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PATTERN BASED PARAMETER SETUP OF THE SNS LINAC*

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Abstract

Theoretical and practical aspects of beam tuning procedures used for the SNS linac are discussed. The SNS linac includes two sections of beam acceleration. Acceleration in the first section up to 185.5 MeV is done with a room temperature copper linac which consists of both Drift Tube Linac (DTL) and Coupled Cavity Linac (CCL) Radio Frequency (RF) cavities. The second section consists of 81 Superconducting RF (SRF) cavities which accelerate the beam to the final beam energy of 1 GeV. The linac is currently capable of delivering an average beam power output of 1.44 MW with typical yearly operating hours of around 4500 hours. Due to the high-power output and high availability of the linac, activation of accelerator equipment is a significant concern. The linac tuning process consists of three stages: model-based setup of amplitudes and phases of the RF cavities, empirical beam loss reduction, and then documentation of the final amplitudes and phases of RF cavities after the empirical tuning. The final step is needed to ensure fast recovery from an SRF cavity failure. This paper discusses models, algorithms, diagnostic tools, software, and practices that are used for these stages.

INTRODUCTION

The Spallation Neutron Source (SNS) is an accelerator-based neutron source. The particle accelerator consists of a 1 GeV linear accelerator (linac) and a 250-meter circumference accumulator ring. The accelerator has been in neutron production mode since 2006. From that time through 2013 the beam power was slowly increased to 1.4 MW until mercury target issues required beam power reduction to maintain high reliability. From 2013 through 2018 the mercury target issues were minimized and the beam power on target was increased up to 1.4 MW. The facility now runs routinely at the 1.4 MW beam power level.

Though there have been significant mercury target reliability issues the accelerator availability at SNS has consistently run above the 90% availability commitment for the facility. Reaching that goal has been a slow and steady process of reducing downtime (see Fig. 1) and trip rates (see Fig. 2) for accelerator equipment. The process for downtime reduction has been to record equipment downtime data and devote resources to the equipment that cause the most downtime. The process for fault frequency reduction was a similar process: record trip statistics and focus resources on the equipment causing the highest frequency of trips.

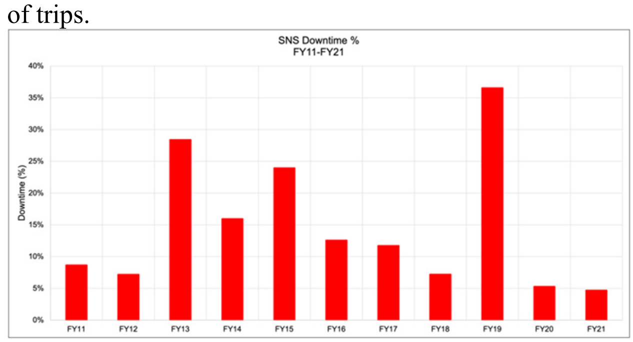

Figure 1: SNS downtime percentage over time.

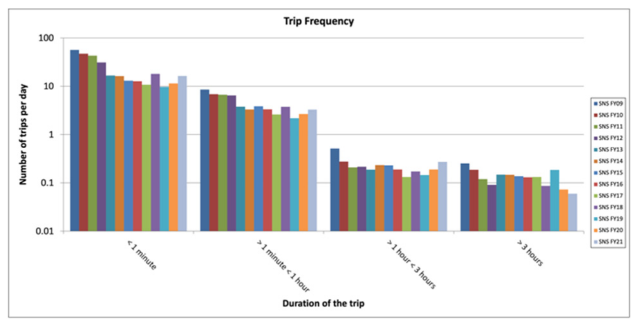

Figure 2: SNS binned trip frequencies over time.

One of the areas of focus for trip frequency reduction centered on the Drift Tube Linac (DTL) and Coupled Cavity Linac (CCL) cavities, called the warm linac. This was because when these cavities fault they cause significant beam loss in the Superconducting Cavity Linac (SCL). The beam loss can negatively impact the SCL performance.

To reduce the negative impact on the SCL the warm linac cavity faults needed to be reduced. One method found to minimize trip rates was to run the warm linac cavities away from design RF amplitude and phase. The beam tune-up algorithms had to be adjusted to routinely recover to the same off-design warm linac RF amplitudes and phases after maintenance periods.

BEAM TUNE-UP PROGRESSION

The warm linac RF setup at SNS from commissioning through the first 5-7 years of operation was done using the application Phase and Amplitude Scanning and Tuning Analysis (PASTA) [1]. This method uses the phase signature method previously demonstrated at Fermilab [2]. The

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PASTA method scans the RF phase over a relatively wide range and compares the measured Beam Position Monitors (BPMs) data to a longitudinal tracking model. The BPMs downstream of the cavity being scanned are monitored and the phase difference between the BPMs is compared against the model for multiple RF cavity field settings. This method worked well but had drawbacks based on the way we have ended up running the warm linac RF cavities amplitudes and phases.

