IMPACT SIMULATION AND THE SNS LINAC BEAM *

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Abstract

Multi-particle tracking simulations for the SNS linac beam dynamics studies are performed with the IMPACT code. Beam measurement results are compared with the computer simulations, including beam longitudinal halo and beam losses in the superconducting linac, transverse beam Courant-Snyder parameters and the longitudinal beam emittance in the linac. In most cases, the simulations show good agreement with the measured results.

INTRODUCTION

The spallation-neutron-source (SNS) linac systems comprise a 2.5-MeV H^- injector, a normal conducting linac which consists of a medium energy beam transport (MEBT), a drift-tube-linac (DTL) with 6 DTL cavities and a coupled-cavity-linac (CCL) with 4 cavity tanks up to 186-MeV, and a superconducting linac (SCL) consisting of 81 niobium cavities in 23 cryomodules for a design energy of 1-GeV. The linac is designed to deliver pulsed H^- beams with a peak beam current of 38-mA, a pulse length of 1-ms, a repetition rate of 60-Hz, and a RF duty factor of 6%. For details of the SNS accelerator complex, see reference [1].

IMPACT is a 3D parallel particle-in-cell (PIC) code based on multi-layer object-oriented design. It can treat several kinds of particle accelerator components such as quadrupoles, dipole magnets, solenoids, and different RF cavities. It includes a 3D space charge model and simulates the absolute beam phase in an RF linac, more information on the code can be found in the user manual and in reference [2]. In beam dynamics studies of the SNS linac systems, we performed several beam measurements and compared the results against the simulations with IMPACT, and we obtained good agreement. However, we noted that it is still far away from a complete benchmark - it requires a large amount of dedicated beam time, which we do not have as the SNS is a user facility with most beam time reserved for neutron production.

TRANSVERSE PARAMETERS

At the SNS, transverse Courant-Snyder parameters are measured with multiple wire scan (WS) measurements in the linac, and fit to the measured RMS beam size with a linac model. At present, the measurement and fitting can be controlled in high-level applications developed in the XAL [3]. An on-line model embedded in XAL is based on TRACE3D [4]. Because the speed of simulations with a model is critically important to online applications, the accuracy is compromised. It is known that in a long linac lattice with multiple RF gaps, whenever emittance growth becomes significant, TRACE3D - which uses a linear transfer map and linear space charge, might not have an accurate solution. However, XAL provides satisfactory performance at the high energy beam transport (HEBT) and at the ring target beam transport (RTBT), where no RF cavity is involved and the effect of space charge is reduced as the beam energy reaches 800 to 900-MeV.

Our first measurement was at the MEBT, only 3.6-m long for 2.5-MeV beams with four beam buncher cavities. Figure 1 shows the wire scan measurements and the fitting to the online model. Beam RMS sizes measured at the first four wires were used to fit for the model, and the fifth wire was used to verify the results. The online model shows a large beam mismatch in the lattice, and the beam sizes measured at the fifth wire suggest that the vertical wire and the horizontal wire in the wire scanner may have been swapped. In the measurement, beam current was reduced to approximately 15-mA to reduce space charge, and the emittance growth could not be a significant issue.

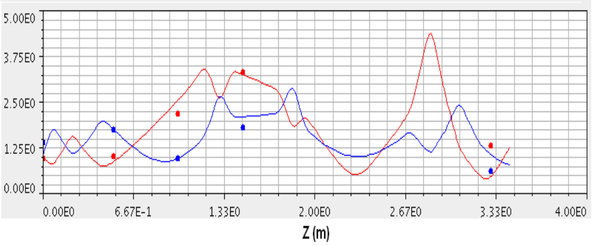

Fig. 1. XAL model and measurement at the MEBT.

A python script was developed to use the same XAL optimizer [5] and fit the WS data using an IMPACT model. The beam Twiss parameters solved were different from those in XAL, and the beam size measurements at the 5th wire had better agreement as shown in Fig. 2.

