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STATUS OF THE SPALLATION NEUTRON SOURCE BEAM TEST FACILITY AND PROGRESS OF BEAM DYNAMICS STUDIES *

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Abstract

The Spallation Neutron Source (SNS) Beam Test Facility (BTF) supports the study of beam dynamics in the front end of a high power LINAC. The BTF combines a replica of the SNS front end, including nearly-identical ion source, RFQ and MEBT, with extensive phase space diagnostics and a FODO transport line. Diagnostic capabilities include direct measurement of 6D phase space distribution and detection of halo distributions to a sensitivity of greater than one part-per-million. The goal of on-going BTF studies is to demonstrate accurate particle-in-cell modeling of halo growth and evolution by leveraging unprecedented accuracy in the description of the initial beam distribution. This work is motivated by operational experience at the SNS, which currently operates with beam loss that cannot be described by any model. This paper summarizes progress in the BTF beam study program as well as diagnostics development and recent upgrades to the beamline configuration.

INTRODUCTION

The goal of ongoing SNS Beam Test Facility studies is to demonstrate accurate modeling of bunch distribution through the medium-energy transport line. Figure 1 outlines the scope of studies: initial bunches can be defined at the 1st diagnostic location, capable of measured 1D to 6D distributions using a slit-scan approach. The simulated bunch can be compared to measurements at the diagnostics near the beamline end, which can diagnose up to 5D phase space distributions.

The BTF was in outage from August 2022 – December 2023, except for a brief RFQ commissioning run in January 2023 [1]. During this outage, the beamline was reconfigured from the previous U-shape (2 90-degree bends) to the current straight layout. This change was motivated by tuning constraints and large benchmark discrepancies attributed to the 90-degree bends.

OUTLOOK FROM 6D PHASE SPACE MEASUREMENTS

One motivation of the BTF studies is to determine the requirements on reconstruction of the initial ion bunch distribution for accurate halo prediction. In many benchmarking studies, the initial distribution is a source of uncertainty due to diagnostic limitations [2, 3].

For this purpose, a full-and-direct measurement of the 6D phase space distribution was developed for the BTF [4]. This measurement allows reconstruction of the distribution $f(x, x', y, y', z, z')$ of the $H-$ bunch at medium energy (2.5 MeV) 1.3 meters downstream of the RFQ exit face. The 6D measurement offers an alternative to typical reconstruction methods that assume $f_{6D} = f(x, x') \cdot f(y, y') \cdot f(z, z')$.

The full 6D measurement has been performed three times, including the initial demonstration described in [4]. The 6D measurements have low resolution and for that reason are not used to define simulation bunches at this point in time. A pathway to improved resolution is described below.

Significant effort has been expended in performing high-resolution 5D measurements of $f(x, x', y, y', z')$, as described in [5, 6]. Although these cannot be used alone to initialize a simulation bunch, they do resolve all significant features, including a hollowed beam core that is obscured in full projections.

The observed features in the 5D measurement have good qualitative agreement with MEBT distributions generated by RFQ simulations (PARMTEQ [7]) [8–10], although the RMS phase space parameters have a significant discrepancy. Bunches from these RFQ simulations can therefore be used to predict the sensitivity of halo modeling to preserving or destroying interplane correlations. This was explored in [10], which found that there is very low sensitivity and that bunch reconstructions that approximate $f_{6D} = f(x, x') \cdot f(y, y') \cdot f(z, z')$ should be sufficient for good model predictions. In simulations of the SNS drift-tube linac, both the output phase space and the rms beam size at all energies showed no dependence on preservation of 6D features. In simulations of the BTF experiment, there were small but measurable differences in the low-density regions of the output phase spaces.

Future plans include advancing the 6D measurement to higher resolution. At higher resolution, the 6D measurements can be used to confirm the results of the above simulation study. Additionally, we will explore sensitivity to

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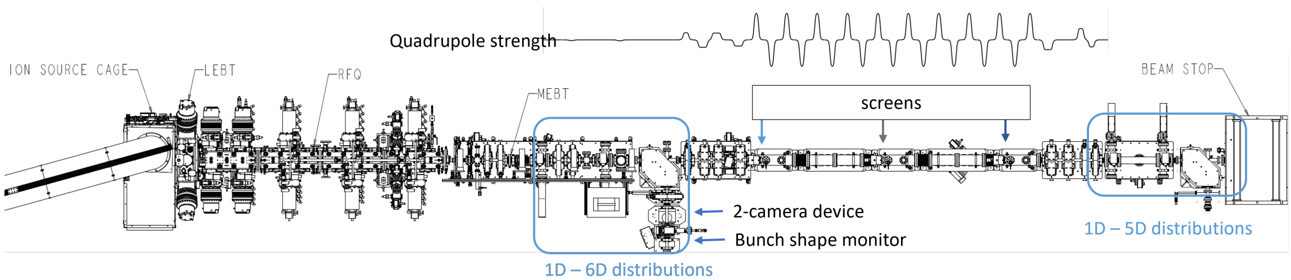

Figure 1: Diagram of BTF beamline with diagnostic locations annotated.

initial halo in the initial bunch. This can be achieved with the high-dynamic range diagnostic described in a later section.

