SNS COMMISSIONING STRATEGIES AND TUNING ALGORITHMS *

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Abstract

The Spallation Neutron Source (SNS) [1] has been recently commissioned. Strategies for the initial beam commissioning of the linac and storage ring will be discussed. The superconducting linac (SCL) commissioning posed unique challenges, in particular accommodating an unanticipated wide range of cavity performance. Methods for setting cavity phases and determination of amplitudes will be discussed. The ring commissioning involved the usual establishment of a circulating beam, and then measurement and correction the tune and beta functions, all with a low intensity beam. Then the gradual increase of beam intensity and phase space painting were investigated. The methods to accomplish these tasks will be discussed. Key factors in the successful commissioning were flexibility in accommodating beam conditions that are different from the design, model based applications, good communication between the different groups, and pre-beam testing.

INTRODUCTION

The SNS is a high intensity pulsed Spallation neutron source designed for an average power of 1.4 MW. Recently the beam commissioning was successfully completed. Although the initial beam commissioning parameters are rather modest compared to the final operating power, beam commissioning does require the simultaneous operation of all major accelerator systems. The accelerator systems were installed sequentially starting from the front end, through the accelerating linac, next to a storage ring and finally to the neutron producing target. Beam commissioning followed the beamline installation.

First we discuss the overall commissioning strategy deployed at SNS. Some commissioning considerations are specific to the SNS and its unique systems, and others are more general in nature. Then there is a brief description of the high level application programming infrastructure. Finally, some specific tuning algorithms are discussed.

COMMMISSIONING CHALLEGES AND STRATEGIES

SNS Specific Approaches

The SNS is the first pulsed proton superconducting linac (SCL) accelerator, and this in itself posed unique challenges. The performance levels of the superconducting cavities were not known until shortly before the beam commissioning. Furthermore, the cavity performance was not stable throughout the commissioning period. Changes in the SCL performance affect the beam energy and downstream storage ring and transport line setups. These considerations led to the need for rapid adjustments and flexibility in accommodating changing equipment performance capabilities.

SNS beam commissioning occurred in 7 separate stages spread over about 3.5 years. These stages lasted typically one or two months with equipment installation activities occurring between commissioning runs. The decision to have beam commissioning activities at an early stage (albeit initially for rather modest lengths of accelerator) allowed early integrated deployment of major systems such as diagnostics, controls, timing and high level applications. Initially deploying these systems over a rather small piece of accelerator simplified the integration process. Although having many beam commissioning stages complicated planning and installation activities, the benefit was well worth this complication.

An early decision in the commissioning planning was to develop a high level application programming infrastructure (XAL) [2], from which many commissioning tools were produced. At SNS, many of the tuning algorithms were developed and programmed by the beam physicists. The same person who wrote the tuning applications was responsible for using it in the control room. Having a single person responsible for understanding the underlying physics, writing the application and deploying it with beam reduced debugging turnaround time.

General Approaches

Some more general commissioning strategies were also followed:

- While the SNS is designed to be the highest power pulsed neutron source, it was commissioned at a very low power with low intensity, short pulse length and low repetition rate. This placed constraints on the diagnostics and control system to sufficiently to cover this wide dynamic range of beam operations.
- Understanding the potential damage of low intensity beam can safely allow bypassing the machine protection system during initial commissioning when beam loss is inevitable. Having this flexibility built in is imperative.
- Testing of diagnostics, controls and applications before beam arrives was done. Especially useful are integrated tests in the control room to the extent possible without beam.
- Good communication between the physics, diagnostics and controls group is also useful. While written requirements are necessary, they were sometimes not sufficient.

XAL APPLICATION PROGRAMMING INFRASTRUCTURE

High level application programs played an important role in the SNS commissioning and were done with the XAL infrastructure [2]. A key XAL feature is a hierarchal description of the accelerator that is configured via a global database [3]. This structure makes creating generic tuning applications that can be applied throughout the accelerator much easier. Since the SNS was commissioned in stages, once a generic application was made to work in an early stage, it was available for use in later stages simply by populating the global database configuration for the new stages.

