BEAM INSTRUMENTATION
FOR THE SPALLATION NEUTRON SOURCE RING[*]

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Abstract

The Spallation Neutron Source (SNS) will be constructed by a multi-laboratory collaboration with BNL responsible for the transfer lines and ring. [1] The 1 MW beam power necessitates careful monitoring to minimize un-controlled loss. This high beam power will influence the design of the monitors in the high energy beam transport line (HEBT) from linac to ring, in the ring, and in the ring-to-target transfer line (RTBT). The ring instrumentation must cover a 3-decade range of beam intensity during accumulation. Beam loss monitoring will be especially critical since un-controlled beam loss must be kept below 10^{-4}. A Beam-In-Gap (BIG) monitor is being designed to assure out-of-bucket beam will not be lost in the ring.

1 THE SNS PROJECT

The SNS will be designed and built by a collaboration of ANL, BNL, LBL, LANL and ORNL for installation at ORNL in 2005. The design consists of a 1 GeV H-minus linac injecting into an accumulator ring at 60 Hz for an average power of 1 MW. Much of the design allows simple upgrade to a 2 MW beam. The H-minus beam from the linac will be transported via the HEBT line to the 220 m circumference ring where it will be stripped to protons. The injected beam will be accumulated over 1 msec with the RF system maintaining a compact bunch. At the end of the injection pulse the single half-microsecond bunch of 1×10^{14} protons will be extracted and transported down the RTBT line to a neutron conversion target.

2 BEAM LOSS MONITORS

Because of the very high average beam power, uncontrolled losses must be kept very low to allow machine maintenance. Controlled losses, such as from H-minus stripping and other expected sources will be intercepted on collimators designed to contain the resulting radiation. All other losses will result in component activation. The Beam Loss Monitor (BLM) system is designed to detect an uncontrolled loss of 1 x 10^{10} protons per pulse (1 part in 10^4 at 1 MW) over the full ring and provide a signal to inhibit further injection. Ion chambers will provide the interlock function and the basic, multi-turn loss data. Eight scintillator-photo-multipliers

(SPM) will serve as fast beam loss monitors (FBLM) observing the losses within the bunch. These will be located in the injection and extraction areas and at high dispersion points. Ion chambers will be located at each quadrupole, at the collimators, and at key injection and extraction loss points. Several relocatable units may be placed local at hot-spots, for a total of 80 channels. The detectors will be mounted close to the beam pipe.

Tevatron type ion chambers [2] as modified for RHIC [3] will be used. The modifications included eliminating Teflon® in the connectors and using isolated BNCs to break ground loops of the cable shields through the BLM aluminum outer case. These BLMs are low cost and reliable, and have good reproducibility and long term stability and low maintainence. Nominal sensitivity is 70 nC/rad. Since the beam cycle is so short most of the signal will come from the electrons, cutting the sensitivity in half. The 10^4 loss limit can occur in a single turn or slowly over the entire cycle resulting in a 10^3 range in signal current. A similar problem in RHIC was solved by using a front-end capacitor to pre-integrate the potential current spike. Signals from the 48 BLMs at the quads will be summed to monitor the 10^4 total Ring loss requirement. Individual ADCs will acquire each BLM signal at the revolution rate. Several seconds of data will be stored locally and be available for replay in the event of a Beam Inhibit.

The FBLMs consist of photomultipliers immersed in liquid scintillator to reduce radiation darkening.[4] Unit-to-unit variation and radiation effects on the scintillator and window of the tube will require periodic re-calibration and individual HV power supplies. The signals will be integrated over the bunch length and read through digitizer channels clocked at the revolution frequency. In addition units may be selected through a wideband multiplexer to be read into a multi-channel fast digitizer (1 GSa/s) to observe losses within the bunch.

