BEAM LOSS MITIGATION IN THE OAK RIDGE SPALLATION NEUTRON SOURCE

M.A. Plum, on behalf of the SNS accelerator team,
Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract

The Oak Ridge Spallation Neutron Source (SNS) accelerator complex routinely delivers 1 MW of beam power to the spallation target. Due to this high beam power, understanding and minimizing the beam loss is an ongoing focus area of the accelerator physics program. In some areas of the accelerator facility the equipment parameters corresponding to the minimum loss are very different from the design parameters. In this presentation we will summarize the SNS beam loss measurements, the methods used to minimize the beam loss, and compare the design vs. the loss-minimized equipment parameters.

INTRODUCTION

The SNS accelerator complex [1] comprises a 1 GeV linac followed by an accumulator ring, with a design average beam power of 1.4 MW at 60 Hz. The present operating power is ~1 MW. With this high beam power, beam loss control and mitigation is critical. To allow for hands-on maintenance, the beam loss should be less than ~1 W/m. Long-term plans call for increasing the beam power to 3 MW or higher, so this corresponds to a fractional loss of less than 3×10^{-7} per meter, which is a very low value compared to previous accelerator systems.

Almost all the 350+ beam loss monitors (BLMs) at SNS are based on ion chambers [2]. Additionally, there are photomultiplier-based neutron detectors and fast BLMs. The neutron detectors are especially important at low beam energies (<100 MeV) where the ion-chamber BLMs have low sensitivity. The signal from each BLM is sampled at typically 100 kHz and the waveforms can be examined and recorded using the accelerator control system. Typical activation measurements are shown in Fig. 1. There are several hot spots spread throughout the complex. The location with the highest activation is just downstream of the charge-exchange-injection stripper foil, caused by the inevitable scattering of the injected and circulating beam by the foil.

BEAM LOSS MITIGATION

The three main methods used to mitigate the beam loss at SNS are: 1) beam halo/tail scraping, best done at low beam energy; 2) increasing the beam size in the superconducting linac (SCL) to minimize the loss due to intra-beam stripping (IBSt) [3]; and 3) empirical adjustment of the magnet and RF set points.

