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FULLY AUTOMATED TUNING AND RECOVER OF A HIGH POWER SCL

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Abstract

Techniques have been developed for a fast (less than one hour), fully automated tune-up a high-power proton Superconducting Cavity Linac (SCL), as well as fully automated recovery from a cavity failure with no human intervention. These methods have been developed and demonstrated at the Spallation Neutron Source (SNS) SCL, but they are applicable to hadron SCL operation in general and will be especially relevant to future ADS applications.

INTRODUCTION

Any existing and future high-power hadron superconducting linacs have tens or hundreds of accelerating superconducting RF cavities. Therefore, the tuning process for these accelerators could take hours with high probability of human mistakes if it is performed by operators. For user facilities shortening the initial tuning setup time as well as the retuning (for different configurations) time is very important for good availability. In the first part of this paper, we describe the tuning process for the SNS superconducting cavity linac [1].

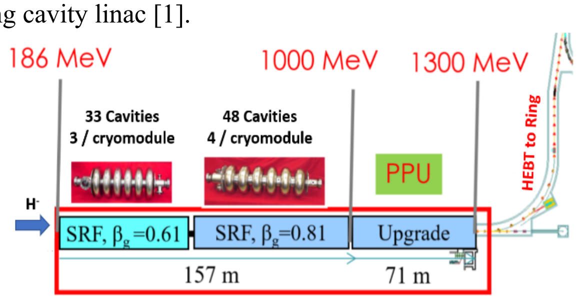

Figure 1: SNS superconducting linac. The last part of the SCL is an empty space holder for future cryomodules of the PPU project.

At this moment, the SCL accelerates H^- ions from 185.6 MeV to 1 GeV (after completion of the Proton Power Upgrade (PPU) project the final energy will be 1.3 GeV). The H^- ions are then injected into an accumulating ring to reduce the beam pulse width from ≈1 millisecond to ≈1 microsecond. The linac repetition rate is 60 Hz producing 1.44 MW of beam power at the exit of the linac.

The SCL configuration is shown in Fig. 1. The acceleration is provided by 81 RF cavities that are enclosed in 23 cryomodules. The RF resonant frequency of all cavities is 805.0 MHz. There are two types of superconducting cavities, one for medium relativistic beta parameter (0.61) and the other high beta (0.81). There is no difference between these types of cavities from the point of view of phase and field gradient control. The working temperature of the SCL cavities is 2 K.

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The SNS SCL is operated with energy margin by leaving the final 1-2 RF cavities on but not accelerating. This is to be able to operate with one or two cavities offline (damaged couplers, mechanical tuner problems etc.). If one of the cavities is turned off during operation, the SCL can be immediately retuned by operators in a matter of minutes. This process also can be automated, and it was demonstrated during an experiment. The topic will be discussed in the second part of the paper.

SCL RF CAVITY SETUP PROCESS

A setup process for an RF cavity includes defining two parameters: field gradient (also called amplitude of the cavity in the control system) and phase. At SNS the amplitude of each cavity in the SCL is defined after initial RF conditioning after extended maintenance periods and before each production period. The amplitude should be as high as possible, but it should be low enough to avoid cavity trips caused by field emission and multipacting.

During the SCL tuning process, amplitudes of the cavities are not changed. If during a production run, particular cavity demonstrates increased trip rates, then the amplitude of this cavity is decreased, or it could be switched off completely. After that, the retuning procedure should follow. The distribution of cavity amplitudes for one of run periods in 2022 is shown in Fig. 2. This figure demonstrates that cavity gradients are not the same even inside each section, and we cannot consider the SCL as a periodic lattice.

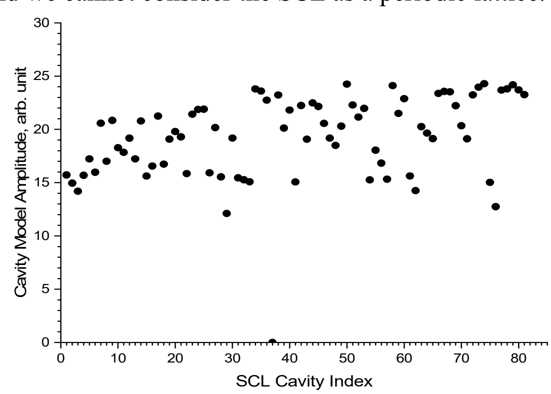

Figure 2: SCL cavity amplitudes on 03.15.2022.

