MODELING AND MEASURING MISMATCHED BEAM TRANSPORT AND HALO FORMATION IN A HIGH-INTENSITY LINAC [*]

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Abstract

Ongoing studies at the Spallation Neutron Source (SNS) Beam Test Facility (BTF) seek to characterize halo formation in the early stages of a high-power linac with specific focus on determining the contribution from mismatched beam transport and to replicate halo measurements using well-benchmarked particle-in-cell simulations. The BTF is a 2.5 MeV, 10- meter test beamline equipped with advanced phase space diagnostics allowing detailed characterization of beam distributions. This paper details recent advances in improved transport of mismatched cases in the BTF, and direct measurements of 2D phase space projections with 6 orders of magnitude in dynamic range.

INTRODUCTION

Halo formation and scraping is a significant source of beam loss in modern accelerators. Understanding the mechanisms of its formation will lead to better mitigation strategies and loss reduction. The Beam Test Facility (BTF) is well equipped for halo studies as it is a Front-End replica of the Spallation Neutron Source (SNS) that produces a high-intensity, medium energy (2.5 Mev) H- beam [1]. This beam travels along a ~10 meter beamline that has the diagnostic capability to conduct 6D measurements [2] and 2D high dynamic range (HDR) measurements [3, 4].

The BTF has two diagnostic stations capable of the HDR measurements needed to study halo formation, between them is a 9.5 cell permanent magnet quadrupole (quad) FODO line with sets of electromagnets before and after. This arrangement allows a wide variety of beam transport conditions between measurement stations and importantly provides the ability to match and mismatch into the FODO line, a diagram of the BTF is shown in Fig 1.

Recently, full HDR characterization of halo for a variety of match and mismatch cases was performed at the BTF [5]. This study attempted to analyze the halo formation of a matched case and four increasingly mismatched cases by taking HDR measurements after transport through the FODO line. However, in-depth analysis of halo formation was limited due to scraping.

PREVIOUS BEAM HALO STUDY

Halo studies at the BTF categorize optics cases by the mismatch factor M, defined using the offset of input Twiss Parameters from the matched Twiss Parameters, where larger M directly relates to larger mismatch [5]. Currently, these studies are confined to equal mismatch in the x and y planes. The magnet settings for these conditions are created using the particle-in-cell (PIC) code PyORBIT [6], and simulated bunches created from sampling 2D measurements taken at the first diagnostic station before the FODO line. This methodology allows determination of how to manipulate the core of the beam to produce desired beam orientations into the FODO line.

Current optics cases are designed from low dynamic range (LDR) measurements as a full HDR characterization had not been completed until recently. This is sufficient to determine sets of magnet currents that produce the desired orientation of the core of the beam, however, it is insufficient to predict the movement of high amplitude particles that are most likely to be scraped along the beamline. When these cases are implemented in the BTF, with available corrector magnets and transmission quads tuned, beam transmission is less than optimal for all mismatch conditions and becomes markedly worse for high mismatch as reported in Table 1. The transmissions reported are measured by comparing beam currents at the beginning of the BTF using a BCM to the end using a faraday cup.

Table 1: Current Beam Transportation Efficiency

Optics Case	Transmission
Matched	95%
M 0.67	94%
M 1.37	93%
M 1.90	90%
M 2.35	86%

A complete set of HDR 2D measurements were taken for all five mismatch conditions, and observation of halo formation was attempted, though restricted due to scraping [5]. From these measurements new simulation bunches were created allowing more accurate prediction of possible scraping locations. It is the goal of this research to use the improved simulation capability to reduce particle loss and increase transmission allowing for cleaner observations of halo formation.

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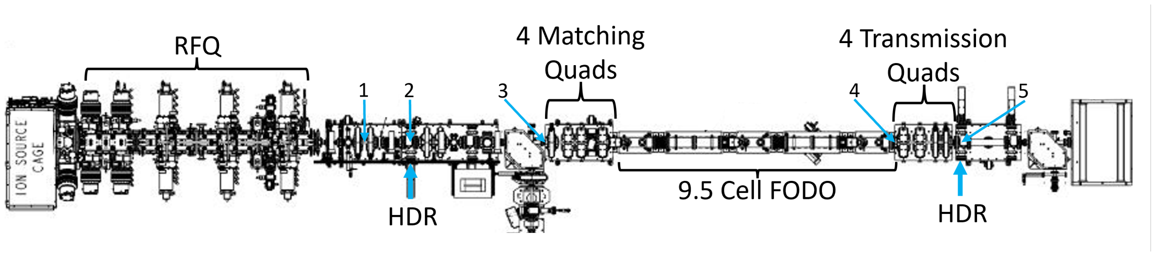

Figure 1: BTF Layout showcasing HDR measurement stations bookending a 9.5-cell FODO line. Sets of four quads before and after FODO line manipulate beam orientation to produce desired mismatch and control transmission respectively. Numbers denote important locations to transmission improvement methodology and analysis.

