MODEL AND BEAM BASED SETUP PROCEDURES FOR A HIGH POWER HADRON SUPERCONDUCTING LINAC

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Abstract

This presentation will review methods for experimental determination of optimal operational set points in a multi-cavity superconducting high power hadron linac. A typical tuning process is based on comparison between measured data and the results of simulations from envelope and single-particle models. Presence of significant space charge effects requires simulation and measurement of bunch dynamics in 3 dimensions to ensure low loss beam transport. This is especially difficult in a superconducting linac where use of interceptive diagnostics is usually restricted because of the risk of SRF cavity surface contamination. The procedures discussed here are based on non-interceptive diagnostics such as beam position monitors and laser wires, and conventional diagnostics devices such as wire scanners and bunch shape monitors installed outside the superconducting linac. The longitudinal Twiss analysis based on the BPM signals will be described. The superconducting SNS linac tuning experience will be used to demonstrate problems and their solution for real world linac tune-up procedures.

INTRODUCTION

The superconducting linac (SCL) of the Spallation Neutron Source (SNS) accelerates negative charged hydrogen ions from 185.6 MeV to 1 GeV providing at its exit 1.4 MW of average power. To have an acceptable level of the linac activation (less than 100 mrem/h for “hands-on” maintenance) beam loss in the accelerator should be very small. The SCL design predicted that this part of the SNS linac should be virtually free of beam loss because of a good vacuum, hydrogen instead of nitrogen as a residual gas, and a big beam pipe aperture. During the commissioning and the power ramp up in 2006 -2007, it was found that the SCL had substantially more beam loss than expected, but still at an acceptable level for the design power level of 1.4 MW. It was found that the beam loss could be reduced by an empirical “step-by-step” procedure of reducing the SCL quadrupole gradients using beam loss as a figure of merit. The design and final production gradients are shown in Fig. 1.

This seemingly counterintuitive measure to reduce beam loss in the SNS superconducting linac was explained by the discovery of an Intra Beam Stripping (IBSt) beam loss mechanism [1,2]. According to IBSt, beam loss is the result of intra-beam collisions of two H^- ions that strip the electron from one of the ions. Then the created neutral hydrogen atoms are lost on the beam pipe. Reducing the quad gradients in the SCL makes the beam transverse size bigger, reduces the beam density, and eventually reduces the collision and stripping rate in the beam. The process of increasing the transverse beam size has its limit when we start to lose ions on the beam pipe.

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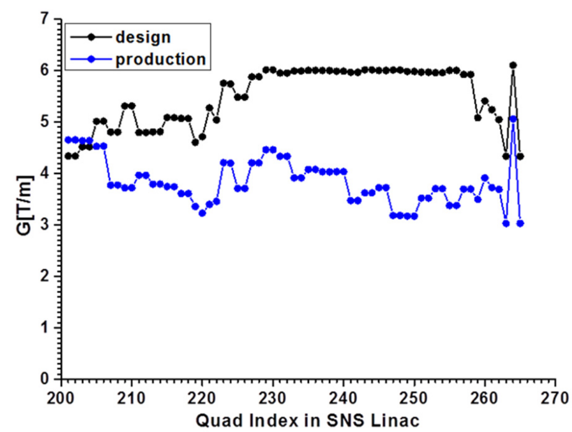

Figure 1: SCL quadrupole gradients.

The disadvantage of using the phenomenological tuning based only on beam loss is that we cannot tell if we have reached the optimal tuning and nothing else can be done. To answer this question we have to create the beam dynamics model of SCL including parameters of all RF cavities and initial conditions of the beam at the entrance of SCL. So far all attempts to build a working model and to get a “matched” beam in the SCL have failed [3]. In the present paper we will discuss work that has been done during the last two years at SNS to build such model, a possible reason why we failed before, and what we want to do in the future.

