MODEL BASED OPTICS STUDIES IN THE MEBT SECTION OF SNS

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Abstract

This paper presents beam dynamics studies for the Medium Energy Beam Transport (MEBT) section of the Spallation Neutron Source (SNS) accelerator. The analysis of measurements is based on the PyORBIT linac model. The diagnostics data includes wire scanner profiles, slit-harp and slit-slit transverse emittances, MEBT rebuncher calibration data, and bunch length measurements. The MEBT is a matching section between the RFQ and a Drift Tube Linac (DTL). It is also a place for beam halo scraping which helps to reduce beam loss in downstream linac sections. The linac simulation code was benchmarked against the diagnostics data.

INTRODUCTION

As with any other hadron accelerator, the Spallation Neutron Source (SNS) H^- linac has a Medium Energy Beam Transport (MEBT) section between the RFQ and the Drift Tube Linac (DTL). The main purpose of the MEBT is the transverse and longitudinal matching of the beam into the DTL. At SNS it is also used for several other purposes. Originally it was a place for a second beam chopper that would improve the rising and falling time of mini-pulses created by the initial chopper before the RFQ. Eventually, it turned out that this additional chopper was unnecessary, and it was removed. Now, the SNS MEBT is a place for beam halo scraping. This scraping significantly reduces beam losses in the superconducting section of SNS. Usually the MEBT scrapers remove 1–1.5% of the beam. At SNS, the MEBT also contains a set of diagnostic devices for beam characterization. They include six Beam Position Monitors (BPM) to measure transverse positions and the longitudinal phase of the bunch center, five wire scanners (WS) for transverse profile measurements, a slit-harp and a slit-slit transverse emittance device, and two beam current monitors (BCMs). In the future we plan to add a laser based Bunch Shape Monitor. The abundance of diagnostics makes the MEBT a good candidate for benchmarking accelerator models with real measurements. Successful benchmarks will allow studying different MEBT optics offline without necessitating beam study time, which is a limited commodity at a user oriented facility like SNS.

The present paper describes the application of two codes for simulations of the beam dynamics in the MEBT. The first code is an OpenXAL online model (OM) [1]. This is an envelope code used in control room applications for fast model-based analysis and predictions. The second code is a part of the PyORBIT code dealing with linac simulations [2]. It is a particle-in-cell (PIC) code similar to other linac codes with some unique features that will be discussed below.

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SNS MEBT

The MEBT optic structure is shown in Fig. 1. The total length is 3.63 meters. It has 14 symmetrically placed quadrupoles and four RF bunchers for longitudinal focusing. The RF bunchers are RF accelerating cavities with one gap. The BPMs are distributed along the MEBT almost evenly. The 5 Wire Scanners are in different places, and the Slit-Harp emittance device is in the drift space before the last group of four quads at the end.

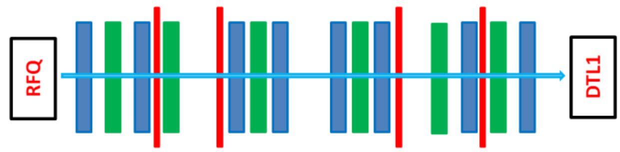

Figure 1: The SNS MEBT structure. Blue and green colors denote horizontally and vertically focusing quads, respectively, and the red signifies RF buncher locations..

To simulate the beam transport through the lattice shown in Fig. 1, we have to know quadrupole field gradients and the maximum energy gain and phases of the bunchers. The quadrupole fields are calculated by the control system by using the currents from power supplies and the known gradient vs. current functions [3]. The buncher model parameters are defined during the tuning of the MEBT.

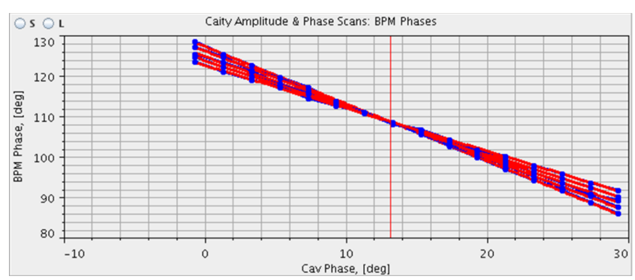

Figure 2: The results of the buncher #4 phase scans for different buncher amplitudes.

Buncher Parameters

The MEBT bunchers keep the beam well bunched to inject into the DTL. The synchronous particle phase of the RF in bunchers should be -90^0 to give zero acceleration to the beam. To set up the phase we perform several phase scans of each buncher for different RF amplitudes measuring the phase response of the BPM downstream. The SNS BPMs measure not only the transverse position of the bunch but also its phase, which is proportional to the arrival time of the bunch at the BPM position. The results of one of these scans are shown in Fig. 2. When the BPM's phase is the same for different RF amplitudes there is no change in the arrival time, and therefore we are

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at the zero-acceleration phase for that RF buncher. The slope of the lines for different RF amplitudes defines different maximum energy gains for the buncher. This gives us enough information for the simple RF cavity model initialization.

