SNS BEAM DIAGNOSTICS: TEN YEARS AFTER COMMISSIONING

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Abstract

The Spallation Neutron Source, a neutron scattering user facility based on a 1.4 MW proton accelerator, has been in operation since 2006. The accelerator beam diagnostics were designed, in large degree, with commissioning unknowns in mind. Today we face new challenges to support stable 1 MW beam power operations and an accelerator upgrade for even higher power. The beam instrumentation problems span a range from mitigating obsolescence of many electronics to developing new techniques for measuring beam parameters important for high power operation. This report describes several examples of the ongoing work: development of new electronics for the Beam Position Monitor (BPM) and Beam Loss Monitor (BLM) systems to replace the aging designs; and development of large dynamic range and high precision beam phase space characterization tools to facilitate model based accelerator tuning.

INTRODUCTION

The SNS accelerator complex consists of an H^- injector, capable of producing one-ms-long pulses with 38 mA peak current, chopped with about 70% beam-on duty factor and a repetition rate of 60 Hz to produce 1.6 mA average current; an 87 MeV Drift Tube Linac (DTL); a 186 MeV Coupled Cavity Linac (CCL); a 1 GeV Super Conducting Linac (SCL); a 1 GeV Accumulator Ring (AR); and associated transport lines. A diverse set of diagnostics is used to monitor various parameters of the beam [1] in the accelerator. Results of the initial beam instrumentation commissioning and operation experience can be found in [2]. The Second Target Station Project (STS) [3] aims at doubling the beam power. This will be achieved by increasing the SCL and AR beam energy to 1.3 GeV and the peak current in the linac to 59 mA.

After completion of the initial beam commissioning and gradual power ramp up, the SNS accelerator complex has been delivering proton beam to the neutron target for about 4500 hours per year with availability exceeding 80%. As shown by a historical plot of the beam power on the target in Fig. 1, the beam power has been mostly above 1 MW since 2010 and close to the design level of 1.4 MW lately.

With the SNS entering routine neutron production operations, the roles and requirements for the beam diagnostics are changing as well. Only a limited subset of diagnostics is absolutely required during steady neutron production: the Beam Loss Monitors to ensure accelerator safety, the Beam Current Monitors for beam accounting, and a multi-wire monitor (the Harp) to validate the beam size on the target. Reliability and maintainability are the most important qualities for these systems. Additional diagnostics are needed to tune the machine after long maintenance periods or significant configuration changes (e.g. taking out of service failed superconducting RF cavities): the Beam Position and Phase Monitors (BPM) and some Wire Scanners. The rest of the diagnostics systems provide convenience for operators (e.g. the Target Imaging System) or are used for machine studies. The main thrust of the machine studies is to create a realistic beam dynamics simulation tool to facilitate machine tuning and improve beam transport.

This paper describes the ongoing development work for selected systems from each category.

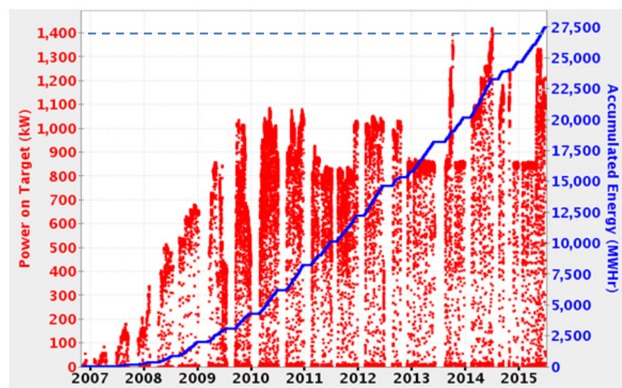

Figure 1: A history of beam power on the target (red points) and accumulated beam energy (blue line). The dashed line shows the design beam power level.