SCL TUNING PROCEDURE

The SNS superconducting linac tuning procedure is performed each time when the accelerator is turned on after an extended shutdown period (several weeks or more), and it consists of the following steps:

- Setting phases of all RF cavities. The phases are set using phase scan data. The process is discussed in details later. The amplitudes of the cavities (field gradients) are not a subject of tuning. These values are defined by the SCL group to be as high as possible and, at the same time, to provide a stable operation.
- Initial quadrupole gradient values are taken from the previous run settings. Then these values are tweaked to minimize beam loss in the SCL and the next section of the accelerator.
- SCL beam loss is further reduced by changing RF parameters in the warm linac. The parameters include all cavity phases, amplitudes, and quadrupole magnetic fields.

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- Eventually the MEBT halo scrapers are used to cut about 1% of the beam and improve beam loss in the warm linac, the SCL, and the transport beam line to the ring injection area.
- The tweaking steps can be repeated iteratively even during the production.

Until recently, the most time consuming step that cannot be done in the production was the setting of the RF cavity phases. During the last two years this procedure has been significantly improved. The next part of the paper describes the progress.

SCL CAVITIES PHASE SCANS

The SCL cavities are phase scanned one by one, and during the scan downstream cavities do not have RF power. A year ago our scan algorithm was as follows: in the process of the scan, we change the phase of the cavity and measure the beam phases along SCL by the Beam Position/Phase Monitors (BPMs). A precisely calibrated pair of BPMs used for Time-of-Flight procedure (TOF) gives the energy of the beam. When the scan data is analysed, and the RF phase corresponding to the maximal energy gain is found, we set the cavity phase shifted down from this point by a predefined phase shift. During several years of operation we tried several strategies for the cavity phase law, but we could not say which is better. Now we are using a constant phase shift of -18^0 without any theoretical consideration. The typical picture of the two BPMs phase difference as a function of the cavity phase is shown in Fig. 2.

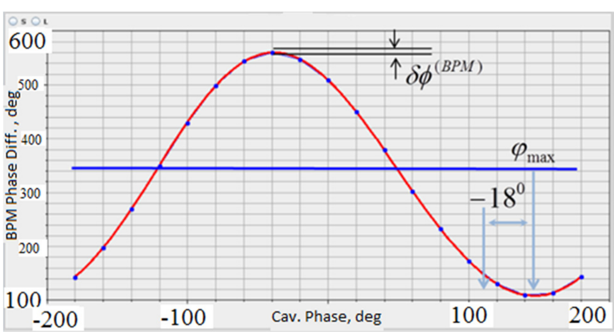

Figure 2: Two BPMs phase difference vs. a SCL cavity phase. The red curve is a two harmonics approximation (see text).

The accuracy of this procedure in finding the maximum of acceleration phase (see Fig. 2) is defined by the following formula:

$$\delta\varphi_{\max} \approx \frac{(\gamma\beta)^3}{\sqrt{N}} \cdot \frac{\delta\phi^{(BPM)}}{\Delta s \cdot E_0 TL}. \qquad (1)$$

where γ, β are relativistic parameters of the beam, N is the number of points in the phase scan, Δs is the distance between the two BPMs, $\delta\phi^{(BPM)}$ is the BPM phase noise, and E_0TL is the maximal energy gain that can be provided by the cavity. According to equation (1) we want to use BPMs that are as far away from each other as possible, and there is a good chance that they will not be a calibrated pair, because their electronics will be in different crates. This will not be a problem for setting the cavity phase, but it means we cannot calculate the precise energy of the beam until we calibrate these BPMs.

