BEAM STUDIES AT THE SNS LINAC *

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Abstract

The most recent beam dynamics studies at the Spallation Neutron Source (SNS) linac, including major beam loss reduction efforts in the normal conducting linac and in the superconducting linac (SCL), and the simulation and measurement of longitudinal beam halo and longitudinal acceptance at the entrance of the SCL are discussed. Oscillation of the beam centroid around the linac synchronous phase and the phase adiabatic damping curves in the SNS linac are investigated with linac longitudinal models and measured with all the linac beam phase monitors.

INTRODUCTION

The SNS is a short-pulse neutron facility. Its accelerator complex consists of a 2.5-MeV H^- injector, a 1-GeV linac, an accumulator ring and associated beam transport lines. The linac has a normal conducting front end approximately 100-m long that includes a medium energy beam transport (MEBT), six drift tube linac (DTL) cavities and four coupled cavity linac (CCL) tanks for beam energy of up to 186 MeV. It includes a superconducting linac (SCL) 160-m long that consists of 81 independently powered 6-cell niobium cavities in 23 cryomodules. There are a total of 96 RF cavities/tanks in the SNS linac including an RFQ in the injector and four beam buncher cavities in the MEBT. In the baseline design, a 1-GeV H^- beam, up to 1.56-MW is accelerated in the linac and injected into the accumulator ring [1].

To form a 250-ns gap required by extraction kickers in the accumulator ring, pre-chopping is performed by the low-energy beam transport (LEBT) choppers in the injector, which deflects 32% of the beam onto the front face of the RFQ with a design rise/fall time of 40-ns. A fast chopper system in the MEBT with a 10-ns rise/fall time removes the “partially chopped” beam from the LEBT chopper and further reduces the beam extinction ratio to below 10^{-4} [1]. During neutron productions, however, the resistance of the LEBT choppers had to be increased to protect the electronic systems because of frequent ion source discharges. Meanwhile, the MEBT chopper is not fully functional; as a consequence the rise/fall time of the choppers increased and beams contaminated the ring extraction gaps.

In August 2005, a beam was successfully accelerated through the entire linac system for the first time during the SCL beam commissioning. Since then, we have achieved a maximum beam energy of 1.01-GeV, a peak beam current of 40-mA, a full pulse length of 1-ms, a beam repetition rate of 60 Hz, and maximum power on target of 550-kW. Years of work may yet be required to reach the design beam power, as some parameters were achieved separately. Beam dynamics studies at the SNS linac are mainly focused on precise and faster linac tune-up techniques, optimizing the transverse and longitudinal lattice, investigating the source of beam instability in the linac, and reducing beam loss and beam activation. Several new beam dynamics techniques have been developed.

LONGITUDINAL LATTICE

In a constant gradient RF acceleration structure with a fixed synchronous phase, whenever the small acceleration approximation applies, phase synchrotron oscillation will experience adiabatic damping. When space charge effects can be ignored, the beam phase envelope will show exactly the same damping but at twice the frequency. Figure 1 shows the root-mean-square (RMS) phase damping in the SNS normal conducting linac in simulations using the IMPACT code [2] with a linear map and zero beam current. The only exception in the linac is at the front of DTL1, where the synchronous phase ramps up from -45° to -30° to capture all the output beams from the RFQ.

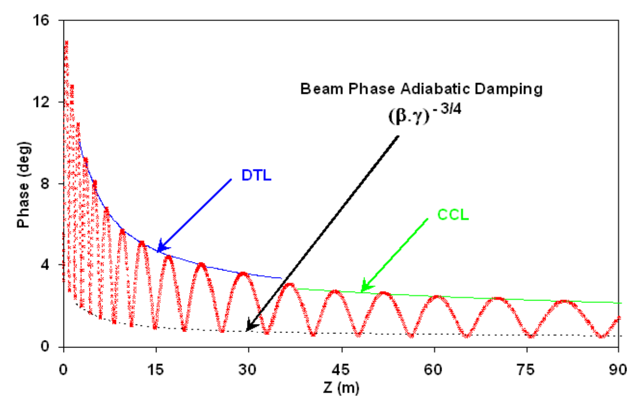

Fig. 1. Phase damping in the normal conducting linac.

