

BEAM DYNAMICS IN THE SNS LINAC AND BEAM TEST FACILITY*

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Abstract

The Spallation Neutron Source linear accelerator is the highest power superconducting hadron linac in the world. Along with this distinction comes the significant complication of deposited power from beam loss, exacerbated by the fact that the linac transports H^- . This paper summarizes our understanding of beam loss in the SNS linac and highlights research being done to improve that understanding. The question of beam loss due to halo has motivated development of a detailed model fidelity project at the SNS Beam Test Facility, which includes unique phase space diagnostics for 4D-6D distributions, and high-dynamic-range 2D distributions.

INTRODUCTION

In the Spallation Neutron Source, beam loss has been a major concern since the early days of operation. During initial commissioning, losses in the superconducting linac (SCL) threatened to limit operation. The source of this loss was eventually determined to be intrabeam stripping of H^- ions [1, 2]. The mitigation was to reduce quadrupole gradients in the SCL to increase average beam size and reduce the probability of H^- collisions. This mitigation was possible due to the generous aperture (8 cm compared to 2–3 cm in the warm linac).

This mitigation of stripping losses is an example of how physical understanding can support large operational shifts. This change to the design optics of the SNS enabled the ramp to 1.4 MW. The SNS linac still operates near this set of optics, with some “drift” in parameters after years of empirical loss tuning.

The question of fully understanding beam loss in a realistic accelerator model is a multi-faceted issue [3], encompassing not only intrabeam stripping but also halo losses, residual gas and field stripping, proton contamination, dark current and other effects. The dominant mechanisms in the SNS linac are understood to be loss from halo scraping and intrabeam stripping. To achieve a subsequent reduction of beam loss that is on order with the intrabeam stripping discovery will

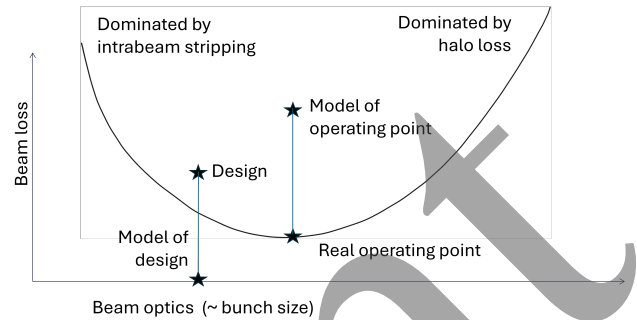


Figure 1: Illustration of beam loss landscape for SNS linac. The linac runs with parameters shifted from design, at an operating point that is understood to balance halo losses with stripping losses. The PIC model for the linac predicts lower losses for design than the best operating point.

require a trusted model of the beam distribution in the linac for a wide range of operating parameters. This would make it possible to redesign the linac optics towards a lower-loss state.

BEAM LOSS IN THE SNS LINAC

The current operating point of the linac is understood to be at a local beam loss minimum, depicted in Fig. 1. Loss tuning for the linac is performed by machine specialists within the operations group, who have developed a mental map of the complex cause/effect relationships of the operating parameters and the measured beam loss signals, as well as the relationship of beam loss signals to measured activation. Through joint effort between operations and accelerator physics group, we have developed a reproducible, loss-minimized machine state that can be restored after shutdowns or beamline disruptions (such as detuned superconducting cavities) [4, 5]. At this state, we are below the commonly accepted limit of 1 W/m losses, with “hotspots” in the linac typically not exceeding 0.3 W/m.

The SNS recently completed the Proton Power Upgrade [6], which raised beam energy from 1 GeV to 1.3 GeV. Along with a modest increase in average beam current, this enabled a ramp of the beam power on target to 2.0 MW in April 2026. Following the completion of the Second Target Station, beam power will increase to 2.7 MW. Beam loss in the linac is expected to rise moderately but remain below the 1-W/m limit. After the first few runs since PPU installation, there is an unexpectedly high activation area near the ring injection, but not at any locations in the linac.

While acceptable linac losses are predicted at 2.7 MW, radiation damage to components in the linac tunnels will accrue faster. Improved methods that keep losses at or below

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historical levels, even as integrated beam power increases, will support accelerator reliability. It is possible that a better optics solution with reduced intrabeam stripping exists. Unfortunately, it will not be so straightforward to find – further increase of beam size in the SCL is not possible, as halo loss will start to dominate, as shown schematically in Fig. 1.

Strategically placed halo collimators at low energies could permit larger beam size / lower peak density in the SCL. At present, the model for the Medium Energy Beam Transport (MEBT) section is not trusted to accurately predict rms beam parameters [7], much less the halo distribution. Installation of scrapers, particularly the vertical scrapers, has not led to reduced losses.

