SPALLATION NEUTRON SOURCE SUPERCONDUCTING LINAC COMMISSIONING ALGORITHMS*

S. Henderson, I. Campisi, J. Galambos, D. Jeon, Y. Zhang, Spallation Neutron Source Project, Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA

Abstract

We describe the techniques which will be employed for establishing RF setpoints in the SNS Superconducting linac. The longitudinal tuneup will be accomplished using phase-scan methods, as well as a technique that makes use of the beam induced field in the unpowered cavity [1].

INTRODUCTION

The Spallation Neutron Source Linac will accelerate a 26 mA average current pulse to 1 GeV at 60 Hz. The SNS linac consists of a 38 mA peak current H^- injector, a six-tank Drift Tube Linac to accelerate the beam to 87 MeV, a four-module Coupled Cavity Linac to accelerate the beam to 187 MeV, and a Superconducting Linac to accelerate the beam to 1 GeV. The SCL consists of two types of cavities, one with geometric beta equal to 0.61 (the "medium-beta" cavity) and another with geometric beta of 0.81 (the "high-beta" cavity) [2]. The medium-beta linac consists of 11 cryomodules with three cavities per cryomodule, while the high-beta linac consists of 12 cryomodules with four cavities per cryomodule, for a total of 81 superconducting cavities. Each cavity is powered by a single 550 kW klystron providing individual cavity phase and amplitude control. The inter-cryomodule segments are maintained at room temperature, and consist of a quadrupole doublet, dipole correctors and beam diagnostics.

While a single klystron per cavity increases the operational flexibility of the superconducting linac, it also means that there are a large number of RF amplitude and phase setpoints to be established. Rapid methods for the tuneup of the linac are essential for routine tuneup and recovery from fault conditions. In this paper we discuss longitudinal tuneup and commissioning algorithms for the superconducting linac. The transverse commissioning algorithms were reported previously [3].

CAVITY PHASE SCANS

The linac beam position monitor system provides a beam phase measurement. Appropriate calibration of the phase signal will provide absolute phase measurements along the linac. This opens the possibility for tuneup procedures that utilize the time-of-flight (TOF) from one BPM to another. In the simplest tuneup algorithm, the difference in phase between two downstream BPMs is recorded as a function of the phase of an upstream cavity. A fitting procedure is then used to determine the input energy, relative beam/RF phase, and RF amplitude of the cavity in question. We assume for the moment that any RF cavities between the one under study and the last downstream BPM are unpowered, and do not affect the beam energy (the more realistic case is treated below).

We have studied the accuracy of the resulting RF amplitude and phase setpoints from this technique using a longitudinal model of the SCL beam dynamics. In this model, the RF cavity is composed of six gaps, and the thin-lens gap transformations are applied to model the phase/energy dynamics [4]. Our simple model agrees well with PARMILA [5] results.

Representative phase scans at various beam energies are shown in Figure 1. For the medium-beta phase scans the drift space between BPMs is taken to be that corresponding to drift through a single unpowered cryomodule, whereas for the high-beta scans, the beam drifts through two unpowered cryomodules.

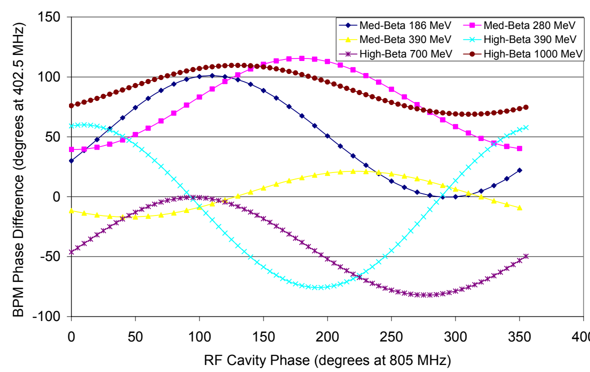

Figure 1: Phase scans for medium and high-beta cavities at entrance, intermediate, and exit energies.

One sees from the figure that due to the high-accelerating gradient large beam phase excursions are expected during a phase scan. These large phase swings make it straightforward to identify and fit the resulting phase scans for the RF setpoints and input energy. In fact, rather accurate guesses for initial conditions to a model-based fit procedure are obtained directly from the raw phase scan data.

Figures 2 and 3 show the results of a study performed on a set of 100 error runs at two energies in the medium-beta and high-beta linacs. In these error runs, a phase scan was calculated for a given input beam energy. An rms BPM phase difference error of 2 degrees was then applied to the simulated data, and the resulting scan was fit with a model-based fit procedure to obtain the input energy, cavity phase and RF amplitude. The figures show

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histograms of the errors in the resulting phase and amplitude values determined from the fit. We see that phase and amplitude setpoints within 1 degree and 1% should be achievable with this method, provided that the errors are statistical in nature, that is, assuming that the systematic errors in the procedure can be minimized.