Multiple bunch shape monitors (BSMs) along the linac could possibly be used to measure the phase damping curves, but using beam phase monitors (BPMs) is more convenient. The latter needs a model of the absolute beam phase in the linac systems with proper phase and energy perturbations introduced into it. Figure 2 shows the beam phase centroid oscillation in the baseline SCL lattice in simulations with a linac longitudinal model. Because the gradient of the SNS superconducting cavity reached 10~20-MV/m, the small acceleration approximation may not be appropriate here. The beam transit-time-factor (TTF) varies widely during the acceleration, so the phase

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oscillation does not follow the adiabatic damping exactly, however, it is still approximately in agreement.

The model phase oscillation and damping curve are helpful in optimizing the SCL longitudinal lattice, since in neutron production, the cavity gradient is scattered from 0 to 18-MV/m, and a smooth longitudinal lattice is important to preserve beam emittance in the linac. During SCL beam commissioning, abnormal phase damping behaviour was found in one of the design lattices; and the longitudinal emittance doubles at the exit of the SCL in simulations with IMPACT [3]. It was also noted that beam phase oscillation and damping are very sensitive to RF errors, and simply comparing the model prediction against an actual measurement with all the linac BPMs could serve as a good linac lattice diagnostic [4]. We measured phase oscillation and damping with the linac BPMs early in the beam commissioning, while the linac RF system was suffering a 3°~5° phase drift [3].

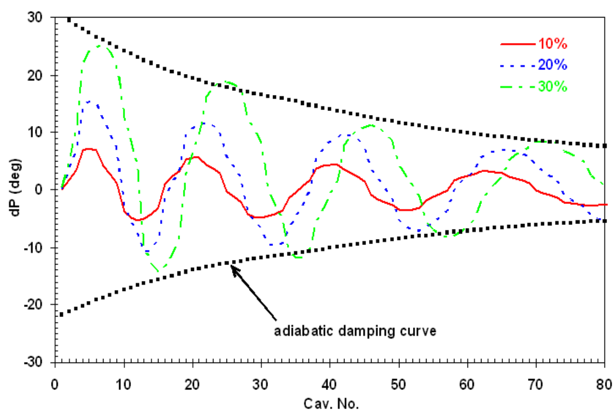

Fig. 2. Phase centroid oscillation and damping in SCL.

Recently, a longitudinal model was developed for the normal conducting linac, and a more precise BPM phase measurement technique was successfully applied to detect RF errors in the normal conducting linac. Fitting the BPM measurement with the linac model helped to tune the normal conducting linac more precisely and correctly, and tackled several RF failures in the linac [5]. However, we had less success in the SCL. Figure 3 shows beam phase oscillations in the SCL longitudinal models (the design lattice and the actually tuned) and the measurement two months ago. Figure 4 shows the model and the most recent measurement before and after the RF reference cable of cavity 08c (at 42-m) was replaced on August 18, 2008. Figure 5 shows the SCL phase oscillation models (the design lattice and the actually tuned) and the linac BPM measurements in February 2006. Obviously, RF drift in the linac system was reduced significantly compared with that in 2 or 3 years earlier, but RF phase drift of approximately 2° still exists in the SNS linac systems.

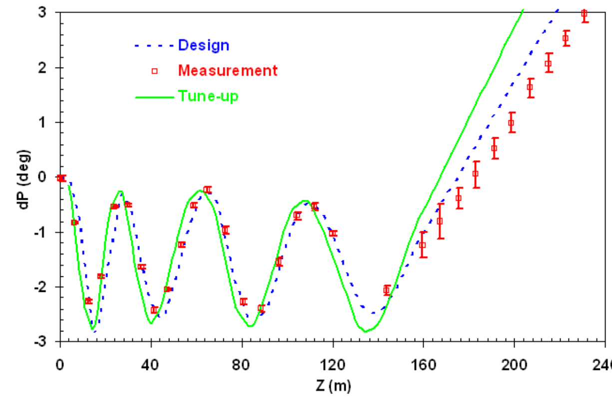

Fig. 3. Phase oscillation in the SCL models (design and the actually tuned) against linac BPMs measurement.

