LONGITUDINAL TUNING OF THE SNS SUPERCONDUCTING LINAC

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Abstract

The SNS superconducting linac delivers proton beam with about 1 GeV of energy driven by self-consistent RF cavities. Here, we present an experience of the longitudinal tune-up of the SNS superconducting linac where a new application for quick RF phase setup and cavity fault adaptation was created. The routine of superconducting linac tune-up, longitudinal beam manipulation, and radio frequency cavity phase scaling for beam state recovery is presented. The application has direct value for beam optics study and will serve as the basis for longitudinal beam-size manipulation for a laser stripping project.

INTRODUCTION

The superconducting linac (SCL) is the biggest part of the SNS accelerator for the final acceleration of the H^- beam from 185 MeV to approximately 1 GeV. This is a very unique hadron machine, consisting of 81 independently powered and controlled cavities. The parameters of amplitude and phase shift can be adjusted individually for each cavity, which reveals numerous possibilities for beam manipulation in both routine neutron production and the many-sided scientific research of hadron beams. Routine beam production only needs an appropriate output beam energy with acceptable losses and reliable cavities that operate with a nonaggressive amplitude of the cavity fields. This is a relatively simple problem with the self-consistent tune-up of the cavity phases adjusted to the appropriate output energy. In practice, it can be performed with the help of a single particle model for longitudinal dynamics that meets all the criteria for a satisfactory neutron production operation. The requirement for smooth longitudinal focusing has been simulated by the XAL model [1] and verified by the IMPACT code; however, it has never been compared with direct measurements [2].

There is a field of scientific problems related to the study of longitudinal and transverse beam optics. For example, the recent study of intrabeam stripping [3, 4] led to a conclusion about the significant effect that core beam optics has on losses. A model of the experimental behavior of a low beta core beam is extremely challenging, and a real attempt at beam manipulation with the help of the model still doesn't work well. For this reason, we need a program that realizes the SCL potential for the study of longitudinal and transverse beam optics.

There is another important project at the SNS called laser stripping [5, 6]. Successful realization of the project requires specific beam focusing, including strong longitudinal bunch shortening to 30 ps or less [6]. Transverse optics adjustment has been pretty well mastered [6]; however, the model of longitudinal shortening has not been developed yet. The SCL has the possibility for the systematic study of the elaboration of the model and final development of the program for longitudinal beam tailoring for the laser stripping experiment.

A previously developed application [7, 8] can perform a tune-up of the SCL using the simple drift-kick-drift longitudinal transport model for RF gaps [9]. The model can calculate the dynamics of the propagation of a single particle through the RF cavities as a function of the amplitudes and phases. The application performs the cavity scans with beam, calculates the parameters of the cavity, and finally, sets the appropriate cavity phase w.r.t. the beam. This procedure has to be repeated for all 81 cavities manually, one-by-one. The application also has an important function in cavity fault recovery; it can quickly recalculate the phases of all the cavities in order to restore output energy within seconds and continue beam production in the case of a cavity failure.

In this paper, we present a new application in place of the old one. The new and old applications have been developed within the XAL environment. The new application has the following new features:

- Completely automatic tune-up of the linac within two hours instead of 8-16 hours of manual tune-up with the previous version;
- Measurement of all BPM phases and amplitudes for use in the detailed measurement and study of longitudinal beam optics;
- Implementation of a more exact model with the Runge-Kutta tracking of particles through the SCL instead of the simplified drift-kick-drift method;
- Adaptation of the model to the live tune-up of the linac;
- Possibility to generate the XML optics data file of the linac for the XAL online model.

The first feature is the most advantageous because it saves a significant amount of valuable beam time and human effort during linac tuning. The next two functions have been added primarily for the potential development of the study of longitudinal beam optics in the future. The function of adaptation of the model to the life accelerator state from its saved state has been added to the program because people continuously manually change the parameters of the accelerator in order to reduce losses. The function of recovery from a cavity failure remains almost the same as in the previous application. The last feature allows the generation of a specific data file for the XAL simulation using up-to-date model parameters.

The paper is organized in the following manner: the first section will describe the basic method of cavity scanning and scan processing, the second will present the application and routine of automatic linac tune-up, and the final section will demonstrate the cavity fault recovery function and problems to be solved in future.

