ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM015

COMPARISON OF DESIGN AND PRODUCTION RF SETTINGS AT SNS NORMAL TEMPERATURE LINAC*

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Abstract

The beam optics in the Spallation Neutron Source (SNS) normal conducting linac has been analyzed at the 1.4 MW beam-on-target operation settings. This section is a room temperature copper linac which includes a Medium Energy Beam Transport (MEBT) section with four re-bunching radio-frequency (RF) cavities, Drift Tube Linac (DTL), and Coupled Cavity Linac (CCL). The Radio Frequency (RF) cavities in this section accelerate H^- beam to 185.5 MeV. For production runs the parameters of RF cavities in this section are chosen by using a combination of models and empirical tuning providing low beam loss and a low rate of discharge events inside the cavities. For some cavities the set parameters are significantly different from the design values. The paper discusses accuracy of these settings and discrepancies between design and real-life high-power production settings in the warm linac section of SNS.

INTRODUCTION

The SNS accelerator includes a linear accelerator which accelerates H^- ions to an energy of 1 GeV, a storage ring accumulating protons for 1 ms, and beam transport lines between the linac, the ring, and the target [1]. The accelerator operates at a repetition rate 60 Hz and provides 1.5 MW average power on the target. The linac has two sections. The first section is a normal temperature linac that consists of an H^- ion source, Radio Frequency Quadrupole (RFQ), Medium Energy Beam Transport line (MEBT), Drift Tube Linac (DTL), and Coupled Cavity Linac (CCL). The structure of this linac with numbers of radio-frequency (RF) cavities is shown in Fig. 1. The second section is a superconducting linac (SCL) that includes 88 accelerating cavities. The RF cavities settings in this part of the SNS linac are very flexible, and they are not considered in this paper. For the production RF settings of the normal conducting linacs the approach is different. The RF parameters are usually set to the design values as close as possible. Until few years ago SNS Operations followed this practice. But after automated tuning procedures were implemented at SNS, they enabled the ability to tune RF system to an arbitrary state, even if it is significantly different from the design. During 1.5 MW operations, the accelerator operators perform step by step empirical tuning to improve beam loss, activation, and reliability of the whole linac. Eventually, empirical tuning reaches a particular set of RF parameters. At first glance, this parameter set contradicts the well-established linac physical designs. Though beam losses are lower than design settings there is no evidence that the parameter set is the optimal or unique. Nevertheless, it is one of acceptable sets for the high-power operation. This paper discusses how this set of parameters is reached, how accurate these parameters are, and why there is no contradiction with commonly used simulation codes.

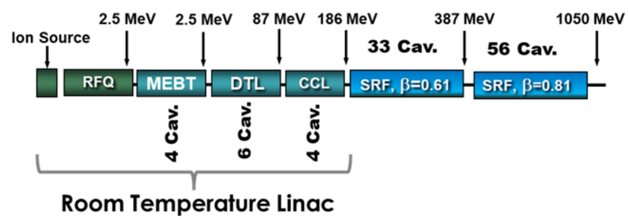

Figure 1: SNS linac.

RF AMPLITUDE AND PHASE SETUP PROCEDURE FOR ONE CAVITY

The normal temperature linac has two types of accelerating cavities. There are 4 MEBT cavities that have only one gap with RF field. Their phases should be set up to no acceleration of the beam. The procedure is described in [2], and it is simple and does not need any model. Other cavities in the DTL and CCL are long structures with tens of accelerating gaps. They are tuned by using a Beam Position Monitor (BPM) inside the cavity. At SNS, the BPMs measure the transverse position of the beam and the arrival time (the phase) of the bunches relative to a signal from the RF distribution line. The schematic of the measurement is shown in Fig. 2.

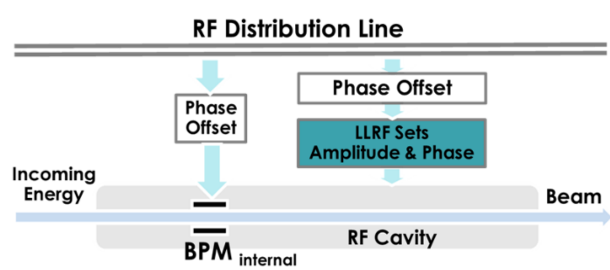

Figure 2: DTL and CCL cavities phase scan scheme.

The method of setting up the phase and amplitude of the RF cavity with several accelerating gaps was developed 30 years ago [3]. It uses a model-based analysis of the

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ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM015

measured BPM phases as a function of a cavity phase scan from -180^0 to +180^0. In our case, as shown at Fig. 2, the beam is accelerated by just a few RF gaps before the BPM. Therefore, there is no need to find a good region for the cavity phase scan like in the classical Delta-T procedure. The BPM signal is aways strong. Using the BPM inside the cavity we are tuning up only a small initial part of the cavity, but this is an equivalent of tuning the whole cavity.