ENVELOP MODEL (OM OF OPEN-XAL)

After we know the parameters of all lattice elements, we can use a model to find the initial parameters of the bunch at the entrance of the sequence by using WS data. The knowledge of the initial parameters gives us full control over the beam parameters in the lattice if our model is correct. A well-established procedure to measure initial Twiss (in the case of an envelope model) includes transverse profile measurements and fitting the RMS bunch sizes. The measurement of the MEBT longitudinal Twiss parameters is not possible at this moment, so we use the design parameters. We checked that the design RMS longitudinal size of 8.5^0 at the end of the MEBT is very close to the value of 9.2^0 extracted from the DTL acceptance scan. The result of fitting RMS sizes in the MEBT with the OM is shown in Fig. 3. For analysis we used the production optics of 2015.11.24 with the peak current 39 mA. Figure 3 shows good agreement with WS measurements except for the horizontal size at the last wire scanner.

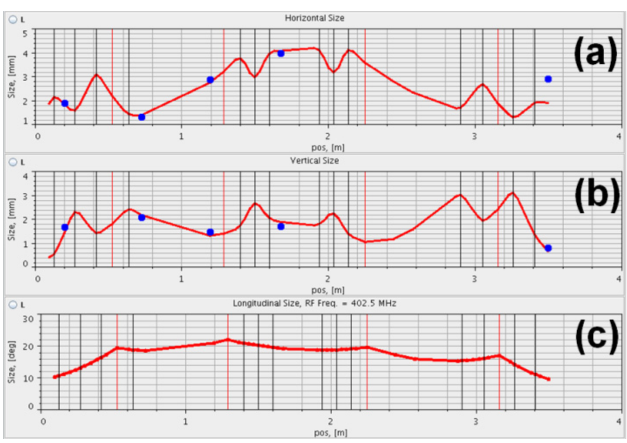

Figure 3: The RMS sizes of the bunch in the SNS MEBT. (a),(b),(c) are horizontal, vertical, and longitudinal RMS sizes, respectively. The red line is taken from the Online Model, and blue points are WS results. The vertical black lines are centers of quads, and the red ones are the RF bunchers.

PYORBIT LINAC MODEL

For PIC simulations codes, there are two ways to get information about the initial bunch distribution by using the WS profiles. The first method is the same as for the envelope model. We use RMS sizes of the bunch in the fitting procedure, and we obtain the Twiss parameters of the bunch at the entrance. Another approach is a tomography-like technique where we find an initial bunch that will give us not only RMS beam sizes at WSs, but also the correct transverse profiles [4]. In our case we used a more direct approach based on the presence of the emittance data in both transverse directions and the ability of the PyORBIT code to perform backward tracking of the bunch in the accelerator lattice.

Bunch Backward Tracking in PyORBIT

The MEBT emittance device is installed in the drift space before the last four quads (see Fig. 1). It is a combination of slit-slit and slit-harp devices. The slit-slit configuration is used for low noise and high dynamic range emittance measurements. The emittance of the core part of the bunch can be measured in either configuration. The measured horizontal and vertical phase space densities of the bunch are saved, and they are used later as particle distribution densities by PyORBIT. The longitudinal distribution is a water-bag with the design Twiss parameters. The PyORBIT code uses these distributions to generate the coordinates of the macro-particles that represent the bunch in simulations. To track these macro-particles from the emittance device to the beginning of the MEBT, PyORBIT uses the following approach: the equation of motion of the macro-particles is invariant relative to the time reversal, so we just change the initial conditions (reverse initial velocities of macro-particles), and then we track particles through the backward lattice that is between the emittance device and the start of the MEBT. In PyORBIT we use x, x', y, y', z, dE coordinates, and the time reversal is done by the following transformation

$$x' \Rightarrow -x'; y' \Rightarrow -y'; z \Rightarrow -z \qquad (1)$$

The longitudinal transformation in (1) describes the head-to-tail reflection. The energy of the particle stays the same. After we track this bunch to the beginning of the MEBT, we have to transform it back, and then we keep it as the initial bunch formed by the RFQ.

There are two assumptions in this algorithm that we cannot check at this moment. First, we assume that the bunch has the design longitudinal Twiss parameters and that the longitudinal distribution is a water-bag. Second, we assume there is no correlation in the distributions between the three directions. At SNS there are some efforts underway to experimentally check these assumptions [5].

Measurements and Analysis Results

To check the agreement between analyses based on the two available SNS models, we performed three series of WS and emittance measurements in 2016 and used Online Model and PyORBIT backtracking to get the Twiss parameters at the MEBT entrance. The results of the studies are shown in Table 1 where the RMS Twiss and unnormalized emittance parameters are shown in units of [mm/mrad] and [π*mm*mrad] respectively. The three sets of measurements were taken at three month intervals for different production setups: different ion sources, RFQ amplitudes, and peak currents from 35 to 39 mA. The Twiss parameters found by OM and PyORBIT analysis demonstrate a satisfactory agreement. Some disagreement is not surprising because of the significant differences in the models (envelope and PIC codes) and a drawback in

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the SNS Online Model that cannot account for the destructive overlapping of the quadrupole fields of six MEBT quads at the center [3]. The PyORBIT code takes into account this overlap.

