ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-THAA005

PROGRESS TOWARDS HALO MODELING AT THE SNS BEAM TEST FACILITY *

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Abstract

The SNS beam test facility is a model of the SNS front end (source through medium-energy transport). On-going work at the BTF focuses on accurate modeling of the beam distribution to enable the prediction of halo losses (<100 parts per million). This presentation will discuss the latest progress towards this goal, including recent results after a reconfiguration of the test beamline. Good agreement within the 90% beam core is shown for a 30 mA beam at 2.5 MeV.

INTRODUCTION

The aim of research at the SNS Beam Test Facility (BTF) is to demonstrate accurate modeling of bunch evolution including space charge and early halo growth. The project uses advanced beam phase space measurements developed at the BTF, including a full-and-direct 6D phase space measurement and a high-dynamic-range 2D phase space measurement capable of more than 6 orders of magnitude in dynamic range. The scope of the project is to characterize an initial bunch (1.4 meters downstream of the RFQ) at 2.5 MeV, reconstruct the distribution for simulation, and compare to measured output at the end of the 2.5 MeV beamline (12 meters downstream of RFQ).

We show the performance of the model at 30 mA RFQ output. This is below typical beam currents in the SNS linac. Ongoing efforts to build a benchmark case at 50 mA include use of a large-aperture ion source capable of higher LEBT current. This benchmark is limited to "optimal" transport near the matched solution for the FODO line.

SIMULATION MODEL PARAMETERS

The current best benchmark case uses the PyORBIT code [1]. This case uses 200,000 macroparticles and a maximum space charge step of 1 cm to model a 30 mA beam from the "input" position (1.4 meters downstream of the RFQ) to the "output" near the beamline end. The model also includes a "multi-bunch" field solver, which takes into account the fact that, due to debunching, the 402.5 MHz bunches start to overlap in the FODO section of the beamline.

The section of lattice under study contains 10 electromagnet quadrupoles and 19 permanent magnet quadrupoles in a FODO arrangement (108 degrees phase advance per cell). The quadrupole focusing function is drawn in Fig. 1. The field model consists of soft-edged, pure quadrupole fields parameterized by magnet geometry.

BENCHMARK CASE AT 30 mA

Reconstruction of the input distribution is done from 3 2D phase space projections, under the assumption $f_{6D} = f(x,x') \cdot f(y,y') \cdot f(\phi,dE)$. Transverse phase space measurements $f(x,x')$ and $f(y,y')$ used a 2-slit system and Faraday cup. The dynamic range of this measurement is limited to 10^2. The longitudinal phase space $f(\phi,dE)$ is done with a dipole, vertical slit and bunch shape monitor, as well as two vertical slits upstream of the dipole for energy resolution. At the time of the transverse measurements, the RFQ transmitted 30 mA and for longitudinal, 32 mA.

The output distributions $f_{out}(x,x')$ and $f_{out}(y,y')$ are measured using the slits and Faraday cup at the end of the beamline. No longitudinal measurement is possible at this location. The output distributions are characterized at 30 mA from the RFQ.

Figure 2 shows the latest result from model/measurement comparison at the end of the beamline (approximately 9.5 meters downstream of the input). The density contours are at the 79%, 32%, 10% and 1% levels. The measurement of input phase space had a relatively low dynamic range of 10^2, although the emittance diagnostic is capable of dynamic range in excess of 10^6.

The bunch evolution between diagnostic areas is shown in Fig. 1. This plot includes data points from measured beam profiles from 1D slit-scans measurements. The rms calculation includes a threshold at 1% of the peak density. The rms value is sensitive to the tail distribution, therefore the discrepancy in rms sizes is consistent with the contour plots in Fig. 2.

TRANSPORT MATRIX ELEMENTS

Measurement of lattice matrix elements allows an independent benchmark of subsections of the BTF lattice. This measurement requires scanning the coordinates of a (x,x',y,y') collimated beamlet and measuring the response with a sensitive luminescent screen.

Table 1 compares the measured matrix elements to simulated values for the same optics case investigated above.

* This work relies on expertise and support from SNS Operations and the Research Accelerator Division at ORNL. The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (https://www.energy.gov/doe-public-access-plan). This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics. This work has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. This research used resources at the Spallation Neutron Source, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.
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ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-THAA005

