A FAULT RECOVERY SYSTEM FOR THE SNS SUPERCONDUCTING CAVITY LINAC*

J. Galambos, S. Henderson, Y. Zhang, SNS, ORNL, Oak Ridge TN, 37830, U.S.A.

Abstract

One reason for the Spallation Neutron Source (SNS) adoption of superconducting cavities, was the possibility of fault tolerance. Namely, the ability to rapidly recover from a cavity failure, retune the downstream cavities with minimal user disruption. While this is straightforward for electron machines, where beta is constant, it is more involved for the case of proton machines, where the beta changes appreciably throughout the Superconducting Linac (SCL). A system for quickly calculating new cavity phase setpoints in the event of the change in one or more cavity amplitude and or phase settings has been developed. Typical phase adjustments are in the 100 – 1000 degree range. This system has been tested on the SNS SCL in both controlled tests and a need based cases. This scheme and results will be discussed.

INTRODUCTION

The SNS uses a Superconducting RF Cavity linac (SCL) as the primary means of particle acceleration. There are 81 independently powered cavities in the SRF portion of the linac, which nominally increase the beam energy from 186 MeV to 1000 MeV. Since only two geometric beta cavity families are employed, there is considerable flexibility in the possible beam energy throughout the SCL. However, each cavity's phase relative to the klystron's RF must be independently set. In order to take advantage of the SCL's flexibility, it is necessary to quickly adjust the cavities phase settings when an upstream cavity phase or amplitude changes (e.g. a klystron problem). While this is straightforward in the case of electron machines where β = 1 it is more complicated for the case of proton machines, where the beam β value changes appreciably throughout the SCL.

We have developed a model based method to quickly provide new cavity phase setpoints in the evebt of a change in a cavity's amplitude or phase. It requires first measuring each cavity phase setpoint and cavity field level by a beam based means during an initial tune-up. The cavity phase setpoint of each cavity is used as an arrival time map for nominal conditions. Using known cavity positions, the changes in the beam arrival time (hence cavity phase setting) because of a change in an upstream cavity's phase and or amplitude are calculated based on the changes in the beams velocity throughout the linac. This method has been successfully tested on the SNS SCL with up to 10 simultaneous changes in cavity settings. The method and some example applications are described.

* ORNL/SNS is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

METHOD

Model

A simple drift-kick-drift longitudinal transport model between the RF gaps is employed [1]:

$$\Delta W = qE_0 TL\cos\phi_{0,}$$

$$\Delta\phi = \frac{qE_0 L}{mc^2\beta_1^{\,2}\gamma_1^{\,3}} kT^{'}\sin\phi_0\,,$$

$$\phi_0 = \phi_1 + l_1\frac{d\phi_1}{dz} - \Delta\phi$$

$$\phi_1^{+} = \phi_0 + l_2\frac{d\phi_0}{dz}$$

where q is the particle charge, E_0 is the integrated gradient over the entire length L of the RF structure, k is the wave number, l_1 is the distance from the cell entrance to the center, l_2 is the distance from the cell center to the cell exit, φ_1 (ϕ^{+}_1)is the RF phase at the cell entrance (next downstream cell entrance), mc^2 is the rest energy, β_1 and γ_1 are the relativistic factors at the first half cell, T, and T' are the transit-time factors which are taken from the SUPERFISH [2], φ_0 is the particle phase at the gap center, $\Delta\varphi$ is the phase change due to beam acceleration in the RF gap and ΔW is the energy gain received at the gap center. Each cavity's cell positions are assumed to be at the ideal design values.

Initial Cavity Setup

Before the cavity scaling can be employed, it is necessary to use a beam based method to set each cavity phase relative to the RF, and to determine each cavity field value (E_0). This is possible to do in different ways [3], but we typically use a phase scan technique to provide this information which involves scanning the cavity phase over 360 degrees and measuring the phase difference between two downstream phase detectors. This is done with a minimal beam intensity so as to not cause appreciable beam loading effects in intervening cavities [4]. Then the cavity field (E_0) beam phase offset from the klystron offset, and input beam energy are solved for to best match the measurement data. This scheme is depicted schematically in Figure 1 and a typical result is shown in Figure 2.

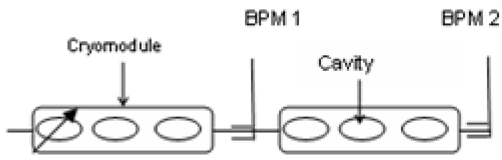

Figure 1: Schematic of the phase scan technique for determining the beam phase relative to the RF, where the BPMs provide an absolute beam phase measurement.

