BEAM DYNAMICS STUDIES AND BEAM QUALITY IN THE SNS NORMAL-CONDUCTING LINAC*

A. Aleksandrov, D. Bartkoski, P. Chu, S. Cousineau, V. Danilov, G. Dodson, J. Galambos, S. Henderson, D. Jeon, M. Plum, M. Stockli, Spallation Neutron Source Project, Oak Ridge National Laboratory, Oak Ridge, TN, 37830, USA

Abstract

The Spallation Neutron Source accelerator systems will provide a 1 GeV, 1.44 MW proton beam to a liquid mercury target for neutron production. The accelerator complex consists of an H- injector capable of producing 38 mA peak current, a 1 GeV linear accelerator, an accumulator ring and associated transport lines. The linear accelerator consists of a Drift Tube Linac, a Coupled-Cavity Linac and a Superconducting Linac which provide 1.5 mA average current to the accumulator ring. The staged beam commissioning of the accelerator complex is proceeding as component installation progresses. Recently, the normal-conducting linear accelerator was beam commissioned. A number of beam dynamics and beam quality measurements will be reported, including the measurement of transverse emittances in the H- injector, and the evolution of halo and emittance along the linac.

INTRODUCTION

The Spallation Neutron Source linear accelerator consists of a 2.5 MeV, 38 mA H- front-end injector, a six-tank 402.5 MHz Drift Tube Linac to accelerate the beam to 87 MeV, a four-module 805 MHz Coupled Cavity Linac to accelerate the beam to 187 MeV, and a superconducting linac to accelerate the beam to 1 GeV. At baseline parameters, the linac will accelerate a 38 mA peak current, 1 msec long beam pulse at 60 Hz. This beam pulse is chopped with 68% beam-on duty factor to give a 26 mA macropulse current (a 1.5 mA average current) which provides a 1.5 MW beam to the accumulator ring. Beams of these intensities require careful control of their transverse and longitudinal distributions in order to minimize beam loss. Strict beam loss criteria of less than 1W/m have been established to allow hands-on maintenance of activated accelerator components. As a result, understanding and control of the beam quality, emittance growth and halo development in the SNS linac is of paramount importance.

The Warm Linac has been commissioned in stages in four separate beam commissioning runs over the past 2 years [1]. In this paper we summarize the various beam dynamics and beam quality measurements and studies that have been performed. Table 1 summarizes a number of beam dynamics and performance measurements.

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ION SOURCE AND LEBT EMITTANCE

The Spallation Neutron Source uses Cs enhanced, RF driven multicusp ion sources to generate the ~50 mA of H^- beam [2]. An electrostatic telescope focuses the beam into the RFQ that is 12 cm downstream of the ion source extraction aperture. There is not enough space to insert diagnostic equipment and therefore ion source and LEBT emittances are being studied on the ion source test stand, a duplicate of the ion source and LEBT on the H^- injector. The ion source test stand features a diagnostics chamber in lieu of the RFQ. The current exiting the test LEBT is measured with a beam current toroid and a suppressed and shielded Faraday cup. Two Allison emittance scanners [3] can be inserted to measure the horizontal and vertical emittance of the H^- beam as it would be injected into the RFQ. As one can see in Fig. 1 the horizontal emittance (circles) is larger than the vertical emittance (diamonds) due to the transverse magnetic field in the extraction aperture that steers the extracted electrons onto a dump at high voltage. The open symbols shows results from LBNL before the ion source and LEBT were mounted to the RFQ. The solid symbols represent results obtained on the ORNL test stand. Recent improvements on the emittance scanners [4] make these measurements preliminary.

Table 1: Beam parameters achieved during commissioning

Parameter	Baseline /Design	Achieved	Units
MEBT Transverse Output Emittance	0.3	0.29 (H), 0.26 (V)	π mm mrad (rms,norm)
DTL1 Transverse Output Emittance	0.3	0.40 (H), 0.31 (V) ±0.10 (systematic)	π mm mrad (rms,norm)
DTL6 Transverse Output Emittance	0.3	0.32 (H), 0.39 (V)	π mm mrad (rms,norm)
MEBT Bunch Length	18.5	18	Degrees rms
CCL1 Bunch Length	2.8	7.4	Degrees rms

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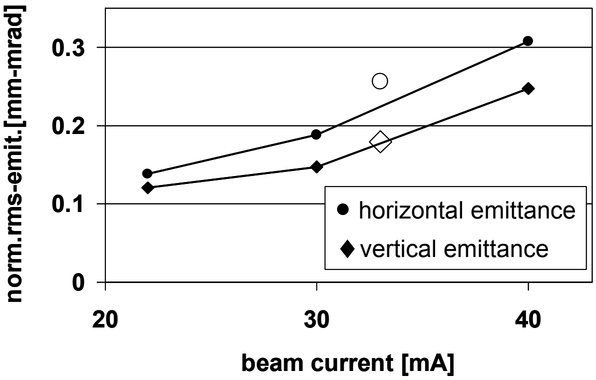

Figure 1: LEBT output emittance measurement results.