Four Stages of SCL RF Phases Tuning

For the beam-based setup of SCL cavity phases we use a well-known Time-of-Flight (TOF) method. To measure the time-of-flight we have Beam Position Monitors (BPM) that are installed after each SCL cryomodule. In addition to the transverse deviation of the beam from the center, these BPMs can measure the beam bunch phase relative to the RF reference line and the amplitude of a signal generated by bunches passing through BPM.

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The cavities are tuned one by one. When we perform a phase scan of a particular cavity, there are no RF fields in any of the downstream cavities. It is achieved by not applying RF to these cavities when the beam pulse is triggered. The beam repetition rate is 1 Hz during the tuning, so RF cavities remain stable by still pulsing at 59 Hz. Excluding only 1 RF pulse does not create instability in the control system of SNS cryogenic facility that supplies 2 K helium to keep the cavities cold.

During the beam-based tuning, we use very short (around 0.5 us beam pulse) with 6 times reduced (relative to the production conditions) beam peak current of approximately 5 mA. It means there is not beam loading in the downstream cavities that can affect our TOF measurements.

There are four stages in the SCL tuning process:

- Setting up cavity phases using a TOF-like approach without any knowledge of BPMs timing calibration.
- Measuring the beam energy using the SNS ring.
- Perform BPM timing calibration by backward analysis of the cavities phase scan data collected during the first stage and assuming the energy measured during the second stage.
- Perform a model-based analysis of the phase scans using known timing calibration of BPMs and save model parameters for a possible retuning in the future.

Initial Phase Scan of SCL Cavities

The cavity scan includes changing the cavity phase from -180^0 to $+180^0$ and recording the beam bunch phases from two BPMs downstream of the cavity. The cavity and the BPMs have their own phase offsets from the RF reference line as shown in Fig. 3. At this stage we assume all these phase offsets are unknown to us.

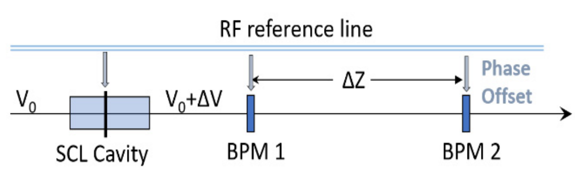

Figure 3: SCL cavity phase scan TOF scheme.

The BPM phase difference is defined by the velocity of the bunch and the distance between BPMs

$$\Delta\phi_{BPM} = \omega_{BPM} \cdot \frac{\Delta z}{V_0+\Delta V} + const;\ \Delta V \ll V_0 \qquad (1)$$

where ω_{BPM} is a BPM's Fourier analysis frequency, Δz is a distance between BPMs, V_0 and ΔV are velocity and a change in velocity after exiting the cavity. The change in the velocity is small, so at the first order it is proportional to small energy change:

$$\Delta V \sim \Delta E \sim U_{RF} \cdot cos(\varphi_{RF} + \delta\varphi_{RF}) \qquad (2)$$

where U_{RF} is an effective voltage of the cavity, φ and $\delta\varphi$ are the cavity phase and a phase shift relative to the RF reference line. Therefore, the phase difference between BPMs will be at the first order a "sine"-like function of the cavity phase:

$$\Delta\phi_{BPM} \cong A_{\phi} \cdot cos(\varphi_{RF} + \delta\varphi_{RF}) + const \qquad (3)$$

The BPM phase is proportional to the time of bunch arrival at BPM's position, so a minimum of function (3) will define a cavity phase for a maximal acceleration of the beam. After the cavity phase value is found, we reduce it by a value that we call a synchronous phase. If we do not have any preliminary information about cavities, we use -15^0 at the beginning. Usually, we keep synchronous phases from the previous production run as a start point for SCL tuning. The function (3) and the chosen synchronous phase is shown in Fig. 4. The measured values are not exactly a "sine"-like function, so we also add the second harmonic to (3) during the analysis. During the scan, the phases measured by BPMs cannot go beyond $\pm180^0$, so we add or subtract 360^0 to get a smooth curve in Fig. 4. To get exact number of 360^0 that we should apply, we use data from BPMs between BPM1 and BPM2 (see Fig. 3).

