MEASUREMENTS AT PEAK OPERATIONAL BEAM CURRENT IN THE SNS BEAM TEST FACILITY *

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Abstract

Work at the SNS Beam Test Facility has focused on high dimensional and high dynamic range measurements of the medium energy (2.5 Mev) beam distribution. This is motivated by the need to understand and predict beam losses down to one-part-per-million. The initial demonstration of full-and-direct 6D phase space measurement was done at a current of 40 mA transported through the RFQ. Since that demonstration, more detailed studies have been performed at lower transported currents (in the range 30 mA and below). This is due to a hardware change - recent runs utilize the original SNS RFQ, which after a decade of service in the SNS achieves transmission significantly below design (50-60%, vs >80%). A short run in 2023 with a newly-commissioned RFQ enabled maximum transmission. Preliminary results from beam distribution measurements during this run are discussed.

INTRODUCTION

A new RFQ for the SNS was received and commissioned in early 2023 [1]. Commissioning with beam took place at the SNS Beam Test Facility (BTF), which is equipped for detailed diagnosis of the beam distribution after the RFQ. Beam was available for study for approximately two weeks during commissioning.

Recent BTF studies [2] have characterized the beam out of the original SNS "RFQ1." The performance of RFQ1 has degraded after > 10 years of service in the SNS. This degradation includes both instability at full power operation and reduced transmission (~ 60%, compared to 90% design). RFQ1 operated for four years in the BTF after being retired from the SNS. During this time, the peak output/MEBT current achieved was 35 mA. During RFQ3 commissioning, beam studies were performed at 41 mA, 90% transmission.

Recent work at the BTF has focused on characterizing the beam distribution at the RFQ output, including full 6D measurements, for the purpose of improving predictions of linac beam transport and halo growth. Such characterization is also useful for benchmarking RFQ simulations. Previous work [2] compared measurements with RFQ1 to predictions from simulations using PARMTEQ[3]. This work reported that measured rms longitudinal emittances were 20 – 30% lower than simulated.

One complication in [2] was comparing low-transmission measurements with design-transmission simulations. The reason for low transmission in RFQ1 is not currently known. For the purpose of comparing MEBT emittances, the simulated beam current was artificially reduced at the RFQ output face to match the measured MEBT current. Measurements with RFQ3 performing at design values offer a much better case for comparing model to measurement.

This paper reports measurements from characterization of RFQ3 beam parameters at the BTF, with comparison to PARMTEQ simulation and RFQ1 measurements.

DEPENDENCE ON RFQ VANE VOLTAGE

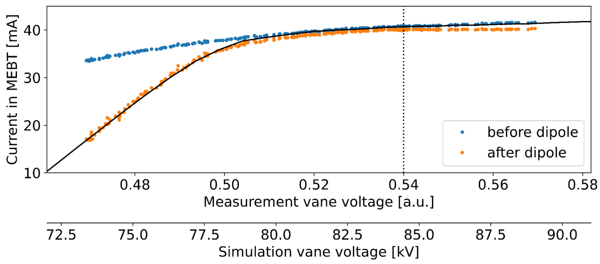

Figure 1: Transmitted current, before and after 90° bend. Simulation (solid black line) assumes 48 mA input current. The vertical dotted line indicates nominal setpoint.

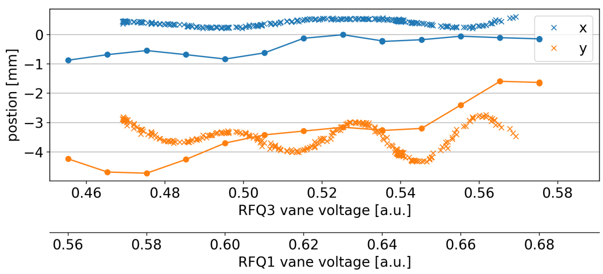

Figure 2: Position measured at BPM located 1 meter downstream of RFQ exit. marker x = RFQ3, o = RFQ1.

Several parameters were measured as a function of RFQ vane voltage. For these measurements, vane voltage is controlled through an uncalibrated amplitude. For comparison to simulation, the calibration is inferred by using it as a scal-

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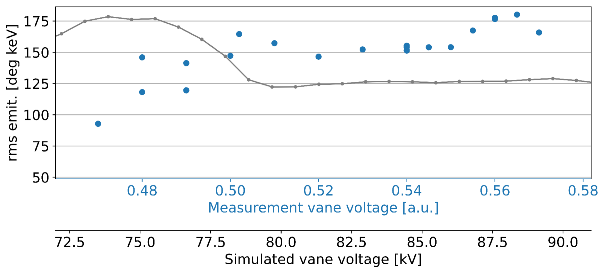


Figure 3: Measured rms longitudinal emittance dependence at bunch center $(x, x', y' = 0)$, compared to simulation of full projection. A correction is applied for systematic errors affecting phase width.

ing parameter to get good agreement in the transmission curve (Fig. 1).

