# TRANSVERSE MATCHING PROGRESS OF THE SNS SUPERCONDUCTING LINAC*

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*Abstract*

Experience using laser-wire beam profile measurement to perform transverse beam matching in the SNS superconducting linac is discussed. As the SNS beam power is ramped up to 1 MW, transverse beam matching becomes a concern to control beam loss and residual activation in the linac. In our experiments, however, beam loss is not very sensitive to the matching condition. In addition, we have encountered difficulties in performing a satisfactory transverse matching with the envelope model currently available in the XAL software framework. Offline data analysis from multi-particle tracking simulation shows that the accuracy of the current online model may not be sufficient for modeling the SC linac.

## INTRODUCTION

The Spallation Neutron Source (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 SNS linac has a normal conducting front end approximately 100-m long that includes a medium energy beam transport (MEBT) line, six drift tube linac (DTL) cavities and four coupled cavity linac (CCL) tanks for beam energy of up to 186 MeV, and a superconducting linac (SCL) 160-m long that consists of 81 independently powered 6-cell niobium cavities installed in 23 cryomodules, with a design output beam power of 1.56 MW [1].

Because of the high beam intensity and the SRF technology, no beam intercepting diagnostic device is allowed in the SCL. Laser wire (LW) beam profile monitors are used for transverse profile measurements and for performing beam matching. For more details about the nine LW monitors installed in the SCL see reference [2]. The usual matching process include LW measurements first, and then fits to the measured beam size with an envelope model in the XAL [3], which is applied online in the control room. For offline analysis, we use the multi-particle tracking code IMPACT [4]. Currently, the later is still not appropriate for online application because of lengthy computational times, but it has been proved to be a very helpful tool to analyze the SNS linac [5].

Beam matching in the SNS linac with the online model has not been a success thus far. Fortunately, beam loss in the linac system is not very sensitive to the beam matching condition: even without a good transverse match, we are able to control the SCL beam loss to a tolerably low level ($10^{-5}$ to $10^{-4}$) for 1 MW neutron production, thanks to a very robust linac design. A lot of efforts have been taken to address potential problems with laser wire measurements since it is a relatively new diagnostic device. However, offline analysis with multi-particle tracking simulation shows that a major issue is the model itself. We previously attributed all the problems of the model to nonlinear issues such as emittance growth, chromatic aberrations, etc, but ignored errors associated with basic linear optics, which are more important.

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## FIRST MATCHING ATTEMPT

Based on the linear envelop model, we performed beam transverse matching with laser wire measurements in 2008. The effort failed: instead of reducing the beam size beating in the SCL, it actually made both the horizontal and vertical planes worse. Figure 1 shows the laser wire measurements and the beam model obtained by a fitting those measurements, before any matching was done. Figure 2 shows the same plot after the matching.

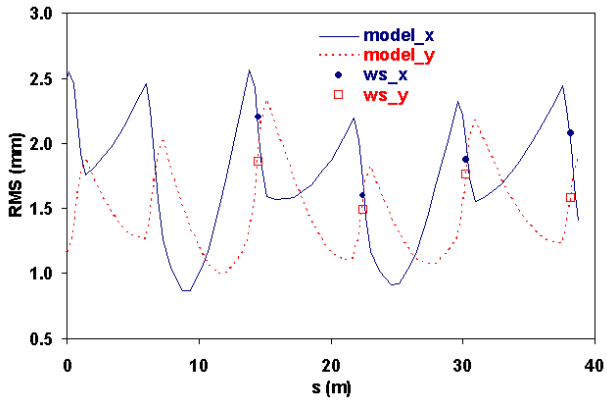


Figure 1: LW measurements (markers) and envelope model (lines) before a transverse matching in the SCL.

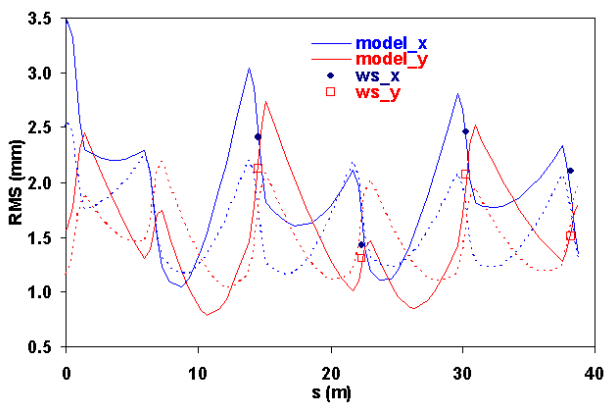


Figure 2: After transverse matching, the beam size beating in both horizontal and vertical planes is worse (solid lines) than the model predicted (dashed lines).

