MODEL BENCHMARK WITH EXPERIMENT AT THE SNS LINAC

A. Shishlo[†], A. Aleksandrov, Y. Liu, M. Plum, ORNL, Oak Ridge, TN 37831, USA

Abstract

The history of attempts to perform a transverse matching in the Spallation Neutron Source (SNS) superconducting linac (SCL) is discussed. The SCL has 9 laser wire (LW) stations to perform non-destructive measurements of the transverse beam profiles. Any matching starts with the measurement of the initial Twiss parameters, which in the SNS case was done by using the first four LW stations at the beginning of the superconducting linac. For years the consistency between data from all LW stations could not be achieved. This problem was resolved only after significant improvements in accuracy of the phase scans of the SCL cavities, more precise analysis of all available scan data, better optics planning, and the initial longitudinal Twiss parameter measurements. The presented paper discusses in detail these developed procedures.

INTRODUCTION

The SNS SCL is the world's first of the kind high power hadron superconducting linac. It accelerates H[-] ions from 186 MeV to 1 GeV with 81 six-cell niobium elliptical superconducting RF cavities [1]. There are two types of superconducting cavities in SNS: the first is optimized for relativistic beta of 0.61 (medium beta subsection), and the second is optimized for beta of 0.81 (high beta). The cavities are enclosed in 23 cryomodules with inside temperatures of 2 K. There are 3 and 4 cavities per module for the medium and high beta sections respectively. Between modules there are doublets of quadrupoles to provide the transverse focusing.

Commissioning of the superconducting linac started in July 2005, and in 2009 SNS reached 1 MW beam power. During the power ramp up, an unexpected beam loss in the SCL was encountered. Eventually, this beam loss was reduced to the acceptable level by empirically lowering the field gradients of the SCL quadrupoles without understanding the loss mechanism. That led to efforts by the accelerator physics group to understand and to control the beam sizes in the SNS superconducting linac. Later the mechanism of the unexpected beam loss was identified as the Intra Beam Stripping (IBSt) process [2,3]. This explained our success in the loss reduction, but it did not give us the model-based control over the beam sizes in the SCL. This paper describes our path in developing such a model-based SCL optics control.

In the present paper we are going to describe three basic components that allowed us to successfully benchmark the model against the measured SCL beam parameters. First, we developed a procedure to measure the initial transverse Twiss parameters with acceptable accuracy. Second, we speeded up the SCL RF cavity tuning process and improved the accuracy of the phase scan data analy-

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† shishlo@ornl.gov

sis. Finally, we developed an original method of measuring the longitudinal Twiss parameters based on the Beam Position Monitor signals.

SNS SCL DIAGNOSTICS

In contrast to normal conducting linacs, the SNS superconducting linac is not allowed to have insertable destructive beam diagnostic devices to avoid surface contamination of the SCL cavities. Instead of wire scanners the SCL has 9 laser wire (LW) profile monitors [4]. As shown in Fig. 1, four of them are placed at the beginning of each of two (medium and high beta) sections, and the last one is at the end of SCL.
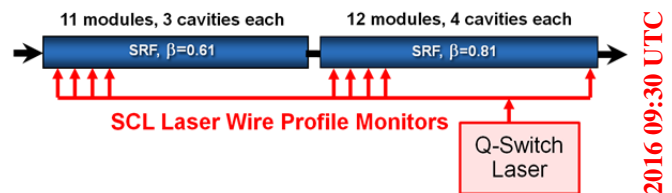

Figure 1: Positions of the 9 laser wire stations in the SNS SCL.

The LW system distributes the laser beam to intercept the H[-] ion beam, which removes the second electron. This creates neutral hydrogen, which will be eventually lost inside the SCL. The photo-detached electrons are collected, and their total charge is measured [4]. This signal is proportional to the density of the ion beam. By using a system of mirrors the laser beam can be moved in vertical and horizontal directions providing the ion beam profiles in both planes. The amount of beam loss created by the LW system is negligible, and it can be used even during 1 MW operations.

