BEAM TRANSVERSE ISSUES AT THE SNS LINAC *

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Abstract

The Spallation Neutron Source (SNS) linac system is designed to deliver 1 GeV pulsed H^- beams up to 1.56 MW. As beam power was increased from 10 kW to 830 kW in less than three years, beam loss in the accelerator systems – particularly in the superconducting linac (SCL), became more critical. In the previous studies, beam loss in the SCL was mainly attributed to longitudinal problems. However, our most recent simulations have focused on the transverse issues. These include multipole components from magnet imperfections and from dipole corrector windings of the SNS linac quadrupoles. The effects of these multipoles coupled with other transverse errors as a new possible cause of beam loss will be discussed.

INTRODUCTION

The Spallation Neutron Source (SNS) is a short-pulse neutron scattering facility. The accelerator complex consists of a 2.5 MeV H^- injector with a peak beam current of 38 mA, a 1 GeV linac, a 248 m accumulator ring and beam transport lines. The superconducting linac is approximately 160 m long; it includes 81 independently phased 6-cell niobium cavities and provides acceleration for H^- beams from 186 MeV out of a normal conducting linac to 1 GeV [1]. From October 2006 to April 2009, beam power was ramped up from 10 kW to 830 kW, and beam loss became more crucial as the power ramped up. Beam loss and residual activations may impact hands-on maintenance and reduce availability of the accelerator complex. In the SCL, beam loss above 1 W/m may also severely interrupt the normal operation.

Beam loss in the SCL is approximately 2×10^{-4}, while the design expected is no more than 1×10^{-5}. In the previous studies, the SCL beam loss was mainly attributed to longitudinal beam halo and the SCL limited acceptance [2]. But after several beam experiments with significantly increased SCL acceptances failed to reduce the beam loss, we have focused on other issues. All the previous studies did not suggest any possible transverse cause of beam loss in the SCL, especially since the beam pipe has an aperture of 8 cm, much larger than the 2 or 3 cm of the upstream normal conducting linac. However, we recently analyzed multipole components in the linac quadrupoles, and found out that under certain conditions, these tiny components can cause significant beam loss in the SCL.

DODECAPOLE AND 60° RESONANCE

The multipole components of all the linac quadrupoles were measured with rotating coils. In the measurements, the effects of additional dipole corrector windings are also measured. The results are listed in Table 1. Dodecapole components (m=6) of the quadrupoles are 30 to 60 units; in a ring magnet, it is generally less than 10. Sextupole components (m=3) are approximately 300 units (sum of normal and skew terms) from the dipole corrector.

Tabl e 1: Multipole Components of the Linac Quads

Multipole (units: 1×10^{-4})	m = 6	m = 3	m = 3 From dipole
CCL	38.0 (0.1)*	3.7 (2.9)*	N\A
SCL	28.9 (4.2)*	-6.9 (-1.3)*	193.5 (207.9)*

* Skew term

The effects of the multipole fields are simulated with ORBIT [3] for the SCL dummy sections where no RF cavity exists and the effects of space charges ignored. In the simulations large sextupole components do contribute to the growth of beam tails, however, not enough to cause significant SCL beam loss. This result follows from the fact that the sextupole strength is proportional to the dipole strength and, in the routine operations, dipole corrector strengths are minimal. However, the dodecapole contributions are different because of their extremely non-linear properties. In one transversely mismatched case, the maximum emittance is increased by 5 times, although the beam rms emittance remains the same. This case is shown in Fig.1, along with a matched case where the maximum beam emittance is preserved, because in the simulations, the two quadrupoles in a doublet are identical, so that in the matched case, dodecapoles of the two quadrupoles may cancel each other.