XAL includes a beam modeling capability [4], which was critical in the commissioning. Modeling was a key part of the RF cavity tuning, beam steering and focusing, as well as unraveling unanticipated observations. Ability to quickly apply model based analysis and matching was quite useful. The model includes particle and envelope (with space charge) tracking, to permit beam centroid and beam size predictions which were used for comparison with measurements. It also includes longitudinal tracking methods used in the primary linac RF tuning algorithms. All references to model uses in this paper refer to this "online model".

Another XAL feature is an application template. This provides a quick-start for GUI application developers, provides a common look and feel for applications, and allows seamless upgrades of all applications. The template made it possible for physicist developers with minimal programming experience to write tuning algorithm applications.

XAL also has a common set of tools that are sharable among applications. These tools include plotting, optimization (used in matching model to beam measurements), database retrieval, signal scanning packages, and correlation (pulse-to-pulse) methods.

TUNING ALGORITHMS

Warm Linac Applications

Several methods for setting RF phase and amplitude were used. For the Drift Tube Linac (DTL) commissioning a scheme involving insertion of an energy degrader followed by a Faraday cup downstream of each DTL tank was used [5]. The DTL phase and amplitude are varied, and only settings for which the beam acceleration is sufficient for the beam to penetrate the energy degrader are detected by the Farady cup. Comparing the shapes of the detected beam vs. cavity phase and amplitude to model predictions allows calibration of the DTL phase and amplitudes settings. This method worked, but required insertion of an intercepting device in the beam, operation at low currents (< 20 mA) and at short pulse lengths (< 50 μsec). Also the traditional "Delta-T" phase scan method was employed [6,7] to find DTL phase and amplitude setpoints, but required many iterations to converge, and a required a good initial guess for the amplitude and phase. In the end, the most useful method for setting the DTL phase and amplitudes was with a "signature-matching" method [8], with an application called "Pasta"[9]. This method involves scanning the cavity phase at different amplitudes and measuring downstream beam arrival times using Beam Position Monitors (BPMs), which also give phase readings. Using a longitudinal model with variable input beam energy, cavity phase and cavity amplitude calibrations, model results are matched to the measured BPM phase difference shape. The cavity phase scan can be over 10's to 100 degrees and still get reasonable beam transmission suitable for matching. With these wide scan ranges, quite unique BPM phase difference signatures are produced, and with today's computing power these can be matched with the model in the control room during commissioning. This method has the advantage of not requiring any insertion devices, and easier convergence on the correct cavity settings, however, it requires accurate BPM phase measurements. An example of a Pasta scan for a DTL tank is shown in Figure 1. For the Coupled Cavity Linac, the Delta-T and Pasta methods were available, but the Pasta method is the preferred SNS tune-up method for the entire warm linac. For the DTL, all the quadrupoles are permanent, and for the CCL the focusing magnets were run at their design values.

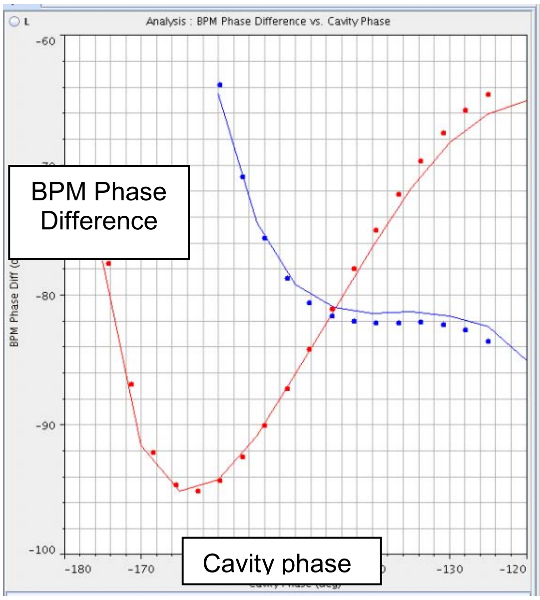

Fig. 1. Example signature phase scan method for setting a DTL linac cavity phase and amplitude. The difference in downstream arrival times (BPM phase difference) vs. cavity phase is shown for model (dots) and measurement (lines) for two cavity amplitudes.