ISBN 978-3-95450-115-1

SCAN

For the modeling of the longitudinal dynamics of the beam in the linac, it's necessary to perform an experimental cavity measurement procedure to determine the model parameters. Scanning of each cavity of the linac over 360 degrees of klystron phase offset provides the necessary parameters for the longitudinal dynamic models after scan processing. The principal scanning scheme shown in Figure 1 is a measurement of the center-of-mass dynamic parameters of the downstream beam accelerated by the cavity.

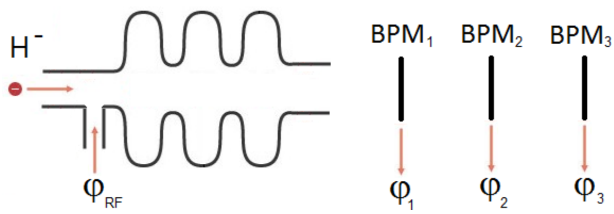


Figure 1: Schematic of the cavity scan technique with the help of BPM phase measurements of the beam.

Measurement of the beam phase is an additional function of BPM that occurs at the SNS. The beam arrival phase represents the time of beam arrival t_i via the BPM$_i$ frequency: $\varphi_i(\text{deg.}) = 360 f t_i$, where f=402.5 MHz is the BPM operation frequency. Figure 2 shows a raw cavity scan of the BPM phases of the downstream beam as a function of the cavity phase shift φ_{RF}.

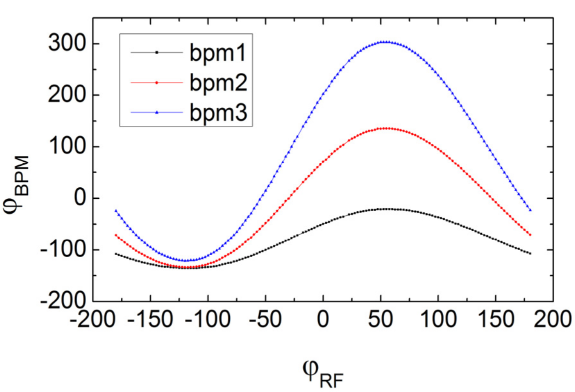


Figure 2: Typical example of a cavity scan measured at the superconducting linac of the SNS.

In this way, we can calculate the velocity of the beam and its energy as a function of the cavity phase φ_{RF} via the time of the beam flight between two BPMs. It should be noted that the BPM pair must share the same reference oscillator to accurately measure the time of flight, and that there is 360 n degrees phase ambiguity that must be resolved using knowledge of the approximate beam energy. At this time the BPM pair synchronization presents a laborious technical procedure of manual calibration of electronics.

MODELS

The next step of the linac tune up is processing the obtained scan using the models. In this section we consider two models: the drift-kick-drift model [9] that has been used in previous applications and the new model, which is based on the direct Runge-Kutta integration of a single particle. The first model has the following parametric form for output energy: $\mathrm{T_{out}} = f(T_{in}, A, \varphi_0, \varphi_{RF})$, where the model parameters of the cavity A, φ_0 as well as the input energy of the beam T_{in} can be easily calculated by matching the experimental scan $\mathrm{T_{out}}(\varphi_{RF})$. Consequent scanning of all the SCL cavities provides a complete model of the linac with parameters A_i, φ_{0i}, where $i = 1\ldots81$. In this way, we can control the energy of the beam by setting the cavity phases φ_{RFi}. The second model considers the 1D relativistic dynamics of the charged particle through the fields of RF cavities given by the formula: $E_i(z,t) = E_0 f_i(z)\sin(\omega_{RF}t + \varphi_0 + \varphi_{RF})$. Here, $f_i(z)$ is a function of the field distribution in a cavity. Figure 3 shows an example of the ideal field distribution for low beta cavities of the SNS.

