BEAM MEASUREMENT AND SIMULATION AT THE SNS

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Abstract

The overview of the Spallation Neutron Source (SNS) linac lattice, diagnostics, and beam dynamics is presented. The models and model-based tuning procedures of the warm and superconducting parts of the SNS linac are discussed. There are significant discrepancies between simulated and measured losses in the superconducting part of the linac. The possible reasons for these losses and their relation to the beam dynamics are discussed.

INTRODUCTION

At present time the SNS accelerator complex routinely delivers 1 MW proton beam to the mercury target which makes it the most powerful pulsed spallation source in the world. The SNS accelerator consists of a 1 GeV linac and an accumulator ring. This paper will discuss the SNS linac structure, the beam dynamics, comparison between models and measurements, and losses in the SNS linac.

SNS LINAC

The SNS linac includes a front-end, six 402.5 MHz drift tube tanks (DTL), four 805 MHz coupled cavity linac (CCL) sections, and two sections of a superconducting linac (SCL) with cavities designed for relativistic factors 0.61 and 0.81 (so-called medium-β and high-β SCL sections). The structure and design output energies are shown in Fig. 1. The DTL and CCL are room temperature RF structures. The SCL cavities operate at a temperature of 2°K. The SNS front-end (FE) consists of a negative hydrogen-ion source, a low energy beam transport line (LEBT), an RFQ that accelerates the H^- beam to an energy of 2.5 MeV, and a medium energy beam transport line (MEBT) that matches the beam for the DTL entrance. The ion source and RFQ are designed to deliver 38 mA peak current, but now the FE can provide up to 45 mA which we are not using in production.

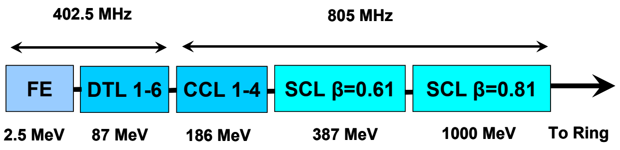

Figure 1: SNS linac structure.

SNS Linac Beam Dynamics

A primary goal in the SNS linac design was to minimize potential damage and radioactivation of the accelerator resulting from beam halo generation and uncontrolled losses [1]. According to the design parameters, the losses should not exceed 1 W/m. Some conditions were imposed to minimize halo generation [1]:

- The zero-current phase advances (transverse and longitudinal) per period never exceed 90^0.
- To avoid the second order parametric resonance, the transverse and longitudinal phase advances do not cross except in DTL tank 1 and CCL module 4 where matching considerations prevail.
- The transverse and longitudinal phase advances per meter are smooth functions along the linac. This feature minimizes possible mismatches and helps to create a current independent design.

Other source of potential halo and emittance growth are resonant modes. They can develop in the beam itself and cause beam energy exchange between transverse directions. The analysis of such resonances for 52 mA peak current showed that the SNS linac is too short for noticeable beam degradation [1].

The analysis of the beam dynamics of the superconducting part revealed a surprisingly tolerant design [2]. The deviation of the electric fields of the SCL cavities from the design values by as much as $\pm 30^0$ appears to have minimal effect on the beam performance. This low sensitivity is, in part, a direct result of the nature of the SCL linac where each cavity's phase can be adjusted individually. In contrast, the normal-conducting DTL and CCL are synchronous structures where each gap in any cavity is phase-locked to its neighbor, and its phase is not adjustable.

SNS Linac Beam Diagnostics

A suite of beam diagnostics devices defines what kind of information we can get for analysis and for tuning the linac. The available SNS linac beam diagnostics include:

- Beam-position monitors (BPM). The 60 SNS linac BPMs are able to measure the beam position, beam intensity, and beam phase on a mini-pulse-by-mini-pulse basis. The ability to measure the beam phase is an absolute necessity to tune up RF phases of linac cavities.
- The SNS linac Beam Current Monitor (BCM) system consists of 10 fast current transformers. The accuracy of the current measurement is not enough to see beam losses below the 1% level.
- Wire Scanners (WS) are used for interceptive measurements of transverse beam profiles in the MEBT, DTL, and CCL. Wire scanners in the MEBT measure the charge of electrons stopped in the wire and all other WSs measure charge induced by secondary emission from the wire.
- To measure transverse beam profiles in the SCL, 'laser wire" (LW) stations are used. LW uses a non-intrusive method based on photo-ionization of the

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negative ions of the beam and detection of the detached electrons. The replacement of traditional WS by LW was suggested to avoid possible contamination of superconducting cavities.

