THE DEVELOPMENT OF COMPUTATIONAL TOOLS FOR HALO ANALYSIS AND STUDY OF HALO GROWTH IN THE SPALLATION NEUTRON SOURCE LINEAR*

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Abstract

Computational tools have been developed to quantify the halo in the Spallation Neutron Source (SNS) linear accelerator by analyzing beam profiles and identifying the halo particles using the Gaussian area ratio and kurtosis methods. Simulations of various injection quadrupole magnet settings using three types of initial simulated distributions, along with an analysis of their phase space and rms properties, provides insight into the development of halo in the SNS linac. Finally, comparisons with machine beam profile data, taken at the same conditions as that of the simulated data, show how accurately the simulations model the beam and its halo development and provide a better understanding of the best matching quadrupole settings with which to minimize beam halo and losses.

SPALLATION NEUTRON SOURCE

The Spallation Neutron Source (SNS) is a third generation pulsed neutron source recently completed at the Oak Ridge National Laboratory in Oak Ridge, Tennessee. An ion source produces 1 millisecond macropulses of H^- ions. The Radio Frequency Quadrupole (RFQ) creates micropulses at 402.5 MHz. Choppers are used to create 300 nanosecond gaps from the macropulse for clean extraction from the ring. The resulting 645 ns minipulse is accelerated to 2.5 MeV and injected into the main accelerating structure. Drift Tube Linac (DTL) and Couple Cavities Linac (CCL) structures are used to accelerate the beam to 186 MeV. The superconducting linac accelerates to 1 GeV. The resulting protons are accumulated in the ring and delivered in 1 microsecond pulses to the liquid mercury target.

MINIMIZING BEAM LOSSES

Excessive beam loss and subsequent activation of accelerator components is a limiting factor in the performance of high-intensity accelerators. The design beam power of the SNS is 1.44 MW. As a result, minimization of beam loss is of paramount importance to allow “hands on” maintenance of the accelerator. Beam losses can arise from many types of errors but, for a well tuned machine, the main contributing factor comes from large amplitude halo particles. If a beam is injected into the accelerator with mismatched phase-space orientation, halo particles are generated which lead to beam loss.

*SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.

HALO PRODUCTION AND CONTROL

Since focusing in the DTL utilizes permanent magnets, the primary quadrupoles used for matching in the linac are at the end of the Medium Energy Beam Transport (MEBT). Four quadrupoles Q11, Q12, Q13, and Q14 are used to control matching into the linac. The focus of this study is to determine the optimal quadrupole settings that optimize this matching. Wirescanners at the end of the MEBT and each DTL tank (see Figure 1) are used to measure beam profiles and are compared with simulation.

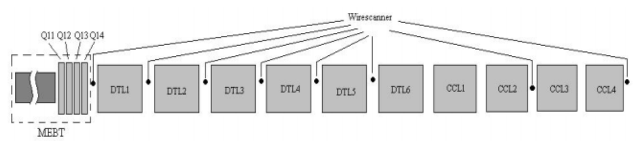

Figure 1. Wirescanner positions in SNS.

HALO QUANTIFICATION

To quantify halo a method was developed which considers the ratio of beam to beam tails in a transverse beam profile. Unlike the Kurtosis method [1], this method is not as sensitive to outlying particles and was found to be more useful for our experimental data due to the lower signal to noise ratio found in our raw profile data.

The Gaussian area ratio method [2] attempts to quantify the “non-Gaussian” component of the beam profile. After the data is filtered, it is fitted to a Gaussian of the form

$$f(x) = Ae^{\frac{-(x-\mu)^2}{2\sigma^2}} . \qquad (2)$$

In order to represent the core, a Gaussian fit is performed on the top (90 percent) of the profile since most profiles greatly resemble Gaussian’s in this region of the beam core. Figure 2 shows the area ratio method with the Gaussian core and halo tails. Dividing the total

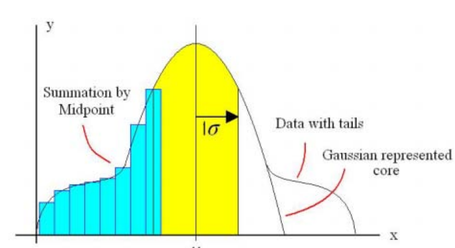

Figure 2. Pictorial representation of the area ratio method.

area by the area under the Gaussian outside 1 σ gives a ratio of the tails to the core and, therefore, a quantitative measure of the halo present.

