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MODEL/MEASUREMENT COMPARISON OF THE TRANSVERSE PHASE SPACE DISTRIBUTION OF AN RFQ-GENERATED BUNCH AT THE SNS BTF*

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Abstract

The research program at the SNS Beam Test Facility is focused on resolving observed model/measurement discrepancies that preclude accurate loss prediction in high-power linacs. The current program of study is focused on deploying direct 6D measurements to reconstruct a realistic model of the initial beam distribution at the RFQ output. This detailed characterization also provides an opportunity for benchmark of RFQ simulations. Here we compare PARMTEQ predictions against 5D-resolved (x, x′, y, y′, w) phase space measurements of the BTF H- bunch, focusing on the transverse distribution. This work is an extension of previous research, which focused on the longitudinal phase space.

INTRODUCTION

The application of accelerator modeling to predict beam loss will require significant improvement in model accuracy. This includes a more complete description of the initial beam distribution. Typical reconstruction methods rely on fully projected phase space distributions and assume no interplane correlations. Beams with 3D space charge break this assumption, as shown in Ref. [1] for bunches in the Beam Test Facility (BTF) at the Spallation Neutron Source (SNS). Subsequent work has focused on advancing measurement capabilities in order to map the initial 6D beam distribution with enough accuracy to enable predictive modeling of beam halo.

A previous publication on BTF measurements compared data from high-dimensional phase space measurements to predictions from RFQ simulations. This work reported that measured emittances were 20 – 30% lower than predicted in the most realistic simulation case [2]. However, observed space-charge-driven longitudinal-transverse dependencies [1] are reproduced in simulation.

The comparison in Ref. [2] is limited to the longitudinal distribution. This paper extends this comparison from the perspective of the transverse bunch distribution using 5D distribution measurements. This comparison is facilitated by higher transverse resolution enabled by reducing the measurement dimension from 6D to 5D.

MEASUREMENT APPROACH

The BTF is a replica of the SNS front-end, consisting of H- ion source, 65 keV LEBT, 402.5 MHz radiofrequency quadrupole (RFQ) and 2.5 MeV MEBT. The 6D diagnostic is located at the beginning of the MEBT, 1.3 meters downstream of the RFQ. The BTF beamline includes periodic FODO section followed by a second 5D-capable phase space diagnostic.

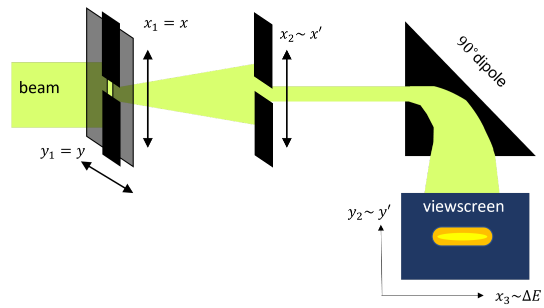

Figure 1: Geometry of 5D measurement apparatus.

This paper discusses a measurement of the 5D distribution, $\int d\phi f(x, x', y, y', \phi, w)$, 1.3 meters downstream of the RFQ exit. Here w is the spread in kinetic energy relative to the mean energy of the bunch. The measurement apparatus uses 3 slits and a phosphor-coated viewscreen, illustrated in Fig. 1. The resolution in the slit coordinates is nearly 4× higher than for the 6D measurement, which requires at least 23 hours. The dynamic range is also improved, from 2 to 3 orders of magnitude, as a result of reducing the number of slits inserted. The 5D data discussed here is a result of two measurements: (1) 4 hours on 12/3/2022 with 30.2 ± 0.3 mA RFQ output current and (2) 7.6 hours on 7/15/2022 at 26.73 ± 0.06 mA.

The position of the 3 slits and the 2 viewscreen axes of are converted to phase space coordinates using matrix operations. The pixel intensity values are linearly interpolated onto a regular grid in phase space coordinates using the griddata function in scipy [3]. The resolution along the viewscreen axes is reduced to avoid high memory load. After processing the 5D density is defined on a regular grid in (x, x', y, y', w) coordinates. The 30.2 mA data is interpolated to a 33 x 41 x 32 x 101 x 200 grid. The 26.7 mA data is interpolated to a 45 x 45 x 45 x 50 x 80 grid.