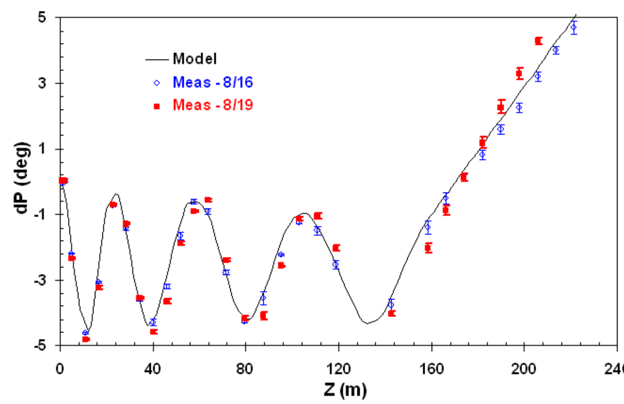

Fig. 4. Phase oscillation in the SCL models against the measurement before and after the RF reference work.

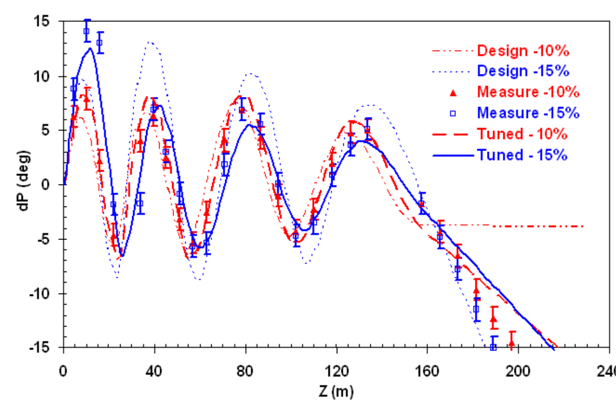

Fig. 5. Phase oscillation in the SCL in February 2006.

Beam loss and residual activation in the SCL is higher than anticipated in the design. Because the loss is very sensitive to upstream cavity phase or amplitude change and less sensitive to the upstream matching quadrupoles or all the quadrupoles in the SCL, it is considered mainly as a longitudinal problem – an issue not studied thoroughly in the linac design stage. The synchronous phase of the SCL changed from -17.4° to -20.5°, and the longitudinal acceptance increased to 220-deg*MeV. This reduced the SCL beam loss but it was not as significant as a more accurate fine tuning of all the upstream normal conducting linac cavities would be.

Beam phase and energy scans are performed in the first superconducting cavity (at a reference phase of -90°). Using all the beam loss monitors (BLM) in the linac and a beam current monitor (BCM) at the exit we successfully measured the longitudinal acceptance at the second SCL cavity, which shows close agreement with the model prediction. The beam acceptance demarcation was used as a virtual beam shutter, so beam bunch shape, beam energy profile, and longitudinal RMS emittance are also measured with this recently developed technique. In the meantime, beam longitudinal halo\tails are shown in the measurements [6].

Figure 6 shows a bunch shape measurement in four scans, bunch width (sigma) is approximately 3.2°, comparable to the nominal design of 2.7°. Figure 7 shows the beam longitudinal density contours at three different reference phases to include the effects of beam change and errors of the model in these scans. The repetitions for the 50~60% beam contours are acceptable, the beam longitudinal RMS emittance in this measurement is approximately 2.9-deg*MeV - 2.2 times the nominal design beams. SCL longitudinal beam emittance in different measurements are generally between 1.4 and 2.3 times the nominal design. It agrees with independent BSM measurements in the CCL, between 1.2 and 2.0 times [7].

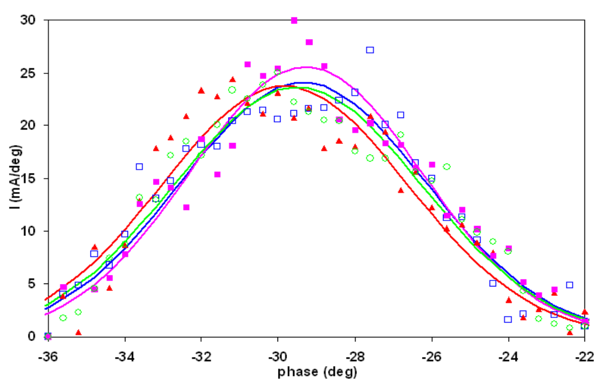

Fig. 6. Bunch shape measurement in 4 phase scans.

