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MEASUREMENT AND MODELING OF BEAM TRANSPORT IN THE FODO LINE OF THE SPALLATION NEUTRON SOURCE BEAM TEST FACILITY*

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Abstract

Ongoing studies at the Spallation Neutron Source- (SNS) Beam Test Facility (BTF) seek to understand and model bunch dynamics in a high-power LINAC front-end. The BTF has recently been upgraded with a reconfiguration from a U-shaped beam-line to a straight beam-line. We report the current state of model benchmarking, with a focus on RMS beam sizes within the FODO line, and directly after. Beam measurement is obtained via three camera/screen pairs in the FODO line, and via slits after. This presentation discusses the methodology and results of these measurements.

INTRODUCTION

The Beam Test Facility (BTF) was designed to study the beam dynamics of the Spallation Neutron Source (SNS) at medium energy (2.5 MeV) after acceleration through its radio frequency quadrupole (RFQ). To accomplish this the BTF uses an equivalent H- source and the previously in-use RFQ from the SNS. Since 2018 it has been configured in a U-shaped layout [1], with a focus on making high dynamic range [2] and 6D measurements [3]. Additionally, there is a 9.5 cell permanent magnet quadrupole FODO line, allowing for additional beam transport studies [4].

The BTF follows in the footsteps of the Low Energy Demonstration Accelerator (LEDA) at Los Alamos National Lab (LANL) in the attempt to benchmark medium energy beam evolution [5]. Generally, simulations of high intensity front-ends do not reproduce halo region dynamics. The goal of this project is to show model agreement with measured beam distributions down to loss-level (defined as 1 part-per-million sensitivity). However, the original design of the BTF faced a few issues with achieving this goal.

Firstly, an adequate rms benchmark of the beam-line was never achieved. At best there was a mediocre benchmark for our transmission magnet optics, though the benchmark quality declined for other optics [2,6]. Secondly, the focusing effect from three 90° dipoles along the beam-line led to large rms envelopes and dispersion that constrained tuning. We were also using an idealized dipole model that we suspect was a large source of error. Finally, the emittances at the end of the beam-line were distorted due to uncorrected dispersion and chromaticity in the FODO line. These distortions are very sensitive to beam energy and were difficult to reproduce in simulation.

To simplify the benchmark case, the BTF was reconfigured during a long shutdown from Aug 2022 - Dec 2023. The reconfiguration consisted of taking the second leg of the U and attaching it as a continuation of the first leg with no bends, as shown in Fig. 1. The first dipole of the old configuration was kept in place and a stub section included as it is needed for 6D measurement capability. This paper focuses on benchmarking the BTF in its new configuration, focusing on rms values.

DIAGNOSTIC AVAILABILITY

The straight beam-line has a multitude of diagnostic capabilities, including 1D profiles, intensity limited profiles, and phase spaces from 2D to 6D. The intensity limited profiles use screens that are unable to withstand full beam. The layout of the beam-line and locations of diagnostic measurement capabilities are indicated in Fig. 1.

MATRIX ELEMENTS

The first two sets of slits can be used to create a collimated pinpoint beam, this beamlet can then be detected on the three screens in the FODO line. By moving the collimating slits and measuring the resulting movement of the beamlet on each screen, some transport matrix elements between the first set of slits and each of the screens can be measured. Table 1 compares these measurements to the model.

INTENSITY LIMITED RMS

To analyze the beam within the FODO line a series of screens (locations (3)-(5) in Fig. 1) are used in symmetric locations such that a matched beam would appear identical at each location. There is a screen at the start of the FODO line, one in the middle, and one at the end. These screens can be used to measure beam size and recover rms, however there are a few complications.

Firstly, the screens are intensity limited. Full beam cannot be put on them as it will burn the screens. Instead, slits upstream must be used and scanned to reconstruct full beam. A screen saturation study was conducted, concluding that four slits (locations (1) and (2) in Fig. 1) are needed to avoid screen saturation, resulting in a pinpoint beam that observes no space charge effects. Secondly, proton contamination is