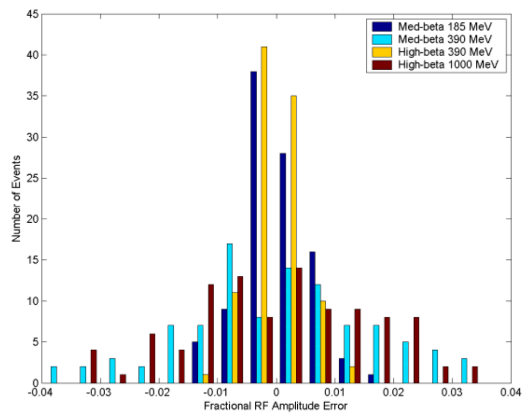

Figure 2: Histograms of resulting fractional RF amplitude errors obtained by model-based fitting in a 100-run error study.

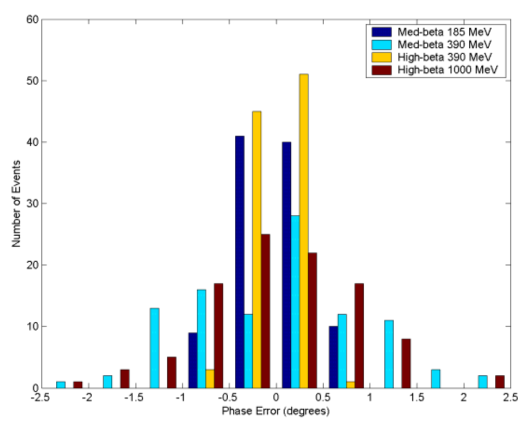

Figure 3: Histograms of resulting phase setpoint errors for various beam energies obtained by model-based fitting in a 100-run error study.

It is possible to perform the linac longitudinal tuneup in an automated "leap-frog" fashion, where one proceeds from cavity to cavity, performing phase scans for each cavity and obtaining starting guesses for the initial parameters of the fit from the phase data itself as mentioned above. This method has been studied in simulation, and an example result is shown in Figure 4. This figure displays the amplitude error (top) and phase error (bottom) along the length of the superconducting linac in a simulated automatic tuneup procedure in which for each cavity a phase scan is performed, BPM errors are applied, a model-based fit is performed, and the cavity phase and amplitude are adjusted based on the fit values. One sees amplitude errors increasing as the beam energy increases, as is expected from the decreasing signal to noise in the TOF measurement as the energy increases. Nevertheless, one sees resulting phase and amplitude errors that are in the range of 1 degree and 1%. We have performed PARMILA simulations with these resulting phase and amplitude error sets and see no measurable reduction in linac output beam quality relative to the ideal design linac.

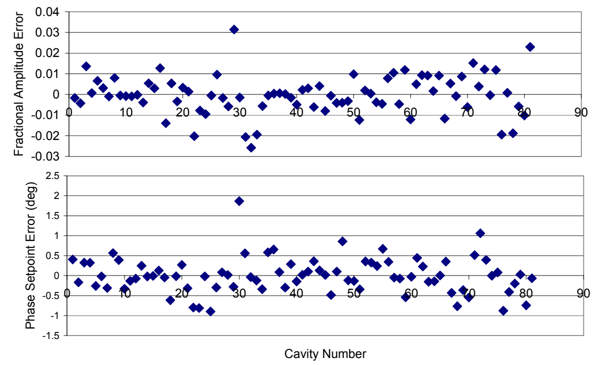

Figure 4: Cavity amplitude and phase errors after one simulated full linac tuneup.

THE BEAM-CAVITY INTERACTION

The results presented above assume that the beam is unaffected while drifting through unpowered cavities. A beam drifting through a superconducting cavity on resonance will excite large fields, and the beam will in turn lose energy, complicating time-of-flight based methods. While this is a complication that requires mitigation in order to make sensible TOF measurements, it opens the possibility for measuring the beam phase and calibrating the cavity field probe based on the beam-induced signals. This approach was explored previously in the context of SNS linac commissioning by L. Young [1]. Beam-bunch arrival time was recently demonstrated experimentally [6].

We developed a code to simulate the beam-induced signals in the cavity, in which the six passband modes are treated as independent voltage phasors with different amplitudes and frequencies; the resulting beam-induced signal is the sum of these phasors. The loaded-Q's and frequencies of these modes have been measured for each cavity, and are used as input to the simulation.