- The SNS Beam Loss Monitor (BLM) system [3] consists of 362 radiation detectors measuring secondary radiation due to beam loss. The BLMs are distributed along the entire SNS machine. SNS uses ionization chambers as its main BLM device because of their simple design and immunity to radiation damage.
- The four Bunch Shape Monitors in the CCL are used to measure the longitudinal bunch distribution. The BSM principle is based on measuring the time structure of secondary electrons emitted from a wire inserted into the beam [4].
- The SNS linac has one transverse emittance scanner installed in the MEBT, but it is not yet fully tested .

COMPUTER SIMULATION CODES

A variety of accelerator simulations codes were used for the SNS design and are being used now for control and offline analysis. Later we will discuss the comparison between their predictions and experimental measurements.

TRACE 3-D

TRACE 3-D is a beam-dynamics program that tracks the envelopes of a bunched beam through a user-defined transport system [5]. Space charge calculations are included as linear forces. TRACE 3-D was used for fast beam dynamics calculations during the early stages of the SNS project. Later the capabilities of TRACE 3-D were implemented in the XAL online model [6].

PARMILA

PARMILA (Phase and Radial Motion in Ion Linear Accelerators) is a computer code used for the design and simulation of proton and heavy ion linear accelerators [7]. It was used for the SNS linac design. The working 1 MW SNS linac is a living proof that PARMILA is capable of simulating a real machine. The PARMILA's algorithm for calculating an RF gap transition was adopted by the XAL online model. Now at SNS, PARMILA is occasionally used as an online tool for matching the beam into the DTL and CCL (under a MATLAB GUI script) and for offline analysis.

IMPACT

IMPACT (Integrated Map and Particle Accelerator Tracking) is a parallel computer PIC accelerator code which includes 3D space charge calculations [8]. In SNS it is used for offline analysis.

XAL Online Model

The XAL online model (OM) is a part of the XAL application programming framework used at SNS [9]. The online model has both envelope and single particle tracking capability. The tracking algorithms were borrowed from TRACE 3-D (magnets, space charge) and PARMILA (RF gaps). The online model was thoroughly benchmarked against both these codes. The XAL OM is a base for tens of XAL applications used for SNS linac tune up and offline analysis.

BUNCH CENTER DYNAMICS

The ability to predict and control the motion of the bunch center is a necessary starting point for any beam dynamics studies and tuning procedures. There are two qualitatively different tasks. The first is orbit control, where we want to put the beam through the center of each component to avoid possible nonlinearities; and the second is to put the bunch through the RF gaps at the design time. There are several XAL applications that perform these tasks. All of them are based on the XAL OM

Orbit Correction

In the SNS linac, orbit correction is routinely performed by using the general XAL Orbit Correction application. This application minimizes the BPM horizontal and vertical readings by changing dipole corrector fields. For the CCL part the results were unsatisfactory in terms of beam losses and activation. The reason was the relatively small number of BPMs in this region (10 BPMs) compared to the number of possible orbit distortion points at CCL quads (47 quads). Because of the small number of BPMs, it is possible to zero the BPM readings by using the available correctors, but it will not necessarily make the orbit flat between BPMs.

A new method called model-based orbit correction was suggested for the CCL part of the SNS linac. The scheme of the method is shown in Fig. 2. First, parameters of the beam at the entrance of the CCL have to be found by using a fitting procedure, BPM readings and the XAL online model. Second, the dipole corrector currents are found to correct the orbit everywhere, not only at the BPM locations. Finally, the resulting settings are sent to the machine.

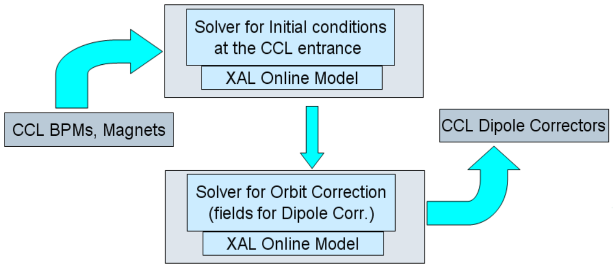


Figure 2: Model-based orbit correction algorithm.