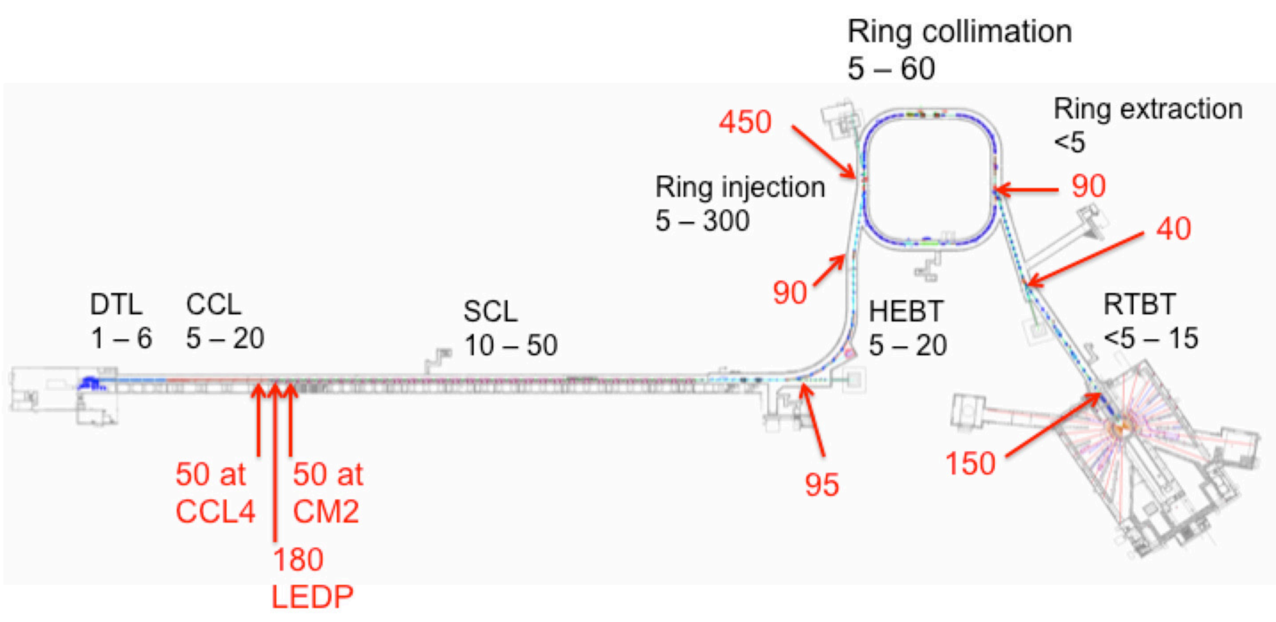

Figure 1: Typical activation levels from 1 MW operations followed by ~48 hours of low-power studies. All numbers are mrem/h at 30 cm from beam line. The numbers in red indicate localized hot spots.

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Scraping

There are four sets of scrapers in the SNS accelerator complex, in the medium energy beam transport (MEBT) at 2.5 MeV, in the high energy beam transport (HEBT) straight section at 1 GeV, in the HEBT arc for momentum scraping, and in the Ring. In most typical cases almost all the scraping is done with the MEBT scrapers, as we have found these to be most effective.

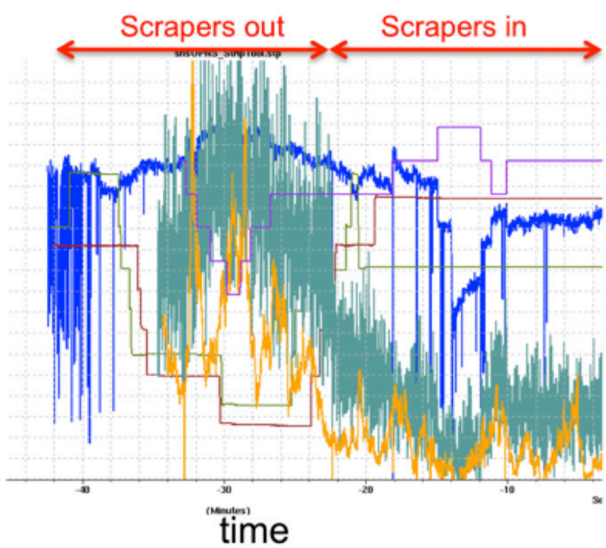

Figure 2: Beam loss reduction due to low energy scraping. Magenta, light green, and violet show the scraper positions. Blue shows the beam charge, and orange and dark green show BLM signals. The beam loss is reduced up to 60% by scraping 3% of the beam.

The MEBT scraper system has one pair of left-right scrapers, and also the MEBT chopper target, which can be pushed into the beam tail to provide some scraping to the top of the beam. Figure 2 shows a typical result. When all three scrapers are inserted enough to strip a total of 3% of the beam, the beam loss is reduced by up to 60% at certain locations, primarily in the Coupled Cavity Linac (CCL) warm linac, the beginning of the SCL, and the ring injection dump beam line.

These scrapers produce a measureable reduction in the beam halo/tails, as can be seen on the MEBT slit-and-collector emittance scanner results [4] shown in Fig. 3. The measurable effectiveness continues into the Drift Tube Linac (DTL), as can be seen by the reduction in the non-Gaussian tails on a wire scanner measurement shown in Fig. 4. However, by the time the beam reaches the High Energy Beam Transport (HEBT) at the exit of the Linac, there is very little measureable difference in the beam profile with and without MEBT scraping, as shown by the halo/tail measurement in Fig. 5. Nevertheless, as shown in Fig. 2, there are still large loss reductions at certain points downstream of the HEBT due to MEBT scraping, especially in the Ring injection dump beam line.

Beam Loss Reduction by Beam Size Increase

The majority of the beam loss in the SCL, and possibly also in the DTL and CCL, is due to intra-beam stripping. The reaction rate is proportional to the beam density to the second power, so by increasing the beam size the beam loss can be reduced. This was empirically discovered during the SNS power ramp up phase, before the IBSt mechanism was understood.