MODELING THE SNS LINAC

Accurate prediction of beam loss in the linac requires a particle-in-cell (PIC) model capable of predicting realistic beam distributions. Much work at SNS has been performed to benchmark to the OpenXAL rms envelope model [8], as well as the ORNL PIC code PyORBIT [9]. There has additionally been an attempt with IMPACT [10].

While some attempts at local benchmarks have shown promising results [5, 11], these examples have not been global (for the whole linac, or applying to all parameter settings). Recently, the PyORBIT PIC model was used to understand beam loss at production settings, in an attempt to understand the advantage of current production settings over design [12]. The model predicted 2% losses in the warm linac, which is orders of magnitude over acceptable loss rates. Similarly, despite many efforts to do rms matching of the beam in the DTL [13] and CCL [14], these solutions have not lowered losses.

Model-based beam loss prediction encompasses calculations of intrabeam stripping rates. Calculations for the SNS predict losses on the order of 10^{-5} of total current [1]. These calculations assume a Gaussian distribution and can be done relatively quickly. Recently, a method for efficiently calculating stripping rates for arbitrary distributions has been developed [15]. So far, it is not clear how to benchmark these calculations beyond order-of-effect.

BEAM TEST FACILITY RESEARCH

The SNS Beam Test Facility (BTF) [16], shown in Fig. 2, is a small test stand that is currently supporting research in beam halo formation and PIC model fidelity. The BTF front-end is identical to the SNS front-end, with identical H^- ion source, radiofrequency quadrupole (RFQ) and first 2 MEBT quadrupoles. The BTF has been a platform for detailed studies of the H^- beam distribution and related diagnostics development since initial commissioning in 2016 [17].

The goal of the ongoing BTF research is to test the capability of our PIC code to accurately predict evolution of beam distributions at medium energy (2.5 MeV), with the goal of learning how to run high-fidelity models with realistic halo distributions. This tool would enable design of intentional halo collimation in the SNS linac. There are

also more general beam dynamics topics that can be studied, including the mechanism for fast halo growth in mismatched beams.

Available Diagnostics

Significant diagnostic development was motivated by the BTF halo project. The first investment was in high-dimensional phase space measurements. The first full-and-direct measurement of the H^- beam distribution is described in [17]. This measurement used 4 collimating slits and a bunch shape monitor to map the complete 6D phase space. Subsequent development resulted in high resolution 5D phase space measurements [18].

In parallel, the development of a 2D phase space measurement with wide dynamic range was under development. The goal of this measurement was to sample 2D phase space projections with 6 orders of magnitude in dynamic range. This was realized in 2020 [19]. This measurement enables detection of beam halo down to the level of the 1 W/m loss limit. The high-sensitivity measurement uses 2 collimating slits, with a scintillating screen as the charge detector. A beam distribution measured with this method is shown in Figure 3.

6D Beam Distributions

The findings of high-dimensional beam distribution measurements are reported in several publications and summarized here [20]. Briefly, interplane dependencies between transverse and longitudinal planes were detected in the beam 1.3 meters downstream of the RFQ. These manifested as a hollowed-out beam core, which was shown to be the result of space charge [18, 21]. Simulations of the SNS Linac predict that reconstructing an initial bunch with this core structure intact will have no effect on downstream beam evolution. Simulations for the BTF beamline predict a subtle (but detectable) effect [22].

Beam Halo Observations in the BTF

The FODO section of the 2.5-MeV beamline was designed to provide sufficient phase advance for halo growth with a compact footprint [16]. The FODO line has a bare lattice phase advance of 105 degrees per cell, and 9.5 FODO cells. Although this is only 4–5 envelope oscillations, this is seen in measurement and experiment to be enough to drive measurable beam halo by the end of the 13-meter beamline [16].

For the purposes of this study, halo is defined as heavy tails in the distribution at the level of 10^{-4} – 10^{-6} of total current density, regardless of formation mechanism. Figure 3 shows contours out to the 10^{-5} level. This region is below the level at which nonlinear “shoulders” or “tails” are commonly seen in 1D and 2D phase space diagnostics. Halo-level particles carry sufficient power that aperture scraping would elevate losses above acceptable levels. For a 1 MW beam, loss of more than one particle-per-million per meter will exceed the 1 W/m limit.