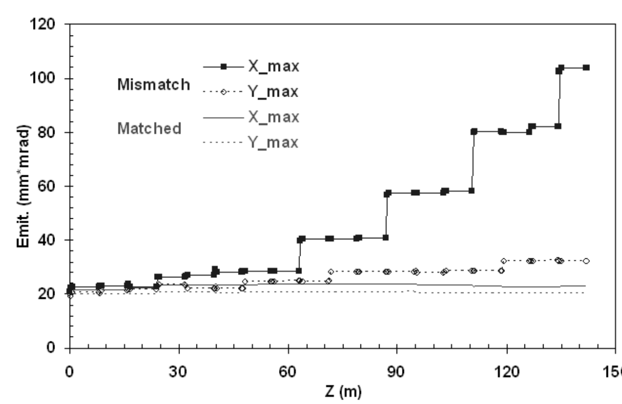

Figure 1: The maximum beam emittance in a mismatched and in a matched case, affected by the multipole components.

In simulations, when the dodecapole is reduced from 30 to 10 units in the mismatched case, the maximum beam emittance can be preserved. Therefore, we may conclude that multipole components in the SNS linac quadrupoles are too large; they had not been considered seriously in

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the design. Further simulation studies show that even in the mismatched case, we can still preserve the maximum beam emittance by reducing the doublet-lattice phase-advance from the design of 60° to approximately 50°. We realized that there is a 60° weak resonance in the linac, and we call the resonance a weak one because it appears only when contributions of dodecapoles are significant. In a real linac, multipoles of each quadrupole also depend on assembly, can be much worse and different, and beams may not be perfectly matched. Thus, the 60° resonance could become a beam loss problem for the SNS linac.

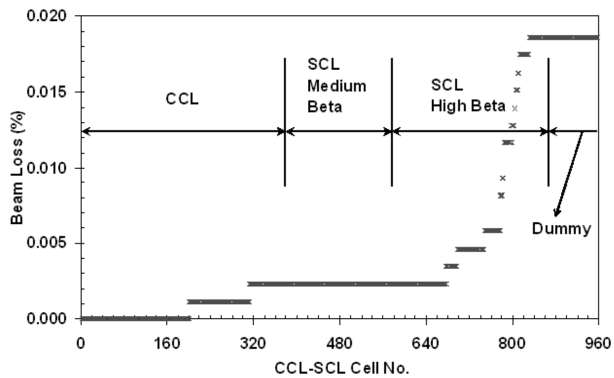

Fig 2: Beam loss in the SNS linac due to the dodecapoles.

In the simulations with PARMILA [4], for the nominal design beams without any artificial halo, and the baseline design lattice without any error or misalignment, the contributions of the dodecapoles in an extreme case may cause beam loss in the SCL, as shown in the Fig.2. In this extreme case, dodecapoles of neighboring quadrupoles in a doublet add rather than cancel one another. There is very little possibility that the linac quadrupoles installed in the tunnel are all so unfavorable, but it is known that halo and mismatches exist, along with misalignments and errors of the components. Therefore, it is possible that $1\sim2\times10^{-4}$ beam loss in the SCL is caused by dodecapoles. Likewise in PARMILA simulations, reducing dodecapole components from 30 to 10 units eliminates the beam loss.

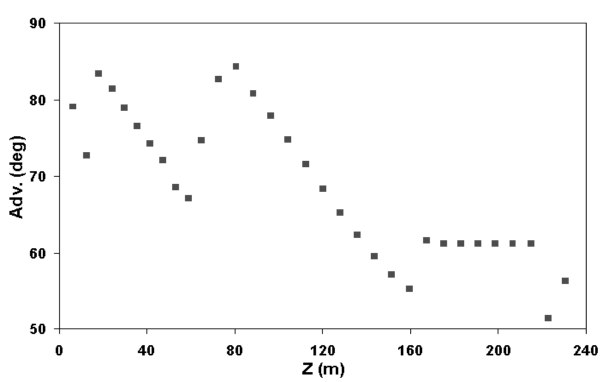

Figure 3: Phase advance of the SCL baseline lattice.

Because dodecapoles of the CCL quadrupoles are larger than that of the SCL quadrupoles, and the CCL has a smaller beam aperture (3 cm) than the SCL (8cm), we expect beam loss to be more serious in the CCL. But the simulation does not show this, presumably because of the 60° resonance in the SCL lattice. Fig.3 shows zero current phase advances in the SCL baseline lattice, most cells are 60° or above; while Fig.4 shows those of the CCL, half of the lattice is below 60°. In the SCL, dodecapoles could kick particles in almost the same directions, but in the CCL, the situation is different - most kicks are random.

