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BEYOND RMS: UNDERSTANDING THE EVOLUTION OF BEAM DISTRIBUTIONS IN HIGH INTENSITY LINACS

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Abstract

Understanding the evolution of beams with space charge is crucial to design and operation of high intensity linacs. While the community holds a broad understanding of the mechanisms leading to emittance growth and halo formation, there is outstanding discrepancy between measurements and beam evolution models that precludes prediction of halo losses. This may be due in part to insufficient information of the initial beam distribution. This talk will describe work at the SNS Beam Test Facility to directly measure the 6D beam distribution. Full-and-direct 6D measurement has revealed hidden but physically significant dependence between the longitudinal distribution and transverse coordinates. This nonlinear correlation is driven by space charge and reproduced by self-consistent simulation of the RFQ. Omission of this interplane correlation, common when bunches are reconstructed from lower-dimensional measurements, degrades downstream predictions. This talk will also describe the novel diagnostics supporting this work. This includes ongoing improvements to efficiency of the 6D phase space measurement as well as recent achievement of six orders of dynamic range in 2D phase space.

INTRODUCTION

Modern high-power accelerators seek to maximize particles on target while minimizing losses along the beamline. Beam halo is a contributor to beam losses. The primary driver of halo is understood to be interactions of individual particles with collective modes of the core. Despite the ability of modern particle-in-cell codes to resolve these dynamics, observed model/measurement discrepancies are well above the halo level. The most likely explanation is incomplete information encoded in simulation. This includes the initial 6D macroparticle distribution as well as description and assumptions for external field elements (magnets and RF cavities). Accuracy of the initial distribution is an oft-cited explanation for discrepancies, as standard diagnostics resolve only the primary correlations but do not characterize interplane-dependencies.

This article summarizes the status of work at the Spallation Neutron Source (SNS) Beam Test Facility (BTF) to understand the source of model/measurement discrepancies and advance capabilities for prediction of losses due to halo.

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PRIOR WORK AT THE SNS BEAM TEST FACILITY

The BTF is a replica of the SNS front end that includes a suite of diagnostics for full characterization of the beam distribution [1]. Previous activities at the BTF include demonstration of full-and-direct 6D measurement [2] as well as demonstration of 10^6 dynamic range in imaging of 2D phase space projections [3].

Defining Realistic Distributions in 6D Phase Space

The first full 6D measurement was reported in [2] for a 40 mA, 402.5 MHz H^- beam measured 1.3 meters downstream of the RFQ. This measurement revealed a dependence of the particle beam longitudinal distribution on transverse coordinates. This is an interplane correlation that is not included in reconstruction methods that assume $f(x,x',y,y',z,z') = f(x,x') \cdot f(y,y') \cdot f(z,z')$. This correlation is visualized in Fig. 1 for a 25 mA beam in the BTF.

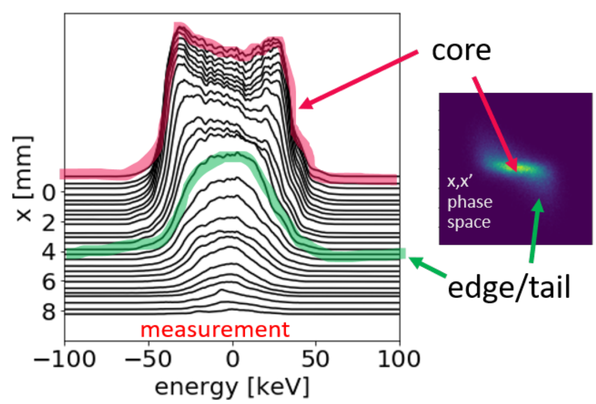

Figure 1: Visualization of the observed transverse-longitudinal dependence. Each curve is the energy distribution of particles located in (x,x',y,y'), where $x',y,y' \sim 0$ and x varies from beam edge to core. The unannotated figure is originally published in [4].

Reference [2] observed a dependence of this feature on beam current; at lower currents, the bimodal energy distribution seen in the core vanishes and there is no transverse-longitudinal dependence. A space charge driven origin for this coupling is explored in [4]: longitudinal hollowing of the beam core can be driven as an initially uncorrelated distribution with nonlinear space charge components expands at the transition from RFQ to MEBT.