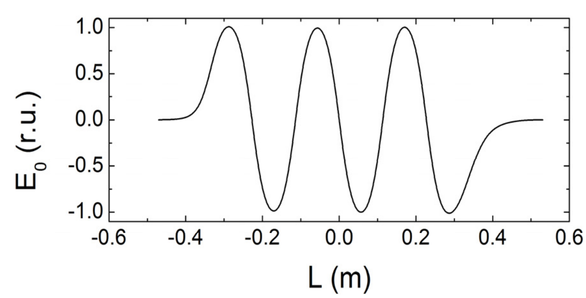


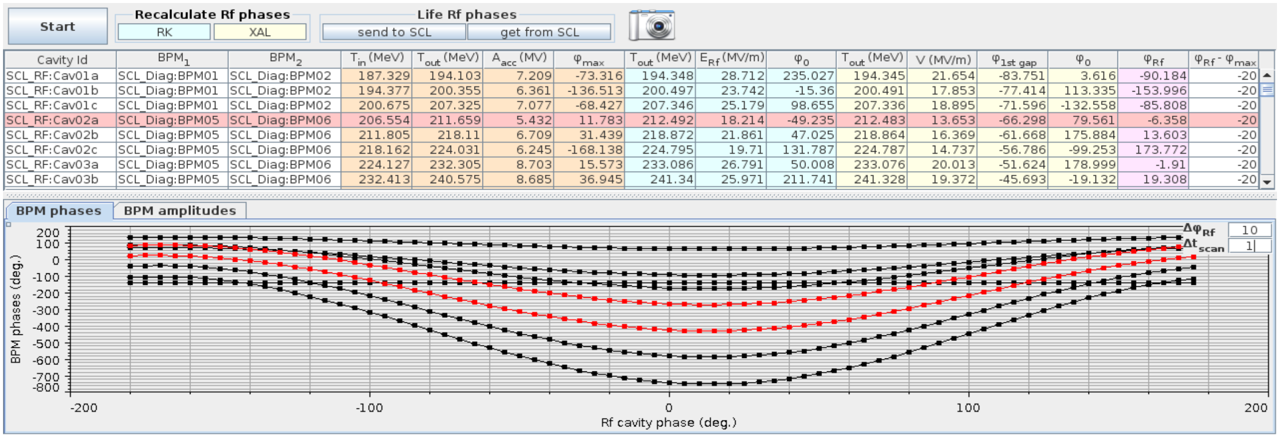
Figure 3: Example of the electric field distribution along the z axis for one of the SCL cavities calculated by the SUPERFISH program.

The function for output energy can be presented as: $\mathrm{T_{out}} = f(T_{in}, E_0, \varphi_0, \varphi_{RF})$ where the cavity parameters E_0 and φ_0 can be found by matching the experimental scan.

After the scan is performed, it is necessary to set up the appropriate cavity phase for the maximum possible acceleration and provide longitudinal focusing. The accelerator physics team of the SNS determined semi-empirically the phase φ_{RF} to be approximately 20 degree less than the phase of maximum cavity acceleration. The phase of maximum acceleration can be quickly found using the Fourier series interpolation of the scan $\mathrm{T_{out}}(\varphi_{RF})$. Three terms of the Fourier series is enough to find the maximum acceleration phase with a precision of 0.1 degree.

After the linac tune-up, and a comparison of the two models, we have revealed a very small discrepancy between the models, within 0.5 MeV for energy.

ISBN 978-3-95450-115-1



Cavity Id	BPM_1	BPM_2	T_{in} (MeV)	T_{out} (MeV)	A_{acc} (MV)	φ_{max}	T_{out} (MeV)	E_{Rf} (MV/m)	φ_0	T_{out} (MeV)	V (MV/m)	$\varphi_{1st\ gap}$	φ_0	φ_{Rf}	$\varphi_{Rf} - \varphi_{max}$
SCL_RF:Cav01a	SCL_Diag:BPM01	SCL_Diag:BPM02	187.329	194.103	7.209	-73.316	194.348	28.712	235.027	194.345	21.654	-83.751	3.616	-90.184	-20
SCL_RF:Cav01b	SCL_Diag:BPM01	SCL_Diag:BPM02	194.377	200.355	6.361	-136.513	200.497	23.742	-15.36	200.491	17.853	-77.414	113.335	-153.996	-20
SCL_RF:Cav01c	SCL_Diag:BPM01	SCL_Diag:BPM02	200.675	207.325	7.077	-68.427	207.346	25.179	98.655	207.336	18.895	-71.596	-132.558	-85.808	-20
SCL_RF:Cav02a	SCL_Diag:BPM05	SCL_Diag:BPM06	206.554	211.659	5.432	11.783	212.492	18.214	-49.235	212.483	13.653	-66.298	79.561	-6.358	-20
SCL_RF:Cav02b	SCL_Diag:BPM05	SCL_Diag:BPM06	211.805	218.11	6.709	31.439	218.872	21.861	47.025	218.864	16.369	-61.668	175.884	13.603	-20
SCL_RF:Cav02c	SCL_Diag:BPM05	SCL_Diag:BPM06	218.162	224.031	6.245	-168.138	224.795	19.71	131.787	224.787	14.737	-56.786	-99.253	173.772	-20
SCL_RF:Cav03a	SCL_Diag:BPM05	SCL_Diag:BPM06	224.127	232.305	8.703	15.573	233.086	26.791	50.008	233.076	20.013	-51.624	178.999	-1.91	-20
SCL_RF:Cav03b	SCL_Diag:BPM05	SCL_Diag:BPM06	232.413	240.575	8.685	36.945	241.34	25.971	211.741	241.328	19.372	-45.693	-19.132	19.308	-20