SIMULATIONS AND MATCHING

In order to simulate the beam dynamics, PARMILA [3] code was used. The 3D Picnic space charge routine [4] was used to propagate three types of initial distributions from the beginning of the MEBT through the DTL to the end of the CCL. Varying each of the four quadrupoles at the end of the MEBT by +10% and -10% about the nominal value for the same machine settings gave nine cases with which to compare experimental and simulation results. A Waterbag distribution, a Gaussian distribution, and a reference distribution were used in the simulations. The reference distribution was derived from x and y beam emittance measurements [5] and does include some initial halo.

RESULTS

Experimental wirescanner profiles were acquired for the nine quadrupole settings with a peak beam current of 25 mA. Figure 3 shows wirescanner profiles at different locations in the linac, for nominal matching quadrupole set points. The data clearly shows non-Gaussian tails.

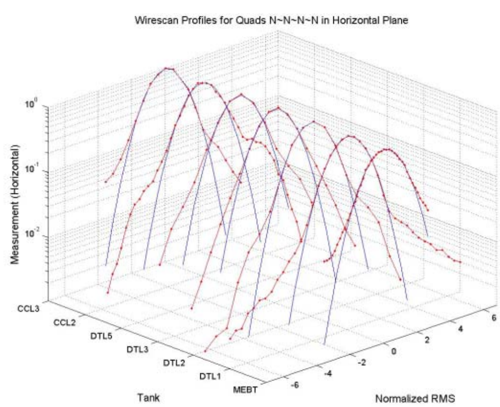

Figure 3. Horizontal wirescanner profiles for the nominal case.

Beam profiles were analyzed using the area ratio method and the resulting area ratios are plotted for the horizontal plane for nine quadrupole set points in Figure 4. Many of the cases have high area ratios at the beginning of the DTL and then decrease throughout the CCL. Most measured cases show a decrease in halo at the end of the CCL. Simulations for the same quadrupole settings show a similar trend of halo decreasing at the end of the CCL (see Figure 5). For both simulated and the experimental data, halo is most sensitive to Q12 and Q13. The halo growth trends, however, do not show good agreement between experimental and simulated data. When comparing measured and simulated vertical halo trends, there is less agreement than in the horizontal direction. Experimental vertical halo peaks in different locations than simulation and does not decrease at the end of the CCL as in simulation.

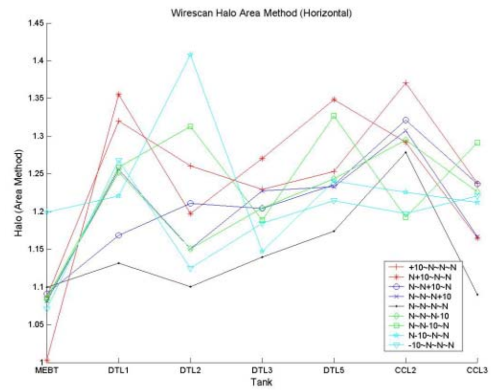

Figure 4. Horizontal experimental halo data.

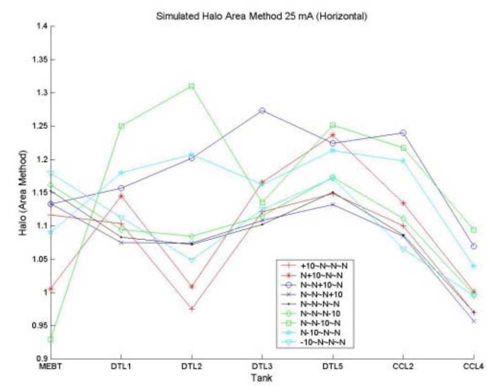

Figure 5. Horizontal simulated halo data.

Simulations lead to the conclusion that halo decreases near the end of the CCL, meaning the beam becomes more Gaussian in our quantification method and should therefore have less halo. However, since the area ratio method only uses data outside 1 sigma in order to provide better comparison of the small signal in the tails, information about the core size is not evident in the halo plots. Emittance growth due to mismatch can be explored in simulations. Figure 6 shows an increase in emittance in

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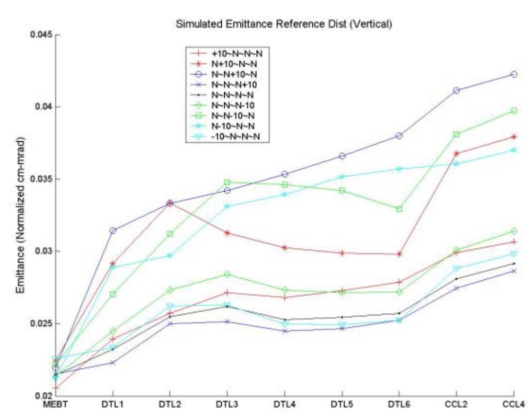

Figure 6. Simulated vertical emittance growth.