Fig. 1 shows the measured and simulated transmission curves. In addition to vane voltage, input/LEBT current was also a free parameter. A LEBT current of 48 mA produced 41 mA (85.4% transmission) at the design voltage 83 kV. For these simulations, the LEBT bunch was reconstructed from test stand measurements of the projected LEBT distributions $f(x, x')$, $f(y, y')$ as described in [2].20,000 macroparticles are used for simulations in Figs. 1 and 3.

Figure 2 shows the dependence of MEBT beam steering on vane voltage, using a BPM one meter downstream of the RFQ exit. One observation during RFQ1 runs was that there was a strong steering dependence on vane voltage, particularly in the vertical plane. Presumably this arises from poor field flatness. RFQ3 shows a weaker dependence.

Figure 3 shows dependence of longitudinal rms emittance on vane voltage. The emittance is $\sim$ 25% larger than expected from simulation. This is opposite to observations with RFQ1, which were previously reported to be $20-30\%$ lower than simulated (e.g., Fig. 11a in [2]). This comparison was complicated by the low RFQ transmission, as well as low input current, that resulted in 20.5 mA output/MEBT current during studies.

The device used to measure longitudinal emittance collimates the distribution in the x, x', y' planes [2]. Therefore, the measurement represents the partial projection $f(\phi, w) = \int dy \tilde{f}(y, \phi, w, x = x' = y' = 0)$, whereas the simulated value accounts for all macroparticles (full projection $f(\phi, w) = \int\int\int\int dxdydx'dy'\tilde{f}(x, y, x', y', \phi, w)$). In both cases, the threshold for rms calculation is set at 1% of peak density in $f(\phi, w)$. This may account for some deviation with simulation values, but in high dimensional measurements we observe these values to typically be quite close (within 5%).

For RFQ1 measurements, the size of the slit used to constrain the energy variable w was measured to be 0.17 mm wide. The slit used in RFQ3 measurements is 0.2 mm wide. Both slits are wide enough to cause significant inflation in the measurement of longitudinal phase profiles (as described in [2]). Following the same approach as [2], a correction factor of 75% was applied to the measured rms emittance values in Fig. 3.

MEBT EMITTANCES

Table 1: Comparison of RMS parameters for measured and simulated distributions 1.3 meters downstream of RFQ exit.

Parameter	RFQ1	RFQ3	simulated
MEBT current [mA]	20, 29	38.8	42.8
z emittance [deg. keV]	105, 139	147	131
rms ϕ [deg.]	4.9, 5.6	5.0	4.4
rms w [keV]	21.3, 26.0	29.9	30.8
MEBT current [mA]	35.0	40.9	42.8
x emittance [mm mrad]	3.6	3.6	3.9
rms x [mm]	2.5	4.0	3.9
rms x' [mrad]	1.8	0.9	1.2
y emittance [mm mrad]	3.6	3.7	3.6
rms y [mm]	4.0	4.4	4.3
rms y' [mrad]	0.9	0.9	0.9

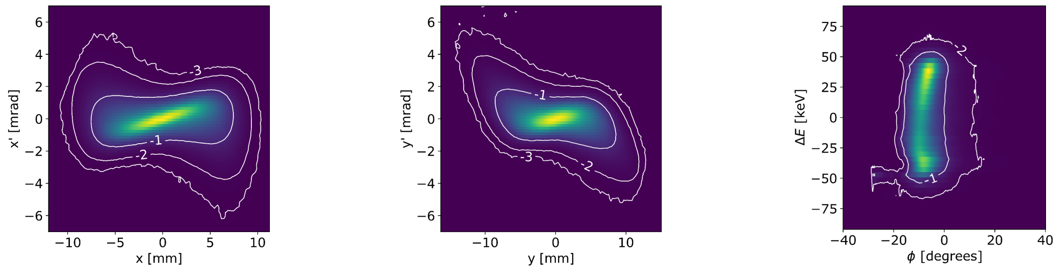
For the nominal operating point, the measured/simulated beam distributions are compared at the location of the phase space diagnostic (1.3 meters and 4 quadrupoles downstream of the RFQ exit). The measured distributions for the RFQ3 run are shown in Figure 4. Comparison to rms values for RFQ1 measurements and simulation are shown in Table 1. Rms numbers are calculated from measurements with thresholding at 1% of peak density for each projection. This simulation tracks 10,000,000 macroparticles with 50 mA input current for vane voltage 83 kV. The transverse parameters represent full projections of the 6D phase space $f(x, x', y, y', \phi, w)$. The longitudinal parameters represent the partial projection $f(\phi, w) = \int dy \tilde{f}(y, \phi, w, x = x' = y' = 0)$ as described above.