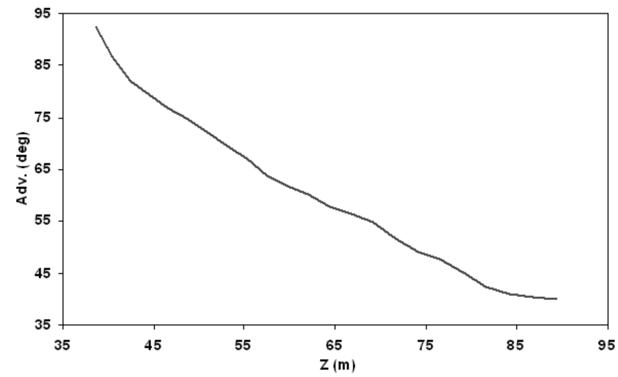

Figure 4: Phase advance of the CCL design lattice.

In experiments, beam losses in the SCL, particularly in the second half decreased by 50% when the quadrupoles strength was reduced. Fig.5 shows beam losses measured with all the SCL beam loss monitors. Fig.6 shows the zero current phase advances for the nominal case and for the case of reduced quadrupole strengths. The loss reduction could be an evidence of the 60° resonance, but it could also be explained as better transport of low energy tails through the reduced quadrupole strengths.

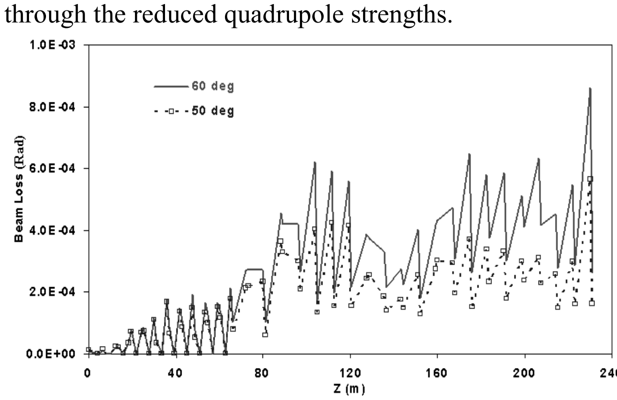

Fig. 5: Loss decreased with reduced quadrupole strengths.

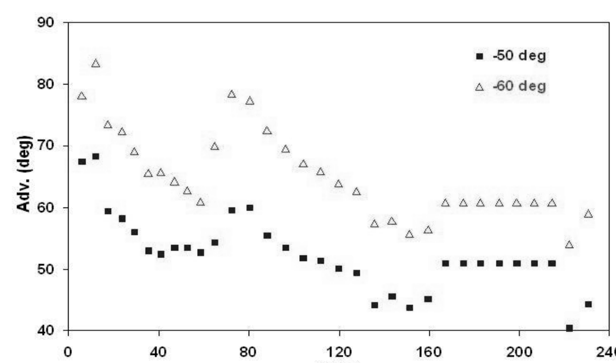

Fig. 6: SCL phase advances for nominal and reduced quads.

Beam studies are necessary for reducing quadrupole strength and phase advance of the SNS superconducting linac to avoid the 60° resonance. Because of non-linear RF defocusing of SC cavities, zero-current phase advance required in the SCL could between 40° and 50°. And phase advance is also affected by space charge effects and the depressed phase (coherent) may drop to between 20 and 30°, some beam particles might be close to the unstable zones of the lattice. It is still very difficult to accurately model beam loss at an order of 10^{-5} to 10^{-4}.

MATCHING WITH SHORT QUADS

Short quadrupoles – where length is comparable to aperture – have been studied for many decades, but the topic often requires renewed analysis [5, 6]. All the SNS linac quadrupoles belong to the category of short quads. Consequently, the focal length of the hard-edged model is different than that of the actual quadrupole when correctly considering the fringe fields. Typical parameters of the SNS linac quadrupoles are listed in table 2, and the errors of focal length are significant in the Medium Energy Beam Transport (MEBT) – up to approximately 3%.