Warm Linac Fault History

There must be a balance between the physicist perspective of running at design and operational perspective of running off design to maintain high beam availability. During the commissioning phase and first few years of running, the warm linac RF cavities amplitudes and phases were set to design at the beginning of each run period and attempts were always made to maintain the nominal design amplitude and phase. Eventually the priority shifted from maintaining nominal design settings to settings that lowered beam losses and RF trip minimization. During runs the RF amplitudes and phase were empirically adjusted (see Fig. 3) to minimize beam losses and trip rates.

The issue was at the beginning of each new run period the field and phase would be restored to the design settings, and the same process would occur; the fields and phases would be adjusted to minimize beam losses and RF cavity trip rates. It was soon understood that operations needed the ability restore the RF amplitude and phase to previous setups at the start of a run instead of starting at design.

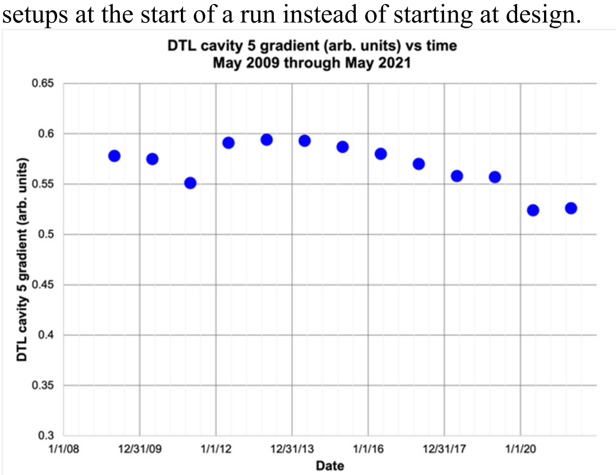

Figure 3: DTL cavity 5 field setting over time. Before 2015 the field was set using PASTA. Once the method was switched to pattern based 360-degree scan setup it enabled the ability to move the field setting away from design and set it based for minimum fault rate. The continual decrease in field may indicate a developing issue with the DTL5 cavity.

Warm Linac Tuner Wizard Application

The easiest solution would be to just restore RF setpoints from the previous run. The issue is there are no guarantees the RF field or phase calibrations or offsets or the BPM phase calibrations or offsets will be the same after maintenance is performed. New pieces of hardware can introduce differences in calibrations or delays which will make the previous settings incorrect.

The PASTA software does allow for individual cavities to have saved profiles which can be a starting point for the next tune up. This works well until, for example, a phase offset changes. When a phase shift occurs an expert is required to understand the data and properly set the phase and amplitude scan ranges. This significantly slows down the process and does not allow the ability for operations to perform the setup process. To try to simplify the process an additional application was developed called the RF phase shaker application. The application adjusts each cavity RF phase one at a time while monitoring the change in downstream BPM phase. The data are then compared against the model to determine whether the cavity setting was at design. The process did work well but was only good for the beginning of the run for the initial setup. As soon as the RF cavity amplitudes or phases were moved away from the design the RF phase shaker app was no longer a good diagnostic to determine the proper setup.

Operations requested to physicists to keep the RF amplitude settings for warm linac cavities at previous run settings. The request is a bit flawed because just restoring to previous settings will not work as described previously. Operations discussed the issue with Low-Level Radio Frequency (LLRF) experts, and the decision was made to restore RF amplitude settings based on saved net RF power settings (forward – reflected power). The reasoning was that detectors for RF power are regularly calibrated and should be reliable for determining the proper relative RF amplitude setting. This change only solves the issue of amplitude, but the issue with phase offsets remained. With RF amplitudes set away from design, the RF phases must also be moved away from design to maintain minimal beam losses downstream. PASTA does not have the ability to set phases off design, so a new application was needed.

The warm linac tuner wizard was created to solve these issues. The wizard follows a similar method as described in [2]. The RF cavity phase is scanned over a 360-degree phase range, and BPM phase data are compared against the model to determine amplitude and phase distance from design. At SNS the BPMs are installed internal to each cavity. One BPM is placed before the first RF gap and one at the end of the cavity. The change made for the warm linac tuner wizard was to use BPMs within the cavity being scanned to determine the amplitude and phase distance from design.

It was unclear whether using internal BPMs would be possible due to the response of the BPMs relative to their location within the cavity. The first BPM response may not produce a low error fit that translates to a reproducible low beam loss setup. It was also unclear whether a low error fit would be possible based on the response of a BPM late in the cavity after the beam traverses so many RF gaps.