Superconducting Linac Applications

The Superconducting linac (SCL) posed special commissioning constraints. While the warm linac consisted of 10 cavities all of which had to run at the design values, the SCL consists of 81 independently powered cavities, none of which had to run at their design value. The final operating SCL fields were not known until days before the start of commissioning, and sometimes the safe operating level of cavities would change. These uncertainties necessitated a flexible setup procedure. Figure 2 shows the distribution of some cavity operating field levels at different times during commissioning. Note the large spread about the design values and the large number of cavities that were sometimes unavailable (i.e. at 0 field).

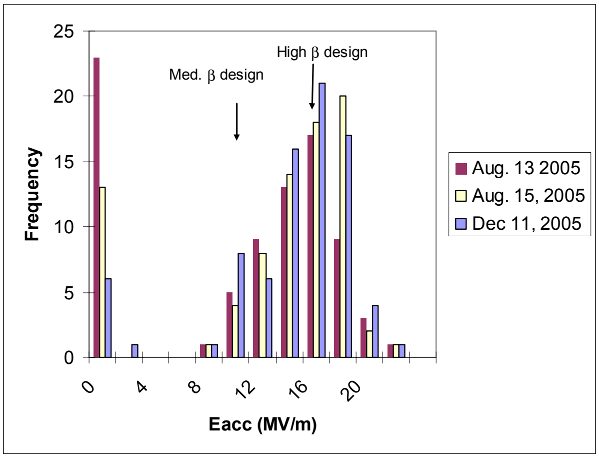

Fig. 2 Distributions of SCL cavity performance for different tune-up periods.

Each SCL cavity was operated at its maximum safe operating field. Thus it was only necessary to set the phase for each cavity. However there are 81 cavities in the SNS SCL, and these need to be powered up sequentially. This means running beam through the entire SCL to a dump at the end. Additionally the last CCL module was tuned by transporting beam to the end of the linac. This entailed transporting a beam down the SCL linac spanning an energy range from 157 MeV to ~ 1000 MeV. To facilitate this, several quadrupole lattices were configured beforehand at 7 intermediate energies through the tuneup range. As cavities were properly tuned up to the energy corresponding to an intermediate lattice energy, these lattices were uploaded to the machine. This allowed transporting beam down the entire linac over a wide energy range, with tolerable beam loss rates. An application called "Energymanager" was used to create the intermediate lattice settings and upload them to the machine. The lattice generation typically started by scaling the design quadrupole fields with the $B\rho$ corresponding to the expected energy gain for the SCL cavity levels being used. Additional magnetic field optimization was done in certain matching sections.

The SCL cavity phase setpoints were found using a phase scan method similar to that described above for the warm linac [10]. In this case, each cavity's phase is scanned 360 degrees, and the phase difference between two downstream BPMs monitored. Matching the measured observation to model predictions provides the entrance and exit beam energy to the cavity, the proper phase setpoint, and the actual cavity field. Generally the exit energy from a cavity was close to the entrance energy found for the next cavity. Since these are independent measurements for each cavity, one has a good knowledge of the beam energy throughout the tuning procedure. Figure 3 shows an example phase scan for one cavity.