Fig. 3 shows one of the resulting DTL2 cavity phase scan as an example. The BPM used is located after 9 accelerating RF gaps at the beginning of the cavity. The simulations were performed with the Online OpenXAL model [4]. The agreement shown at Fig. 3 was achieved by changing four parameters of the model: energy of the incoming beam, BPM's and the cavity phase offsets (Fig. 2), and the amplitude of the cavity. The BPM's phase offset defines the vertical shift of the whole plot, and the cavity phase offset defines the horizontal shift. The amplitude of the cavity defines the vertical range of BPM's phases, and the incoming beam energy modifies slightly the shape of the curve.

The scan parameter in the model is the phase of the first RF gap in the cavity. The cavity design defines the values of this phase and the amplitude of the cavity. In reality the amplitude of the cavity is usually lower than the model values to reduce the probability of arcing. This information enables the ability to correct the low-level RF cavity amplitude and phase settings within the control system.

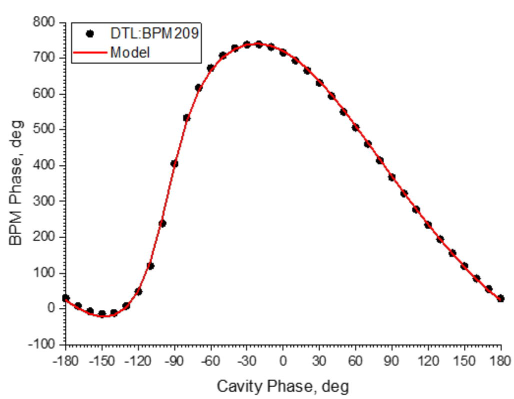

Figure 3: Cavity DTL2 phase scan and OpenXAL model simulation results.

Analysing the fitting results from the data shown in Fig. 3 gives estimated errors. In that case, for the incoming beam energy, the error was 0.021 MeV for the measured value of 7.618 MeV and the design value of 7.524 MeV. There is no way to change this value without changing the parameters of the upstream cavities (changing upstream cavities to compensate has not be attempted). The BPM and cavity phase offsets errors are on the level of 1°, and the cavity amplitude setting from the fit has about 1% error. The errors of the parameters for other cavities in the normal conducting linac have the similar values.

WARM LINAC SETUP PROCEDURE FOR HIGH POWER OPERATION

The tuning procedure described in the previous section was implemented in an OpenXAL application called the Warm Linac Tuner Wizard. The main window of this application is shown in Fig. 4. The table at the left upper corner is the main control element of the application. Selecting any row in this table shows the result or the progress of the phase scan of the selected cavity. After the buttons "Start" which is under this table is pushed, this application goes through all cavities in the warm linac and performs their phase scans, fitting the scan data, and, if requested, sets up the cavity phase and amplitude. All of this is done without operator intervention and takes about 25 minutes for all 14 cavities.

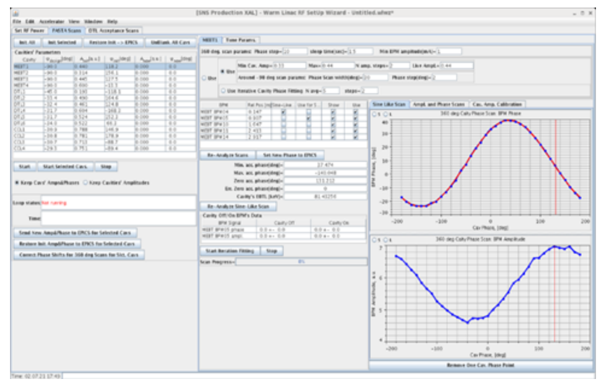

Figure 4: SNS OpenXAL Warm Linac Tuner Wizard.

One key feature of this application is a "non-destructive" scan. Following empirical tuning this scan is necessary to find the new operating point relative to the model design. After the scan of each cavity, the control system phase and amplitude of the cavity are restored to existing values, and physical values like the first RF gap physical model phase and the amplitude of the cavity relative to the design are recorded for future use. That allows the operators to save all model-related RF system parameters, after they perform the empirical tweaking the real parameters to reduce beam loss in all sections of the linac and trip rates of selected cavities. Using this method allows for fastt restoration of the warm linac physics parameters even after serious repairs of low-level controller modules of cavities, the RF signal distribution line, or cables replacement.