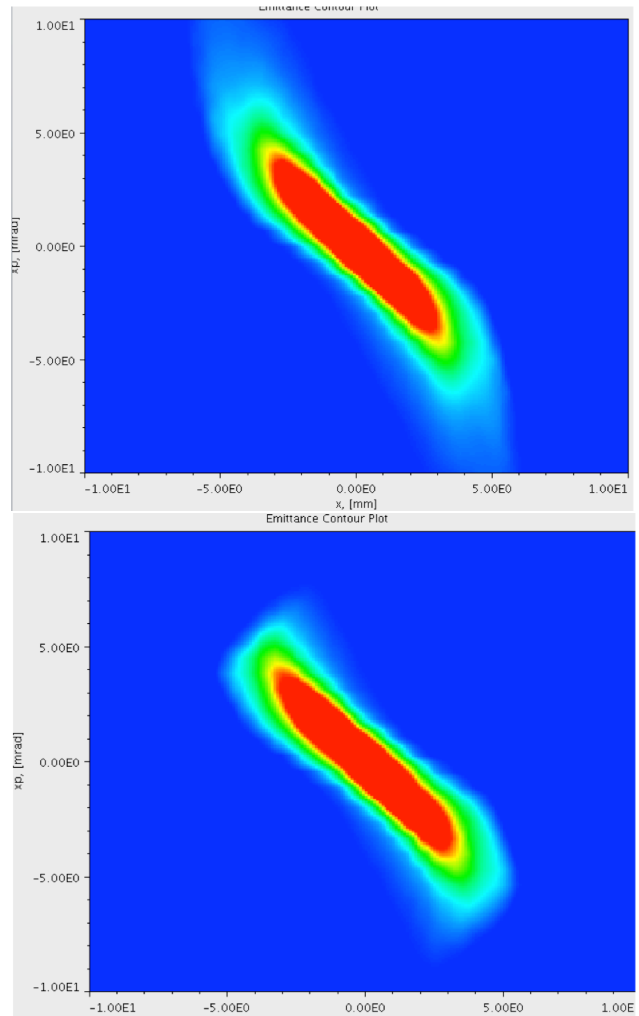

Figure 3: MEBT horizontal emittance scanner with and without scraping. The beam halo/tails are cut off by the scraping.

Beam loss improvements can be obtained by reducing the density in both the longitudinal and transverse planes. In our case it is simplest to make the transverse beam sizes bigger by reducing the SCL quadrupole gradients by up to 40%. Any further reduction causes an increase in the beam loss simply because the beam is getting too big. We are investigating further beam loss reduction by optimizing the beam-size oscillations by fine-tuning the quadrupole gradients. Figure 6 shows the reductions in quadrupole gradients, and Fig. 7 shows the corresponding beam loss reduction.

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Beam Loss Reduction by Magnet and RF Phases Adjustments

When the SNS accelerator complex is operated with the quadrupole gradients and RF phases set to the design values the beam loss is high. We have empirically found that the loss can be reduced by at least of factor of two by making small adjustments to the matching quadrupole gradients and to certain RF phases.

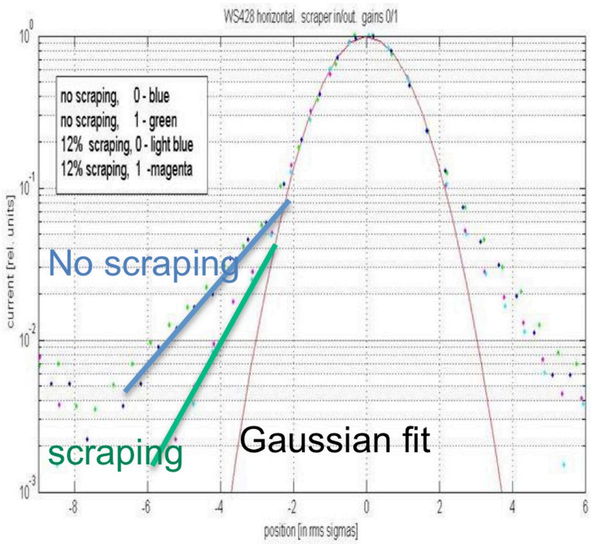

Figure 4: Two large-dynamic-range wire scanner profile measurements about two-thirds of the way along the DTL, with and without MEBT scraping. The blue and green lines show the non-Gaussian halo/tails.