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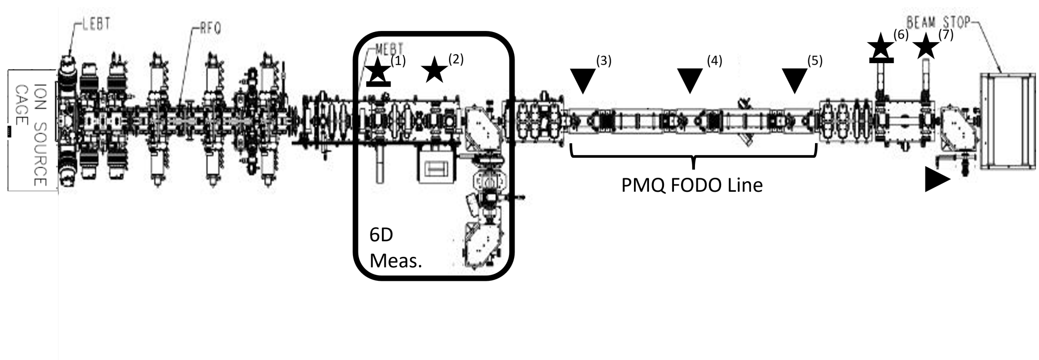

Figure 1: Layout of straight BTF configuration. The symbols represent diagnostic locations. Triangles: intensity limited profiles. Stars: profiles. Underlined Stars: phase space. Box: 6D measurements. Note: at each star there is a set of both horizontal and vertical slits.

Table 1: Transport Matrix Elements

Slits to FODO Start			
	Sim.	**Meas.**	**|Δ|**
M11	-0.359	-0.388 ± 0.000	0.03
M12	0.161	-0.262 ± 0.002	0.42
M33	-0.724	-0.761 ± 0.001	0.04
M34	-0.859	-0.937 ± 0.002	0.08

Slits to FODO Middle			
	Sim.	**Meas.**	**|Δ|**
M11	-0.155	-0.240 ± 0.001	0.08
M12	-0.697	-0.855 ± 0.003	0.16
M33	0.051	-0.131 ± 0.009	0.18
M34	-0.320	-0.434 ± 0.017	0.12

Slits to FODO End			
	Sim.	**Meas.**	**|Δ|**
M11	0.171	-0.002 ± 0.002	0.17
M12	-0.998	-0.955 ± 0.006	0.03
M33	0.774	0.649 ± 0.002	0.12
M34	0.473	0.390 ± 0.003	0.08

also detected on the screens, however at the screen locations they are offset from the main beam and so can be easily excluded from data sets. Finally, a separate camera is used to observe each of these screens. To make this possible each screen is on an actuator arm at a 45° angle to the beam. On the other end of the arm is a mirror at a counter 45° angle to send light from the screens to the cameras. The issue is that this setup for the first and second screens is not flush with the beams and a skew is observed in the camera measurements. This skew is correctable by linear transformation of the camera image to minimize skew.

In order to measure the full beam profile with the collimating slits, many images are recorded while scanning the slits across the phase space footprint. To get enough of the beam shape to measure beam profile at the screens the slits must be scanned around the full size of the beam. This results in images that contain no beam on the screen, all images above a signal threshold of 1-2% (dependent on noise of camera used) are summed to create a composite image. A profile is created from this composite image then the Wiener smoothing function is used and the profile is thresholded at 5% of max intensity as shown in Fig. 2. From this profile rms is calculated (Table 2).

Table 2: Beam rms Values at Screens

FODO Line X-RMS			
	Sim. (mm)	**Meas. (mm)**	**% Diff.**
Start	1.403	1.380	1.67
Middle	1.134	1.425	20.42
End	0.816	0.900	9.33

FODO Line Y-RMS			
	Sim. (mm)	**Meas. (mm)**	**% Diff.**
Start	1.205	1.220	1.23
Middle	0.846	0.476	77.72
End	1.797	1.434	25.31

The resulting profiles and rms are then compared to simulated results created using PyORBIT [7] and an input bunch created from measured data. To create the bunch, three 2D measurements are done in (x, x'), (y, y'), and (ϕ,dE), then interpolated to form the full bunch. This bunch is used for all simulations in this paper. To compare to the measured profiles at screens the simulation is ran without the space charge solver, and bunch statistics are calculated in a similar manner. At each screen location a histogram is created from the output bunch, which is wiener smoothed and thresholded at 5% of max intensity. All profiles are normalized by area (Fig. 2).

