PATH TO BEAM LOSS REDUCTION IN THE SNS LINAC USING MEASUREMENTS, SIMULATION AND COLLIMATION

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Abstract

The SNS linac operation at its design average power currently is not limited by uncontrolled beam loss. However, further reduction of the beam loss remains an important aspect of the SNS linac tune up and operation. Even small "acceptable" beam loss leads to long term degradation of the accelerator equipment. The current state of model-based tuning at SNS leaves an unacceptably large residual beam loss level and has to be followed by an empirical, sometimes random, adjustment of many parameters to reduce the loss. This talk will discuss a set of coordinated efforts to develop tools for large dynamic range measurements, simulation and collimation in order to facilitate low loss linac tuning.

INTRODUCTION

The SNS linac has demonstrated successful operation at the design average beam power of 1.4 MW with acceptable uncontrolled beam loss [1]. However, beam loss mechanisms study and mitigation methods development remains to be on top of the accelerator physics and beam instrumentation tasks list for the following reasons:

- The "acceptable" uncontrolled beam loss is typically defined by the possibility of hands-on maintenance on the accelerator equipment, which corresponds to a dose rate of <100 mRem/hour at 30 cm from the beam pipe, a few hours after beam shutdown. The actual residual activation of the SNS linac is typically lower than that but the long term damaging effect to the equipment in the tunnel from the prompt radiation is important as well. The observed slow degradation of the plastic cable insulation and water hose materials is certainly due to irradiation. Degradation of the superconducting cavities performance is observed as well and in many cases can be correlated to elevated beam loss in the vicinity. Further beam loss reduction is certainly beneficial for long term stable operation.
- The last step in the process of low-loss linac set up involves manual tweaking of many parameters. This step is poorly documented and can be done by only few experienced people. It can be time consuming in case of a significant change of the linac configuration. A knowledge based set up procedure is highly desirable
- The SNS power upgrade and the Second Target Station plans envision doubling the average beam power and adding another beam pulse flavor. This will require cutting the fractional beam loss at least by half to keep the prompt radiation and activation levels on the same level.
- Model-based methods of beam loss control are crucial for future high power linacs. The SNS linac is an ideal test bench for beam instrumentation and loss mitigation methods development.

Reduction of the beam loss in the SNS Super Conducting Linac (SCL) using knowledge of beam dynamics rather than blind tweaking is our first goal. This paper describes the tools and methods we think will be required to achieve this goal.

BEAM LOSS IN SCL

The main mechanism of beam loss in SCL is believed to be the intra-bunch stripping [2]. The rate of loss is proportional to the bunch density therefore increasing the transverse and longitudinal bunch core sizes is an effective way of beam loss reduction. A low loss SCL optics configuration with enlarged bunch size was found empirically and is still in use for high power operation. Only recently a reliable model of RMS beam dynamics in SCL was established [3], which shows not perfectly RMS matched beam for the current optics. The mismatch causes the beam size maximum and minimum to deviate from the average. The increased bunch size maximum prevents further enlargement of the average size; the decreased bunch minimum size creates local bunch density peaks with larger loss rate. We expect to reduce the intra-beam stripping losses using the model to find a better matched optics. However, any further attempt to increase the average RMS bunch size will be limited by the beam halo touching the beam pipe. The current ratio of the beam pipe aperture to the maximum loss limited transverse bunch size is about ${}^{76mm}/_{7mm} \approx 11$, indicating presence of a significant halo. As a result, having an accurate control of the RMS bunch size is not enough for decreasing the intra-beam stripping - the halo also needs to be controlled.

The exact origin of the halo is not known but we can tell for sure that at least part of it comes from the injector. The easiest method of reducing this part is collimation (or scraping) of the large amplitude particles in the MEBT (a 2.5MeV transport line between the RFQ and the linac).