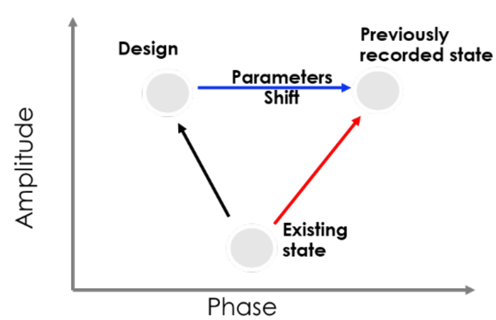

Figure 5: Setting up previously recorded RF cavity parameters from an arbitrary state using Warm Wizard.

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The diagram describing this approach is shown in Fig. 5. In this case the existing state (in terms of physics parameters) is different from the previously recorded. The diagram in Fig. 5 uses the physical model defined cavity amplitude and phase of cavity's first RF gap. Their relations to the real control system values are found after the "non-destructive" scan. For the phase, it is a phase offset shown in Fig. 2, and for amplitude, it is percentage of the design value. After these parameters are known we can apply the necessary changes to the cavity phase and amplitude to restore the previously recorded state in Fig. 5.

RF SYTEM PARAMETERS FOR HIGH POWER RUN AND ANALYSIS

An example set of physics parameters for the warm linac cavities is shown in Table 1. It was measured during the high-power production run on 02.07.2021. For some of the cavities the deviation from the design value is more than 10° for phases and as big as 45% for the amplitude. Nevertheless, they are real settings for low beam loss and activation. It is a great example of the flexibility of the superconducting cavity linac and the SNS linac overall.

Table 1: Warm Linac RF System Parameters

Cavity	Design φ_{synch}, deg	A/A_{design} %	Production φ_{synch}, deg
MEBT1	-90.0	145	-100.6
MEBT2	-90.0	131	-85.6
MEBT3	-90.0	132	-103.5
MEBT4	-90.0	129	-91.6
DTL1	-45.0	106	-43.6
DTL2	-33.4	103	-44.4
DTL3	-32.4	99	-19.6
DTL4	-31.7	101	-30.7
DTL5	-31.7	92	-25.2
DTL6	-34.0	97	-34.4
CCL1	-30.9	93	-16.7
CCL2	-30.8	95	-21.6
CCL3	-30.7	98	-23.9
CCL4	-29.3	93	-18.3

The parameters in Table 1 were produced by the Tuner Wizard shown in Fig. 4 which analyses the scan data with the XAL Online Model [4]. This model includes only the envelope model of the beam, and it cannot be used to study and to predict beam loss.

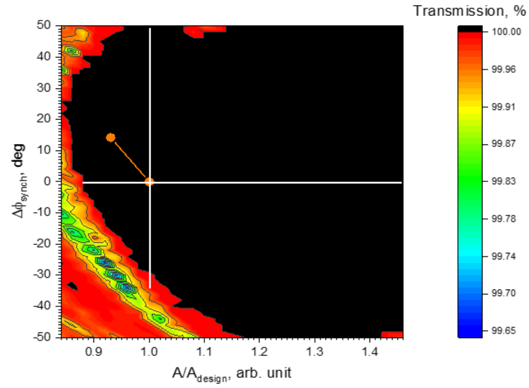

Figure 6: Transmission through the SNS warm linac as a function of amplitude and phase deviation from the design for CCL1 cavity.

To simulate beam loss, we apply the linac part of the PyORBIT code [5]. It is a Particle-in-Cell (PIC) simulation code that allows the ability to estimate how many particles will be lost during acceleration in the linac. First, we estimated the effect of a deviation from the design for only one cavity at the time. It means we kept all other warm linac cavities at the design settings. Fig. 6 shows the full transmission regions for the CCL1 cavity in the amplitude-phase coordinates plane. This cavity was chosen to show as an example, because it has the biggest phase deviation from the design in Table 1. As we can see there is a big region of parameters that provide 100% transmission through the warm linac. The orange points are the design and the working point from Table 1. The other cavities show similar big regions of parameters with 100% transmission, so the high level of discrepancy between design and production parameters is not surprising or contradictory to the classical PIC code. Unfortunately, when we applied all production parameters from Table 1 to the linac model, we saw about 2% beam loss in the beginning of CCL.

CONCLUSION

There are several conclusions from our studies. First, the SNS warm linac shows significant flexibility related to the RF system operational parameters. It is not as flexible as the SCL linac where you can tune beam around a failed RF cavity. In the warm linac you must have all long cavities operational. Second, this found flexibility does not directly contradict to classical linac models. Third, applying the found parameters to the model, shows beam loss that is absent during high power beam operation. A possible cause of this disagreement could be the fact that we used different models to extract and to apply these parameters. Other reasons could be unknown initial beam conditions and imperfections in the real elements of the warm linac which will be hard to find. Finally, we plan to continually study the model-based linac tuning approaches in hopes of finding causes for the disagreements.

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