SIMULATION APPROACH

A PARMTEQ [4] model of the SNS RFQ design is used to predict the beam distribution at the MEBT entrance. This paper presents results from the "realistic case" using measured LEBT distributions. More details can be found in Ref. [2]. The input beam current is assumed to be 50 mA. The vane

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Table 1: RMS Parameters for Simulated and Measured Beam at 26 mA, with Threshold at 1% of Peak

Parameter	**Simulated**	**Measured, 5D**
ϵ_x, mm-mrad	3.68	3.19
α_x	0.42	0.61
β_x, m	3.66	1.91
σ_x, mm	3.67	2.43
σ_{xp}, mrad	1.09	1.49
ϵ_y, mm-mrad	3.61	3.16
α_y	1.23	0.50
β_y, m	3.83	3.66
σ_y, mm	3.72	3.40
σ_{yp}, mrad	1.53	1.04
σ_w, keV	21.7	22.2

voltage was increased by 9% over the SNS design value of 83 kV based on preliminary results from x-ray spectrometry. This had the effect of increasing both transverse emittances by approximately 7% at the RFQ exit.

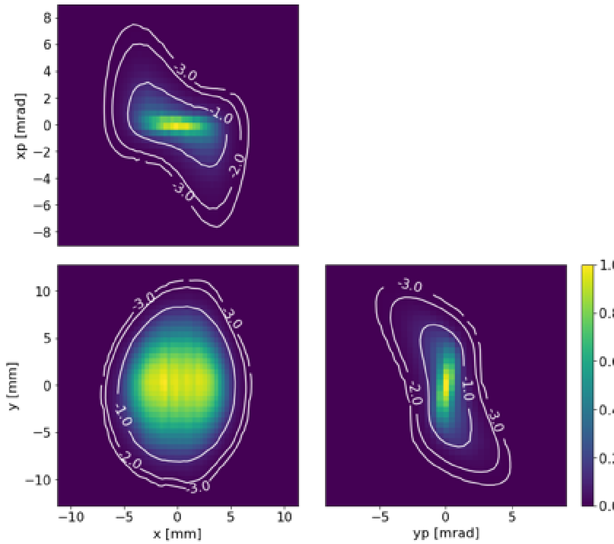
A PyOrbit [5] model is used to propagate beam 1.3 meters from the RFQ output to the measurement plane. One significant difference between model and measurement is that the real RFQ transmission is much lower than predicted in simulation (60%, compared to 84% in the model). To compensate for this, in the simulation the beam current is reduced at the RFQ/MEBT transition from the 42 mA to the lower currents measured in the MEBT (30.2 mA and 26.7 mA). This inconsistency is expected to have a small effect on the transverse distribution. Decreasing the input current in the RFQ simulation by 10 mA causes a 3% and 6% change to the rms beam sizes in x and y, respectively.

In order to generate plots for comparison to measurements, the macro-particle distribution is binned in a 5D histogram in coordinates (x, x', y, y', w) on a grid of size 33^5. 10^6 particles were used in simulation to obtain sufficient good resolution of features in high-dimensional slices. For this grid size, 10^6 particles is enough to resolve densities down to 0.2%, comparable to the measurement sensitivity of 0.1%.

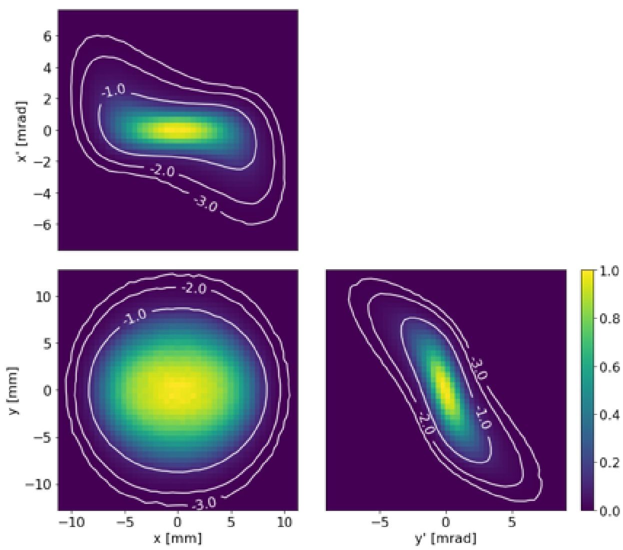
COMPARISON

The rms Courant-Snyder parameters can be calculated from the projected distributions. A fractional threshold of 1% is applied to the 2D density projections before calculating rms. Table 1 reports the rms parameters for the fully projected phase spaces, as well as the rms energy width. Both emittances are lower than predicted from simulation by about 15%.

There is a difference in phase space orientation for both planes, as reflected in the rms ellipse parameters. This is apparent in the fully projected views, shown in Figs. 2a and 2b.



(a)



(b)

Figure 2: Fully projected phase space and spatial distributions, for 26.7 mA beam from (a) 5D measurement and (b) simulation. Contour lines are in the logarithmic scale, showing extend at 10%, 1% and 0.1% of the peak density in 2D.

Bunch Distribution

The rms analysis does not tell the full story, as the result of space charge in the H^- ion bunch is to drive transverse-longitudinal coupling that alters the beam distribution. One observation from Ref. [2] was that longitudinal hollowing observed at the center of the distribution is reproduced from simulations starting with a realistic (but not x-y correlated) 4D beam at the RFQ entrance.