OBSOLESCENCE MITIGATION EFFORTS

The original set of SNS diagnostics was designed about 15 years ago, which is quite a significant time in the electronic components industry. Many of the parts became or are becoming obsolete and many of them do not have a direct replacement suitable for drop in replacement. We have a sufficient amount of spare parts for supporting operations in the short term but replacement electronics need to be developed for long term sustainability. This task is easier in some regards compared to developing the original diagnostics: we know precisely what is needed for operation as all uncertainties of the machine commissioning already have been resolved; there is less schedule pressure; and there is less equipment to install at once. On the other hand, there are additional constraints: the available operational budget and manpower is significantly smaller compared to the construction project. Therefore, we use the following approach to all new electronics design:

ISBN 978-3-95450-176-2

1. New systems are a drop-in replacement for the existing system in size, power requirements, controls system interface, pick-ups, cable plant, etc. This allows staged replacement of the electronics one-by-one or in groups.
2. New designs are optimized for easier maintenance with all unnecessary functions or future development options removed unless they will be required for the power upgrade. In practice, this usually simplifies designs because the original electronics had various options for commissioning uncertainness e.g. switchable gains etc.
3. Non-interceptive diagnostics have a 60 Hz data acquisition rate. This became feasible for many diagnostics with the latest advances in digital electronics.
4. New electronics have no custom designed digital boards, only commercial-off-the-shelf solutions should be used. This requirement is dictated by the available expertise in the Beam Instrumentation Group. A typical configuration following this principle is shown in Fig. 2.

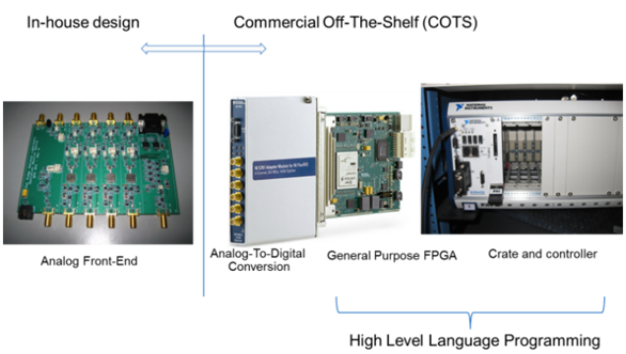

Figure 2: A typical system configuration for new BI electronics designs.

Short descriptions of the new electronics designs for the two largest beam diagnostics systems are given below.

Beam Loss Monitors

The SNS BLM system consists of 362 detectors measuring the secondary radiation due to beam loss. The BLMs are used as sensors in the machine protection system for shutting off the beam if the integral loss is above a certain threshold. The ionization chamber (IC) is the main detector type in the BLM system due to its simple design and immunity to radiation damage. In addition to the ICs we use several types of photo-multiplier tube based detectors (PMTs). The old BLM multichannel electronics are based on VME chassis and use custom designed and obsolete commercial cards. The electronics are programmable for use with different types of detectors in different locations. One VME IOC serves 32 channels of BLMs [1]. The new design is based on NI cRIO technology [3]. The only custom design piece of electronics is analog front-end preamplifier (AFE). The two flavors of the AFE and four flavors of chassis listed in Tables 1 and 2 cover all the SNS needs. An assembled AFE PCB is shown in Fig. 3. A complete BLM chassis is shown in Fig. 4.

Table 1: Parameters of the Four Different Flavors of the New BLM Chassis

Flavor	Number of signals	Number of HV	Number of MPS	AFE
ITSF	8	8	1	none
IC	16	4	16	LG amp
Target	8	8	0	HG amp
ND	8	8	8	LG amp

Table 2: Parameters of the Low (LG) and High (HG) Gain AFE Preamplifiers of the New BLM Electronics

AFE	Gain (Ohm)	Min current (nA)	BW (Hz)	Sampling rate (kS/s)
LG	600k	2	200k	1000
HG	100M	0.01	1	100

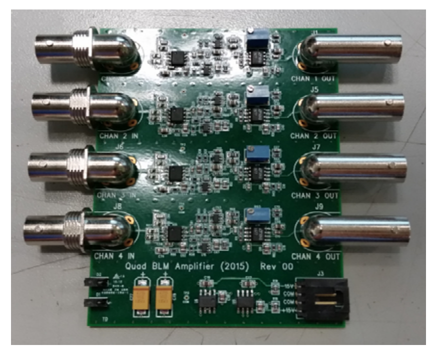

Figure 3: Assembled BLM AFE board.

Figure 4: New BLM electronics chassis in the rack.