3 BEAM CURRENT MONITORS

The circulating current in the ring will be monitored using a Beam Current Transformer (BCM) designed to handle the 2 x 10^{14} protons which will be required for a 2 MW beam. In this case the peak current can reach 100 A so care must be taken to prevent saturation of the transformer core. The signal droop is must be less than 0.1% during the 1 msec accumulation period, requiring a decay time

constant of about 1 second. The rise time is specified at 50 nsec. A Supermalloy tape wound core with 9.5-inch ID, 3" width and 14" OD, will be used to fit over the 8-inch beam pipe. Tests on a similar, smaller core, indicate that a resistor-damped winding of 100 turns with a 1 Ohm load will meet these specification with acceptable ringing. The transformer signal will be processed by a switchable gain amplifier followed by a gated integrator. The output will be proportional to the charge in the ring on each revolution. This will be sampled and held for acquisition at the revolution frequency by an ADC. A second current transformer optimized for high frequency response will monitor the bunch current. Transformers are commercially available which will provide nano-second rise time with low droop over the 550 nsec bunch length, and will tolerate the high peak current. [5] The fast transformer signal will be processed by a gain switching amplifier and acquired by a dedicated channel of a very fast ADC (1 GSa/s).

4 BEAM IN GAP (BIG) MONITOR

Any beam present in the gap (out of the RF bucket) will be driven across the extraction magnet at the end of the cycle, representing a potentially large loss. This beam may have been a residual of poor chopping, or due to longitudinal dynamics in the Linac or Ring. Observing beam next to a 4 order-larger bunch is very difficult. It is unlikely that a BCM will be able to do this although the possibility of making a coarse measurement is being studied. This would utilize a transformer similar to the ring BCM but with overshoot <0.1% after 100 nsec. Compromise of rise time and droop would be required to meet this specification.

A second approach would measure the gap beam and also clean the gap, which would be important in meeting the loss specification. The gap beam would be kicked into a collimator where it would be observed with a gated FBLM. The rise time of the kicker must be much less than the 290 nsec gap width so a full aperture kicker is not practical. However, by resonantly kicking at the vertical betatron tune over many revolutions a much smaller kick is required. The hardware might be similar to that of the RHIC Damper [6] which uses commercially available MOSFET banks to supply 5 kV, 120 A, 10 nsec rise and fall pulses to a transmission line kicker. Burst frequency is greater than 1 MHz, permitting turn-by-turn kicking. Power dissipation limits the kicks to about 100 per msec at 60 Hz. The 5m straight section downstream of the extraction Lambertson magnet is available for the BIG kickers. For a 5m kicker and the above pulser, each kick gives about a half milliradian deflection, so the beam would hit the collimator in about 25 turns, fast enough at normal tune spread and machine chromaticity conditions.

5 BEAM POSITION MONITORS

Design goals for beam position monitor (BPM) system are shown in Table 1.

Table 1.   BPM Design Goals

Parameter	Value
Lowest intensity	5×10^{10} protons
Highest intensity	2×10^{14} protons
Range of measurement	±20 mm
Accuracy	±1 mm
Stability of filtered orbit – long term	±1 mm
Stability of filtered orbit – short term	±0.15 mm
Resolution of filtered orbit	0.15 mm rms
Period of filtered orbit	100 turns
Resolution of turn by turn position – low intensity	1 mm rms
Depth of turn by turn buffer	>50 turns

For robust operation with the changing bunch shape, measurements should rely on signals at the fundamental and the lowest harmonics of the revolution frequency. The 402.5 MHz linac microstructure will be present only on the most recently injected bunches. Additional receivers could be added to a few channels to observe the injected beam in the presence of circulating charge, allowing parameters such as the space charge tune shift to be measured. A dual plane, shorted stripline electrode will be located at each of the 48 quadrupoles. The typical aperture at these locations is 200 mm. With a 250 mm length, the striplines will provide a signal that is sufficient at low intensity, yet not excessive at high intensity. They will also provide reasonable coupling to the 402.5 MHz linac bunching frequency and its next harmonic. Since the main quads trim windings are powered in families, beam based alignment is not practical, so the required position accuracy will be obtained by an initial calibration of the electrode alignment and on-line calibration for the electronics. The initial calibration could utilize the surveyed antenna technique developed for RHIC [7] while the online calibration could utilize signal injection into the orthogonal plane.