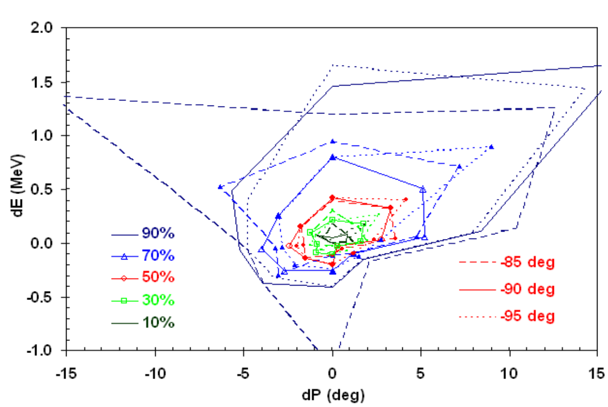

Fig. 7. Longitudinal measurement at 3 reference phase.

SCL beam longitudinal halo/tails both in the beam phase and in the energy space are characterized by those scans across the acceptance boundaries while all the linac BLMs and the BCM data are recorded. Figure 8 shows an energy scan with the BLMs and BCM measurements. It does not give much quantitive information about the amount of beams in the tails, but it shows that the beam energy tails are > 3-MeV, and the measurable size of the beam longitudinal tails is comparable to the SCL longitudinal acceptance.

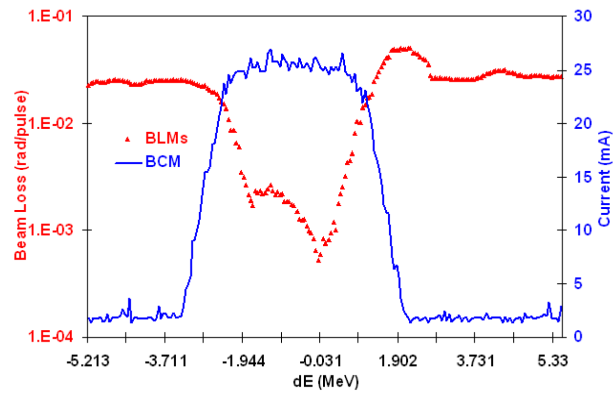

Fig. 8. Beam energy scan with BLM and BCM records.

TRANSVERSE LATTICE

Transverse beam Courant-Snyder parameters in the linac are measured with multiple wire scans (and in the SCL, laser wires), and fit the measured beam RMS size to an on-line model based on TRACE3D [8], and the most recent development of the on-line model and XAL, see reference [9]. Beam transverse matching could be performed using the same model and fit for a few matching quadrupoles to manipulate beams - a technique successfully applied in high energy beam transport (HEBT) and in ring target beam transport (RTBT) lines where no RF cavity exists. Because TRACE3D is a linear map code, not a multiple particle tracking program, high-order effects and beam emittance increase in an RF gap are not included in the model. When the simulation involves a mismatched lattice comprising RF structures and includes beam emittance growth, it is highly likely that beam matching based on the TRACE3D model will not have an accurate solution. Previously during neutron production, beam matching in the linac did not help reduce beam loss, and all of the linac quads were usually either set to the design or manually adjusted to reduce beam loss in the linac.

Figure 9 shows a beam Twiss parameter measurement at the MEBT using XAL. Beam RMS sizes measured at the first four wires are used to fit the on-line model, and the fifth wire is used to verify the solution. The on-line model shows a very large mismatch in the lattice, and the beam size measured at the fifth wire suggests that the wire scanner perhaps has the vertical wire and the horizontal wire swapped. The flexibility obtained by other models is studied; e.g., when IMPACT is used instead, the measurement shows a much better agreement with the model prediction in Fig. 10, and no wire is swapped.

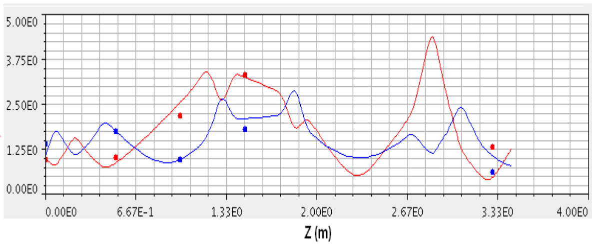

Fig. 9. On-line model and measurement at the MEBT.