In addition to the LW system, the SCL has 32 stripline beam position monitors (BPMs) installed along the linac between cryomodules and in the cavity-free part of SCL. The BPMs measure the transverse positions of the beam, the arrival phases of the H[-] bunches, and the amplitudes of the 402.5 MHz harmonics (the bunch frequency) of the sum of all four stripline quadrant signals. This amplitude signal can be used for beam peak current measurements or for a longitudinal Twiss parameter analysis, as will be shown below.

The SNS superconducting linac also has a distributed system of Beam Loss Monitors (BLMs), but we are not going to discuss beam loss related issues in this paper.

BEAM TRACKING MODELS

Several accelerator codes were used for the SCL data analysis. Two codes used in the first SCL transverse matching attempt [5] were a "Particle In Cell" (PIC) code IMPACT [6] and an "envelope" tracking Online Model (OM) from the SNS programming infrastructure XAL [7].

The problem with using the IMPACT code was a long calculation time needed for analysis [6]. It took tens of hours to calculate the initial transverse Twiss parameters from the four first LW profiles. Therefore, IMPACT could be used only for offline analysis, which was difficult to combine with biweekly accelerator physics study time and with conditions in the warm (upstream) part of the linac changing daily to keep beam loss and RF systems tripping rate low.

The Online Model is an envelope tracking accelerator code similar to TRACE3D. The OM tracks the envelope parameters through the SCL lattice using transport matrices for each quadrupole, for each RF gap in the accelerating cavities, and for each drift space. The space charge kicks are accumulated in the total transport matrix describing the transformation of the envelope from the beginning to an arbitrary point in the SCL. The parameters of the lattice, such as the quadrupole field gradients, are synchronized with the control system. The field gradients and phases of the superconducting cavities should be supplied to the model after an analysis of the SCL phase scans.

It takes only a few minutes to analyse LW data at the beginning of the SCL with the Online Model, but for a long time we could not get agreement between this model and the full set of LW data [5]. At that time, the OM was considered to be inappropriate to track beam parameters through the whole SCL. In [5] it was also stated that there is a difference in matching parameters predicted by the IMPACT and the OM codes. Later we found that these differences are caused by parameters of the RF system used by each model. If we use consistent parameters in the models the results will be the same. The Fig. 2 shows the benchmark of the Online Model with the PyORBIT code, which is another PIC code developed at SNS.
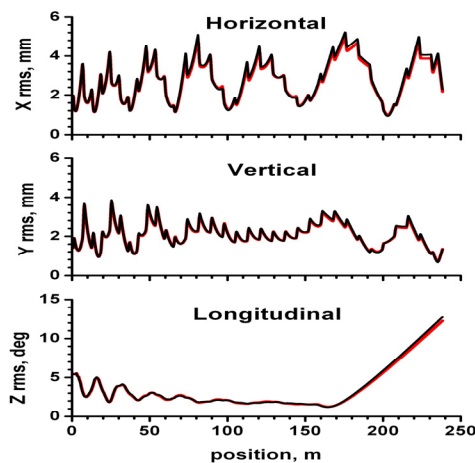

Figure 2: RMS sizes of the beam along the SNS superconducting linac. The black curve is for the PyORBIT code, and the red is for the OpenXAL Online Model.

Because of its nature the OM is more convenient than the PIC based codes for RMS size analysis. Of course we must always be vigilant regarding the linearity of all ele-

ments in the lattice and possible envelope instabilities. Fortunately the SNS SCL is a good example of this type of lattice. All analysis described in this paper was performed by using the OpenXAL Online Model.

TRANSVERSE TWISS PARAMETERS

For PIC codes the initial Twiss parameters are found by using the general non-linear fitting method to reproduce RMS sizes from the multiple profile measurements. To find the Twiss by using the Online Model we use a more direct technique described in [8]. Let's consider one plane. The transformation coordinates of the particle between the beginning of the lattice and the profile measurement device are defined by the transport matrix from OM

$$
\begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = \begin{pmatrix} m_{1,1}^{(1)} & m_{1,2}^{(1)} \\ m_{2,1}^{(1)} & m_{2,2}^{(1)} \end{pmatrix} \cdot \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}
\tag{1}
$$

where x and x' are the transverse coordinates of the particle at the initial and LW position points, and m is the transport matrix between these points.