Table 2: SNS Linac Quads Parameter and Focal Error

T (MeV)	Q_L (m)	Q_R (m)	G (T/m)	f (m)	df (%)
2.5	0.061	0.016	36	0.104	2.01
2.5	0.066	0.021	26	0.133	2.51
87	0.06075	0.0175	42	0.541	0.47
87	0.09769	0.0177	26	0.543	0.30
186	0.104	0.024	18	1.104	0.25
186	0.38	0.04	5	1.088	0.19
1000	0.505	0.1238	4	2.802	0.54

Fig.7 shows simulated zero-current beta functions in the MEBT, from the hard-edged quadrupoles and from the short quadrupoles with fringe fields, both cases using a linear map. The differences of beta functions caused by the 2~3% focal errors of the two quads models appears insignificant in the figure. However, after we investigate the matter more carefully, and calculate the relative errors of beta functions in the MEBT, as shown in Fig.8, the effects are not negligible.

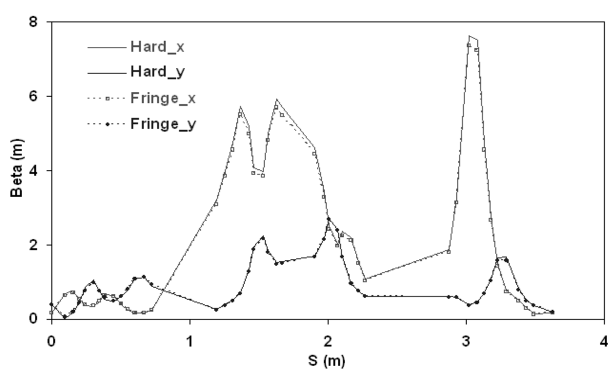

Figure 7: MEBT beta functions with different quads models.

In Fig.8, most beta function errors in the MEBT are no more than 10%; but the maximum error (25%) occurs near the first wire scanner location. This finding could explain the reason that we did not have a correct beam model built for transverse matching from beam profile measurements using the MEBT wire scanners. Moreover, at here, no field interference between adjacent quadrupole is considered, another major difference between an over-simplified model and the complex real world. In MEBT, distances between two quadrupoles are comparable to the apertures, and strong interferences exist. The effects may not only change the effective length of the quadrupole, but also alter the equivalent magnet center. This is a more serious problem to the standard quadrupole model [7].

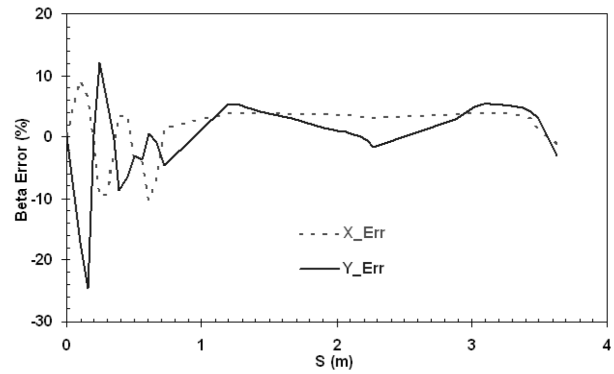

Figure 8: MEBT beta function errors with different models.

CONCLUSIONS

The ultimate goal of > 90% availability and > 1 MW beam power is a great challenge to the SNS accelerator complex. However, it offers us a unique chance to study more about beam loss and residual activation in the accelerator systems. We have successfully ramped up beam power in the past 3 years, while investigating different mechanisms of beam loss in the linac. Because the loss level of 10^{-5} to 10^{-4} is imperceptible - beyond any accurate computer model or direct measurement, some effects which could often be ignored at other systems must be studied with great care at SNS, such as the weak 60° resonance, fringe fields of short quadrupoles, and many other issues which are not covered in this paper.

ACKNOWLEDGEMENTS

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