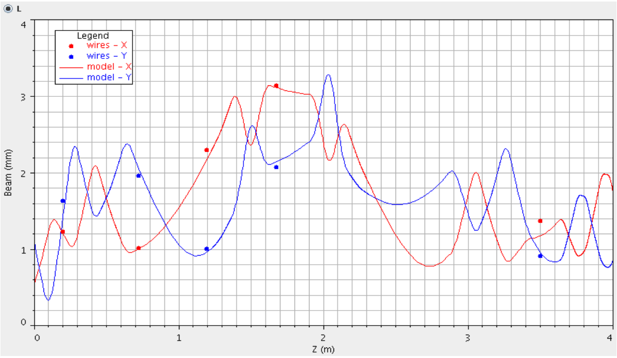

Fig. 2. IMPACT model and measurement at the MEBT.

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The second measurement was performed with laser wire beam profile monitors (LWs) [6] at the SCL. The first six LWs (at 5 to 100-m) were used to fit for the model, and the 7th wire (at 230-m) was used to verify. Figure 3 shows the LWs measurements against the SCL design lattice. There are some beam mismatches in the design lattice because it comes from an optimization for beam beta functions with XAL. Note also that the SCL injection beam is quite different from the design since we did not perform beam matching in the upstream linac. Figure 4 shows the optimized results with IMPACT, and the agreement at the 7th laser wire is very good. Normalized transverse beam emittance both in the horizontal plane and the vertical plane, was approximately 0.36-mm*mrad - in agreement with WS measurements at the HEBT, and at the CCL.

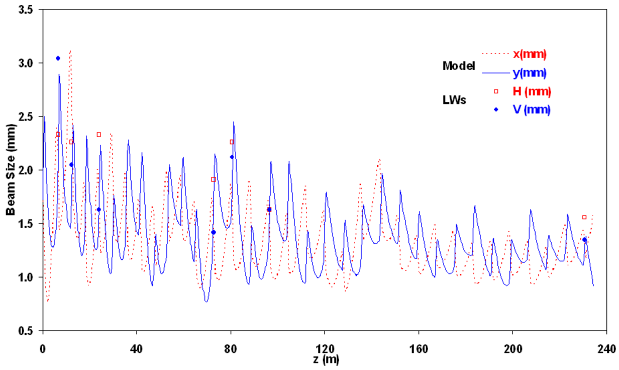

Fig. 3. SCL design beam and the LWs measurements.

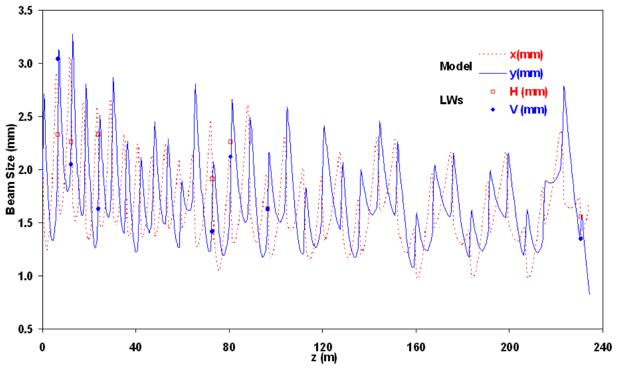

Fig. 4. IMPACT model and the LWs measurements.

SCL transverse beam mismatches are much worse in the measurements than in the design, and transverse matching through the entire linac systems is necessary to correct the problem. But we do not have a good model to do the job, as was mentioned earlier; beam matching through the linac with the XAL might not be sufficiently accurate. But even if the accuracy can be satisfied, it is not practical currently to match beams with the IMPACT model at the SNS linac systems: an attempt to match one piece of the linac requires one or two weeks in our cluster, and it is not a sound practice to set linac quads according to WS data taken two weeks earlier. A few iterations usually are necessary for such tasks because of errors in the model and changes in the actual equipment, and only a computer code with a speed comparable to XAL could be applied practically.