It is also possible the halo is formed during acceleration in the warm linac due to effect of the space charge. Matching the bunch RMS Twiss parameters to the lattice is believed to mitigate this effect. If the perfect match is not possible or the halo is formed even in the RMS matched beam then the minimum loss is achieved as a compromise between matching the RMS parameters to

ISBN 978-3-95450-178-6

minimize the intra-beam stripping and matching the halo Twiss parameters to minimize the halo size in SCL. Two of the above mitigation techniques, the halo matching and the MEBT collimation, require or benefit from using halo measurement and computer modeling as will be discussed in the following sections.

We do not discuss the RMS bunch size measurement and modeling techniques in this paper because they are well covered in another presentation at this workshop [3].

HALO MEASUREMENT AND MODELING

The halo, as defined below, has a relatively low charge density. However, the actual number of particles in the halo can be large for high intensity beams. Therefore, in many situations it is not difficult to detect the halo or quantify its density in "more" or "less" terms. The loss monitors of various kinds do this quite reliably in all high intensity accelerators. In the context of this paper we are interested in the different kind of measurements, ones which can be used in computer modeling of the halo. The detailed particle distribution in 6D phase space is generally required to initiate particle tracking using Particle-In-Cell (PIC) codes. In many practical cases, however, an assumption of no coupling between the horizontal, vertical and longitudinal planes can provide sufficient accuracy allowing use of a set of three independent 2D phase space measurements. An experimental verification of this assumption will be discussed in the later sections.

Halo Definition

We will use the definition of halo recently agreed upon by a representative group of beam instrumentation experts [4]. In short, the beam charge distribution inside the vacuum chamber can be separated to three parts: the beam core, the beam halo and the transition (the transition is often called "shoulders", "tails" etc.). These parts are characterized by the charge density relative to the peak density. The boundaries are not defined exactly but for the majority of the cases the beam core boundary is at about 10^{-2} level, the beam halo is at 10^{-4} -10^{-6} level and below. The low boundary of the halo region is decreasing with higher intensity beams, obviously, but the 10^{-4} -10^{-6} range represents a good reference number for a large range of today's accelerators and is the current state-of-the art in beam measurements. In the context of this paper we add to the halo definition a notion that the halo extends far from the beam core, it has a negative effect on an accelerator operation, and this effect has to be mitigated.

Direct Phase Space Measurement at Low Energy

The 2D phase space can be measured relatively easily at low energy (particles have to have sub-millimeter range in a solid material) using the slit-slit scan technique. A general measurement set up is shown in Fig. 1. A similar slit-grid arrangement is often used but the slit-slit arrangement allows achieving the required dynamic range much easier [5] because of the possibility of using a single high quality detector. In addition, this configuration allows using various mitigation techniques to suppress the effect of slit scattering - the main factor limiting the dynamic range of the system. For example, the SNS MEBT emittance scanner uses a Faraday cup located downstream of the DTL tanks. The H^- particles convert to proton when scattered by the slit edge, arrive to the DTL entrance in the decelerating phase and therefore are lost before reaching the detector. An example of a large dynamic range profile generated from the measured 2D emittance is shown in Fig.2. The measurements using large bandwidth current detector are shown by the solid lines; the measurements using charge integration from a neutron detector are shown by the circles. As one can see the systems has sufficient dynamic range for measuring halo if good temporal resolution is not required.

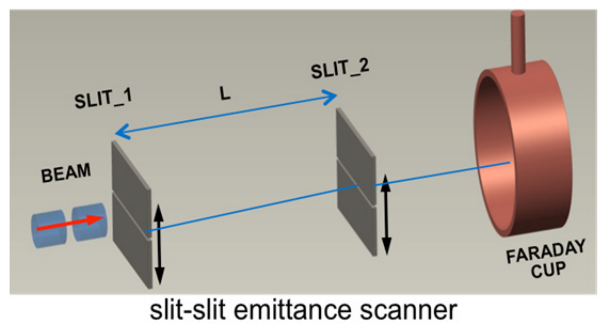

Figure 1: A schematic view of a slit-slit emittance scanner.