However, a similar correlation is observed to exist at the output of self-consistent RFQ simulations (also described

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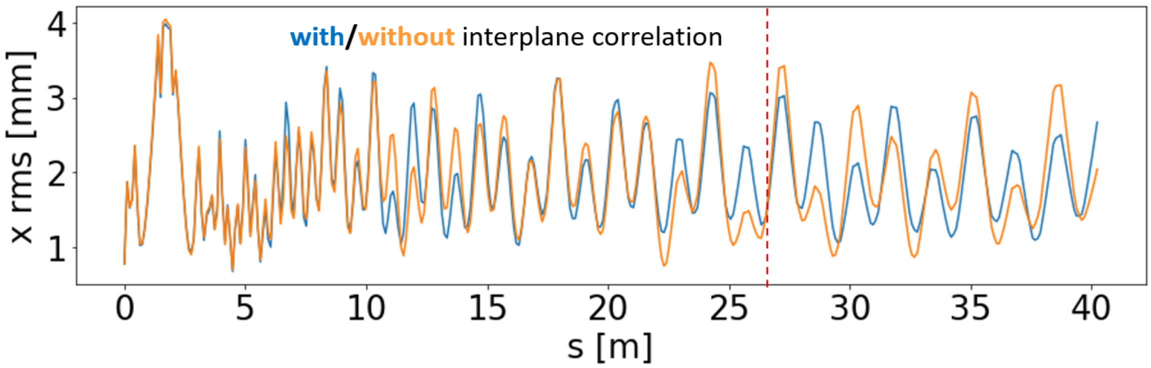

Figure 2: Comparison of horizontal beam size through PyORBIT simulation of SNS MEBT and DTL.

in [4]). Therefore, this correlation can be understood as a signature of space charge driven dynamics within the RFQ.

Despite favorable comparison of the high-dimensional features of the beam distribution, bunches generated from simulation of the SNS RFQ currently have limited applicability to highly accurate distribution predictions. A reconstruction of the rms longitudinal emittance measured at the BTF shows measurements 20-30% lower than predicted by PARMTEQ, using a measured LEBT distribution as the input condition [5]. This discrepancy can be attributed to uncertainties of the true RFQ parameters.

High Dynamic Range Phase Space Imaging

The ability to fully characterize halo to the relevant "loss level" at the BTF has recently been demonstrated [3]. This measurement, which uses slit scans to image 2D phase space projections, is a complete characterization of the halo distribution. The "loss level" is defined as 10^6 dynamic range, required to resolve one part-per-million halo losses which is motivated by the ≤ 1 W/m loss goal of the SNS design [6]. In order to reach 10^6 range, it was necessary to (1) clean proton contamination by measuring charge after the first 90° dipole, (2) collect charge optically by inserting a scintillating view screen and integrating the 2D image and (3) employ range-stitching of two different camera gains. The response of the screen is shown in [3] to be linear, thanks in part to defocusing of the beam at the screen location.

OUTLOOK FOR HALO STUDIES

Future work at the BTF will focus on resolving discrepancy between measurement and simulation of beam evolution, using the unique information available in the 6D diagnostic. The goal is to define a simulation bunch based on the full 6D phase space measurement and compare evolved distributions against the high dynamic range 2D phase spaces.

A preliminary investigation into the sensitivity of transverse evolution to the observed correlations is shown in Fig. 2. In this simulation, the bunch produced by RFQ simulation is propagated in a PyORBIT [7] mode of the SNS medium energy transport (MEBT) and drift tune linac (DTL). Two cases are shown: one for evolution of the fully correlated bunch and one with the interplane dependencies artificially removed. In the second case, the particle indices between the three planes are randomly permuted, while preserving the ordering and correlations in (x, x'), (y, y') and (ϕ, w) (where $w = E - E_s$). Both bunches contain 4.1×10^6 macroparticles at 41 mA current.

While the rms envelopes are initially close, there is a slow divergence between the two cases. At certain beamline locations, particularly at quadrupole locations, the rms predictions are very different. Figure 3 compares the evolved distribution at a location in the DTL where the rms ellipse is very similar between the two cases. Here the tail distributions are significantly different. It is expected, although not shown here, that the halo distribution will also be different.

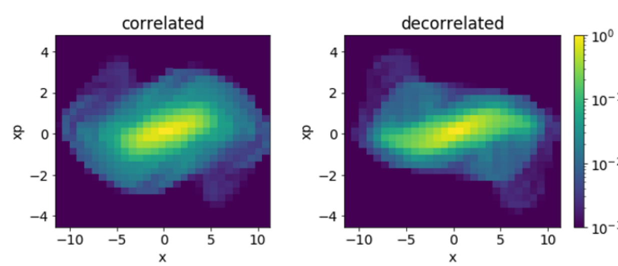

Figure 3: Phase space plots comparing results from different initial distributions in simulation of SNS MEBT and DTL. Projection is taken at location indicated in Fig. 2 by red dashed line.