LONGITUDINAL EMITTANCE

Recently, longitudinal emittance measurement became available at the SCL entrance by beam phase and energy scans with beam current monitor (BCM) measurement [7]. In a single experiment, the measured beam bunch size, beam energy spread and longitudinal RMS beam emittance are usually highly repeatable. Figure 5 shows an IMPACT simulation of the longitudinal beam profiles at the second SCL cavity, through the normal conducting linac. The nominal design linac lattice and all the injection beam parameters use the design, except that the longitudinal emittance is two times the design value. Figure 6 shows that of the beam measurement, RMS emittance in this measurement is approximately 3.0-deg*MeV.

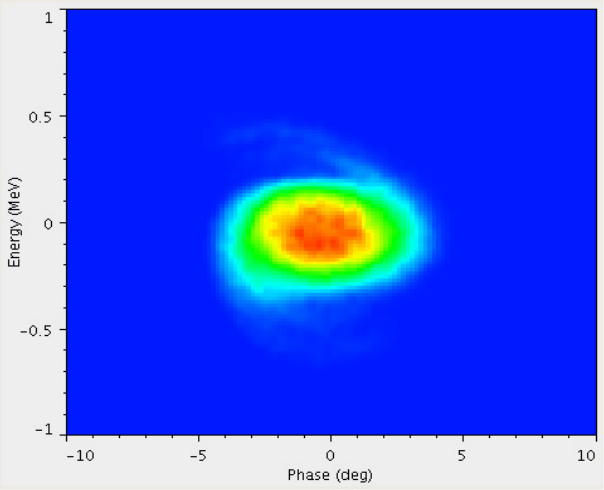

Fig. 5. IMPACT predicted profiles at the SCL entrance.

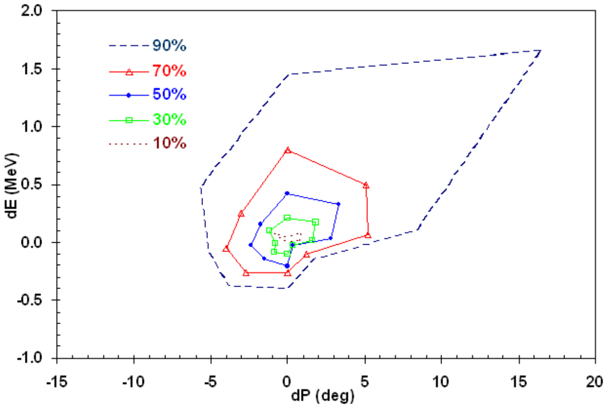

Fig. 6. Measured beam profiles at the SCL entrance.

In simulations with IMPACT, when the DTL6 phase is shifted by 6°, significant longitudinal mismatches and space charge effects in the CCL will cause a longitudinal beam emittance increase of approximately 30%. Figure 7 shows the simulation result with the DTL6 phase shifted by 6°. We shifted the DTL6 phase by the same amount in the equipment, and measured the beam longitudinal profiles at the SCL, as shown in Fig. 8. Beam RMS emittance in this measurement is approximately 4.5-deg*MeV, about a 50% increase from the emittance in the nominal linac. Considering that the error in the measurement method is approximately 20%, the injection beam parameters are not necessarily the nominal design values, and the linac may not be tuned exactly to the design without any error, the agreement between the IMPACT prediction and the RMS emittance measurement is satisfactory.