The newly developed procedure consists of three stages. During the first stage, all cavities are scanned and the phases are setup based on un-calibrated pairs of BPMs. All information (BPM phases and electrodes sum signals) are stored for a future analysis. The BPMs phase difference is approximated by a two harmonics function

$$\Delta\varphi_{BPM}(\varphi_{RF}) = \sum_{i=1,2} A_i \cos(i \cdot \varphi_{RF} + \Delta_i). \qquad (2)$$

This approximation does need the cavity model. The second harmonic amplitude in formula (2) it typically 2 3% of A_1 at the beginning of SCL, and it will introduce $2\text{-}3^0$ error for the maximal acceleration phase if we do not account for it. As the energy increases along the SCL this second harmonics contribution goes to zero.

During the second stage, we transport the beam coming out of SCL into the SNS ring, and use the ring as an energy measuring device. That allows us to calibrate the phases all the BPMs involved in the measurements going down from the ring to the beginning of SCL. After all BPMs calibration, we can calculate the beam energy after each cavity and for each cavity phase point during the scan. We want to emphasize that we do not need a model up to this point of the procedure.

During the last stage, we use the model to analyse the scan data for each cavity using all available BPMs. As a result we have the synchronous phases and the amplitude of the cavities in the model. The phase shifts for this analysis could be a little different from the values used as input on the first stage. They are more precise, because in the first stage we used only two BPMs. As a model we use the XAL Online Model (OM) [4]. The OM is an envelope tracking accelerator code similar to TRACE3D.

Eventually, we developed the online application that we use in the control room for SCL phase tuning. The time needed for the scans was reduced from 6-8 hours in the early days of SNS to 20-25 minutes with the accuracy of the phase shift about 1.0^0. We also added the possibility to scan the existing settings without changing the final cavity phases. This allows us to initialize OM for the accelerator settings found empirically by optimizing beam loss.

In the next subsections we are going to discuss several results obtained after using the developed SCL phase scan application.

Stability of the Scan Results

The SNS accelerator is a user facility with a limited time for accelerator physics. A relatively short time of the new SCL phase scans allowed performing different beam dynamics studies which could not be done before. One of them was the investigation of the stability of the phase scan results. Figure 3 shows the difference between live cavity phases which were set during four consecutive SCL scans. Each scan took about 20 min.

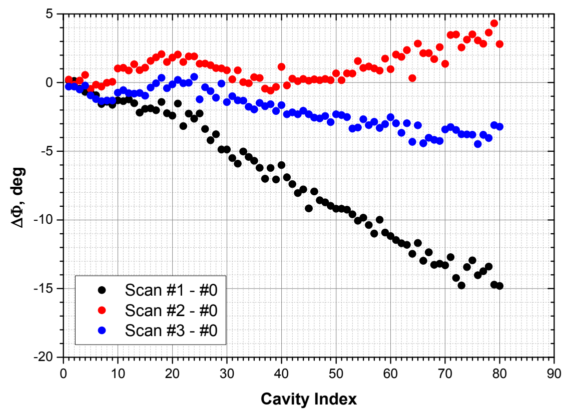

Figure 3: The SCL cavitiy phase differences for four consecutive phase scans.

Despite the very significant differences in the cavity phases all four scans give us the same beam loss in the SCL, and all of them can be used as a starting point for the final SCL tuning. This can be explained by the fact that cavity to cavity phase differences are very small – about 0.25^0. We have a 20^0 difference at the end only because we have 81 cavities.

At this moment we do not have a good explanation of this effect, but we suspect that it is somehow indirectly related to a tunnel temperature time variation. The tunnel temperature oscillates with a period about 1.5 – 2 hours, but it is small, and it cannot cause the 20^0 phase change directly. The BPM phase noise during the production shows 0.5 – 1.0^0 degree variation only.

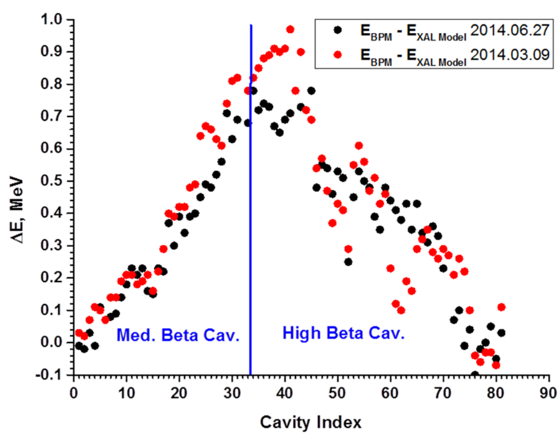

Figure 4: The difference between calculated and measured by BPMs energies along SCL.