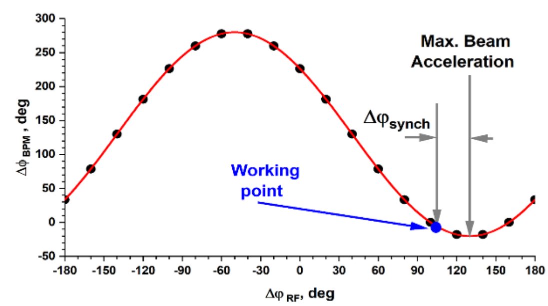

Figure 4: Phase scan of SCL RF cavity.

The accuracy of cavity phase for the maximal beam acceleration is better when BPMs are far away, and the amplitude of the curve in Fig. 4 is big relative to the beam phase jitter (vertical errors) for each measured point in this figure. On the other hand, the BPM amplitude signal, which is defined by bunch length, should be high enough to reliably get BPM's phase. These are considerations for choosing BPM pairs for each cavity.

Generally, this type of phase scan along the whole SCL should include quadrupole adjustments to account for the beam energy change in the scan process and to provide a good beam transport to the end of the section. Fortunately, at SNS we do not need this because of a big beam pipe and cavity apertures (82 mm).

The described process of the cavity phase setup does not need any information about cavity amplitude, phase offsets for cavity and BPMs, and even distance between BPMs. Usually, we use scan steps of 20^0 or 15^0 for 81 cavities, and the scan time for the entire SCL is 30-45 minutes. The process is automated.

Measuring Final Beam Energy after SCL

The timing calibration of the BPM system could be performed in different ways. Before commissioning of the SCL linac, it was calibrated by our beam instrumentation group, but later we abandoned this practice due to workforce shortage. We implemented the procedure that includes measuring the beam energy using the SNS ring and

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calibrating BPMs downstream of the last SCL cavity where the beam trajectory is still in a straight line, and the energy is constant. This approach and its verification are described in [2]. This stage of the tuning process (if it is needed) is not fully automated, and it involves the system-experts but only in the control room and for a short period of time (10-15 minutes).

When the timing calibration parameters of BPMs in this section are found, we keep them inside the tuning application, and they usually do not change without repairs of the RF distribution line, BPM software updates, or cable replacement.

Timing Calibration of SCL BPMs

After the previous stage, we have a set of calibrated (known phase offsets from the RF reference line) BPMs. They are physically downstream of the last SCL cavity. Combining these data with the phase scan of the next upstream cavity which has an uncalibrated BPM after it, we use data for all phase points in the scan to estimate the phase offset of this BPM, and we add this BPM to the set of calibrated ones. Going upstream through all cavities, we reach the start of SCL, and we know phase offsets for all BPMs including errors of this parameter. It should be emphasized again that up to this point no cavity model is involved in the analysis. Following the BPM offset calibration the application moves downstream, from beginning of the SCL to the end, calculating the physical parameters for each cavity.

SCL Model Initialization

After the previous stage, we can calculate the energy of the beam for each cavity phase value during the scan. Also, we can check that BPM phases are linearly proportional to the BPM position at any of these points. This supports our assumption about an absence of beam loading effects from the downstream cavities. For each cavity we get the energy at the entrance interpolating scan data from the neighbouring upstream cavity. Knowing this energy and the function of the exit energy as the cavity phase we can calibrate the cavity model. Operating with energy only allows us to ignore the relations between BPM and cavities phase offsets.

At SNS most applications for the control room are based on OpenXAL a high-level accelerator control environment implemented in Java and Jython [3,4]. This environment includes an accelerator online model which in turn has SNS superconducting cavity model [5]. The model describes the superconducting cavity as a set of 6 zero-length accelerating gaps. Each gap has its own voltage and transit-time factor (TTF) as functions of the beam energy. The relative ratio between gap voltages is calculated from the simulated field in the whole cavity, and TTF functions are from this field longitudinal distribution. The cavity has one normalization factor for all 6 gaps which we call a cavity amplitude. The phase of the cavity is defined by the phase of the first accelerating gap in the cavity. The amplitude and phase offset between model and the RF distribution line are found by optimizing these parameters to the best agreement with the output energy as the function of the cavity phase. This function has a "sine"-shape like the one shown in Fig. 4. Our estimation for accuracy of the cavity amplitude and phase are 1% and 1 degree respectively.