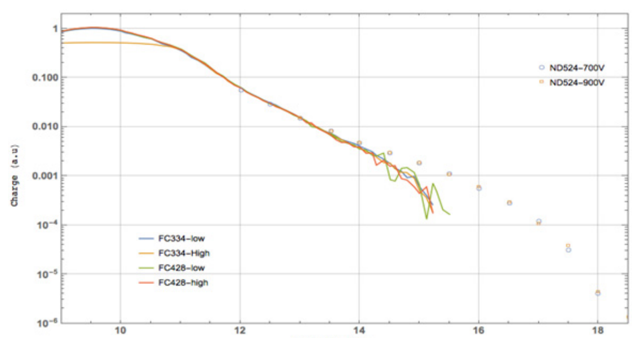

Figure 2: An example of large dynamic measurement with the SNS MEBT slit-slit system.

Direct Phase Space Measurement at High Energy

The only method for direct emittance measurement at high energy successfully demonstrated to date is the laser wire emittance scanner [6]. This method is suitable for H^- beams only. The best currently achieved dynamic range of 10^3 can be possibly improved by an order of magnitude but further extension to the halo region is limited by the laser beam quality. Nonetheless, this diagnostic can be very useful for benchmarking other techniques described below.

Reconstruction of 2D Phase Space Distribution from a Set of 1D Projections

The so-called phase space tomography allows finding the 2D emittance using several 1D projections (profiles)

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measured at different angles in phase space. The method has been demonstrated for transverse and longitudinal phase space. The dynamic range of the reconstructed 2D emittance depends on the dynamic range of the profiles and the method of reconstruction. An example of a reconstruction with 10^3–10^4 dynamic range which used four profiles measured by a wire scanner with 10^4 dynamic range and several iterations of the MENT algorithm is shown in Fig. 3. A reasonably good agreement is observed down to the 10^{-4} level. This result is very encouraging but further development of the method is required to extend the dynamic range to the halo region.

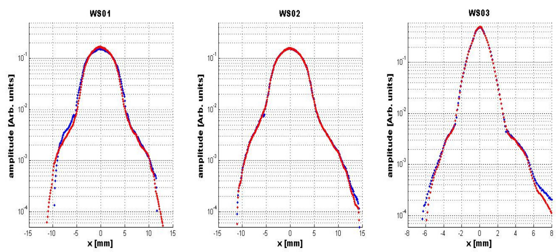

Figure 3: Comparison of measured (red) and obtained from results of 2D emittance reconstruction with large dynamic range (blue).

An example of using the reconstruction technique for measuring the effect of a transverse collimation in the MEBT on the beam distribution at the end of SCL is shown in Fig.4. The panel (a) shows the horizontal emittance measured by the MEBT emittance scanner with no collimators. The panel (b) shows the emittance with the left collimator plate inserted to intercept ~1-2% of the beam charge. The panel (c) shows the particle distribution generated from the emittance obtained using the MENT reconstruction for four profiles measured in the HEBT. The red dots correspond to the case with no collimation and the blue dots correspond to the case with one scraper inserted. The emittance reduction is obvious from the plot. The collimated distribution looks symmetric left to right despite a significant asymmetry in the initial distribution. The most plausible explanation is a complete homogenization of the distribution due to non-linear forces during transport through the linac. But it is also possible that the emittance reconstruction process is not accurate enough to reveal the asymmetry. This example emphasizes the importance of measurements benchmarking when dealing with low level details of beam distribution. The laser emittance measurements can be used to validate the MENT reconstruction at least within the dynamic range of 10^3–10^4.