Energy Tracking in SCL with XAL Online Model

As it was described in the previous section, after analysis of the phase scan data we have the synchronous phases and the amplitudes of all cavities. At the end, all these cavities are combined into one lattice, and the synchronous particle is tracked through this SCL model. To check the accuracy of our model we compared calculated output energies after each cavity with the energies determined from the BPM data. The results are shown in Fig. 4.

Figure 4 demonstrates the repeatability of the data and shows two easily distinguished parts. The left half of Fig. 4 is for the "medium-beta" type of cavities, and the right half is for the "high-beta" one. It is logical to assume that our models for the two types of the SNS superconducting cavities are not perfect, and they show different tendencies providing an almost perfect cancelation at the end of the SCL which we consider accidental. The investigation of this model vs. measurements discrepancy and the model modification is in our plans for the future.

RF Cavities Synchronous Phases

As it has been mentioned before, at the beginning of the tuning, the phase shifts (which approximately are equal to synchronous phases) of all RF cavities are set to -18^0. After the tuning they are not the same, but until recently we did not measure them.

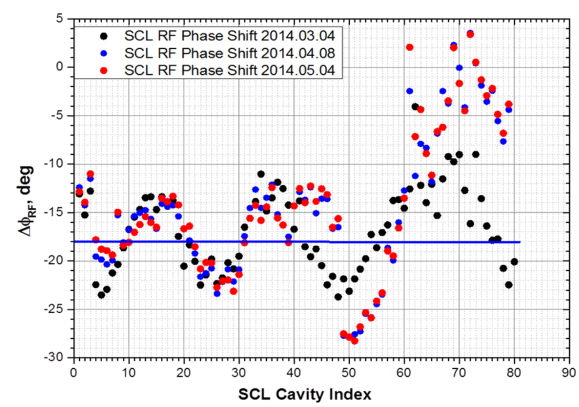

Figure 5: The SCL cavities' phase shifts during the production.

Fig. 5 shows three sets of the synchronous phases measured during the 2013-2014 winter-spring production cycle of SNS. Surprisingly, the synchronous phases are far from the initial -18^0. They are also not constant in time because of continuing beam loss tuning during the production. Nevertheless these phases provide an acceptable level of beam loss in the SCL. Moreover, they give us the local minimum of the beam loss despite being so far from the design values. This result shows the flexibility of the beam dynamics in the superconducting linac.

The results shown in Fig. 5 could explain why previous attempts to study SCL beam dynamics were not always successful. Very often studies were performed on the production machine settings assuming the phase law used for the initial tune. As we see the real phase setting can be far from it.

INITIAL TWISS PARAMETERS

After SCL phase scans and analysis we have all the data for the SCL model, but we have to find the parameters of the beam at the entrance of SCL before doing any model

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based tuning. It is a non-trivial task, because the SNS superconducting linac does not have any interceptive diagnostics which could contaminate the surface of the RF cavities. For the transverse beam profile measurements in SCL we use laser wire stations (LW) [5]. LW is similar to an ordinary wire scanner, but it uses a laser beam to intercept the H$^-$ beam and measure the total charge of electrons created in the photo-detachment process. For the longitudinal Twiss parameters measurement we use the new techniques based on BPM signals [6].