VALIDATION OF LATTICE MODEL

At present, the largest model/measurement discrepancies appear to be caused by errors in the lattice parameters. The beam transport optics in the BTF consists of 14 electromagnet quadrupoles on independent, bipolar power supplies, as well as a FODO section containing 19 permanent magnet quadrupoles (PMQs) at 108 degrees phase advance per cell. The quadrupole focusing function is illustrated in Fig. 1. Until recently, the beamline also contained two 90° bends in order to achieve a compact footprint. In the configuration with bends, benchmarking attempts failed to show good prediction of rms-level features in the output bunch.

A recent example of model prediction for the new configuration (without bends) is discussed in detail in [11]. This work makes extensive use of viewscreen/camera systems in the FODO section. Early model benchmarking attempts utilized a single measurement apparatus: the slit-slit emittance device at the end of the beamline. It was found early on after installation of the FODO section that transport was very sensitive to PMQ parameters. This motivated the installation of viewscreens at three locations in the FODO, to allow a phased approach to lattice validation.

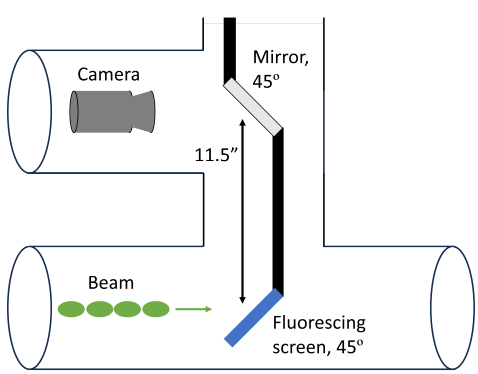

Figure 2: Diagram of FODO viewscreen diagnostic.

Figure 2 illustrates the FODO section viewscreens. Three screens are located at three symmetry points in the FODO lattice. Each system consists of a screen/mirror pair at 45°, which can be actuated into the beam path.

Many model improvements have been needed to obtain the results shown in [11]. This includes implementation of a soft-edged profile for the quadrupoles, most importantly the PMQs. The geometry of the Halbach-style PMQs has an analytic expression for the longitudinal field profile. [12] explored implementation of a 3D analytic PMQ model, which includes all nonlinearities arising from the geometry. This work found that the 1D model for the longitudinal field profile is sufficiently accurate, and 3D fields do not need to be considered for these elements.

DIAGNOSTIC UPGRADES

Two important diagnostic upgrades have recently been implemented that will support the beam dynamics studies at the BTF.

High Dynamic Range Phase Space Measurement

The goal of BTF modeling is to obtain accuracy in output distributions down to the halo level (100 to 1 parts per million). This requires a measurement range of 10^6 in beam density. This achievement was reported in [13], using cameras as optical charge collectors. The initial high dynamic range (HDR) apparatus used a single camera, switching between two exposure/delay settings to achieve a wide range.

A new HDR apparatus has been installed. This system uses two off-axis cameras to simultaneously record data, halving measurement times. The apparatus is shown in Fig. 3. A diagram of the HDR slit-slit emittance method is shown in Fig. 4.

Improved Bunch Shape Monitor

Measurements of phase distributions use a bunch shape monitor. In the BTF, the longitudinal emittance device consists of a 90° bend + slit for energy selection, following by a bunch shape monitor for phase distribution. A "2D BSM" concept, realized by Radiabeam [14], enables the possibility of simultaneous measurement of phase and energy distributions.

The premise, shown in Fig. 5, is to design the deflecting fields and focusing optics of the secondary electrons to preserve the horizontal distribution. By placing the BSM in a region of tunable dispersion, the energy-phase distribution f(z,z') can be measured by imaging the secondary electrons.