DTL1 and then a decrease through the DTL with an overall increase at the end of the CCL. The simulated emittance and halo data lead to the conclusion that the halo particles are "consumed" by the size of the beam core. A larger overall beam is not necessarily better than a small core with large halo

Initial Distribution Dependence

One natural question regards the sensitivity of the halo growth was to the initial particle distribution. Figure 7 shows simulated area ratios using a Gaussian distribution which has little or no initial tails.

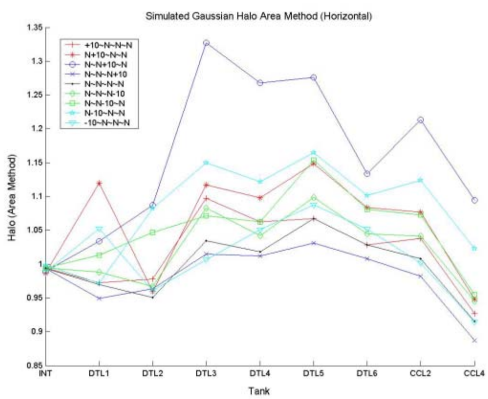

Figure 7. Simulated Gaussian initial distribution.

The Gaussian halo data shows relatively little halo growth compared with the reference distribution except for highly mismatched cases. The waterbag distribution, which has no initial tails, showed less halo growth as might be expected.

Our analysis shows that, while some halo growth may be attributed to initial halo, the halo is primarily dependent on quadrupole matching and for initial distributions with no initial halo.

Phase Space Orientation

Simulations indicate that the apparent decrease in halo may be attributed to emittance growth and, therefore, growth of the Gaussian core. Experimental data does not follow the same halo trend as simulation. One possible explanation is the orientation of the halo particles in phase space. As the beam rotates in phase space the tails may or may not be visible when the beam profile is projected onto a particular axis. Therefore the apparent disappearance of halo in the experimental data could be a result of the relative phase space orientation of the core and halo at the measurement locations. This needs more investigation.

Profile Comparison

Figure 8 shows four comparisons of simulated and measured profiles. The Gaussian core is normalized in order to compare the beam tails. While these are a very small sample of the profile data taken, they show how simulations accurately modelled the profile shape in many cases. Often simulated profiles had the same shape but underestimated the amplitude of the halo.

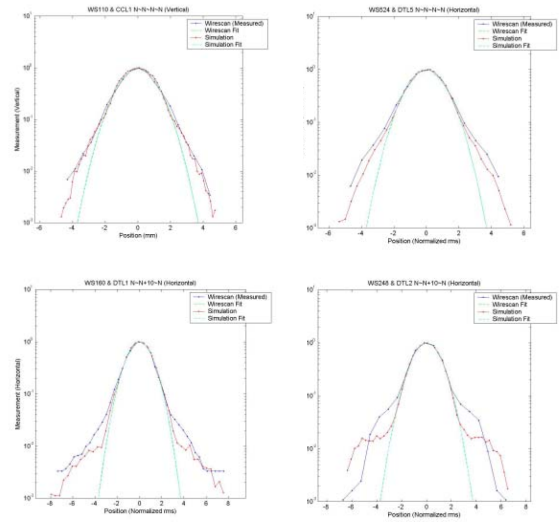

Figure 8. Comparison between simulated and measured profiles

Not all comparisons were as accurate as those shown in Figure 8 and only partial success is claimed.

CONCLUSIONS

Comparison between experimental data showed partial success. While the halo data trends had considerable discrepancies, simulations could reproduce many of the profile shapes. Simulations showed a decrease in halo with an increase in emittance leading to the conclusion that the core size increases and effectively consumes the halo particles, while experimental data only showed this to a limited degree. Finding a distribution that more accurately represents the beam is currently being sought in order to resolve the differences between the simulations and measured profiles. Phase space orientation of the halo particles relative to the core could also explain the apparent disappearance and reappearance of halo at different locations in the linac. While a concrete solution to halo production and emittance growth in SNS has not been found, much progress has been made in understanding how to more fully optimize the machine to minimize beam losses.

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