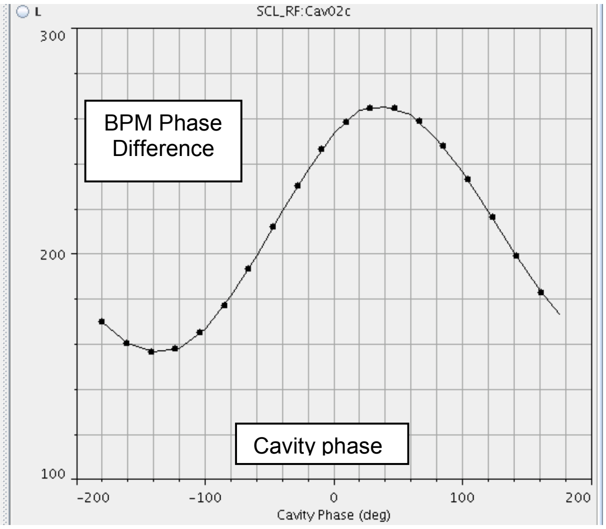

Fig. 3. An example phase scan method for setting an SCL cavity. The difference in downstream arrival times vs. cavity phase scan is shown for model (dots) and measurement (lines) over a full 360 degree scan.

Having a model based tuning algorithm and database configured description of the SCL proved useful in developing a scaling technique to automatically predict new cavity phase setpoints in the event of cavity failure(s). Using the initial cavity phase setpoints as a map of arrival times at each cavity, using a longitudinal tracking method and with knowledge of the cavity positions (from the database configuration), it is possible to predict the change in downstream arrival times if upstream cavities are changed. The changes in arrival times can amount to > 1000 degrees of cavity phase setting. This method was tested, and worked well, opening the possibility for rapid recovery and retuning in the event of cavity failure.

Ring Tuning Algorithms

The transport line and storage ring commissioning was also subject to an uncertain beam energy, as discussed in the SCL section. The Energymanager application was used to scale the magnet fields to the energy predicted from the SCL tune-up procedure in the SCL. This worked quite well. Initial Ring commissioning was done with a single turn of injected beam (called a mini-pulse), as compared to the design goal of 1000 injected turns. Also initial beam commissioning was done with push button, or 1 Hz beam operation, so complete beam loss was tolerable. The initial steps in Ring commissioning were to get beam to the Ring (through the HEBT transport section), adjust the injection settings and dipole correctors to get beam circulation in the Ring, clean the closed orbit, set the extraction kicker amplitude and timing to direct beam to a dump in the the extraction line (RTBT), and then inject, store and extract a few mini-pulses. This was done in about three days. A strategy used here was to go as far as possible identifying issues and working around them when possible, and stop later to fix problems in parallel.

One example application used in the Ring commissioning was the "BPM viewer" application. This application is a good example of a technique to assimilate information from many sources and present it in a useful way to the commissioner (see Figure 4). It provides a view of the beam position around the ring as a series of bars. Moreover, at each position a pulse-by-pulse history of the position can be displayed as a rolling set of bars at each position. This was quite useful for tuning, as a convenient way to visualize tuning progress over the entire ring.

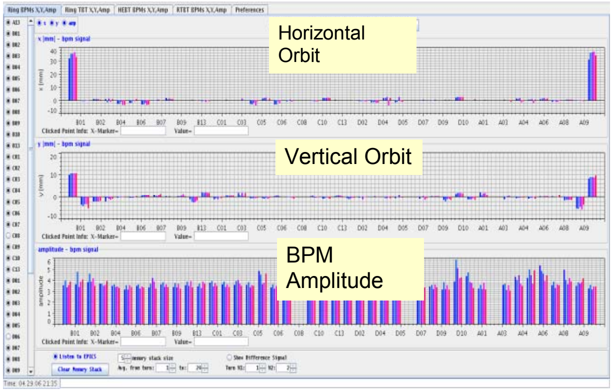

Fig. 4. The Ring BPM viewer display is an example of a way to display information from many sources (e.g. BPMs around the ring) with a rolling time history (multiple bars at each BPM position.