By squaring of both sides of the first equation of the system (1) and averaging over the whole ensemble of particles in the bunch, we have the expression for the squared RMS beam size

$$
\langle x_1^2 \rangle = m_{1,1}^{(1)\,2} \langle x_0^2 \rangle + 2 m_{1,1}^{(1)} m_{1,2}^{(1)} \langle x_0 x_0' \rangle + m_{2,2}^{(1)\,2} \langle x_0'^2 \rangle
$$

By using several profile monitors or modifying the optics of the lattice we can get as many different transport matrices and equations for the RMS beam sizes as we want (let's say *N*). Combining the all equations we get the following matrix equation for our problem

$$
\begin{bmatrix} \langle x_1^2 \rangle \\ \dots \\ \langle x_N^2 \rangle \end{bmatrix} = \begin{bmatrix} m_{1,1}^{(1)\,2} & 2 m_{1,1}^{(1)} m_{1,2}^{(1)} & m_{2,2}^{(1)\,2} \\ \dots & \dots & \dots \\ m_{1,1}^{(N)\,2} & 2 m_{1,1}^{(N)} m_{1,2}^{(N)} & m_{2,2}^{(N)\,2} \end{bmatrix} \begin{bmatrix} \langle x_0^2 \rangle \\ \langle x_0 x_0' \rangle \\ \langle x_0'^2 \rangle \end{bmatrix}
$$

This is a typical linear Least Square Problem with the measured RMS sizes on the left side and the unknown initial beam correlation parameters on the right side. The solution gives the Twiss parameters and their errors if the RMS size errors are known [8].

The described algorithms should work directly if there is no space-charge force in the bunch dynamics. In the presence of space charge the transport matrices will be dependent on the initial Twiss parameters for the longitudinal and transverse directions, and on the beam peak current. As for the longitudinal Twiss parameters, we can blindly use the design parameters, or we can use methods described in this paper later. For the transverse parameters the transport matrix dependency makes the equations transcendental, and there is no exact analytic solution for them.

To find the initial Twiss parameters in the presence of strong space charge a two-step method was used. In the first step, a general nonlinear fitting package was used to

find the parameters that reproduce the measured profiles with minimal deviations. Then the transport matrices generated by the OM for these initial Twiss parameters were used in the matrix equation to get a new set of these parameters and their error estimation. If these two sets were close enough assuming their errors, we concluded that the problem was solved. This method does not guarantee a unique solution, because the fitting routine can find several local minima. This situation can be resolved by increasing the number of measurements with the lattice configurations providing the reduced errors. These additional measurements should be planned ahead by using the preliminary estimation for the initial Twiss. The rule of thumb from Ref. [8] is a $90^0/(N-1)$ betatron phase advance between each measurement. The exact effect of each additional measurement should be estimated. Unfortunately in general even these measures cannot guarantee a uniqueness of the solution and correctness of the error estimation. However, this should not stop us from trying this approach.

Based on the described algorithm we re-analysed the LW data from our previous measurements in [5] and found that we had bad optics for the Twiss parameter analysis, and errors for the parameters were too big to make them useful for the Online Model. Later we performed a series of measurements with different optics settings for the first four LW stations in the SCL. To be confident we eliminated the space charge effect by attenuating the beam right after RFQ, and switching off all RF cavities in the first four cryomodules. The result of comparison between LW data and the OM simulations is shown in Fig. 3.
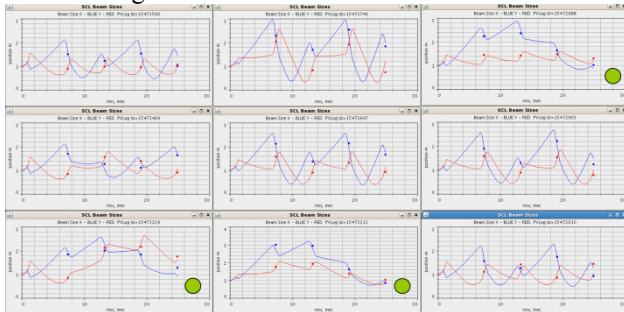

Figure 3: RMS sizes of the beam in the first four cryomodules. The blue/red color is for horizontal/vertical sizes. Points are for LW measurements, and curves are results of the XAL Online Model.