IMPROVING OPTICS CASE

The current optics case loses particles at various locations along the BTF, and at the most mismatched conditions, loses particles within the FODO line according to HDR simulations. Improved optics will reduce loss at scraping locations around adjustable electromagnets, however, the increased information on high amplitude particle oscillations makes it apparent that the M=1.90 and M=2.35 cases have too high of mismatch to fit in the aperture of the FODO line. Further study of these cases will cease and optics improvement will focus on the three remaining conditions. Particle loss is then confined to three locations; before the matching section, in the matching section, and after the FODO line. To improve transmission, magnet settings in these sections need to be adjusted.

The improvement of optics is handled differently between two sections of the BTF: before and after the FODO line. All quads before the FODO line need to be adjusted solely in simulation as the beam orientation into the FODO line is precise and optics adjustments outside of simulation cannot ensure the level of mismatch. All corrector magnets and the quads after the FODO line can be guided by simulation and adjusted empirically as they are only needed to maximize transmission to the final measurement station. To this end optics improvements follow these steps:

1. HDR bunch creation by sampling 2D measurements from the first diagnostic station (location 2 in Fig. 1).

   $$f(x,x',y,y',z,de) = f(x,x')f(y,y')f(z,de) \tag{1}$$

   Note: High dimension measurements at the BTF have shown low inter-plane correlations predicating the accuracy of above method [7].

2. Backwards-tracking simulation to move bunch upstream by 2 quads (location 1).

3. Creation of many candidate initial optics cases up to matching quads (location 3).

4. Optimization of matching quads to produce matched and mismatched beams for each candidate case.

   Note: The optimization of this section is performed with LDR bunches created by thresholding HDR bunches at the 10^{-2} level, ensuring the core of the beam is orientated correctly into the FODO line.

5. Implementation into BTF and manual optimization of remaining magnets to maximize transmission.

6. Comparison of transmission to select best optics case.

With this process many optics cases were tested and one selected that had the highest transmission and improved upon the previous optics. This new case has increased transmission while producing the desired levels of mismatch into the FODO line. The relative increase in transmission is reported in Table 2 and the simulated rms evolution compared in Fig. 2.

Table 2: Transmission Comparison

Optics Case	Old Trans.	New Trans.
Matched	95%	97%
M 0.67	94%	97%
M 1.37	93%	96%

NEW HDR MEASUREMENTS

The improved initial optics case was implemented in the BTF and we have begun taking new HDR measurements. Currently, measurements of the matched and M=0.67 conditions have been completed at the end of the beamline, with further work to be done to complete the rest of the needed measurements. To avoid a reduction in data points due to the dropping of the M=1.90/2.35 conditions the additional conditions of M=0.37/1.05 will be added.

Comparison between the new and old measurements can be done at the measurement location, however, a more interesting location to compare them is at the output of the FODO line (location 4 in Fig. 1). The beam at each mismatch condition for the new and old optics is designed to have near the same core orientation and rms width at the entrance of the FODO line. Comparing how they differ after exiting can only be done at the exit of the FODO line, 4 quads upstream of the measurement location (location 5 in Fig. 1). This is due to the final transmission quads being tuned on a case by case basis depending on what gives the best transmission, causing the paired new and old beam cases to have different magnet settings from the FODO exit to the measurement location. Therefore, all cases are backtracked to the FODO exit, by creating bunches using their transverse HDR measurements and longitudinal data from simulation, as we only have the capability to measure longitudinal data at the first