Other ring specific applications included tune calculations. One way this was done was to measure the beam position at a single point in the ring, for many turns using a single injected mini-pulse. The oscillation observed could be either fit by a sine wave or analyzed by an FFT to provide the tune. Another method used was to inject the beam off axis and observe the beam position around the ring for a few turns, and fit with a sine-wave to provide the tune. The tune adjustment was done by pre-calculating changes in the ring quadrupole power supplies to give desired tune changes. Methods for checking the measuring the beta function values [11] included measuring the turn-by-turn beam positions around the ring while varying individual quadrupole power supplies.

Another area of concern in the SNS Ring is understanding the beam characteristics at the injection foil. A ring injection application was available to measure the beam positions around the ring for the first turn. The online model used this information to calculate the position and angle of the beam at the foil. This application also provided dipole corrector settings in the injection line just upstream of the foil, required to correct the injected beam position and angle to the design values. Beam size in the injection line was measured with an emittance station consisting of a set of three profile measurements (wire scanners). Matching the beam Twiss parameters to meet the measured beam sizes was done throughout the linac where profile measurements were available.

Finally the beam to target commissioning aimed primarily to ensure a good understanding of the beam shape and position striking the target. Ultimately there will be ~ 1 MW on the target and it is crucial that the beam has the right power profile and size to meet strict requirements. A limited lifetime viewscreen was available for the initial beam on target commissioning, and proved quite useful. The injection painting schemes were tested while the viewscreen was available to verify the required power distribution profile on target. Importantly, there are three wire profile and one harp measurement of the beam upstream of the target. Using these beam profile measurements and model extrapolations to the target, we were able to verify the ability to predict the beam profile on target, which will be the only capability of determining target power distribution after the viewscreen is gone.

General Purpose Tuning Techniques

One technique used throughout the accelerator was an "orbit difference" method. This technique involves taking a set of beam position measurements, changing a magnet setting, and observing the difference in the beam position downstream (or "orbit difference"). The measured orbit difference is compared to the difference predicted by the model for the given change in the magnet. An example application of this technique using a dipole corrector magnet in the Ring is shown if Figure 5. This technique has the advantage that initial conditions of the beam are not needed. It is useful for identifying issues in BPM polarity, corrector polarity, and magnet field as a function of current mapping.

The XAL infrastructure provided a number of general purpose tools used throughout the accelerator. One example is a general purpose scan program This allows setup of a quantity to be varied in a prescribe fashion, and other quantities to be measured, with many options available like averaging and filtering. This was quite useful, since it is difficult to anticipate all studies one would like to perform, and scanning / measuring is a common technique for tuning.

Other general purpose tools included the orbit display and orbit correction. Once users became familiar with its use in one sequence, trajectory straightening in other sequences is straightforward. The beam loss display tool is one of the most common displays used, and when BPMs were not available, steering by loss minimization was done.

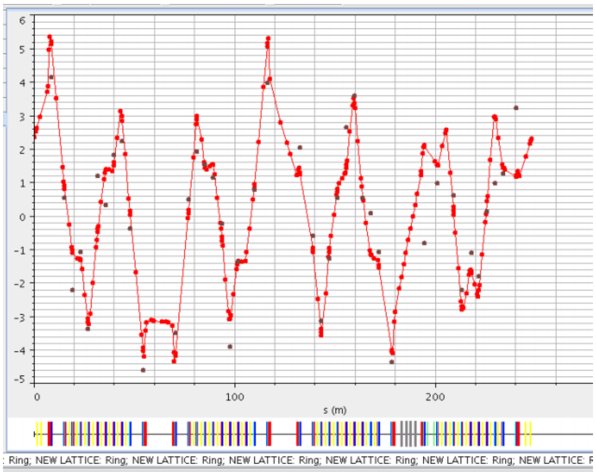

Fig. 5 Orbit difference application in the ring, showing the change in beam position due to a dipole corrector change. Brown dots are BPM measurements, red lines are BPM measurementrs

Many tuning techniques were possible with GUI applications. But it is impossible to anticipate everything. To accommodate unexpected studies, scripting was used. It is much easier to deploy and develop a script based tuning method, than a bullet proof GUI application. At SNS we used primarily a Java version of the common python scripting language called jython. All XAL classes are directly usable in jython. Some example uses of scripting were beam-based alignment of BPMs, Twiss parameter matching of beam profile measurements, and data acquisition (e.g. BPM data for jitter analysis). Many of the scripting methods that proved useful, later evolved into full GUI based applications.