Figures 2a and 2b do not show any inter-plane dependencies, which for the BTF beam are typically hidden in full projection views. This dependence is best visualized by examining slices in the high-dimensional phase space.

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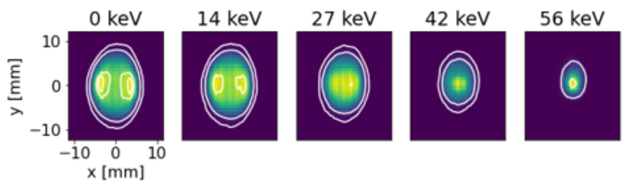
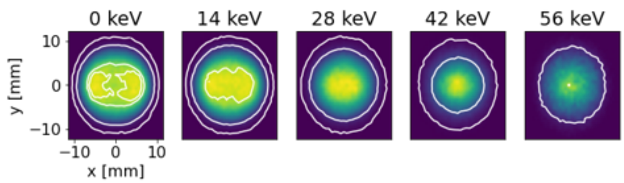


(a)



(b)

Figure 3: View of the partially projected spatial distribution (integrated in x',y',ϕ and sliced in w) at 30.2 mA for (a) measured 5D distribution and (b) simulated distribution. Contour lines are in the logarithmic scale, showing extend at 89%, 79%, 10% and 1% of the peak density at 0 keV.

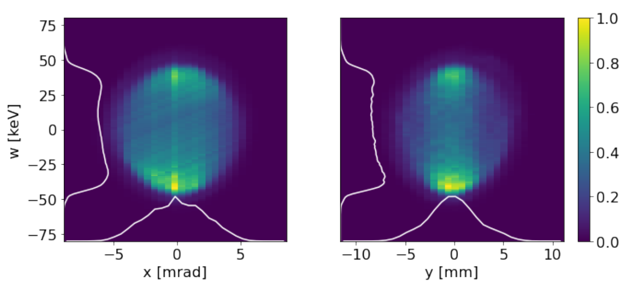


Figure 4: Measured energy-transverse distributions at the bunch core for 30.2 mA MEBT current, at slice $x' \approx y' \approx 0$ and $y \approx 0$ (left), $x \approx 0$ (right).

In Figs. 3a and 3b, a "partially projected" 1D-slice view shows the dependence of the transverse spatial distribution on longitudinal energy coordinate w. At the measurement location, the bunch is de-bunching and highly correlated in $\phi - w$. Therefore, the approximation $w \approx \phi$ is useful for interpreting this view. Here, it is clear that there is transverse spatial hollowing, primarily in the horizontal plane, near the longitudinal beam core.

This transverse hollowing in the core resembles previous observations of longitudinal hollowing (e.g., Fig. [3] in Ref. [1]). The signature for this measurement at 30.2 mA is shown in Fig. 4.

Although the model/measurement comparison is restricted to the diagnostic location 1.3 meters downstream of the RFQ, the simulation bunch can be evaluated at any point in the beamline. At the RFQ exit, there is no apparent transverse hollowing. This suggests that the hollowing emerges in the first meter of transport, as the beam transitions from a strong focus in the RFQ to the more weakly-focusing MEBT. The initial kick from nonlinear space charge imprints in the velocity distribution, locking in the annular shape as discussed in Ref. [6]. Conversely, the longitudinal hollowing is already present at the RFQ exit (noted in Ref. [2]), and therefore must be a result of space charge dynamics within the RFQ.

DISCUSSION AND OUTLOOK

Research at the BTF is aimed at enabling loss-level prediction capability by seeding simulations with an accurate model of the initial bunched beam. This paper described the results of direct measurement of a 5D distribution $f(x, x', y, y', w) = \int d\phi f(x, x', y, y', \phi, w)$ at the RFQ output. This detailed view provides a basis for comparison to simulated predictions from RFQ simulation beyond rms benchmarking.

Despite disagreement in the rms parameters and RFQ transmission, the transverse-longitudinal dependencies are reproduced in simulation. This includes observation of transverse hollowing that has not been previously reported. The rms discrepancy indicates that the PARMTEQ-generated bunch is not a good tool for predictive modeling. However, it remains a useful tool for predicting how fully-correlated 6D bunches will influence simulated predictions of beam extent including halo. Future work includes repeating this measurement with a new SNS RFQ of identical physics design, which is expected to have transmission much closer to design.

While the measurement of initial distribution continues to improve, parallel efforts are focused on predicting bunch evolution to the end of the BTF beamline in support of halo studies. In Ref. [7], this same 5D measurement is used to compare with measurements of the evolved distribution at the end of the beamline, and shown to be useful for understanding transverse-energy correlations.

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