In addition to the poor matching obtained, according to the online model, we also noticed that model-fitted initial Twiss parameters in the SCL had changed before and after the beam matching; if they had remained the same, we should have observed a much improved matching according to the model predictions (dashed lines, in Fig. 2). We do not understand the exact reason for the large change. Since the same model software works in the high energy beam transport (HEBT) and the ring target beam transport (RTBT) lines with conventional wire scanners, the failure of this SCL matching attempt was initially wrongly assumed to be due to errors of the laser wire measurements.

Extensive laser wire measurements were subsequently performed, and they showed that the laser wires actually produce very precise beam size measurements (within about 5%). Additionally, in most measurements, the SCL injection beams are usually quite stable – except the first 20 μs of the beam pulse, which may vary by several tens of percent from pulse to pulse due to the ion source transient and the linac low-level RF feed forward learning. This portion of the beam pulse should be avoided for transverse matching or beam profile comparison purposes.

## USING DIFFERENT MODELS

We performed several SCL transverse beam matching attempts with the online model then, and the results are scattered randomly: after transverse matching, sometimes it improves beam matching in the horizontal plane but deteriorates it in the vertical plane, while at other times the opposite is true. It is noted that the online model works in the HEBT and RTBT, where no RF cavities exists, nor significant space-charge effects. However, in other sections of the linac which contain RF acceleration and significant space-charge effects, the performance has not been a satisfactory, even with conventional wire scanners. We tested the same beam size fitting technique using the multi-particle tracking simulation model, IMPACT, during offline analysis, and it proved that the major problem with the SCL beam matching is indeed the model.

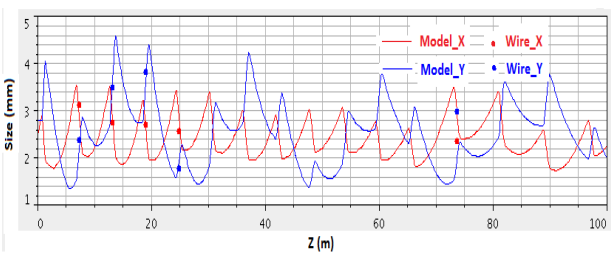


Figure 3: Fitted initial beam Twiss parameters with the online model: x and y swap against the 5th LW measurements.

Figure 3 shows a typical beam Twiss parameter fit performed with the online model: The beam sizes at the first 4 LWs (markers) were fit, and the fit (lines) was checked against the 5th LW measurements (at Z ~74 m). The fit clearly does not agree with the measurements, since the two planes, horizontal – x, and vertical – y, are swapped. Using the same techniques with IMPACT instead, the beam size measurements in both planes agree closely with the multi-particle tracking simulation model, as shown in Fig. 4.

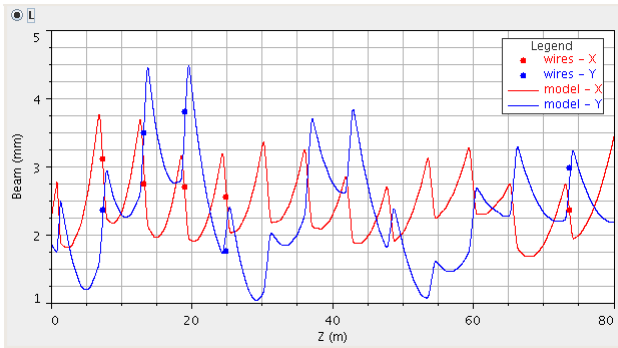


Figure 4: Fit injection beam Twiss parameters with IMPACT: both planes agree closely with beam size measurements.