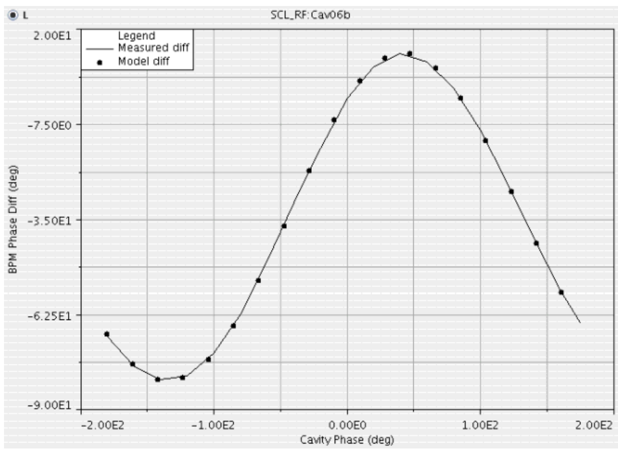

Figure 2: Typical phase scan result showing the measured beam phase difference vs. the cavity phase. Lines are measurements and dots are model predictions with matched values for field, RF phase offset to the beam, and input beam energy.

Cavity Phase Scaling

Using the measured cavity amplitudes and the known cavity positions, the arrival time of the beam at the start of each cavity "*n*" is calculated with the model and tabulated:

$$t_n = \int_0^L \frac{dl}{v},$$

where v is the beam velocity throughout the linac. If a cavity(s) amplitude or phase is changed, the downstream arrival time will be altered. The new arrival time at each cavity (t_n^*) is straightforward to calculate with the model using the modified E_0 and ϕ_0 for each cavity. The change in each cavity's phase setpoint ($\delta\phi_n$) is:

$$\delta\phi_n\,(\text{deg}) = 360(t_n^* - t_n)(\text{sec})\,f\,(Hz) + \delta\phi_{slip}^n$$

Where f is the cavity frequency and $\delta\phi_{slip}$ is the change in the phase slip through the cavity because the beam energy has changed from the nominal input energy. The phase slip is the change in beam phase from gap to gap caused by the beam having a beta different from the cavity design geometric beta. The $\delta\phi_{slip}^n$ term is usually small (<10 degrees) and is found by numerical iteration.

ERROR ESTIMATE

Cavity Position Uncertainty

The inherent uncertainty in the cavity positions in the cooled-down SCL cryostats leads to some error in the scaled phase setpoints. Figure 3 shows the cavity phase scaling error for different errors in the assumed cavity position, and different changes in the beam energy due to cavity failure. Even at the lower energy range of the SNS SCL, with a 1 cm cavity position error and a 10-20 MeV cavity failure induced beam energy change, the scaled cavity error is < 1degree

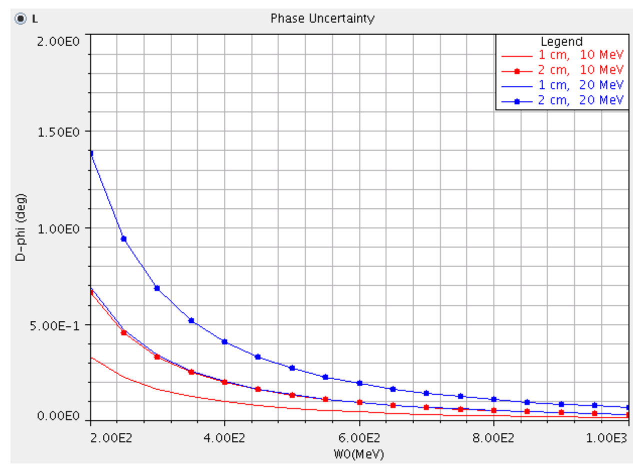

Figure 3: Cavity phase scaling error vs. beam energy, arising from cavity position uncertainty. Cases are shown for 10 and 20 MeV beam energy changes due to cavity failure. .

Beam Energy Change Uncertainty

There is also uncertainty in the scaled cavity phase setpoints due to errors in the predicted beam energy change due to a cavity failure. Figure 4 shows this error vs. beam energy for uncertainties in the beam energy change of 0.5 and 1 MeV, and for drift distances of 1.5 and 4.5 m. These distances are typical distances between adjacent cavities (the higher end being for cross cryomodule + a missing cavity case). This error is more significant, and indicates the importance of accurate prediction in the change of beam energy. Note 1 MeV is ~ 10% of a typical cavity energy gain, so the 1 MeV predicted energy gain error is quite large. This error can approach 10 degrees for a single downstream cavity at low energies.

MACHINE APPLICATIONS

The methodology described here has been incorporated in an application program and successfully used in the SNS linac. As a first example, a single upstream cavity (number 7 out of 81) was turned off and all the downstream cavity phase setpoints adjusted. Figure 5 shows the change in the cavity phase setpoints for this case. The phase changes amounts to over 1000 degree phase change at the downstream end of the linac. As a check after these changes were applied and the beam restored, a phase scan (as described above) was performed on the last cavity, and the scaled phase setpoint was within 1 degree of the measured value. Also the final beam energy was within 1 MeV of the predicted exit energy (the total beam energy change was ~ 12 MeV).