Empirical Beam Loss Reduction in SCL

The SNS design of the SCL did not predict any noticeable beam loss because of large aperture and ultra-high vacuum in this section. Nevertheless, during the commissioning and power ramp up there was substantial beam loss and activation were measured. The beam loss was reduced by increasing transverse beam sizes. Later, it was found that this beam loss is caused by the intra-beam stripping mechanism (IBSt) which is universal for H- beams [6,7]. At this moment, IBSt is not included in any SNS simulation models. The common practice of beam loss tuning in SCL is an empirical beam loss reduction by changing cavities phases and quadrupoles gradients after the initial 4-stages setup. This beam loss tuning continues during the production run when the tuning time is not limited. Later, we perform the full RF phases scan without really changing the final cavity phases and use these results as a pattern for future initial setups.

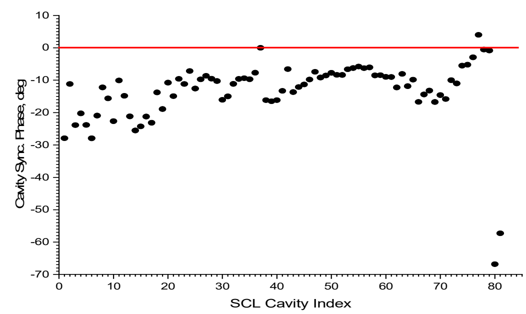

Figure 5: Synchronous phases of SCL cavities on 03.15.2022. Two last cavities are in reserve and do not provide full acceleration.

One typical set of synchronous cavity phases is shown in Fig. 5. It demonstrates somewhat chaotic structure which could be a reflection of cavity amplitudes in Fig. 2. Because of the empirical approach, we are not sure that the found beam loss minima is global, and unsure if it can be improved.

LOST CAVITY AUTOMATED COMPENSATION EXPERIMENT

After the model initialization, we are ready to calculate changes in the real machine if we need to change cavity amplitude (assuming linear dependency between the model and the control system cavity amplitude) or synchronous phase for one or several cavities. Calculations for this change take less than one second. The main reason for the cavity amplitude change (decreasing it in most cases) is an elevated trip rate or a quench. Usually, during initial tuning we set the last 1-2 cavities in the SCL at -90^0 synchronous phase (no acceleration) as a reserve to use them in the future to maintain the same beam energy output even with degradation of some cavities upstream. The synchronous phase changes are also necessary for some beam physics

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experiments, and it is done fast without performing new SCL phase scans. The accuracy of the model predicted final energy after retuning is about 1.5 MeV on the top of 1 GeV beam. The difference between the model-based prediction and the real results is not understood. At this time, it is theorized that the cavity model must be improved.

As for the transverse optic changes during the adjustment of RF cavity phases, we usually do not need to make changes, because energy differences are small.

Failed Cavity Compensation Experiment

It is not a frequent event, but from time to time we at SNS lose functionality of one of the SCL cavities during neutron production runs. After this, operators follow a standard technical procedure: documenting beam and cavity parameters, vacuum, calls to experts, detuning the cavity from the resonance frequency, and, finally, retuning the downstream cavities to get the same beam output energy, and restoring the production power. The last part is not different from the retuning for the cavity amplitude change described in the previous subsection.

The beam downtime is usually around 15-30 minutes, and it is not considered as a main threat to the 90% availability of the whole facility. That is the reason why not much effort was put to automate the recovery process for this type of event. Nevertheless, a possibility of the beam recovery automation is important question for future of Accelerator Driven System (ADS) accelerators. They will need fast recovery in a matter of seconds or less, so we implemented and tested the automated recovery to the full production power after one cavity failure [8].

The SNS power on the target restoration was automated, but some initial preparations were needed to avoid the lengthy process of software development for steps that can be done manually in advance. The preparations for the experiment included

- The failed SCL cavity was chosen to be intentionally tripped and switched off. It was a cavity in the middle of SCL to avoid quadrupole gradients retuning.
- The new cavity real phases were calculated to keep the synchronous phases the same for all downstream cavities except two last ones that were used to correct the final energy. The table with new phases was stored in the operating memory of the tuning application.
- These new phases were tested in the live machine. Waveforms of Adaptive Feed Forward (AFF) RF systems were generated with the retuned beam. These waveforms are used to compensate beam induced loading effects in cavities in addition to feedback system. The AFF waveforms also were stored in the application memory for each cavity downstream.
- After that the initial settings and production power were restored.