MEBT EMITTANCE

The 65 keV beam from the IS/LEBT is accelerated to 2.5 MeV in a 402.5 MHz RFQ. A Medium Energy Beam Transport line chops and matches the beam in all three planes for subsequent acceleration in the DTL. The MEBT beam optics do not maintain strict axial symmetry due to the chopping geometry, so emittance growth and halo development in the MEBT is a subject of experimental and theoretical study [5].

An inline slit/collector dual-plane emittance station was recently installed in the MEBT. A typical horizontal emittance measurement for a properly tuned MEBT is shown in Figure 2. At the design, 38 mA peak current, we measure horizontal and vertical emittances of 0.29 and 0.26 π mm mrad (rms, normalized) respectively. These values are less than our design goal of 0.30 π mm mrad (rms, normalized).

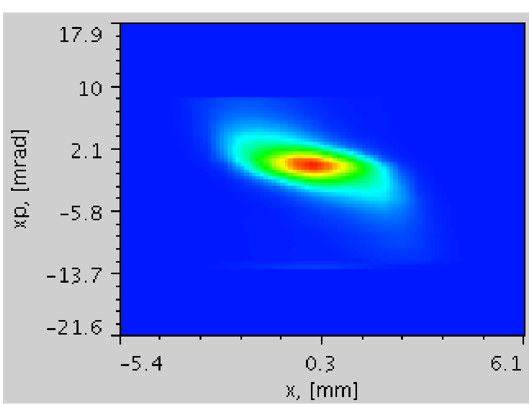

Figure 2: Horizontal emittance measurement in the MEBT at 38 mA peak current. The distribution has an rms normalized emittance of 0.29 π mm mrad.

BEAM PROFILE STUDY

Transverse beam profiles

Wire scanners are used throughout the MEBT, DTL and CCL for transverse beam profile measurements. Our experience shows that the existing SNS wire scanners can be reliably used for measuring tails down to ~10^{-3} level. We achieved a reasonably good agreement between the model predictions for the beam envelope and the rms beam sizes measured during commissioning [6]. We are concentrating our efforts on studying beam tails beyond the rms size because beam loss in the warm linac is one of our primary concerns. We have identified the three major sources of the tails: those originating in the injector, non-linear forces in the MEBT, and mismatch at the transitions between different linac focusing structures. Mitigation strategies are described in [5] and include halo scraping in the MEBT, modification of the MEBT optics and development of proper matching algorithms.

A pair of scrapers was installed in the middle of the MEBT during the last beam run. The effect of the scraper can be clearly seen on the profiles measured in the DTL. Figure 3 shows horizontal beam profile measured after the DTL Tank 3 with the scraper inserted (blue circles) or retracted (green squares). When the scraper is inserted the profile of the remaining beam has a Gaussian shape down to at least 4 rms beam sizes or the 10^{-3} level. This measurement confirms that some part of the tails in the beam originates in the Front End and can be removed using a simple scraping system.

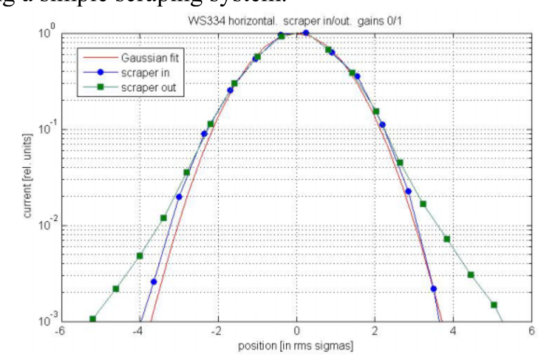

Figure 3: Effect of the MEBT scraper on the beam profile measured in the DTL. Blue circles – scraper is in; green squares – scraper is out; solid red line – Gaussian fit.

The optimal transverse matching between the MEBT and the DTL is achieved by adjusting strengths of the four last quadrupoles in the MEBT (permanent magnet quadrupoles are used in the DTL). We found that a Gaussian profile is a good approximation for the best matched beam in simulations therefore the figure of merit in our matching experiment was the closeness of the measured profiles to a Gaussian. Figure 4 shows the effect of MEBT matching quadrupole adjustments on the beam profile. The measured beam profile follows a Gaussian distribution to ~4 rms beam sizes when optimum matching is achieved. Deviation from the optimum produces well pronounced tails.

We plan to use a similar procedure for matching at the DTL to the CCL transition. Preliminary results related to the rms beam size measurements can be found in [6].

Longitudinal beam profiles

The longitudinal profile of the bunch can be measured in the MEBT using a laser-based diagnostic system [7] at a single location and in the CCL using Beam Shape Monitors (BSM) [8] at three locations in module 1.