Longitudinal Twiss Parameters along SCL

In [6] it was shown that the sum signals of all four electrodes of a stripline-like BPM can be used to get information about the longitudinal Twiss parameters at the entrance of the superconducting cavity after the analysis of the phase scan. Later in [7] it was demonstrated that each cavity in the SNS SCL can be used as a measuring station for the longitudinal Twiss, and a good agreement between measurements and the simulations with the XAL Online Model was observed for the beam at low peak current.

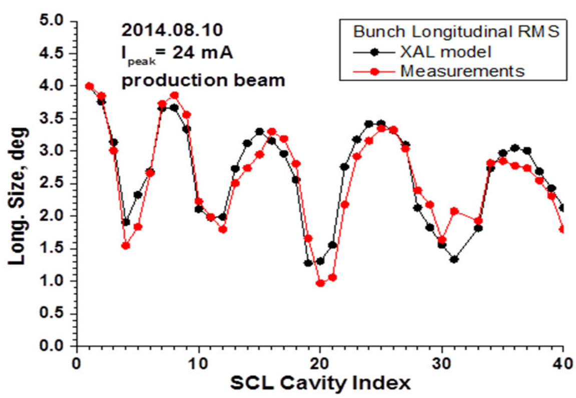

Figure 6: The longitudinal bunch size along SCL.

The latest results of the longitudinal Twiss analysis for a 24 mA peak current beam in SCL are shown in Fig. 6. The measurements were performed for the production setting of the accelerator. The picture demonstrates that our production beam is unmatched longitudinally in SCL. There is no surprise in this fact, because no effort to match the beam has been made. The beam loss has a low sensitivity to the individual cavity phase, so the loss optimization could be done only globally by finding the optimal setting for each SCL cavity at once.

The results of the analysis are shown only for the first half of 81 cavities in SCL. When the energy of the beam becomes higher, the longitudinal focusing/defocusing effect of the cavity on the beam becomes weaker, and we cannot get the Twiss parameters from the BPM signals. Figure 6 shows that for future planning we can use the combination of the model and the initial parameters at the first cavity to predict and to control the longitudinal bunch size in SCL.

Transverse Twiss Parameters

Details of the process of measurement and analysis of the initial transverse Twiss parameters with the laser wire stations in SCL are described in [7]. The only difference here is that we implemented the procedure of simultaneous measurements of the transverse and longitudinal parameters as it was promised in [7]. Figure 7 shows a comparison between the model based fit and beam RMS sizes measured for the production setup in SCL.

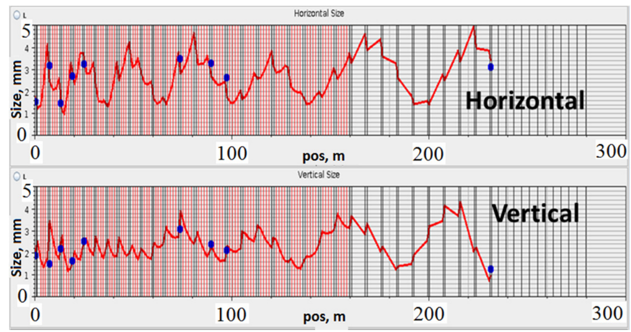

Figure 7: The horizontal and vertical RMS beam sizes along the SCL. The red lines are simulation results, and blue points are measurements with LW stations.

From the Fig. 7 it is clear that the production beam is also unmatched in the transverse plane. Surprisingly, these conditions provide low beam loss, and attempts to improve losses further were not successful. It could be that the sequence of our actions during the tuning process gave us a combination of longitudinal and transverse mismatch with a local minimum in beam loss. We hope that simultaneous matching in all directions will help to reduce losses. At this moment, we do not have an application that can do this matching. In Fig. 8 we demonstrate that by reducing and optimizing quad fields in SCL, we can get the beam with a better matching in the transverse plane.