To start the experiment the operator intentionally sent signal that stopped supplying RF power to the cavity. This signal stopped the beam, and our high-level application began the beam restoration process. First, it started the detuning process of the switched off cavity. It must be done to avoid cavity excitation from the beam which in turn causes beam loss downstream. When beam bunches pass through the cavity, they will induce an electromagnetic field at the bunch frequency. If the cavity is still at or near the resonant frequency (bunch frequency), the beam will be decelerated and will arrive at the wrong synchronous phase at the entrance of the next cavity. The cavity frequency detuning is done mechanically, so it is not fast. Figure 6 shows cavity's resonant frequency shift as a function of time. Our experience says that the detuning of 7 kHz is sufficient to avoid significantly elevated downstream beam loss. It means that downtime will be at least 10-15 seconds which could be unacceptable for ADS accelerators.

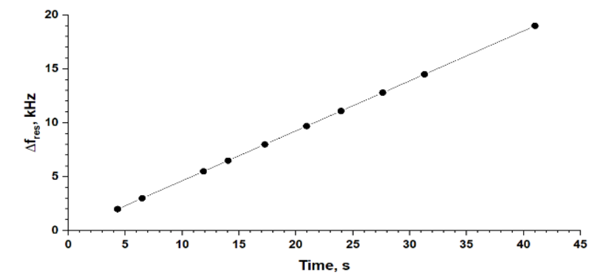

Figure 6: Time dependency of cavity's resonant frequency shift during the cavity detuning process.

The uploading of the new cavity phases and AFF waveforms is a fast process, and it was done at the start of the "damaged" cavity detuning process. The beam at 1 Hz repetition rate was restored after 5 seconds after the start of the experiment. The repetition rate was increased to 60 Hz during the next 60 second because of administrative restriction for SNS operations. Without this restriction it can be done instantly. Figure 7 shows time dependency of the normalized beam loss. It also shows that if we can tolerate increased beam loss for some period, we can reduce the downtime to at least 5 seconds which still could be unacceptable.

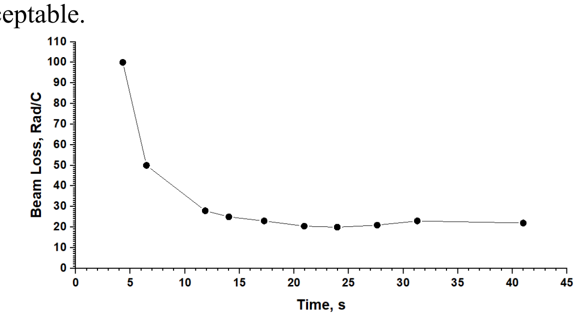

Figure 7: Time dependency of the average beam loss along SCL normalized to the charge delivered to the target.

The average beam loss of 20 rad/C corresponds to a beam fraction loss less than 10^{-4} [7], and less than 1 W/m for 250 meters long SCL. In addition to that, the beam loss at SNS superconducting linac is caused mainly by the IBSt process for H^- beam. It is expected that future ADS accelerators will use protons so beam loss should be a less significant issue. As an example, when SNS accelerated protons instead of negative hydrogen ions, beam loss was reduced by at least a factor of 30 [7], so the time of cavity detuning to the acceptable losses could be reduced for protons even further than 5 seconds.

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CONCLUSION

At SNS automated tuning and fast retuning of a superconducting cavity linac that includes tens of accelerating cavities has been demonstrated. The SCL is a very flexible system capable of delivering megawatt power beam even after one or several cavities are disabled.

It also was shown that it is possible to automate a fast beam power recovery after losing one of the SCL cavities. In the SNS case the best achieved recovery time was approximately 5 seconds. In shortening this time, two problems were identified. The first is a mechanical detuning of the cavity resonance frequency though it is probably possible to speed up this process without damaging the cavity. The second is the unknown Adaptive Feed Forward waveforms of the low-level RF control system in downstream accelerating cavities. A model-based algorithm for generating these AFF waveforms should be developed.

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