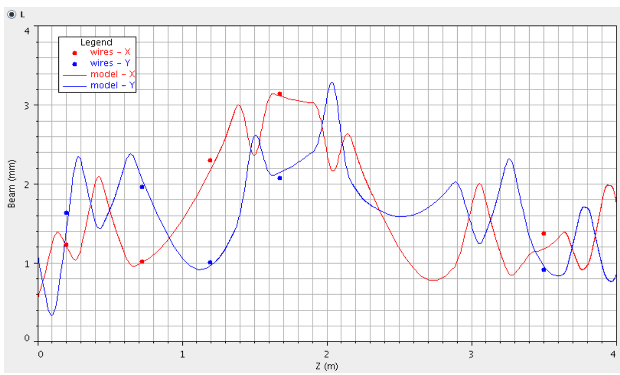

Fig. 10. IMPACT and measurement at the MEBT.

In the measurement, beam current is decreased to approximately 15-mA to reduce space charge effects [10]. However, as the MEBT consists of four beam bunchers, the on-line model shows a certain inefficiency for the lattice, which is only 3~4-m long. The beam emittance growth is not very significant. In this case, beam matching in the linac with the on-line model is suspect, although it takes as little as a minute to find a solution. IMPACT yields a better result, but running the code takes almost a week in a cluster of 80 CPUs. And it is not practical to match beams with wire scan data taken one or two weeks earlier because of errors in the model and changes in the actual machine; a few iterations usually are necessary.

Besides transverse matching, beam trajectory correction in the linac is important to reduce beam loss and residual activation. It is performed by optimizing to the on-line model matrixes with the least square algorithm, including all dipole correctors and all BPM measurements. Beam trajectory correction in the linac using the on-line model is often helpful to reduce the beam loss in the normal conducting linac as the beam aperture is only 2~3-cm. But it is not very effective in the SCL, as the aperture is large: 8-cm, and a 1~2-mm beam trajectory oscillation may not cause any serious beam loss problem. Figure 11 shows a beam trajectory in the SCL after a correction.

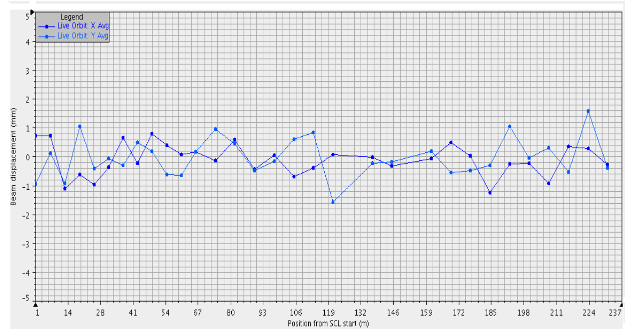

Fig. 11. Beam trajectory in the SCL after correction.

In the neutron production previously, residual activation in the CCL and in the CCL-SCL transit region was high. Note that only 10 BPMs are installed in the CCL, where 48 quads and approximately 32 dipole correctors exist, and there are uncertainties in the trajectories between BPMs. The Quads Shaker application [11] was developed to address this problem. Beam offset in the quads is obtained from the BPM response matrix measurement by scanning the gradient of the quads, and then fitting and optimizing the beam offsets with all the available dipole correctors [11]. The CCL beam trajectories are finely corrected with the new technique, and beam loss and activation are significantly reduced in the CCL. Figure 12 shows one of the CCL beam trajectories after Quad Shaker was used. Note also that the minimum loss still requires manual adjustment of a few dipole correctors.

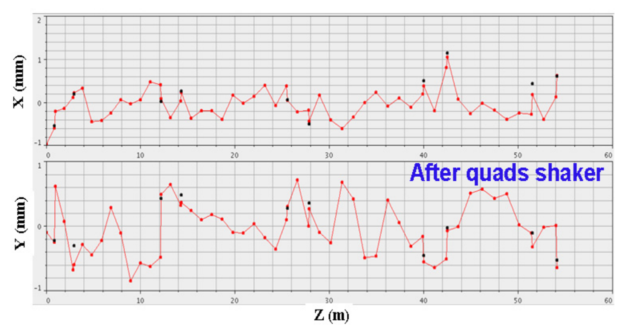

Fig. 12. Beam trajectory in the CCL after Quad Shaker.