The eventual goal for halo studies is to perform simulations that include the 6D measurement as the initial condition of the bunch. Supporting highly accurate simulations requires reducing measurement error in the 6D bunch as well as in the description of the BTF lattice model.

Improvements to 6D Measurement

The first ever 6D measurement reported in [2] took place over 32 hours of continuous measurement at 5 Hz repetition rate. Despite the long data collection time, the resolution and dynamic range were both low. The scan followed a rectilinear grid pattern with a grid size of 10 in five of the six dimensions [8]. This is insufficient to resolve the sharp

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features in the high-dimensional views (as shown in Fig. 1). Additionally, the dynamic range was only 10^1. Higher range and resolution can be achieved with longer scan times, but the scan time scales poorly, $\propto n^D$ for grid size n and dimensionaly D. The combination of several strategies can significantly boost scan performance.

First, the rectilinear grid pattern suffers from the curse of dimensionality. In 6D space, the ellipsoidal bunch volume is much smaller than the total scan volume. This is illustrated in Fig. 4. For a grid pattern in an n-dimensional hypercube, as n increases the fraction of measurement points in the beam signal region drops off sharply. This can be alleviated through two means.

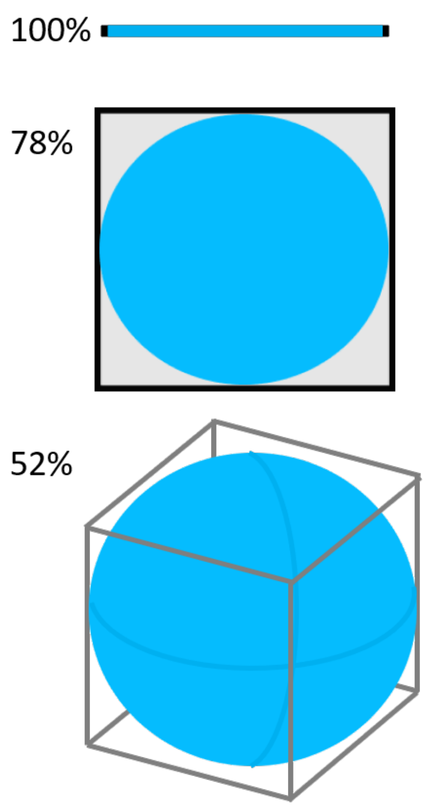

Figure 4: Diagram representing shrinking volume of n-sphere compared to a bounding hypercube. In this case, the sphere represents the bunched beam and the hypercube the rectilinear scan grid. In six dimensions, the sphere only fills 8% of the area of the cube.

First, reducing the scan dimension will have an enormous impact, due to the scaling $t \propto n^D$. As described in [2], D = 5 due to use of an imaging screen within the Bunch Shape Monitor (BSM) to capture the distribution in the sixth dimension (phase). As a camera has two available axes, it is possible to reduce dimensionality to D = 4. A preliminary design for a 2D BSM has shown it is feasible to image both energy spread and phase at the BSM screen.

A higher fraction of non-zero points ($> 50\%$) can be achieved through alternative scan patterns which spend more time in the signal region. Currently the approach is to develop routines which sample in a spherical volume, which is re-scaled and linearly correlated to overlap with the bunch in the scan coordinates.

True "smart scans" would employ a machine (ML) learning model that learns an appropriate pattern through feedback from a measurement-based reward function. A supervised learning model was tested for two-dimensional BTF scans, using the routine described in [9]. Although this routine could reconstruct the 2D phase space from fewer points than the usual grid scan, the predicted scan time was longer. This was due to latency in slit motion data must be measured along continuous paths rather than point-by-point. Furthermore, this and most readily available routines are developed for 2D point-wise imaging. These typically scale poorly at 4+ dimensions. An ML approach to scanning will need to be tailored to the capability of the existing apparatus.

Other avenues for improved scan resolution include increasing the repetition rate to 10 Hz. Progress since the initial measurement includes upgrade of the energy slit. The energy-selecting vertical slit in [2] had a width of 800 µm. This was identified as a large source of error [5], as the energy width δw causes a spread in arrival phase at the BSM. Recent operation with an new energy slit of manufactured with 100 µm has significantly reduced this error.

Refinement of Lattice Description

To support the planned work, the accuracy of the field models used in the PyORBIT simulation must be improved to better reflect true conditions in the BTF. The effort to characterize and refine the magnet models has been ongoing since the BTF footprint was expanded in 2018, which included addition of a periodic-focusing FODO line comprised of Halbach-style permanent magnet quadrupoles (PMQ), as described in [1]. Both the peak field and quadrupole density is higher in the FODO line than the surrounding medium-energy sections.