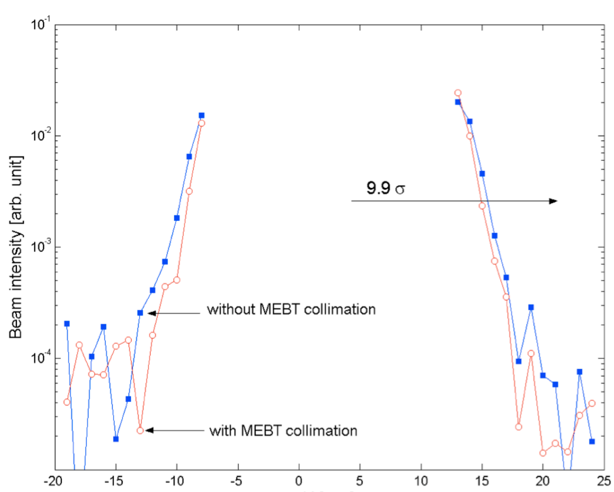

Figure 5: Beam halo/tail measurement in the HEBT with and without MEBT scraping. There is little difference between the two profiles.

The largest deviation from the design RF phases is 11 deg. at the beginning of the SCL, for the example shown in Fig. 8, taken from the most recent tune up. This is most likely due to a longitudinal beam distribution with long tails that can extend out to 40 deg, as shown in Fig. 9. The minimum beam loss case is very sensitive to certain RF phases. Just one degree can double the beam loss at certain locations.

As the SNS accelerator complex has matured, we have worked to bring the quadrupole gradient set points in line with simulation codes. The concept is that model-based adjustments that have a physics basis are better than random adjustments that may lead to a localized minimum in beam loss, or to an operating point that is difficult to sustain.

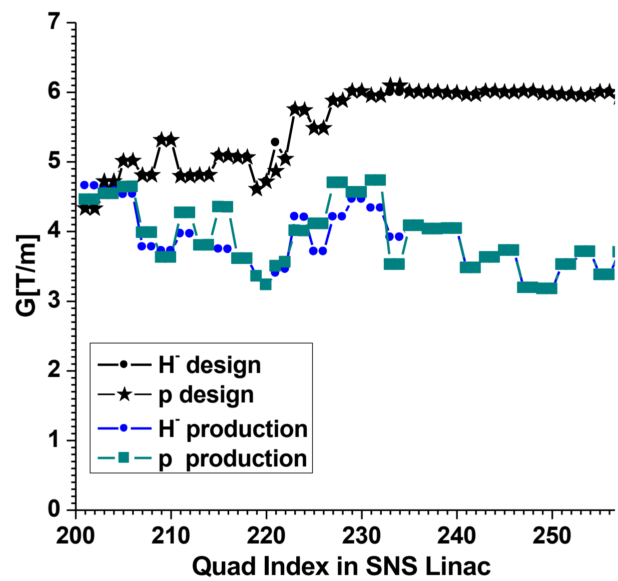

Figure 6: Quadrupole gradient reduction used to minimize the beam loss in the SCL. Reproduced from [3].

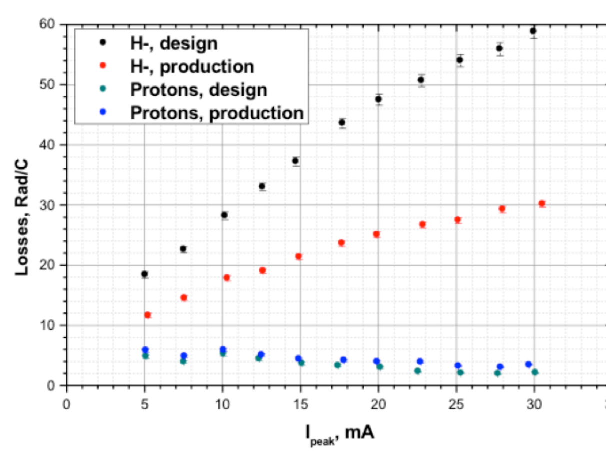

Figure 7: Beam loss for two different optics cases, as a function of ion source current, for both protons and H^-. The beam loss for the reduced SCL quadrupole gradients, shown in red, is about half. Reproduced from ref. [3].

