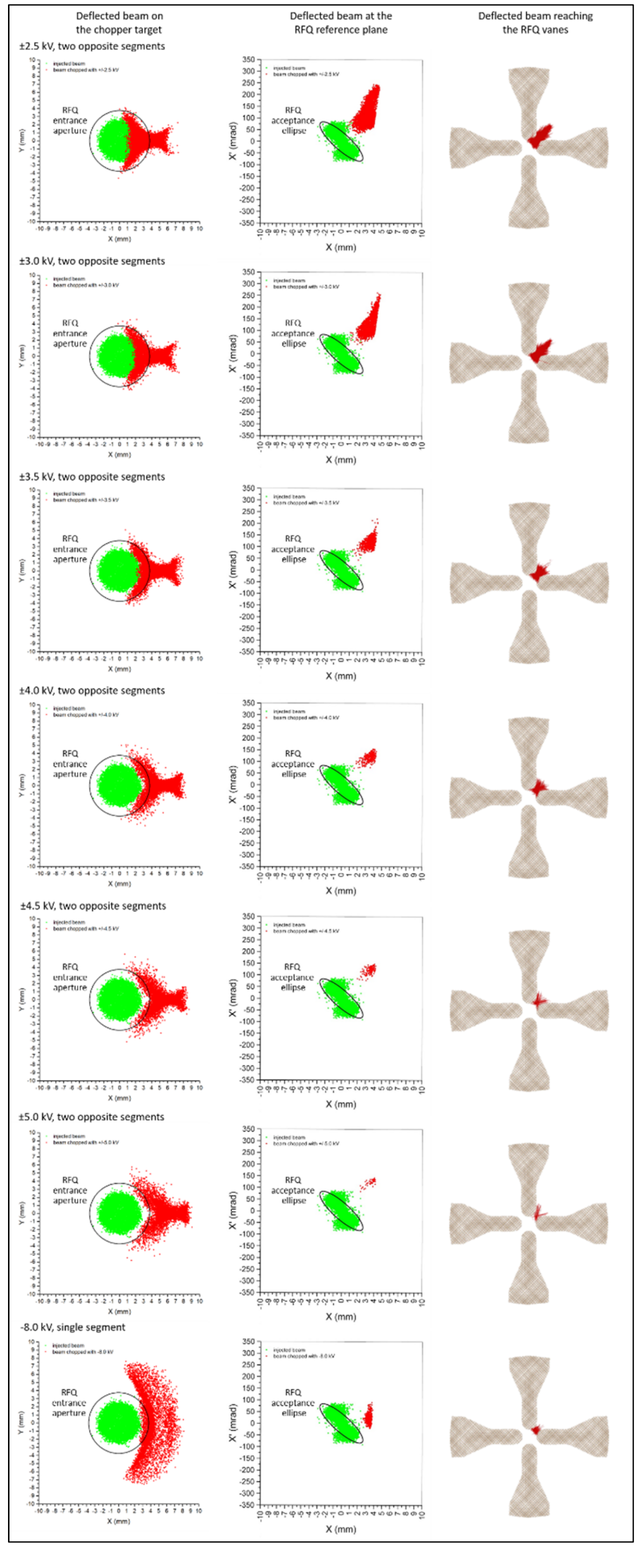

Figure 12: Simulation outputs for chopping with ±2.5, ±3.0, ±3.5, ±4.0, ±4.5, ±5.0 kV on opposing segments or -8.0 kV on a segment of lens-2.

ISBN: 978-3-95450-200-4 doi:10.18429/JACoW-ICAP2018-WEPAF02

Concern with Beam Scraping on lens-2

As shown in Figure 13, for the same voltage difference, the Ex field inside the lens-2 aperture is substantially lower for the case of 2-segment chopping pattern compared to the two-pair pattern, especially in the outer region along the Y axis. So, much higher voltage difference is needed to achieve the deflection for the outer ions, but the ions in the center of the beam will start to scrape the lens-2 electrode if the voltage amplitude is too high, e.g. ±4.5 kV as shown in Figure 14.