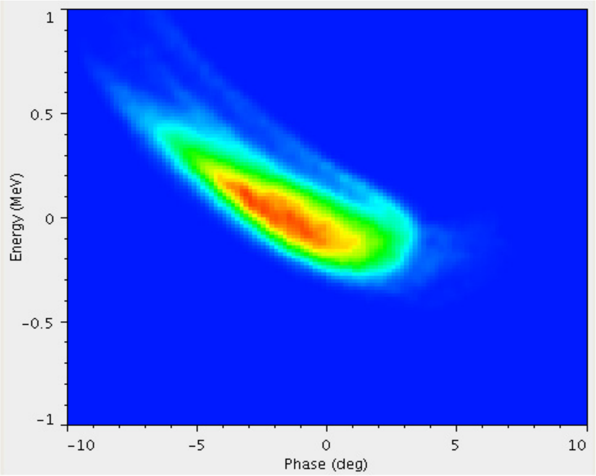

Fig. 7. IMPACT model of DTL6 phase shifted by 6°.

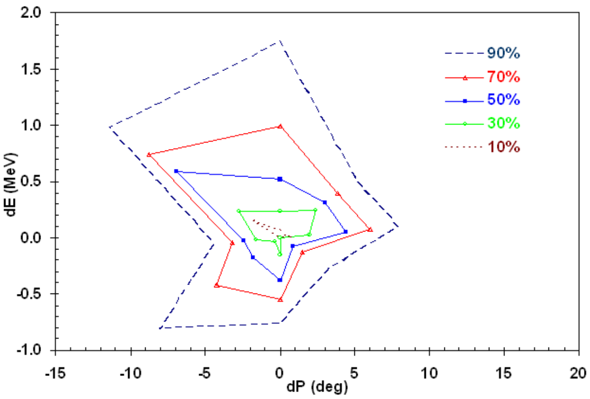

Fig. 8. Measured beam profile for DTL6 phase shifted.

BEAM HALO AND BEAM LOSS

The performances of beam core computations using IMPACT in the longitudinal space and in the transverse planes could be satisfactory, as having been discussed previously. Other issues include beam halo and beam loss, which are difficult to simulate accurately for the space charge forces with beams in other RF buckets and the large amount of macro particles involved. Because unexpected beam loss and activation in the SCL occurs in neutron production, this topic becomes more and more important as the beam power ramps up. In IMPACT simulations, moderate lattice errors including 2% quad errors, 2% RF cavity gradient and 2° phase errors could cause an emittance increase in the linac that is significant, but not sufficient to cause SCL beam loss with the design injection beam parameters.

Transverse halo\tails in the injection beams are usually cleaned up in the normal conducting linac which has an aperture of 2~3-cm. No beam loss is expected in the SCL as it has an aperture of approximately 8-cm, which is different from the longitudinal beam halo\tails. In the simulations with IMPACT and in beam measurements, longitudinal tails caused beam loss in the SCL. Figure 9 shows simulated beam loss in the linac with RFQ beam tails for three different lattices: large RF error (RF error), nominal design (No error) and ~10% gradient decrease for all the re-bunchers in the MEBT (MEBT RBs). Pursuing the design features, and a fine tuning of the linac could mitigate beam loss.

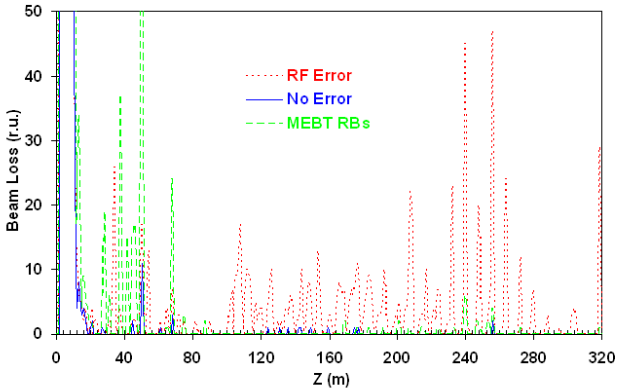

Fig. 9. RFQ beam halo loss in the linac in simulation.