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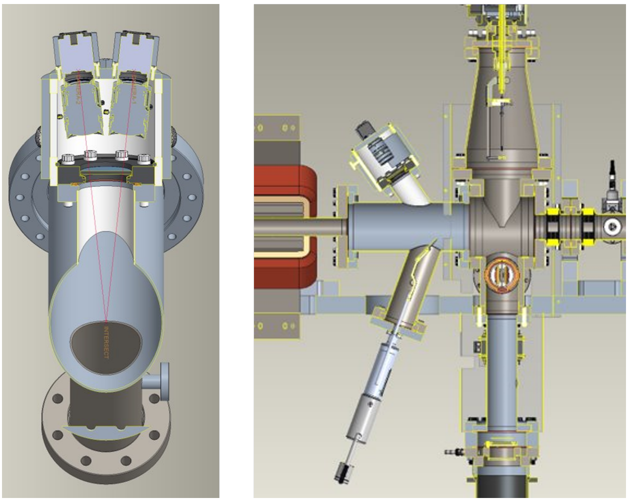

Figure 3: Drawings of 2-camera system.

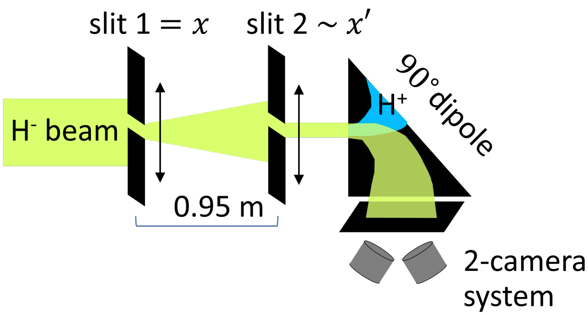

Figure 4: Diagram of 2-camera high-dynamic range diagnostic.

The device, delivered by Radiabeam in April 2024 (shown in-situ in Fig. 6), will both improve phase resolution and enable more rapid measurement of the longitudinal phase space. This improved BSM can be incorporated into the 6D measurement for an order-of-magnitude decrease in measurement time.

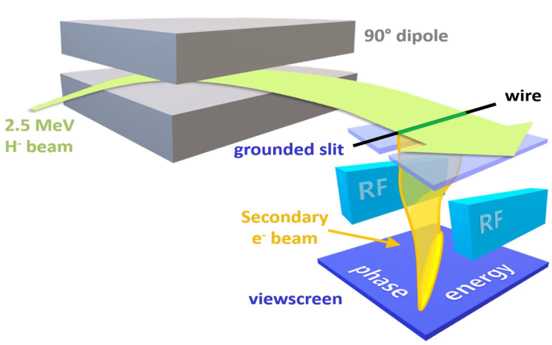

Figure 5: Diagram of 2D BSM concept.

SUMMARY

Studies at the SNS BTF continue to pursue the goal of improving model performance in order to predict halo distributions. Development of the full-and-direct measurement of the 6D bunch distribution has resulted in a detailed view of interplane dependencies that are invisible in 1D and 2D projections. However, simulation studies predict that for the SNS and the BTF, good prediction of downstream distributions do not require a fully-correlated initial bunch and reconstructions from 2D phase space projections should be sufficient. A reconfiguration of the beamline to remove 90° bends has improved agreement between the lattice model and measurements. Recent diagnostic upgrades will enable better characterization of initial bunches and more rapid iteration between measurement and simulation.

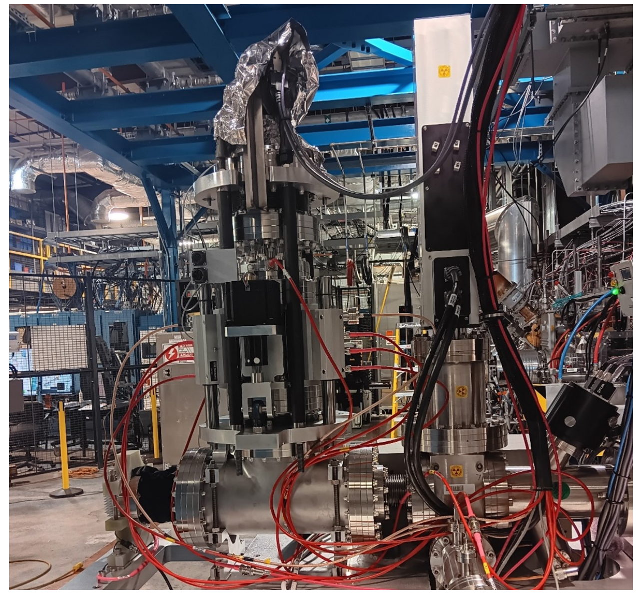

Figure 6: Photograph of new BSM installed in the BTF stub.

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