Disagreements between the online model and IMPACT have been known to us for a long time. Some suspected that IMPACT might be wrong, because the online model is essentially converted from TRACE3D [6], while the latter agrees with PARMILA [7]; others were concerned that there are several high-order, nonlinear terms, such as: beam emittance growth from space-charge, chromatic aberrations of the linac quadrupoles, RF acceleration nonlinearities, etc, which might be significant in the superconducting linac. Very recently, bugs in the online model for both RF acceleration and space-charge were found and fixed [8].

It is possible to perform transverse beam matching based on laser wire beam profile measurements using the online model before the bugs were fixed, or even without using any linac model at all. However, the process is very time consuming, and it also requires some luck. Figure 5 shows a SCL beam matching with the online model before the bugs been fixed, and in this case, the targeted Twiss parameters were from IMPACT instead. However, we now know that it was merely a coincidence.

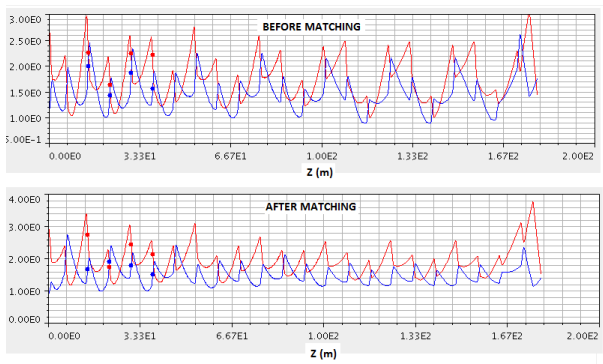


Figure 5: Before and after the SCL beam matching using the online model before the bug fixes. Both planes could be improved.

Before the bugs in the online model were fixed, errors in the initial beam Twiss parameter fits were on the order of 50%, which could explain the reasons for our previous failures in the SCL beam matching. But even after the fix, the errors remain as high as 30%, and one still can not expect sufficient accuracy. As a comparison, IMPACT often shows an uncertainty less than 10%. But even today, we still could not use IMPACT for this kind of online application, unless a supercomputer could be dedicated to the linac online beam matching, as it requires a multi-particle tracking simulation for several ten hours with PC. Or, we need to wait for Moore's law to be continued for a few more years.

There are two other potential solutions: 1) first, extract the linear transfer maps of the SCL lattices using multi-particle tracking simulation models, such as IMPACT, and then apply the beam transverse matching technique based on these more accurate matrices which are derived directly from particle tracking, or 2) add several basic linear optics terms which are missing in the online model, such as: fringe fields of RF cavities [9] and fringe fields of short quadrupoles, a more robust model than the current thin-lens approximation of the SRF cavities, and additional high-order, nonlinear components which are significant, until the envelope model becomes accurate enough. Both of the two solutions require very extensive model analysis, in addition to a lot of beam study time. But beam study time is limited due to the requirement of more than 90% availability for neutron production. While for the model analysis, a question arises: Is it worth? Time consuming transverse beam matching in the SNS linac system offers almost no impact on beam loss, while a low loss is the primary goal – if not the only goal - of the SNS linac beam optics study.

## MATCHING VERSUS BEAM LOSS

As previously mentioned, beam loss in the SNS linac, particularly in the SCL, is not sensitive to beam transverse matching. For example, in the case of SCL beam matching as shown in Fig. 5, there is almost no noticeable beam loss difference before and after matching. And because of the model issues, perhaps we have never achieved a very good beam matching through the entire linac system, which is unfortunate. In the past several years of neutron production and beam optics study, the beam matching condition in the SCL and in other sections of the linac have varied greatly, but we do not observe any significant loss reduction even for the best matching condition. On the contrary, sometimes, the opposite is true.

Figure 6 shows the SCL beam matching for a neutron production run at relatively lower power, approximately 180 kW, compared with Fig. 4 which is for high power, 1 MW. The SCL beam is much better matched as most of the linac quadrupoles are close to the design. But for high power production, because the linac beam loss becomes more critical, a lot of quadrupoles have to be manually adjusted away from the design to achieve a minimum beam loss. The total fractional SCL beam loss in the better matching case, as shown in Fig. 6, is much larger – by about a factor of two that of the worse matching case as shown in Fig. 4. However, loss reduction in the case of worse transverse matching might have nothing to do with the transverse matching itself. Because in this case, all the quadrupole strengths and transverse phase advance of the SCL lattice are reduced by 20% [10]. Even for the same quadrupole strength and transverse phase advance, we do not have a clear picture of the relationships between the observed beam matching and the SCL beam loss.