The use of this method reduced losses and activation in the CCL. The accuracy of the orbit prediction in the CCL is usually better than 0.2 mm. In other parts of the linac the model based predictions are not so accurate. Fig. 3 shows the comparison between measured and calculated orbit differences in the SCL. The orbit differences were created by changing the first dipole corrector in the SCL to create different conditions of the beam at the SCL entrance. It demonstrates not only the substantial difference between model and the real BPM data, but also a coupling between the horizontal and vertical planes. The coupling can be explained by a random rolling angle for the SCL quads with amplitude about 0.5^0, which is a little bit higher than the design limit 0.3^0, but the overall difference between the model and measurements is not understood at this moment. This discrepancy is not big, and the general orbit correction algorithm is working very well in this region.

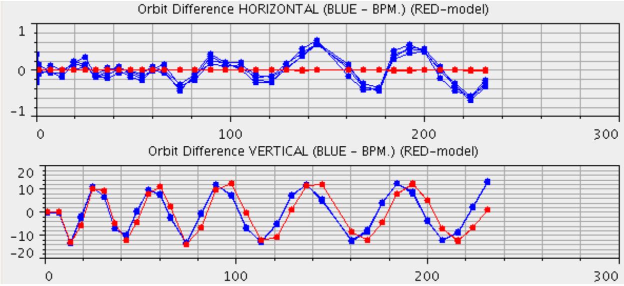


Figure 3: Orbit difference trajectories in SCL.

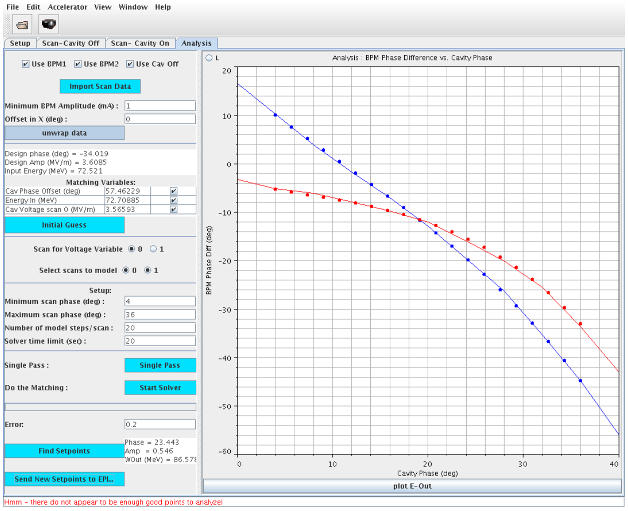
Another region of the linac where the XAL online model cannot predict the orbit with an accuracy better then 0.5 mm is the MEBT. The MEBT has two triplet quads where the magnets are so close that their fringe fields overlap. Correction to integrated focusing strength has to be taken into account [10]. Unfortunately, this correction is not constant and should be calculated each time the current in the magnet coil is changed. This feature will be implemented in the next version of the XAL online model.

Longitudinal Beam Center Dynamics

The longitudinal tuning of the SNS warm linac is also based on the XAL online model, which implemented the PARMILA model for RF gaps as a thin elements. There are two XAL applications for this task. The first is a widely used Delta T phase scan technique developed by Crandall [11], and the second is a "phase signature matching". The Delta-T procedure uses a linear part of the BPM phase response during a phase scan of an upstream RF cavity. The "phase signature matching" can be used in a wider RF phase region where the response is not linear, but the transmission is still good. The snapshot of the signature matching application (PASTA) with measured and simulated BPM phase responses is shown in Fig. 4.

During SNS production runs, it is convenient to have the ability to check that cavity phases and amplitudes are tuned correctly. To check and to correct the longitudinal tuning without interruption of neutron production, the "longitudinal shifting" method with a small phase shift for RFs was developed.

The "longitudinal shifting" method is based on a comparison of simulated and measured BPM phase shifts after a simultaneous small phase shift (it really means time) of all RF cavities in a linac sequence. In the single-particle model these cavities' phase shifts are equivalent to a time shift of a particle entering the linac sequence. As a result, the downstream BPM phases, which are the times when the beam center arrives, change. Comparing simulated and measured BPM phase changes we can make conclusions about differences between design amplitudes of cavities and their real values.



☑ Use BPM1 ☑ Use BPM2 ☑ Use Cav Off

Minimum BPM Amplitude (mA) : 1
Offset in X (deg) : 0

Design phase (deg) = -34.019
Design Amp (MV/m) = 3.6085
Input Energy (MeV) = 72.521

Matching Variables:

Cav Phase Offset (deg)	57.46229	☑
Energy In (MeV)	72.70885	☑
Cav Voltage scan 0 (MV/m)	3.56593	☑

Scan for Voltage Variable ● 0 ○ 1
Select scans to model ● 0 ● 1

Setup:
Minimum scan phase (deg) : 4
Maximum scan phase (deg) : 36
Number of model steps/scan : 20
Solver time limit (sec) : 20

Single Pass :
Do the Matching :

Error: 0.2

Phase = 23.443
Amp = 0.546
WOut (MeV) = 86.578

Hmm – there do not appear to be enough good points to analyze!