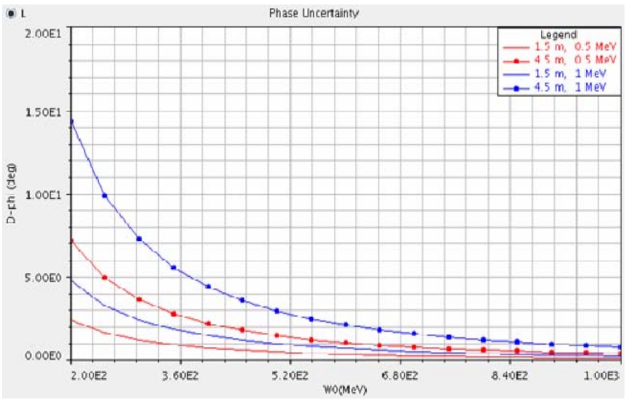

Figure 4: Cavity phase scaling error vs. beam energy, due to beam energy gain uncertainty. Cases are shown for 0.5 and 1 MeV beam energy change uncertainty and for cavity separations of 1.5 and 4.5 m.

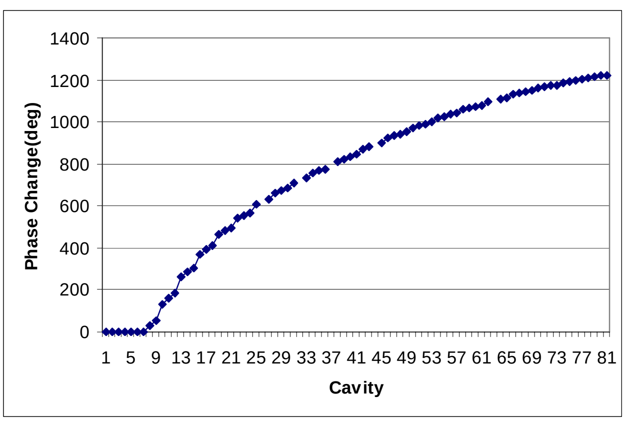

Figure 5: The predicted cavity phase setpoint change resulting from turning off cavity 7. The last cavity phase setpoint was checked with a phase scan and found to be within 1 degree of this prediction.

Another test of this scheme was when 11 cavities amplitude setpoints had to be reduced by 10-50%, and 1 cavity was turned on (previously not energized). The resulting cavity phase setpoint changes are shown in Figure 6, along with the phase setpoint error spot-checked by phase scans at a few intervening cavities. In this case there are 100's of degrees of cavity phase changes, and the phase setpoint errors are within ~ 4 degrees.

SUMMARY

A model based cavity fault recovery system has been developed. The phase scaling system has been applied several times at SNS, for both testing and for actual need based situations. No discernable change in beam loss pattern is observed when this system is applied, although we are only operating at low beam powers presently. The method is fast – it takes only seconds to calculate and send the new setpoints. This technique saves about a day's time required to marching through the entire SCL performing phase scans to individually set each cavity.

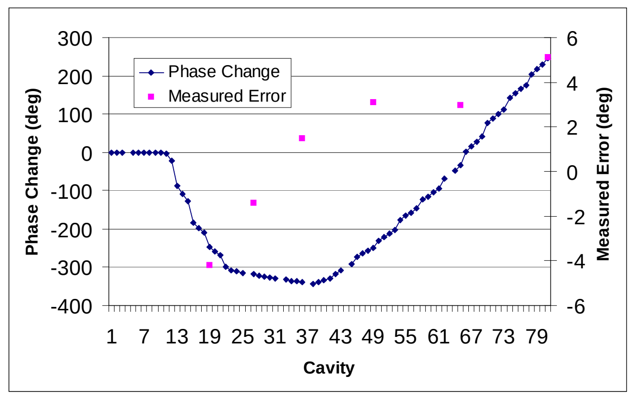

Figure 6: The predicted cavity phase setpoint change resulting from turning on cavity 10 and reducing 11 additional downstream cavity amplitudes. Some phase setpoint errors (checked by the phase scan) are indicated.

REFERENCES

[1] P. Lapostolle, M. Weiss, "Formulae and Procedures Useful for the Design of Linear Accelerators", CERN-PS-2000-001(DR), (2000).
[2] J. Billen, L. Young, "POISSON SUPERFISH", LA-UR-96-1834, LANL (2000).
[3] Y. Zhang, et.al., "Comparison of SNS Superconducting Cavity Calibration Methods", these proceedings.
[4] D. Jeon, et. al., "Beam Loading Effects on Phase Scan for Superconducting Cavities", these proceedings.