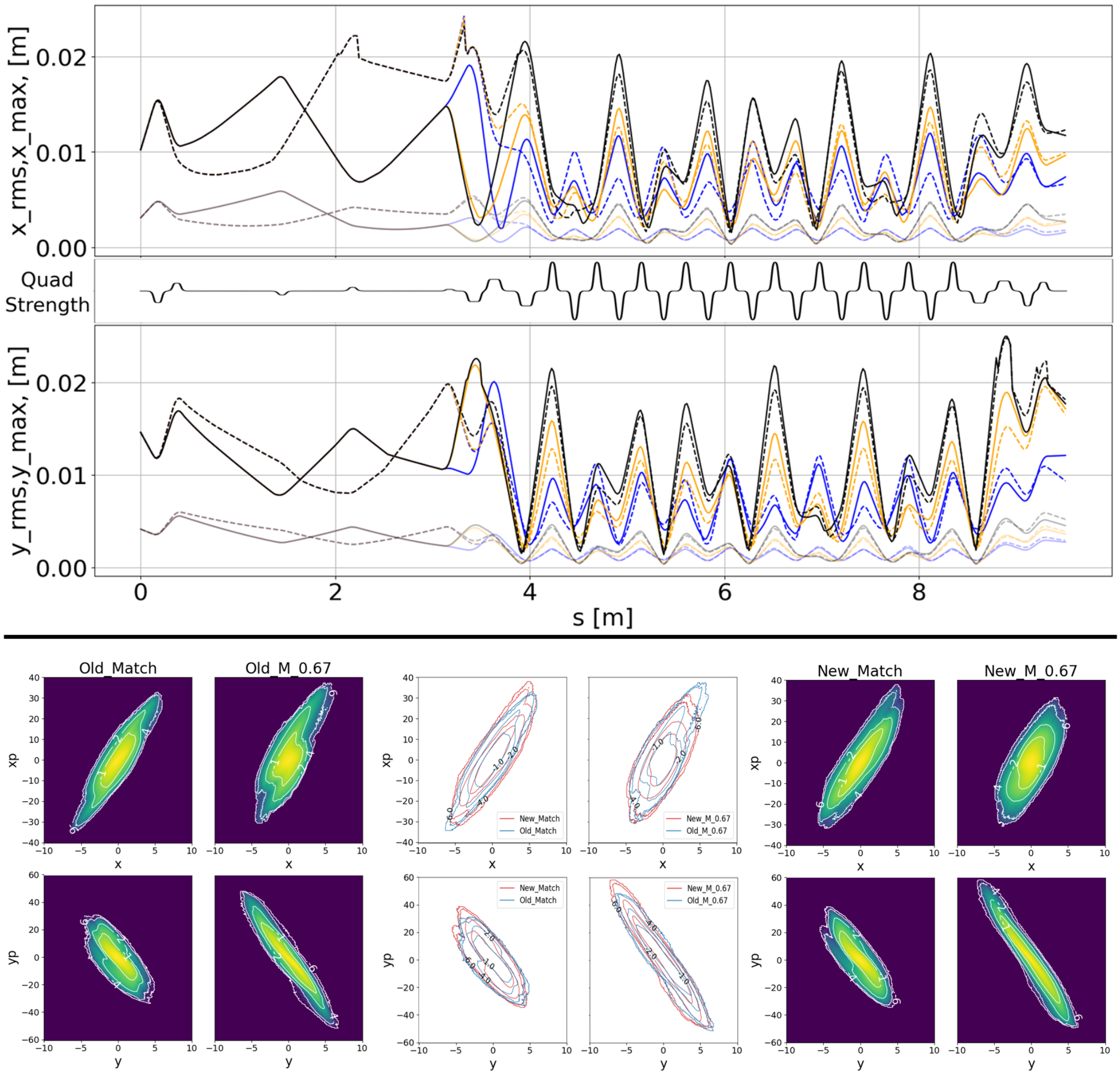

Figure 2: Top: Simulated rms evolutions of old (dotted) and new (solid) optics cases with x evolution in the top graph and y in the bottom, in each the max amplitude is shown in bold and the rms in light. For each case the three mismatch conditions of matched (blue), M=0.67 (orange), and M=1.37 (black) are shown. In the middle is a scaled example of the quad strengths for a single optics case. Bottom: Phase spaces of reverse propagated measurements at the FODO exit. The top row consists of x,xp measurements and the bottom row of y,yp. The six columns alternate between matched and M=0.67 measurements. The four figures on the left are the measurements of the old optics case and the four on the right the new, in the middle are the contours of the old and new overlaid. All contours are in log scale (levels: $10^{-1}, 10^{-2}, 10^{-4}, 10^{-6}$) of peak density.

measurement station (location 2 in Fig. 1). The backtracked bunches are then compared in Fig. 2 where it can be seen that the beam contours differ with the optics change, and their rms-widths are reported in Table 3.

Table 3: Full Beam RMS Widths

Optics Case	Hor. [mm]	Ver. [mm]
New Match	1.40	1.36
Old Match	1.17	1.20
New M=0.67	0.96	2.00
Old M=0.67	0.94	1.78

CONCLUSION AND WHAT'S NEXT

Improvements in transmission have been achieved though not perfected. This will aid in the goal of studying the relation between mismatch and halo formation though further improvement would be beneficial. The additional information from these measurements adds to the understanding of scraping in the BTF and another iteration of optics cases may further increase transmission. Along with this correctors will be added before and after the FODO line to aid in controlling beam centroid motion [8]. Beyond optics improvement, work is being done to analyze the same mismatch conditions with attenuation to adjust the space charge effects during transport.

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