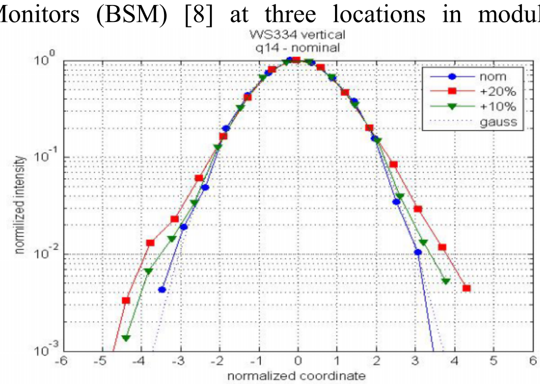

Figure 4: Effect of the MEBT matching quad change on the beam profile measured in the DTL. Blue circles – nominal "best match"; green triangles – nominal +10%; red squares – nominal +20%; dash – Gaussian fit.

The longitudinal bunch profiles measured with the mode-locked laser system are shown in Figure 5. The bunch has a symmetric Gaussian-like profile when the upstream RF rebuncher phase is set to the nominal (left picture). The rms bunch length vs. the rebuncher phase is shown in Figure 5 on the right. The measured values (squares) are in good agreement with the PARMILA prediction (stars). This measurement confirms that longitudinal bunch parameters are close to the design. We didn't have enough sensitivity for a reliable measurement of the bunch tails.

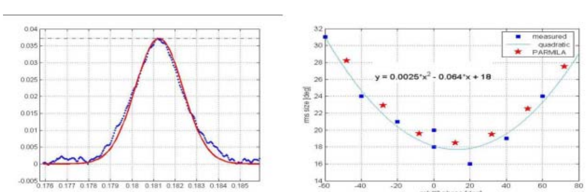

Figure 5: Left: longitudinal bunch profile measured with a mode-locked laser in the MEBT (blue) and Gaussian fit (red). Right: rms bunch length vs. the rebuncher phase: measurements – squares; simulation – stars; solid line – quadratic fit.

The bunch profiles measured at three locations in CCL module 1 using the BSM are shown in Figure 6. They have Gaussian-like shapes without significant tails but the rms widths are significantly larger than expected from the simulations. The plot on the bottom right shows all available experimental data taken with different linac tunes at different currents (asterisks) and the bunch width predicted by PARMILA (stars). There is factor of 2-3 difference even in the best case.

We don't have the possibility for direct measurements of the bunch length in the DTL but some information can be derived from the DTL acceptance scan data. Figure 7 shows a comparison of the measured acceptance curve width (which is related to the bunch length) with the simulations. The measured width is consistently shorter than the simulations predict (this is because the measurements were done at lower current than the simulation) until DTL Tank 5.

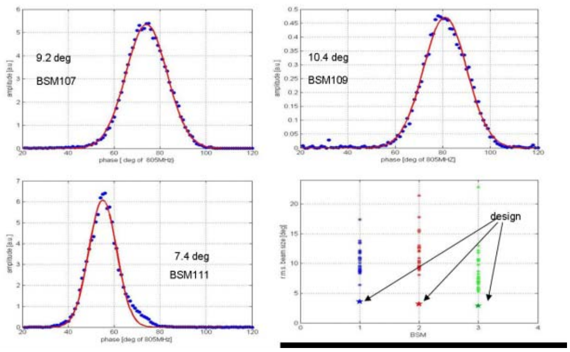

Figure 6: Longitudinal bunch profile measured at three BSM stations in CCL module 1 (dots) and Gaussian fits (solid line). Bottom right: rms bunch widths for all measurements (asterisks) and the design values (stars).

The measured width for Tank 5 is significantly larger than predicted, suggesting that bunch lengthening starts there. We had several other anomalies with tank 5: large output energy deviation from the design [9], necessity to run the following tank at RF power higher than design, very high X-ray radiation localized at one drift tube, and the inability to reach the nominal RF duty factor due to vacuum degradation. Finally, we opened the tank for inspection and found a piece of paper inside. Though we can't offer a precise explanation, we believe that all observed anomalies are related to the tank contamination and should be resolved when it is cleaned. Further experimental study is planned for the next beam run.

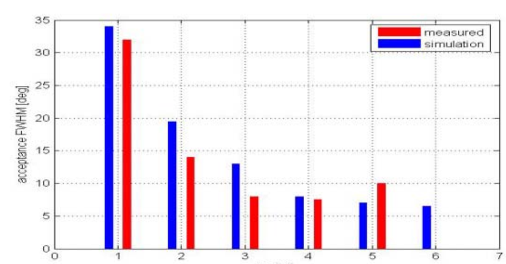

Figure 7: The measured (red) and simulated (blue) widths of the DTL acceptance curves vs. the tank number.

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