Figure 3 shows the RMS beam sizes for 9 different combinations of quadrupole fields between the first 4 SCL cryomodules. Three of these combinations use optics that follow the Twiss parameters error minimization rules, and they are marked by green dots. These measurements were used to find the initial Twiss that was used for the rest of the random quad settings. Figure 3 demonstrates that the XAL Online Model can be successfully used for the initial Twiss measurements, and the laser wire stations give us the correct RMS sizes of the beam. It also points out that to use the Online Model for the production optics, we have to pay attention to other parameters of the OM, such as the RF parameters and the initial longitudinal Twiss (to treat the space-charge effects correctly).

RF CAVITY PARAMETERS IN THE SCL

To perform realistic simulations with the Online Model we have to specify the correct field gradient and phase for each RF cavity in the SCL. Each SCL cavity in the OM is a combination of six accelerating gaps. The phase of the cavity's model is defined as the phase of the synchronous particle at the first cavity's gap. Until recently to get correspondence between the cavity model parameters and the live machine we used a cavity phase scan. This involves collecting the phases of two BPMs right after the cavity. During the scan the cavity phase changes from -180^0 to $+180^0$, all downstream cavities have the RF pulse blanked so they will not affect the beam, and the number of bunches in the pulse train is limited to about 200 to avoid beam loading of the cavities.

The phase of the beam measured by the BPM is defined by the time of arrival (the distance divided by the velocity)

$$\varphi_{BPM}^{(i)} = \Delta\varphi_{RF}^{(i)} + \frac{z^{(i)}}{\beta c} \cdot \omega_{BPM} \quad i = 1,2 \qquad (2)$$

where $\beta, z^{(i)}, \omega_{BPM}, \Delta\varphi_{RF}^{(i)}$ are the relativistic parameter of the beam and the position, frequency, and phase offset relative to the RF synchronization line of the BPM, respectively.

For two synchronized BPMs (with the same phase offset) the velocity (and the energy of ions) of the beam can be found directly from the measured BPM phase difference. Comparing the measured and simulated BPM phase difference as a function of the cavity phase we find the model parameters. This method had a drawback. The two BPMs must be synchronized, which requires the BPMs' electronics to be located in the same crate, and limits distance between them in the lattice. This can lead to relatively big errors in the RF model parameters.
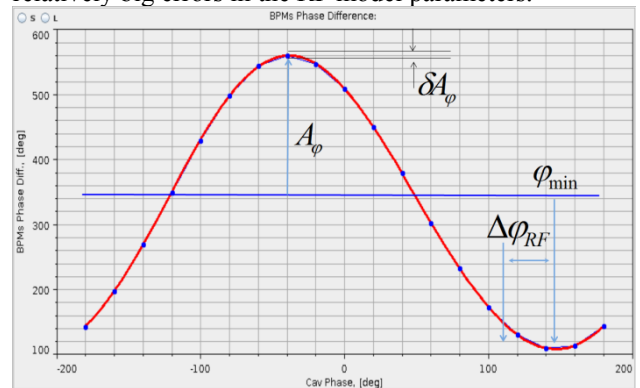

Figure 4: BPMs' phase difference vs. SCL cavity phase. Points are measured values and the curve is a result of the XAL Online Model.

Figure 4 shows a typical picture of the cavity phase scan results. The cavity phase for maximal acceleration (see φ_{min} in Fig. 4) is defined by the minimal difference

between BPMs phases. The error in this parameter is defined by

$$\delta\varphi_{\min} \approx \frac{1}{\sqrt{N}}\frac{\delta A_\varphi}{A_\varphi} \approx \frac{1}{\sqrt{N}}\frac{\delta\phi_{BPM}}{A_\varphi} \qquad (3)$$

where N, A_φ, $\delta\phi_{BPM}$ are the number of cavity phase points, the amplitude of the "sine"-like curve in Fig. 2, and the BPM phase measuring error respectively.