The measurement of longitudinal phase was affected by the width of the energy slit, as mentioned above. For the RFQ3 measurements, the "virtual slit" method with a virtual slit width of 0.03 mm was used to correct for inflated phase profile widths [4]. Two measurements are shown for RFQ1: one at 20 mA [2] with correction for slit width, and one at 29 mA with "narrow" $\leq$ 0.15 mm slit.

Transverse parameters are quite close for all three cases. There are larger variations in the longitudinal parameters. While the RFQ3 emittance is larger than seen in both RFQ1 and simulation, the energy width is closer to simulation. Measured rms phase widths are all larger, which may be due to remaining uncorrected phase width inflation. In general, phase is the most difficult dimension for obtaining high accuracy (measurements use a bunch shape monitor).

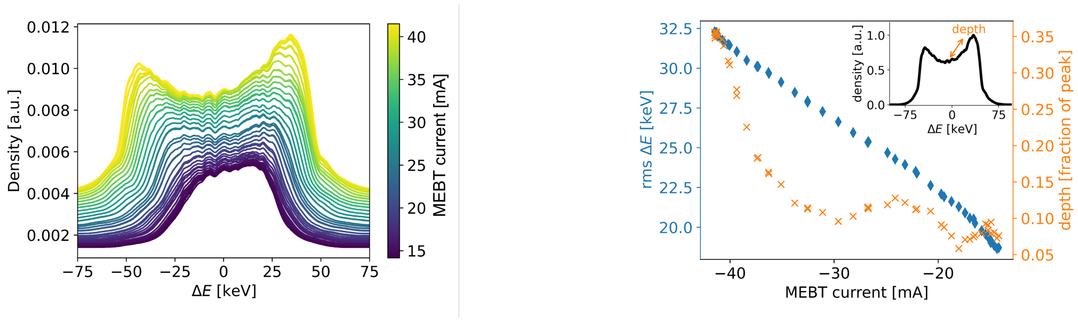
SPACE CHARGE DRIVEN CORRELATIONS

One observation in studies of RFQ1 [2, 5] (and previously RFQ2 [6]) was dependence of longitudinal energy distribu-



(a) Horizontal (b) Vertical (c) Longitudinal

Figure 4: Fully projected phase space distributions in (a) horizontal and (b) vertical planes. (c) longitudinal phase space for marginal (core particles) projection. Longitudinal phase space is shown with large linear $\phi \times w$ correlation removed. Contour lines are in the logarithmic scale, showing extent at 10%, 1% and 0.1% of the peak projected density.



(a) (b)

Figure 5: Dependence of (a) longitudinal distribution $f(w) = \int\int dy' d\phi \tilde{f}(y', \phi, w, x = x' = y = 0)$ and (b) $f(w)$ rms width and hollowing depth on transmitted current.

tion on transverse position. Near the bunch core the beam is longitudinally hollow, outside the core it is convex. The hollowing is observed to be dependent on beam current.

This dependence can be probed by reducing LEBT/input current and measuring the energy distribution in the transverse core. This is done by reducing the voltage on one of the electrostatic LEBT lenses, causing a tunable fraction of the beam to exceed the transverse RFQ acceptance. For the RFQ3 run, it was possible to reduce transported beam current from 41 mA to 15 mA through LEBT lens detuning.

The distribution $f(w, y') = \int d\phi \tilde{f}(y', \phi, w, x = x' = y = 0)$ is measured by inserting 3 slits (to collimate x, x', y) and, after a 90° dipole, inserting a viewscreen that images $g(w, y')$. Figures 5a and 5b show, respectively, the energy distribution and rms width for varying MEBT current. For a 10 mA change in transmitted current, there is a 15% change to rms energy spread, which is comparable to the variations shown in Table 1. At this time there is not enough data to separate RFQ differences from ion source performance.

Figure 5b also quantifies the depth of energy hollowing versus MEBT current. This measurement reproduces behavior seen in RFQ1 scans of LEBT focusing. 5D measurements of $\int d\phi f(x, y, x', y', \phi, w)$, which capture both transverse-longitudinal and longitudinal-transverse correlations [7], are similarly consistent between RFQ1 and RFQ3.

CONCLUSION

Characterization of the SNS RFQ3 beam parameters has been completed during commissioning at the SNS Beam Test Facility. Simulations with PARMTEQ have reproduced with good accuracy the transverse rms parameters, particularly emittance (although discrepancy remains with other details, such as tail distribution). There are some differences in longitudinal phase space between both RFQs and simulation. Longitudinal emittances are higher than previously reported. Signatures of space charge driven coupling between the planes are consistent with observations from RFQ1 and RFQ2 at the BTF.

After RFQ3 is installed in the SNS linac, RFQ2 will be retuned and installed in the BTF. This will provide further opportunity for benchmarking of RFQ simulations with near-design transmission, as well as support continued study of halo growth/transport in a regime with MEBT currents comparable to the SNS linac. Ongoing work aims to understand the root of degraded RFQ1 transmission and effects on the output beam distribution.

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