Beam Position and Phase Monitors (BPM)

Beam phase monitors are the main tools for the linac tune up which utilizes time-of-flight algorithms. Position measurements are used for trajectory correction, ring

ISBN 978-3-95450-176-2

injection set up and centering the beam on the dumps and target. Both the phase and the position are measured by the BPM system, using 160 4-lobe strip-line pick-ups installed along the beam path. Narrow-band RF front-end electronics is used in the linac and the HEBT. Base-band front-end electronics is used in the ring and the RTBT. The existing BPM electronics consist of custom designed PCI boards installed in a rack-mounted PC running the LabView program under the Windows XPe operating system. One chassis per BPM is used for both linac and ring systems [1].

The new BPM electronics, both linac and ring style, use NI PXIe chassis and FlexRIO FPGA technology [4]. The only custom designed piece of electronics is the Analog Front End (AFE) board. The linac BPM AFE design is based on the SNS LLRF input card design [5]. The 402.5 MHz or 805 MHz signal from the pick is down-converted to 50 MHZ in the AFE. The 50 MHZ IF is digitized by an ADC, processed in an FPGA and transferred to an EPICS IOC. One PXIe crate can support up to six linac style BPMs. A set of six BPM electronics in the SNS MEBT is shown in Fig. 5.

Figure 5: The new BPM electronics for the SNS MEBT in the rack.

The new linac BPM electronics demonstrated good performance during beam tests as demonstrated by Fig. 6 which shows beam phase measurements during several hours using the old (blue) and the new (green, red and white) electronics. The new system shows less noise because it can take advantage of its 60 Hz acquisition capability for signal averaging.

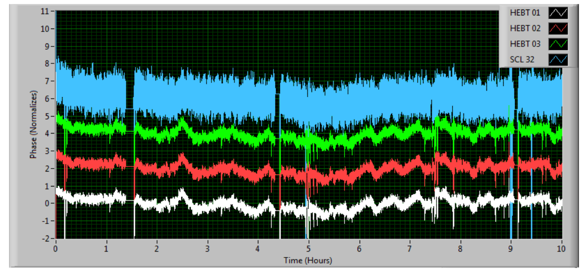

Figure 6: A comparison of the beam phase measured by the old (blue) and the new (green, red, and white) linac BPMs. The old BPM data were acquired and plotted at 1 Hz trigger rate, and the new BPM data were acquired at 60 Hz, averaged, and then plotted at 1 Hz.

The ring BPM electronics operate in base band with 5 MHz bandwidth. The main challenge is the required dynamic range of about 60 dB. The old system used a fast gain switching during the 200 ns gaps in the beam pulse. The new electronics will have two separate channels with low and high gain. The two signals will be independently digitized by multi-channel ADCs, combined in an FPGA processor and transferred to an EPICS IOC. One PXIe crate can support up to eight ring style BPMs. A diagram of the ring BPM prototype AFE is shown in Fig. 7.

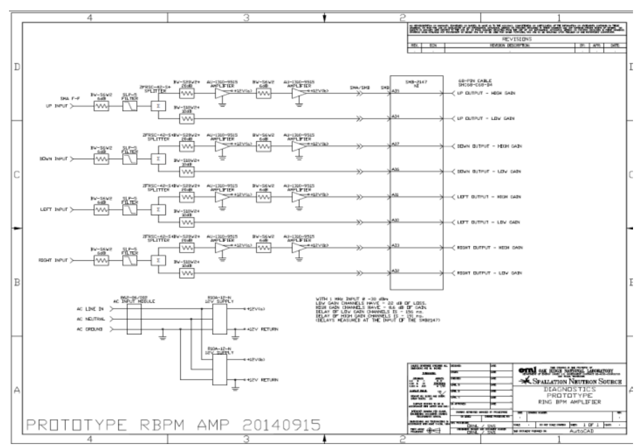

Figure 7: A block diagram of the prototype ring BPM AFE.