Figure 4: The XAL phase signature application (PASTA). The results for the DTL-6 tank tuning. Model results are points, and curves are messurements.

The results of the RF phase shifting for the DTL and CCL sections of a well tuned linac are shown in Fig. 5. The drawback of this method of longitudinal tuning correction that it is mostly sensitive to the amplitude of the cavity, and all corrections should be done sequentially for one cavity at the time.

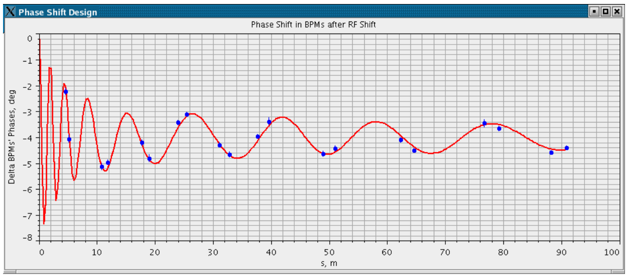


Figure 5: The BPM phase shifts in the DTL and CCL sections as a function of distance from the beginning of the sequence. Red color is for the XAL online model, blue points are BPM data.

The SCL tuning procedure is based on the same phase signature matching method, but it is simpler because each SCL cavity has only six RF gaps, and the phase response from BPMs to the cavity phase scan is almost sinusoidal. Based on the great flexibility of the SCL linac to set the phases of cavities individually, a phase scaling technique was developed. It allows instant recalculation of the SCL cavity phases using the XAL model if one or even two cavities will fail.

Overall all these examples show that we are confident in our understanding of the beam center motion in the SNS linac.

TRANSVERSE MATCHING

Transverse beam matching in the SNS linac is performed by fitting wire scanner or laser wire beam profile measurements with a model, calculating Twiss parameters at the entrance of the matching section, and modifying matching quads to provide the matched beam. For the DTL and CCL sections of the linac, the XAL online model is used. In a case of zero peak current the initial Twiss parameters can be found exactly for the measured beam sizes at three locations. In the presence of nonzero space charge effects, there is no analytical solution for this problem. We use a generic optimization technique, and there is no guarantee that the solution is unique. In practice the fitting time is less than a minute, and results are satisfactory in the sense of beam sizes and losses. Fig. 6 shows an example of a matched beam in CCL.

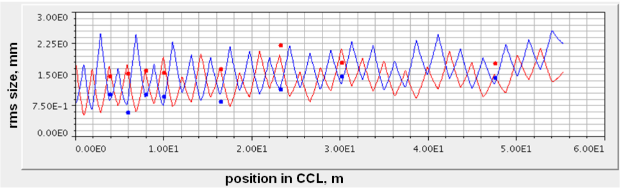


Figure 6: The transverse beam sizes in the CCL after matching (blue is horizontal and red is vertical). Points are WS data, and lines are the model results.

Unfortunately, for the SCL part of the linac the XAL online model cannot get consistent matching results. The possible reasons for this have been discussed in [12]. We have also tried to use the IMACT code for the SCL transverse matching. IMPACT is a multi-particle code with an exact 3-D space charge solver, so it is relatively slow, and it takes significant time to calculate the matching configuration even on a parallel cluster. The results are better with respect to beam size excursions in the SCL, but losses were not reduced by this type of matching [12].

BEAM LOSSES

Reducing the losses for constant beam power is the main goal of the accelerator tuning. After several years of effort, a configuration that provides a local minimum of losses was found. At this moment, it is not clear that the losses cannot be improved further. The typical losses in the CCL and SCL are shown in Fig. 7. The distribution of the losses in CCL is far from that predicted in simulations with the warm linac imperfections [13], and according to the design, we should not see any losses in the SCL with a nominal initial distribution [2]. Another interesting feature of this empirical tune is that in the SCL the resulting quadrupoles settings are significantly lower compared to the design ones (see Fig. 8.). This is counterintuitive for our model, because we would expect the lower quad fields to give bigger beam and higher losses in the SCL. For the CCL the empirically found quad settings are only few percent different from the design values and only in the beginning of CCL (the matching region).

