ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-THZBA4

CHARACTERIZATION AND MODELING OF HIGH-INTENSITY EVOLUTION IN THE SNS BEAM TEST FACILITY*†

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Abstract

Modern high-power accelerators are charged with delivering reliable beam with low losses. Resolving the complex dynamics arising from space charge and nonlinear forces requires detailed models of the accelerator and particle-in-cell simulation. There has historically been discrepancy between simulated and measured beam distributions, particularly at the low-density halo level. The Beam Test Facility (BTF) at the Spallation Neutron Source is outfitted to study beam evolution in a high-power linear accelerator MEBT. This includes capability for high-dimensional measurements of the post-RFQ beam distribution, including interplane correlations that may be the key to accurate simulation. Beam is transported through a 4.6 m FODO channel (9.5 cells) to a second distribution measurement stage. Plans for validating simulations against BTF measurements of beam evolution in the FODO channel are discussed.

INTRODUCTION

Modern high-power accelerators are charged with delivering reliable beam with low losses. For future facilities, which aim for order-of-magnitude power increase above existing state-of-the-art, tighter control over beam loss is required. In the >10 MW class, losses should be controlled to within one part-per-million to maintain a safe accelerator environment [1].

A pervasive source of uncontrolled loss is beam halo. Halo is the low-density particle population composing a "heavy-tailed" (above-Gaussian) feature in the beam distribution. Due to the large extent, this small fraction of beam contributes disproportionately to scraping losses. This paper adheres to the definition outlined in [2, 3]: halo is phase space feature emerging at densities below 10^{-4} of peak.

The SNS beam test facility (BTF, see Fig. 1) is a replica of the SNS front-end system. It is comprised of an H^- ion source, 2.5 MeV/402.5 MHz RFQ and alternating-gradient MEBT. The BTF is a multi-use test facility. In addition to being used for commissioning new diagnostics and accelerator components, it supports beam physics studies. In particular, the BTF is equipped with both high-dimensional and high-dynamic range capabilities for diagnosis of beam distribution. The focus of the ongoing BTF beam physics program is the halo-inclusive benchmarking of front-end beam evolution.

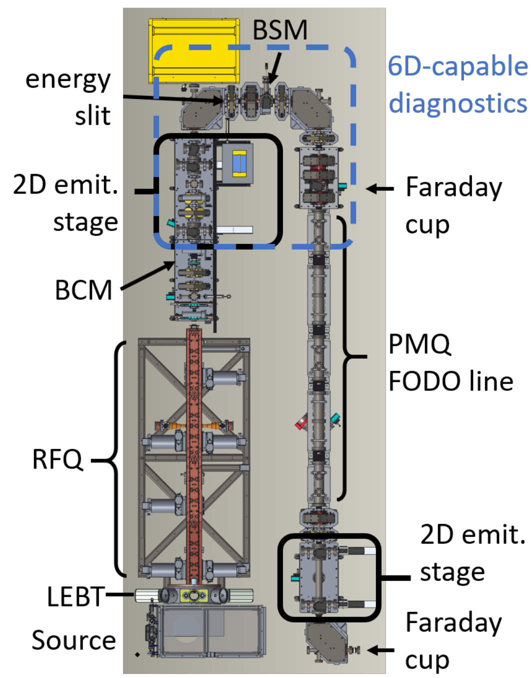

Figure 1: Diagram of major BTF components and relevant diagnostics.

PRIOR WORK AND STATE OF THE ART

Many preceding studies have similarly focused on characterizing halo. The landmark study at the Low Energy Demonstration Accelerator (LEDA) at LANL was accompanied with a detailed simulation study [4, 5]. In this study, PIC simulations were unable to consistently reproduce the RMS beam profiles, much less accurately predict the low-level features (down to 10^{-4} of peak). The source of errors was judged to be incomplete understanding of the initial beam distribution.

Since then, it has been demonstrated that agreement at the core/RMS level is possible with PIC codes. In particular, the benchmarking effort at the GSI UNILAC tested a selection of codes and showed agreement over a range of optics configurations for heavy ions [6]. However, extending predictions to the required 1 ppm halo level is still a major hurdle.