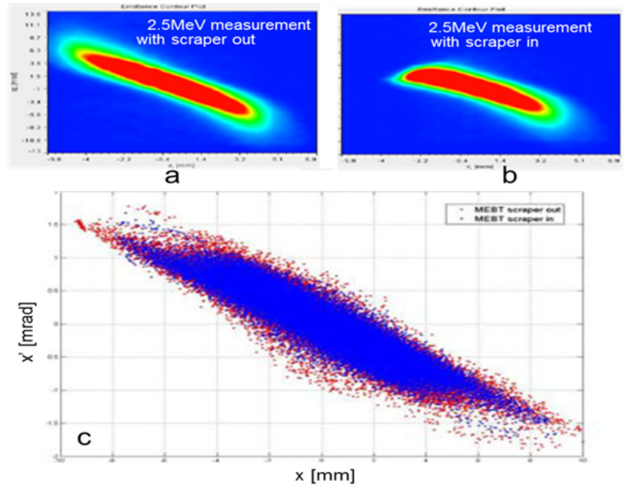

Figure 4: An example of emittances reconstruction from 1D profiles as explained in the text.

Characterization of Particles Distribution in Phase space

A convenient way of visualizing general properties of the 2D phase space distribution is plotting the phase space density vs. the normalized radius according to the following procedure:

- generate N particles using measured 2D phase space distribution as a probability function as illustrated by the panels (a) and (b) in Fig. 5.
- transform the particles coordinates x, x' to new coordinates: $x_n = {}^{x}\!/\!\sqrt{\beta_{RMS}}$;
- $x'_n = {}^{\alpha_{RMS}\cdot x}\!/\!\sqrt{\beta_{RMS}} + x'\beta\gamma\sqrt{\beta_{RMS}}$, where

  $\alpha_{RMS}, \beta_{RMS}$ are the RMS Twiss parameters, $\beta = {}^{v}\!/\!{}_{c}$, and γ is the relativistic factor
- calculate $r = \sqrt{x_n^2 + x_n'^2}$
- count number of particles N_r within $r \cdot dr$ circular bands as illustrated by the panels (c) and (d) in Fig.5.
- plot $n(r) = {}^{N_r}\!/\!{}_{2\pi r dr}$ vs. r in semi log scale as illustrated by the panel (d) in Fig.5.

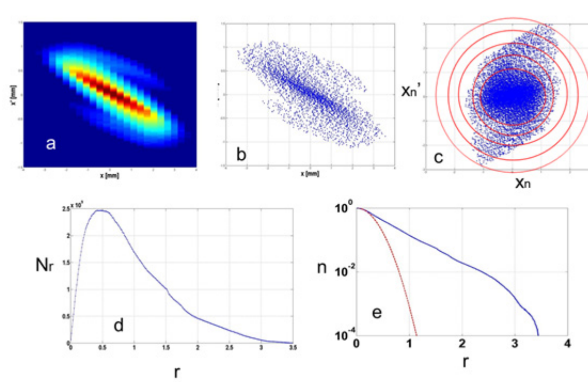

Figure 5: An illustration of making a phase space density plot generation as explained in the text.

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The plot of n vs. r is independent of the beam energy or location along the beam line. It can be used for comparing general distribution properties for different accelerators or even different particles species. An example of phase space density plots for the distributions from Fig. 4c is shown in Fig. 6. A reduction of the tail in the HEBT due to scraping in the MEBT is clearly seen but the dynamic range is not sufficient to make any conclusion about the halo.

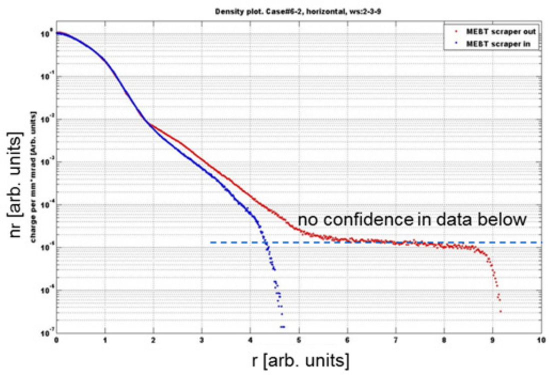

Figure 6: A phase space density plot for beam distributions in Fig.4c.