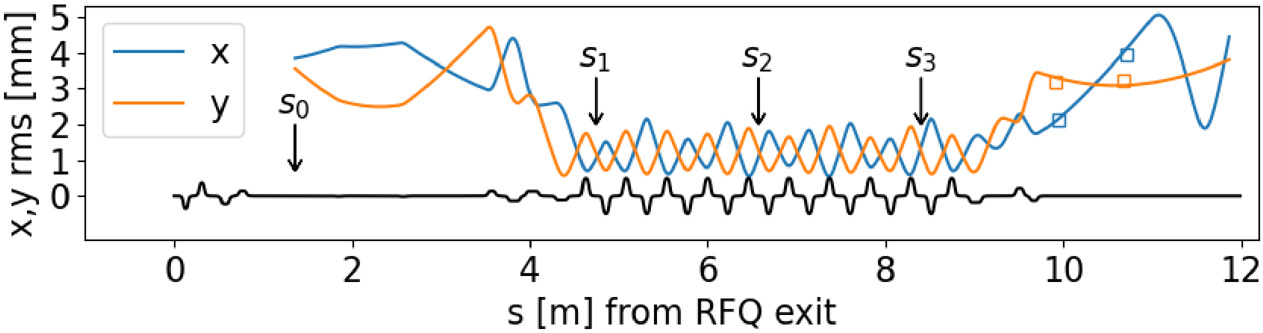
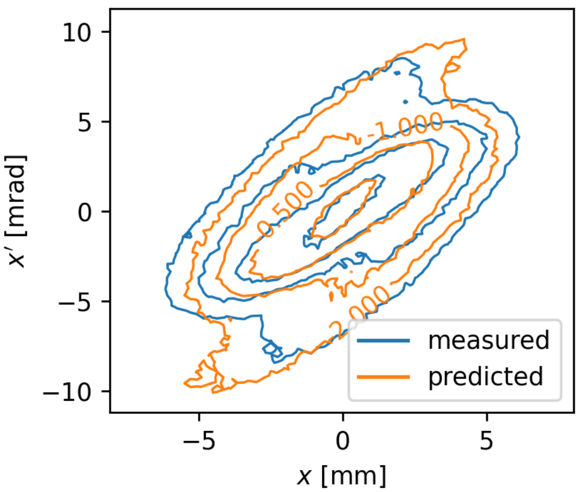
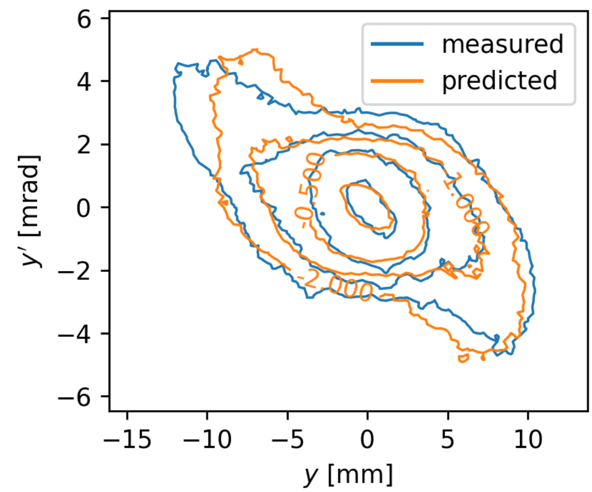


Figure 1: Simulation of rms size evolution between first diagnostics area and final beamstop. The square markers show comparison to measurements made with slit scans using the diagnostics area at the end of the beamline. s_0 indicates the position of the first slit in the first diagnostics area. s_1 to s_3 are diagnostic screen locations, referenced in Table 1.



(a) Comparison of horizontal phase space



(b) Comparison of vertical phase space

Figure 2: Comparison of model to measurement for a 30 mA beam at the location of the second diagnostic stage, after FODO line.

Matrix elements can be measured between the first slit position and 3 screens at the beginning, middle and end of the FODO section.

This comparison is comparable to the results reported in Ref. [2], but here simulation uncertainty is included. This uncertainty stems from the fact that the luminescent screen used to detect the beam is tilted at 45°, as drawn in Fig. 3. As a result, the s-coordinate where the beamlet impinges on the screen is not well known and will vary during a single measurement. The uncertainty in the measurement is derived from the covariance matrix of a least squares fit and is uniformly very low.

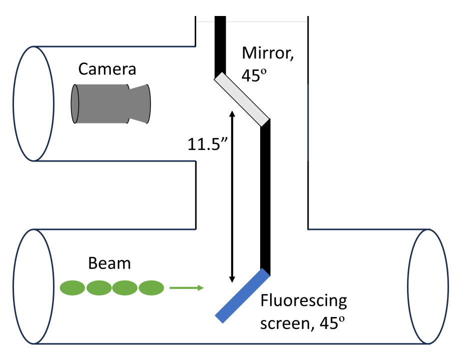


Figure 3: Diagram of FODO viewscreen diagnostic, reproduced from Ref. [3].

PROJECT OUTLOOK

Previous benchmark attempts showed worse agreement [2, 4]. Results pre-2023 included 2 90° bends in the 2.5 MeV beamline. The beamline reconfiguration to remove these bends dramatically improved results, although the exact reason is not clear. Contributing factors likely include:

- the 90° bend model was not sufficiently realistic (for example, there were no fringe fields)

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Table 1: Comparison of measured and simulated beam transport matrix elements. Positions s_0 to s_3 are indicated in Figure 1.