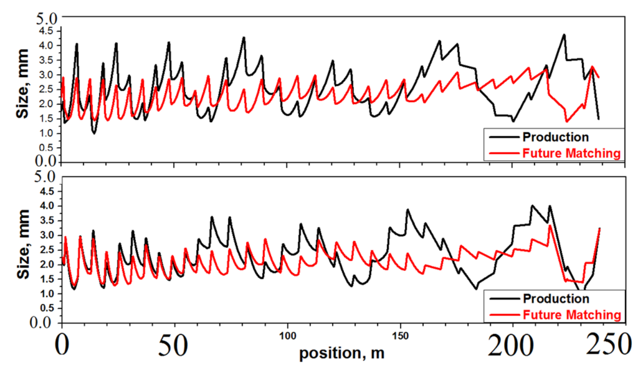

Figure 8: The horizontal and vertical beam sizes for the production and a future matching.

FUTURE TUNING CONSIDERATION

There are some details that could complicate the future beam loss reduction in SCL. First, we have to keep in mind that all transverse and longitudinal matching will be done based on the RMS sizes. We do not account for existing non-Gaussian distributions that were observed in transverse profile measurements. An example is shown in Fig. 9. If by matching we reduce the RMS size, the central part will have higher density and will cause elevated beam loss due to the IBSt loss mechanism.

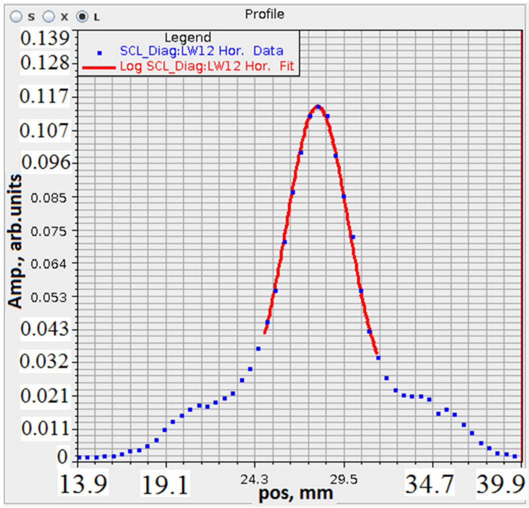

Figure 9: The horizontal density distribution of the beam at the SCL Laser Wire station 12.

From this point of view, it would be beneficial to eliminate the long tails in Fig. 9. It means that we should pay more attention to the warm part of linac and should improve the quality of the beam at the SCL entrance. In [8] it was shown that in the J-PARC linac the non-Gaussian tails in transverse distributions can be reduced by changing the amplitudes of the upstream cavities.

Another problem in beam loss reduction could be the presence of halo. The Fig. 10 shows the horizontal phase space distribution at the end of SCL measured with a laser based emittance device.

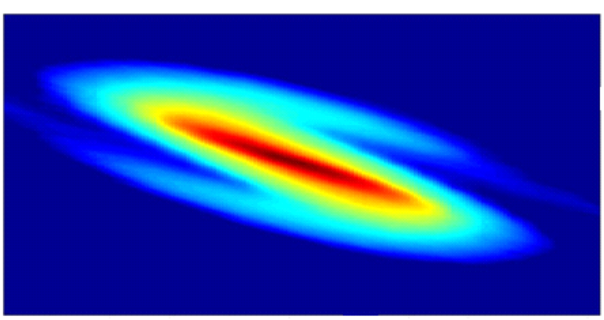

Figure 10: X-X' phases space density after SCL [9].

Another issue is that in all our simulation tools that we are using right now we track the envelope of the beam. If we try to make the beam big as possible to reduce IBSt effect we inevitably will put some beam halo on the beam pipe surface. It means we have to use particle tracking codes in our planning. None of the existing codes was validated for this purpose.

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CONCLUSION

The developed methodology for the beam dynamics characterisation in the superconducting linac shows beam parameters at SNS SCL are far away from the design. Despite this the SNS linac delivers 1.4 MW power with acceptable beam loss and beam line activation. The next step in our studies should be a model based tuning of SCL beam loss.

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