BEAM LOSS REDUCTION USING COLLIMATION AT LOW ENERGY

There is experimental evidence of beam halo already present in the SNS MEBT. This means it is created in the ion source and the RFQ, which do not have any practical means of beam distribution control. The most efficient way to clean the beam from the halo formed in the injector is to collimate it at as a low an energy as possible while the particles can be still stopped by a relatively thin block of a material. A typical low energy collimator is shown in Fig. 7. The problem usually is to find a free space in the beam line. As a result the collimators are often placed where space is available and the beam line optics needs to be adjusted for effective collimation, i.e. the halo needs to have the correct orientation in phase space. This is much easier to achieve if 2D emittance measurements of the halo are available as illustrated by Fig. 8 where the vertical emittance at the scrapers location in the SNS MEBT is shown. The scraper edges shown by the dashed lines are at 90° in phase relative to the halo, which explains why the vertical scraper at this location turned out to be not useful for reducing beam loss. In order to make the collimator efficient the emittance needs to be rotated by 90° while preserving other constraints of the MEBT optics: phase advance between the RFQ exit and the horizontal collimators, the required Twiss parameters at the MEBT exit, the available quadrupole magnets strength. An example of the MEBT optics modification satisfying the requirements is shown in Fig. 9 and the corresponding emittance rotation in Fig. 10. It was not easy to find this solution even with help of a model and is practically impossible by an empirical tuning. It has not been proved experimentally yet that this new optics allows for lower losses in SCL compared to the original optics. The scraper efficiency should be better but it is possible that more halo will be created due to the large vertical beam size variation.

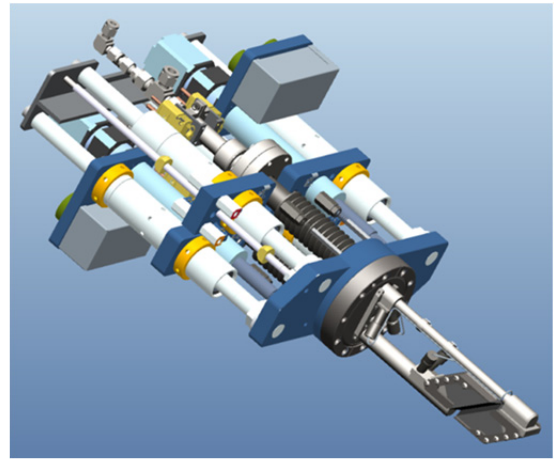

Figure 7: A model of the SNS MEBT vertical scarper.

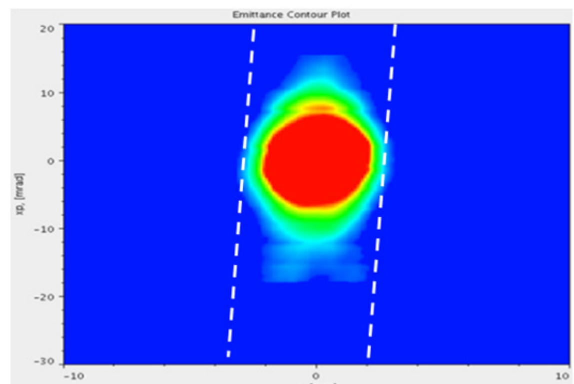

Figure 8**:** The measured vertical MEBT emittance orientation relative to the scraper edges (dashed lines).

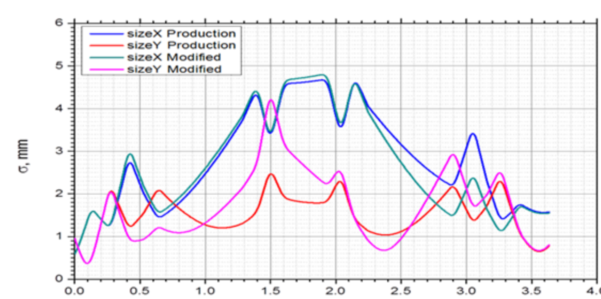

Figure 9: The measured vertical MEBT emittance orientation relative to the scraper edges (dashed lines).