In turn A_φ is defined by the distance between BPMs Δz, the relativistic beam parameters γ and β, and a maximal energy that the cavity can give to the beam $\Delta E_{\max}$

$$A_\varphi \approx \Delta z \cdot \frac{1}{(\gamma \cdot \beta)^3} \cdot \Delta E_{\max} \qquad (4)$$

The formula (4) shows that to reduce the error in the cavity phase settings, it is better to use two distant BPMs even sacrificing the synchronization between them.

Eventually we developed a three stage SCL RF settings process:

- First, we scan the phase of the SCL cavities one by one, recording phases of all BPMs. For each cavity we set the phase by subtracting the design synchronous phase from the maximal acceleration phase (see Fig. 4). The phase scan curve is approximated by a two harmonics function. At this stage we do not need the model and synchronized BPMs.

- Second, after completing the phase scans we send beam into the SNS ring and use it as a device to measure the energy. After the final beam energy is known we analyse the BPMs' phase offsets in (2) for all BPMs after the last RF cavity. Then we track these offsets upstream in the SCL analysing the whole scan data. We do need the model at this stage, but at the end we have all BPMs synchronized (phase offsets are known) and ready to use in the model-based analysis. The BPMs' phase offsets calculated during this stage can be saved and used in the future.

- In the last stage we use the scan data with synchronized BPMs to get the model RF parameters for each cavity. The initialized model allows us to retune the SCL linac in a matter of seconds in the case of emergency when, for instance, one of the cavities should be shut down.

The process described above was automated by implementation into an OpenXAL application called "The SCL Tuner Wizard". Automation eliminated possible human errors and sped up the scan procedure. Today it takes about 40 minutes to tune the SCL RF system and to initialize the Online Model compared to about 8 hours in the past.

One of the useful features of the SCL Tuner Wizard is its ability to perform a "non-destructive" scan of an existing configuration. In these types of scans we perform all phase scans as usual, but at the end we do not set new

phases to the cavities. We just keep the phase that we had. The rest of analysis is performed as usual. These "non-destructive" scans were used to analyse the 1 MW production tunes when all RF settings, including the SNS normal conducting linac, were considered as "fair game" to reduce the beam loss in the SCL. Fig. 5 shows the synchronous phases of the cavities for one of the 1 MW production settings. In Fig. 5 we see that the real cavity phases in the SCL are far from the initially set -18^0, which would be used in the transverse size matching procedure without the aid of the fast "non-destructive" scan. This factor was another contribution to our failure to perform SCL beam matching in the past.
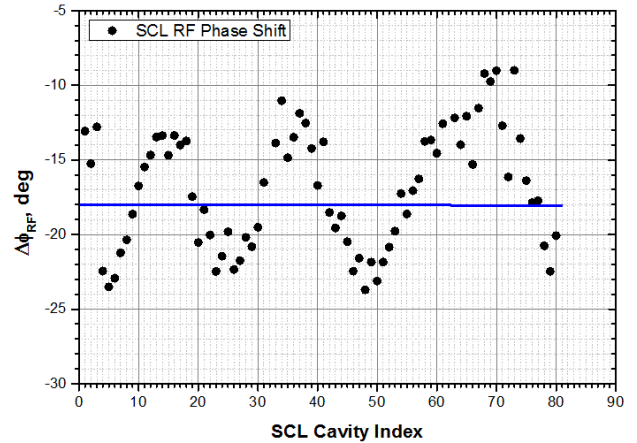

Figure 5: The synchronous phases of the SCL cavities on 2014.03.04. The points are measured phases, and the blue line defines -18^0 phases that were set before the beam loss reduction linac parameter tweaking.