* This manuscript has been authored by UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725 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 United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).
† This work has been partially supported by NSF Accelerator Science grant 1535312.
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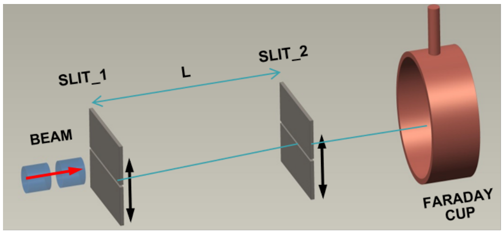

Figure 2: A simplified schematic of 2D slit-scan emittance measurement. Not pictured is a 90° dipole before the Faraday cup to clean signal of scattered H^{+}.

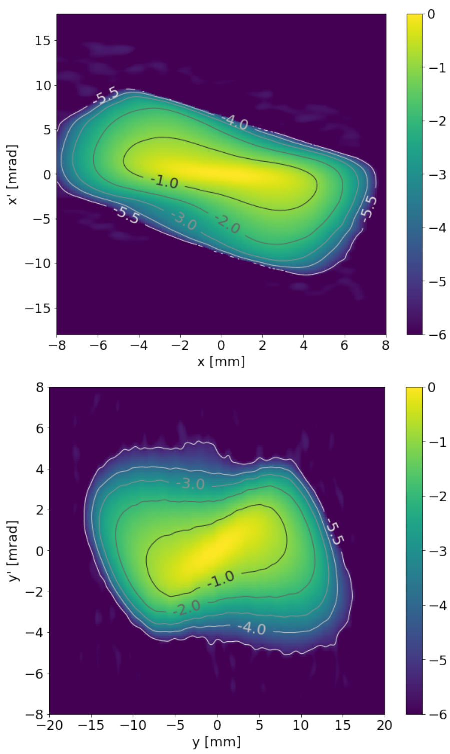

Figure 3: 2D emittance measurements from 1st emittance stage, in logarithmic scale with threshold applied at 10^{-6}.

6D Phase Space Measurement

Typical characterization of a beam distribution includes independent measurement of the emittance projection in the three planes (x, y, z). This approach assumes that interplane correlations are negligible. The BTF has been equipped to directly measure the full 6D phase space distribution, including all correlations. The initial proof-of-principle measurement showed an unexpected correlation between transverse axes and forward energy [7]. This correlation, which is seen to have a dependence on beam intensity, may play a key role in influencing downstream evolution, particularly when 1-ppm accuracy is required.

HIGH DYNAMIC RANGE EMITTANCE

High-dynamic range diagnosis of halo is an inherently challenging task. The results of preceding experimental studies have not exceeded 10^{-4} (eg, [4, 8, 9]). In addition, prior studies have relied on 1D transverse profiles to characterize halo. When using 1D measurements, it is necessary to have multiple measurement points to reconstruct full halo extent (in case halo has large momentum spread but small position spread at the diagnostic location). There is also insufficient information for tracking of the sampled distribution. For halo studies at the BTF, 2D emittance will be characterized to the 10^{-6} level. This is an improvement on current state of the art in both range and dimensionality.

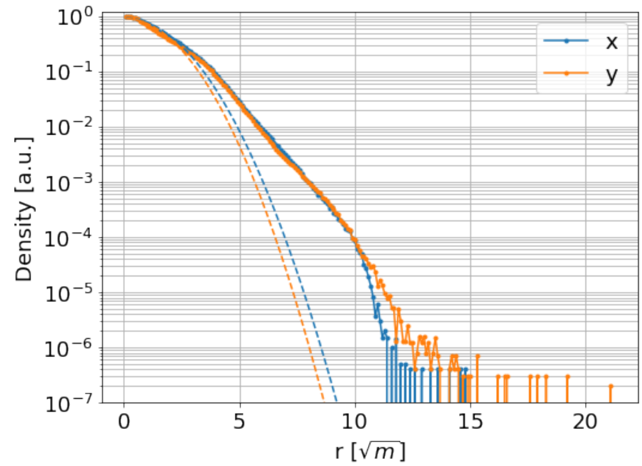

Figure 4: Radial distribution of 2D emittance measurements at 1st emittance stage, including Gaussian fits (dashed lines). Horizontal plane is shown in blue, vertical in orange.

For the 2.5 MeV BTF beam in low-power configuration it is possible to use the slit-scan technique for distribution sampling. A diagram of the apparatus for 2D slit-scan emittance measurement is shown in Fig. 2. The transverse emittance slits are 200 µm wide with 0.94 m separation. Total charge passed through the slits is collected on a Faraday cup. The signal is amplified before being sent to a 24-bit analog-to-digital converter.