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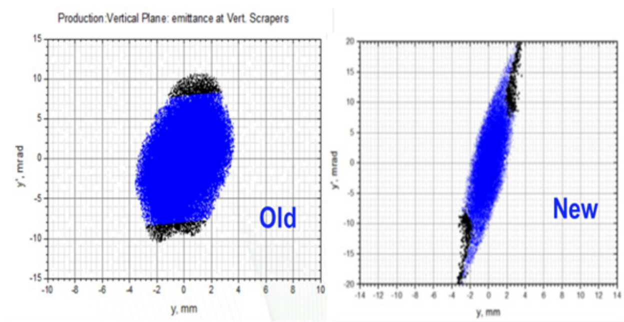

Figure 10: The measured vertical MEBT emittance orientation relative to the scraper edges (dashed lines).

SUMMARY AND FUTURE PLANS

A number of measuring tools, data processing techniques and simulation codes [3] are been developed to facilitate model based beam loss reduction in SNS SCL. There need to be a way to characterize the beam halo in a form suitable for use in simulation codes. Ultimately, the 6D phase space distribution is required but only 1D or 2D projections can be measured with sufficiently large dynamic range. We are equipping two experimental facilities for directed development and exploration of methods of beam distribution reconstruction from lower dimensionality projections – one for low beam energies, and one for high beam energies.

1. The SNS HEBT beam line having a straight section containing several individually settable quadrupole magnets, five large dynamic range wire scanners and a laser wire emittance scanner is an ideal test bench for large dynamic range MENT or other reconstruction methods development. A layout of the beam line is shown in Fig.11.
2. The SNS BTF [7] has equipment for direct measurement of 6D phase space distribution. This experiment will verify the accuracy of the assumption of un-correlated degrees of freedom in the input beam and provide a benchmark tool for various methods of constructing 6D distributions out of lower dimensionality projections. A FODO beam line is being designed to repeat the Los Alamos LEDA experiment on halo development [8]. This experiment will test the importance of RMS core matching for preventing halo formation in a beam transport line. A layout of the SNS BTF is shown in Fig. 12.

ACKNOWLEDGEMENT

This manuscript has been authored by UT-Battelle, LLC, under Contract No. DE-AC0500OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for the United States Government purposes. The Department of Energy will provide public access to these

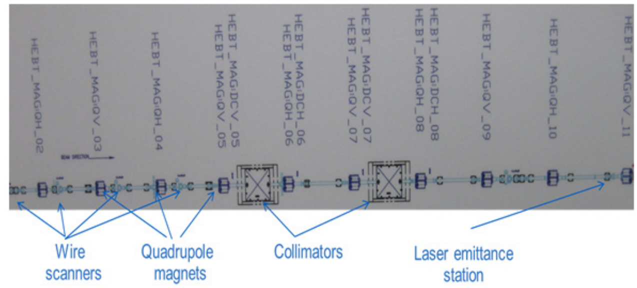

Figure 11: A layout of a beam line for large dynamic range tomographic reconstruction techniques development.

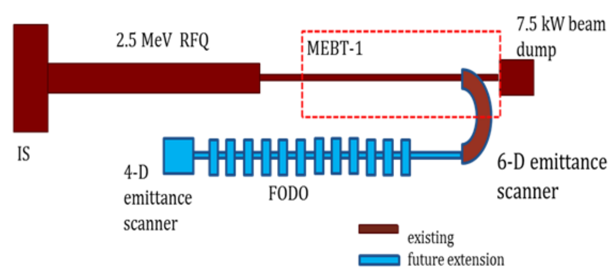

Figure 12: A layout of the SNS Beam Test Facility.

results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

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