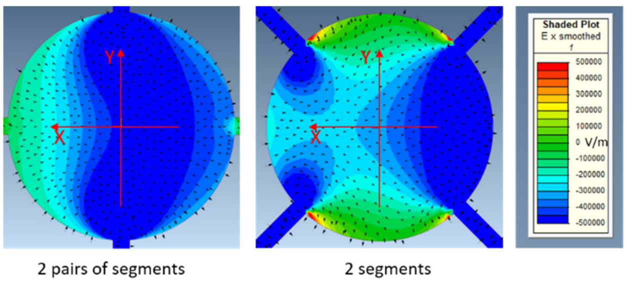

Figure 13: Comparison of Ex field distributions of the two-pair and two-segment chopping.

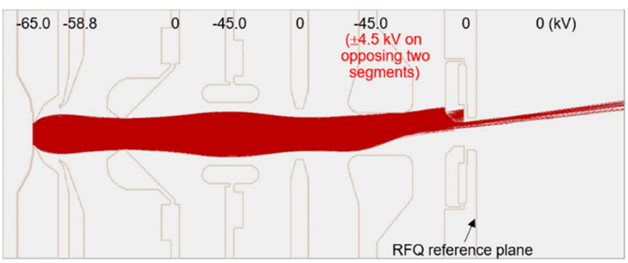

Figure 14: Beam scraping on the lens-2 electrode.

SUMMARY

A description of the SNS H$^-$ injector with LEBT beam chopper was given. Beam simulations were conducted for the present beam chopping pattern, which involves activation of all four HV pulsers at the same time. Simulations indicate voltage amplitude higher than the presently limited 2.5 kV is desired to minimize ions impacting on the RFQ vane tips. An ongoing effort to upgrade the chopper pulser hardware to enable higher voltage capability was discussed, ±3.5 kV has been achieved on a test-bench and ±5.0 kV is expected with further development. With the prospect of higher voltage capability by new design pulsers, possible alternative beam chopping patterns which involve activation of only two or even just one pulser at a time were explored. The proposed new chopping patterns will significantly reduce the stress on the HV switches due to reduced switching frequencies. But, beam simulations suggest higher voltage amplitude, ±4.0 kV or above, is required to deflect the beam out of the RFQ acceptance ellipse with reasonable separation. Clearing the RFQ vane from impacting ions requires even higher voltage amplitude, but beam scraping on lens-2 will become a concern.

REFERENCES

[1] R. Keller, R. Thomae, M. Stockli, and R. Welton, "Design, Operational Experiences and Beam Results Obtained with the SNS H$^-$ Ion Source and LEBT at Berkeley Lab" in *AIP Conf. Proc.*, vol. 639, pp. 47, 2002.

[2] Martin P. Stockli, Robert F. Welton, and Baoxi Han, "Record productions establish RF-driven sources as the standard for generating high-duty-factor, high-current H- beams for accelerators", *Rev. Sci. Instrum.*, vol. 89, pp. 052202, 2018. doi:10.1063/1.5025328

[3] J. W. Staples, J. J. Ayers, D. W. Cheng, J. B. Greer, M. D. Hoff, and A. Ratti, "The SNS Four-phase LEBT Chopper", in *Proc. PAC'99*, New York, NY, USA, Mar-Apr 19999, pp. 1961-1963.

[4] SIMION, https://simion.com/

[5] PBGUNS, https://www.far-tech.com/pbguns/

[6] V. Peplov, B. Han, R. Saethre, and M. Stockli, "Alternative configuration and timing control for beam chopping system at the SNS linac", in *Proceedings of the IEEE 21st International Conference on Pulsed Power (PPC)*, Brighton, UK, 2017

[7] Vladimir V. Peplov, and Robert B. Saethre, "Performance of High Voltage Bipolar Pulse Generator with Fast Push-Pull Solid-State Switch Modules", to be published.