MEASUREMENTS OF INITIAL LONGITUDINAL TWISS PARAMETERS

To correctly account for the space-charge effects in the OM model we have to know the longitudinal RMS bunch size along the entire SCL. The realistic SCL RF cavity parameters will allow the model to track the longitudinal size through the SCL if we know initial longitudinal Twiss parameters. At SNS we developed an original method to measure these parameters based on the BPM signals [9]. One of the BPM signals in SNS is proportional to the amplitude of the harmonics of a summed beam signal from all four stripline electrodes. The frequency of the harmonics is called the BPM frequency. This signal is defined by the formula

$$u_\omega = C \cdot J_\omega / I_0(\omega R /(\beta\gamma c)) \qquad (5)$$

where C is a calibration constant, J_ω is an amplitude of the beam current harmonic at the BPM frequency ω; R is the radius of the pickup aperture; c is the speed of light; β and γ are relativistic factors; and I_0 is the modified Bessel function.

In the case of a Gaussian longitudinal bunch density distribution the J_ω is defined by the longitudinal RMS length of the bunch s_z

$$J_\omega \approx \exp(-(\omega \cdot s_z)^2 / 2) \qquad (6)$$

According to formulas (5,6) the BPM amplitude signal can be used to measure the longitudinal bunch length if we calibrate the BPMs. Considering BPMs as analogues of wire scanners and RF cavities as "quadrupoles" acting in the longitudinal phase space, we used the algorithms described for the transverse directions to find the Twiss parameters at the entrance of each RF cavity [9].

Figure 6 shows the RMS bunch length along the SCL measured for the 1 MW production RF and quadrupole settings. This picture demonstrates that longitudinally we have un-matched beam, which also was not expected in our matching attempts in the past.
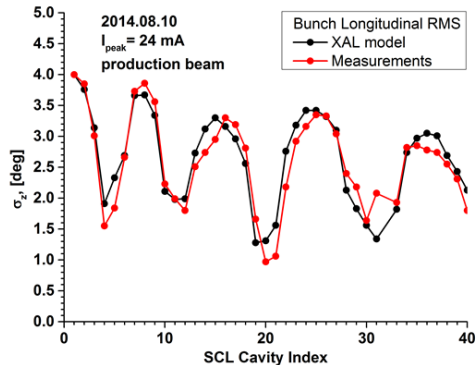
Figure 6: The RMS bunch length along the SCL. Measurements were performed by using the method described in [9].

XAL ONLINE MODEL BENCHMARK

Eventually all three components of the Online Model initialization (transverse and longitudinal Twiss parameters and the SCL RF settings analysis) were integrated into the OpenXAL SCL Tuner Wizard application. It allowed obtaining consistent measurements for offline analysis. Fig. 7 shows a snapshot of the application with a benchmark between the Online Model and a set of Laser Wire data for all 9 stations. As we can see, the agreement between the Online Model and measured data is much improved. Therefore, we can declare a victory and can say that we are ready to try matching in the SCL again. Now it will be based on the benchmarked OpenXAL Online Model.
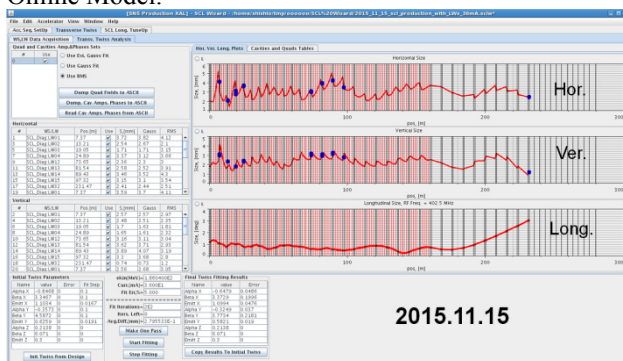

Figure 7: Snapshot of the SCL Tuner Wizard application with the LW measured beam RMS sizes along the SCL as blue dots and red lines as results of Online Model simulations.

CONCLUSION

The successful benchmark of the OpenXAL Online Model was performed with transverse RMS beam sizes measured by the Laser Wire stations in the SNS superconducting linac. It has been achieved by careful measurements of the lattice and beam parameters for the model initialization. The successful model benchmark opens an opportunity for another attempt of beam matching in the SNS SCL.

ACKNOWLEDGMENT

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