Pattern Based Setup Performance

The application was developed with the operational setup in mind: minimize beam setup time and restore to the previous tune. The scanning process is nearly automated.

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Beam loading impacts the reproducibility of the setup, so the beam current is reduced during the scanning. The SNS complex is thoroughly detailed in [3]. The nominal 1 millisecond long beam pulse is reduced to 1 microsecond. The beam chopping occurs in the Low Energy Beam Transport (LEBT) just upstream of the RFQ. The reduction to 1 microsecond is important because if a longer beam pulse is used the beam loading will cause a phase slew from the inability of the LLRF for the RFQ to compensate. With the short pulse the RFQ cavity response time is too slow to react to the beam loading. There is an aperture restriction device downstream of the RFQ which is inserted to further reduce the beam current for the DTL and CCL cavities.

There are 4 Medium Energy Beam Transport (MEBT) bunching cavities, 6 DTL cavities, and 4 CCL cavities. The beam energy acceleration is from 2.5 MeV to 87 MeV in the DTL and from there up to 186 MeV in the CCL [3].

The application begins in the MEBT performing 360-phase scans of each cavity using single BPMs downstream of each cavity. All downstream cavities are "beam blanked" meaning the downstream RF cavities do not pulse when there is a beam trigger. The cavity is scanned 360 degrees and the design point is found. Then the application adds a phase offset relative to the design (saved previously after empirical tuning). MEBT RF amplitudes are not adjusted run to run. Figure 4 shows an example scan from a MEBT RF cavity.

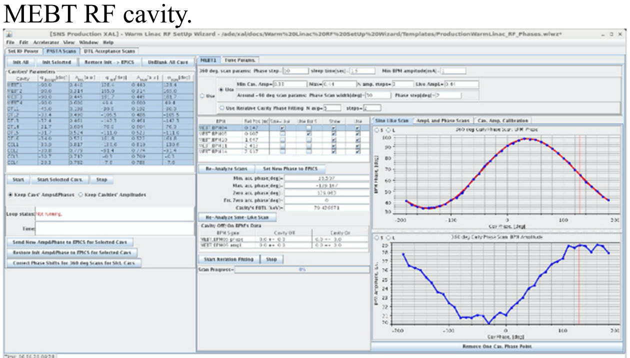

Figure 4: Warm linac tuner wizard window showing a MEBT cavity scan. The top plot on the right shows the BPM phase as a function of the RF cavity phase. The lower plot is the beam current seen by the BPM used during the scan.

For the DTL and CCL the application performs the same 360-degree scan and compares the field and phase on the BPM relative to the model. The application then sets the amplitude and phase based on the previously saved amplitude and phase offsets.

The pattern fitting errors in amplitude and phase are on the order of 1%. An example scan for DTL cavity is shown in Fig. 5. This is a BPM late in the cavity which changes the shape of the sinusoid due to the many RF gaps before the BPM.

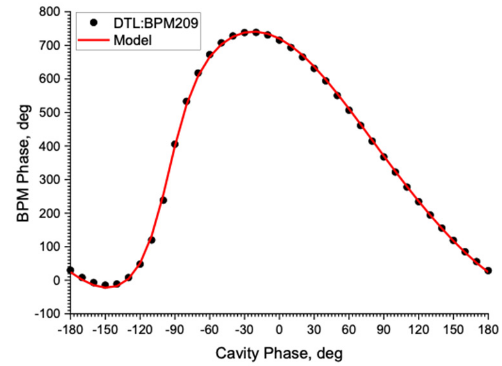

Figure 5: Example of a DTL cavity 2 phase scan showing the model (red line) and the BPM data (black points).

Pattern Based Setup Process

The process below details how to perform the RF and beam setup.

1. Perform a 360-degree RF phase scan while recording the phase from the BPMs located within the RF cavity being scanned.
2. Compare the BPM phase data to the model BPM phase prediction to find the difference from the design (in amplitude and phase).
3. Adjust RF amplitude and phase to design based on the measured differences in Step 2.
4. Perform empirical tuning to minimize beam losses and trip rates.
5. Perform Steps 1 & 2 again to document the new difference from design but do not change RF amplitude and phase back to design. Store the amplitude and phase offsets from design.
6. In the future perform Steps 1 & 2 but then use the amplitude and phase offsets found in Step 5 to set amplitude and phase to the same difference from design.

CONCLUSION

The warm linac tuner wizard allows operations to restore the RF setup quickly to the previous run setup based on the offset from the design RF amplitude and phase. This recovery method has significantly reduced the tune up time for the linac enabling the near immediate return to the minimum beam loss setup.

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