The excitation of a cavity depends strongly on the power spectrum of the beam, and therefore depends on the beam current, linac microbunch length, beam macropulse length and the detailed shape of the macropulse. Figure 5 shows simulation results for the phase of the beam induced cavity field signal in a high-beta cavity at 466 MeV, with 38 mA peak current in a 50 μs square beam pulse with 3 degree rms linac bunch length. One sees that by the end of the beam pulse, the resolution of the phase signal is better than one degree. The higher-frequency ripples are due to the nearby $5\pi/6$ mode which is only 0.8 MHz from the π mode. We conclude that measurement of the phase of the beam induced signal offers the potential for a very precise beam/cavity relative phase measurement. The existing low-level RF control system for the SNS linac already provides the capability for measuring this beam-induced signal. Since the beam-induced signal lies at the decelerating phase, it is straightforward to then establish the proper synchronous phase for stable acceleration.

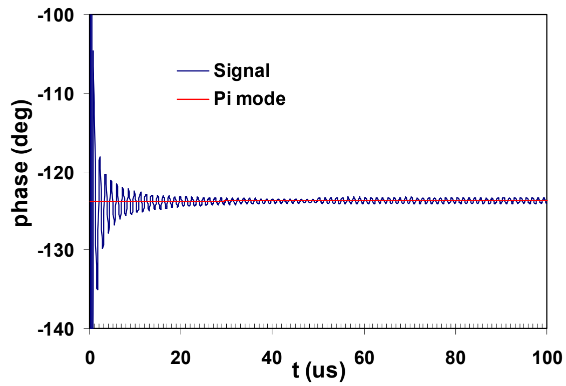

Figure 5: Phase of the signal induced by a drifting beam in an SNS superconducting cavity. See the text for beam parameters.

As pointed out in ref [1], the accuracy of this method for determining beam phase depends strongly on the cavity detuning from the resonant frequency; 100 Hz detuning results approximately in a 1 degree phase measurement error.

Because very large fields can be induced in a SC cavity near resonance by a drifting beam, phase scans which require the beam to drift through several unpowered cavities could be compromised due to energy loss in those cavities. Since the beam commissioning will be carried out primarily with short beam pulses of 50-100 μs width, the beam power spectrum is quite broad, extending several tens of kHz from the cavity resonant frequency of 805 MHz. It is therefore necessary to detune the unpowered cavities during a phase scan to minimize their impact. Figure 6 shows the induced cavity field amplitude for various amounts of cavity detuning. We

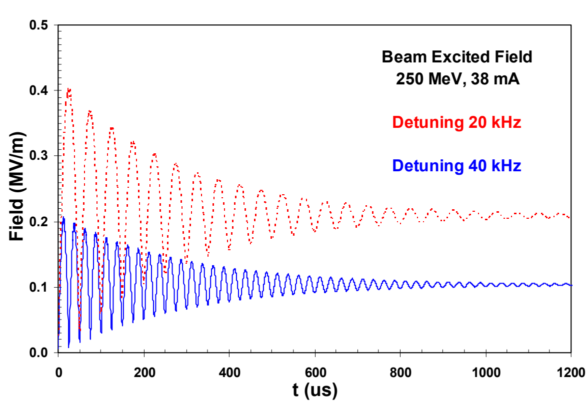

Figure 6: Beam induced field amplitudes in a medium-beta cavity for 250 MeV, 38 mA, 1.2 msec beam pulse.

anticipate detuning the cavities by approximately 30 kHz when carrying out a phase scan.

Figure 7 shows the influence of the beam-cavity interaction on a cavity phase scan in conditions which will be typical in SNS linac commissioning. The Figure shows the simulated BPM phase difference measured in two downstream BPMs for a 250 MeV, 20 mA, 50 μs ramped beam pulse, where the beam drifts through two unpowered cavities to reach BPM1, and then through three unpowered cavities to reach BPM2. One sees that with 30 kHz of cavity detuning the phase scan is affected at the few degree level, which is adequate for linac tuneup.

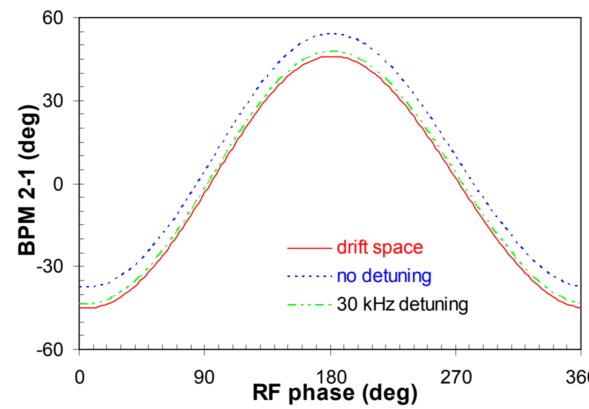

Figure 7: Beam phase difference vs. RF cavity phase including drift through unpowered cavities. The "drift space" curve corresponds to no beam-cavity interaction.

CONCLUSIONS

We have presented two techniques to determine the RF setpoints in the superconducting linac. The first relies on time-of-flight methods, while the second utilizes the beam induced fields in a superconducting cavity. These methods will be explored and compared in the upcoming commissioning run in late summer 2005.

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