	Sim.	Meas.
$s_0 \rightarrow s_1$		
M11	-0.35 ± 0.03	-0.26 ± 0.00
M12	-0.05 ± 0.09	-0.41 ± 0.00
M33	-0.63 ± 0.05	-0.66 ± 0.00
M34	-0.79 ± 0.09	-0.84 ± 0.00
$s_0 \rightarrow s_2$		
M11	0.07 ± 0.03	0.05 ± 0.00
M12	-0.76 ± 0.09	-0.97 ± 0.00
M33	-0.26 ± 0.05	-0.32 ± 0.00
M34	-0.76 ± 0.09	-0.70 ± 0.00
$s_0 \rightarrow s_3$		
M11	0.43 ± 0.03	0.28 ± 0.00
M12	-0.91 ± 0.09	-0.96 ± 0.01
M33	0.30 ± 0.05	0.23 ± 0.00
M34	-0.15 ± 0.09	-0.16 ± 0.00

- The combination of large dispersion and large energy spread likely led to scraping between the bends. Scraping upstream of the FODO line can lead to significant and non-intuitive distortion in the output phase space.

- The combination of uncorrected dispersion and large energy spread caused significant, energy-dependent distortion of the measured phase spaces

- High transverse divergence of the bunch downstream of the FODO line increased sensitivity to magnet parameters. Two additional quadrupoles were recently added to improve control in this region.

The comparison of modeled/measured transport matrix elements suggests a discrepancy in the linear quadupole function, especially in the horizontal plane. However, the description of the linear focusing strength of the quadrupoles is sufficient for good agreement in this case, which represents near-optimal optics for the BTF. The plan of study includes exploring tail/halo growth with mismatched modes, which will result in larger local envelope sizes and likely will require tighter constraints on the quadrupole parameters.

A hypothesis of this project is that a very complete and accurate description of the initial bunch distribution $f_{6D}(x, x', y, y', \phi, dE)$ is needed for good simulation results. A simulation study motivated by 5D and 6D phase space measurements found low sensitivity to the presence of observed interplane dependencies [5]. For the BTF experiment, simulations predict that the assumption $f_{6D} = f(x, x') \cdot f(y, y') \cdot f(z, z')$ should give good results above the 0.01% threshold. Therefore, the omission of full-6D correlation is not likely to be the cause of the discrepancy reported here.

The good agreement in the core but not the tails shown in Fig. 2 suggests that nonlinear terms may play a role, either arising from the magnetic elements, or from space charge. An earlier study of the nonlinear components of the permanent magnets as designed predicts a small effect [6], but this same study should be extended to include electromagnet quadrupoles and design errors.

The data used for this benchmark case had limited dynamic range ($\leq 10^2$). Recent high dynamic range measurements (10^6) of the initial bunch at 46 mA transmitted current show that the tails drop off sharply, and no extended halo is observed. Future studies will focus on the necessary sensitivity of the input bunch measurements for good predictions, as well as characterize the halo extent at the end of the beamline.

SUMMARY

A recent model/measurement benchmark at the SNS Beam Test Facility shows good agreement for evolution of the bunch 90% core from RFQ output to end of the 2.5 MeV test beamline. This benchmark breaks down for the extended tails of the bunch (1%-10% level), suggesting there is a nonlinearity that is not accounted for. A measurement of transport matrix elements suggests that some small correction to the linear quadrupole fields may also be required.

REFERENCES

[1] A. Shishlo, S. Cousineau, J. Holmes, and T. Gorlov, "The particle accelerator simulation code PyORBIT", *Procedia Comput. Sci.*, vol. 51, no. 1, pp. 1272–1281, 2015. doi:10.1016/j.procs.2015.05.312

[2] T. Thompson, A. Aleksandrov, A. Zhukov, A. Hoover, and K. Ruisard, "Measurement and modeling of beam transport in the FODO line of the Spallation Neutron Source Beam Test Facility", in *Proc. IPAC'24*, Nashville, TN, USA, pp. 943–946, 2024. doi:10.18429/JACoW-IPAC2024-TUAN2

[3] K. Ruisard *et al.*, "Status of the Spallation Neutron Source beam test facility and progress of beam dynamics studies", in *Proc. IPAC'24*, Nashville, TN, USA, pp. 3206–3209, 2024. doi:10.18429/JACoW-IPAC2024-THPC75

[4] Ruisard, K. "Exploring initial distributions at the beam test facility", 5th ICFA Mini-Workshop on Space Charge. (2022), https://conference.sns.gov/event/335/contributions/507/attachments/870/8189/Space%20charge%20workshop_v2.pdf

[5] A. M. Hoover, A. V. Aleksandrov, S. M. Cousineau, K. J. Ruisard, A. P. Shishlo, and A. P. Zhukov, "The Impact of High-Dimensional Phase Space Correlations on the Beam Dynamics in a Linear Accelerator", in *Proc. HB'23*, Geneva, Switzerland, pp. 68–72, 2024. doi:10.18429/JACoW-HB2023-TUC1C2

[6] T. E. Thompson, A. V. Aleksandrov, T. V. Gorlov, K. J. Ruisard, and A. P. Shishlo, "Effect of Three-Dimensional Quadrupole Magnet Model on Beam Dynamics in the FODO Line at the Spallation Neutron Source Beam Test Facility", in *Proc. HB'23*, Geneva, Switzerland, pp. 65–67, 2024. doi:10.18429/JACoW-HB2023-TUC1C1