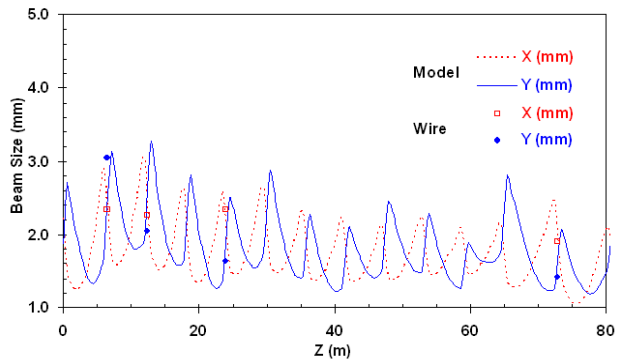


Figure 6: Beam matching of the SCL for 180kW production.

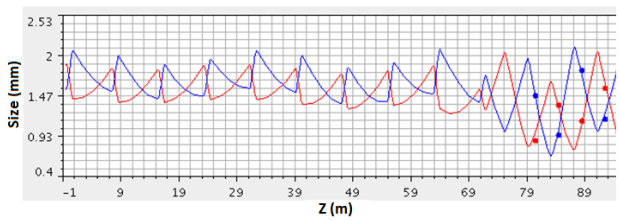


Figure 7: SCL beam matching before beam loss reduction.

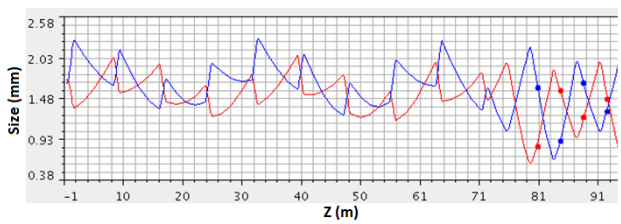


Figure 8: SCL beam matching after beam loss reduction.

Usually, beam matching in the SCL is not great, as the injected beam may not be exactly the same as the design. But occasionally, we can start from a well-matched linac with the initial design lattice, as shown in Fig. 7. For production tuning to reduce beam loss in the linac and in the downstream beam transport lines, several upstream linac quadrupoles have to be adjusted manually. After the loss reduction, we may end up with a mismatched linac lattice, as shown in Fig. 8. Should we conclude that a worse transverse matching in the SCL is preferable for beam loss reduction? Certainly not, because at other times, we do observe that a smooth linac lattice and improved matching reduce beam loss, though the loss reduction is not dramatic.

In the SCL, beam matching and beam loss are likely tied to two different aspects of the beam: one relates to the beam core only, requires manipulation of beam size,

while the other solely concerns a halo of $10^{-5}$ to $10^{-4}$ of the beam particles, which has a much greater impact on the beam loss.

We still consider that it an important task to improve transverse beam matching in the SNS linac. First, a fully matched beam through the entire linac, which we have never achieved before, might make a greater difference than what we have observed from better matching conditions in merely a few short sections of the linac. Second, improve matching may reduce beam halo generation from the superconducting linac itself, and reduce beam loss and residual activation at downstream accelerator subsystems, such as the ring injection area. Third, a better matched beam through the entire linac system may serve as a good start point, and could make the beam loss reduction task much easier. Last but not least, for the SNS power upgrade project, the total length of the superconducting linac and the beam intensity will increase significantly, and in this case, beam matching could become necessary.

## SUMMARY

Laser wire beam profile monitors have become an important diagnostic device in the SNS superconducting linac, used during both routine neutron production as well as during accelerator beam dynamics studies. We have encountered problems using the online model to perform a satisfactory transverse matching based on laser wire profile measurements, and a major obstacle is the accuracy of the model currently available in the control room. The beam loss is not very sensitive to the matching condition and is controlled more effectively by manual adjustments of the linac optics with sensitive beam loss monitors. Thus it is not critical to perform transverse matching in this SC linac for beam loss reduction purposes. But a more accurate linac model which could be applied online in the control room is still necessary in order to achieve matching success.

## ACKNOWLEDGEMENT

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