The DTL quadrupole gradients are by definition operated according to design, since they are permanent magnets. The CCL gradients are now also operated at their design values, starting in August 2012. The SCL quadrupoles are discussed above, and the HEBT quadrupole gradients are shown in Fig. 10. These latter

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quadrupoles are mostly operated according to their design values, with the biggest exceptions being at the beginning and end of the HEBT, where the beam is matched from the SCL to the HEBT, and from the HEBT to the Ring. The beam loss in the injection dump beam line is very sensitive to changes in the HEBT quadrupole gradients.

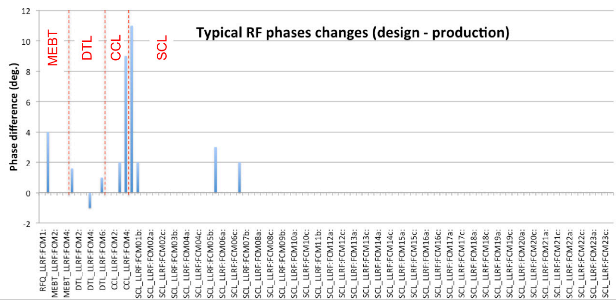

Figure 8: RF phase changes needed to minimize the beam loss. The biggest changes are at the beginning of the SCL.

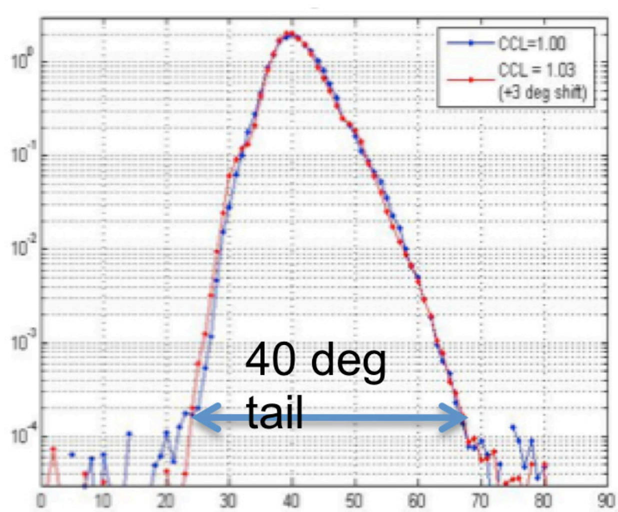

Figure 9: Longitudinal beam profile measurement, showing tails that extend out to 40 deg.

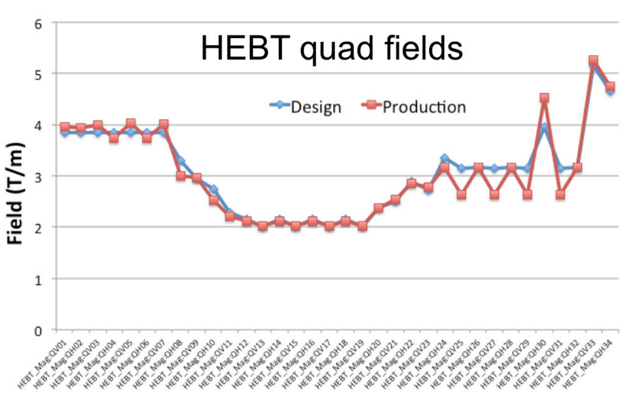

Figure 10: Quadrupole gradients for the HEBT quadrupoles, design vs. the low loss (production) tune.

Although we are moving to more model-based quadrupole gradient settings, the beam remains poorly matched throughout much of the linac and beam lines, starting with the initial match from the MEBT to DTL. In some parts of the accelerator complex attempts to match the beam produces large beam losses. Figure 11, for example, shows the rms beam sizes in the beginning of the HEBT for the low-loss production tune, determined by measuring the beam profiles at the wire scanner stations (indicated by the dots on the plot), and then adjusting the input beam parameters in an envelope model to achieve the best fit to the measured rms beam sizes. Ideally the plot would show beam sizes corresponding to a regular FODO lattice, but in reality it shows large and irregular beam size oscillations in the horizontal plane. Plots for some other parts of the linac show similar results.