UNSOLVED PUZZLES

As mentioned previously, beam loss and residual activation in the linac, particularly in the SCL, are much higher than anticipated in the original design. Figure 13 shows the measured residual activations in the linac after 24 hours cooling of 340 and 480-kW neutron production (10-day operation). The hottest activation spot in the entire linac is between cryomodules 2 and 3 (CM2-CM3). To achieve the design beam power of 1.56 MW in the linac, it is necessary to reduce beam loss by a factor of 2 to 3 in the SCL, so identifying the source of beam loss is very important. Both measurements and simulations show that the beam loss in CM2-CM3 is caused by the DTL phase tails (beam energy is approximately 90-MeV) [10].

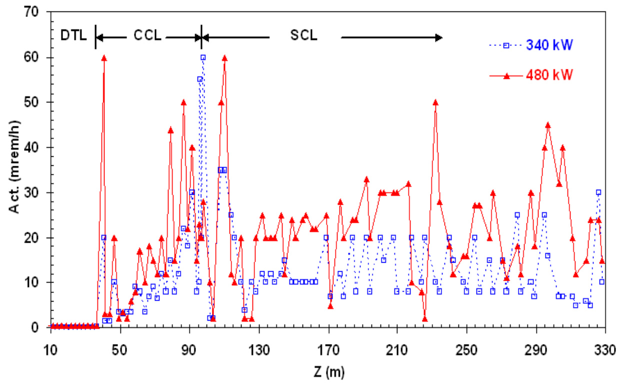

Fig. 13. Residual activation in the SNS linac systems.

Figure 14 shows the model predicted SCL longitudinal acceptance (Accpt) versus the CCL output beam spaces when a 360° beam phase tail exists at the CCL entrance. The blue area represents the IMPACT simulation with 3D space charges (IMPACT), and the red area represents single particle transport by XAL without space charge. The agreement between the two models is not great; however, both show that the CCL beam occupies a space larger than the SCL acceptance. But how the longitudinal tails could grow that big, and whether that is exactly what happens in the SNS linac, remain to be answered. Not all of the simulations of transverse beam tails\halo in the normal conducting linac yielded significant beam loss in the SCL because of the apertures; therefore, beam dynamics studies are focused on the longitudinal space.

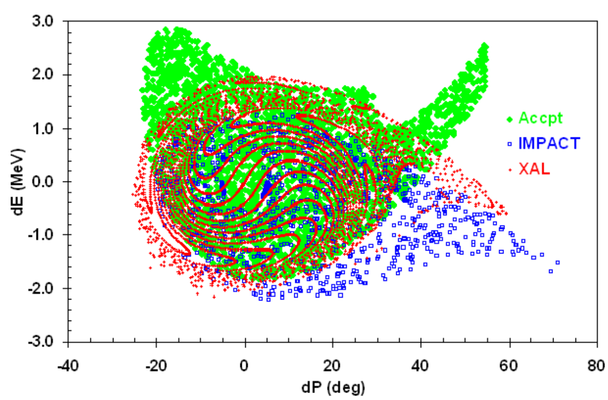

Fig. 14. SCL acceptance and the CCL output beams.

In simulations, if we assume large phase tails exist at the RFQ beams, and the linac has significant RF errors (DTL6 phase is shifted by 6° in the simulations), beam losses in the SCL may roughly agree with the linac BLM measurements. The simulation results (RF Error) are shown in Fig. 15. The figure also shows the SNS linac systems both with the baseline design without RF error (No Error), and with a gradient decrease approximately 10% in the MEBT rebunchers (MEBT RBs) resulting from ~25% RF power reduction compared to the original design. It shows that reducing RF errors in the linac, especially in the normal conducting linac, and increasing the gradient of the MEBT rebunchers to its design value could significantly reduce beam loss in the linac.

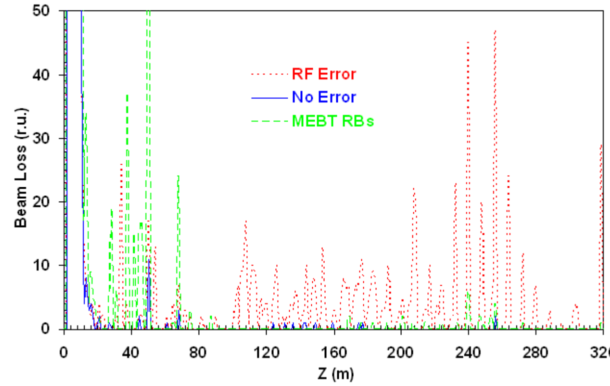

Fig. 15. Beam loss in the SNS linac from the RFQ tails.