MACHINE STUDY DIAGNOSTICS

Significant machine study efforts are devoted to creating a reliable beam dynamics simulation model, which would allow model based tuning of the accelerator. This development is evolving from the center of mass motion model to the RMS envelope model, and finally, to the large dynamic range particle-in-cell model. The single particle model uses only BPM data. Its deployment shortened the linac tuning time from 10-20 hours to 2-3 hours. The RMS envelope model requires transverse and longitudinal profile data provided by the wire scanners (WS), the laser wire (LW) and the beam shape monitors (BSM). These diagnostics perform sufficiently well to allow finishing the model development in the next 1 or 2 years. The longitudinal profile measurements are on the

ISBN 978-3-95450-176-2

edge of the required resolution and we are actively searching for improvements [6]. The most difficult part is to develop a high resolution PIC model capable of predicting beam loss at the 10^{-4} level and below. This requires measuring as many parameters of the beam 6D distribution with large dynamic range as possible in as many places as possible. The minimum useful dimensionality of data for a PIC model is 2D emittance. We have developed a high resolution emittance measurement system in the 2.5 MeV MEBT [7]. We also have a large number of wire scanners throughout the machine. The dynamic range of the current wire scanner system reaches 10^5 as shown in Fig. 8 and we expect it to increase further with multiple pulses data averaging, if needed.

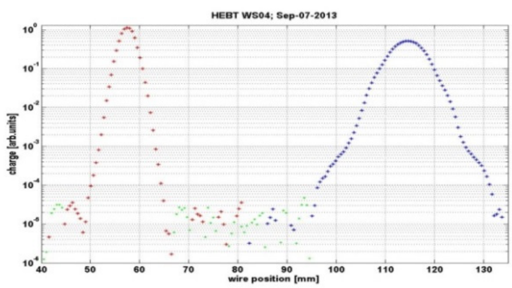

Figure 8: Transverse beam profiles (vertical - red, horizontal - blue) measured with an SNS wire scanner.

A method is required to reconstruct 2D emittances from the 1D profiles without loss of dynamic range. The MENT tomographic reconstruction [8] has shown the most promising results thus far. A reconstructed emittance with 10^3 dynamic range is shown in Fig. 9. A direct emittance measurement using a laser emittance scanner at the 1 GeV end of the SNS linac [9] is used to validate the reconstruction accuracy.

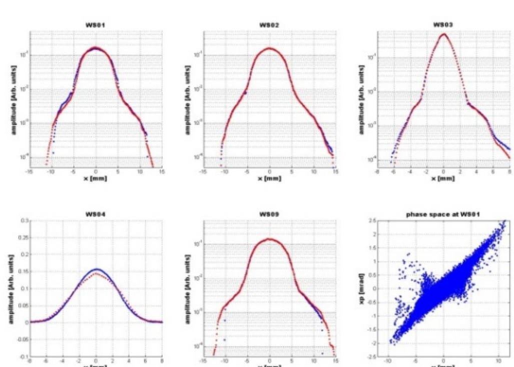

Figure 9: A comparison of measured (red) and calculated from reconstructed emittance (blue) beam profiles. The beam phase space footprint reconstructed using the MENT algorithm is shown in the bottom left plot.

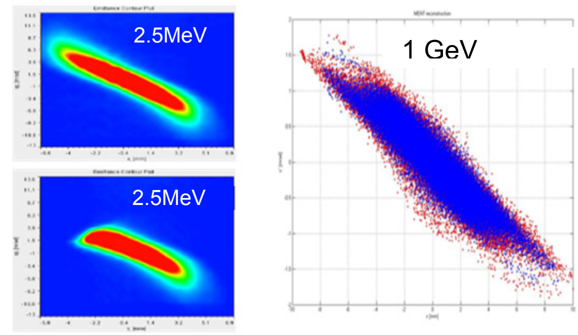

Figure 10: An example of measurements used for beam dynamics studies in the SNS linac.

An example of measurements used for beam dynamics studies in the SNS linac is shown in Fig. 10. The upper left plot shows the beam emittance in the MEBT with the MEBT horizontal scraper retracted. The bottom left plot shows the beam emittance with the scraper inserted to remove a few percent of the beam charge. As the scraper is just a few meters upstream of the emittance scanner its shadow is clearly seen on the image. The right plot shows the measured beam emittance at the end of the linac, in red with the scraper retracted and in blue with the scraper inserted. It is easy to see that the scraper insertion results in emittance reduction but there is no discernable scraper shadow on the image because particles mix up in transport from the MEBT to the end of the linac. This kind of measurement is a sensitive tool for a PIC model set up and validation.

ACKNOWLEDGEMENT

Material for this presentation was provided by SNS Beam Instrumentation Team members: Wim Blokland, Richard Dickson, Cary Long and Sasha Zhukov.

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

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ISBN 978-3-95450-176-2