The signals from the electrodes will be carried on coaxial

cables to centrally located electronics. Low frequency noise will be rejected by high-pass filters with a corner frequency of a few hundred kHz. For measurement of the circulating beam, the passband of the electronics will extend to a few MHz and the signal will be digitized with at least 12 bit resolution well above the NyQuist frequency. The common mode dynamic range of over 60 dB will be handled by log amplifiers or by programmable gain amplifiers. Preliminary analysis has shown that this simple approach can meet the design goals. With a design that places high-speed digitizers early in the signal processing chain, the resulting data rates will be a concern. If the digitizer system contained onboard digital filtering, the data rate across VME could be significantly reduced. Turn by turn data would be delivered at a sustained rate of about 145 kbytes/s/digitizer and averaged orbit data would be delivered at 1.4 kbytes/s/digitizer. The local Controls processor will calculate position and apply corrections before delivering data to the console level applications.

6 DAMPER/TUNE MONITOR

While specific requirements for a damper have not been established, a 2 m section of beam pipe has been reserved for a tune meter/damper. A system similar to that in the AGS [8] will be installed. Signals from the BPMs will be used. The average orbit at the kicker will be subtracted to determine the bunch error and the required kick amplitude obtained from a look-up-table. The kick is delayed using a FIFO and applied to the bunch on a later turn. The digital acquisition and processing electronics for each beam position monitor has sufficient memory to store the position for the entire cycle. A spectral analysis of this data will be used to find the integer and fractional tune.

7 BEAM PROFILE MONITOR

The high beam current density in the ring makes the use of an ionization profile monitor (IPM) very attractive. An IPM measures the spatial distribution of ions or electrons freed by ionizing collisions of the beam with residual gas in the vacuum chamber. Similar devices in the past have collected ions but have suffered from space charge defocusing by high intensity beams. This problem can be reduced by collecting the electrons and embedding the device in a stabilizing magnetic field. The electrons will be swept from the beam pipe by a transverse electric field, amplified by an 8x10cm microchannel plate (MCP), and collected by a circuit board with strip anodes oriented parallel to the beam axis. A magnetic field, parallel to the sweep electric field, counters the defocusing effects of space charge and recoil momentum. For the 2 MW beam the maximum space-charge field will be about 10^5 V/m. In a magnetic field of 0.1 T, an electron subject to this field will travel parallel to the collector channels at 10^6 m/s with a gyration radius of 70 μm. Profile broadening by the space-charge field will be insignificant. An electric field of 150kV/m will remove electrons in under 10ns producing a maximum longitudinal drift of less than 1.0cm. The energy spectrum of recoil electrons extends to 3.0 MeV but over 95% will have energies <500 eV. The 0.1T field will confine a 500 eV electron to a Larmor radius of <0.8 mm which is 2% of the beam radius. For a field ≥0.1T most of the electrons will be collected on the anodes over which they are formed. Three permanent magnet dipoles will be used to provide electron confinement without perturbing the beam orbit.

The 120 π mm-mrad full-beam (5σ) emittance (2 MW) gives a beam diameter at β=10m of 35mm. The transverse profile is approximately rectangular due to the smoke-ring distribution in phase space. Collimators in the Ring restrict the 5σ emittance to 180 π mm-mrad and a maximum diameter of 84mm. The collector board will have 64 anodes 1.4mm wide and 74mm long, covering a width of 90mm. The full beam will produce signals in 50 channels. At $5x10^{-9}$ Torr, $2x10^{14}$ protons will produce $3.7x10^4$ electrons (about 740 per channel). An MCP operated at a gain of 10^4 will deliver a current of 2 μA to each channel, but to improve statistics in the tails the signals must be integrated over a number of turns. For beam studies early in the cycle the pressure will be raised locally and integration over more revolutions will be required.

8 REFERENCES

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