The slit-scan emittance measurement offers a trade-off between number of dimensions and signal-to-noise ratio. For the 200 µm slits, approximately 1 decade of range is sacrificed per dimension. Based on 1D profiles demonstrating 10^{7} dynamic range, 10^{6} range is achievable in the 2D emittance scan. $10^{5.5}$ range is demonstrated at the first emittance stage shown here in Fig. 3. This data-set includes range stitching of amplifier gain at the 10^{-3} level.

The phase space distribution for the measurement in Fig. 3 is shown in Fig. 4. The distribution features are collapsed to 1D through a transformation to normalized coordinates ($x_N = x/\sqrt{\beta}$, $x'_N = (\alpha x + \beta x')/\sqrt{\beta}$), then radial coordinate ($r = \sqrt{x_N^2 + x_N'^2}$) [3]. Heavy tails above the Gaussian prediction are apparent, starting at 10^{-1} and extending in the halo level. The Gaussian fit is made with a threshold at 10% of the peak density.

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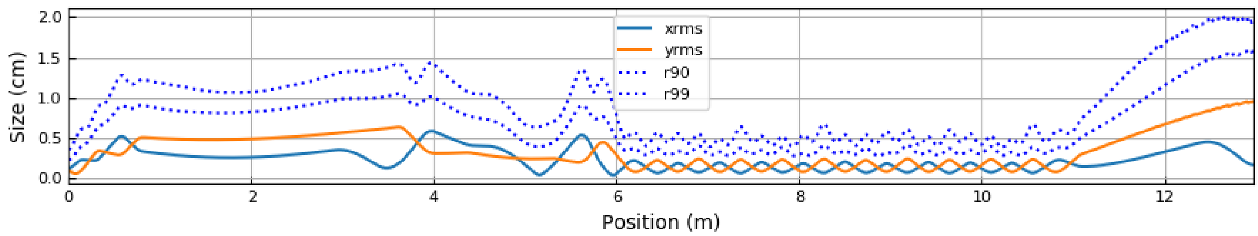

Figure 5: Simulated evolution of rms beam profile through full BTF lattice in PyORBIT with initial conditions based on transverse emittance measurements. Dotted lines indicate 90% and 99% extent.

CURRENT COMMISSIONING STATUS

In 2018 an extension to the original BTF footprint was installed. The extension, which is pictured in Fig. 1, includes a 4.6-meter 19-element magnet permanent quadrupole FODO line followed by a second emittance measuring stage. The FODO extension was designed to support halo studies, with strong focusing to support 4–5 mismatch oscillations. This is shown in simulation to be sufficient to drive noticeable halo [10].

A PyORBIT [11] simulation of ideal transmission through optimized BTF lattice is shown in Fig. 5. Effort in the last run cycle focused on optimizing transport to the end of the extended beamline and testing the accuracy of the accelerator model. Early commissioning results are described in [3].

Recent progress includes the utilization of an existing LEBT chopper to clean low-energy particles from longitudinal emittance measurement. In addition, dispersion was corrected using a model+empirical tuning approach. After correction, dispersion was measured to be $D = -0.8$ cm, $D' = 0.04$ at 1.6 m upstream of the final beamstop. Losses are slightly larger than reported in [3]. The latter was empirically tuned to optimize transmission, while this data excludes achromatic quads from the tuning.

SUMMARY AND FUTURE PLANS

The 2.5 MeV Beam Test Facility will be used to characterize halo evolution in greater detail than previous studies. The goal of planned studies is benchmarking evolution through the BTF MEBT to 1 ppm. This is motivated by the need to limit losses within this range for future high-power accelerators. In support of these studies we demonstrate the 2D high-dynamic-range capability at the first emittance stage. A dispersion-corrected solution has been verified with measurement, and work on comparing simulated beam evolution against measurements at the final emittance stage has begun.

In the future, the 6D direct phase space measurement will be repeated at higher resolution. Simulations seeded with a fully-correlated initial distribution will be compared with high-dynamic-range transverse emittance measurements after the FODO line. Measurements will be taken for both matched and mismatched transport through the FODO line, as mismatch oscillation is a well-known source of nonlinearity understood to drive halo formation.

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