First results of systematic study of the beam distribution at the end of the BTF beamline as a function of mismatch in the

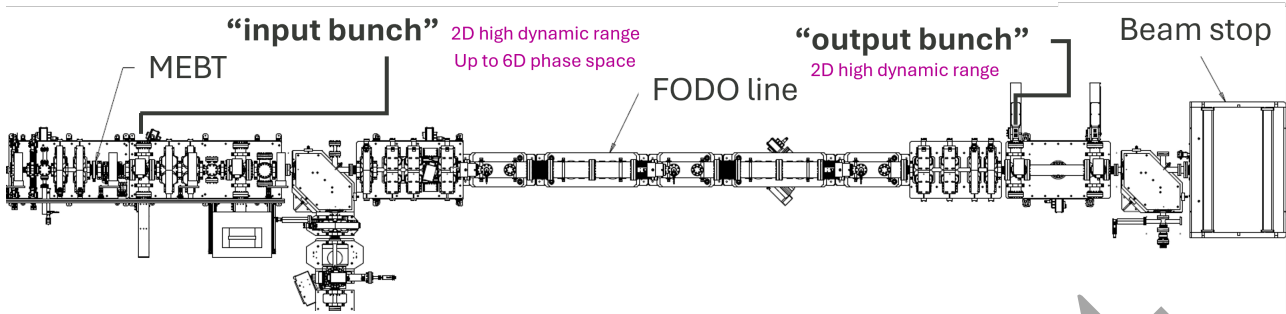


Figure 2: Scope of Beam Test Facility project in advanced phase space diagnostics and modeling for beam halo. The input bunch used for simulation can be characterized with either high-dynamic-range or high-dimensional phase space diagnostics. The output bunch at the end of the 2.5 MeV beamline is compared to high-dynamic-range phase space measurements.

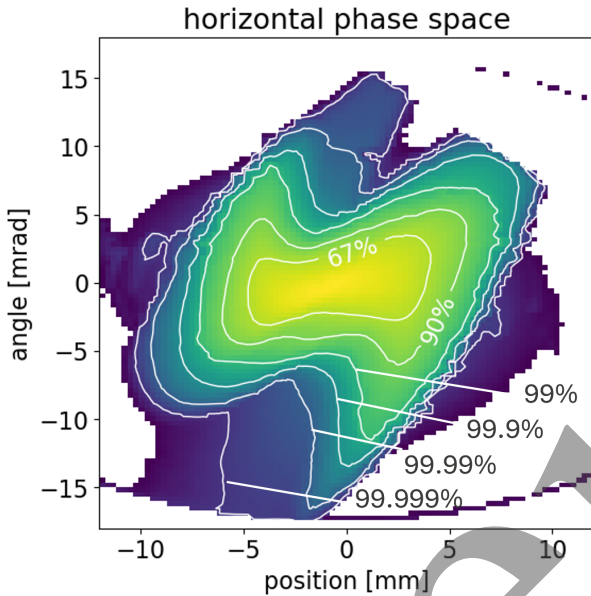


Figure 3: Phase space for 52 mA H^- beam at end of the BTF 2.5 MeV beamline, measured with high-dynamic-range phase space diagnostic. The contours are labeled by the percentage of measured signal they contain. The threshold for measured signal is $3 \times 10^{-6} \times \max(\text{signal})$. Features below the 99.999% contour are artifacts from the scanning pattern, which proceeded along ellipses in the phase space.

FODO section was reported in [23]. In these measurements, we see nonlinear tails grow considerably with mismatch, with increasing area containing current densities $10^{-4} - 10^{-6}$ times the peak.

Modeling the BTF Beamline

The BTF beamline extension was commissioned in 2019. The first goal was to obtain an “rms-level” benchmark for the beam core, based on phase space measurements with three orders-of-magnitude dynamic range. This goal was not achieved until early 2024, after reconfiguring the BTF beamline to remove two 90° bends [24]. In this new format, good agreement for the beam core was found quickly, as illustrated in Figure 4.

The benchmark simulation for the BTF uses the particle-in-cell code PyORBIT [9]. A repository with measured phase space distributions and PyORBIT run files needed to reproduce the benchmark simulation is at [25]. This case is for matched FODO optics, and uses phase space measurements taken at “typical” dynamics range (3 orders of magnitude).

For comparison of the 99% beam distribution, we find 200,000 macroparticles are sufficient. To fill out the tails to the 10^{-6} fractional level, as many as 10^9 macroparticles may be necessary. This exceeds the number of real particles in a single bunch.

A few other relevant simulation details are listed below:

- 40 mA average current per RF period (402.5 MHz),
- 3D space charge kick every 1 cm for total simulation length 8.5 meters,
- space charge kick includes contribution from neighboring bunches,
- a hard-edged approximation is used for electromagnet quads, and soft analytic profiles for the short FODO quads,
- there are no multipole components in the quadrupole elements.

The quadrupole models used in this benchmark are the simplest model that makes good predictions for the matched bunch core. For the 10 electromagnet quadrupoles in the benchmark study, which had lengths from 9.6–14.6 cm, a hard-edged model does well. Replacing this model with a soft profile from an enge-function fit has a small effect. For the model of the 19 permanent-magnet FODO quadrupoles, which have length 7.5 cm, an analytic soft profile [26] is critical for good results. Implementing analytic field maps for the FODO quads (with all nonlinearity “as designed”) has a negligible effect [27]. We are planning to investigate the effect of nonlinear components of all quadrupoles “as built” based on rotating coil measurements.