BEAM-LINE END MEASUREMENTS

At the end of the beam-line there is a second set of slits (locations (6) and (7) in Fig. 1) that can be used to measure the beam. They can withstand full beam and can measure both profiles and transverse phase space distribution. Since the beam is not collimated, these measurements include the

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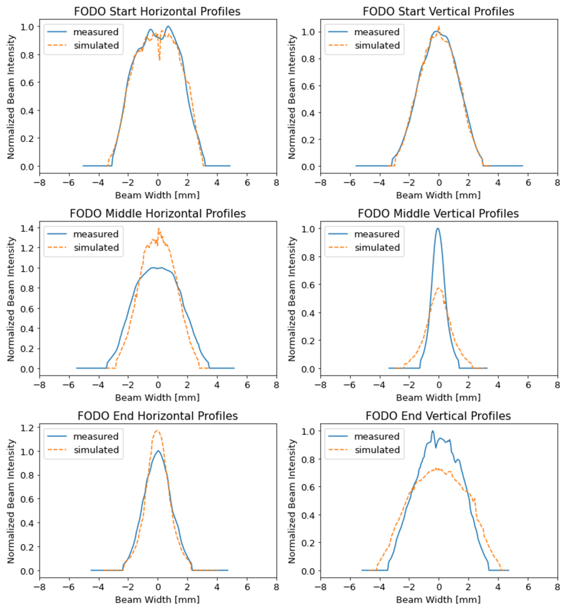

Figure 2: Beam profiles at each of the screens within the FODO line.

effect of space charge through the beam-line. At each slit a profile is created by scanning the slit across the beam, then wiener smoothed and thresholded at 5% of max intensity. The same simulation procedure as previous is followed, though it is now ran with space charge effects, and compared to measurement (Table 3)(Fig. 3). These same slits can also be used to measure 2D emittances by scanning sets of slits in the same plane. These measurements are compared to simulated results in Fig. 4.

Table 3: Beam rms Values at Slits

Beam-Line End X-RMS			
	Sim. (mm)	**Meas. (mm)**	**% Diff.**
First Slits	2.048	2.277	11.29
Second Slits	3.013	3.031	0.59

Beam-Line End Y-RMS			
	Sim. (mm)	**Meas. (mm)**	**% Diff.**
First Slits	3.335	3.841	1.23
Second Slits	1.980	3.164	77.72

CONCLUSION

Re-configuring the BTF from the U-shaped design to the current straight layout has improved the benchmark case. It has also removed observed distortions in emittance at the end of the beam-line. Current evidence points to remaining inconsistencies resulting from errors in the magnetic lattice model. Moving forwards we will use computational models of magnets alongside manufacturer data, as well as conduct beam-based calibrations of our electromagnets in order to improve the simulation model. We are also considering comparing PyORBIT results with results generated from other codes.

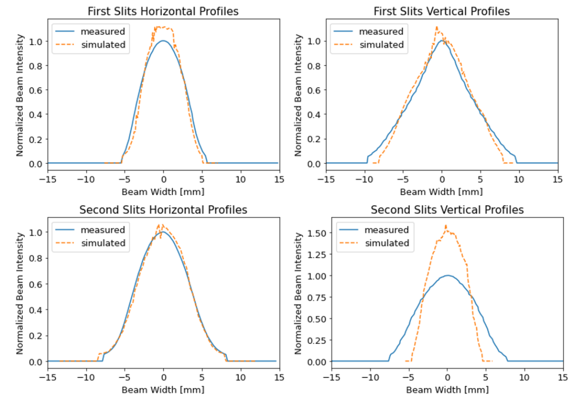

Figure 3: Beam profiles at end of beam-line.

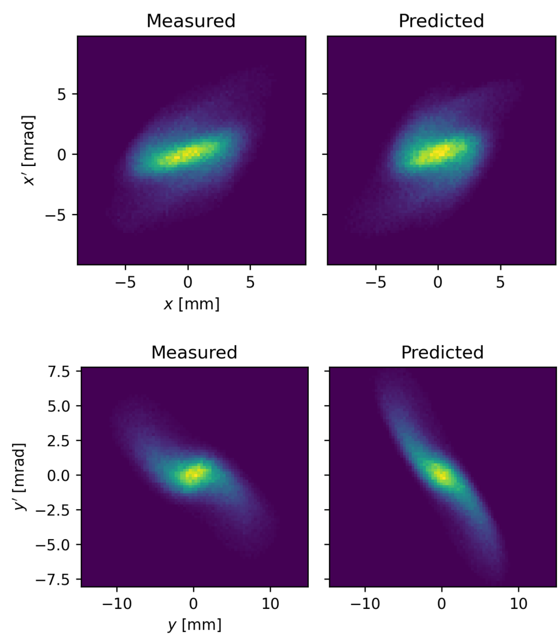

Figure 4: Beam phase space at end of beam-line.

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