Figure 5 illustrates the evolution of the simulation model by comparing the horizontal phase space projections at the end of the beamline to measurement. The measurement is done with a two-dimensional slit scan and Faraday cup charge collector. The initial model (left-most plot) assumed a hard-edged field model for all elements. The PMQ model was based on the physical length and measured integrated gradient. Replacing the PMQ model to an analytic, overlapping soft-edged profile using the expression in [10] had a large favorable effect.

The next biggest change was to model the effect of overlapping bunches. Unlike the SNS, the BTF MEBT does not include rebuncher cavities and the beam expands longitudinally. Overlap between the bunches occurs before the FODO line entrance and does affect evolution on the order illustrated in the figure. Multi-bunch modeling capability was developed for PyORBIT. The approach assumes a periodic boundary condition at the head and tail of the bunch, with length equal to the RF cycle.

Despite the reasonable agreement in the horizontal plane, further work remains to reconcile large discrepancies in the

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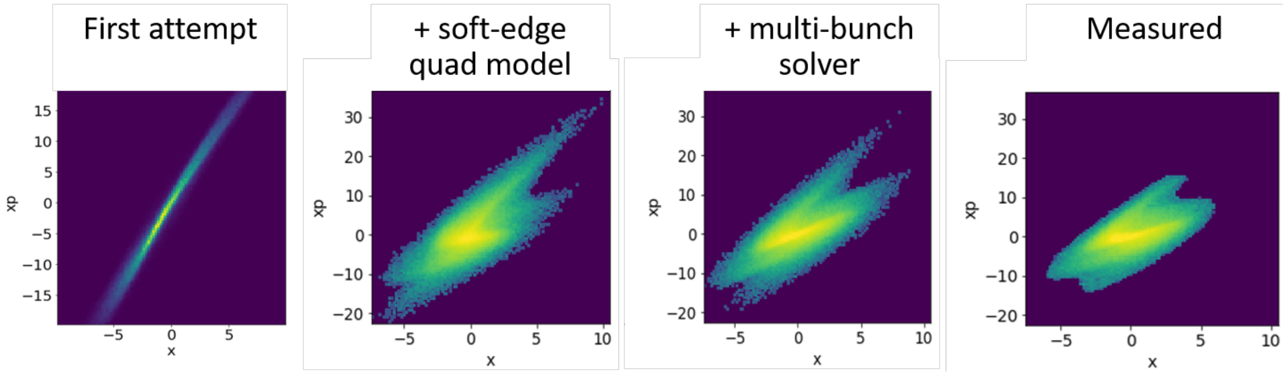

Figure 5: Comparison of horizontal phase space at end of BTF beamline between three simulation models (left plots) and measurement (right-most plot). The color scale is logarithmic. Axes units are in x: mm and xp: mrad.

vertical plane. The origin has been traced to the presence of measurable dispersion in the vertical plane driven by orbit offset in the quadrupoles. Vertical dispersion can easily be measured in the BTF by scanning the energy slit across the beam and recording vertical motion on a downstream view screen or 1D slit-scan. At the end of the beamline, vertical dispersion as high as 0.4 m has been measured. This can be compared to peak horizontal dispersion of ~ 1 m between the first two 90° dipoles. The effect of dilution in the vertical phase space is apparent in simulation. Dispersion magnitudes similar to measurement can be recreated with individual quadrupole misalignments of 1 mm.

CONCLUSION

In summary, the novel 6D distribution measurement at the SNS Beam Test Facility supports further progress in understanding and modeling evolution of high intensity beams. The goal of reaching resolution of one part-per-million halo losses supports operation of existing and future high power facilities. It is expected that knowing the realistic and fully-correlated 6D distribution of the bunched beam will be necessary to support this level of beam loss accountability. This is supported by the prior observation of interplane correlations typically over-looked in measurement-based bunches. Also, as shown here, the absence of hidden 6D correlations affects the rms width and tail distribution of evolved beams in the SNS linac.

Progress towards halo prediction at the BTF requires improvement to the 6D measurement apparatus and lattice model used in PyORBIT simulation. In measurement, improved resolution is necessary to fully resolve the high dimensional features. This is possible through both increasing the scan efficiency and reducing scan dimension. For modeling, large discrepancies have been resolved by refining assumptions in a first-principles model. Most importantly, evolution through the FODO line section is heavily influenced by the magnet profile and the overlap of neighboring bunches. A known but so far unresolved source of discrepancy is vertical orbit errors contributing to emittance dilution.

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