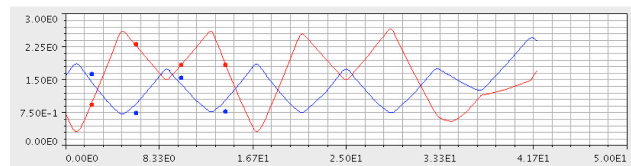

Figure 11: rms beam sizes in the beginning of the HEBT. Blue indicates the vertical plane, and red indicates the horizontal plane.

Large-dynamic-range profile measurements show non-Gaussian beam halo/tails starting as soon as the DTL, as shown in Fig. 12. In this figure the purple shows the results for the low-loss production tune. There are non-Gaussian tails as large as 30% of the peak, starting from the first wire scanner in the DTL. The blue shows profiles for the case of beam matched to the entrance of the DTL. The halo/tails are minimal at first, as expected, but then develop along the length of the DTL, and then persist throughout the linac and transport lines.

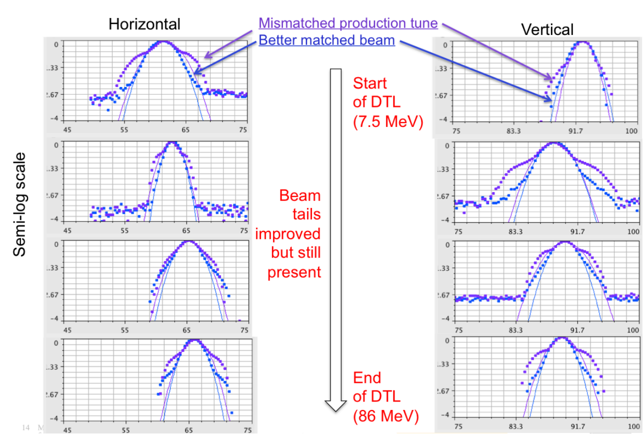

Figure 12: Normalized beam profiles along the DTL, for the matched and low-loss production cases. The solid lines show Gaussian fits to the data.

A possible hypothesis to explain the large tails in the low-loss tune is to first recognize that the Twiss parameters of the halo/tails are not the same as for the core of the beam. This is evident from the MEBT emittance scan shown, for example, in Fig. 3. The tails could be from the ion source, or collective effects, or non-linear fields, etc. Since beam loss is caused primarily by

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the halo/tails, the low-loss tune is the one which best transports the halo/tails, not the one that has the best match of the core of the beam to the lattice.

SUMMARY

The magnet and RF set points needed to minimize the beam loss are in some cases very different than the design values predicted by the simulation codes. Beam profile measurements show large non-Gaussian halo/tails as high as 30% of the peak, and also show that the core of the beam is not well matched some of the accelerator sections. An on-going emphasis in the accelerator physics program at SNS is to understand the causes of the non-Gaussian tails, and to develop methods to minimize and control them. We are also working to improve our modeling codes to more accurately represent the actual accelerator complex, with the goal of operating the accelerator with minimal beam loss according to set points entirely predicted by the models.

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REFERENCES

[1] S. Henderson, in Proceedings of the 2007 IEEE Particle Accelerator Conference (IEEE, New York, 2007), Vol. 1– 11, p. 1252.

[2] A. Zhukov, “Beam Loss Monitors (BLMs): Physics, Simulations and Applications in Accelerators,” Proceedings of the 2010 Beam Instrumentation Workshop, Santa Fe, p. 553 (2010).

[3] A. Shishlo et al., “First Observation of Intrabeam Stripping of Negative Hydrogen in a Superconducting Linear Accelerator,” Phy. Rev. Lett. 108, 114801 (2012). Also A. Shishlo et al., “H^- and Proton Beam Loss Comparison at SNS Superconducting Linac,” IPAC2012, New Orleans, Louisiana, USA, p. 1074 (2012).

[4] A. Shishlo, “Beam Dynamics Issues in the SNS Linac,” PAC2011, New York, p. 12 (2011).

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