One of the sources of beam tails\halo might be the partially chopped beams at the linac front end. In simulations with IMPACT, transverse kicks caused an increase in beam longitudinal emittance through transverse-longitudinal space coupling. In measurements with a CCL BPM, beam phase in a pulse shows some amplitude dependence and likely originated in the LEBT choppers (see Fig. 16, time is not in a linear scale). Beam studies show significant beam loss reduction in the ring extraction areas and in the RTBT lines as a result of turning on the MEBT chopper, which is designed to clean-up a large amount of partially chopped beams [12]. No beam loss reduction was observed in the linac, however. In principle, if the linac beam loss is related to partially chopping, a beam loss reduction of up to ~50% should have been observed with the MEBT chopper correctly tuned.

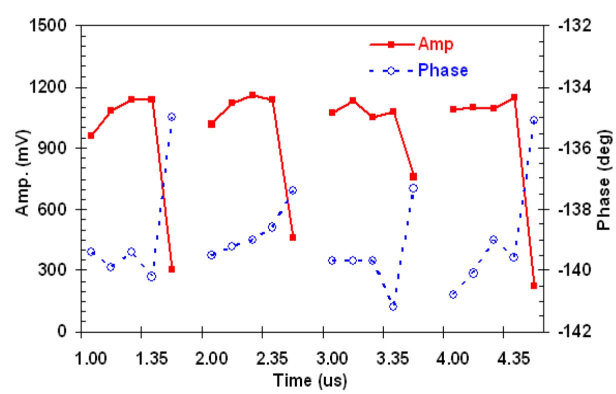

Fig. 16. CCL BPM phase and amplitude measurement.

Increasing the SCL longitudinal acceptance should help reduce linac beam loss, and that is a very simple, fast remedy in computer simulations. In the linac longitudinal model, decreasing the SCL synchronous phase from -20.5° to -25° may double the acceptance to 440-deg*MeV; and at -35°, it is above 600-deg*MeV and sacrifices approximately 100-MeV of the output energy.

Figure 17 shows the linac model prediction of the SCL acceptance at -35° (blue squares) and, of the CCL output beam phase space (red triangles). However, after the linac RF cavity phase was scaled [13] to the new synchronous design, no beam loss reduction was observed in the SCL; although the simulations showed a factor of two to three reduction in beam loss.

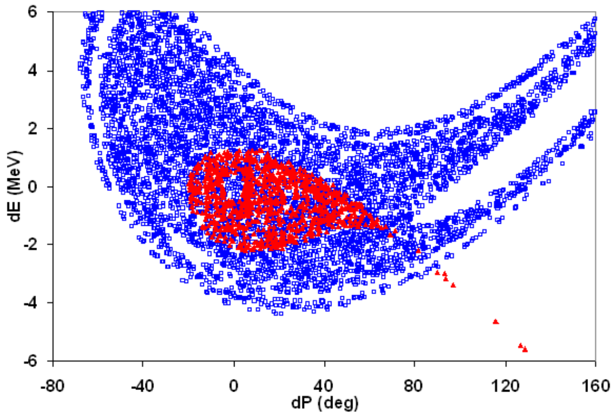

Fig. 17. SCL acceptance at -35° and CCL output space.

SUMMARY

Several beam dynamics studies were performed at the SNS linac with conventional and newly developed techniques. Longitudinal beam tails\halo was shown, but the origin of the halo is not fully understood. Characterizing the beam halo on the order of 10^{-4} to 10^{-5} and reducing the fractional beam loss in the linac to below 10^{-4} are very challenging. Some known problems should be addressed first for the MEBT rebunchers, LEBT and MEBT beam choppers, performance of the RFQ, and correct transverse beam matching through the entire linac. Beam loss in the linac, especially in the SC linac, is one of the major concerns associated with further ramp-up of SNS beam power, and a factor of two to three beam loss reduction is needed to reach the design goal.

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