Finally, a program to provide save-compare-restore (SCORE) was used extensively. By its nature beam commissioning involves many parameter adjustments, and it is easy to quickly get lost from a good tune. Being able to conveniently snapshot the machine settings when progress is made (save), compare live settings with a save set to understand what is different (compare) and quickly get back to a good tune (restore), was essential.

Summary

The SNS was commissioned in stages, which had the advantage of early deployment of all the systems necessary for tuning, e.g. controls, timing, diagnostics and high level physics applications. This approach also had the advantage of incremental development, i.e. not having to test and use a large number of systems and applications all at the same time. Another key feature of the SNS commissioning strategy was use of a high level application programming infrastructure developed and used by physicists. Importantly this infrastructure included online modeling capability of the machine in its active state.

REFERENCES

[1] http://www.sns.gov

[2] J. Galambos, C.K. Allen , C. Chu, S. Cousineau, V. Danilov, J. Patton, T. Pelaia, A. Shishlo, "XAL Application Programming Structure", Proc. of the Particle Accelerator Conf., Knoxville TN, 2005, http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/ROPA001.PDF

[3] J. Galambos, C. Chu, J. Patton, T. Pelaia, A. Shishlo, "Database Use in Application Programming at SNS", 10th ICALEPCS Int. Conf. on Accelerator & Large Expt. Physics Control Systems. Geneva, 10 - 14 Oct 2005, http://elise.epfl.ch/pdf/P3_092.pdf

[4] C. K. Allen ,C. A. McChesney, , C. M. Chu, J. Galambos, T. Pelaia, "A Novel Online Simulator for Applications Requiring a Model Reference", http://accelconf.web.cern.ch/AccelConf/ica03/PAPERS/WE116.PDF .

[5] D. Jeon, "Comparison of Techniques for Longitudinal Tuning of the SNS Drift Tube Linac", Proc. of the Particle Accelerator Conf., Knoxville TN,2005, http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/WPAT071.PDF

[6] K.R.Crandall. The Δt Tuneup Procedure for the LAMPF 805-MHz Linac. LANL Report LA-6374-MS, June 1976.

[7] A. Feschenko et. al., "Development and Implementation of ?T Procedure for the SNS Linac", Proc. of the Particle Accelerator Conf., Knoxville TN,2005,http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/FPAE049.PDF

[8] T.L. Owens, M. B. Popovic, E. S. McCrory, C. W. Schmidt, L.J. Allen, "Phase Scan Signature Matching for Linac Tuning", Particle Accelerators, 1994, Vol 98, p. 169.

[9] J. Galambos, A. Aleksandrov, C. Deibele, S. Henderson, "PASTA – An RF Phase Scan and Tuning Application", Proc. of the Particle Accelerator Conf., Knoxville TN, 2005, http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/FPAT016.PDF

[10] S. Henderson, et. al., "Spallation Neutron Source Superconducting Linac Commissioning Algorithms", Proc. of the Particle Accelerator Conf., Knoxville TN, 2005,http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/FPAE058.PDF

[11] S. Henderson, P. Chu, S. Cousineau, V. Danilov, J. Holmes, T. Pelaia, M. Plum, "Techniques for Measurement and Correction of the SNS Accumulator Ring Optics", Proc. of the Particle Accelerator Conf., Knoxville TN, 2005, http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/WOAC009.PDF .