Table 1: Beam Twiss Parameters at the RFQ Exit

Code	α_x	β_x	ε_x	α_y	β_y	ε_y
OpenXAL	-1.2	0.11	3.6	2.7	0.25	3.8
PyORBIT	-0.9	0.12	3.8	2.2	0.27	3.2
OpenXAL	-1.7	0.13	3.5	2.8	0.27	3.7
PyORBIT	-1.0	0.12	3.8	2.2	0.26	3.3
OpenXAL	-1.4	0.12	4.9	2.9	0.31	4.2
PyORBIT	-0.7	0.08	4.0	2.7	0.30	3.3

WSs Data vs. Emittance Measurements

Fig. 4 shows the agreement between transverse RMS sizes of the beam calculated by the PyORBIT backtracking and measured by WSs. The agreement between measurements and reconstruction is not perfect, but overall it is not so bad. Figure 4 like Figure 3 demonstrates the noticeable disagreement between the model and the RMS horizontal size reported by WS14.

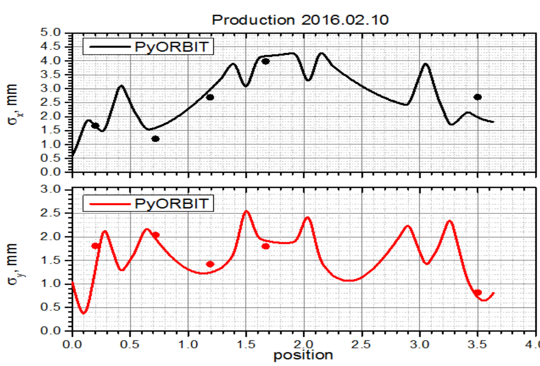

Figure 4: The horizontal (black) and vertical (red) RMS sizes of the beam in the MEBT during production on 2016.0210. Lines are from the PyORBIT reconstruction, and points are WS data.

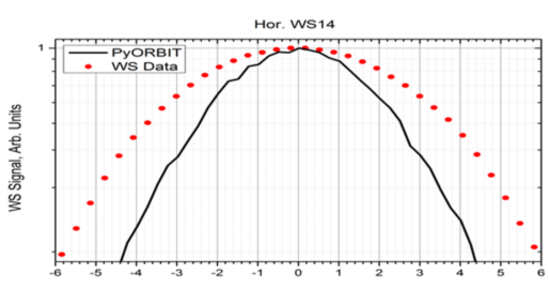

Figure 5: The horizontal profiles at MEBT WS14. The line is a PyORBIT reconstruction, and the points are WS data.

The model and measured transverse horizontal profiles at WS14 are shown in Fig. 5. They clearly indicate a big difference that we could not explain. The discrepancy between the models and the measurements at WS14 has been seen constantly, so we suspect some defects or unknown mechanism widening the horizontal profile. At the end of 2016 the Wire Scanner was replace by a slit device with the current detection in the DTL. This would eliminate any possible electron reflections from the beam pipe in the MEBT. It did not change our results and proved that WS14 is working correctly. We are still working on this problem.

CONCLUSIONS

A new approach for the initial distribution reconstruction was successfully applied to the MEBT section of the SNS linac. The approach is based on the emittance measurements somewhere in the lattice and the backtracking of measured distributions to the beginning of the lattice. In the presented cases we did not take into account any possible correlation between horizontal and longitudinal directions.

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REFERENCES

[1] J. Galambos *et. al.*, “The SNS Application Programming Infrastructure”, in *Proc. EPAC’04*, Lucerne, Switzerland, pp. 2855-2857.

[2] A. Shishlo, S. Cousineau, J. Holmes, T. Gorlov, “The Particle Accelerator Simulation Code PyORBIT”, *Procedia Comput. Sci.*, 51, pp. 1272–1281, 2015.

[3] A. Aleksandrov, J. Staples, “3-D calculations of field distribution in the MEBT quad and effect of the fringe field on beam dynamics”, in *Proc. PAC’01*, Chicago*, USA, 2001*, pp. 1746-1748.

[4] V. Dimov *et al.*, ”Emittance Reconstruction Techniques in Presence of Space Charge Applied During the Linac4 Beam Commissioning”, in *Proc. HB’16*, Malmö, Sweden, 2016, pp. 433-438

[5] B. Cathey *et. al.*, “6D Phase Space Measurements of Low Energy, High Intensity Hadron Beam”, presented at IPAC’17, Copenhagen, Denmark, May 2017, paper TUPVA146, this conference.