The bunch shown in Fig. 4 was transversely matched in the FODO line. The initial results of mismatch studies show a linear phase shift error (for example, Fig. 5 in [23]). We do

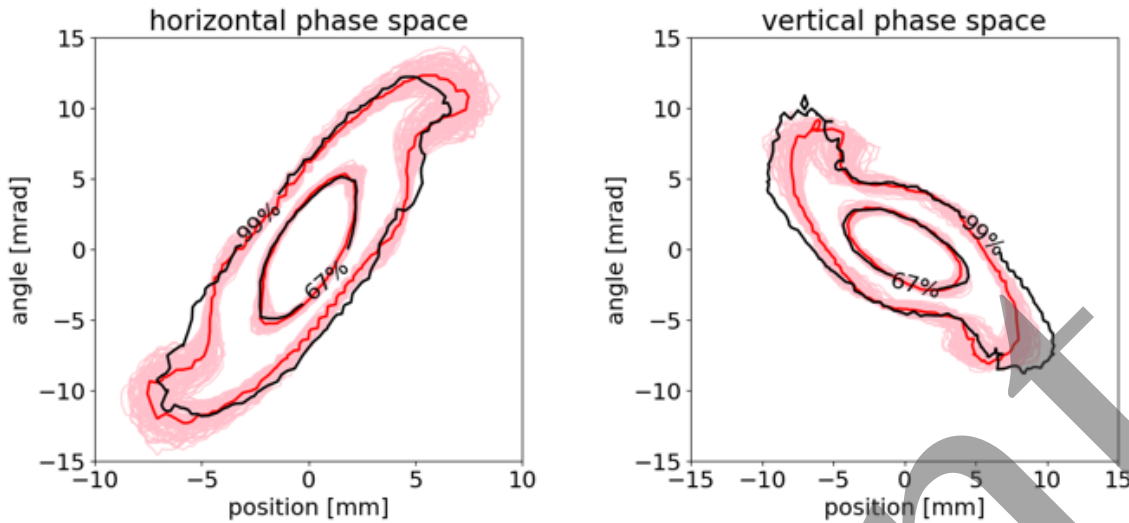


Figure 4: Comparison of horizontal (left) and vertical (right) phase space at the end of the BTF beamline (“output bunch” in Fig. 2). The solid black lines are contours of the measured distribution. The red contour is the simulated distribution. The pink contour distributions are generated by 100 simulations with random normal errors in quadrupole gradients (0.5%) and bunch energy (1%).

not understand why. It could be that the mismatched envelope is more sensitive to gradient errors. Data and simulation files for this case are available in [25].

Centroid Motion in the BTF

To date, benchmark simulation studies have not included centroid motion. There is limited information about the real trajectory, with only one beam position monitor (BPM) located 1 meter downstream of the RFQ exit. The position of the slit collimators when inserted into the beam are known precisely, but not referenced to the pipe center - they can be used for measuring centroid differences but not absolute position.

The pipe aperture diameter is 4.2 cm, and the rms beam size in the sections before and after the FODO can be as large as 0.5 cm. For initial benchmarking studies, which did not use the high dynamic range phase space diagnostic but instead compared phase spaces with a sensitivity of at most 10^{-3} relative to the peak, there was no visible scraping. Now that the high dynamic range diagnostic is used regularly, it is apparent that scraping occurs at multiple locations along the transport line. Additionally, the highest transmission measured since the beamline extension was installed (which includes everything past the first 90° bend) is 97%, indicating that scraping is significant.

The BTF was designed with the assumption that there would be a trajectory offset in the LEBT (60 keV low-energy transport) and RFQ. Two pairs of steerers are co-located in the first two quadrupoles to correct the initial offset. It has become apparent that these two correctors are not sufficient to maintain good control through the 2.5 MeV beamline.

We plan to add 2 additional pairs of correctors - one pair before the FODO entrance and one after. As there is little room for dedicated coils in the compact beamline, we

will provide a steering kick via current imbalance between the 4 coils of each quadrupole. In the meantime, optics designed to minimize halo scraping have been designed and implemented, as discussed in [28].

SUMMARY

Dynamics leading to beam loss in the SNS Linac are not well understood from a physics perspective. Although the causal relationships between tunable parameters and measured losses are empirically known, the lack of a trusted model makes it difficult to explain these relationships. A global, validated linac model is needed to support new strategies to control SNS losses.

The Beam Test Facility halo project continues to progress towards validating PIC code predictions of beam halo growth in a simplified test stand experiment. Although success in the BTF project will not immediately improve SNS linac modeling, some knowledge can directly transfer. For example, the BTF phase space measurements can be directly applied to models of the SNS MEBT, which operates with cavity parameters “off-design” for unknown reasons.

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