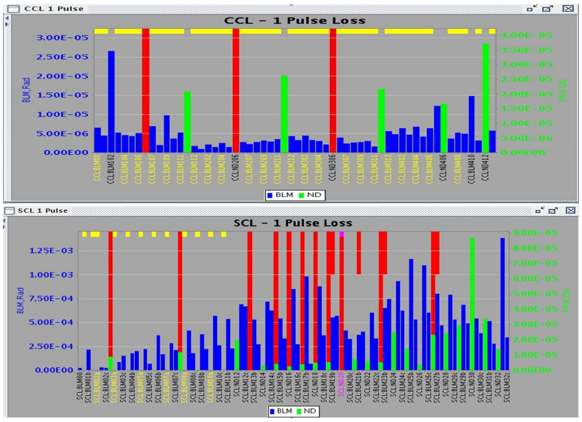


Figure 7: The distribution of the production losses (blue) in CCL (top) and SCL (bottom).

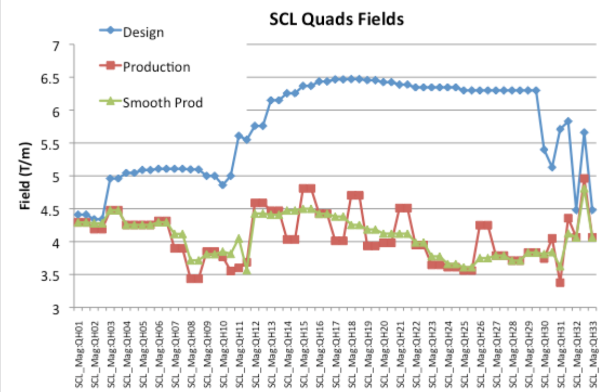


Figure 8: The quad gradients for design, production and “smoothed production” (courtesy of John Galambos).

A failure to explain the SCL beam losses on the base of existing simulation codes suggests that our models do not include one or more possible mechanisms of losses.

INTRA BEAM STRIPPING

A mechanism of losses in the SNS linac that is missing in any model being used at SNS was suggested by Valery Lebedev [14], and it was called Intra Beam Stripping (IBS). IBS take into account a reaction

$$H^- + H^- \rightarrow H^- + H^0 + e \qquad (1)$$

that occurs inside the bunch of negative ions of hydrogen. The hydrogen atom will not be affected by the linac lattice and will be lost somewhere downstream. The cross section of this reaction has a plateau between hydrogen velocities 1.0×10^{-4} and 1.0×10^{-2} the of speed of light, and the value on this plateau is about 3.6×10^{-15} cm^2. The rms relative velocities in the SNS linac bunches in the center-of-bunch frame are in this range (see Fig. 9.).

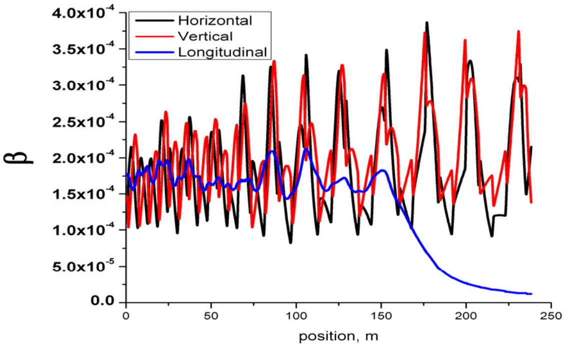


Figure 9: The rms velocities in the SCL in the center of the mass frame of the bunch. The XAL online model simulations.

According to the estimation in [14], a relative total beam loss at the end of the SNS linac due to this mechanism will be 1.5e-4, and the average power density of loss in SCL is about 0.13 W/m for a 1MW production run. The suggested mechanism predicts that the usage of weaker transverse focusing will produce a larger beam and less IBS. This conclusion agrees with the SNS linac observations, and IBS definitely should be incorporated into simulation models.

CONCLUSIONS

The comparison of computer model predictions with measurements related to the dynamics of the single particle motion shows that we have a good understanding of this type of dynamics. As for multi-particle parameters, it is more difficult to reproduce the measurements related to the properties of the beam, such as Twiss parameters and transverse and longitudinal distributions. The existing discrepancies could be related to the space change simulation uncertainties, because we did not perform reliable longitudinal emittance measurements. The work on systematical usage of SNS beam shape monitors is in progress.

At this moment we do not have a realistic model for beam losses. The one unaccounted potential mechanism for the observed losses is intra beam scattering. IBS should be included into the simulation code for the SNS project.

ACKNOWLEDGEMENTS

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