The hottest beam activation spot in the entire linac is between cryomodules 2 and 3 (CM2-CM3); it is caused by beam tails at the CCL entrance. Figure 10 shows the beam loss measurement when the CCL1 phase is shifted by 100° to simulate those off energy particles. Beam loss peaked at CM2-CM3, and no beam loss was measurable in the nc. linac for the 10-nC beams. Figure 11 shows that in the simulation with IMPACT for the same case, beam loss in CM2-CM3 has a pattern very similar to that in the measurement. However, more beam is lost in the CCL, so obviously the simulation differs from the measurement. Is there something wrong in the simulation?

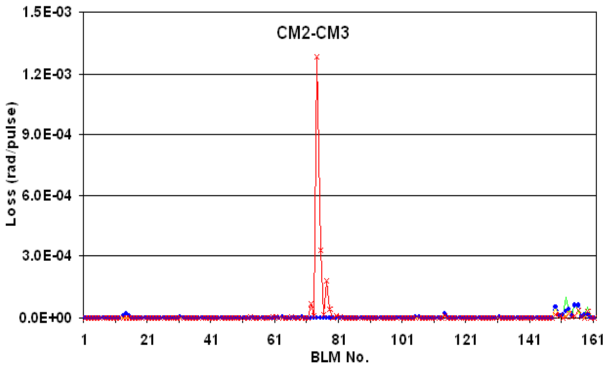

Fig. 10. Measured DTL phase tail loss in the linac.

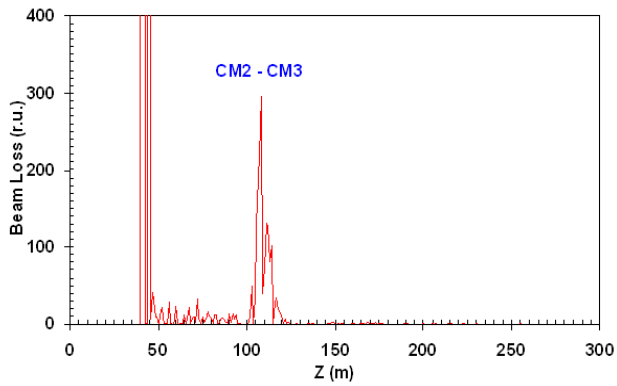

Fig. 11. Simulated DTL phase tail loss in the linac.

It is known that BLMs in the normal conducting linac are much less sensitive to beam loss events than are the SCL BLMs. In the measurements, we dumped 10-nC beams to the CCL with the DTL4 phase shifted by 100°, see results in Fig. 12 (DTL4). The figure shows some CCL BLM response with this small amount of beam, but compared with the background, it is barely above the BLM noise. We might conclude that BLMs in the CCL are not as sensitive to the amount of beam used in the study and assume there is no problem with the simulation. Because we are reluctant to risk the cryomodules by dumping more beam charge in the measurements, a concrete conclusion requires a beam current measurement at the SCL entrance. Unfortunately, that will not be done this year.

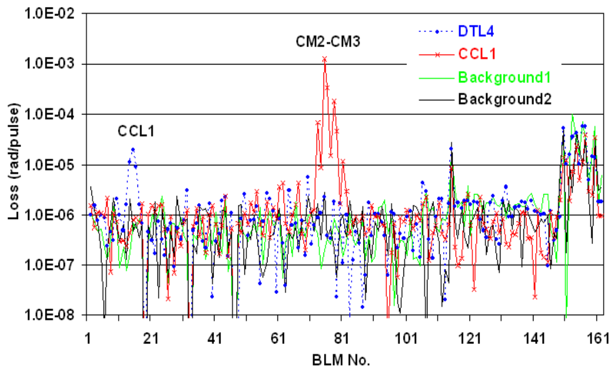

Fig. 12. Measured beam tail loss in CCL and in SCL.

CONCLUSION

Beam dynamics studies of the SNS linac systems were performed with IMPACT simulations and measurement of beam core including RMS beam size, transverse Twiss parameters, and longitudinal emittance are in good agreement with the simulation results. Both simulation and measurement show that longitudinal beam halo\tails caused beam loss in the SCL, but further beam studies are necessary for this important topic.

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