Figure 4: Control program for the tune-up and rescaling of the cavity phases of the SNS superconducting linac.

This is a good demonstration that the simplified drift-kick-drift model is reliable, is precise when compared to the exact model, and can be confidently applied to the energy manipulation of the linac. The benefit of the model is that it performs computer calculations much faster than the direct-integration method when the code is properly designed.

LINAC TUNE-UP APPLICATION

The new program for tuning up the superconducting linac and its further rescaling has been written within the XAL development environment [1]. Figure 4 shows the main window of the program. After starting the program, it performs its measurement and analysis, scan-by-scan, automatically calculating the model parameters in the table. The main challenge in the practical implementation of the program is the continuous control of the scan fault and handling beam faults. The program stops and waits until the normal conditions are restored. The tests demonstrated high reliability of the program's performance for linac tune-up without any operator action. The cavity fault adaptation function has also been found to be reliable. Figure 5 presents the cavity phase setup in terms of the deviation from the maximum acceleration phase.

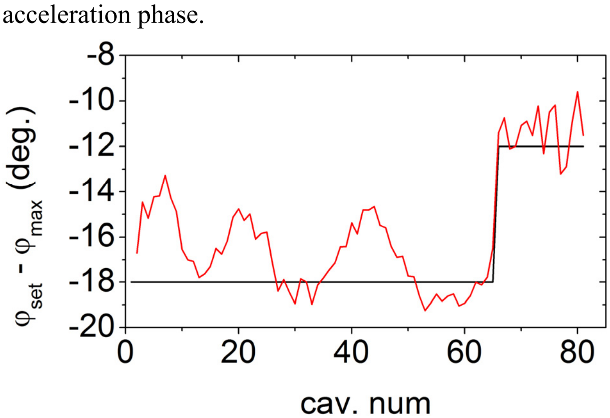


Figure 5: Study of the cavity fault adaptation function.

The straight-line curve (-18 deg. for 1 to 65 cavities and -12 deg. for 66 to 81 cavities) shows the targeted phase setup of the linac. The red curve shows the actual measured phase setup after the first cavity was turned off and the rescaling function was applied. The fault recovery scaling algorithm is good to within ~2 degrees throughout the linac.

The new application has the ability to update model parameters from the live linac setup because operators can manually change cavity phases during loss tuning.

In conclusion, the accuracy of the application is bound by the accuracy of the BPM energy measurement because different pairs of BPMs have different technical phase synchronizations that provide the beam energy measurement error of 1-2 MeV. This is a problem to be resolved in future. Another factor, the drift of the input linac beam parameters, leads to the continuous drift of the linac setup.

ACKNOWLEDGMENT

This research was sponsored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy. The author thanks colleagues from the accelerator physics group of the SNS for their direction and valuable advice during the implementation of the work. A special thanks goes out to Sang-ho Kim for the cavity fields.

REFERENCES

[1] J. Galambos, et al, PAC'05, Knoxville, Tennessee, May 2005, p. 79.
[2] Y. Zhang, IPAC'10, Kyoto, Japan, May 2010, p. 26.
[3] A. Shishlo, et al., Phys. Rev. Lett., 108, (2012) 114801.
[4] A. Shishlo et al., this conference.
[5] T. Gorlov et al., Phys. Rev. STAB 13, 050101 (2010)
[6] T. Gorlov, et al, PAC'11, New York, NY, March 2011, p. 2035.
[7] J. Galambos et al., LINAC'06, Knoxville, Tennessee, August 2006, p. 174.
[8] Y. Zhang et al., EPAC'08, Genoa, Italy, June 2008, p. 3461.
[9] P. Lapostolle, M. Weiss, "Formulae and procedures useful for the Design of Linear Accelerators", CERN-PS-2000-001(DR), (2000).